Title: Searching for the Higgs Boson with the ATLAS Experiment

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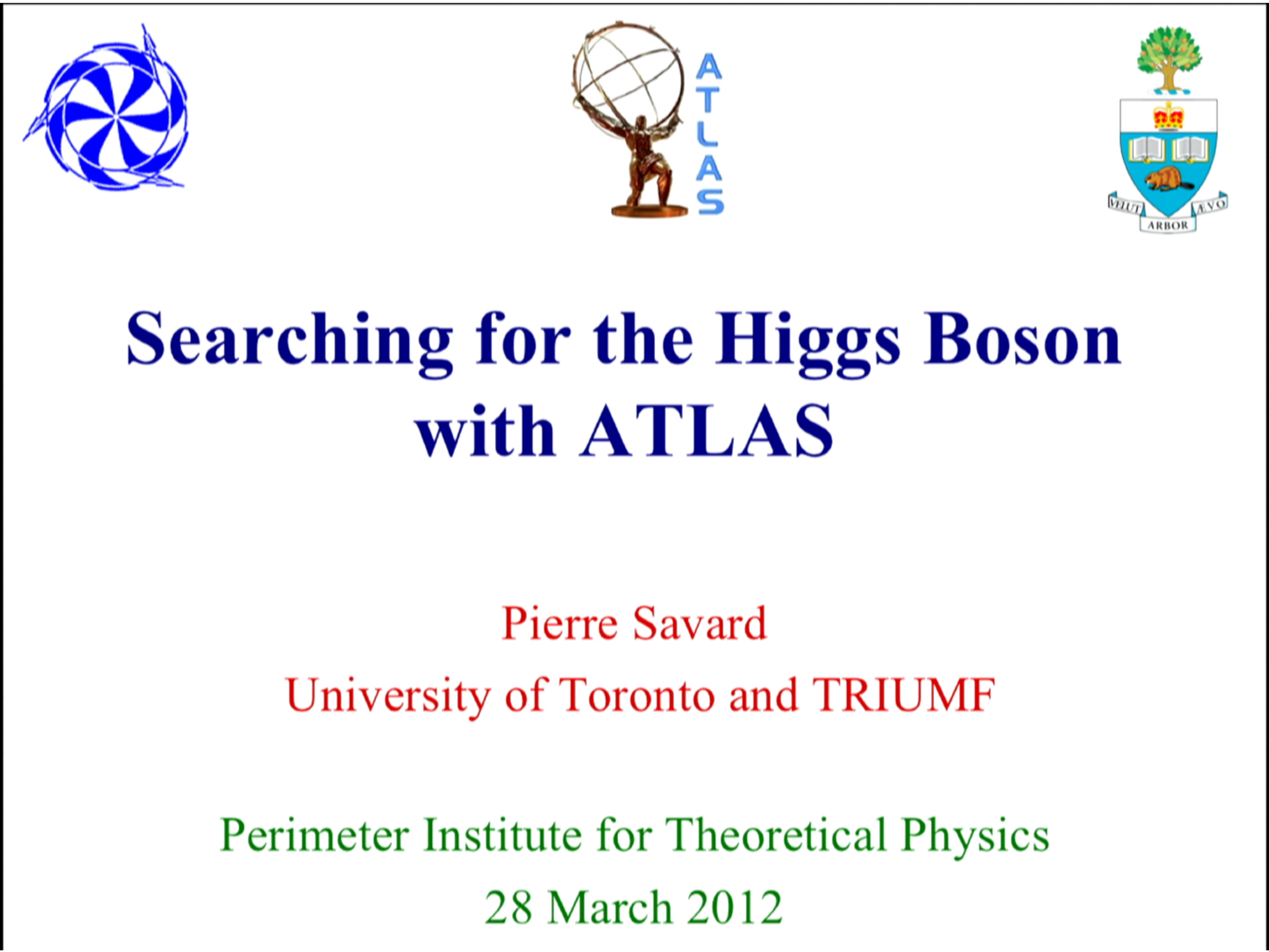
Abstract:



Searching for the Higgs Boson with ATLAS

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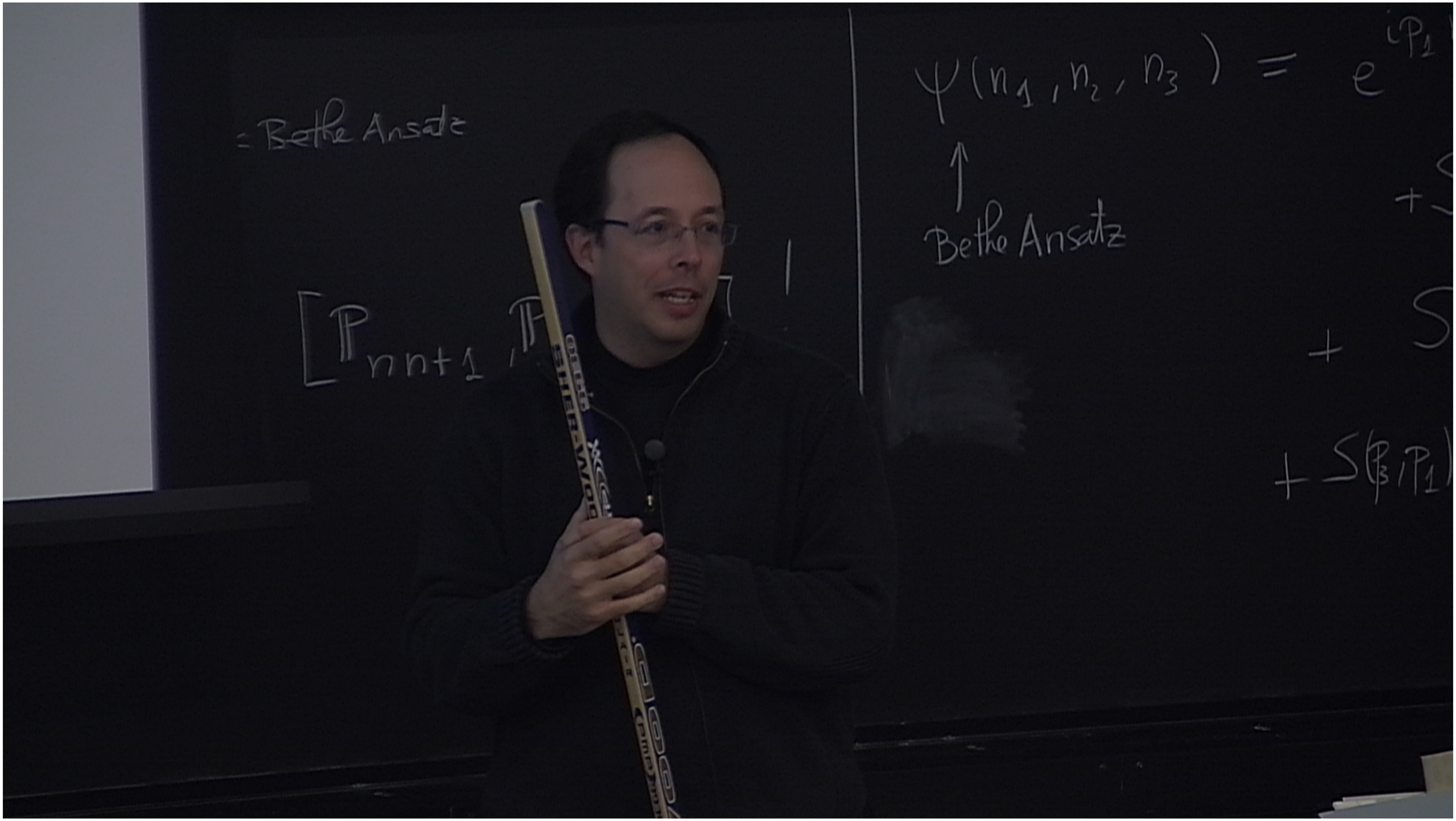
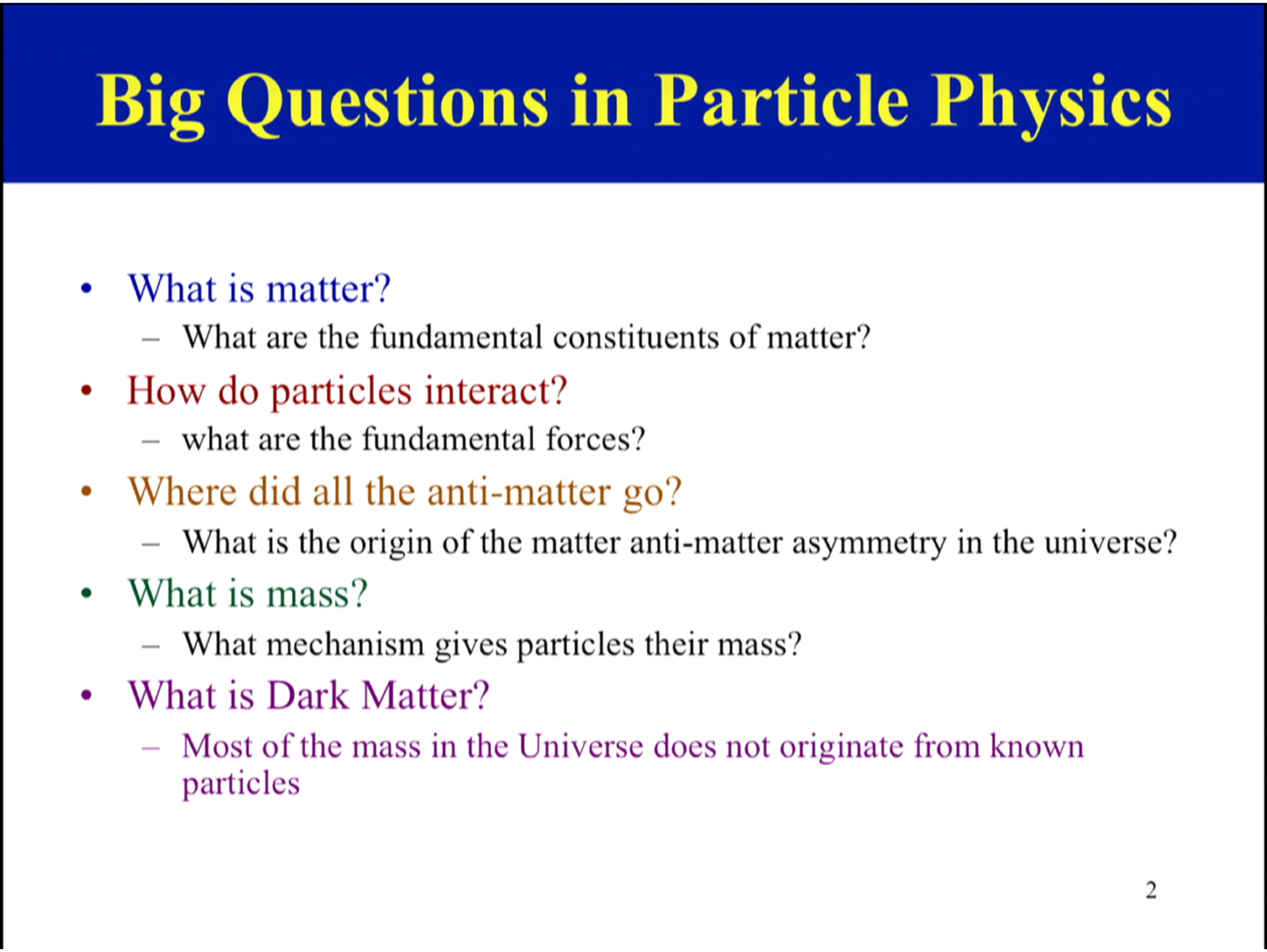
28 March 2012


= Bethe Ansatz
$[\mathbb{P}_{n\,n+1}, \mathbb{P}$
$\psi(n_1, n_2, n_3) = e^{ip_1}$
Bethe Ansatz
$+ S(p_3, p_1)$



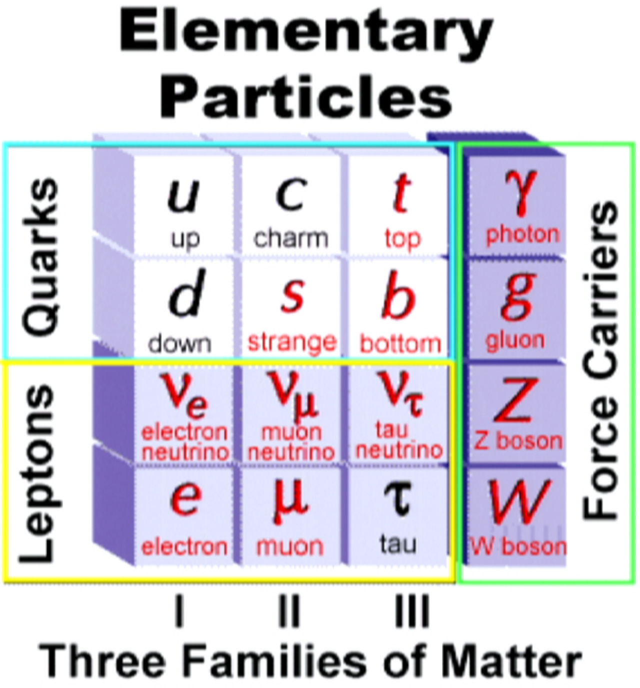
Big Questions in Particle Physics

- What is matter?
  - What are the fundamental constituents of matter?
- How do particles interact?
  - what are the fundamental forces?
- Where did all the anti-matter go?
  - What is the origin of the matter anti-matter asymmetry in the universe?
- What is mass?
  - What mechanism gives particles their mass?
- What is Dark Matter?
  - Most of the mass in the Universe does not originate from known particles

The Standard Model

Standard Model describes:

- 12 fermions , spin 1/2 particles in 3 generations:
  - 6 quarks
  - 6 leptons
- 3 forces mediated by bosons, spin 1 particles:
  - electromagnetic (photons)
  - strong (8 gluons, massless)
  - weak (W+,W-,Z) (massive!)
- What about the Higgs Boson, Gravity, Dark Matter?



