Higgs Searches at the LHC

Cibrán Santamarina

Universidade de Santiago de Compostela

THE HIGGS MECHANISM

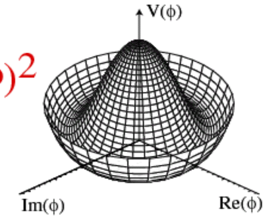
THE HIGGS MECHANISM: GAUGE BOSON AND FERMION MASSES

HIGGS FIELD

Complex weak isospin scalar doublet Φ with scalar potential $V[\Phi]$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad V[\Phi] = \mu^2\Phi^\dagger\Phi + \lambda\,(\Phi^\dagger\Phi)^2$$

$$(\lambda > 0,\ \mu^2 < 0)$$



STANDARD MODEL

Yang-Mills $SU(2)_L \times U(1)_Y$

massless gauge bosons W_μ and B_μ

and *massless* fermions ψ

$$\mathcal{L} = -\frac{1}{2}\boldsymbol{W}_{\mu\nu}\cdot\boldsymbol{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$+\left|\left(i\partial_\mu - g'\frac{Y}{2}B_\mu - g\frac{1}{2}\boldsymbol{\tau}\cdot\boldsymbol{W}_\mu\right)\Phi\right|^2 - V(\Phi)$$

$$+\ \bar{\psi}_L\gamma^\mu\left(i\partial_\mu - g'\frac{Y}{2}B_\mu - g\frac{1}{2}\boldsymbol{\tau}\cdot\boldsymbol{W}_\mu\right)\psi_L$$

$$+\ \bar{\psi}_R\gamma^\mu\left(i\partial_\mu - g'\frac{Y}{2}B_\mu\right)\psi_R$$

SPONTANEOUS SYMMETRY BREAKING

One component acquires non-zero vacuum expectation value

$$<0|\Phi|0> = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \longrightarrow \Phi(x) = \frac{1}{\sqrt{2}}\exp\left(i\frac{\xi\cdot\tau}{2v}\right)\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

MASSIVE GAUGE BOSONS

$$W^\pm_\mu = \frac{1}{2}(W^1_\mu \mp iW^2_\mu) \qquad M_W = \frac{gv}{2}$$

$$Z_\mu = -B_\mu\sin\theta_W + W^3_\mu\cos\theta_W \qquad M_Z = \frac{M_W}{\cos\theta_W}$$

$$A_\mu = B_\mu\sin\theta_W + W^3_\mu\cos\theta_W \qquad M_\gamma = 0$$

MASSIVE FERMIONS

Yukawa couplings of Higgs to fermions

$$g_f\left[\bar{\psi}_L\Phi\psi_R + \bar{\psi}_R\Phi^\dagger\psi_L\right]$$

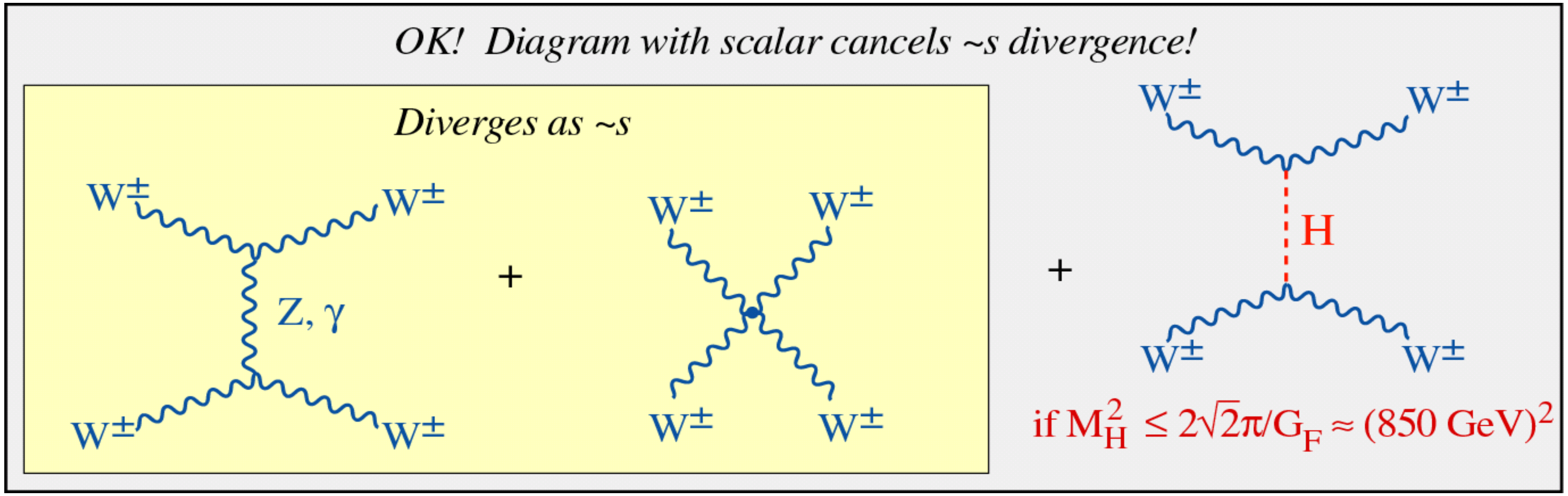
$$e.g.,\ m_e = \frac{g_e v}{\sqrt{2}}$$

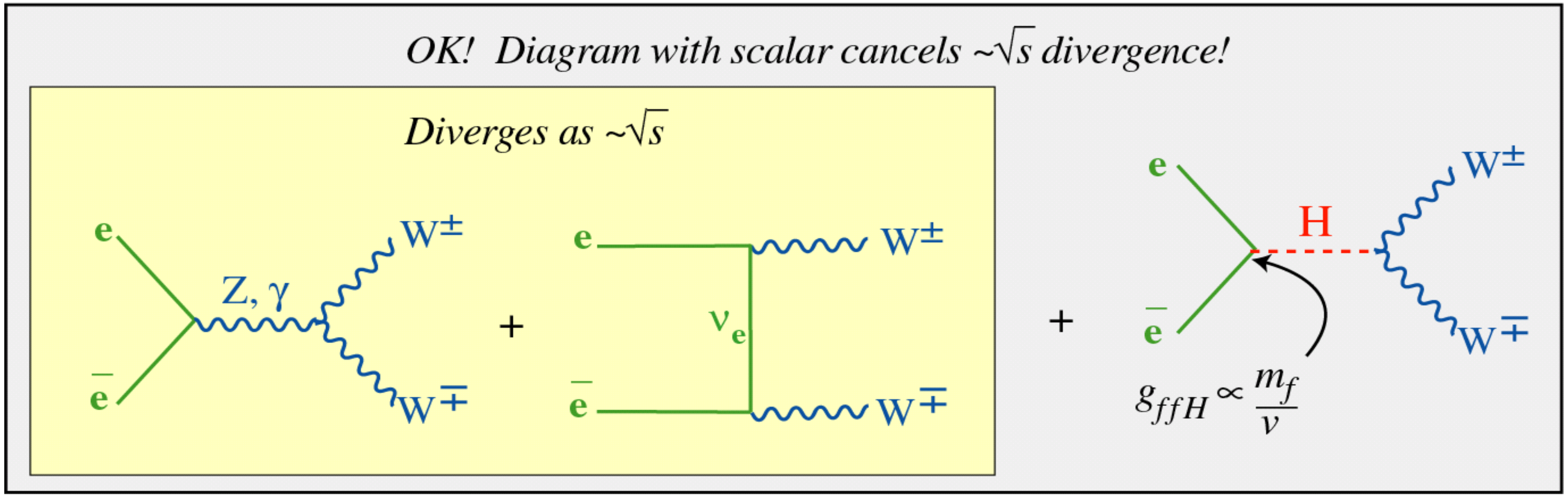
Requires a massive scalar field $\Rightarrow$ the Higgs Boson

Higgs Mass ($v\sqrt{\lambda}$) is a free parameter and must be determined by experiment

More than mass

The scalar field is needed to keep unitarity (at tree level) and renormalizability
Either a Higgs or something else is needed.





Charged Higgs

Minimal Supersymmetric Standard Model.

Supersymmetry eliminates Gauge Hierarchy Problem, yields GUT-Scale unification of couplings and provides a dark matter candidate.

Needs two Higgs doublets

Requires two Higgs doubles of opposite Hypercharge (one for up-sector, one for down-sector)

$$\Phi_{(Y=-1)} = \begin{pmatrix} \phi_1^{0*} \\ -\phi_1^- \end{pmatrix} \quad \Phi_{(Y=+1)} = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

5 physical Higgs bosons

2 charged : H^+ and H^-

2 CP even neutral : H and h

1 CP odd neutral : A

Higgs masses derivable from MSSM parameters

H^+, H^-: $M^2 = M_W^2 + M_A^2$ (at tree-level)

h : $M < M_Z$ (at tree-level) → 130 GeV (rad. corr.)

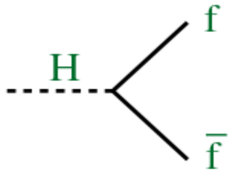
The Minimal Supersymmetric Standard Model does not completely solve the Hierarchy problem the NMSSM is a extension leading to a different Charged Higgs scenario.

Other Possible Scenarios (2)

INVISIBLE HIGGS SCENARIO

New weakly interacting massive particles could easily saturate Higgs decay width (e.g., LSP Neutralinos with RPC: $H \rightarrow \chi^0 \chi^0$)

e.g., light Higgs: small decay width to fermions



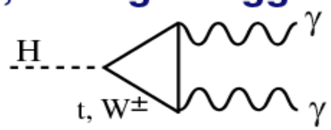
$\Gamma_H < 17$ MeV if $M_H < 150$ GeV

$\approx \frac{m_f^2}{v^2}$; $v = 175$ GeV

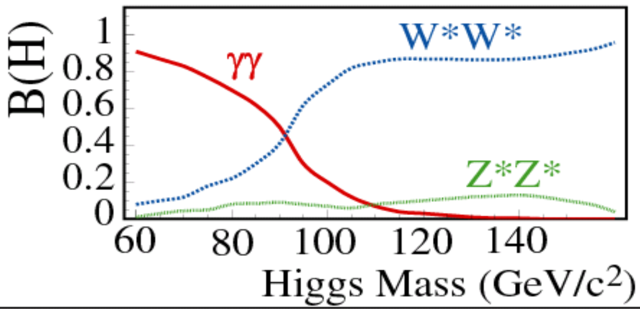
Invisible decays! Producing lots of Higgs and missing them all!

FERMIOPHOBIC HIGGS SCENARIO

In SM $H \rightarrow \gamma\gamma$ is suppressed, and light Higgs below WW and ZZ threshold



Models exist which reduce or eliminate coupling to fermions!



Photonic decays of light Higgs!

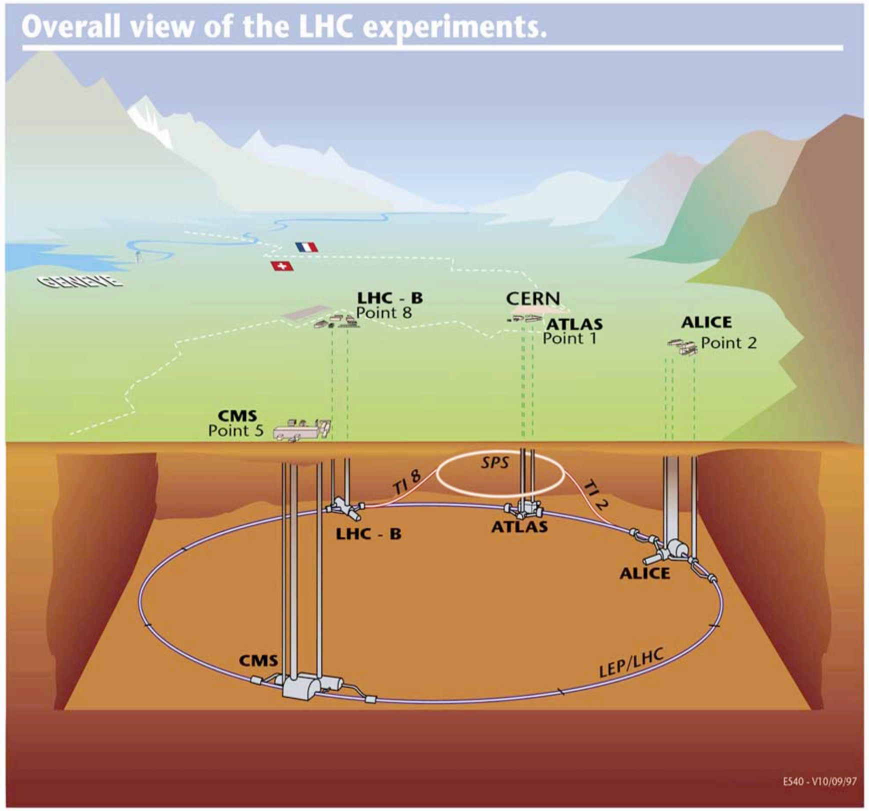
Cibrán Santamarina
Universidade de Santiago de Compostela

Other Possible Scenarios (3)

- Higgs as a composite resonance (technicolor or compositeness models).
- Extra dimensions.
- Little Higgs (need of at least one new particle to stabilize the Higgs mass)
- NO HIGGS scenarios:
    - The Chiral Lagrangian Model (an old friend of the High Energy Group in Santiago). Leads to High Mass WZ resonances.
    - Higgsless models.

The Large Hadron Collider

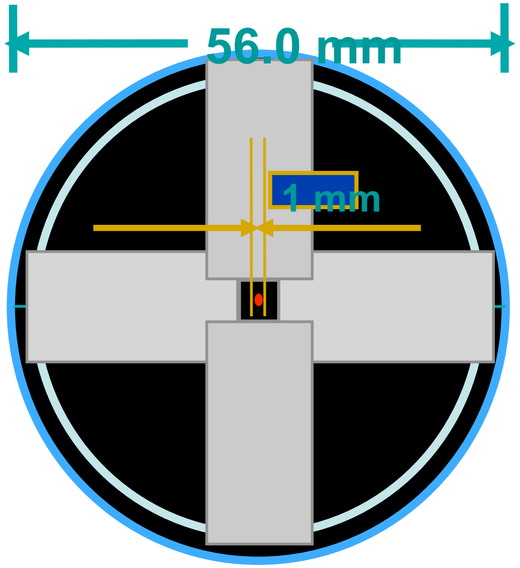
- **At CERN:** 4 main experiments
- **Proton beam:** 3.5-4.0 TeV.
- **Design & construction:** 20 years.
- **Price:** €3600 millions.
- **Placement:** 27 km tunnel 3.8 m wide100 m depth.
- **Luminosity:** $7.7x10^{33}cm^{-2}s^{-1}$
- **Bunch crossing:** 50 ns
- **Protons per bunch:** $\sim 10^{11}$
- **Beam radius:** 16.7 µm

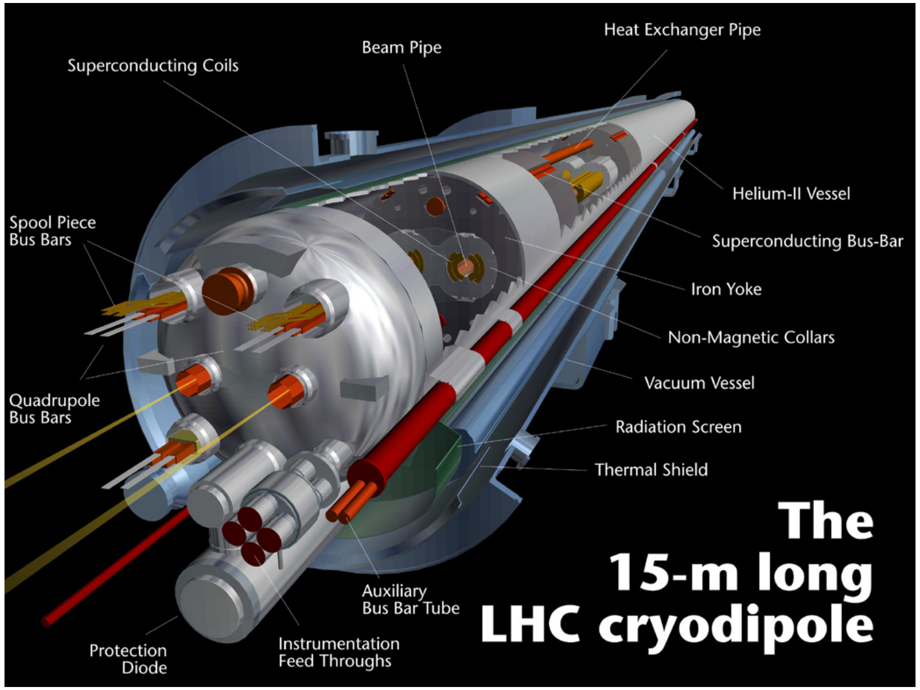


Cibrán Santamarina
Universidade de Santiago de Compostela

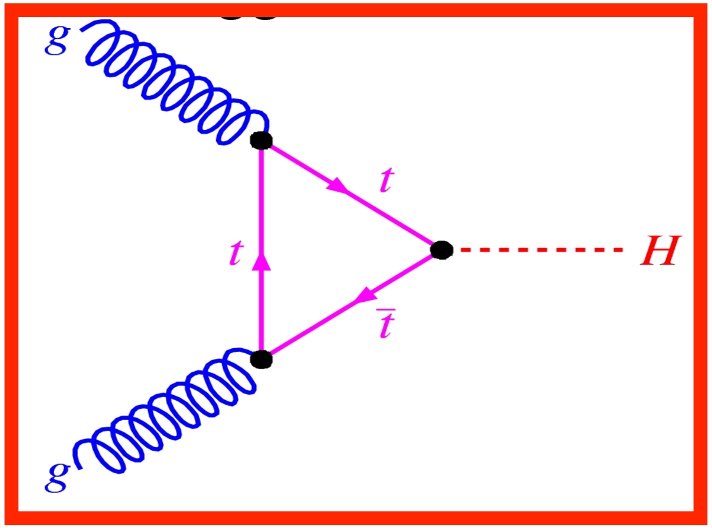
Quiz

- The LHC dipoles are colder than outer space.
- What is the temperature of the outer space?

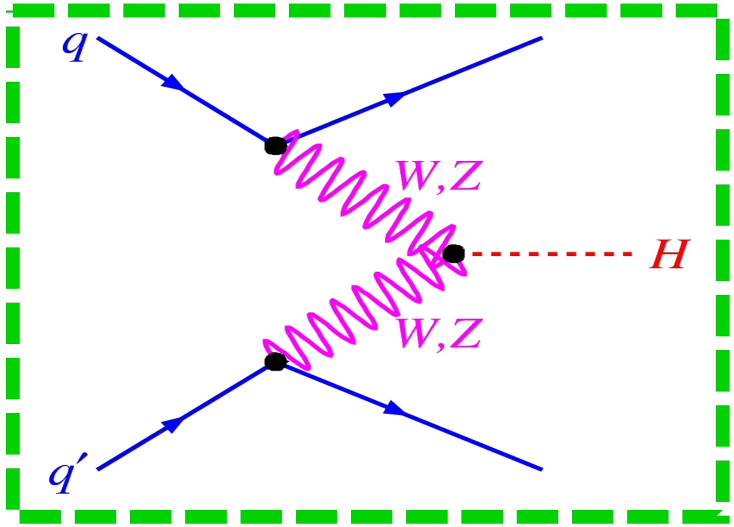




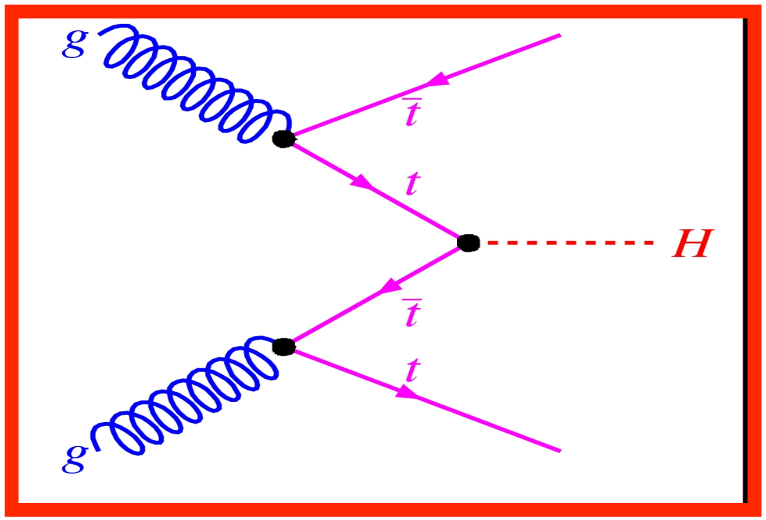
Higgs Production



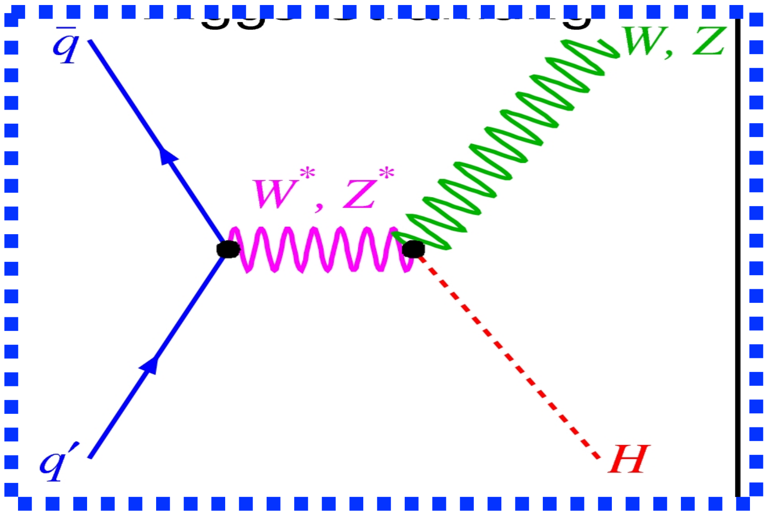
Gluon Fusion



Vector (Weak) Boson Fusion



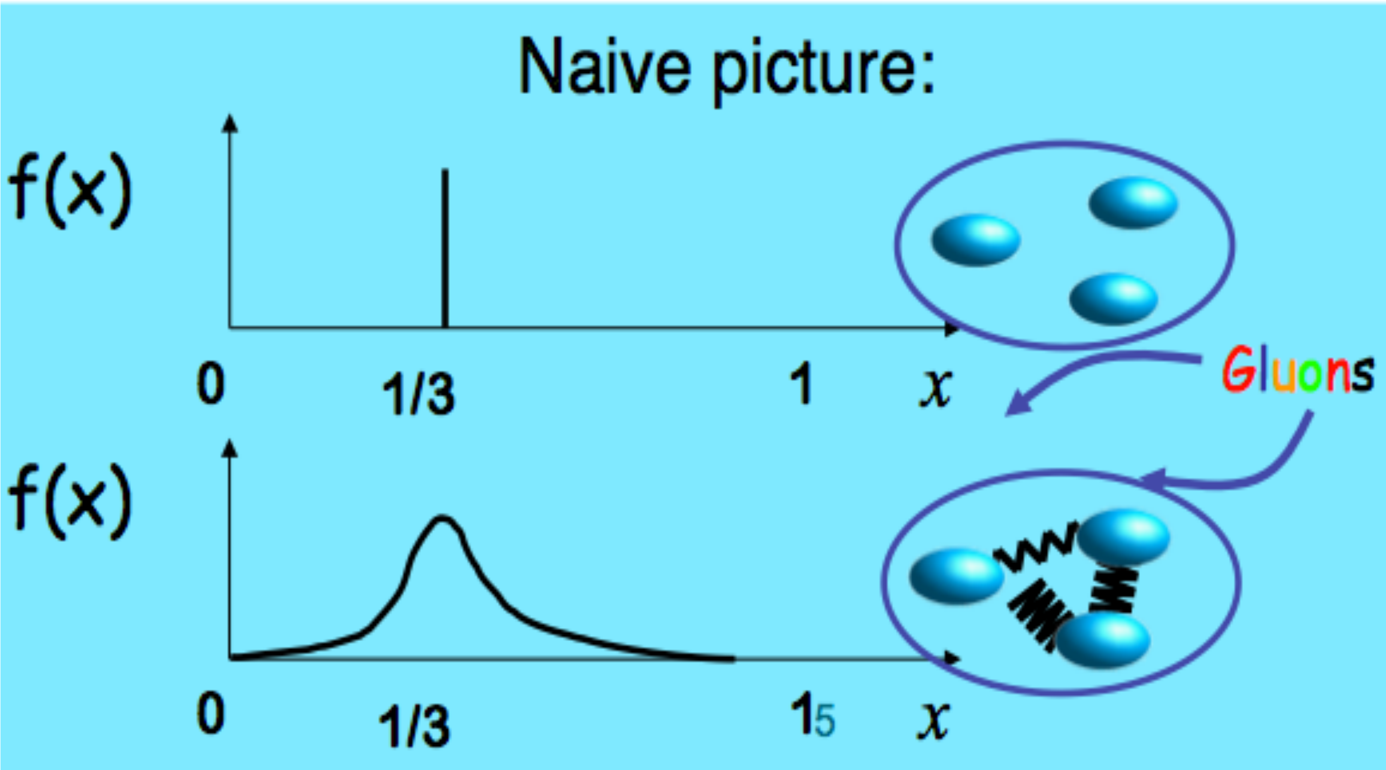
Top Fusion

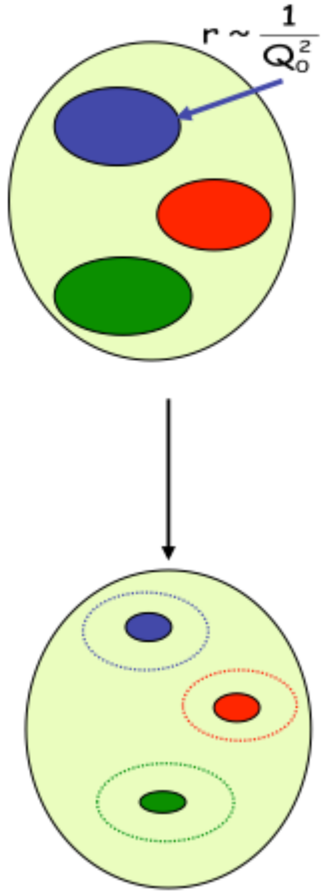


Higgs-strahlung Associated to W/Z

Proton at LHC

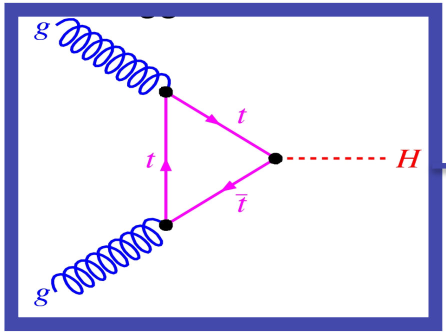
-Protons made of quarks and gluons
- At LHC energies 9 gluons per quark!!
- Proton is a gluon ball

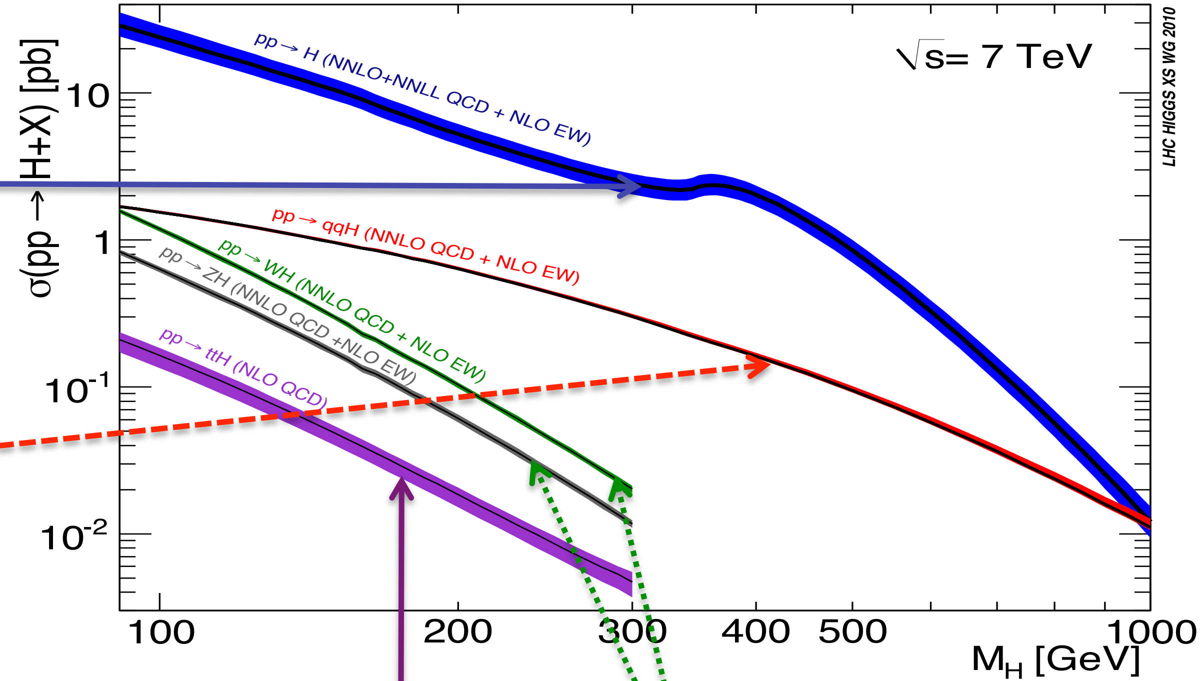




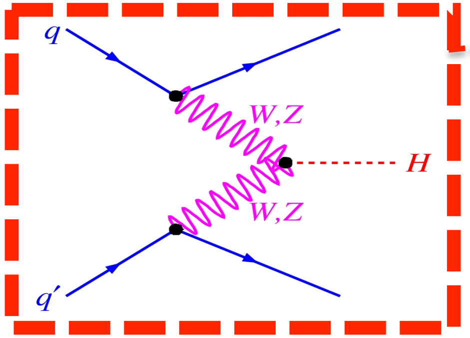
SM LHC Higgs production

Gluon Fusion

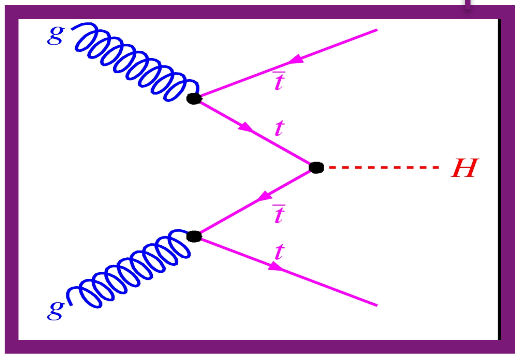




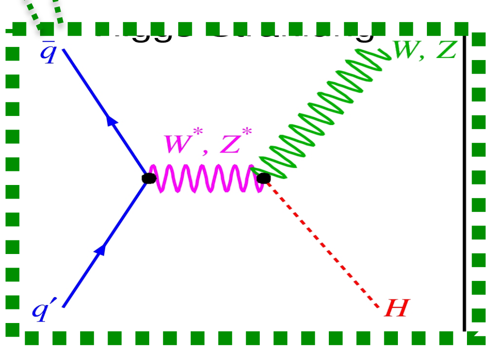
Vector Boson Fusion



M_H = 125 GeV/c^2	
gg	~15 pb
VBF	~1.2 pb
ttH	~0.08 pb
W,ZH	~0.57-0.32 pb



Top Fusion

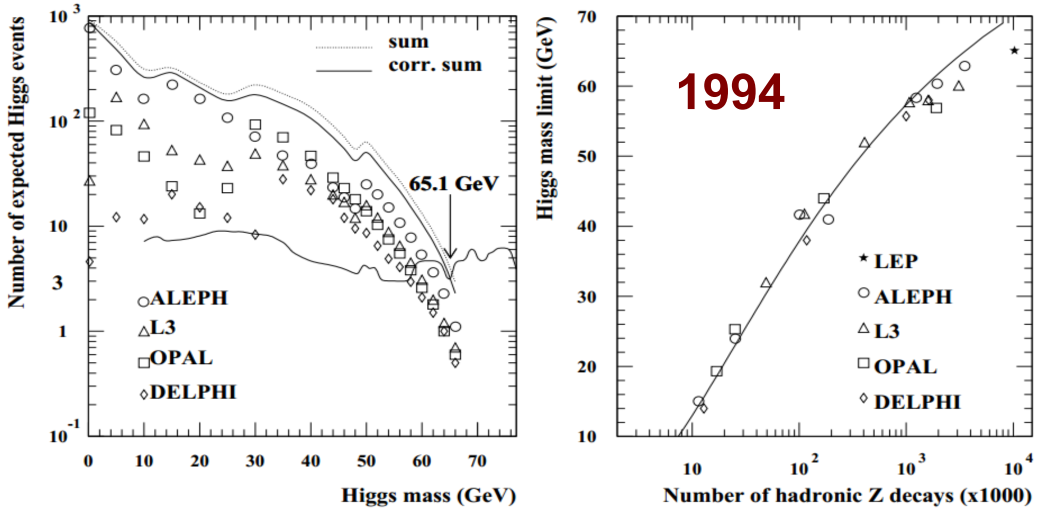


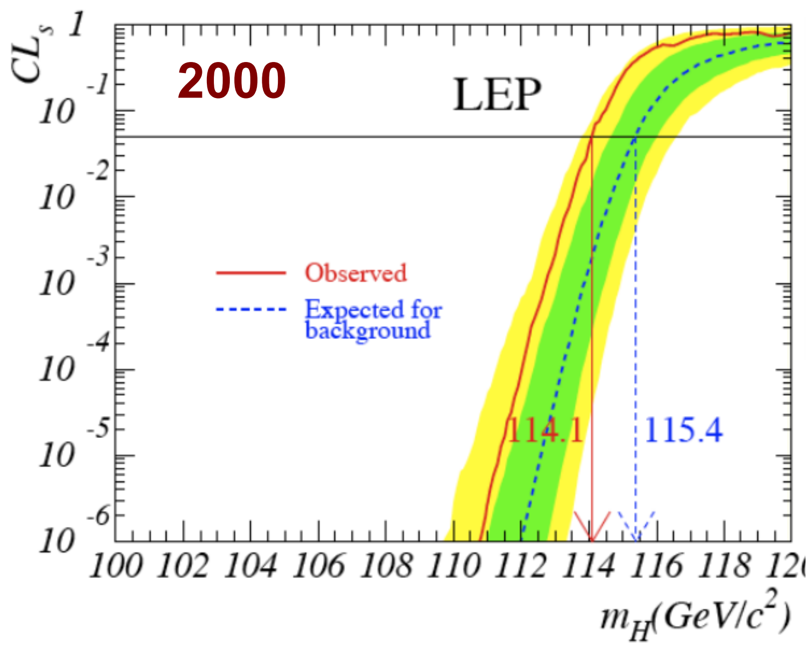
Associated to W/Z
(Higgs-strahlung)

Cibrán Santamarina
Universidade de Santiago de Compostela

SM LHC Higgs historical

- When did the search for Higgs started?
- Not really feasible before W and Z discovery in 1983.
- Real search started at LEP in 1989:
  - Associated production.
  - Alef, first paper in 1989. Exclusion: 32 MeV/c² to 15 GeV/c² at 95% C.L.
  - Combination of 1994.
- 1990s:
  - Need for larger energies: LEP2 (electron), *Superconducting Super Collider or LHC (hadrons).*
- 1995s: CDF and D0 at Tevatrón: quark top, with large mass of 175 GeV.
  - This mass implied the possibility of seeing the Higgs at Tevatron.
- LEP 2: increased center of mass energy up to 206 GeV:
  - Enough to find a Z → Z*H up to 115 GeV/c².
  - Finished in 2000.
  - Best limit m_H>114.1 GeV.

