An experimental overview of the Scalar Boson

Lydia Iconomidou-Fayard

invisibles 15 School 14th-20th June, 2015
Place: Madrid sierra

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Comprendre le monde, construire l'avenir®

The topics of this Lecture

Goal: Describe the main tools that have been necessary for the Scalar Boson Discovery

The LHC machine

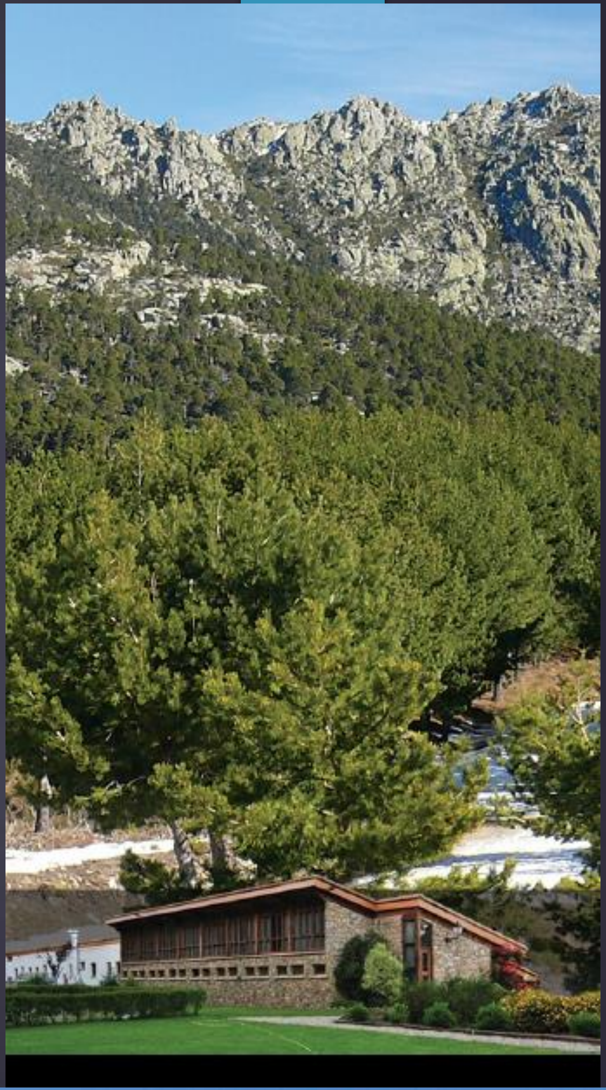
The ATLAS and CMS experiments

The particle signatures in the detectors

The main Higgs decay channels

The Scalar Boson passeport:
Its mass, its couplings, its properties

Results from both experiments
(more on ATLAS….)



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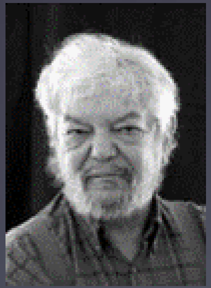
And Kibble, Hagen, Guralnik

Introduction of a scalar field with non-zero vacuum expectation value after a temperature T > T_C



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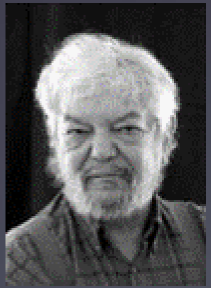
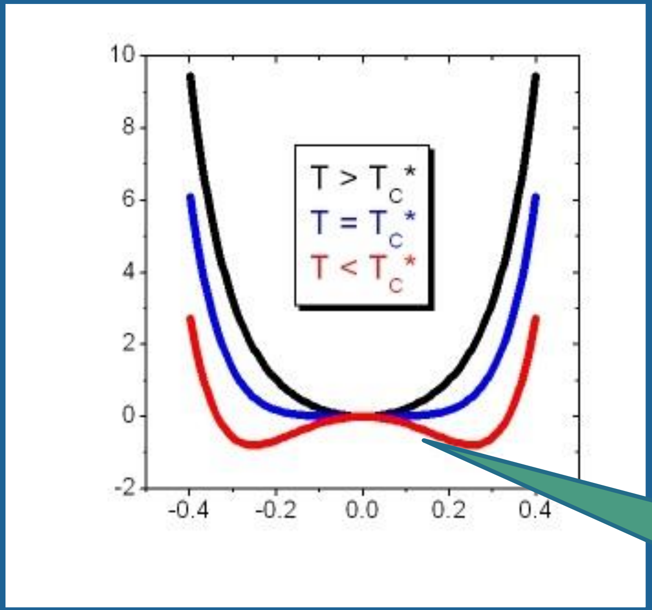



Introduction of a scalar field with non-zero vacuum expectation value after a temperature $T > T_C$

$$V(\phi^*\phi) = -\mu^2(\phi^*\phi) + \lambda^2(\phi^*\phi)^2$$



Vacuum: $dV(\varphi^*\varphi)=0$
For $v = \sqrt{-(\mu^2/\lambda)}$ = 246.2 GeV

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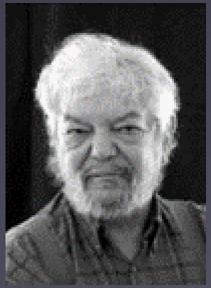


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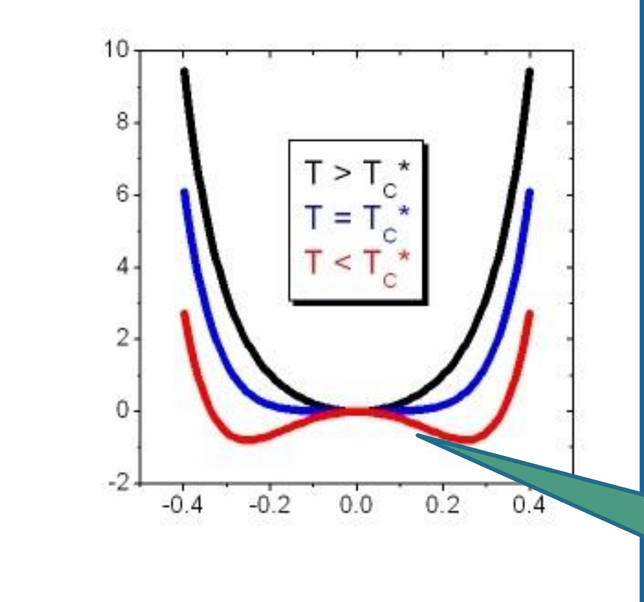

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Implications for the Electroweak Interactions

→The fundamental particles, appearing in the lagrangian initially with zero mass, become massive through their interaction with the scalar field.

→Gluons and photons remain massless

→The EW intermediate bosons W and Z become heavy

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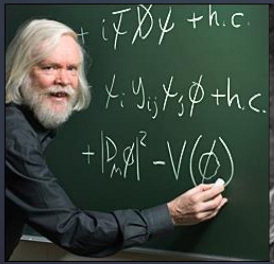

Dimitri Nanopoulos

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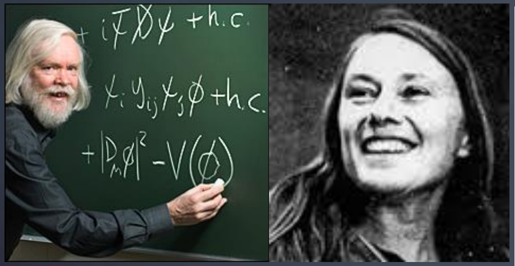

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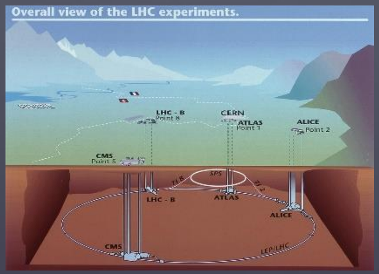
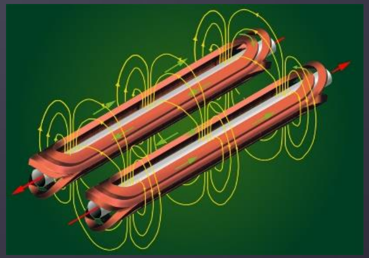
1983 : Discovery of W+- and Z bosons at CERN- UA1 & UA2 detectors, with the predicted masses

Indirect proof for the mechanism

The main tool :
The Large Hadron Collider at CERN





The CERN laboratory

Founded in 1954. Constructed around the French-Swiss frontier

Today
→ 21 member-states
→ 6 observers
→ 42 collaborators
→ 17 contacts

10000 scientists from 113 Universities

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A series of major discoveries

1) Discovery of Neutral currents 1973
2) Discovery of W & Z bosons 1983
3) Search and measurement of the Direct CP violation in the Kaon system (1988-2001)
4) Number of lepton families (LEP, 1991)
5) Prediction of the top mass (LEP)
6) Evidence and Study of the quark-gluon plasma
7) Creation of anti-Hydrogen in the lab (2002)
8) The Scalar Boson (2012)

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The LHC genesis

~1980

1984

1992

1994

1995

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March: India and Russia announce financial support to LHC
December: Canada contributes to LHC . Cooperation protocol with US

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Thanks to the contributions of non-member states , the Council approves the LHC construction in a single step

Remember: The short life of SSC (1983-1993) The American project

Tunnel with circumference of 87Km, project started in 1983. Foreseen energy 20TeV per beam.

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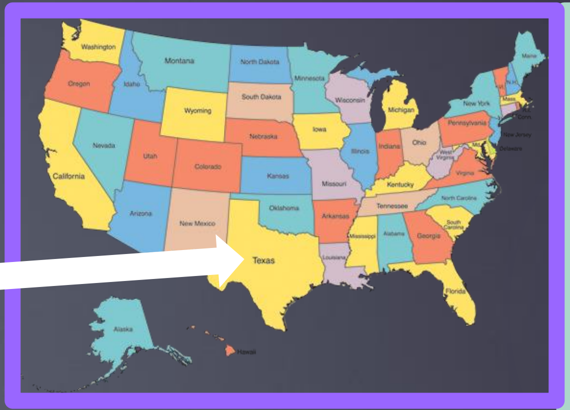

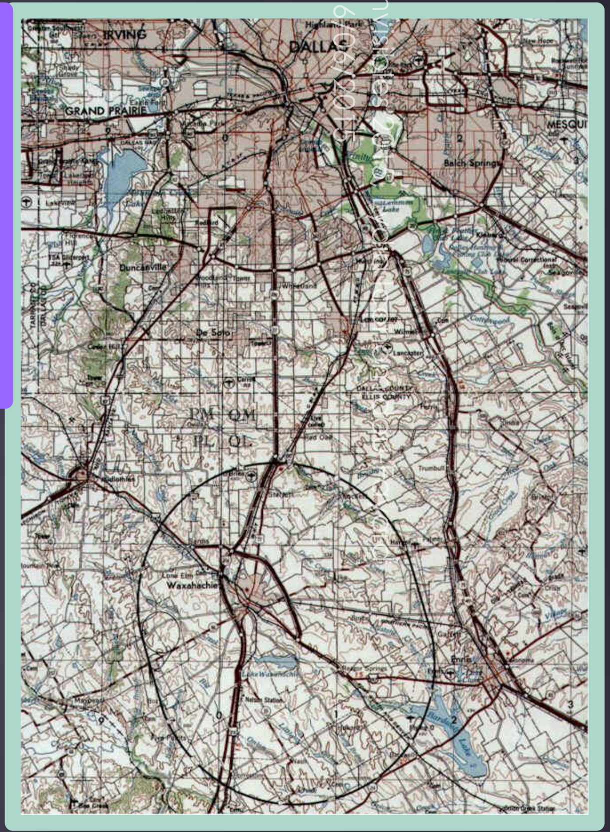

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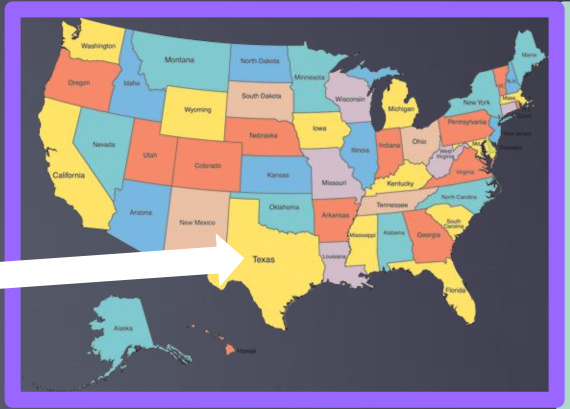

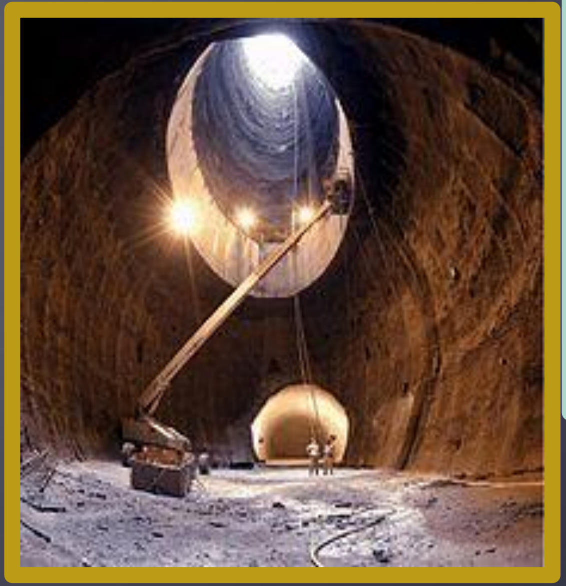

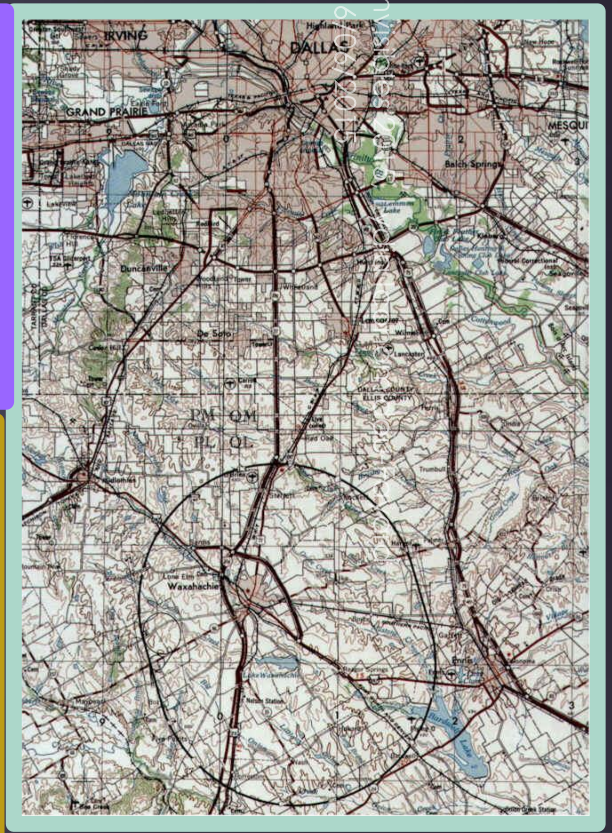

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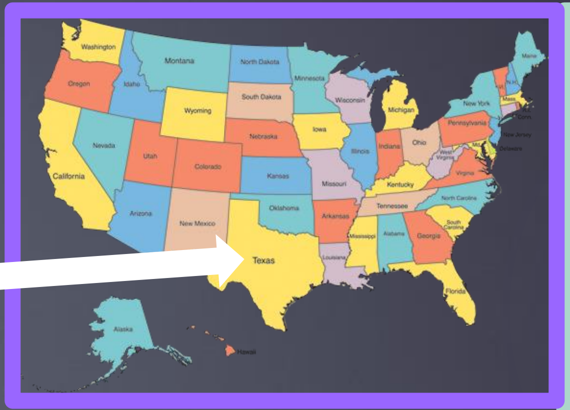
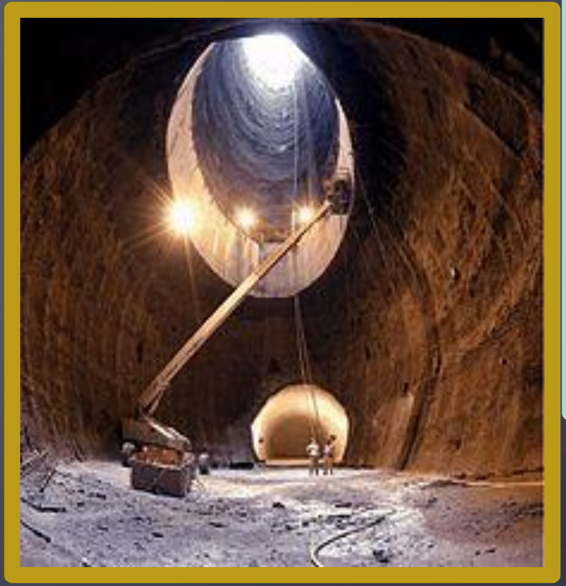
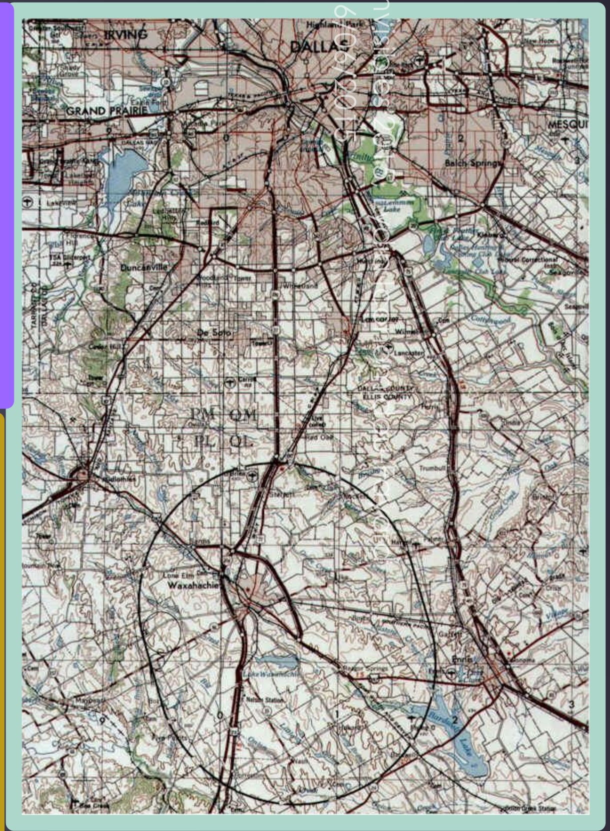
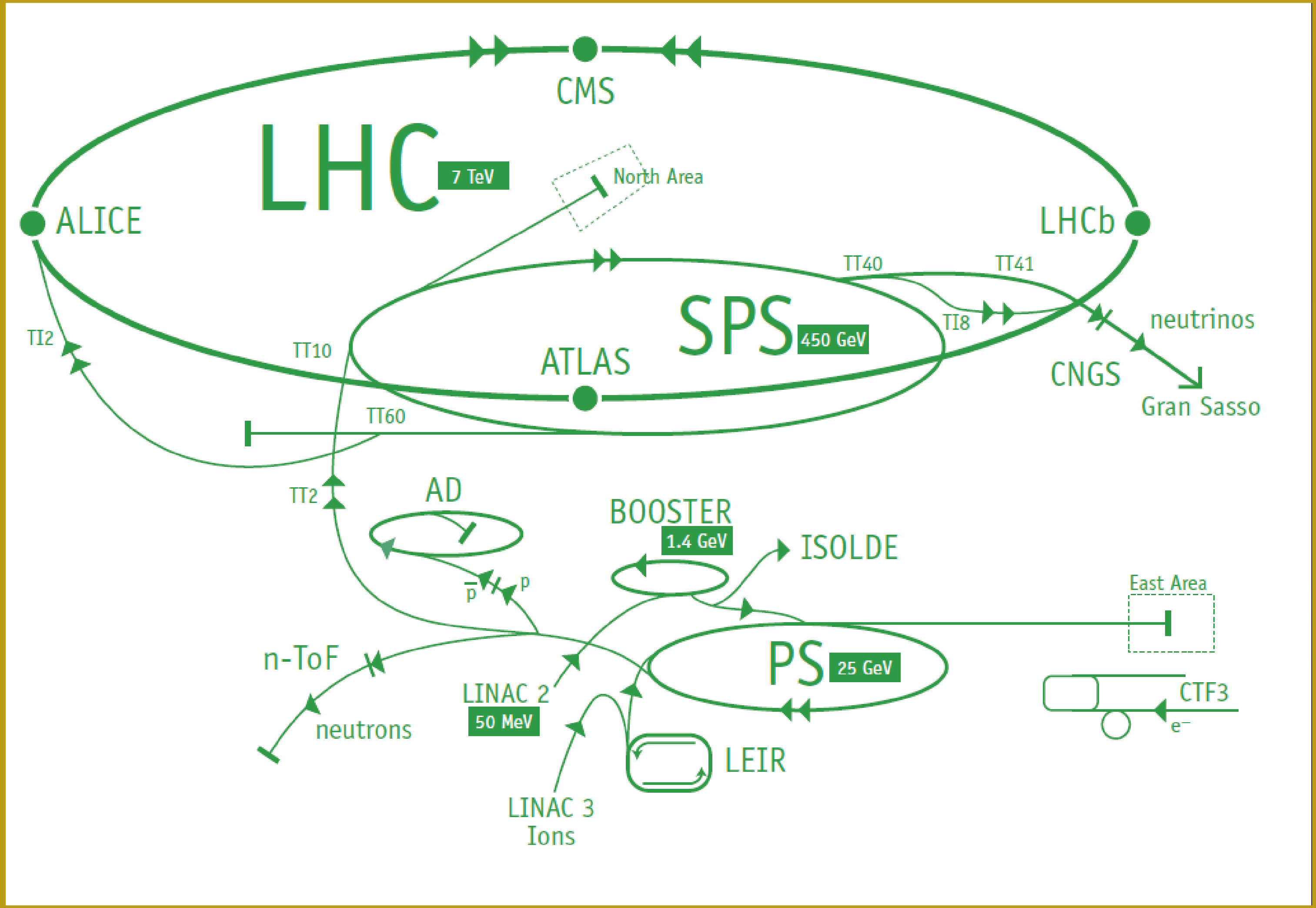
- In 1993 the project is abandoned by the US Senat
- Involved American physicists start to think about joining European project. Positive decision on 1995







The Lord of the Rings



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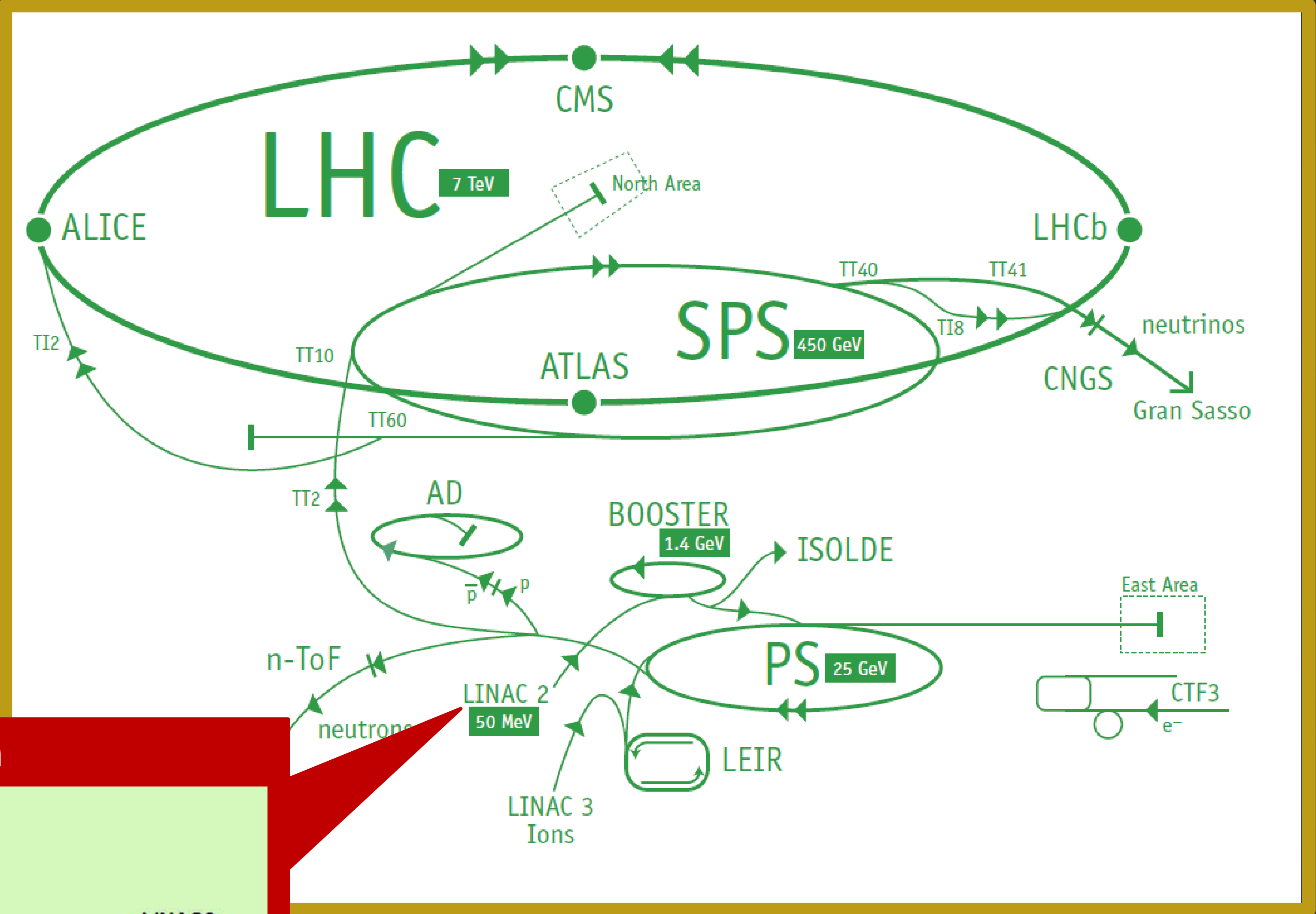
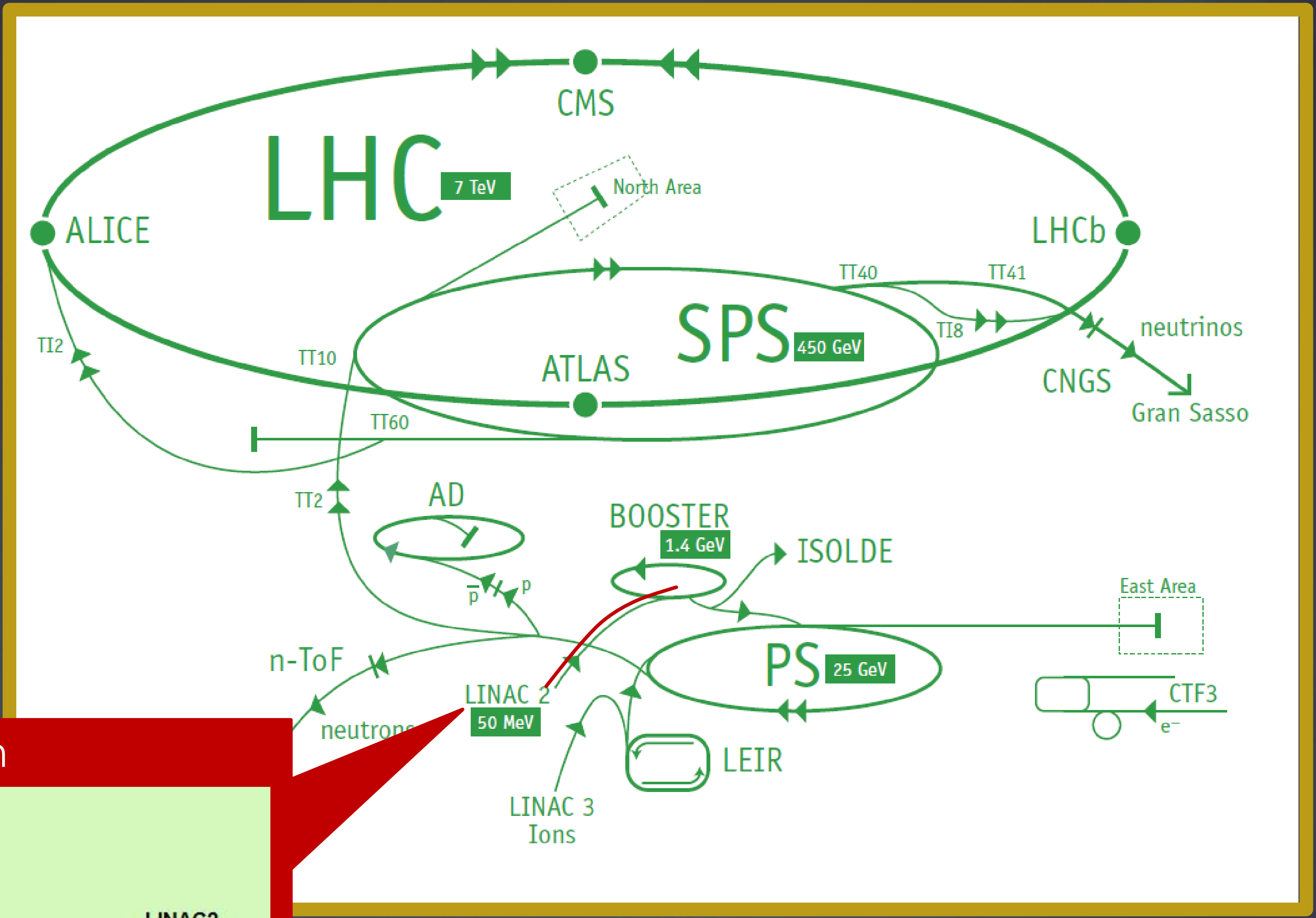


Proton production

The Lord of the Rings



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50 MeV	31.4	Linac 2

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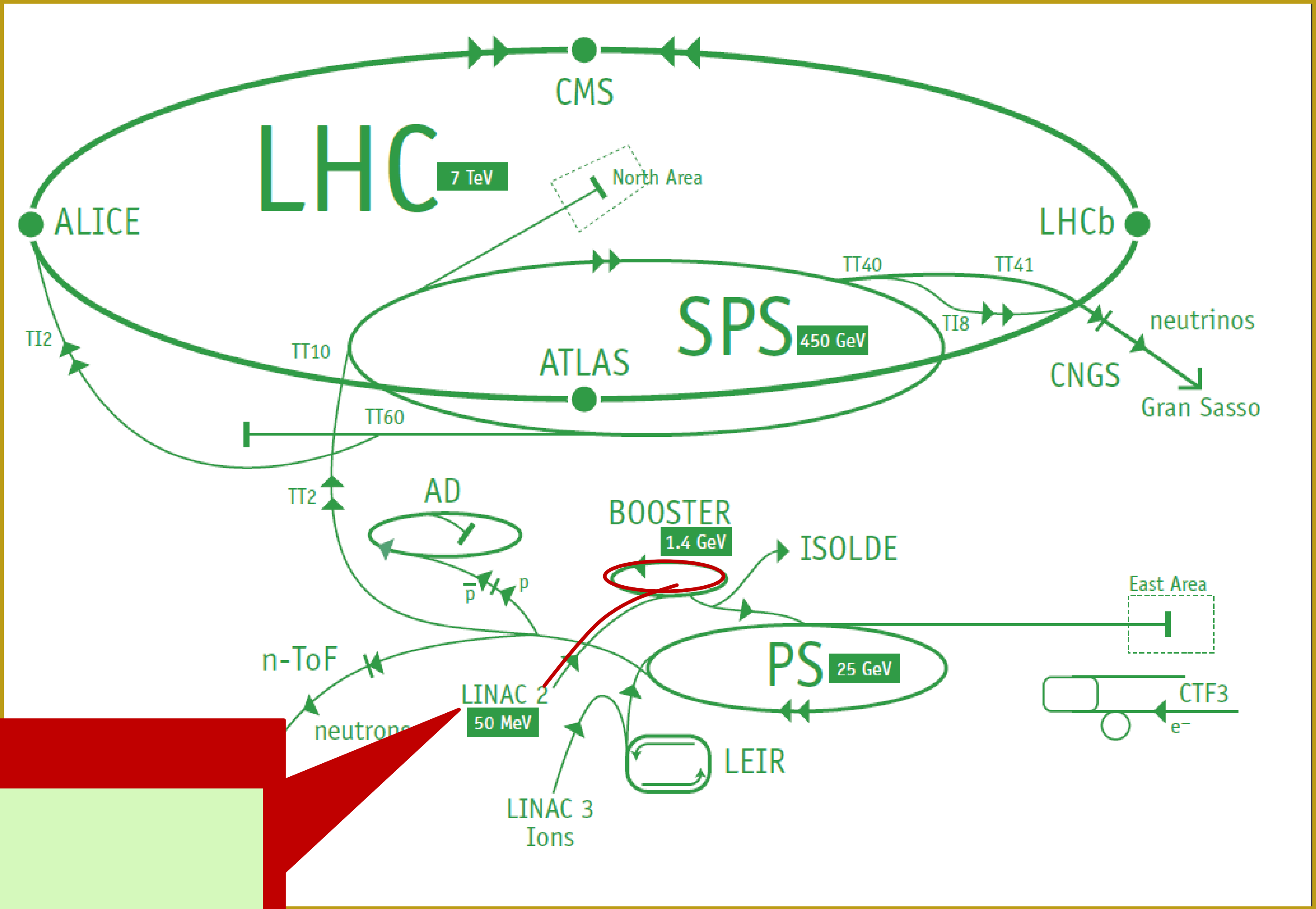

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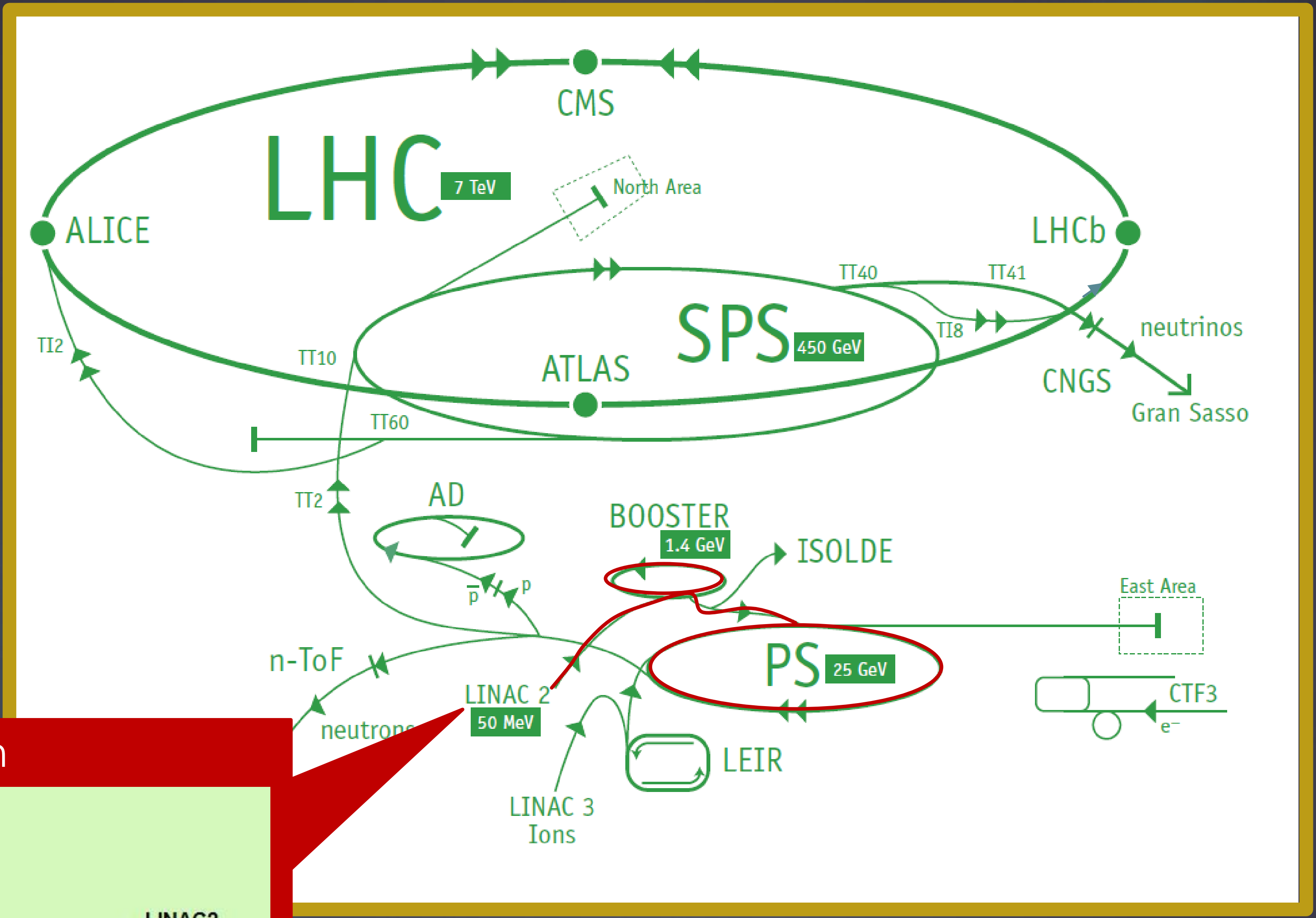

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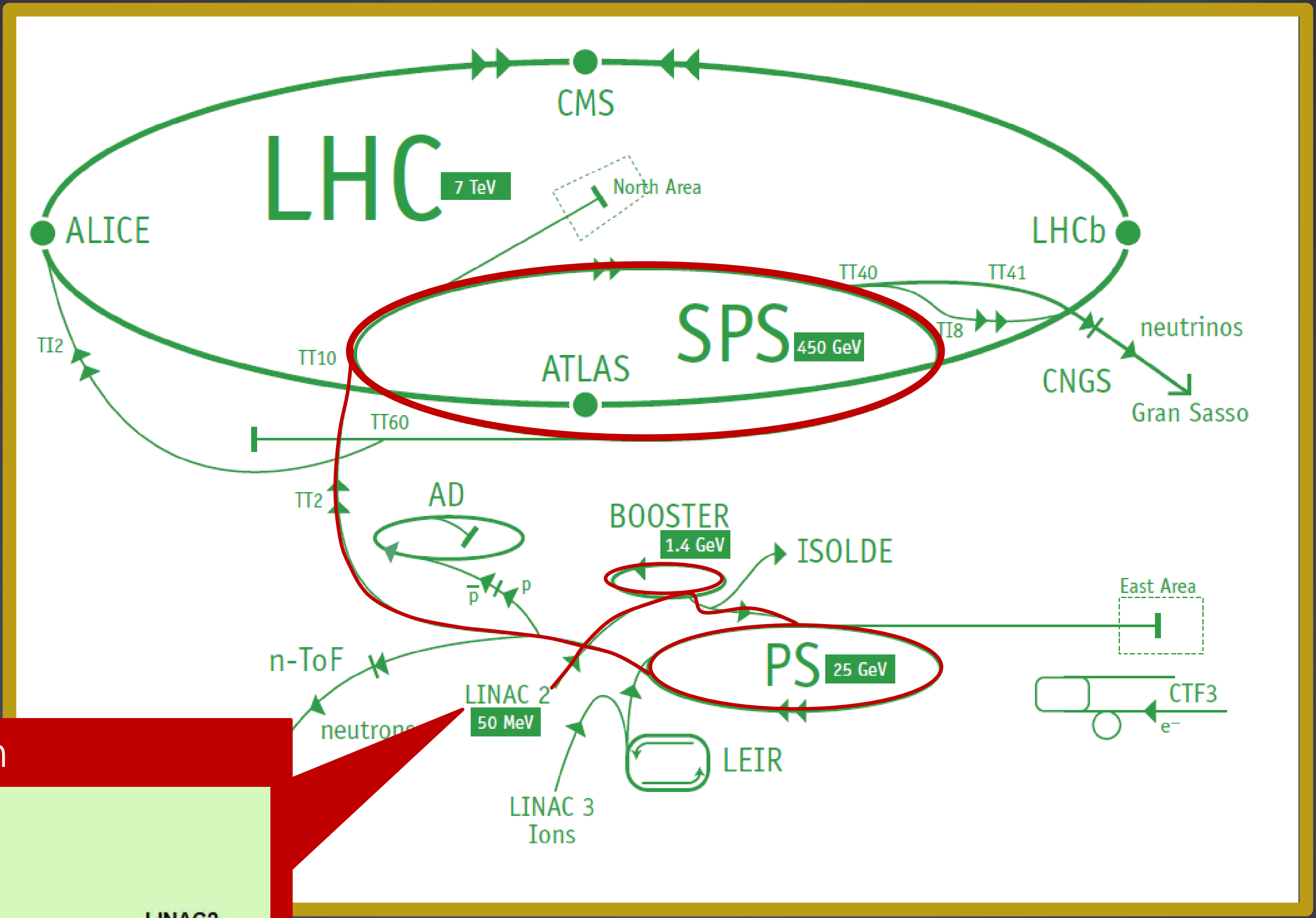

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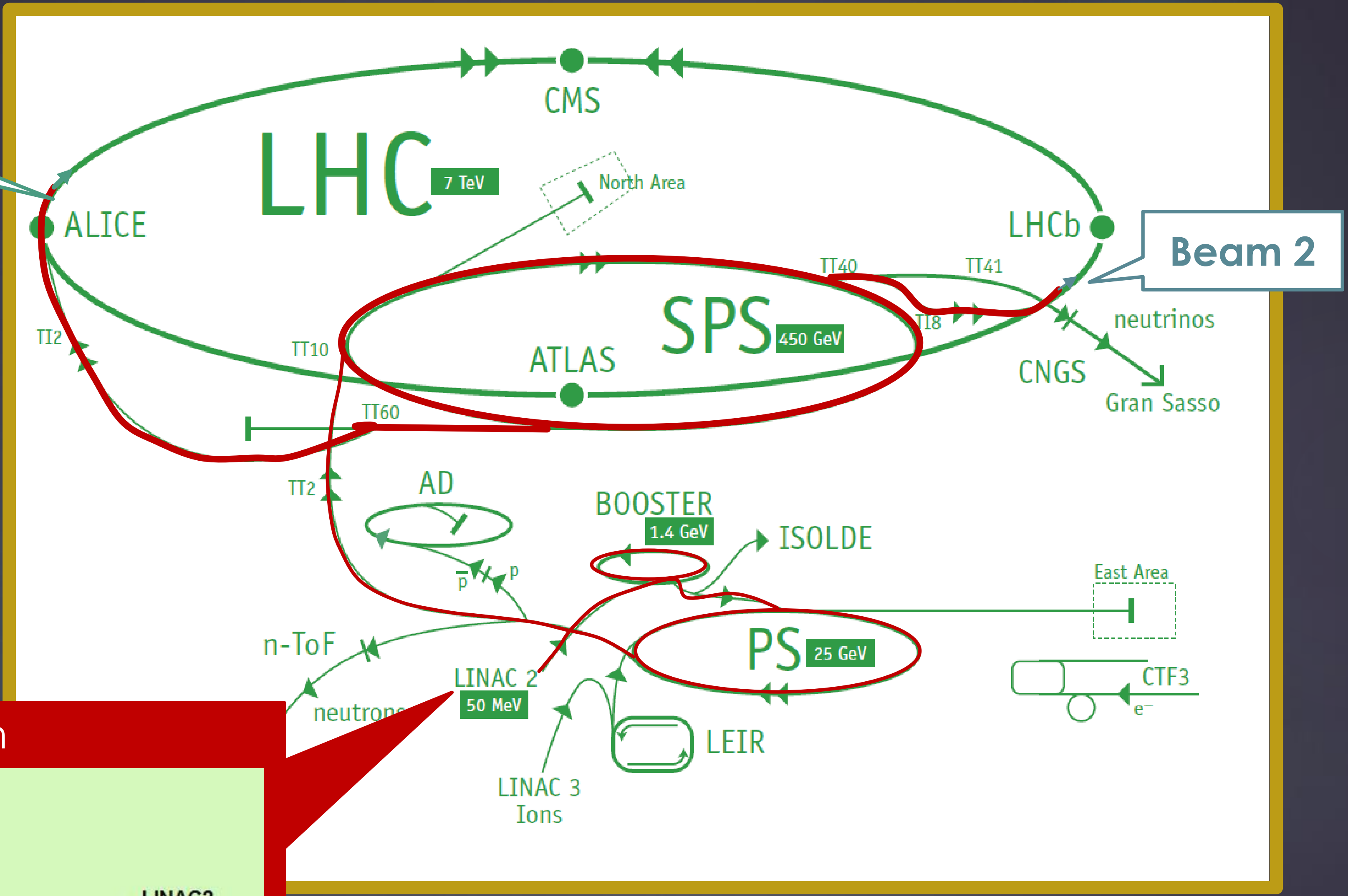

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7 TeV	99.9999991	LHC

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Among them :
→1232 dipole superconducting magnets
→392 main quadrupoles ; to keep tight beam dimensions
→Higher order multipoles (6-8-10) to correct imperfections
→Insertion magnets

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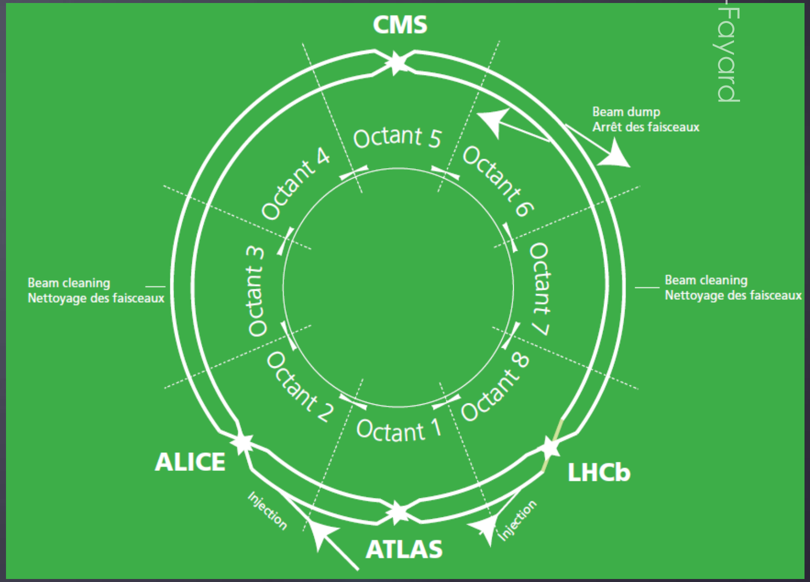

Working unit of LHC: the octant
8 sectors that are independently furnished and powered.

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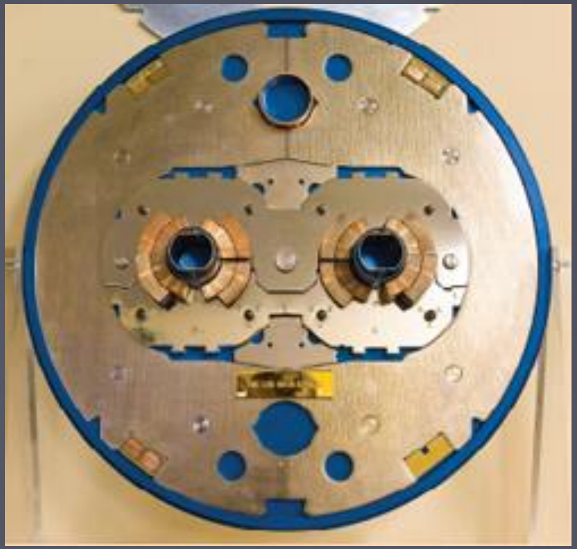
Dipole coils operate at 1.9K to flow the 11kA of current necessary to produce the 8 Tesla (for 7 TeV beam) without thermal loss in the superconducting Niobium-Titanium cables



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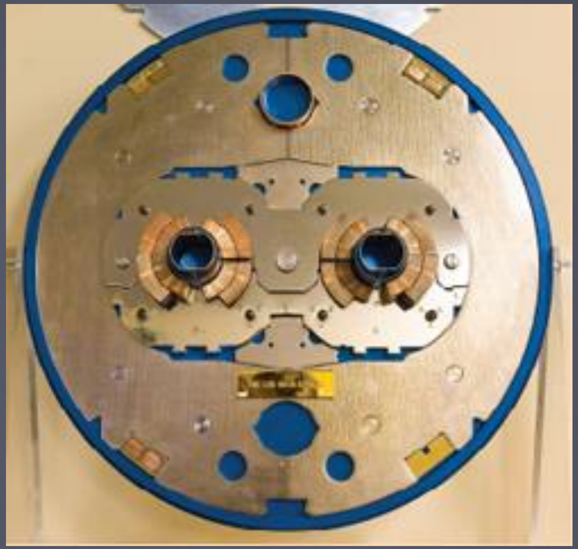
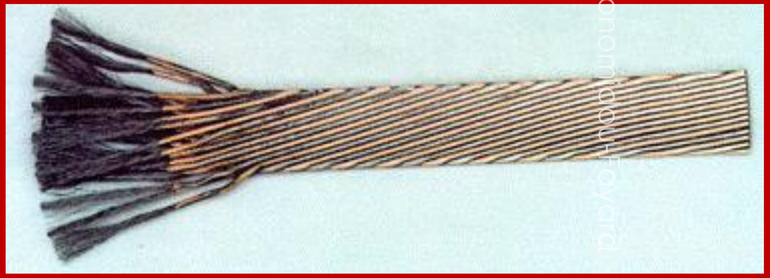
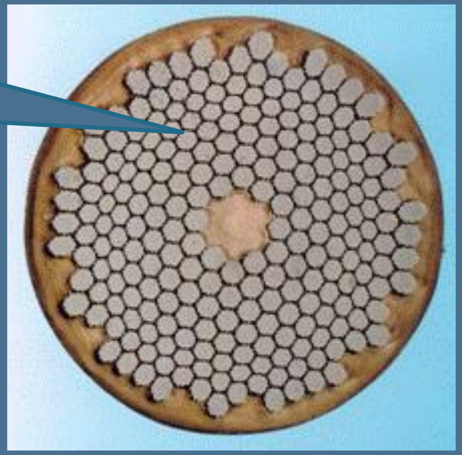


A cable = 36 twisted 15mm strands



A strand : 6000 – 9000 filaments of 7μm NbTi alloy.



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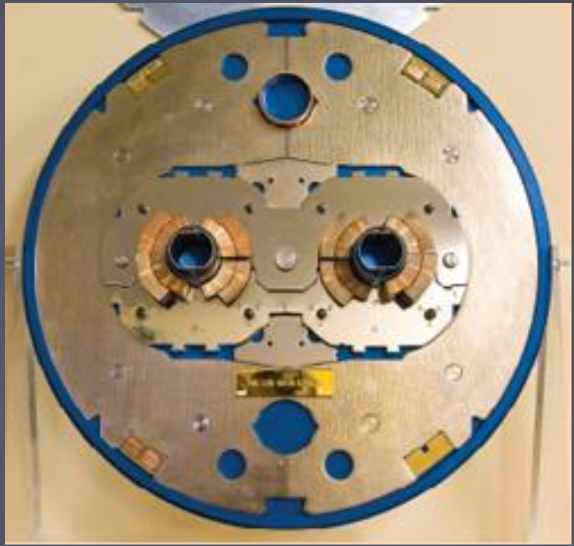

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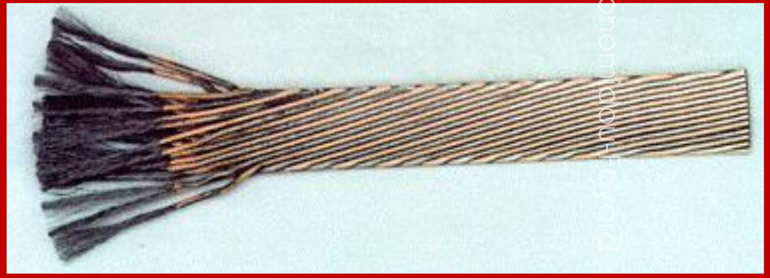

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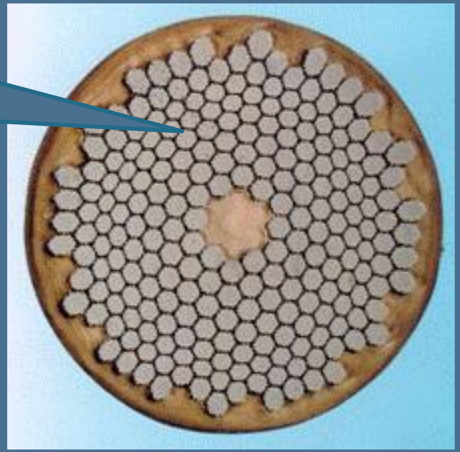

270000 Km of strands

Train and stock the magnets ready for installation

Initially : All magnets trained to reach 8 Tesla

Fully tested for leak tightness, mechanical and electrical integrity, instrumentation, field quality

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Stored in the fields around CERN, waiting for installation in the tunnel

The vacuum in the LHC

Three separate vacuum systems

Insulation vacuum for helium distribution
50Km of piping at 10^{-6} mbar

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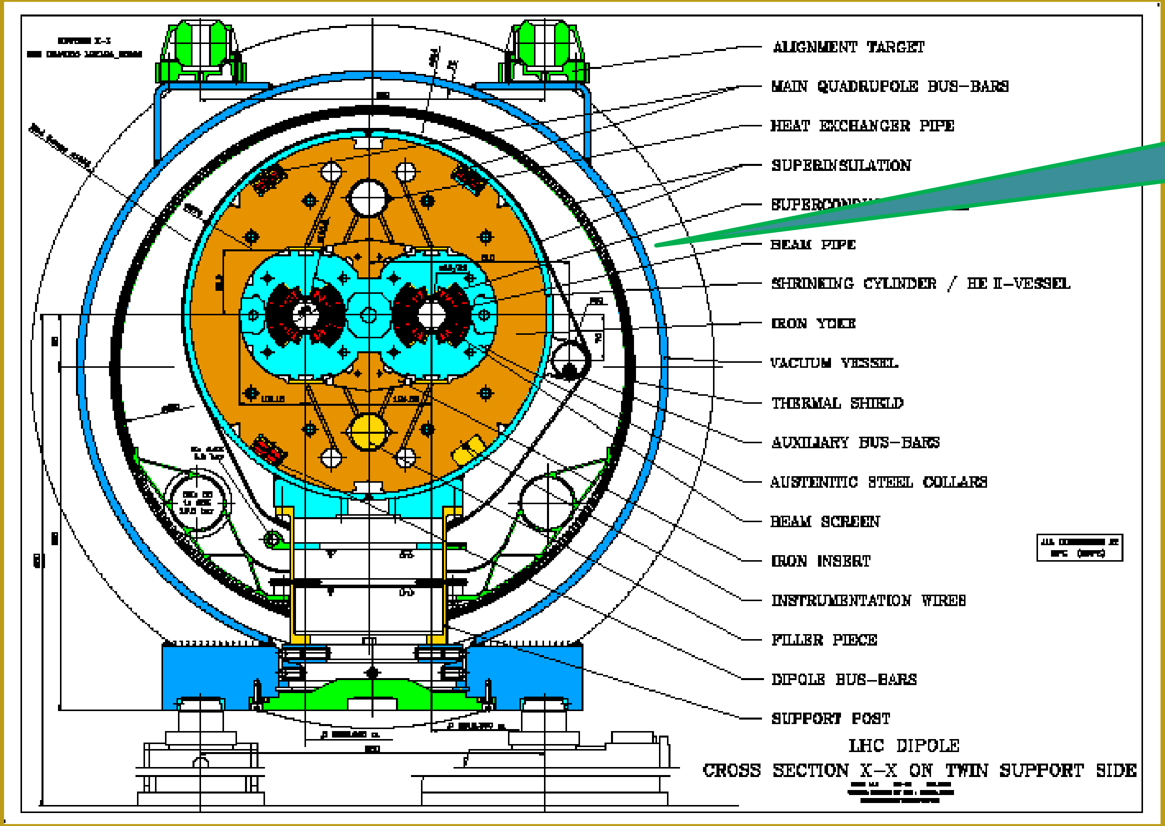
Insulation vacuum for the cryomagnets



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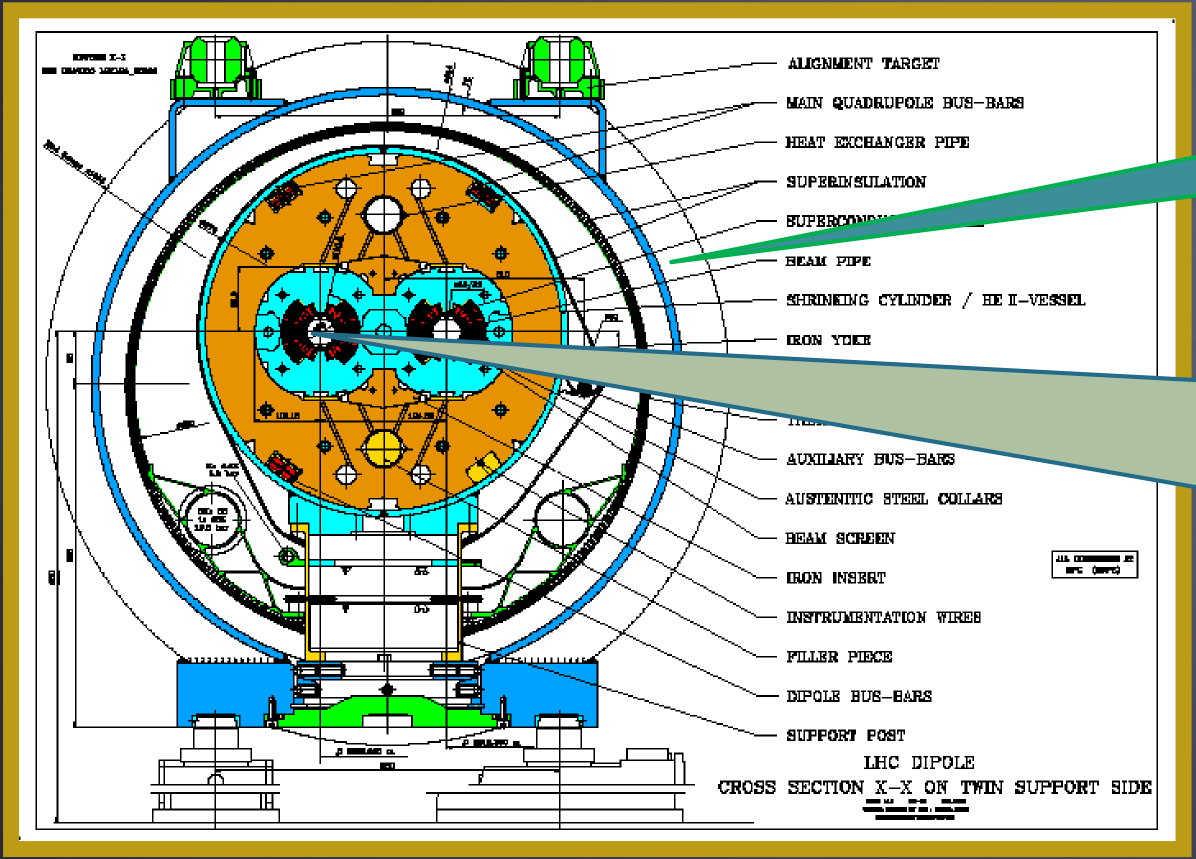
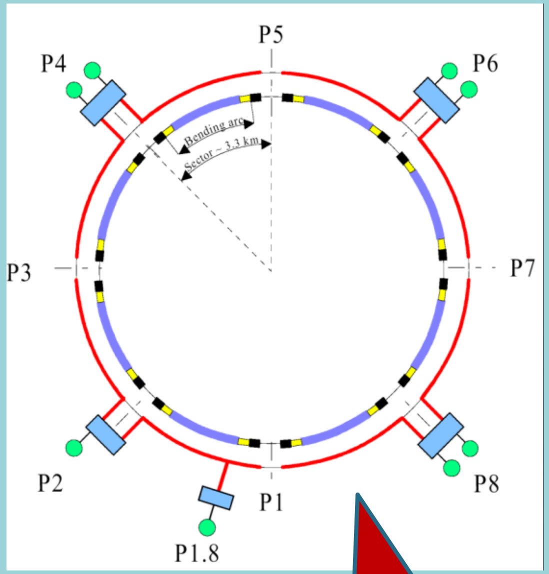


Ultra- high vacuum in the beam pipes 48 Km of the arc sections (at 1.9K) and 6 km of straight lines at room temperature)

10^{-11}mbar

Cooling down the LHC sectors



5 cryogenic islands,
8 cryogenic plants
(one per sector)

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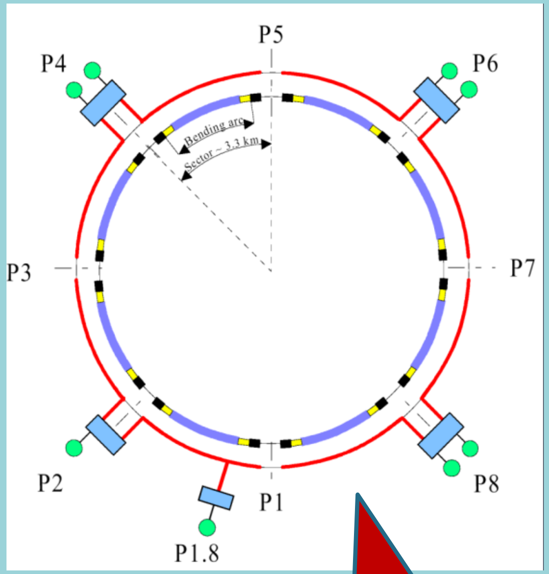

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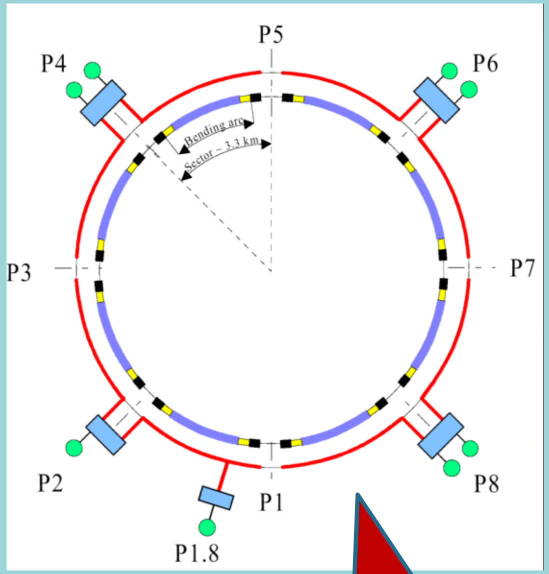

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Done in three steps

- ➔ 10 Ktons of liquid nitrogen to cool down the Helium at 80 K

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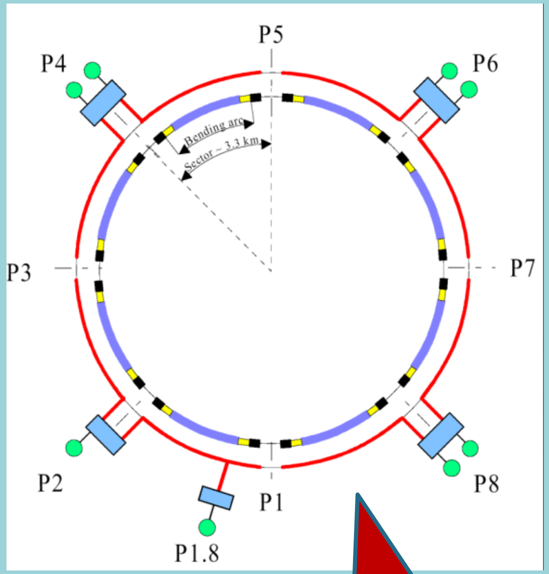

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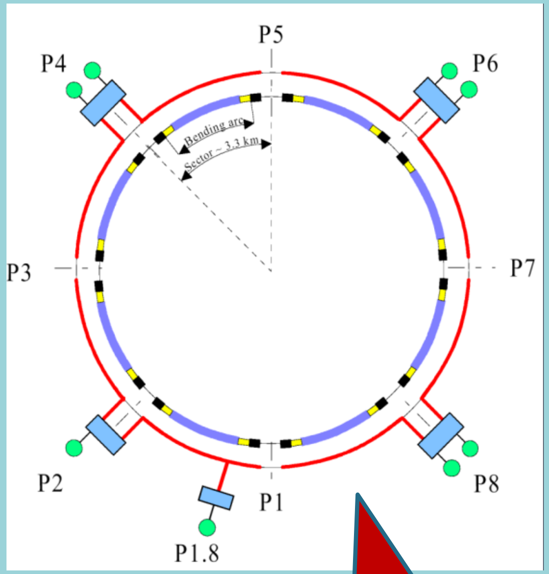

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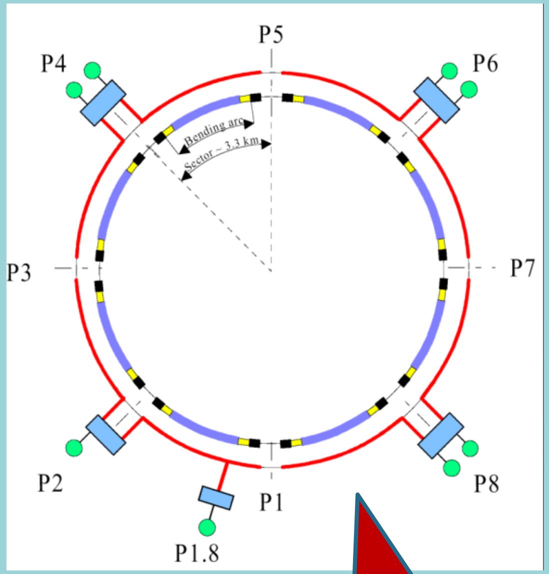

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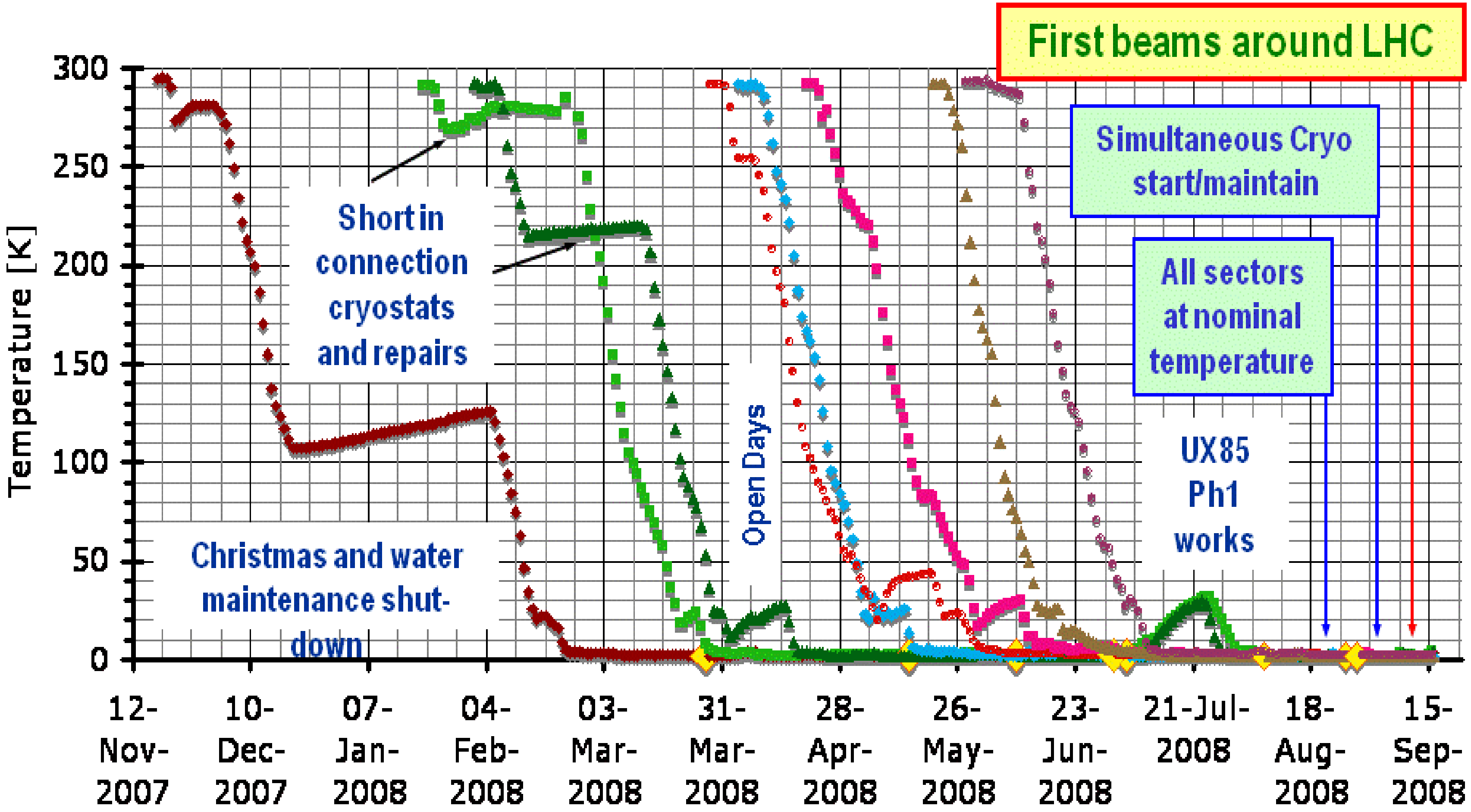
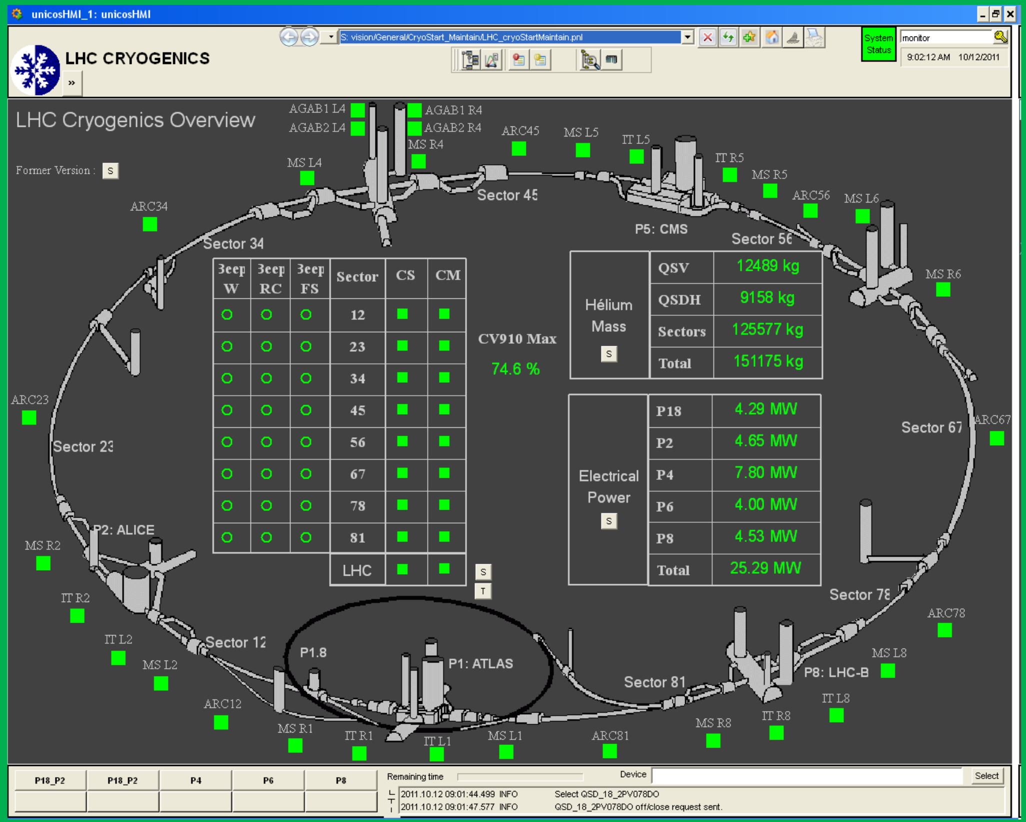
- The helium is then refrigerated down to 1.9 K where it is superfluid. In that temperature, NbTi cables have the best capacity to keep high currents for 8Tesla field.

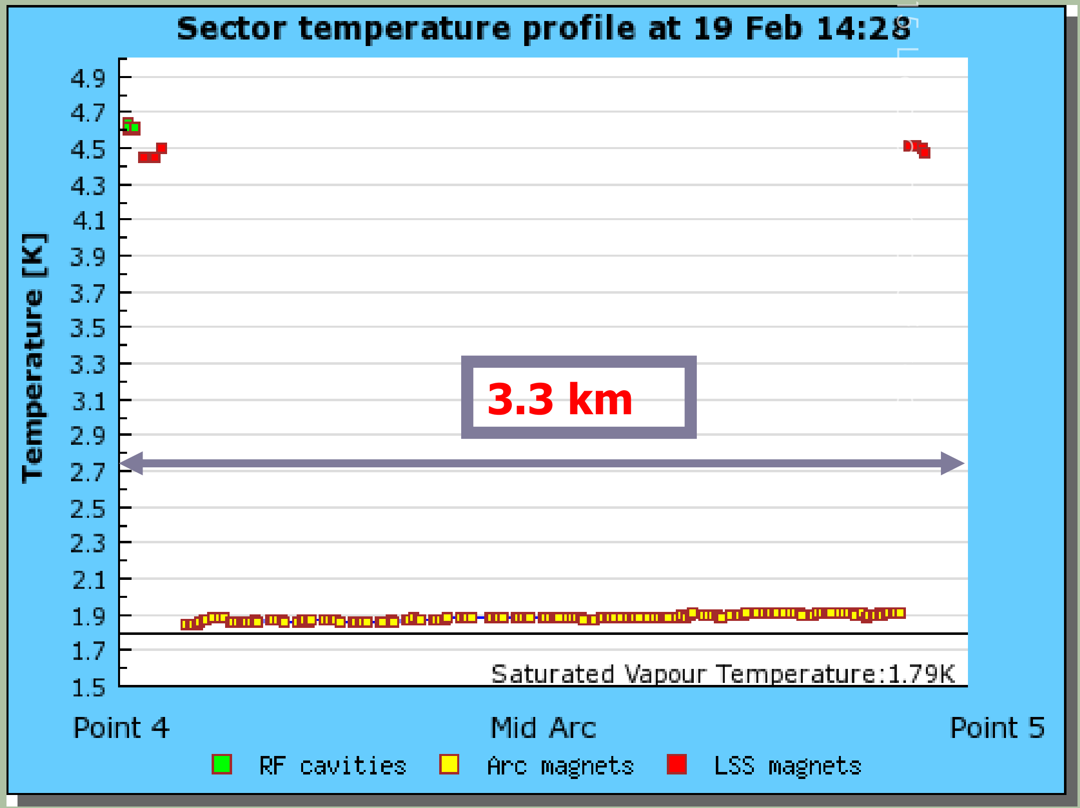
First cool-down the LHC sectors



Long learning period : finally one sector / month

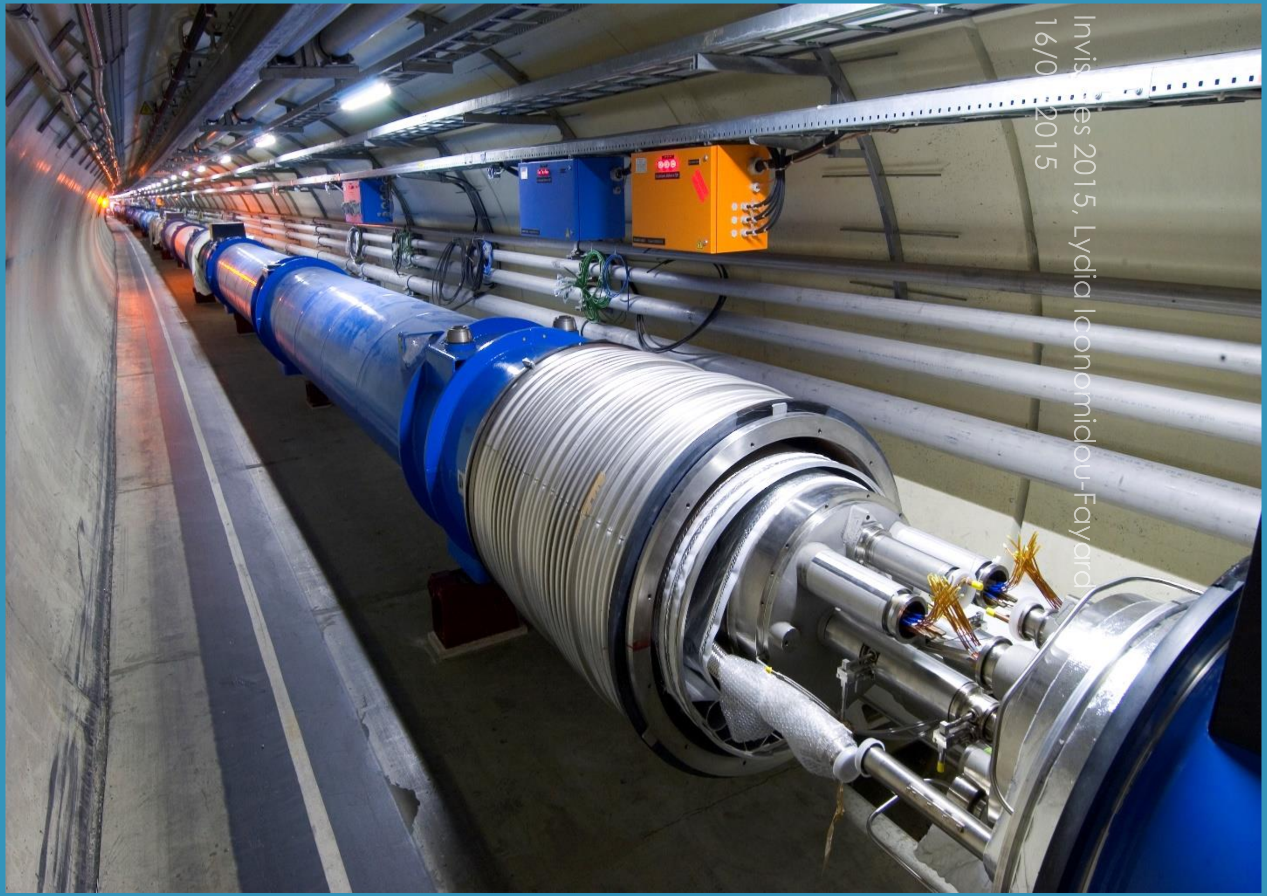
Strict monitoring of the LHC cryogenic systems





Building-up the LHC

A titanic achievement



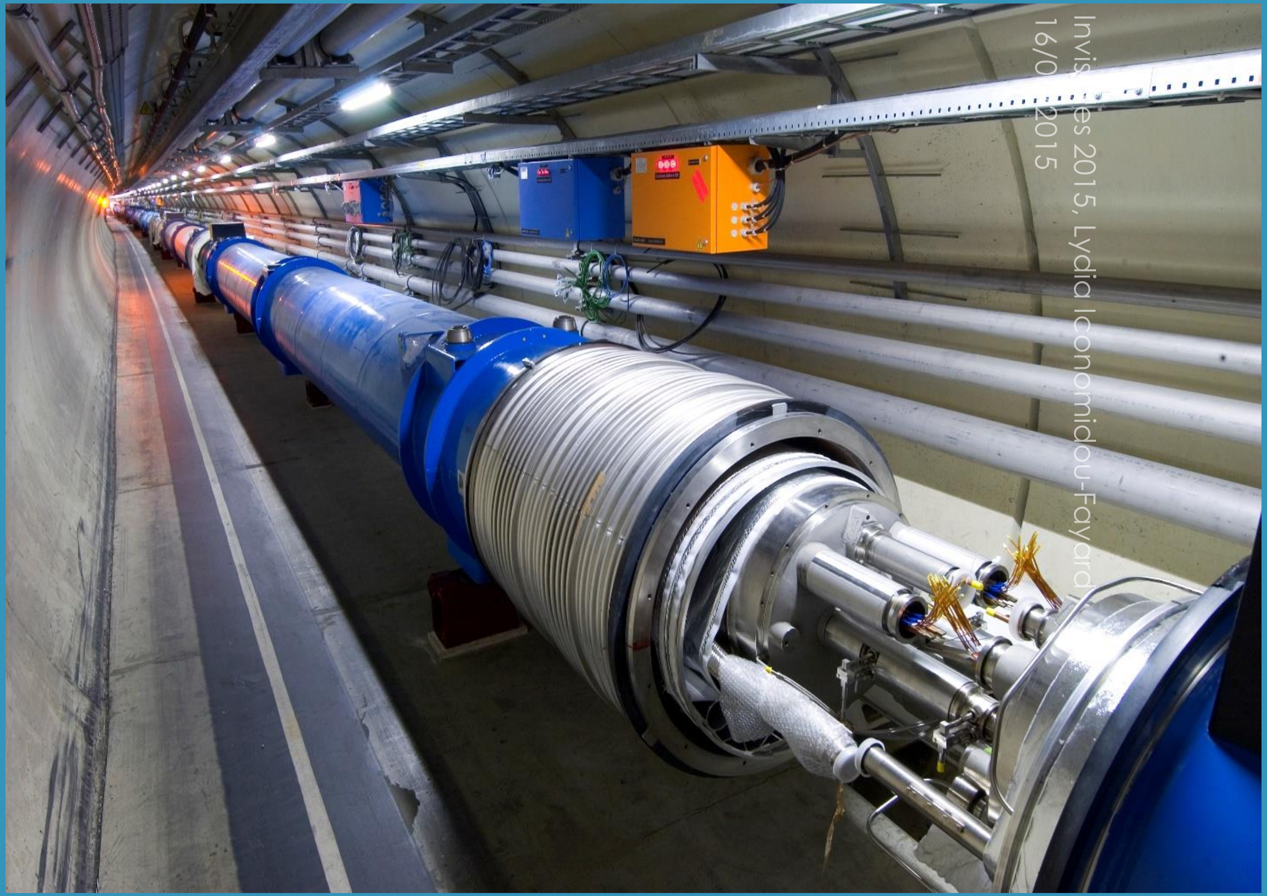
Building-up the LHC

A titanic achievement

Went through several bad surprises and numerous crises

Delays, failures, accidents, UFO, SEE…

Few examples of encountered issues in some of the next slides



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Beam vacuum chambers interconnects
The bellows crisis and repair

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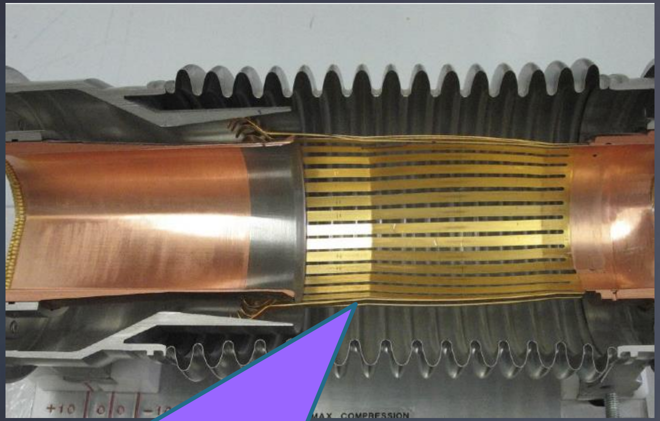

To mitigate the thermal shrink-expansion movements during cooldown-warmup operations

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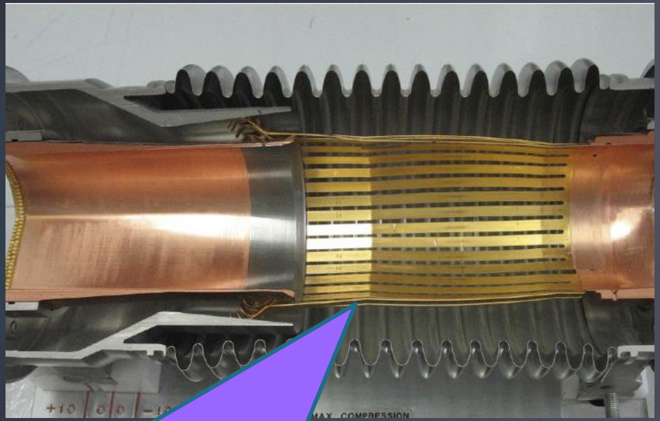

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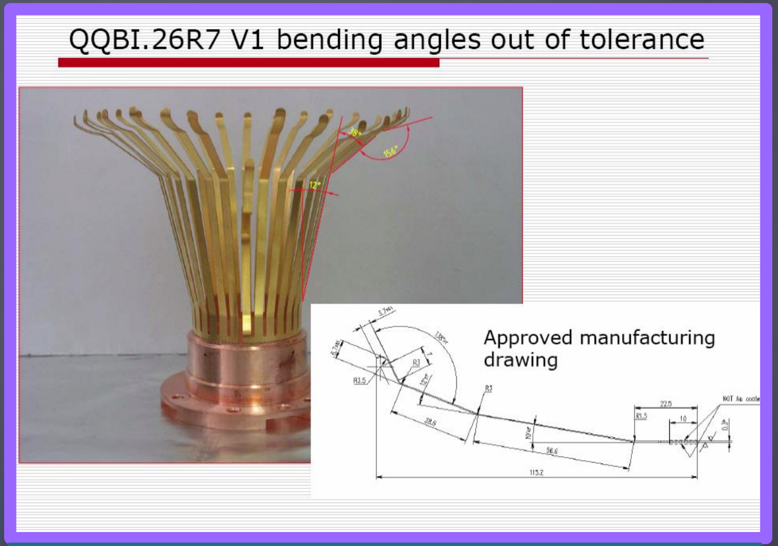

P.Strubin CERN TE departement

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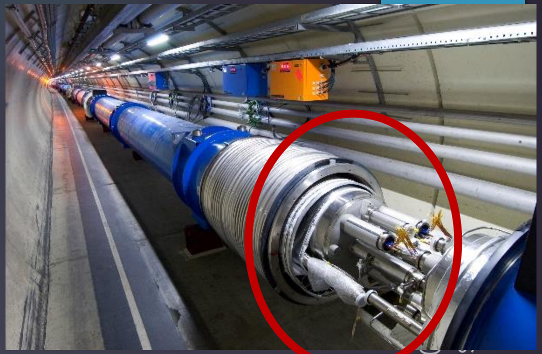

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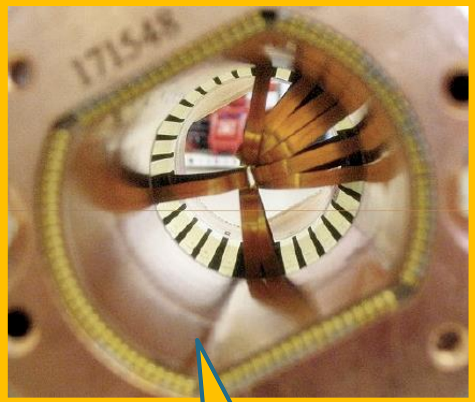
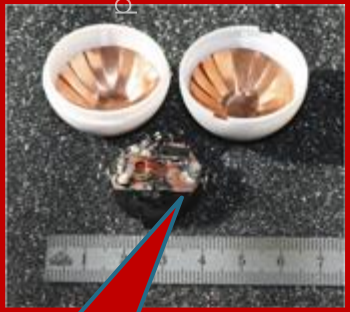
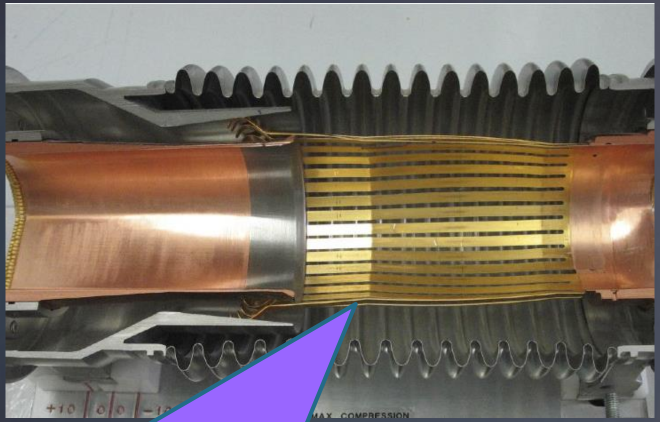


Damaged bellow



Detection ball



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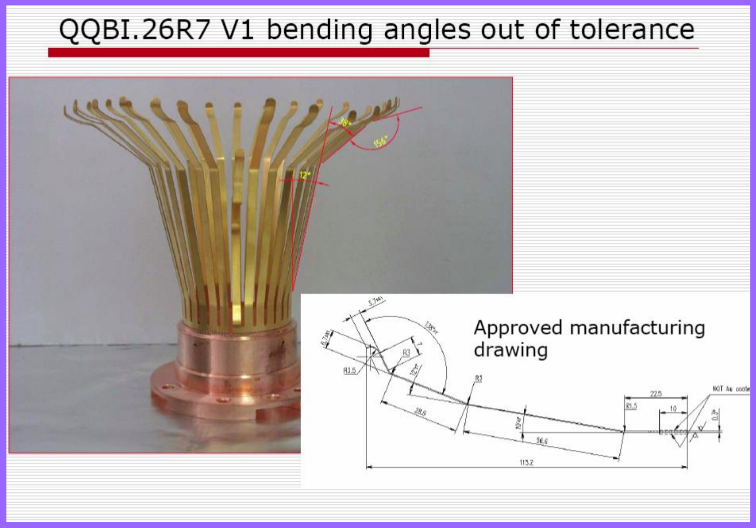

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→Violent warm-up at few interconnections in Sector 3-4.