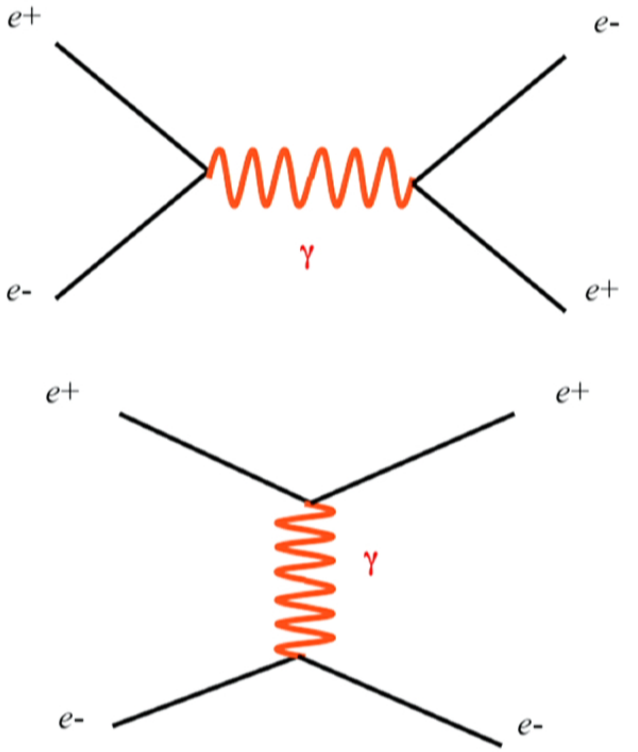
Elementary Particles

	I	II	III	Force Carriers
Quarks	u up	c charm	t top	γ photon
Quarks	d down	s strange	b bottom	g gluon
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
Leptons	e electron	μ muon	τ tau	W W boson

Three Families of Matter

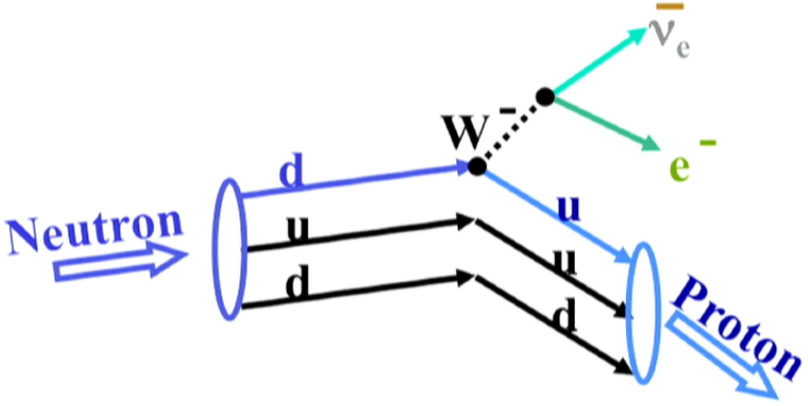
Fundamental Forces

- The Standard Model of particle physics is a quantum field theory in which forces are mediated by the exchange of "virtual" particles (**$\Delta E \Delta t > h/4\pi$**)
- We know of 4 forces:
  - Electromagnetic
  - Weak
  - Strong
  - Gravity*
- The force mediator particles are bosons: particles with integer spin
- The mediator particle for the electromagnetic force is the well known photon



The Weak Force

- The mediator particles for the weak force are 3 massive bosons: W+, W-, and Z^0
- Because the meditators are massive, the force is short range (**$\Delta E \Delta t > h/4\pi$**)
- The weak force can change one quark or lepton into another (charged current)
- Having massive mediators creates theoretical problems (violates local gauge invariance which is necessary for renormalizability)

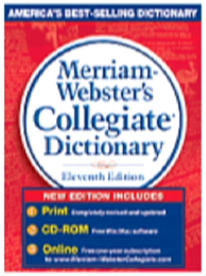


$$\mathbf{n \rightarrow p^+ + e^- + \nu_e}$$

What is Mass?

- Newton, definition #1 of Principia:

  “the quantity of matter is the measure of the same, arising from its density and its bulk conjointly” (?) (maybe: $m = \rho V$)

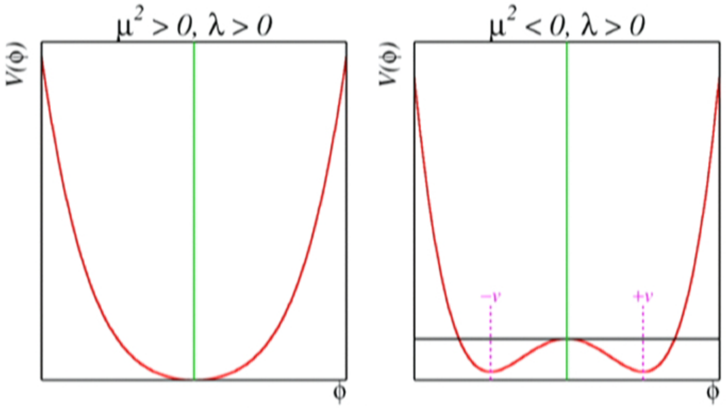


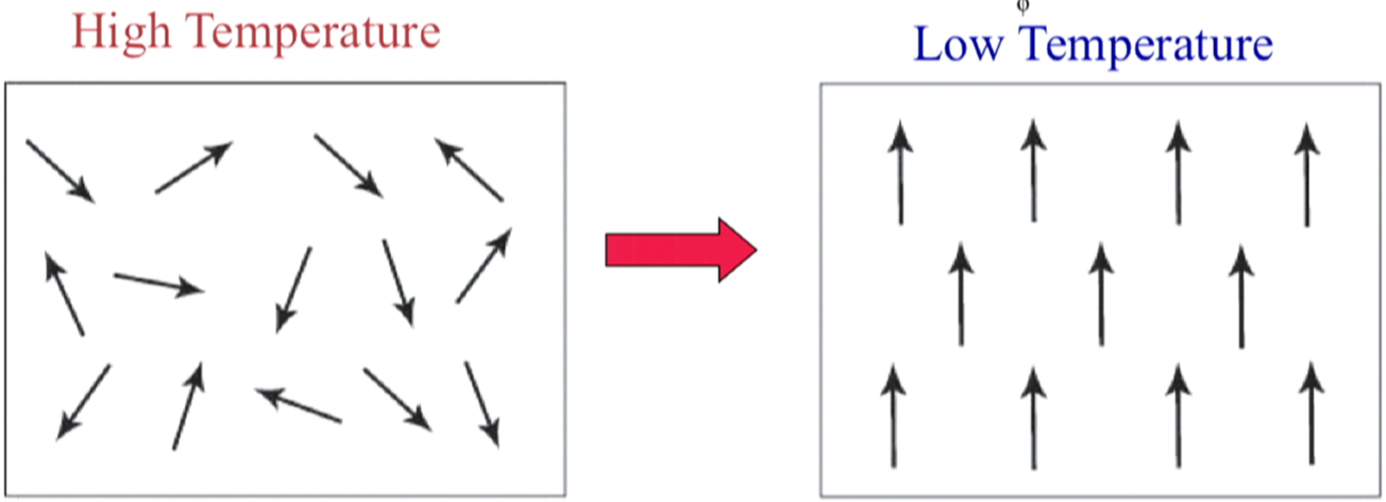
- Merriam-Webster dictionary:

  “the property of a body that is a measure of its inertia and that is commonly taken as a measure of the amount of material it contains and causes it to have weight in a gravitational field”

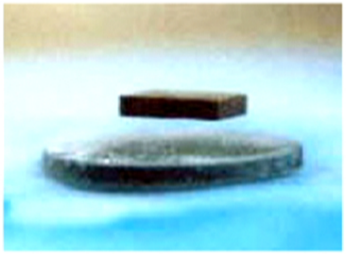
Spontaneous Symmetry Breaking

Example: What happens to a ferromagnet when cooled below critical temperature





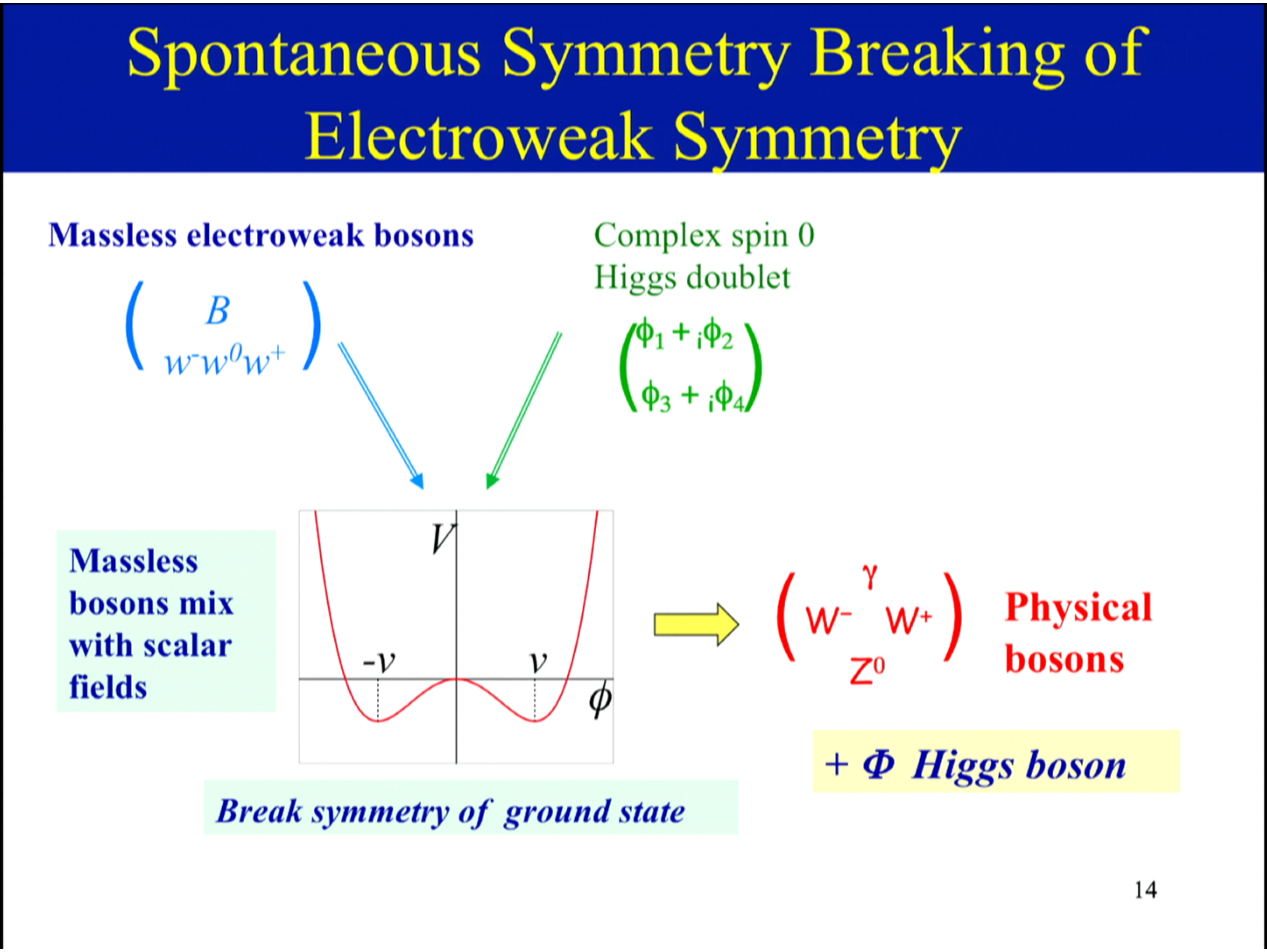
Meissner Effect Analogy



- Cooper pairs form (BEC) condensate below T_c $\sim 10^0$-10^2 K. Condensate disturbed by EM field (photons)
- Short range force, attenuation length $\sim 10^{-6}$cm
- equivalent to photon acquiring a mass

- Higgs condenses below T_c $\sim 10^{15}$K. Condensate disturbed by weak bosons
- Short range force, attenuation length $\sim 10^{-16}$cm
- W/Z bosons acquire mass

"Cosmic superconductor"



Spontaneous Symmetry Breaking of Electroweak Symmetry

Massless electroweak bosons

$\begin{pmatrix} B \\ W^- W^0 W^+ \end{pmatrix}$

Complex spin 0
Higgs doublet

$\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$

Massless bosons mix with scalar fields

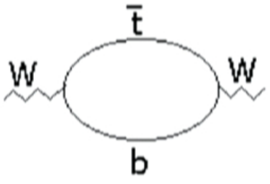
$\begin{pmatrix} & \gamma & \\ W^- & & W^+ \\ & Z^0 & \end{pmatrix}$ **Physical bosons**

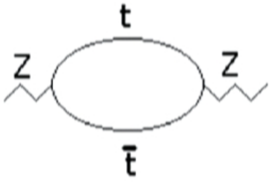
+ Φ Higgs boson

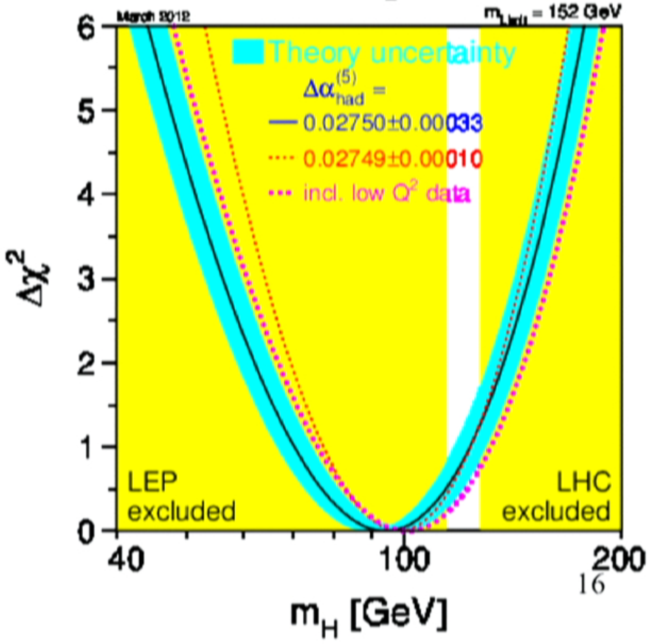
Break symmetry of ground state

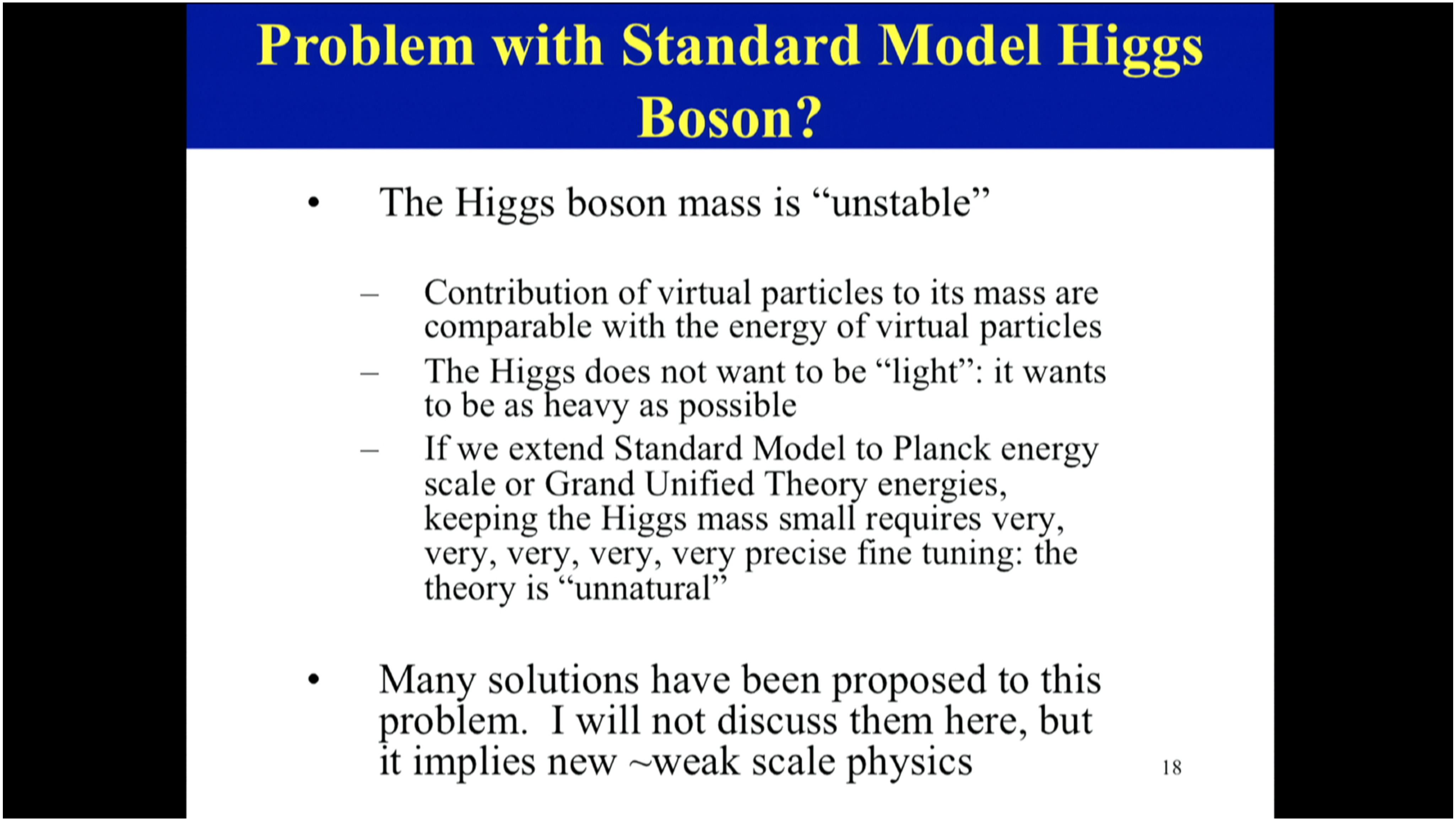
The Virtual Higgs Boson

- The Higgs boson (if it exists) will affect particles in ways that we can measure
  - Contribution of virtual particles affect a particle's mass
  - Example: top quark mass was estimated before top was officially discovered