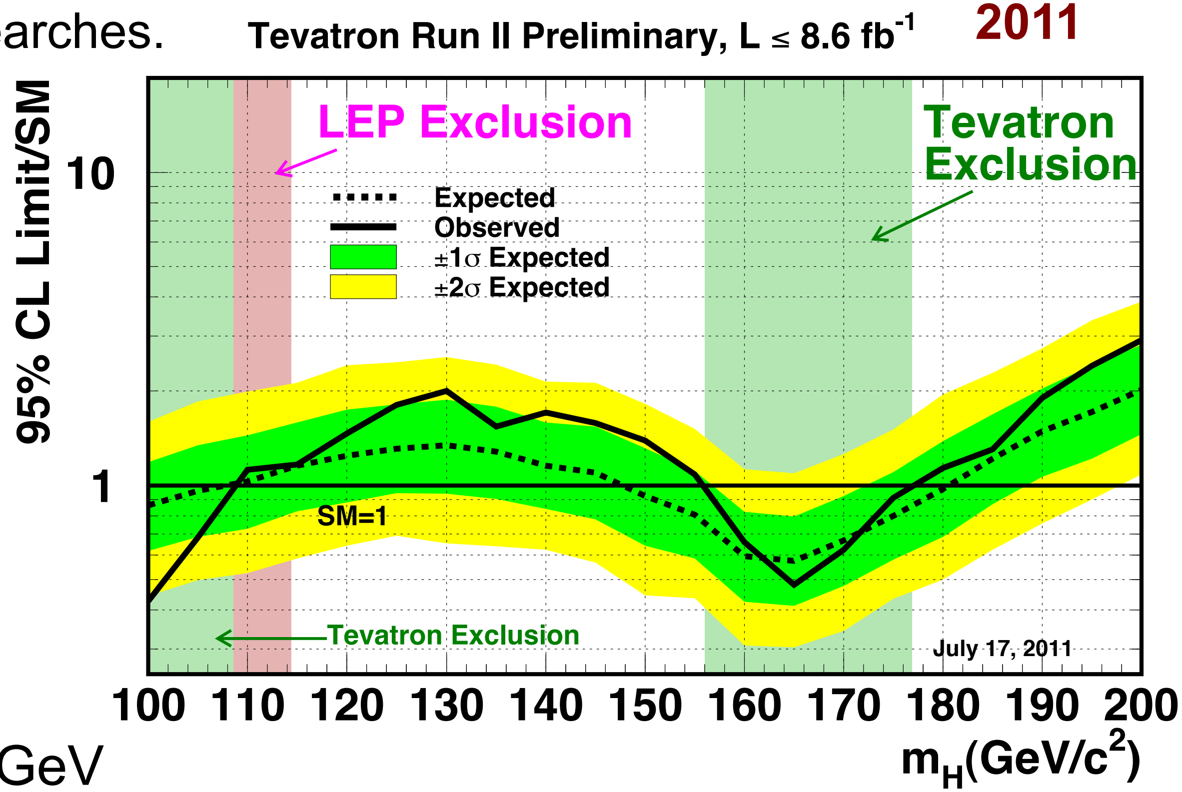




SM LHC Higgs historical (2)

-Tevatron. Combo of analysis.
-H->WW decays in higher mass searches.
-LEP and EW constraints.

2011



- Direct searches.
  - LEP: M_H>114.1 GeV
  - Tevatron: $|M_H-166|$>10 GeV
- Indirect constraints from precision EW measurements.
  - $M_H= 96^{+31}_{-24}$ GeV, M_H<169 GeV at 95% CL (standard fit)
  - $M_H= 120^{+12}_{-5}$ GeV ,M_H<143 GeV at 95% CL (including direct searches)

Cibrán Santamarina
Universidade de Santiago de Compostela

Detecting the Higgs

SM LHC Higgs decays

-Coupling to leptons:

$$\Gamma(h \to l^+l^-) = \frac{G_F M_l^2}{4\sqrt{2}\pi} M_h \beta_l^3 \qquad \beta_l \equiv \sqrt{1 - 4M_l^2/M_h^2}$$

-Coupling to quarks:

$$\Gamma(h \to q\bar{q}) = \frac{3G_F}{4\sqrt{2}\pi} M_q^2 M_h \beta_q^3 \left(1 + 5.67\frac{\alpha_s}{\pi} + \ldots\right)$$

-Coupling to vector bosons:

$$\Gamma(h \to W^+W^-) = \frac{G_F M_h^3}{8\pi\sqrt{2}} \sqrt{1 - r_W}(1 - r_W + \tfrac{3}{4} r_W^2)$$

$$\Gamma(h \to ZZ) = \frac{G_F M_h^3}{16\pi\sqrt{2}} \sqrt{1 - r_Z}(1 - r_Z + \tfrac{3}{4} r_Z^2), \qquad r_V \equiv 4M_V^2/M_h^2$$

-Coupling to vector bosons with one off-shell (very important), to gg and to gZ also possible.

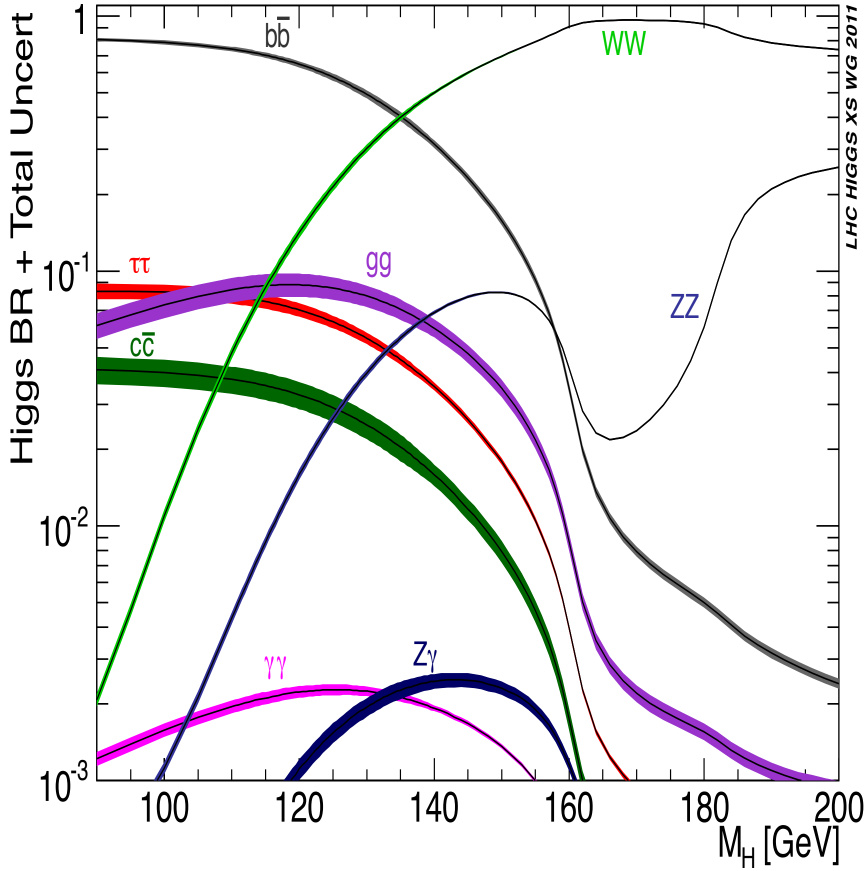
SM LHC Higgs decays

-SM Higgs coupling proportional to the lepton mass.
-Also proportional to the vector boson mass (stronger coupling).
-Coupling to gluons and photons through triangle b, t or W loops.
-Light Higgs, the most complex scenario.
-Intermediate and heavy mass Higgs, easy due to golden channels like:

$$H \rightarrow \gamma\gamma$$

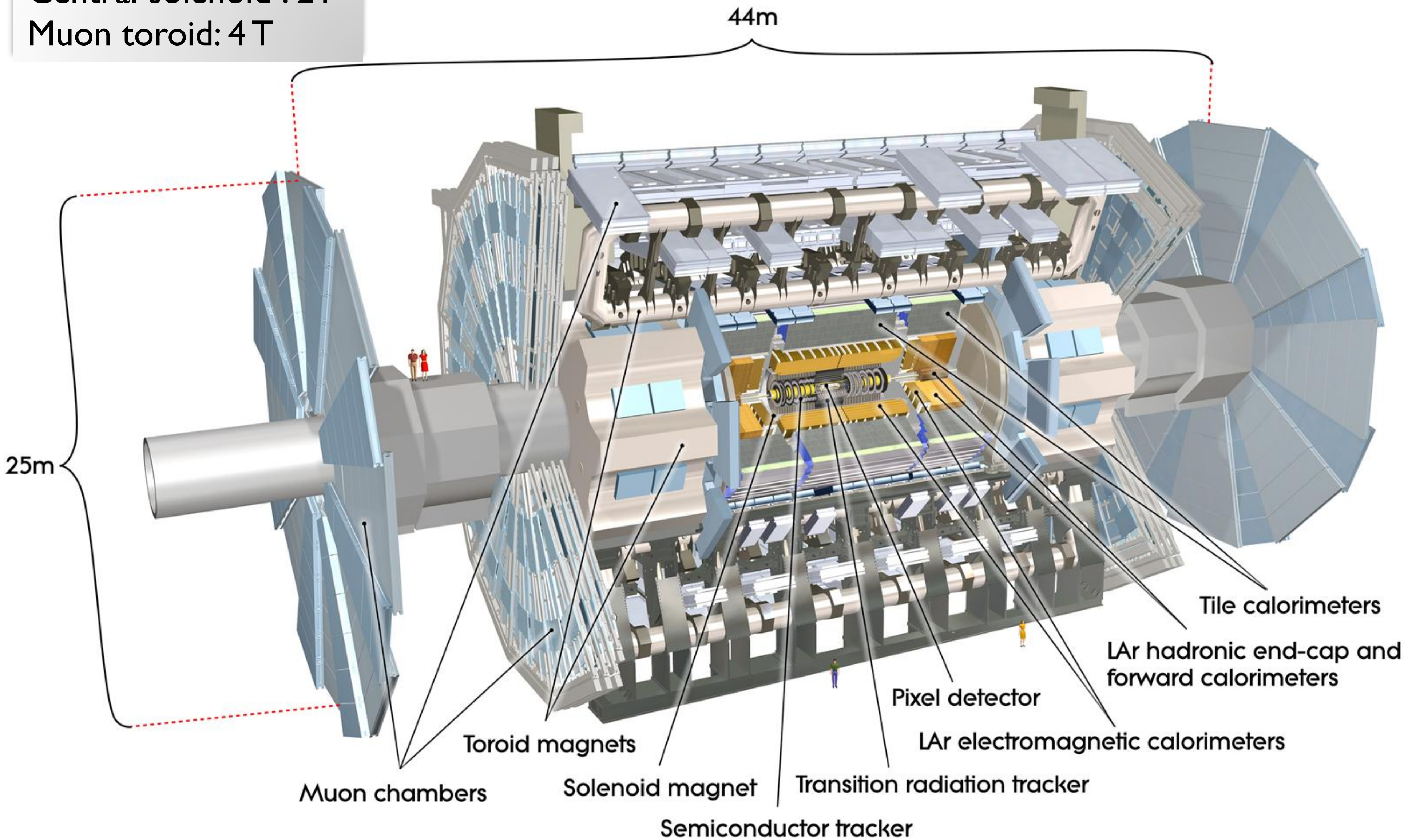
$$H \rightarrow ZZ^{*} \rightarrow 4l\ (4\mu/4e)$$

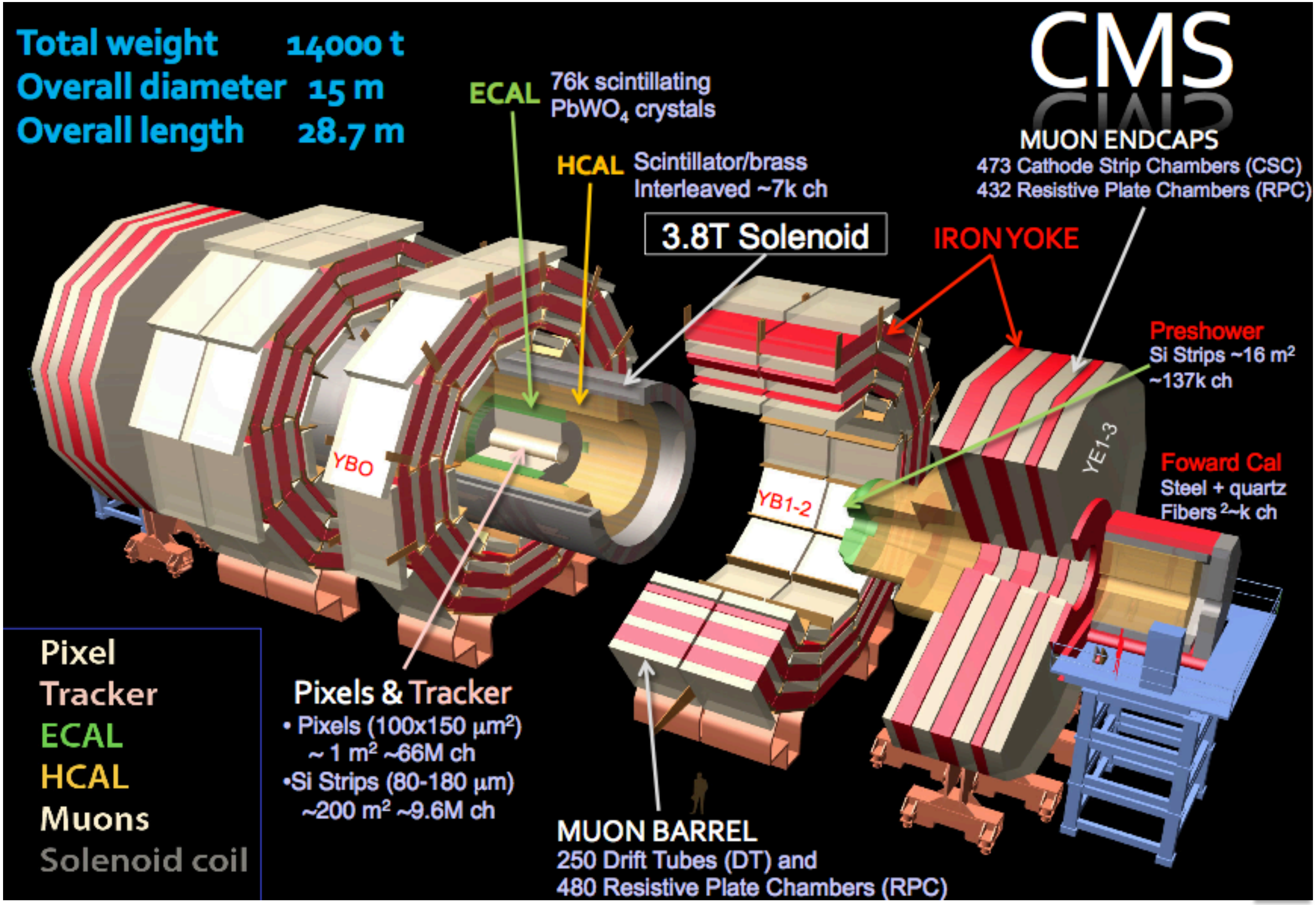
$$H \rightarrow WW^{*} \rightarrow 4l\ (2\nu - 2\mu/2e)$$



ATLAS

Weight: 7000 t
Central solenoid : 2T
Muon toroid: 4 T





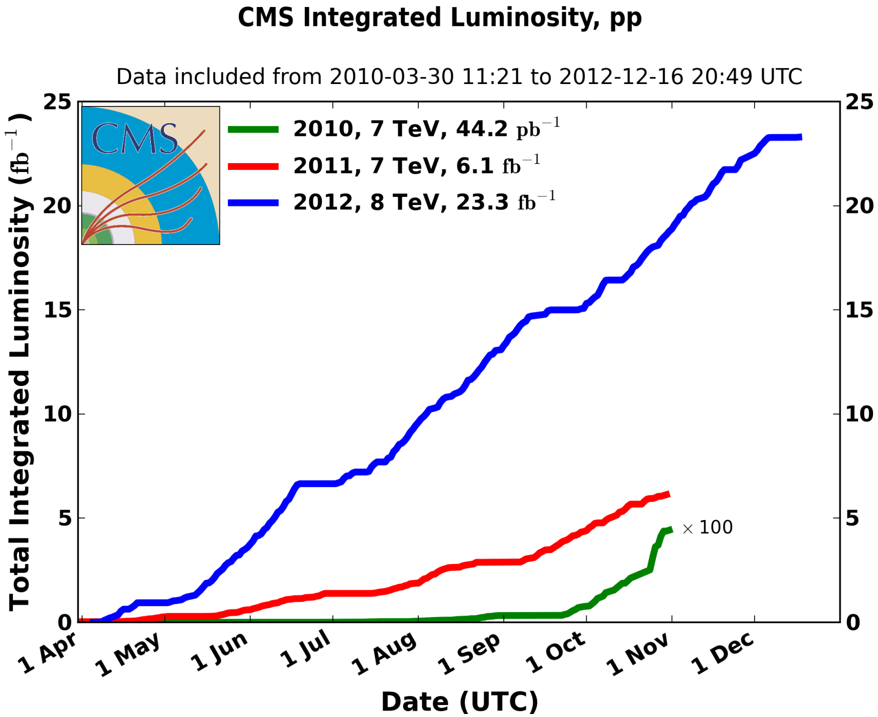
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL
76k scintillating
PbWO4 crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m2
~137k ch
Foward Cal
Steel + quartz
Fibers 2~k ch
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm2)
~ 1 m2 ~66M ch
•Si Strips (80-180 μm)
~200 m2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

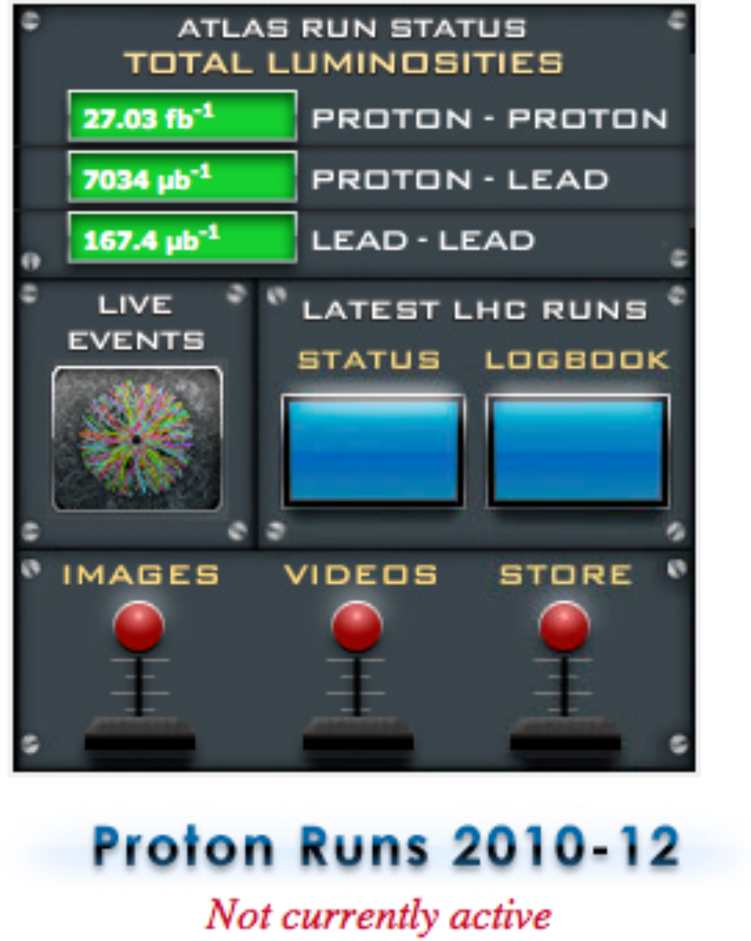
ATLAS and CMS

CMS is 30% heavier than the Eiffel Tour

Cibrán Santamarina
Universidade de Santiago de Compostela

Data taking





Highest luminosity = $7.73 \cdot 10^{33}$ cm^{-2}s^{-1}

Total Collisions = $1.80 \cdot 10^{15}$ = 1 800 000 000 000 000

Recorded luminosity = 27.03 fb^{-1}

Cibrán Santamarina
Universidade de Santiago de Compostela

Quiz

- Assuming they exist.
- How many SM Higgs has the LHC produced in ATLAS and CMS?

Cibrán Santamarina
Universidade de Santiago de Compostela

Quiz

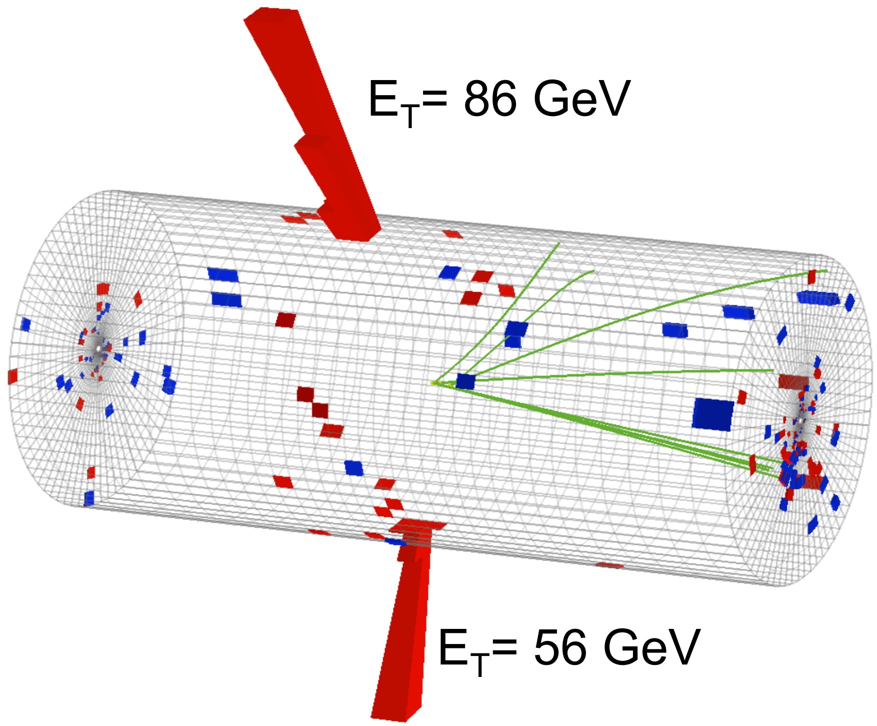
- Assuming they exist.
- How many SM Higgs has the LHC produced in ATLAS and CMS?

$$17 \text{ pb} \times 25 \text{ fb}^{-1} = 17 \times 25000 = 425000$$

Approximate!! (the x-section is not the same at 7 and 8 TeV)

$H \rightarrow \gamma\gamma$

- Tiny branching fraction (10^{-4})
- Simple and rare signature:
  - isolated high p_t photons
  - mass narrow peak
- Di-photon mass resolution: **excellent performance of EM calorimeter.**
  - *In situ* calibration from $\pi^0 \rightarrow \gamma\gamma$, $E_{e'}$ p_e, $Z \rightarrow e^- e^+$

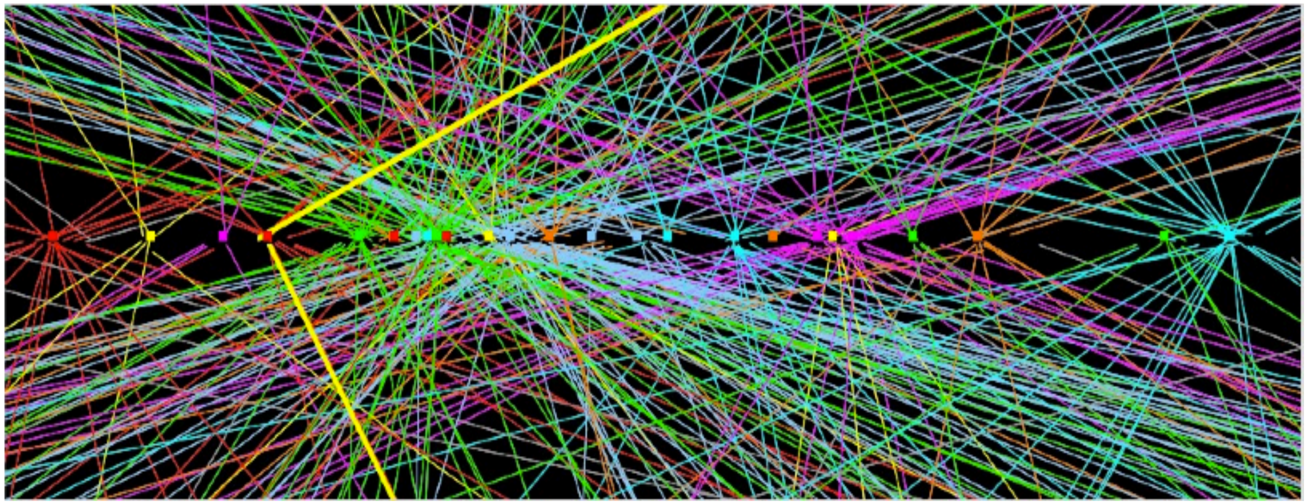


- Resolution given by:

$$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$$

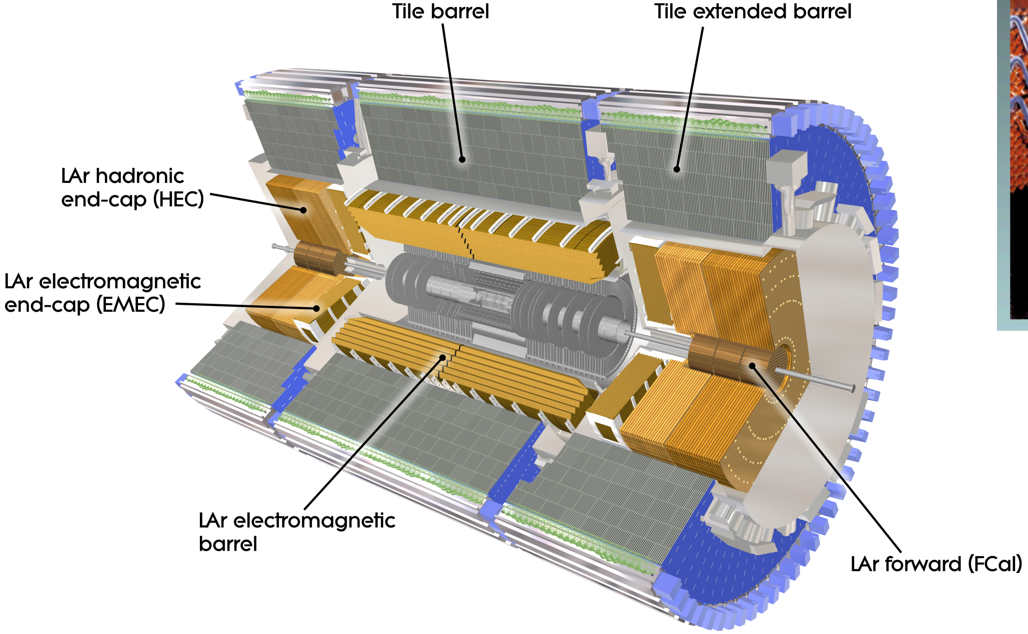
α=opening angle of the two photons

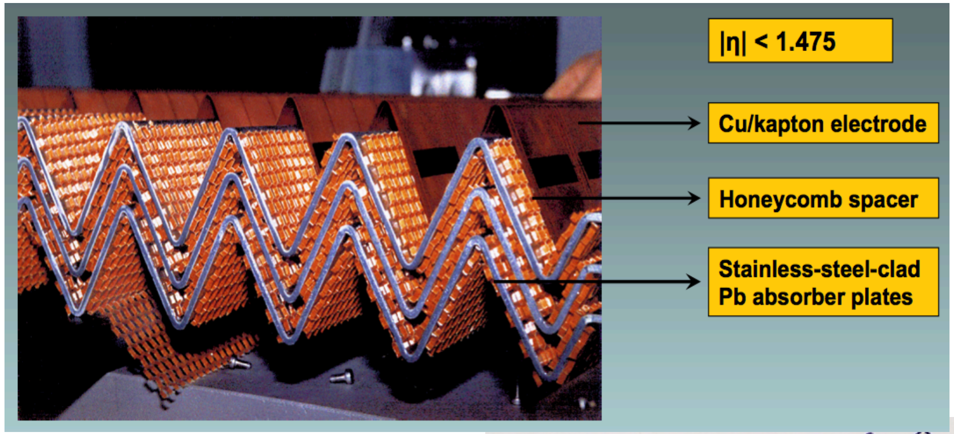
- Pile-up: big enemy of resolution

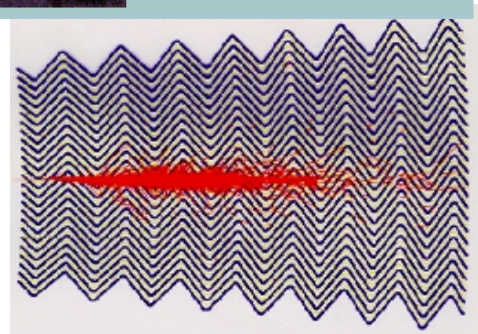


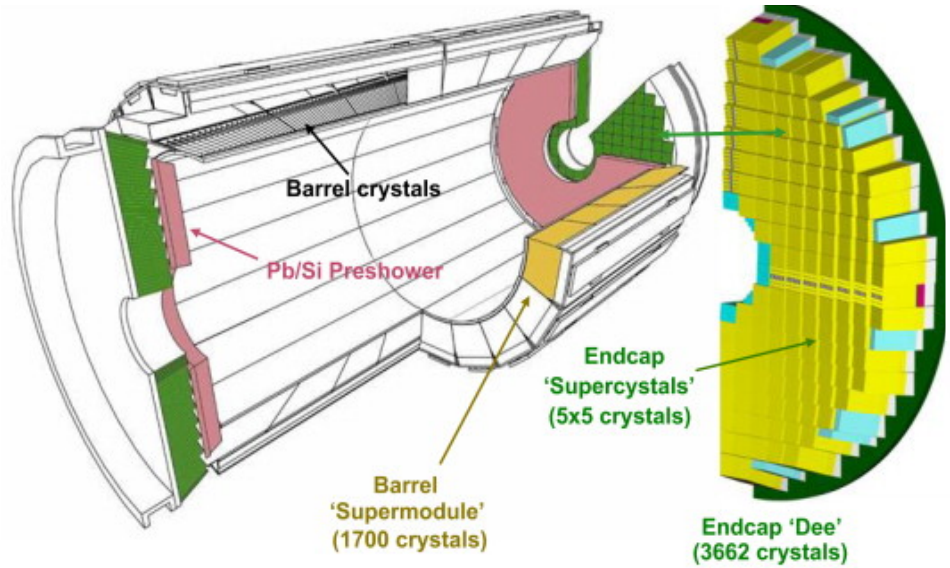
Cibrán Santamarina
Universidade de Santiago de Compostela