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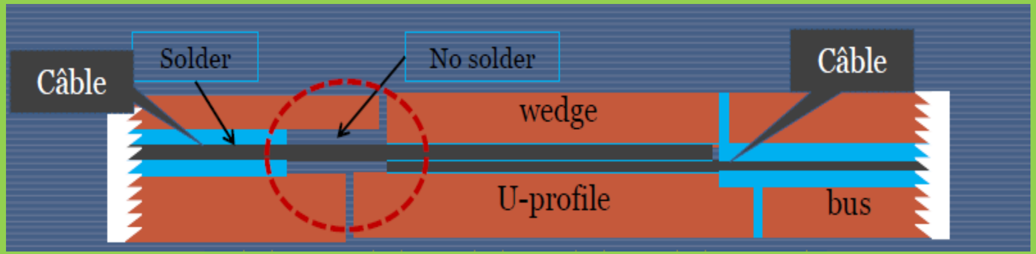

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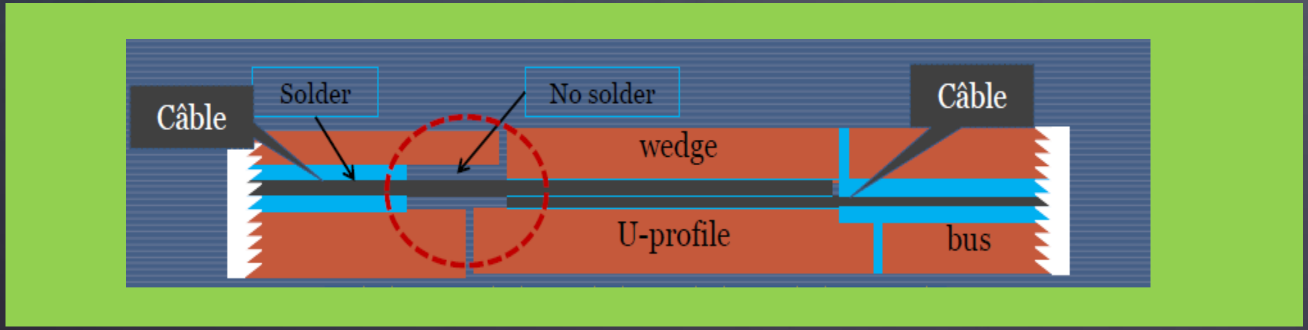

→Warm-up sectors

→39 Dipoles and 14 quadripoles repaired or exchanged

→Consolidation of the busbars along the LHC ring, Installation of additional safety procedures

→ 18 months delay in LHC operations

LHC beams: few important numbers

4mn20 to fill one beam with 1380 (in 2012) proton bunches from SPS, separated by 50 ns (7m)

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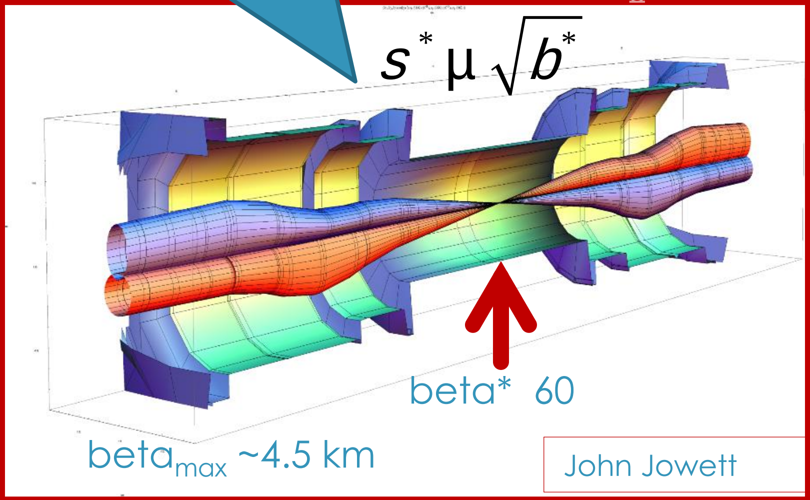
Beam size adjusted along the LHC rings. Squeezed-down close to interaction points



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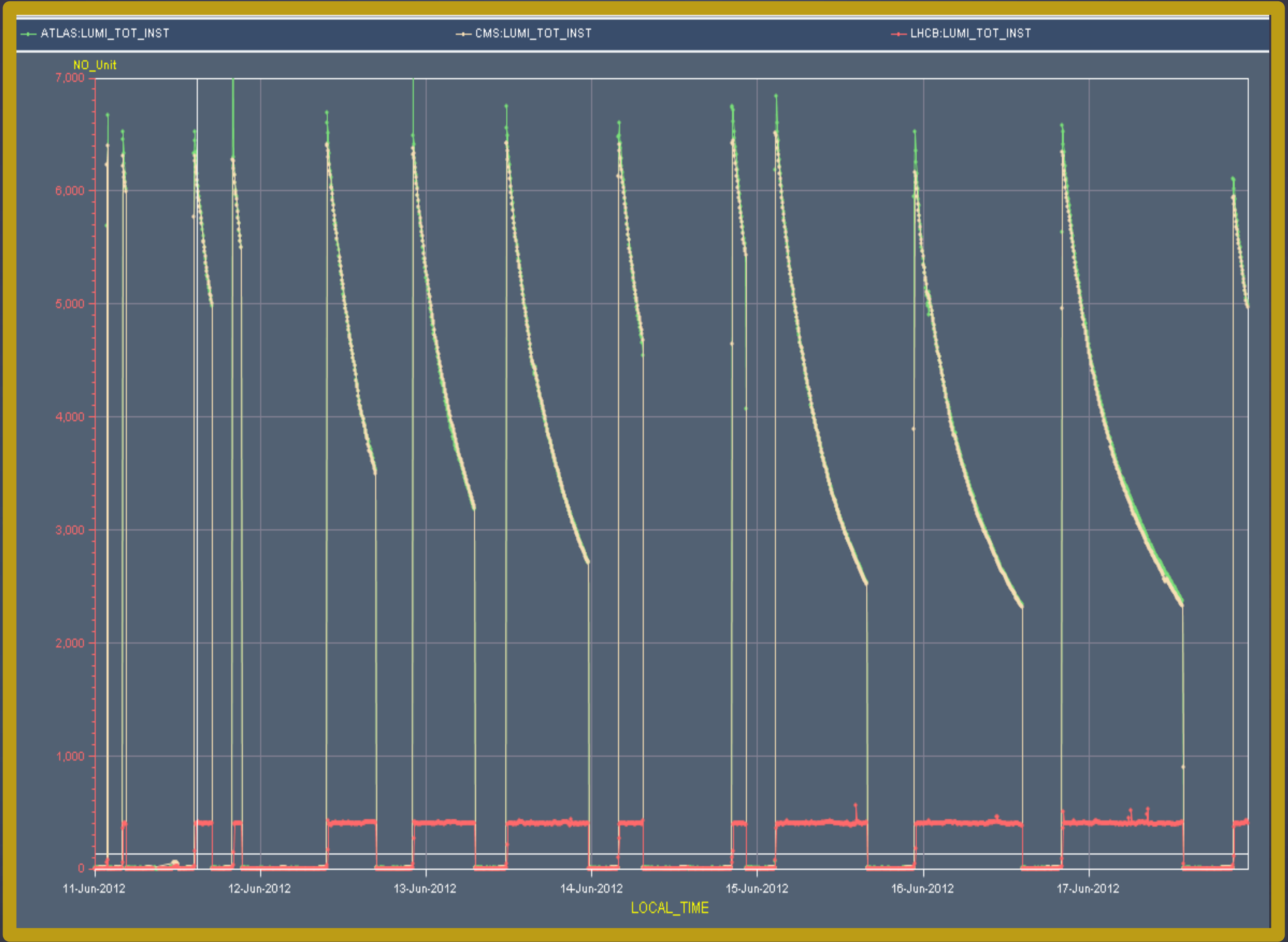

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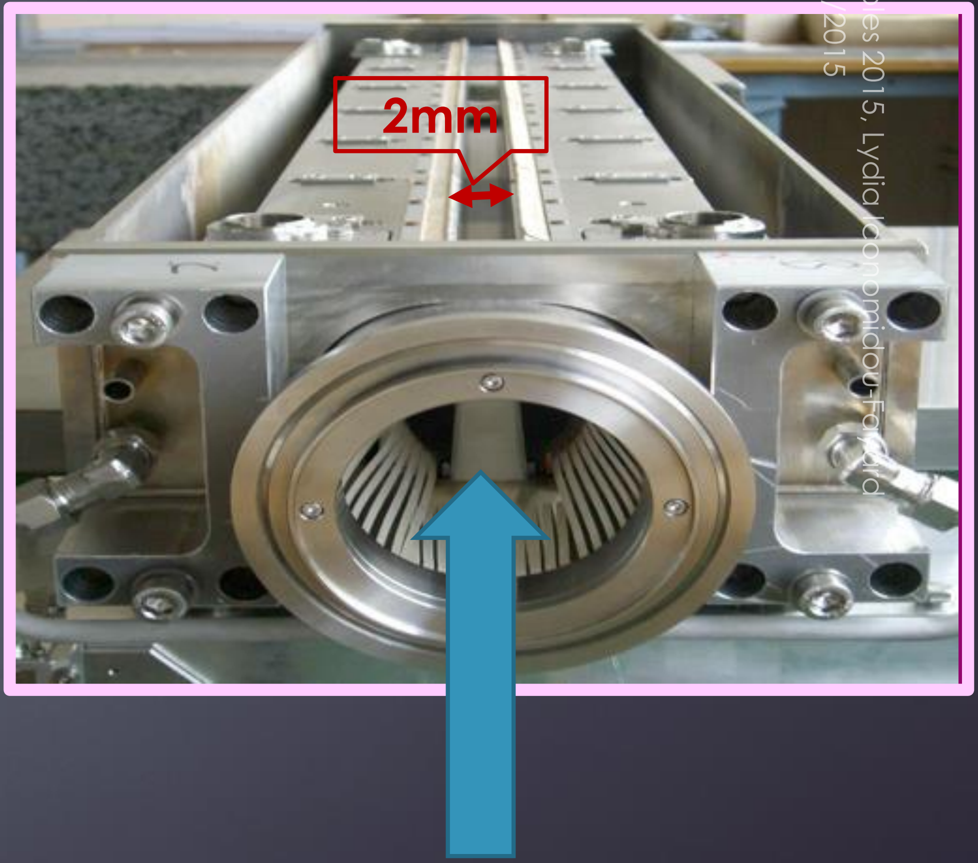

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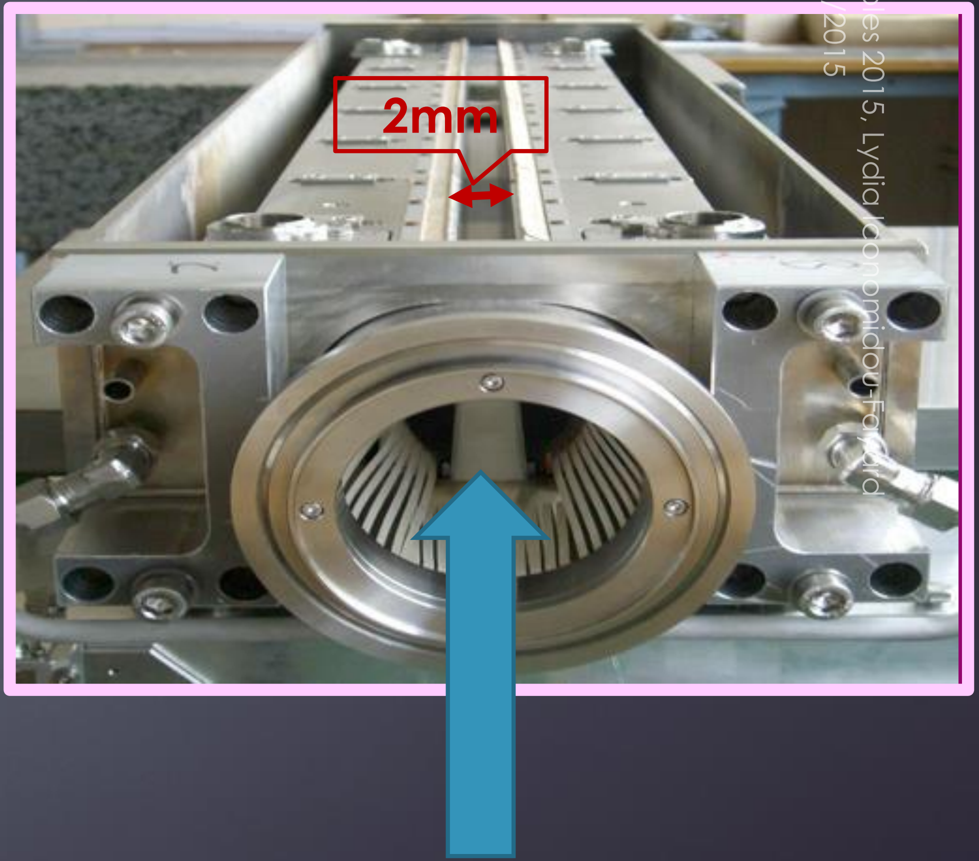
- Very satisfying functioning during Run1



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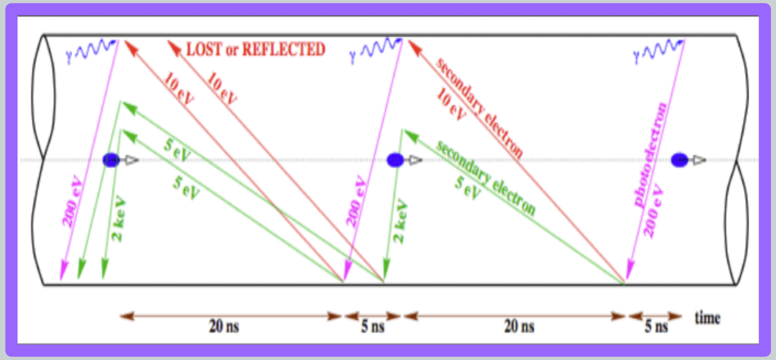

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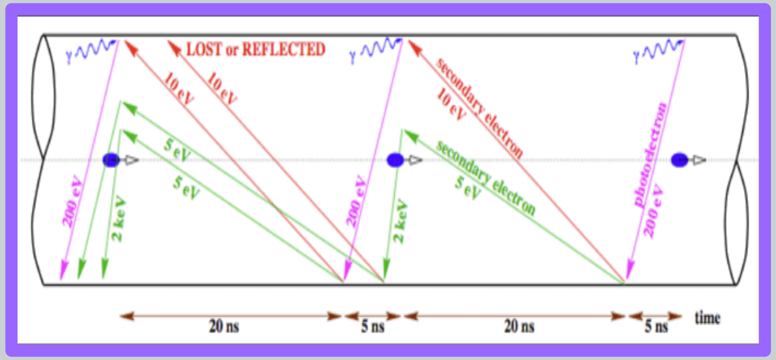

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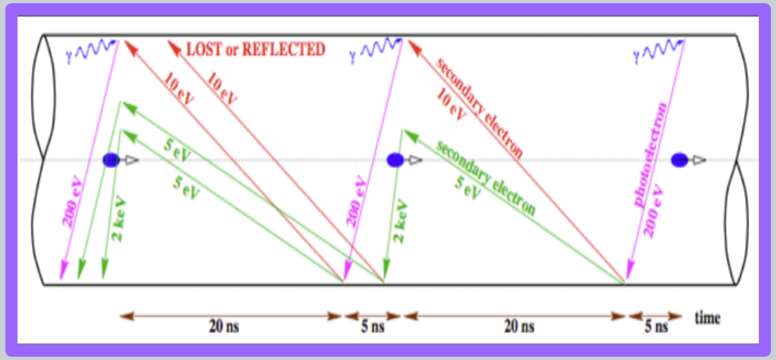

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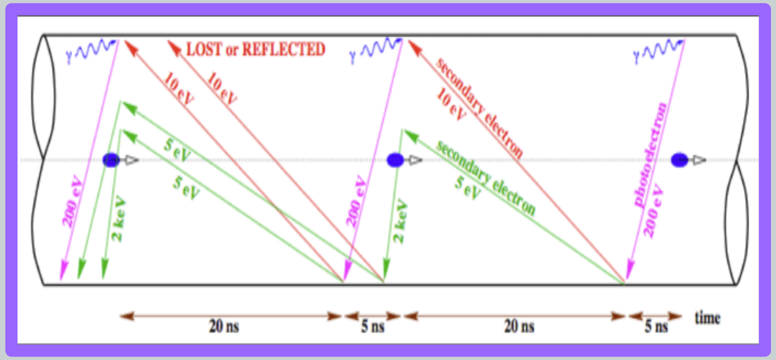

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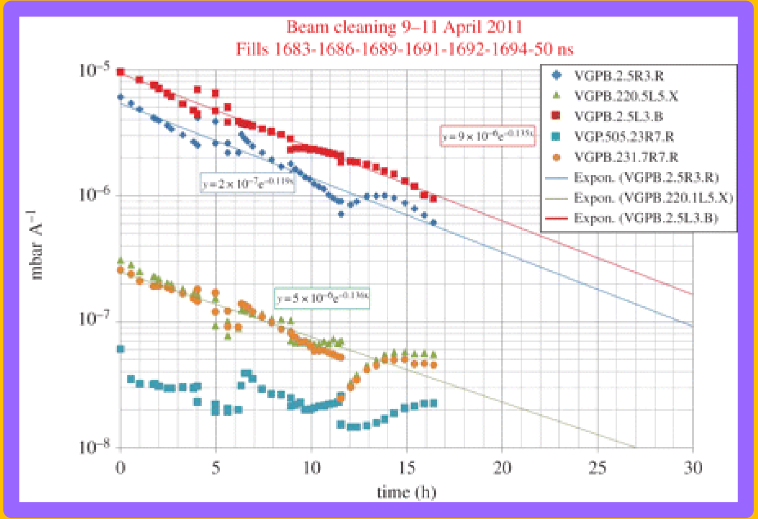
Clean the pipe walls and pump the dust. ➔ Impressive improvement!



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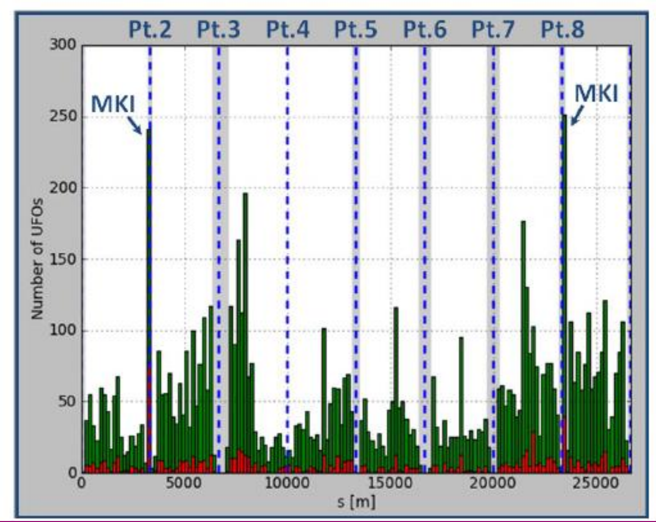

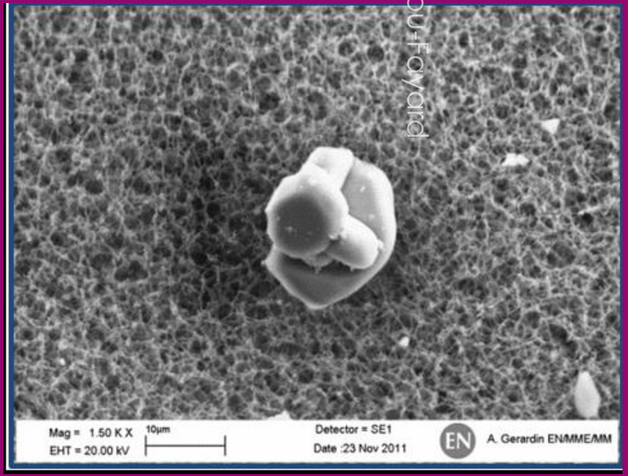

The end point of the LHC beams

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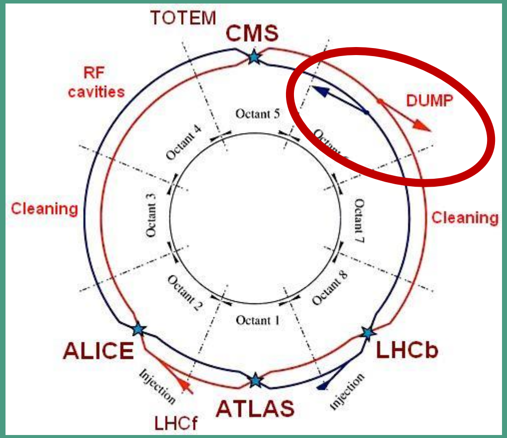

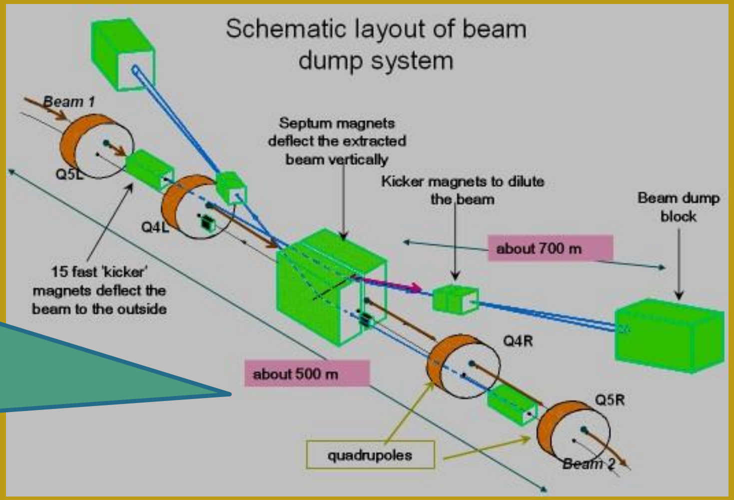

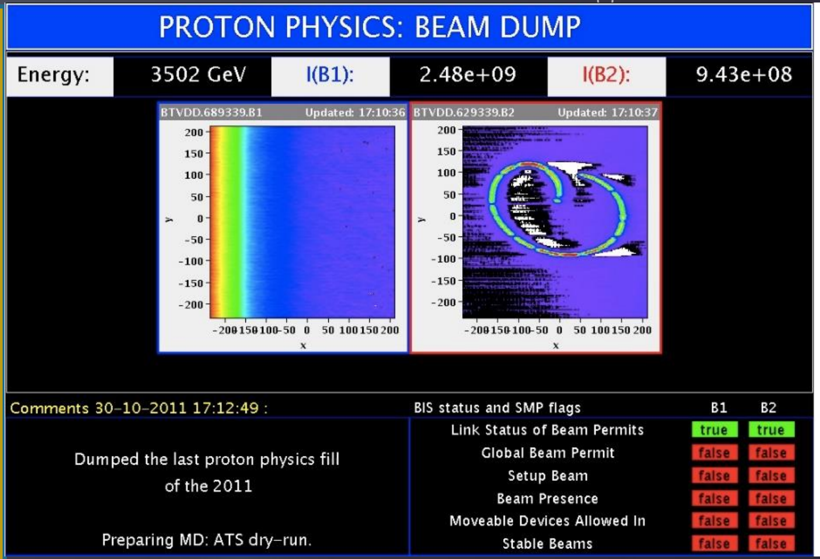

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M. Lamont, Journal of Physics: Conference Series **455** (2013) 012001

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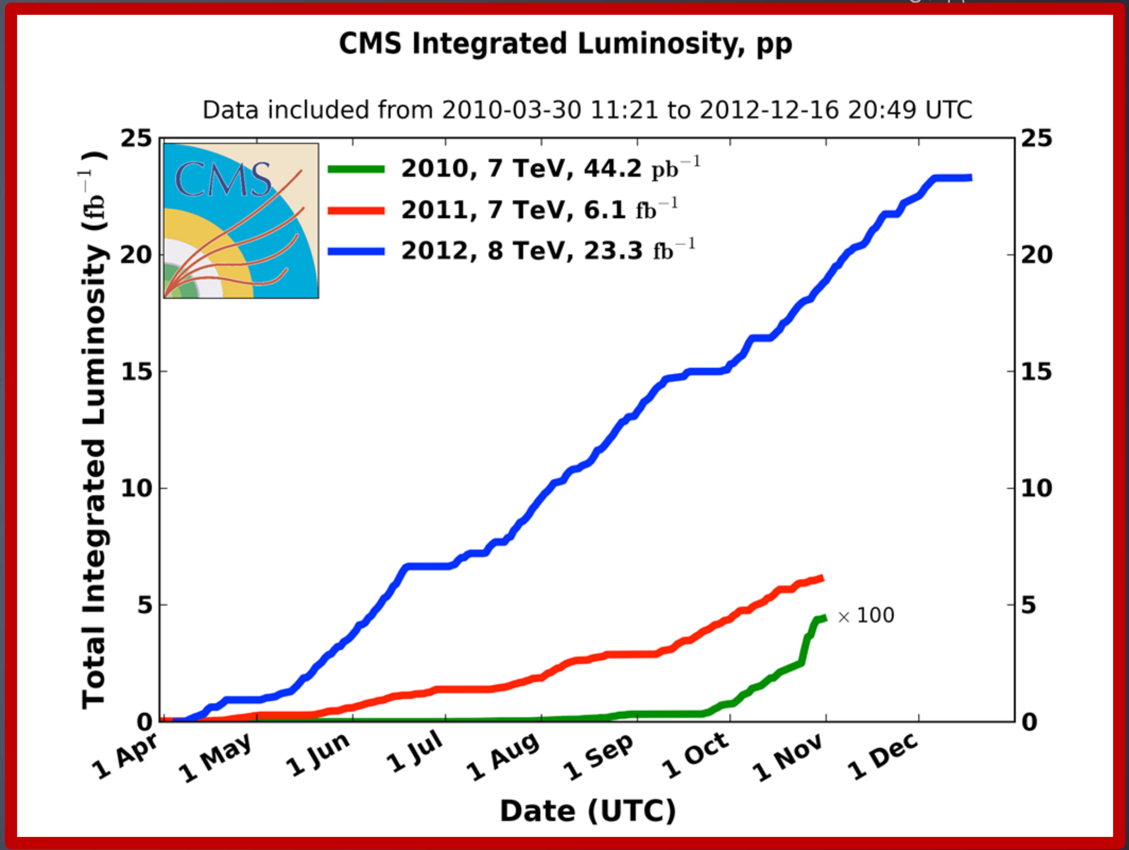

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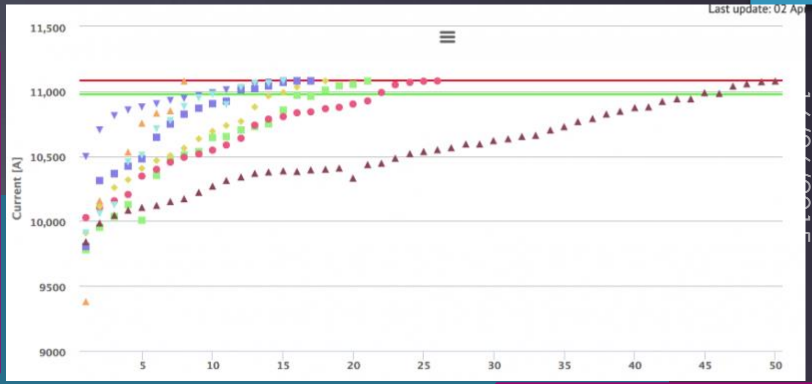
The secret: the excellence of expert and technical teams working on a prototype machine of unprecedented hi-tech

SMACC project : Closure of the last interconnection – 18.06.2014
Activity led by A Musso (TE-MSC)


The main 2013-14 LHC consolidations
1695 Openings and final reclosures of the interconnections
Complete reconstruction of 1500 of these splices
Consolidation of the 10170 13kA splices, installing 27 000 shunts
Installation of 5000 consolidated electrical insulation systems
300 000 electrical resistance measurements
10170 orbital welding of stainless steel lines
1
2
3
4
5
6
7
8
9
10
11
12
18 000 electrical Quality Assurance tests
10170 leak tightness tests
4 quadrupole magnets to be replaced
15 dipole magnets to be replaced
Installation of 612 pressure relief devices to bring the total to 1344
Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

We are experiencing Run 2

- All magnets trained at 7TeV
- Working energy for 2015 : 6.5TeV



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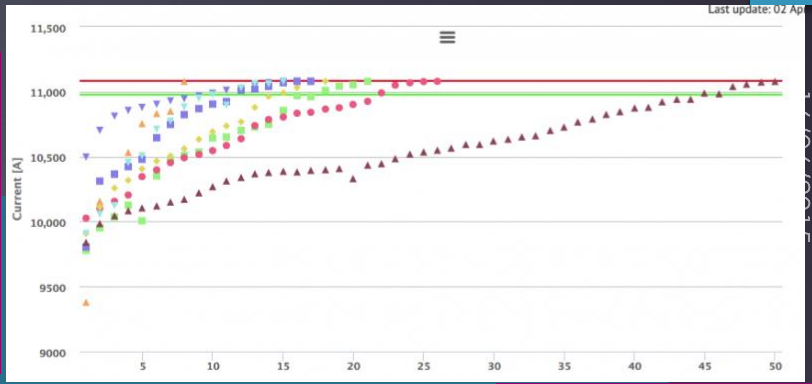

Nb of days

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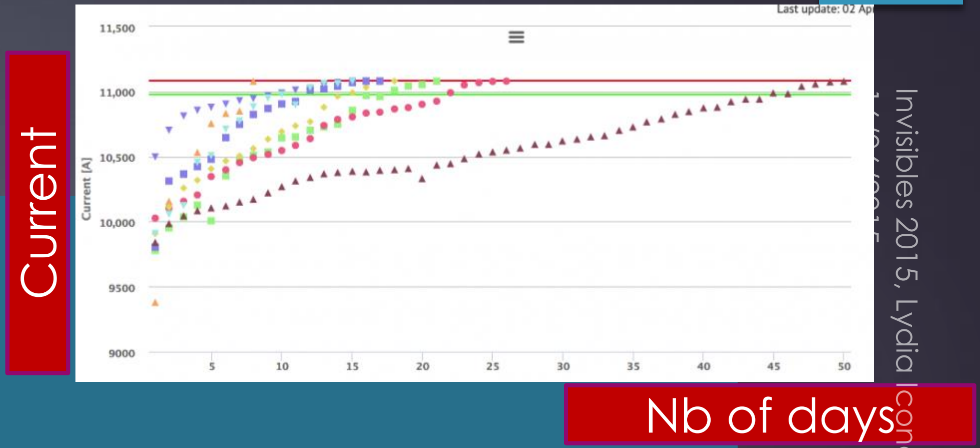

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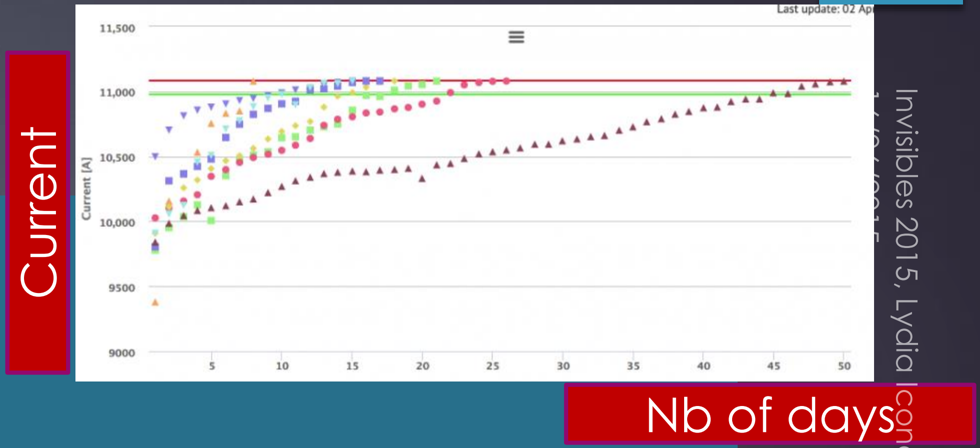

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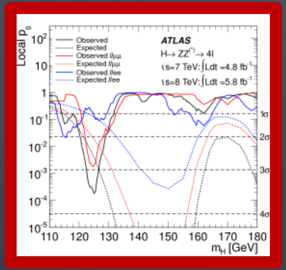
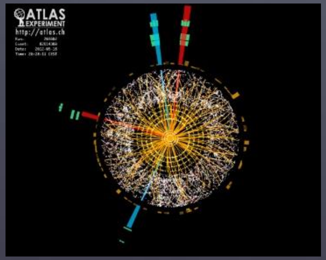
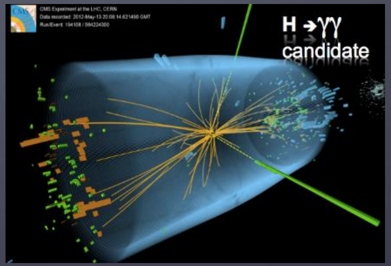
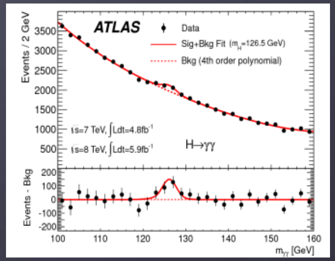
- Starting with 50ns (as in 2011 and 2012) and then go down to 25ns bunch to bunch spacing to keep the pileup lower. Warnings:
  - → possible beam-beam interactions and electron cloud issues
  - → higher UFO rate

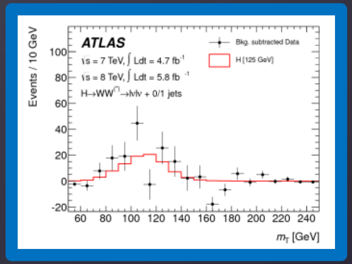
The LHC detectors or how to take Higgs pictures











Observing particles emerging in HE collisions

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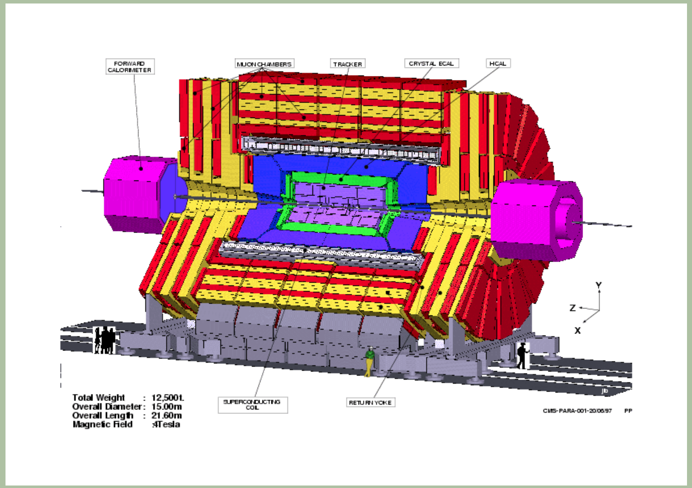
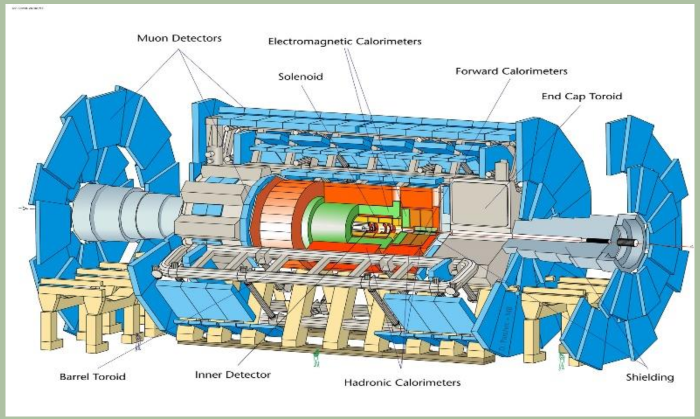
    - Detectors must identify efficiently the hunted signatures and highly discriminate the background.
    - Unexplored kinematical regime →Guarantee the observation of the unexpected..

Constraints for a LHC detector

➔Be as hermetic as possible





Constraints for a LHC detector

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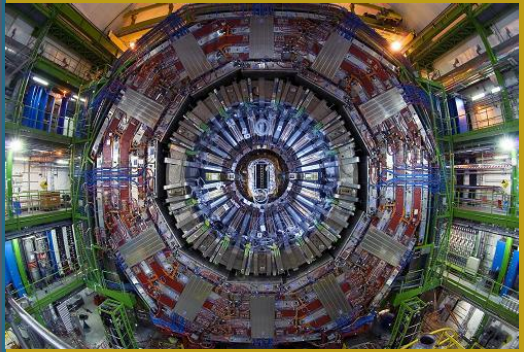
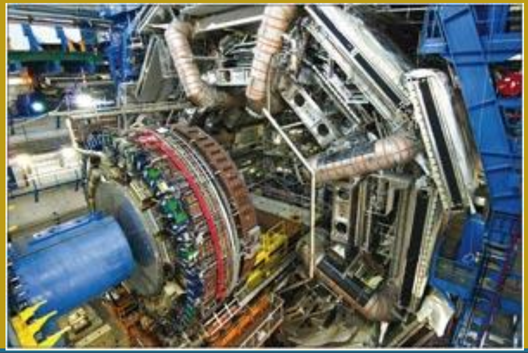
➔Be stable with time

➔Long run periods
➔Huge detectors with imbricated elements involving poor accessibility





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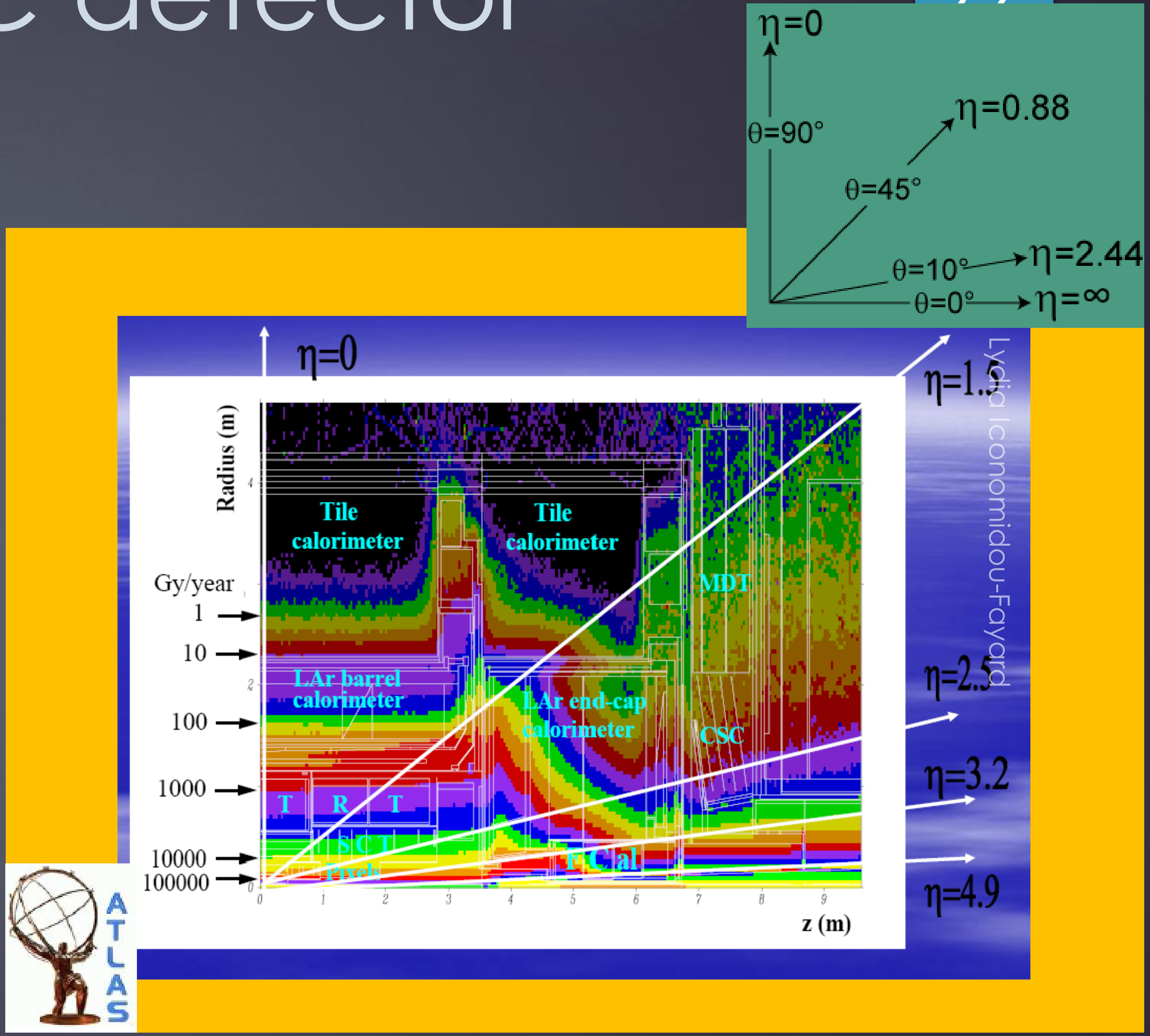

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→Stand the high event rates

Use pipelined-multilayer deadtimeless triggers

- → Decrease the 40 MHz initial rate down to few 100 Hz. First level synchronous, next ones asynchronous
- → Keep only the interesting signatures for the physics analyses

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➔Ensure precise energy and momentum measurements in a large dynamic range

The interesting physics processes give particles with P_T from few GeV to few hundreds of GeV

Constraints for a LHC detector

→Be as hermetic as possible

→Be stable with time

→Be as hard as possible to radiations

→Stand the high event rates

→Ensure precise energy and momentum measurements in a large dynamic range

→Provide high background rejection

Detector design must be optimized such to allow the discrimination between signal and background signatures.

Particles going through matter

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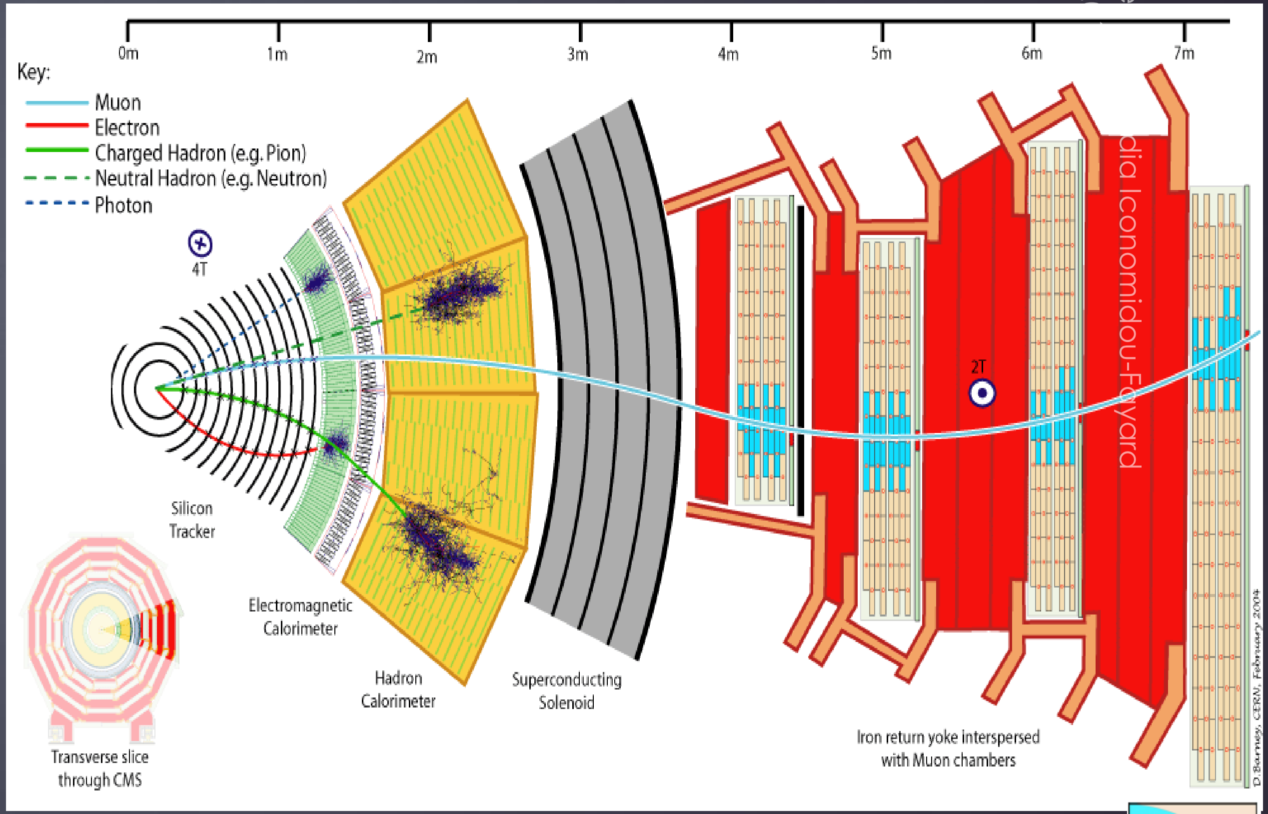

Calorimeters for the Higgs

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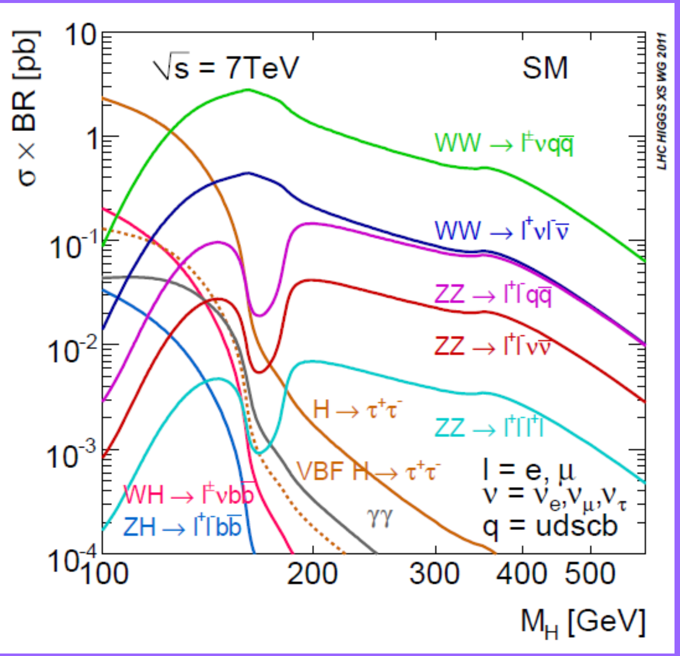

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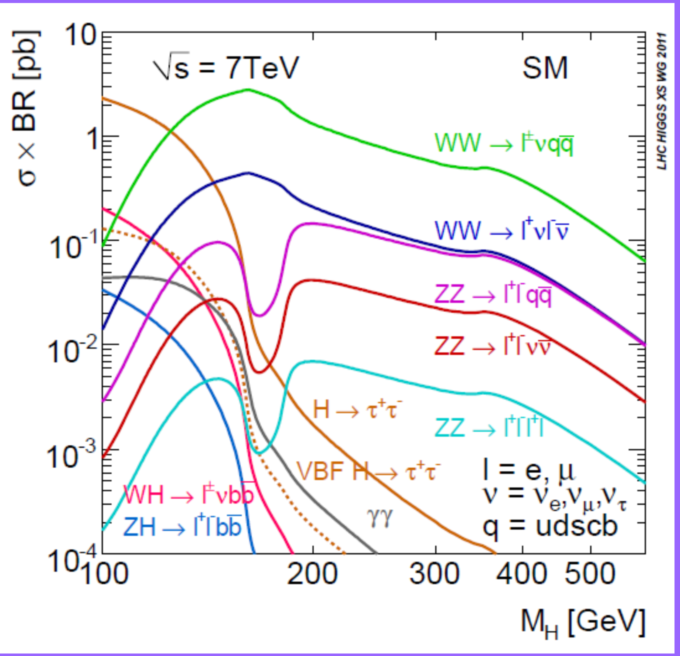

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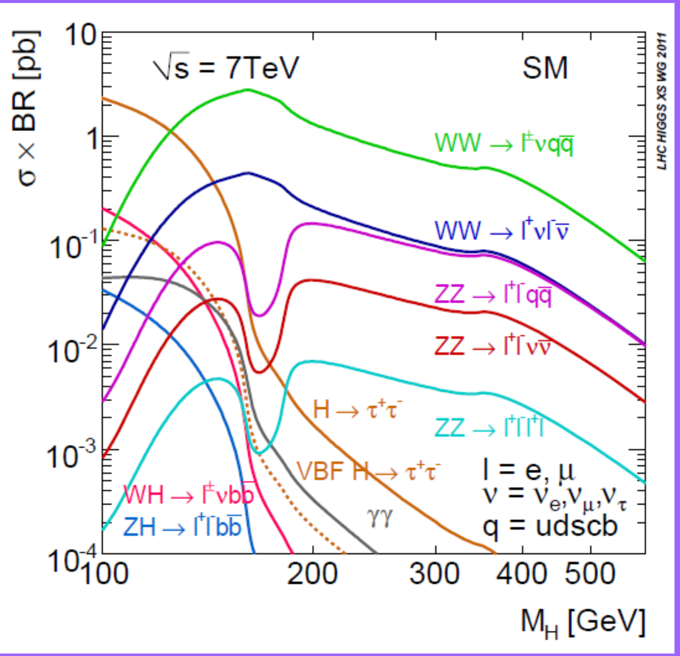

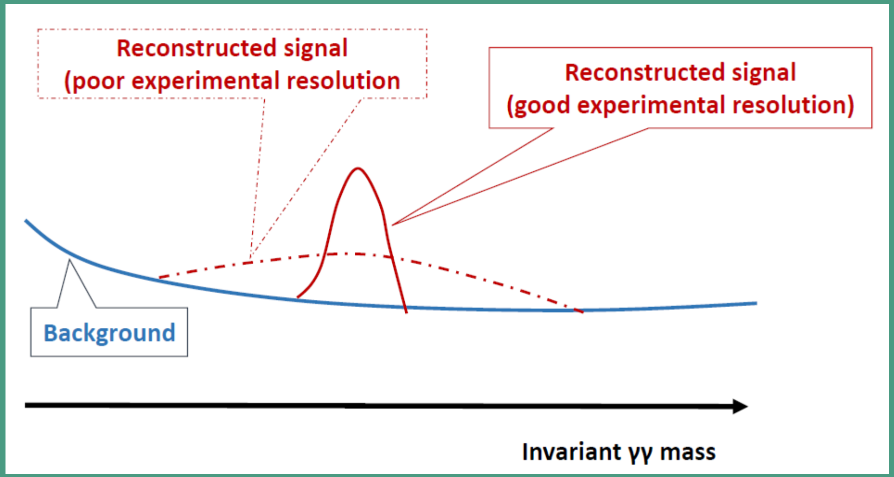

The CMS electromagnetic Calorimeter

Crystals of lead Tungstate
Collect the scintillation light with APD photodiods

61200 Crystals (2.2 x 2.2 x 23 cm3) in barrel (67 t)
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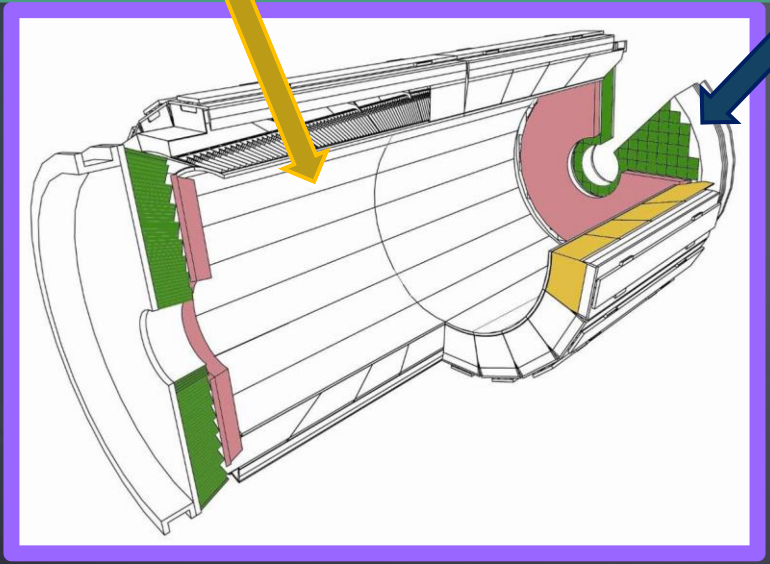

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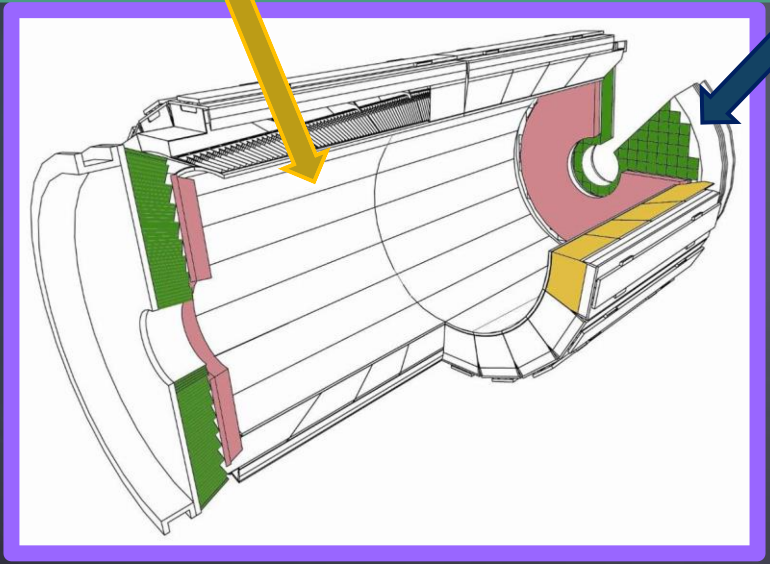

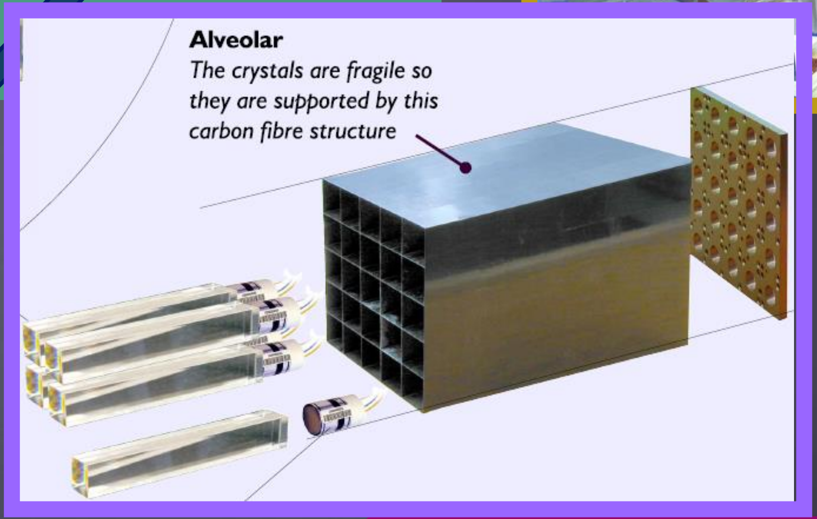

$$\frac{\sigma(E)}{E} = \frac{2.4\,\%}{\sqrt{E}} \oplus \frac{142\,\mathrm{MeV}}{E} \oplus 0.44\ \%$$

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Radiation length X_0

$$X_0 = \frac{716.4\ A}{Z(Z+1)\log(287/\sqrt{Z})}$$

The traversed distance after what the electron loses 1/e of his energy

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Moliere radius R_M

$$R_M = 0.0265\ X_0\ (Z+1.2)$$

The radius of the cylinder that contains 90% of the released energy around the electron

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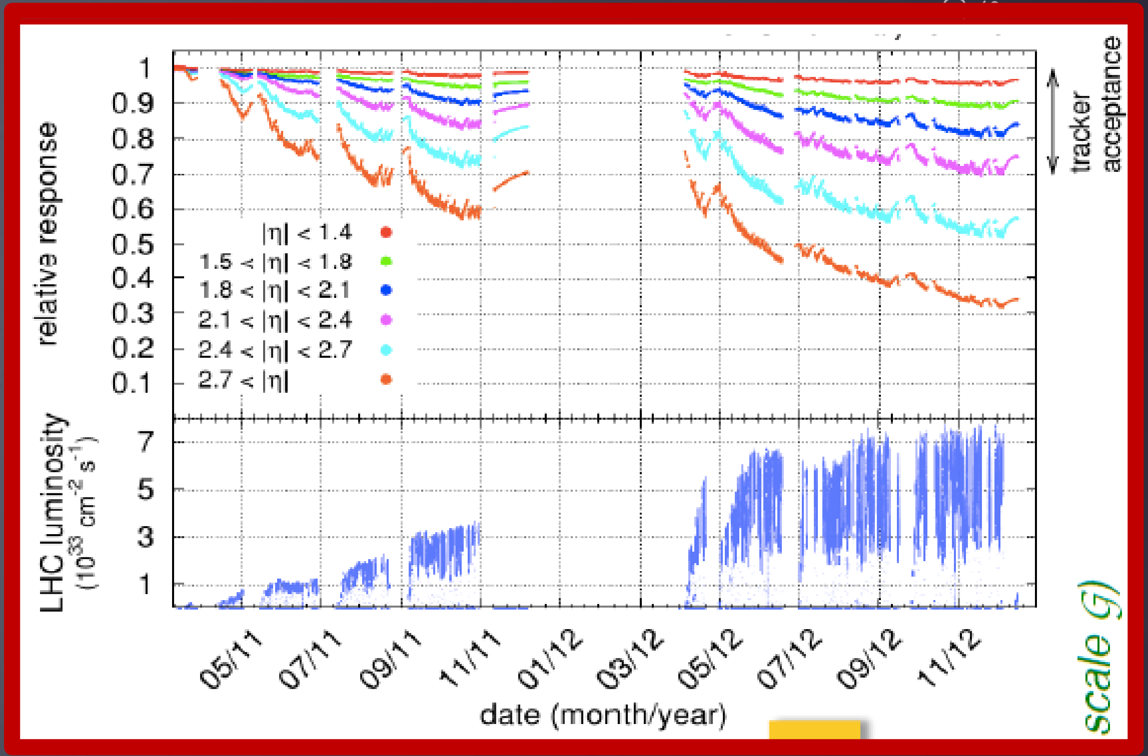

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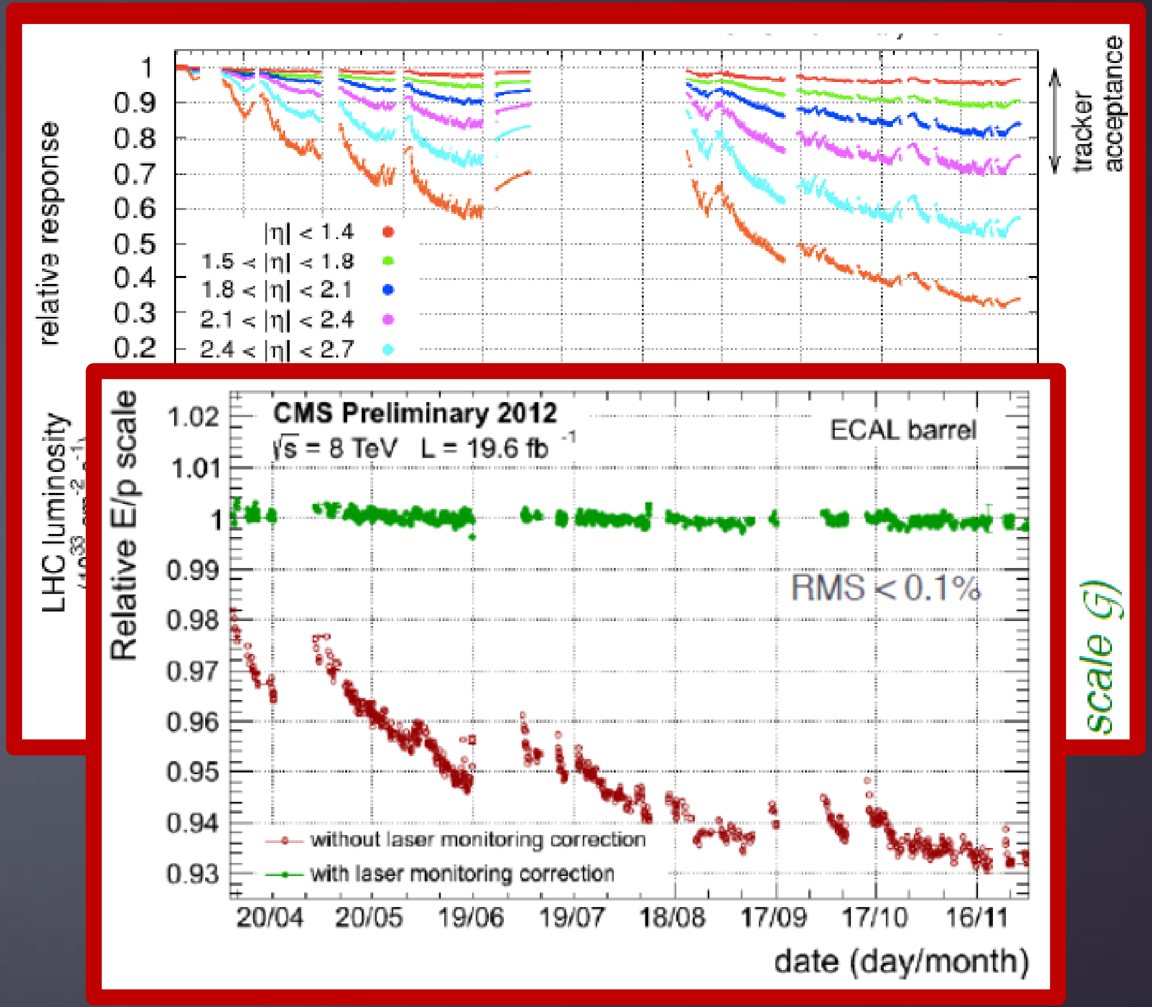

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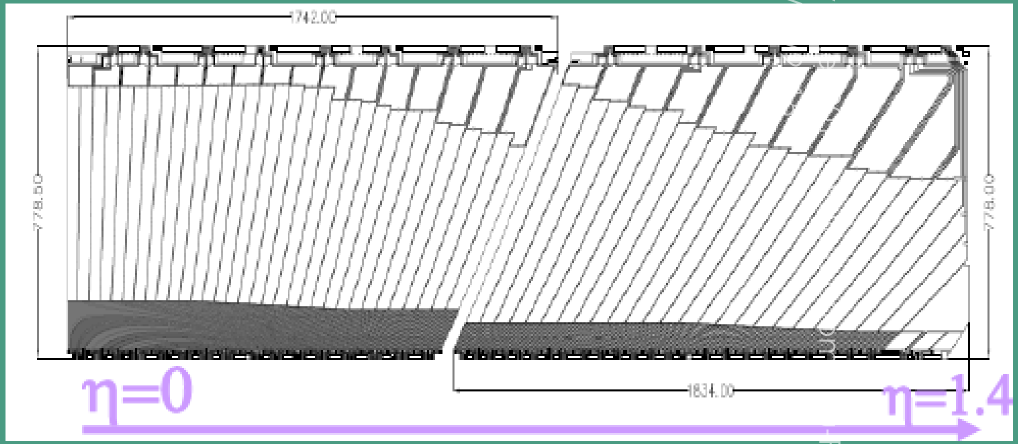

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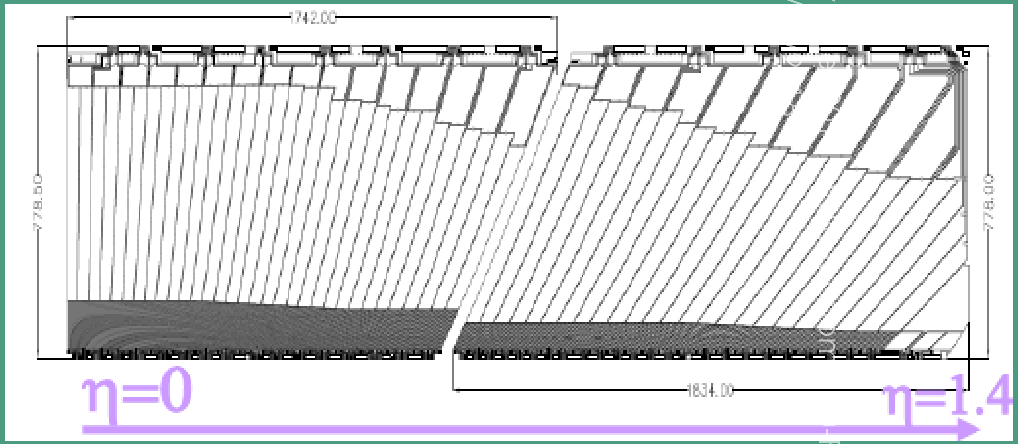

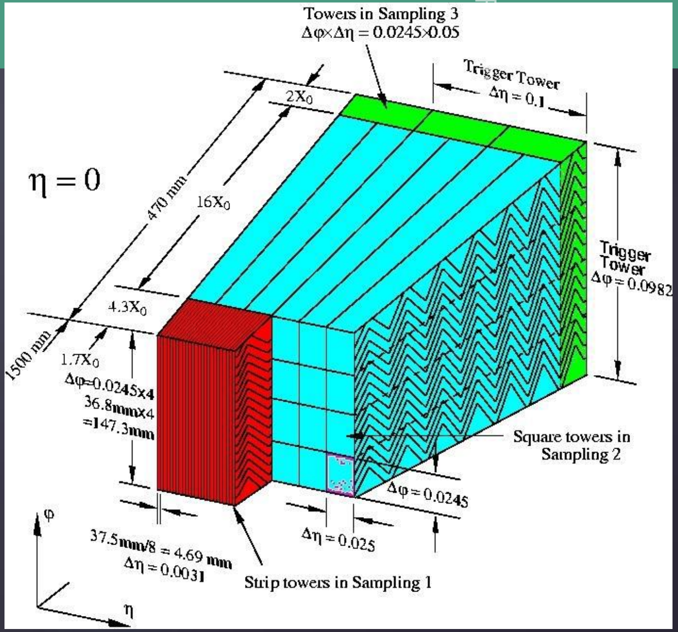

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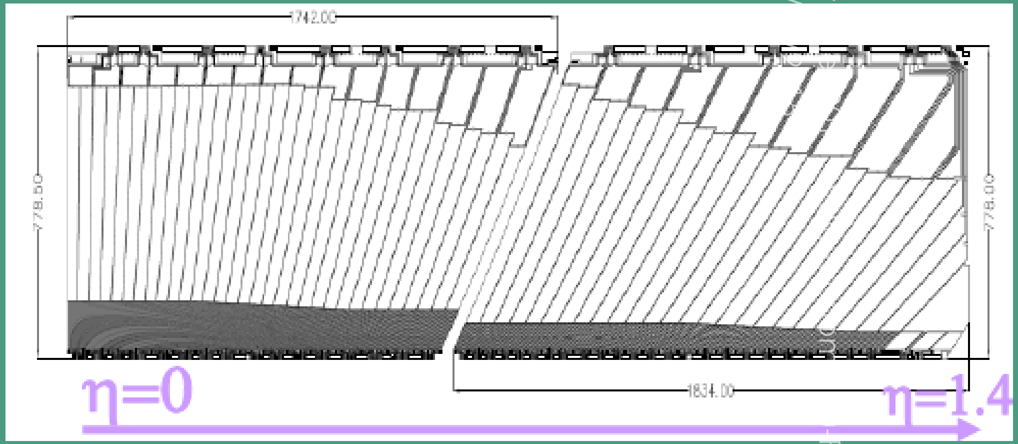
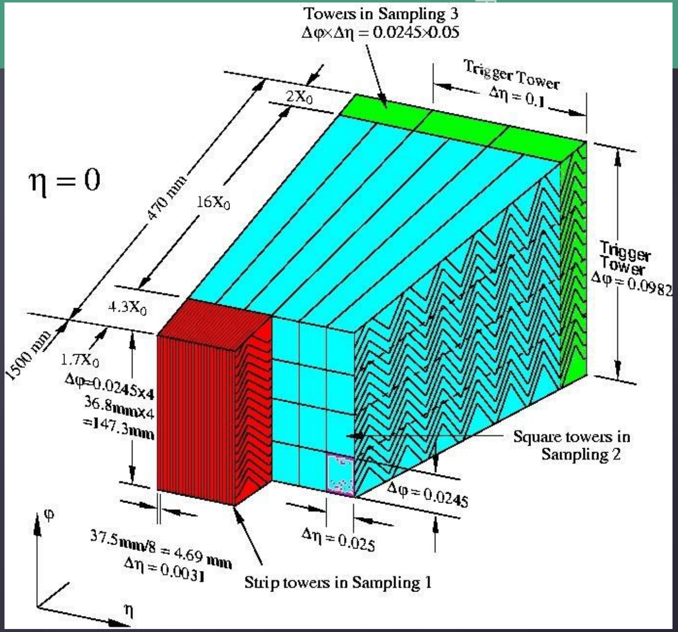
→A total ~180000 channels





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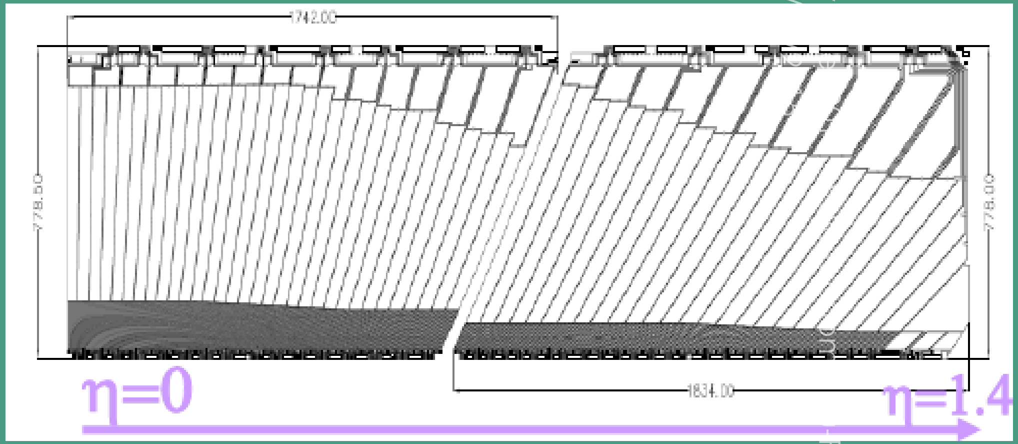
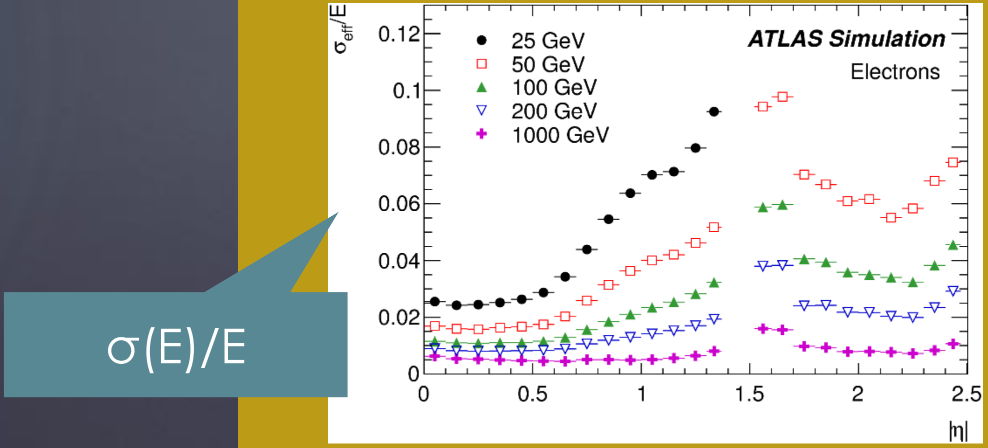
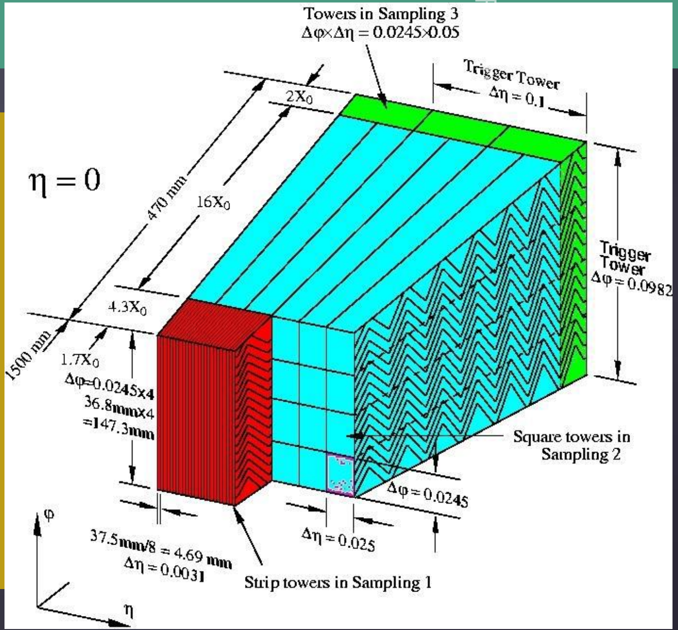
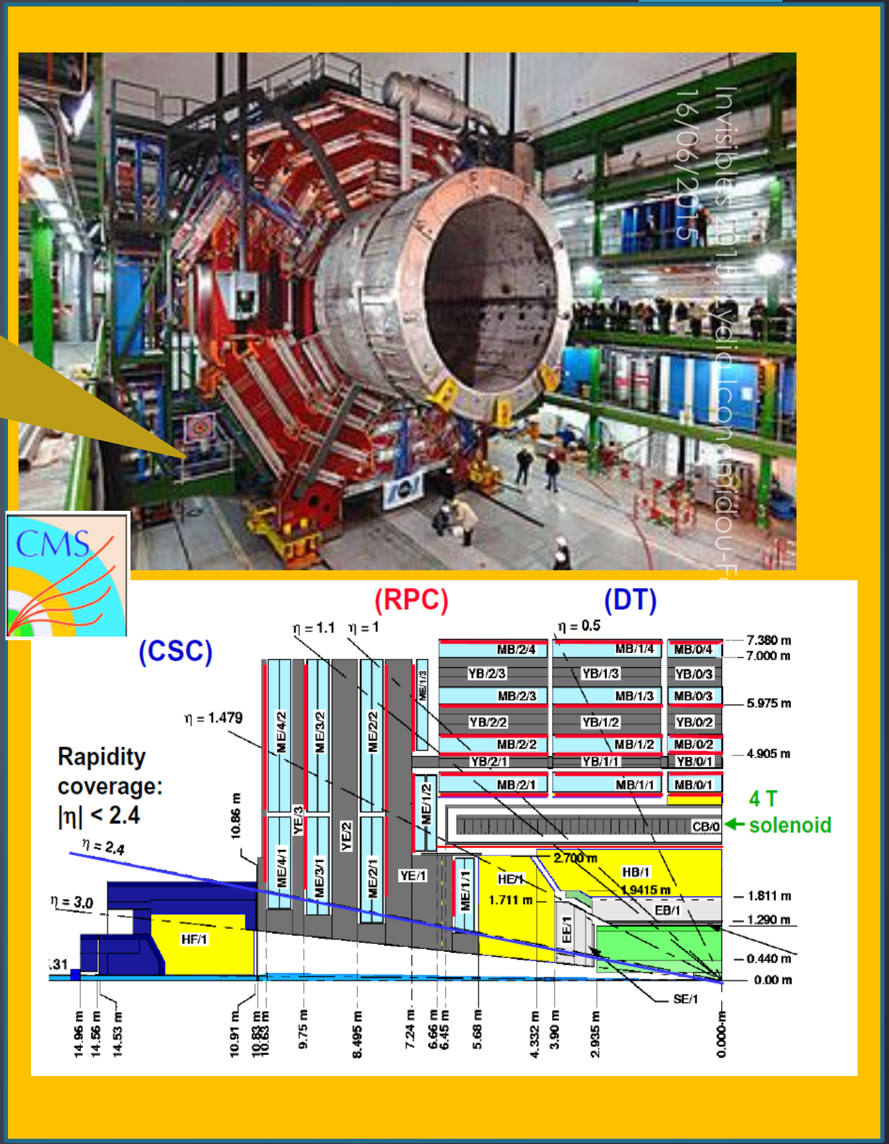






Muon systems in ATLAS and CMS

Solenoid supraconducting magnet with a 4 Tesla field
4 stations of chambers interleaved between the iron yoke.