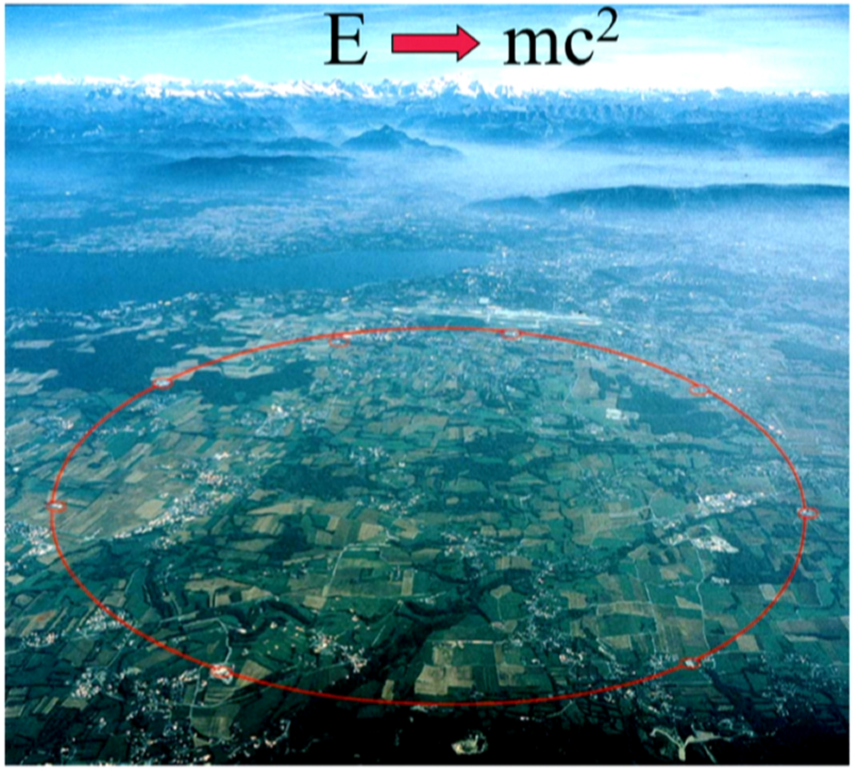


Problem with Standard Model Higgs Boson?

- The Higgs boson mass is "unstable"
  - Contribution of virtual particles to its mass are comparable with the energy of virtual particles
  - The Higgs does not want to be "light": it wants to be as heavy as possible
  - If we extend Standard Model to Planck energy scale or Grand Unified Theory energies, keeping the Higgs mass small requires very, very, very, very, very precise fine tuning: the theory is "unnatural"
- Many solutions have been proposed to this problem. I will not discuss them here, but it implies new ~weak scale physics

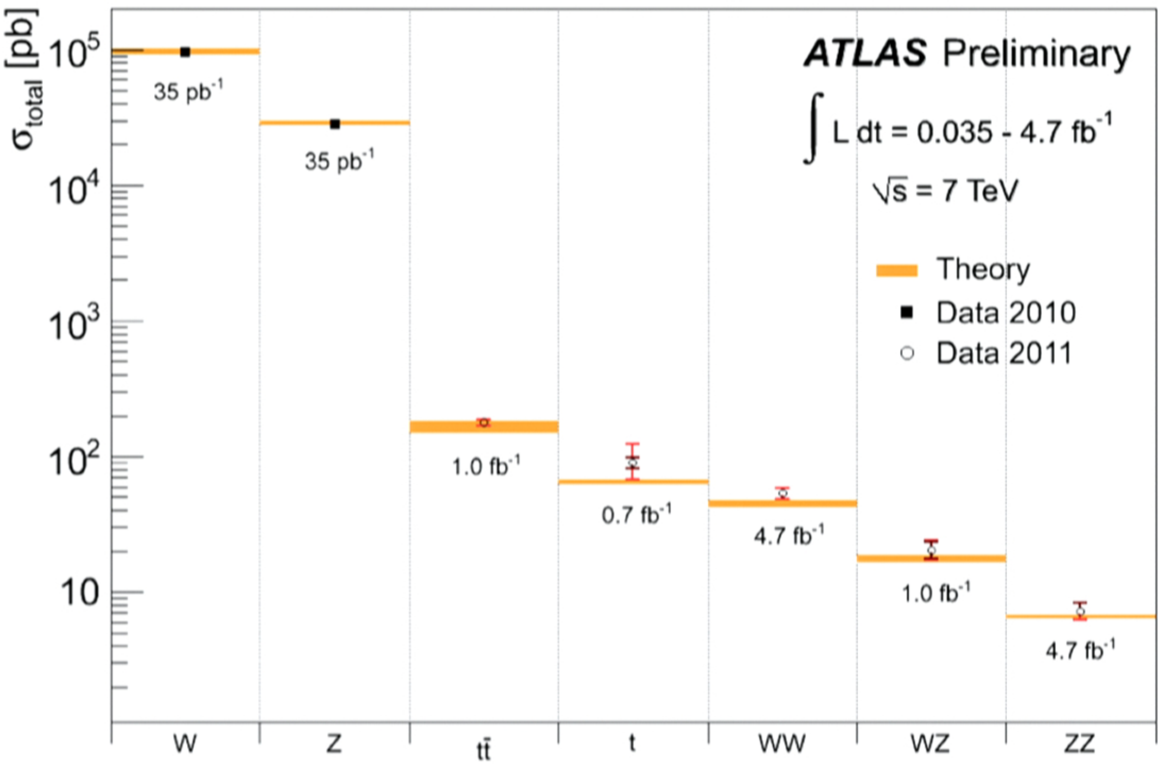
The Large Hadron Collider

- A 26 km long collider at CERN near Geneva
- Collides protons on protons at centre of mass energy of 7-8 TeV, every 50ns
- Produces up to ~300-700 million collisions per second
- 2011 dataset ~150 times larger than in 2010
- Hope to reach 13-14 TeV in 2014

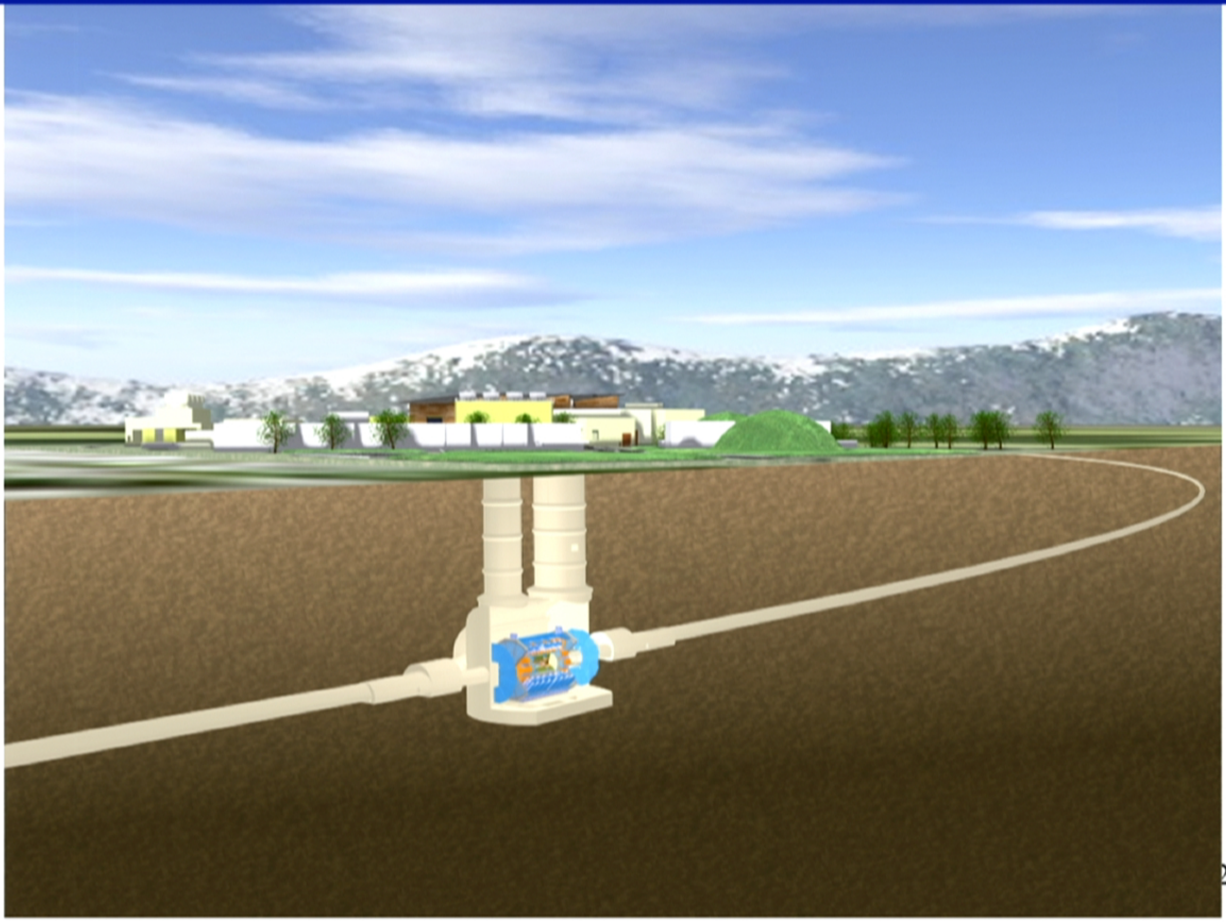


$E \rightarrow mc^2$

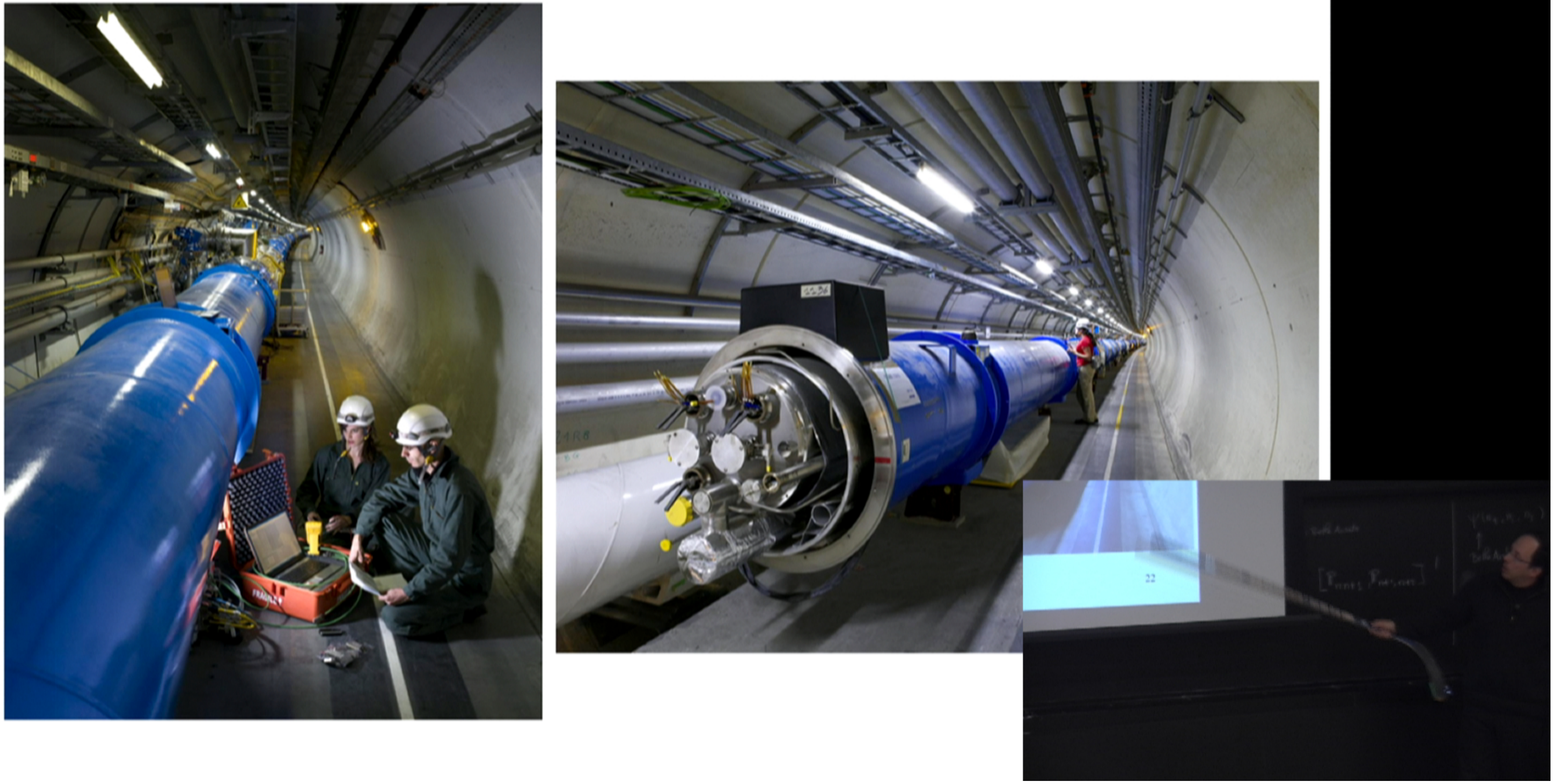
Why so many Collisions?



