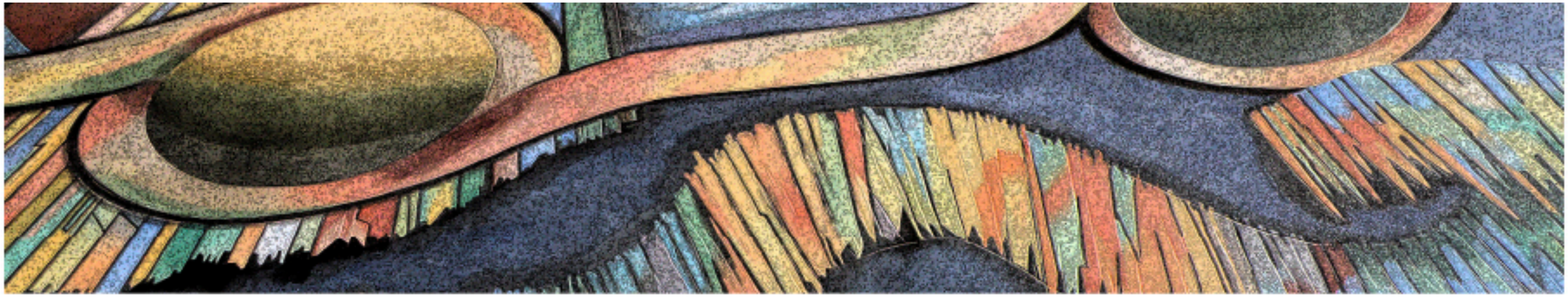


UiO : Department of Physics
University of Oslo

Observing the* Higgs boson

Alex Read (U.Oslo)

Oslo Winter School 2018

Skeikampen, Norway

* The one announced at CERN 04.07.2012

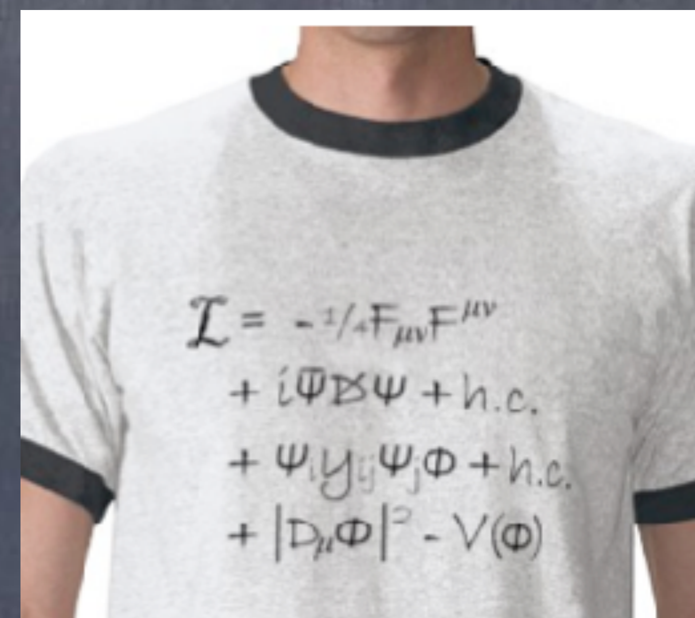
The Research Council of Norway

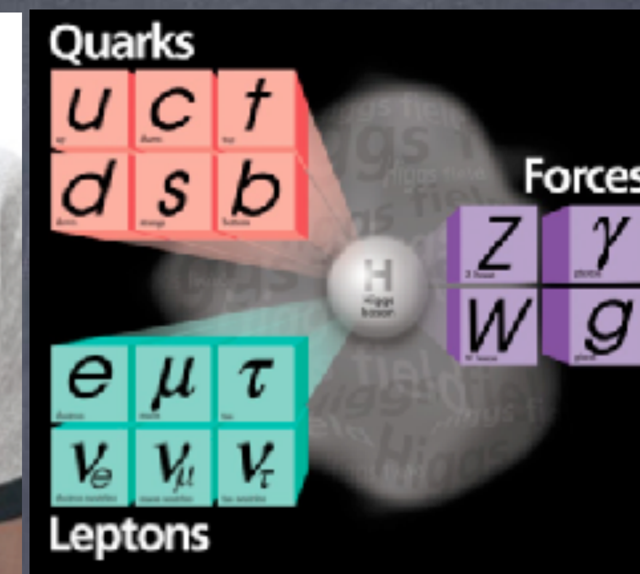
Outline

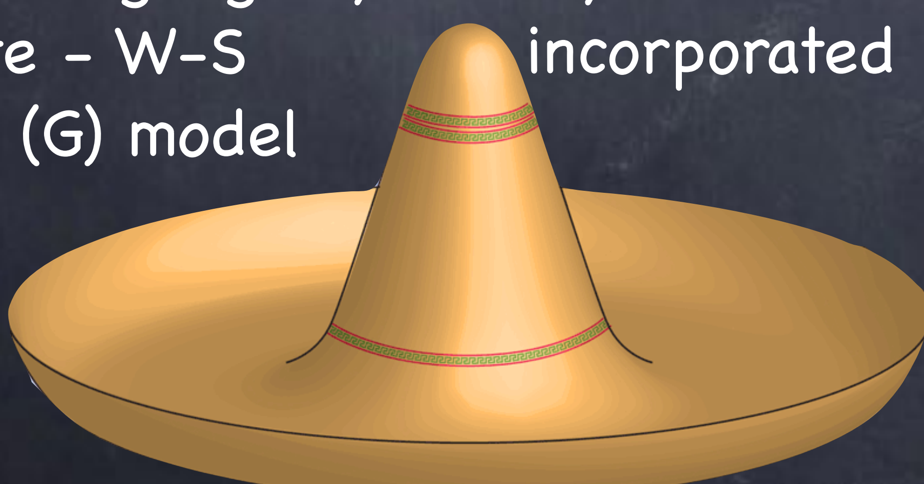
- Recap SM, Higgs boson production @ LHC
- ATLAS and CMS experiments
- Discovery of the Higgs boson

The Higgs boson….
…an integral part of the SM

- Renormalizable relativistic QFT with local gauge invariance $U(1)_Y \times SU(2)_L \times SU(3)_C$
- Success of QED, high-energy behaviour of 4-fermion weak interactions, drives electroweak unification to propose massive gauge bosons (confirmed e.g. at CERN in 1980's and indirectly in the 70's)
- Higgs/BEH/GABEGHHK'tH-mechanism breaks gauge symmetry in the vacuum state - W-S incorporated it in EW (G) model







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

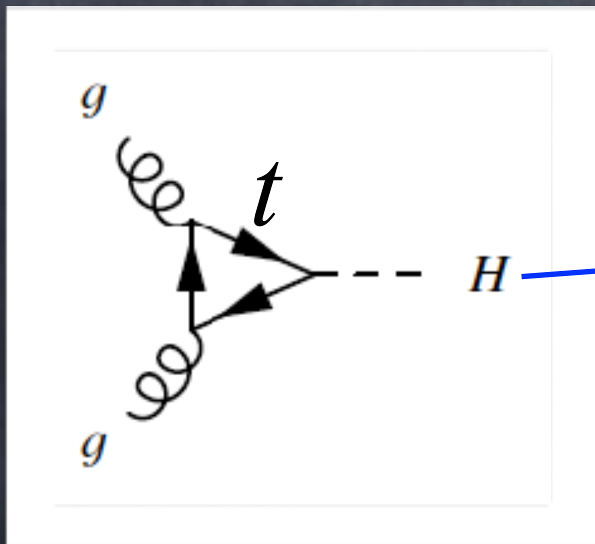
$$v = \sqrt{\frac{-\mu^2}{\lambda}}$$

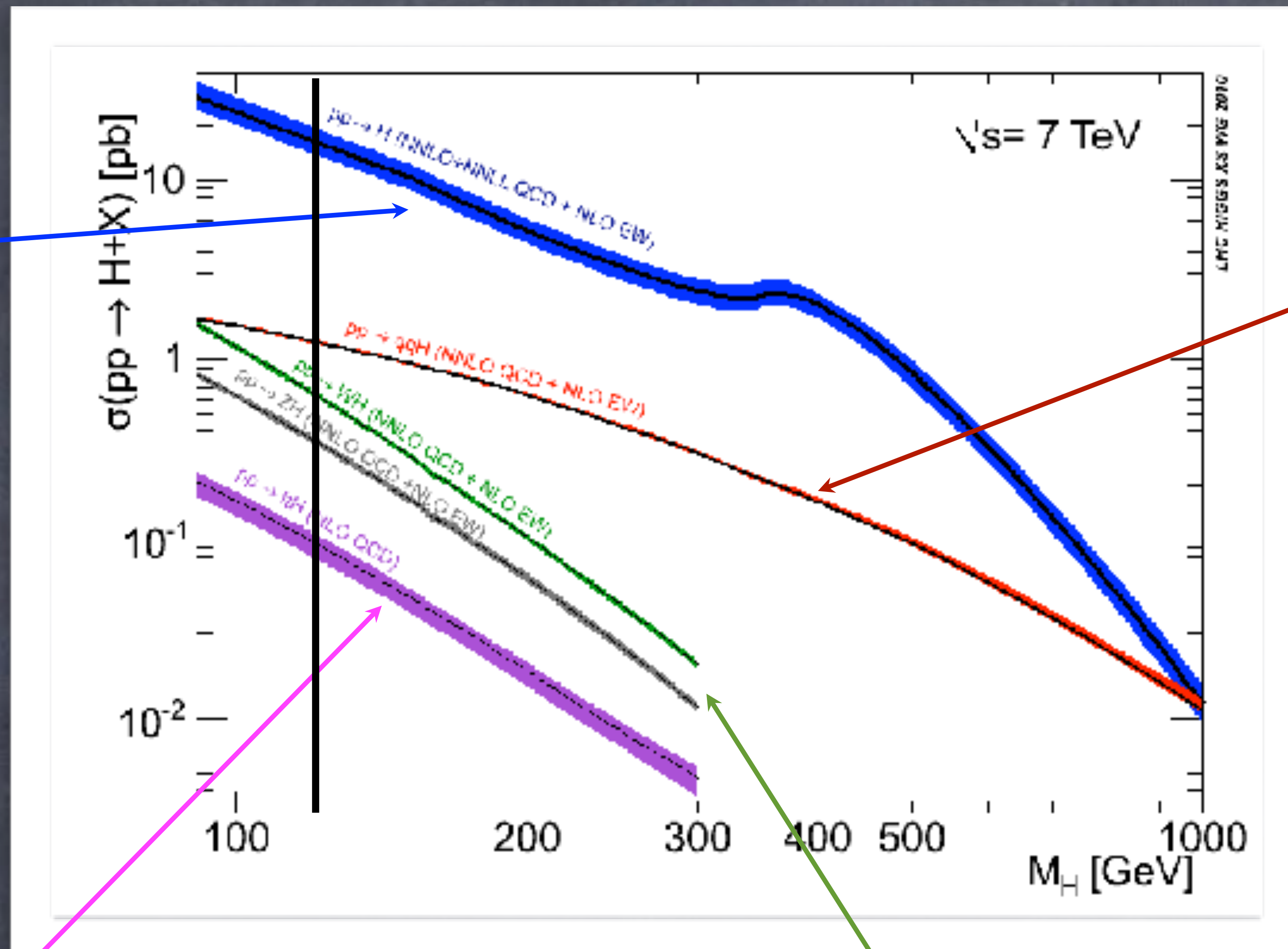
$$g = \frac{e}{\sin\theta_w},\ m_W = \frac{gv}{\sqrt{2}},\ m_Z = \frac{m_W}{\cos\theta_W}$$

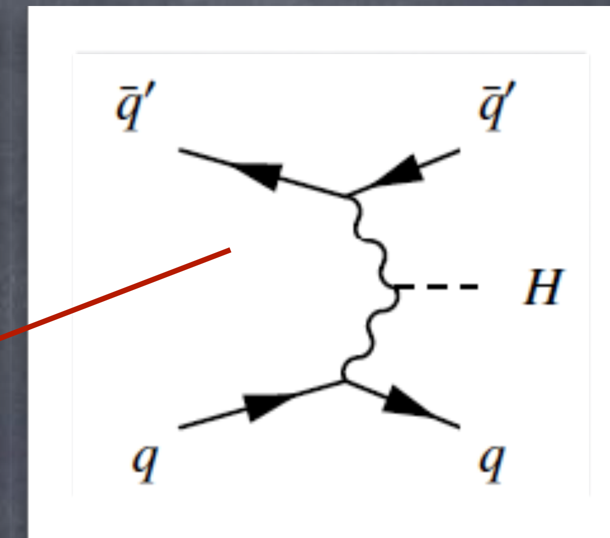
$$m_H^2 = -2\mu^2$$

$$m_f = \frac{vg_f}{\sqrt{2}}, \Gamma_f \sim m_f^2 * n_c$$

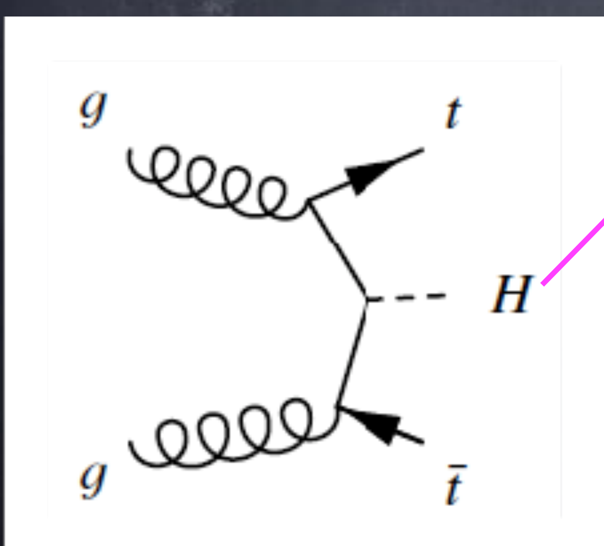
Higgs production @ LHC



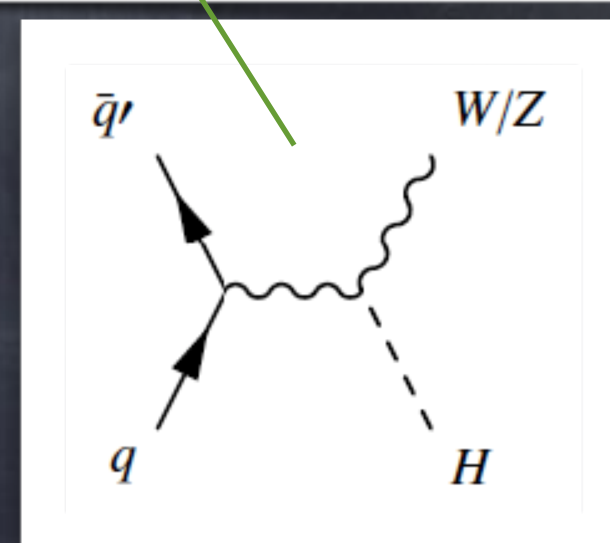




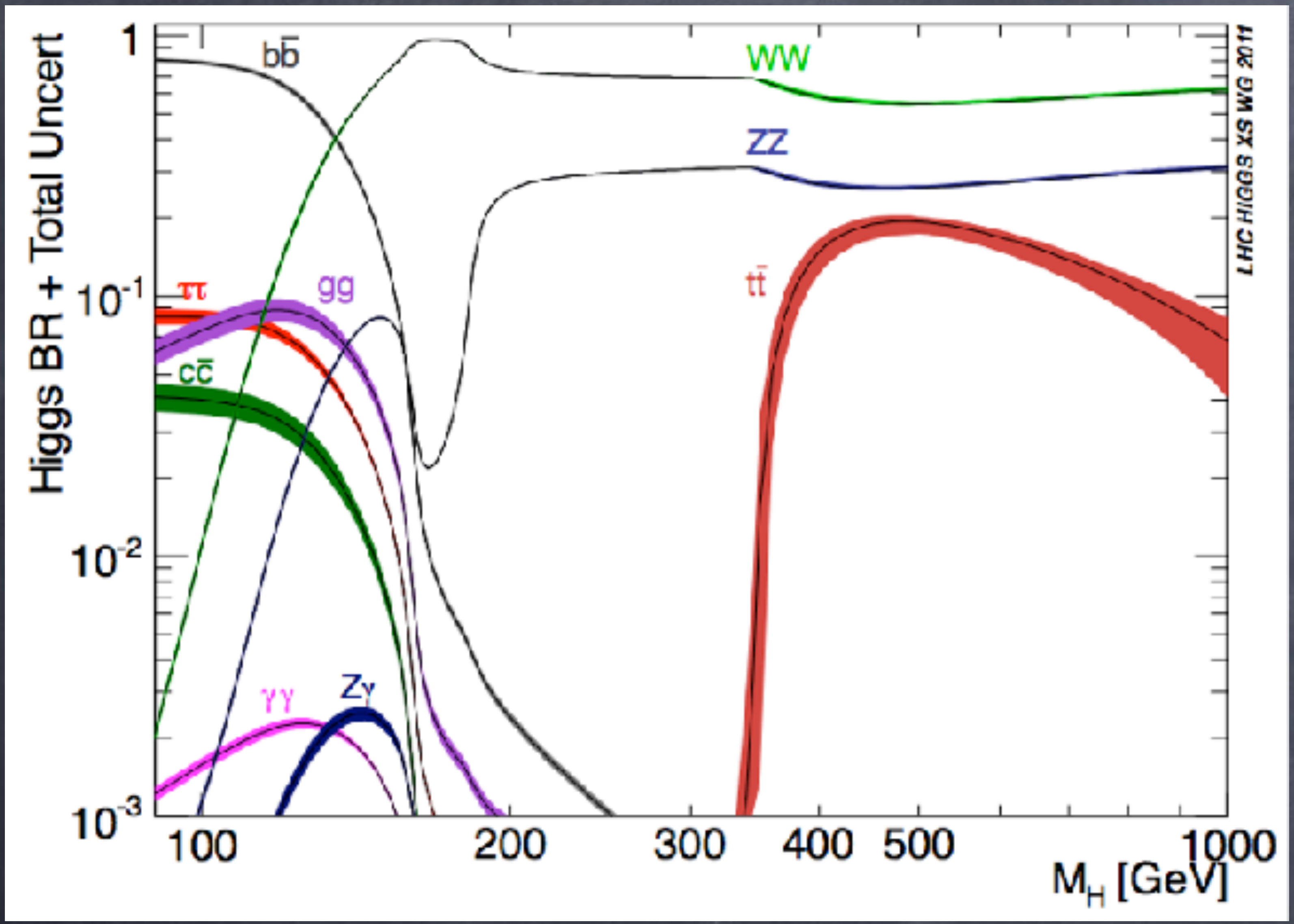
VBF



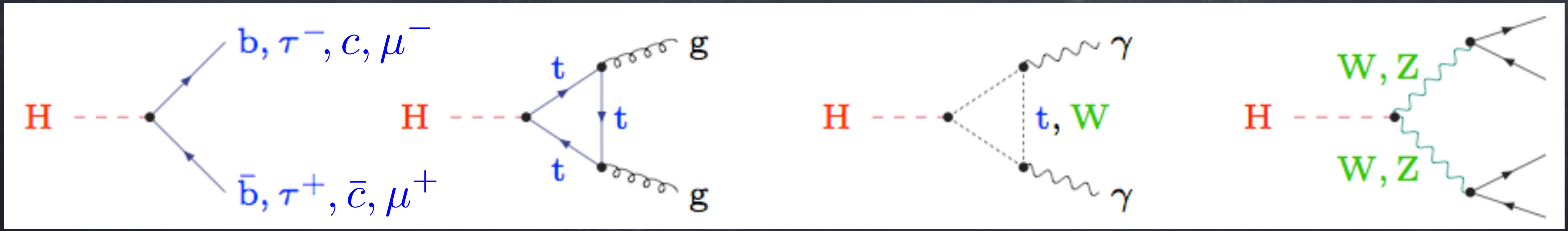
Compiled by LHCXSWG



From m_H to branching fractions



- Assumes no invisible (BSM) width



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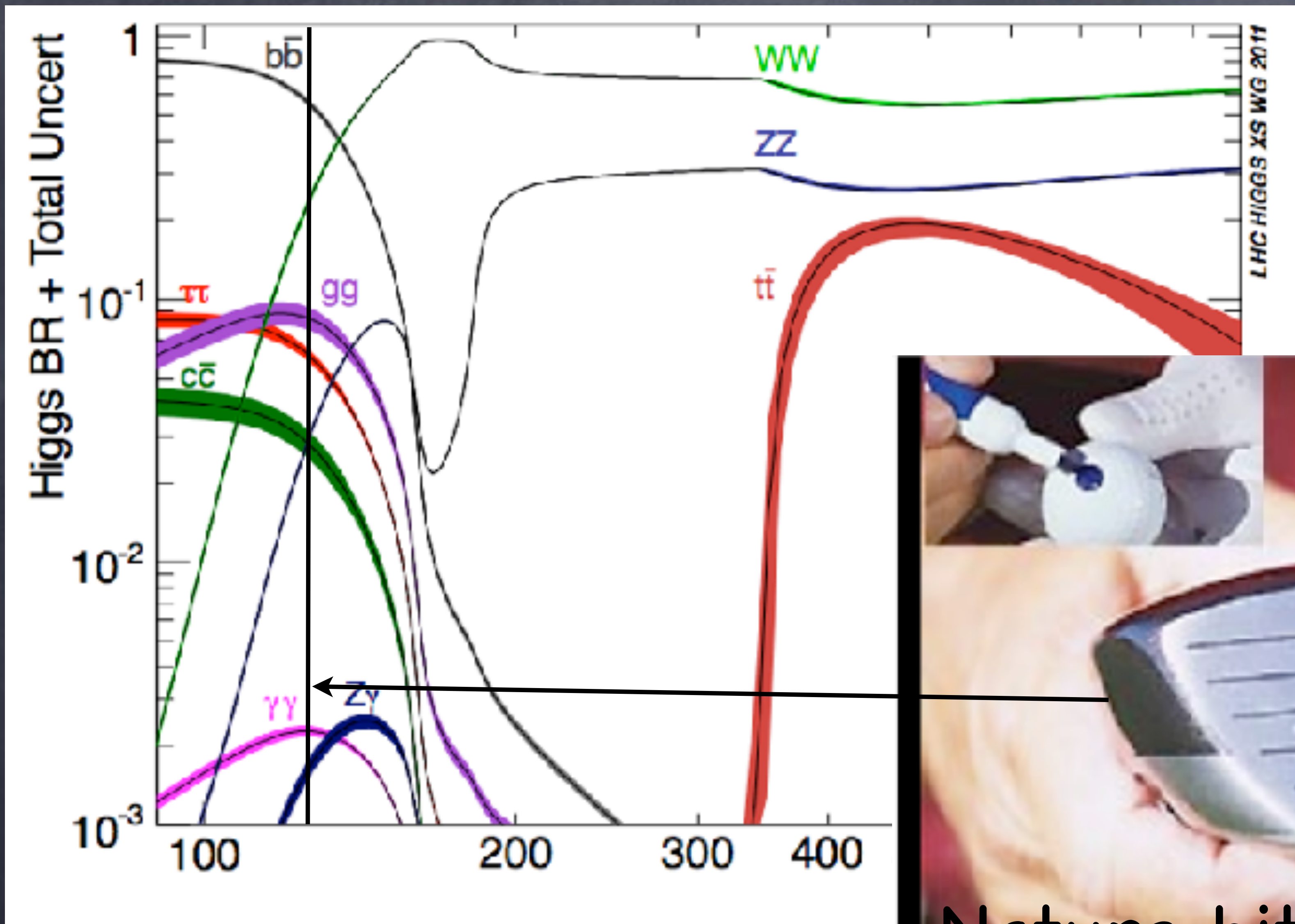