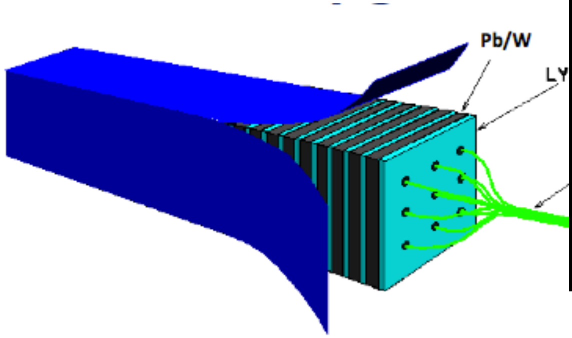
Calorimeters

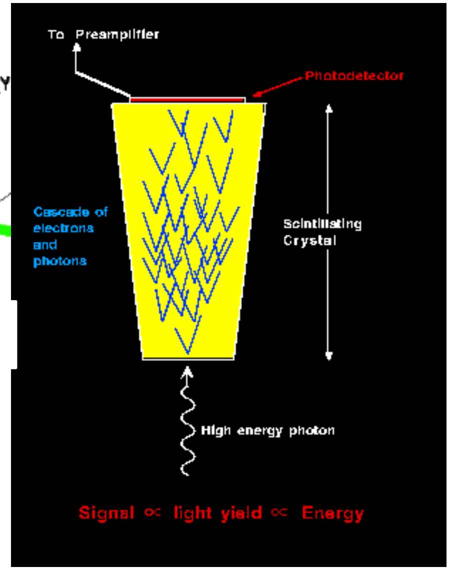






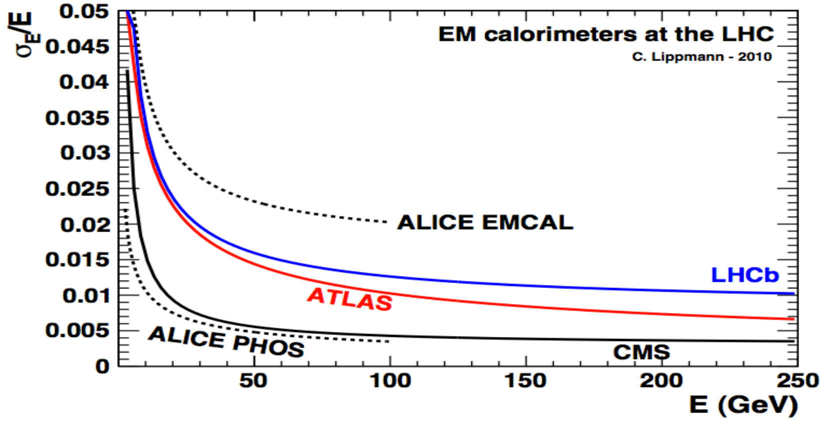


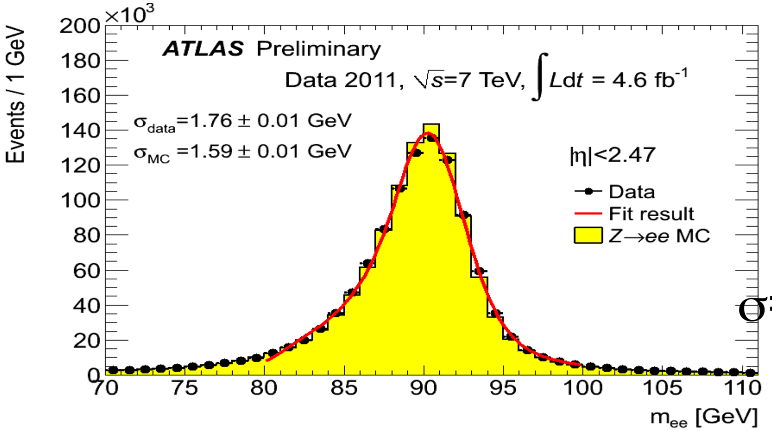




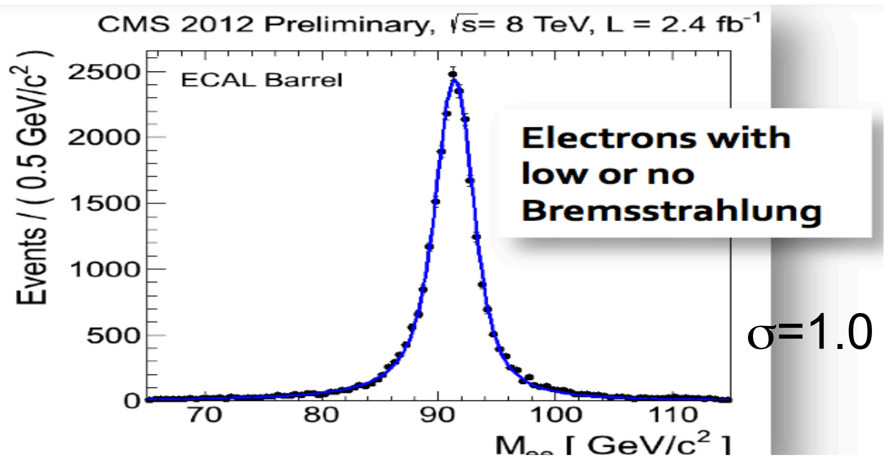
$H \rightarrow \gamma\gamma$

- ATLAS advantage:
  - Calorimeter fine first sampling allows pointing to primary vertex.
- CMS advantage:
  - Better resolution.
- Resolution not affected by pile-up.
- Energy Scale optimized with MC.

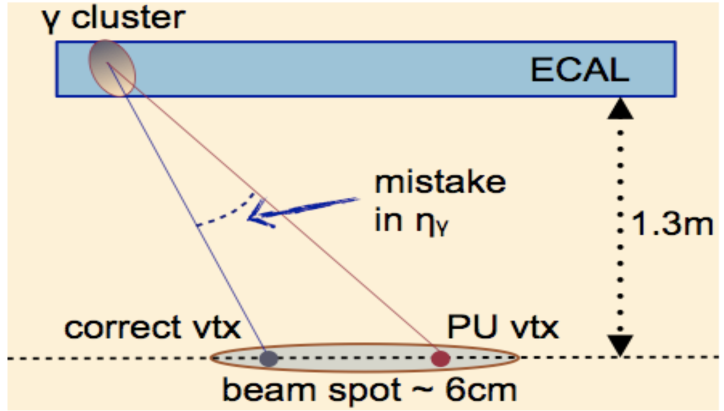


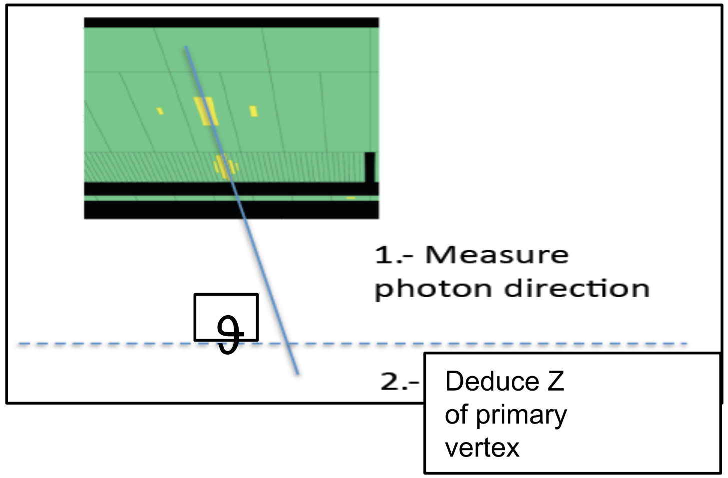


σ=1.76 GeV



σ=1.0 GeV





Quiz

- The largest inelastic process in the LHC is di-jet production.
- Jets contain numerous π^0.
- What is, with 98.8% BR, the main decay mode of this particle?

Cibrán Santamarina
Universidade de Santiago de Compostela

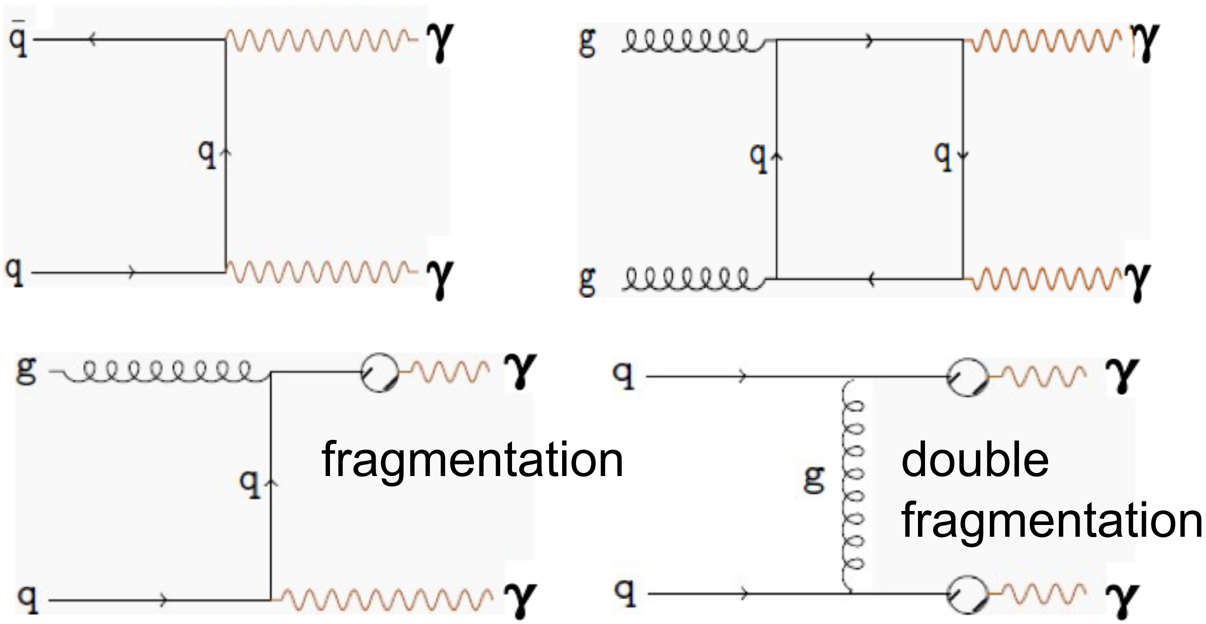
Quiz

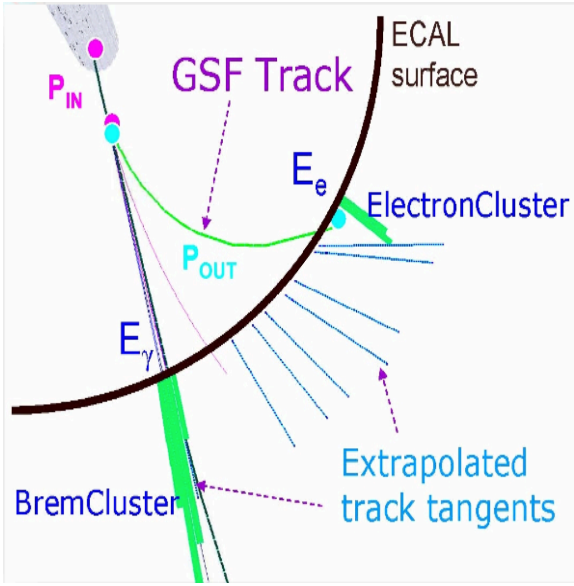
- The largest inelastic process in the LHC is di-jet production.
- Jets contain numerous π^0.
- What is, with 98.8% BR, the main decay mode of this particle?

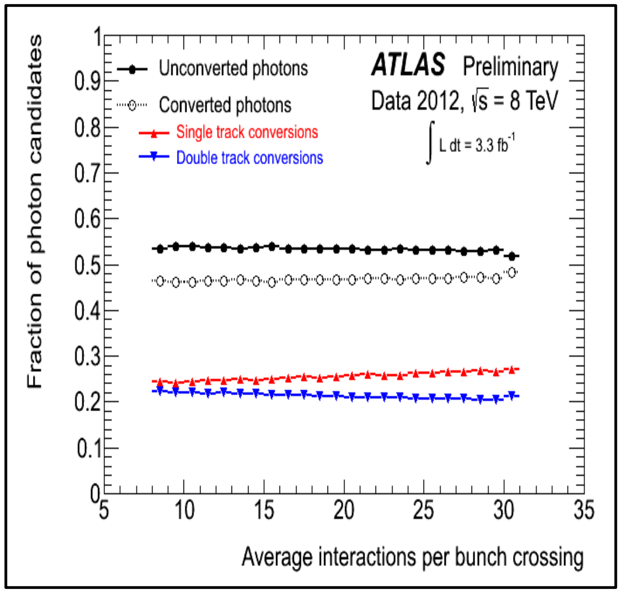
$$\pi^0 \rightarrow \gamma\gamma$$

$H \rightarrow \gamma\gamma$

- σ x BR ~ 50 fb (m_H ~ 126 GeV)
- Expected ~170 signal events on 6300 background.
- Background:
  - Continuous
  - Prompt QCD photons
  - Fake jets (typically 1 jet out of some thousand fakes a photon)
- Selection:
  - high p_T for γ candidates.
  - Photon ID:
    - categories based on η_γ and **conversion probability**.
  - Isolation (corrected for pileup contamination)
  - EM cluster shape: to reject $\pi^0 \rightarrow \gamma\gamma$
  - Electron veto:
    - No associated track.

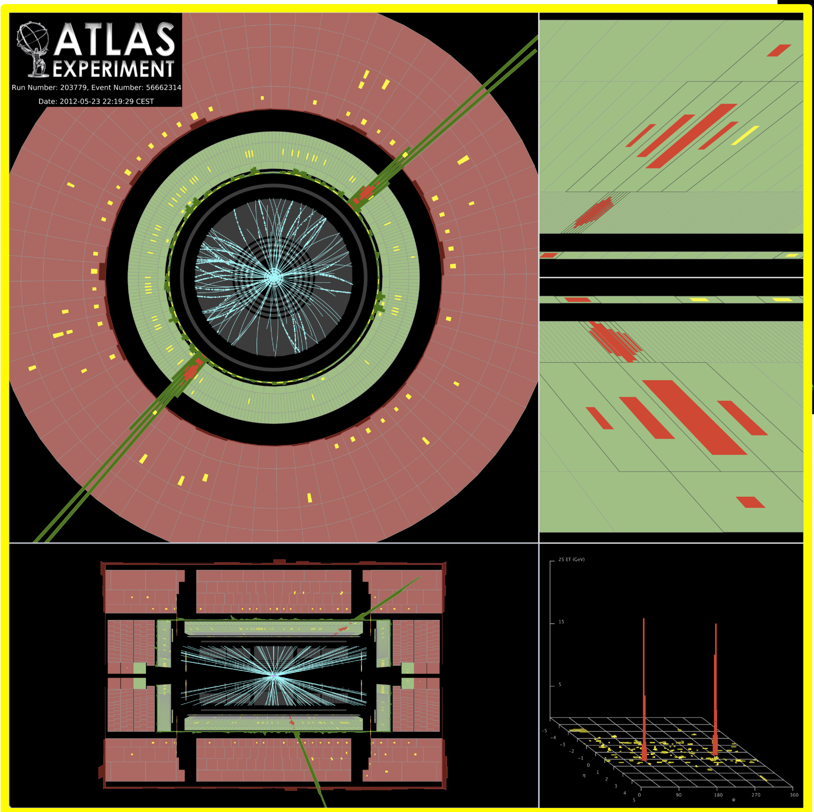


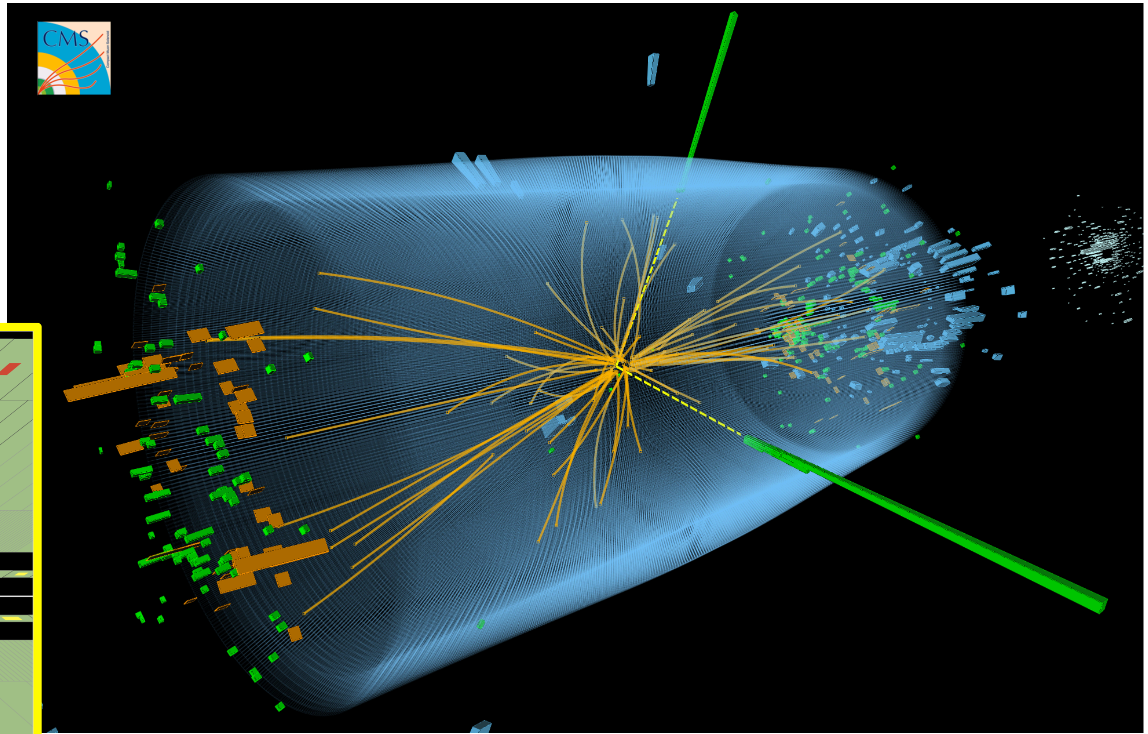




Cibrán Santamarina
Universidade de Santiago de Compostela

H → γγ candidates





Cibrán Santamarina
Universidade de Santiago de Compostela

H → γγ

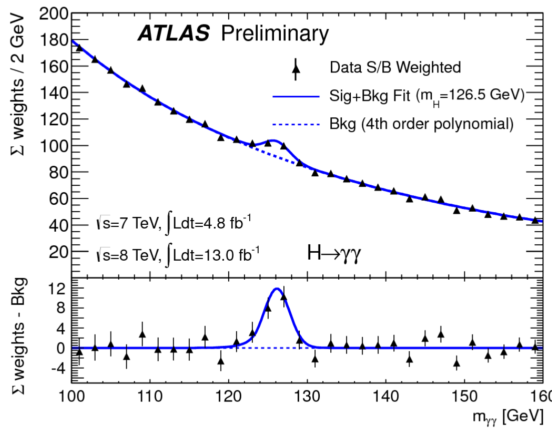
- The analysis is sub-divided into mutually exclusive categories with different mass resolutions and signal-to-background ratios.
- Depends on the calorimeter region the photons are pointing into.
- The existence of converted photons.
- The photon p_T.
- The possibility of additional jets.
  - Sensitivity to VBF production.
- ATLAS: rectangular cuts.
- CMS: multi-variate methods.

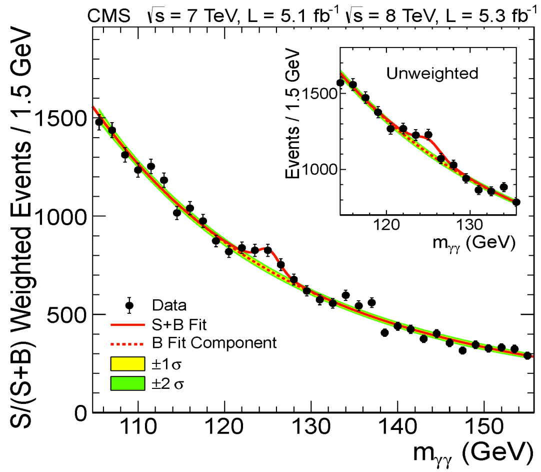
CMS July 2012

	Event categories	SM Higgs boson expected signal (m_H = 125 GeV) Events	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (events/GeV)
7 TeV, 5.1 fb^{-1}	BDT 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	BDT 1	16.3	88%	6%	6%	–	1.26	1.08	37.5 ± 1.3
	BDT 2	21.5	92%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	BDT 3	32.8	92%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	72%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV, 5.3 fb^{-1}	BDT 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	BDT 1	21.0	87%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	BDT 2	30.2	92%	4%	4%	–	1.94	1.55	115.2 ± 2.3
	BDT 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

ATLAS Dec 2012

$\sqrt{s}$ Category	8 TeV N_D	N_S	$gg \to H$ [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]	FWHM [GeV]
Unconv. central, low p_{Tt}	6797	32	93	4.2	1.4	0.9	0.2	3.45
Unconv. central, high p_{Tt}	319	4.7	76	15.2	3.9	2.9	1.7	3.22
Unconv. rest, low p_{Tt}	26802	69	93	4.2	1.7	1.1	0.2	3.75
Unconv. rest, high p_{Tt}	1538	9.7	76	15.1	4.5	3.3	1.2	3.59
Conv. central, low p_{Tt}	4480	21	93	4.2	1.4	0.9	0.2	3.86
Conv. central, high p_{Tt}	199	3.1	77	14.5	4.1	2.8	1.7	3.51
Conv. rest, low p_{Tt}	24107	60	93	4.1	1.7	1.1	0.2	4.32
Conv. rest, high p_{Tt}	1324	8.3	75	15.1	4.9	3.4	1.3	4.00
Conv. transition	10891	28	90	5.6	2.3	1.5	0.3	5.57
High Mass two-jet	345	7.6	31	68.2	0.3	0.2	0.1	3.65
Low Mass two-jet	477	4.7	60	5.1	20.7	12.1	1.6	3.45
One-lepton	151	2.0	3.2	0.4	62.5	15.8	18.0	3.85
All categories (inclusive)	77430	249	88	7.4	2.8	1.6	0.5	3.87

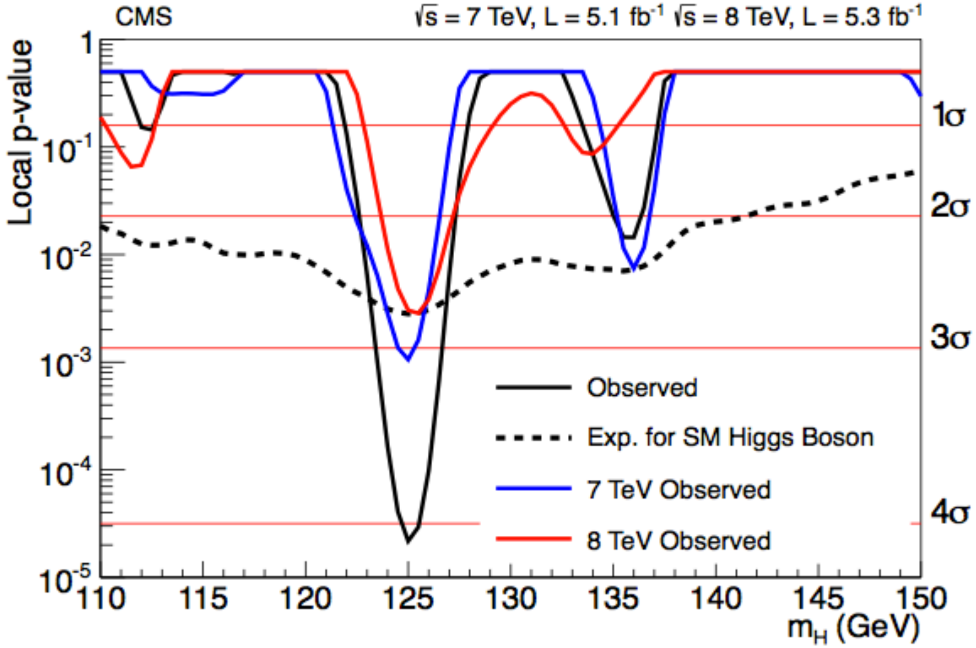


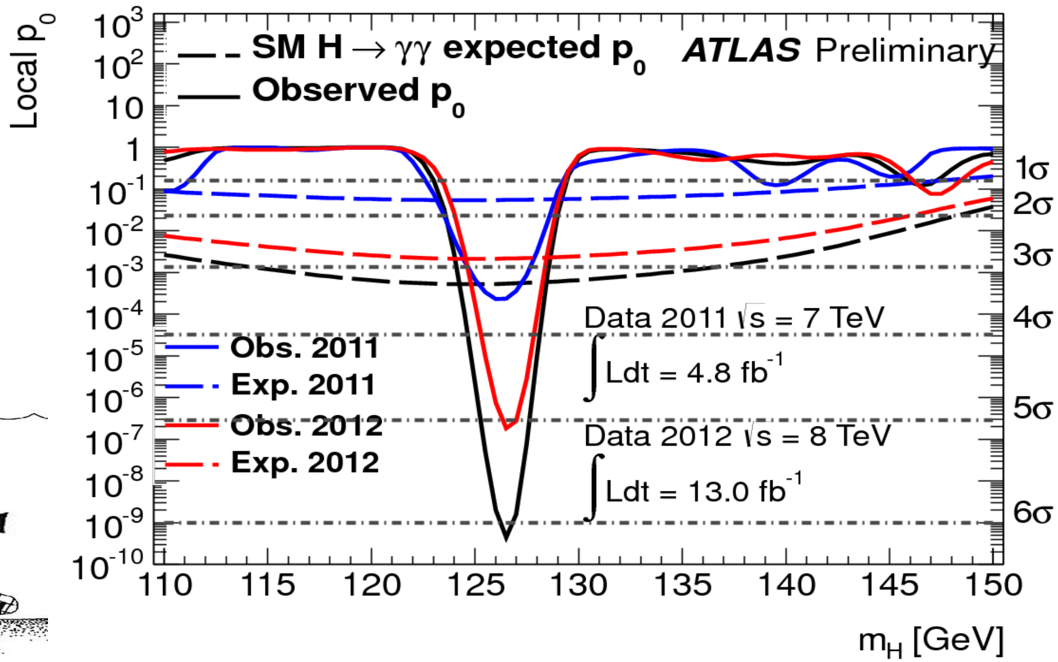


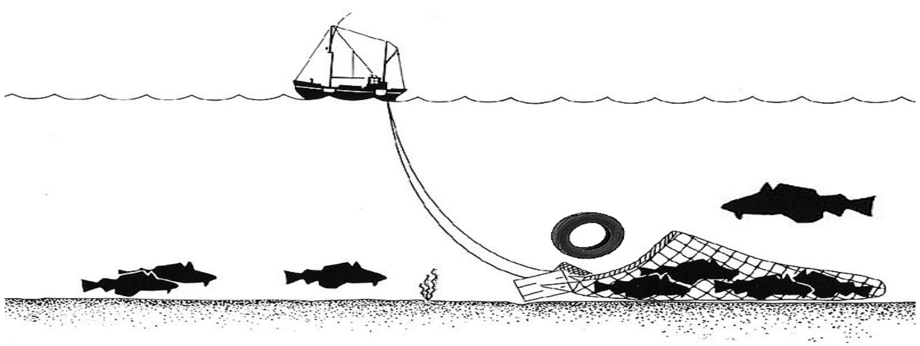
Cibrán Santamarina
Universidade de Santiago de Compostela

Significance of H → γγ

- The p-value is the probability that a background-only scenario produces a fluctuation that reproduces the data.
- The 2011-2012 (up to July) ATLAS and CMS data produce a clear evidence of a decay into two photons: 6.1 σ and 4.1 σ.
- With the look elsewhere effect these significances reduce to 5.6 and 3.2 σ.
- This mode is enough to claim for a discovery (in ATLAS ☺).





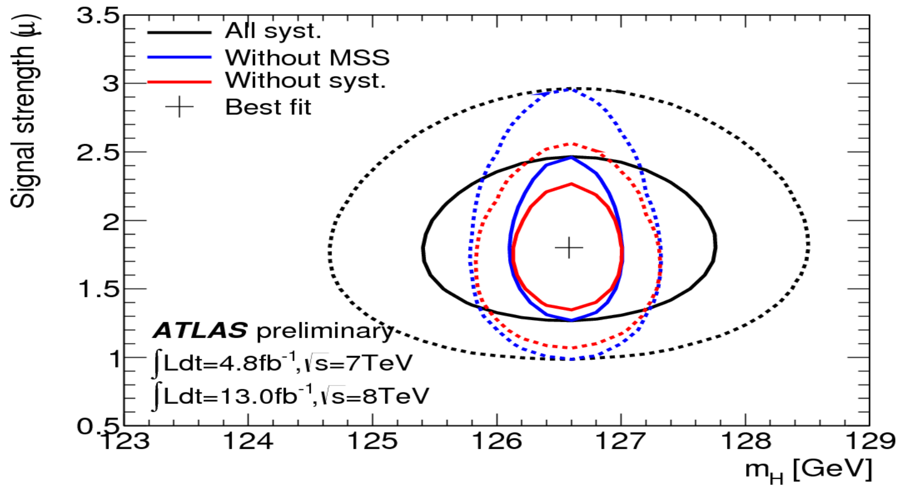


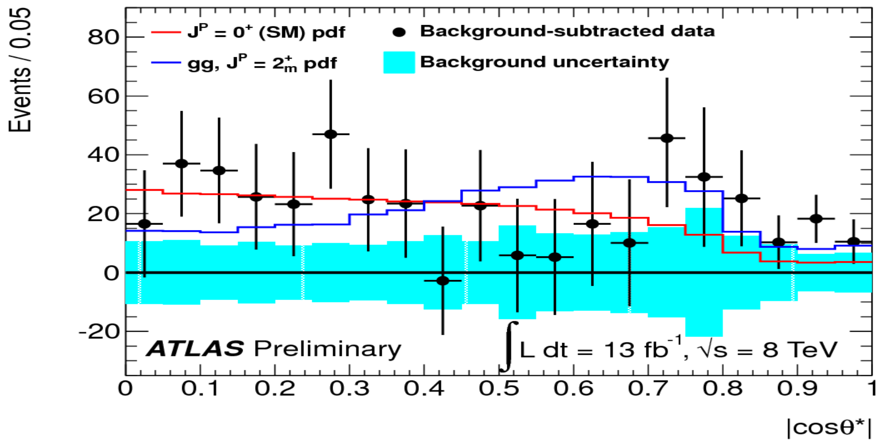
More on H → γγ

*"as we know, **there are known knowns**; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns -- the ones we don't know we don't know"*

D. Rumsfeld

- The known-knowns:
- ATLAS and CMS both measure an excess of events to SM:
  - Latest ATLAS: 1.80 ± 0.30 (stat) +0.21 (syst) +0.20 (theory) x the SM prediction.
- We have a mass measurement (ATLAS):
- 126.6 ± 0.3 (stat) ± 0.7 (syst) GeV
- And we have a spin study:
  - This mode excludes spin-1 states.
  - Minimal graviton-like spin-2 state is discarded by ATLAS.