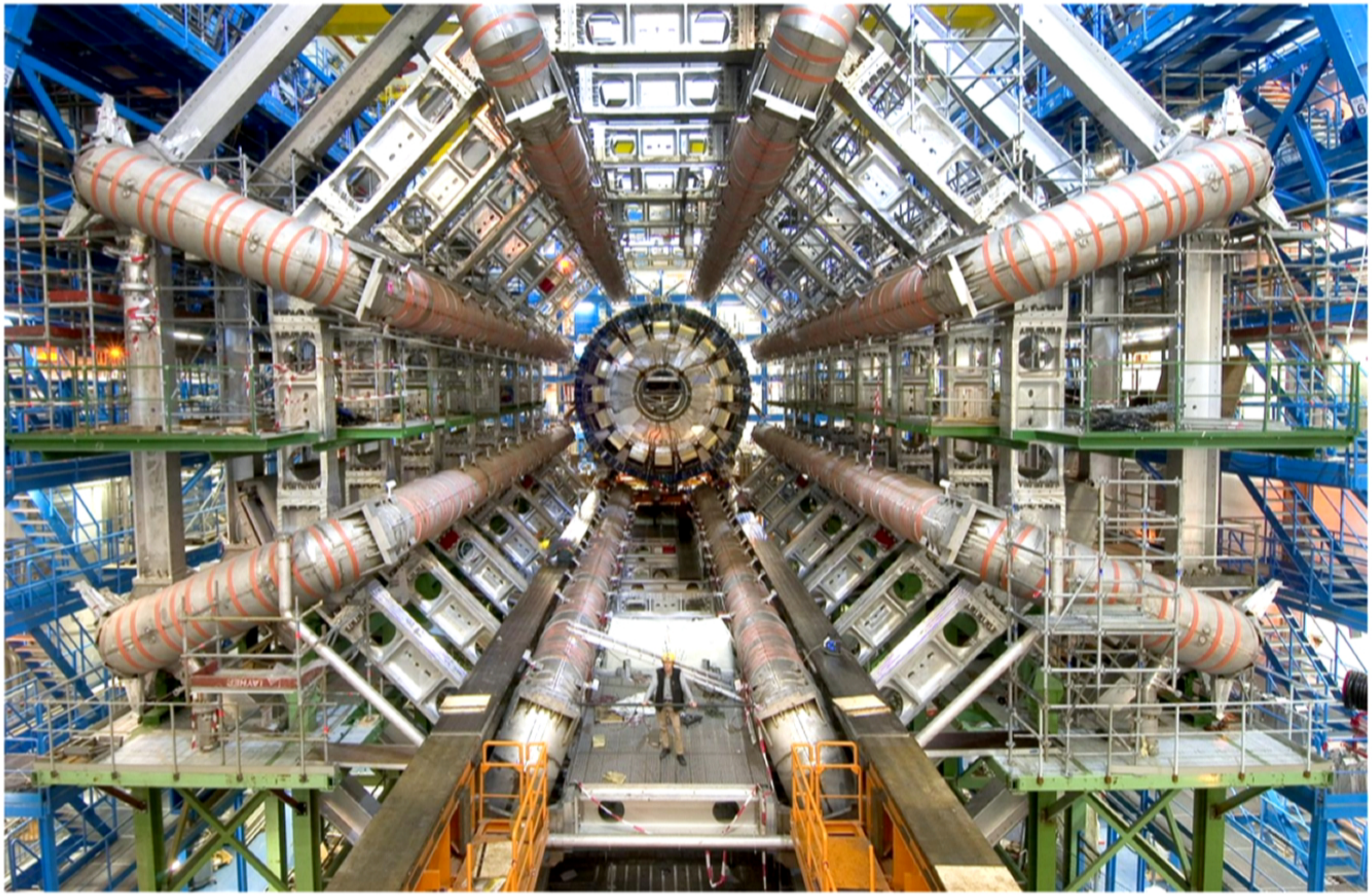
The Large Hadron Collider (2)