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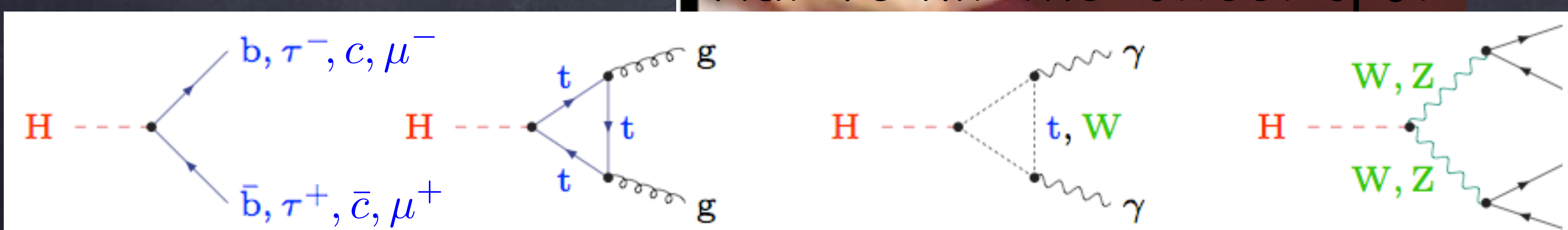
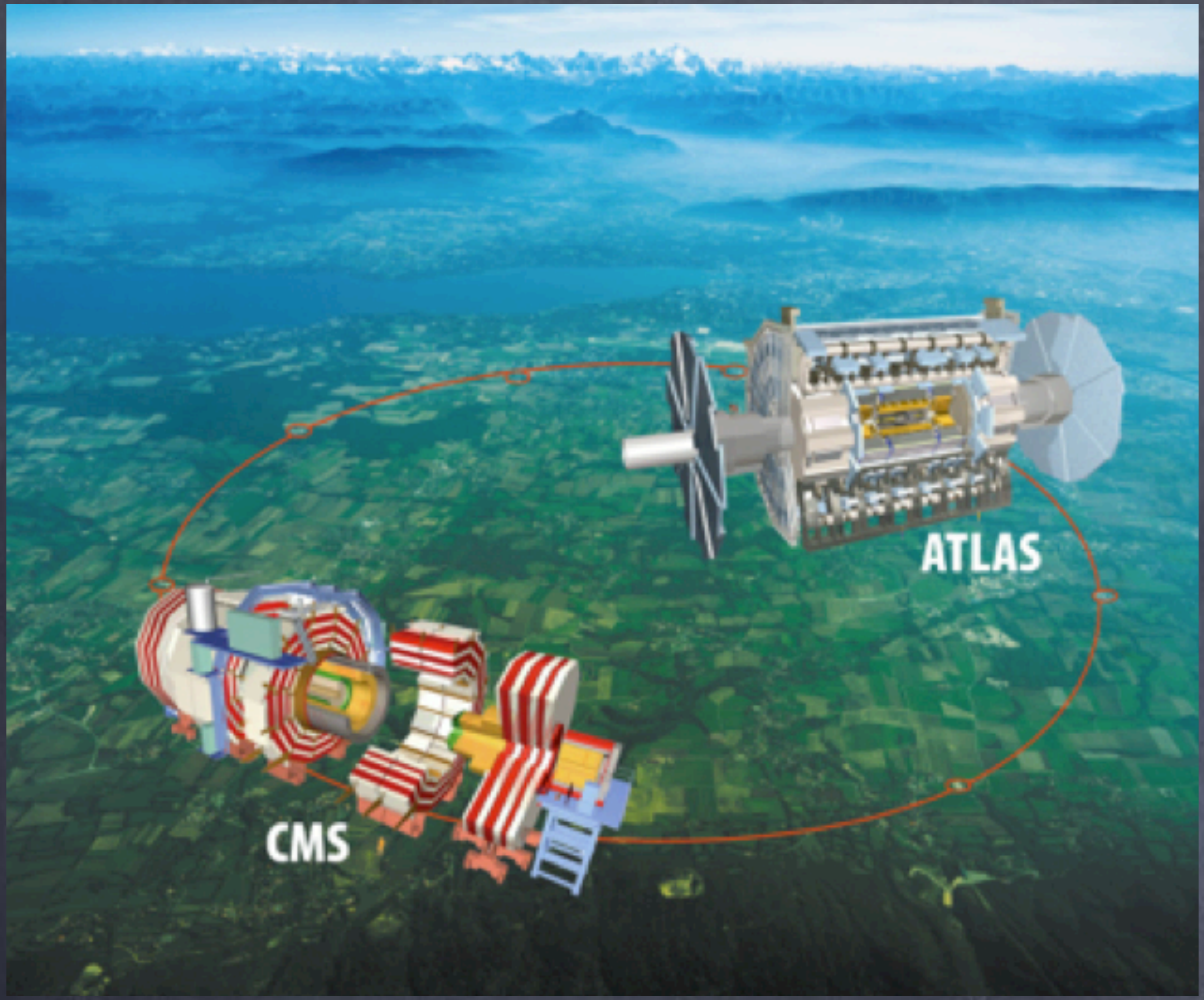


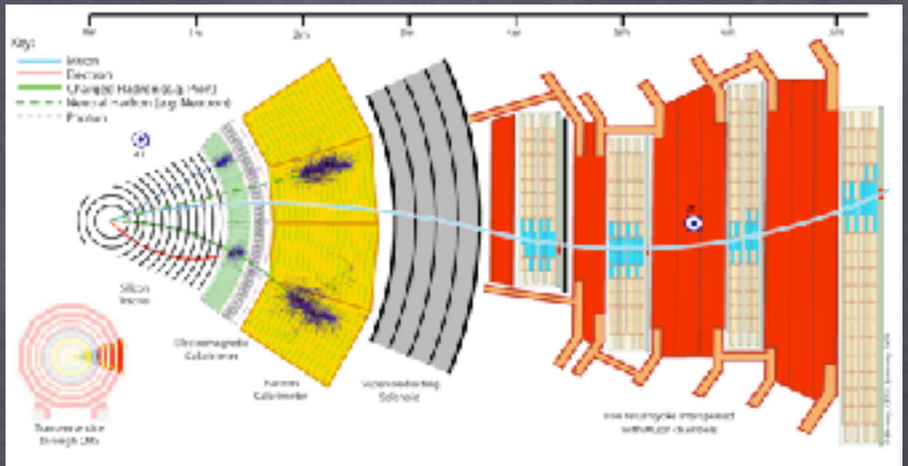
ATLAS, CMS collaborations

CMS, ATLAS experiments

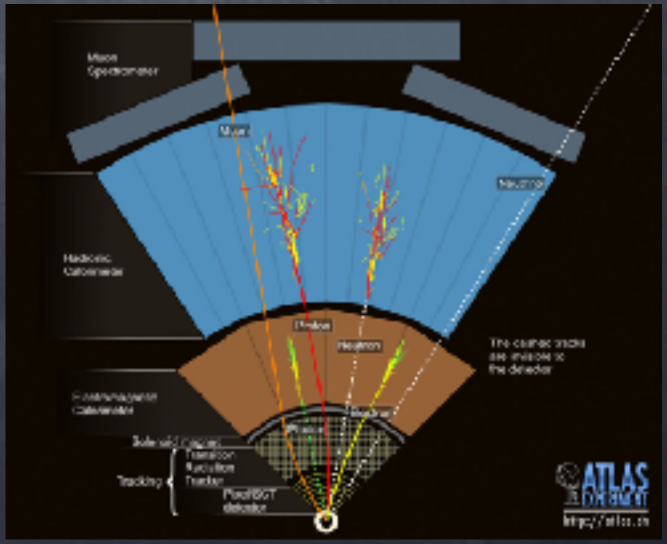


CMS	ATLAS
14 ktons	7 ktons
B=3.8 T	B=2 T
15x29 m	22x45 m

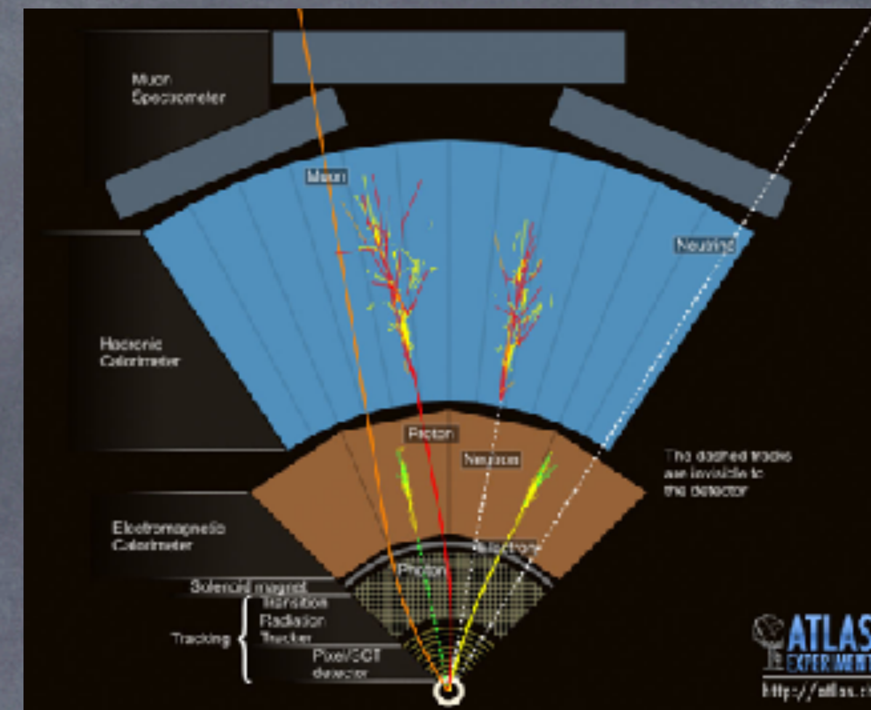
- CMS: Compact, high sol. field, all-Si tracker, crystal ECAL



- ATLAS: Air-core toriod, accordian LAr ECAL

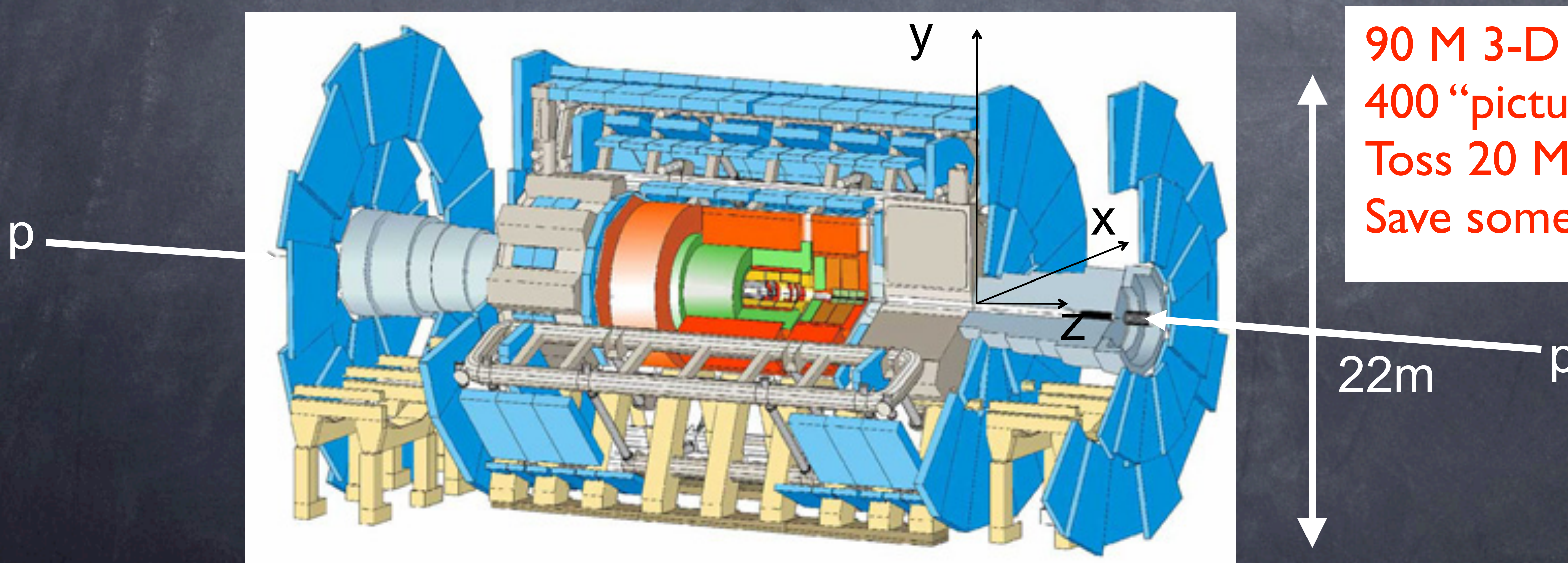


ATLAS-experiment

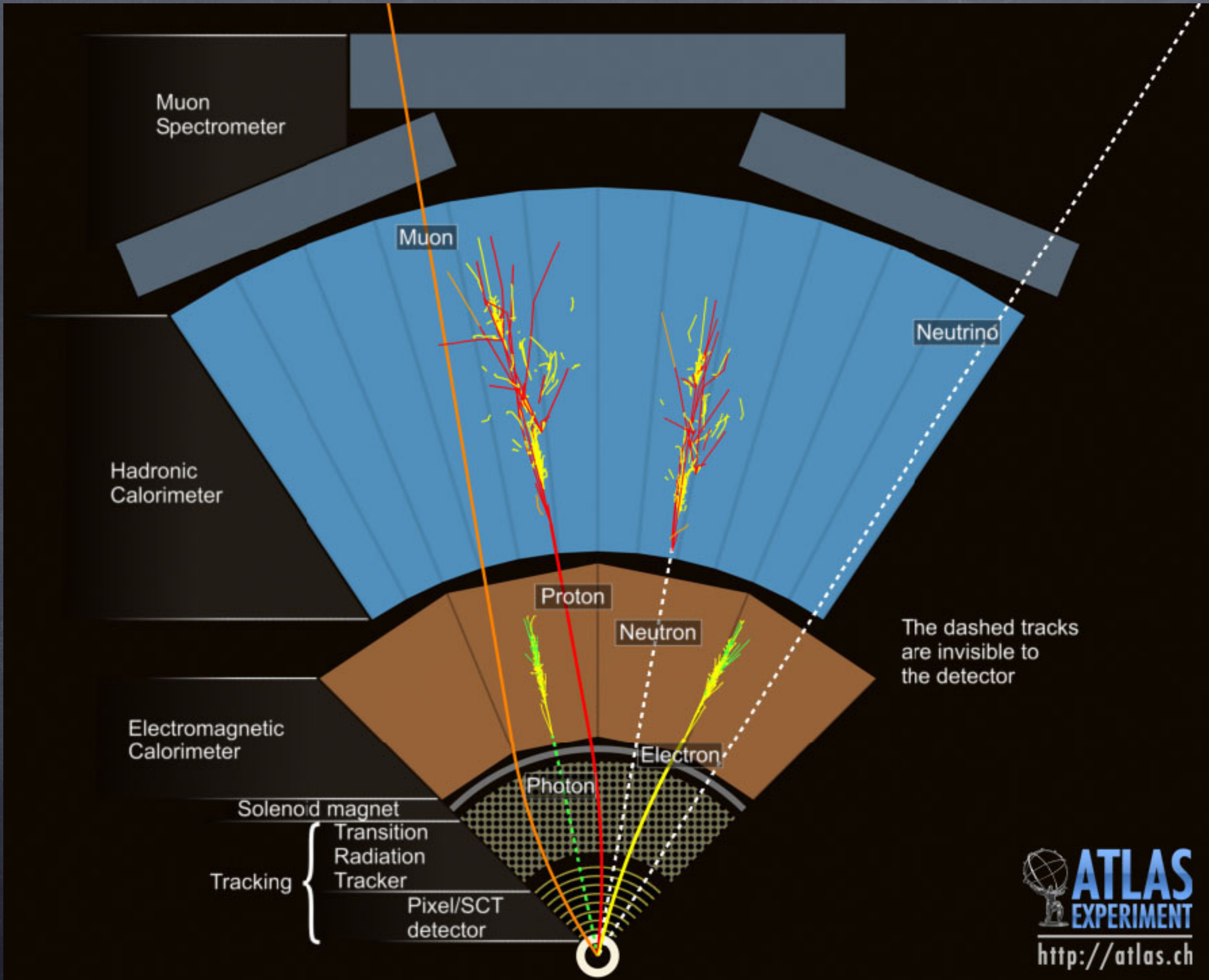


Electrons (stable)
Muons (effectively stable, *why*?!)
Tau-leptons (from decay products)
Jets (from quarks and gluons)
Missing transverse momentum (*why*?!)
(neutrinos, new physics e.g. SUSY)

7000 tonn (~100 tomme Boeing 747er)

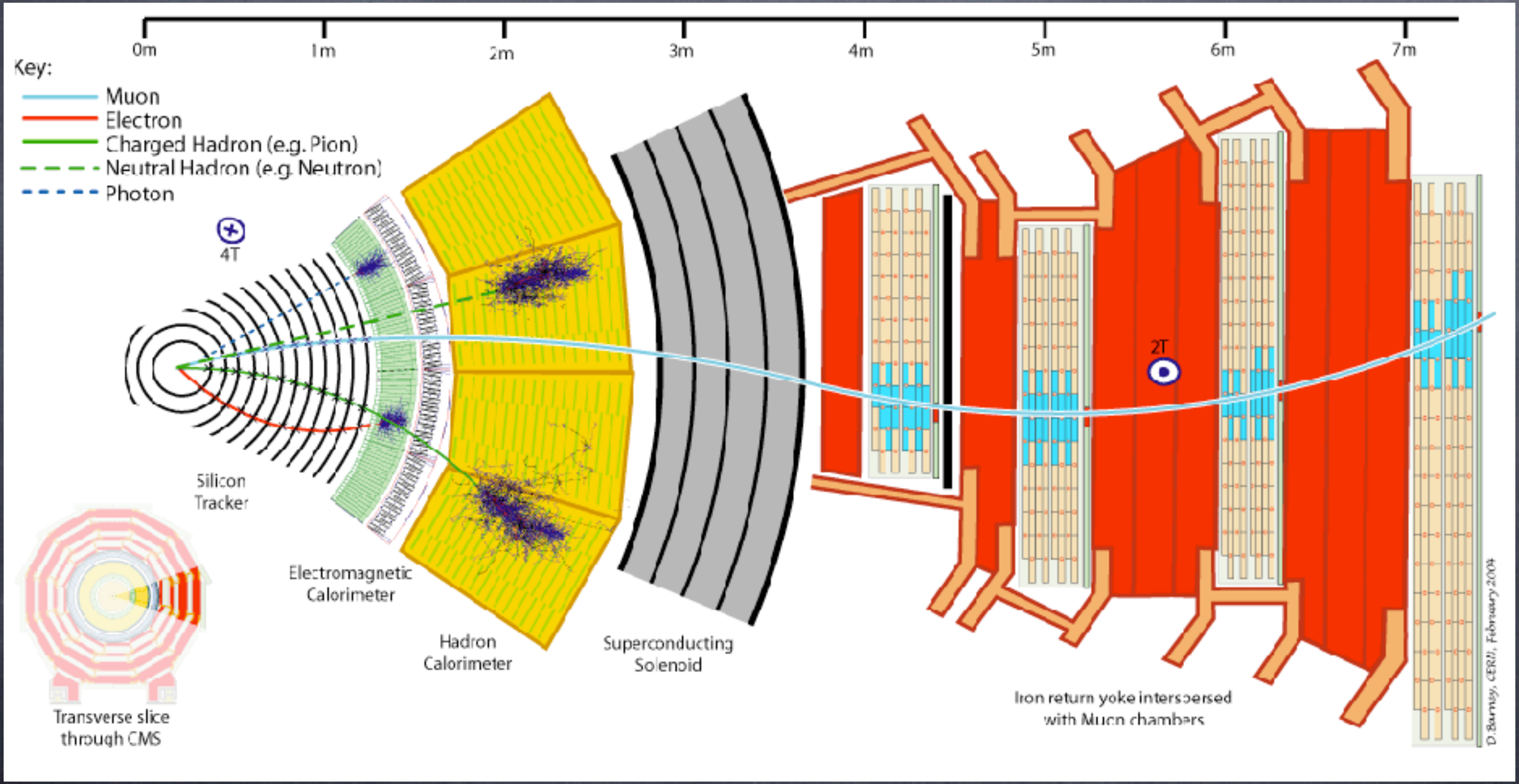


90 M 3-D pixels
400 "pictures"/s
Toss 20 Mpics/s
Save some 1000 TB/yr



Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Proton
Neutron
Neutrino
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

CMS


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

τ–lepton

μ^+ modes are charge conjugates of the modes below.

μ^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^- \nu_e \nu_\mu$		$\approx 100\%$		53
$e^- \overline{\nu}_e \nu_\mu \gamma$	[d]	(1.4 ± 0.4) %		53
$e^- \overline{\nu}_e \nu_\mu e^+ e^-$	[e]	$(3.4 \pm 0.4) \times 10^{-5}$		53
Lepton Family number (*LF*) violating modes				
$e^- \nu_e \overline{\nu}_\mu$	*LF* [f]	< 1.2 %	90%	53
$e^- \gamma$	*LF*	$< 5.7 \times 10^{-13}$	90%	53
$e^- e^+ e^-$	*LF*	$< 1.0 \times 10^{-12}$	90%	53
$e^- 2\gamma$	*LF*	$< 7.2 \times 10^{-11}$	90%	53

τ $J = \frac{1}{2}$

Mass $m = 1776.86 \pm 0.12$ MeV
$(m_{\tau^+} - m_{\tau^-})/m_{\text{average}} < 2.8 \times 10^{-4}$, CL = 90%
Mean life $\tau = (290.3 \pm 0.5) \times 10^{-15}$ s
$c\tau = 87.03\ \mu$m
Magnetic moment anomaly > -0.052 and < 0.013, CL = 95%
$\text{Re}(d_\tau) = -0.220$ to 0.45×10^{-16} $e$cm, CL = 95%
$\text{Im}(d_\tau) = -0.250$ to 0.0080×10^{-16} $e$cm, CL = 95%

Weak dipole moment

$\text{Re}(d_\tau^w) < 0.50 \times 10^{-17}$ $e$cm, CL = 95%
$\text{Im}(d_\tau^w) < 1.1 \times 10^{-17}$ $e$cm, CL = 95%

Weak anomalous magnetic dipole moment

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$\tau^\pm \to \pi^\pm K_S^0 \nu_\tau$ (RATE DIFFERENCE) / (RATE SUM) = (-0.36 ± 0.25)%

Decay parameters

See the τ Particle Listings for a note concerning τ-decay parameters.