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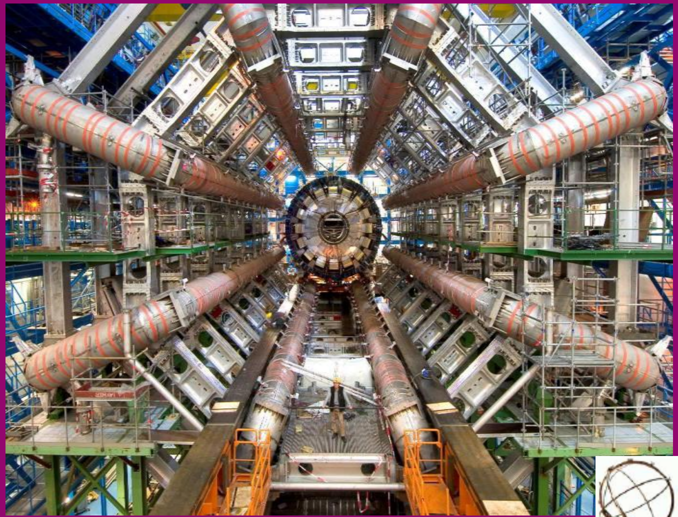

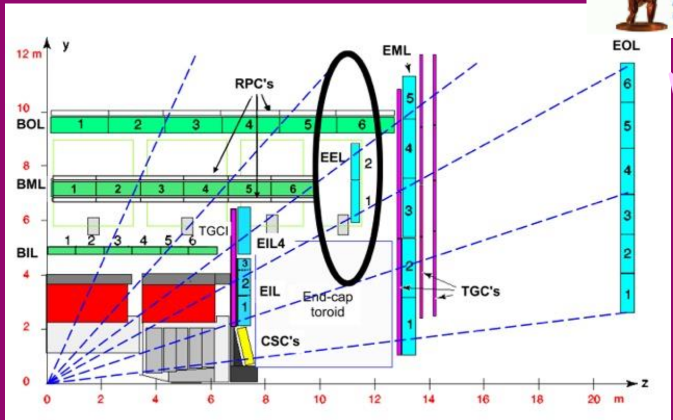

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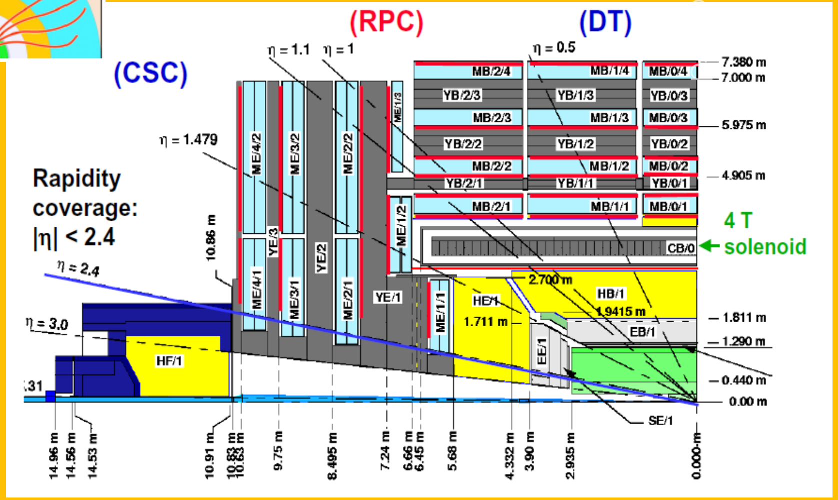
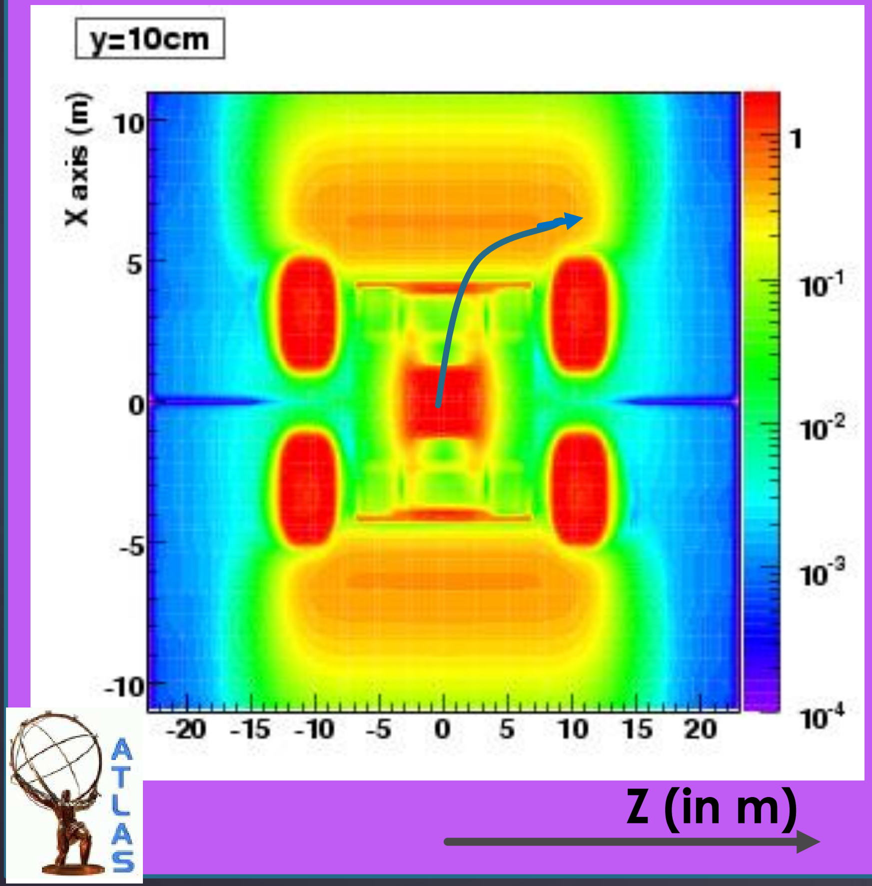
4 stations of chambers interleaved between the iron yoke.

8 torroidal supraconducting coils (0.5-1 Tesla)
3 Stations of chambers
Muons measured in the InnerDetector and in the Muon System



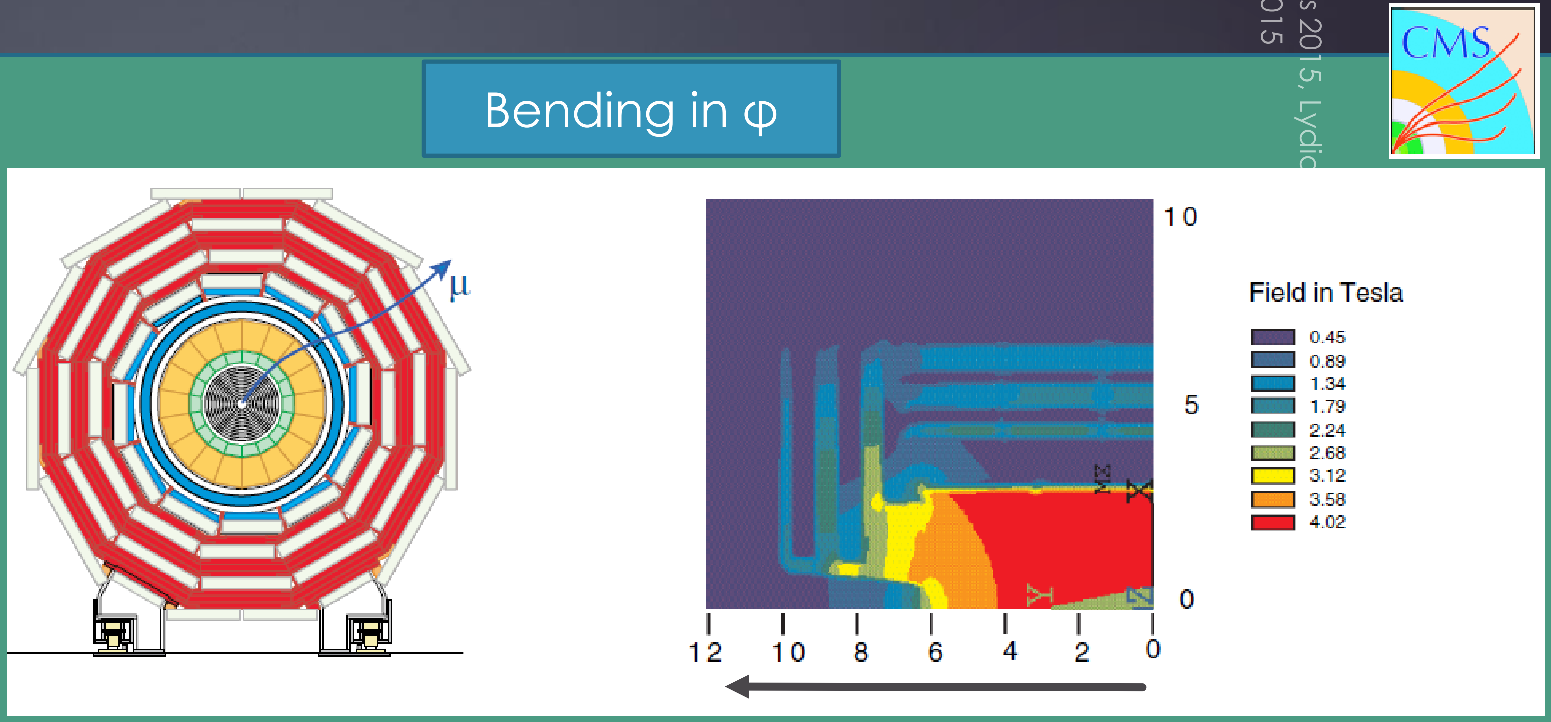
Magnetic fields in ATLAS and CMS

Bending in φ and in Z



Z (in m)

Bending in φ



Z (in m)

The tracking systems of ATLAS & CMS

The Challenges

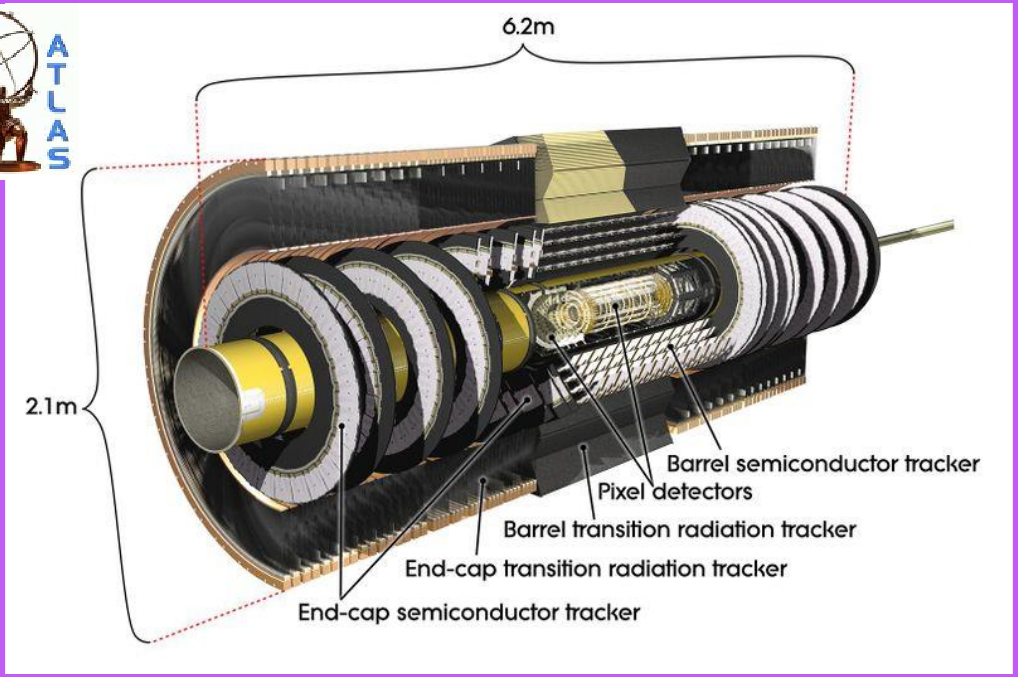
1) Reconstruct the interaction points and the tracks of charged particles with high precision

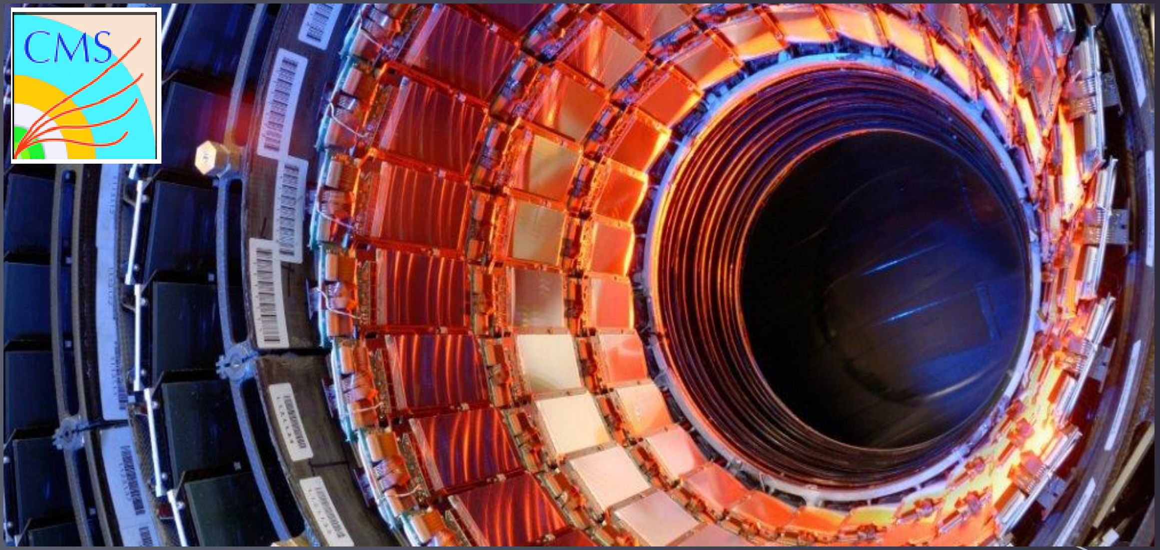
2) High multiplicity environment requires fine granularity of the sensitive detectors to achieve efficient separation

3) Need to go as close as possible to the beam axis and to have sufficient lever arm

4) Amount of tracking detector material has to be kept low before the calorimeters

The tracking systems of ATLAS & CMS





1) **Semiconductor detectors**
----Three layers of high granularity pixels (starting at 4cm from the Interaction Point)
----Four layers of silicon microstrips
2)Transition radiation detector (electron-pion discrimination)

Silicon detectors

1) Three layers of pixels at 4.4, 7.3 and 10.2cm from the interaction point
2) 10 layers of microstrip detectors

Elementary particle reconstruction

Electrons and photons

An « electron candidate » in ATLAS

Definition : « A track in the inner detector pointing to a cluster found in the electromagnetic calorimeter. »

Sliding -window looks for energy deposits >2.5GeV in 3x5 frame 3x(0.025x0.0025) in (η,φ)

Energy seed in 3x5 Et>2.5 GeV

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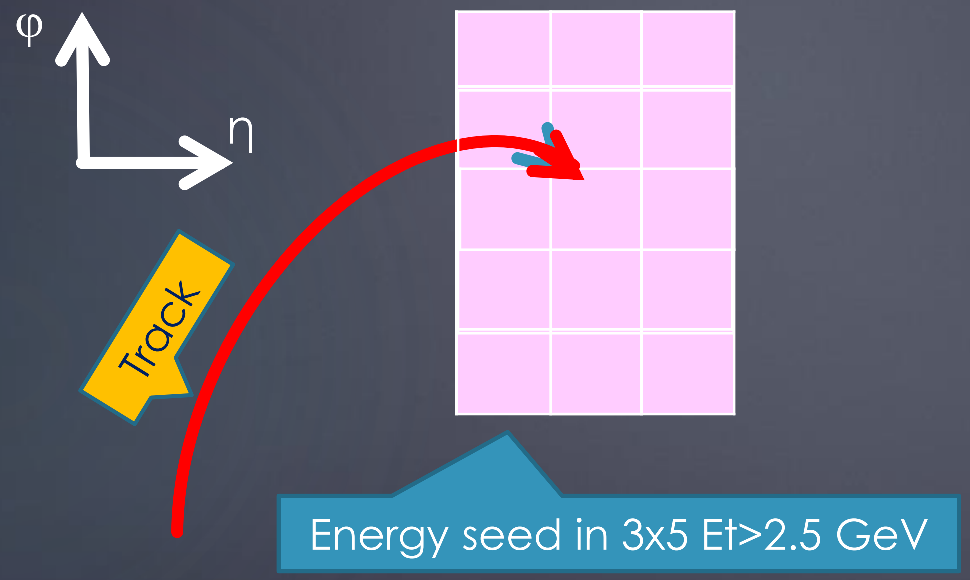
If a track matches the cluster..



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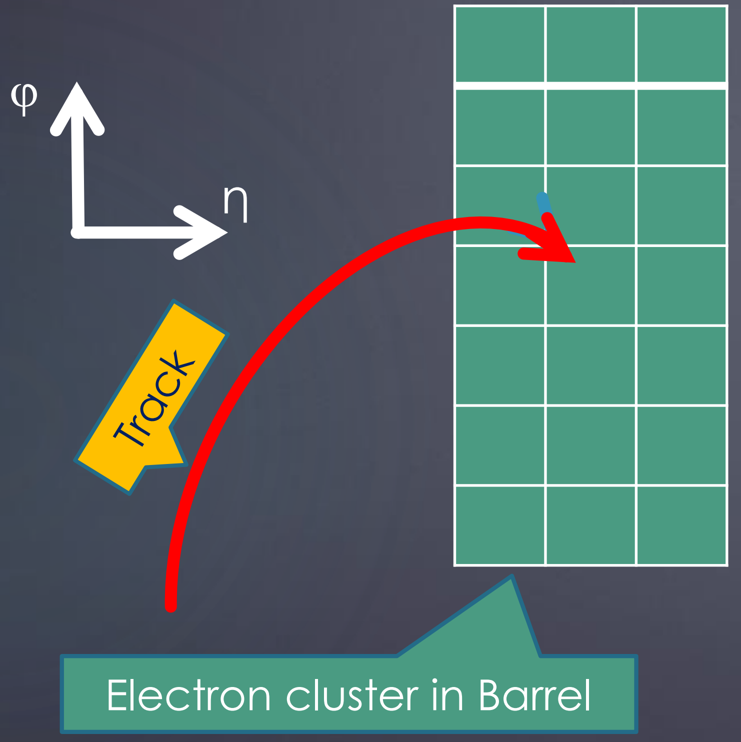

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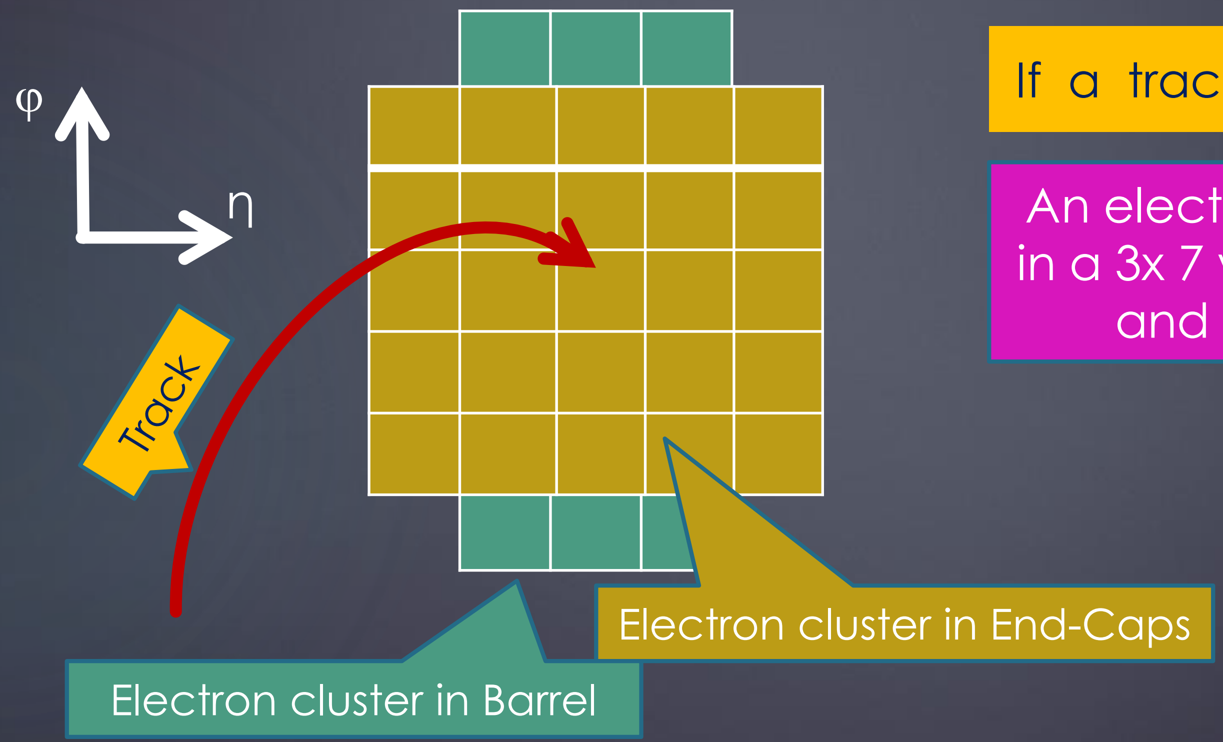

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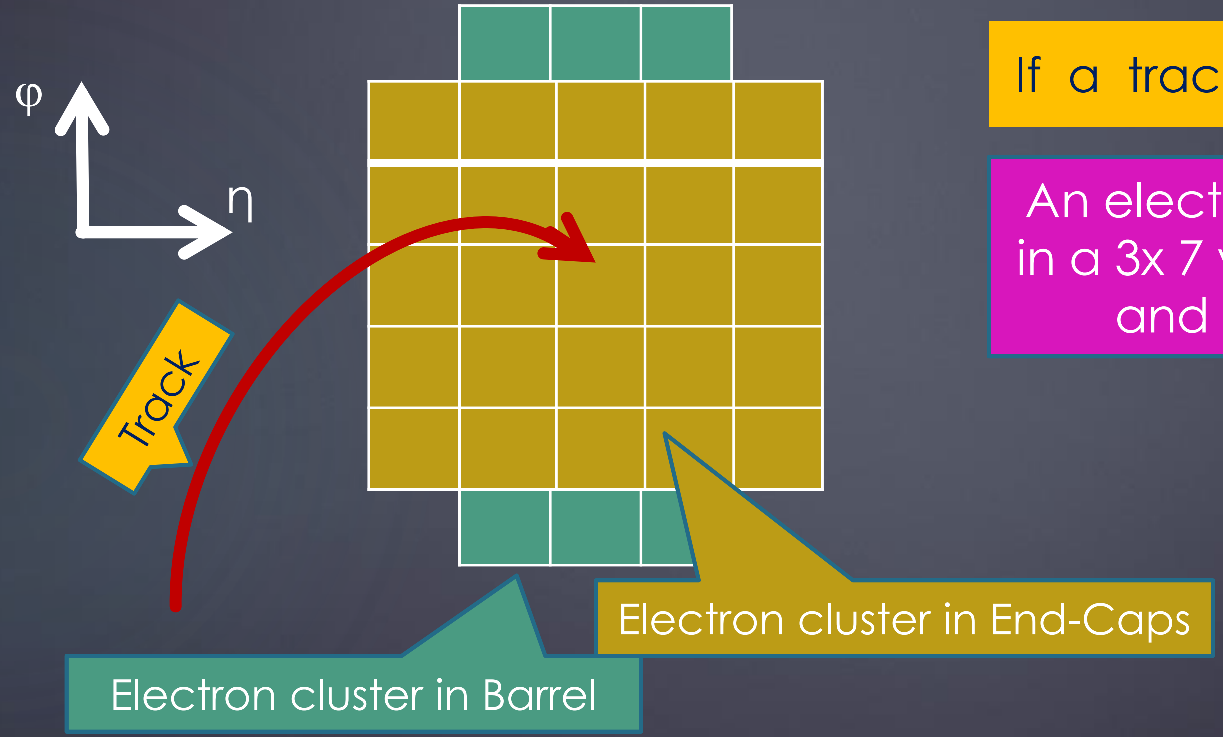

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Electron energy from:
**Deposits in the 3 layers
**Signal in preshower
**Estimated lateral and longitudinal leakage
Electron direction from Track

Bremsstrahlung (1)

An electron radiates photons +-energetic. Consequences:

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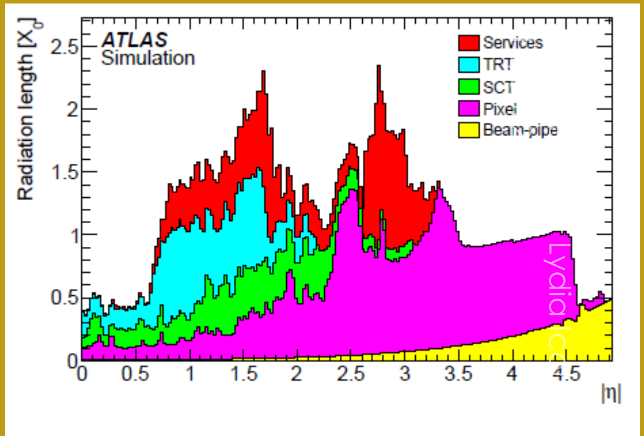
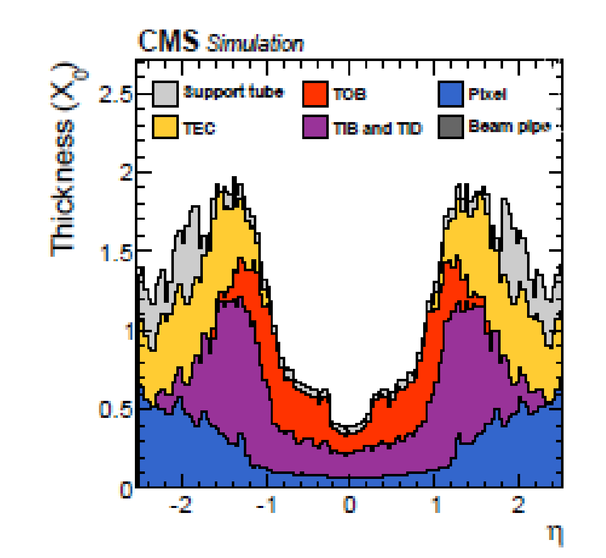
Energy loss, depending on the amount of traversed material





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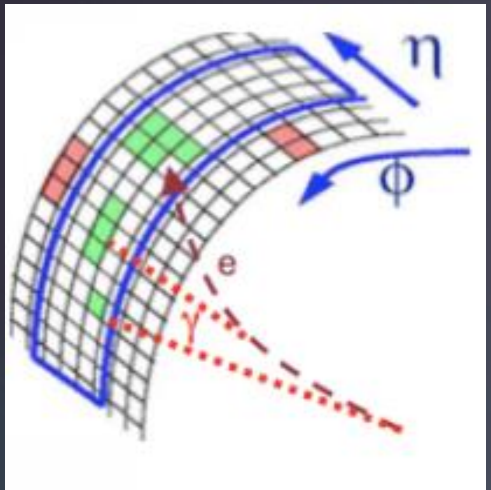

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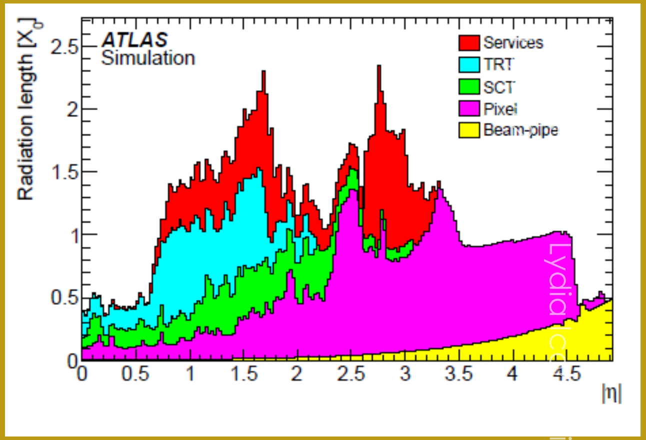

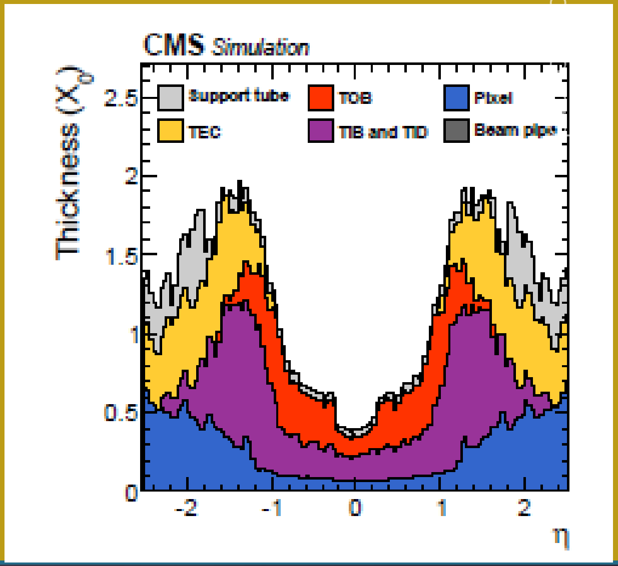

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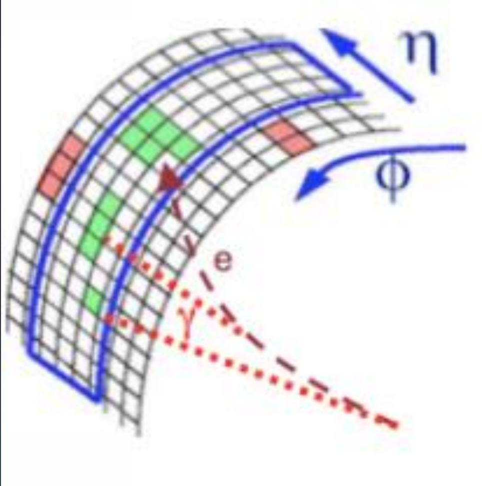

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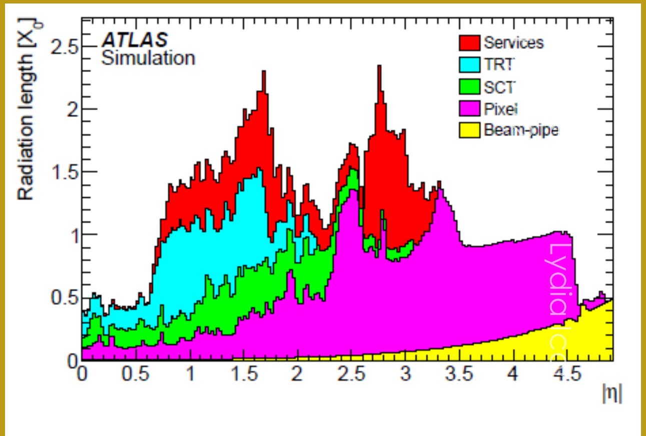
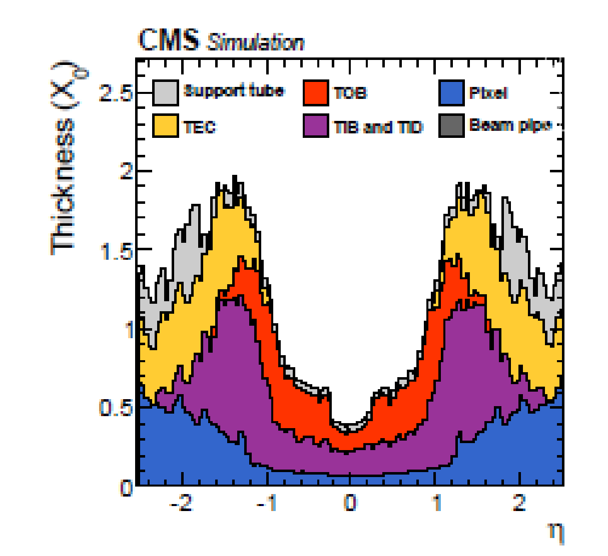
In case of strong magnetic field in the Inner Detector, the initial electron can lead to multiple clusters in the calorimeter

Experiment	Field
CMS	4 Tesla
ATLAS	2 Tesla





Bremsstrahlung (2)

CMS : 33% (85%) of electron energy radiated before the barrel (EndCap) calorimeter.
→Strong field bends the electron far from photons
→"SuperCluster algorithm" to collect the full energy and improve the resolution.
→Specific track reconstruction to take into account the brem.

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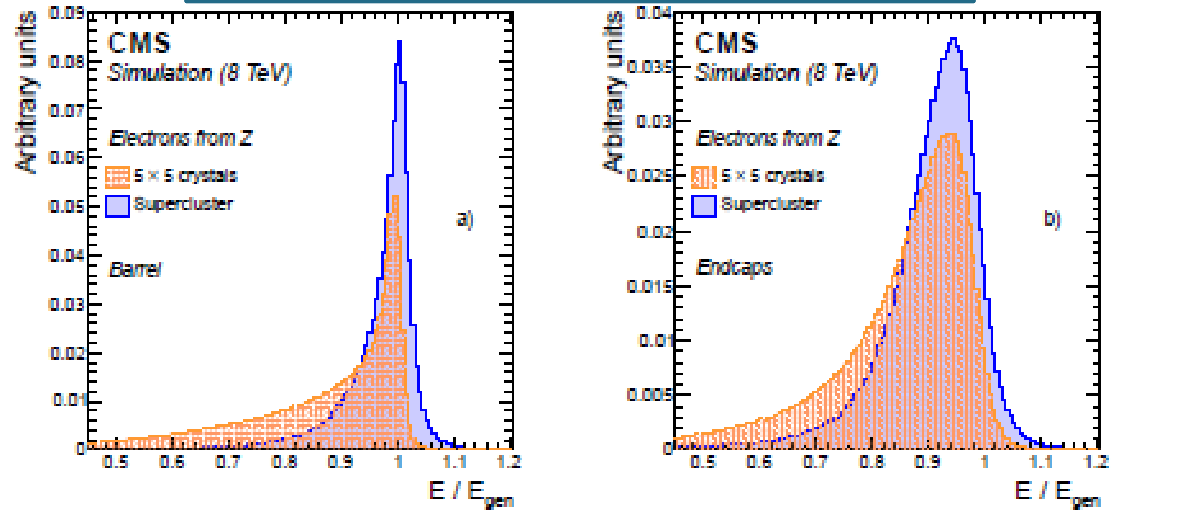
CMS : Emeas/Egen with 5x5 and with SuperCluster



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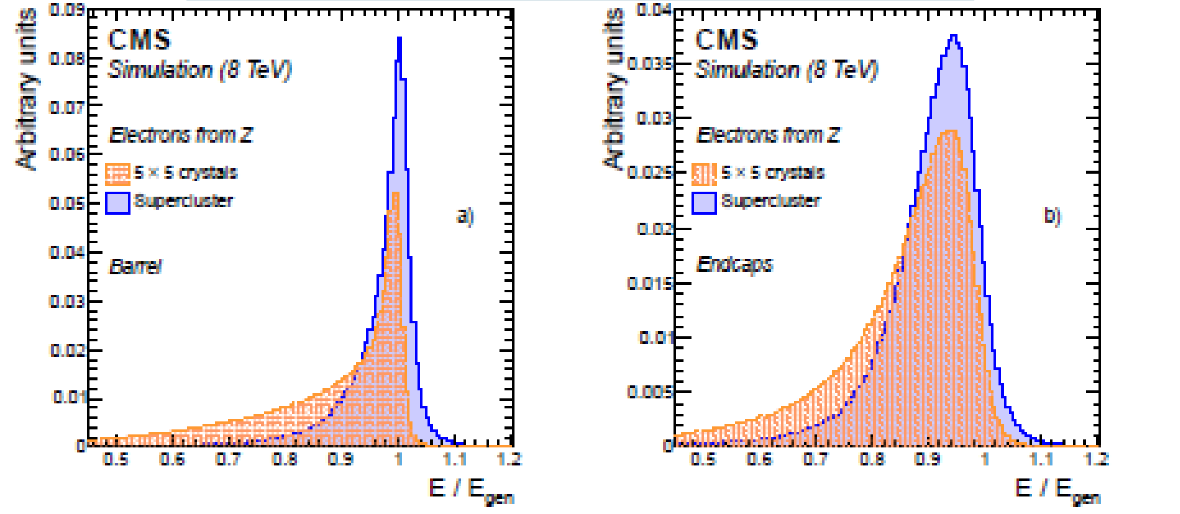

Bremsstrahlung (2)

CMS : 33% (85%) of electron energy radiated before the barrel (EndCap) calorimeter.
→Strong field bends the electron far from photons
→"SuperCluster algorithm" to collect the full energy and improve the resolution.
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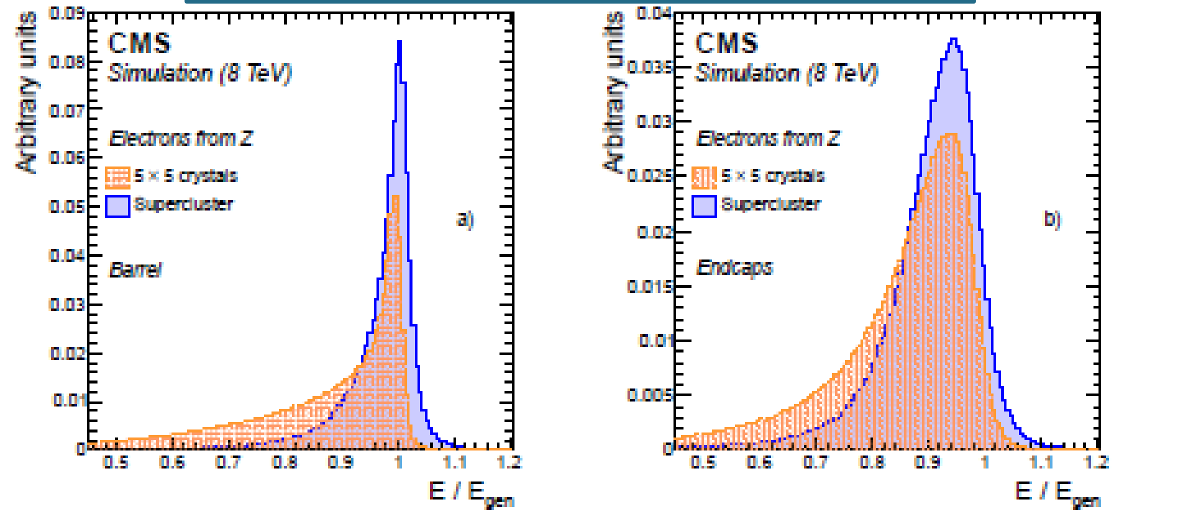
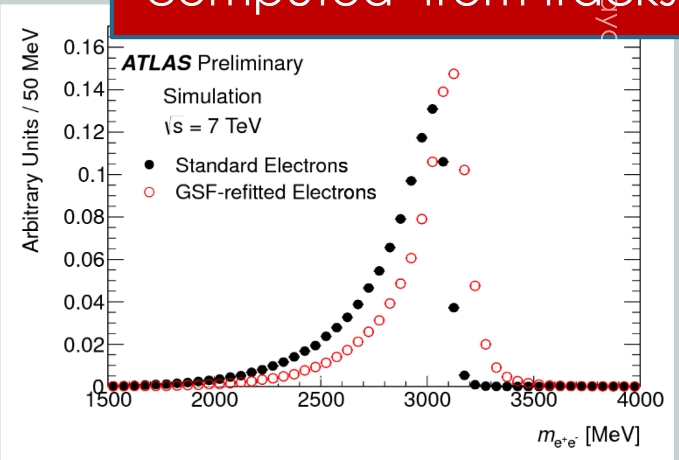


ATLAS : J/Ψ mass computed from tracks



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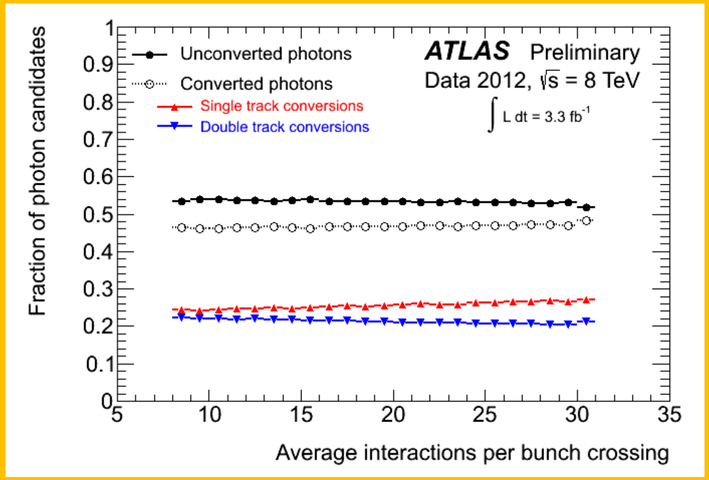

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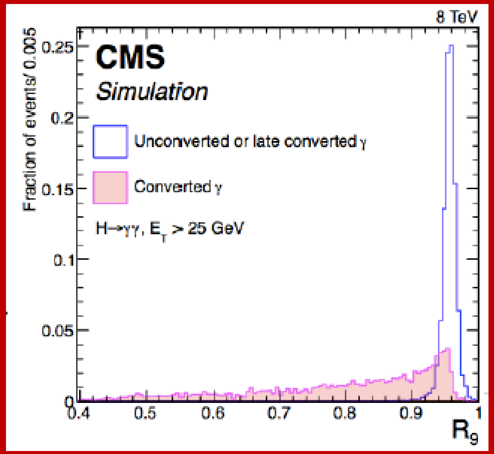

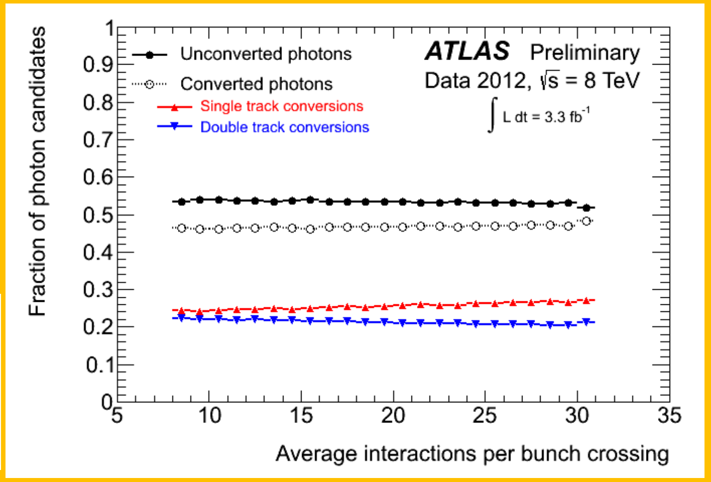

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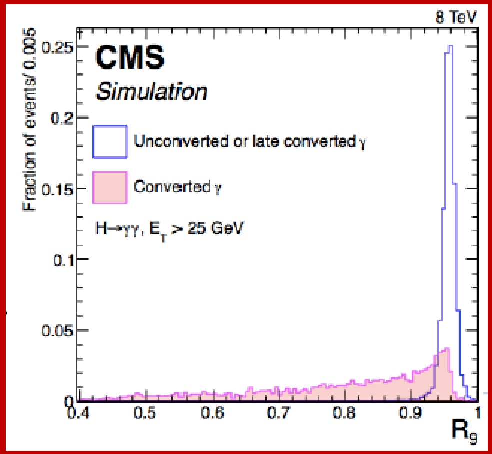
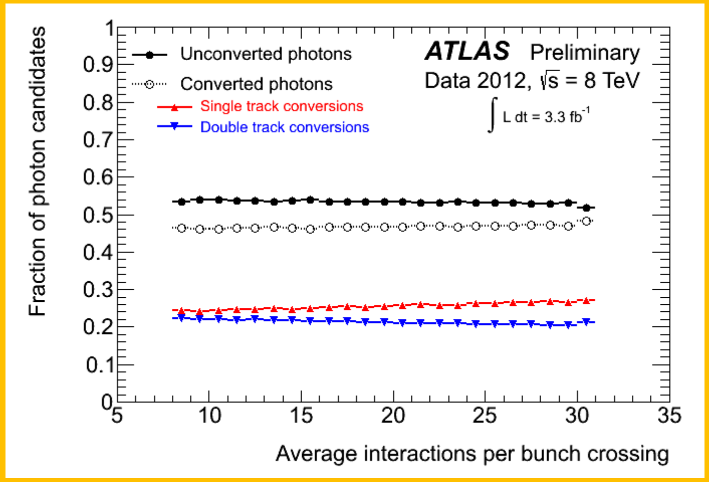
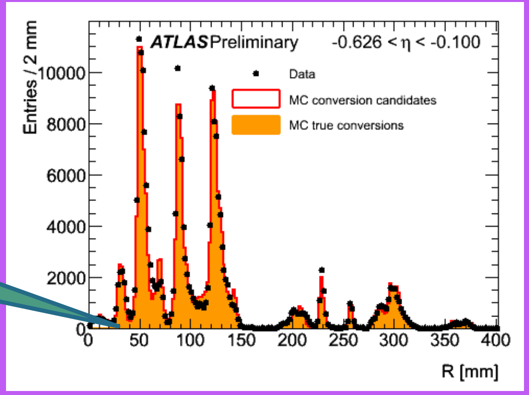




Photon conversions: An estimator of material distribution



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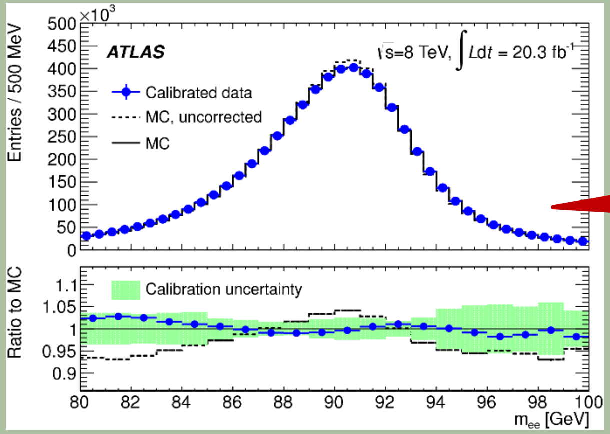

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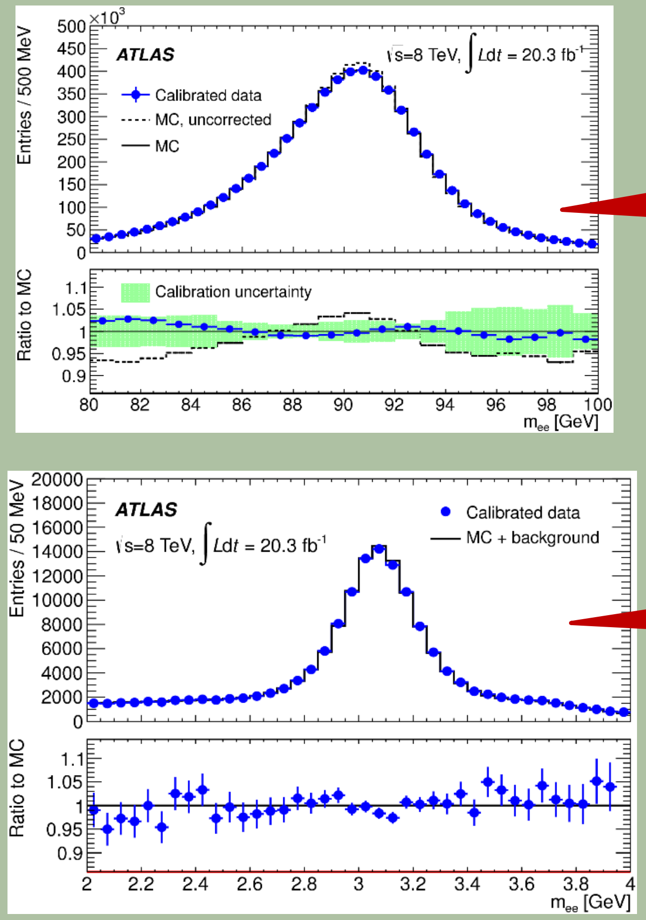

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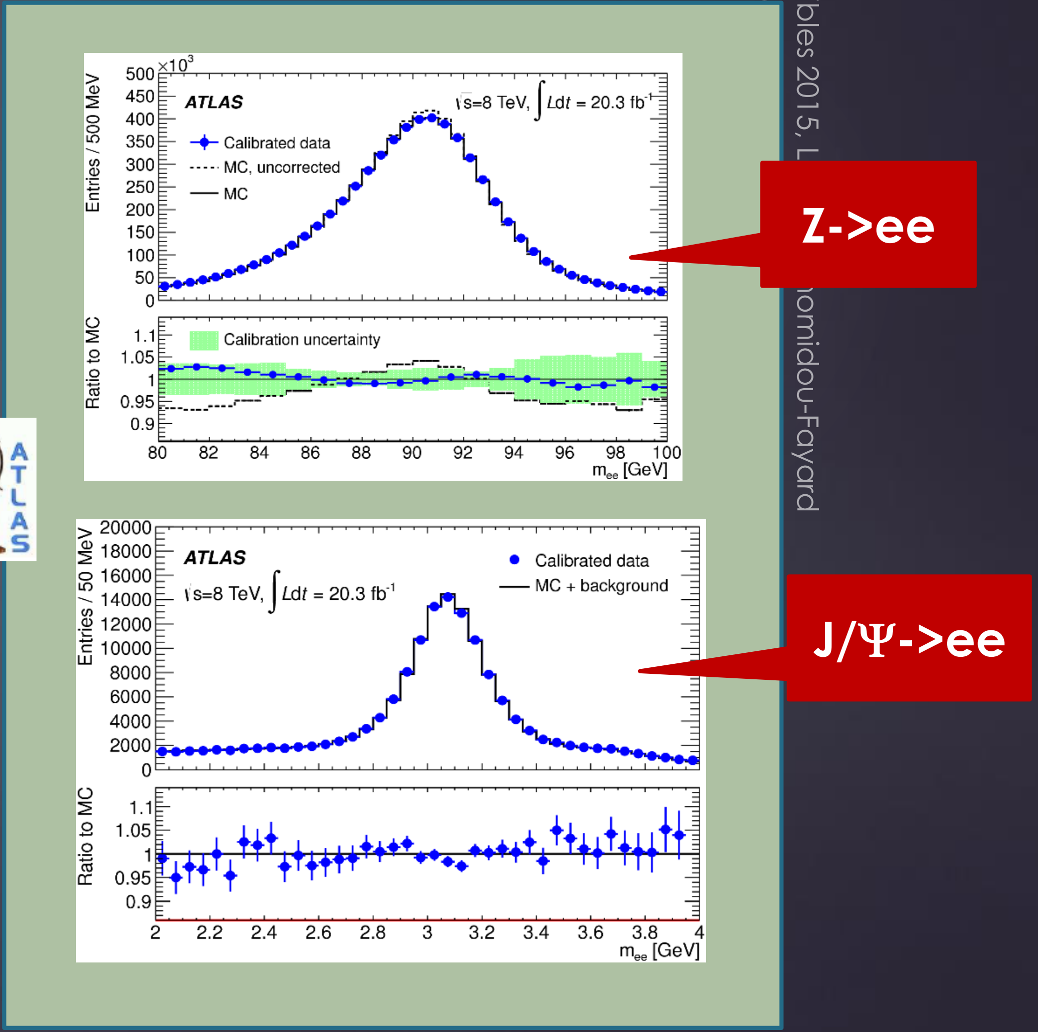
➔W->eν used for E/p tests and also to check the **uniformity.**



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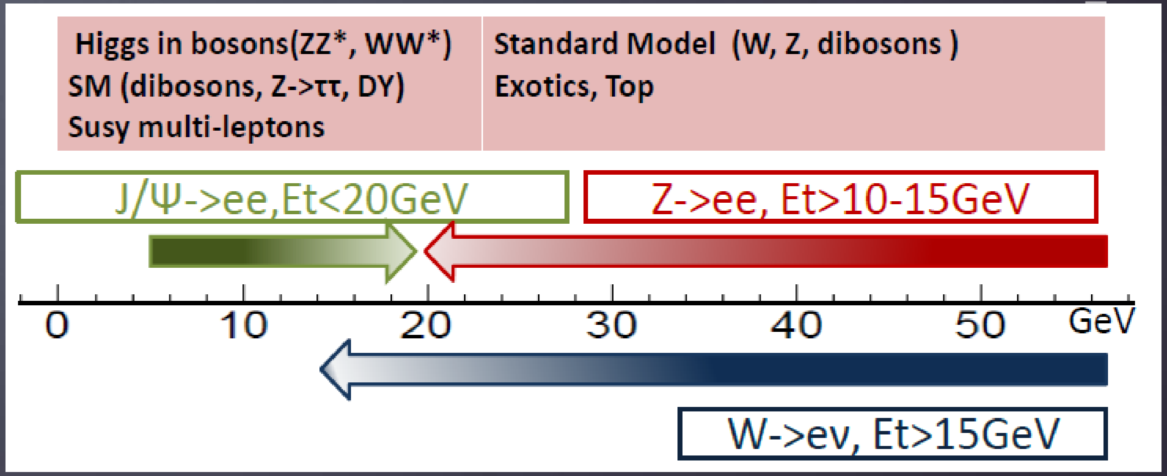
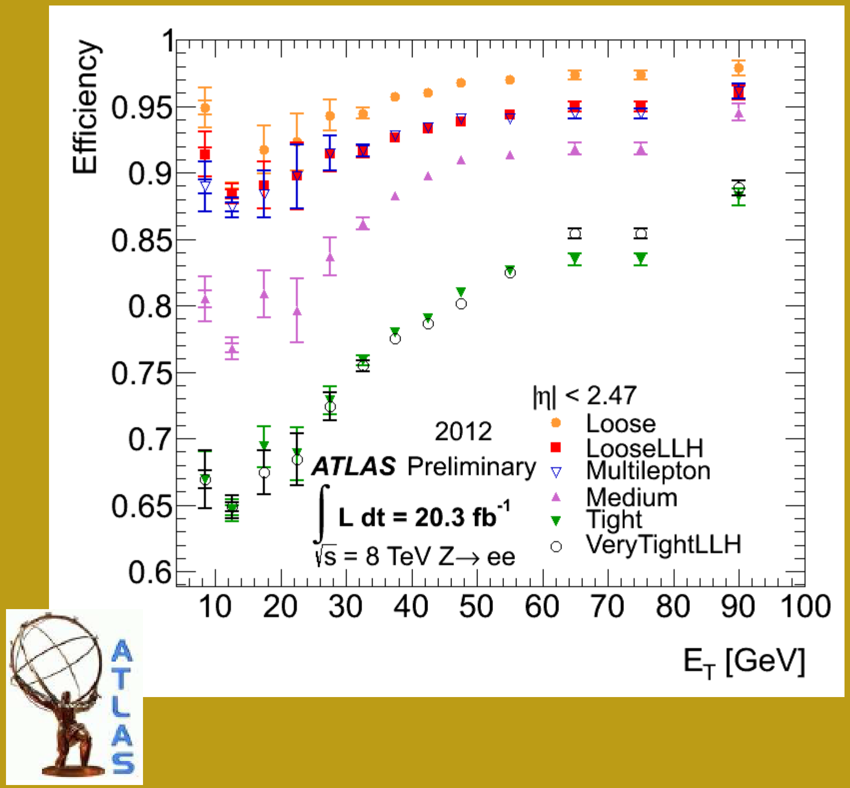
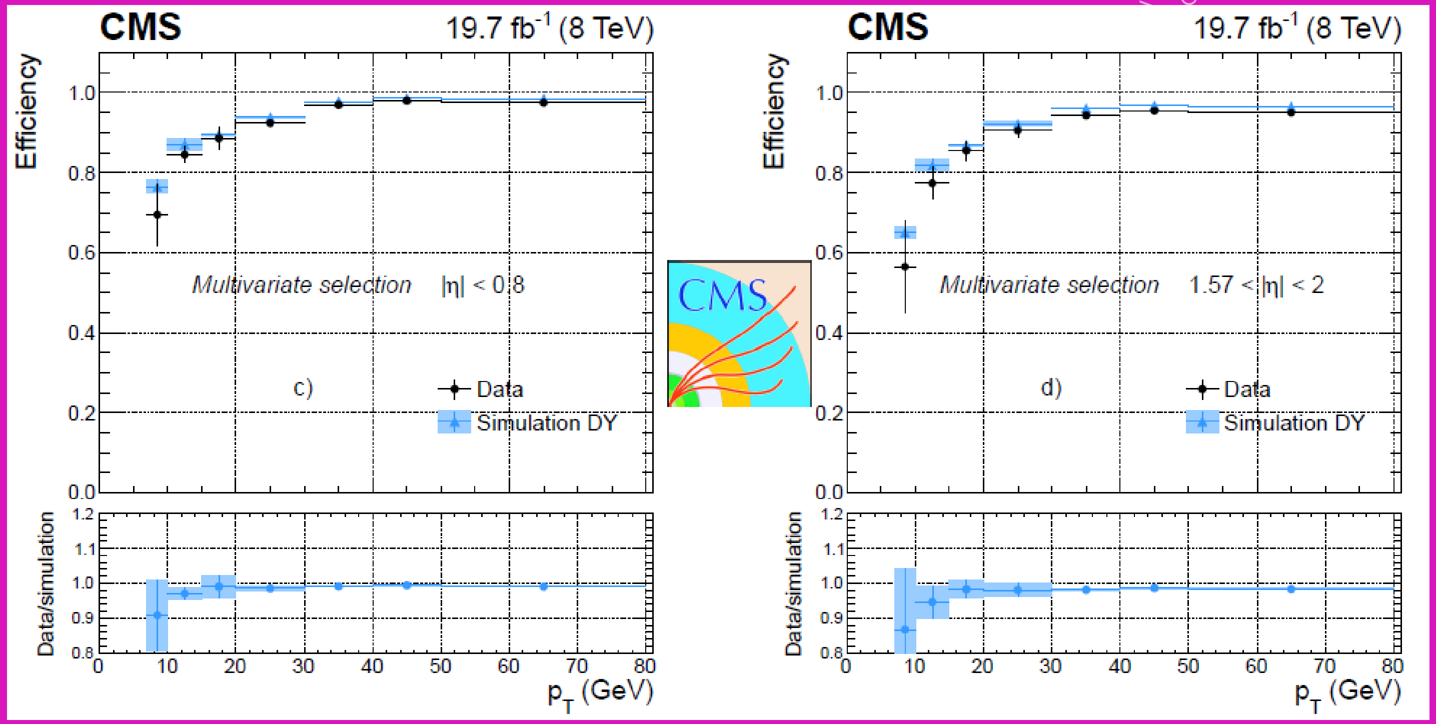
Apply Tag-and-Probe methods in Z->ee, J/ψ->ee and W->eν samples



Examples of efficiencies to electrons



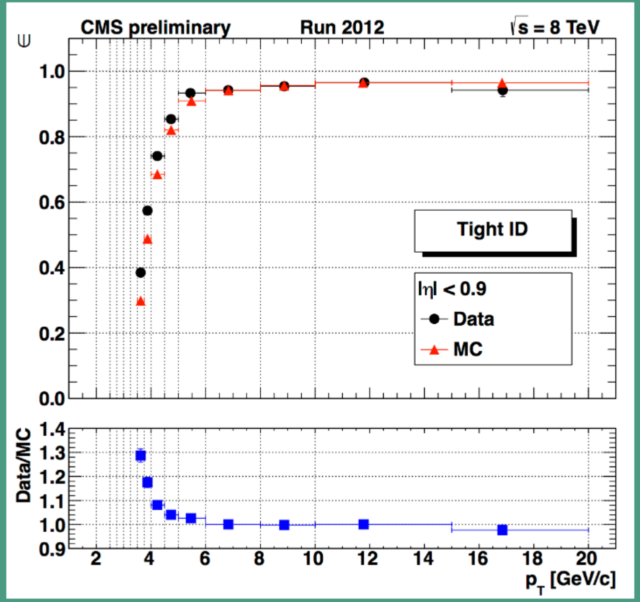


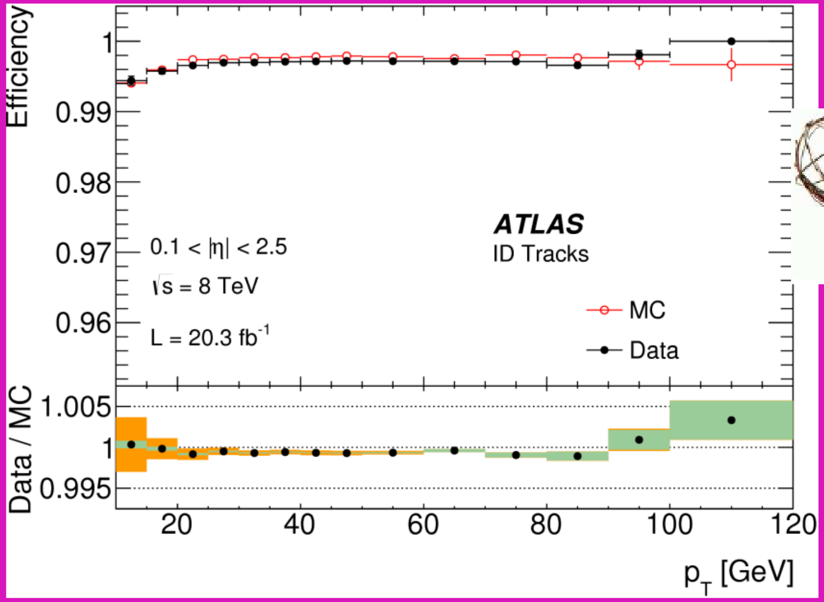
Several Identification menus with increasing rejection

Muons

Efficiencies and resolutions

Muons trajectories reconstructed from both muon spectrometer and inner detectors
Very high efficiency(99%)





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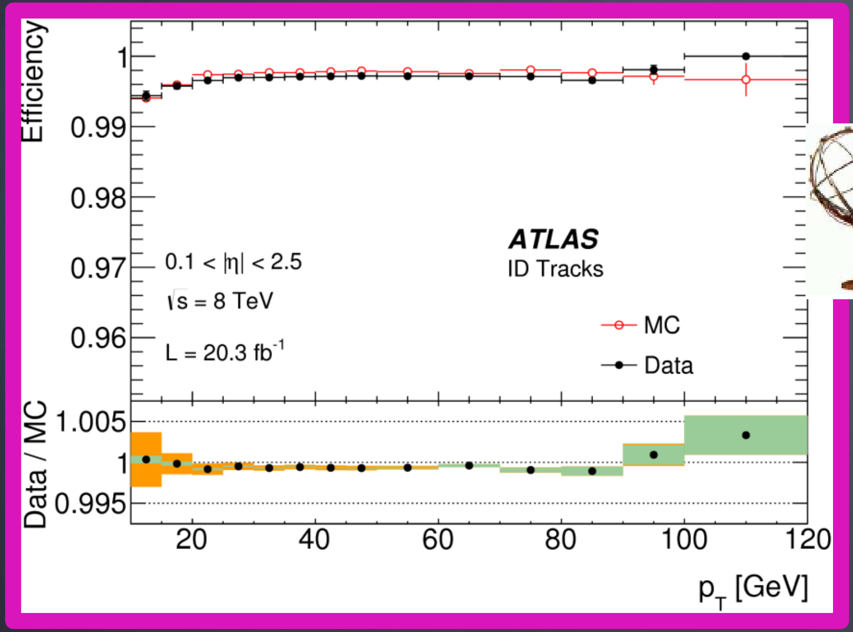
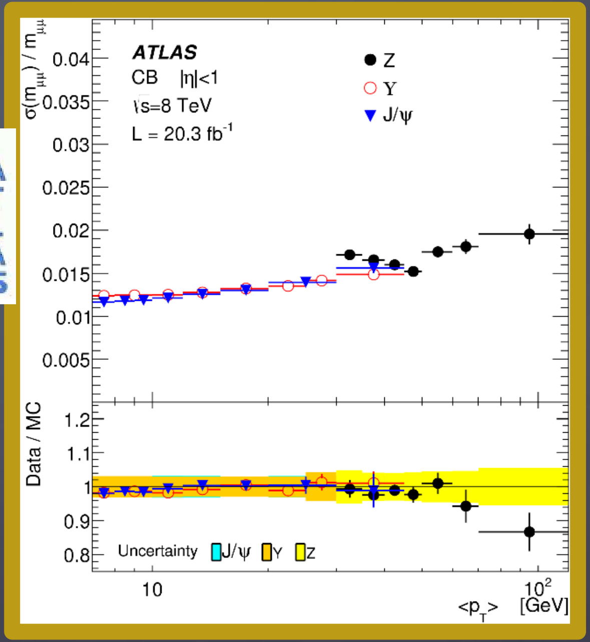
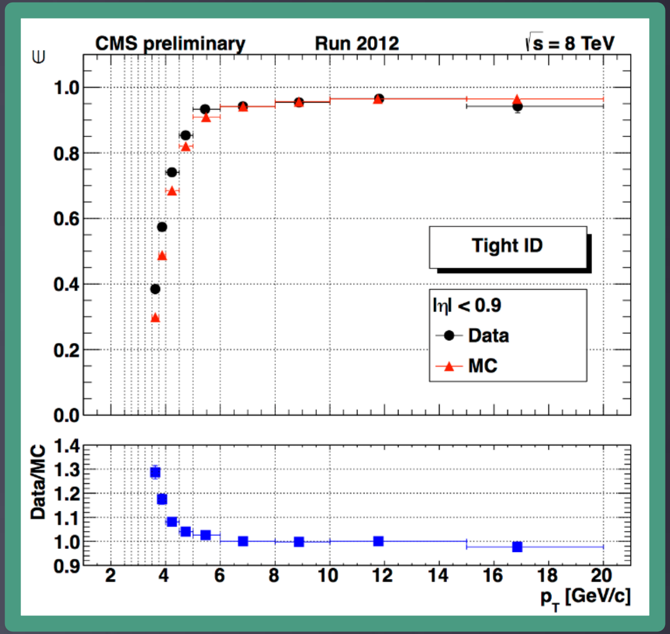


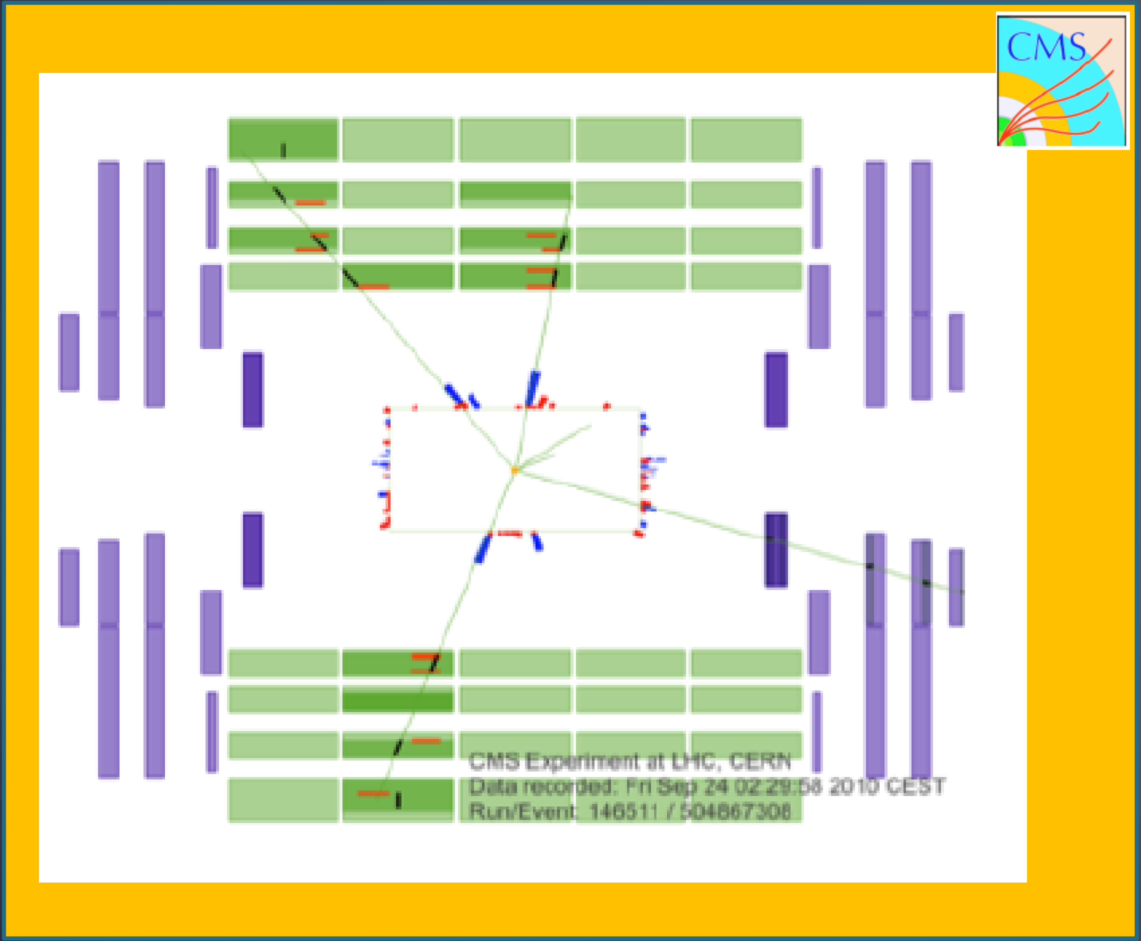


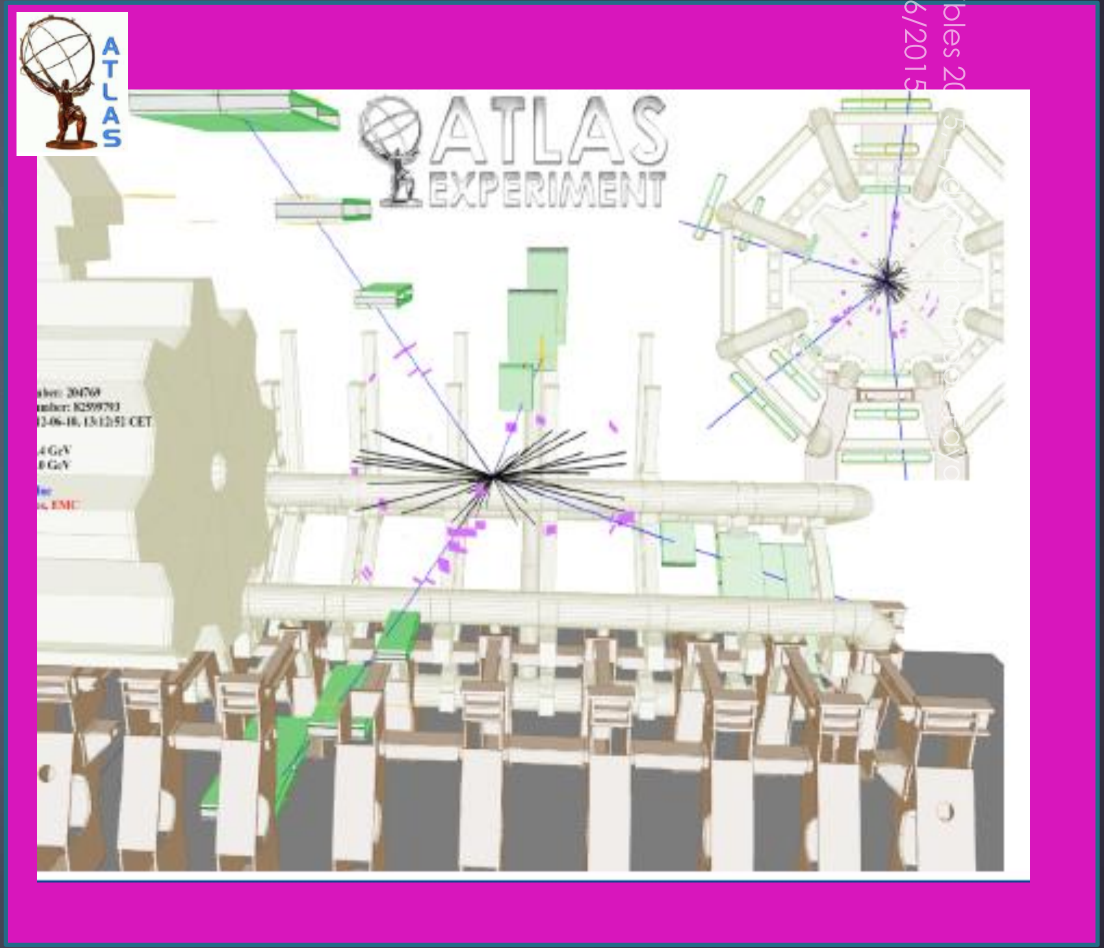


Momentum resolution

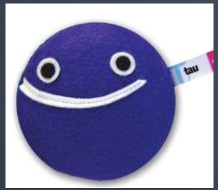
ATLAS : ~< 2% at 50GeV
CMS: ~1 % at 50GeV

Higgs->ZZ*->4muon candidates





Taus



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Tau Decays	Leptonic decays	Hadronic decays
	35.2%	
1-prong		46.7%
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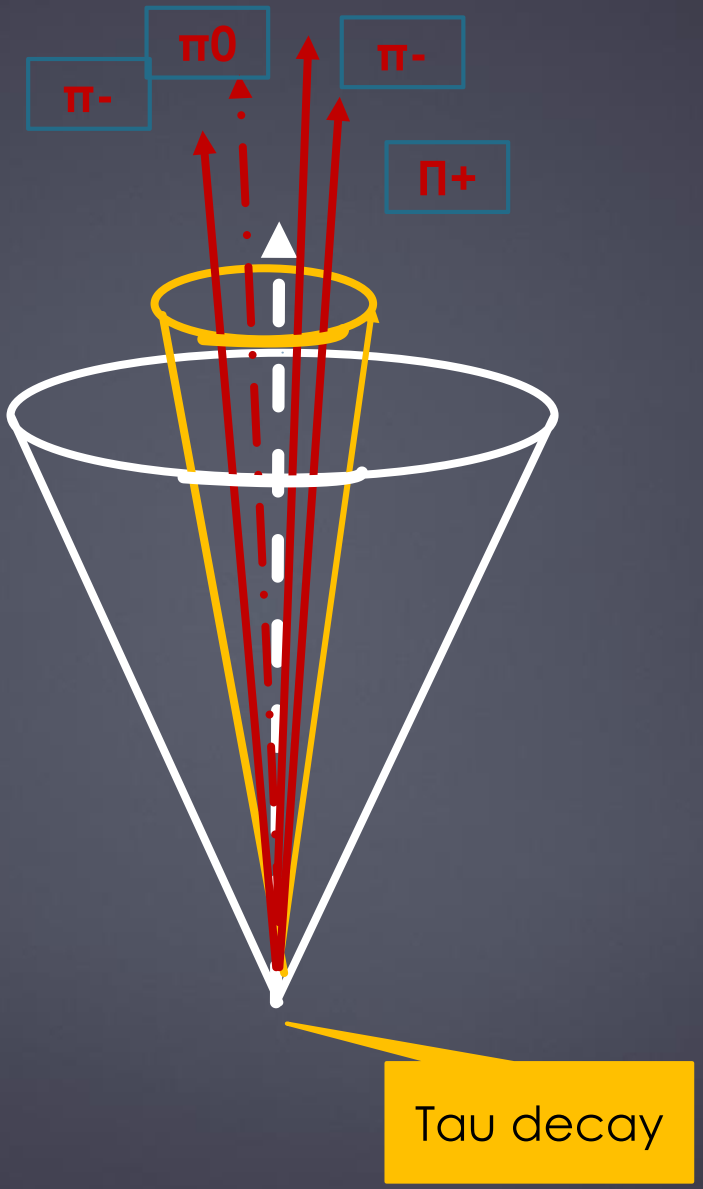

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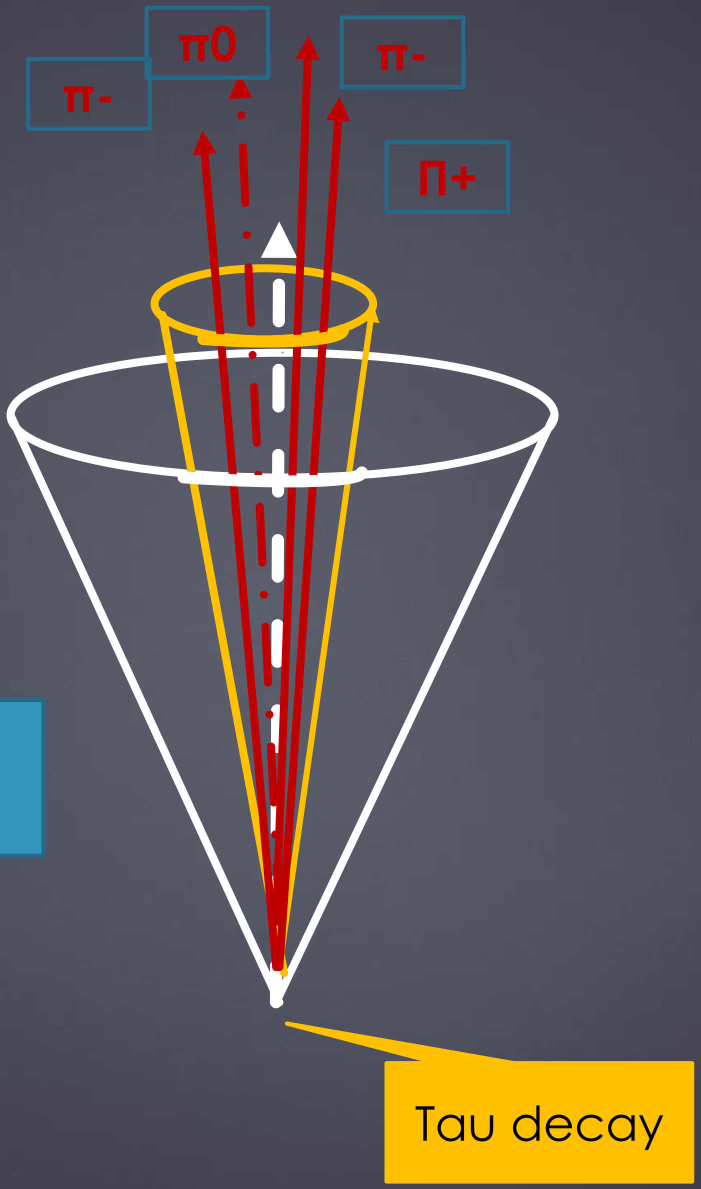