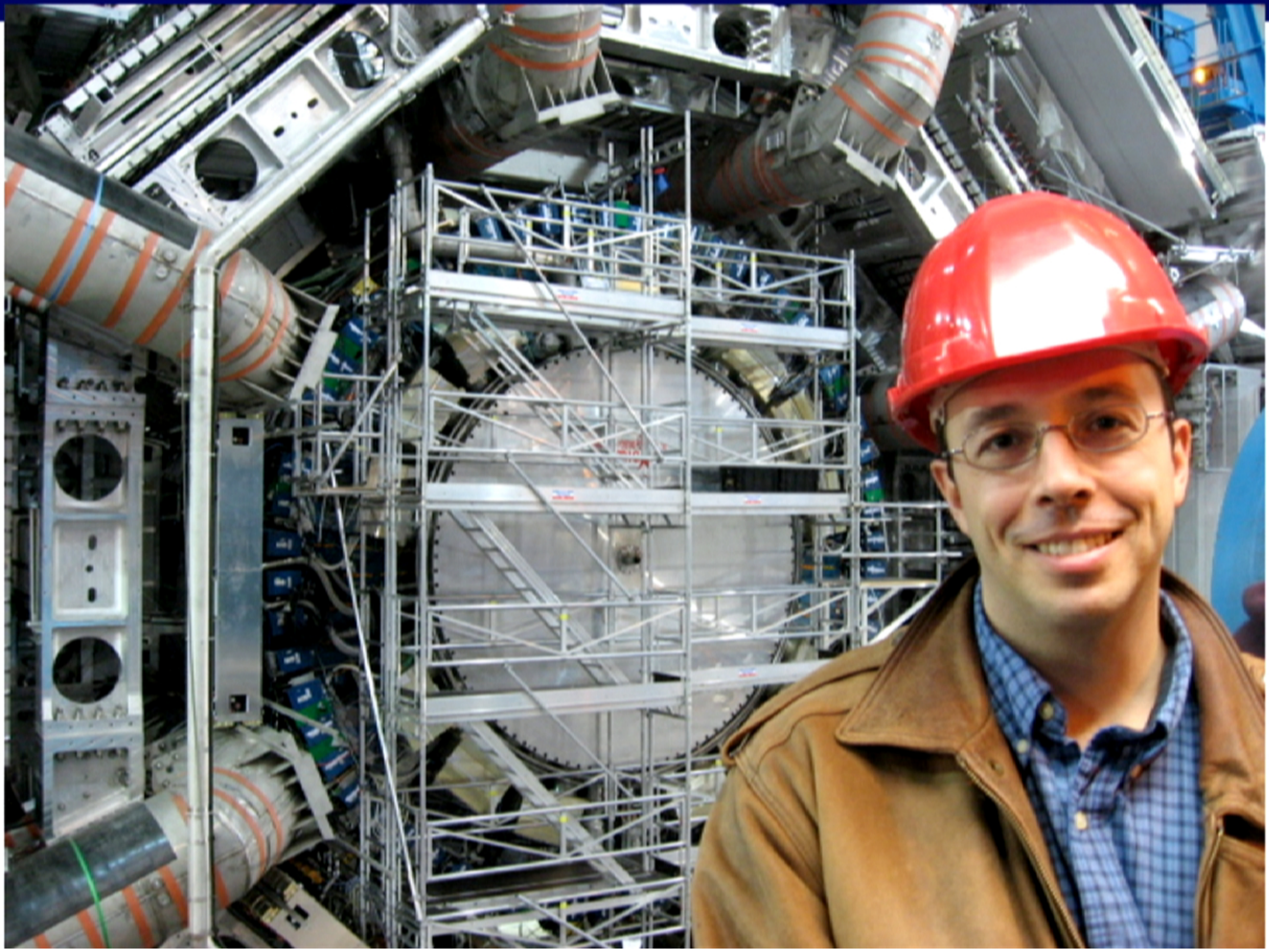
LHC Tunnel

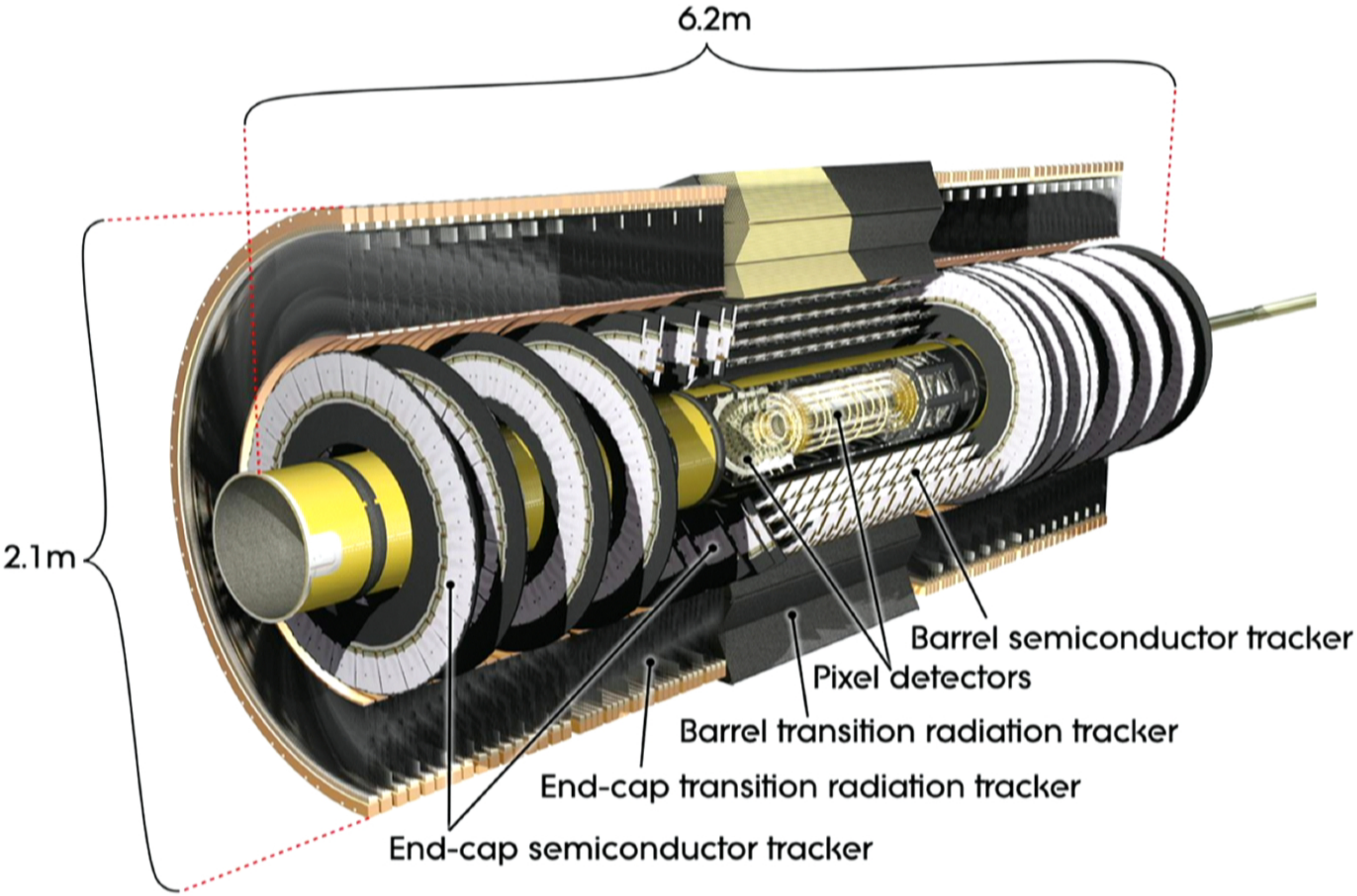


ATLAS Detector without Calorimeter

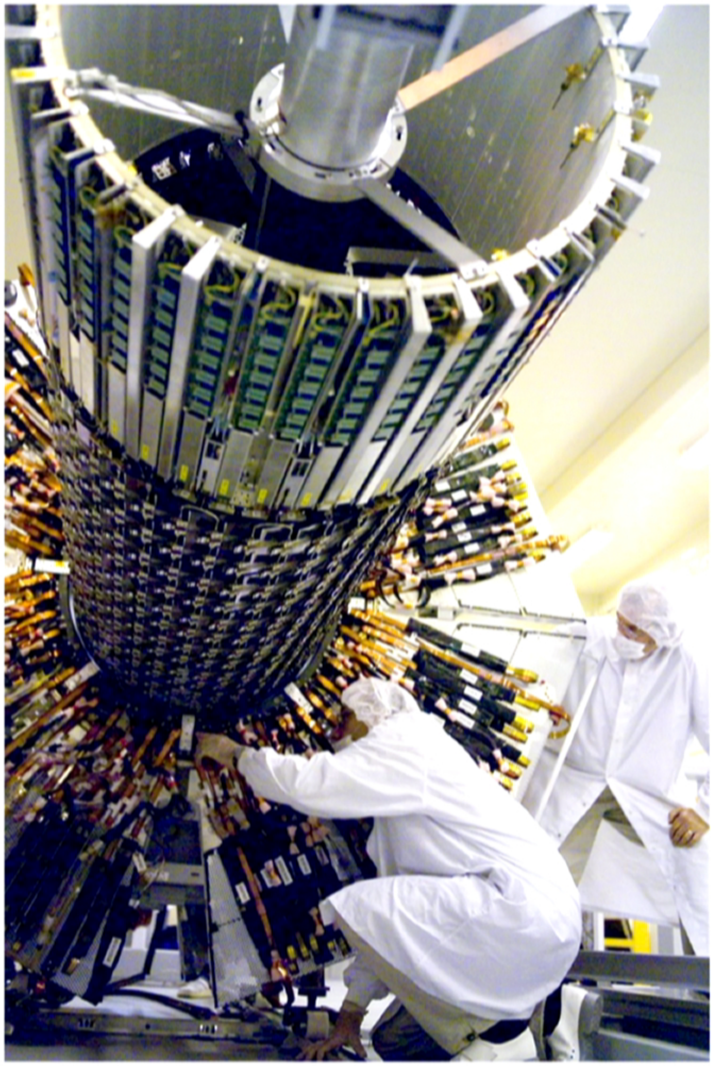


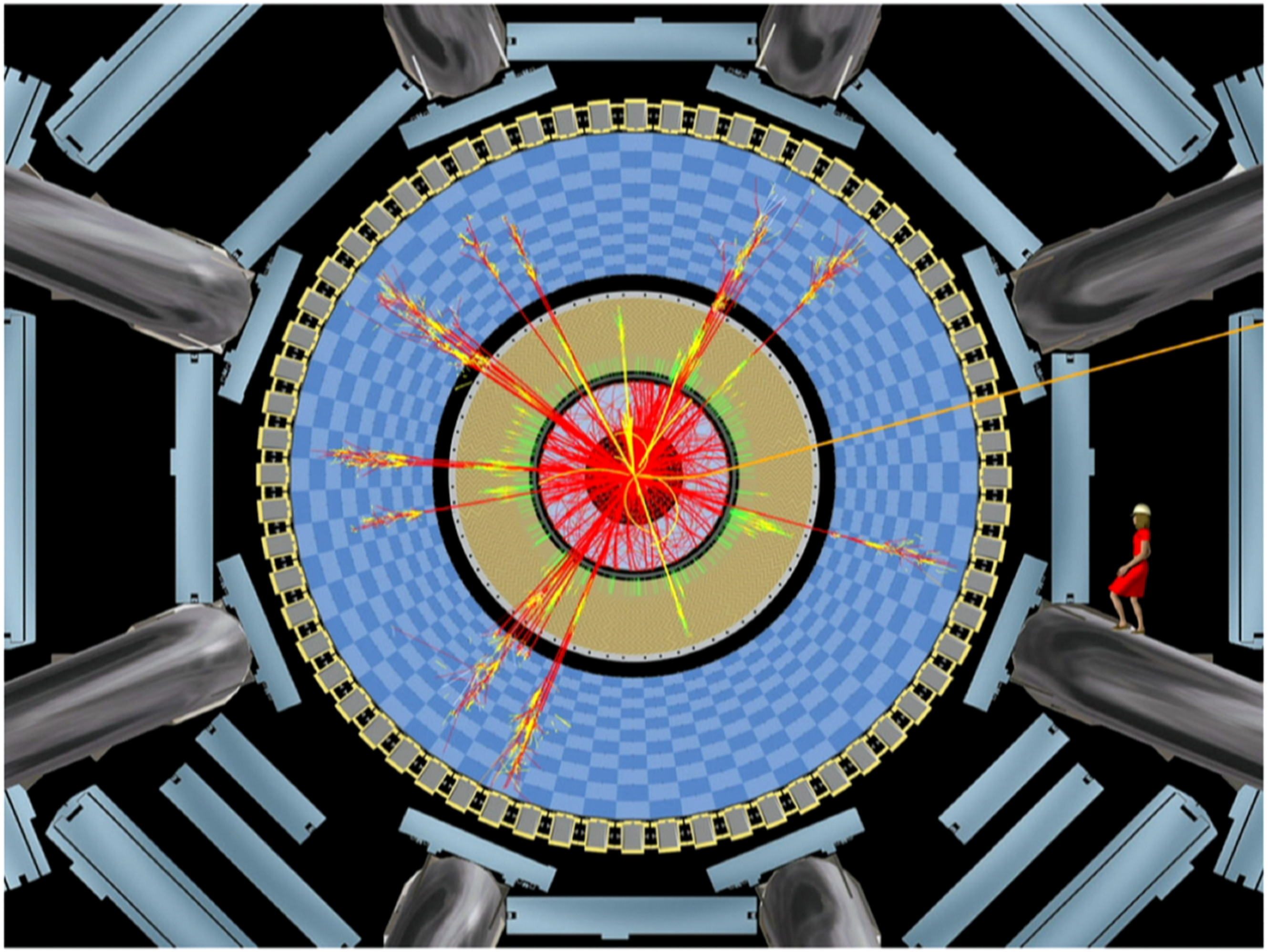
ATLAS Detector with Calorimeter

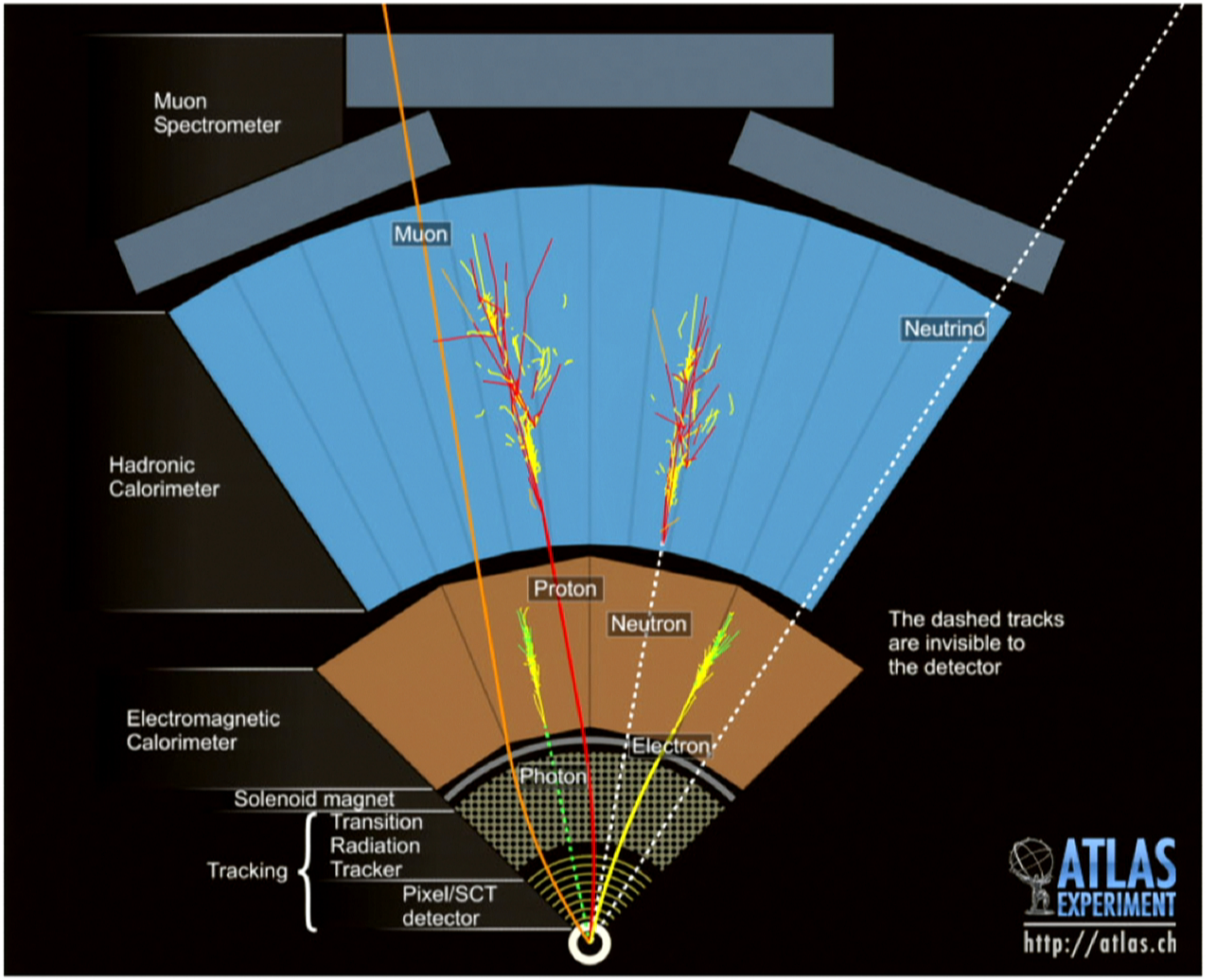



6.2m
2.1m
Barrel semiconductor tracker
Pixel detectors
Barrel transition radiation tracker
End-cap transition radiation tracker
End-cap semiconductor tracker

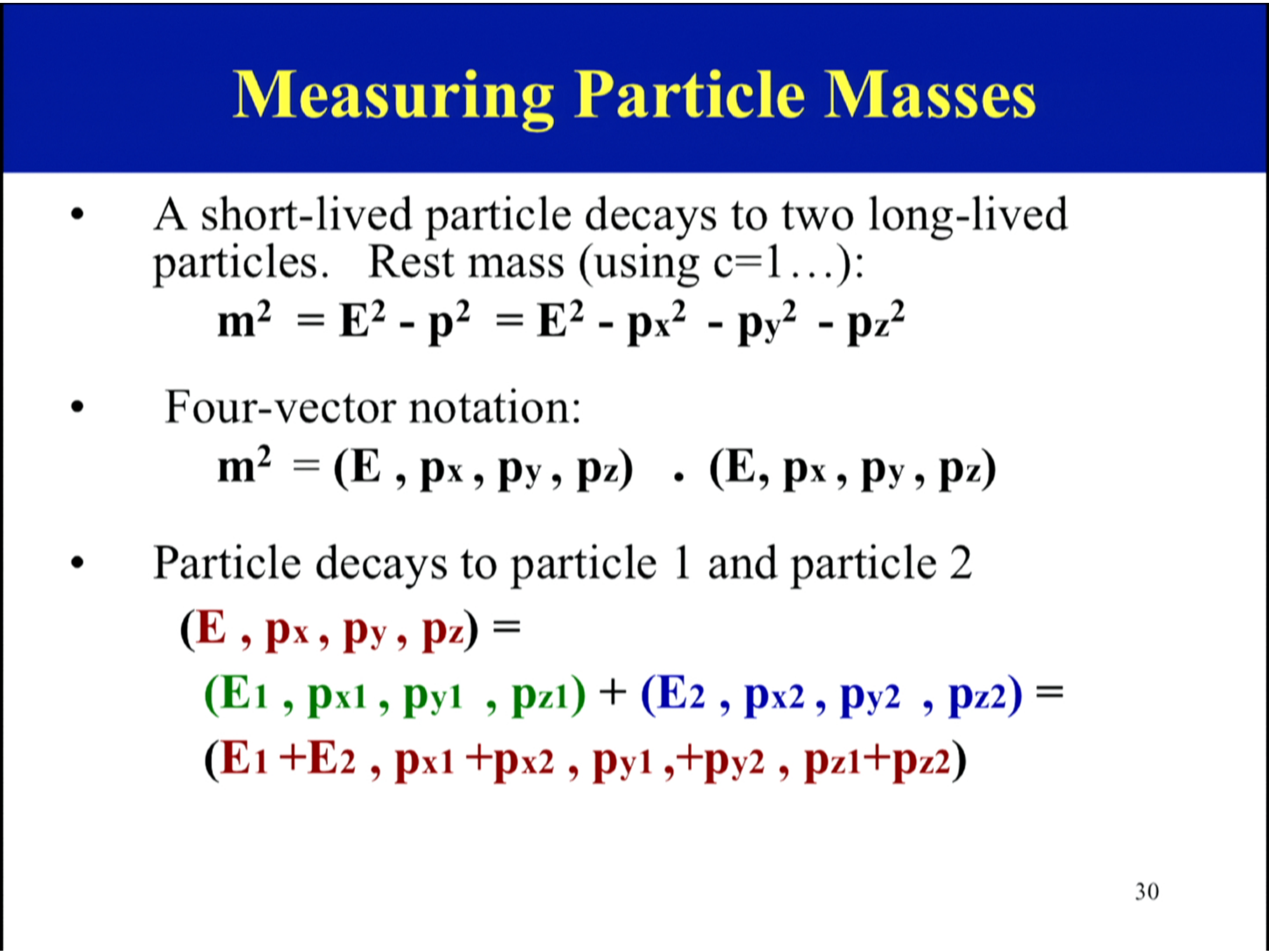

CONVOI EXCEPTIONNEL







The dashed tracks are invisible to the detector



Measuring Particle Masses

- A short-lived particle decays to two long-lived particles. Rest mass (using c=1…):

  $$m^2 = E^2 - p^2 = E^2 - p_x^2 - p_y^2 - p_z^2$$

- Four-vector notation:

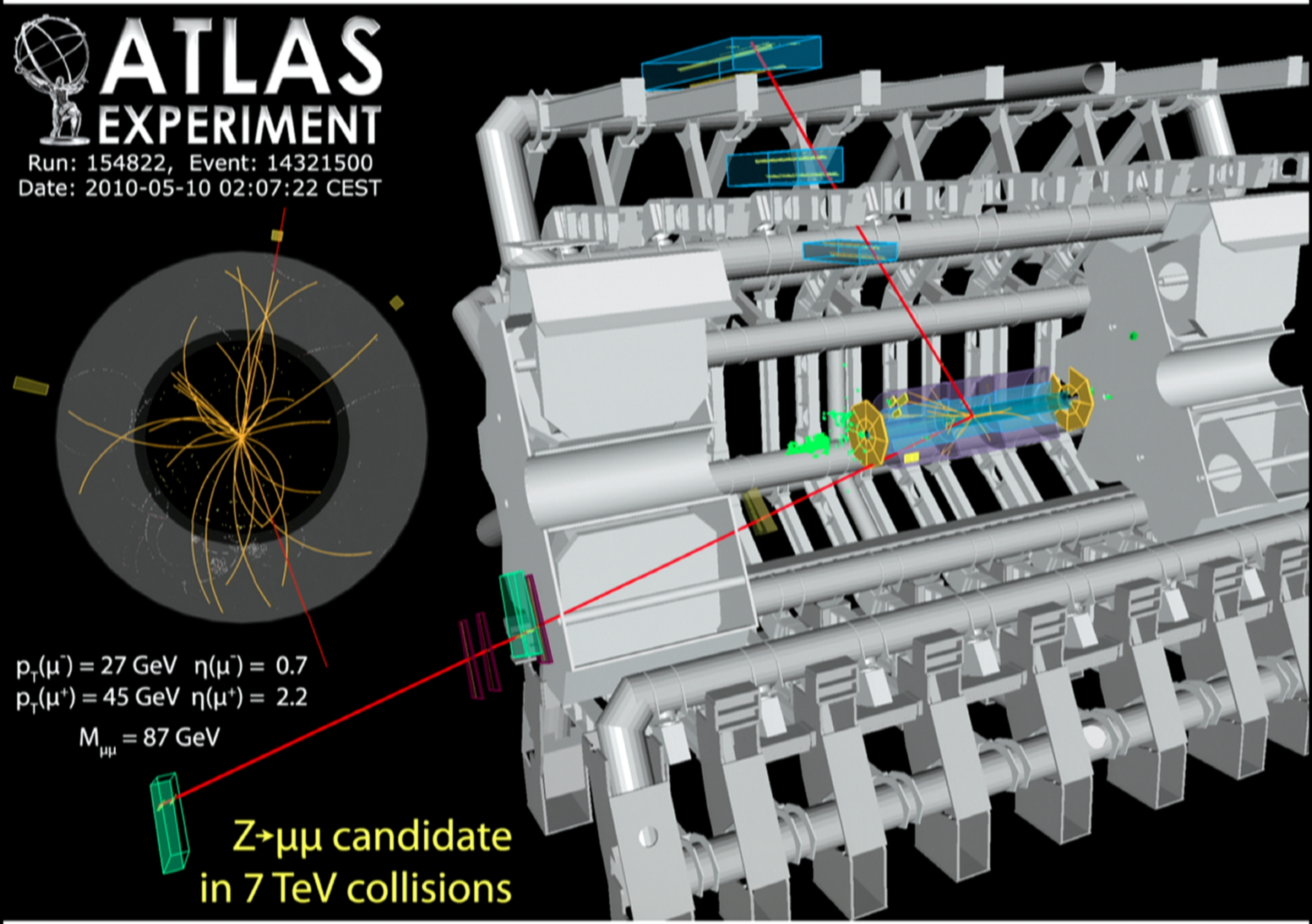
  $$m^2 = (E , p_x , p_y , p_z) \cdot (E, p_x , p_y , p_z)$$

- Particle decays to particle 1 and particle 2

  $$(E , p_x , p_y , p_z) =$$

  $$(E_1 , p_{x1} , p_{y1} , p_{z1}) + (E_2 , p_{x2} , p_{y2} , p_{z2}) =$$

  $$(E_1 +E_2 , p_{x1} +p_{x2} , p_{y1} ,+p_{y2} , p_{z1}+p_{z2})$$



ATLAS EXPERIMENT

Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST

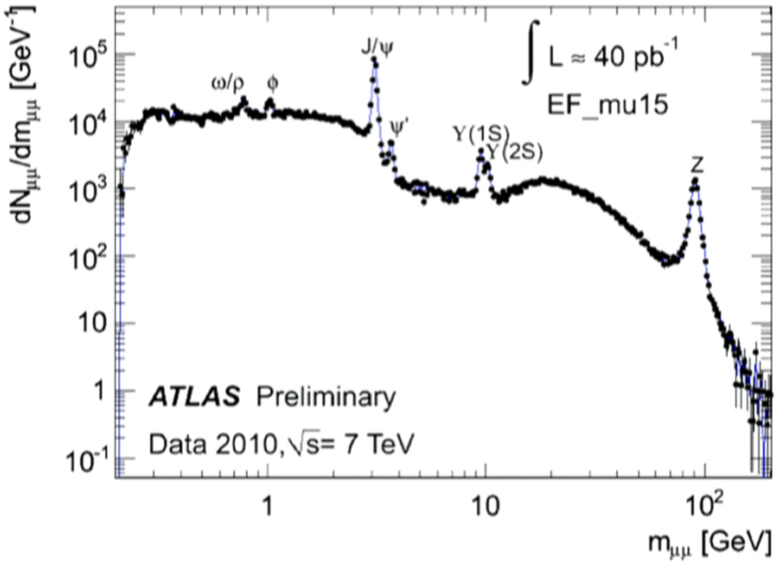
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$