$\rho(e \text{ or } \mu) = 0.745 \pm 0.008$
$\rho(e) = 0.747 \pm 0.010$
$\rho(\mu) = 0.763 \pm 0.020$
$\xi(e \text{ or } \mu) = 0.985 \pm 0.030$
$\xi(e) = 0.994 \pm 0.040$
$\xi(\mu) = 1.030 \pm 0.059$
$\eta(e \text{ or } \mu) = 0.013 \pm 0.020$
$\eta(\mu) = 0.094 \pm 0.073$

$(\delta\xi)(e \text{ or } \mu) = 0.746 \pm 0.021$
$(\delta\xi)(e) = 0.734 \pm 0.028$
$(\delta\xi)(\mu) = 0.778 \pm 0.037$
$\xi(\pi) = 0.993 \pm 0.022$
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$\xi(\text{all hadronic modes}) = 0.995 \pm 0.007$

τ^+ modes are charge conjugates of the modes below. "$h^\pm$" stands for $\pi^\pm$ or $K^\pm$. "ℓ" stands for e or μ. "Neutrals" stands for γ's and/or π^0's.

τ^- DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Modes with one charged particle				
particle$^- \geq 0$ neutrals $\geq 0 K^0 \nu_\tau$ ("1-prong")		(85.24 ± 0.06) %		–
particle$^- \geq 0$ neutrals $\geq 0 K_L^0 \nu_\tau$		(84.58 ± 0.06) %		–
$\mu^- \overline{\nu}_\mu \nu_\tau$	[g]	(17.39 ± 0.04) %		885
$\mu^- \overline{\nu}_\mu \nu_\tau \gamma$	[e]	$(3.68 \pm 0.10) \times 10^{-3}$		885
$e^- \overline{\nu}_e \nu_\tau$	[g]	(17.82 ± 0.04) %		888
$e^- \overline{\nu}_e \nu_\tau \gamma$	[e]	(1.84 ± 0.05) %		888
$h^- \geq 0 K_L^0\ \nu_\tau$		(12.03 ± 0.05) %		883
$h^- \nu_\tau$		(11.51 ± 0.05) %		883
$\pi^- \nu_\tau$	[g]	(10.82 ± 0.05) %		883
$K^- \nu_\tau$	[g]	$(6.96 \pm 0.10) \times 10^{-3}$		820
$h^- \geq 1$ neutrals ν_τ		(37.00 ± 0.09) %		–
$h^- \geq 1\pi^0 \nu_\tau (\text{ex.} K^0)$		(36.51 ± 0.09) %		–
$h^- \pi^0 \nu_\tau$		(25.93 ± 0.09) %		878
$\pi^- \pi^0 \nu_\tau$	[g]	(25.49 ± 0.09) %		878
$\pi^- \pi^0$ non-$\rho(770) \nu_\tau$		$(3.0 \pm 3.2) \times 10^{-3}$		878
$K^- \pi^0 \nu_\tau$	[g]	$(4.33 \pm 0.15) \times 10^{-3}$		814
$h^- \geq 2\pi^0 \nu_\tau$		(10.81 ± 0.09) %		–
$h^- 2\pi^0 \nu_\tau$		(9.48 ± 0.10) %		862
$h^- 2\pi^0 \nu_\tau (\text{ex.} K^0)$		(9.32 ± 0.10) %		862
$\pi^- 2\pi^0 \nu_\tau (\text{ex.} K^0)$	[g]	(9.26 ± 0.10) %		862
$\pi^- 2\pi^0 \nu_\tau (\text{ex.} K^0)$, scalar		$< 9 \times 10^{-3}$	CL=95%	862
$\pi^- 2\pi^0 \nu_\tau (\text{ex.} K^0)$, vector		$< 7 \times 10^{-3}$	CL=95%	862
$K^- 2\pi^0 \nu_\tau (\text{ex.} K^0)$	[g]	$(6.5 \pm 2.2) \times 10^{-4}$		796
$h^- \geq 3\pi^0 \nu_\tau$		(1.34 ± 0.07) %		–
$h^- \geq 3\pi^0 \nu_\tau (\text{ex. } K^0)$		(1.25 ± 0.07) %		–
$h^- 3\pi^0 \nu_\tau$		(1.18 ± 0.07) %		836
$\pi^- 3\pi^0 \nu_\tau (\text{ex.} K^0)$	[g]	(1.04 ± 0.07) %		836

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And 6 more pages!!

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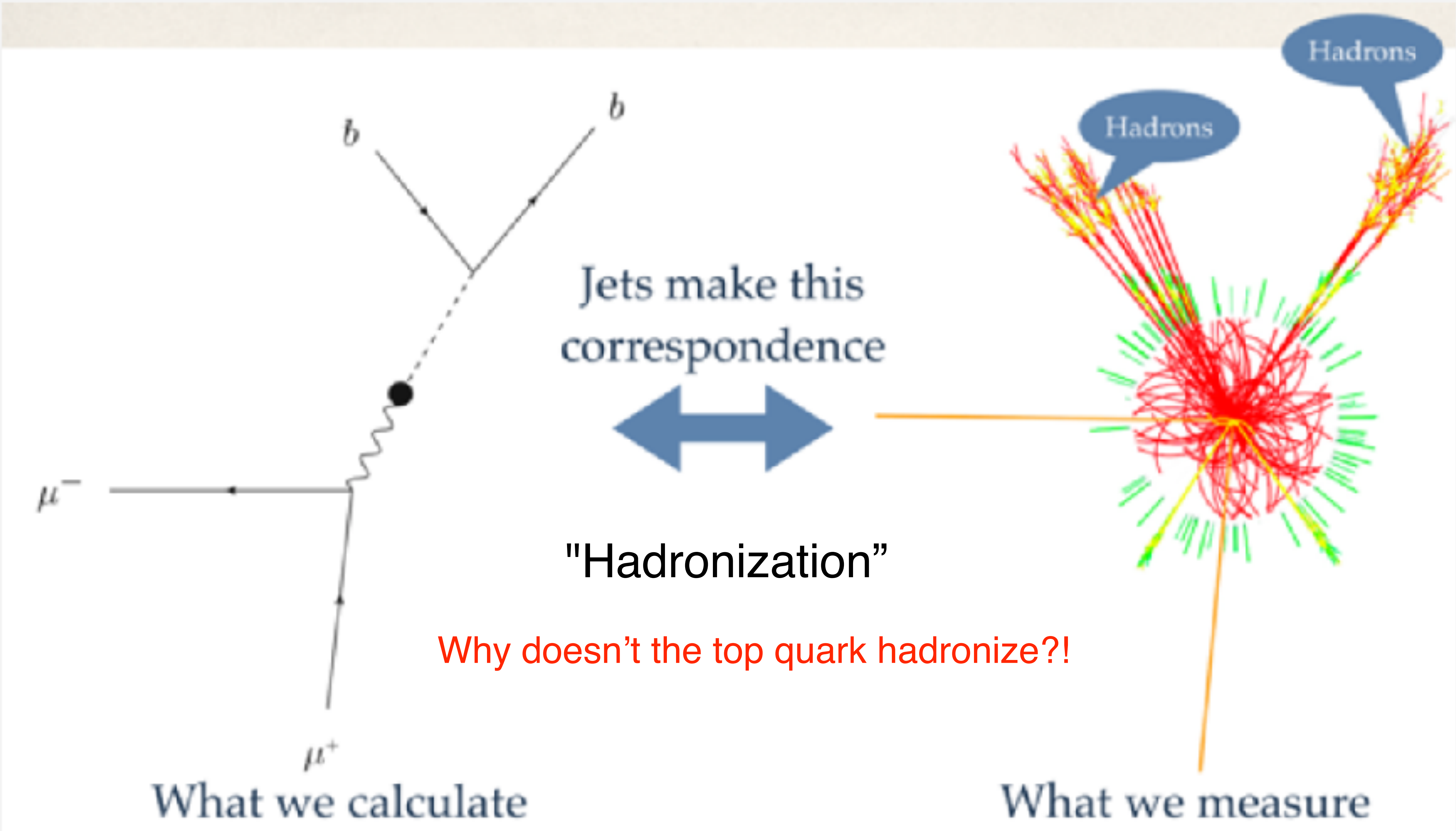
Quark and gluon "jets"



Simulated event from ATLAS Experiment © 2011 CERN

- LHC challenge: Find 10^5 Higgs bosons in 10^{15} proton-proton-collisions.

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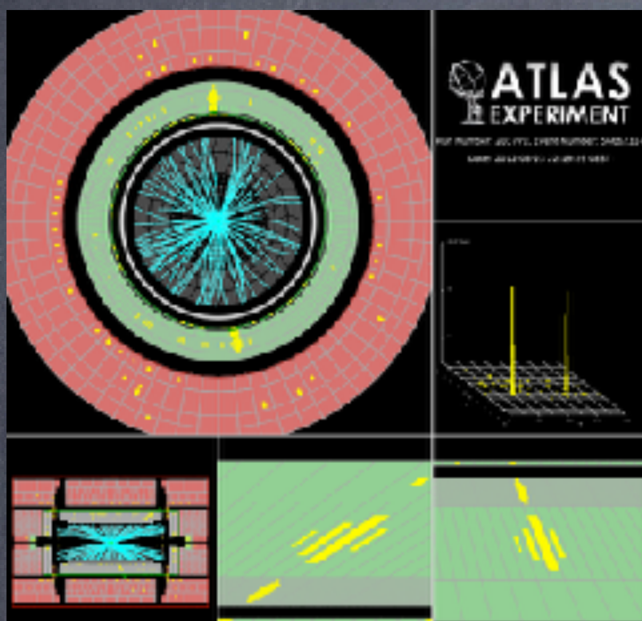
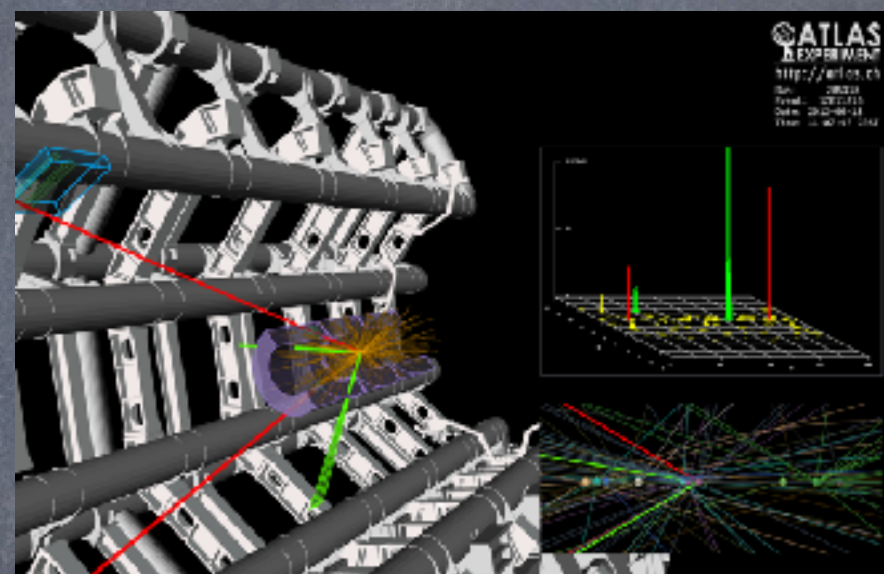
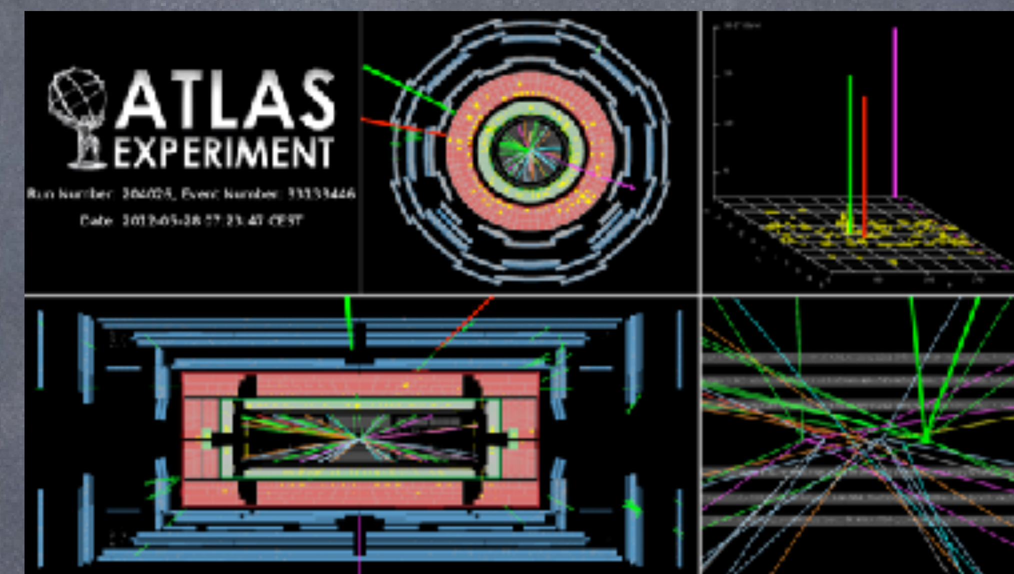
Results 4 July (*), 2012







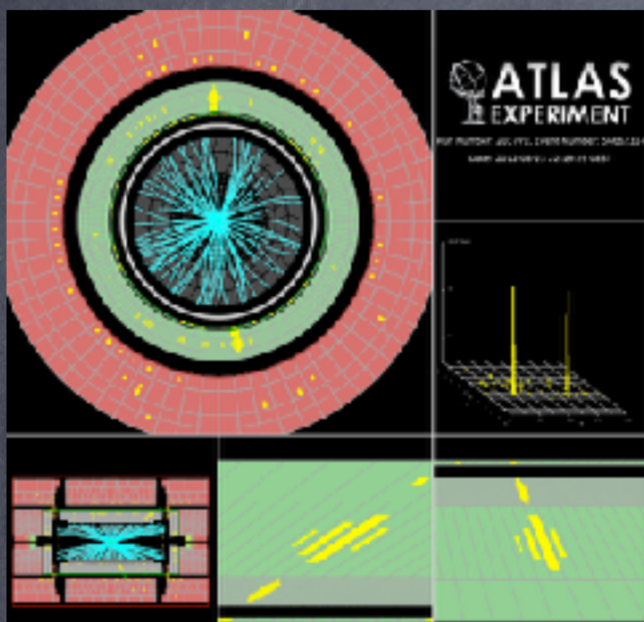
$$H \rightarrow Z^0 Z^0 \rightarrow e^+ e^- \mu^+ \mu^-$$

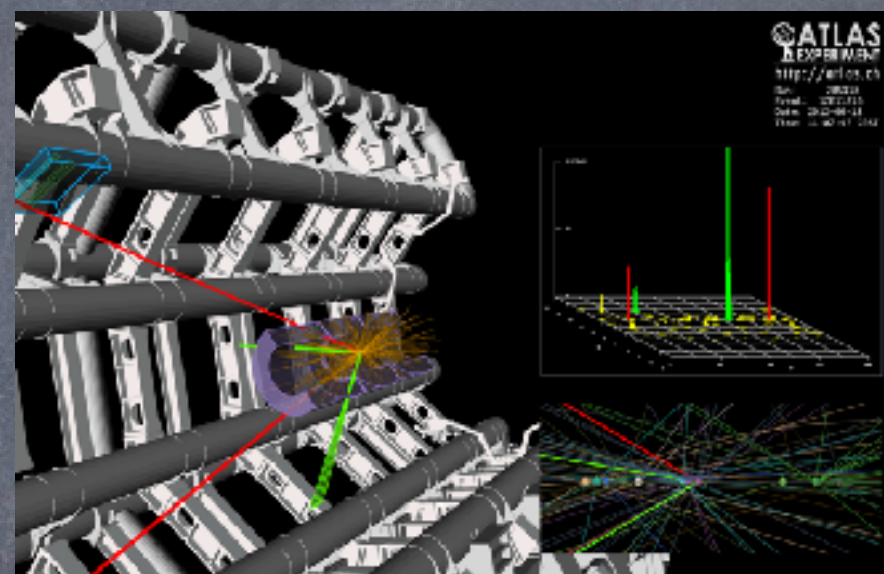
Which is which?!

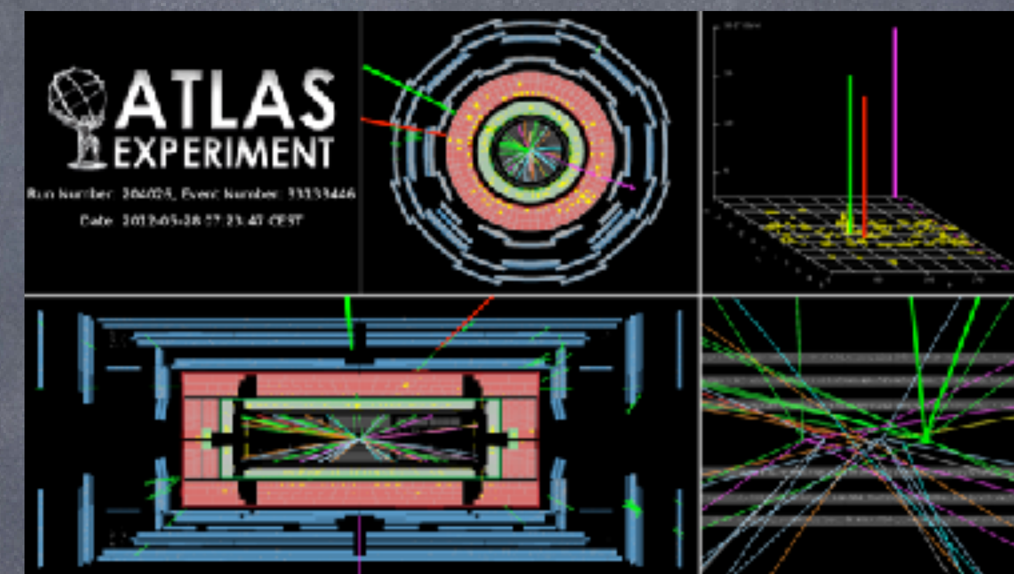
$$H \rightarrow W^+ W^- \rightarrow e^+ \nu_e \mu^- \bar{\nu_\mu}$$

$$H \rightarrow \gamma\gamma$$

Results 4 July (*), 2012







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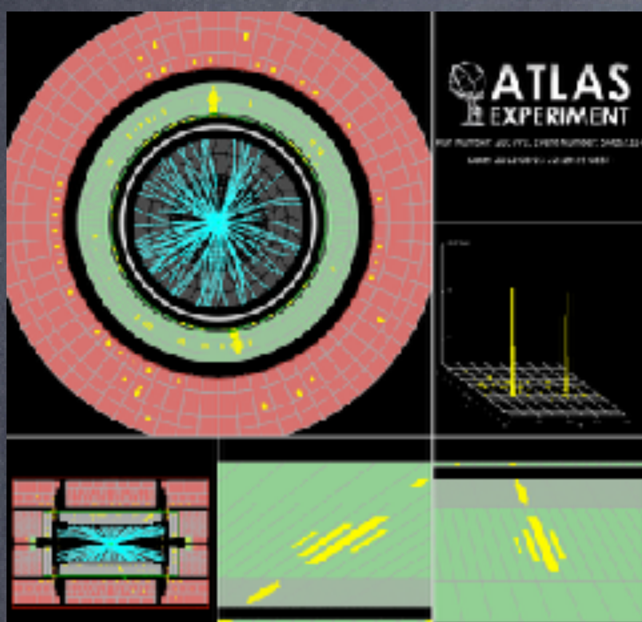
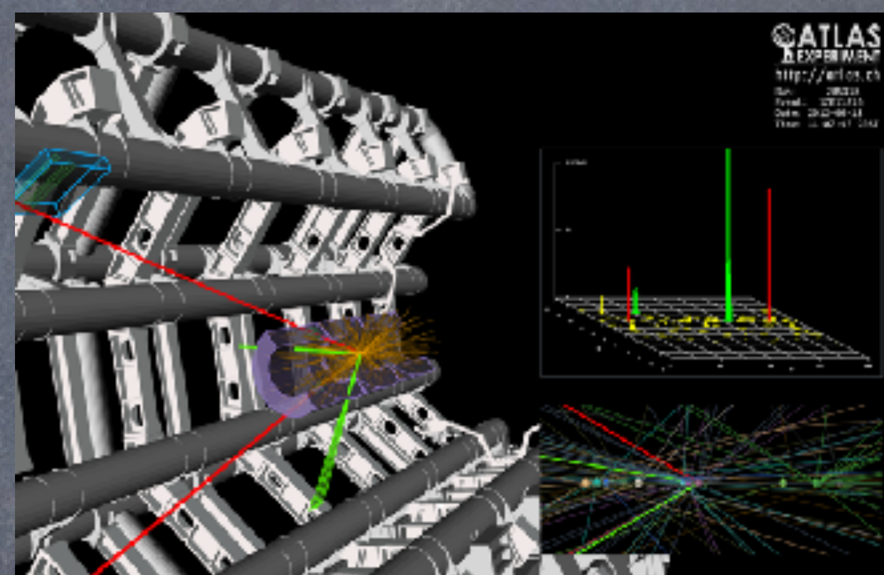
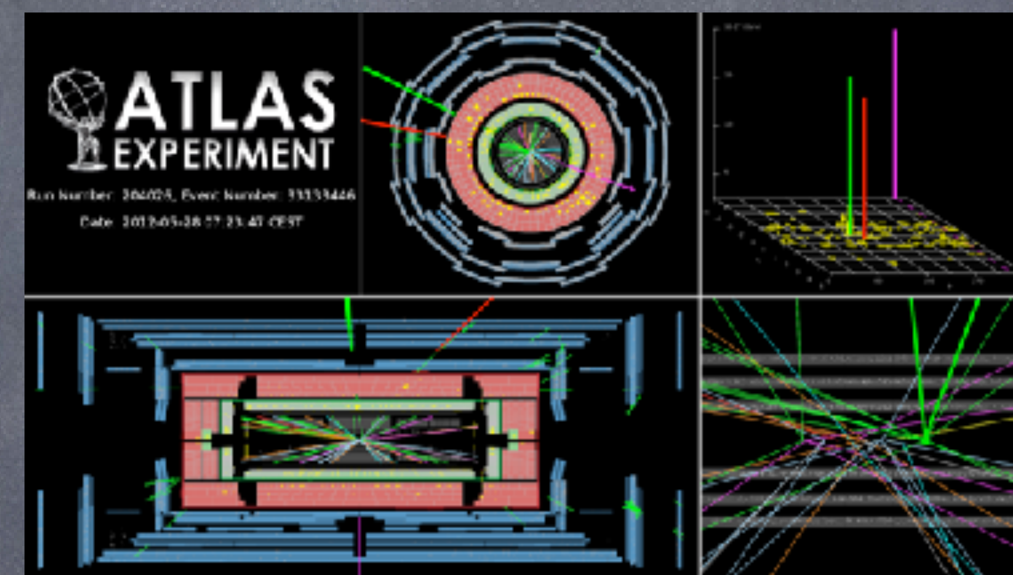
$$H \rightarrow \gamma\gamma$$