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➔ Small number of charged tracks
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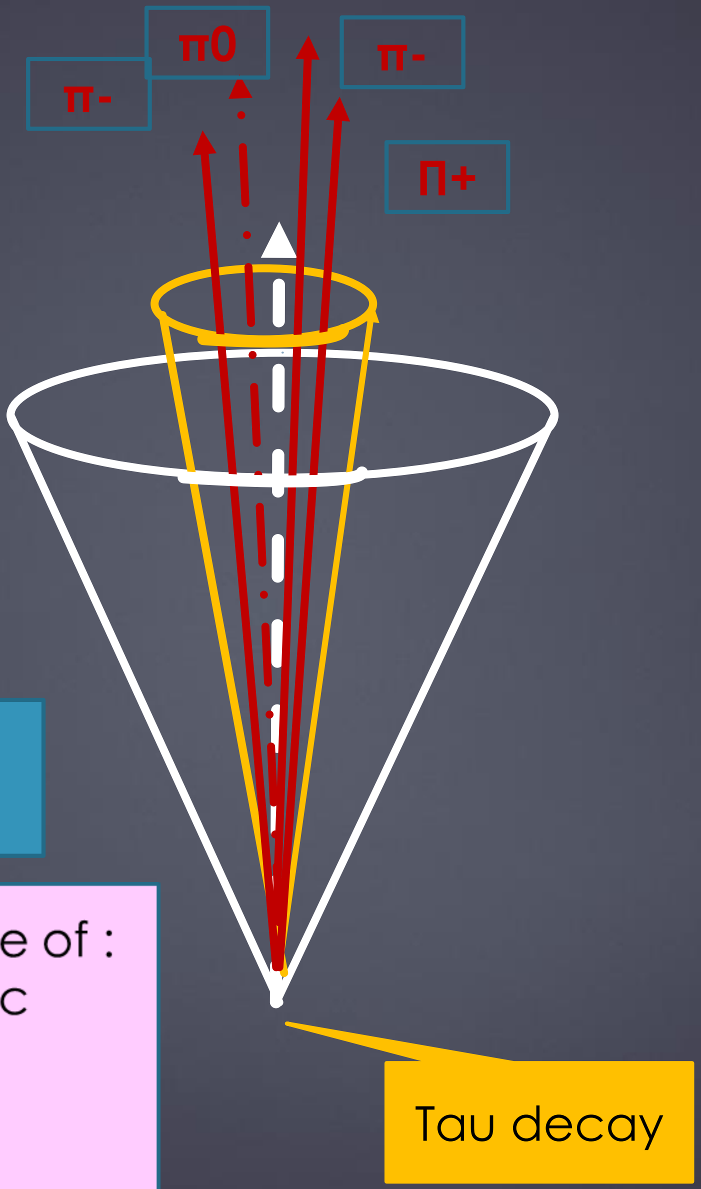

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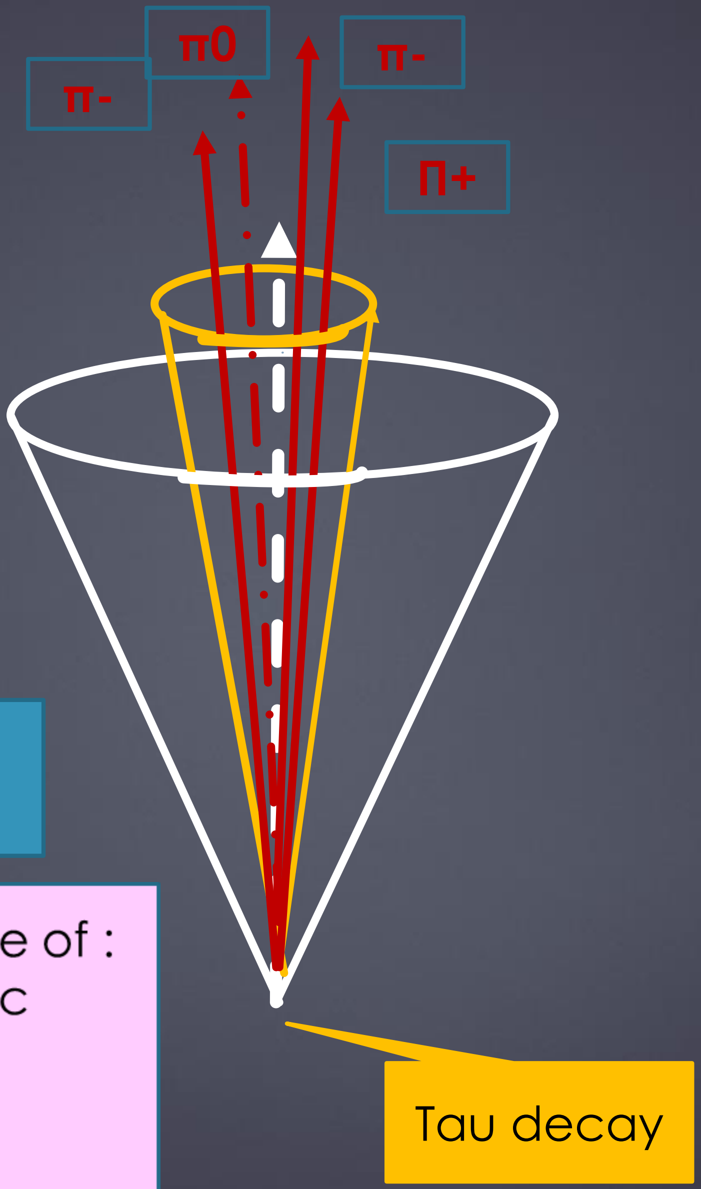

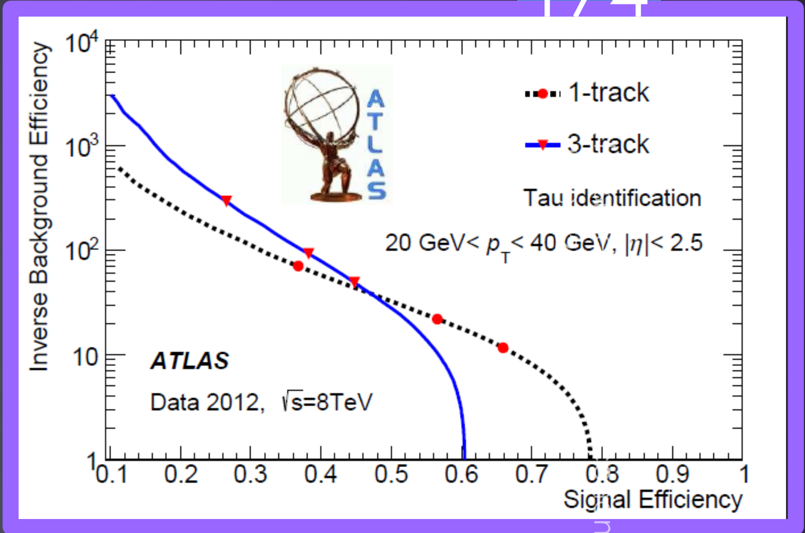

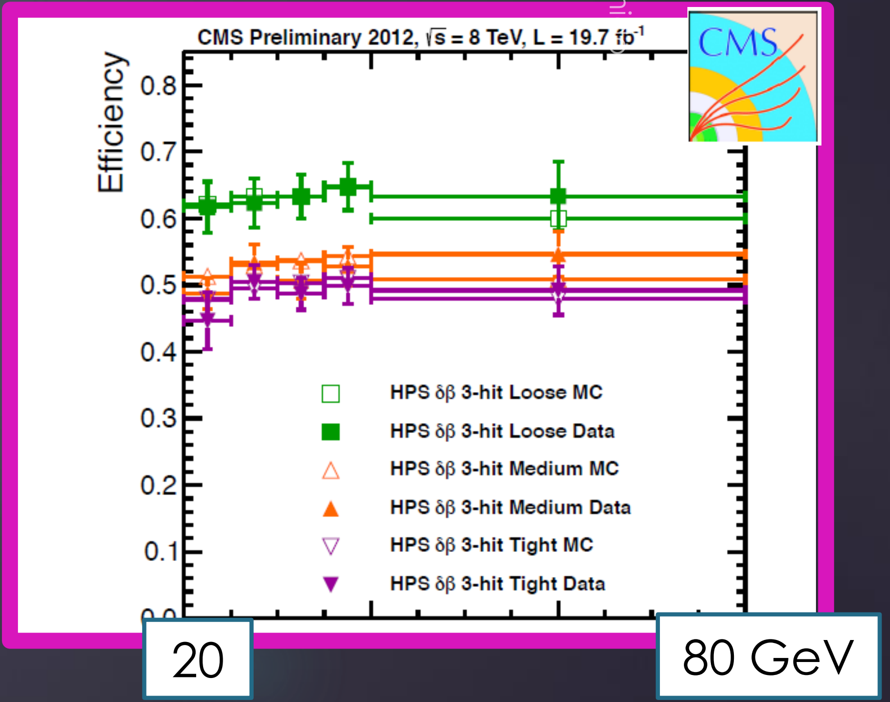

Parton Jets

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High energy partons undergo hadronization and appear in detectors as a spray of particles

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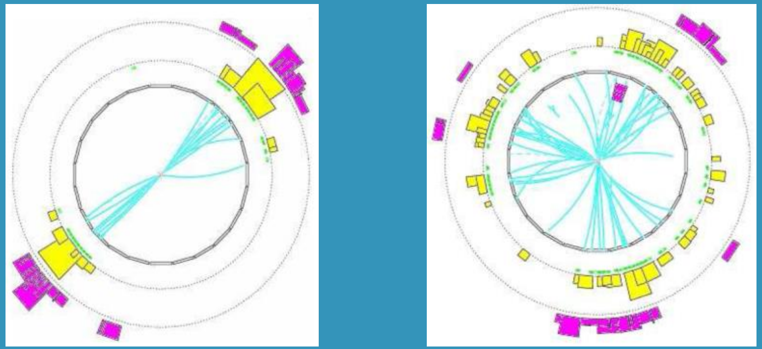

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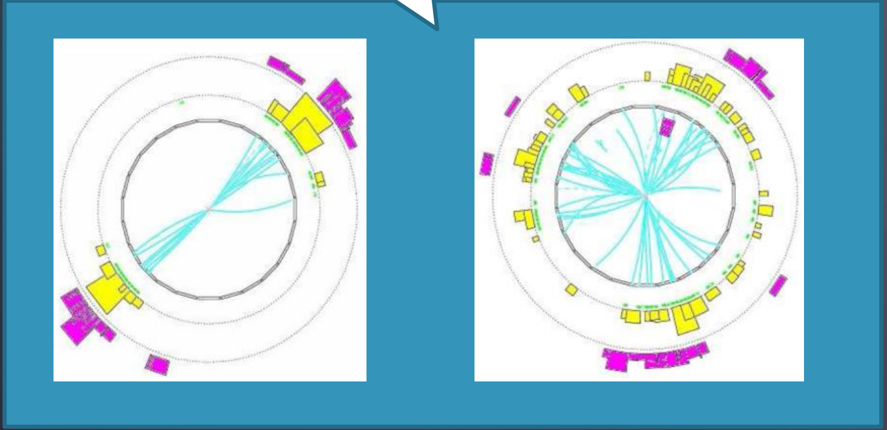

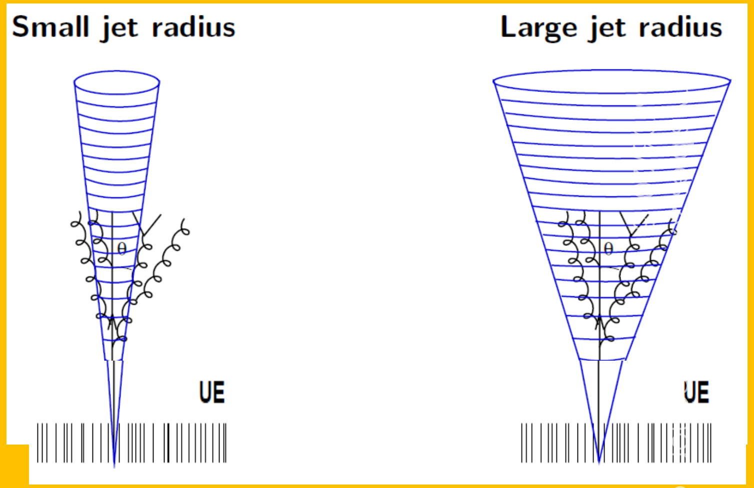

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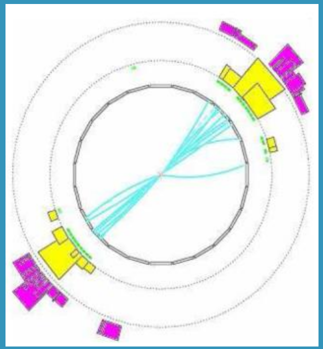
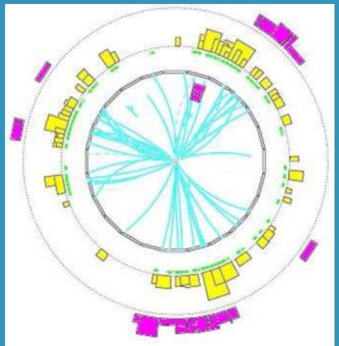
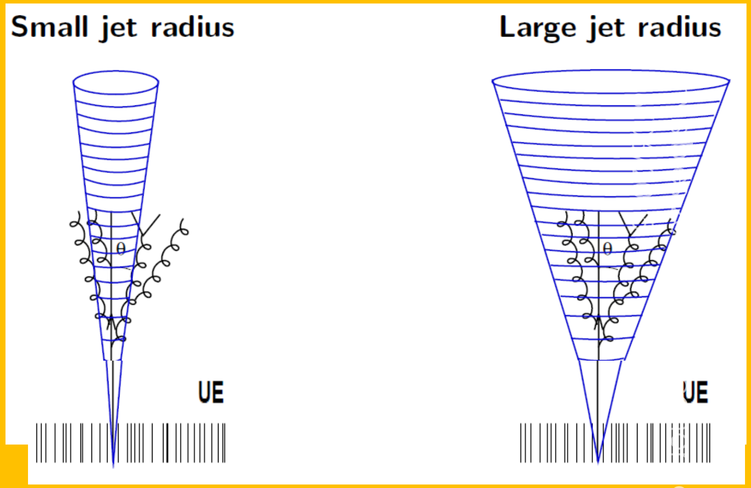
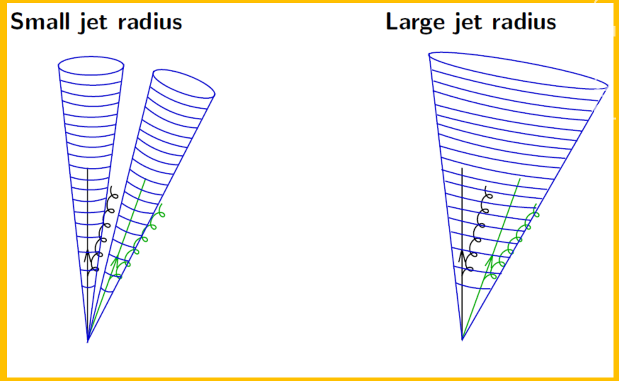




What size of cone?
Large size:
→better for energy containment
→ Bad for pileup, noise and jet separation





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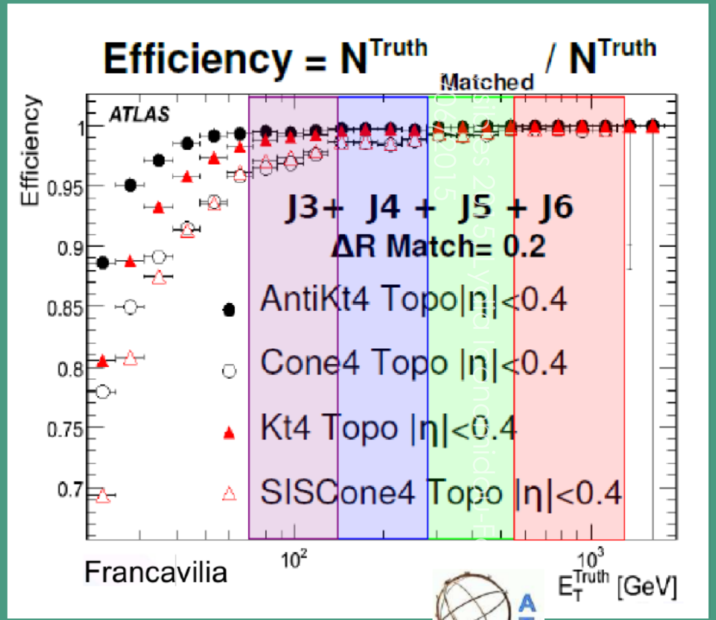

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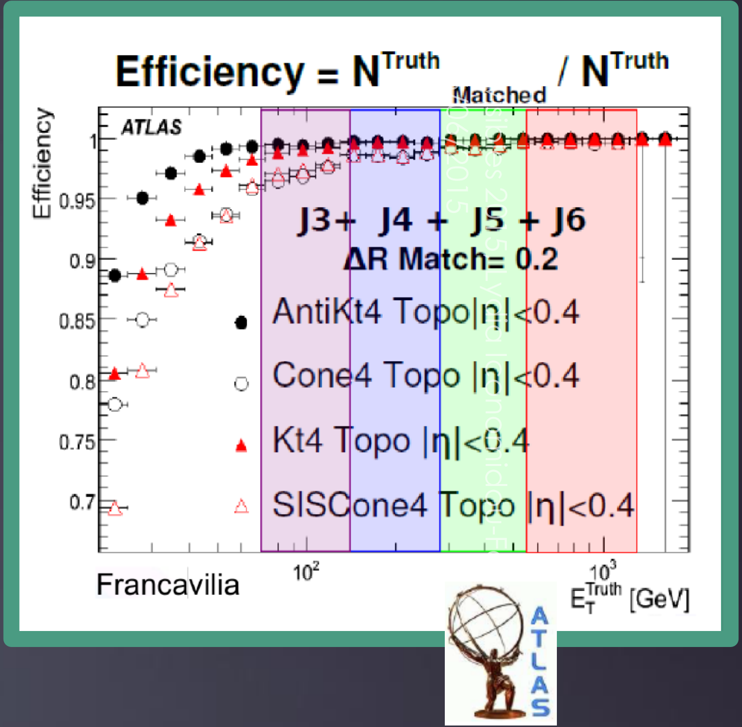

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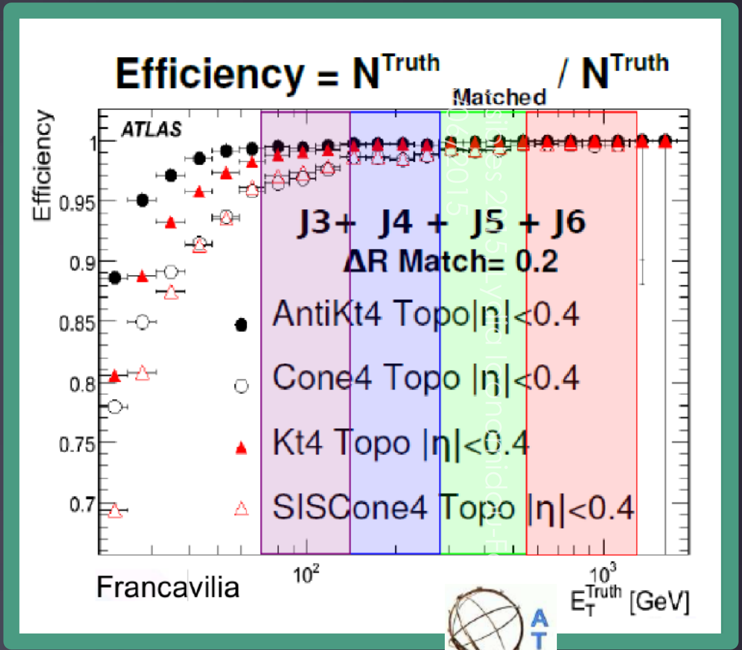

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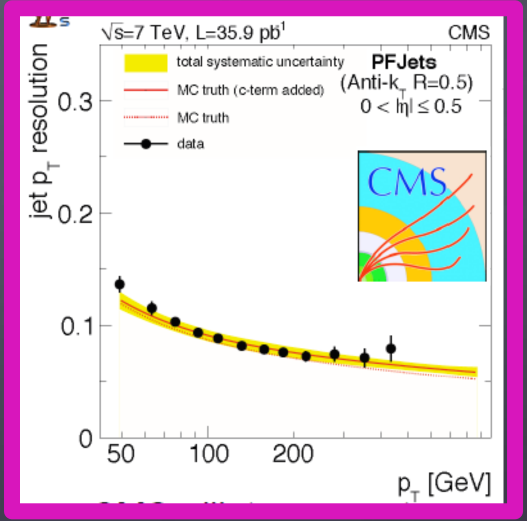

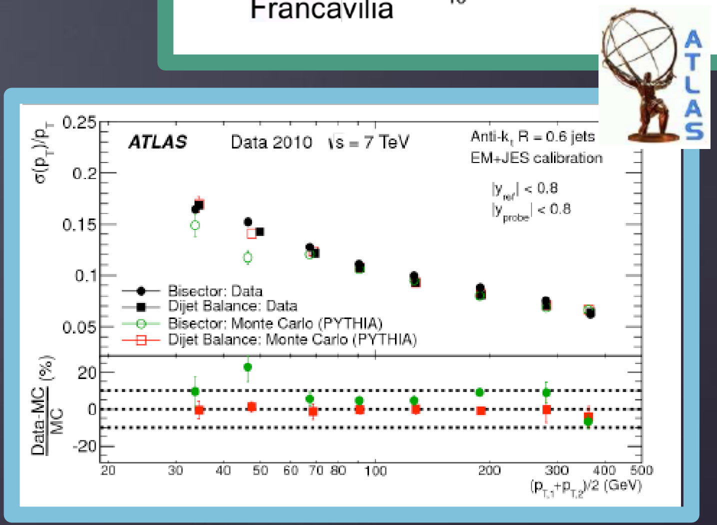

Looking for neutrinos and other ghost particles


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Signature of neutrinos and of new Physics

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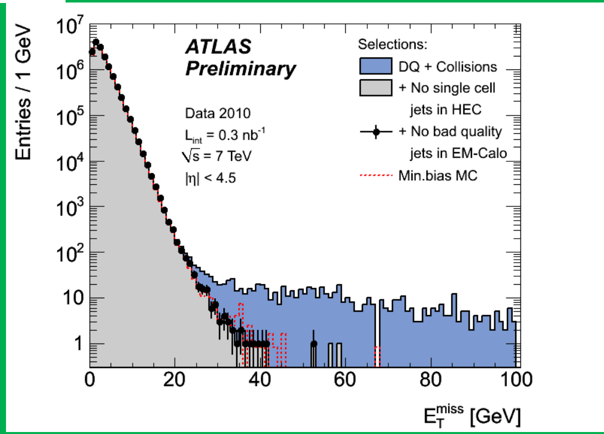
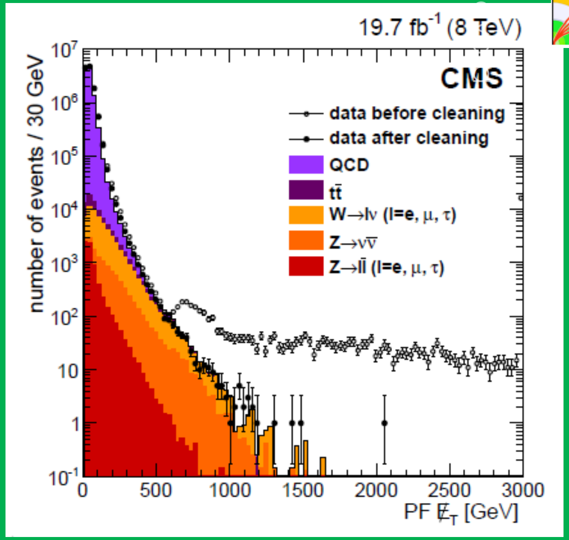
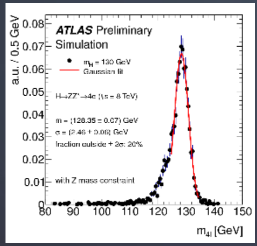
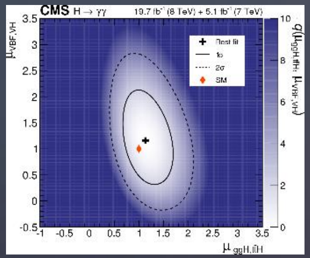
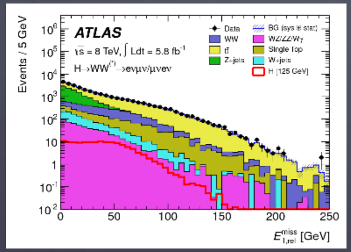


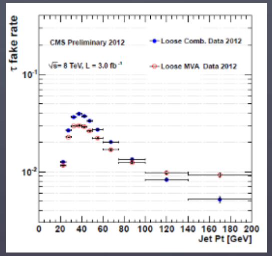


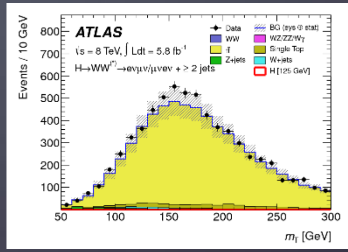
The analyses to identify the Higgs decays and properties

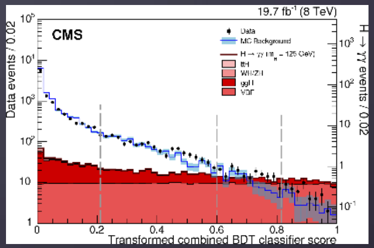




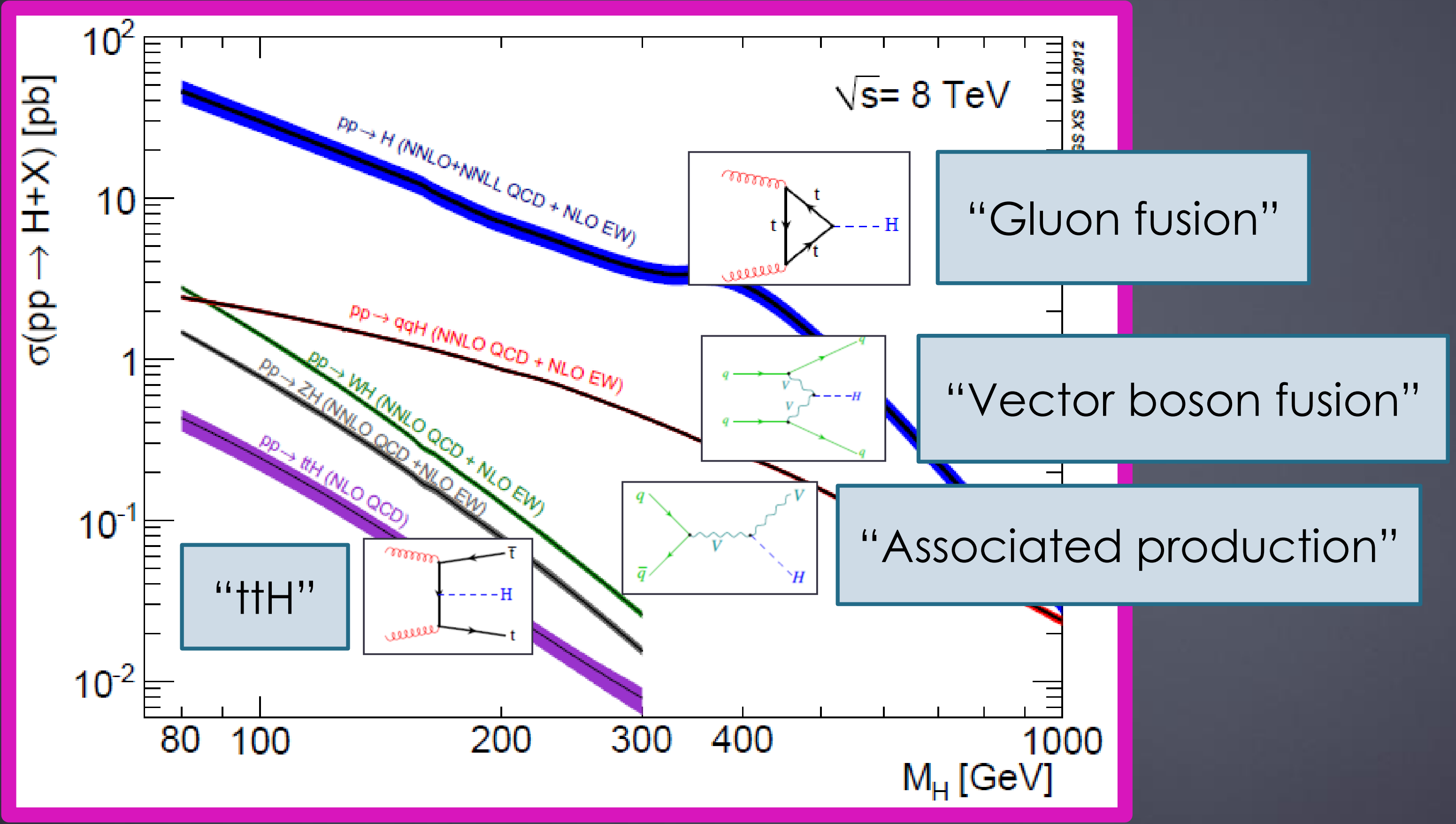








The production channels of the Scalar Boson



For MH=125 GeV

8 TeV	**13TeV**
VBF/ggF ~ 1/12	ggF~x2.3
VH/ggF ~ 1/17	VBF~x 2.4
ttH/ggF ~1/150	VH ~ x.2.0
	ttH ~x3.9

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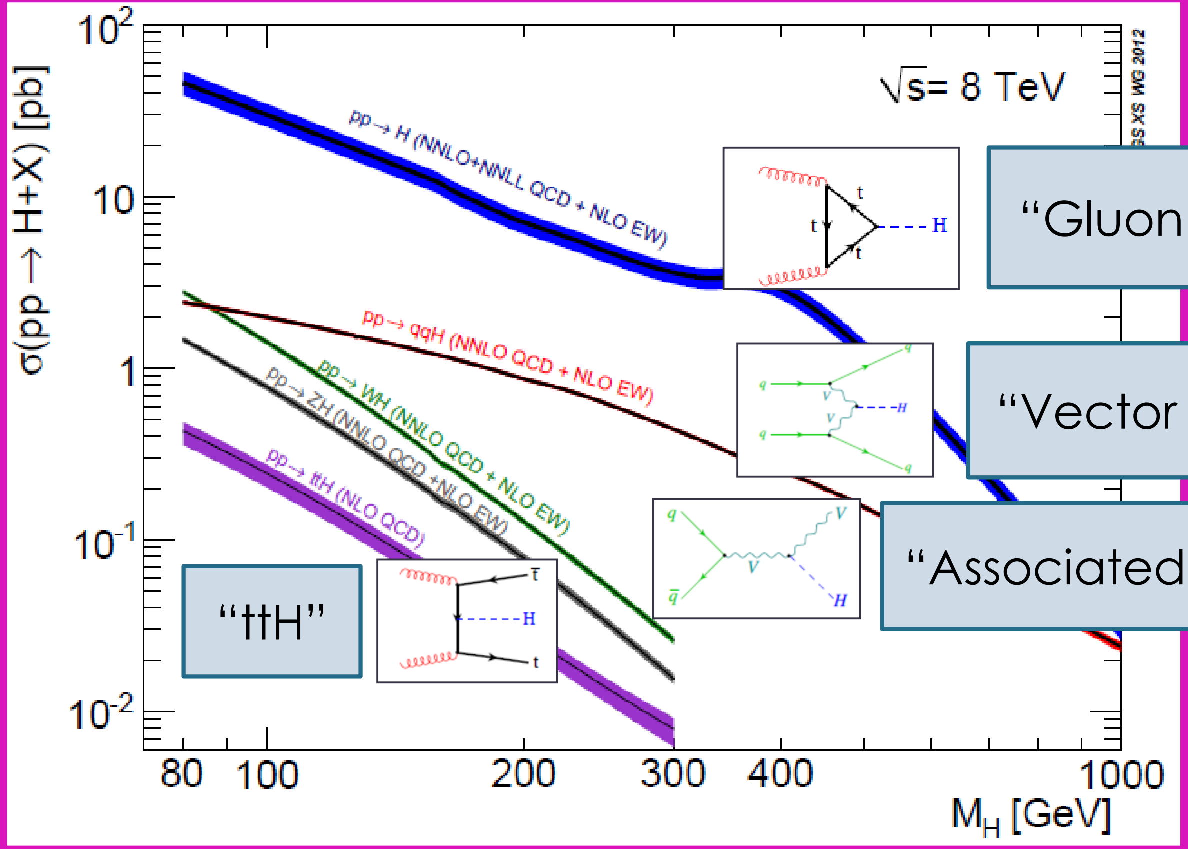

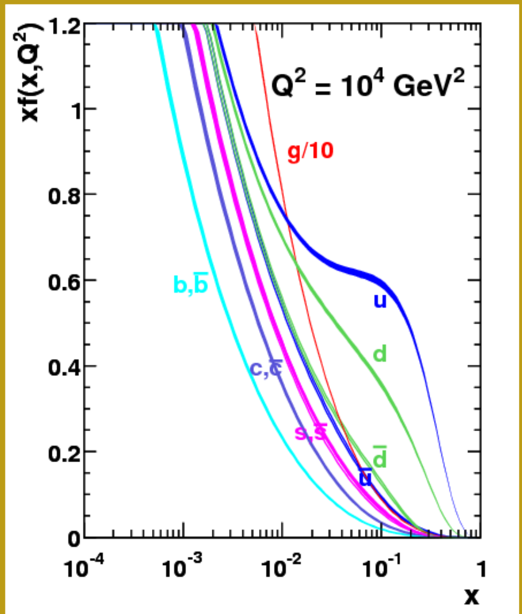

At LHC √S~8TeV
For M~100GeV
X ≈ M/√S = 0.01

For MH=125 GeV

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VBF/ggF ~ 1/12	ggF~x2.3
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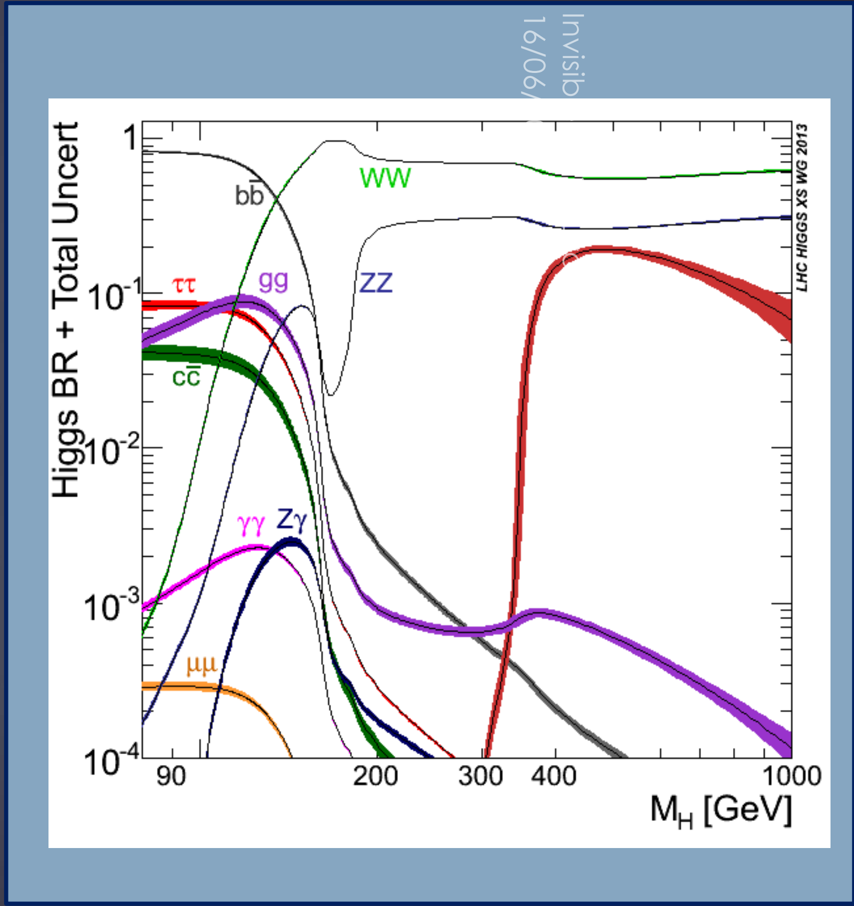
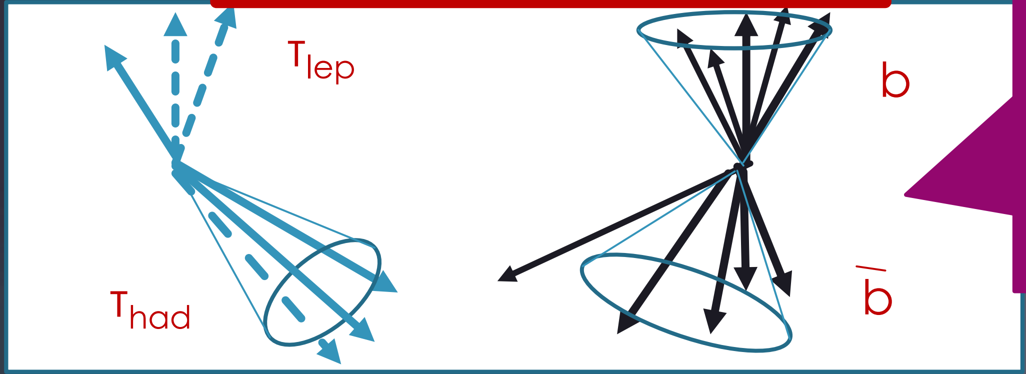
The decay channels of the Scalar Boson



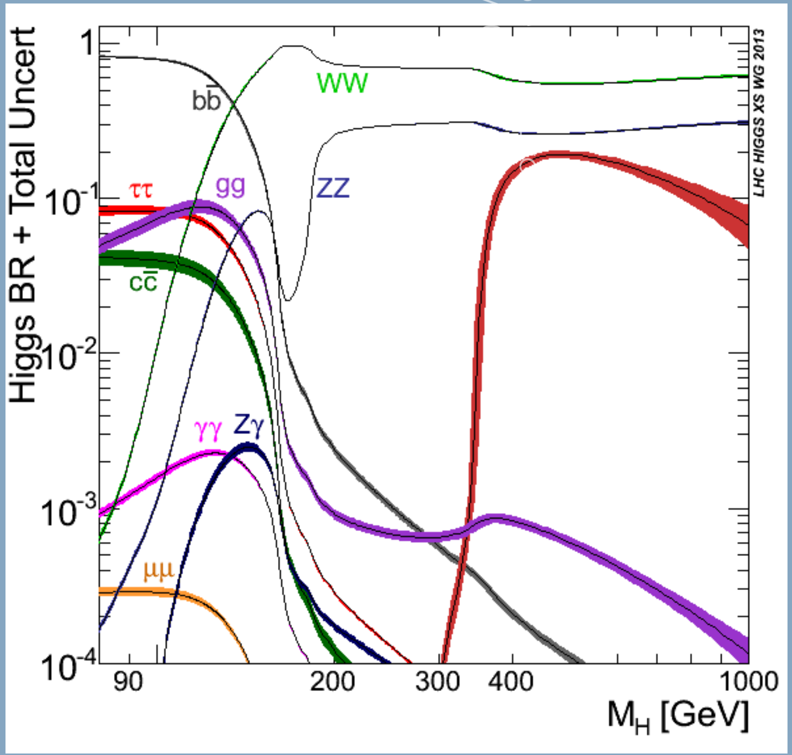
The decay channels of the Scalar Boson

The "abundant" channels



H->bb, H->τ τ :
The highest couplings to the Scalar Boson at ~125GeV

BUT signed by "jets"
Difficult to disentangle from the overflowing QCD background



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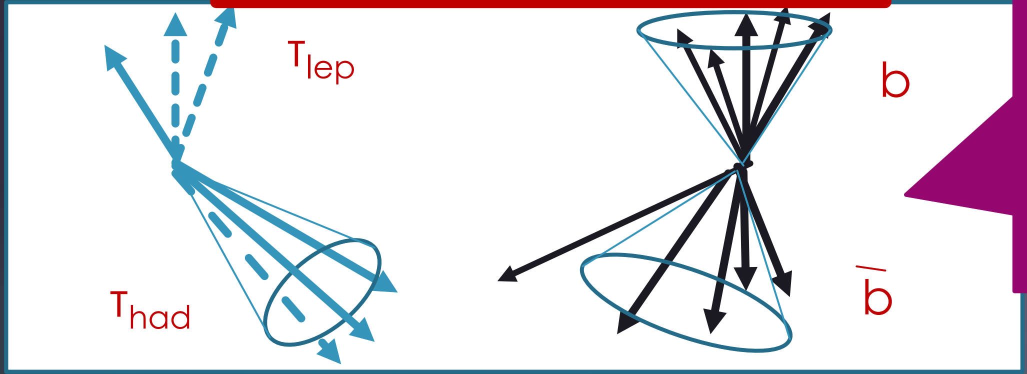

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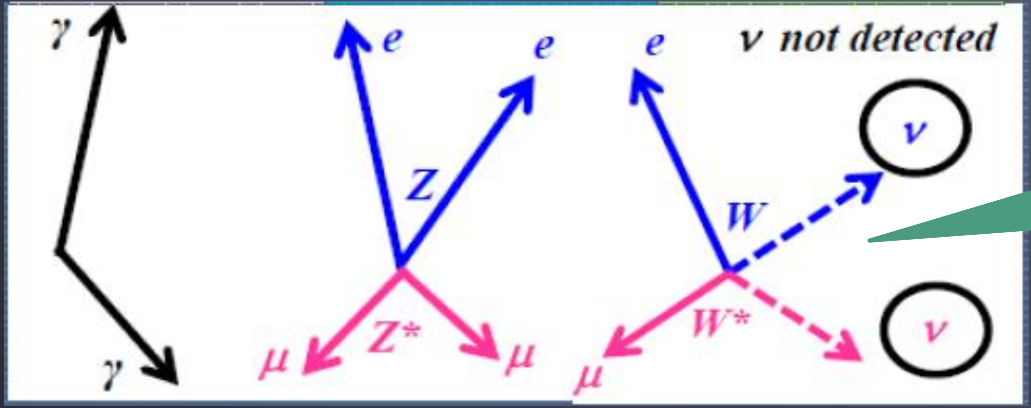
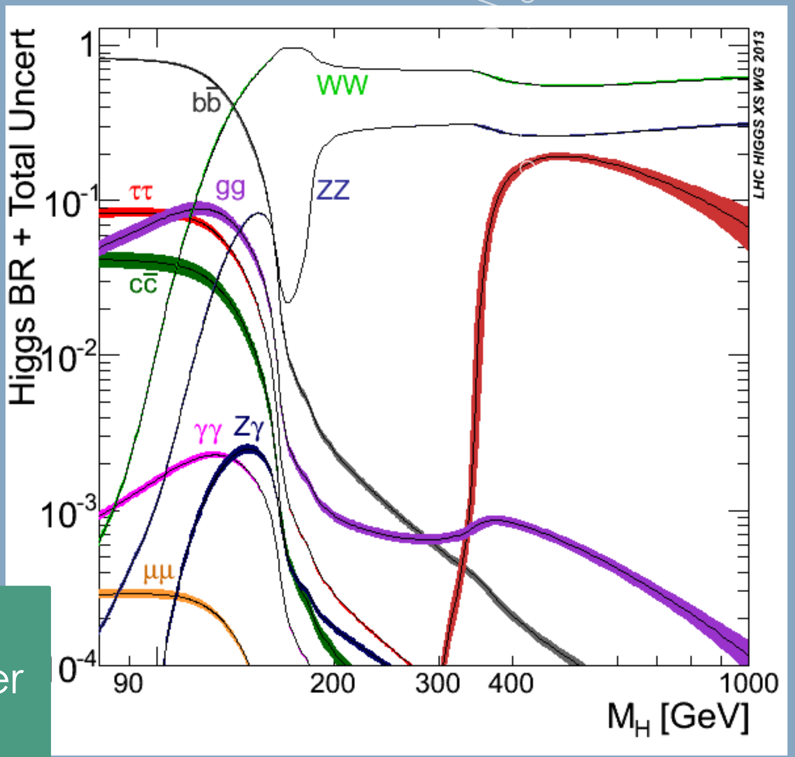
The "easier" channels



H->γγ, H->ZZ, H->WW
Leptonic final states, lower rates BUT
"Easy" to distinguish



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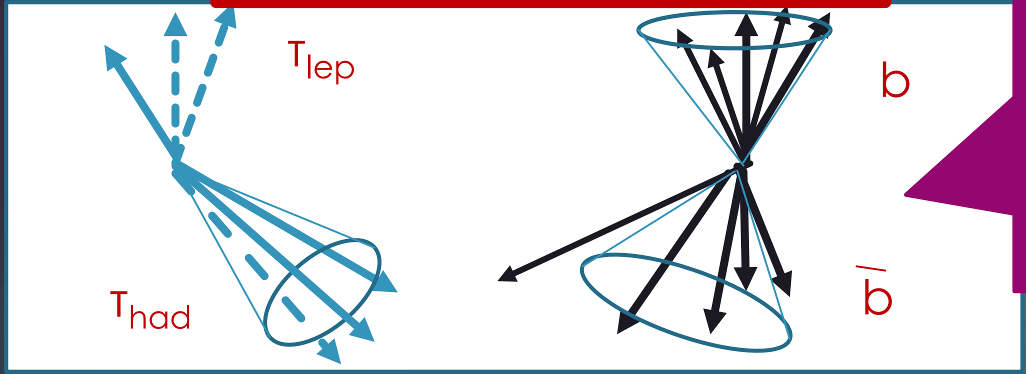

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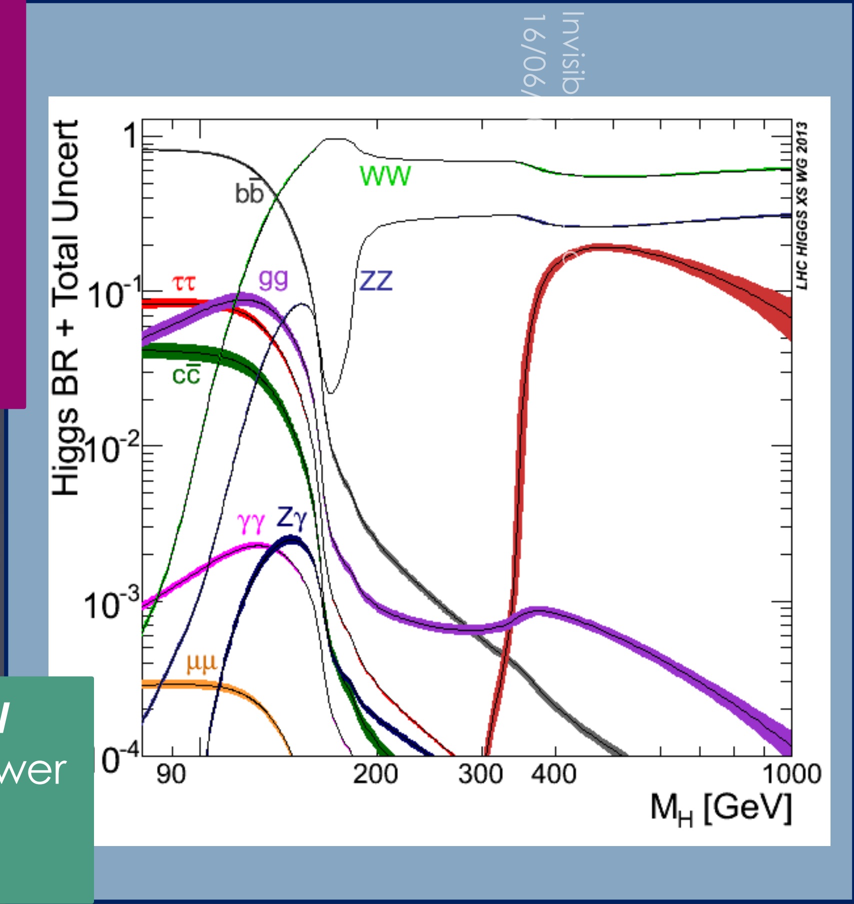

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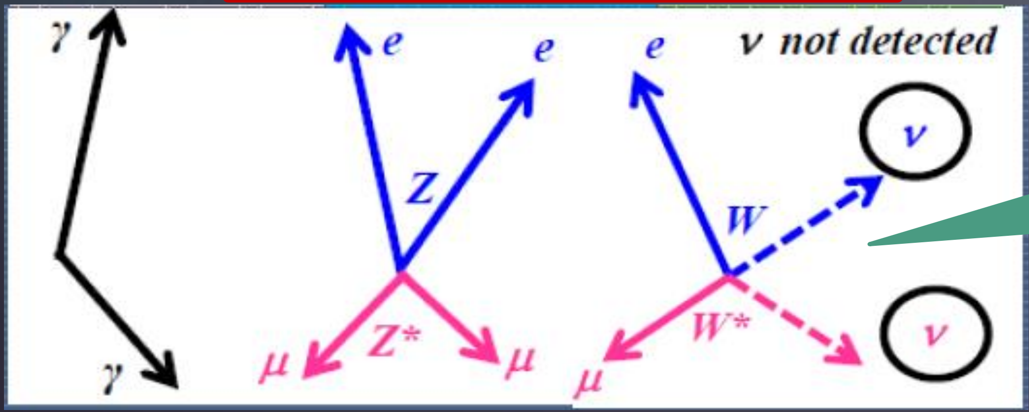

H->γγ, H->ZZ, H->WW
Leptonic final states, lower rates BUT
"Easy" to distinguish

Allow precise mass determination if final state is fully contained

Discussed points

In the following we give the description of the main analysis tips for:

- The main decay channels (observation or-and evidence)
- The Scalar boson mass measurement
- The Scalar boson couplings
- The Scalar boson properties

H->γγ : the historical channel

- ➔Clean signature: 2 isolated high P_T photons.
- ➔ P_{T1}>40GeV P_{T2}>30GeV
- ➔ **Look for a bump in the diphoton mass spectrum**
- ➔Small S/B ~ 0.03

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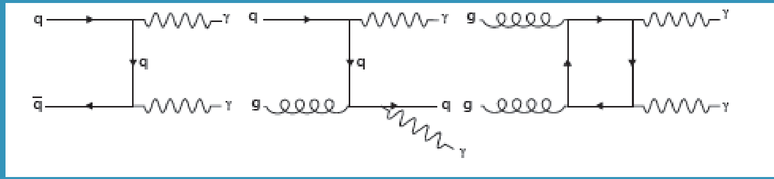
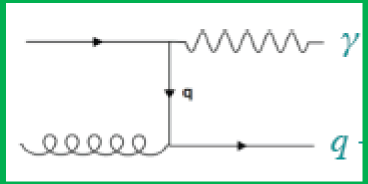
➔ Irreducible background:



Non resonant in Mγγ

➔ Reducible:
γ+Jet (π0),
Jet(π0)+Jet(π0)



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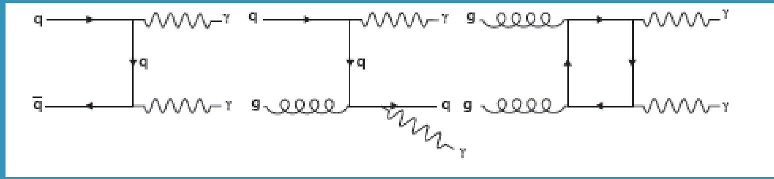

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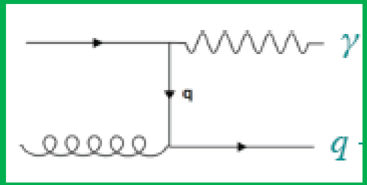
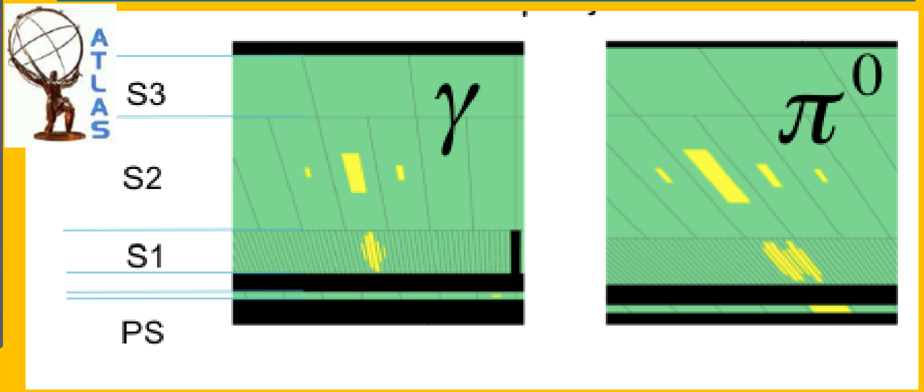


ATLAS

Make use of the fine granularity of the first calorimetric layer.

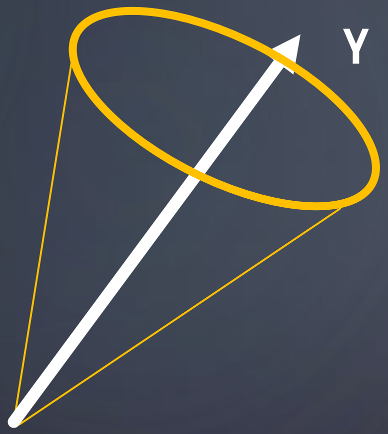


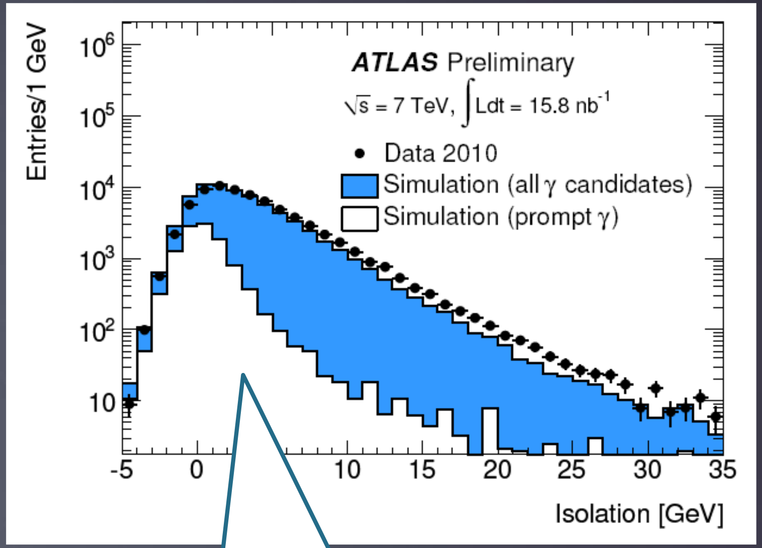
Opening angle of the two photons of a π^0 of P_T=40GeV is ≥0.007, to be compared with strip size=0.003

H->γγ : Measure the Reducible background

A fake photon (mis-identified jet or photon in jet) is surrounded by energy.

➔ Use "isolation" to disentangle genuine from fake photons





Genuine photons
Well isolated

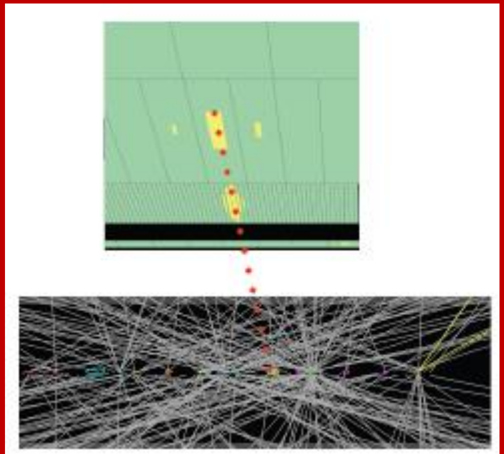
Data driven technic
Use isolation to count and identify the background pollution in regions without signal

H->γγ : The Di-Photon mass spectrum

$M^{2}_{\gamma\gamma} = 2\ E1E2\ (1-\cos\theta)$

→Energies from Calo

→Photon direction from likelihood including the Calo pointing (thanks to the 3-layer segmentation)



Vertex resolution ~ 1.5cm

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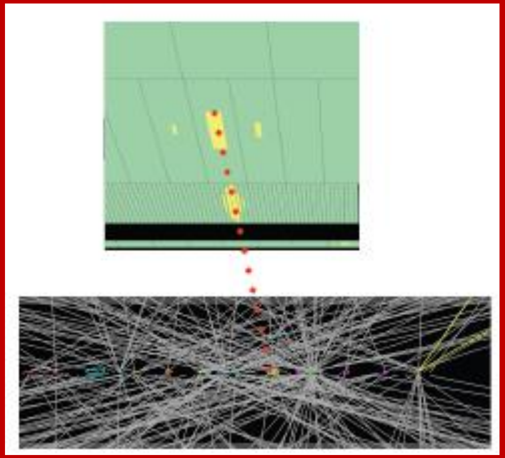

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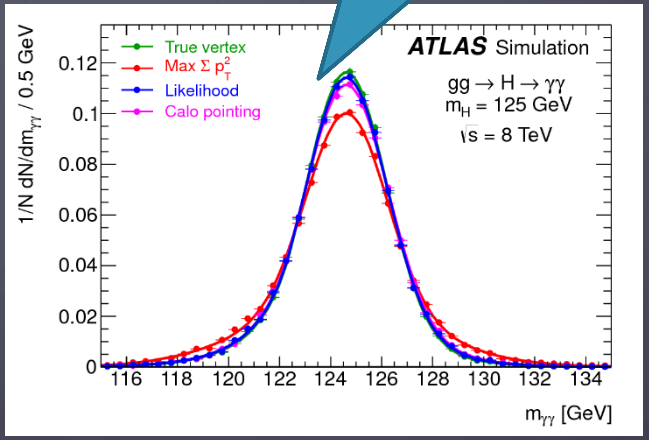
Calo pointing very close to truth. Likelihood improves further the agreement



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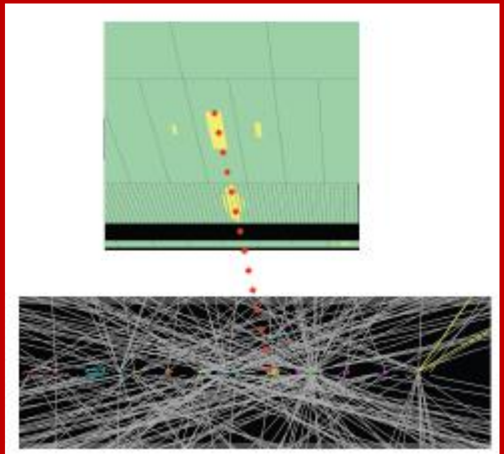

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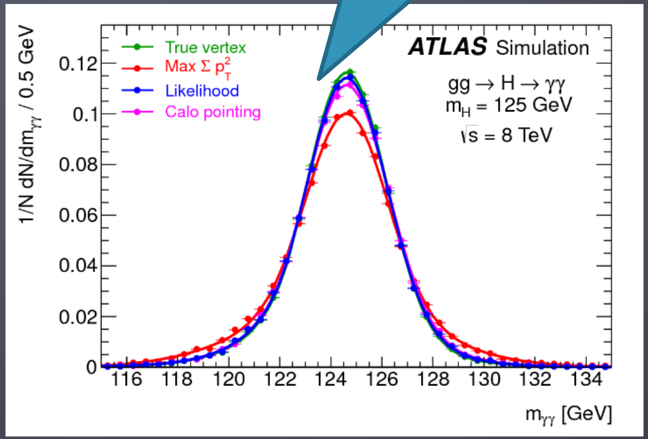
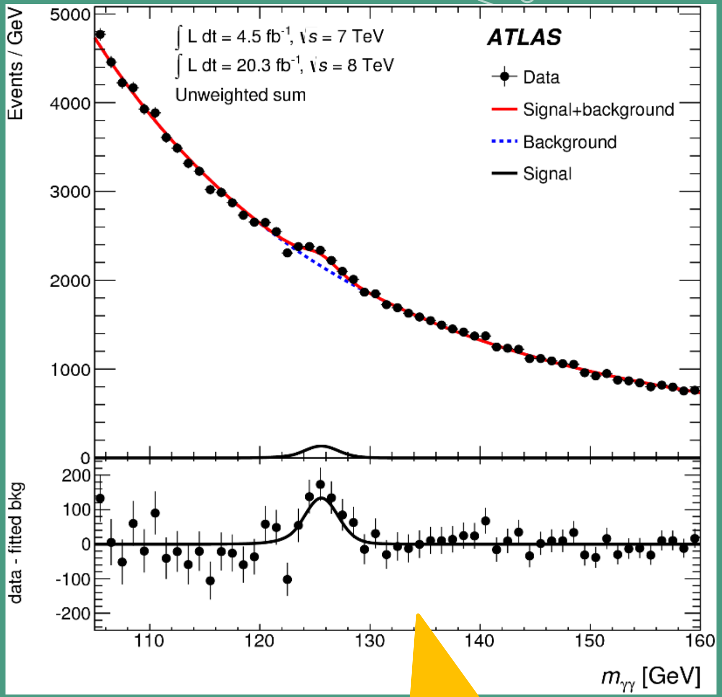
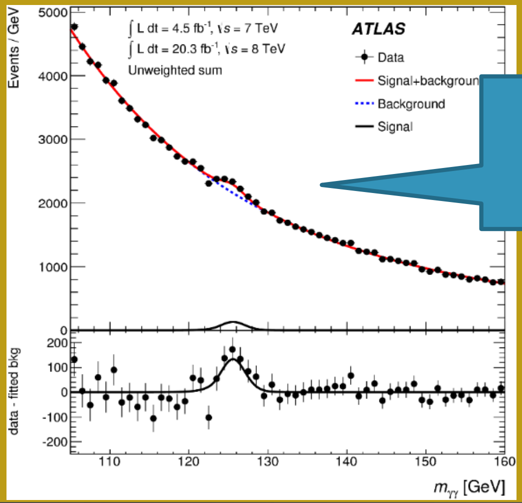




Final state contained
Nice mass peak!

How to extract the "most significant" result from the data?



Inclusive plot

Detector resolution, systematic effects and background yields vary with some kinematical photon variables:
PT, η, conversion status etc..

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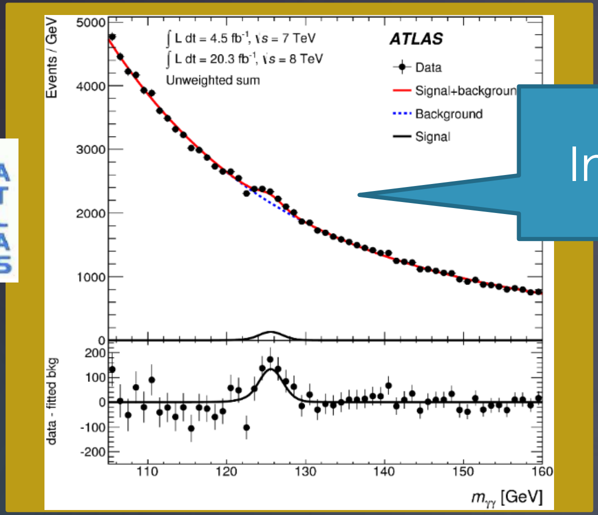

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Split the data in exclusive appropriate categories to optimize the S/B ratios

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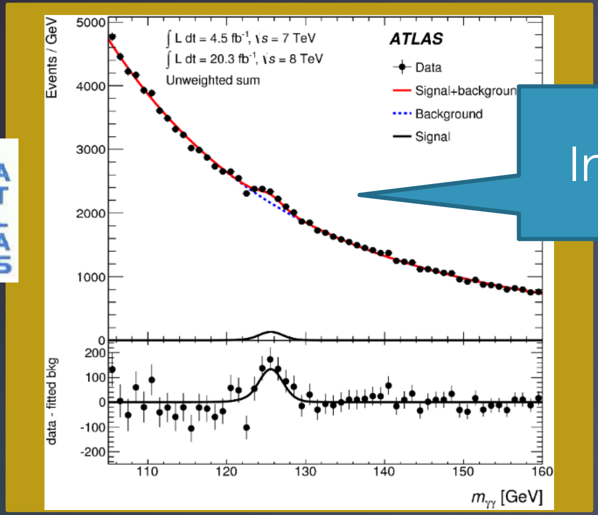


Inclusive plot

Detector resolution, systematic effects and background yields vary with some kinematical photon variables: PT, η, conversion status etc..

Split the data in exclusive appropriate categories to optimize the S/B ratios

Category	n_{sig}	FWHM [GeV]	b in $\pm\sigma_{eff90}$	s/b [%]
		$\sqrt{s}$=8 T		
Inclusive	402.	3.69	10670	3.39
Unconv. central low p_{Tt}	59.3	3.13	801	6.66
Unconv. central high p_{Tt}	7.1	2.81	26.0	24.6
Unconv. rest low p_{Tt}	96.2	3.49	2624	3.30
Unconv. rest high p_{Tt}	10.4	3.11	93.9	9.95
Unconv. transition	26.0	4.24	910	2.57
Conv. central low p_{Tt}	37.2	3.47	589	5.69
Conv. central high p_{Tt}	4.5	3.07	20.9	19.4
Conv. rest low p_{Tt}	107.2	4.23	3834	2.52
Conv. rest high p_{Tt}	11.9	3.71	[illegible]	7.44
Conv. transition	42.1	5.31	[illegible]	1.92

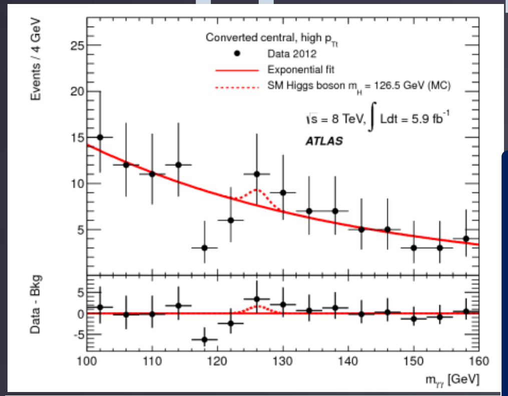
Nb of signal events

Resolution

Nb of backg. events

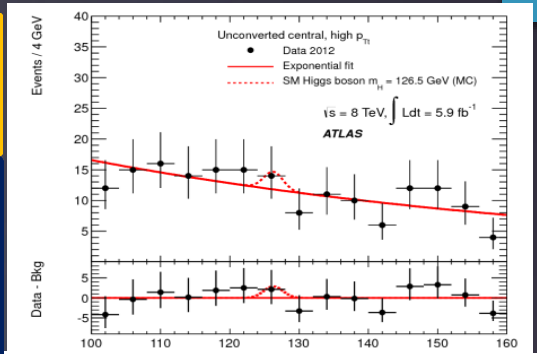
S/B ratio

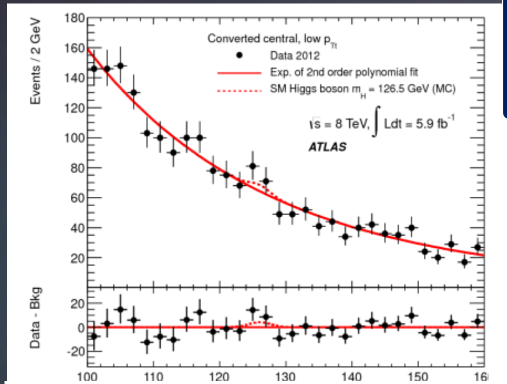
H->γγ : Diphoton mass spectra

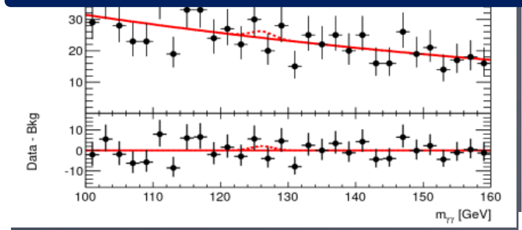


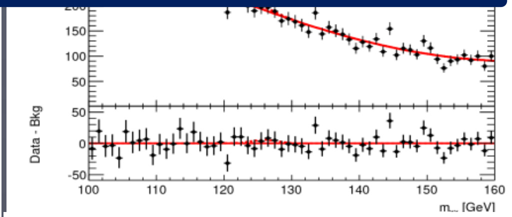
In each Category:

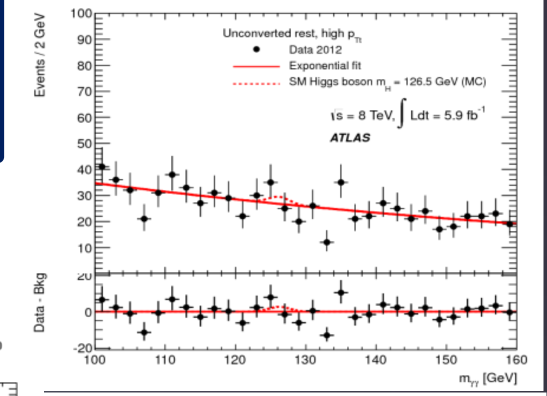
Fit of the signal :
Use a Crystal-Ball function for the bulk of events and a wider Gaussian for tails. Function parameters depend on the category and are extracted from MC

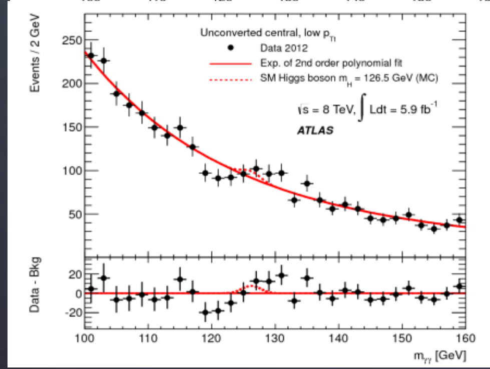


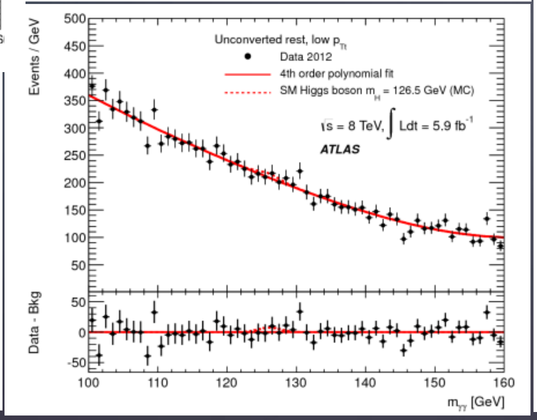


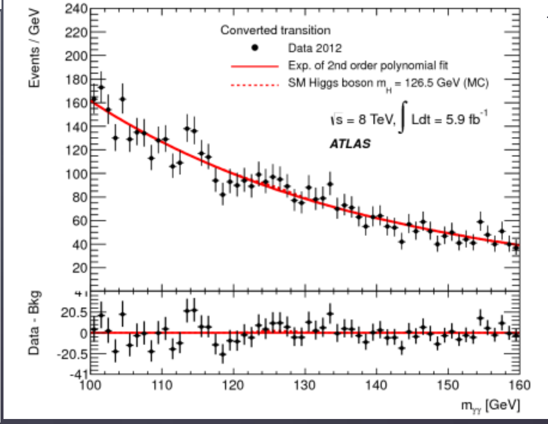


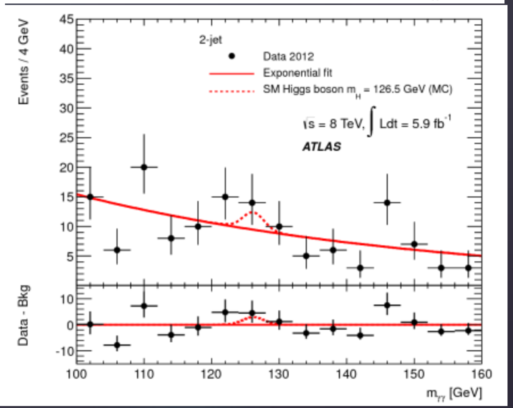




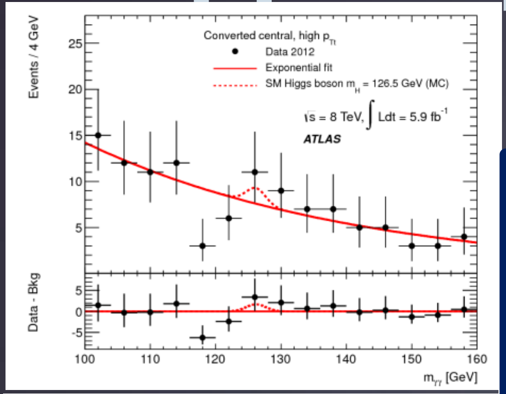


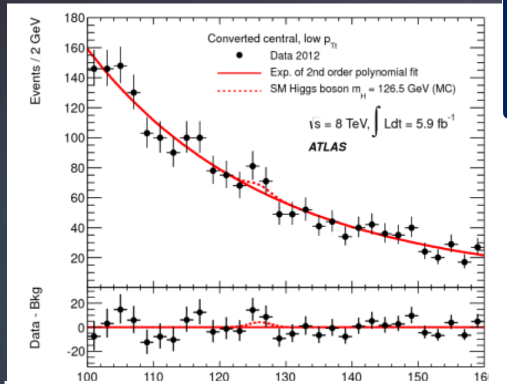


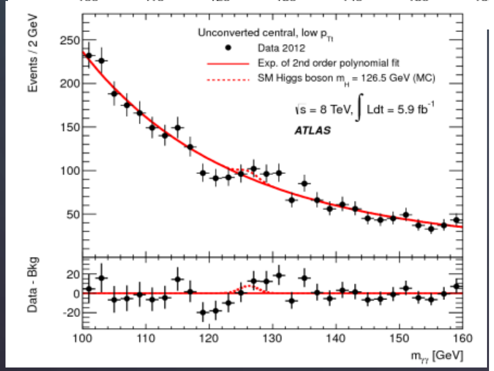


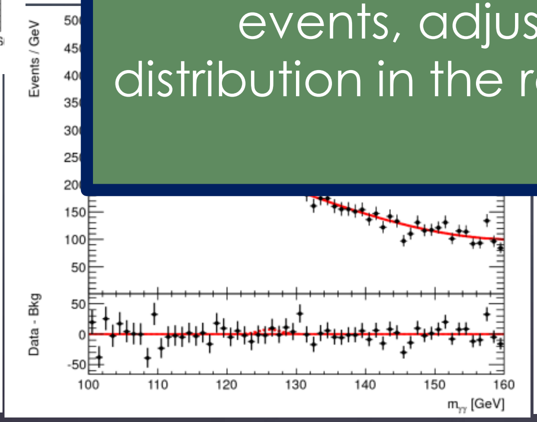


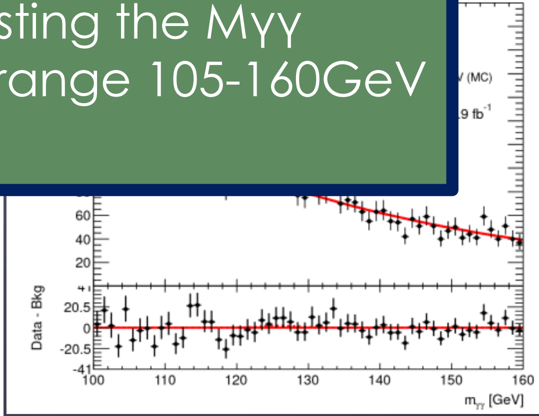
H->γγ : Diphoton mass spectra

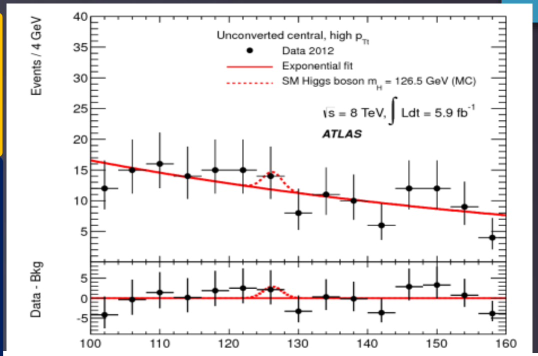


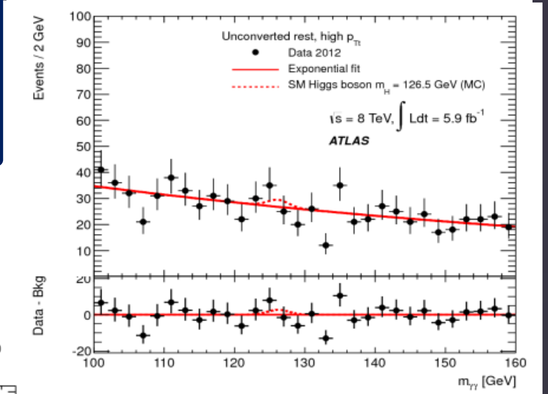


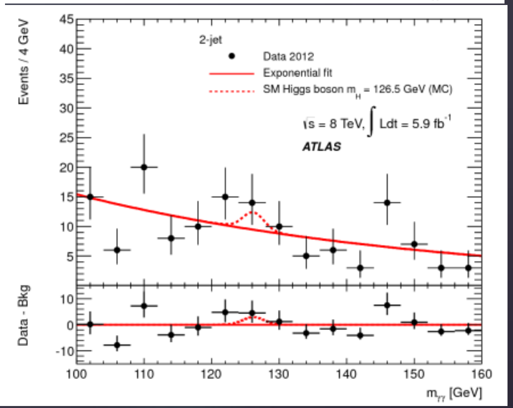












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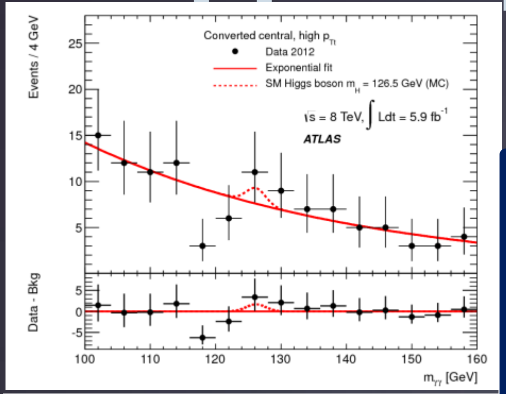

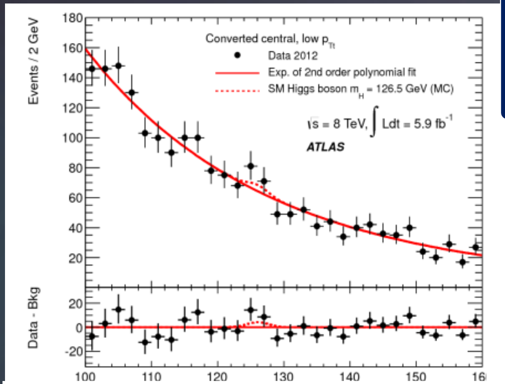

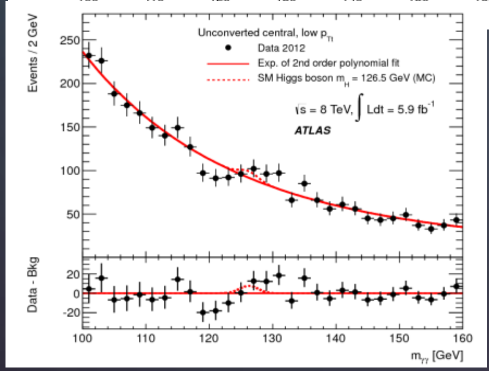

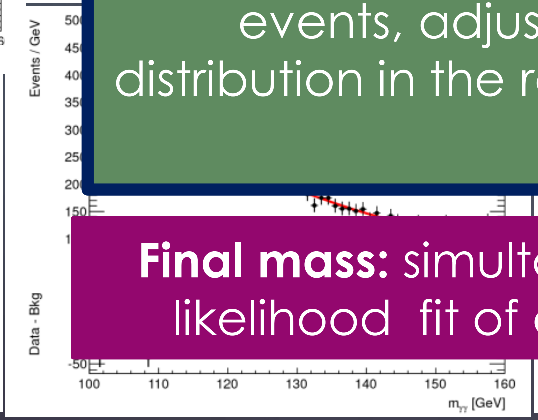

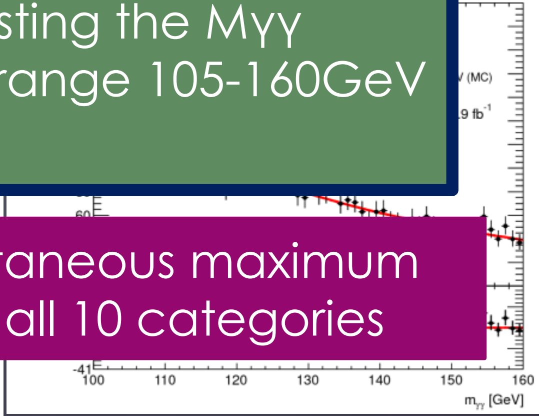

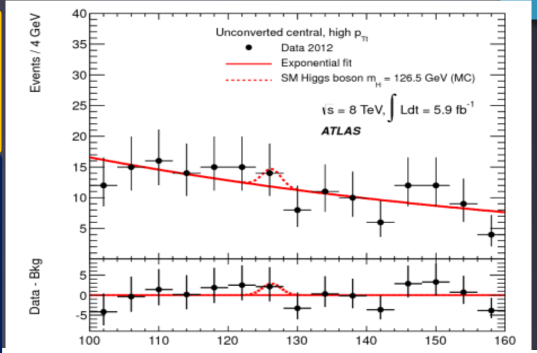

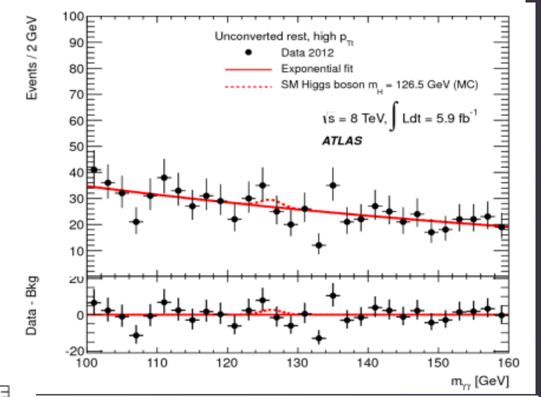

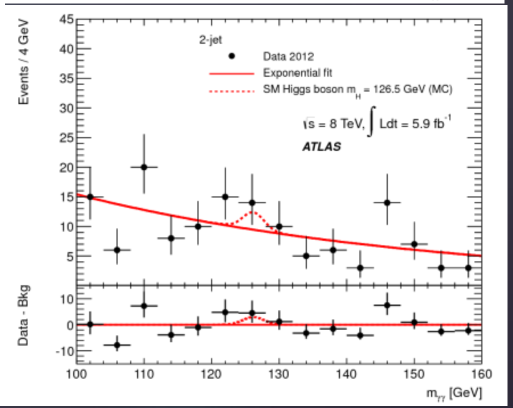

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Final mass: simultaneous maximum likelihood fit of all 10 categories

H->ZZ*->4l (μ,e) : the golden mode

Very suppressed at low H mass.
σ x Br = 2.9 fb-1
But low background !   S/B ~1.5

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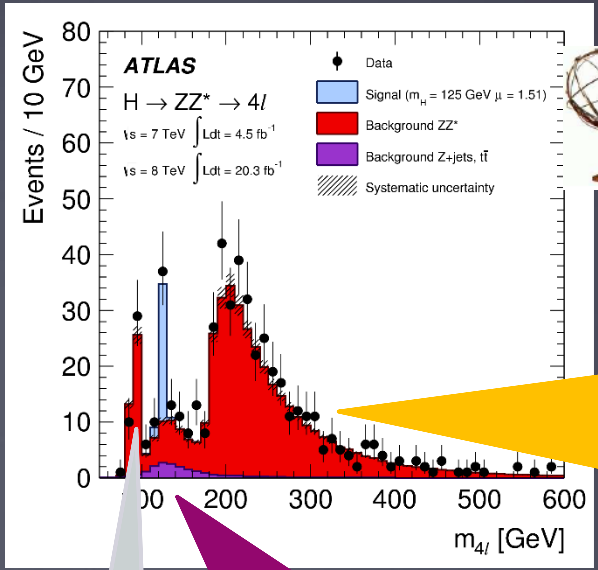
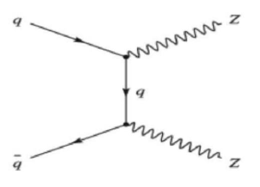
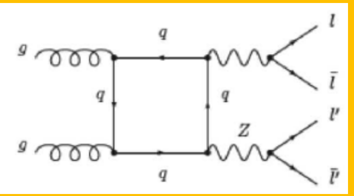
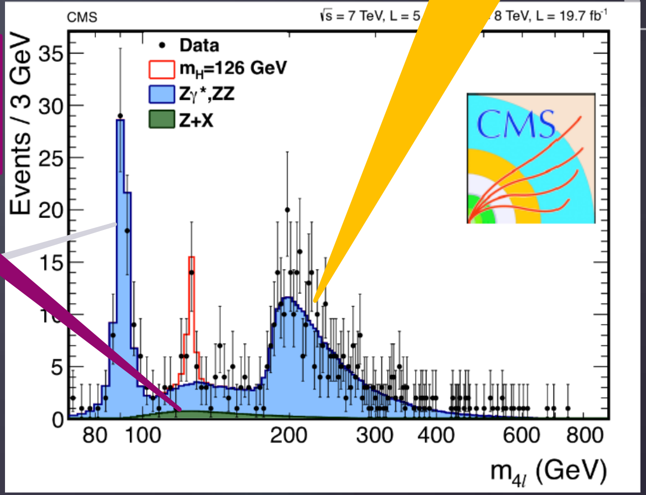


Irreducible ZZ opens-up at~$2M_Z$

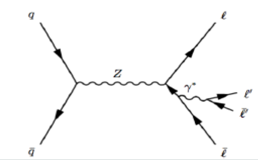




Small reducible from Z+jets, ttbar, ..