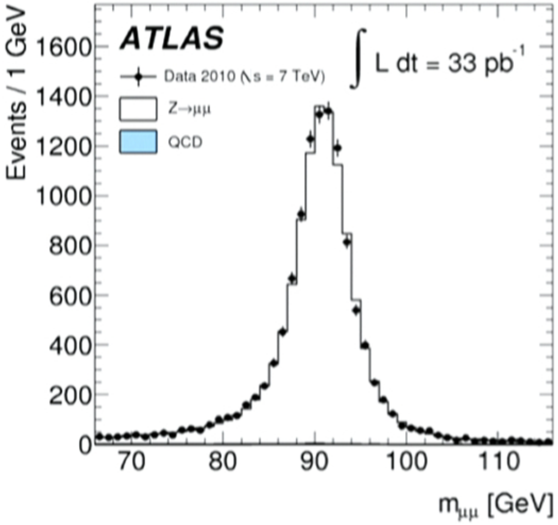
$M_{\mu\mu} = 87$ GeV

$Z \to \mu\mu$ candidate
in 7 TeV collisions

Mass of Muon Pairs

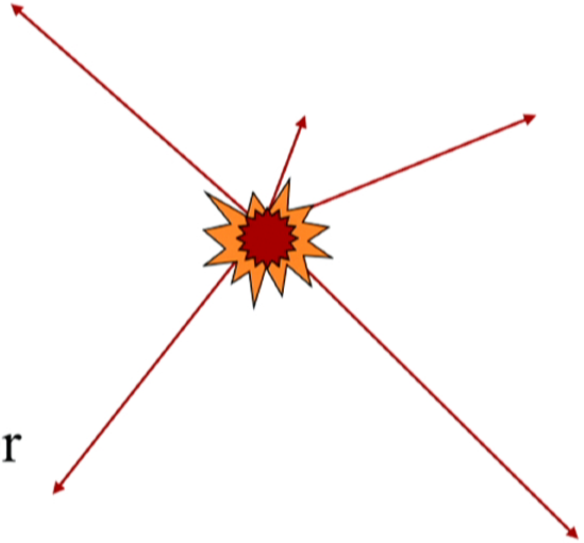
- Require two muons
- Add muon four-vectors
- Plot mass distribution





How do we measure a particle that does not interact?

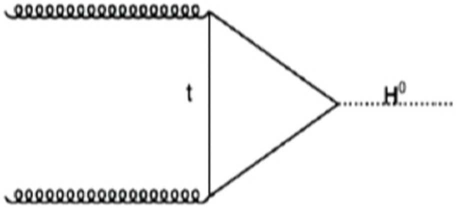
- Conservation of momentum…
- The momentum of quarks inside the protons in the plane transverse to the beam is essentially zero
- By adding the momenta of all observed particles, we can infer the presence of a non-interacting particle



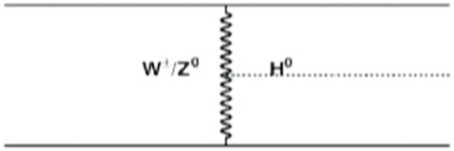
Higgs Production

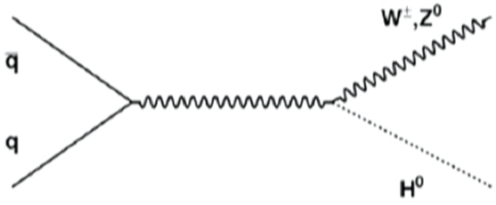
- Higgs production at LHC dominated by “gluon fusion” process
- “Weak boson fusion” is subdominant but has less background

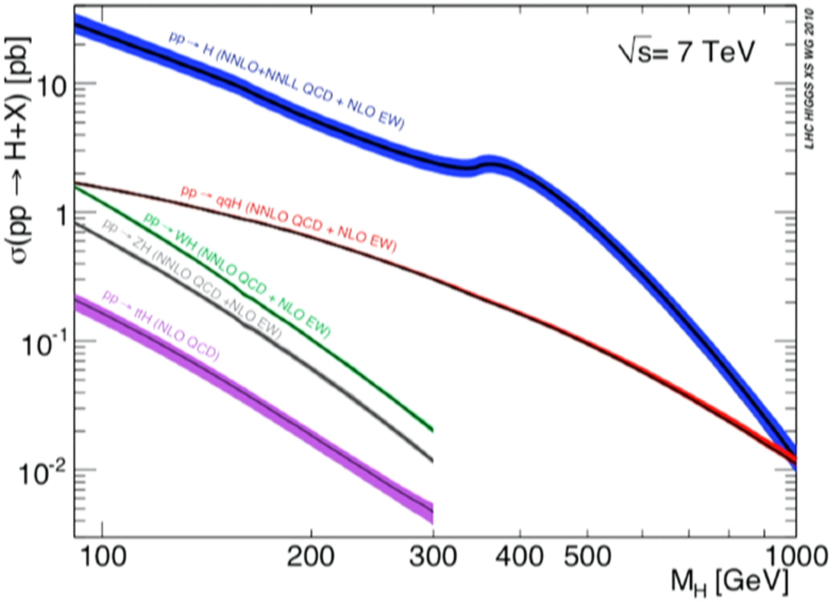
gluon Fusion



Weak Boson Fusion



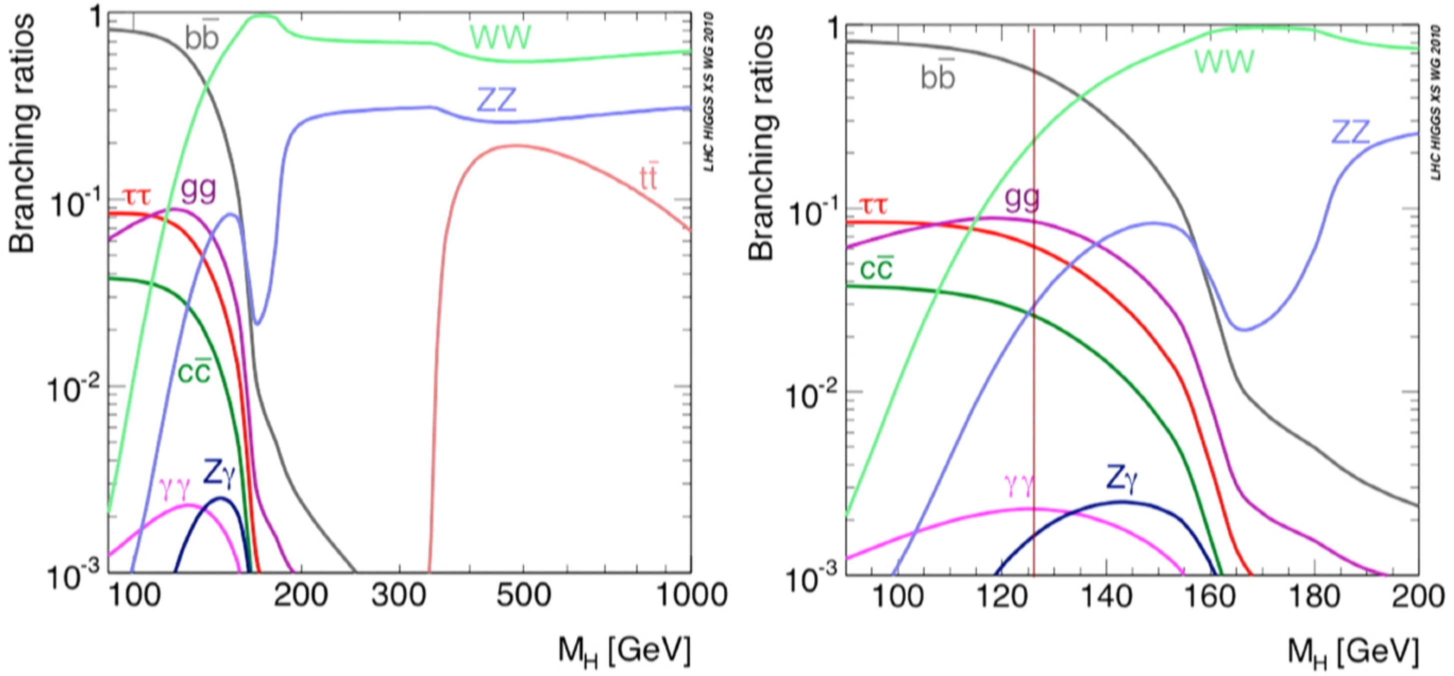


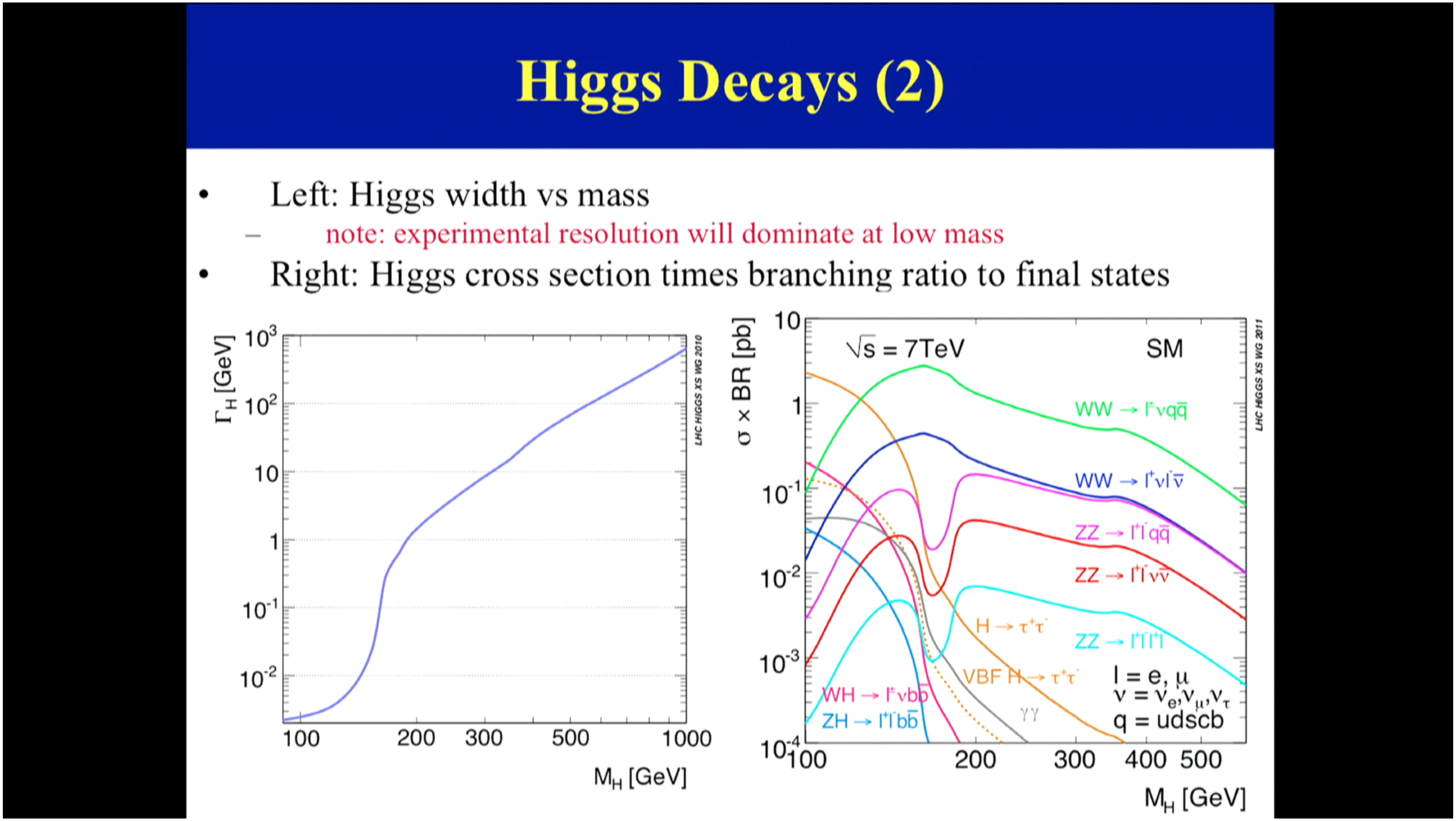


Higgs Decays (1)

- Standard Model is a very predictive theory with respect to the Higgs boson: the only unknown parameter is the Higgs mass

$$\boxed{M_H^2 = 2v^2\,\lambda}$$



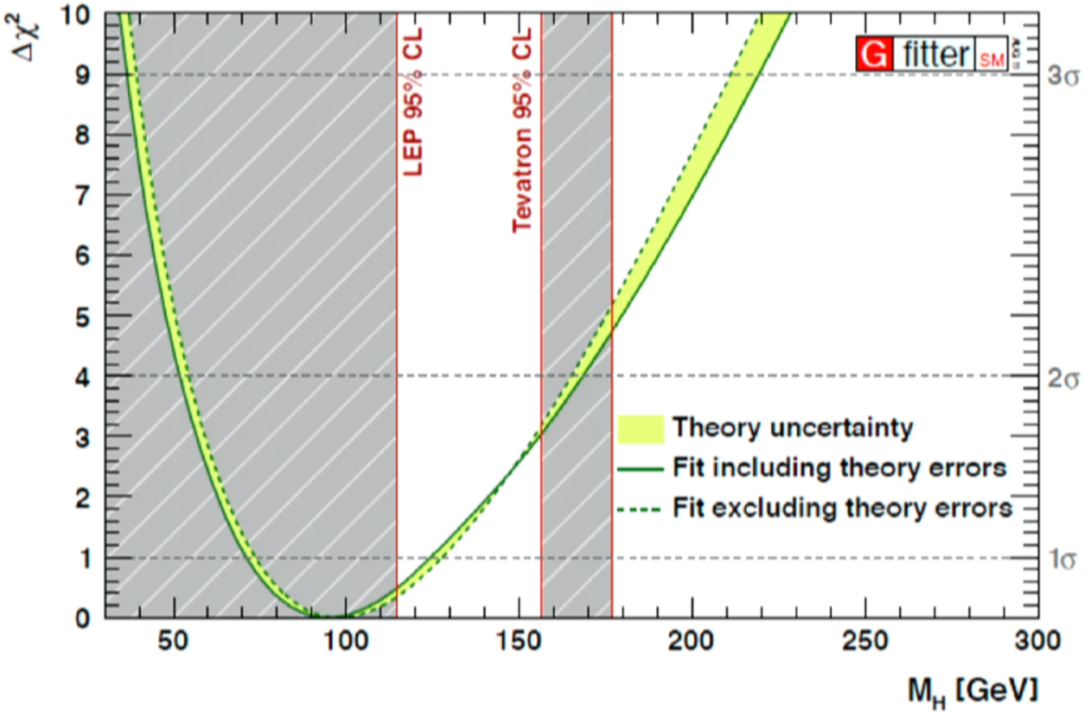


Higgs Decays (2)