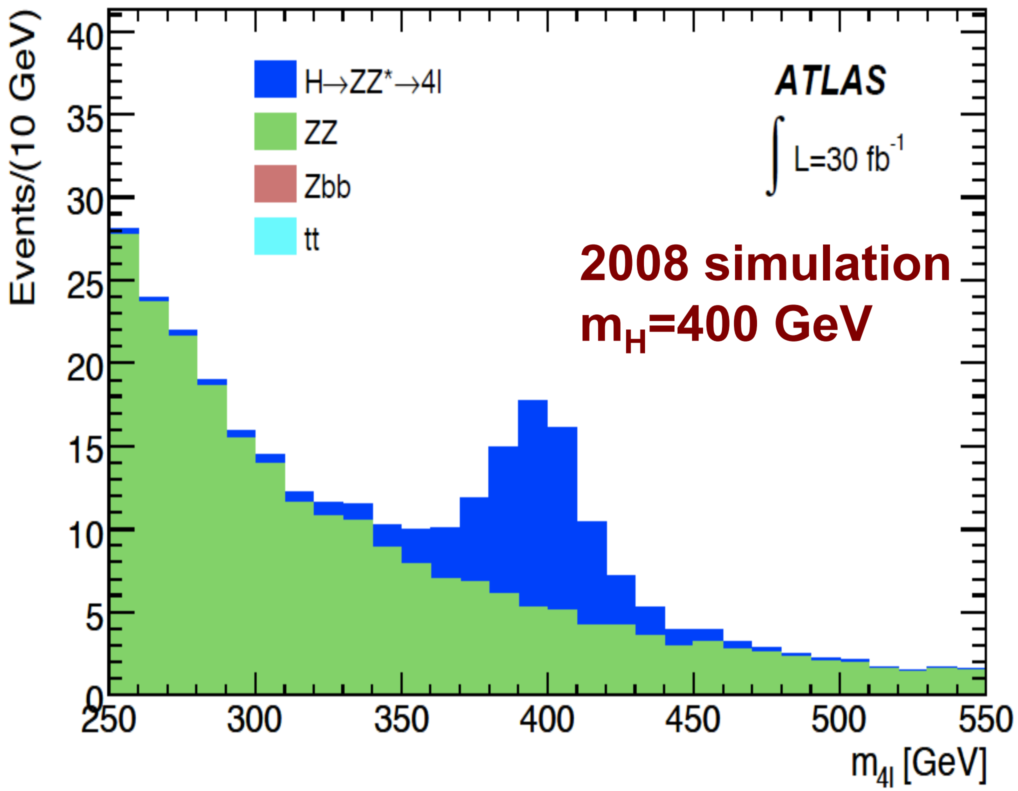
$H \rightarrow ZZ^*$

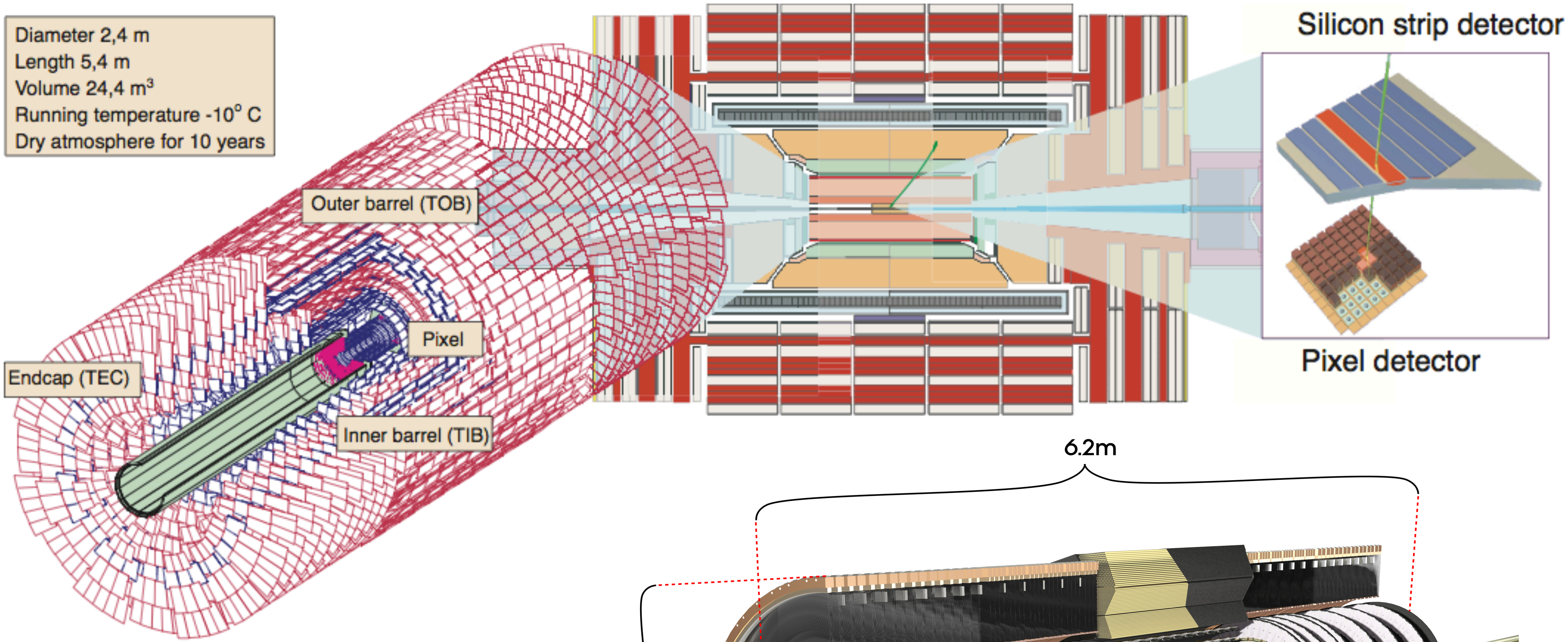
- One off-shell Z.
- Lepton decay of Z required.
- SM predicts tiny rate at ~125 GeV.
- Golden mode at higher mass.
- Mass: fully reconstructed events should cluster in a (narrow) peak:
  - Pure: S/B~1.
- 4 leptons:
  - High p_T.
  - m_{12} within Z mass range.
  - High m_{34} mass.
- Backgrounds:
  - ZZ^*: irreducible
  - low-mass $m_H < 2m_Z$:
    - Zbb, Z+jets, tt with 2 leptons from b-jets or q-jets → l.
    - Suppressed: isolation and impact parameter cuts on softest leptons.

$$H \rightarrow ZZ \rightarrow e^+e^-e^+e^-$$

$$H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$$

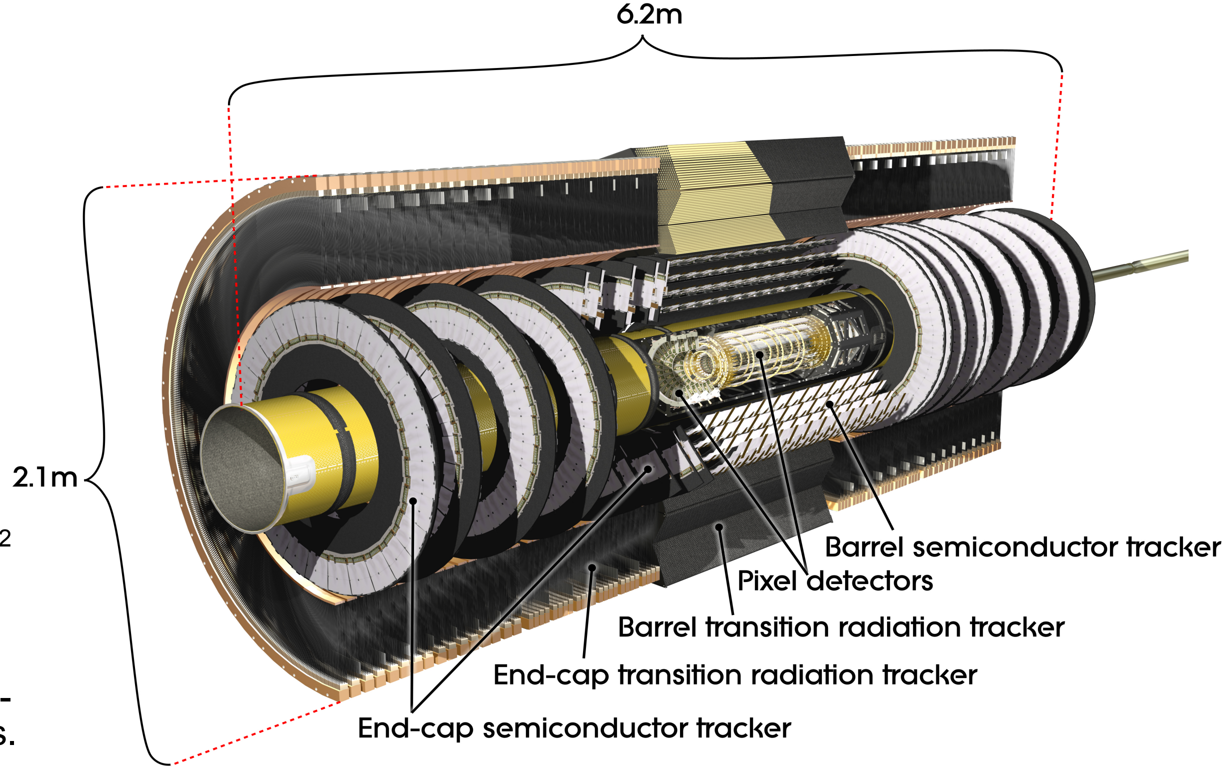
$$H \rightarrow ZZ \rightarrow \mu^+\mu^-e^+e^-$$





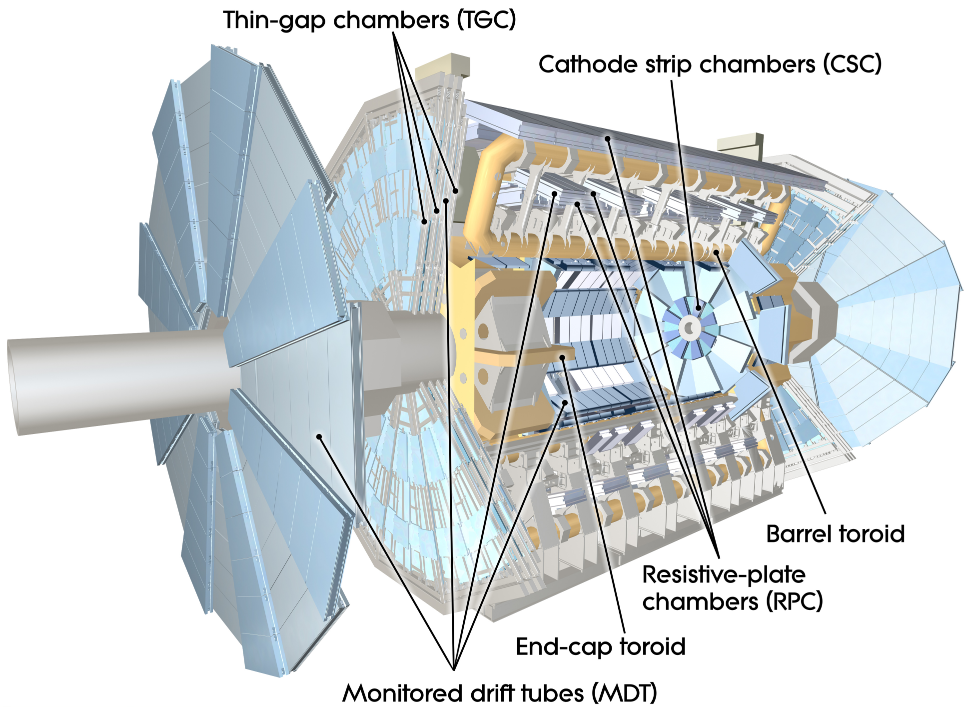
CMS:
- 25000 silicon strip sensors.
- Surface of 210 m^2.
- 75000 APV chips.
- 9600000 channels.

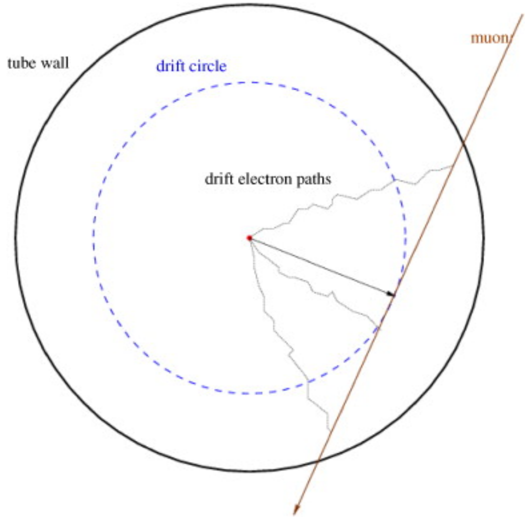
ATLAS:
- Transition Radiation Tracker:353 536 4mm-diameter Kapton straws filled with $Xe/CO_2/O_2$ gas for e ID.
- Semi-Conductor Tracker: 4 barrel layers, 9 disks per end-cap 4088 modules, 6.3M channels.
- Pixel detector:3 barrel layers, 2x3-layer end-cap disks 1744 pixel modules, 80M channels.

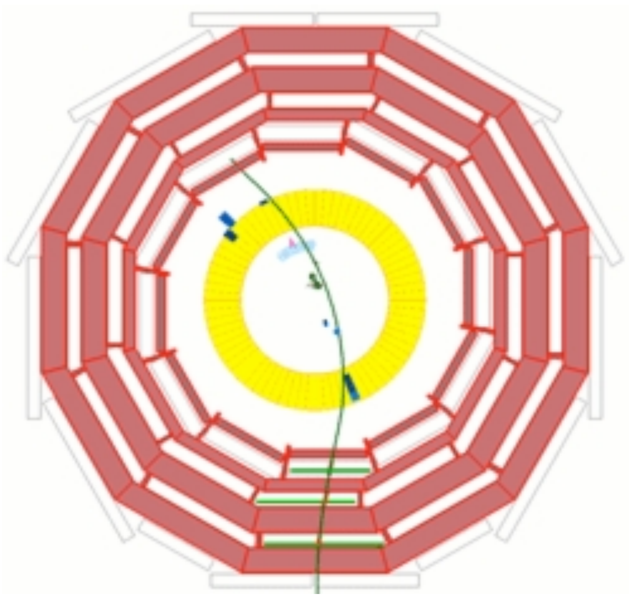


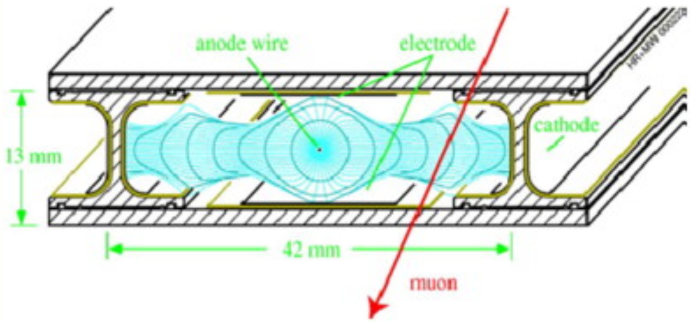
μ detectors

- Chambers measuring muon tracks with high spatial precision. MDTs
- Triggering chambers with accurate time-resolution. RPCs and CSCs.
- ATLAS: Magnetic field provided by three toroidal magnets.
- CMS: Solenoidal field with yoke return.





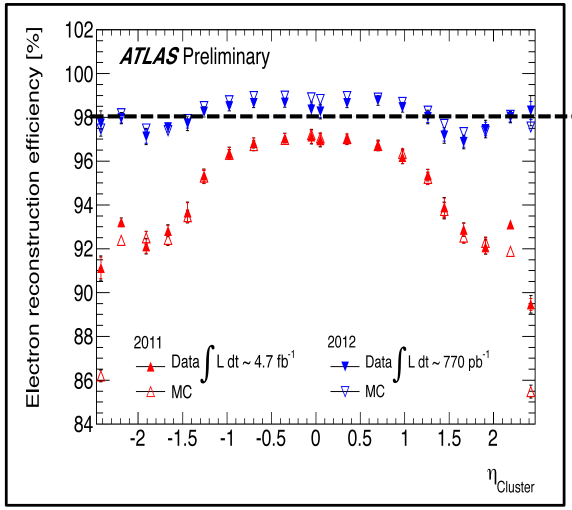


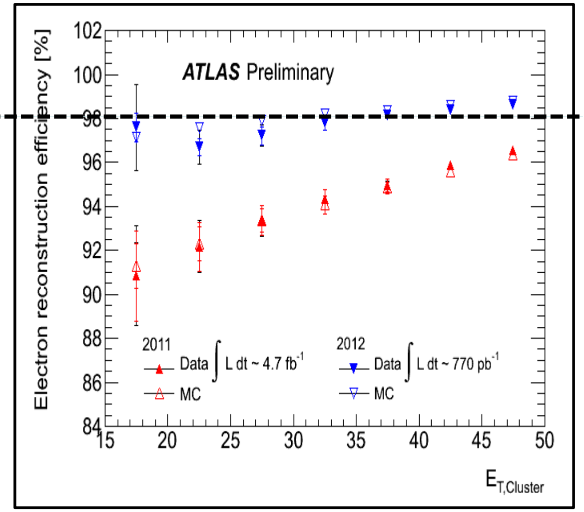


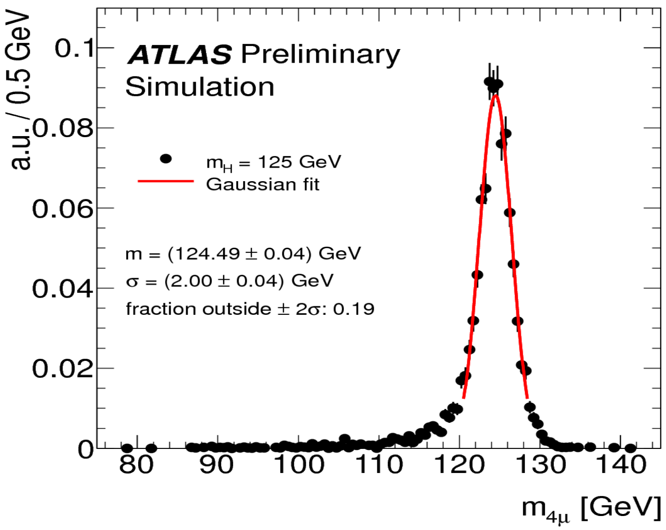
l^+l^- reco performance

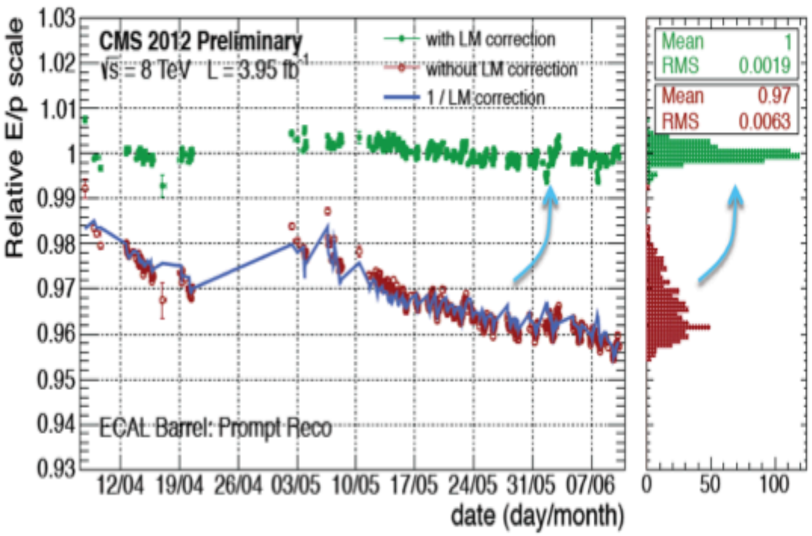
Crucial experimental aspects:

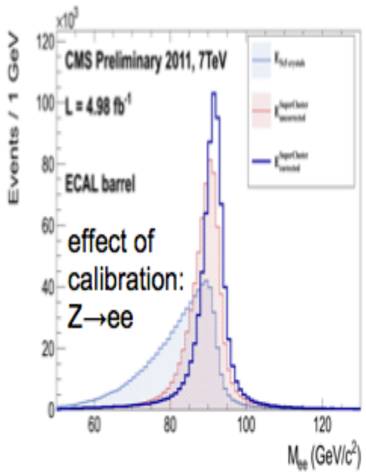
- High lepton reconstruction and identification efficiency down to lowest p_T
- Good lepton energy/ momentum resolution
- Good control of reducible backgrounds (Zbb, Z+jets, tt) in low-mass region.
- Recovery of radiated photons.





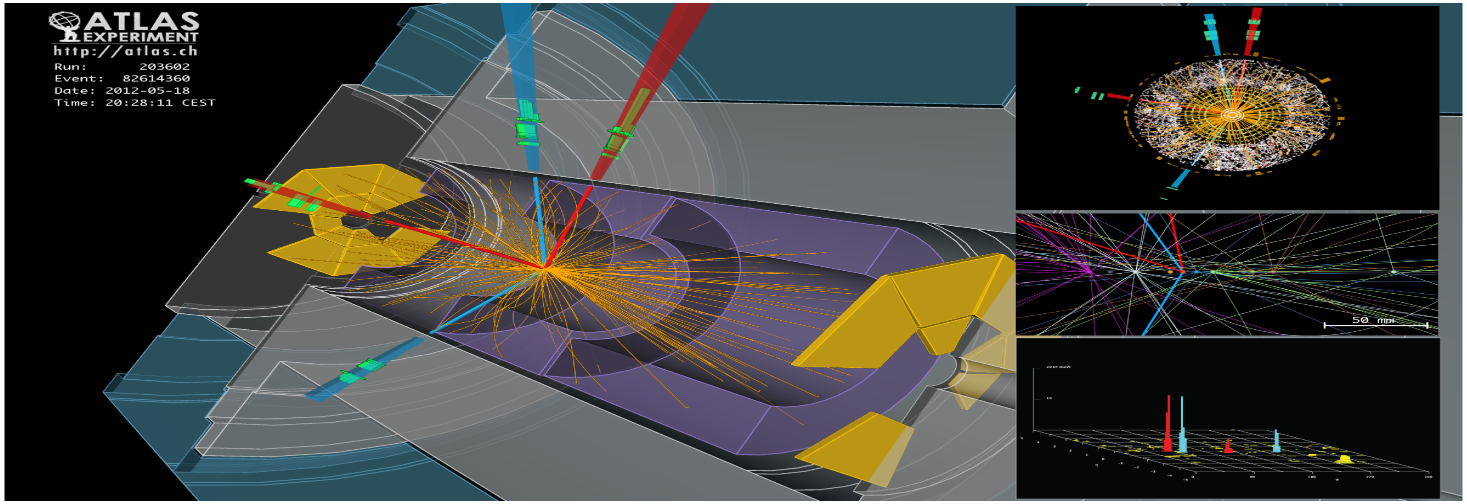


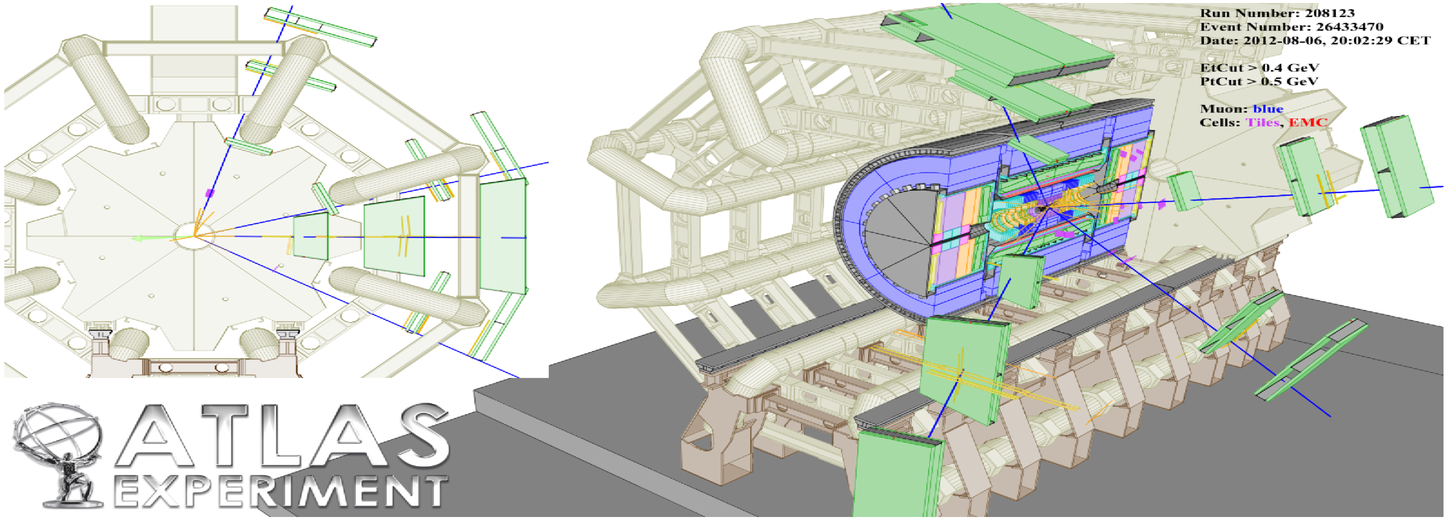




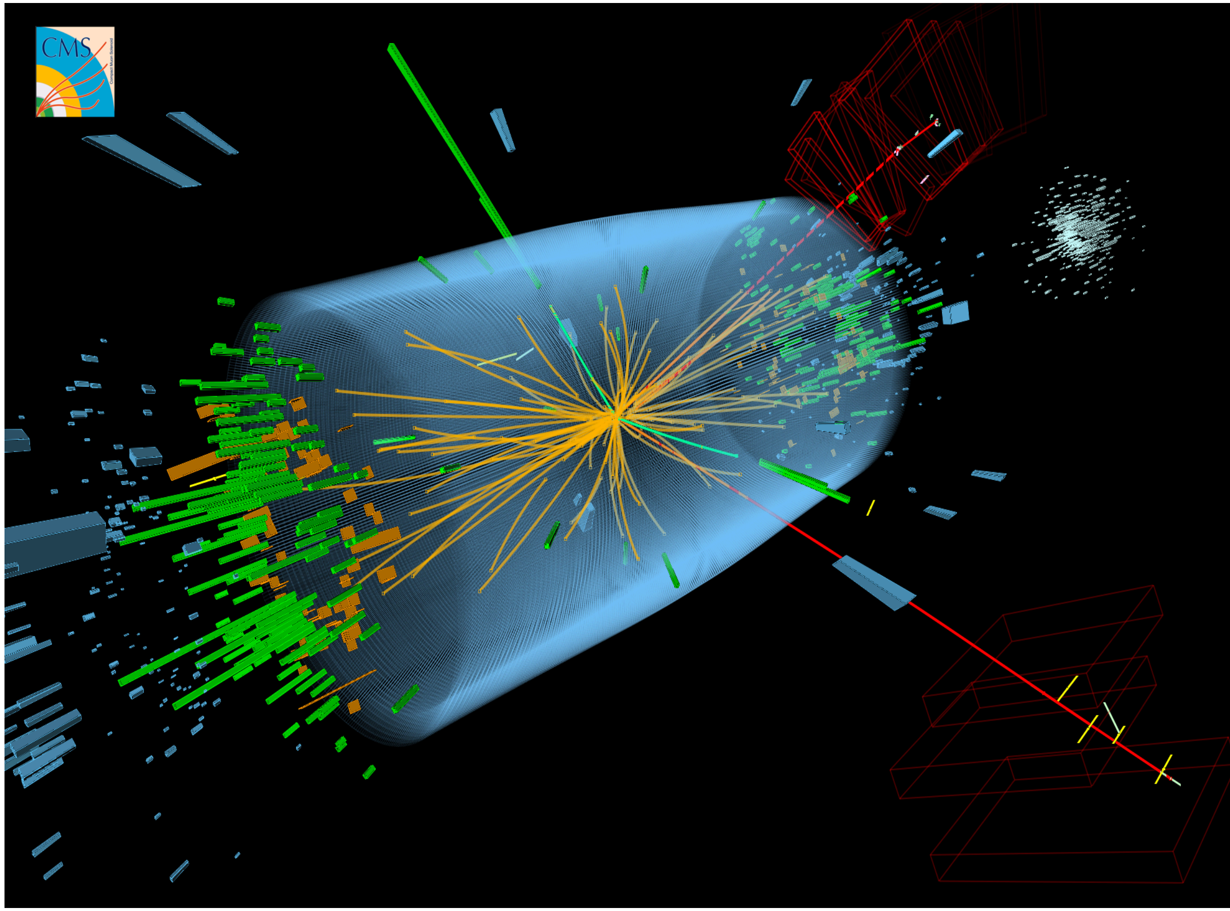
Cibrán Santamarina
Universidade de Santiago de Compostela

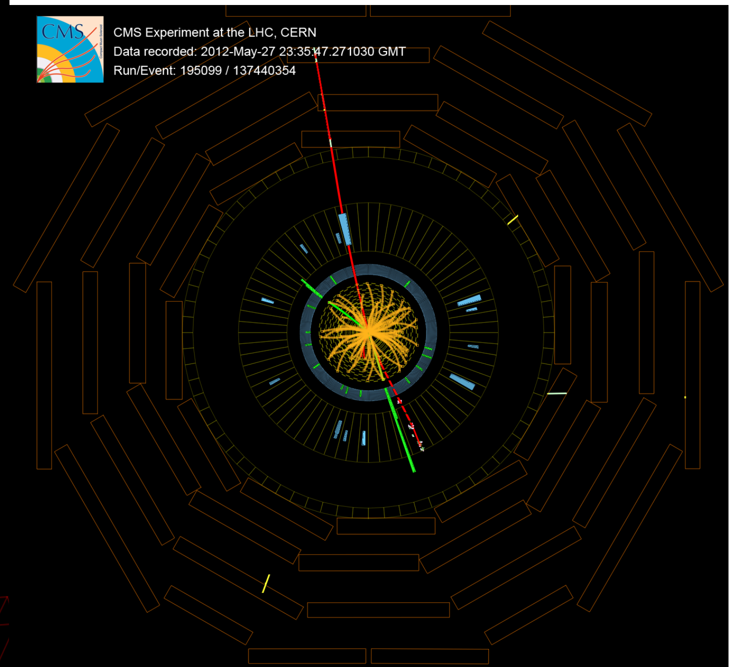
H → ZZ* candidates





H → ZZ* candidates





USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
Cibrán Santamarina
Universidade de Santiago de Compostela

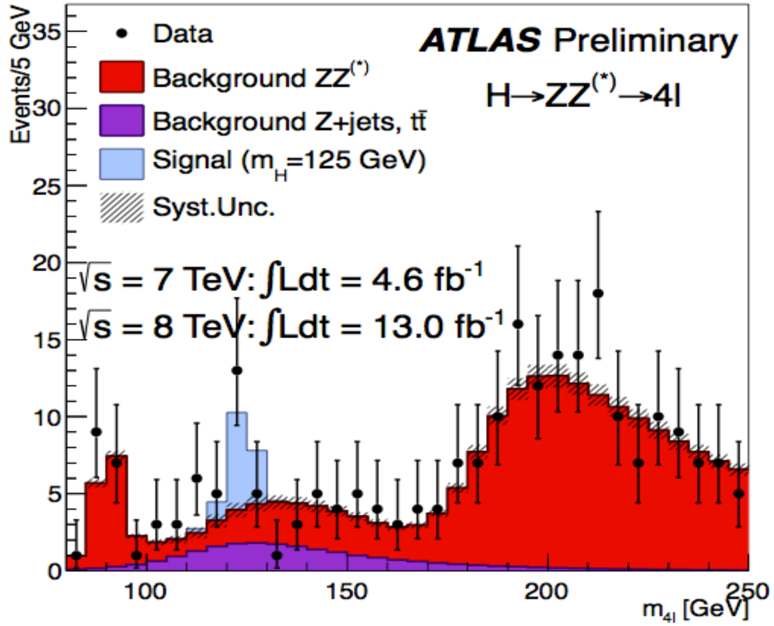
$H \rightarrow ZZ^*$ results

ATLAS

- 4.6 fb^{-1} $\sqrt{s}$=7 TeV and 13.0 fb^{-1} $\sqrt{s}$=8 TeV.
- Maximum combined signal with p0 value of 0.0021% (4.1σ) at m_H =123.5 GeV.
- Fitted m_H=123.5±0.9(stat)±0.3(syst) GeV.
- 9.9 ± 1.3 observed events.