Z->4leptons



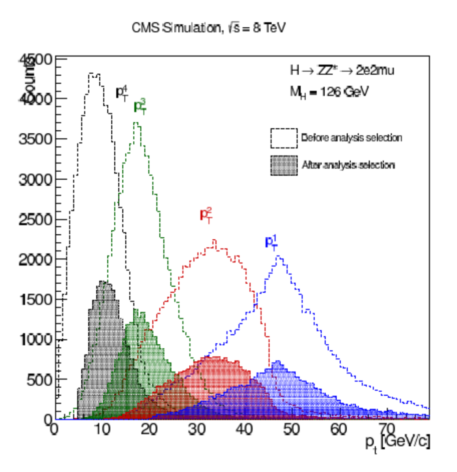
H->ZZ*->4l (μ,e) : the golden mode

Very suppressed at low H mass.
σ x Br = 2.9 fb-1
But low background ! S/B ~1.5

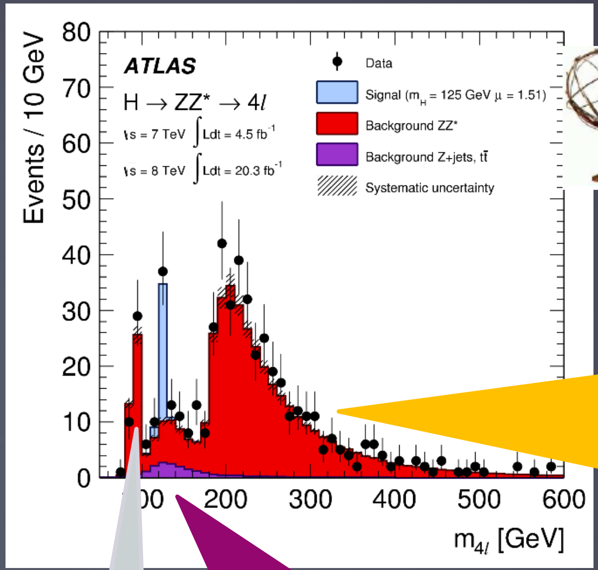
To optimize the detection:

➔The highest reconstruction and identification efficiencies are required for electrons and muons.

➔The low Higgs mass **implies at least 1virtual Z** decaying into low Et leptons.



➔Start efficient detection from P_T = 6(7) GeV, **a challenge**..



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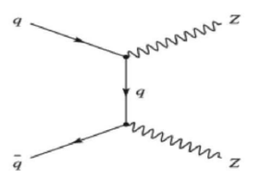

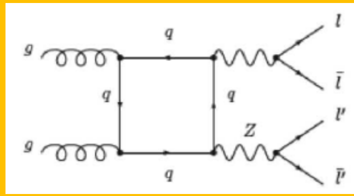

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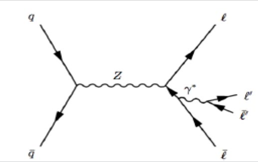

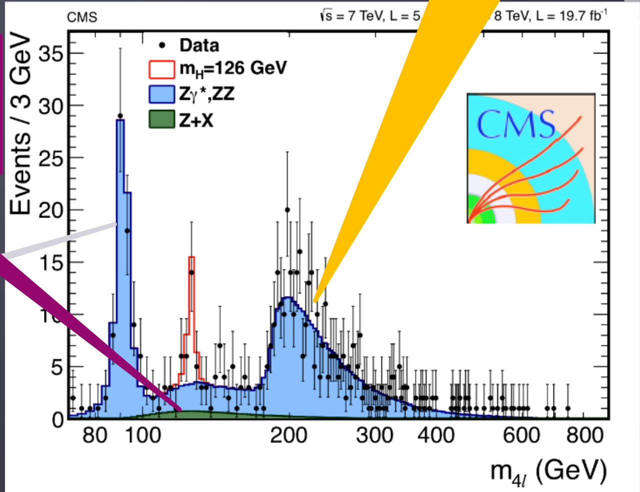

H->ZZ*->4l : Signal and background

Final states: 4e, 4μ, 2e2μ, 2μ2e
Pt>20,15,10,7(6)
"Loose" Identification criteria
The closest to Z mass = M_{12} (50-106GeV)
The second pair M_{34}

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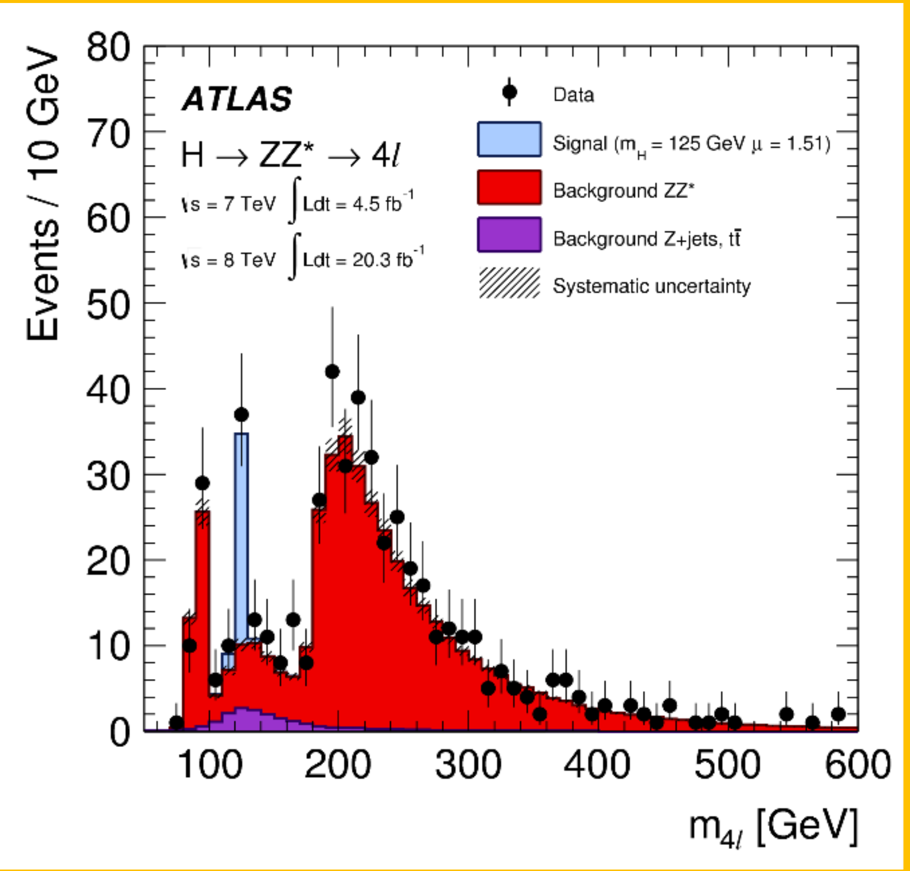

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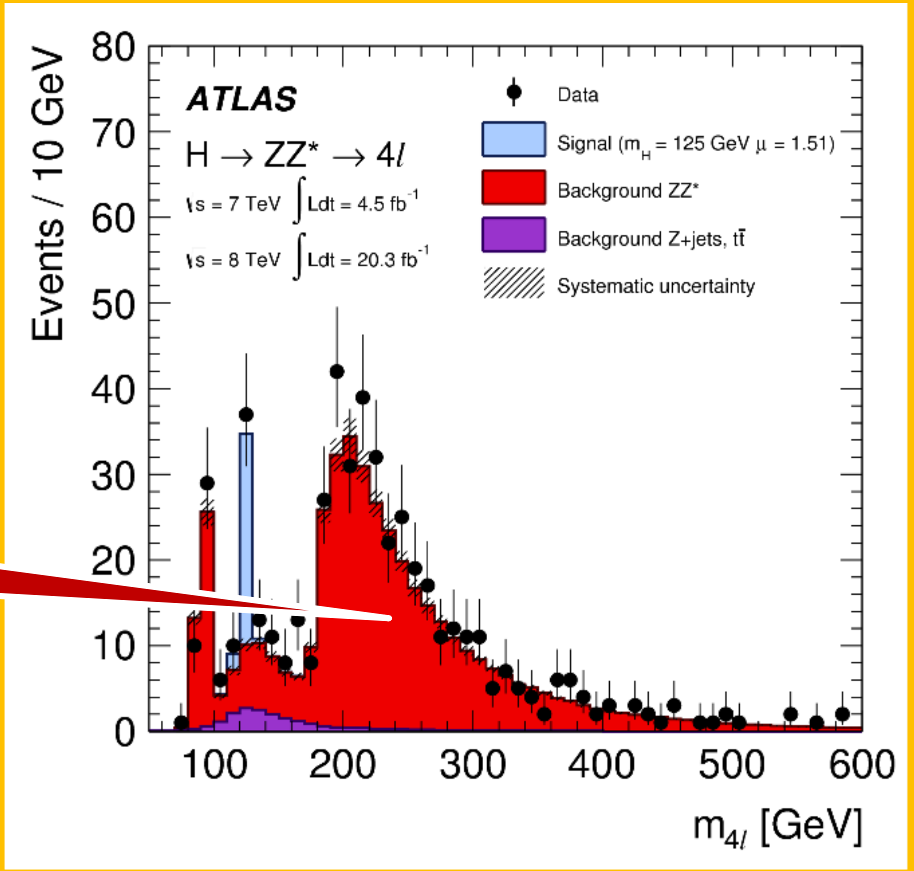

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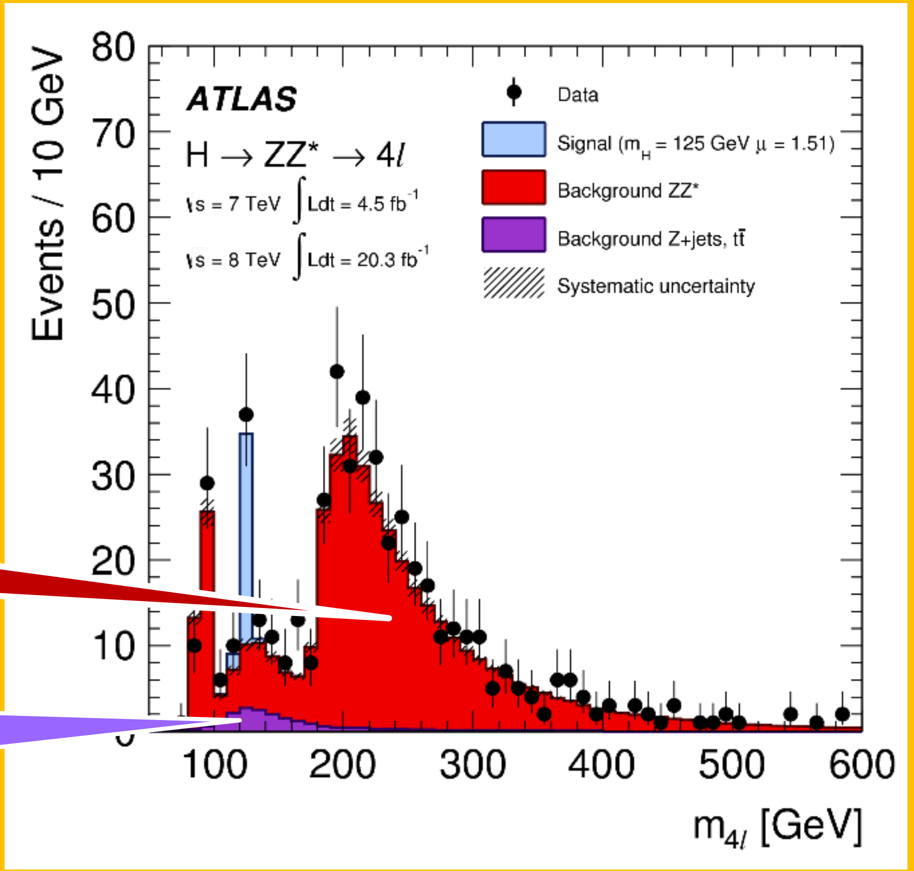
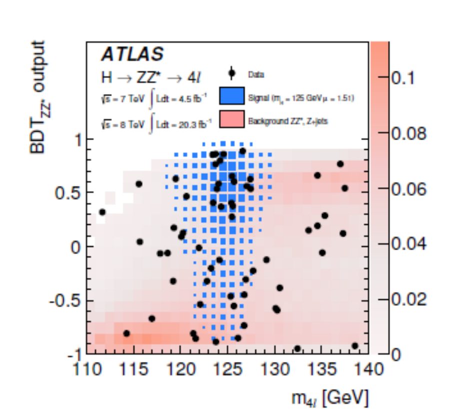
Reducible : Z+jets, ttbar→4l
Sizeable at low 4l invariant mass
Reduced by isolation and
impact parameter criteria



Reducible background depends on the subleading lepton pair flavor.
Data driven measurement in enriched control regions

H->ZZ*->4l :

A BoostedDecisionTree to **better discriminate H->ZZ* from ZZ***:
Uses P_T^{4l}, the 4l pseudorapidity η^{4l} and the Matrix Elements



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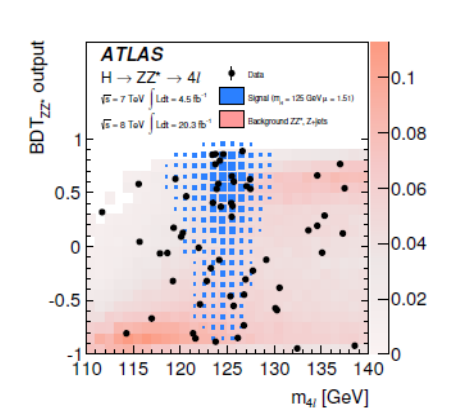

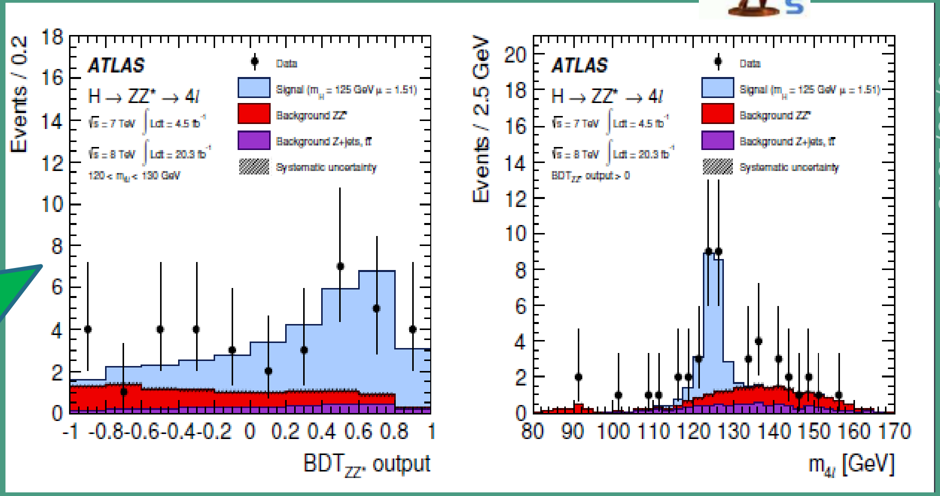

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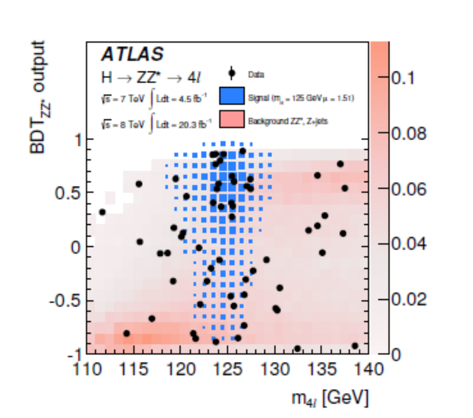
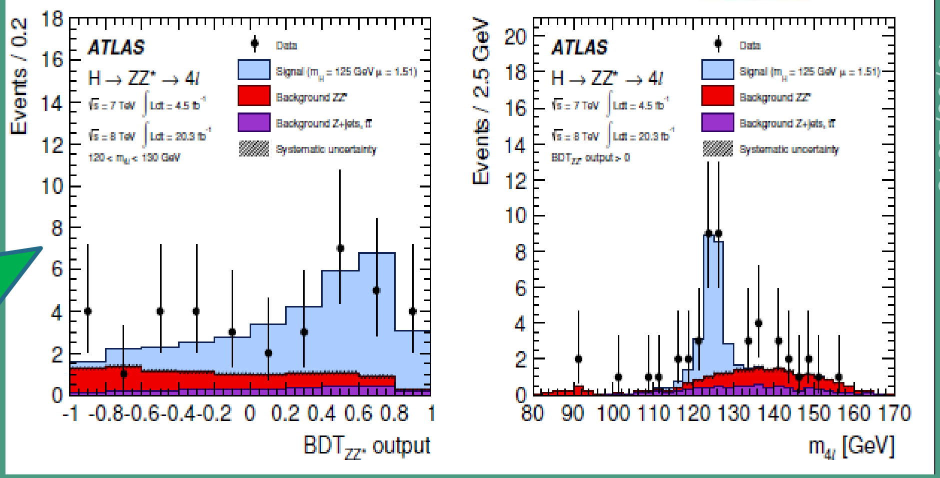


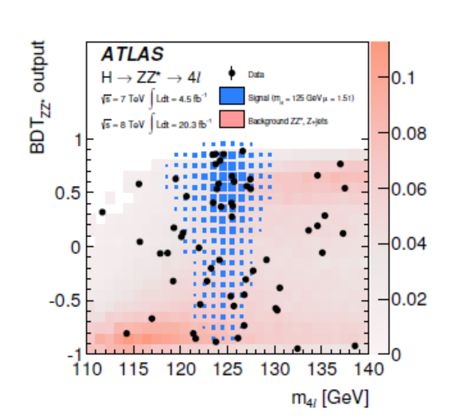


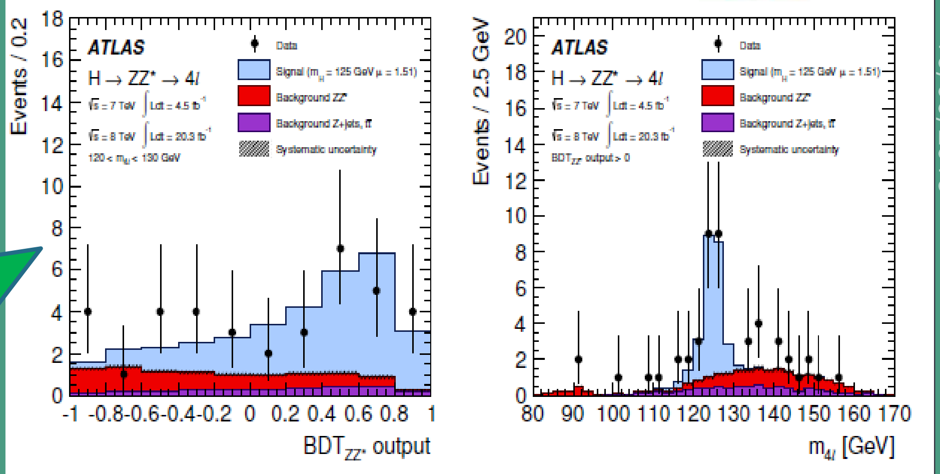
Final state	Signal full mass range	Signal	ZZ^*	$Z+$jets, $t\bar{t}$	S/B	Expected	Observed
			$\sqrt{s}=7$ TeV and $\sqrt{s}=8$ TeV				
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu 2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

In mass range 120-130 GeV

H->ZZ*->4l :

A BoostedDecisionTree to **better discriminate H->ZZ* from ZZ*:** Uses P_T^{4l}, the 4l pseudorapidity η^{4l} and the Matrix Elements





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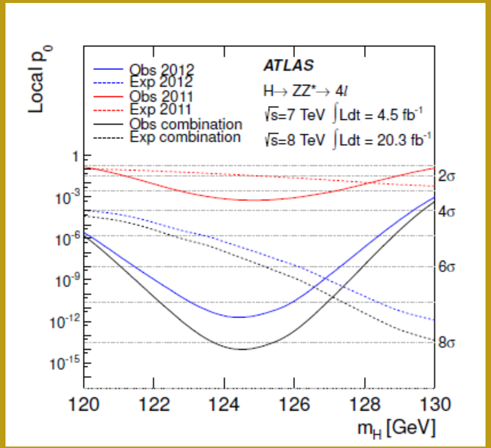

Local P_0 = 8.2 σ (m=124.51GeV)

H->WW*: the abundant

H->WW* : 22% of the decays at M_H=125GeV .

Keep the most sensitive experimentaly channels:
leptonic decays, W->eν, W->μν

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Here, an overview of the selection (in practice much more complexe!)

- ➔Two well identified leptons with opposite sign and Pt>10GeV
- ➔ Well isolated in the tracker and the Calorimeter (to suppress jets)
- ➔ M_{ll}>10 GeV (suppres the DY)
- ➔ $|m_{ll}-M_Z|$>15GeV (suppress the Z)
- ➔ Require high E_T^{miss} and P_T^{miss} (to sign the neutrinos)
- ➔ Count the nb of Jets
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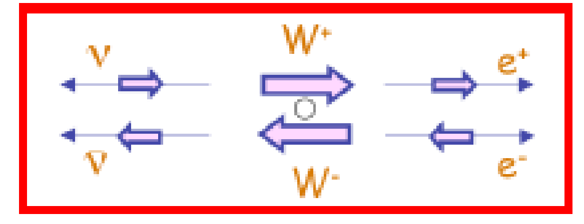
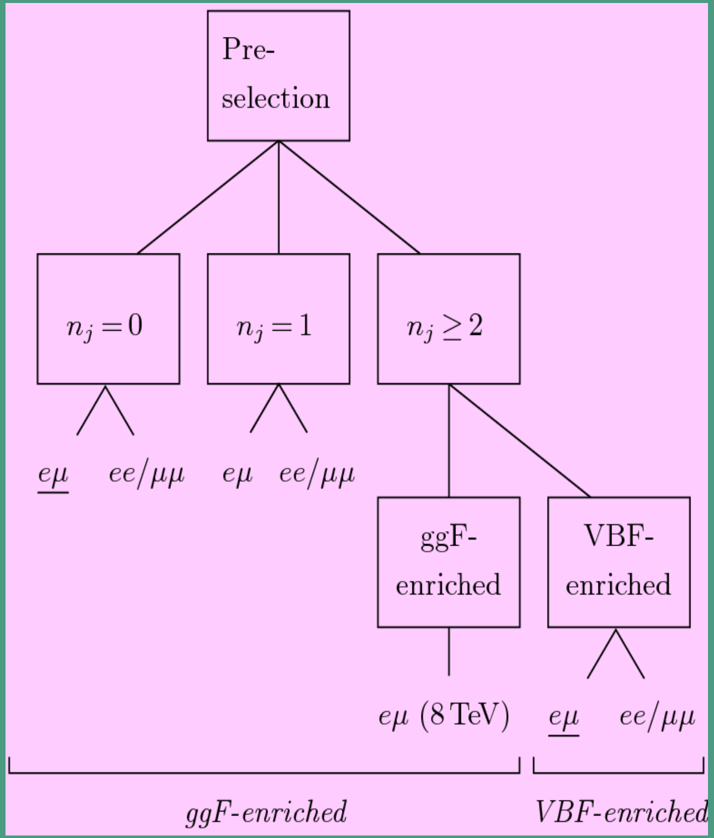
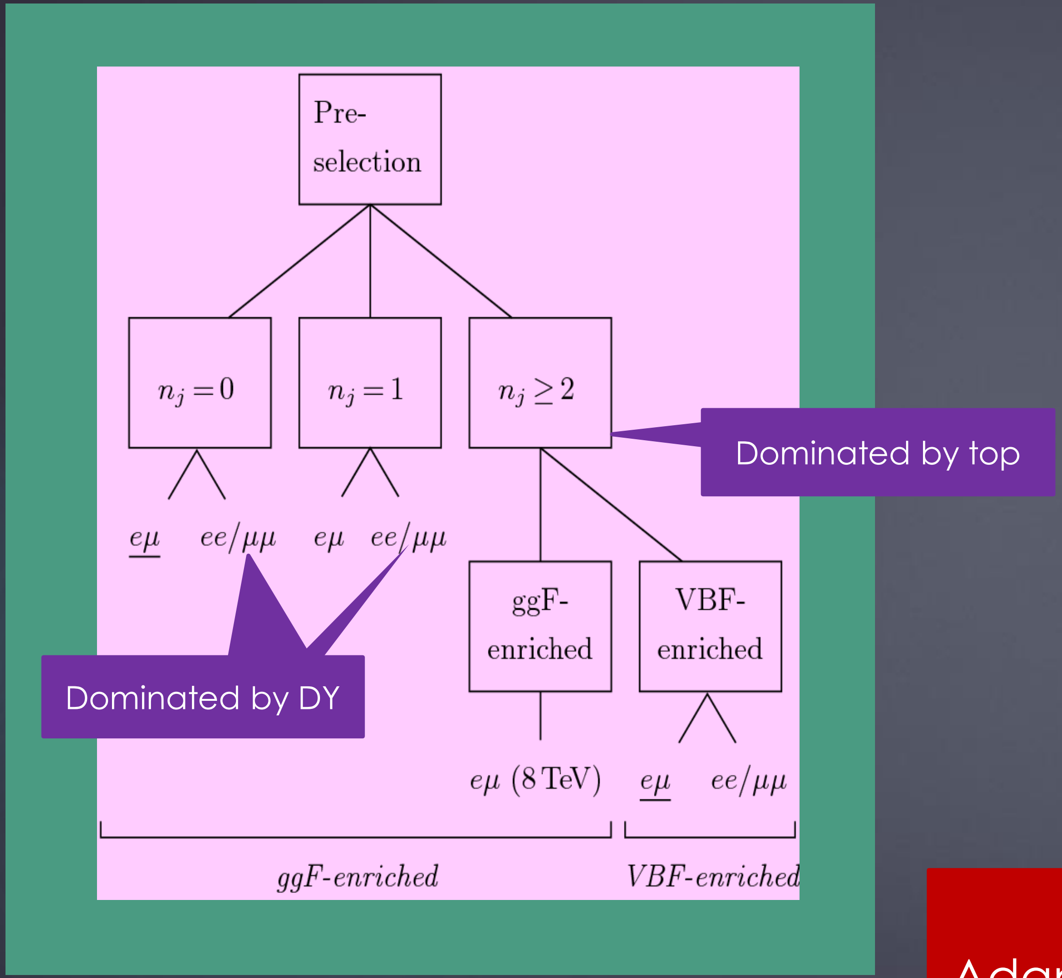


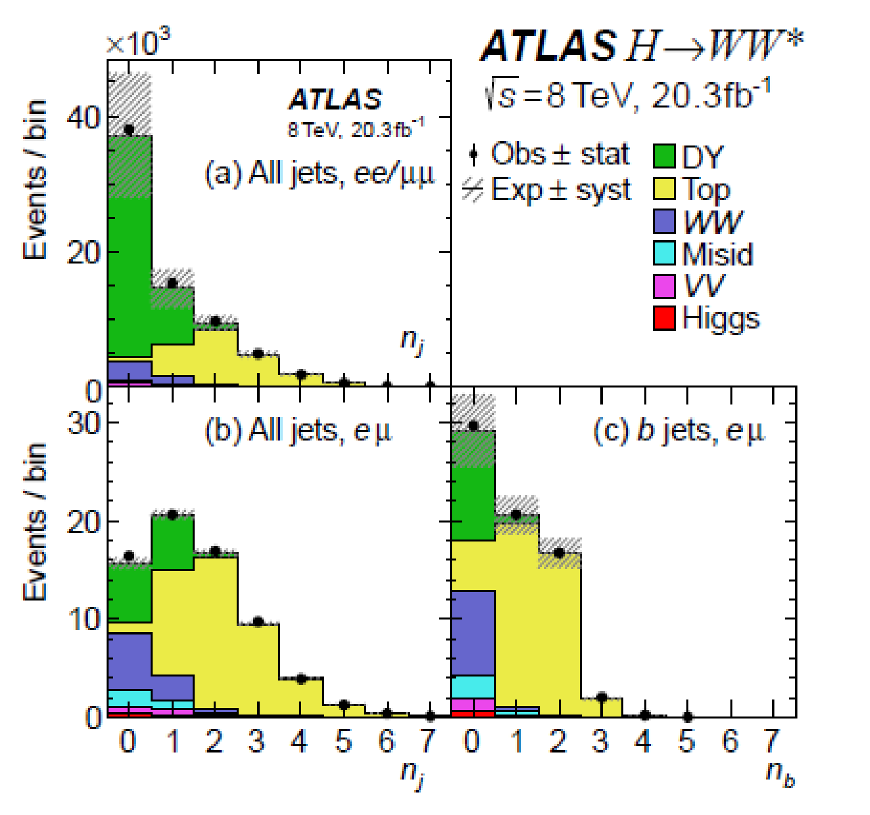
H->WW*->lvlv : Categories



Principle :
Adapt the cuts to the optimize the suppression of the backgrounds = f(category)

H->WW*->lvlv : Categories





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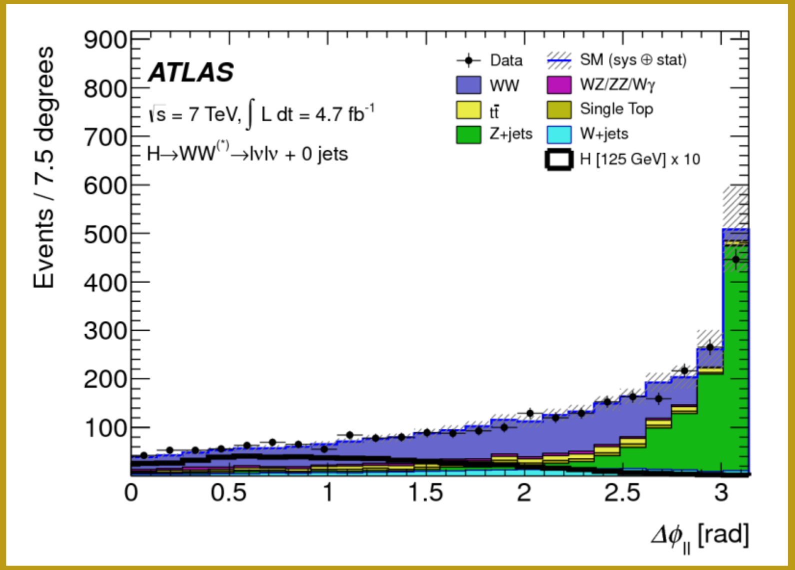
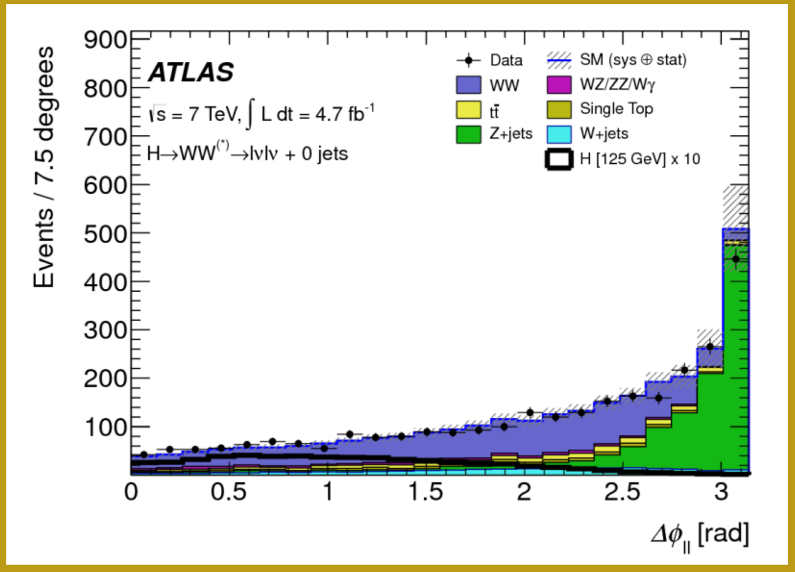
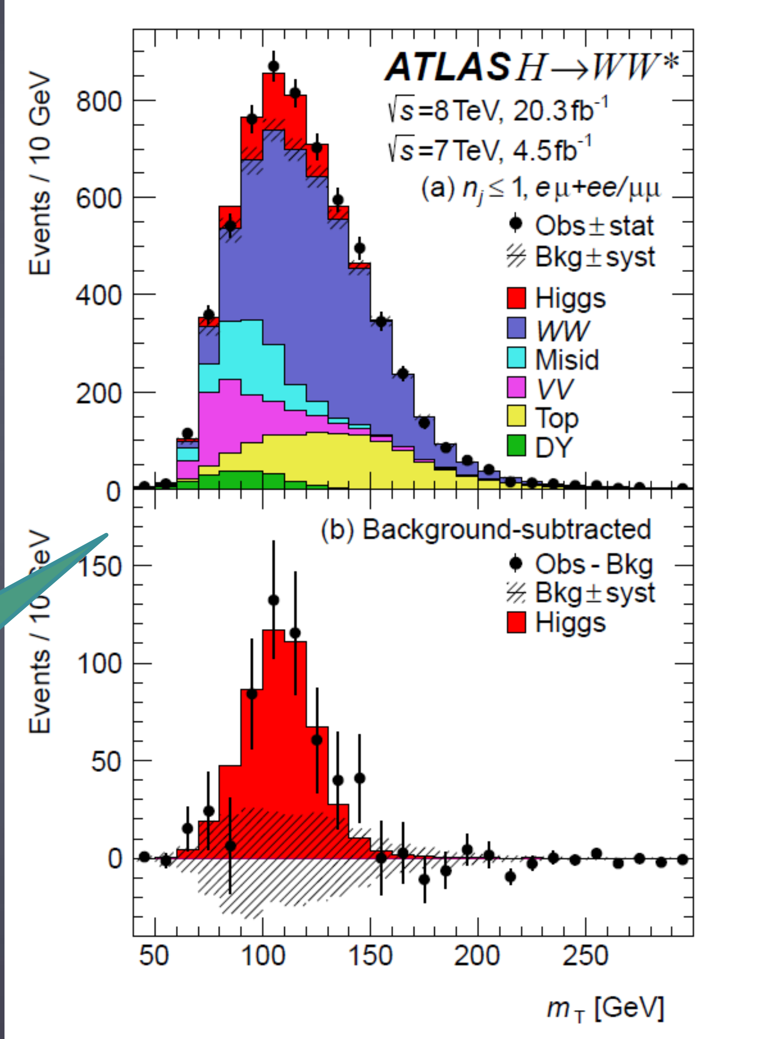
H->WW*->lνlν

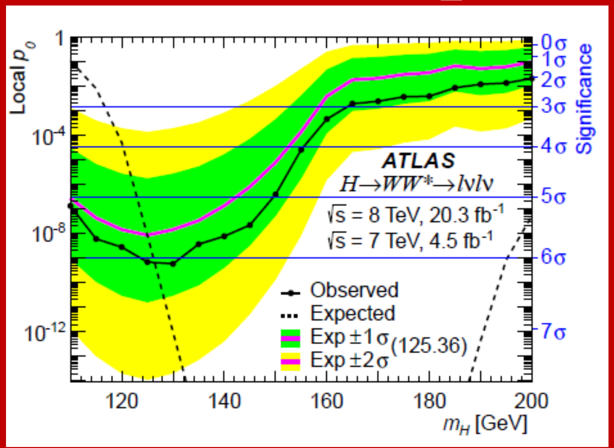


ATLAS
√s = 7 TeV, ∫ L dt = 4.7 fb-1
H→WW(*)→lνlν + 0 jets
Data
SM (sys ⊕ stat)
WW
WZ/ZZ/Wγ
tt̄
Single Top
Z+jets
W+jets
H [125 GeV] x 10
Events / 7.5 degrees
Δφll [rad]

H->WW*->lvlv







$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + p_{\mathrm{T}}^{\nu\nu}\right)^2 - \left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{p}_{\mathrm{T}}^{\nu\nu}\right|^2},$$

The final discrimination

P_0 = 6.5 σ (5.9 expected)

H->$\tau\ \tau$ channel

Crucial decay to test H coupling to fermions
BR H-> $\tau\tau$ = 6% at 125 GeV
S/B ratio ~ 2%

Use all tau decay types

H->τ τ channel

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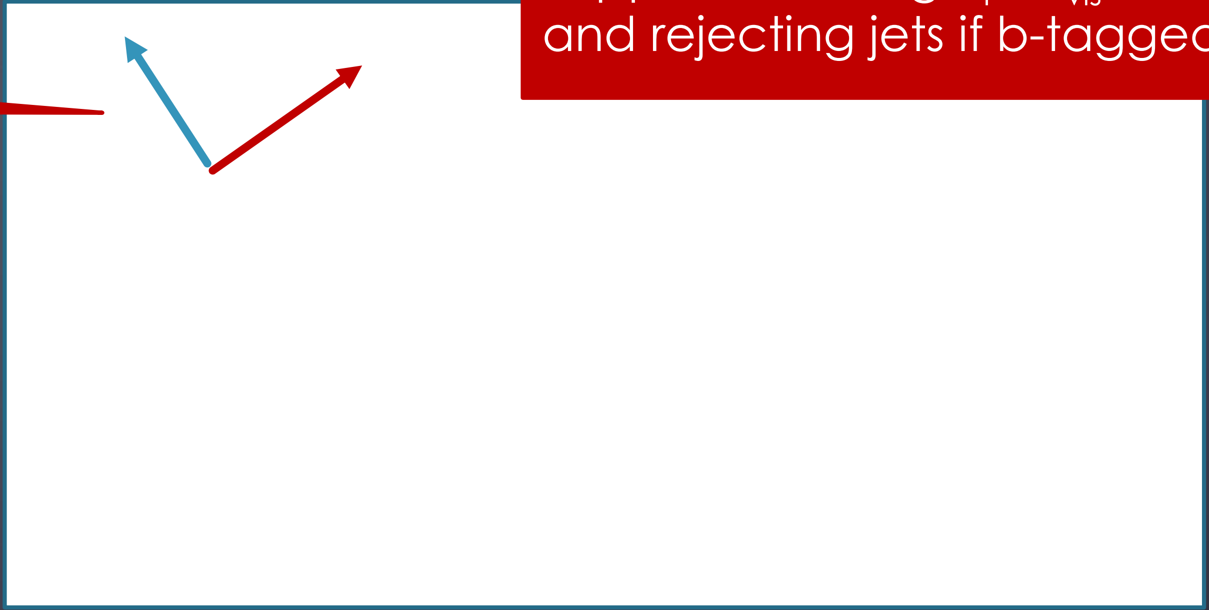
Tau1->leptonic
Tau2->leptonic



Ask for 2 isolated and well identified leptons with OS

Bckg: Z->τ+τ-, Z->l+l-, ttbar
Suppressed using E_T, m_{vis}^{ll} and $\Delta\varphi^{ll}$ and rejecting jets if b-tagged

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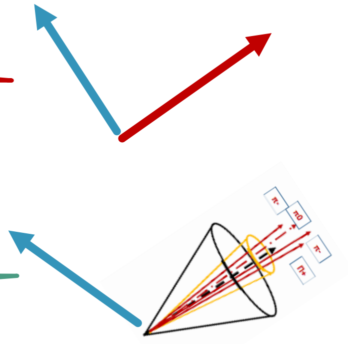

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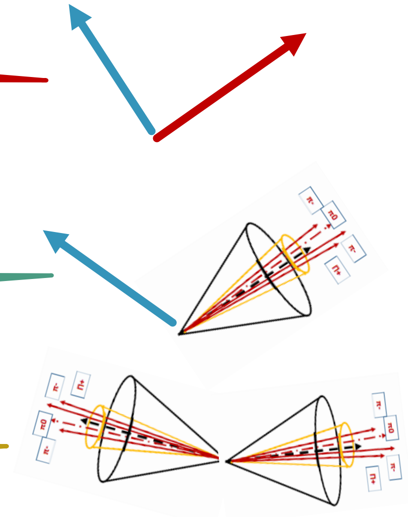

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Bckg: W+jets , ttbar
Suppressed using M_T and rejecting jets if b-tagged

Ask for 2 tau-jets with OS
Bckg : multi jets events
Suppressed by tighter Id and kinematical separation in pseudorapidity

H->τ τ : reconstructing the invariant mass ......

Final state not fully contained because of neutrinos

Apply the "**Missing Mass Calculator**" using all available event info.

➔Solution in 99% of cases

➔Resolution ; ~12-20%

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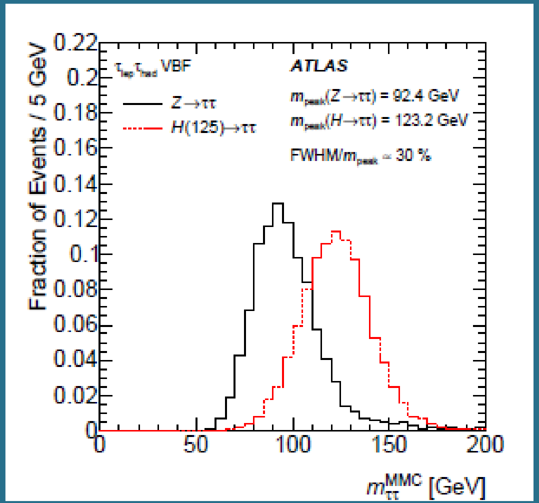

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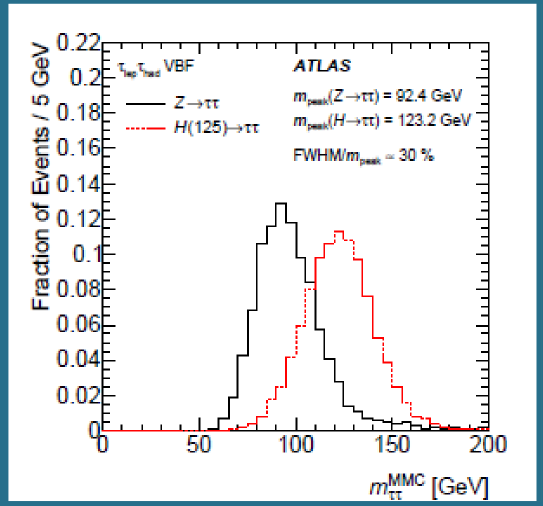

The 3 decay categories are splited further:

--- **VBF :** + 2 high-pt jets with large separation in pseudorapidity

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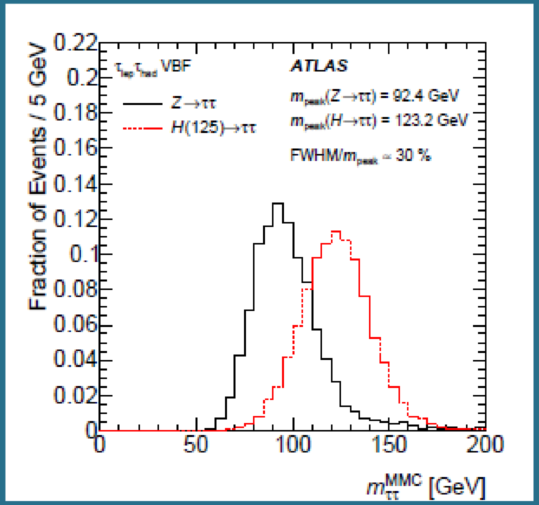

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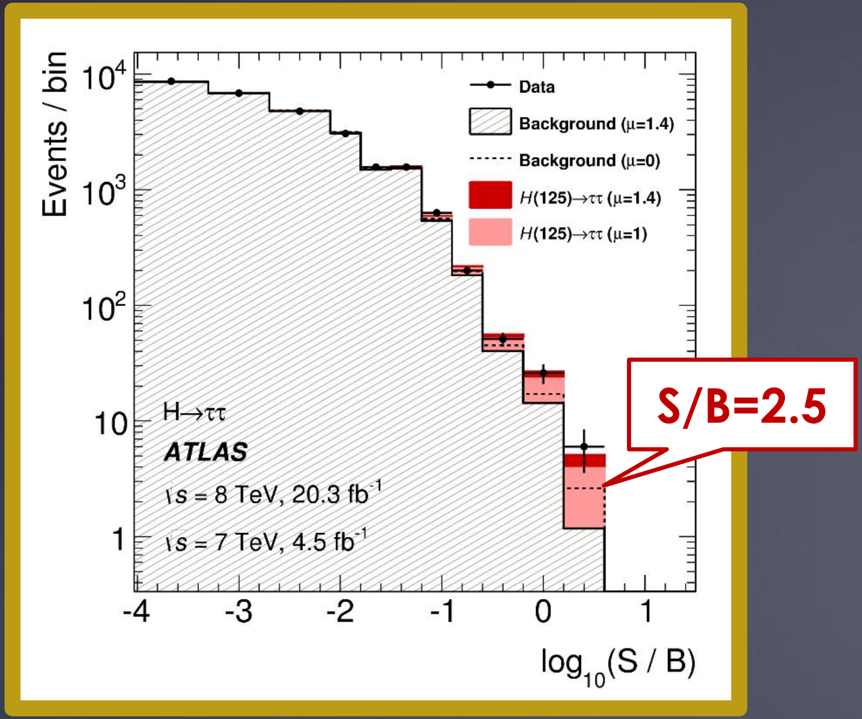
Background checked in specific data control regions

Final discriminant is a Boosted Decision Tree ran for all 6 categories

H->ττ : the ATLAS final result



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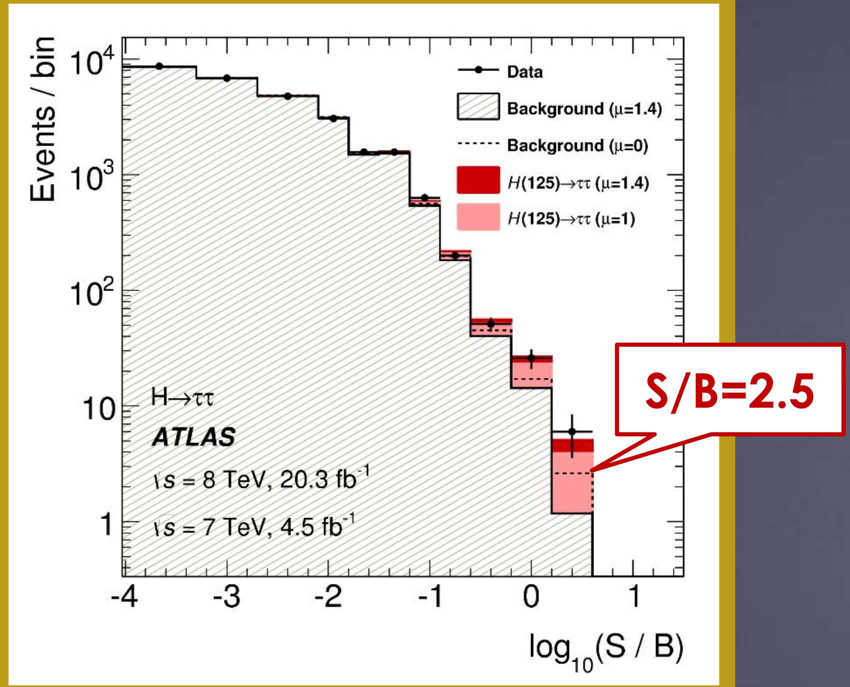

Channel and Category	Expected Significance (σ)	Observed Significance (σ)
$\tau_{\rm lep}\tau_{\rm lep}$ VBF	1.15	1.88
$\tau_{\rm lep}\tau_{\rm lep}$ Boosted	0.57	1.72
$\tau_{\rm lep}\tau_{\rm lep}$ Total	1.25	2.40
$\tau_{\rm lep}\tau_{\rm had}$ VBF	2.11	2.23
$\tau_{\rm lep}\tau_{\rm had}$ Boosted	1.11	1.01
$\tau_{\rm lep}\tau_{\rm had}$ Total	2.33	2.33
$\tau_{\rm had}\tau_{\rm had}$ VBF	1.70	2.23
$\tau_{\rm had}\tau_{\rm had}$ Boosted	0.82	2.56
$\tau_{\rm had}\tau_{\rm had}$ Total	1.99	3.25
Combined	3.43	4.54

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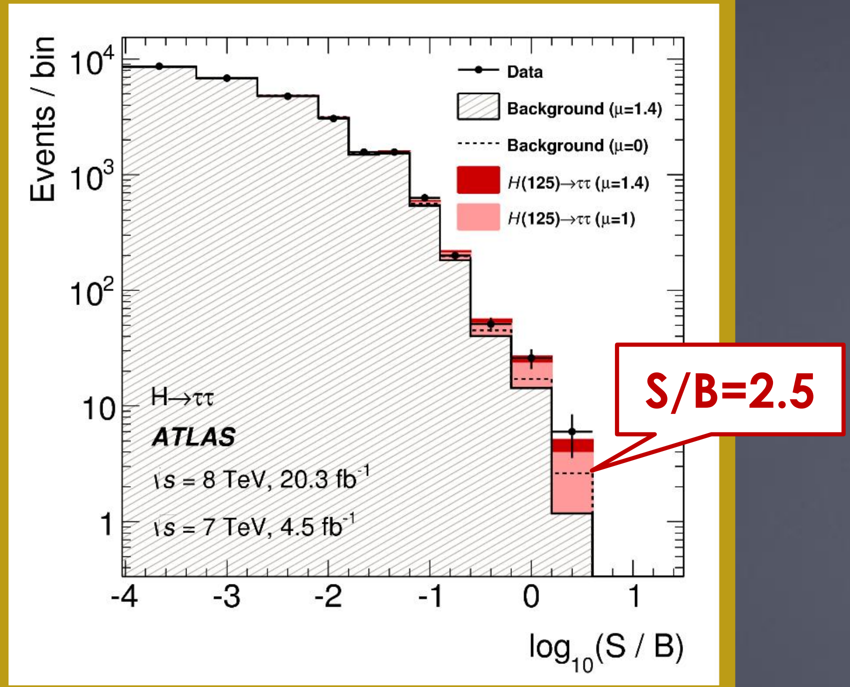

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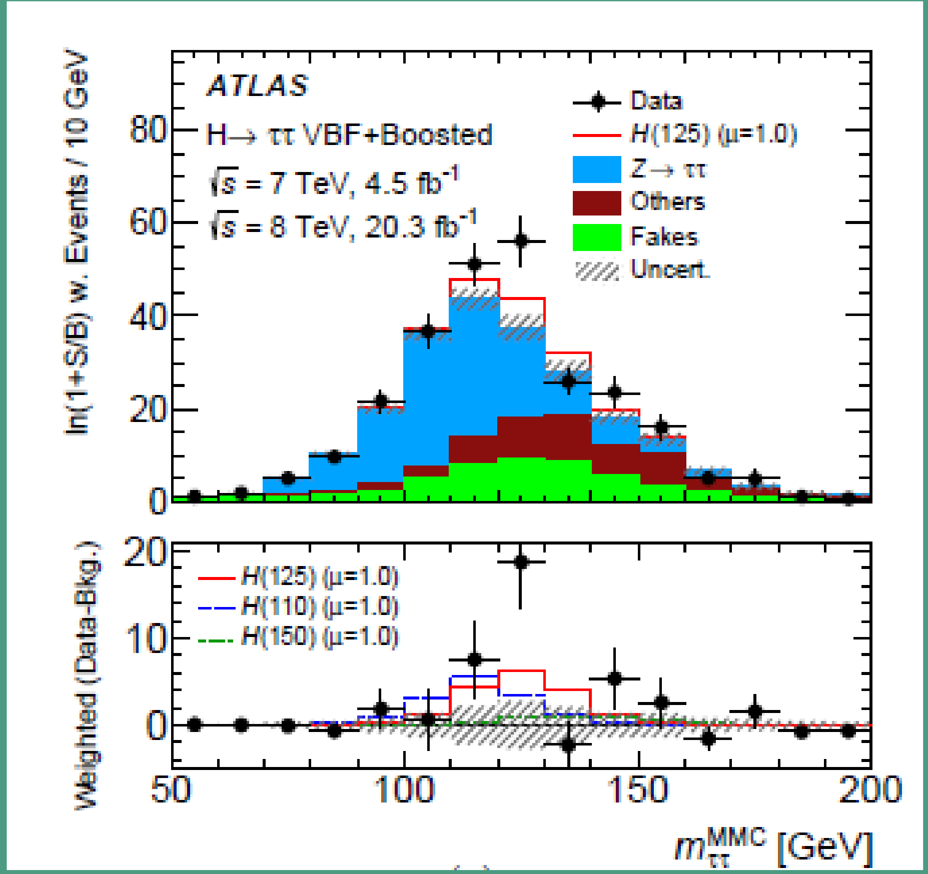
$\tau_{had}\tau_{had}$ Total	1.99	3.25
Combined	3.43	4.54



Significance : 4.5σ (3.4σ expected)

H->bb : the dominant

BR=58% at M_H=125GeV
But overwhelming QCD background

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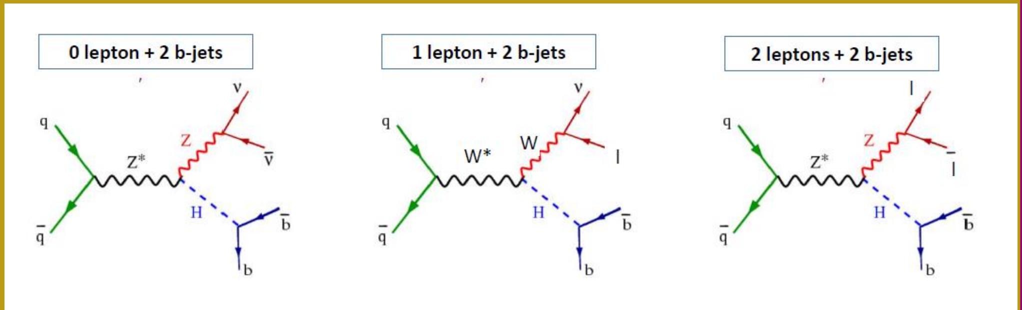

SIGNAL

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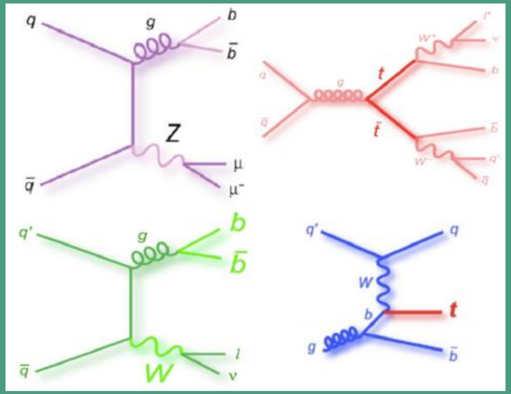
Use **associated Higgs production W(Z)H-> bb** to increase the S/B ratio. Lower production Xsection but easier signatures.

Backgrounds ;
Dibosons (WW, WZ, ZZ)
Bosons + jets
Ttbar, multijets



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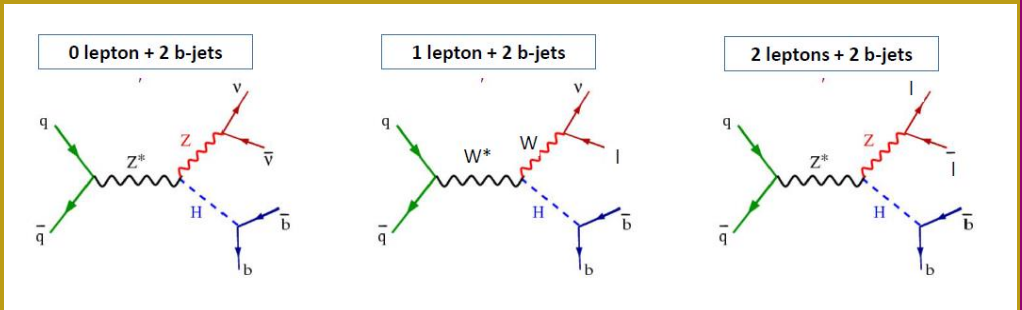

SIGNAL

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B-tagging algorithms, based on multivariate technics.
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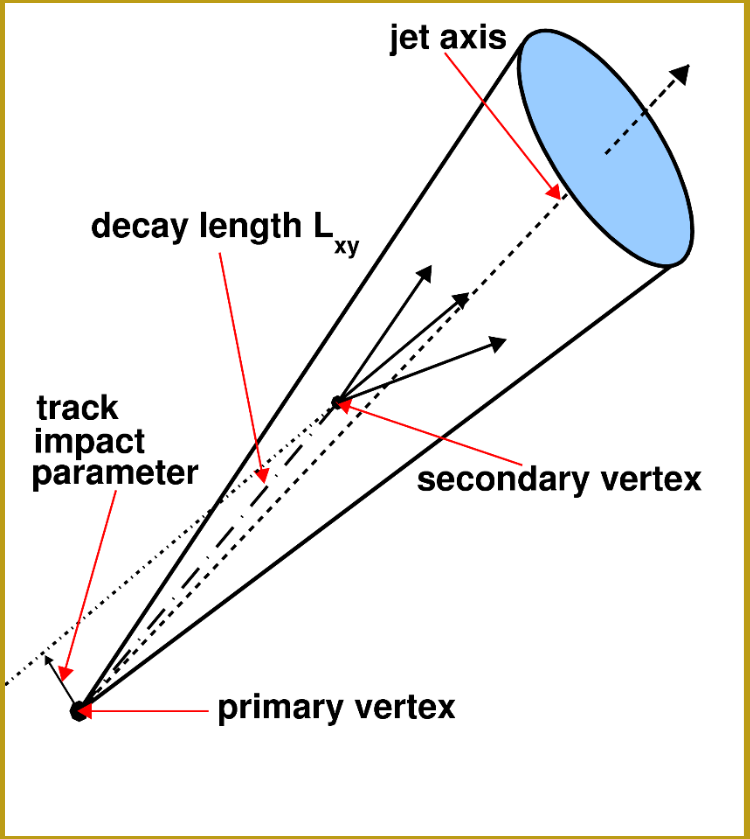

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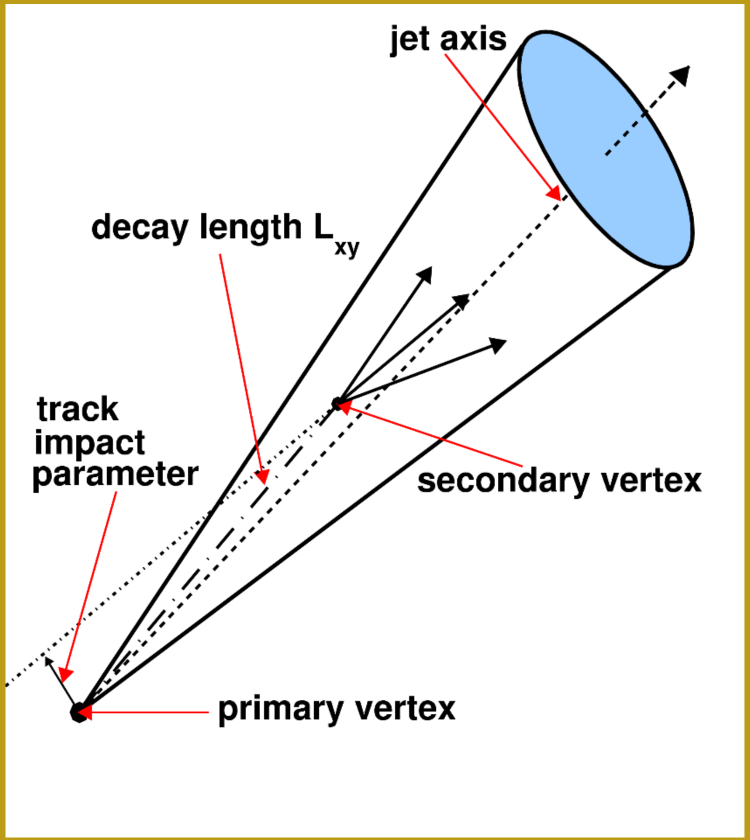

Three b-tag working points;
Loose for 80% b-tag efficiency
Medium for 70% b-tag efficiency
Tight for 50% b-tag efficiency

VH->bb

A discriminant variable :
The bb invariant mass

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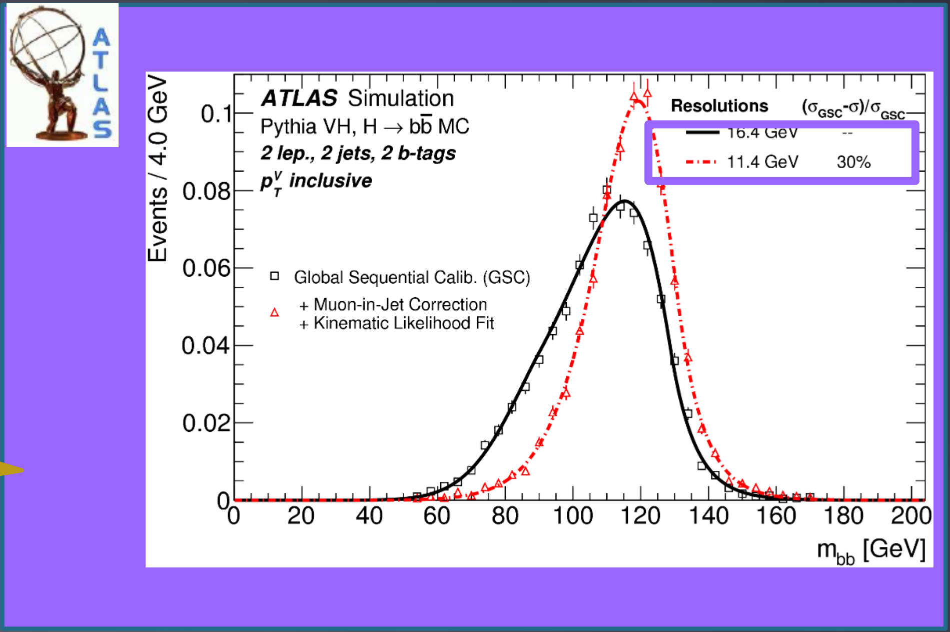
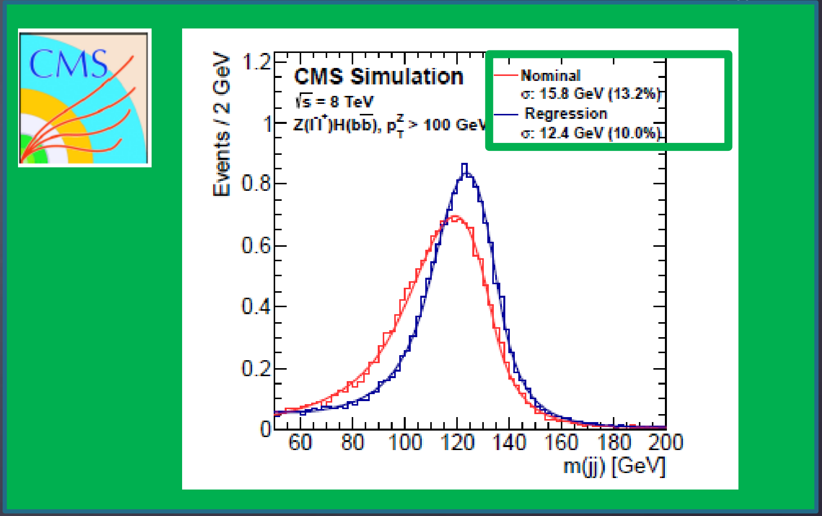
Improve the mass reconstruction

ATLAS: Add the muon momenta on top of the calorimetric jet energy.

CMS : MVA computation





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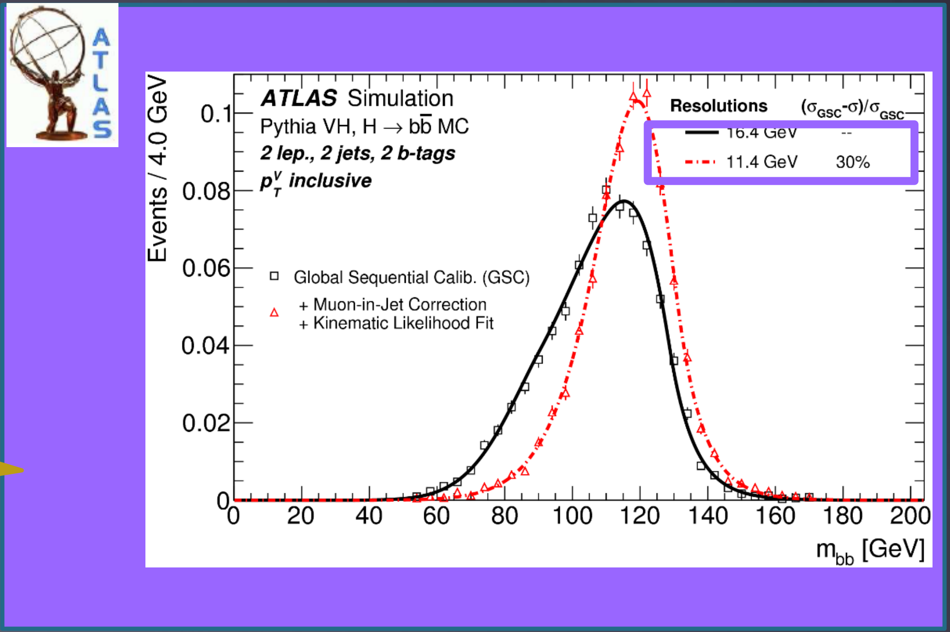
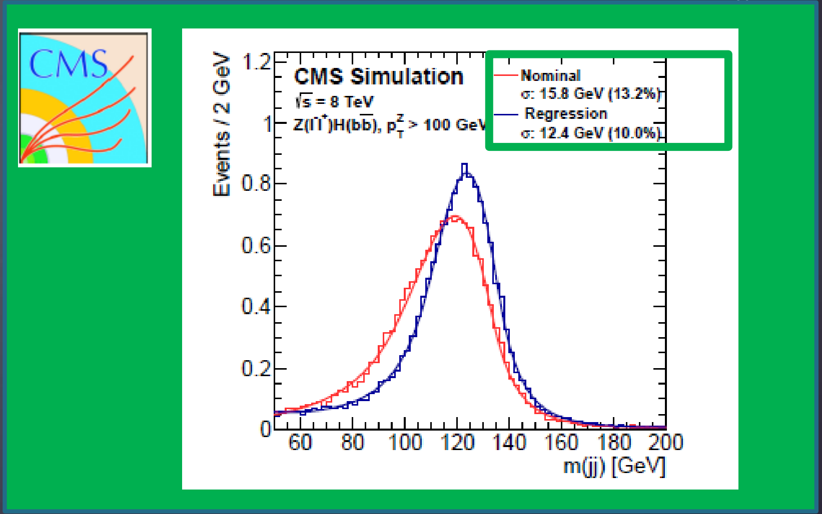


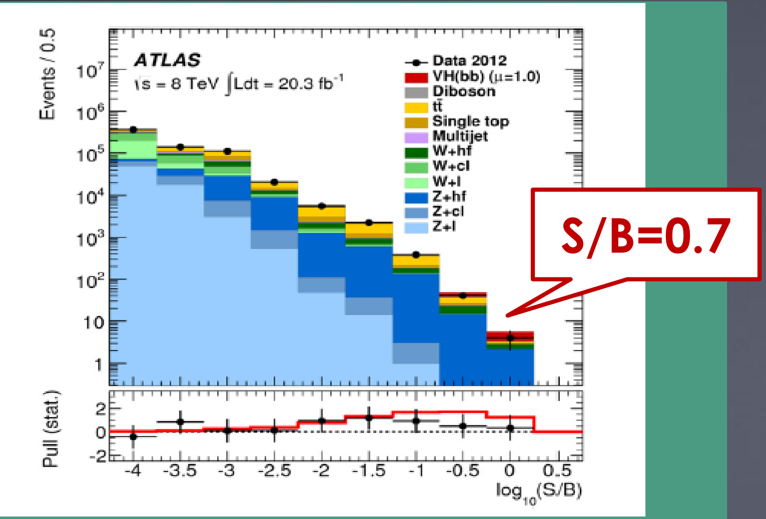


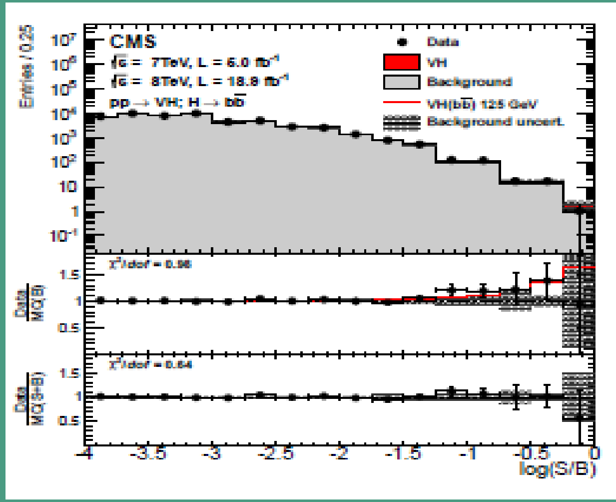
Other discriminant variables : P_T^V , ΔR (b1,b2)

Split in categories
Use a Boosted Decision Tree to improve sensitivity

VH->bb : Can we see something?

Signal and Bkg in bins of S/B





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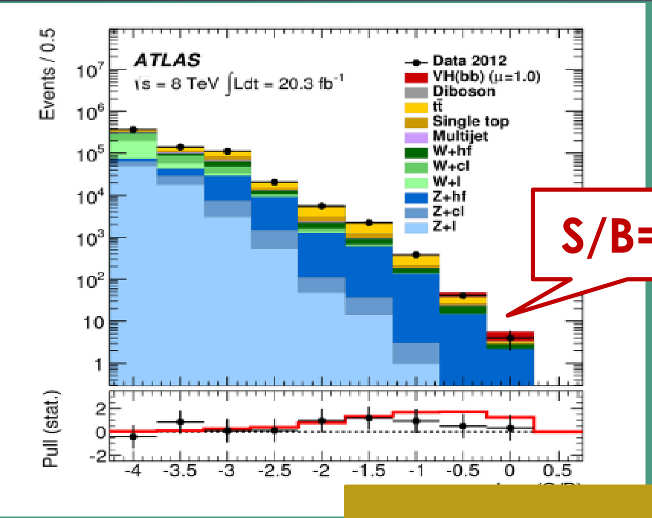
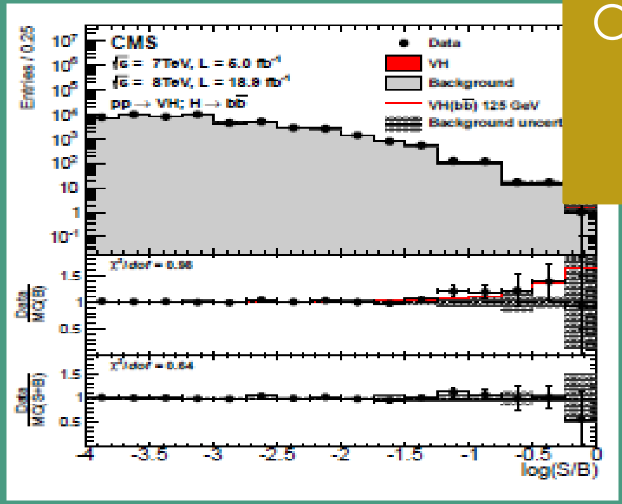
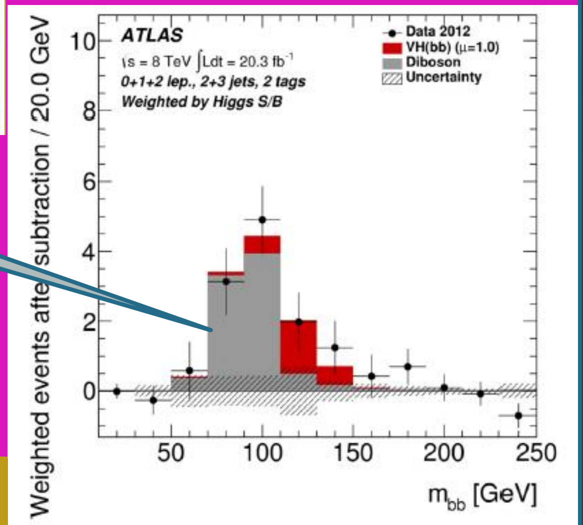


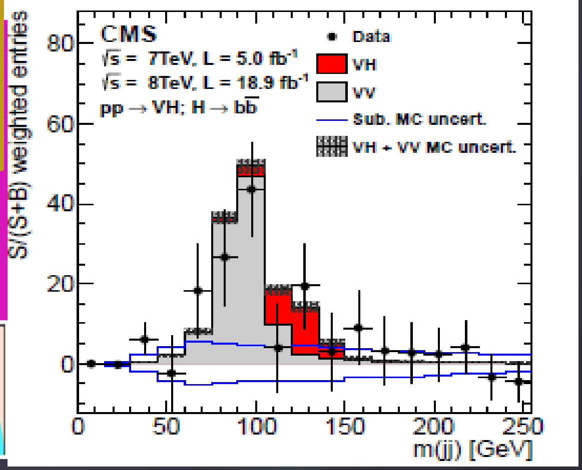
S/B=0.7



Background subtracted data Weighted by S/B



VZ



Observed (expected) significance:
ATLAS : 1.4 σ (2.6)
CMS : 2.1 σ (2.1)

The Scalar Boson Mass

Measured precisely in both, **diphoton and ZZ channels**.

Review here the challenges of the mass measurements and the combination.

H->ZZ*->4l mass measurement

Ingredients:
➔ Data
➔Signal MC at 15 m_H values from 115->130 GeV
➔Background shape and yields from simulation (ZZ*) and data-driven measurements (Z+jets, ttbar..)
➔Unbinned maximum likelihood of the 8 (m4l, BDT) distributions (7 and 8 TeV data X 4 final modes).

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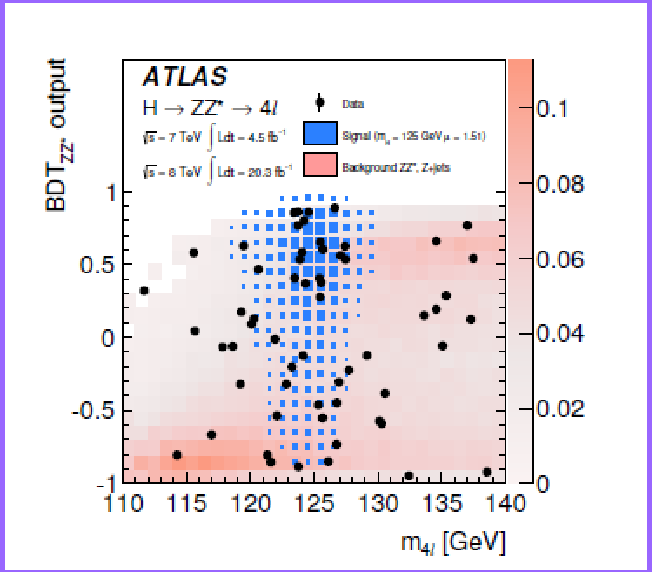

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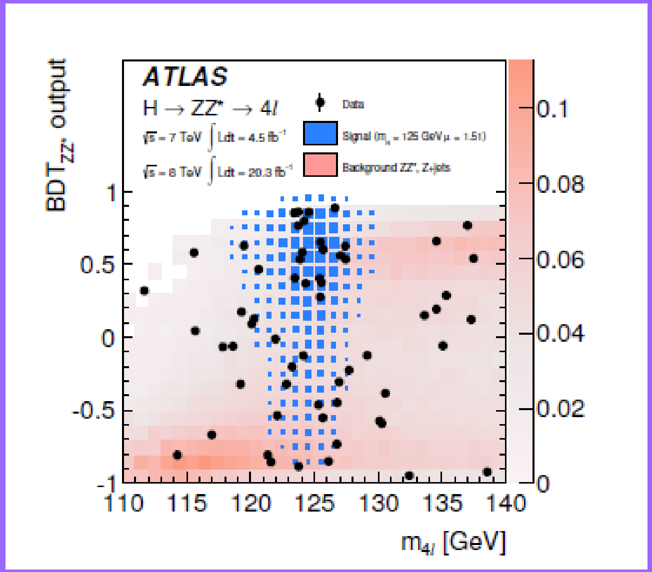

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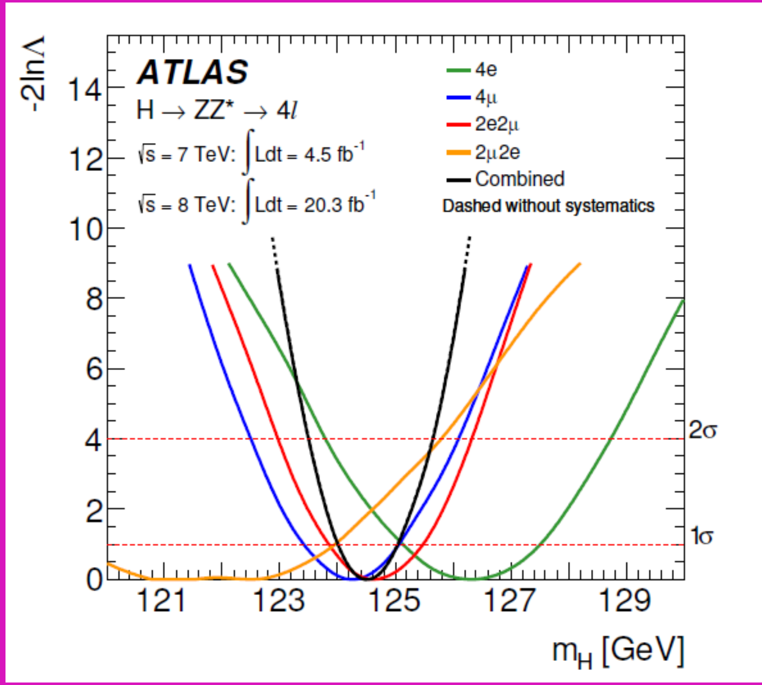

M_H=124.51 ± 0.52 (stat) ± 0.06 (syst)

Electron and muon energy scales

H->γγ mass measurement

Split data in 10 categories

- Unconv. central low p_{Tt}
- Unconv. central high p_{Tt}
- Unconv. rest low p_{Tt}
- Unconv. rest high p_{Tt}
- Unconv. transition
- Conv. central low p_{Tt}
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Unconverted photon categories: **Better resolution** than converted

Central photons ($|\eta|<0.75$): **Better resolution** and smaller energy scale uncertainties

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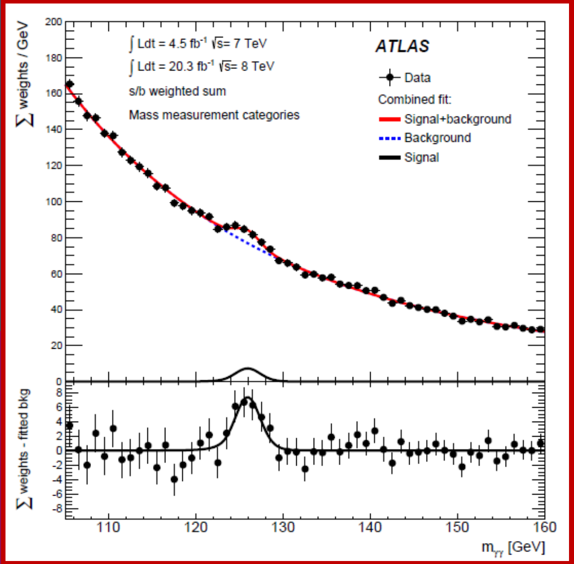

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➔**Background modeling**: Analutical functions in 105-160GeV tested in large dijet, jet+photon and diphoton simulated samples.