- Left: Higgs width vs mass
  - note: experimental resolution will dominate at low mass
- Right: Higgs cross section times branching ratio to final states

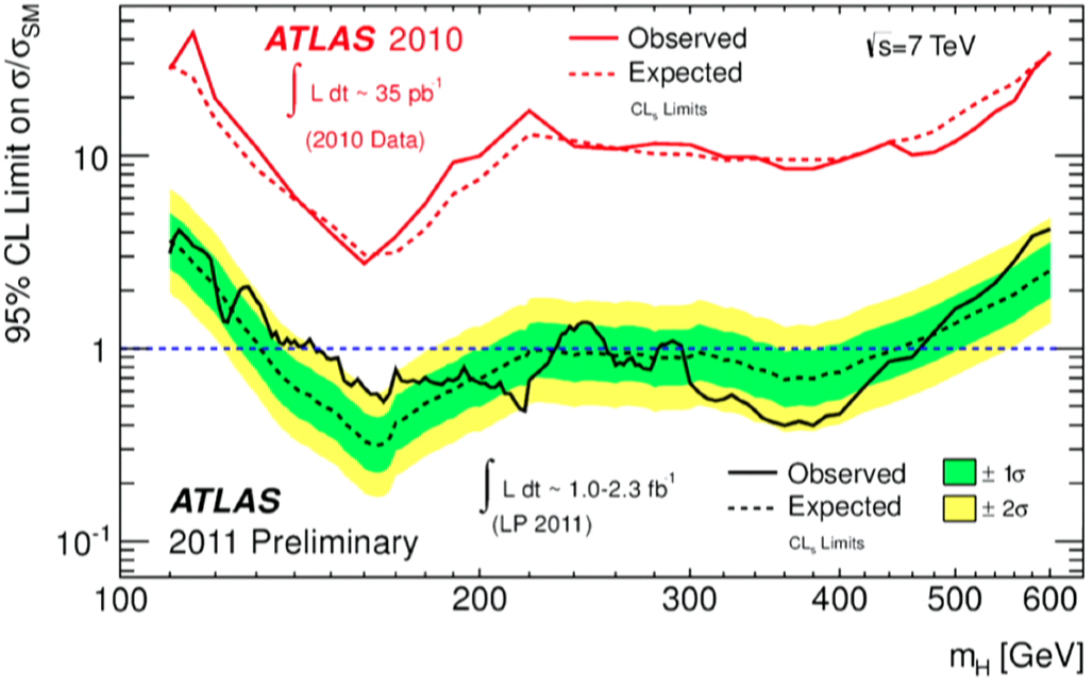
Before LHC: where to expect the Higgs?

- Fits to Standard Model data favors a “light” Higgs Boson
- After 2010, at 95% CL, a 40 GeV window was left for the SM Higgs



Summer 2011: Limits on Higgs Mass

- Results from 2010 and Lepton-Photon 2011: a lot of progress!
- In low mass range: excluded 146-242 GeV (131 GeV expected)



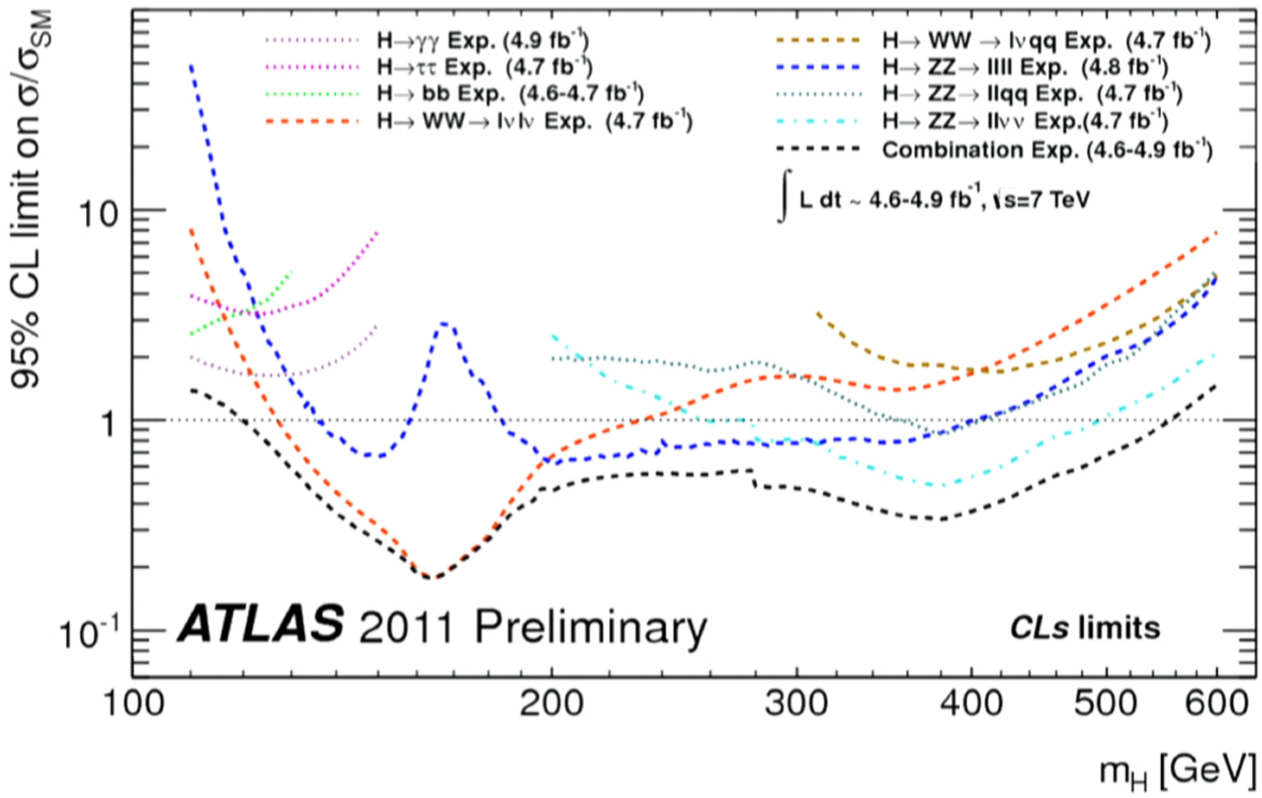
Moriond 2012 ATLAS Results

Sandra Kortner

Searches performend in 12 distinct channels using the full 2011 dataset.

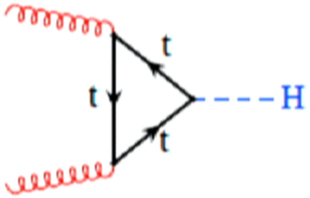
Channel	m_H range (GeV)	Backgrounds	$\mathcal{L}$ (fb^{-1})	Reference
low-m_H, good mass resolution				
$H \rightarrow \gamma\gamma$	110-150	$\gamma\gamma$, γj, jj	4.9	arXiv:1202.1414
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$	110-600	$ZZ^{(*)}$, $Z + jets$, $t\bar{t}$	4.8	arXiv:1202.1415
low-m_H, limited mass resolution				
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$	110-600	WW, $t\bar{t}$, $W/Z + jet$	4.7	CONF-2012-012
$H \rightarrow \tau\tau(ll, lh, hh)$	100-150	$Z \rightarrow \tau\tau$, $t\bar{t}$	4.7	CONF-2012-014
$VH, H \rightarrow bb$	110-130	$W/Z + jets$, $t\bar{t}$	4.7	CONF-2012-015
high-m_H				
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$	200-600	$diboson$, $t\bar{t}$, $Z + jets$	4.7	CONF-2012-016
$H \rightarrow ZZ \rightarrow \ell\ell jj$	200-600	$Z + jets$, $t\bar{t}$, $diboson$	4.7	CONF-2012-017
$H \rightarrow WW \rightarrow \ell\nu jj$	300-600	$W + jets$, $t\bar{t}$, multijets	4.7	CONF-2012-018

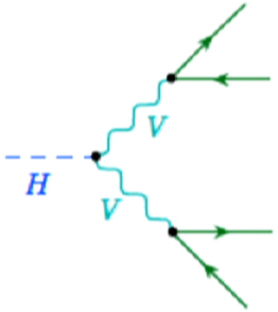
Expected Exclusion Sensitivity

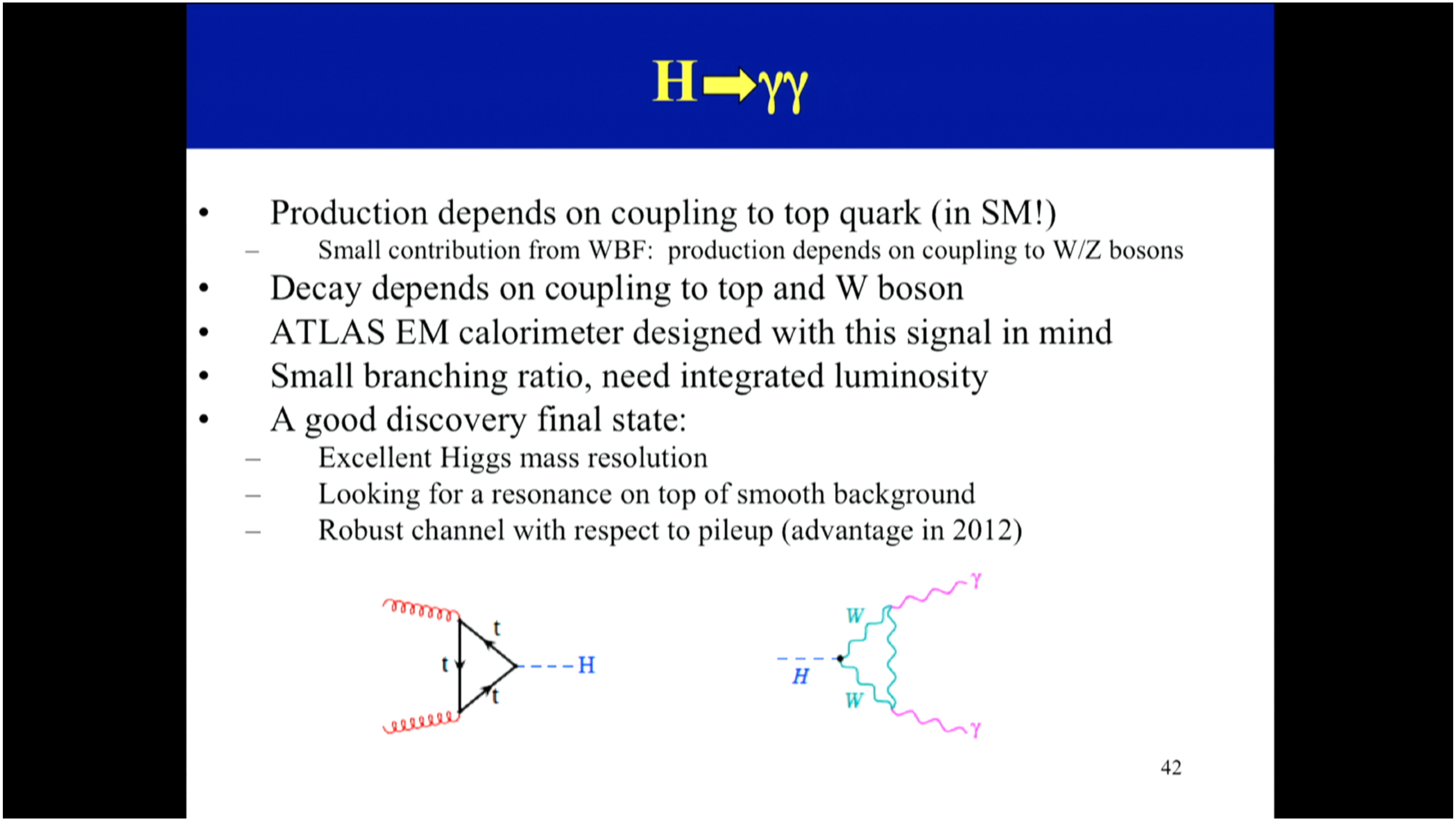


$H \rightarrow WW^* \rightarrow l\nu l\nu$

- Production depends on coupling to top quark (in SM!)
  - Small contribution from WBF: production depends on coupling to W/Z bosons
- Decay depends on coupling to W boson
- Best exclusion sensitivity over most of the low-mass range
- A challenging final state as you go below ~140 GeV:
  - two neutrinos degrade Higgs mass resolution: can't pinpoint Higgs mass
  - Soft leptons for low Higgs mass: larger backgrounds
  - Relies on good understanding of missing ET resolution
  - Many small backgrounds to estimate (and signal contribution is small…)
  - Sensitive to pileup (a challenge in 2012)





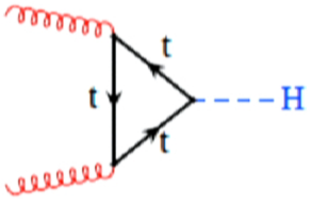


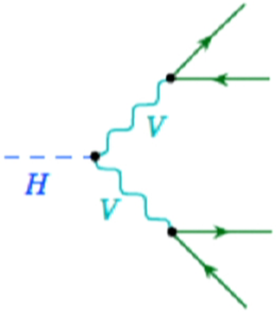
H ➡ $\gamma\gamma$

- Production depends on coupling to top quark (in SM!)
  - Small contribution from WBF: production depends on coupling to W/Z bosons
- Decay depends on coupling to top and W boson
- ATLAS EM calorimeter designed with this signal in mind
- Small branching ratio, need integrated luminosity
- A good discovery final state:
  - Excellent Higgs mass resolution
  - Looking for a resonance on top of smooth background
  - Robust channel with respect to pileup (advantage in 2012)

H→ZZ*→llll

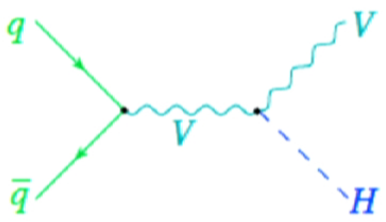
- Production depends on coupling to top quark (in SM!)
- Decay depends on coupling to Z boson
- Small branching fraction to 4-lepton final state (need int. lumi.)
- A good discovery final state:
  - Very low backgrounds
  - Very good Higgs mass resolution
  - Requires good lepton reconstruction efficiencies
    - Can cope with high pileup environment
  - Clear/robust signal of coupling of Higgs to weak bosons

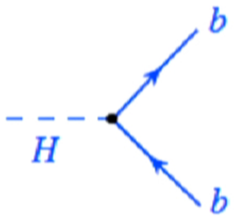




H ➡ bb

- Production depends on coupling to W/Z bosons
- Decay depends on coupling to b quark (important!)
- Small production cross section (but branching ratio is not small)
- A challenging final state:
  - Very large backgrounds (W/Z+jets)
  - Higgs mass resolution is not that good (two jets compared to two photons)
  - Requires good b-tagging efficiency and fake rejection