CMS

- 5.1 fb^{-1} $\sqrt{s}$=7 TeV and 12.2 fb^{-1} $\sqrt{s}$= 8 TeV.
- Significance 4.5 σ at 126.2 GeV.
- Fitted m_H=126.2±0.6(stat)±0.2(syst) GeV

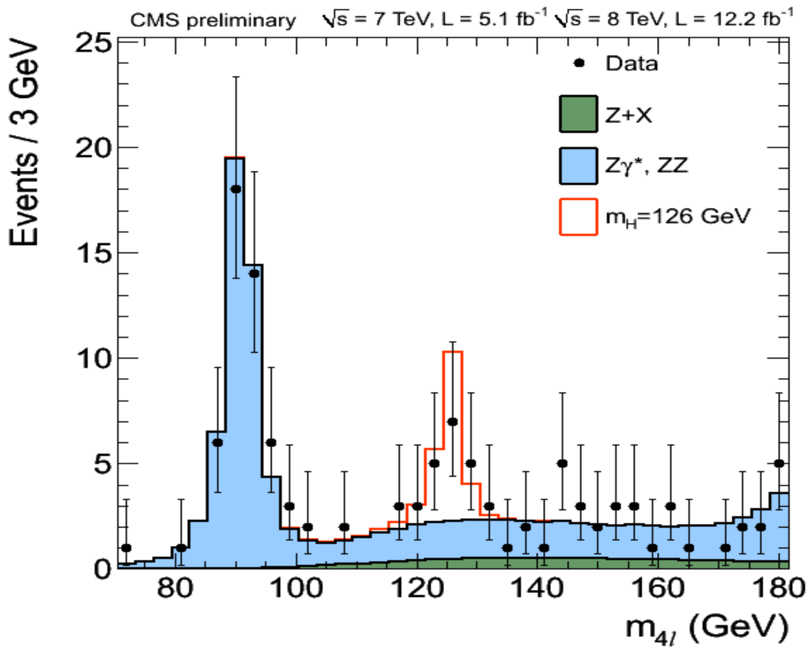


ATLAS Dec 2012

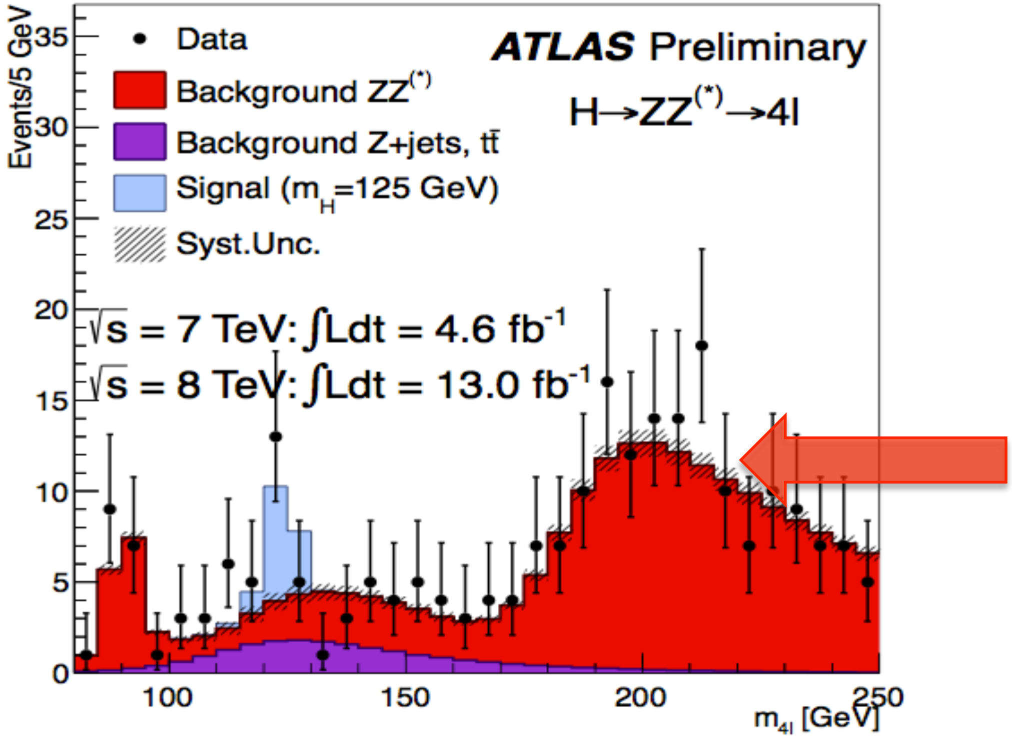
	Signal (m_H=125 GeV)	$ZZ^{(*)}$	Z + jets, $t\bar{t}$	Observed
	$\sqrt{s}$ = 8 TeV and $\sqrt{s}$ = 7 TeV			
4μ	4.0 ± 0.5	2.03 ± 0.09	0.36 ± 0.09	8
$2\mu 2e$	1.7 ± 0.2	0.70 ± 0.05	1.21 ± 0.18	2
$2e2\mu$	2.4 ± 0.3	1.02 ± 0.05	0.30 ± 0.07	4
$4e$	1.8 ± 0.3	0.94 ± 0.09	1.72 ± 0.23	4
total	9.9 ± 1.3	4.7 ± 0.3	3.6 ± 0.3	18

CMS Nov 2012

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	4.7 ±0.6	9.6 ±1.0	12.5 ±1.4	26.8 ±1.8
Z+ X	$3.4^{+3.0}_{-2.3}$	$1.6^{+1.2}_{-0.9}$	$5.6^{+5.4}_{-3.6}$	$10.6^{+5.3}_{-4.4}$
All backgrounds	$8.0^{+3.1}_{-2.3}$	$11.2^{+1.6}_{-1.4}$	$18.1^{+5.6}_{-3.8}$	$37.3^{+6.6}_{-4.7}$
m_H = 125 GeV	2.4 ±0.4	4.6 ±0.5	5.9 ±0.7	12.9 ±0.9
m_H = 126 GeV	2.7 ±0.4	5.1 ±0.6	6.6 ±0.8	14.4 ±1.1
Observed	12	16	19	47



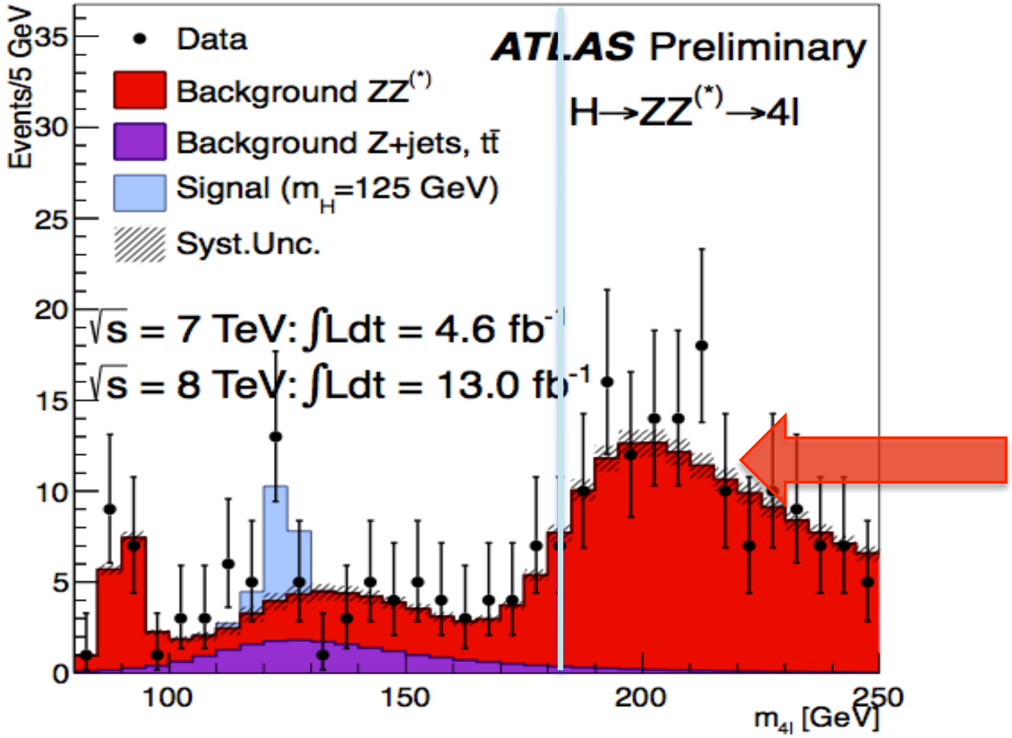
Quiz



Why does this background increase?

Cibrán Santamarina
Universidade de Santiago de Compostela

Quiz



Why does this background increase?

$m_Z = 91.1876$ GeV

$2 \times m_Z = 182.3752$ GeV

$\Gamma_Z = 2.4952$ GeV

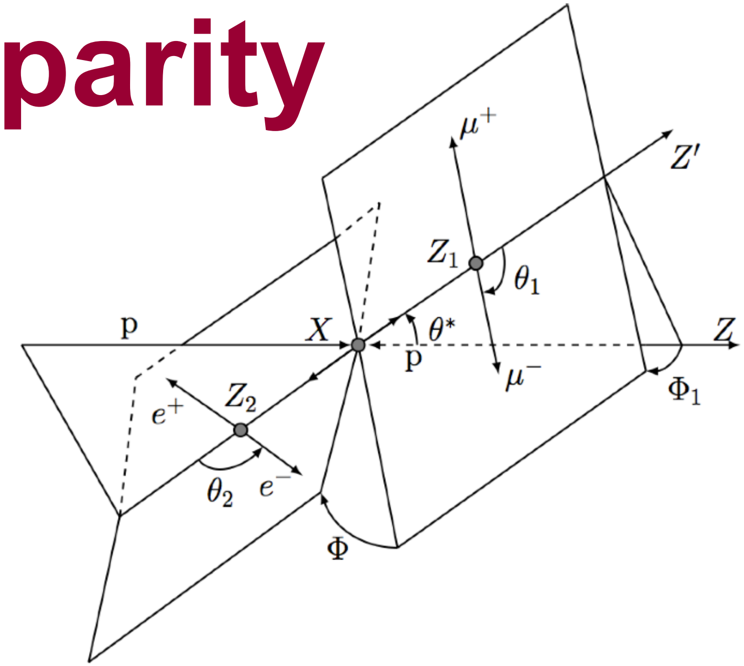
More H → ZZ* results

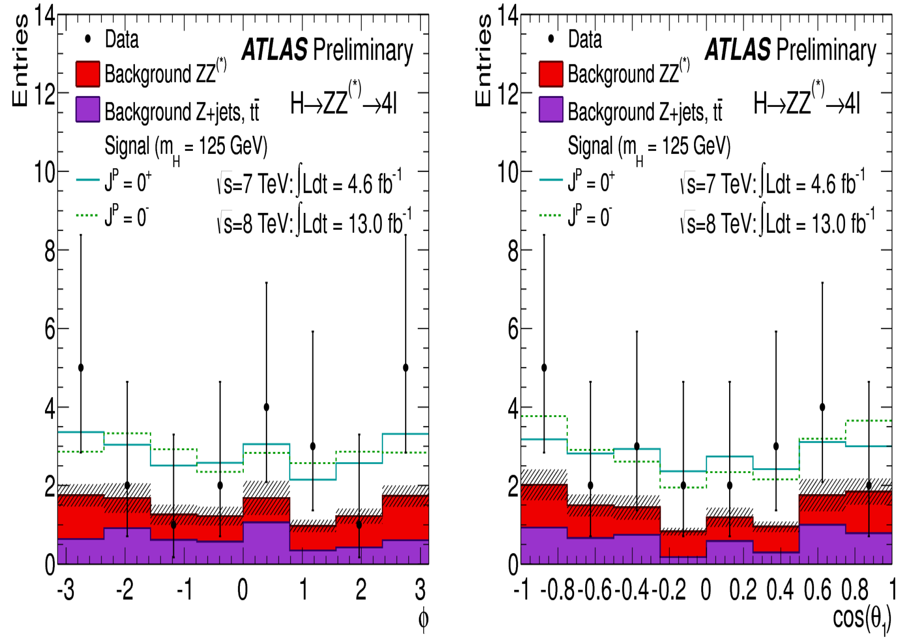
- CMS has searched for Z→ττ modes.
  – No candidates found.

Channel	$2\ell 2\tau$
ZZ background	19.0 ±2.3
Z+ X	20.4 ±6.2
All background expected	39.4 ±6.6
m_H = 125 GeV	–
m_H = 126 GeV	–
m_H = 200 GeV	5.6 ±0.6
m_H = 350 GeV	5.7 ±0.6
m_H = 500 GeV	2.8 ±0.3
m_H = 800 GeV	0.3 ±0.1
Observed	45

H → ZZ* spin-parity

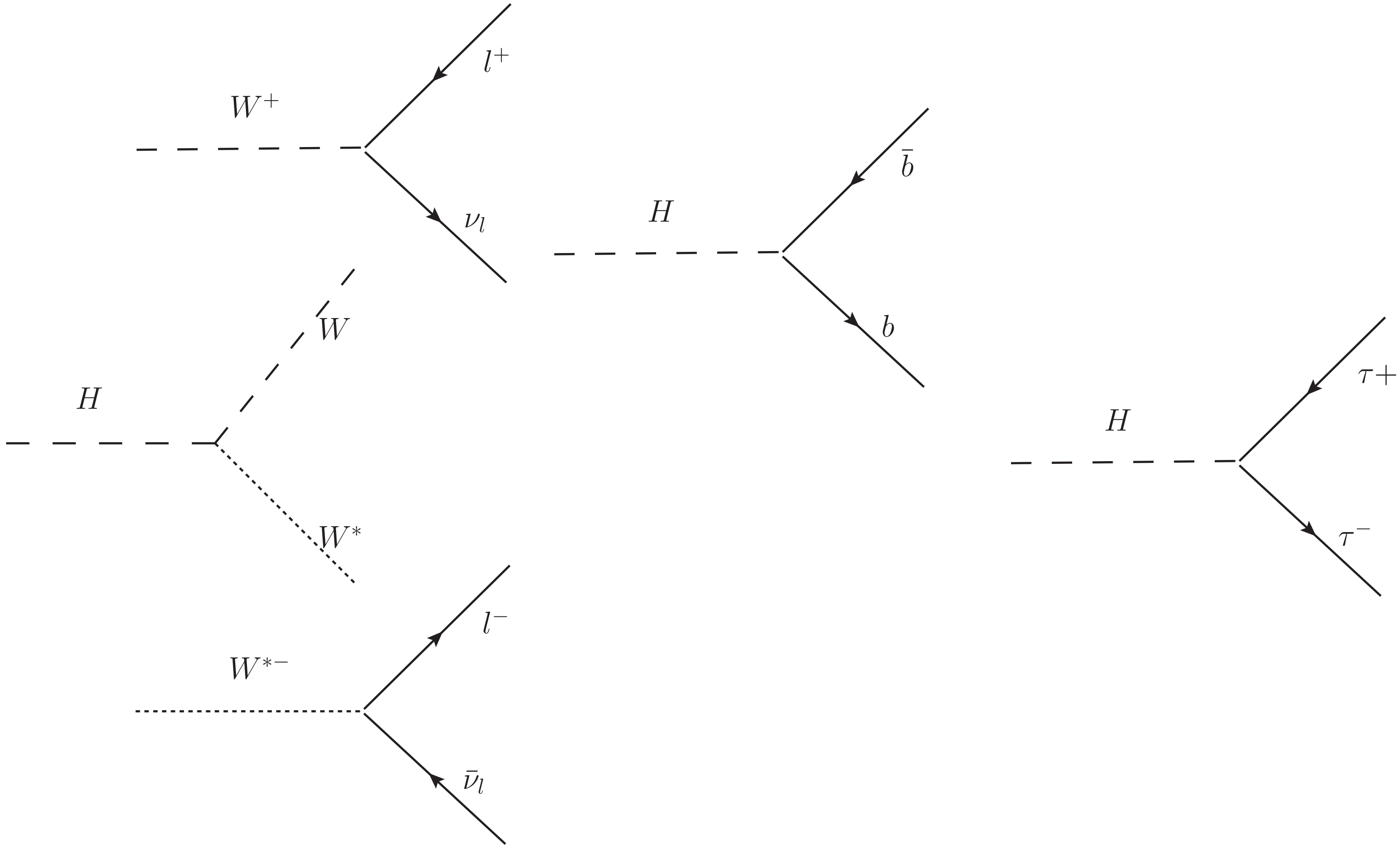
- Measured in lepton angular distributions:
  - θ$_1$ (θ$_2$): angle between negative lepton and Z$_1$ (Z$_2$) flight direction (Z rest frame).
  - Φ: angle between decay planes of 4 leptons in rest frame.
  - Φ$_1$: angle between decay plane of leading lepton pair and plane defined by Z$_1$ vector in 4-lepton rest frame and positive direction of parton axis.
  - θ*: production angle of the Z$_1$ defined in the four lepton rest frame.
- Mutli Variate anlysis.
- ATLAS:
  - (0^+) SM spin and parity remain the favored hypothesis.
  - 0^-, 2_m^+ and 2^- hypotheses excluded at (BDT): 98.9%, 84% and 97.1%.
- CMS:
  - SM hypothesis 0+ consistent with the observation.
  - Assuming observed boson has spin zero:
    - Data disfavor pseudoscalar hypothesis 0^- with a CLs value of 2.4%.
    - Fraction of a CP-violating contribution: f_{a3} = 0.00+0.31. Consistent with SM expectation.





Cibrán Santamarina
Universidade de Santiago de Compostela

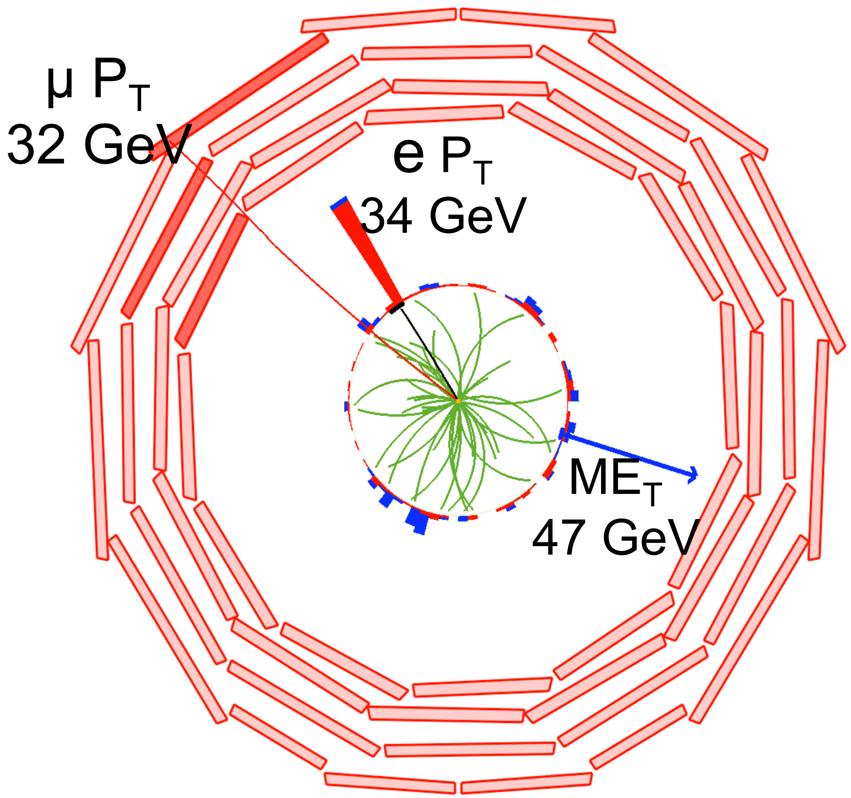
Other Modes



H→W*W→2l2ν

$$H \to WW \to e^{\mp}\nu_e\mu^{\pm}\nu_\mu$$
$$H \to WW \to e^{-}\bar{\nu}_e e^{+}\nu_e$$
$$H \to WW \to \mu^{-}\bar{\nu}_\mu\mu^{+}\nu_\mu$$

- In principle: most sensitive channel over ~ 125-180 GeV (σ ~ 200 fb).
- Challenging: 2ν:
  - No mass peak → "counting channel".
  - Importance of systematic effects.
- 2 isolated opposite-sign leptons, large E_T^{miss}.
- Analysis on jet multiplicities (0, 1, 2-jet bins).
- Backgr: WW, top, Z+jets, W+jets.
  - $m_{ll} \neq m_Z$, b-jet veto, …
  - Topological cuts against "irreducible" WW background:
  - p_{Tll}, m_{ll}, $\Delta\phi_{ll}$ (smaller for scalar Higgs), m_T (ll, E_T^{miss})

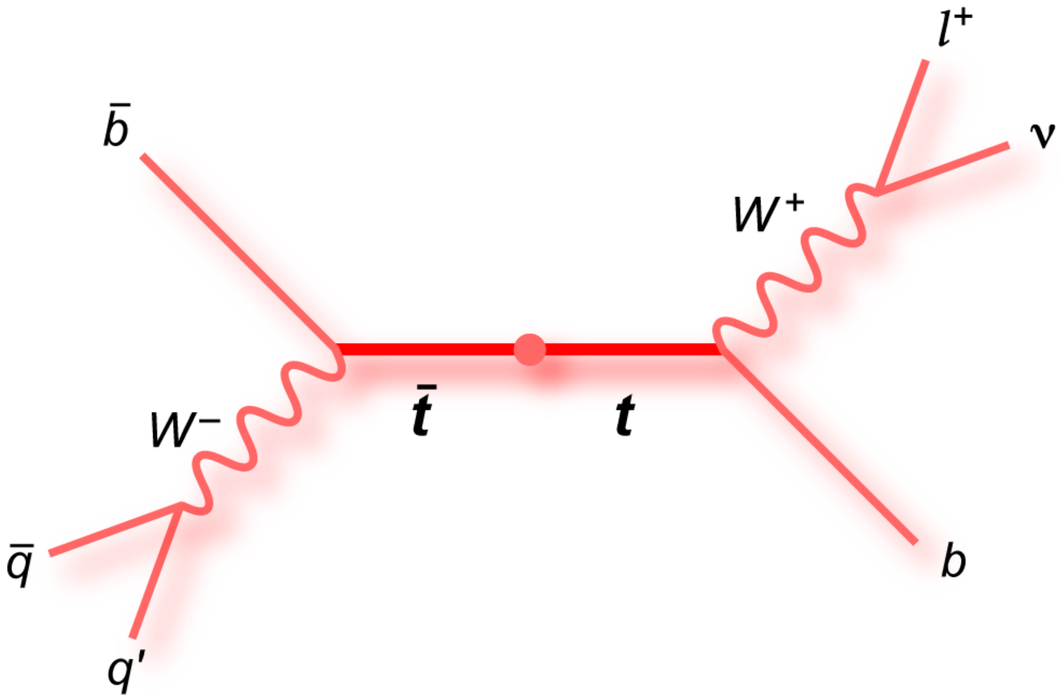


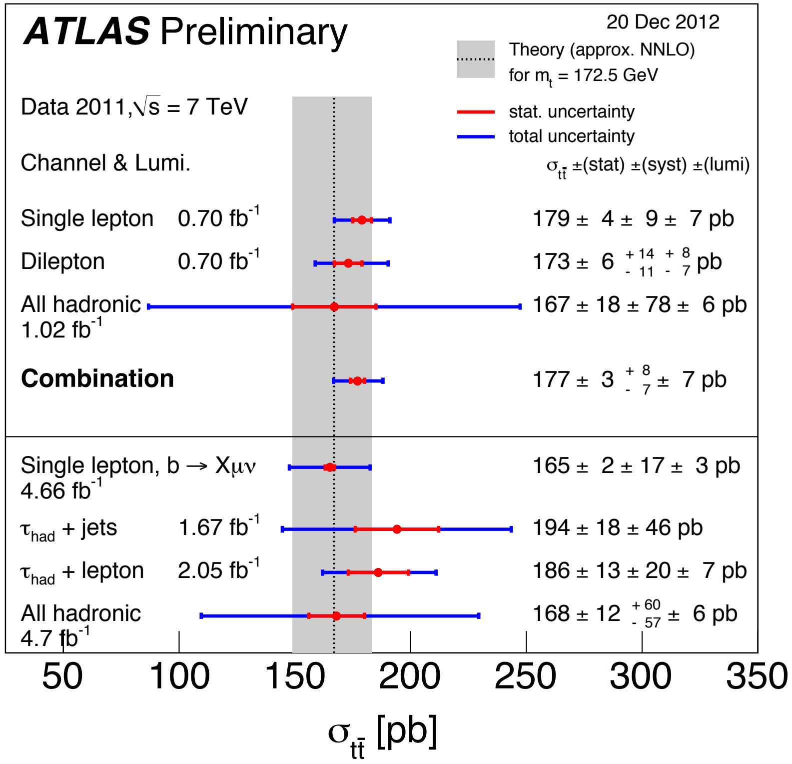
Quiz

Why is t-tbar an important background to $H \rightarrow W^*W$?

Quiz

Why is t-tbar an important background to H→W*W?





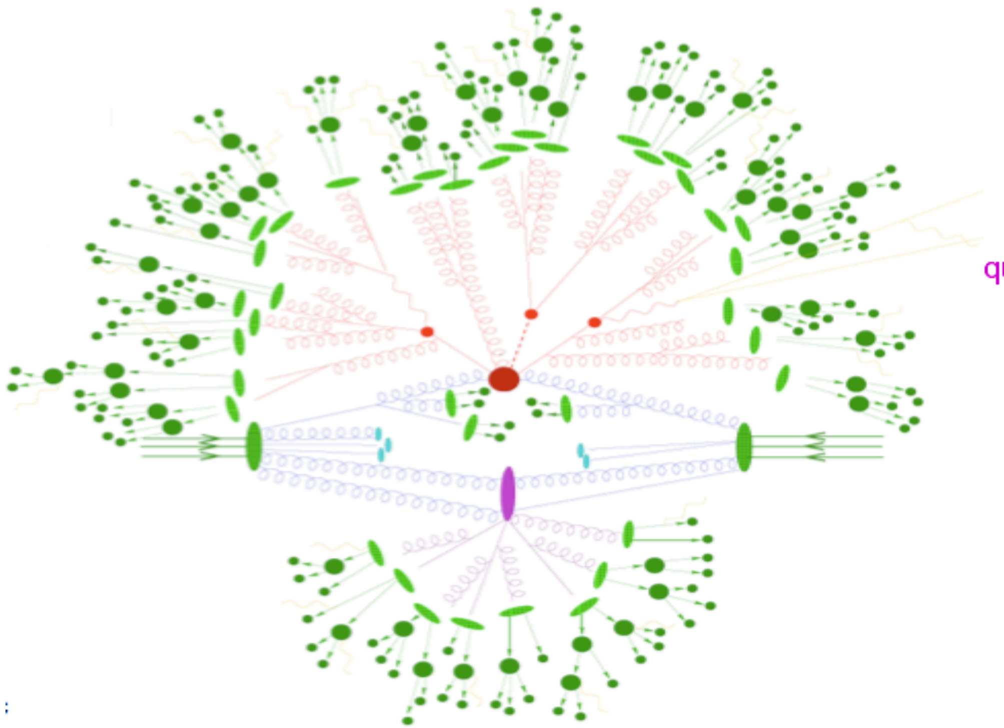
Missing Transverse Energy

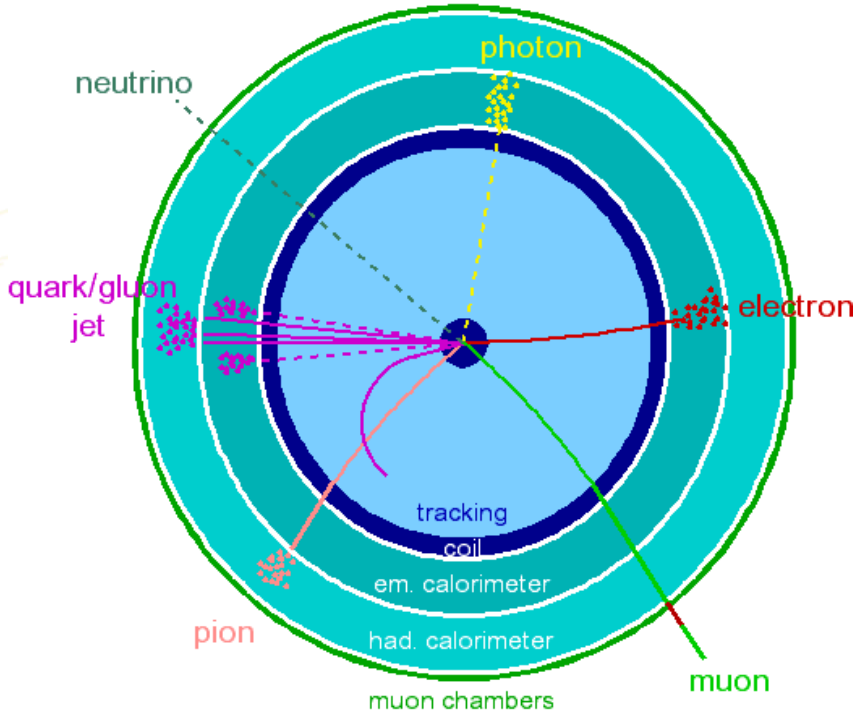
- Two proton beams collide.
- Transverse component of energy=0.
- Conserved after collision.
- The balance needs taking into account jets from the proton fragmentation (underlying event)

$$E_x = \sum_{objects} E_x^i$$

$$E_y = \sum_{objects} E_y^i$$

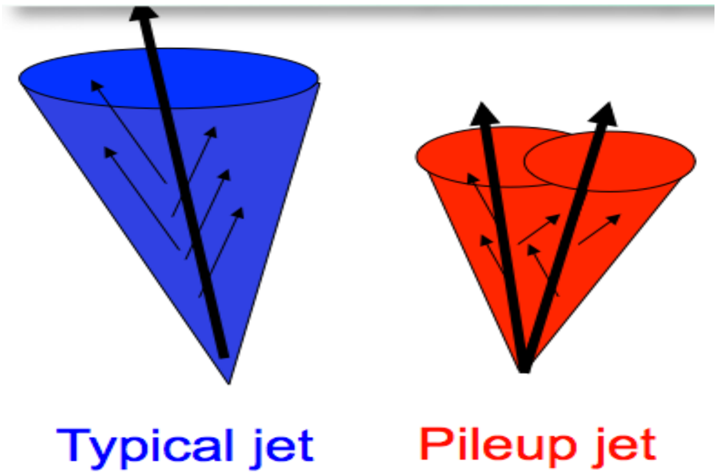
$$\not{E}_T = \sqrt{(E_x)^2 + (E_y^2)}$$





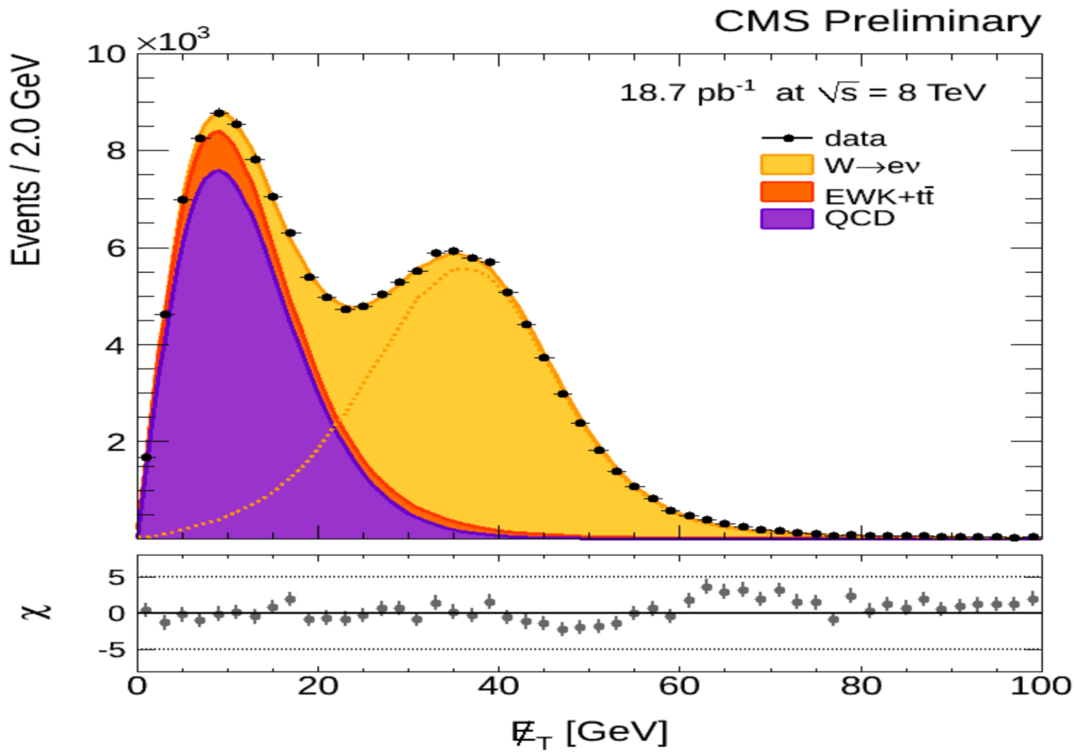
Cibrán Santamarina
Universidade de Santiago de Compostela

Missing Transverse Energy



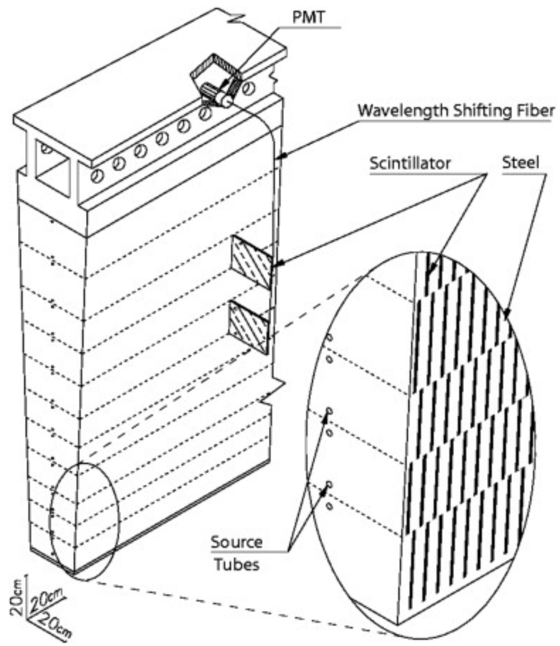
- The fluctuation produced by the UE superimposes to pile-up.
- Example: I know the total height of the people in the audience.
- One person leaves and I can measure each person's height with gaussian shaped 5 cm sigma distribution.
- If there were 2 people in the audience: 5 cm error.
- If there were 30: 27.4 cm error.
- There are ways to improve that (remove pile-up) but there is always an effect.
- Resolution in jet reconstruction: key point.
- For that a good hadronic calorimeter is needed.