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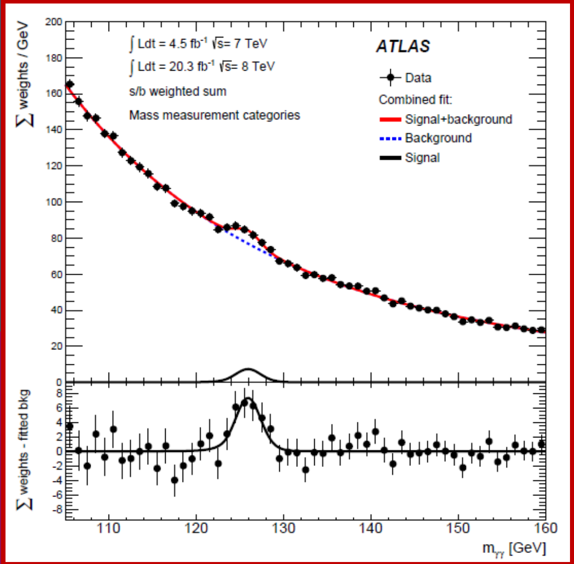

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$M_H = 126.98 \pm 0.42(\text{stat}) \pm 0.28\ (\text{syst})$ GeV

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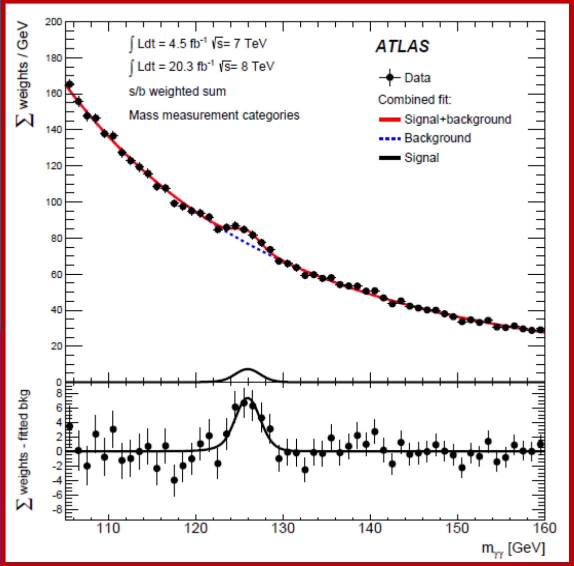
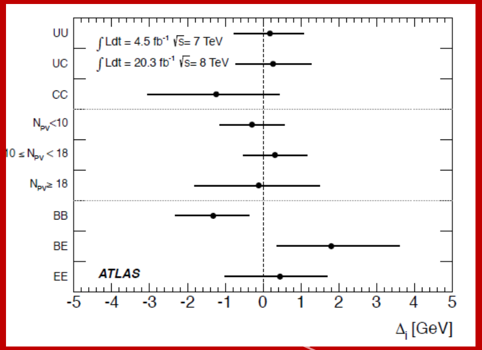


Checks of M_H in other categories



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Issues related to the H->γγ and H->ZZ*->4l mass combination

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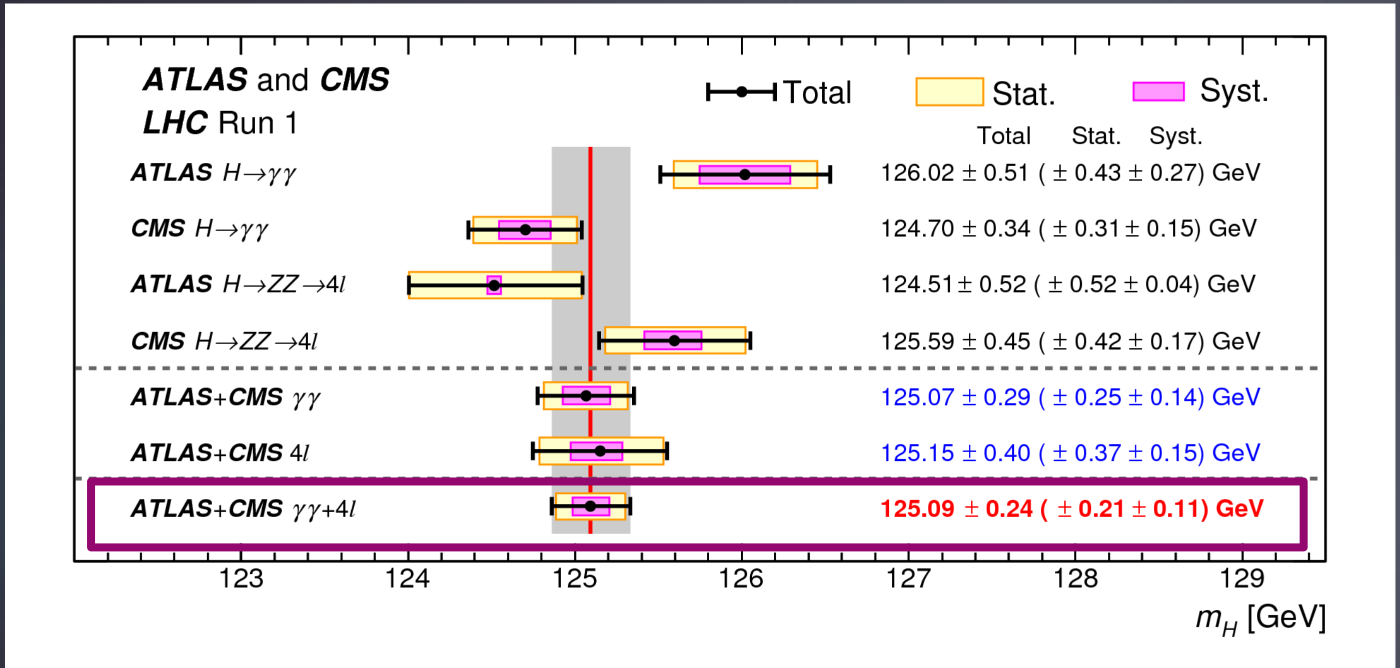
➔ Uncommon uncertainties

Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell non-linearity (layer 2)	60
LAr cell non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\|\eta\| < 1.1$)	50
$H \to \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \to ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

Energy Scale related

Sources of final uncertainties on the Combined ATLAS mass.

The RUN1 Higgs mass combined measurement from ATLAS+CMS



ATLAS : m_H=125.36 ± 0.41 GeV

CMS : m_H=125.02 ± 0.30 GeV

m_H at Run1 known to 240MeV (<0.2% !)
Dominated by statistics

The New boson properties

Its quantum numbers, its width and its couplings to fermions and bosons

The Spin and Parity

The observed decay of the H->γγ restricts the possible Higgs spins to 0 and 2.

At LHC, analyses searched for several scenarii, implying
➔Spin 2 resonances
➔Pure 0+, or 0- BSM Higgs Boson
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dia Iconomidou-Fayard

SPIN 2 Tensor-field $X^{\mu\nu}$ Lagrangian

$$\mathcal{L}_2 = \frac{1}{\Lambda}\left[\sum_V \kappa_V X^{\mu\nu} \mathcal{T}^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu} \mathcal{T}^f_{\mu\nu}\right].$$

Couplings of $X^{\mu\nu}$: k_v to bosons **k_f** to fermions

Production via qq and qg-> Stydy cases:

1) $k_g = k_q$ (universal coupling UC)
2) $K_g \neq k_q$: gives a characteristic high tail to the P_T of the resonance

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Spin 0 mixted CP Lagrangian for W and Z

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{SM}\left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right] - \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\right] - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu}\right]\Big\} X_0.$$

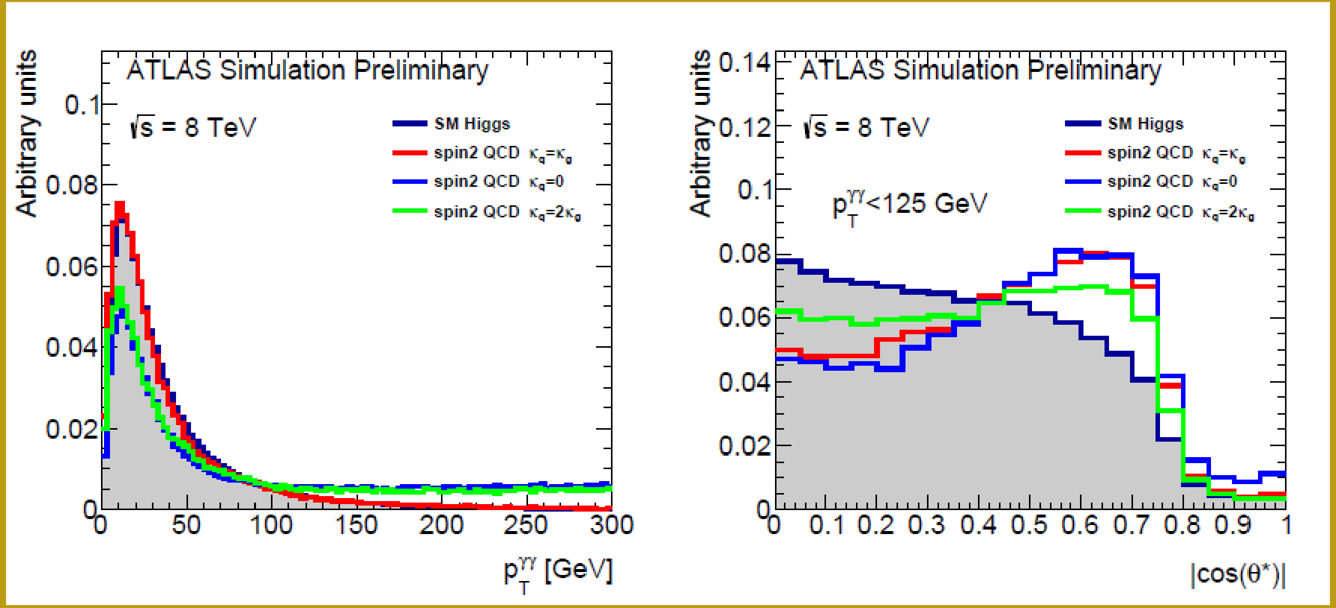
Couplings of X_0 : K_{SM} to standard model, **k_{HVV}** to BSM 0+ et **k_{AVV}** to BSM 0- interactions
Mixing CP-states angle **a, $s_a = \sin a$, $c_a = \cos a$**

J^P	Model	κ_{SM}	κ_{HVV}	κ_{AVV}	α
		Choice of tensor couplings			
0^+	Standard Model Higgs boson	1	0	0	0
0^+_h	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

Spin 0 vs Spin 2 : tested with H->γγ, H->ZZ*->4l and H->WW*->lνlν

H->γγ: Use $P_T^{\gamma\gamma}$ and the angle in the Colins-Sopper frame

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2},$$



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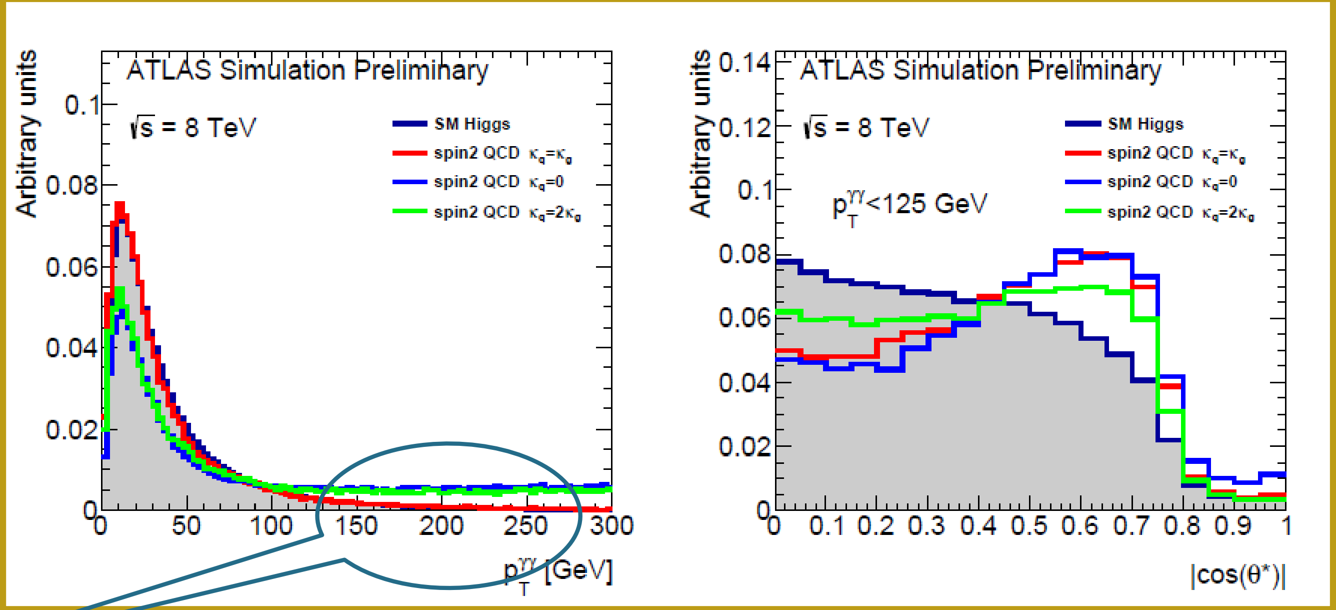

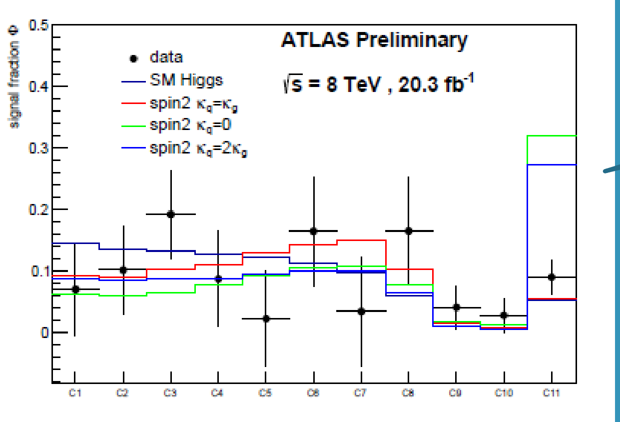

Nbin/Ntot in 10 |cosθ*| bins

Invisibles 2015, Lydia Iconomidou-Fayard
16/06/2015

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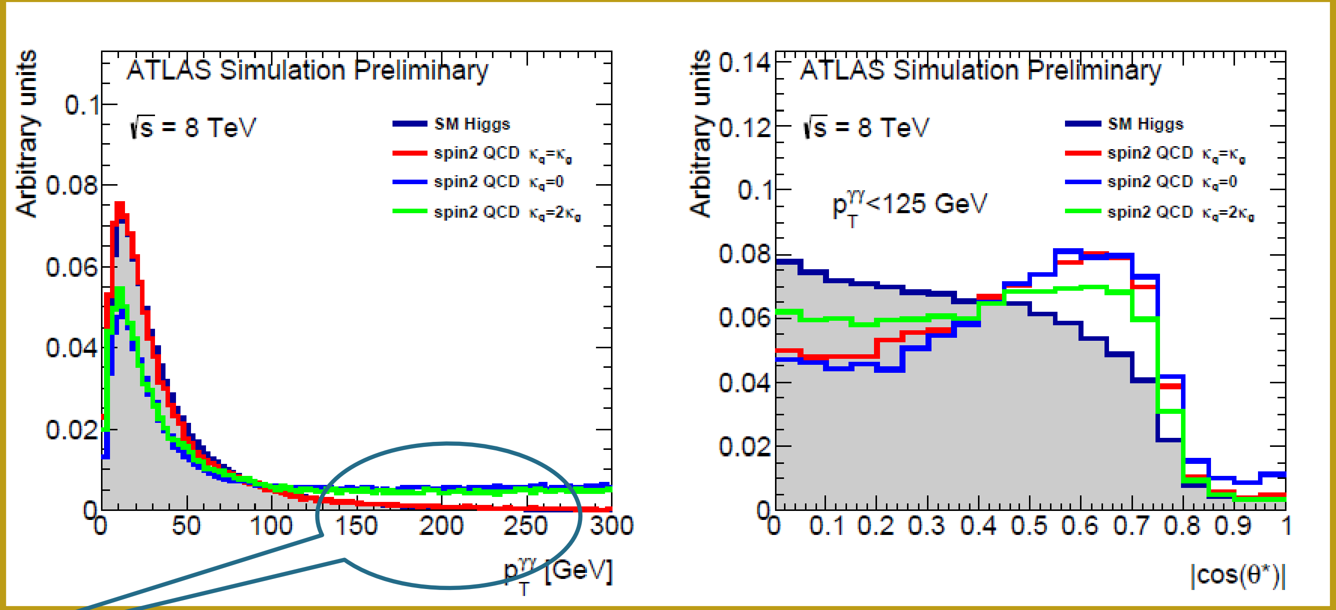
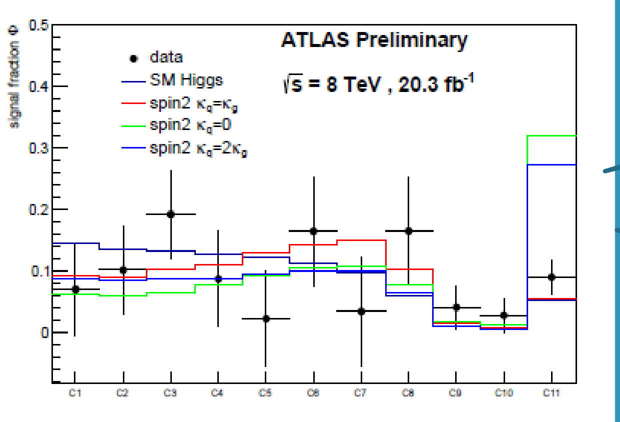


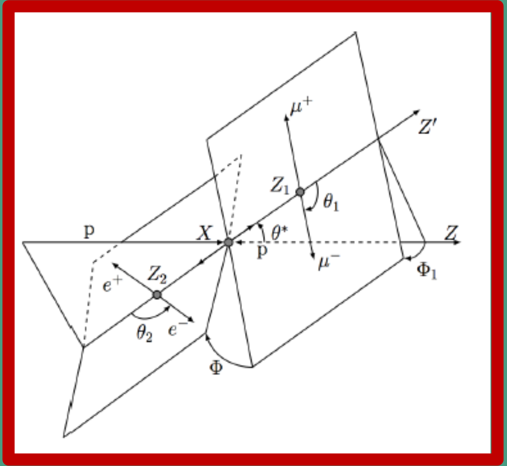


Nbin/Ntot in 10 |cosθ*| bins

High $P_T^{\gamma\gamma}$ region: Spin2 non-UC scenarii strongly disfavoured

Spin 0 vs Spin 2 : tested with H->γγ, H->ZZ*->4l and H->WW*->lνlν

H->ZZ*->4l
Profit from the information on various angles describing the production and decay.
Θ1, θ2: between l⁻ and Zs
Φ : angle of 2 decay planes
Φ1 : leading lepton plane and Z1
θ* : Z1 angle in 4l-rest frame



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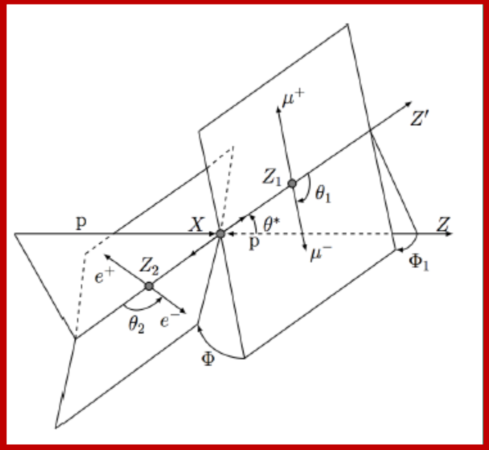

H->WW*->lνlν
Used variables: m^{ll}, P_T^{ll}, m_T, ΔP_T,$\Delta\varphi^{ll}$,$E_{ll\nu\nu}$

Combine them in 2 BDTs to test Spin and Parity

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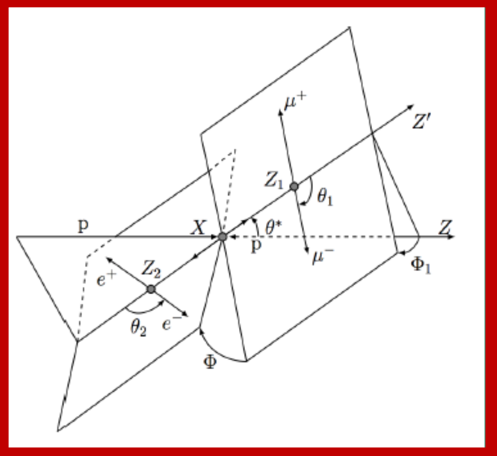

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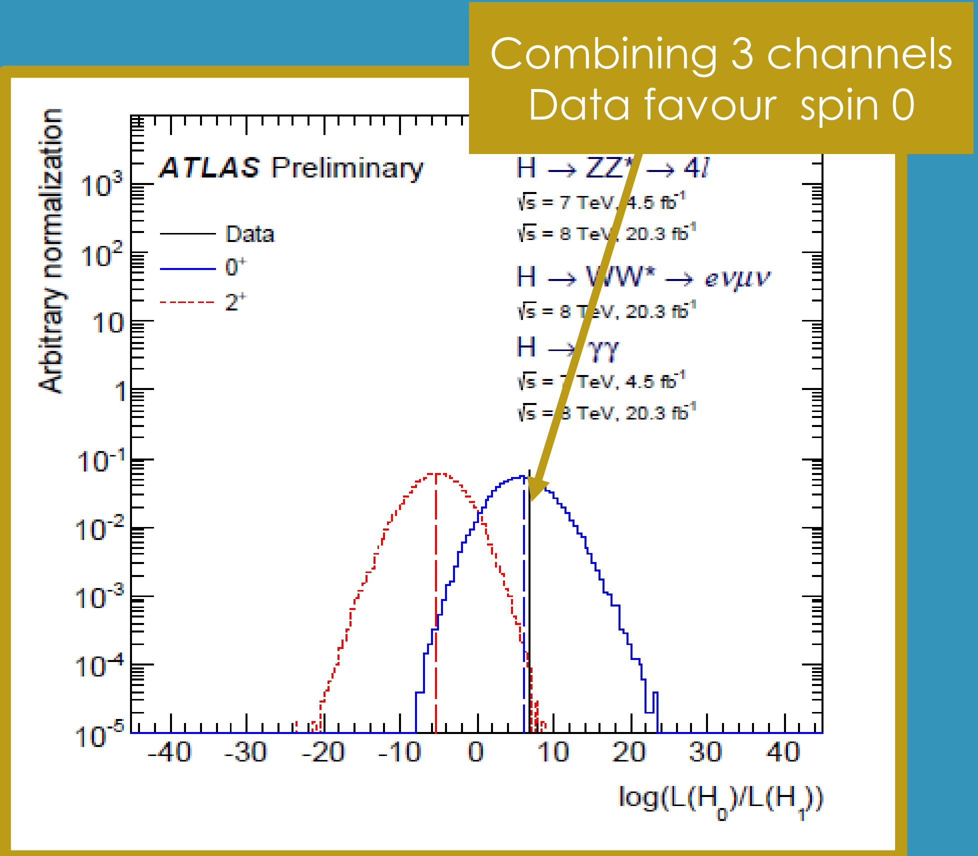
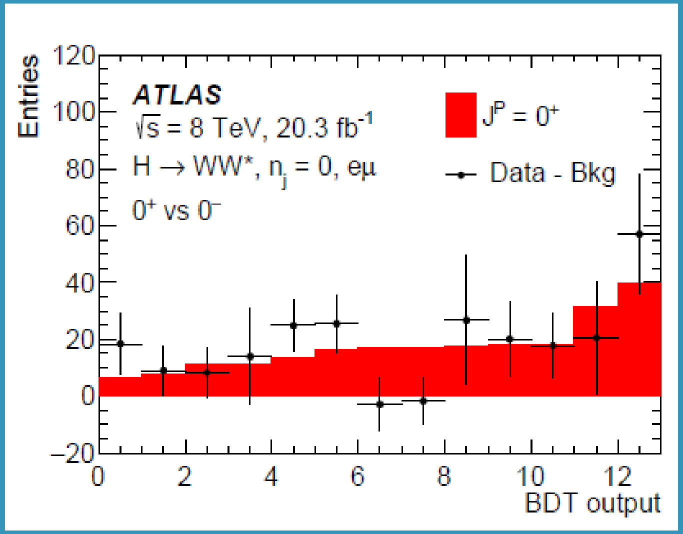


Spin 0, 0+ or 0-?

Exemple: H-WW*->lvlv
BDT output and comparison with scalar hypothesis



Spin 0, 0+ or 0-?

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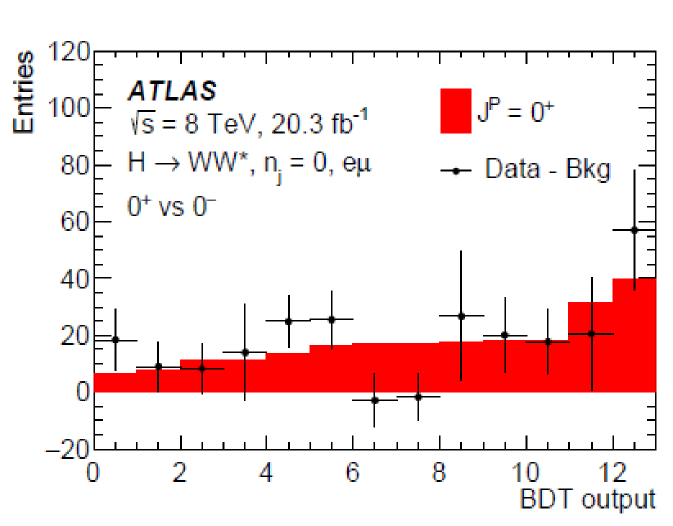
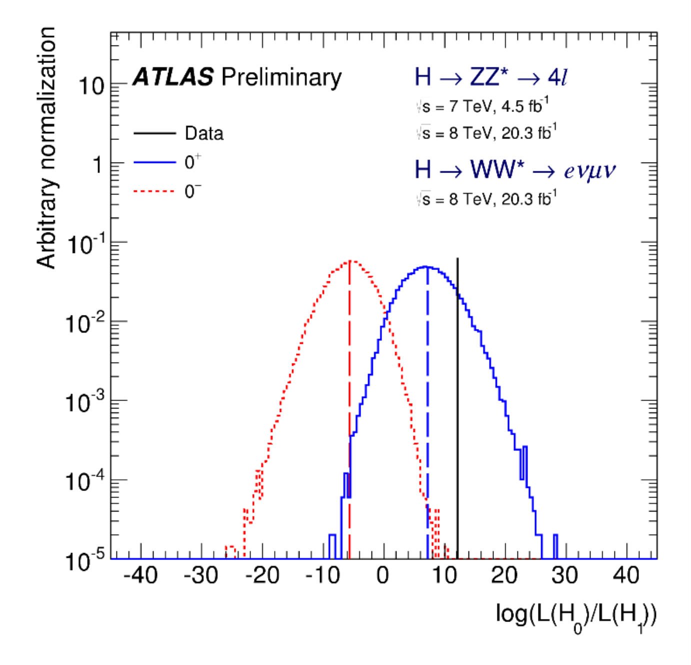
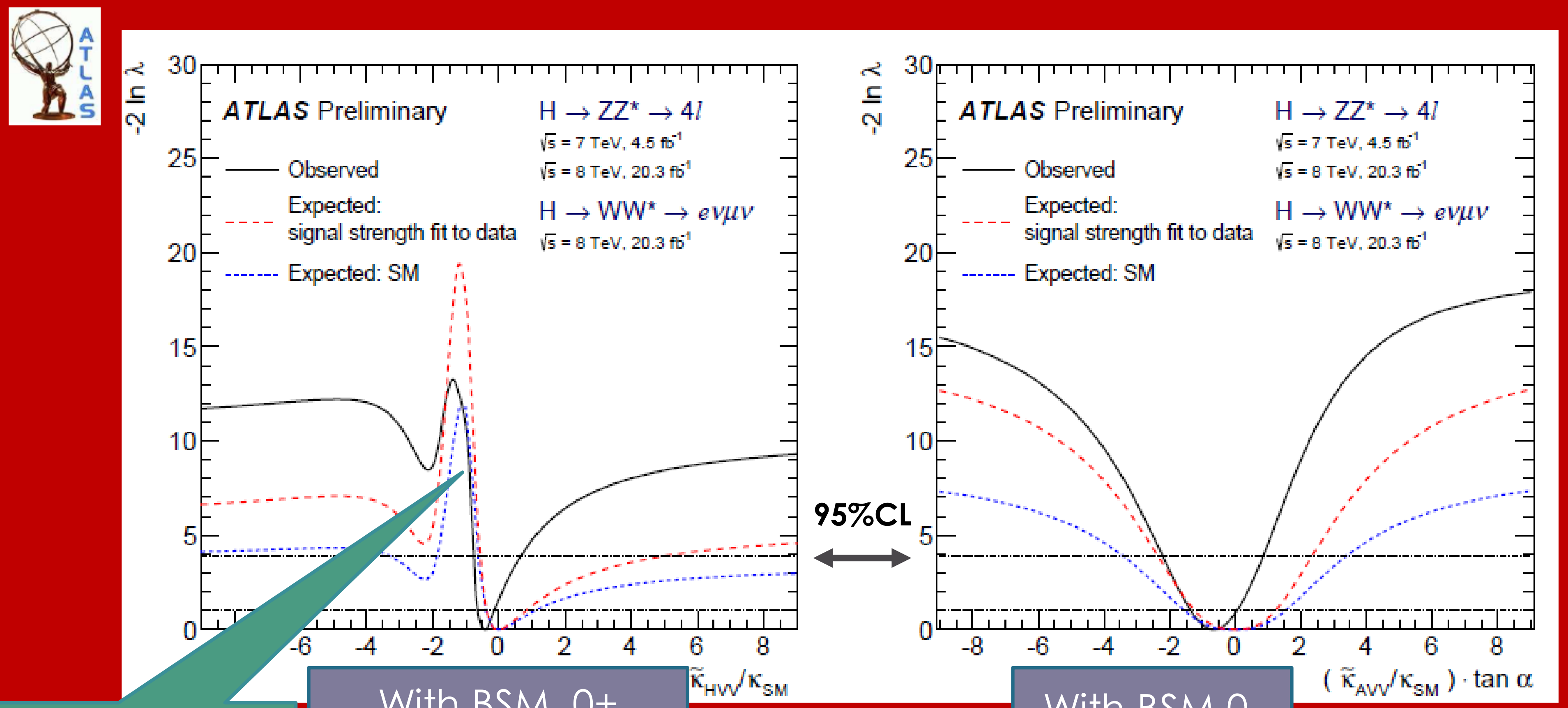


Combined results using both H->ZZ*->4l and H->WW*->lvlv



Data favour 0+

Spin 0+, pure or mixture with BSM?



Interference effects between SM and BSM 0+

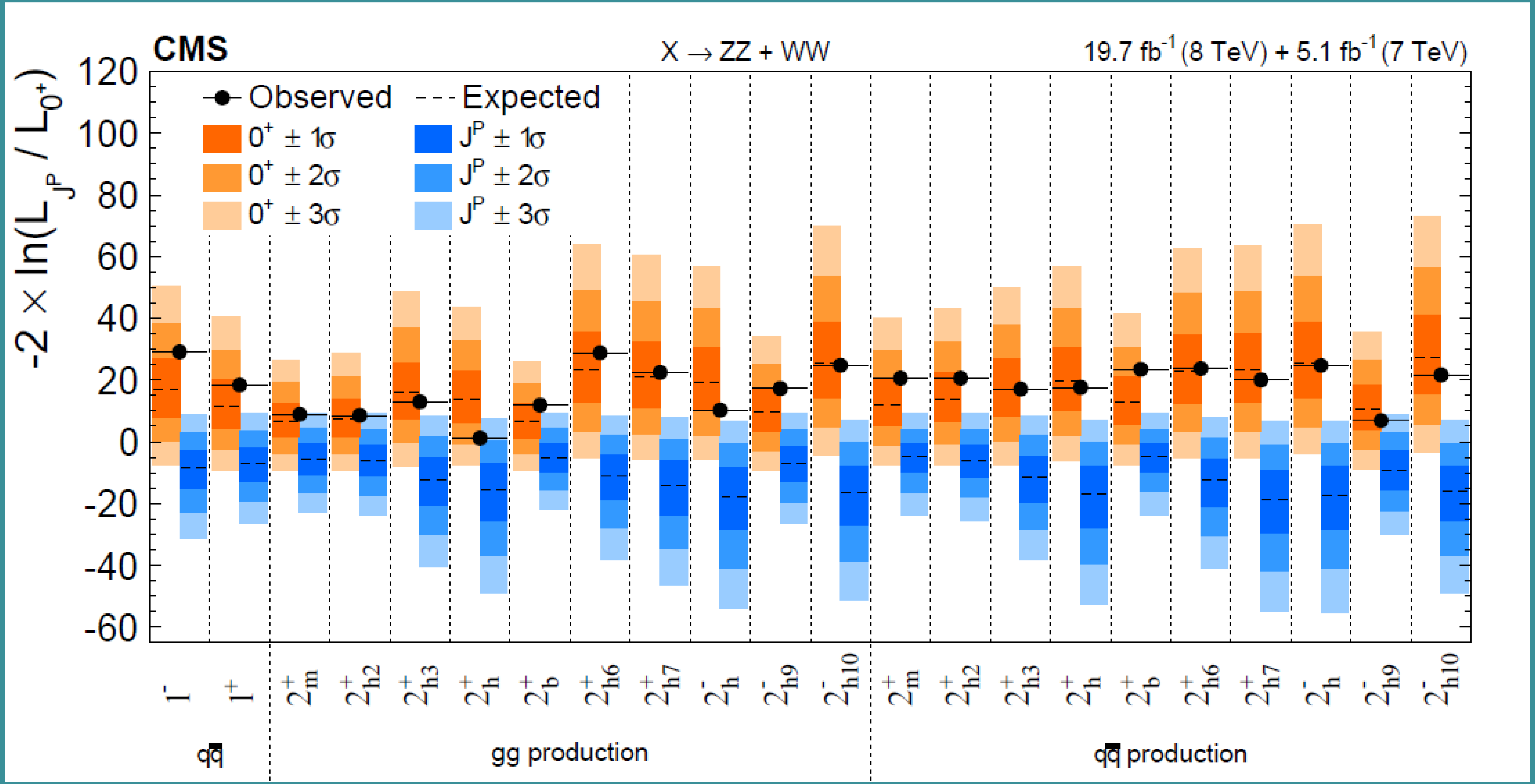
With BSM 0+

<-0.7 and >0.6 excluded

With BSM 0-

<-2.2 and >0.8 excluded

A long list of Spin-Parity models tested



→Data points agree with the 0+ SM prediction

The Scalar Boson Xsections and Branching ratios.

Analyses provide for each decay channel

→ An observation significance (p0)
→Constraints (or measurement) of the Higgs mass
→Constraints (of measurement) of the decay strength, often per production category

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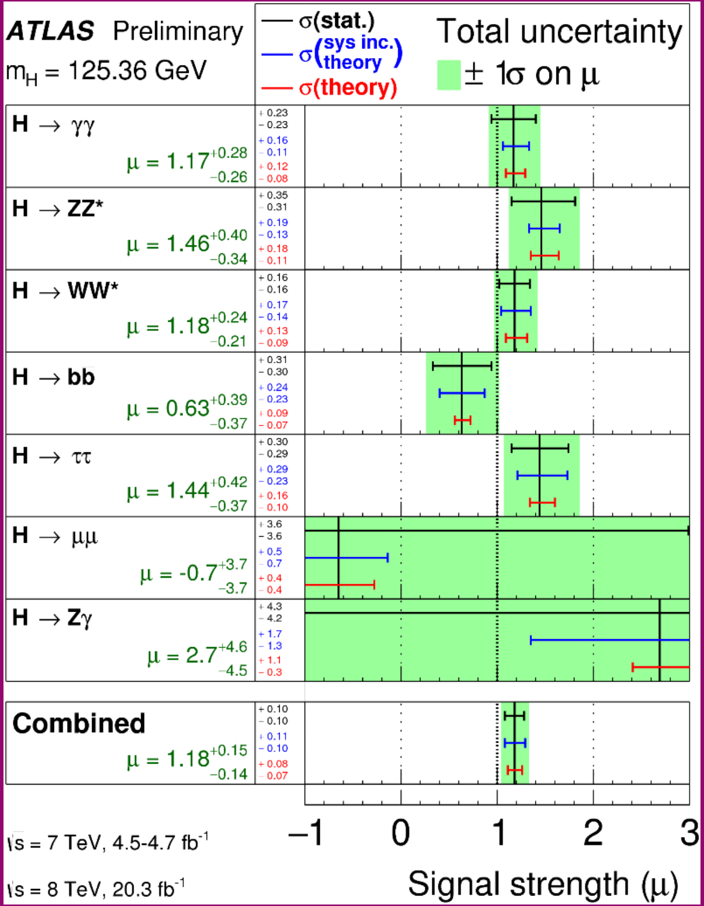
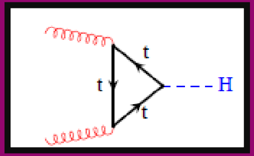
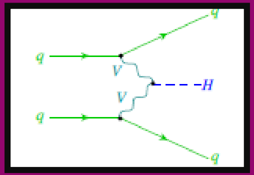


Combined Higgs global signal strength:
$\mu = 1.18 + 0.15 - 0.14$

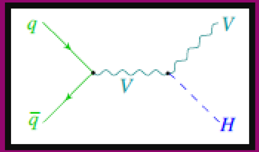
Signal strength for Higgs production mechanisms



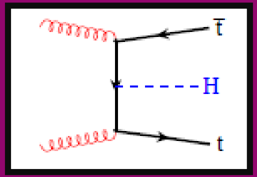
ggF



VBF



VH



ttH

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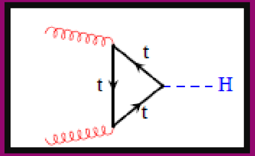

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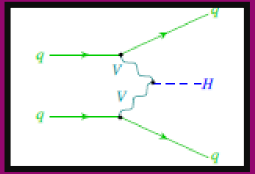

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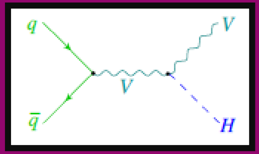

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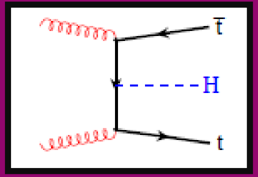

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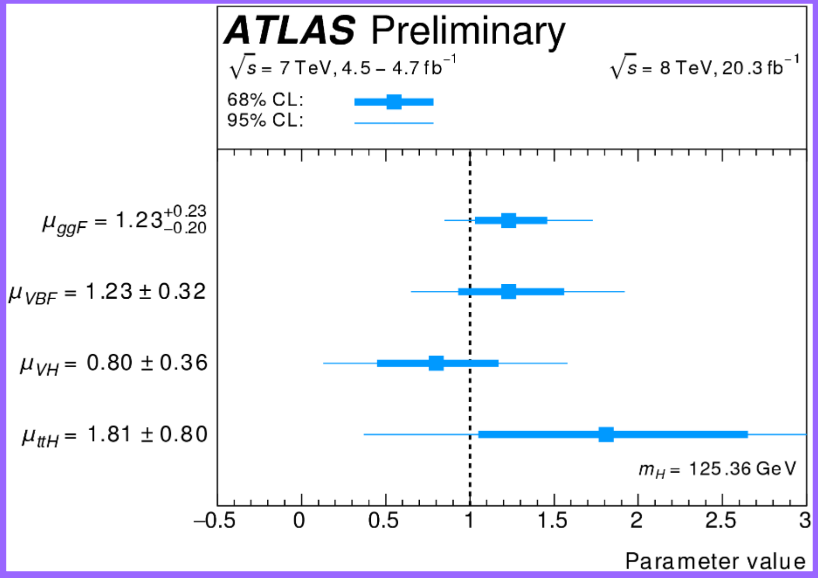

All decay channels together assuming SM Branching ratios

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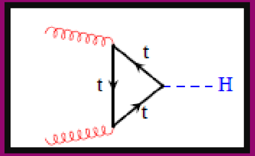

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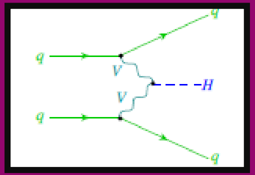

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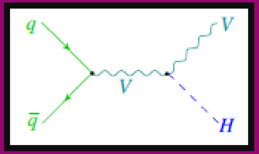

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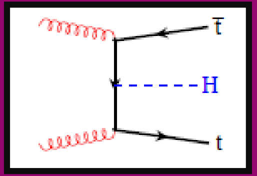

ttH

Coupling to Fermions :
ggF and ttH
Coupling to Bosons :
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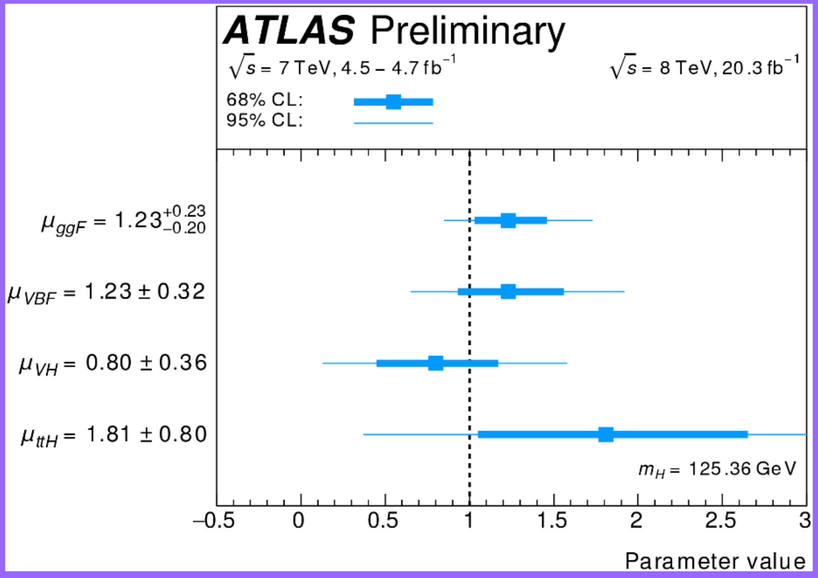

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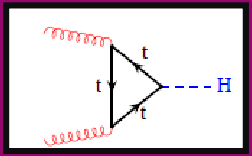

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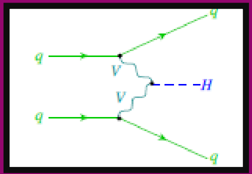

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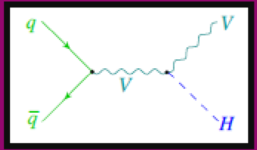

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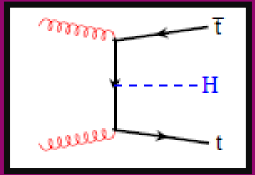

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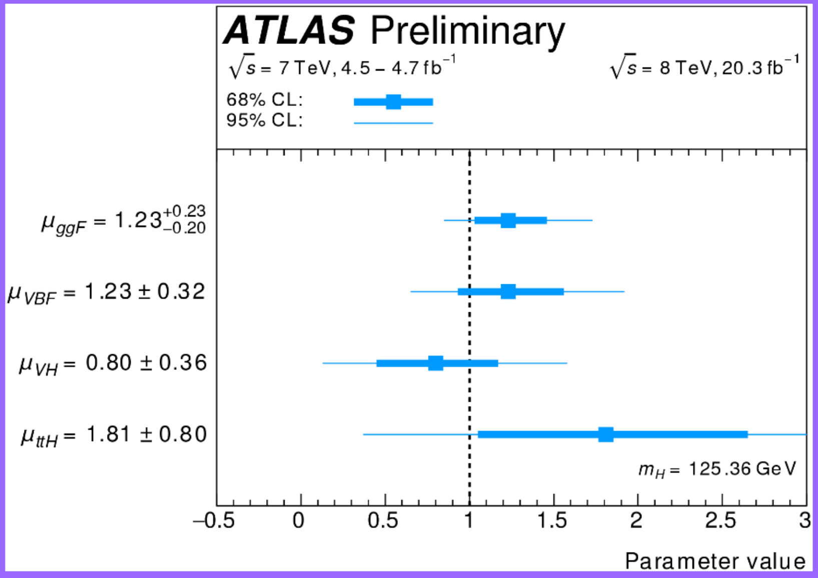
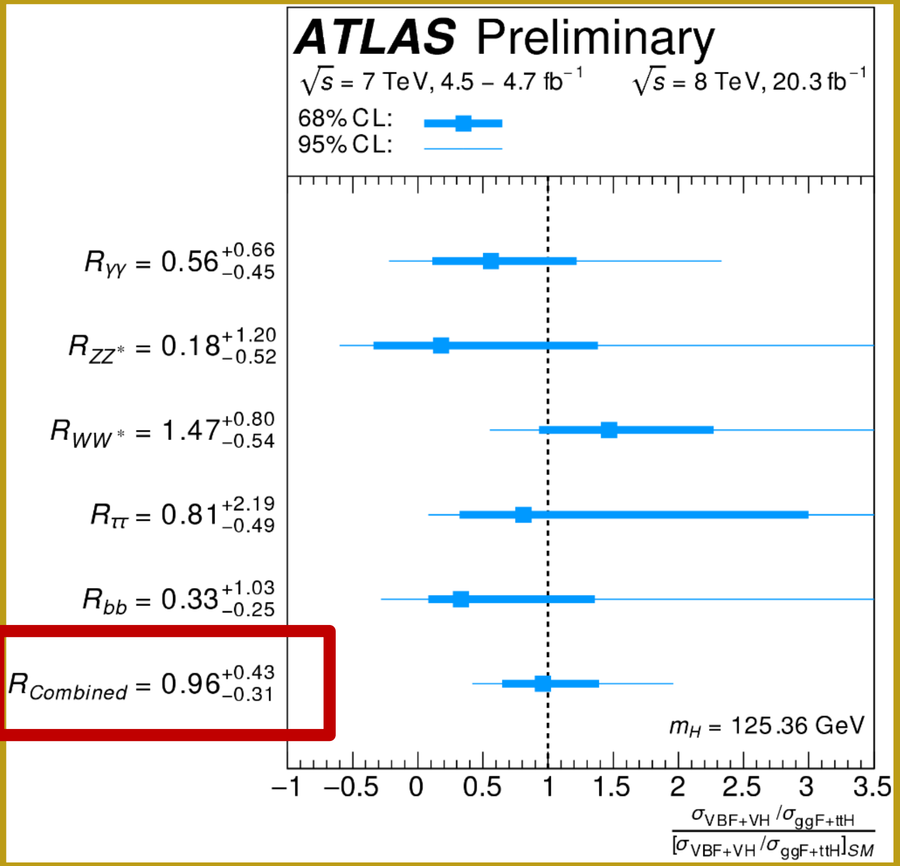
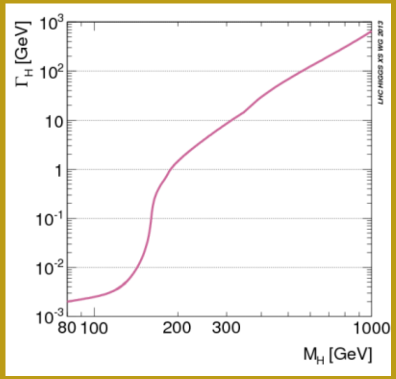


All decay channels together assuming SM Branching ratios

Bosonic & Fermionic coupling ratio
$R = \mu_{VBF+VH} / \mu_{ggF+ttH}$ →decay channel



The Width of the Scalar Boson



Higgs Width Γ_H=f (M_H)

For M_H=125 GeV-> Γ_H^{SM}~4MeV

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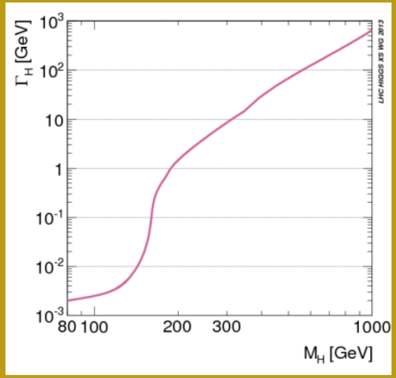

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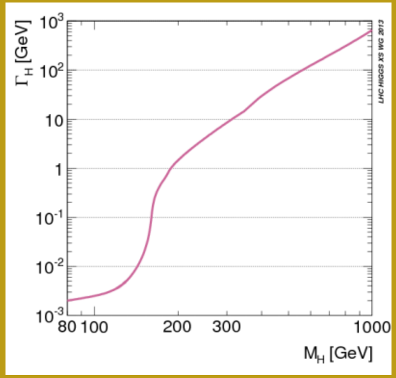

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Ex: H->ZZ*

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At a given measured Xsection, infinite combinations for couplings and width

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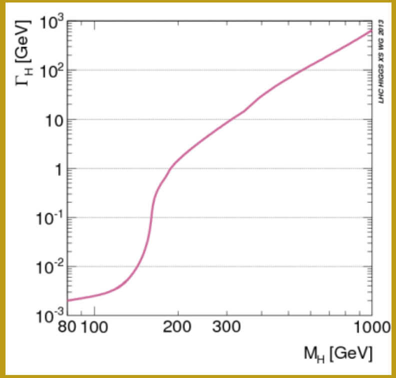

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$$\sigma_{i\to H\to f} \sim \int \frac{\mathrm{d}s \quad g_i^2 g_f^2}{(s-m_h)^2 + m_h^2\Gamma_h^2} \Big|_{s\gg m_h^2} \to \frac{g_i^2 g_f^2}{s}$$

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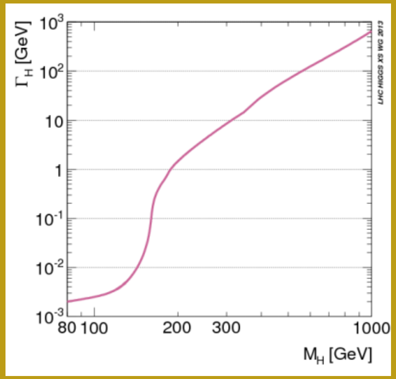

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$$\sigma_{\rm off} \sim g^2_{H\to gg} g^2_{H\to ZZ}$$

$\sim \sigma_H \times \Gamma_H$

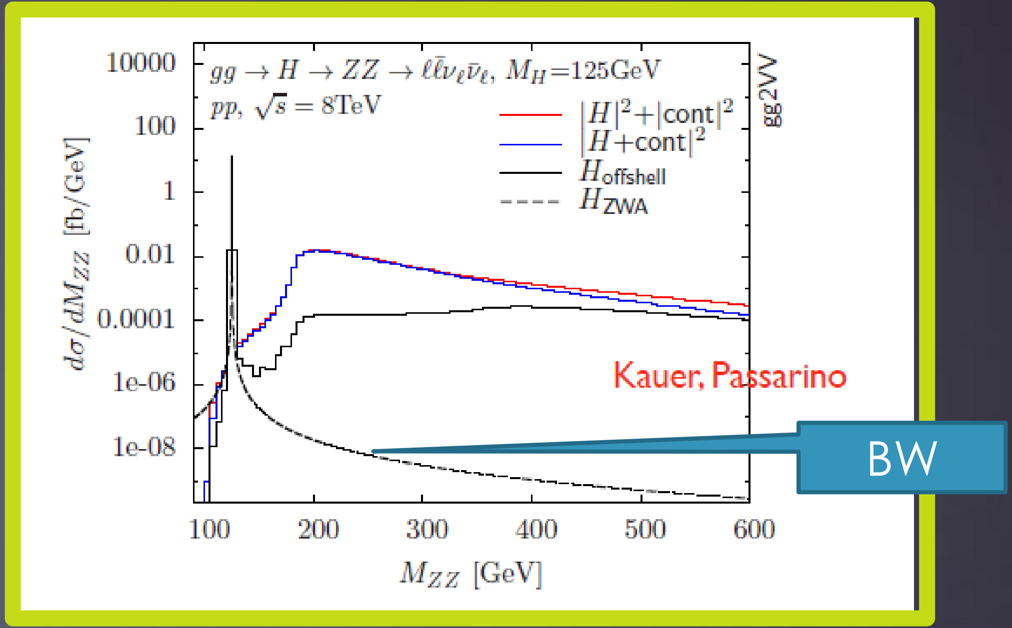
$$\sigma_{\rm off}^{SM} \sim \sigma_H^{SM} \times \Gamma_H^{SM}$$

$$\sigma_{\rm off} \sim \sigma_{\rm off}^{\rm SM} \frac{\Gamma_H}{\Gamma_H^{\rm SM}}$$

Caola, Melnikov
Kauer, Passarino
Campbell, Ellis, Williams

The Width of the Scalar Boson

The traces of Higgs(125) at high M_{ZZ}



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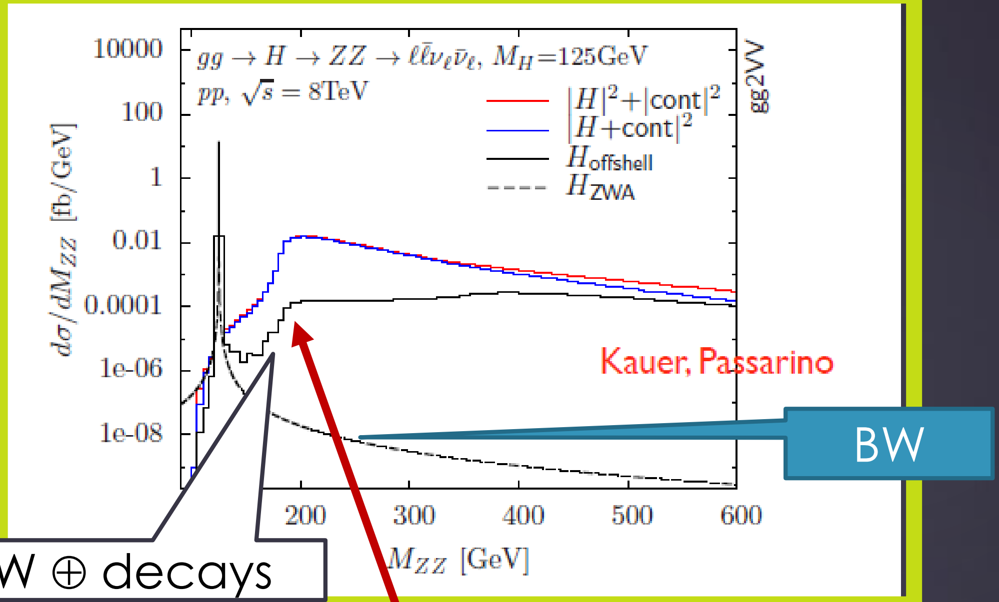

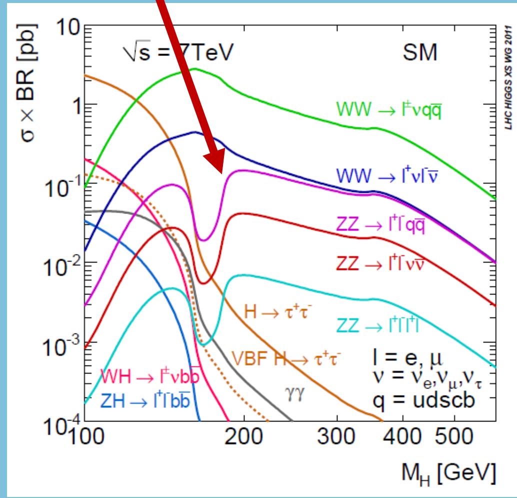

Invisibles 2015, Lydia Iconomidou-Fayard

Caola, Melnikov
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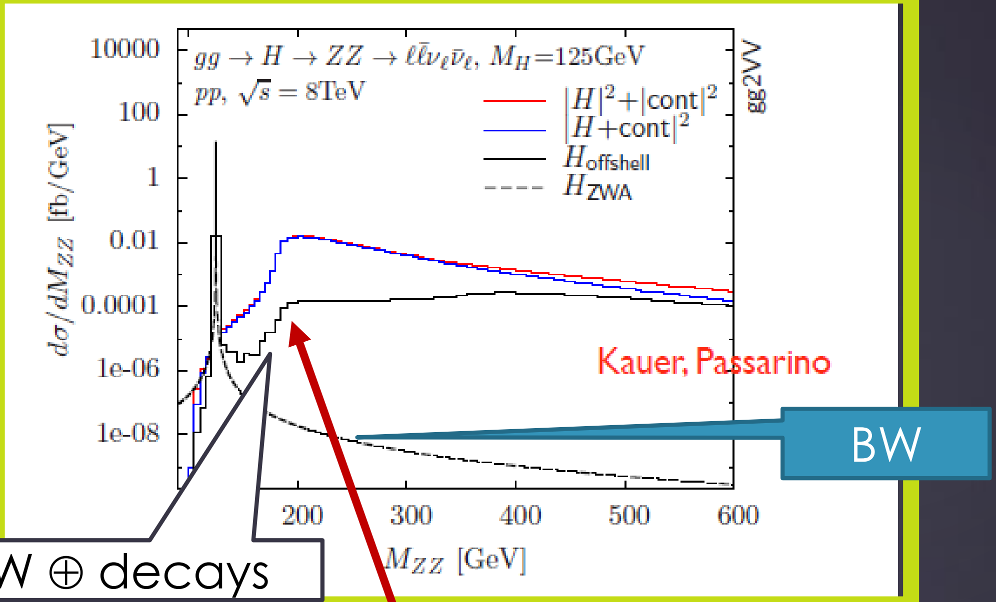

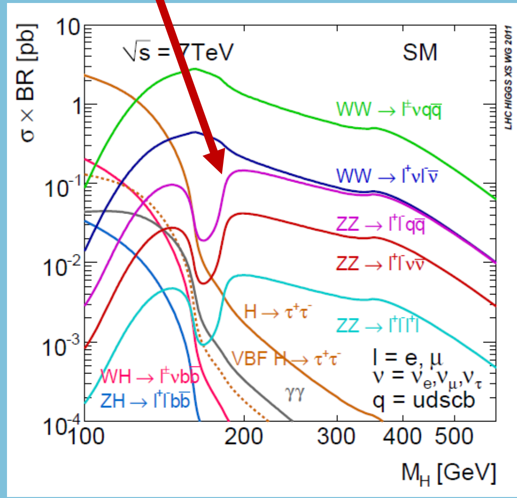

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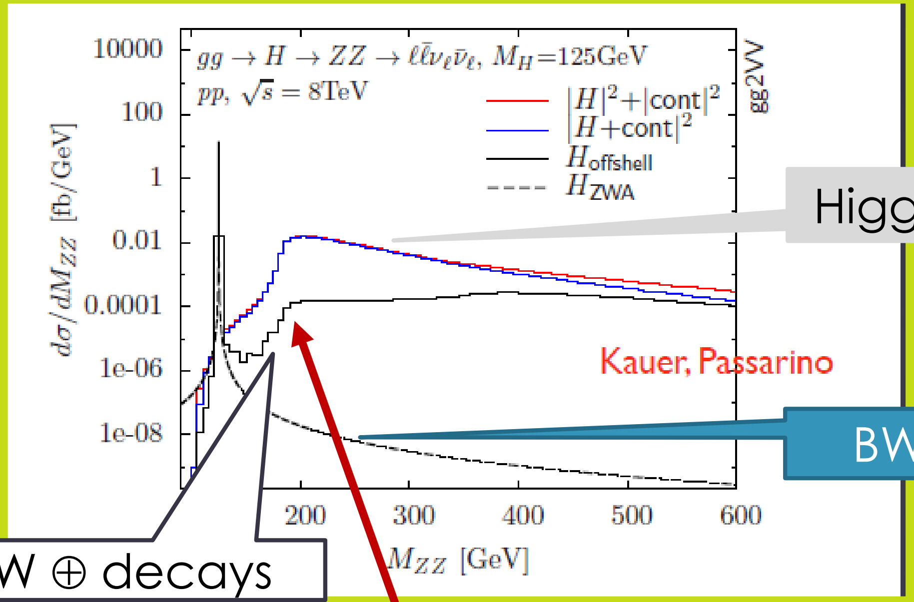

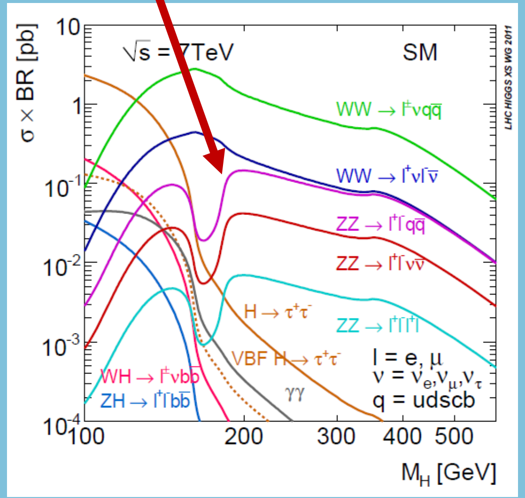

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Moreover: interference effects Between Higgs->ZZ and gg->ZZ

Caola, Melnikov
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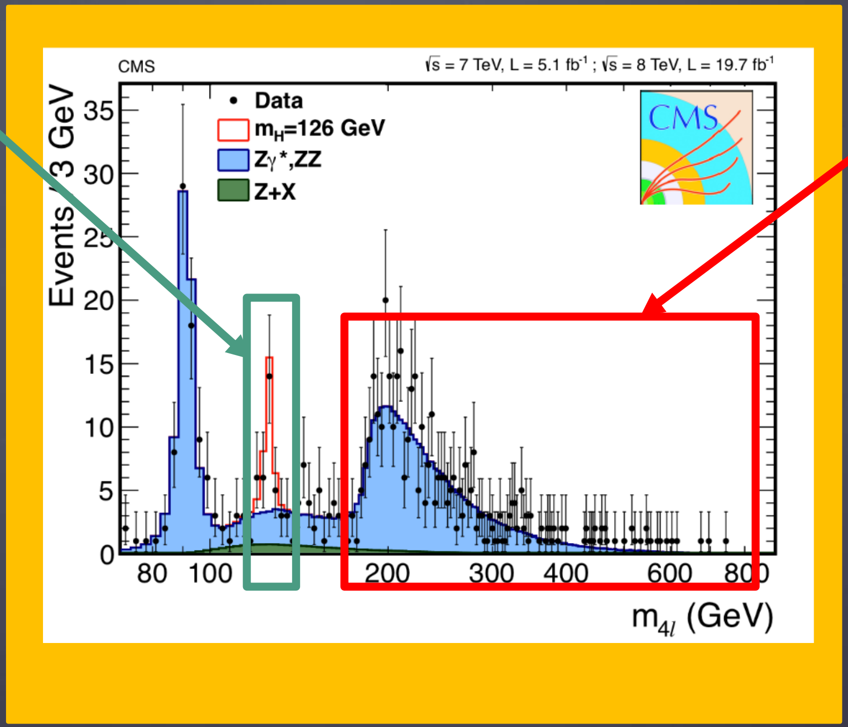
The Width of the Scalar Boson

Measure OFF-SHELL vs ON-SHELL cross-sections with H->ZZ,WW decays in the clean leptonic channels

For ON-SHELL

H->ZZ-> 4l

H->WW->lνlν



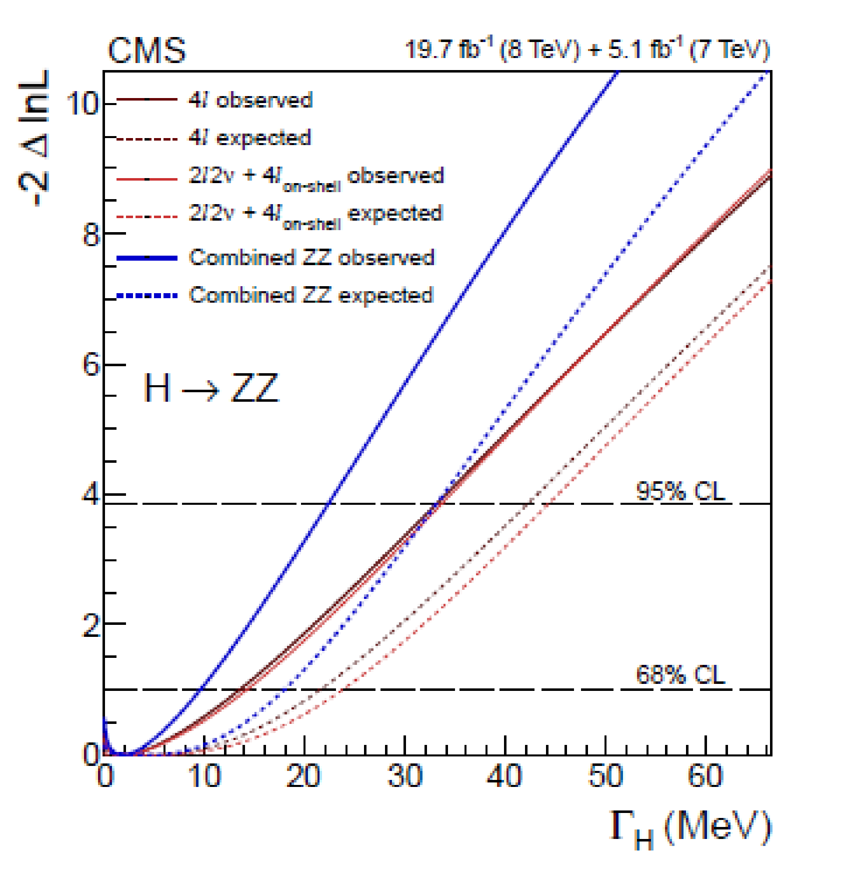
For OFF-SHELL

H->ZZ-> 4l

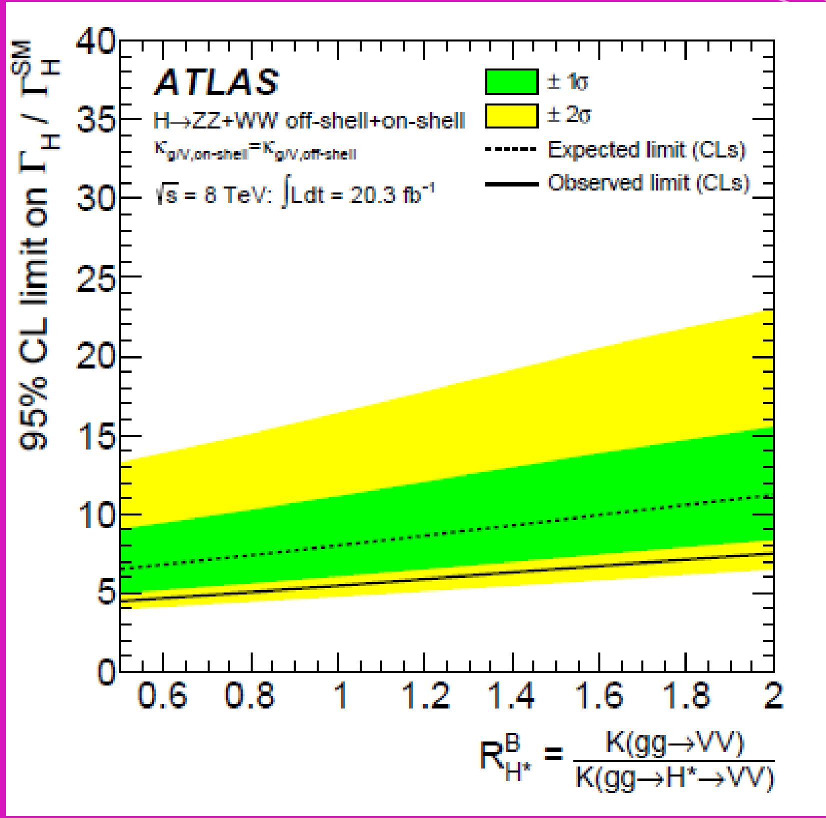
H->ZZ->llνν

H->WW->eνμν

The Width of the Scalar Boson



$\Gamma_H < 22$ MeV (95% C.L.) ($\Gamma_{SM} \sim= 4$ MeV)



$\Gamma_H/\Gamma_{SM} < 5.5$ (95% CL)

The Couplings

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A series of assumptions are necessary
Built-up in common among the 2 experiments

Assumptions for benchmark models for testing the Higgs couplings

1) A single resonance has been discovered with a mass of 125 GeV
2) Higgs production and kinematics compatible with the SM one
3) Narrow width approximation ➔ $$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$
4) Assume CP-even scalar structure
5) Assume that the off-shell measurement depend on the coupling strengths and not on the Width $$\sigma^{\text{off}}(i \to H^* \to f) \sim \kappa_{i,\text{off}}^2 \cdot \kappa_{f,\text{off}}^2$$
6) No running coupling constants $$\kappa_{j,\text{off}} = \kappa_{j,\text{on}}$$

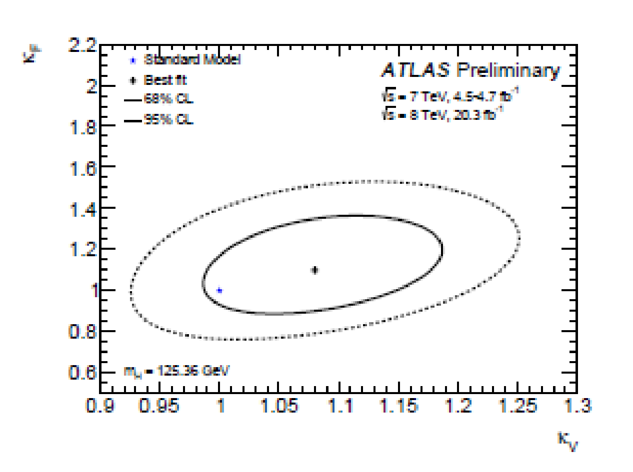
κ = coupling
κ=1 for SM particles

Fermionic vs Bosonic couplings

Assume

Bosons: $\kappa_V = \kappa_W = \kappa_Z$

Fermions : $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu = \kappa_g$



$$\kappa_V = 1.09^{+0.07}_{-0.07}$$
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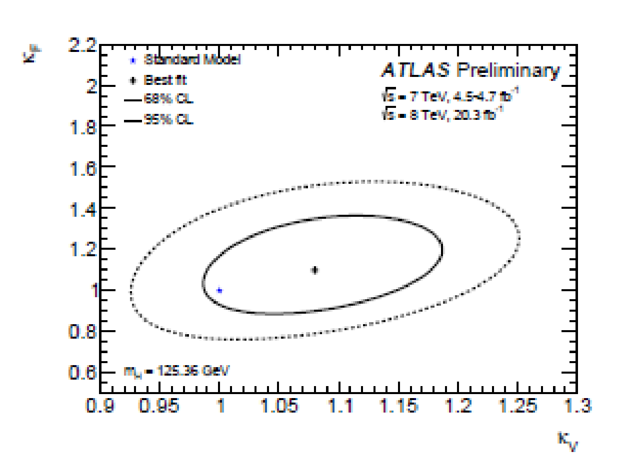

$$\kappa_V = 1.09^{+0.07}_{-0.07}$$
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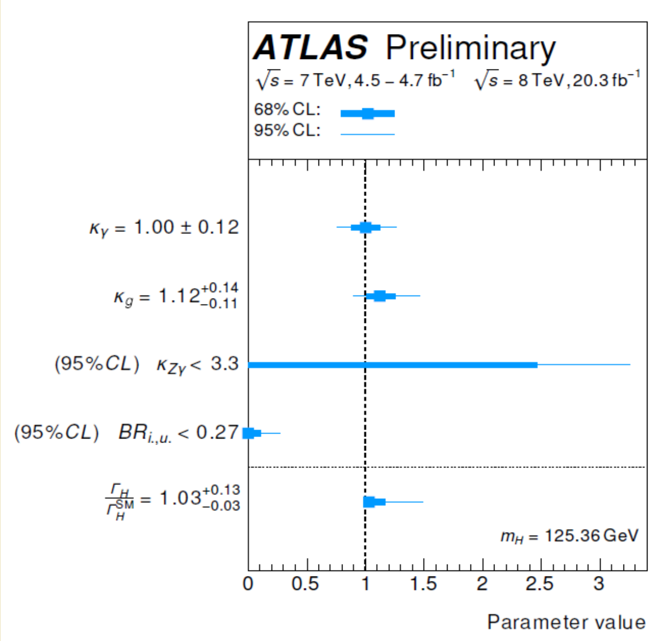
Anything else in the g and γ loops?

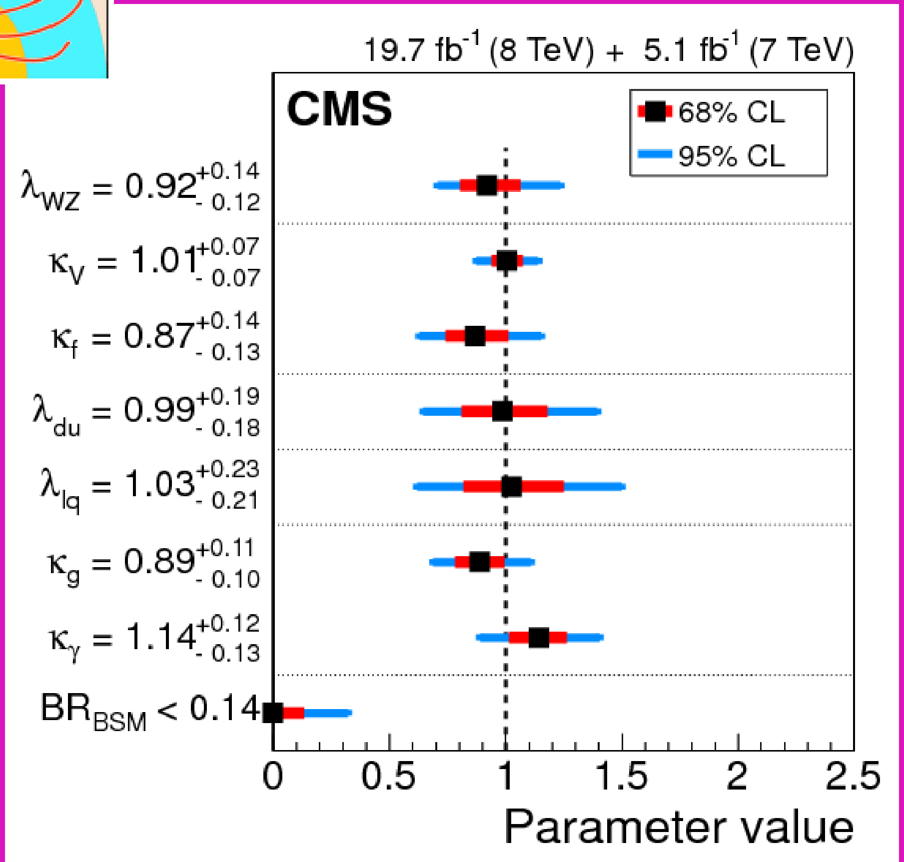
Assume

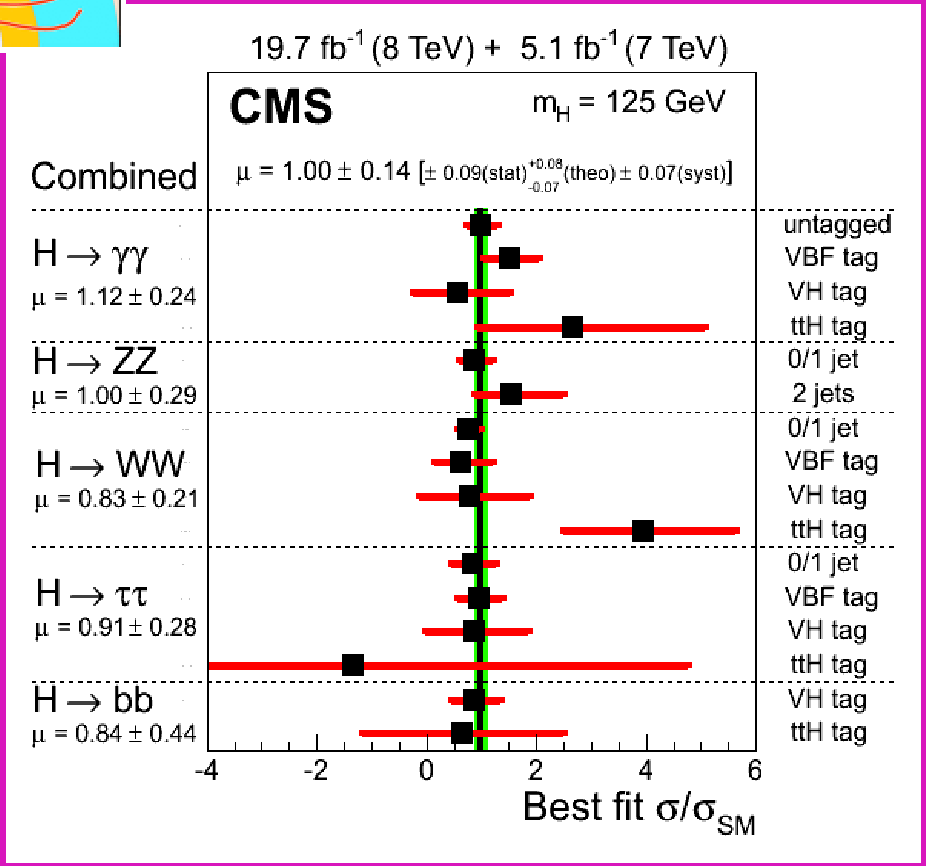
SM couplings for all particles, no constraint on the total Width



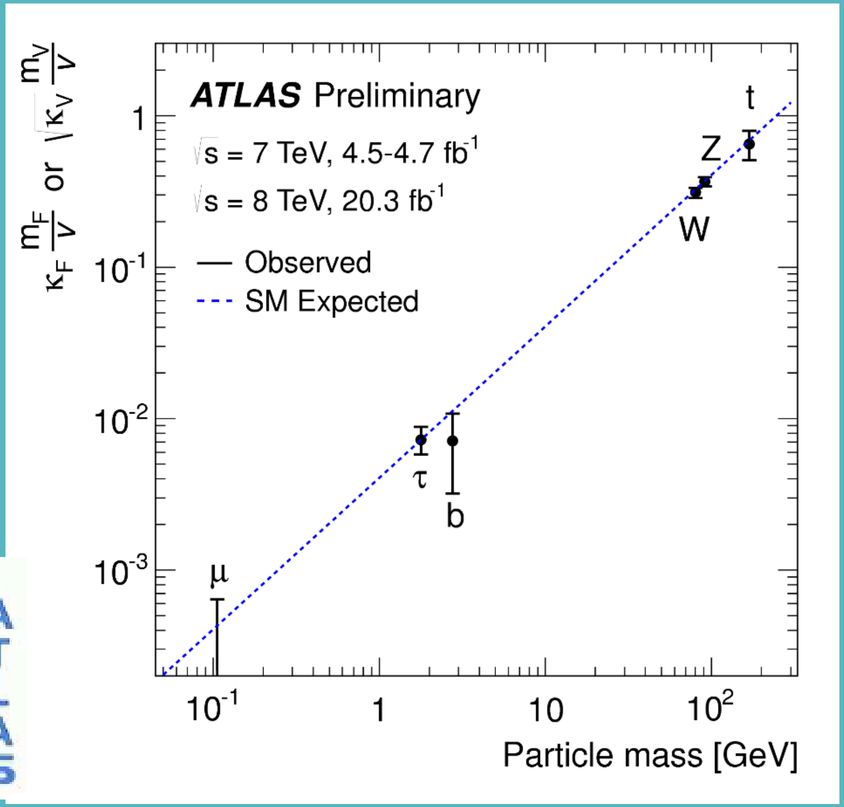
Invisible BR < 0.23 at 95%CL

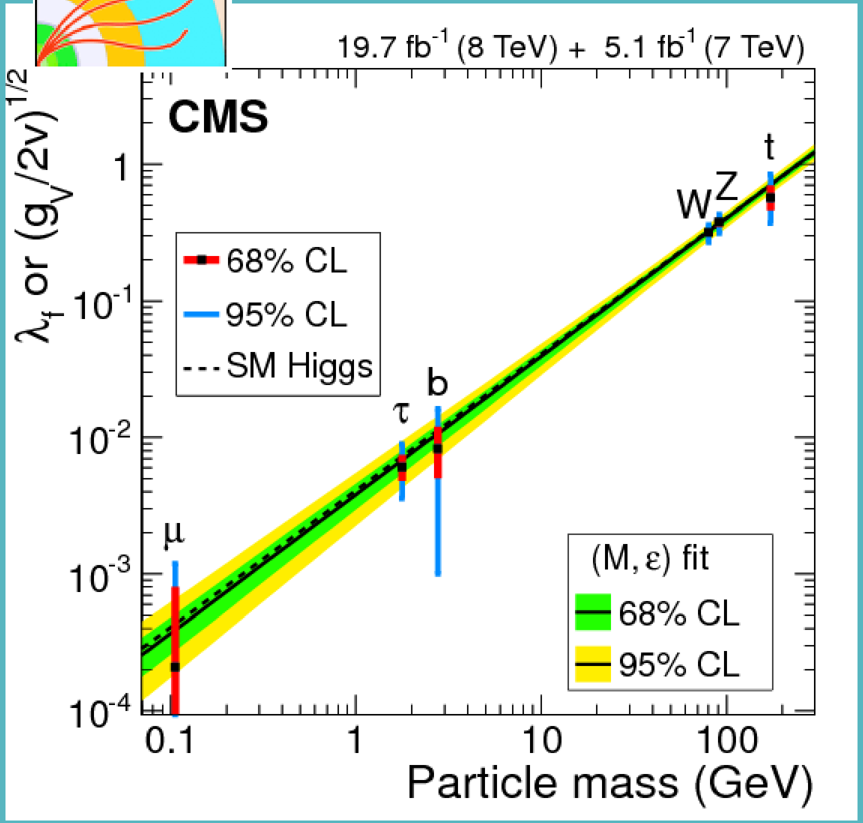
Again couplings..