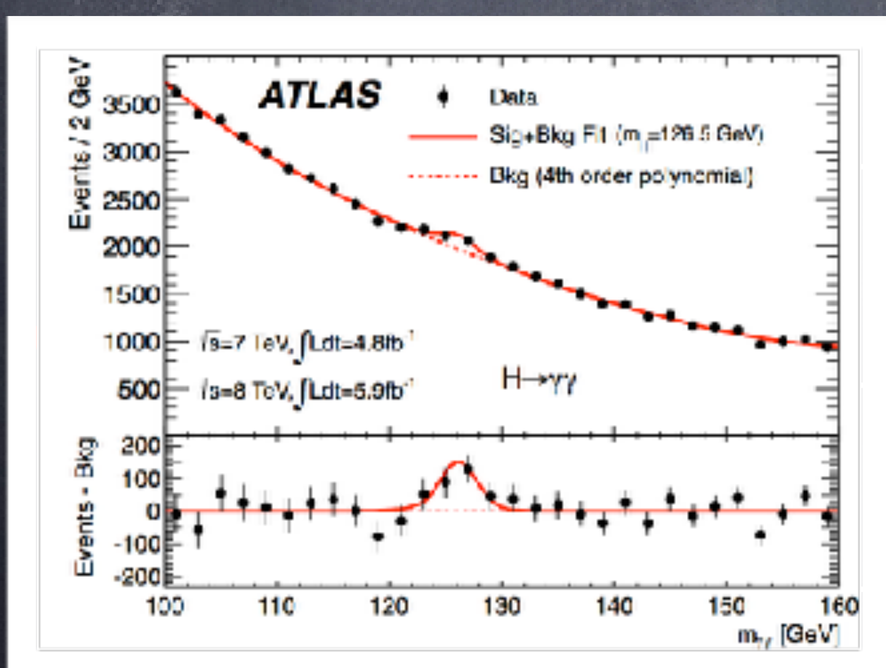
Results 4 July (*), 2012

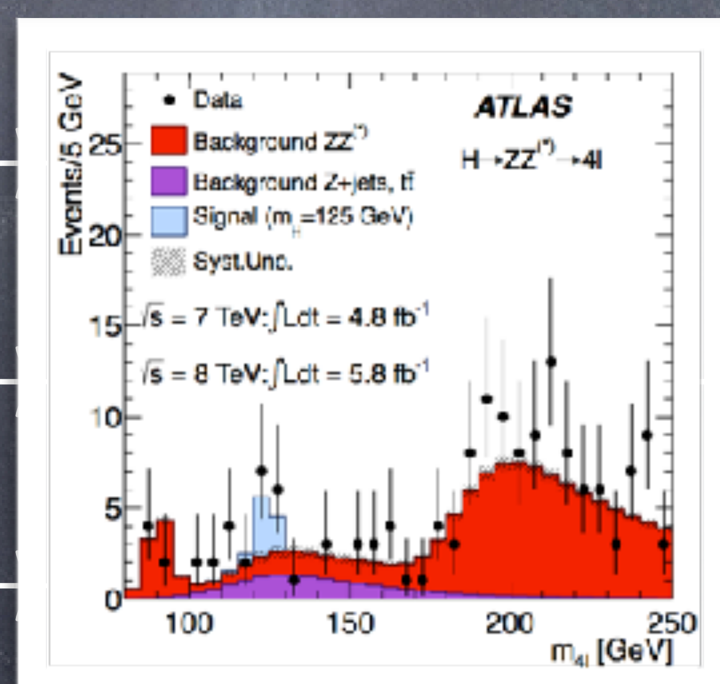


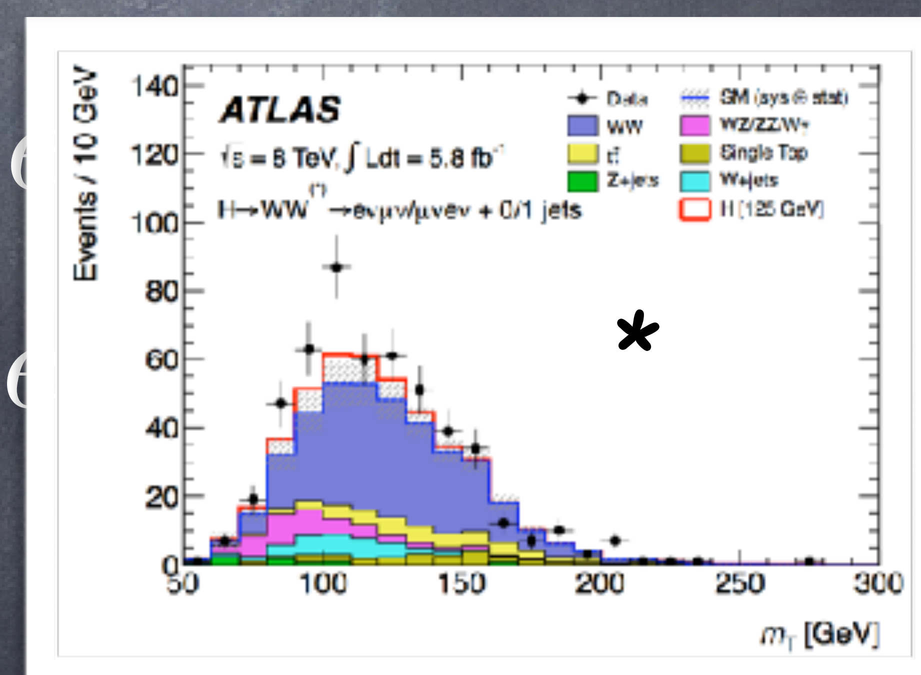




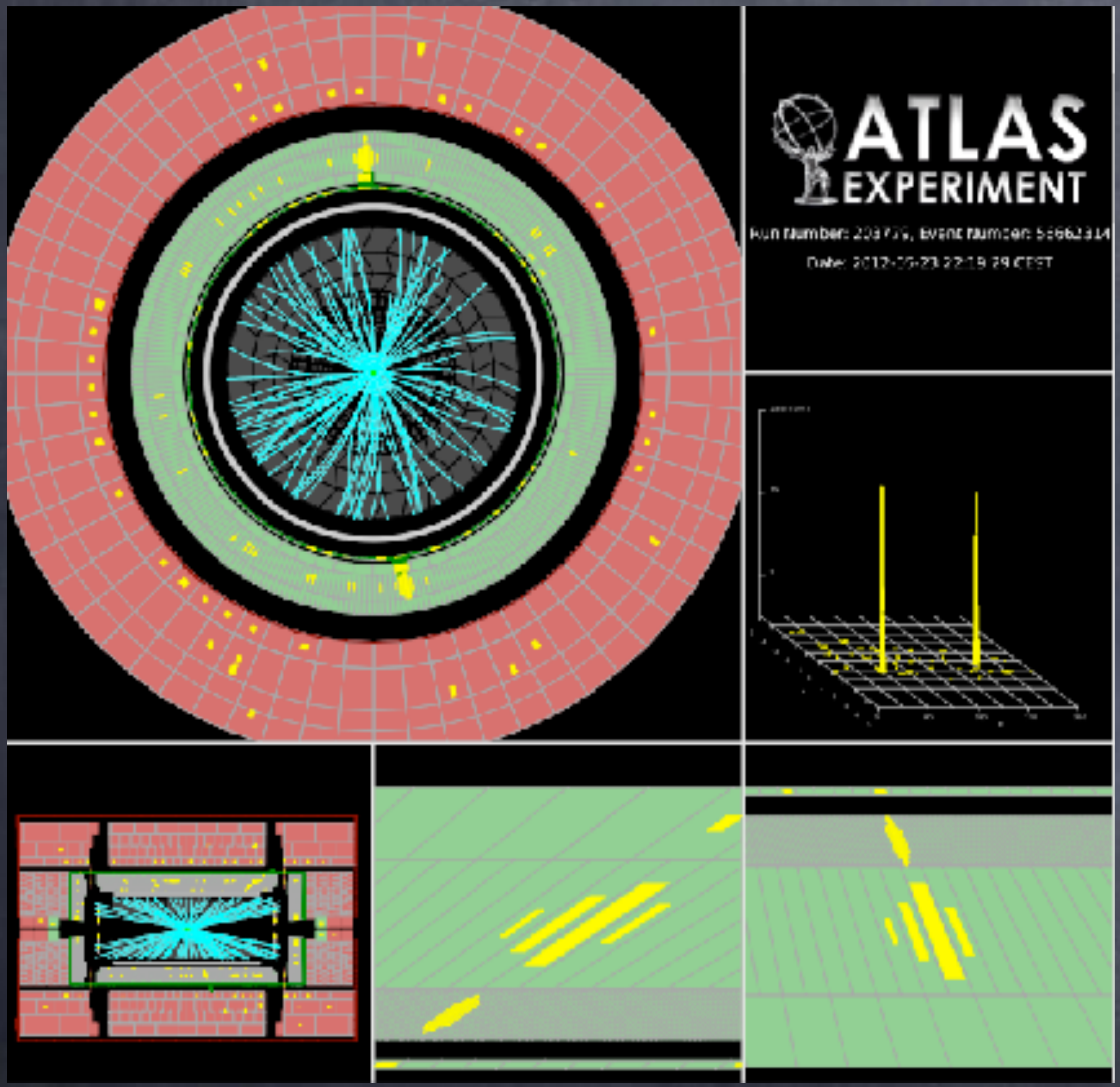


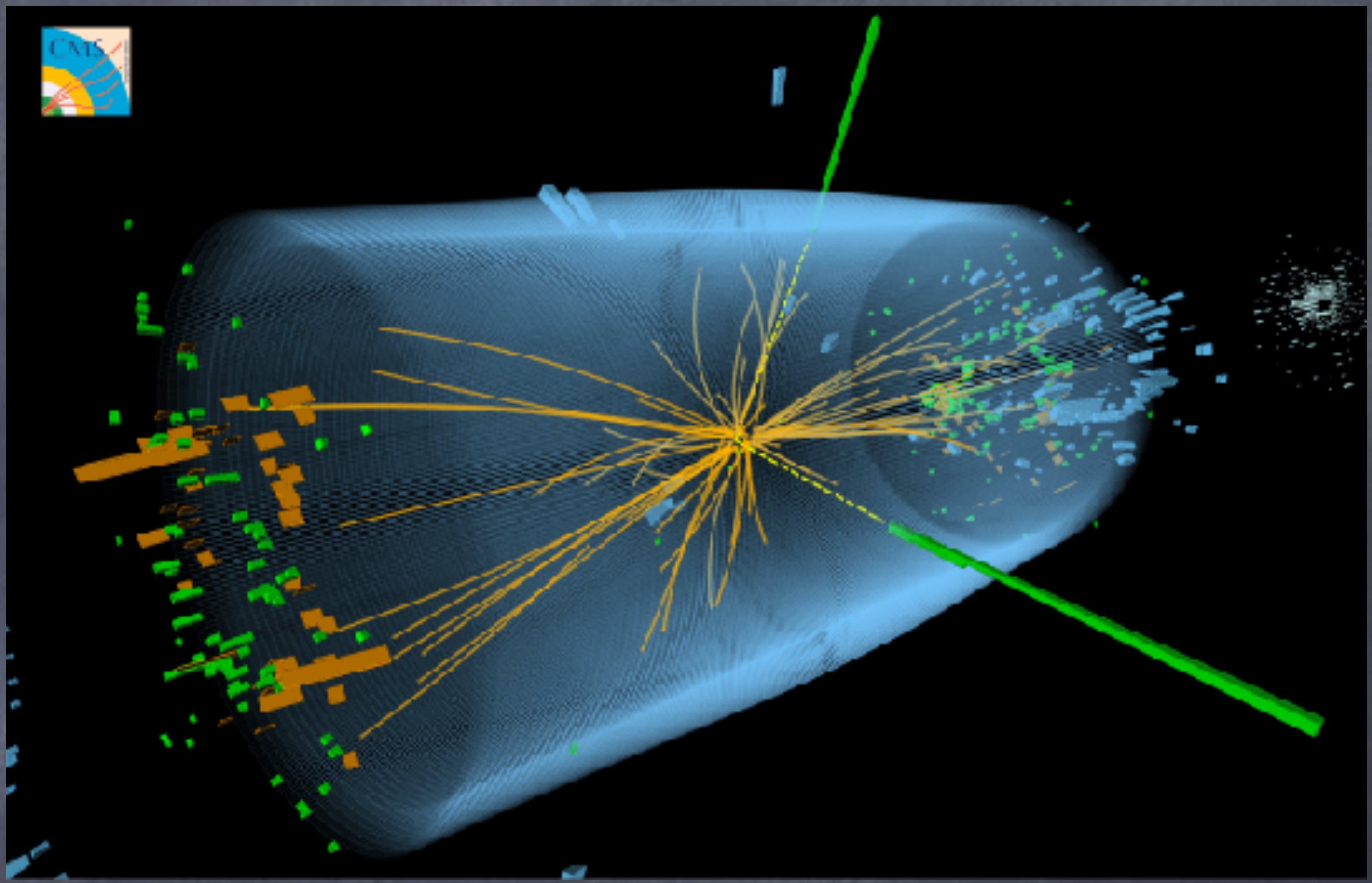






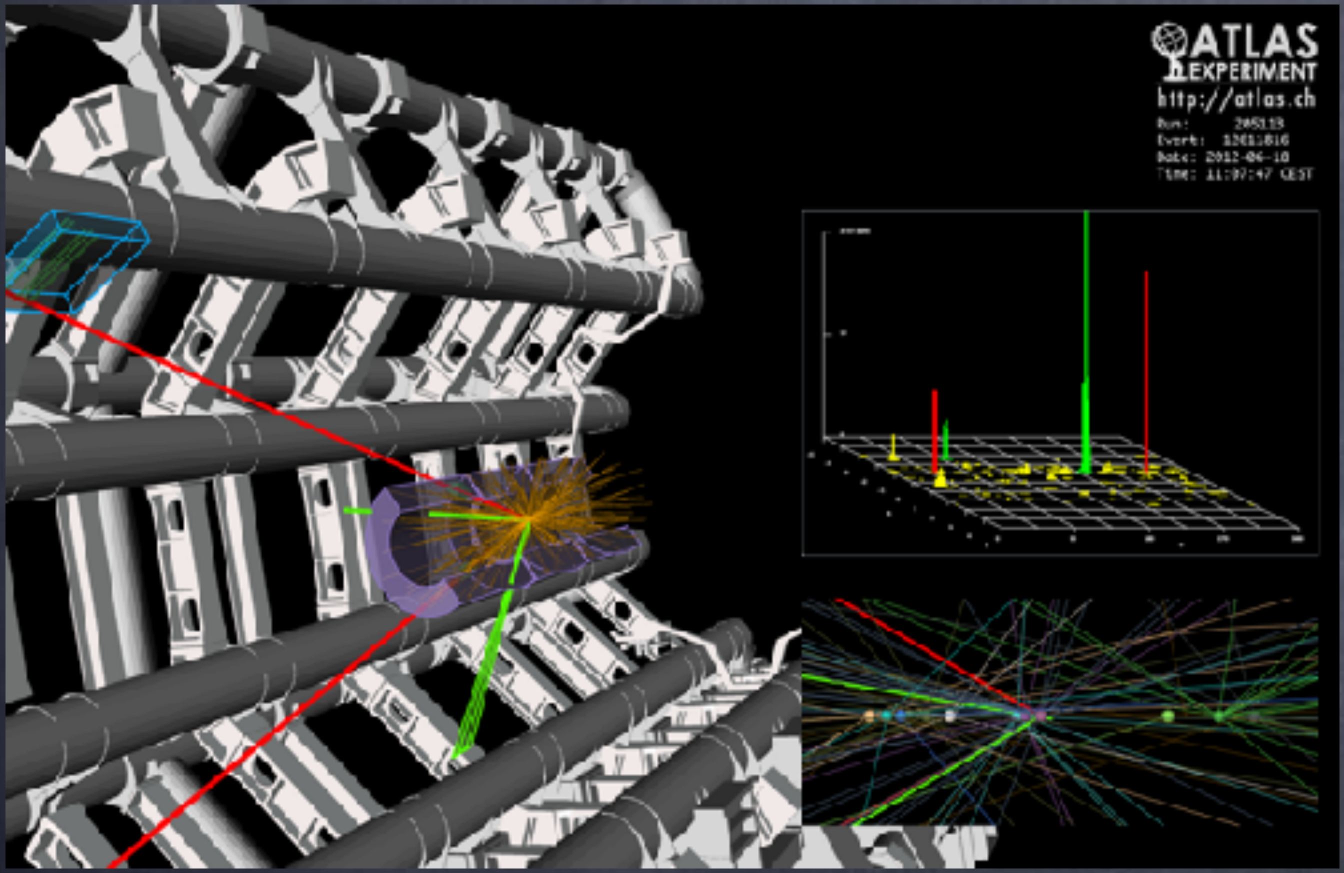
Candidate $H \to \gamma\gamma$

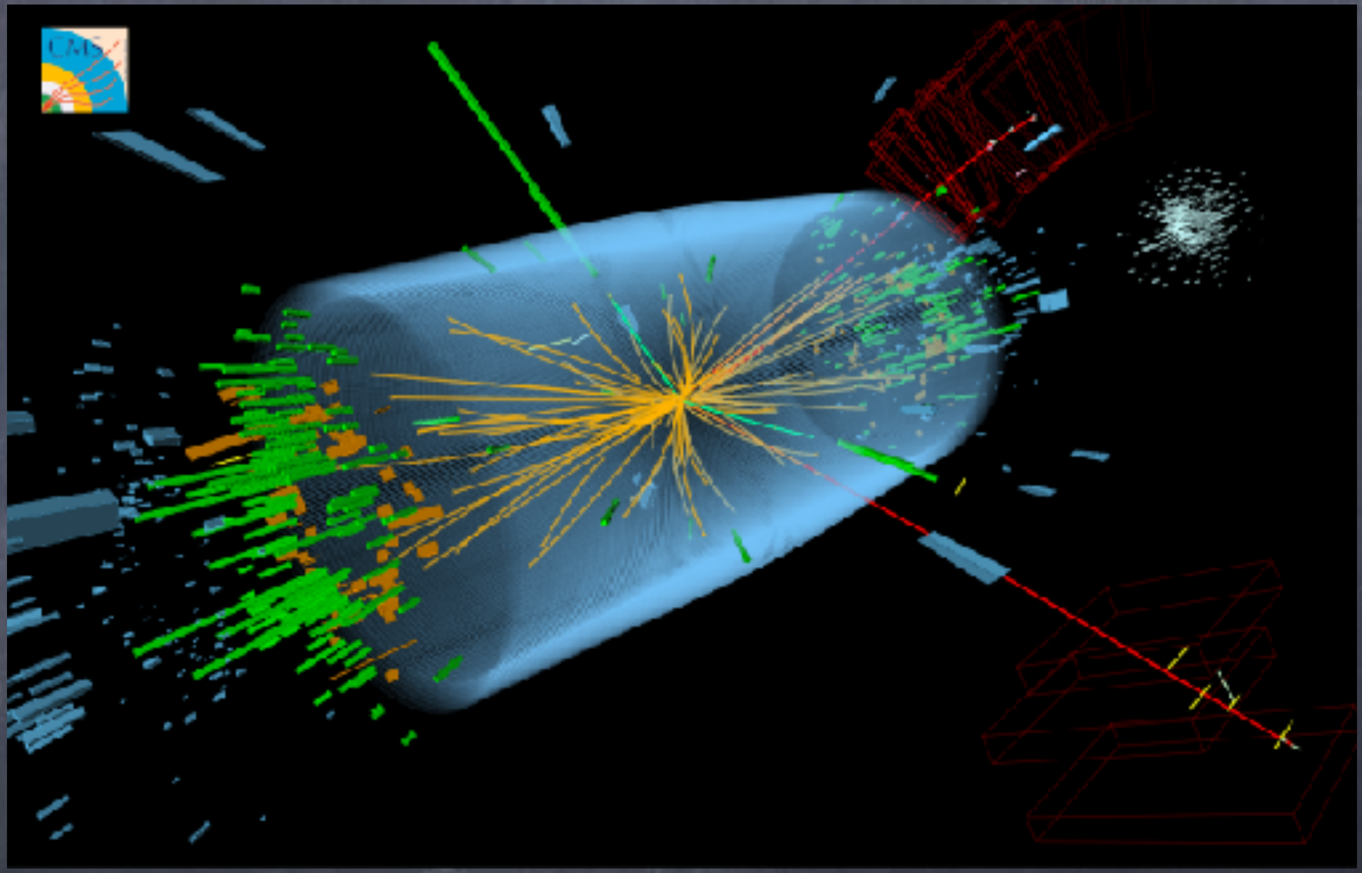




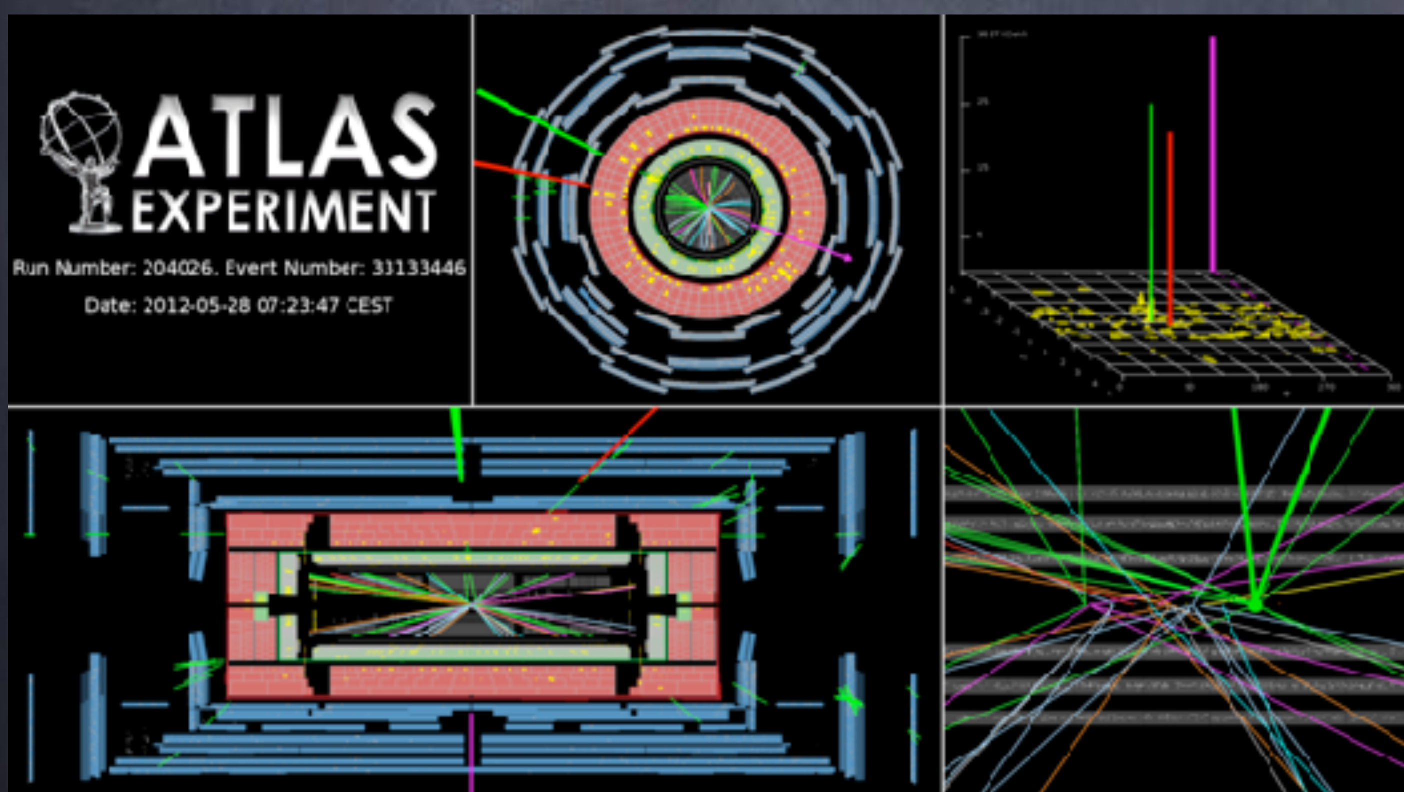
Candidate

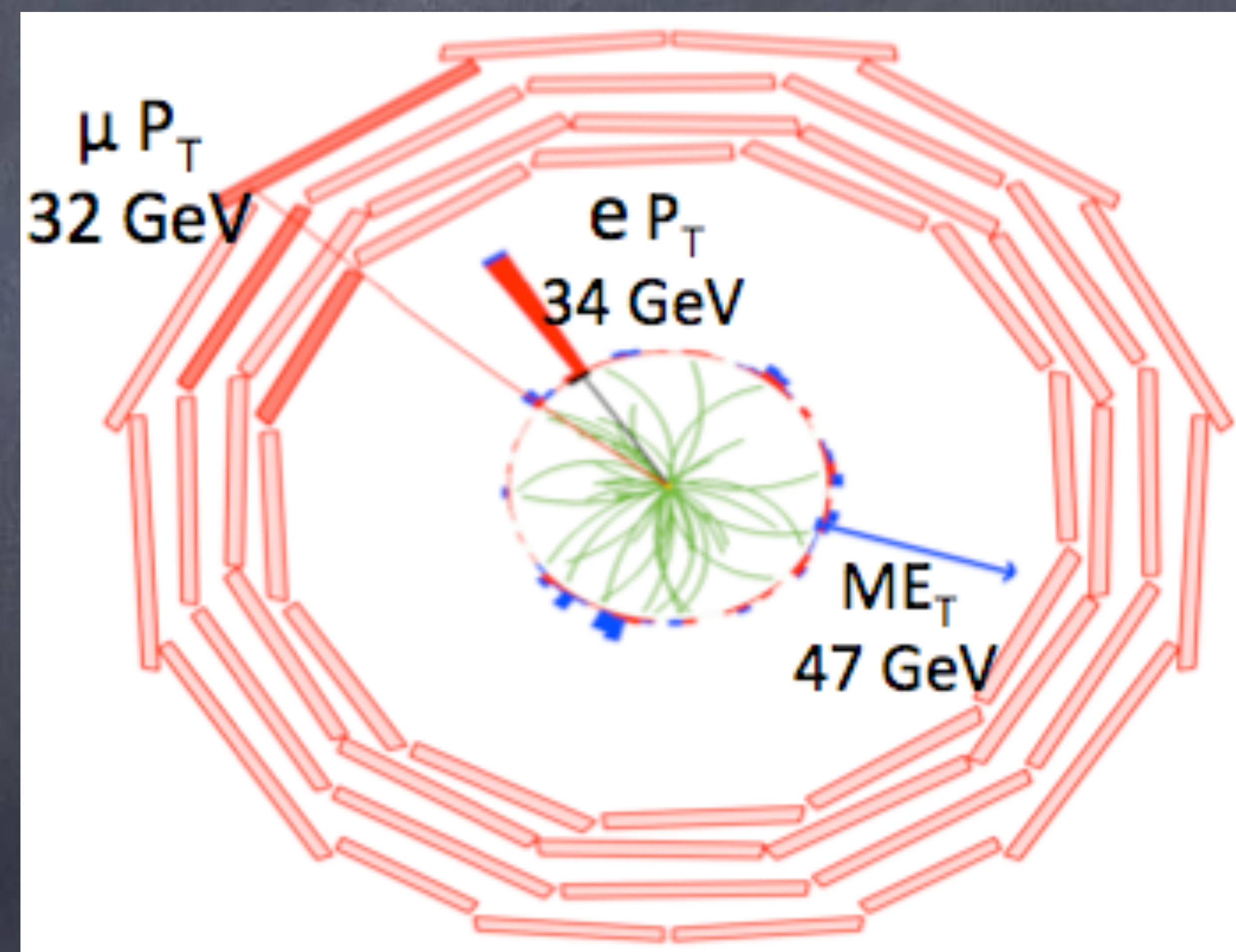
$$H \to ZZ^* \to (e^+e^-)(\mu^+\mu^-)$$





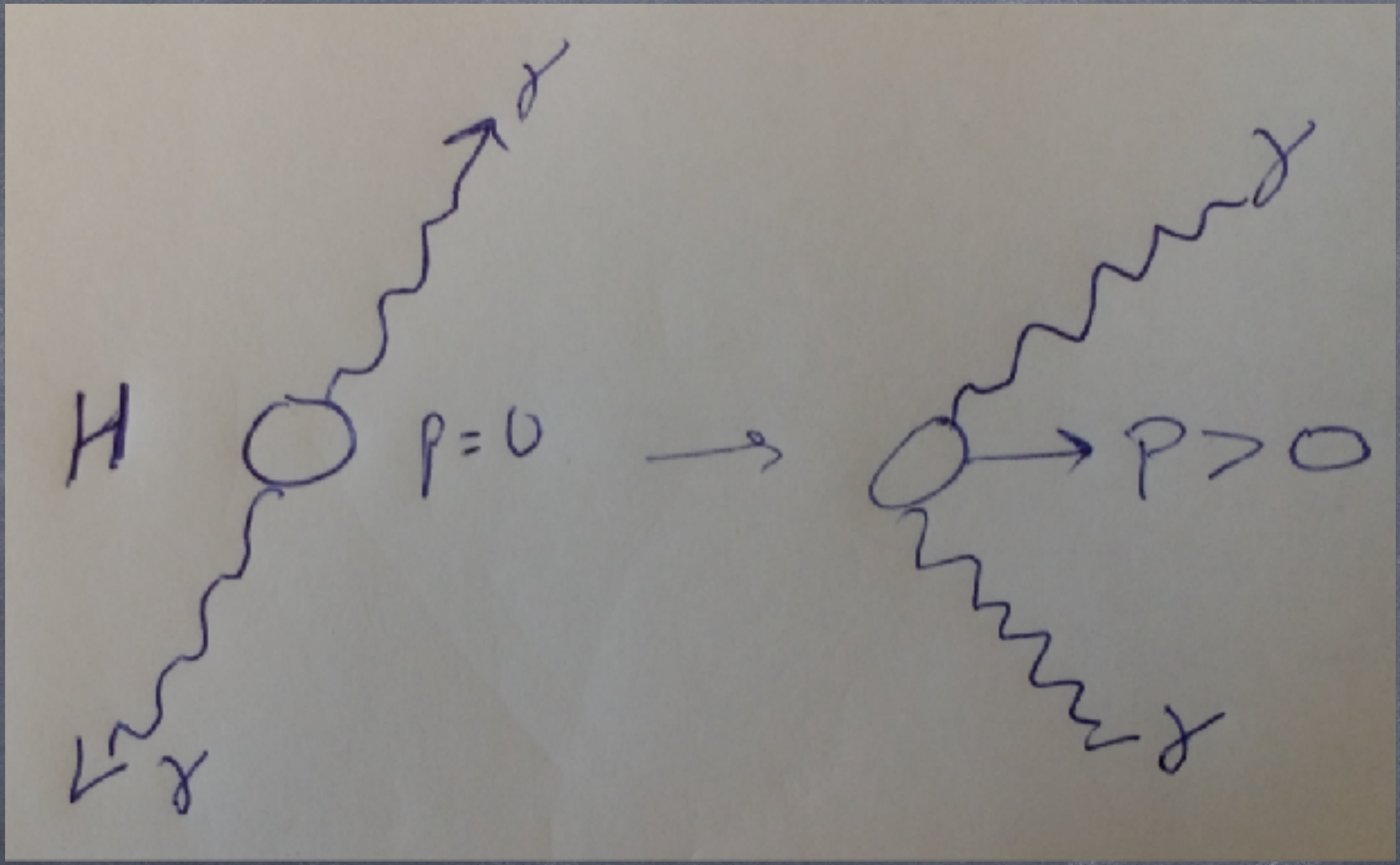
Candidate $H \to W^+W^{-(*)} \to e^+\nu_e\mu^-\nu_\mu$