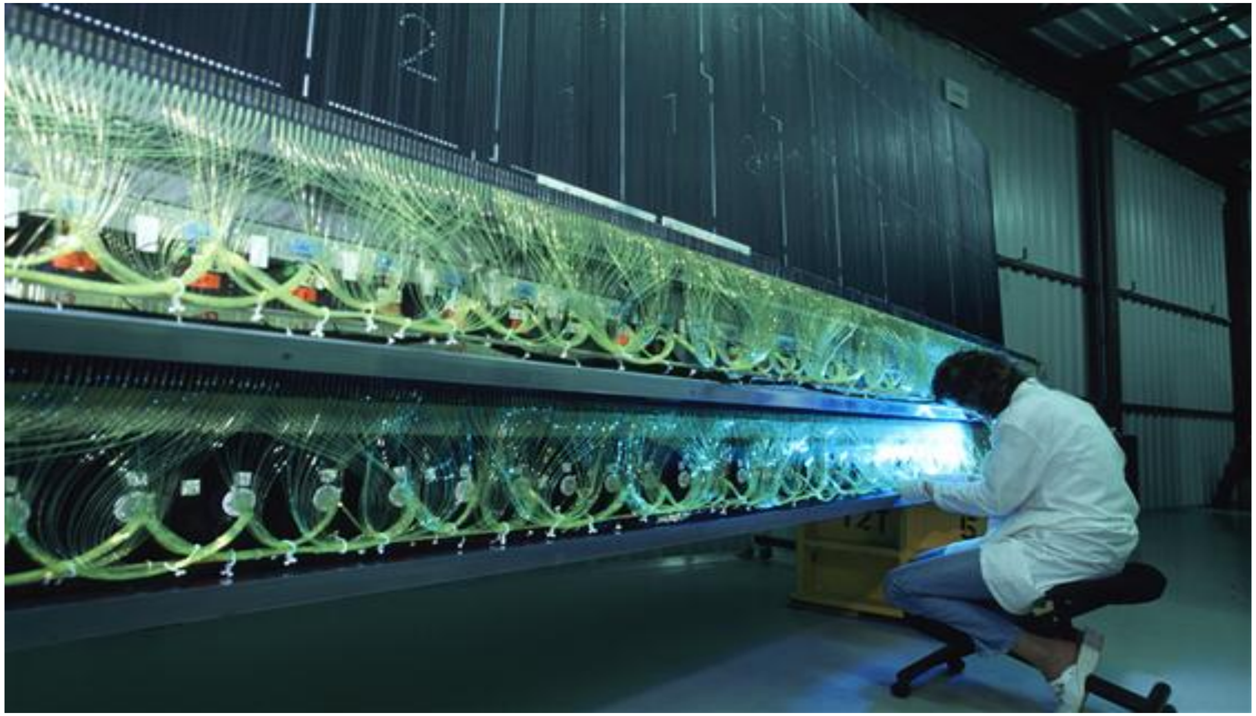
Inclusive W production from CMS

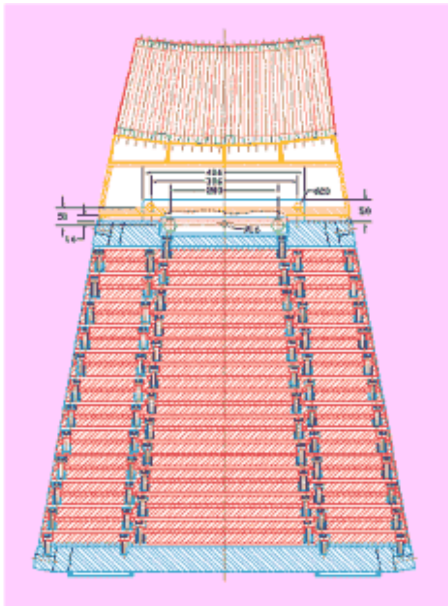


Hadronic Calorimeter

- Detects hadrons.
- ATLAS barrel & CMS: Metal energy-absorbing material interleaved with scintillating tiles that sample energy deposit.
- ATLAS end-cup: Liquid Argon.



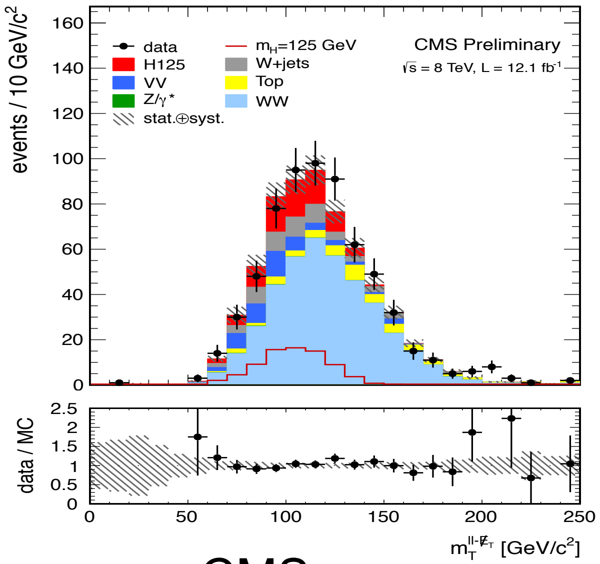


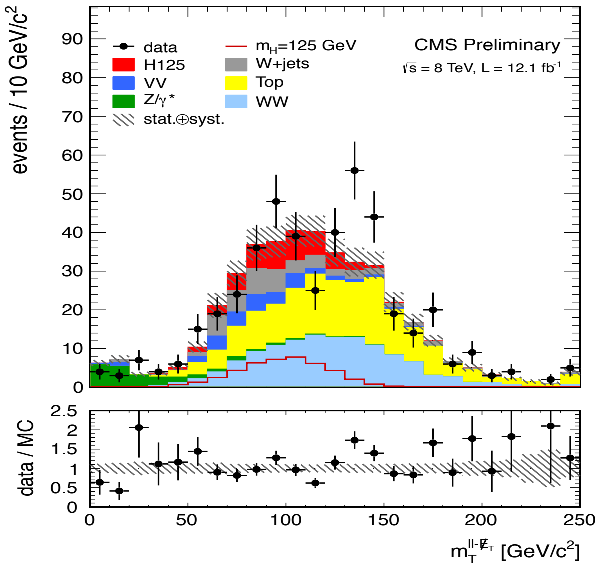


H→W*W→2l2ν Results

Samples categorized by number of additional jets.

$$m_T = \sqrt{(\sum E_T)^2 + (\sum p_T)^2}$$



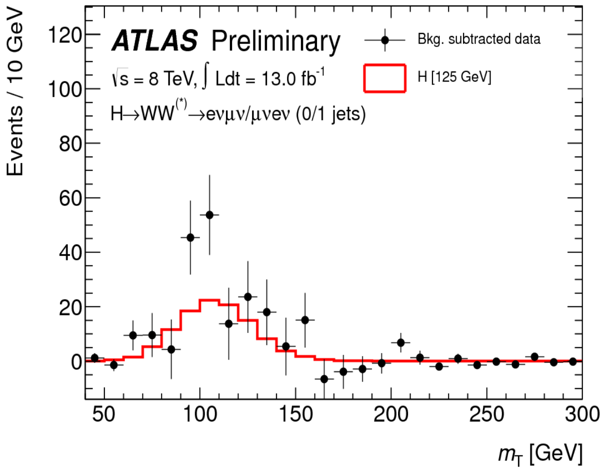


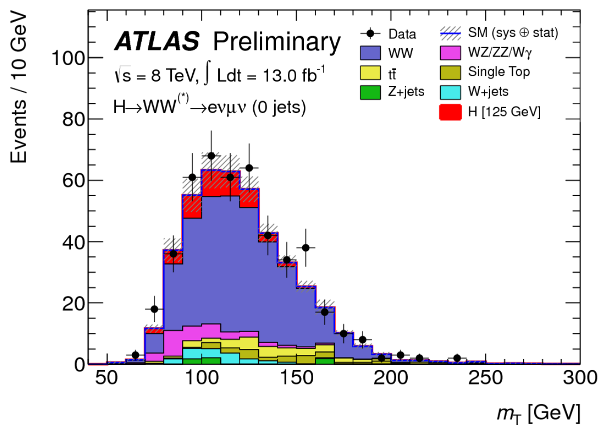
ATLAS

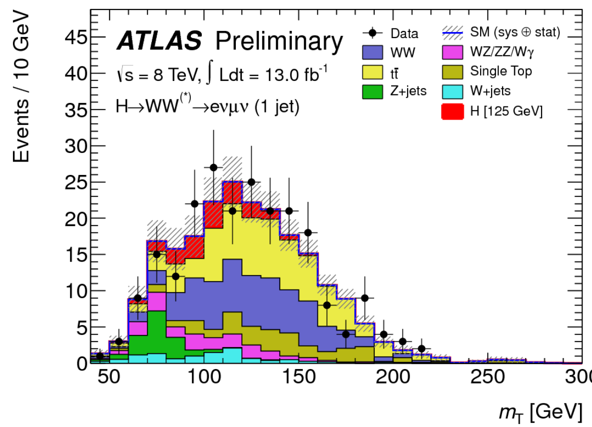
	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + jets	W + jets	Total Bkg.	Obs.
H+ 0-jet	45 ± 9	242 ± 32	26 ± 4	16 ± 2	11 ± 2	4 ± 3	34 ± 17	334 ± 28	423
H+ 1-jet	18 ± 6	40 ± 22	10 ± 2	37 ± 13	13 ± 7	2 ± 1	11 ± 6	114 ± 18	141

CMS

	$H \to W^+W^-$	$pp \to W^+W^-$	$WZ+ZZ$ $+Z/\gamma^{(*)} \to \ell^+\ell^-$	Top	$W+jets$	$W\gamma^{(*)}$	all bkg.	data
0-jet $e\mu$	58±12	203±19	6.6±0.6	11.0±2.	5 44±16	25.6±9.5	291±27	349
0-jet $ee/\mu\mu$	37.0±8.0	140±13	59±18	5.2±1.3	30±11	6.7±2.8	241±25	266
1-jet $e\mu$	27.3±8.0	47.9±7.8	6.5±0.7	49.5±3.3	22.4±8.6	7.1±3.4	134±13	160
1-jet $ee/\mu\mu$	11.8±3.4	24.8±4.1	13.1±3.5	26.7±2.3	6.5±2.8	2.0±1.2	73.0±6.6	92
2-jet $e\mu$	2.8±0.4	0.9±0.5	0.1±0.0	1.5±0.5	0.3±0.2	0.1±0.1	2.9±0.8	2
2-jet $ee/\mu\mu$	1.5±0.2	0.5±0.3	4.4±1.3	0.7±0.2	0.8±0.5	0.1±0.1	6.5±1.5	11





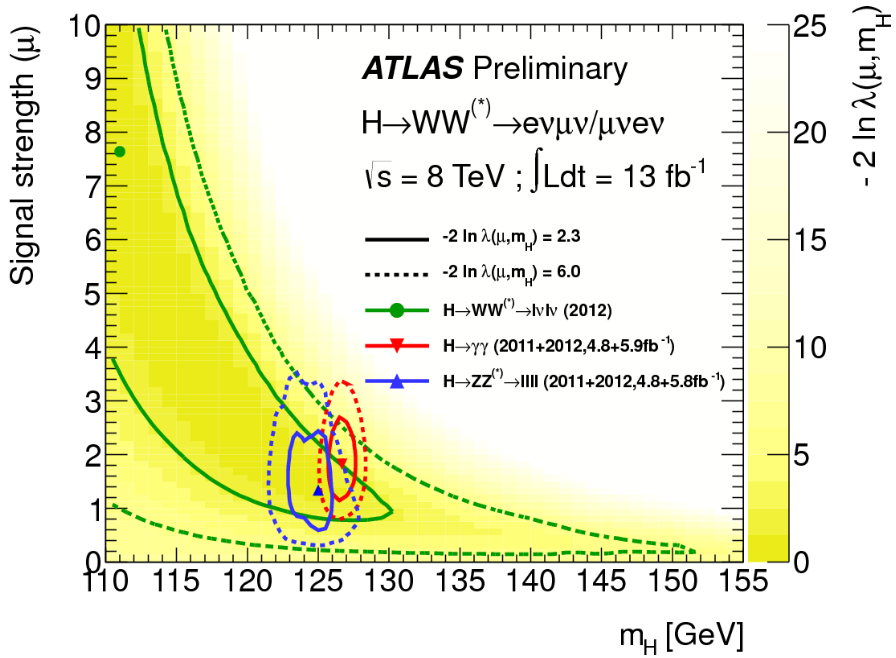


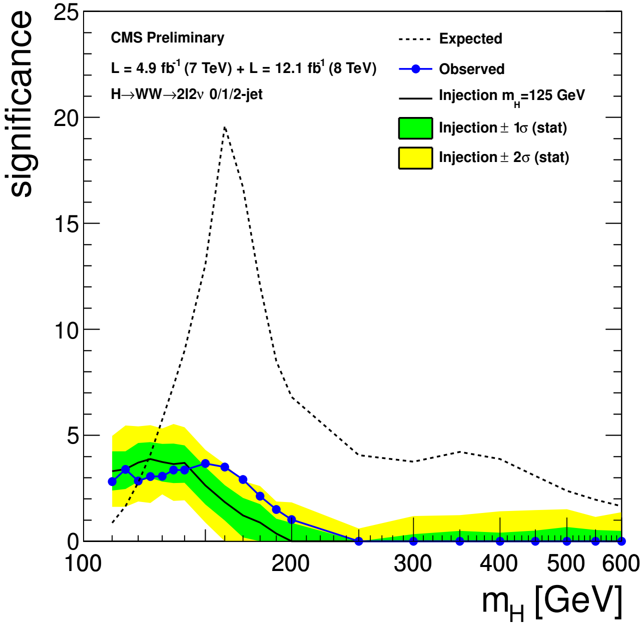
More H → WW* results

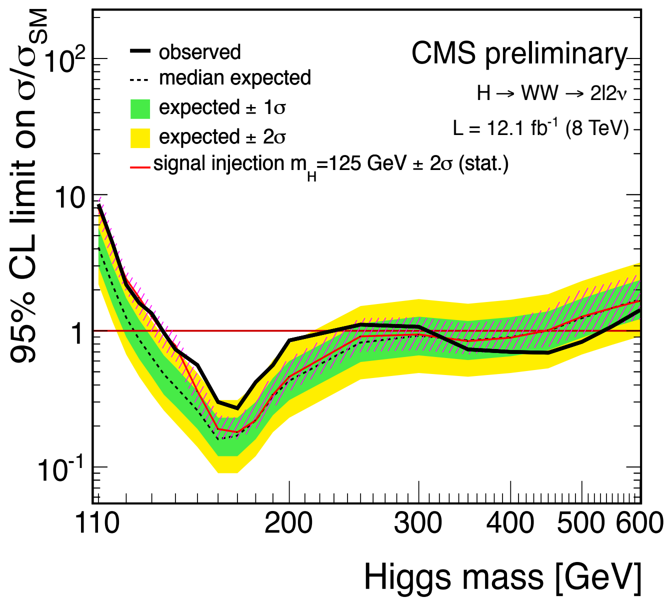
- ATLAS at m_H=125 GeV:
  - p0=4×10^{-3}→2.6 σ
  - σ(pp→H)·B(H→WW) =

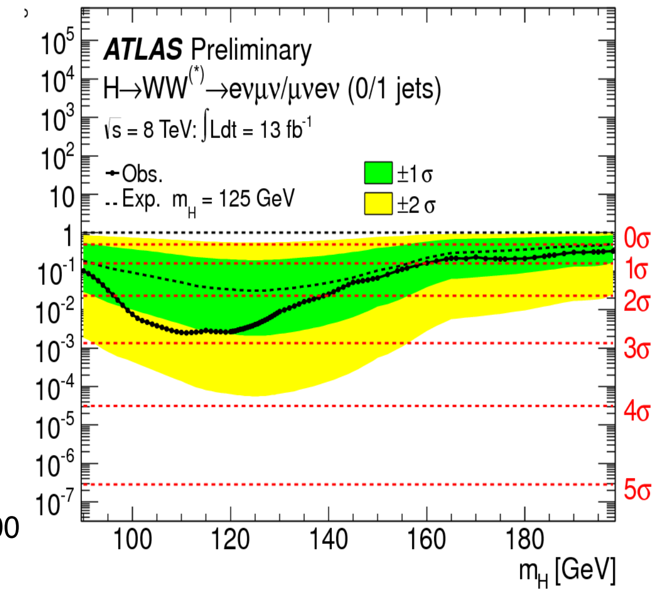
$$7.0\,^{+1.7}_{-1.6}\,(\text{stat})\,^{+1.7}_{-1.6}\,(\text{syst theor})\,^{+1.3}_{-1.3}\,(\text{syst exp})\ \pm 0.3\,(\text{lumi})\ \text{pb}$$

- CMS
  - Significance of 3.1 σ (4.1 expected at SM).
  - No other significant deviations observed:
    - upper limits on Higgs production relative to SM derived.
  - SM Higgs boson excluded in the mass range 128–600 GeV at 95% CL.



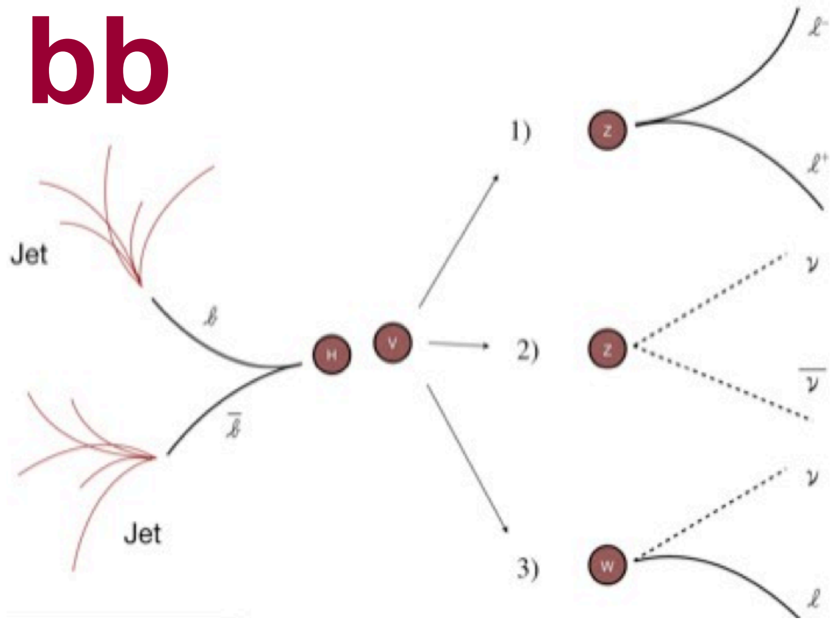


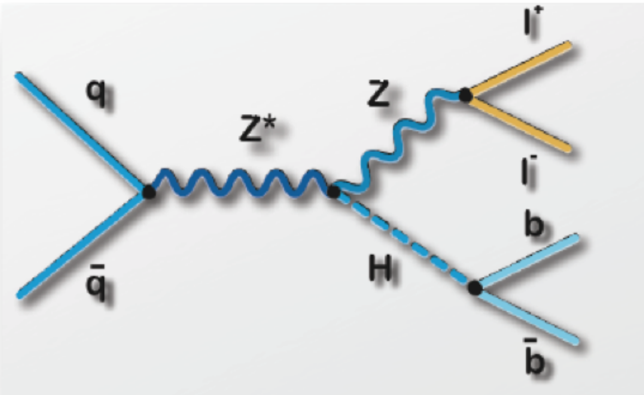


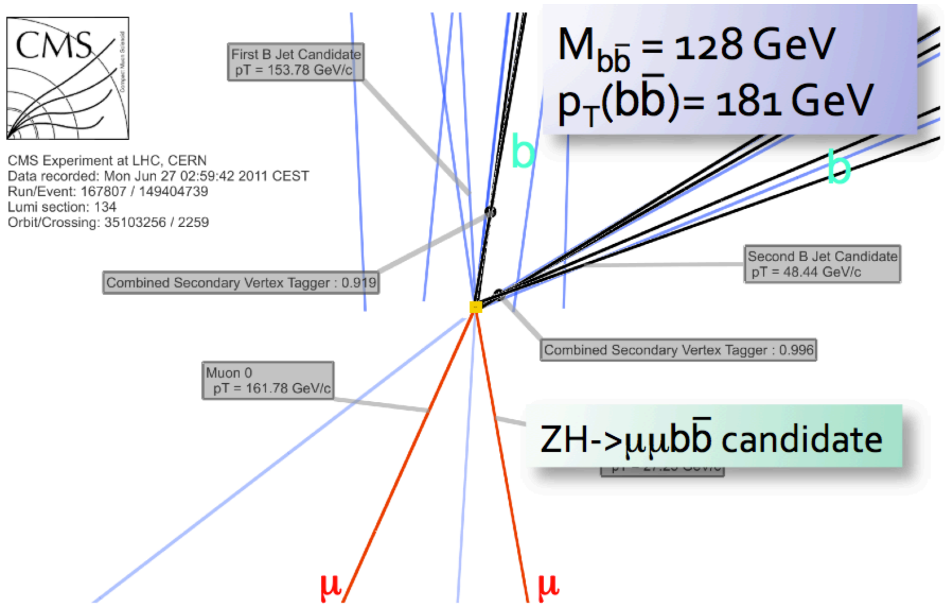


$H \rightarrow bb$

- Largest BR for m_H<130 GeV
- Tests specific production & decay couplings to fermions.
- Caveat: σ_{bb}(QCD)~$10^7 \sigma$xBR(H→bb)
- Searched in associated production.
  - Need a high p_T lepton to trigger and suppress background.
  - 5 categories (depending on W/Z final state)
    - Zνν, Zμμ, Zee, Wμν, Weν
- Jet Energy Scale and b-tagging cornerstones.
- Multi variate analysis.

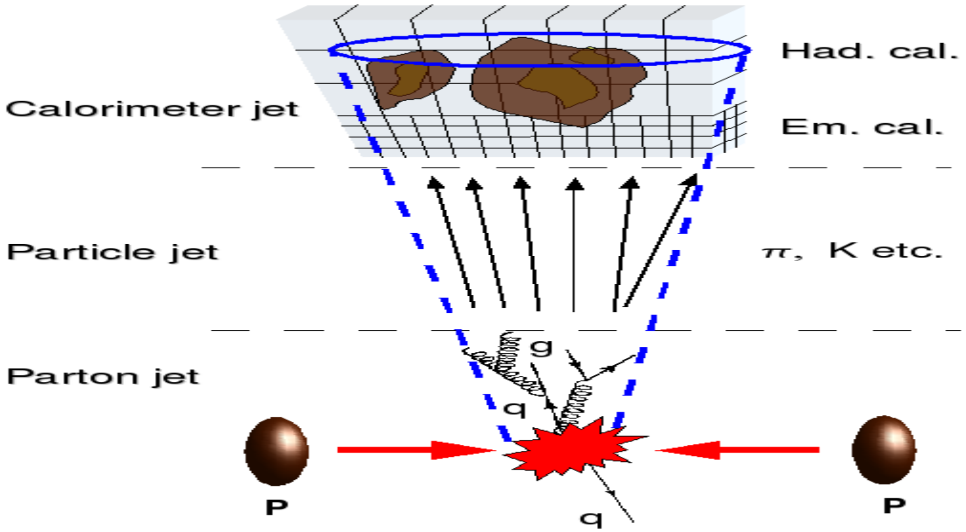


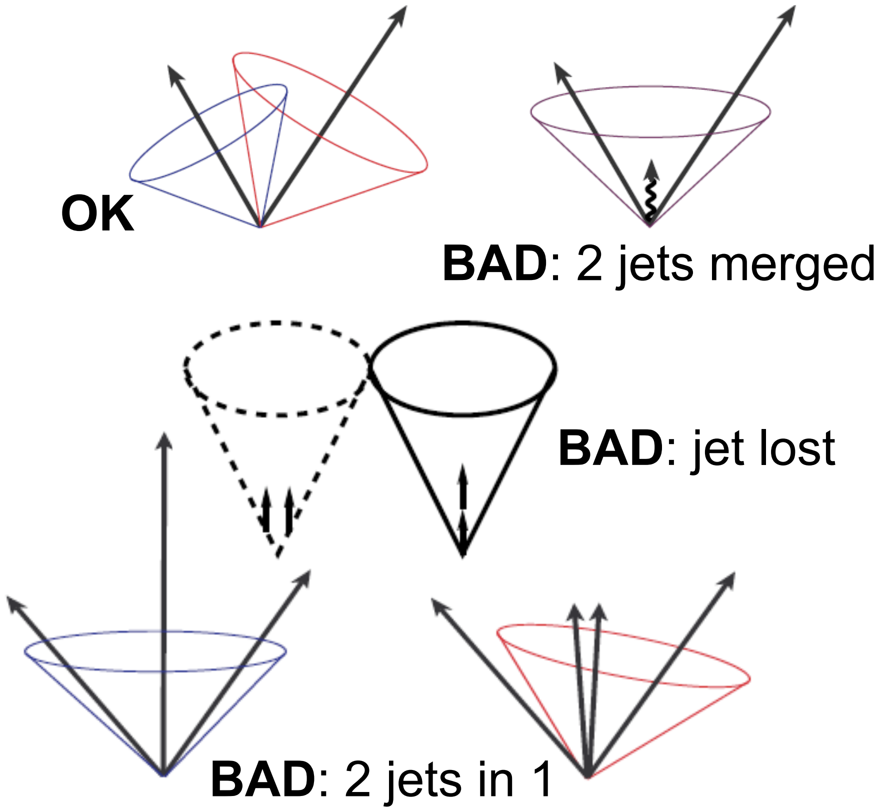




Jets

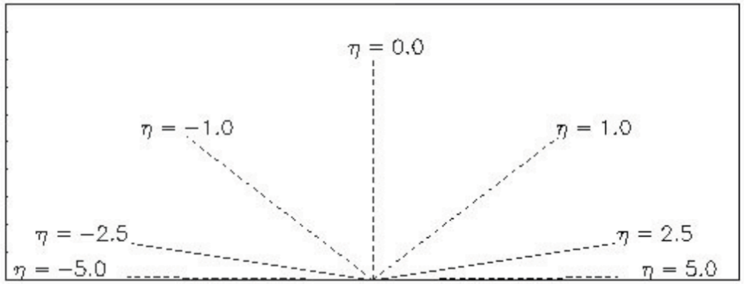
- Quarks-gluons: hadronize producing a Jet.
- **Jet** = collimated spray of high energy hadrons.
- Jet reconstruction aims at reproducing the parton 4-momentum.
  - THEORY: “define” the jet.
  - EXPERIMENT: measure the jet.
- Experimental jets are reconstructed from calorimeter objects (clusters).
- Features in a jet finding algorithm:
  - *Infrared safety:* insensitive to soft radiation.
  - *Collinear safety*: insensitive to collinear radiation.