Coupling summary

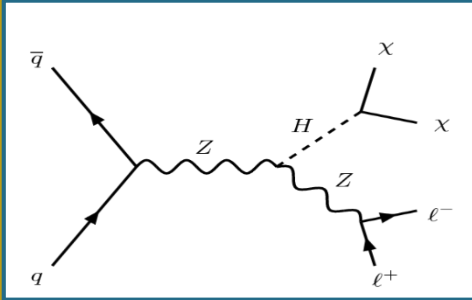




Higgs to invisible(s)?

Dark matter, long lived particles..

Look at ZH mode



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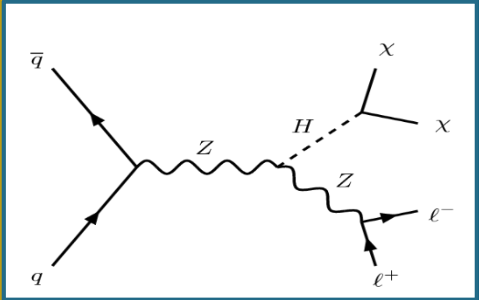

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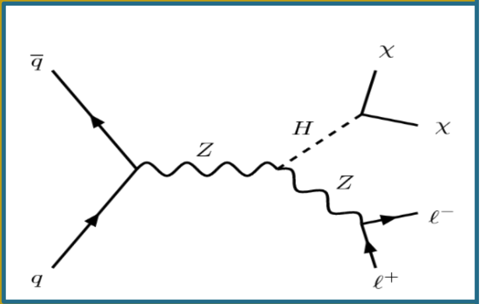
Signal kinematics : Large E_T^{miss}, large $\Delta\varphi$ (P_T^{ll},E_T^{miss}), small $\Delta\varphi$(l,l), no jets.

Dominant backgourdnds: ZZ and WZ, ttbar, W+jets, multijets..

Higgs to invisible(s)?

Dark matter, long lived particles..

Look at ZH mode



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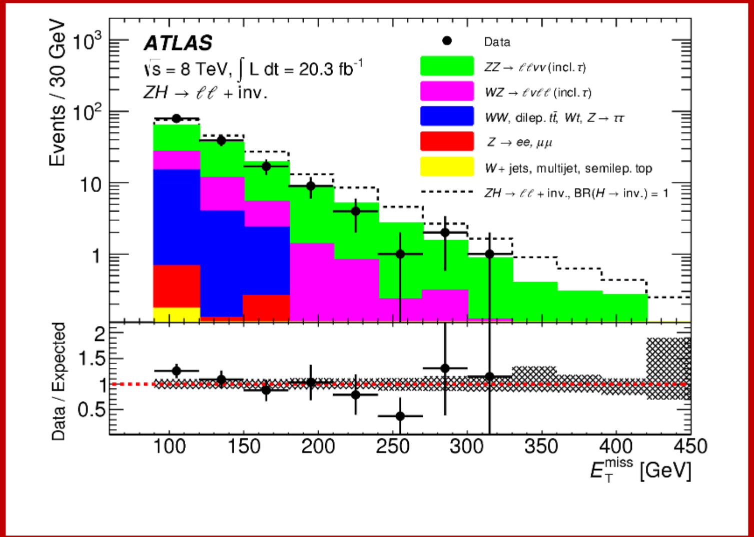

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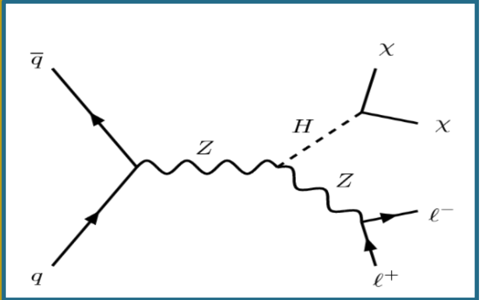

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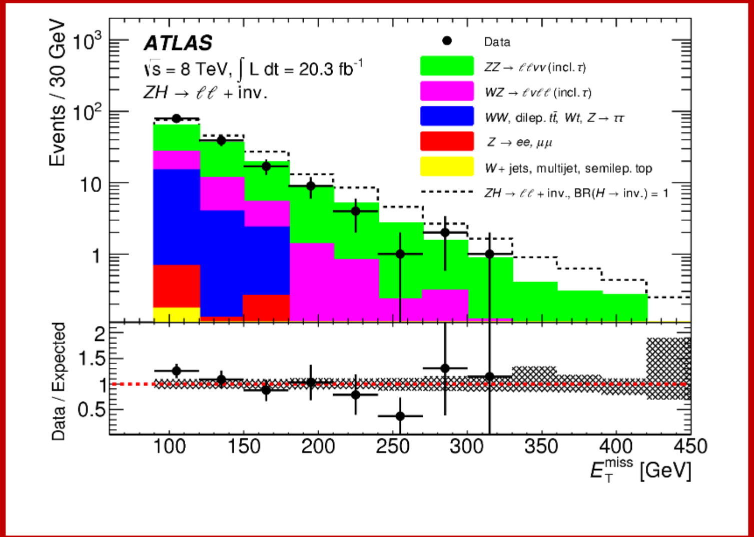

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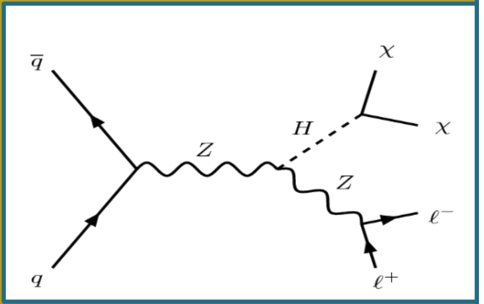

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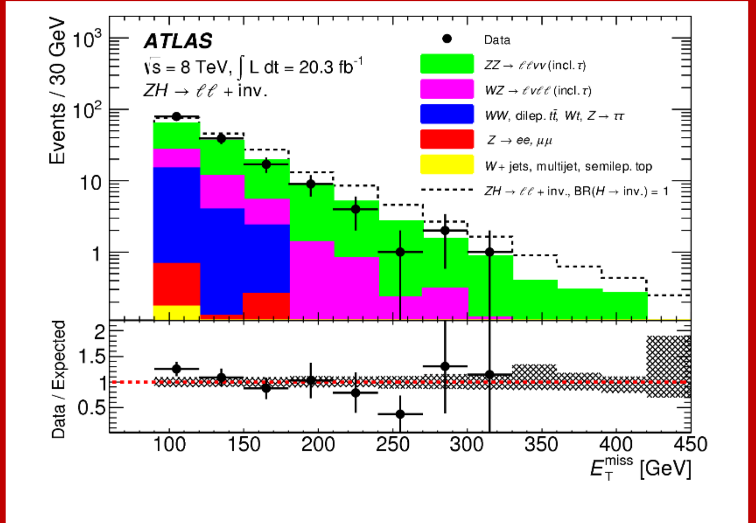

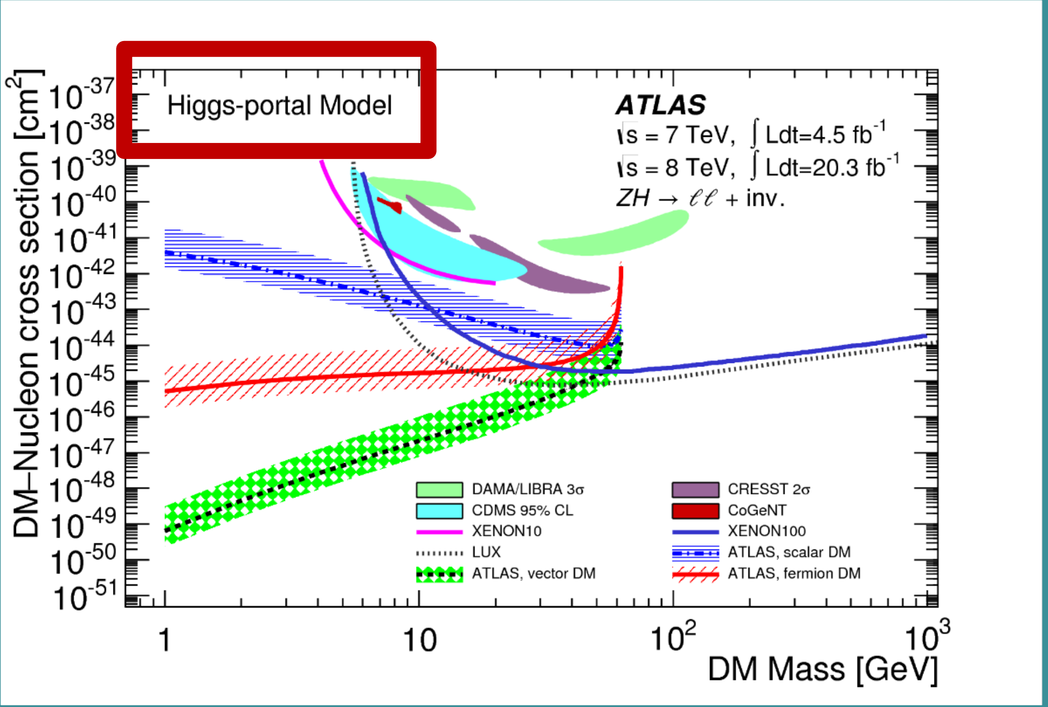

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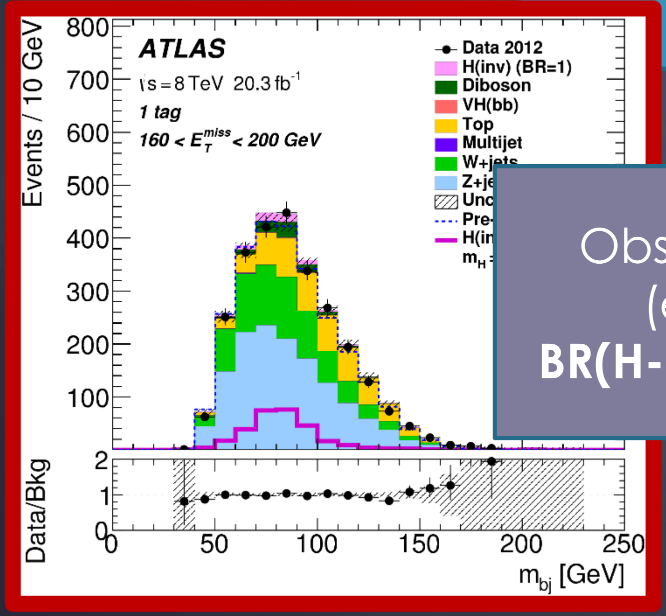

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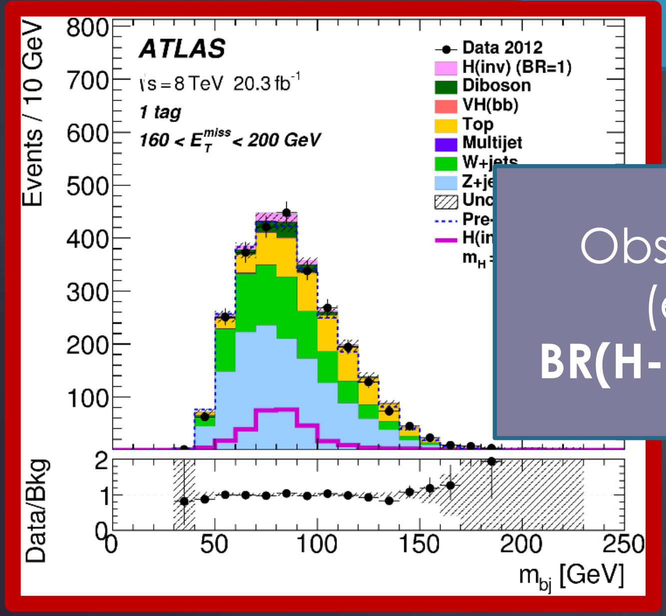

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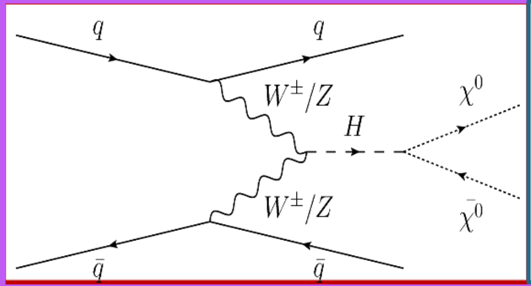
Look at VBF mode



Signature:
Two high energy, well separated-in-eta jets and large E_T^{miss}

conomidou-Fayard

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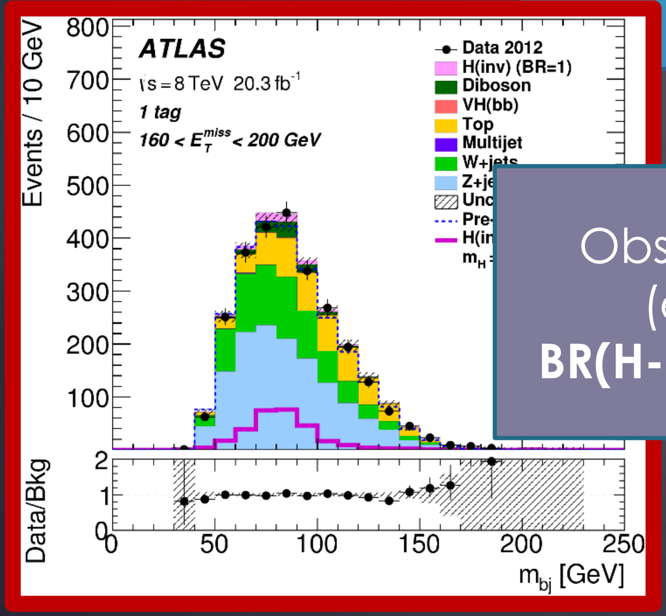

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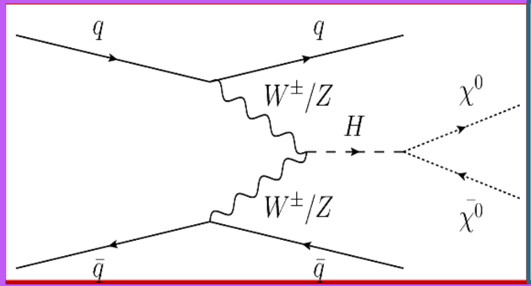

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→Two energetic jets with PT>75 (50) GeV,
 Δη (jet1,jet2) >4.8 and mass(jet1,jet2)>1TeV
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Main backgrounds: W/Z+jets, multijets

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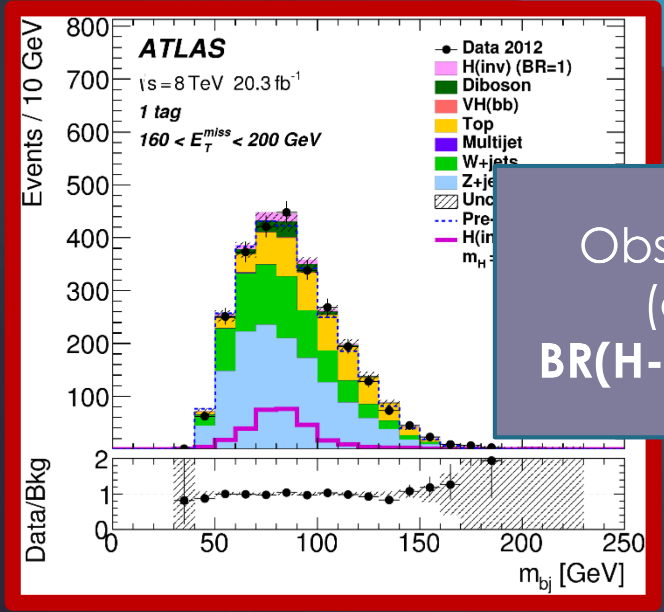

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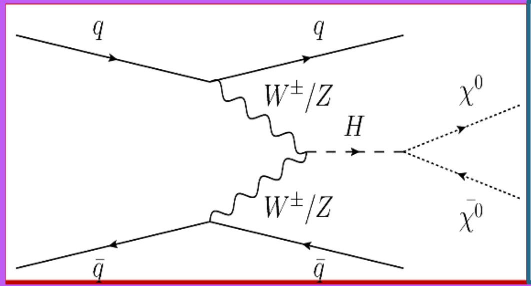

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Main backgrounds: W/Z+jets, multijets

Observed 539 events (exp:576 ± 48)
Br(H->Invisible) < 29% (95% CL)

Conclusions (1)

LHC Run1 was **a rare adventure**, with tremendous accomplishments, several euphoric moments, few distresses and an **unprecedented collective success**

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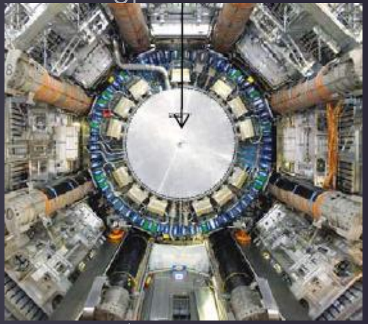

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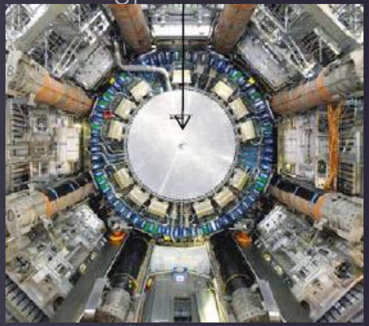

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The **fast discovery of the Scalar Boson** was boosted by the fertile imagination of physicists. It was also the source of an **increasing cooperation and organization between the experimental and theory communities**.

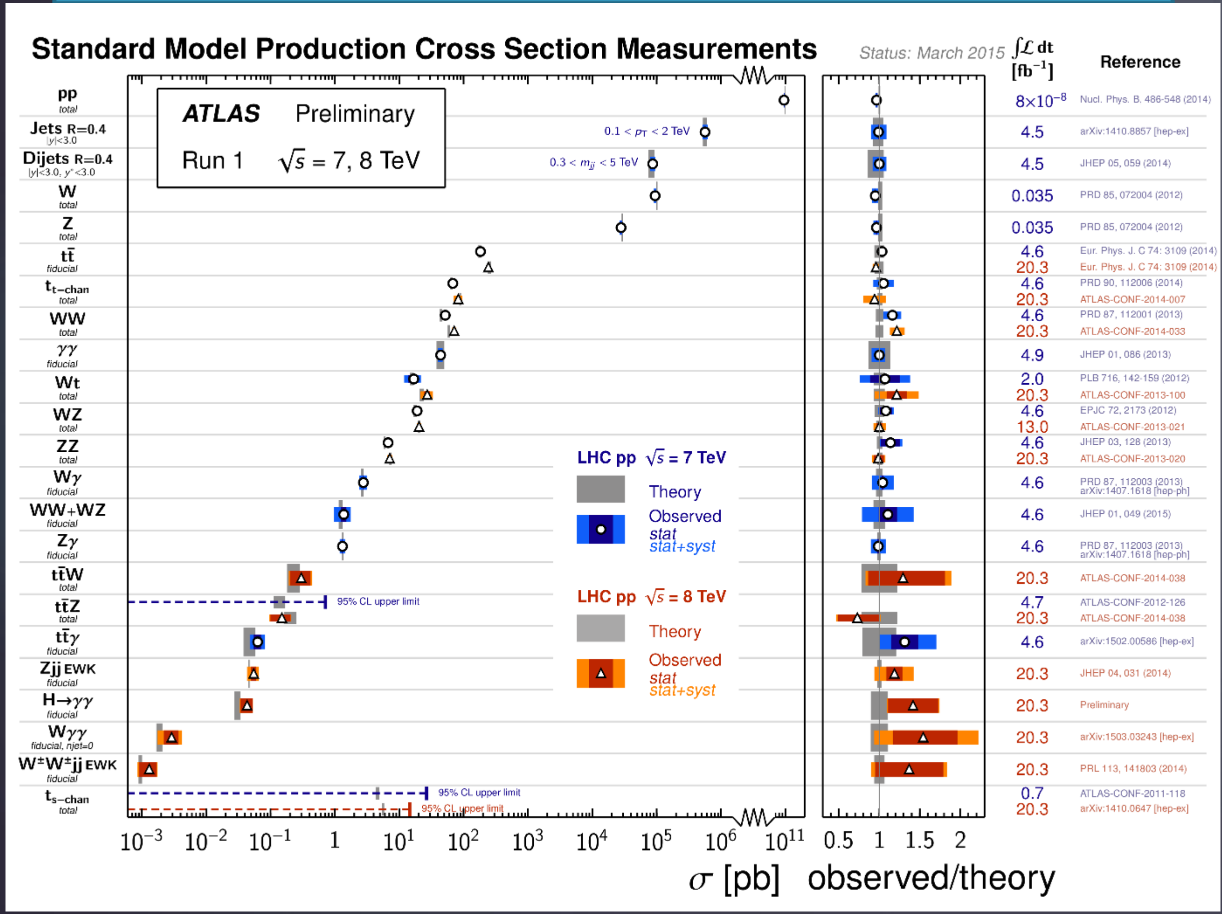
CMS

ATLAS

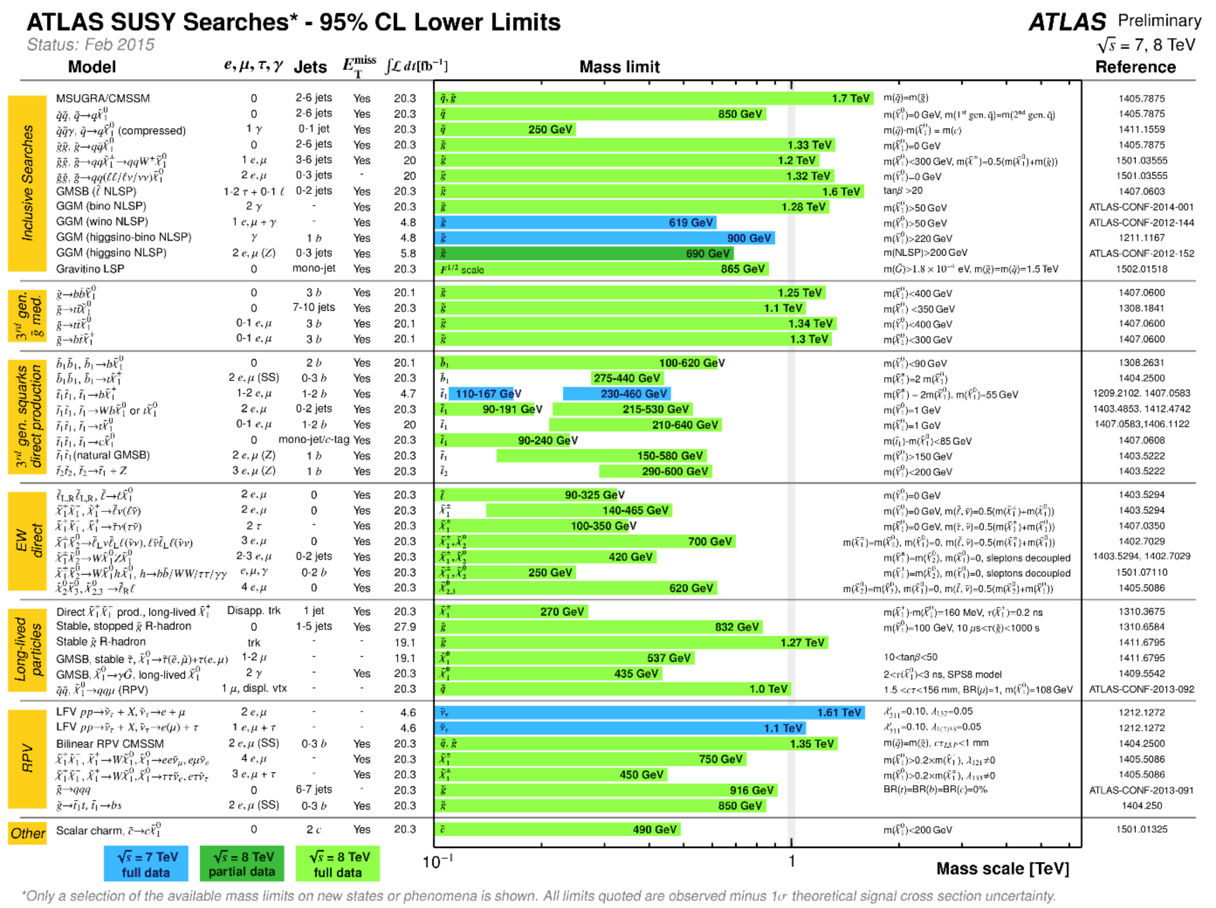
LHC Higgs Cross-Section Working group

Conclusions (2)

From the abundant to rare:
Measurements over 14 orders of magnitude



Searches : A long list of excluded models



Conclusions (3): "We got it"

The scalar Boson ID :

→Mass measured to 0.2%
→Properties compatible with the SM predictions
--- It's a scalar (0+)
--- It's thin (width)
--- It decays to EW vector bosons
---It decays to photons through loops
--- Evidence for VBF production
---Evidence for decays to tau fermion pairs.

The new Scalar Boson it's a portal to more physics topics

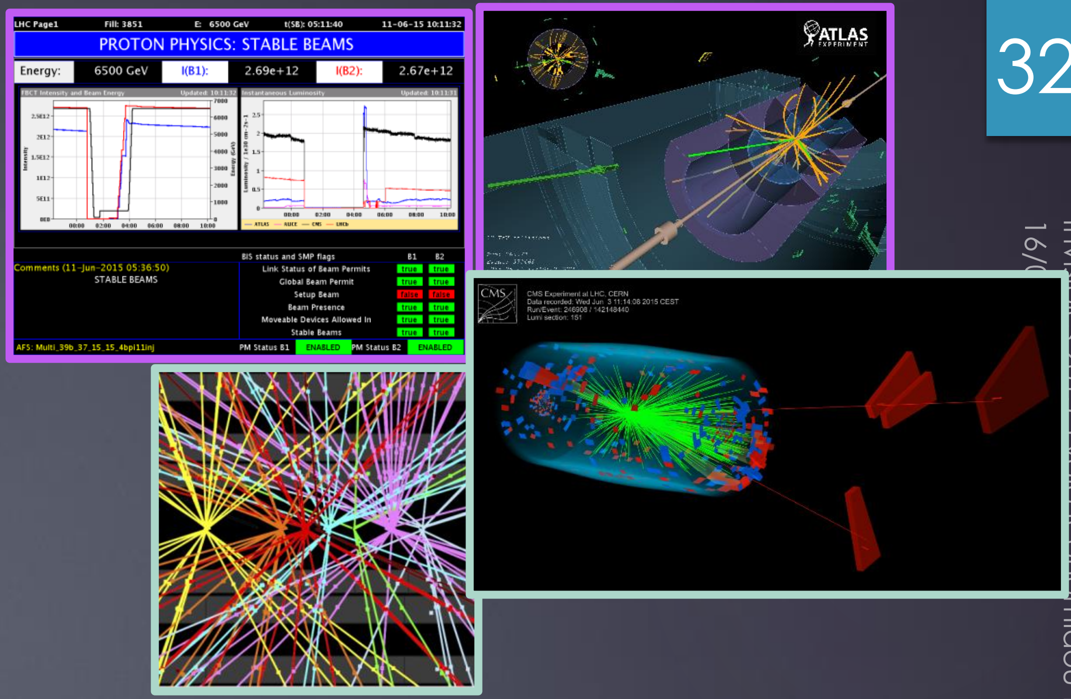
--- Higgs couplings to fermions
--- Differential cross sections
--- Higgs self-couplings(HH,HHH)
--- Rare Higgs decays

The new Scalar Boson it's a portal for New Physics

--- Invisible Higgs decays
--- BSM physics implying additional Higgses

Conclusion (4)

We are starting taking data at 13 TeV !
Expect 100 fb^{-1} in Run2 (by 2018)



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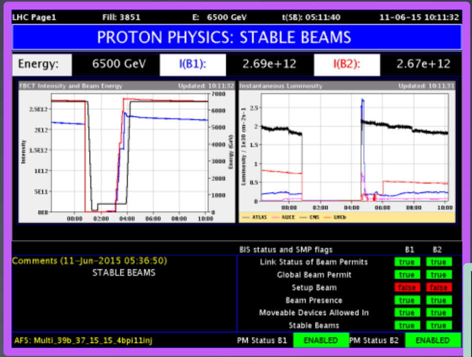
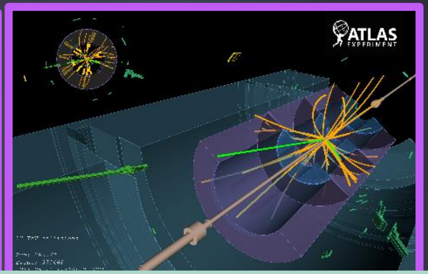
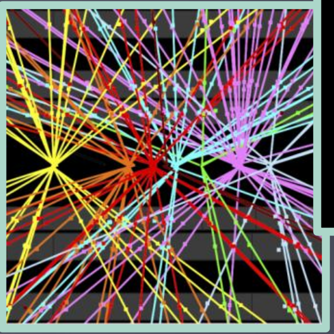
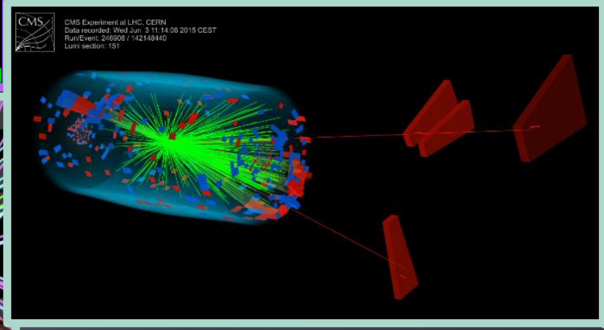
M. Mangano LHCC, 3/6/15









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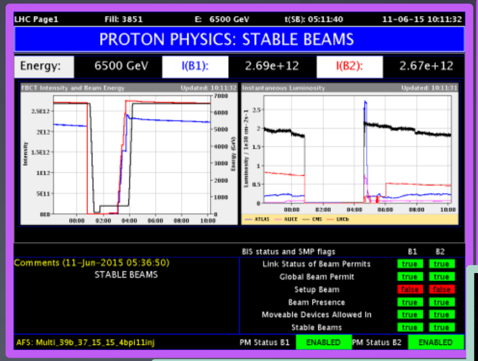

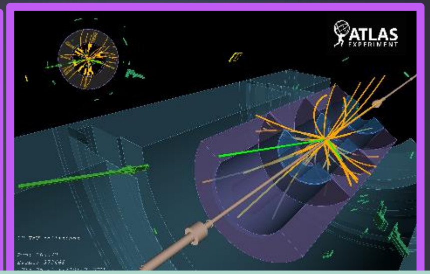

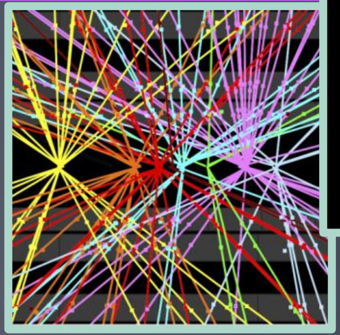

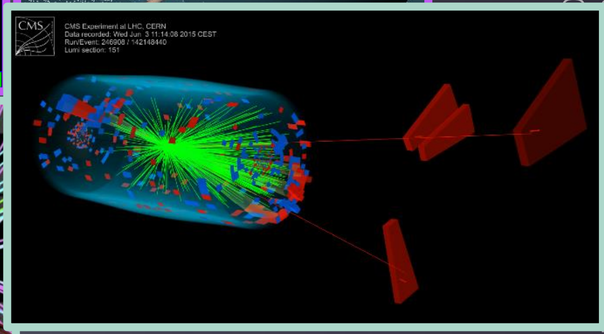

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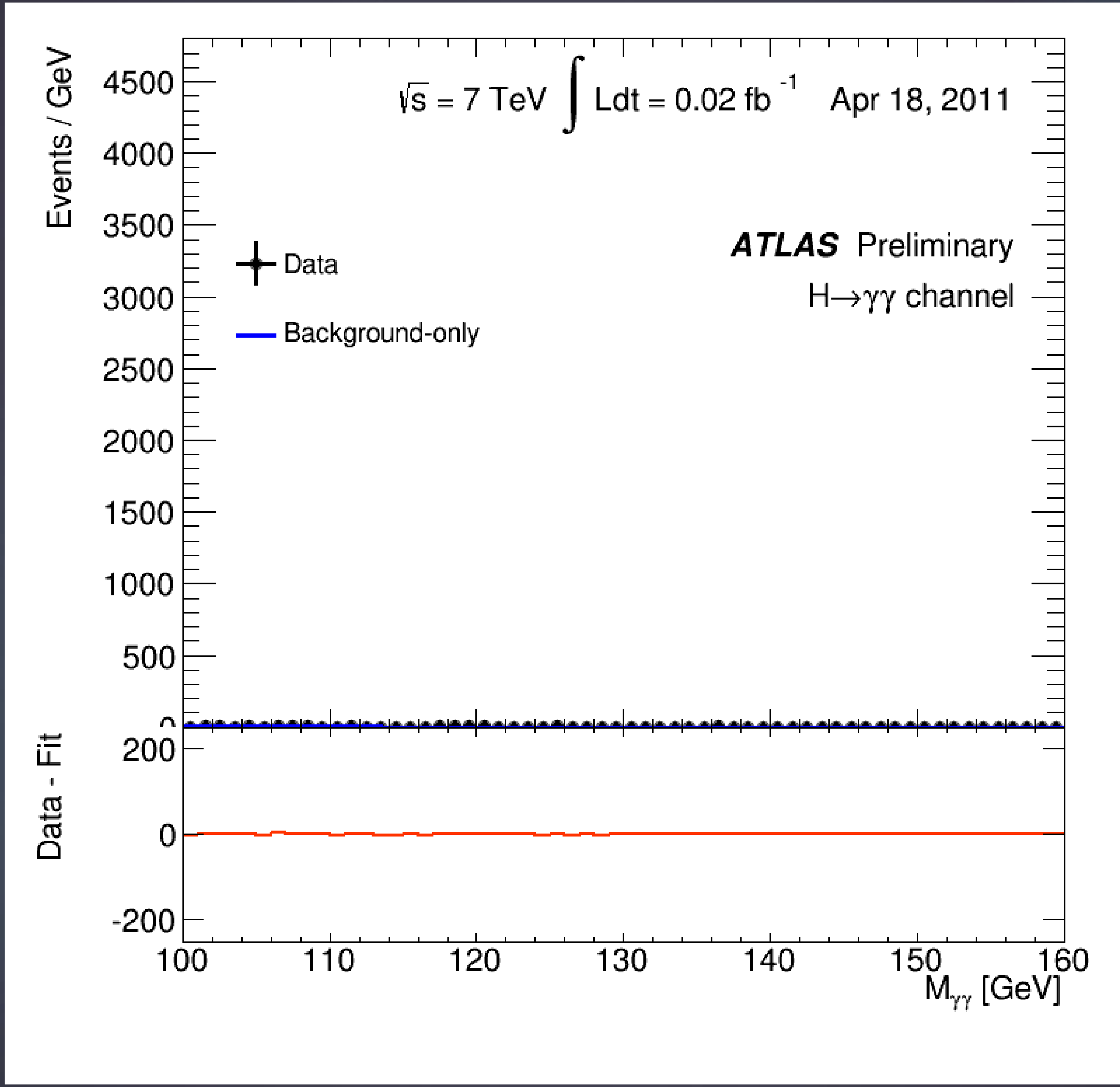
M. Mangano LHCC, 3/6/15

On the Higgs side:

→ Observe H->bb, ttH, confirm H->ττ
→ Gain in precision in the other channels
→ Move from statistically limited to systematically limited measurements
→ Theoretical work to improve the theory uncertainties

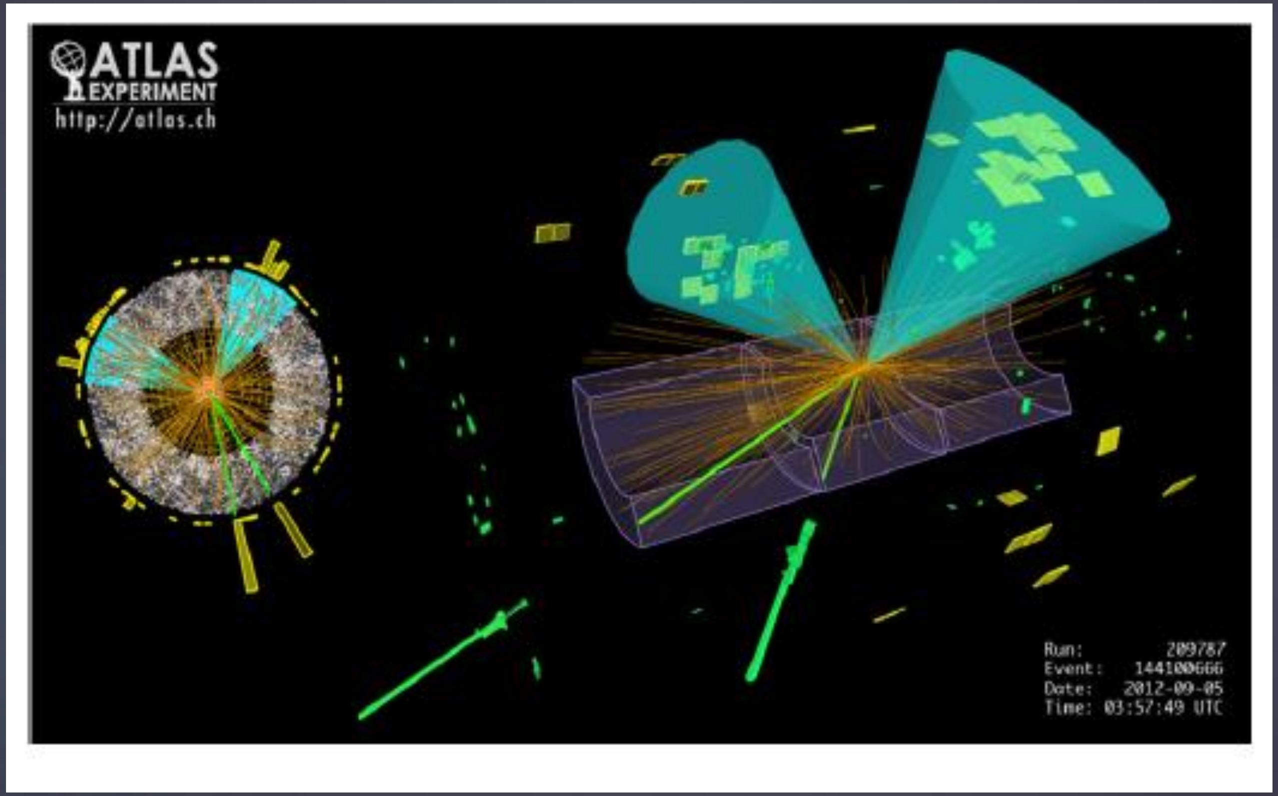
	σ(8 TeV)	σ(13 TeV)	ratio
gg→H	19.3	43.9	**2.3**
VBF	1.58	3.75	**2.4**
WH	0.70	1.38	**2.0**
ZH	0.42	0.87	**2.1**
ttH	0.13	0.51	**3.9**

From Higgs Cross Section WG, @m_H = 125 GeV

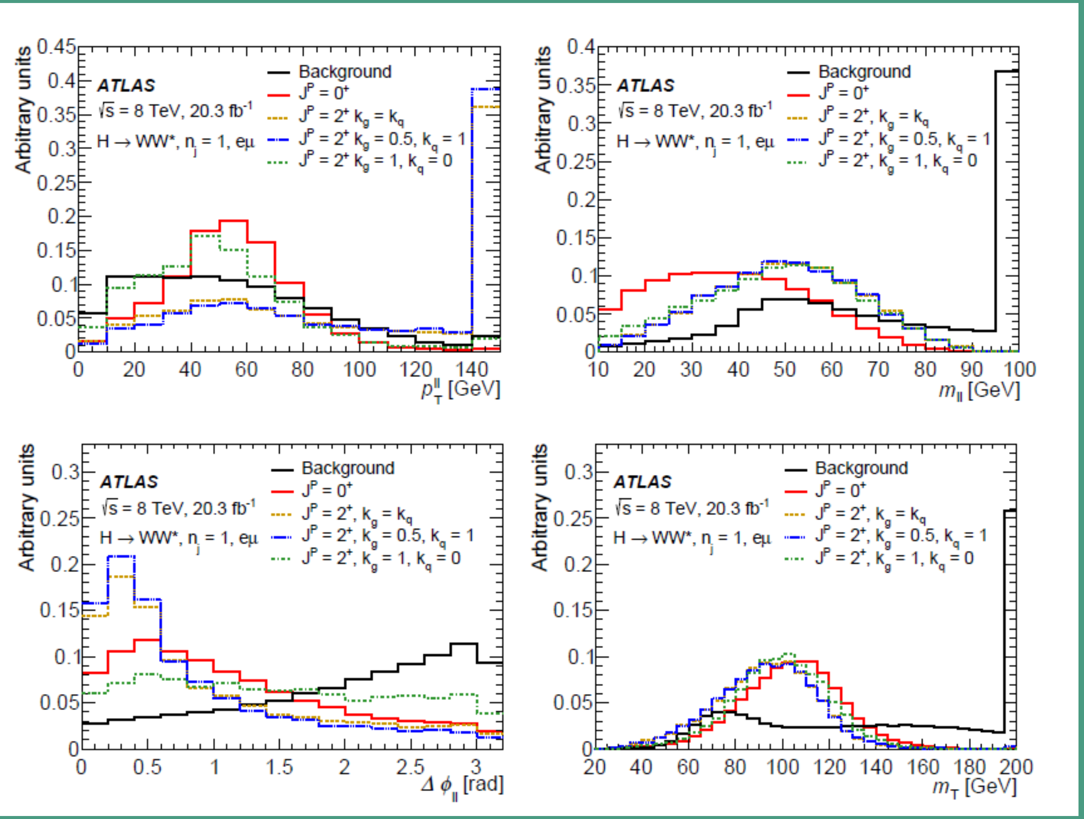


Let's hope for other such new signals coming out from Run2 !

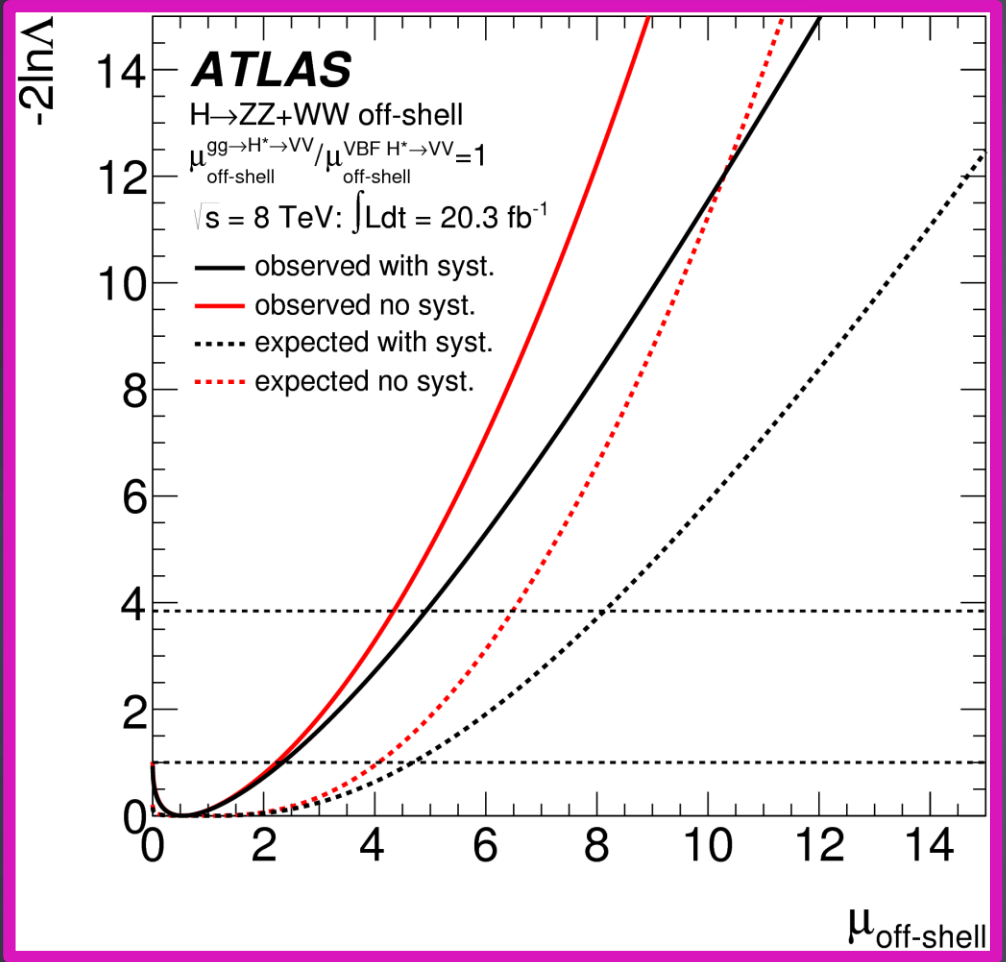
BACKUP


ATLAS
EXPERIMENT
http://atlas.ch
Run: 209787
Event: 144100666
Date: 2012-09-05
Time: 03:57:49 UTC

Spin 0 vs Spin 2 : tested with H->γγ, H->ZZ*->4l and H->WW*->lνlν

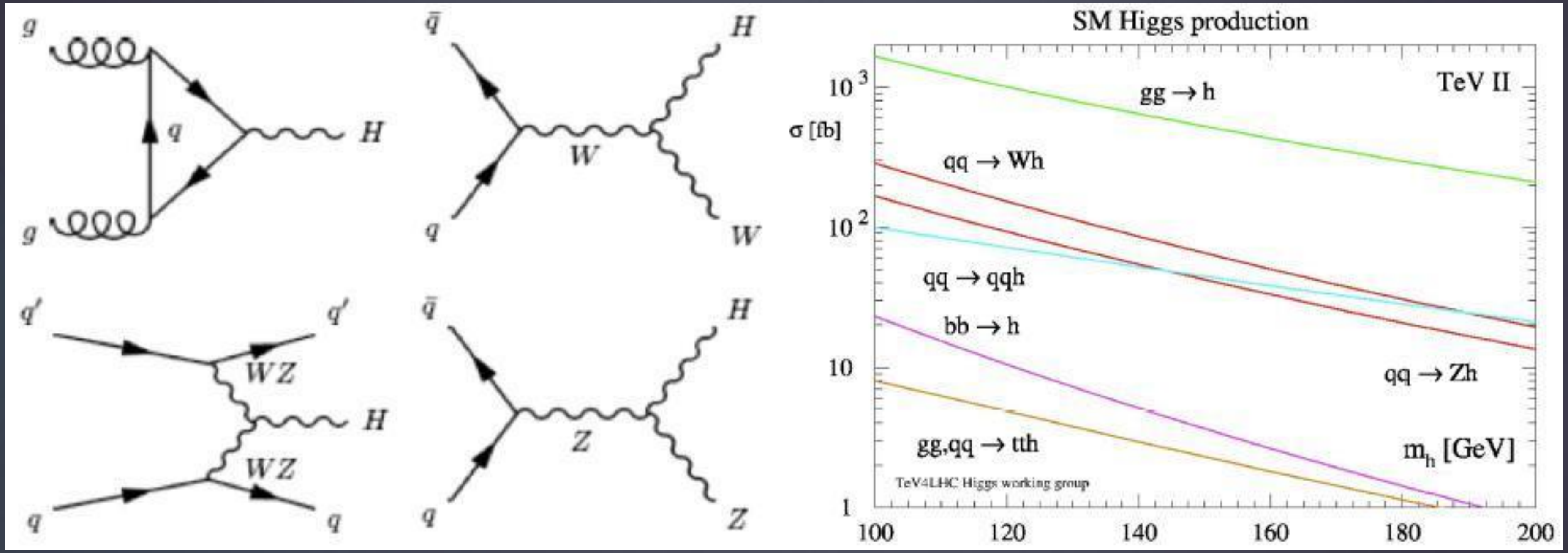


The off-shell strength



$\mu_{off\text{-}shell}$ < 6.2 (8.1 expected) for standard gg->H* and VBF strengths

Scalar boson production at Tevatron (ppbar machine, 1.96TeV)



H-> ττ

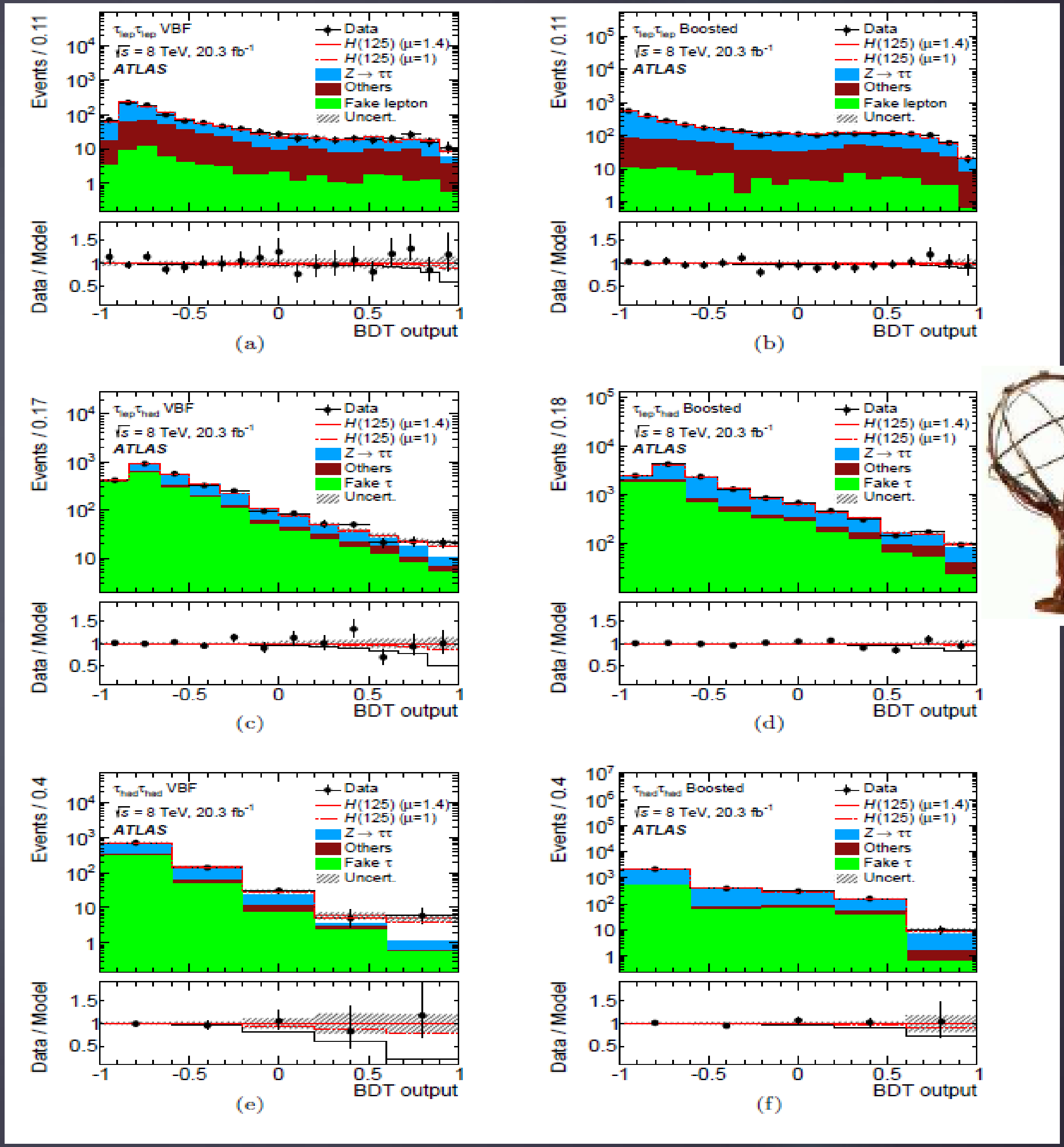
The 3 categories are splited further:

--- VBF : + 2 high-pt jets with large separation in pseudorapidity

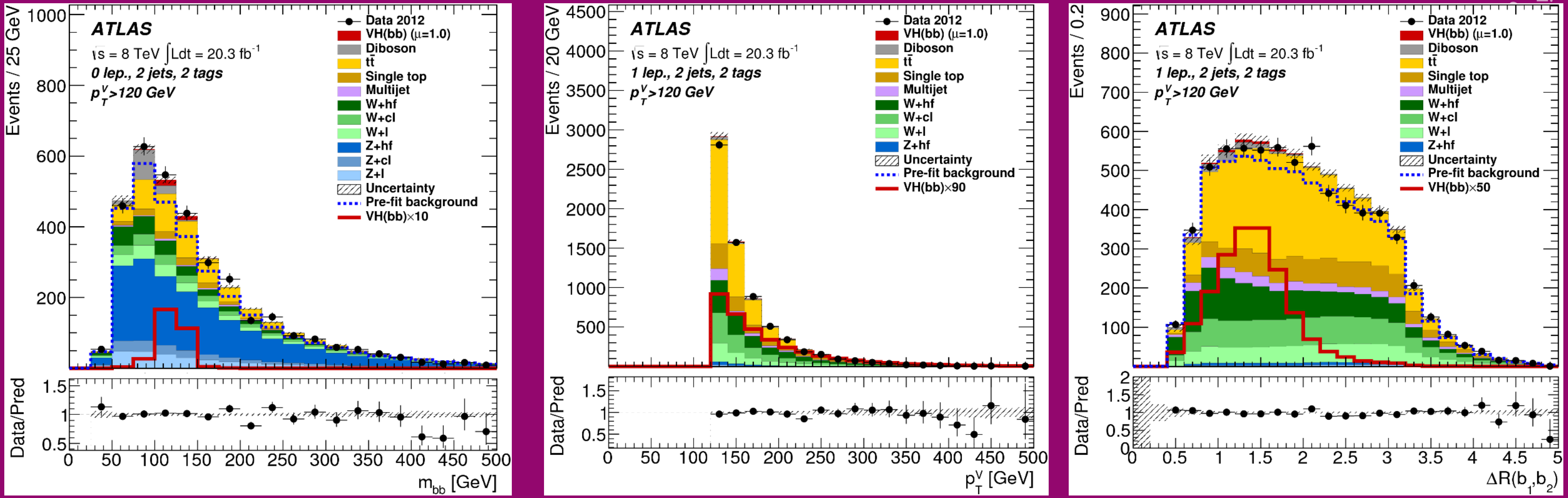
--- Boosted Higgs: no VBF but $P_T^H > 100$ GeV

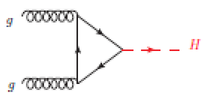
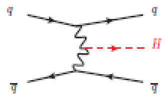
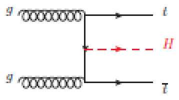
Background checked in specific data control regions

Final discriminant is a Boosted Decision Tree ran for all 6 categoris



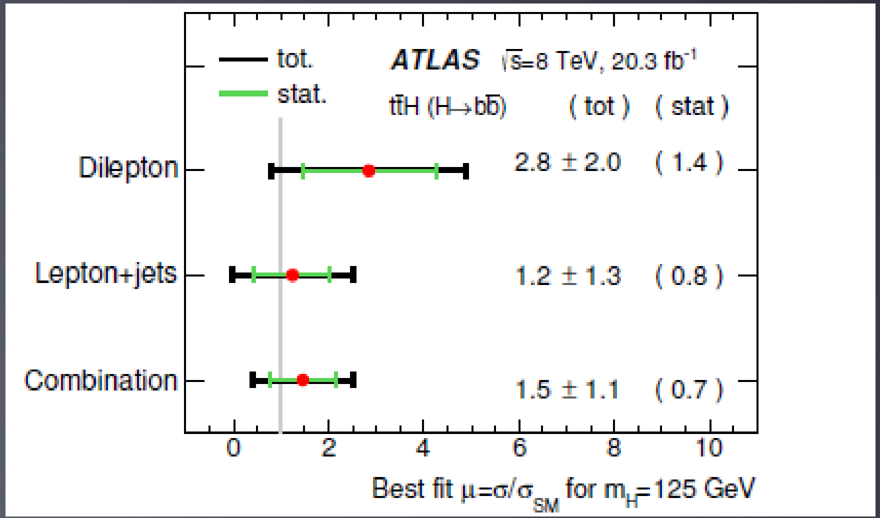
VH->bb


ATLAS
$\sqrt{s}$ = 8 TeV $\int$Ldt = 20.3 fb^{-1}
0 lep., 2 jets, 2 tags
p_T^V>120 GeV
Data 2012
VH(bb) (μ=1.0)
Diboson
$t\bar{t}$
Single top
Multijet
W+hf
W+cl
W+l
Z+hf
Z+cl
Z+l
Uncertainty
Pre-fit background
VH(bb)×10
Events / 25 GeV
Data/Pred
m_{bb} [GeV]
ATLAS
$\sqrt{s}$ = 8 TeV $\int$Ldt = 20.3 fb^{-1}
1 lep., 2 jets, 2 tags
p_T^V>120 GeV
VH(bb)×90
Events / 20 GeV
p_T^V [GeV]
ATLAS
$\sqrt{s}$ = 8 TeV $\int$Ldt = 20.3 fb^{-1}
1 lep., 2 jets, 2 tags
p_T^V>120 GeV
VH(bb)×50
Events / 0.2
$\Delta R(b_1,b_2)$

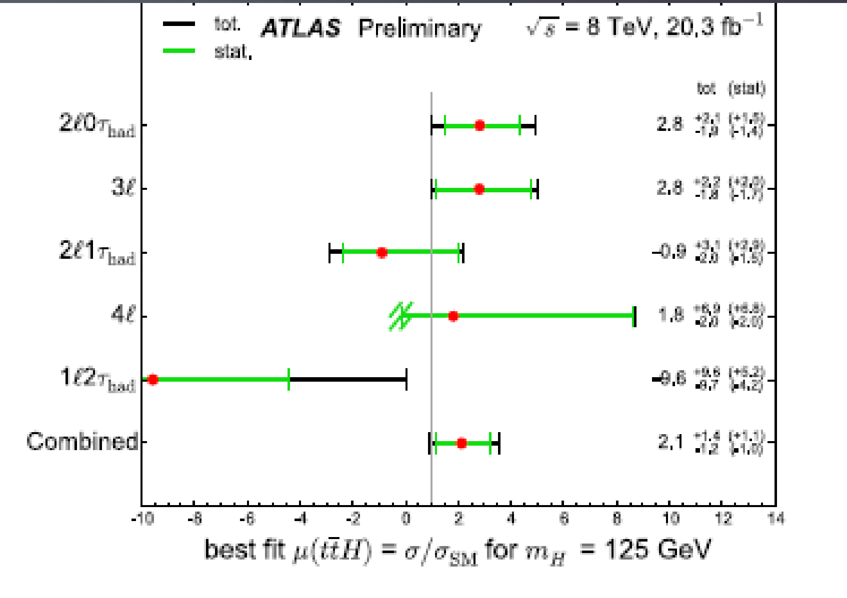
Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ	✓	✓	✓	✓
bb		✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓ (monojet)	✓	✓	

ttH

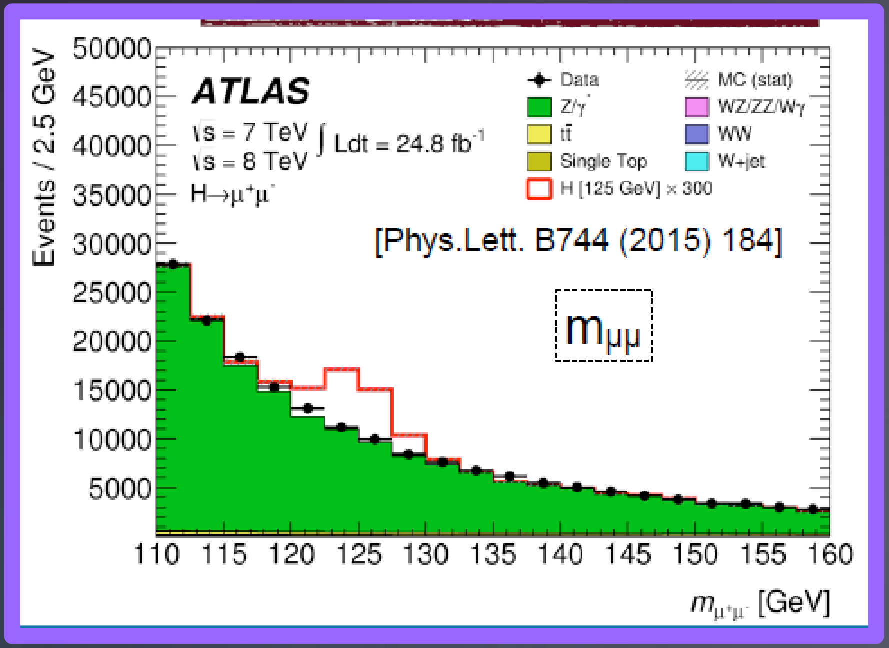
Use H Decay channels H->bb, H->WW*/ZZ*/ττ, H->γγ



Limits on ttH/SM production
3.4(3.1) in bb channel at 95%
4.7(3.7) in multiLepton channel at 95%
6.7 (4.9) in γγ channel at 95%

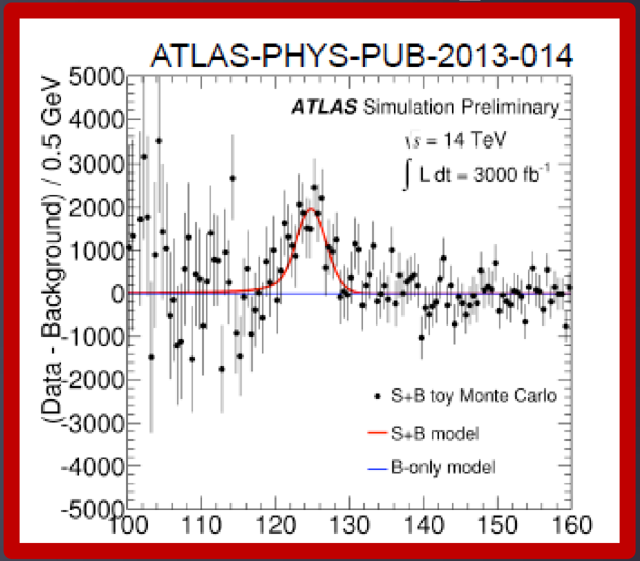


H->μμ



Expectations for next runs

$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%



Fill the LHC with protons

2808 bunches x $1.15\cdot10^{11} = 3\cdot10^{14}$ protons per beam
or, $6\cdot10^{14}$ protons for the two beams (1)

A small commercial hydrogen cylinder contains about 5 kg of gas. So the amount of hydrogen molecules is:

$$n = 5000/2 = 2500 \text{ moles}$$

$$2500 \times 6\cdot10^{23} = 1.5\cdot10^{27} \text{ molecules}$$

$$N = 2 \times 1.5\cdot10^{27} = 3\cdot10^{27} \text{ atoms}$$

Taking into account that the process yields about 70% protons we have:

$$0{,}7 \times 3\cdot10^{27} = 2.1\cdot10^{27} \text{atoms}$$

With (1), this cylinder can be used:

$$2.1\cdot10^{27} / 6\cdot10^{14} = 3.5\cdot10^{12} \text{ times}$$

Since the LHC is filled every ten hours, this cylinder could be used for:

$$10 \times 3.5\cdot10^{12} = 3.5\cdot10^{13} \text{ hours}$$

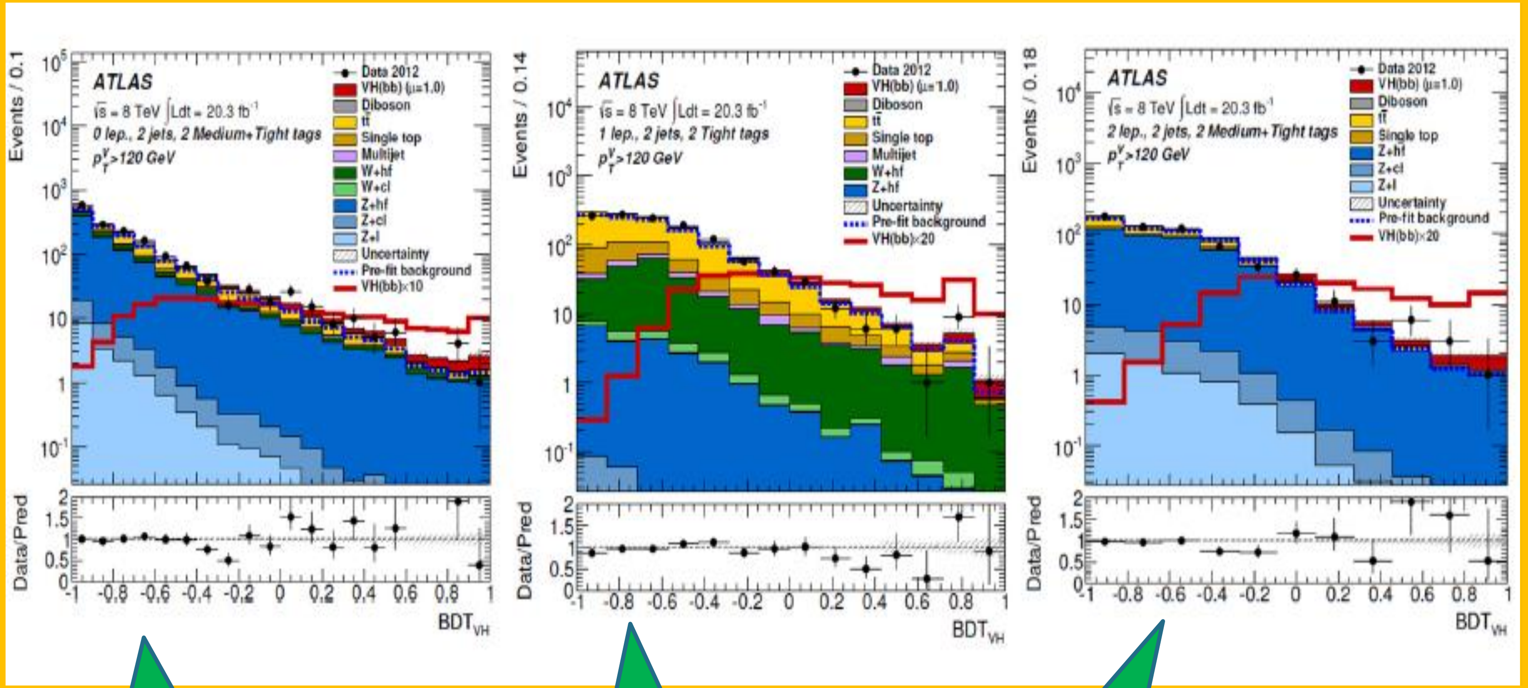
So, about $4\cdot10^{9}$ years

http://www.lhc-closer.es/1/3/10/0

From cold beam tube to Room Temperature beam tubes

VH->bb

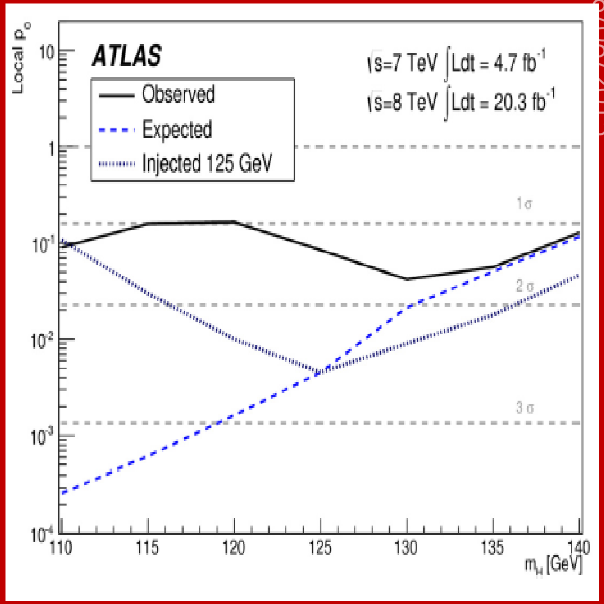
BDT score for the 3 final states



0 lepton – 2Jets

1 lepton-2jets

2 leptons-2jets



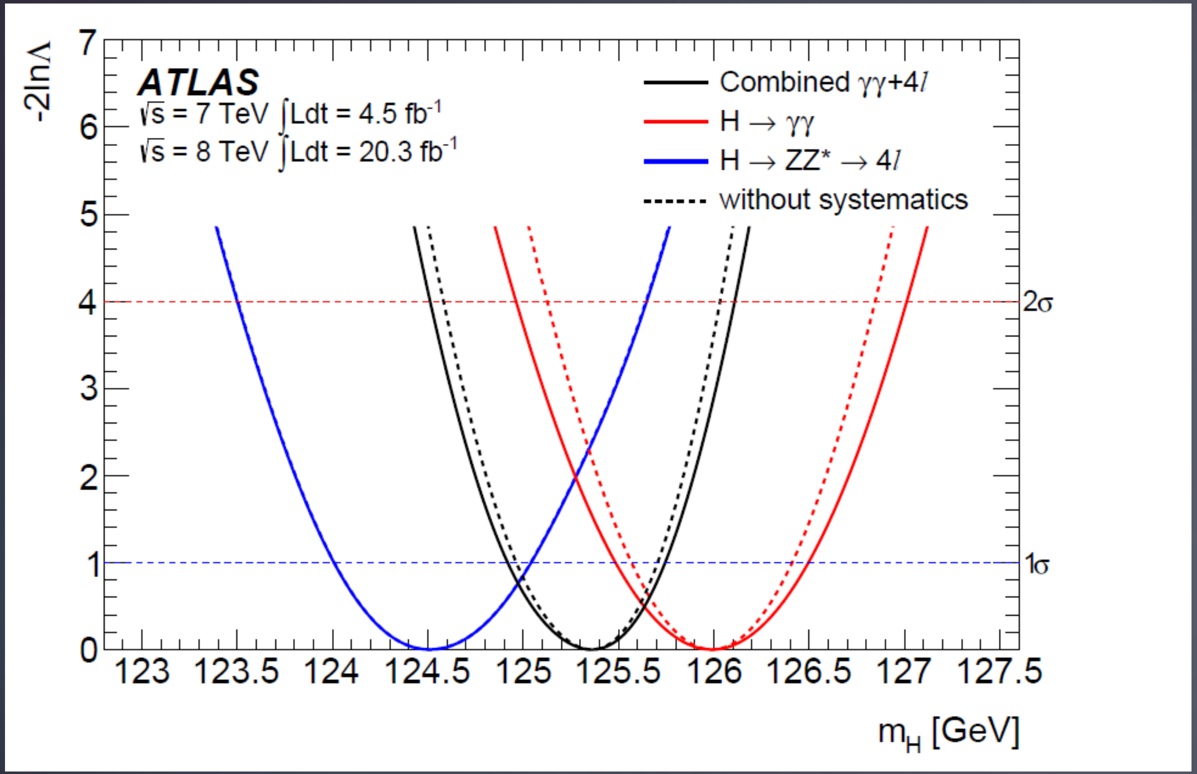
Observed (expected) significance:
ATLAS : 1.4 σ (2.6)
CMS : 2.1 σ (2.1)

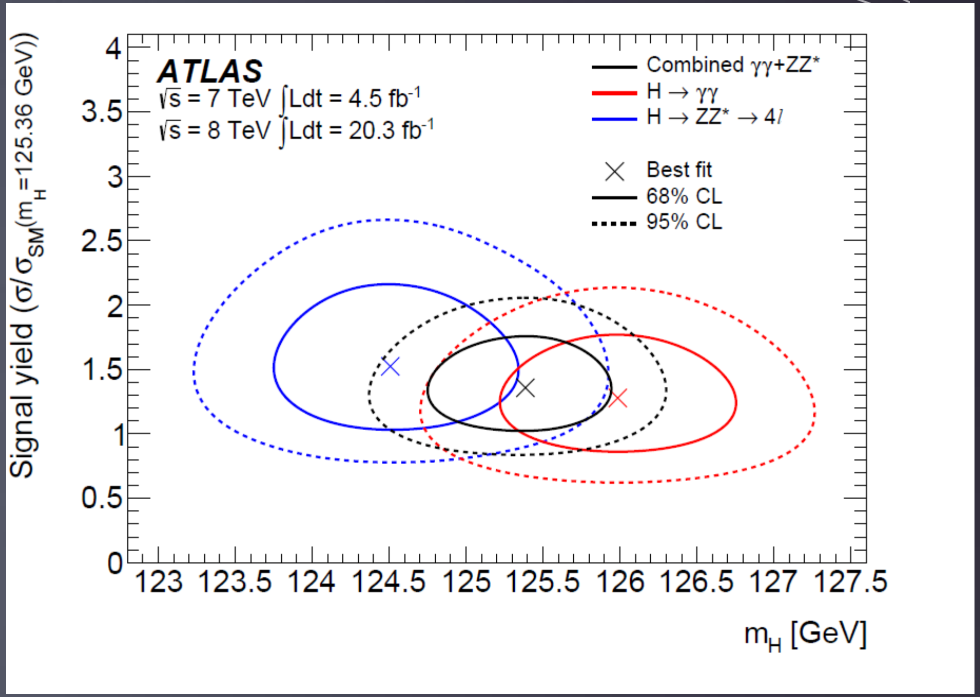
LHC schedule (M.Lamont LHCC June 3)

2015 – latest schedule

Phase	Days
Initial Commissioning	57
Scrubbing	23
Special physics run 1 (LHCf/VdM)	5
Proton physics 50 ns	**9 + 21**
Proton physics 25 ns	**70**
Special physics run 2 (TOTEM/VdM)	7
Machine development (MD)	15
Technical stops	15
Technical stop recovery	3
Ion setup/Ion run	4 + 24
Total	**253 (36 weeks)**

ATLAS Higgs mass

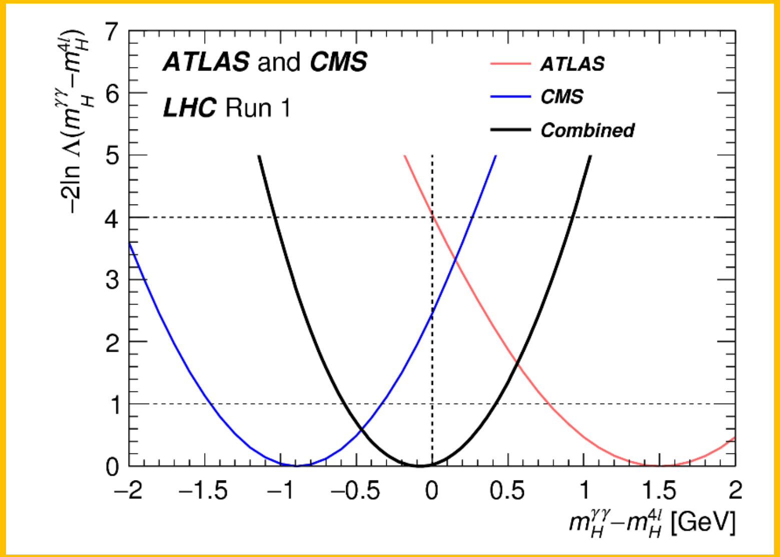


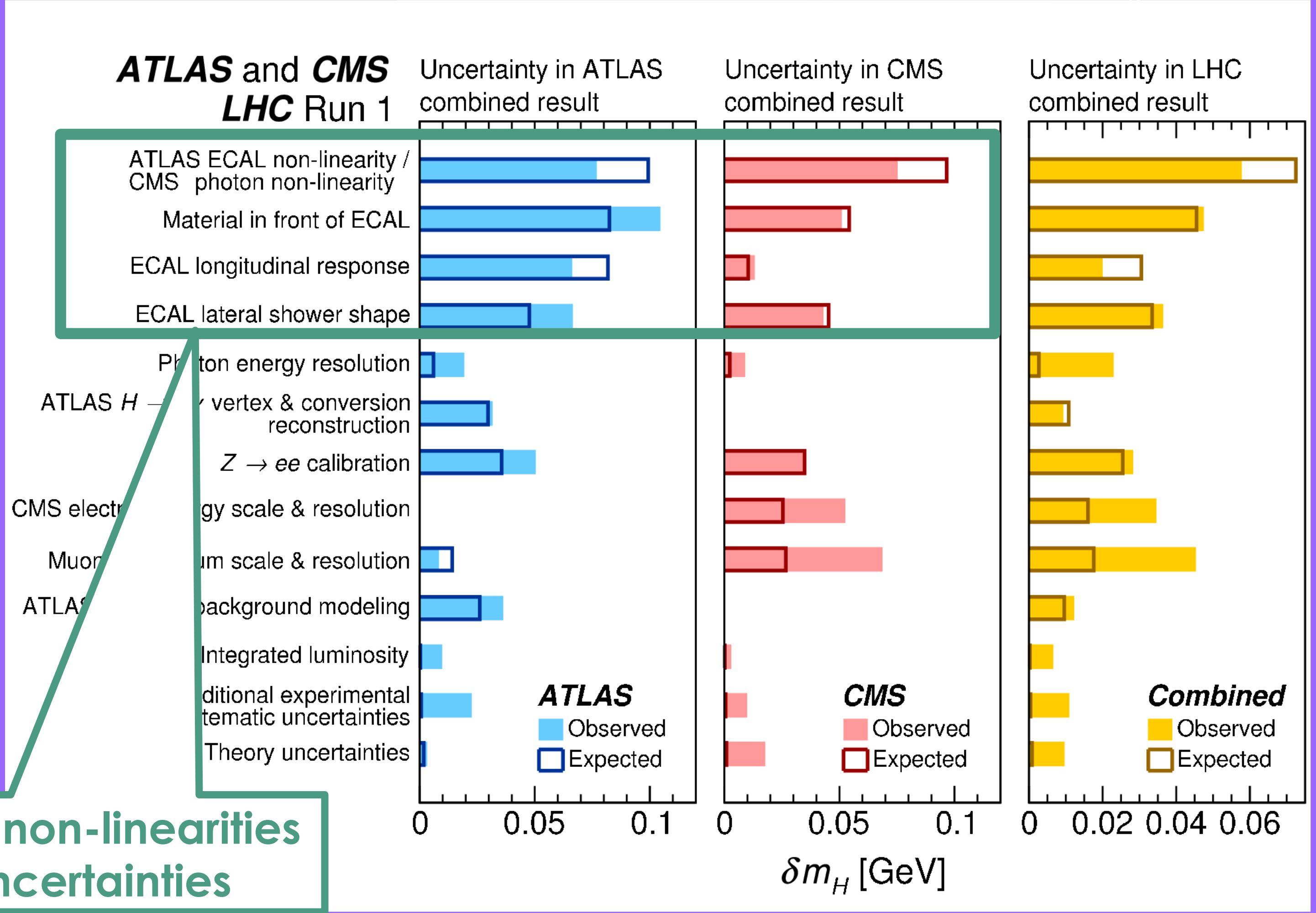


Δm_H= 1.47 ± 0.72 GeV 1.98 σ

The RUN1 Higgs mass combined measurement from ATLAS+CMS

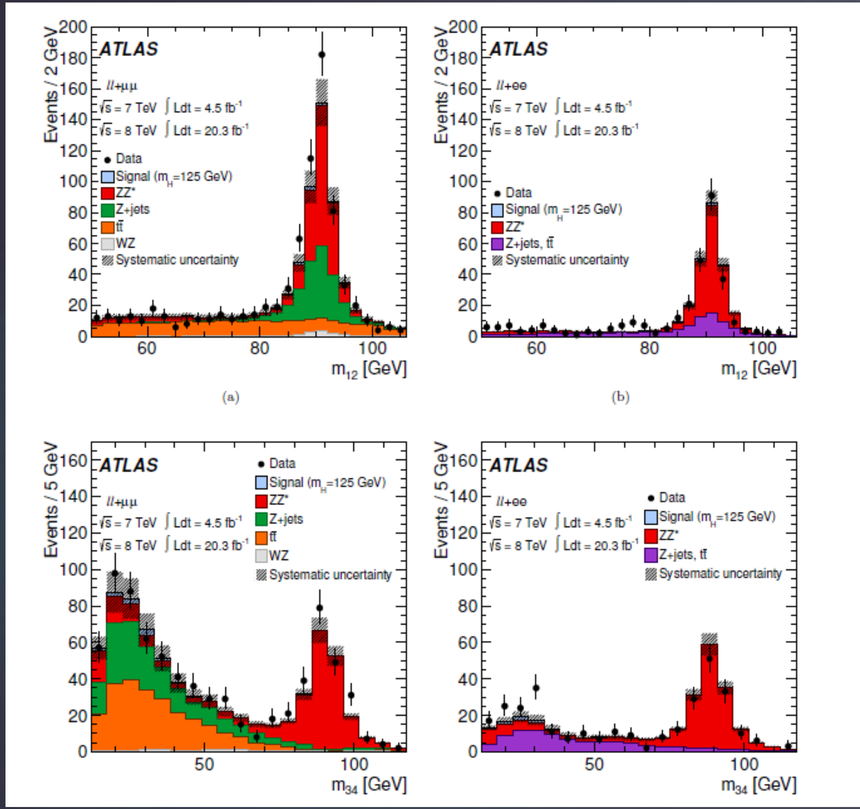
The difference : $m_H^{\gamma\gamma} - m_H^{4l}$





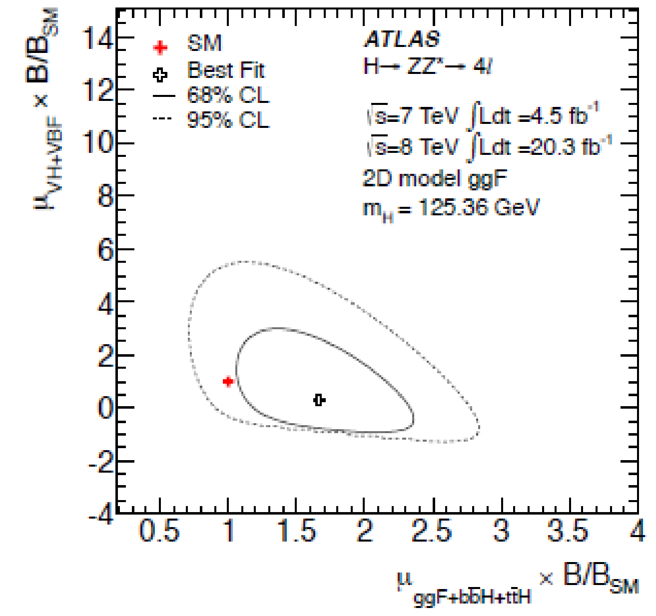
Dominant: residual non-linearities and material uncertainties

H->ZZ*->4l



$$\mu_{ggF+b\bar{b}H+t\bar{t}H} \times B/B_{SM} = 1.66 \,^{+0.45}_{-0.41}\,(\text{stat})\,^{+0.25}_{-0.15}\,(\text{syst})$$

$$\mu_{VBF+VH} \times B/B_{SM} = 0.26 \,^{+1.60}_{-0.91}\,(\text{stat})\,^{+0.36}_{-0.23}\,(\text{syst})$$



6

VBF : Observe 1 event (exp 1.3)

Xsections & Br for $_{MH=125.36}$ GeV

Table 1: SM predictions of the Higgs boson production cross sections and decay branching ratios and their uncertainties for m_H = 125.36 GeV, obtained by linear interpolations from those at 125.3 and 125.4 GeV from Ref. [11] except for the tH production cross section which is obtained from Ref. [26]. The uncertainties on the cross sections are the quadratic sum of the uncertainties on the QCD scales, parton distribution functions and α_s. The uncertainty on the tH cross section is calculated following the procedure of Ref. [11].