“Invariant mass”

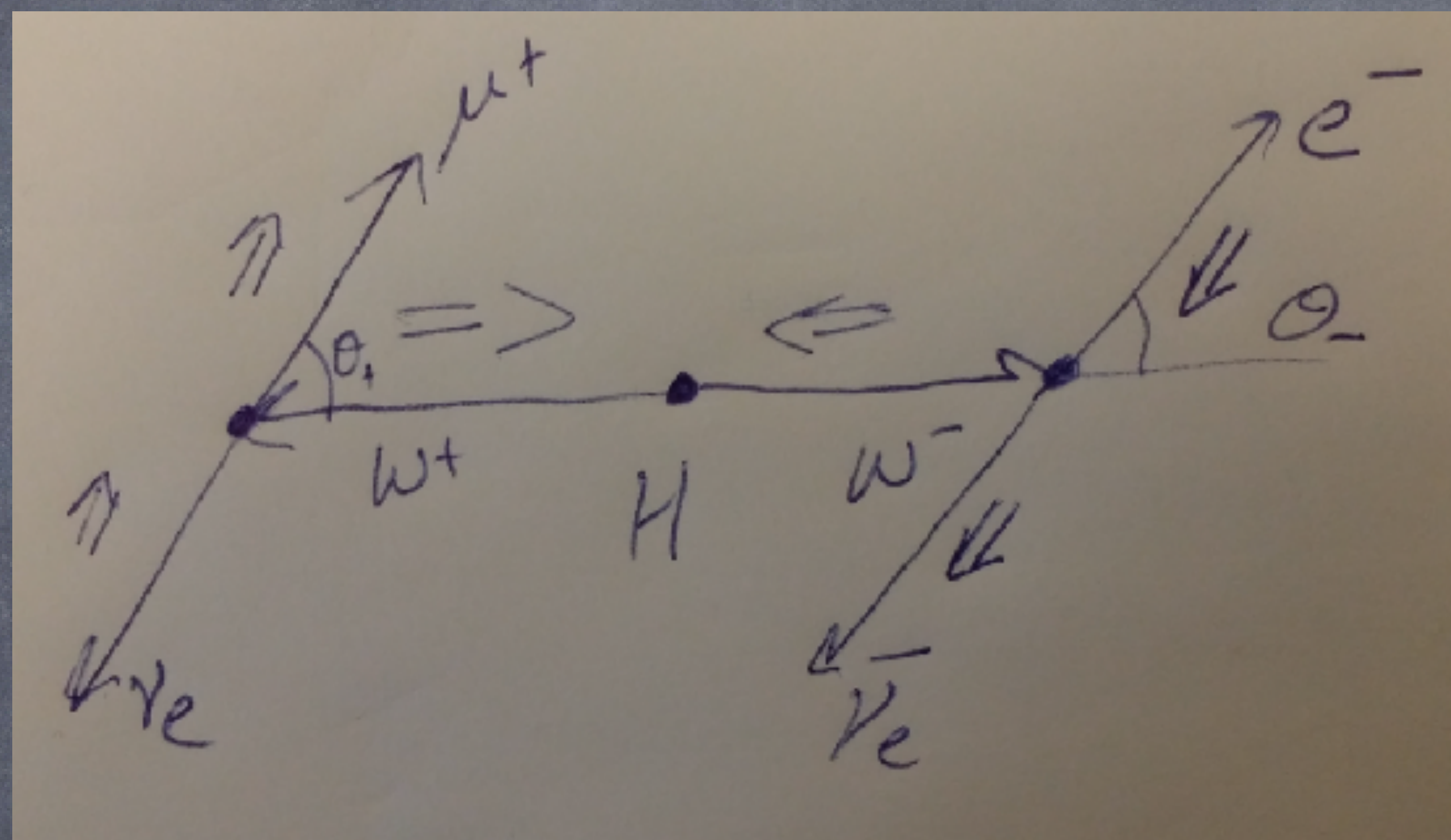
We see the Higgs boson as directly as we see each other!



$$E = mc^2 \rightarrow E^2 = m^2c^4 + p^2c^2$$

Correlations in

$$H \to W^+W^- \to e^+\nu_e\mu^-\bar{\nu_\mu}$$



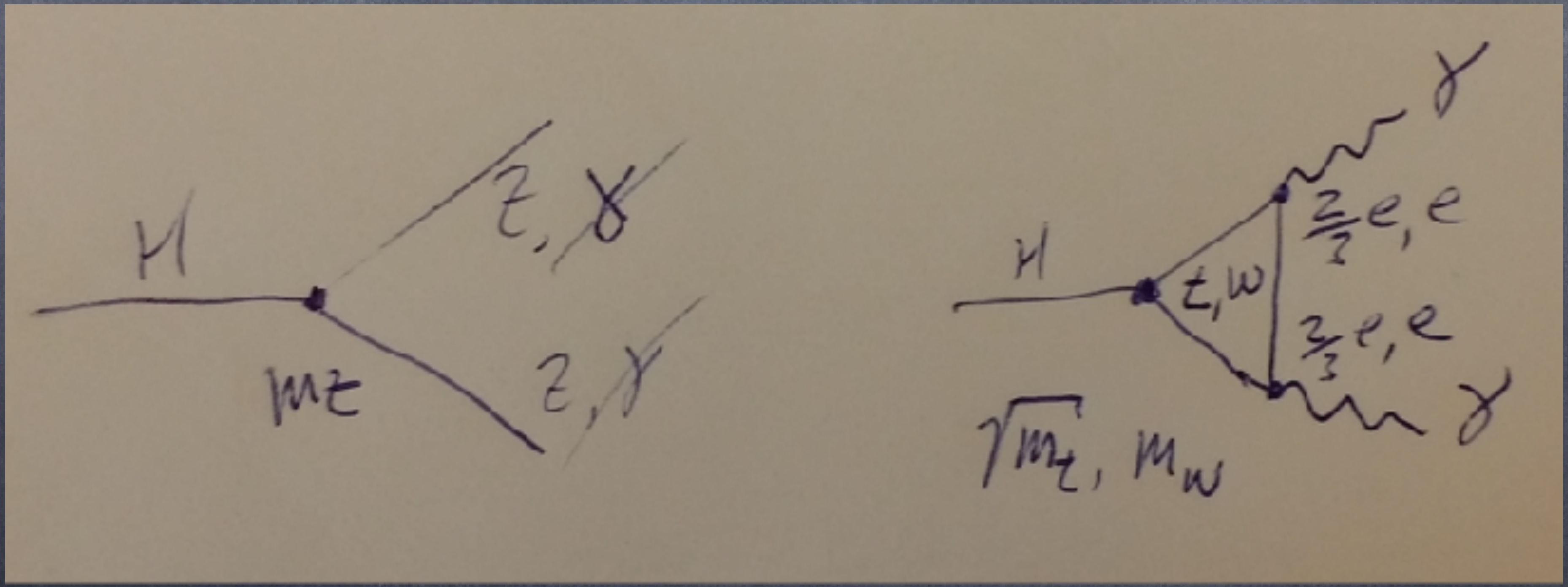
- Will the electron and muon tend to come out aligned or anti-aligned in the detector?!

$H \to \gamma\gamma$??

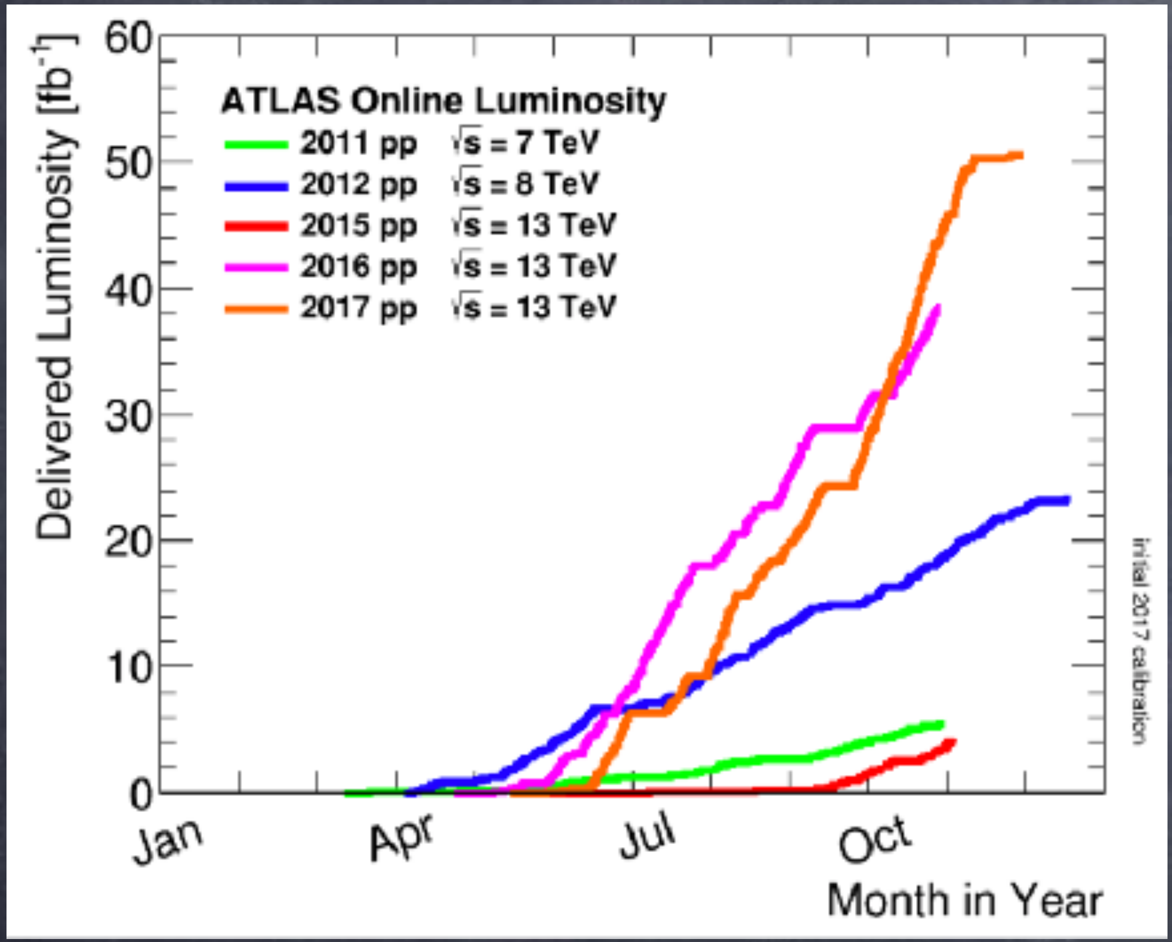
- H is electrically neutral, photon has only electromagentic interactions. How can H decay to $\gamma\gamma$??

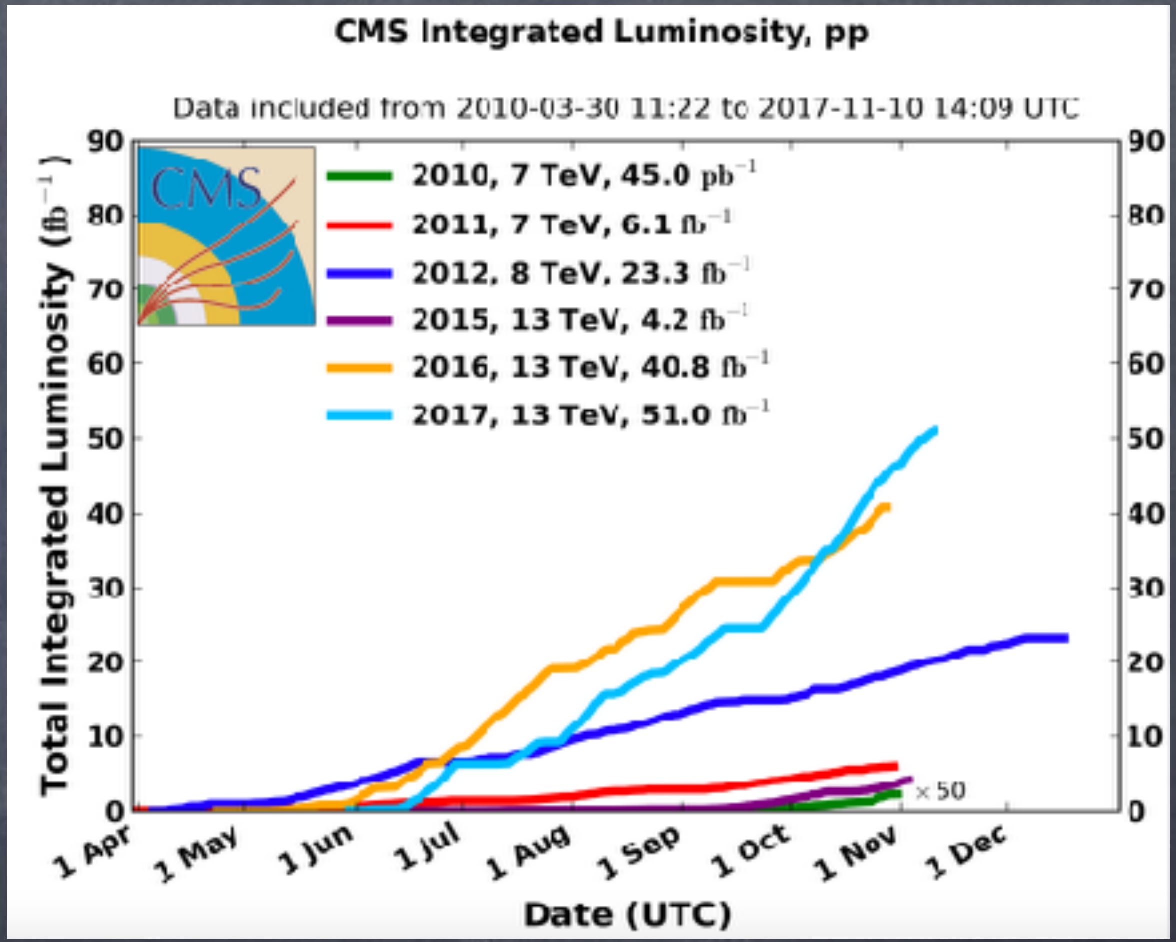
$H \to \gamma\gamma$??