Anti-k_T Jets

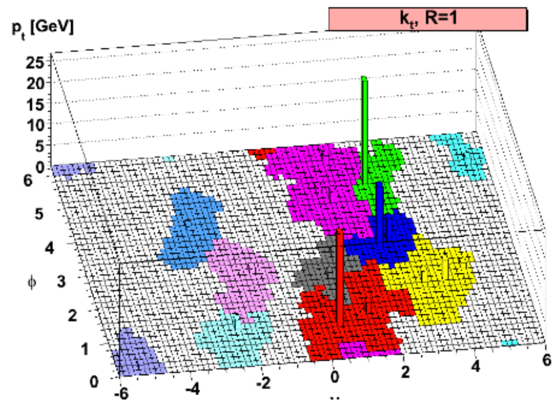
Pseudorapidity η=-ln(tan(θ/2))

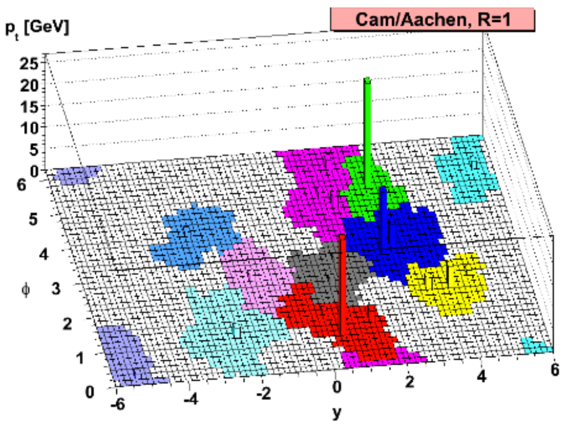


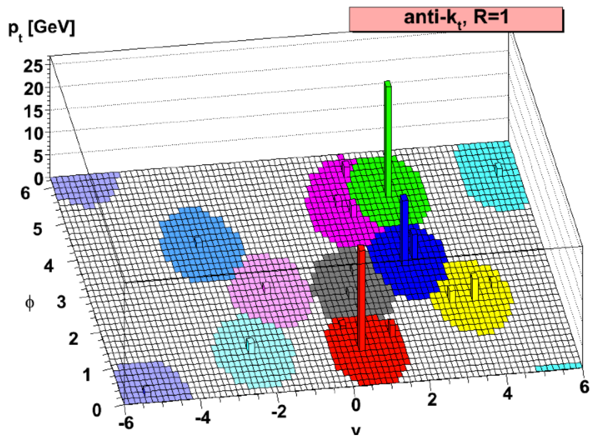
- List of calorimeter *clusters*, (4-vectors) defined by: E, **p**, η.
- Calculate:
  - For each cluster *i*: $d_i = p_{T,i}^{2\alpha}$
  - For each pair (*i,j*) of clusters: $d_{ij} = \min(p_{T,i}^{2\alpha}, p_{T,j}^{2\alpha}) \frac{\Delta\eta^2 + \Delta\phi^2}{D^2}$

    (*D* is a parameter)
- Find minimum of d_i and d_{ij}: d_{min}
- If d_{min} is a d_{ij}, merge clusters *i* and *j. Add result to the cluster list.*
- If d_{min} is a d_i: *i* not "mergeable": *i* is a jet.
- Repeat until: list of clusters empty=all jets found.

If α=1 k_T if α=0 Cambridge-Aachen, if α=-1 anti-k_T.



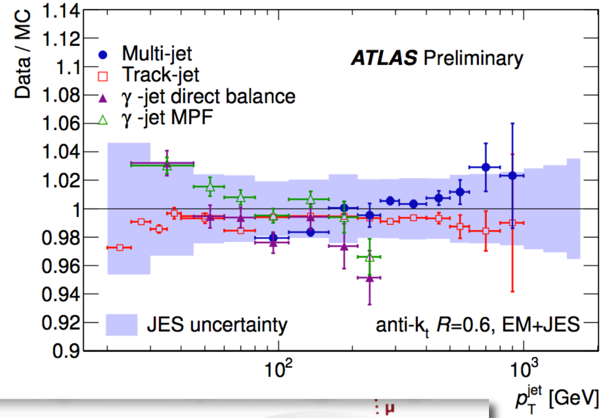


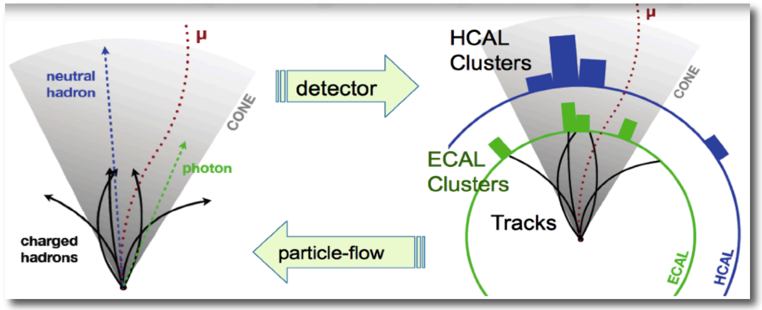


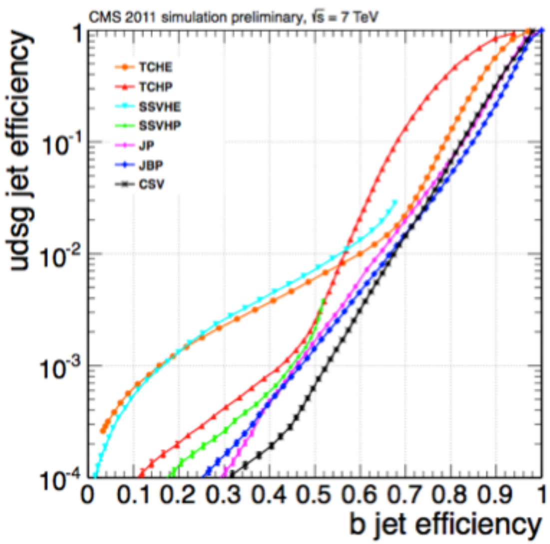
Cibrán Santamarina
Universidade de Santiago de Compostela

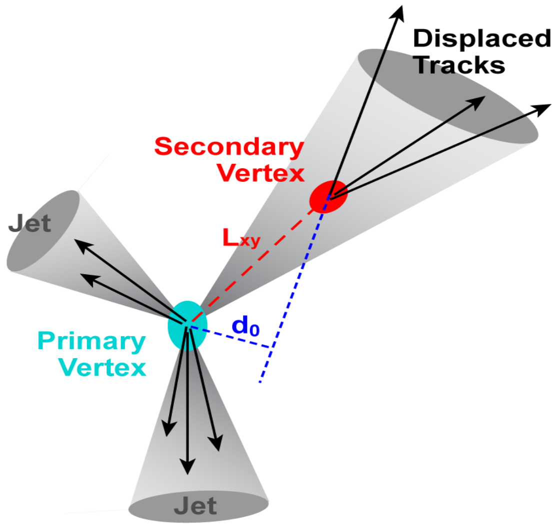
JES and b-tagging

- Not all energy in jets is reconstructed: neutrals, leakage.
- The calculated energy is multiplied by a factor: jet energy scale (JES).
- JES depends on:
  - η and E of the jet.
  - parton nature (g-u,d,s-c-b)
  - …
- Working out you JES is crucial for your analysis:
  - Material/detector studies.
  - Particle flow.
  - Data driven calculations.
- Particles with b-quarks flight ~1cm distance.
- Detecting a displaced vertex in a jet: b-tagging.









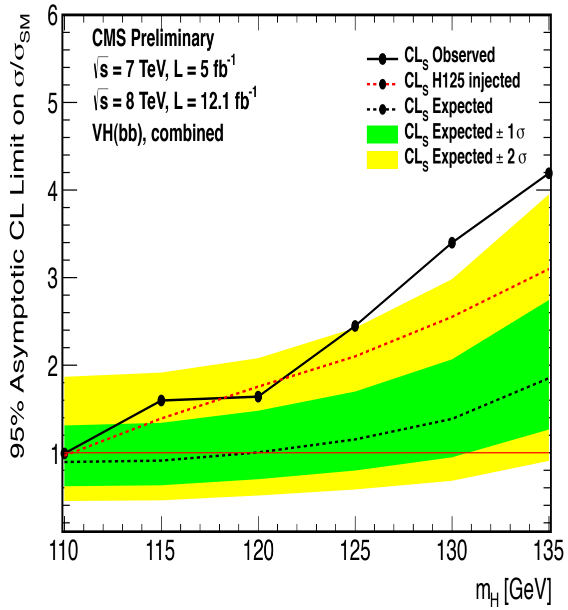
H → bb results

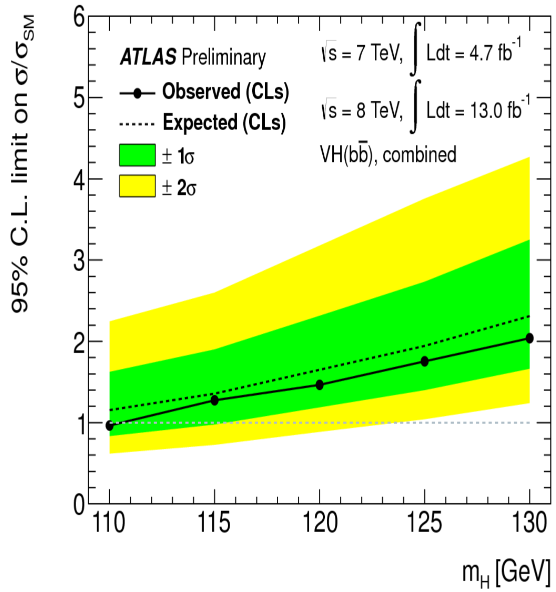
ATLAS:

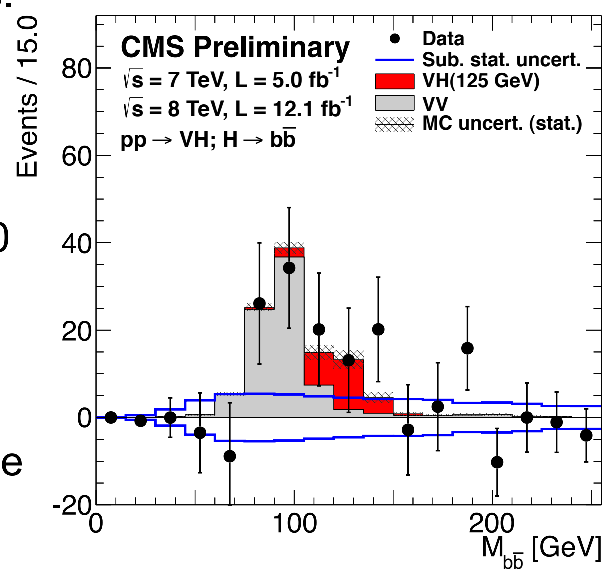
- Dataset: 4.7 fb^{-1} at $\sqrt{s}$ = 7 TeV and 13.0 fb^{-1} at $\sqrt{s}$ = 8 TeV.
- 16 different categories depending on:
  - *number of leptons,*
  - *number of jets*
  - *p_T of the vector boson candidate.*
- No significant excess observed.
- For m_H = 125 GeV: observed (expected) upper limit on production x-section x BR is 1.8 (1.9) times SM prediction for the combined datasets.

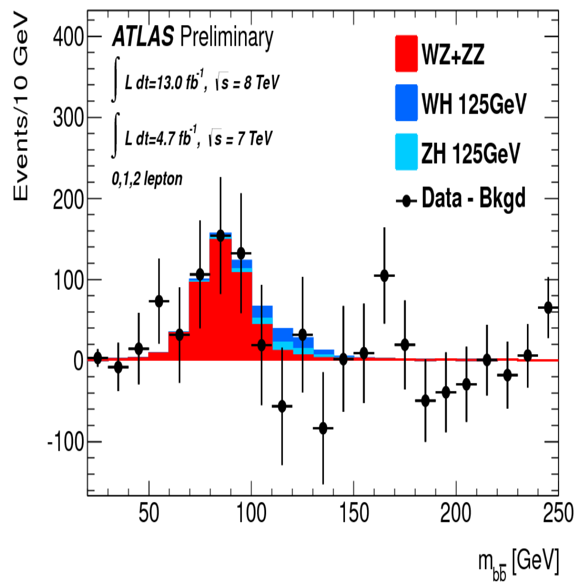
CMS:

- Dataset: 5.0 fb^{-1} at $\sqrt{s}$ = 7 TeV and 12.1 fb^{-1} at $\sqrt{s}$ = 8 TeV,
- BDT selection.
- Upper limits at 95% CL vary from 1.0 to 4.2 times the SM x-section in the mass range 110–135 GeV. I
- At m_H=125 GeV the observed (expected) limit is 2.5 (1.2).
- Excess of events observed above the expected background with local significance of 2.2 σ, consistent with expectation for SM Higgs.





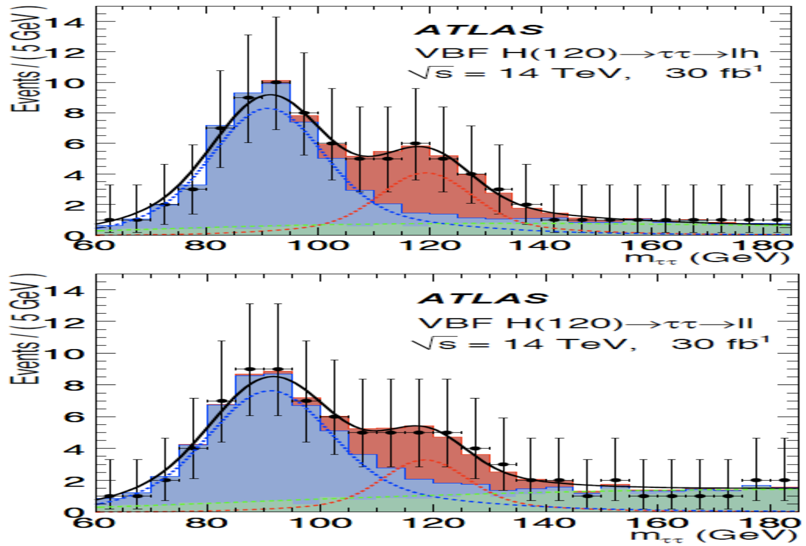


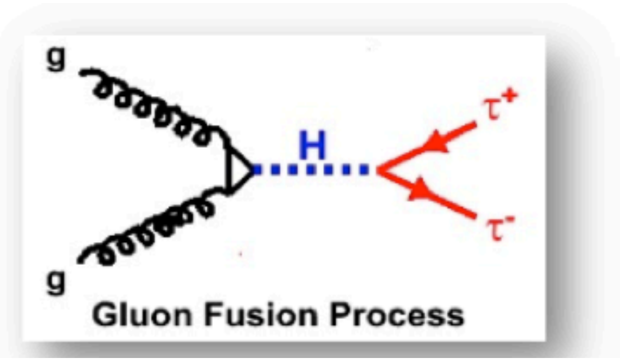


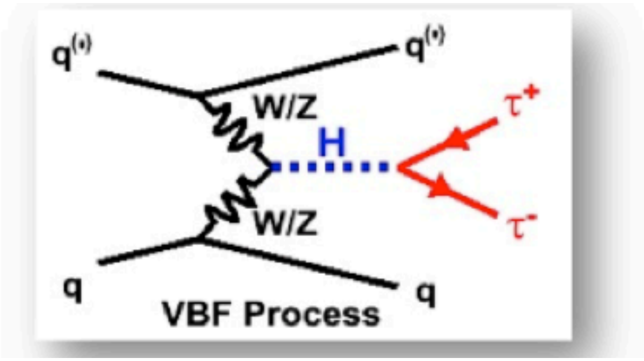
H → $\tau\tau$

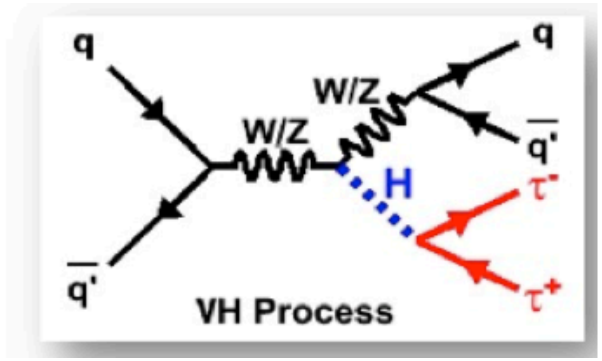
- High σxBR at low mass
- Sensitive to all production modes
- Probes coupling to leptons
- Enhanced σ x BR in MSSM
- Challenging large backgrounds:
  - DY→ττ
  - W+Jets
  - QCD
- Relies on missing transverse energy.
- Assumes collinear approximation: daughters aligned with original τ

2008 simulation



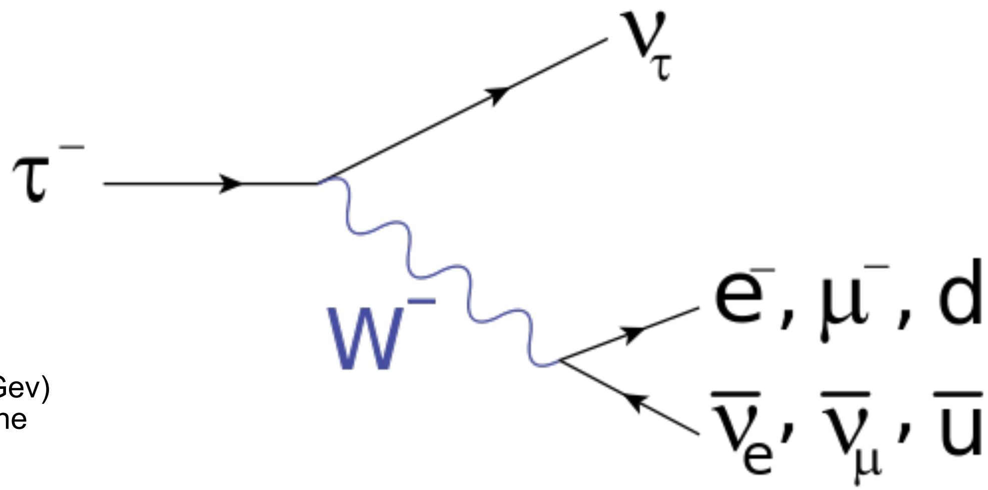


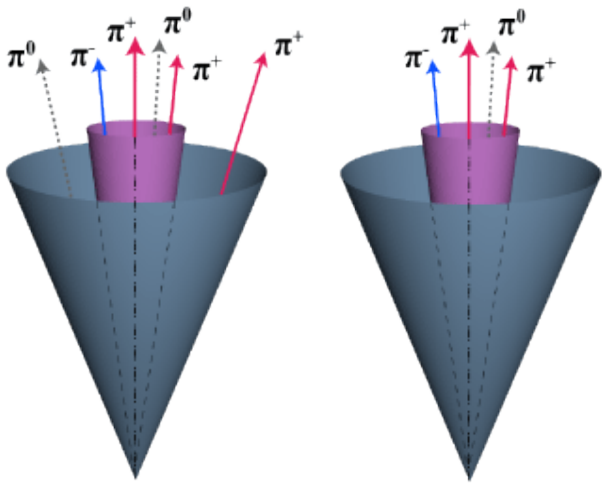


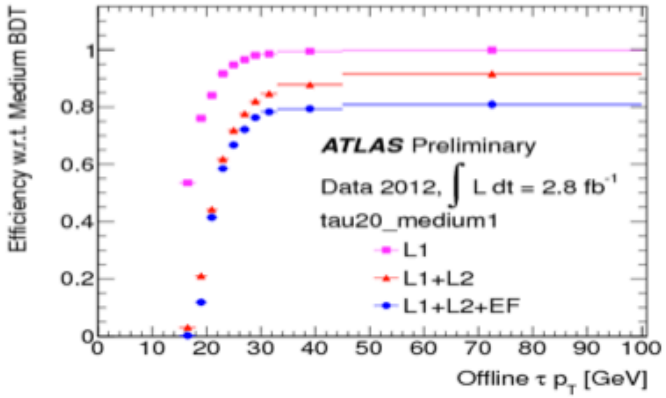


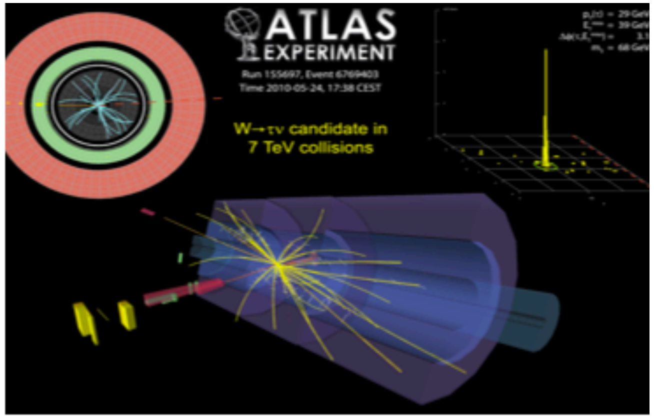
τ reconstruction

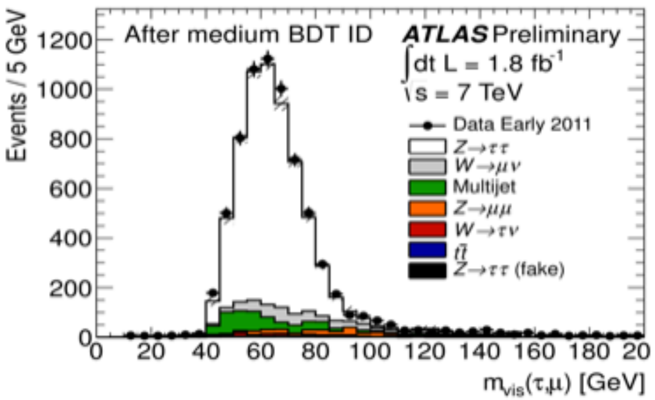
- *τ's decay to hadrons and a neutrino 65% of the time.*
- *Rest 45% leptonic.*
- *Isolation of the τ daughters (lepton or τ-jet) required.*
- *Hadronic τ:*
  - Number of tracks: 1 (49.5%), 3 (15.2%) and very seldom 5 (0.1%) charged particles
  - Lifetime: The τ lifetime ($c\tau$=87μm) and low mass (m_τ=1.78 Gev) produce sizeable decay length. The decay path allows for the reconstruction of the decay vertex
  - Invariant mass.
  - Multivariate discriminator.

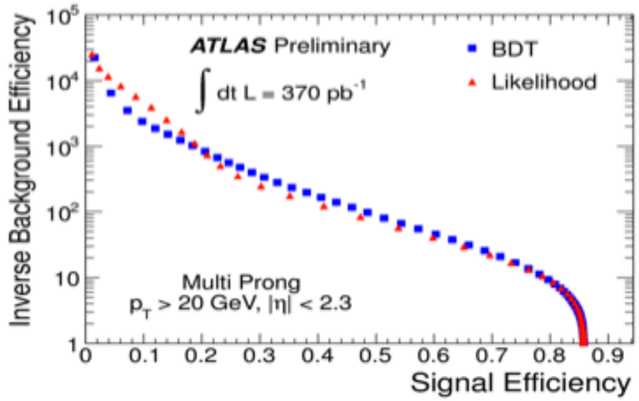












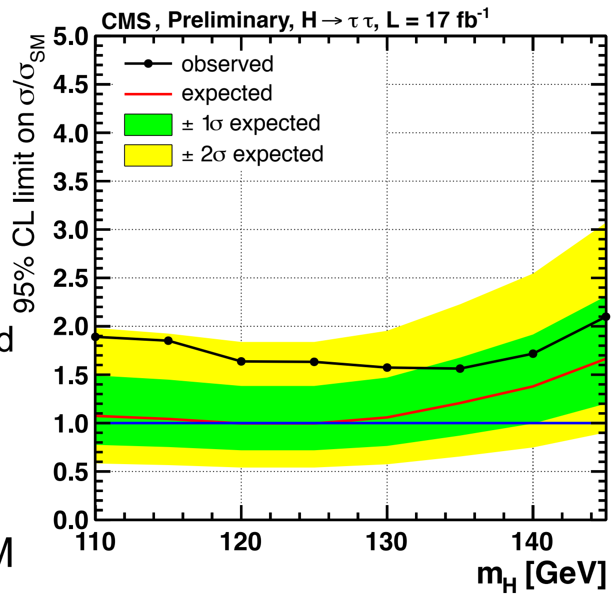
H → ττ results

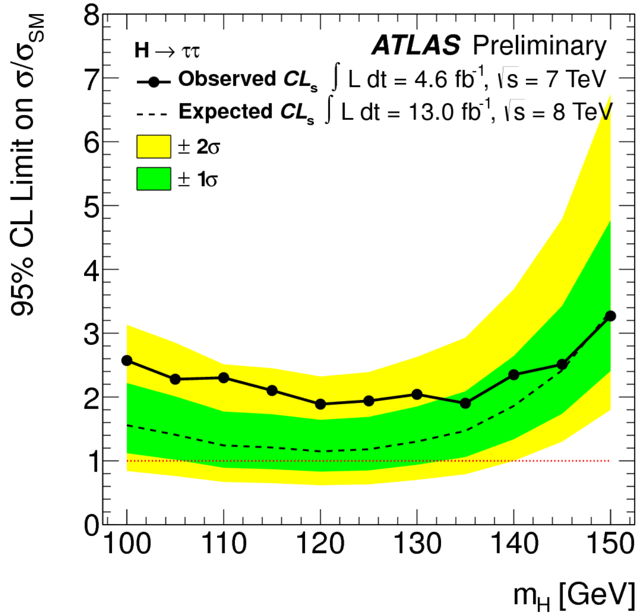
CMS:

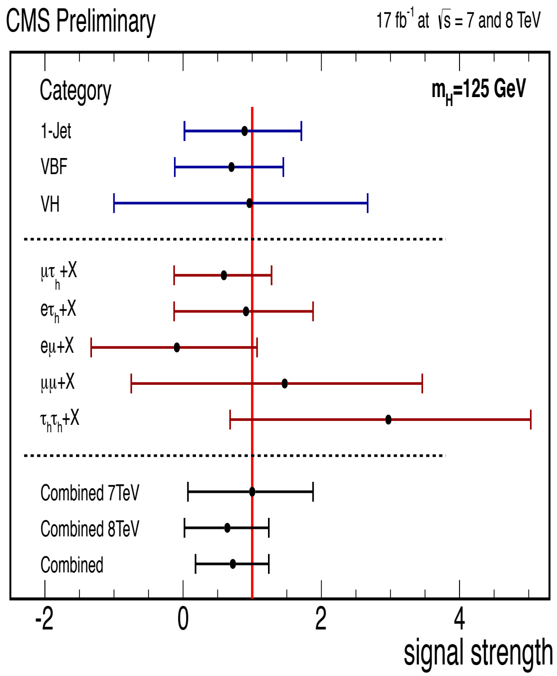
- 17 fb-1 7 and 8 TeV data.
- 5 final states considered:
  - μτh+X, eτh+X, eμ+X, τhτh+X, and μμ+X.
- Final result combined with W/Z associated production Higgs search. W/Z leptonic decay.
- Upper limits on the production SM x-section determined (110 GeV<m_H<145 GeV).
- At m_H=125 GeV exclusion limits of 1.63 observed (1.00 expected) at 95% CL.

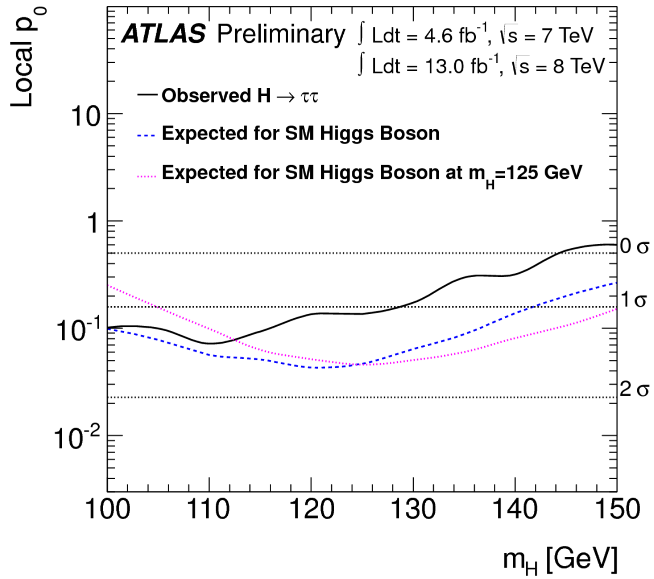
ATLAS:

- H → τlτl , H → τlτhad and H → τhadτhad
- 4.6 fb−1 @ 7 TeV and 13.0 fb−1 @ 8 TeV.
- m_H=125 GeV observed (expected upper limit at 95% CL: 1.9 (1.2) xσ_{SM}.
- For this mass: observed (expected) deviation from background-only local: 1.1 (1.7) σ.





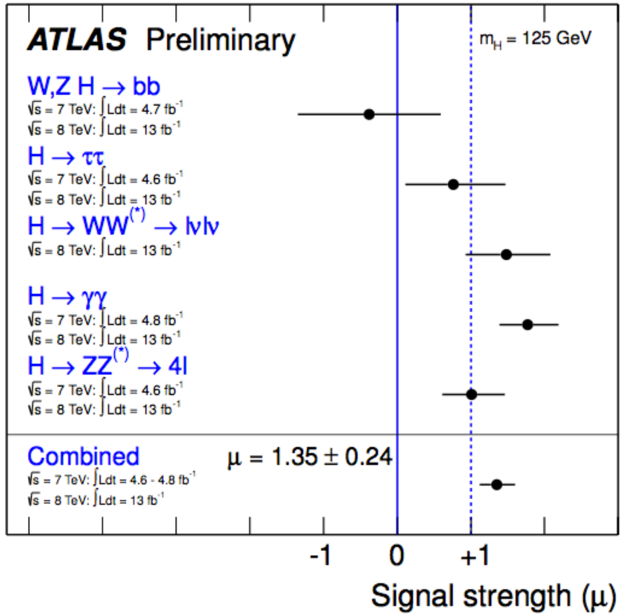


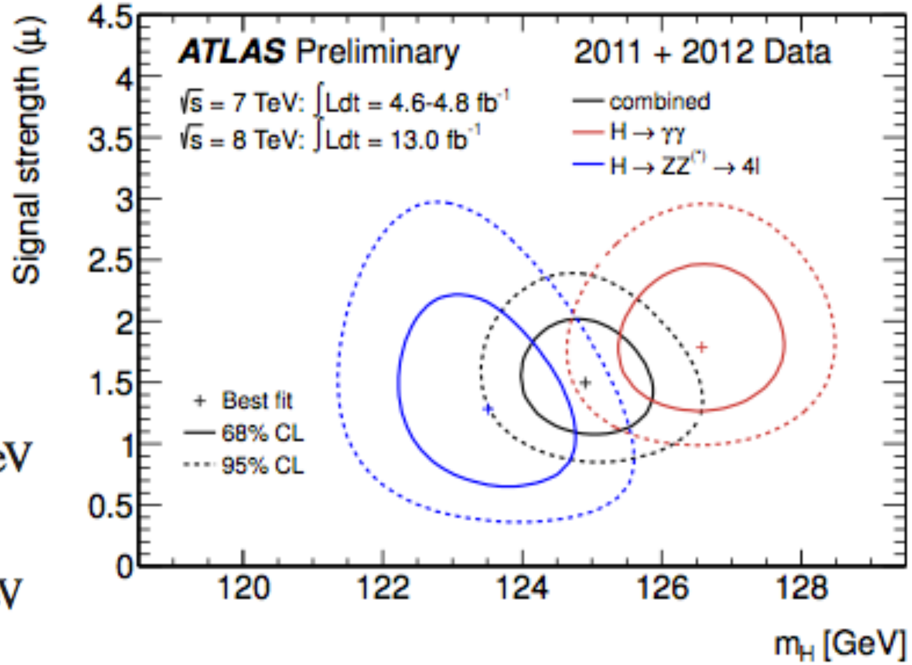


All Together

ATLAS Summary

- A combination of all channels to make a best determination of the mass.
- The signal strength is also used to determine the Standard-Model likeness of the signal. μ = 0 corresponds to the background-only hypothesis and μ = 1 corresponds to the SM Higgs boson signal.
- Two main decay modes give tension (2.7 sigma) in the mass result.