Production process	Cross section (pb) $\sqrt{s}$ = 7 TeV	Cross section (pb) $\sqrt{s}$ = 8 TeV	Decay channel	Branching ratio (%)
ggF	15.0 ± 1.6	19.2 ± 2.0	$H \to b\bar{b}$	57.1 ± 1.9
VBF	1.22 ± 0.03	1.57 ± 0.04	$H \to WW^*$	22.0 ± 0.9
WH	0.573 ± 0.016	0.698 ± 0.018	$H \to gg$	8.53 ± 0.85
ZH	0.332 ± 0.013	0.412 ± 0.013	$H \to \tau\tau$	6.26 ± 0.35
bbH	0.155 ± 0.021	0.202 ± 0.028	$H \to c\bar{c}$	2.88 ± 0.35
ttH	0.086 ± 0.009	0.128 ± 0.014	$H \to ZZ^*$	2.73 ± 0.11
tH	0.012 ± 0.001	0.018 ± 0.001	$H \to \gamma\gamma$	0.228 ± 0.011
			$H \to Z\gamma$	0.157 ± 0.014
Total	17.4 ± 1.6	22.3 ± 2.0	$H \to \mu\mu$	0.022 ± 0.001

Uncertainties on signal Strenghts

Production process	Signal strength μ at $m_H = 125.36$ GeV							
	$\sqrt{s} = 8$ TeV				Combined $\sqrt{s} = 7$ and 8 TeV			
ggF	$1.23^{+0.25}_{-0.21}$	$^{+0.16}_{-0.16}$	$^{+0.10}_{-0.08}$	$^{+0.16}_{-0.11}$	$1.23^{+0.23}_{-0.20}$	$^{+0.14}_{-0.14}$	$^{+0.09}_{-0.08}$	$^{+0.16}_{-0.12}$
VBF	$1.55^{+0.39}_{-0.35}$	$^{+0.32}_{-0.31}$	$^{+0.17}_{-0.13}$	$^{+0.13}_{-0.11}$	1.23 ± 0.32	$^{+0.28}_{-0.27}$	$^{+0.13}_{-0.12}$	$^{+0.11}_{-0.09}$
VH	0.93 ± 0.39	$^{+0.37}_{-0.33}$	$^{+0.20}_{-0.18}$	$^{+0.12}_{-0.06}$	0.80 ± 0.36	$^{+0.31}_{-0.30}$	$^{+0.17}_{-0.17}$	$^{+0.10}_{-0.05}$
ttH	1.62 ± 0.78	$^{+0.51}_{-0.50}$	$^{+0.58}_{-0.54}$	$^{+0.28}_{-0.10}$	1.81 ± 0.80	$^{+0.52}_{-0.50}$	$^{+0.58}_{-0.55}$	$^{+0.31}_{-0.12}$

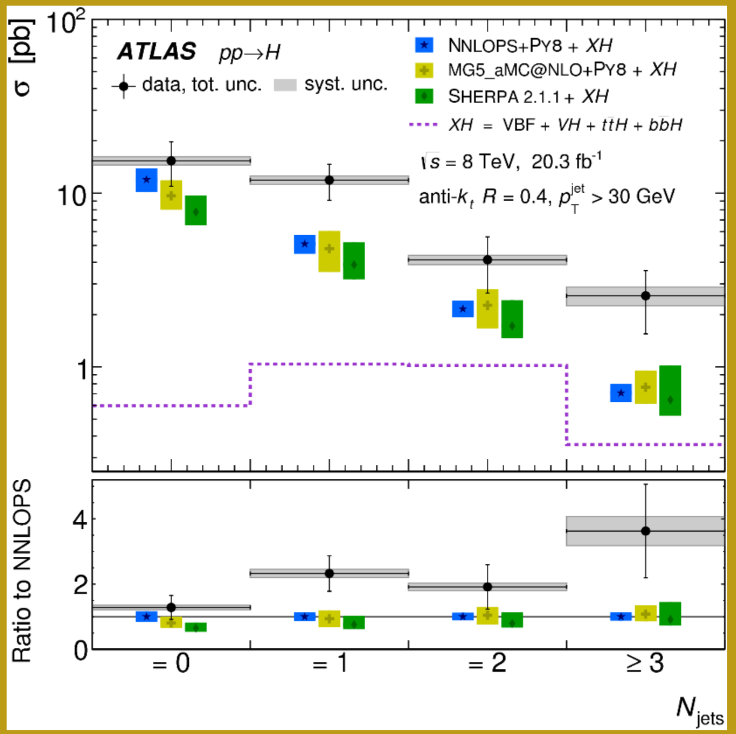
Statistical uncertainties

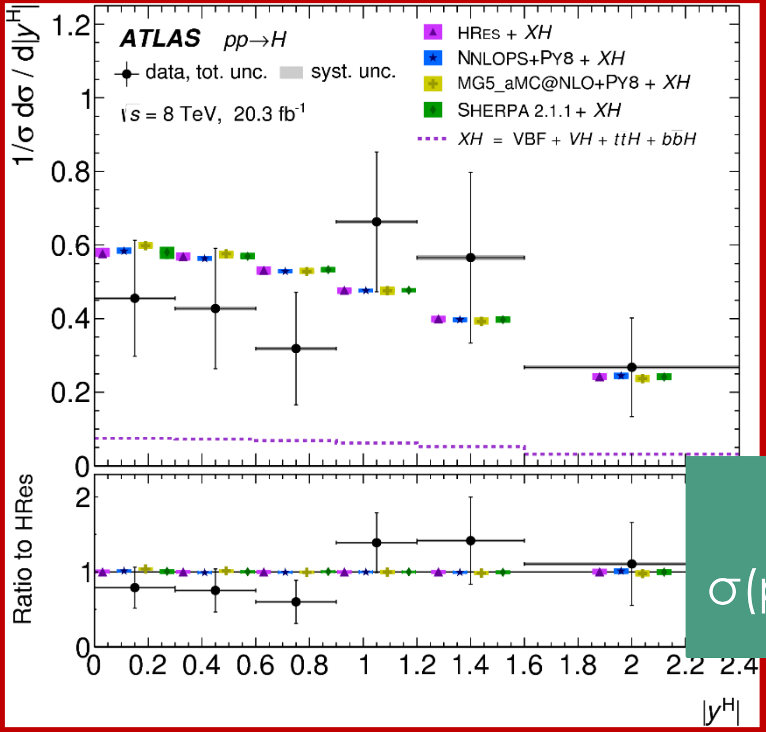
Experimental systematic uncertainties:
Signal and background modeling

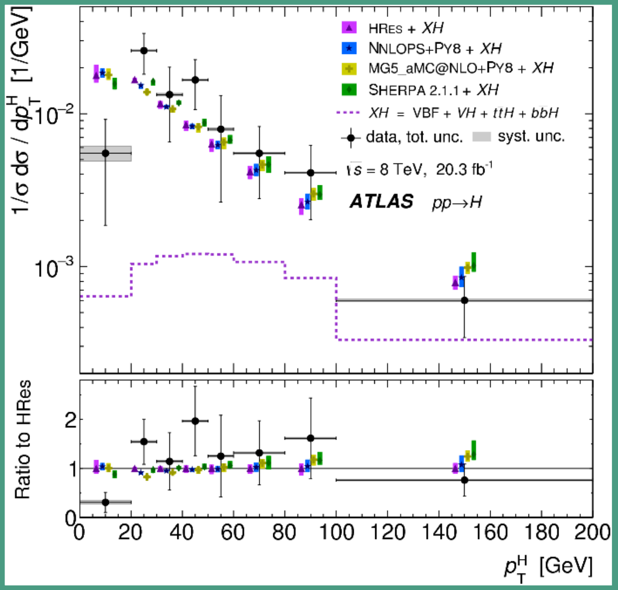
Theory uncertainties on production Xsections, Br's, PDF's, QCD scale etc

Differential Cross sections vs Pt, rapidity, Nb of jets …

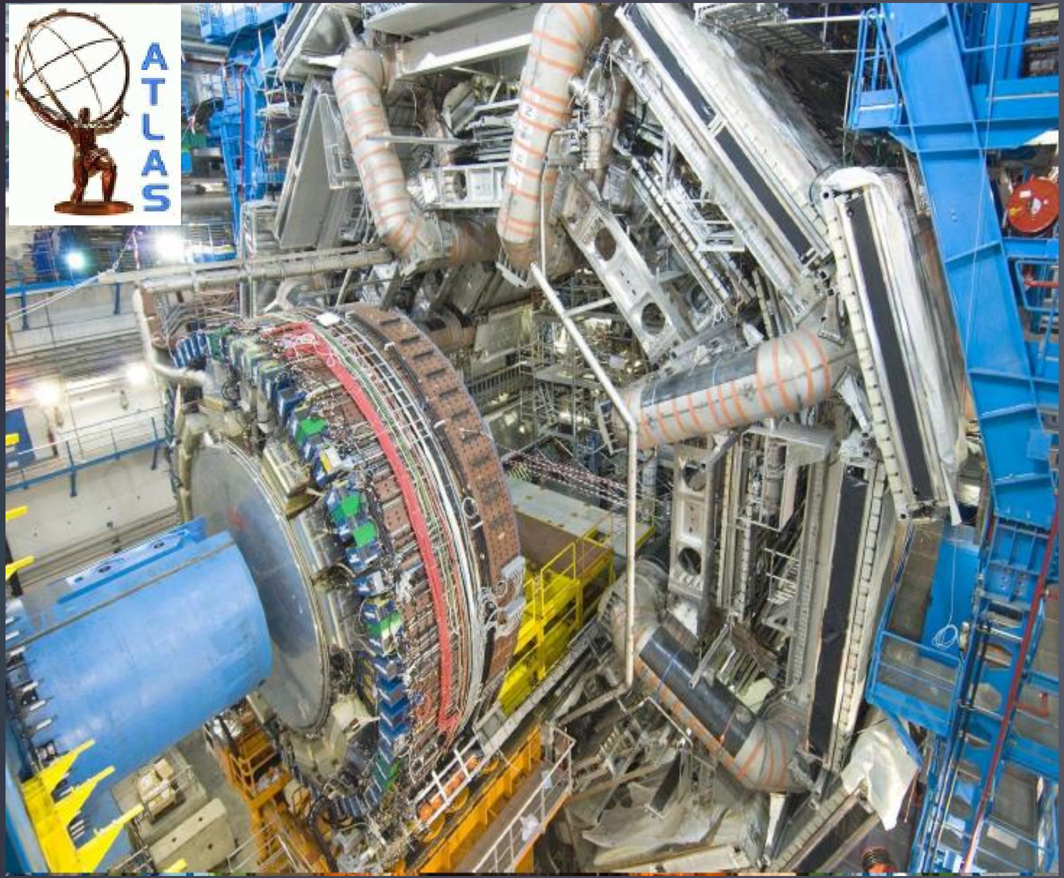
Help at constraining QCD and PDF for ggF and VBF computations looking at different variables
→ Contribute to decrease uncertainties

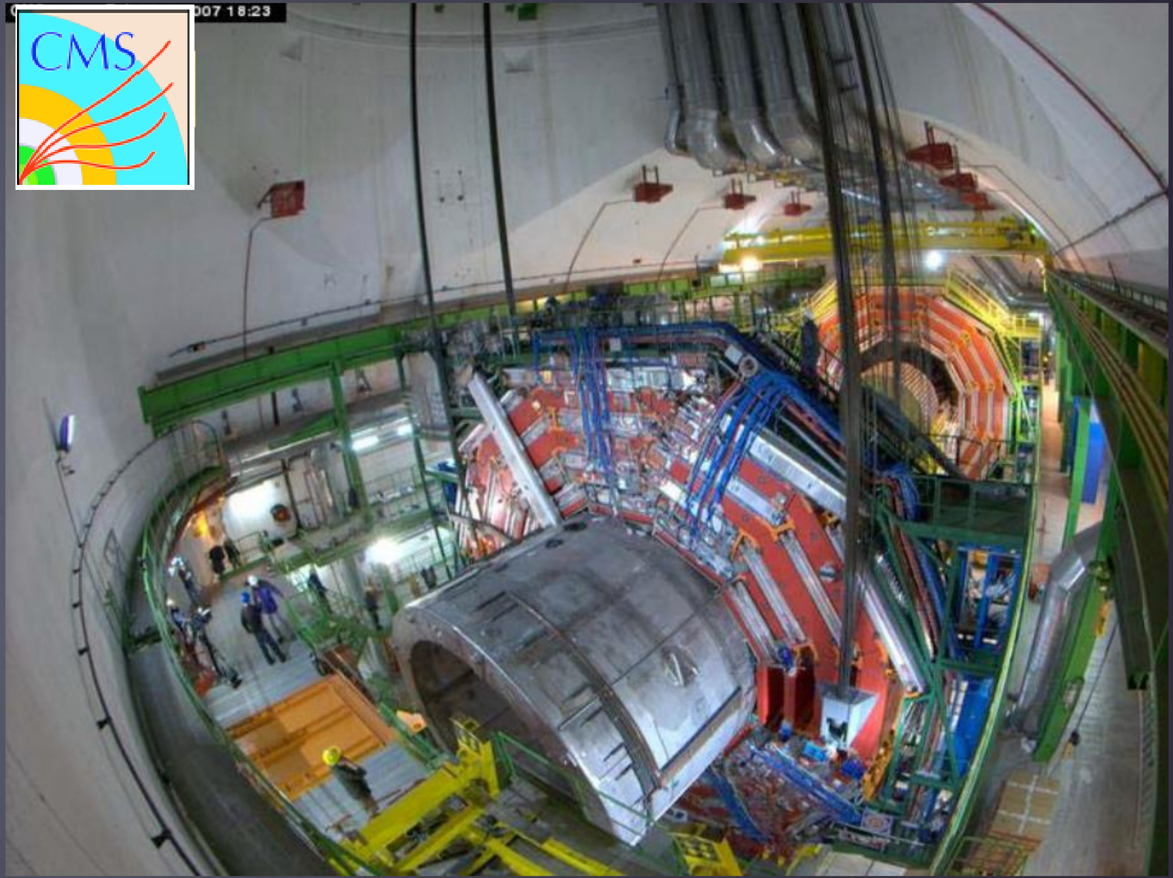






Total cross-section
$\sigma(pp \to H) = 33.0 \pm 5.3(stat) \pm 1.6(syst)$ pb

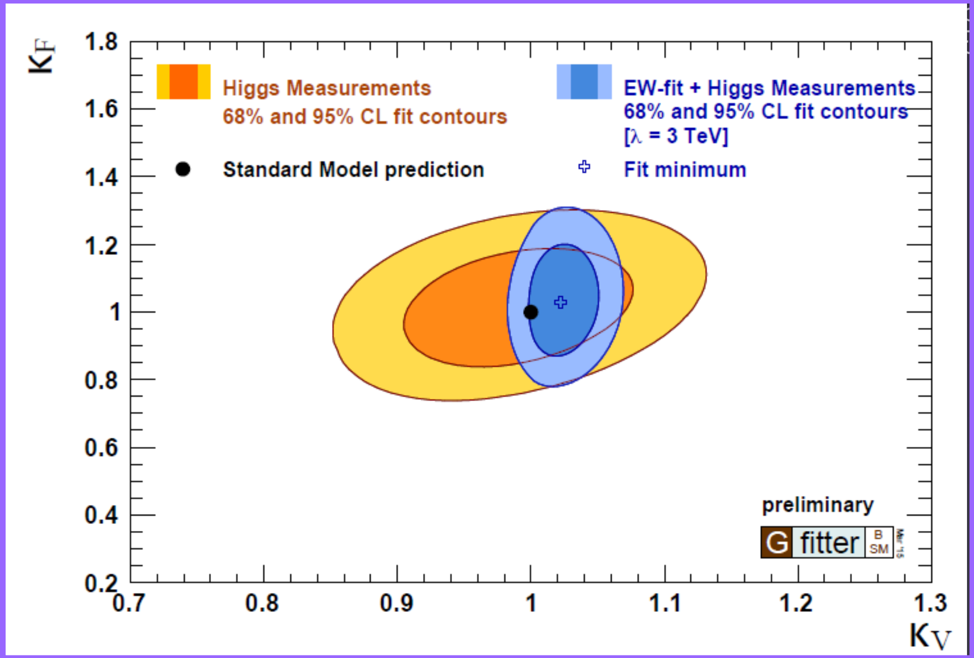

ATLAS

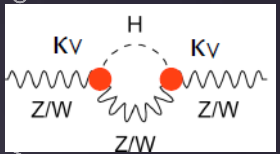

CMS

Global EW fits

M_H [GeV]	125.14 ± 0.24	LHC
M_W [GeV]	80.385 ± 0.015	Tev.
Γ_W [GeV]	2.085 ± 0.042	Tev.
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLD
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP
A_c	0.670 ± 0.027	SLD
A_b	0.923 ± 0.020	SLD
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP
R^0_b	0.21629 ± 0.00066	LEP
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	2757 ± 10	low E
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	low E
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	low E
m_t [GeV]	173.34 ± 0.76	Tev.+LHC

Roman Kogler at Moriond EW 2015 for G fitter





k_V from fit = 1.03 ± 0.02

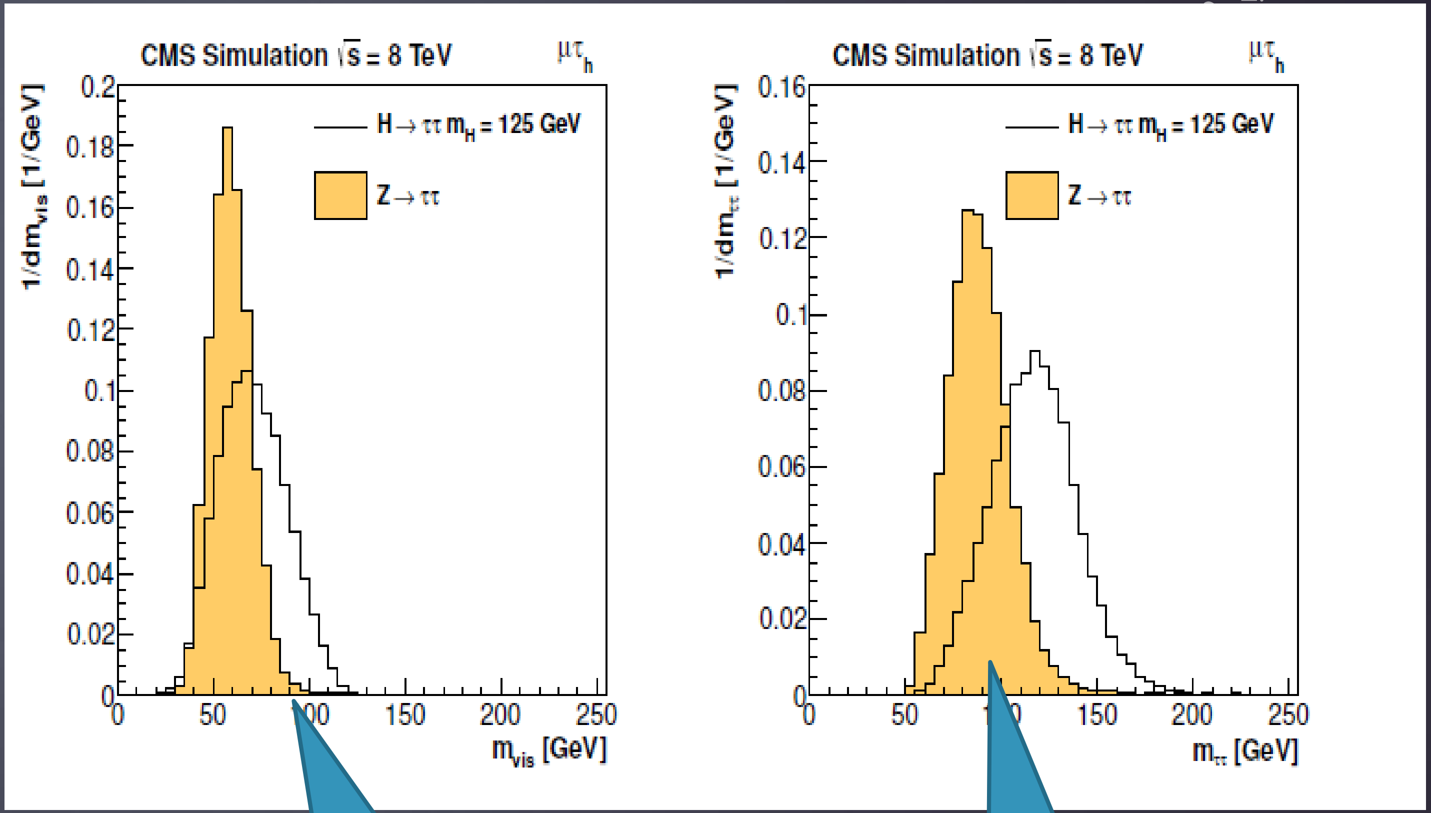
Much more precise than direct measurement

Definition of production categories

	H->γγ	H->ZZ*->4l	H->WW*	H->ττ	H->bb
ggF	No VBF, no VH, no ttH.	No VBF no VH	2 OSleptons and 0,1,>=2 jets	P_T^H>160GeV	
VBF	2 well separated high P_T jets.	2 well separated jets with Mjj>130GeV	2leptons+ >=2 jets	2 well separated jets	
VH	One or two leptons, E_T^{miss} and hadronic decays for W,Z	If no VBF, and >1 lepton	Multileptons (2-3-4), E_T^{miss}		0,1,2 leptons for W/Z + 2 b jets
ttH	t->Wb Leptonic and hadronic decays for W. Btags				

H->tautau CMS

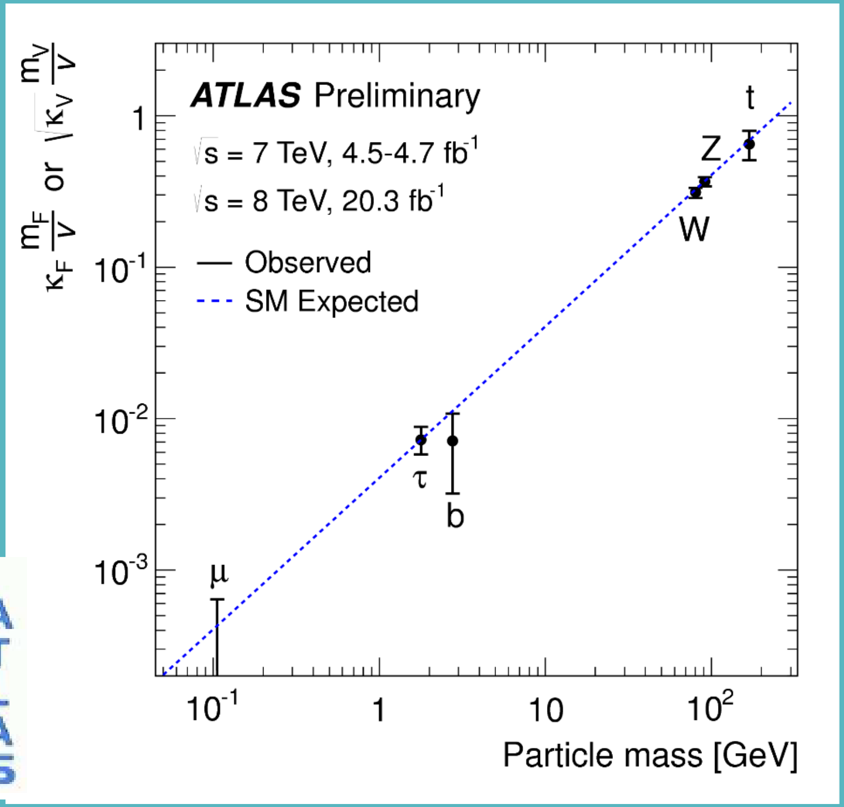
Resolutions on $M_{\tau\tau}$ mass:
10% on had-had
15% on lep-had
20% on lep-lep

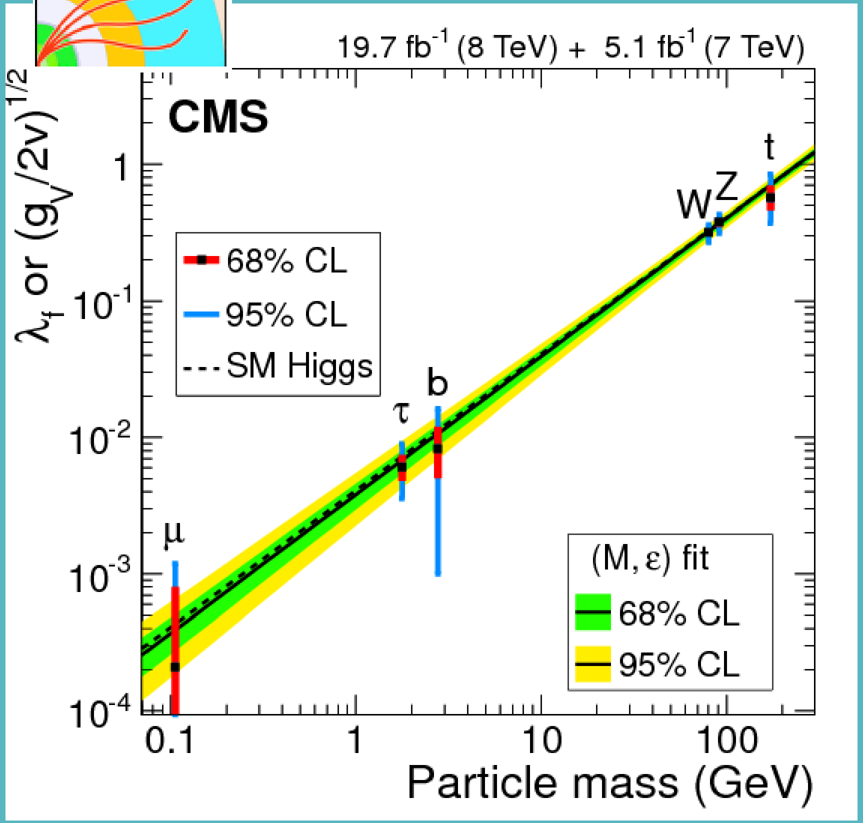


Visible mass

After SVFit

Coupling summary





Energy stored in LHC

Energy stored in the magners

E dipole = 0.5 x L_{dipole} x $I^{2}{}_{dipole}$

For 1232 dipoles 9.4 GJ

1.9 Ton of TNT

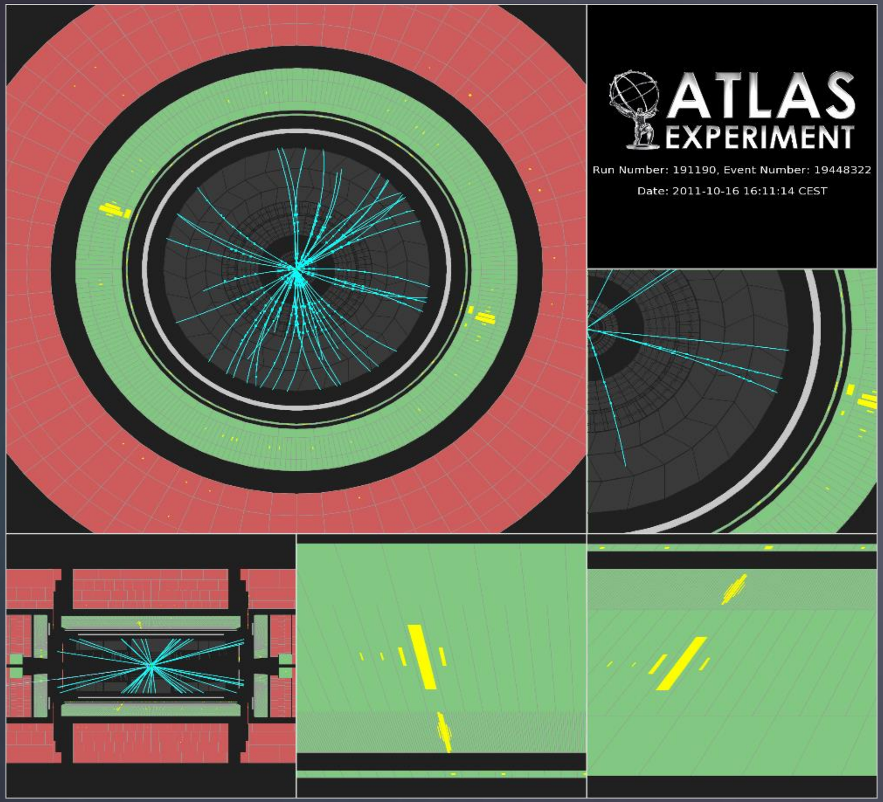
Energy stored in the beams

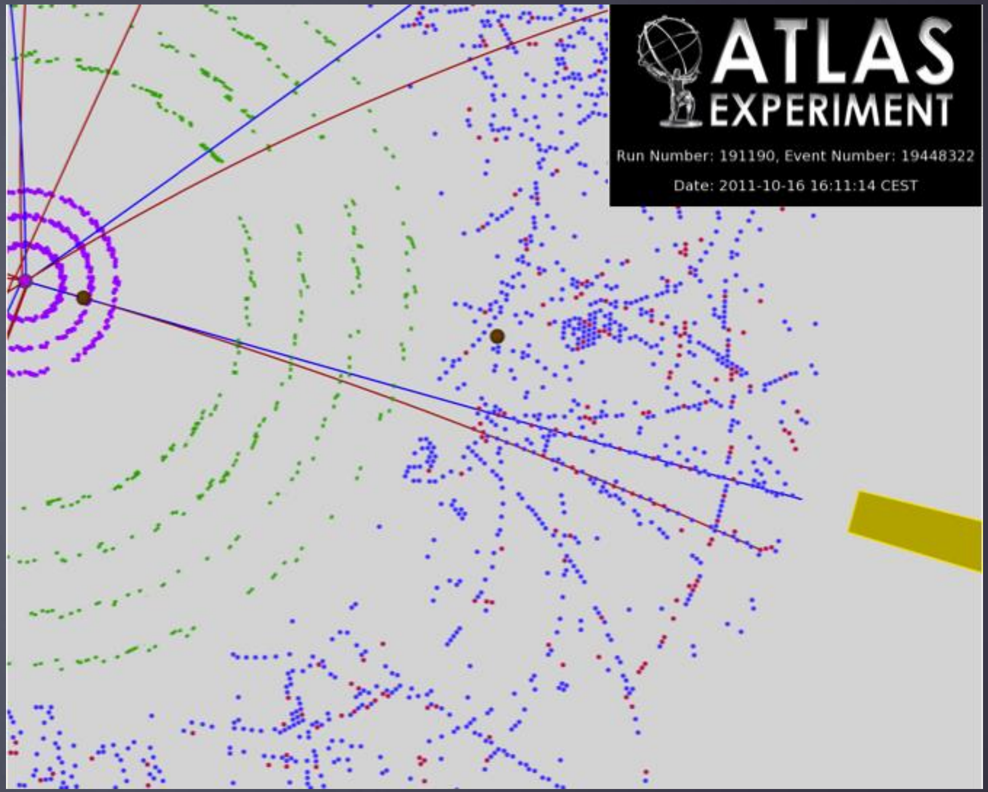
2800 bunches/beam
Each containing 10 11 protons

➔3x 10 14 protons/beam

➔ Stored energy for 7TeV
➔ 362 MJ/beam

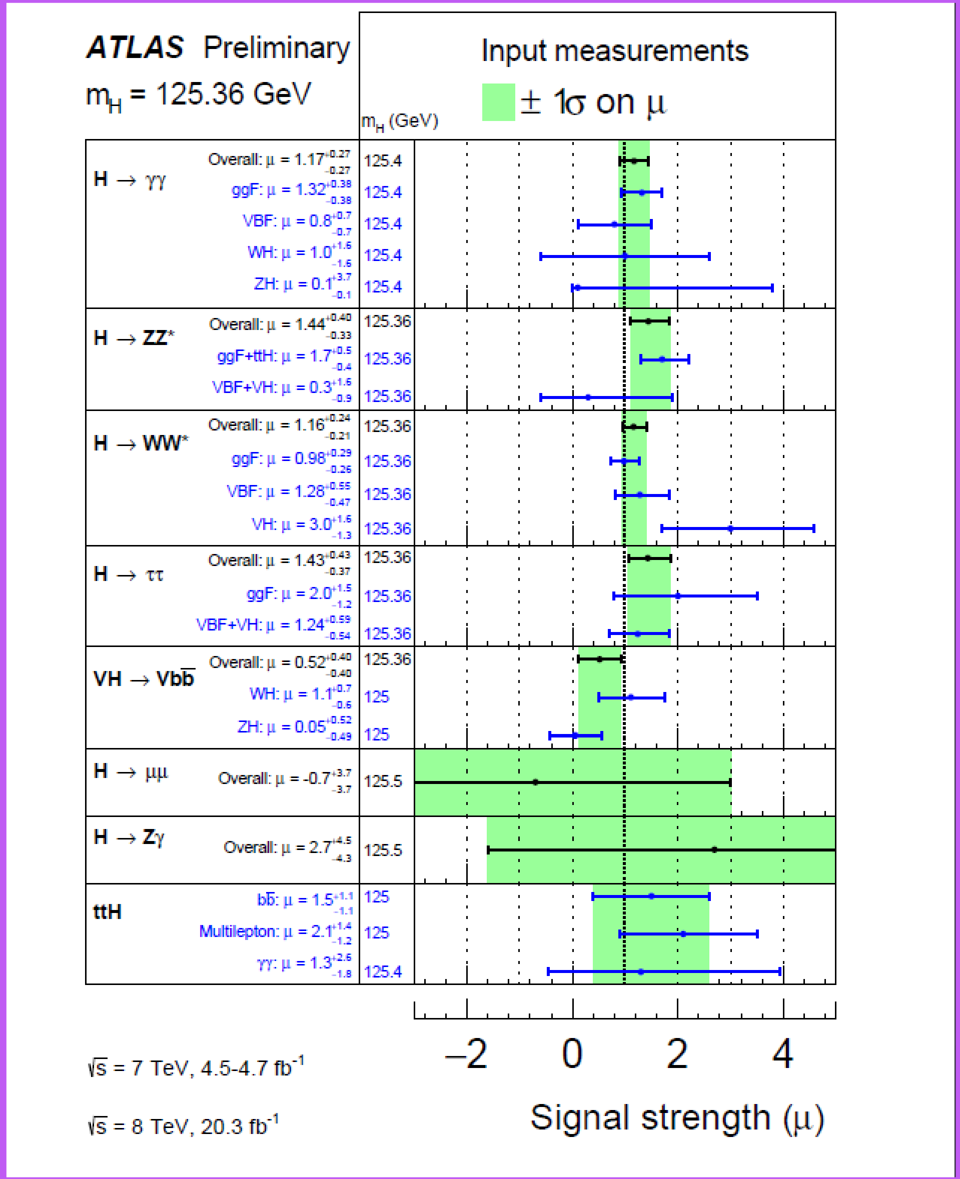
Display of a H->γγ candidate with a converted photon





Analysis	Signal		$\int \mathcal{L}dt$ (fb^{-1})	
Categorisation or final states	Strength	Significance [σ]	7 TeV	8 TeV
$H \to \gamma\gamma$ [12]	1.17 ± 0.27	5.2 (4.6)	4.5	20.3
ttH: leptonic, hadronic			✓	✓
VH: one-lepton, dilepton, E_T^{miss}, hadronic			✓	✓
VBF: tight, loose			✓	✓
ggF: 4 p_{Tt} categories			✓	✓
$H \to ZZ^* \to 4\ell$ [13]	$1.44^{+0.40}_{-0.33}$	8.1 (6.2)	4.5	20.3
VBF			✓	✓
VH: hadronic, leptonic			✓	✓
ggF			✓	✓
$H \to WW^*$ [14, 15]	$1.16^{+0.24}_{-0.21}$	6.5 (5.9)	4.5	20.3
ggF: (0-jet, 1-jet) $\otimes$ $(ee + \mu\mu,\ e\mu)$			✓	✓
ggF: $\geq$ 2-jet and $e\mu$				✓
VBF: $\geq$ 2-jet $\otimes$ $(ee + \mu\mu,\ e\mu)$			✓	✓
VH: opposite-charge dilepton, three-lepton, four-lepton			✓	✓
VH: same-charge dilepton				✓
$H \to \tau\tau$ [17]	$1.43^{+0.43}_{-0.37}$	4.5 (3.4)	4.5	20.3
Boosted: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
VBF: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
$VH \to Vb\bar{b}$ [18]	0.52 ± 0.40	1.4 (2.6)	4.7	20.3
0ℓ ($ZH \to \nu\nu bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, p_T^V > and < 120 GeV			✓	✓
1ℓ ($WH \to \ell\nu bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, p_T^V > and < 120 GeV			✓	✓
2ℓ ($ZH \to \ell\ell bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, p_T^V > and < 120 GeV			✓	✓
		95% CL limit		
$H \to Z\gamma$ [19]		$\mu < 11$ (9)	4.5	20.3
10 categories based on $\Delta\eta_{Z\gamma}$ and p_{Tt}			✓	✓
$H \to \mu\mu$ [20]		$\mu < 7.0$ (7.2)	4.5	20.3
VBF and 6 other categories based on η_μ and $p_T^{\mu\mu}$			✓	✓
ttH production [21–23]			4.5	20.3
$H \to b\bar{b}$: single-lepton, dilepton		$\mu < 3.4$ (2.2)		✓
$ttH \to$ multileptons: categories on lepton multiplicity		$\mu < 4.7$ (2.4)		✓
$H \to \gamma\gamma$: leptonic, hadronic		$\mu < 6.7$ (4.9)	✓	✓
Off-shell H^* production [24]		$\mu < 5.1 - 8.6$ ($6.7 - 11.0$)		20.3
$H^* \to ZZ \to 4\ell$				✓
$H^* \to ZZ \to 2\ell 2\nu$				✓
$H^* \to WW \to e\nu\mu\nu$				✓

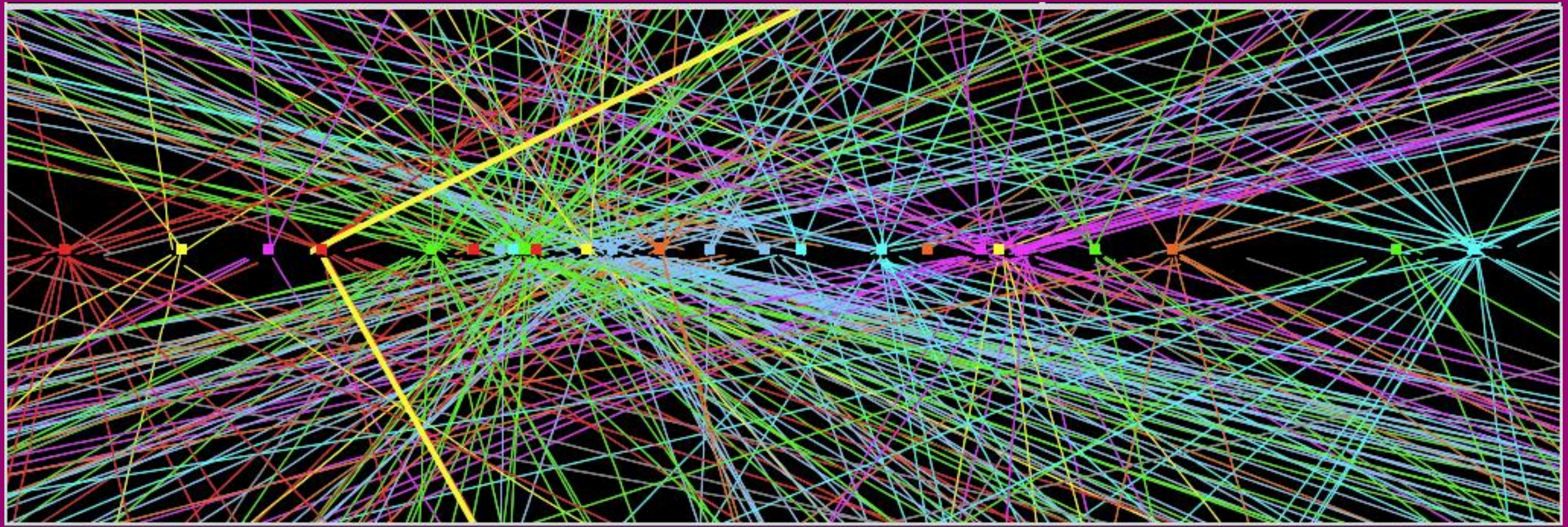
List of individual signal strength measurements



Pileup

2010 (~2events)	2011(~10events)	2012 (~30events)

Z->μμ event with 25 reconstructed vertices 2012 data

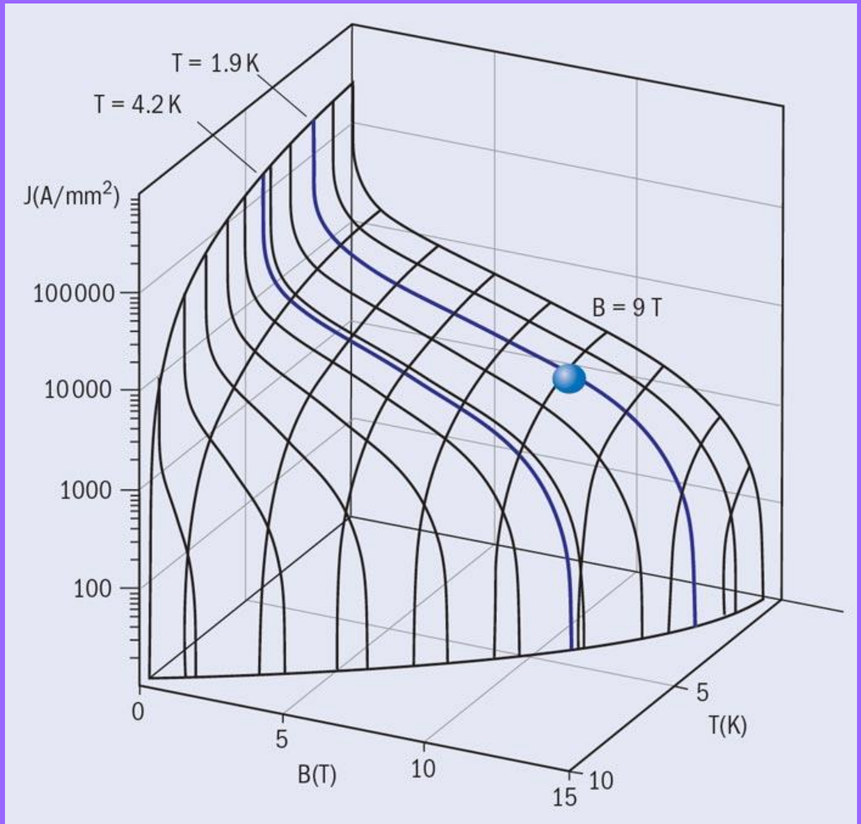


The niobium-titanium properties

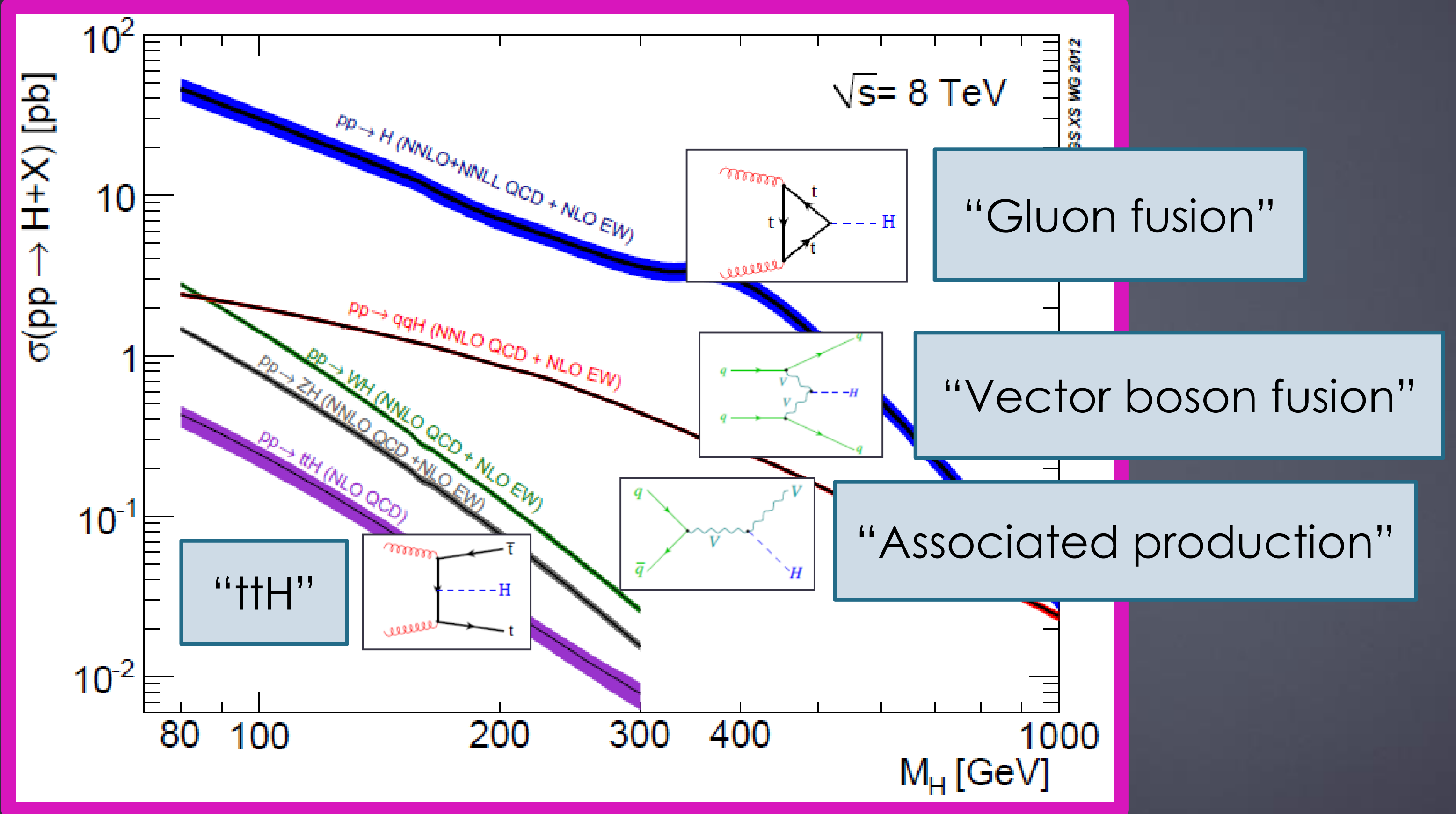
Alloy becoming superconducting at low temperature = 10K.

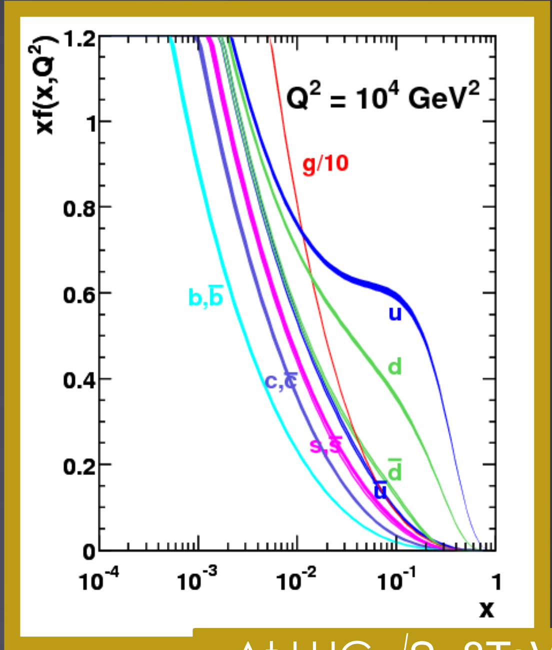
For a given field, NbTi stands higher currents at 1.9K than at 4.2K

LHC dipoles are kept at 1.9-2 K



The production channels of the Scalar Boson





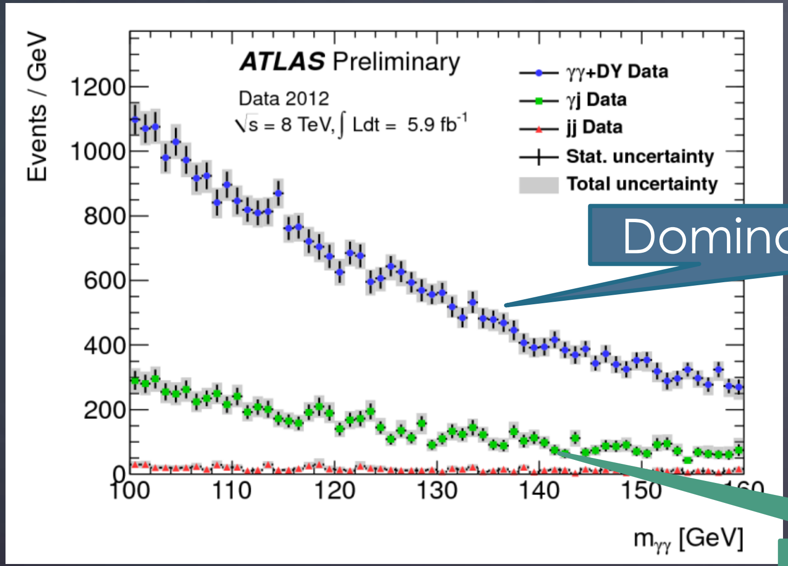
At LHC √S~8TeV
For M~100GeV
X ≈ M/√S = 0.01

Measuring the fraction of fake photons

Principle

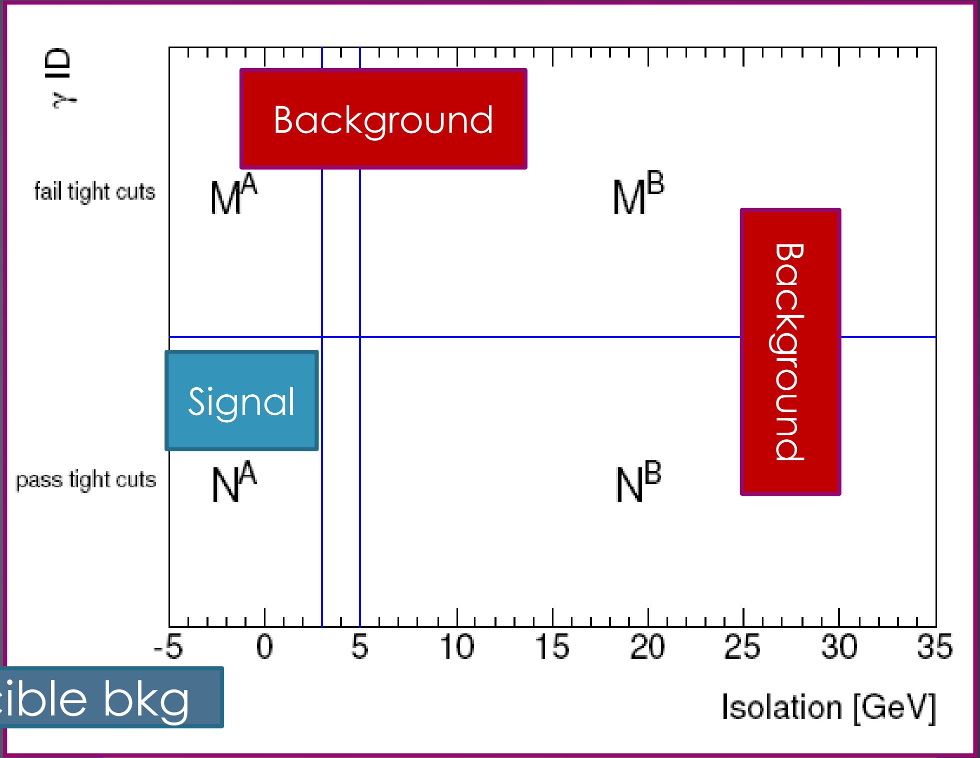
Genuine photons (signal) are ESSENTIALLY in Region NA
(Well isolated-satisfying tight selection criteria)

Fake photons are everywhere



Dominant irreducible bkg

Reducible bkg



In practice, one uses also MC to find the pure signal fraction

Constraints for the LHC and few numbers

- Use the existing LEP tunnel (27 Km long, ~100m under surface)
- Construct superconducting magnets to reach higher fields
- To reach high instantaneous and integrated Luminosities, make proton collisions (no proton-antiproton).
- Choice : Use two parallel rings in the same cold mass to let circulate the proton beams in opposite directions.
- Finally, 4 collision points along LHC to host ALICE, ATLAS, CMS and LHCb

Cost: ~5 Billion of Dollars

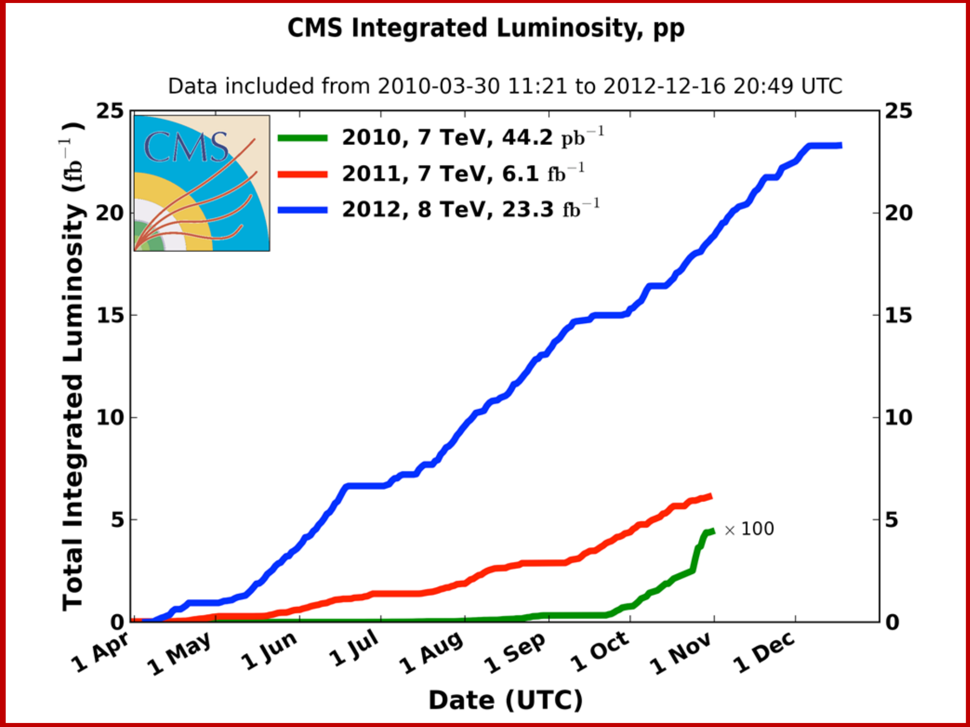
Peak magnetic field 8.3 Tesla

120 tons of Helium needed for cryogenic systems

Power Consumption: 120 MW, as for the Canton of Geneva: 19 MEuros/year

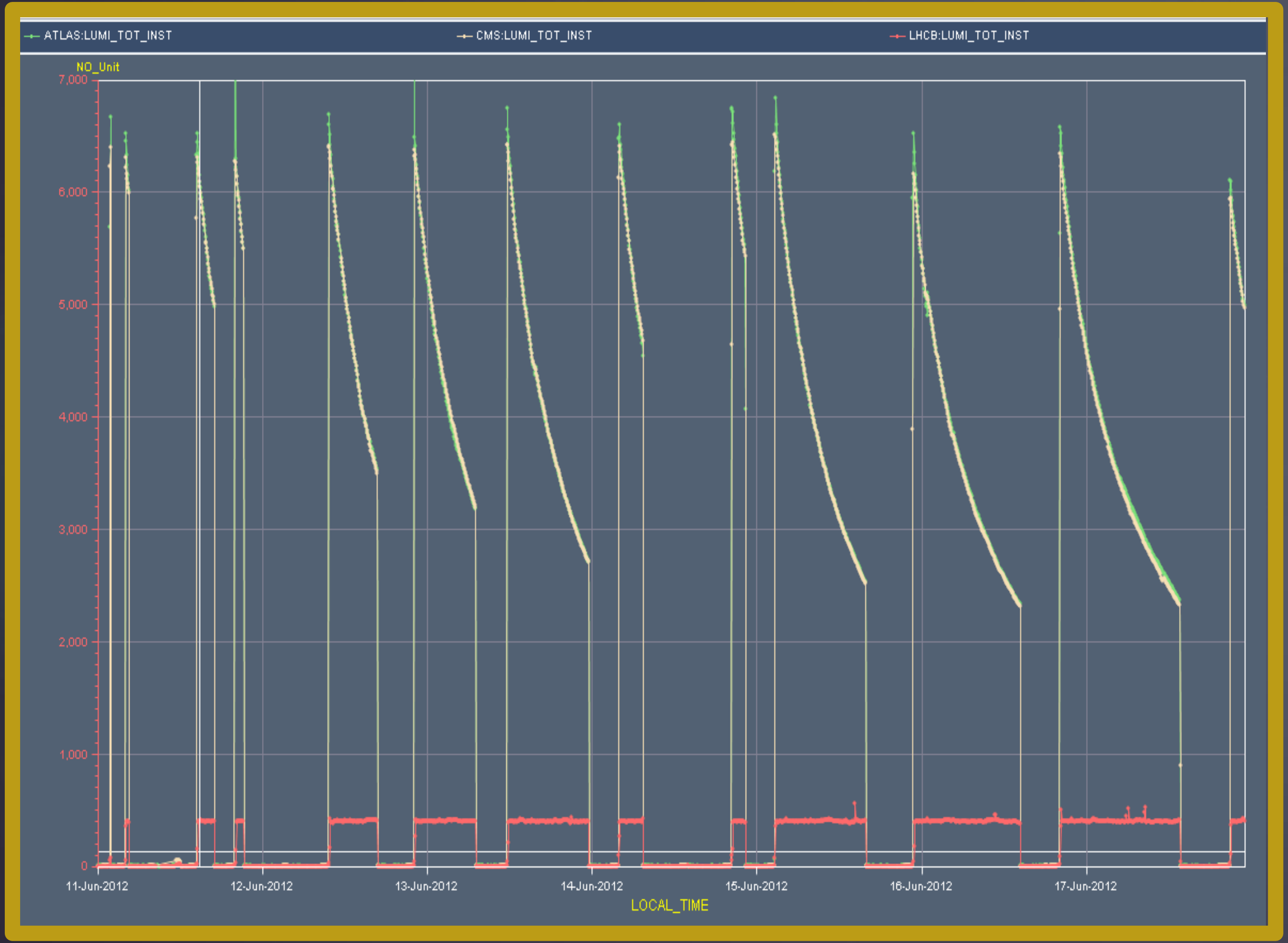
After repair: **Restart in March 2010 .**

Year	Overview	COM energy	Integrated luminosity [fb^{-1}]
2010	Commissioning	7 TeV	0.04
2011	Exploring limits	7 TeV	6.1
2012	Production	8 TeV	23.1



	2011	2012	Design
Energy Per beam	3.5TeV	4TeV	7TeV
Nb of bunches	1380	1380	2808
Bunch spacing (ns)	50	50	25
Beta* (CMS+ATLAS)	1.0	0.6	0.55
Nb of protons per bunch	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Peak Luminosity	3.7×10^{33}	7.7×10^{33}	1×10^{34}
<$nb_{collisions}$> / bunchCross	~12	~30	19

Challenges for the beam lifetime



Fill	Duration	Ibeam	Lpeak [e30 cm-2s-1]	Lint [pb-1]	Dump
2723	2:26	2.03E+14	6406	46.06	Trip of ROD.A81B1, SEU?
2724	1:13	2.03E+14	6329	25.905	Electrical perturbation
2725	7:04	2.05E+14	6520	115.5	Trip of S81
2726	8:58	2.05E+14	6499	142.5	Elecitrical perturbation, FMCM
2728	11:41	2.06E+14	6525	171.5	Operator dump
2729	3:28	2.06E+14	6502	67.7	BLM self trigger
2732	1:52	2.06E+14	6592.5	40	QPS trigger RQX.R1, SEU?
2733	12:34	2.06E+14	6674	183	Triplet RQX.L2 tripped.
2734	15:33	2.01E+14	6257.5	203.5	Operator dump
2736	17:29	2.02E+14	6465.5	233	Operator dump
2737	3:36	1.99E+14	6021	66.1	RF Trip 2B2
Tot	51.1%			1301	

51% of time in stable beams; total **1.3 fb^{-1}** in one week

M. Lamont, 18 June 2012

The end point of the LHC beams

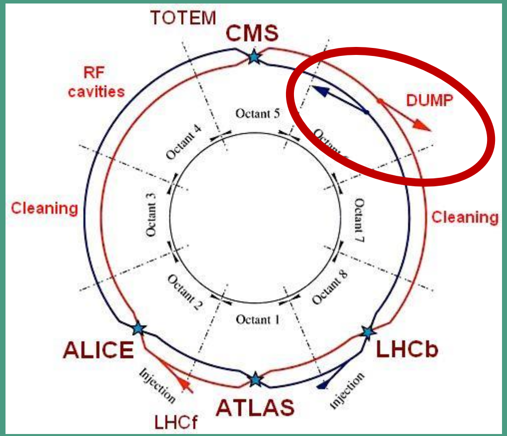
Want to dump the beams when

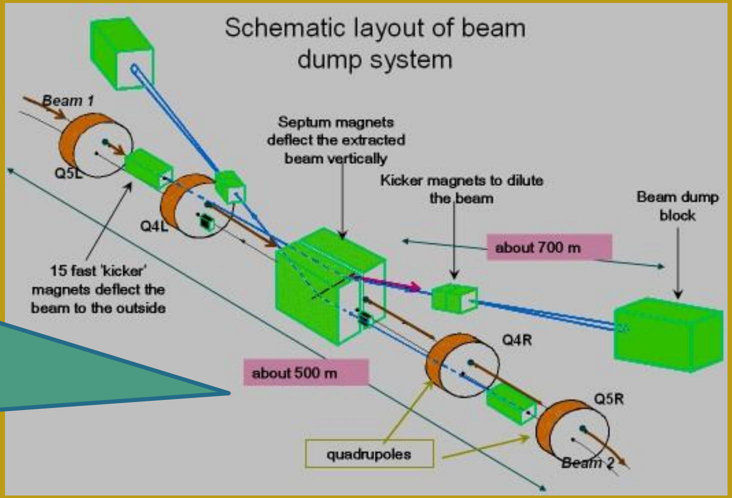
1) The beam quality has been deteriorated

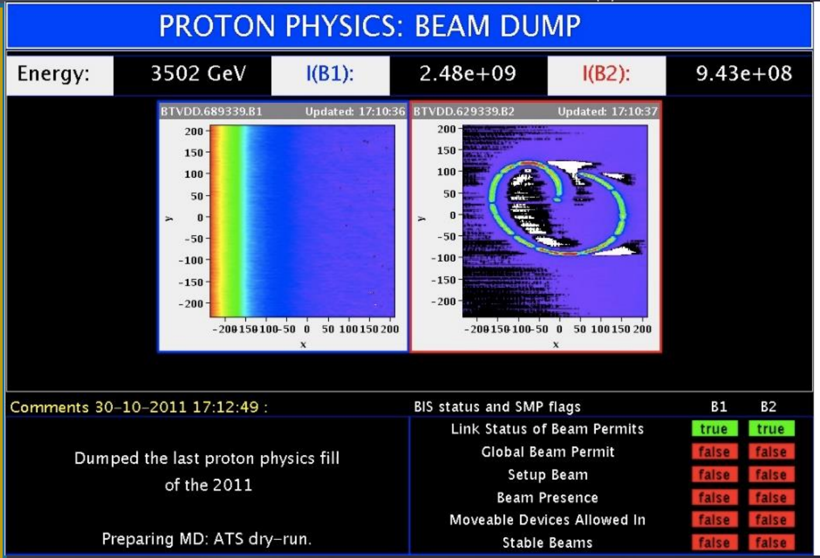
2) the Beam loss monitors (BLM) installed along the machine detect activity beyond the safety threshold

During tests:
7MJ energy of a dipole released into a spot of the coil

© P.Pugnat







Combined M_H from H->γγ and H->ZZ*->4l channels, in ATLAS

Profiled Likelihood ratio

$$\Lambda(m_H) = \frac{L(m_H\,,\,\hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(m_H)\,,\,\hat{\hat{\theta}}(m_H))}{L(\hat{m}_H,\hat{\mu}_{\gamma\gamma},\hat{\mu}_{4\ell},\hat{\theta})}\,.$$

Θ =" Nuissance parameter" == systematic uncertainties

$\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\theta}$

== **Maximum Likelihood Estimates (MLE),** are the values of parameters that maximize $\Lambda(m_H)$.

$\hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(m_H)\,,\,\hat{\hat{\theta}}(m_H)$

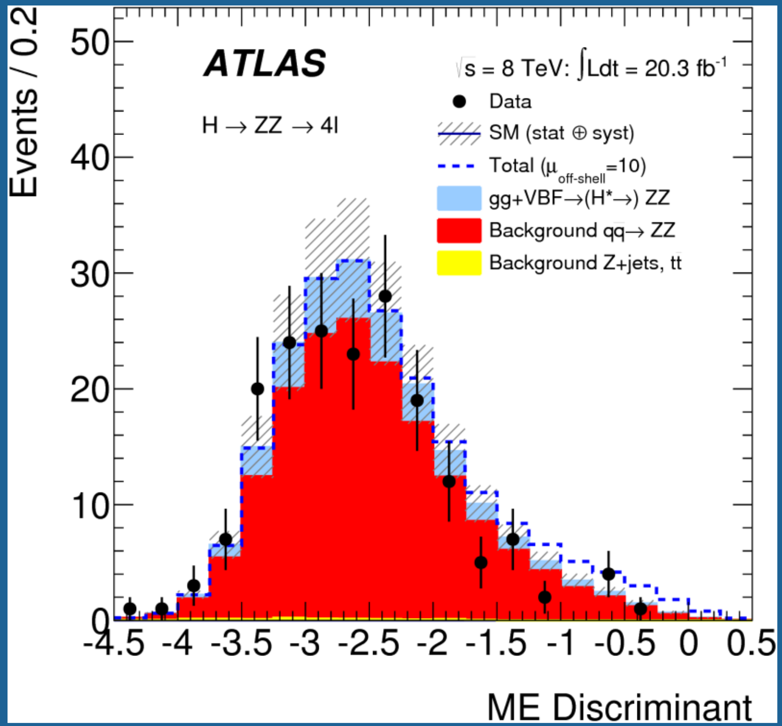
==**Conditional Maximum Likelihood Estimates(CMLE)** are the values of parameters that maximize $\Lambda(m_H)$ at fixed m_H

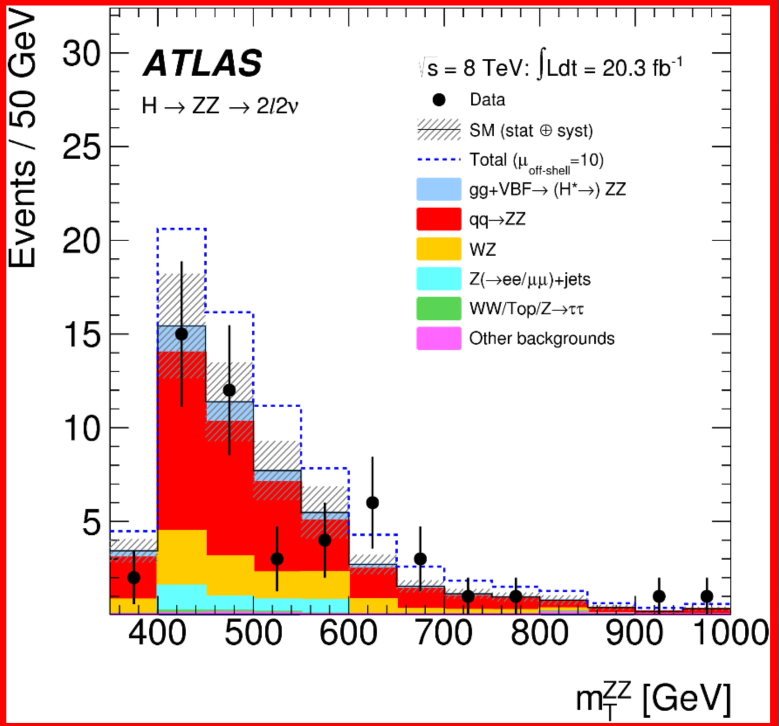
Example: the dominant uncertainties for H->γγ mass (in %)

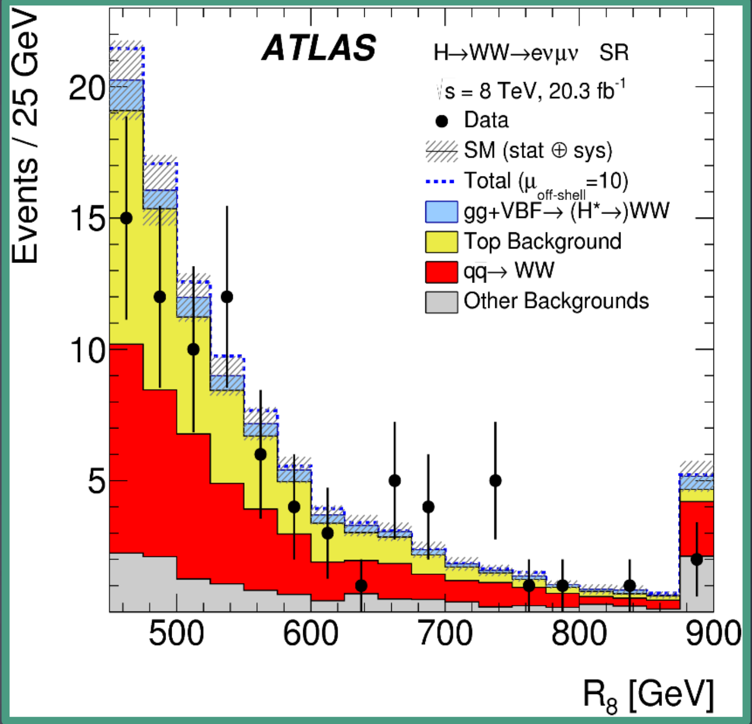
Class	Unconverted Central low p_{Tt}	Unconverted Central high p_{Tt}	Unconverted Rest low p_{Tt}	Unconverted Rest high p_{Tt}	Unconverted Trans.	Converted Central low p_{Tt}	Converted Central high p_{Tt}	Converted Rest low p_{Tt}	Converted Rest high p_{Tt}	Converted Trans.
$Z\to e^+e^-$ calibration	0.02	0.03	0.04	0.04	0.11	0.02	0.02	0.05	0.05	0.11
LAr cell non-linearity	0.12	0.19	0.09	0.16	0.39	0.09	0.19	0.06	0.14	0.29
Layer calibration	0.13	0.16	0.11	0.13	0.13	0.07	0.10	0.05	0.07	0.07
ID material	0.06	0.06	0.08	0.08	0.10	0.05	0.05	0.06	0.06	0.06
Other material	0.07	0.08	0.14	0.15	0.35	0.04	0.04	0.07	0.08	0.20
Conversion reconstruction	0.02	0.02	0.03	0.03	0.05	0.03	0.02	0.05	0.04	0.06
Lateral shower shape	0.04	0.04	0.07	0.07	0.06	0.09	0.09	0.18	0.19	0.16
Background modeling	0.10	0.06	0.05	0.11	0.16	0.13	0.06	0.14	0.18	0.20
Vertex measurement	0.03									
Total	0.23	0.28	0.24	0.30	0.59	0.21	0.25	0.27	0.33	0.47

Split the uncertainties of the 2 channels (ZZ*->4l and 2γ) in **correlated and uncorrelated nuisance parameters**

The Width of the Scalar Boson







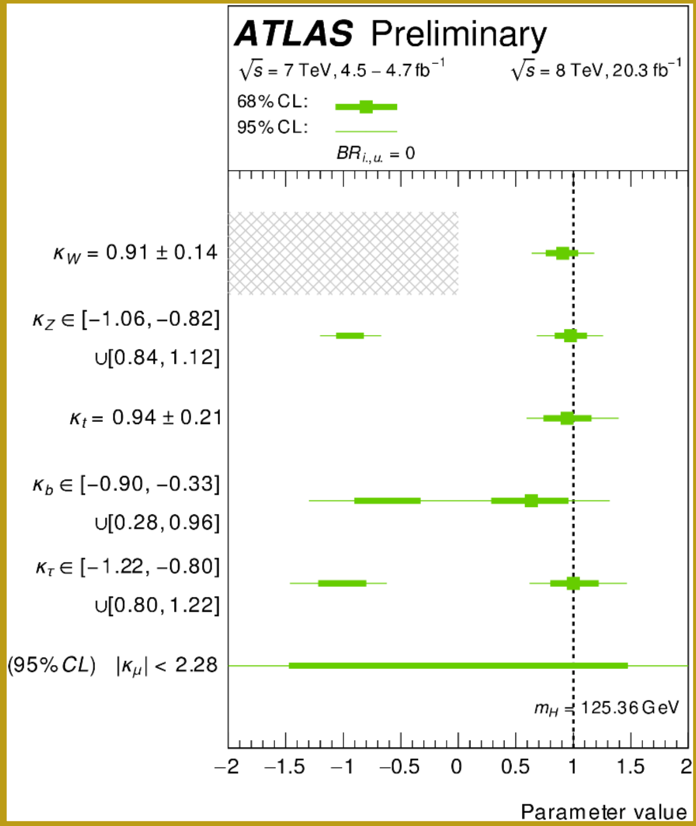
ZZ->4l
ME discriminant combining
8 variables for events
With 220GeV<m_{4l}<1000GeV

ZZ->2l2v
Presence of neutrinos
Look at m_T^{ZZ} in the region
380 GeV-1000GeV

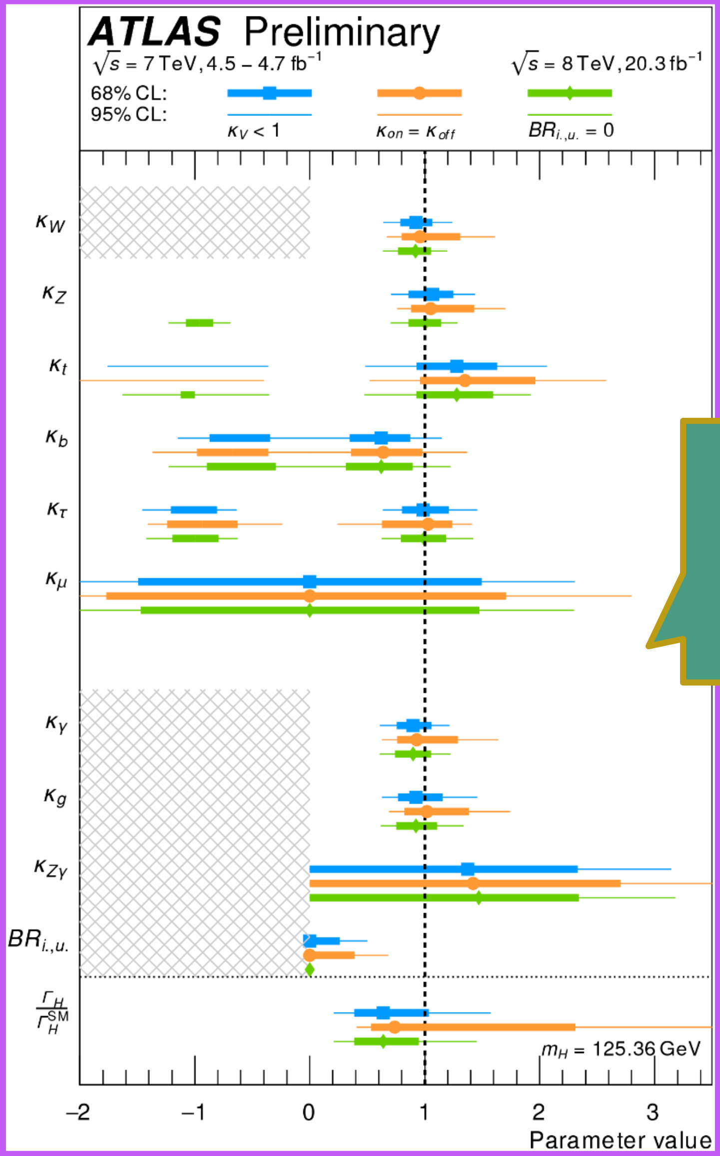
WW->eνμν
Combine m_T^{WW} and m_{ll}

$$R_8 = \sqrt{m_{\ell\ell}^2 + \left(a \cdot m_T^{WW}\right)^2}.$$

Generic beyond SM models: individual couplings



Assumptions : Only SM particles in loops, no Invisibles➔ Check Kappas



Assumptions: no-SM contributions in loops and allowing invisible width