- H is electrically neutral, photon has only electromagentic interactions. How can H decay to $\gamma\gamma$??

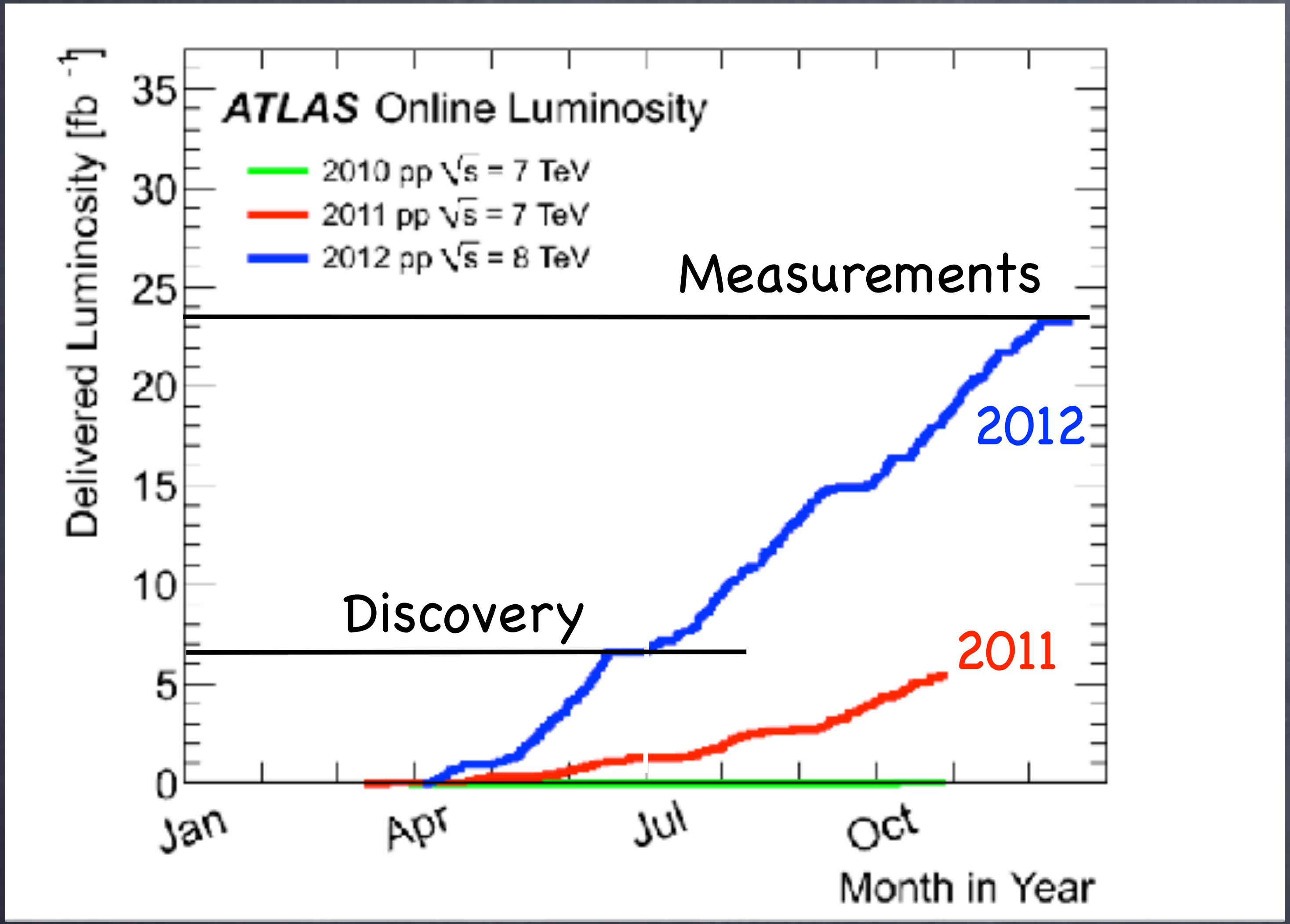


LHC data samples



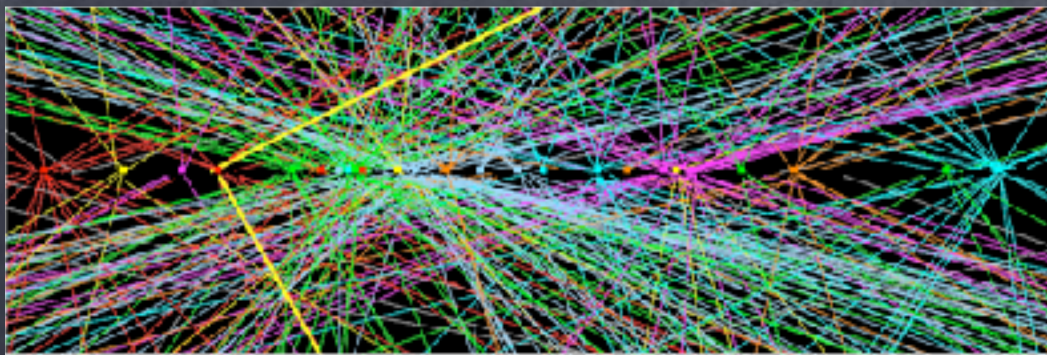


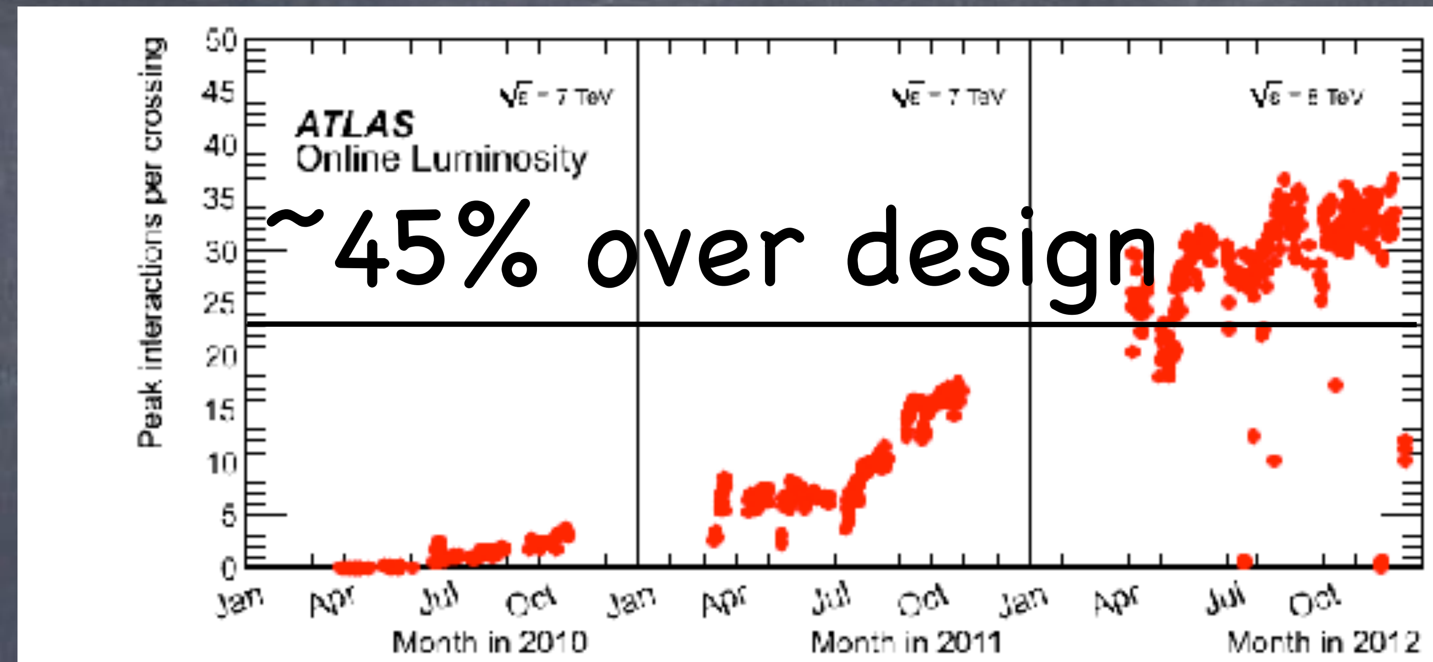
LHC data samples



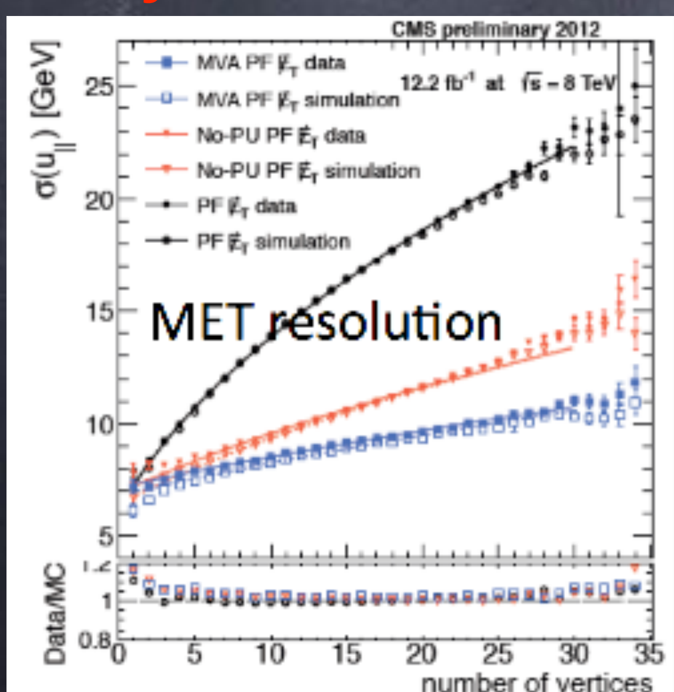
- Similar for CMS

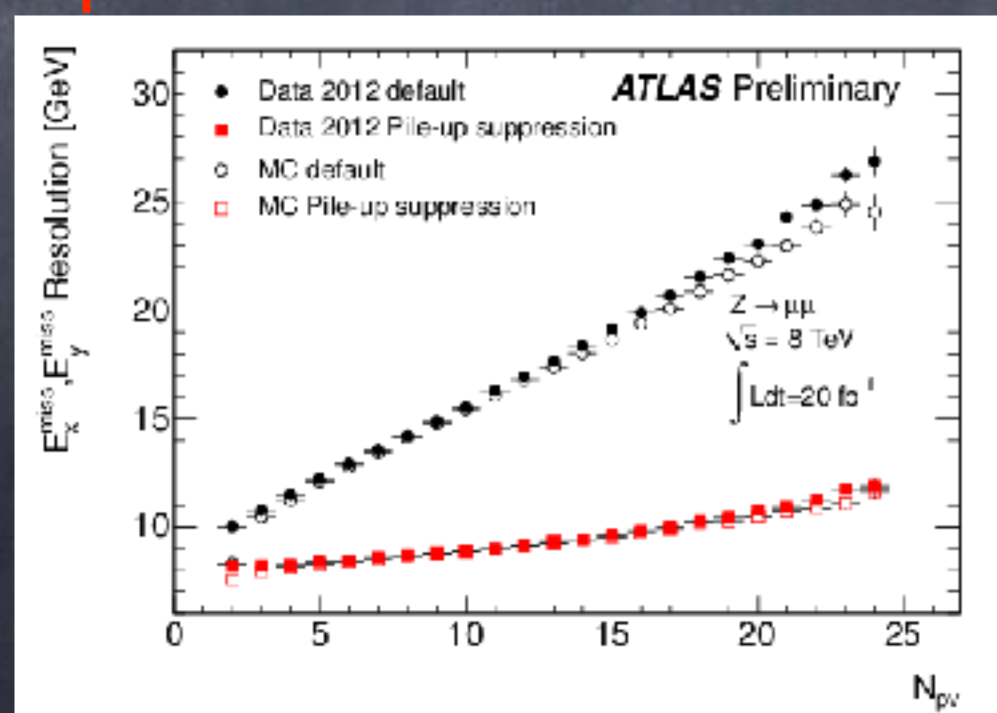
Pile-up challenge

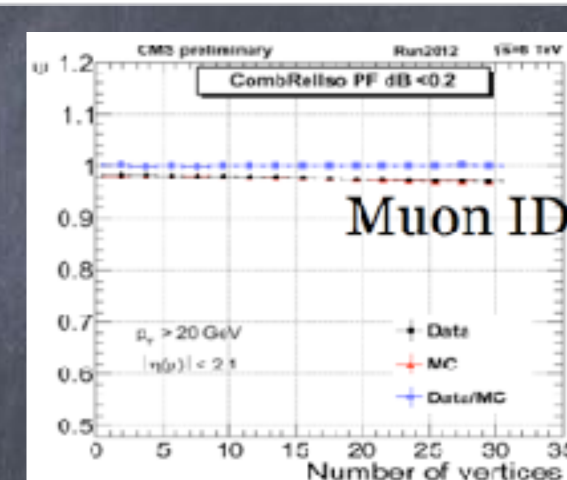


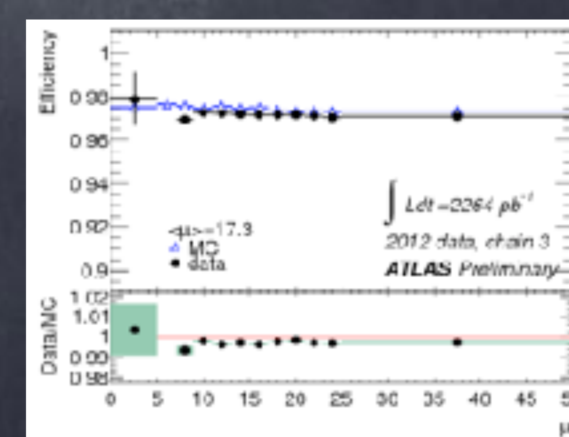


Why is this trend a problem?!