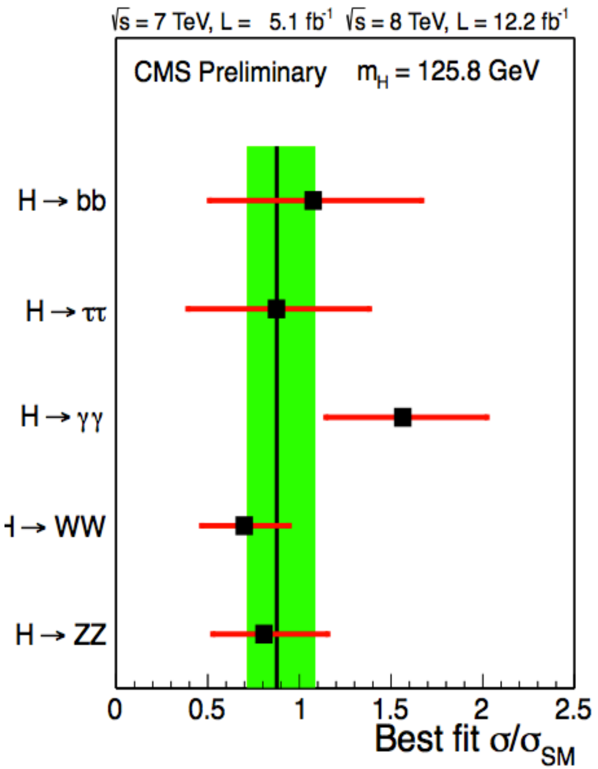


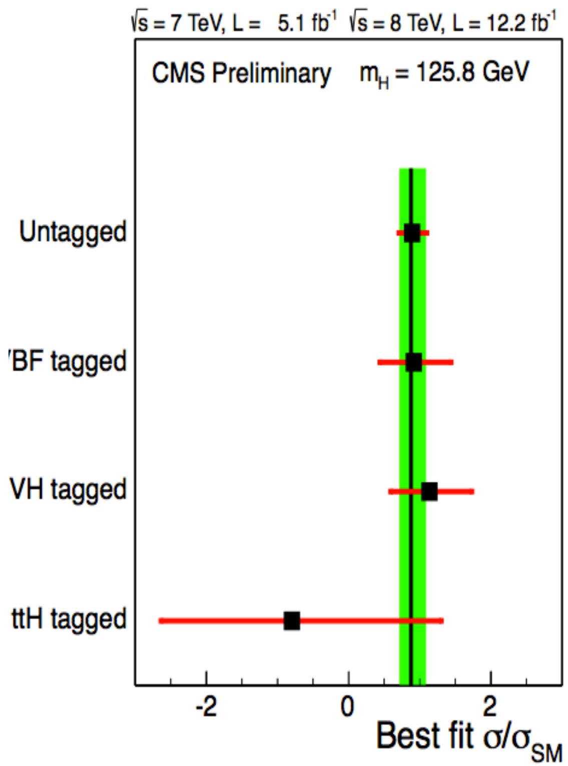
$$m_H = 125.2 \pm 0.7\ \text{GeV} = 125.2 \pm 0.3\,(\text{stat}) \pm 0.6\,(\text{sys})\ \text{GeV}$$

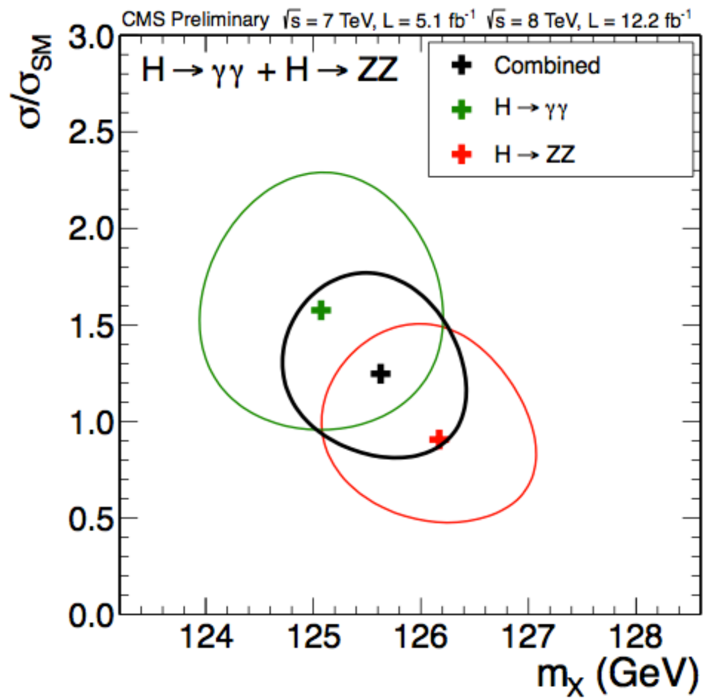
$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 3.0^{+1.1}_{-1.0}\ \text{GeV} = 3.0 \pm 0.8\,(\text{stat})\ ^{+0.7}_{-0.6}\,(\text{sys})\ \text{GeV}$$

CMS Summary

- Significance of boson is 6.9 σ.
- m_H = 125.8 ± 0.4 (stat) ± 0.4 (syst) GeV.
- The event yields of different decay modes and production mechanisms: consistent with the SM Higgs boson.
- Consistency of the couplings of the boson the with SM Higgs tested without significant deviations.
- Assuming J=0 the data disfavour the pseudo-scalar hypothesis 0^- with a CLs value of 2.4%.

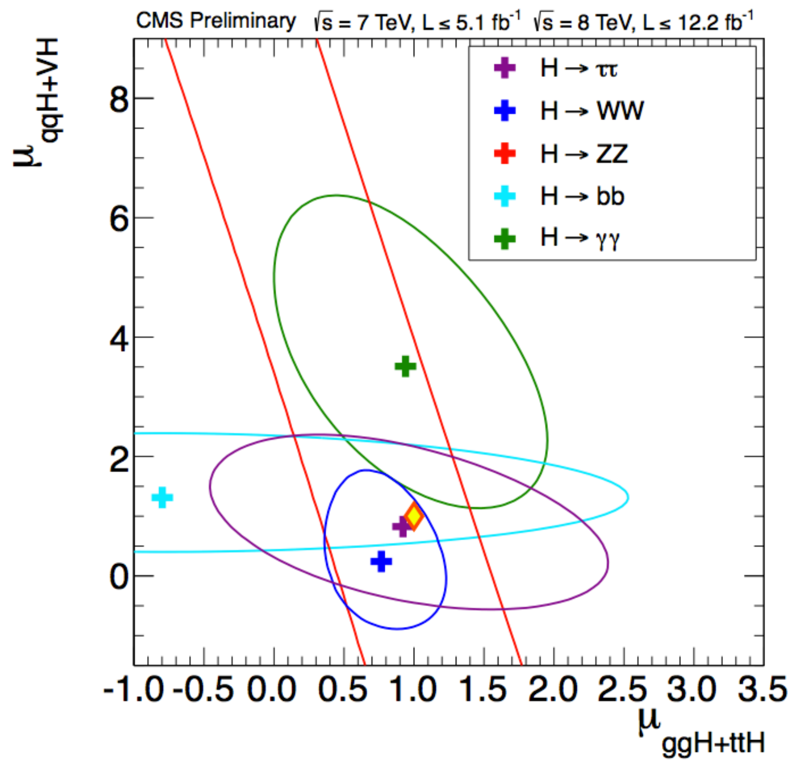


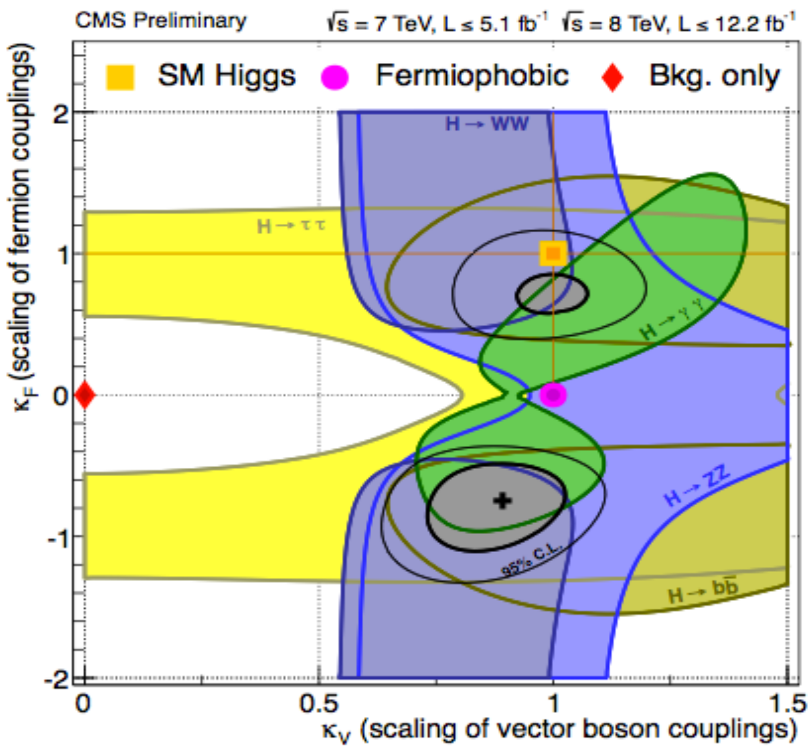




CMS Summary

- Beautiful plots on production and decay couplings.

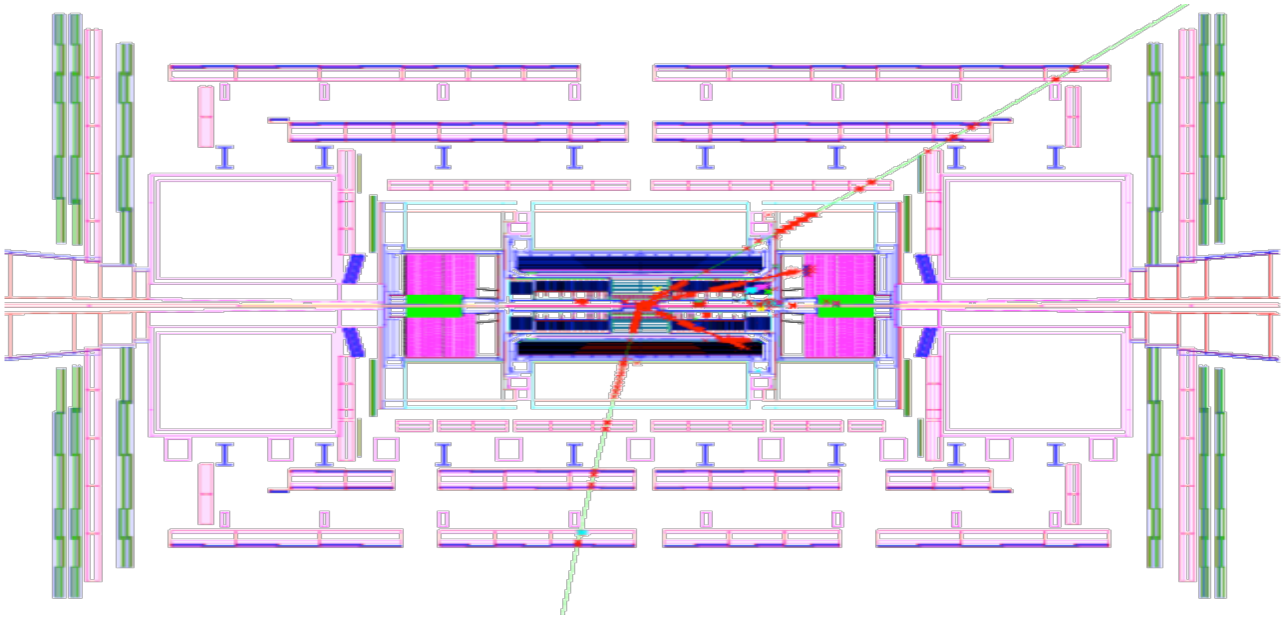




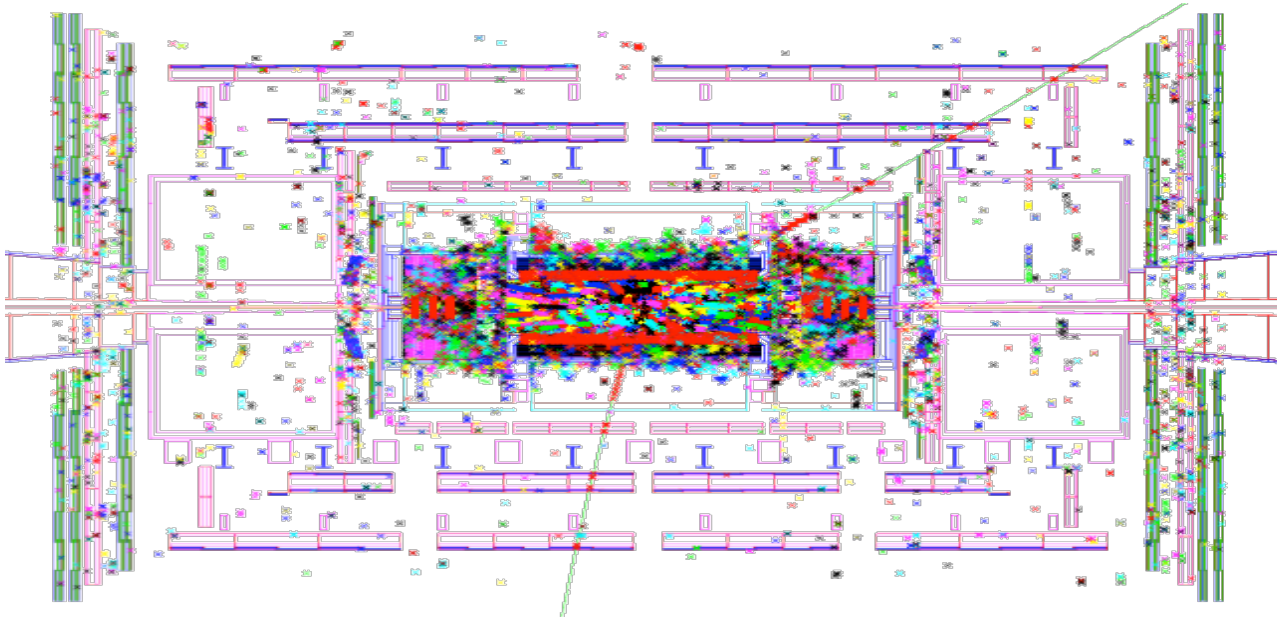
Cibrán Santamarina
Universidade de Santiago de Compostela

The End

Is this boson a SM lonesome cowboy?



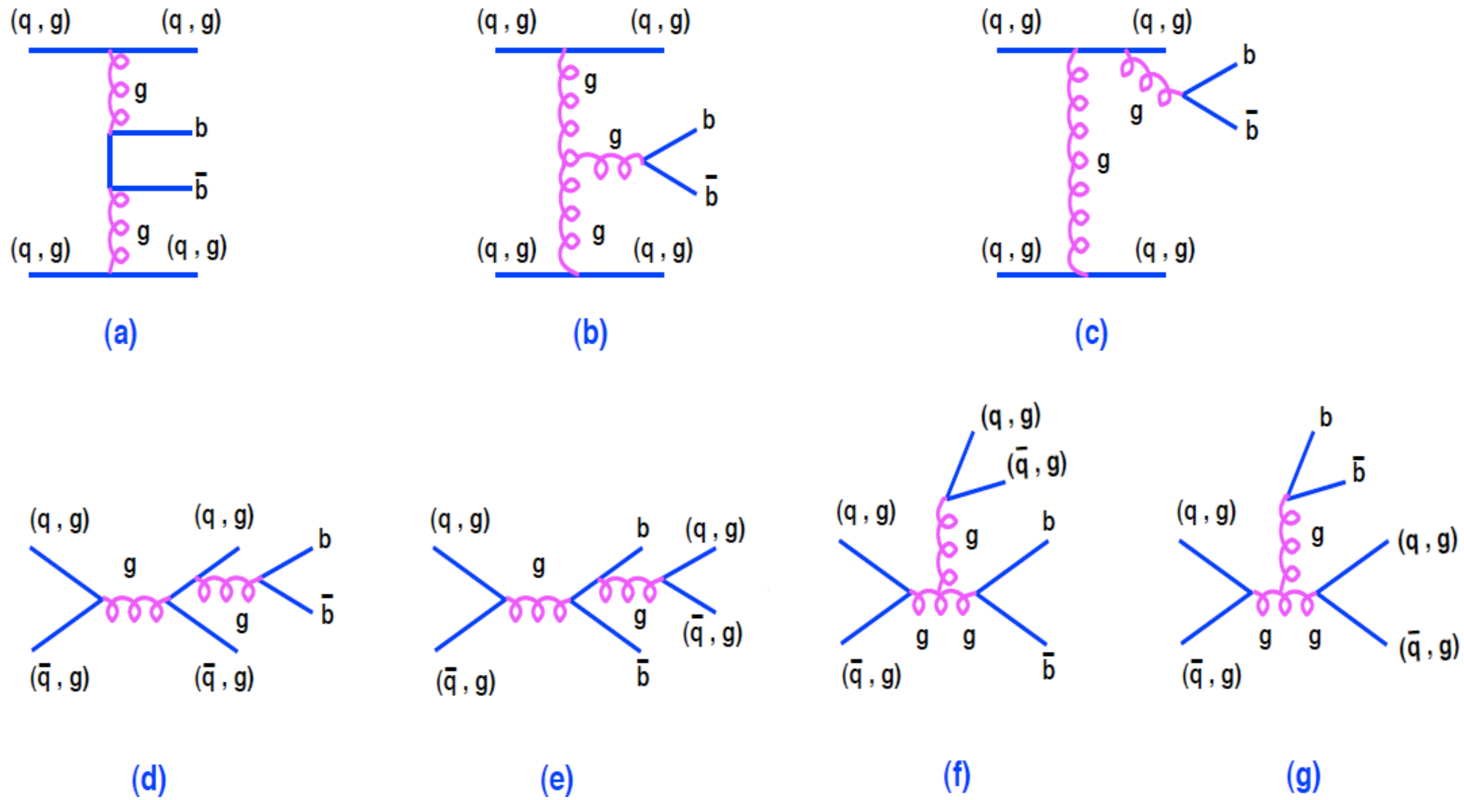
Higgs → ZZ → 2e+2μ



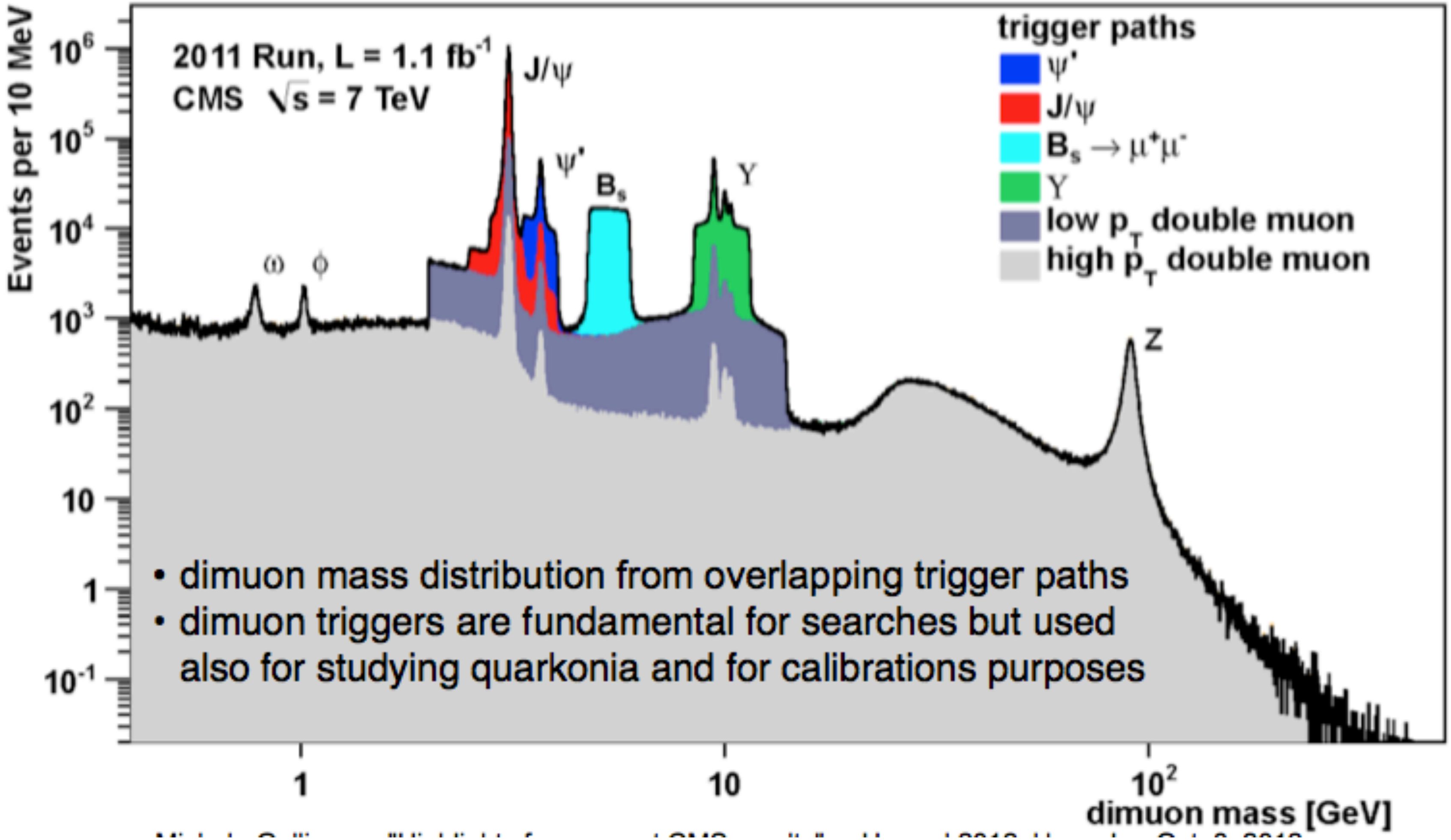
Higgs → ZZ → 2e+2μ

Channels for Light Higgs

- Experimental data show a preference for a light Higgs M_H~116 GeV/c^2.
-There the situation is quite messy.
-The largest cross section channel: $H \rightarrow b\bar{b}$
-Overwhelmed by the huge multi-jet cross section.



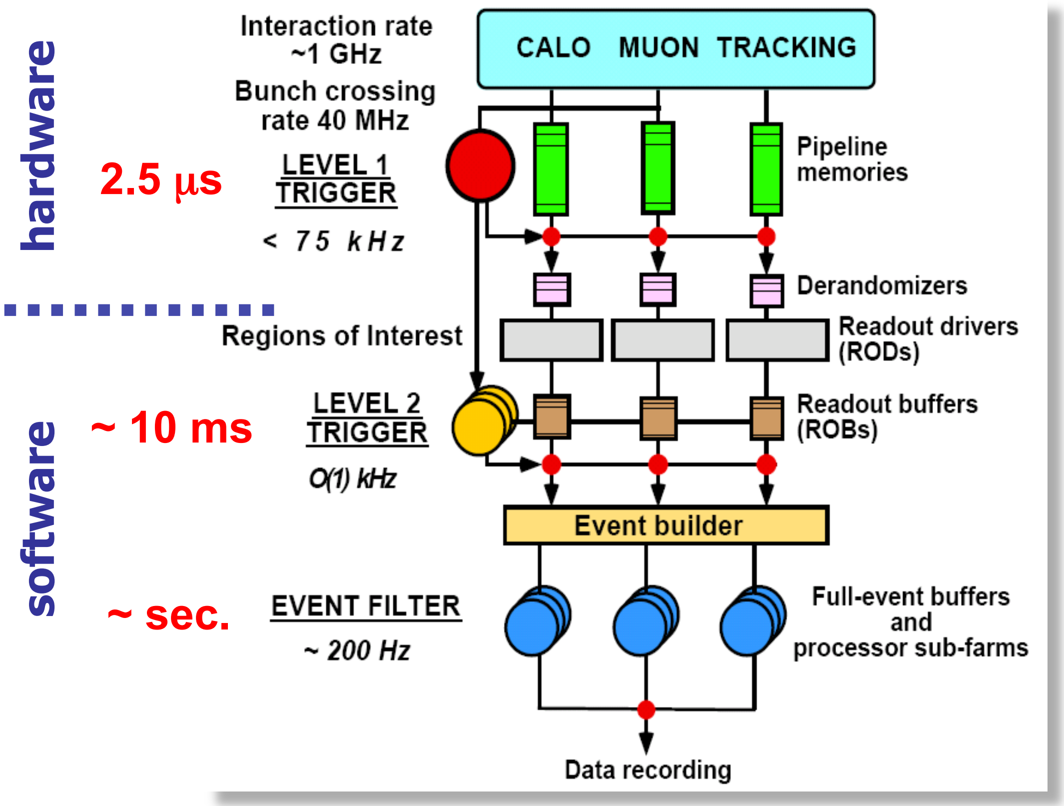
The Standard Model in CMS

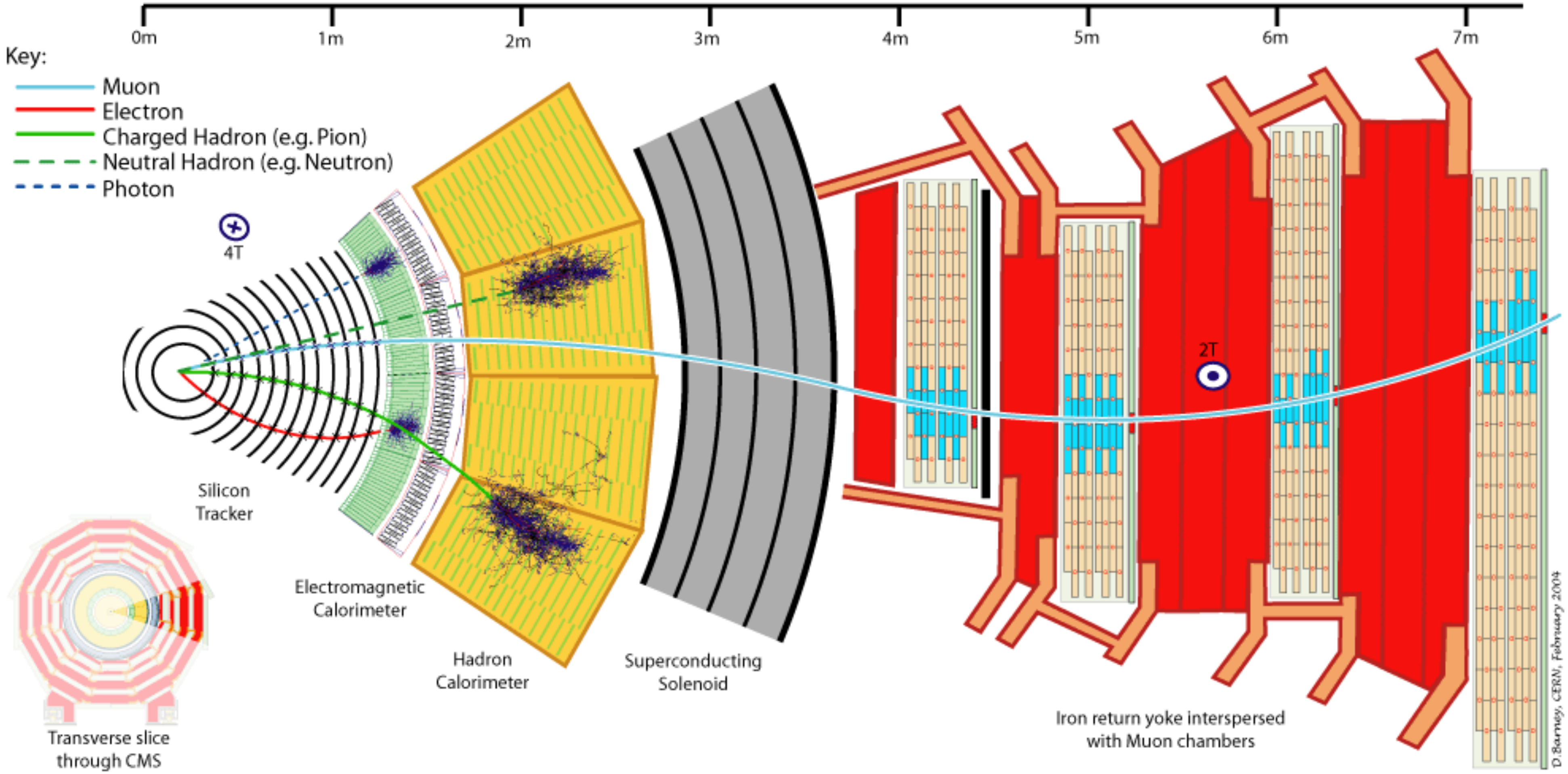


ATLAS Trigger

ATLAS TRIGGER:
3 LEVELS

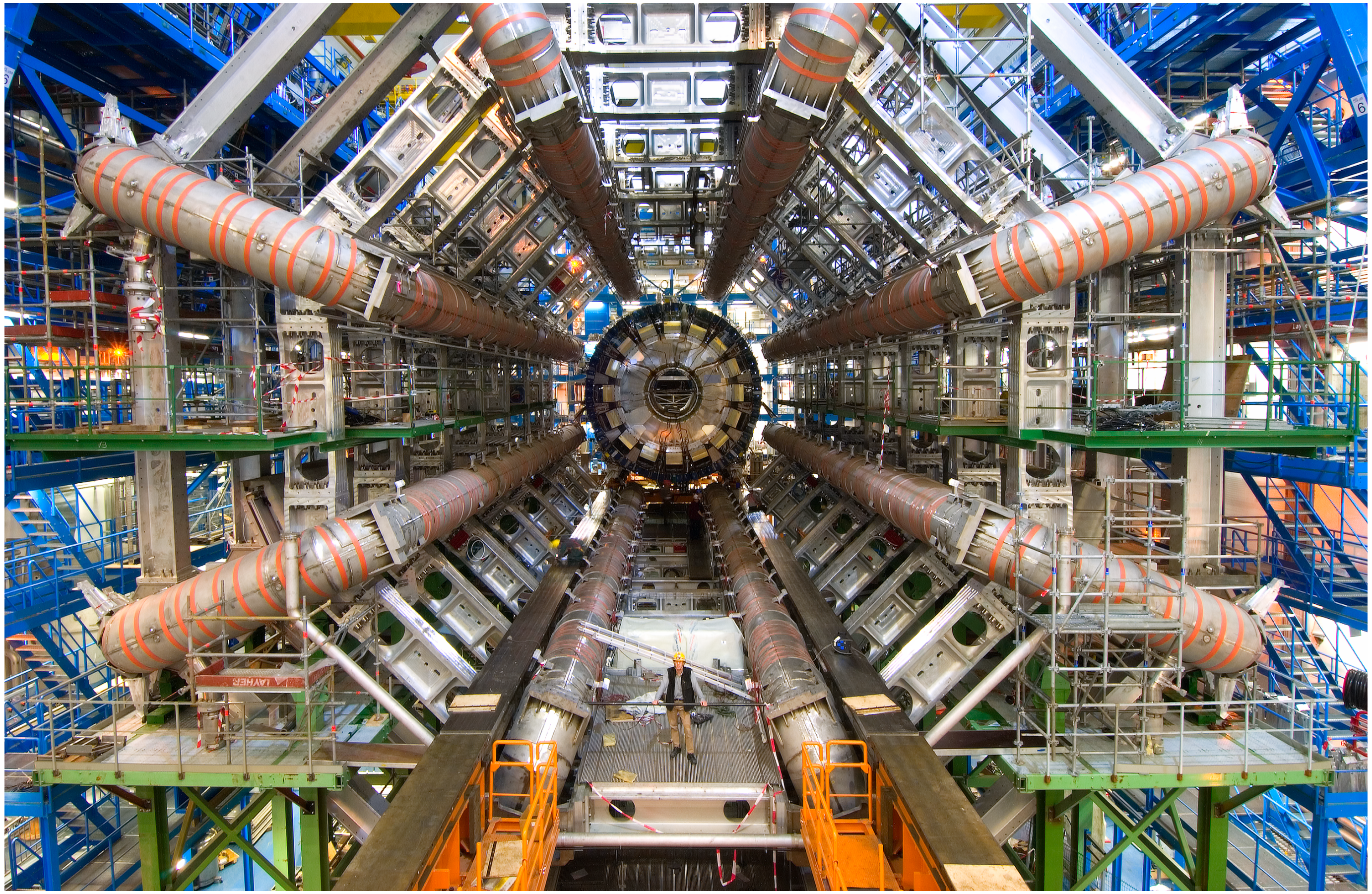
- L1 custom built electronics.
- L1 decision and positions of particle/jet candidates transmitted to the HLT.
- L2 and EF constitute the HLT.
- HLT software analysis of event fragments by dedicated algorithms in PC farms.





0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

TOROID



The outer toroidal magnetic field is produced by eight very large air-core superconducting barrel loops and two end-caps. 26 m long and 20 m in diameter, and it stores 1.6 gigajoules of energy. Its magnetic field is not uniform.