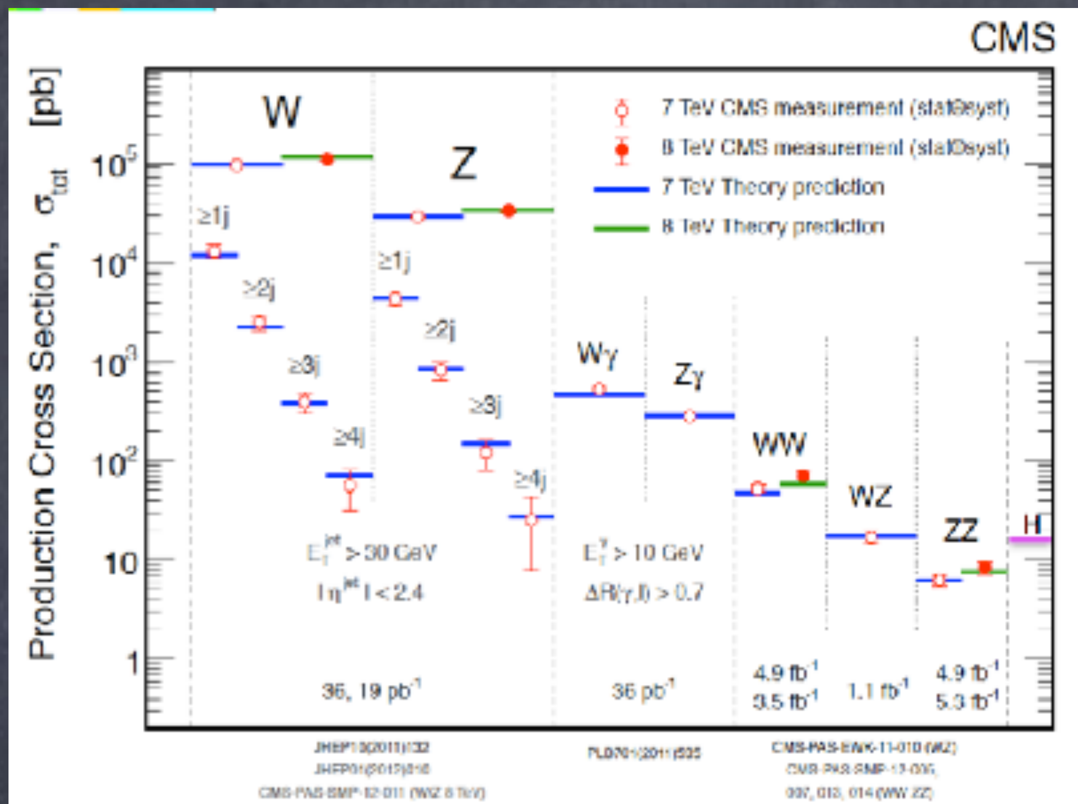


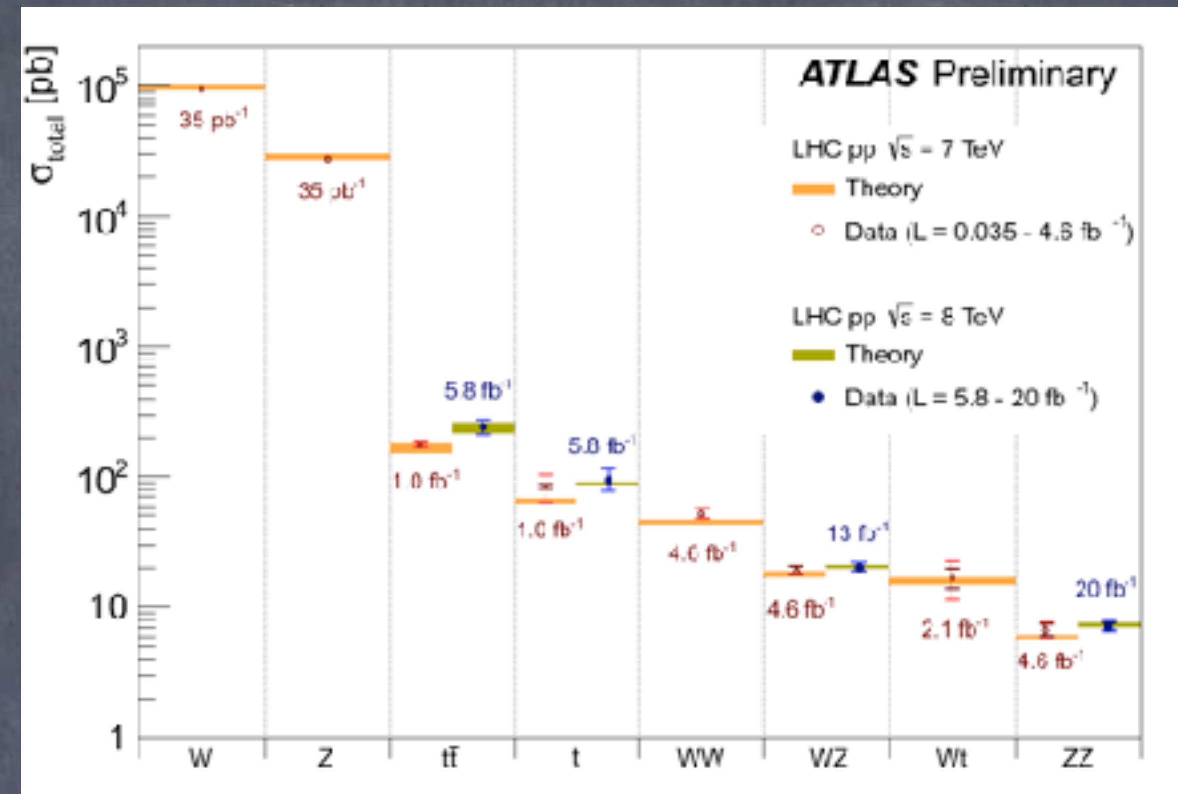


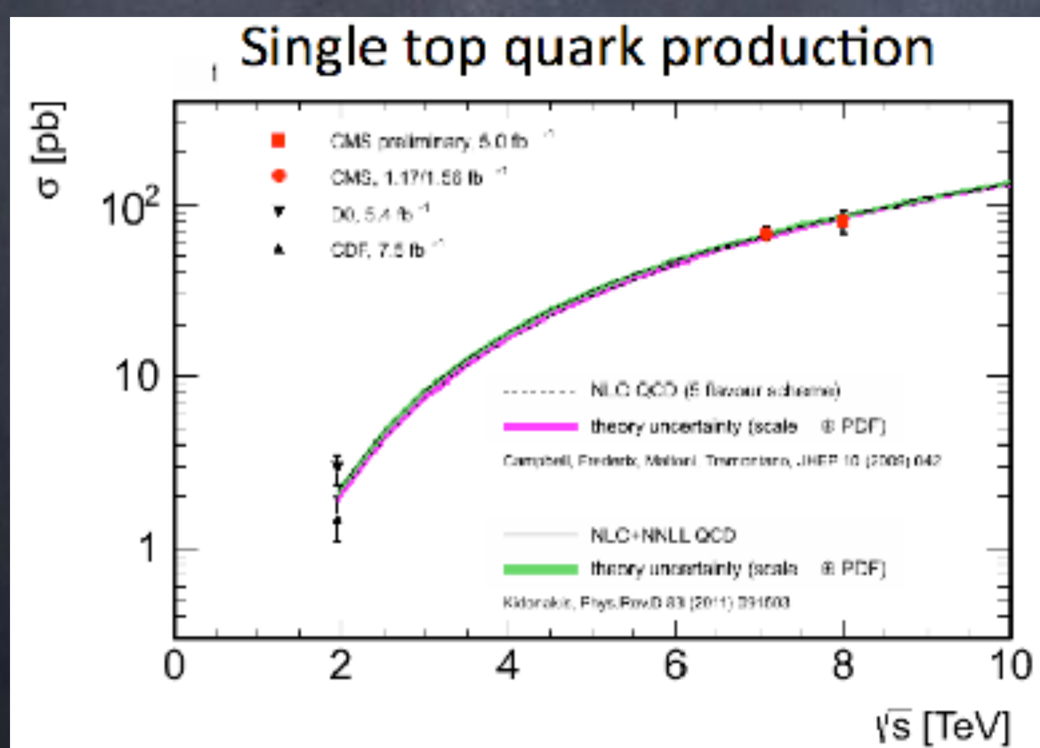


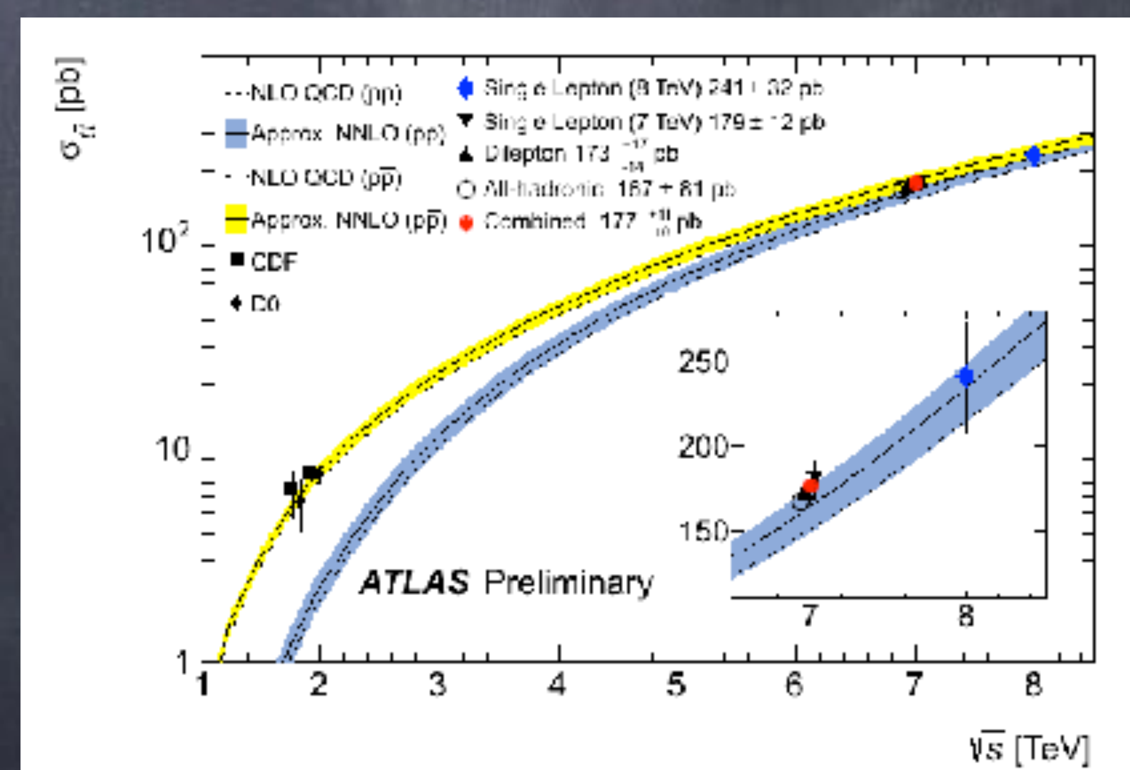


Standard "candles" ✓

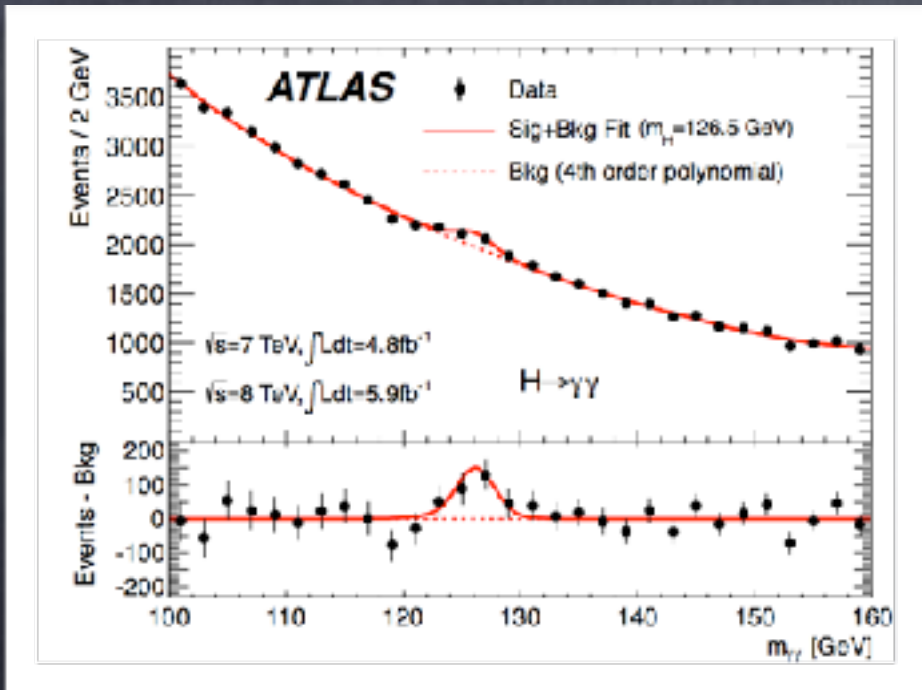


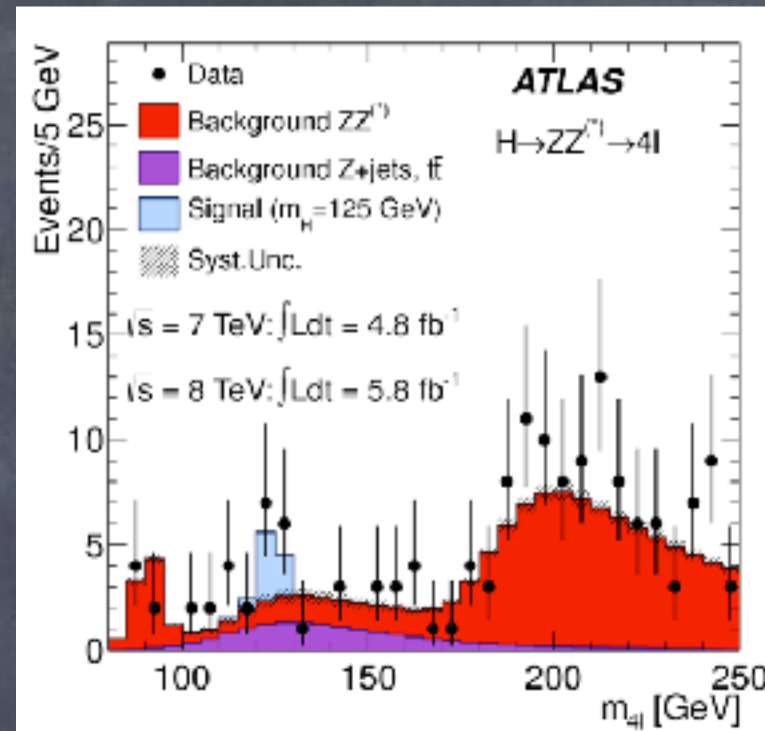


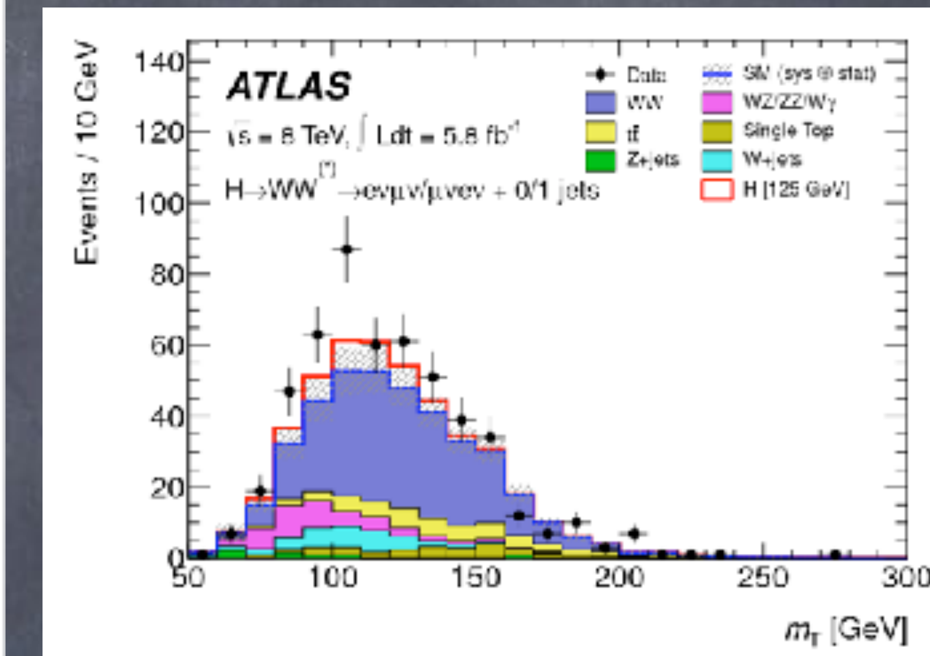


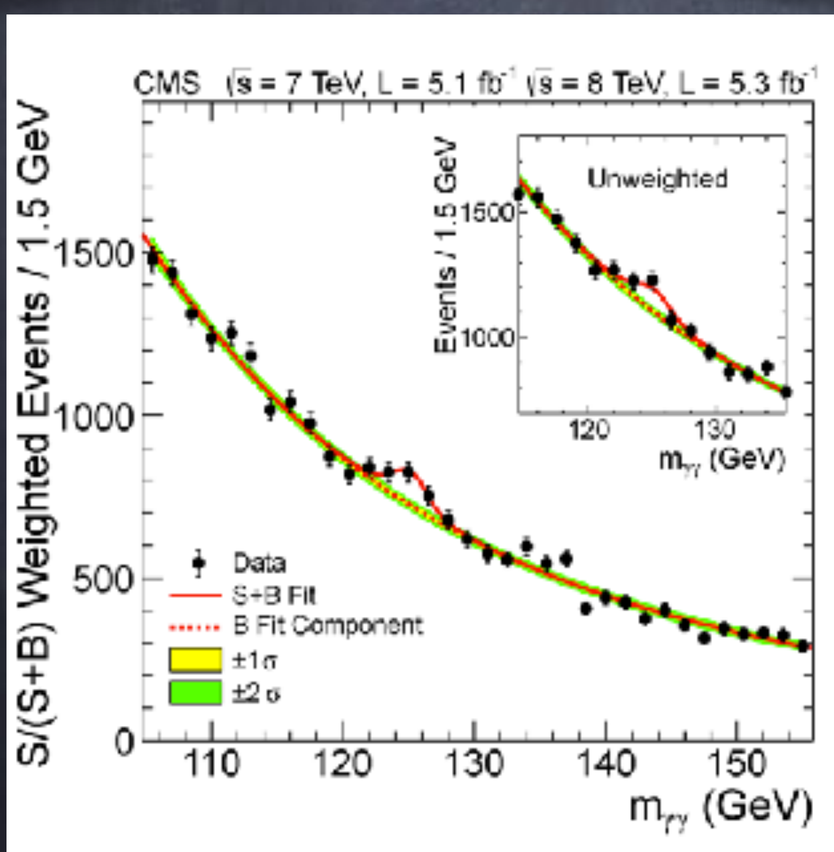


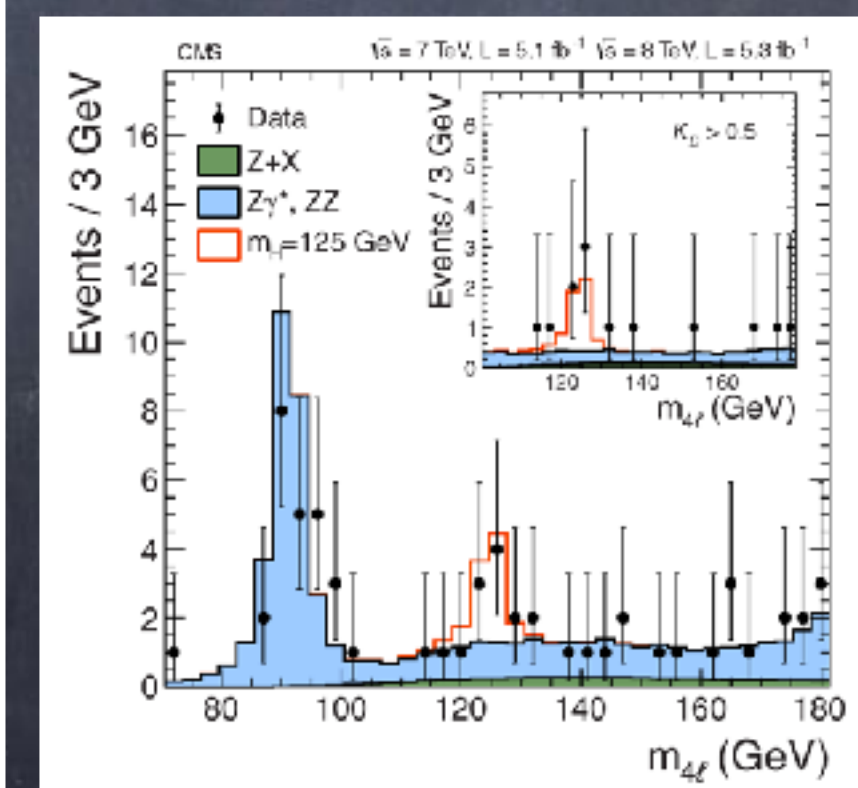
July, 2012

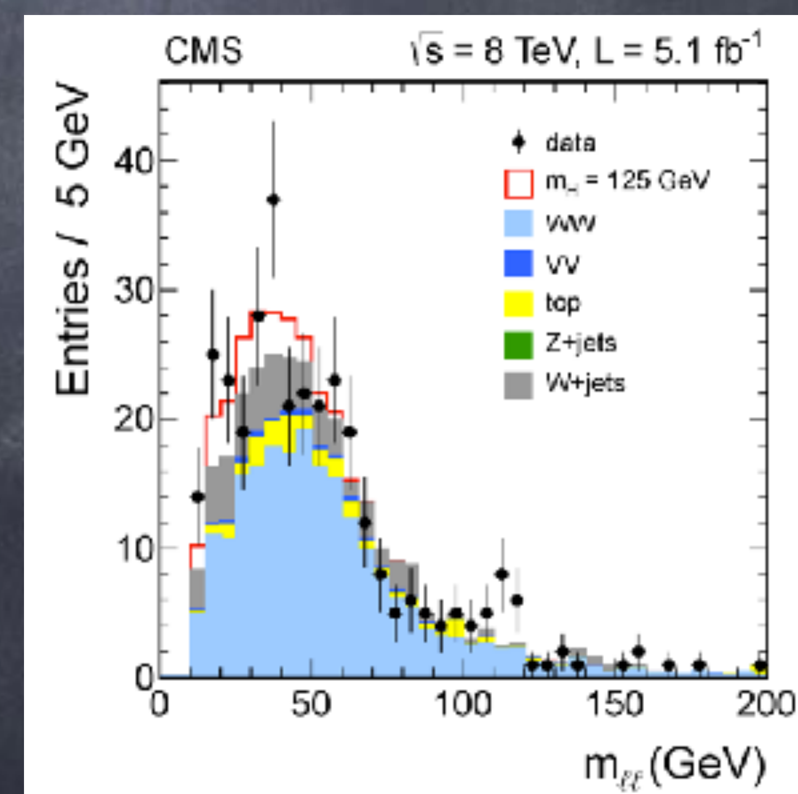

ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
Events / 2 GeV
Events - Bkg
√s=7 TeV, ∫Ldt=4.8fb⁻¹
√s=8 TeV, ∫Ldt=5.9fb⁻¹
H→γγ
m_γγ [GeV]


Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Syst.Unc.
ATLAS
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹
Events/5 GeV
m_4l [GeV]

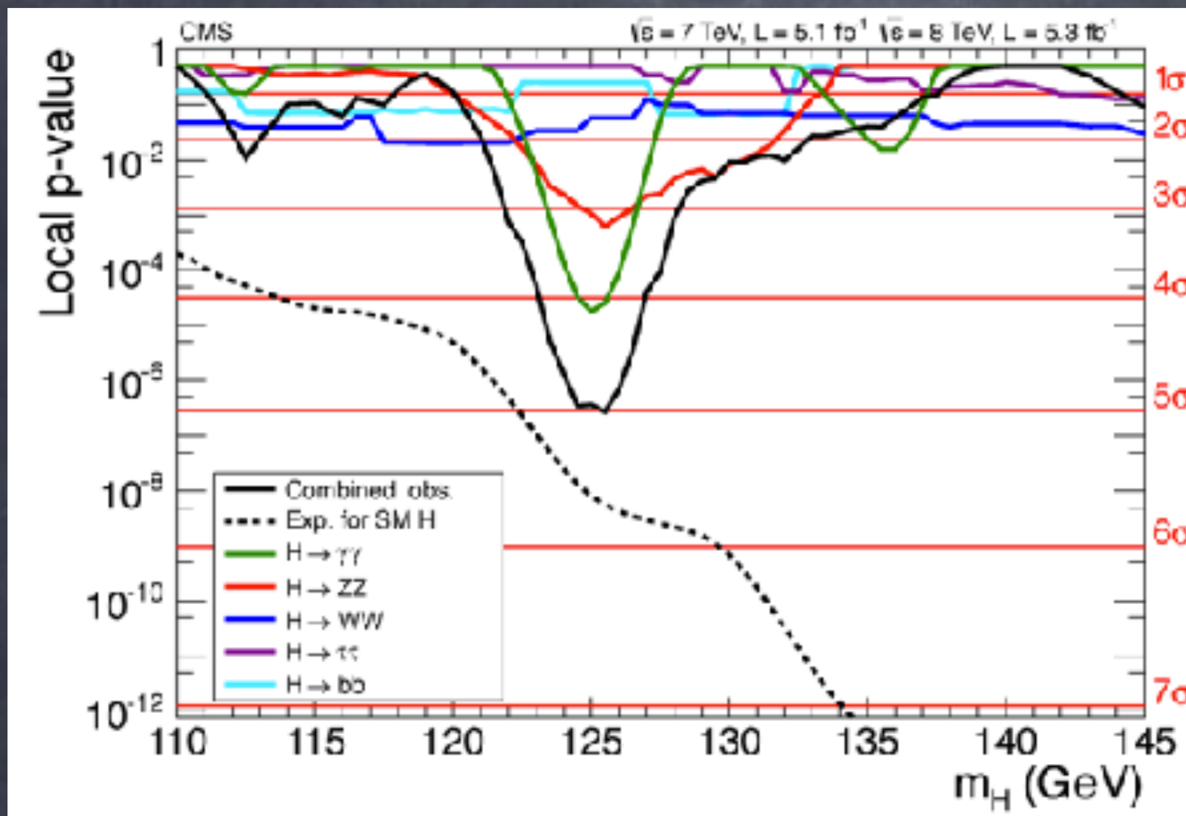

ATLAS
√s = 8 TeV, ∫ Ldt = 5.8 fb⁻¹
H→WW(*)→eνμν/μνeν + 0/1 jets
Events / 10 GeV
m_T [GeV]

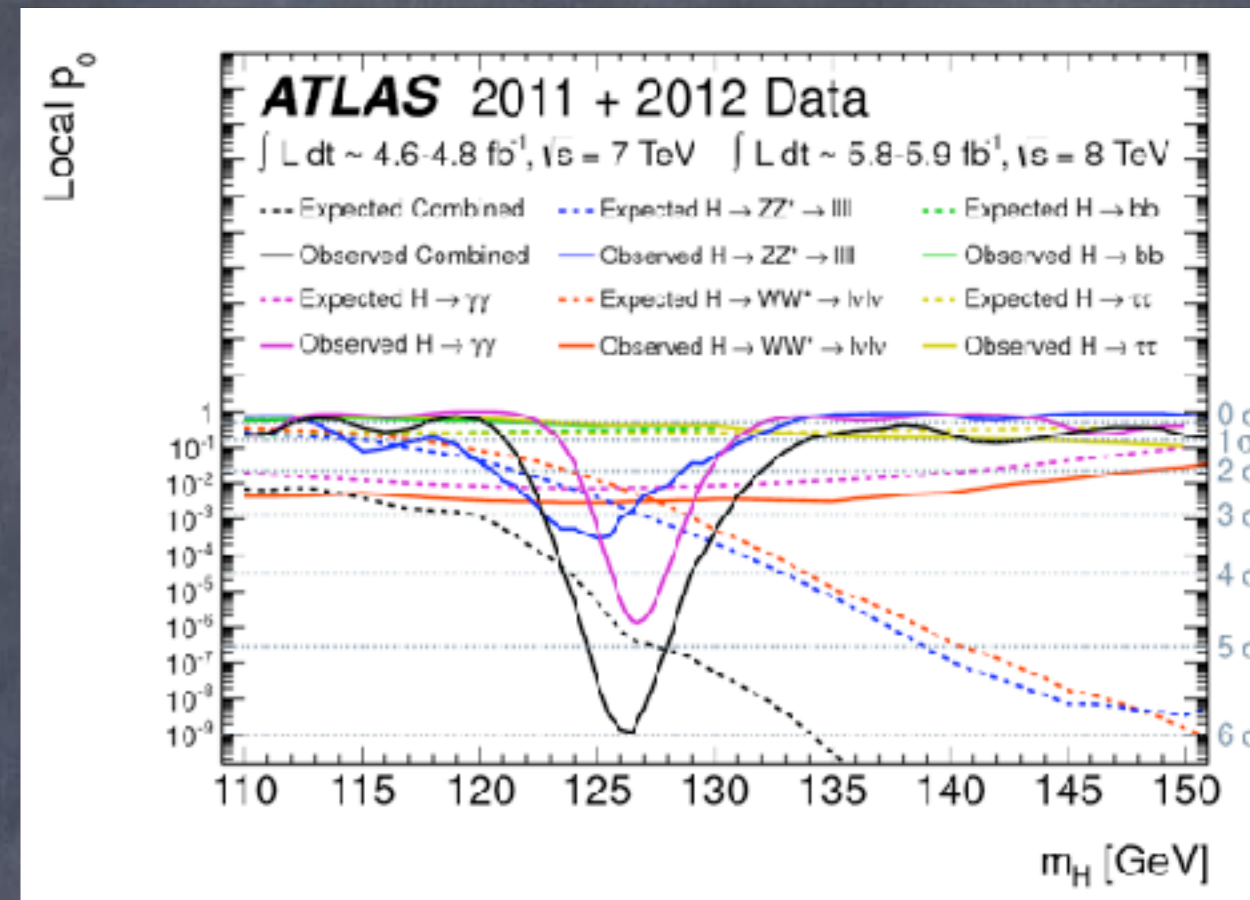

CMS √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 5.3 fb⁻¹
Unweighted
Events / 1.5 GeV
m_γγ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2σ
S/(S+B) Weighted Events / 1.5 GeV
m_γγ (GeV)

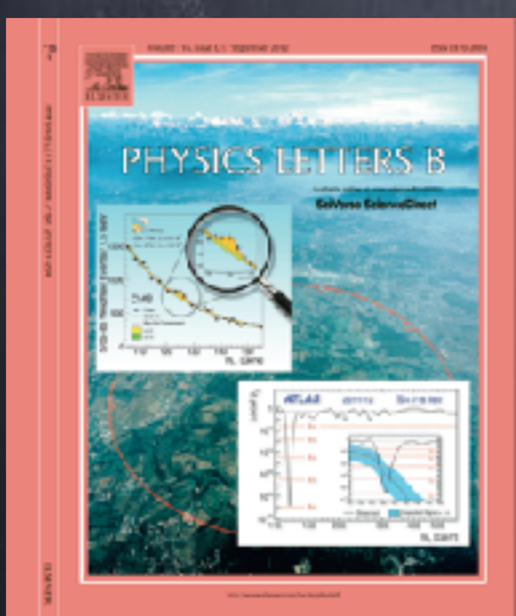

CMS
Data
Z+X
Zγ*, ZZ
m_H=125 GeV
Events / 3 GeV
m_4ℓ (GeV)


CMS
√s = 8 TeV, L = 5.1 fb⁻¹
data
m_H = 125 GeV
WW
VV
top
Z+jets
W+jets
Entries / 5 GeV
m_ℓℓ (GeV)

A new boson, “Higgs-like”







- Combination of all channels and data available at the time
- 2 experiments with 5σ at ~same mass
- The most sensitive channels making the impact

Since July 2012:
From “a Higgs-like boson”
to
“a Higgs boson”

Statistics miniworkshop

chaired by Louis Lyons (Imperial College-Unknown-Unknown)

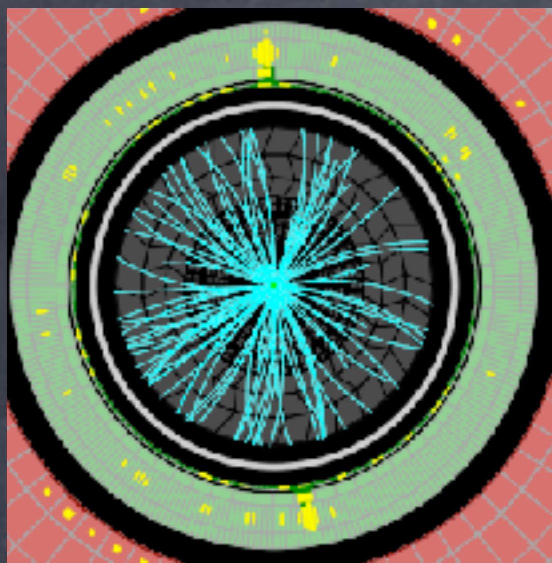
from Wednesday, 13 February 2013 at **08:00** to Thursday, 14 February 2013 at **18:00** (Europe/Zurich)
at **CERN**

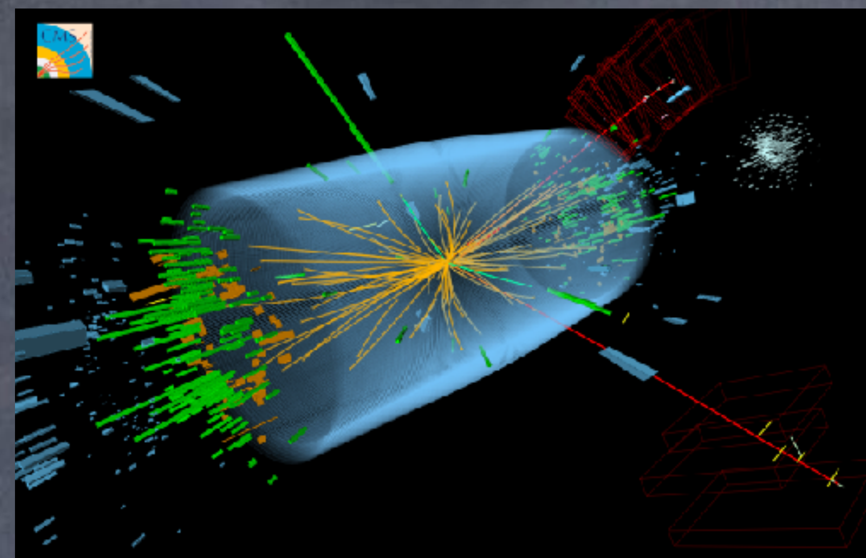
Description WHAT WE HAVE LEARNT FROM THE LHC HIGGS SEARCH?

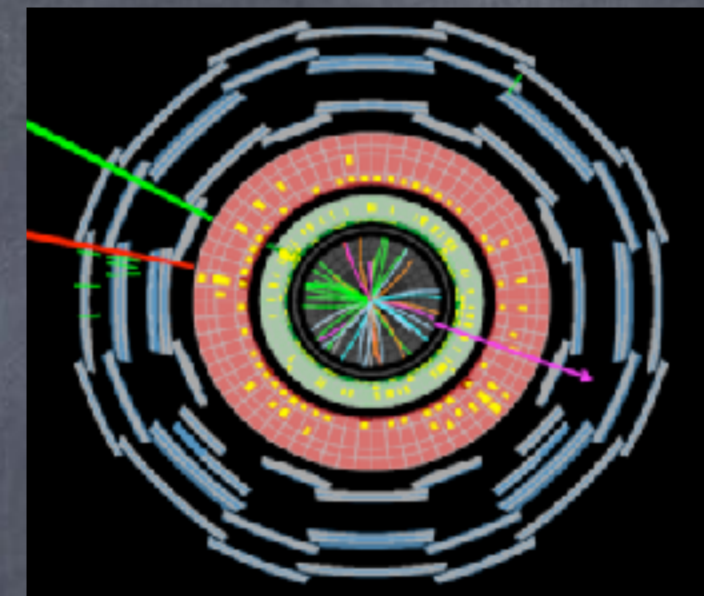
BASIC IDEA OF MEETING:
Now that we have actually searched for and found a Higgs-like boson, we should have a small meeting to try to decide what we have learnt about the statistical issues involved, and to consolidate our experience.

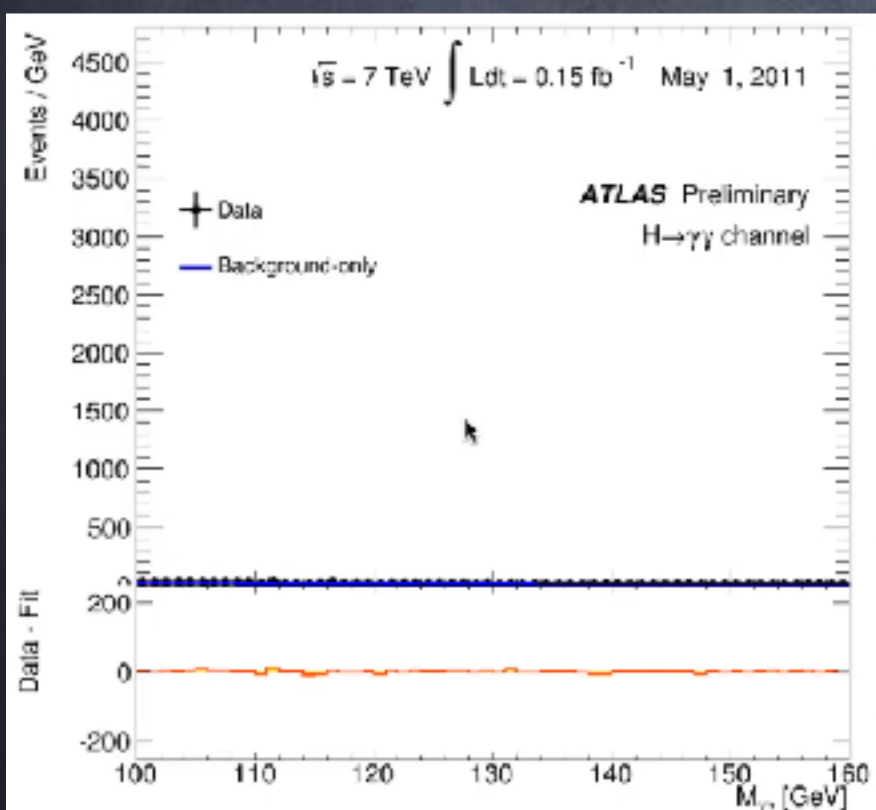
- While van Dyk asserted that he would advocate a different quantification of the evidence for a Higgs boson, he acknowledged that the ATLAS and CMS analyses must be among the most rigorous statistical treatments of a complex scientific data set "on the planet".
- Profile-likelihood ratio machinery (RooStats/RooFit/MINUIT) put us in position to rapidly (!!) advance from limits and discovery to measurements!

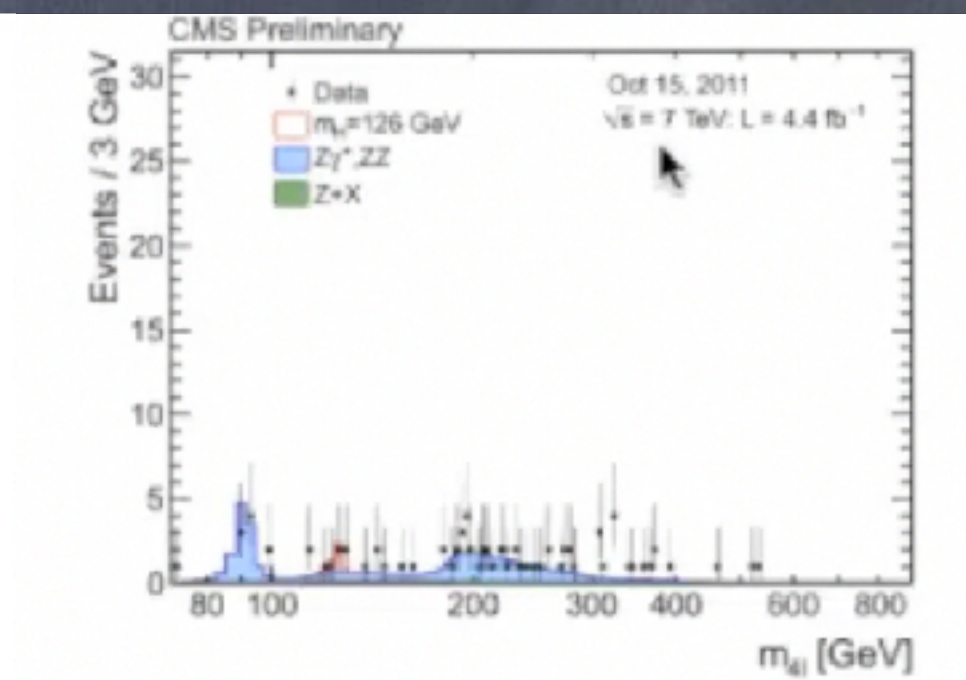
Rest of 2012: The signals grew...

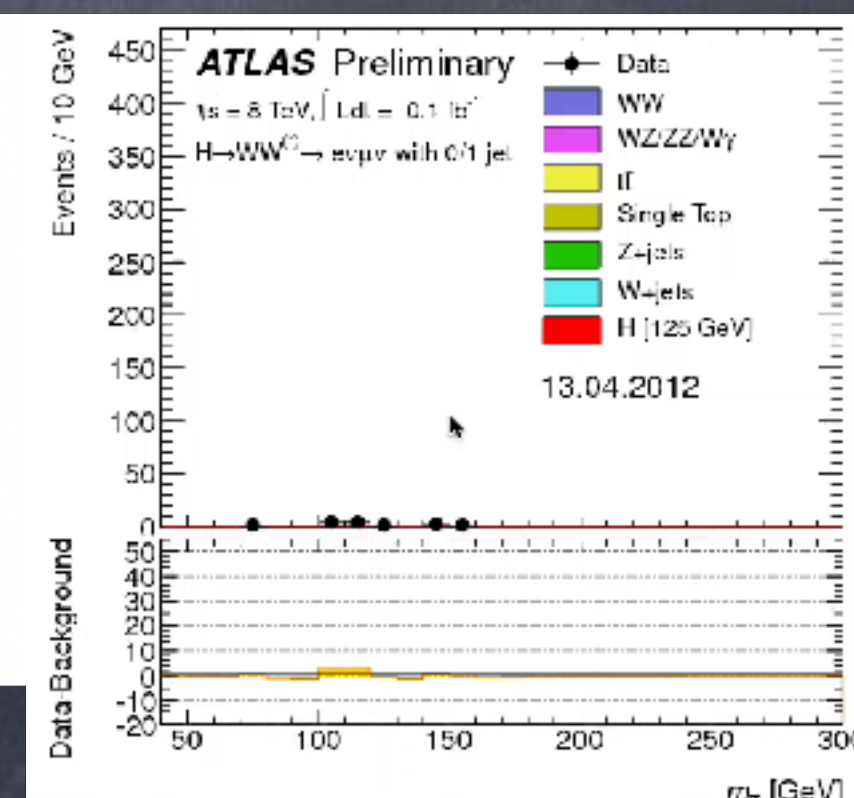




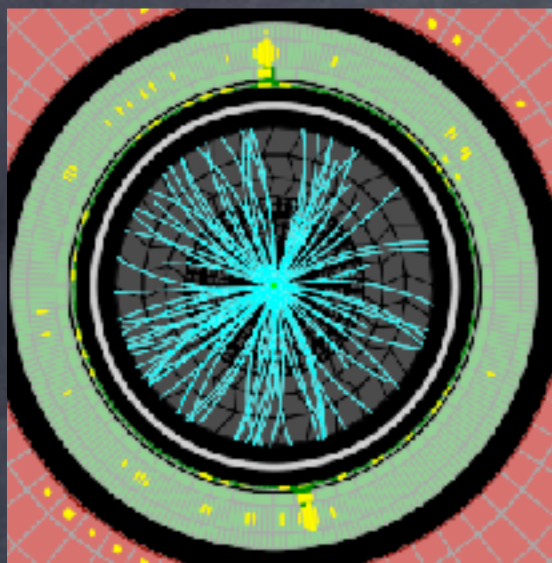


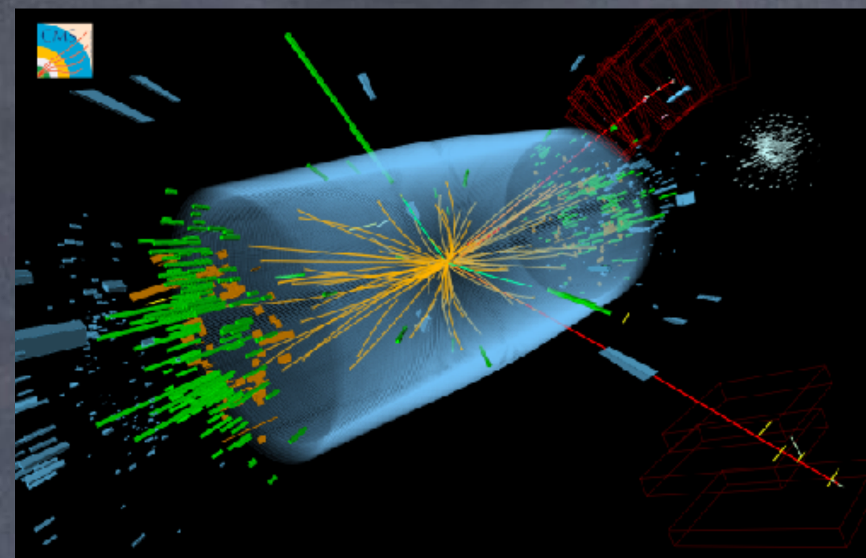


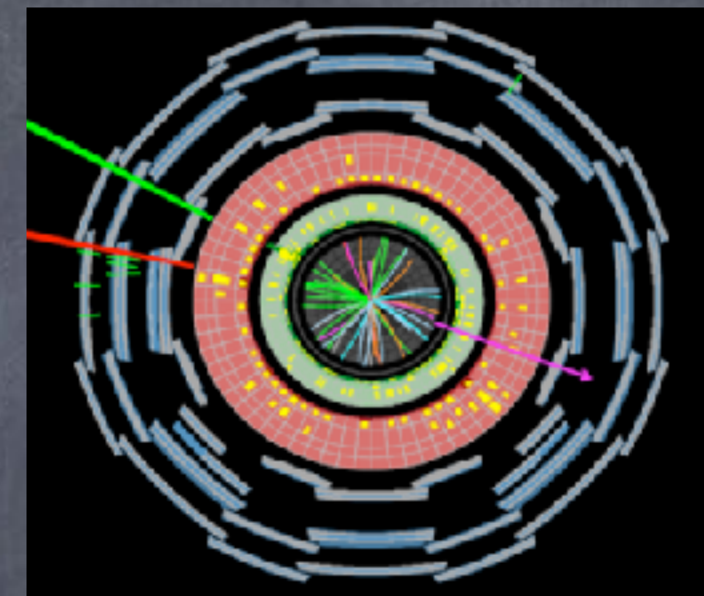


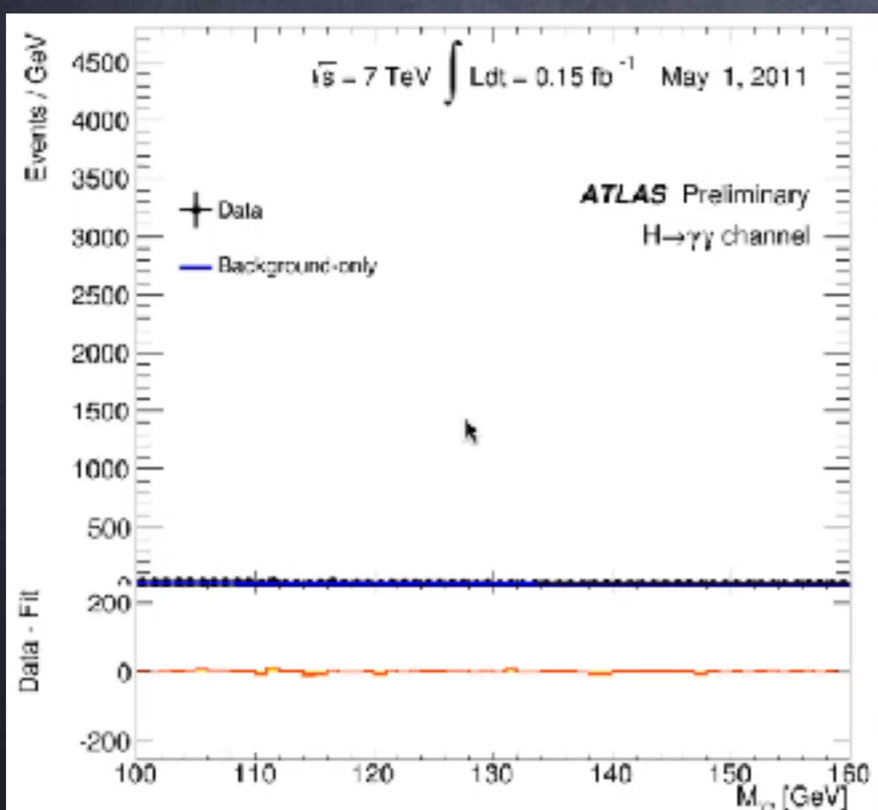


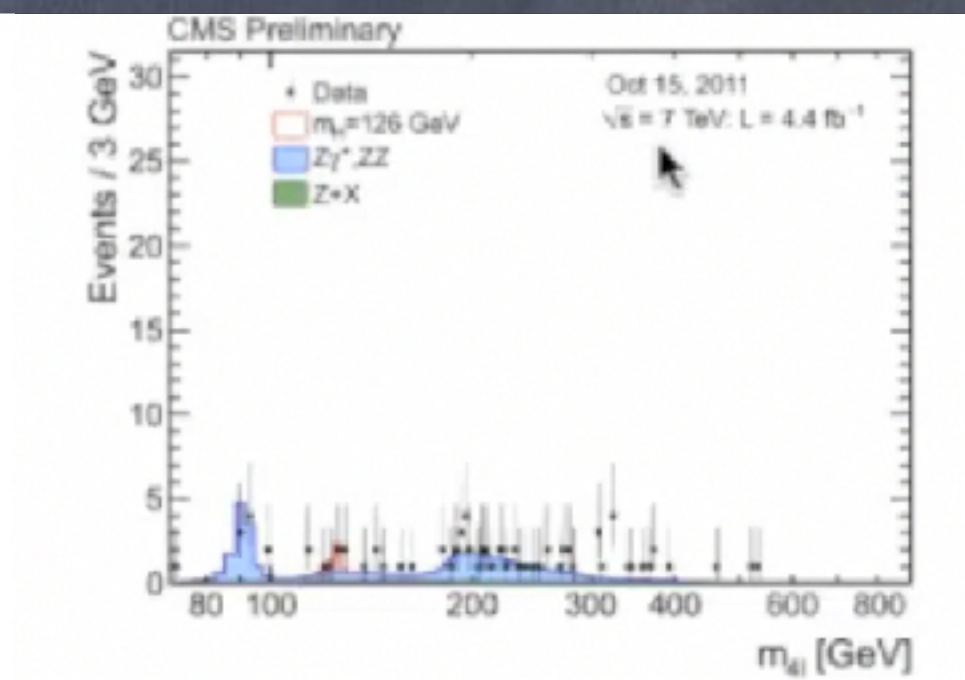
Rest of 2012: The signals grew…

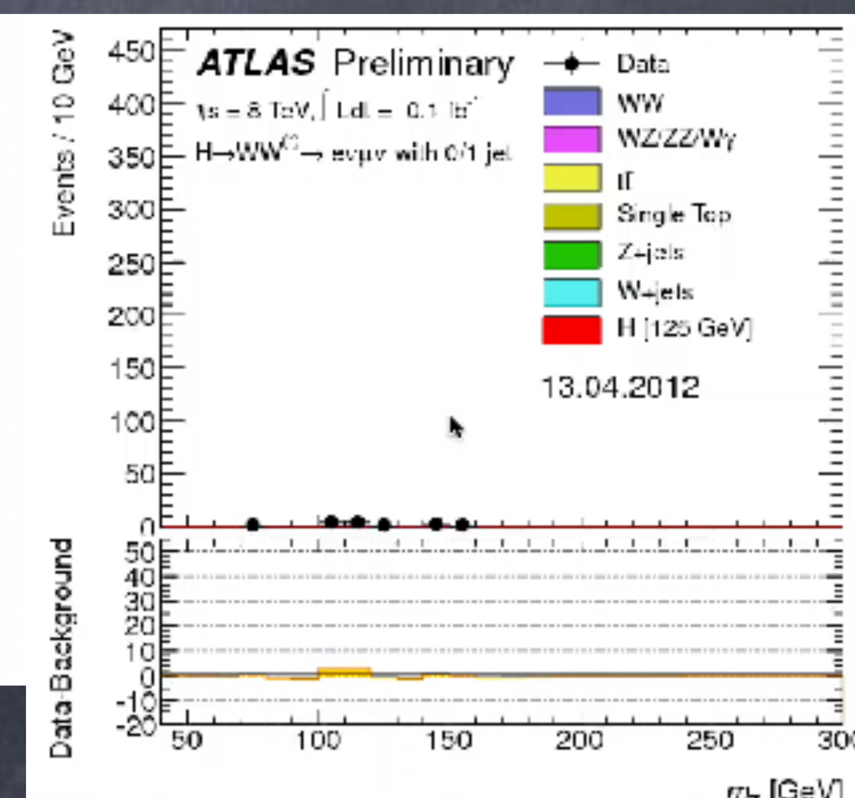












Mass of the Higgs boson (Run 1 data only)

Expt.	Chan.	m_H	stat	syst
ATLAS	$\gamma\gamma$	126,8	0,2	0,7
CMS	$\gamma\gamma$	125,4	0,5	0,6
ATLAS	4l	124,3	0.6/0.5	0.5/0.3
CMS	4l	125,8	0,5	0,2
ATLAS	Comb	125,5	0,2	0.5/0.6
CMS	Comb	125,7	0,3	0,3

(Optimistic back of the envelope 125.6±0.3)

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$

Conclusions

- Far beyond any reasonable doubt we have started to measure and test in detail the properties of a Higgs boson, which in every way is so far consistent with the minimal SM ($J^P=0^+$, SM couplings in production and decay, no unexpected invisible decays)