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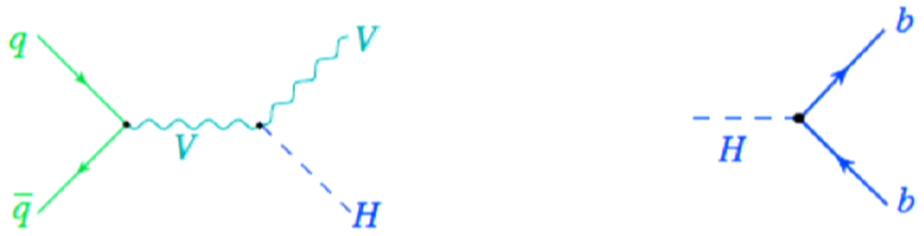
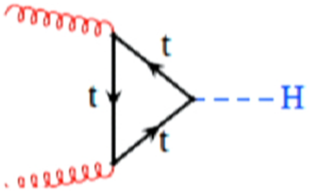
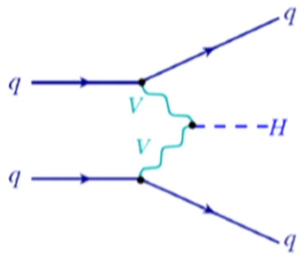
  - Higgs mass resolution is not that good (two jets compared to two photons)
  - Requires good b-tagging efficiency and fake rejection

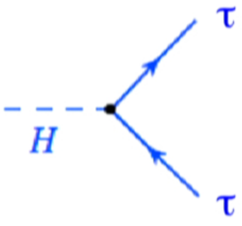


$H \rightarrow \tau\tau$

- Production depends on coupling to top quark (in SM!)
  - Also look at WBF production: coupling to Z/W bosons
- Decay depends on coupling to tau lepton (important!)
- Cross section times branching ratio is relatively high
- Challenging final state:
  - Large backgrounds
  - Sensitive to pileup, will be an extra challenge in 2012

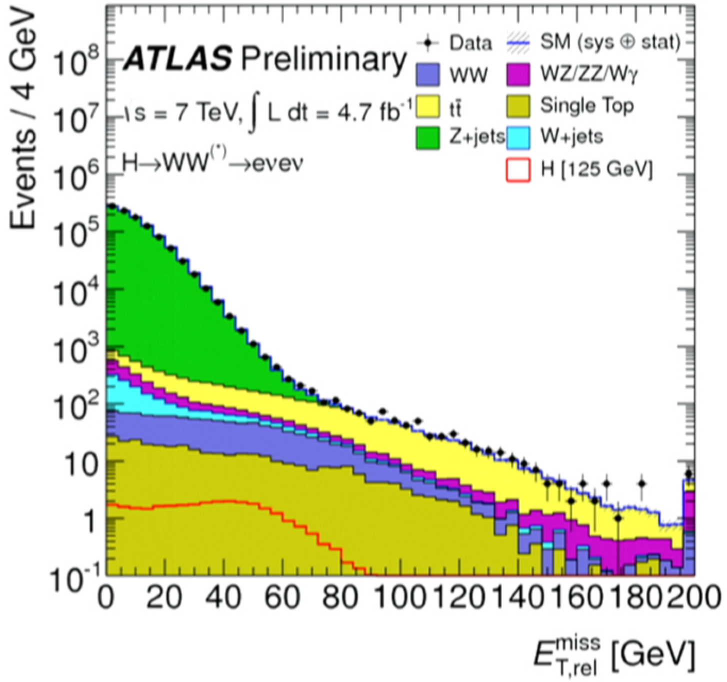


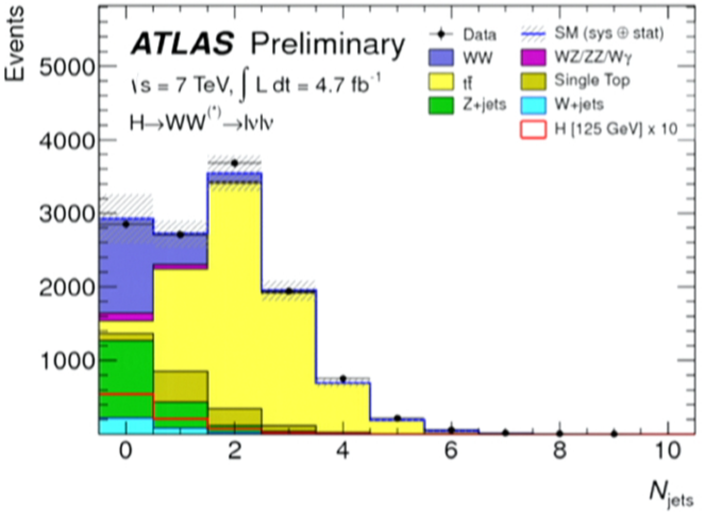




$H \rightarrow WW^* \rightarrow l\nu l\nu$ (1)

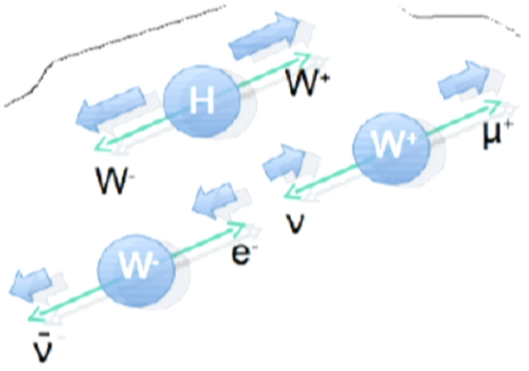
- Multijet background suppressed by requiring 2 isolated leptons
- Z/DY background reduced with cuts on M_{ll} and missing E_T
- Top background rejection achieved with jet multiplicity cut and b-tagging veto

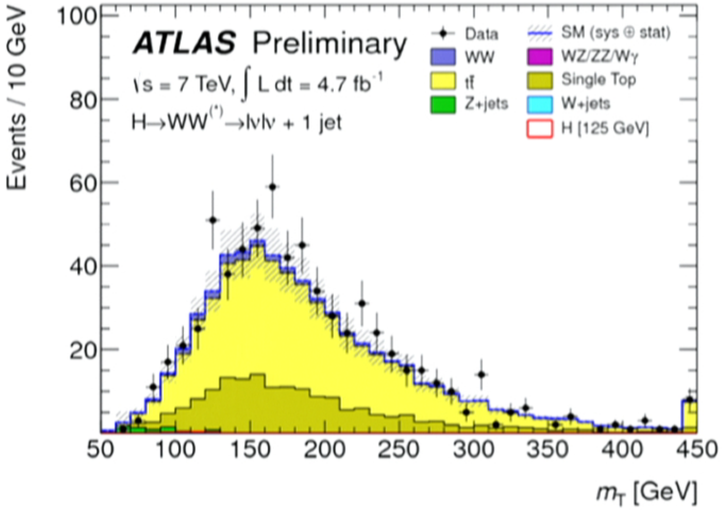


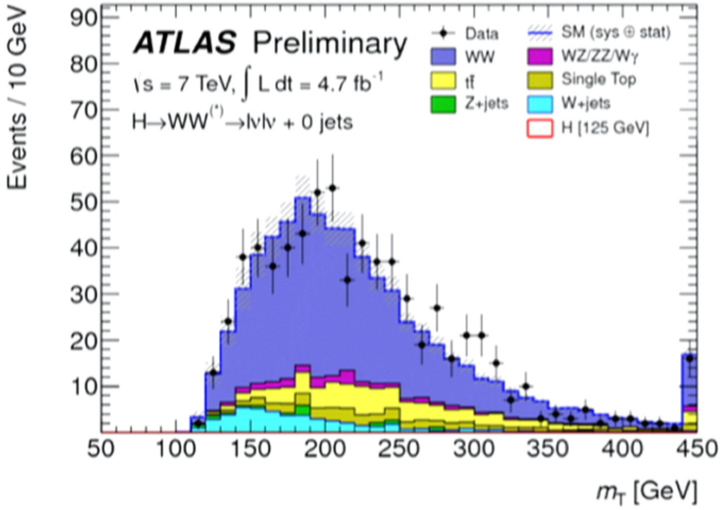


$H \rightarrow WW^* \rightarrow l\nu l\nu$ (2)

- Event selections exploit specific kinematic features and angular distributions of Higgs (e.g. angle between leptons is small)
- Main background normalization estimated from control regions:
  - WW: use regions at large M_{ll} and $\Delta\phi(ll)$
  - Top background estimated by requiring a b-tagged jet and dropping other cuts



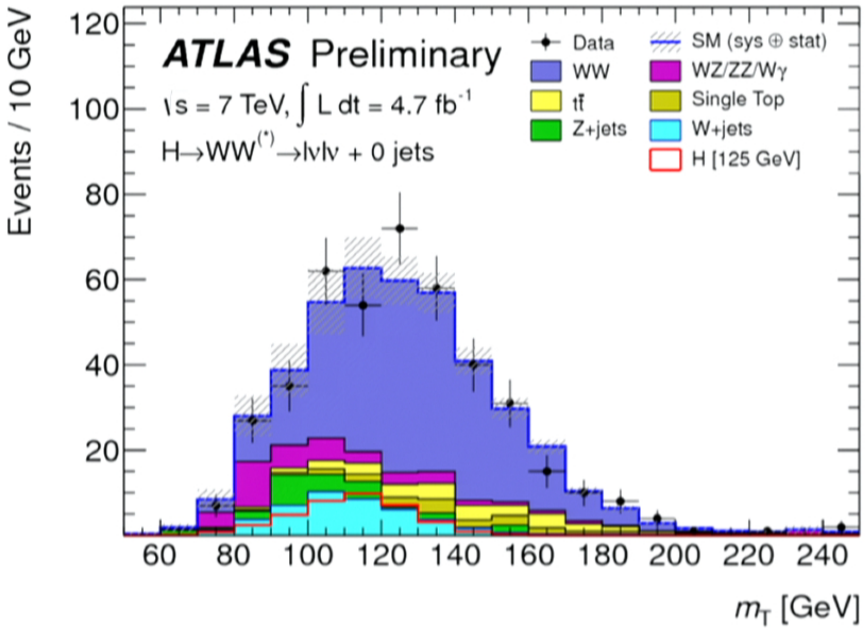




H → WW* → lνlν (3)

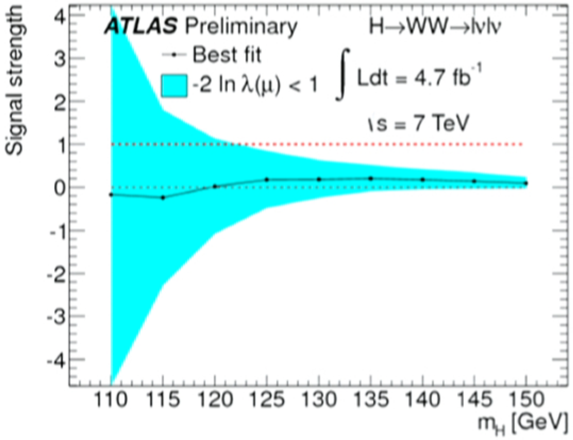
- Reconstruct Higgs candidate transverse mass

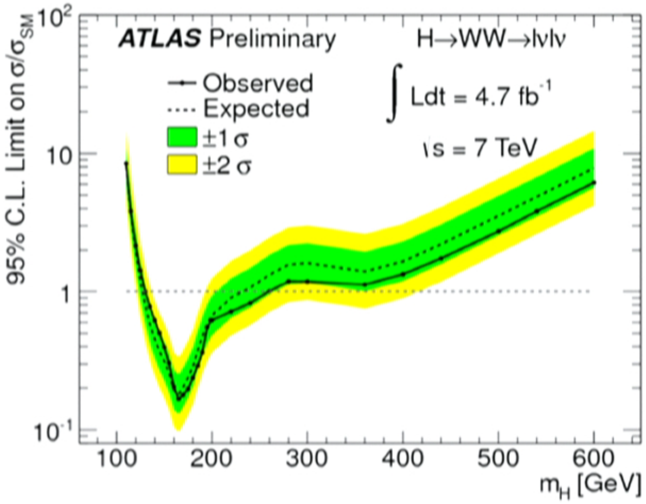
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

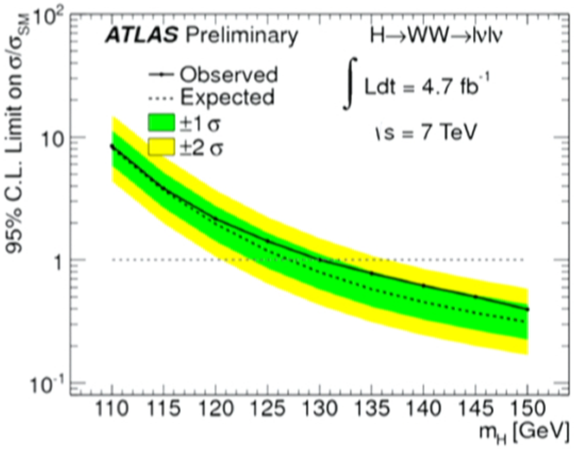


$H \to WW^* \to l\nu l\nu$ (4)

- Results with 4.7 fb^{-1}
- Observed exclusion: 130-260 GeV
- Expected exclusion: 127-234 GeV

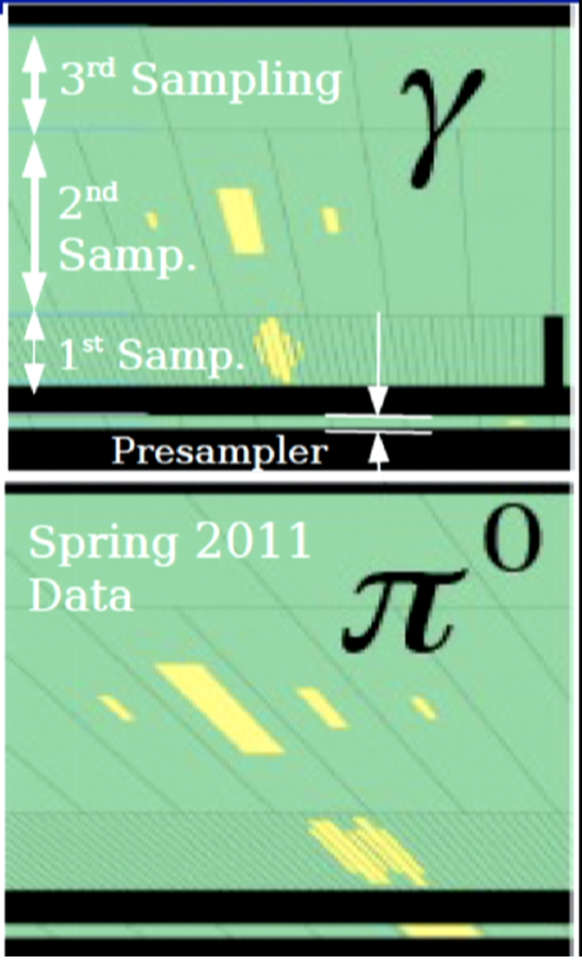






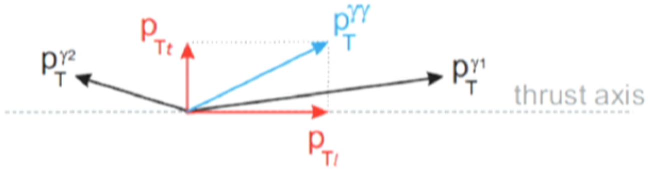
$H \rightarrow \gamma\gamma$ (1)

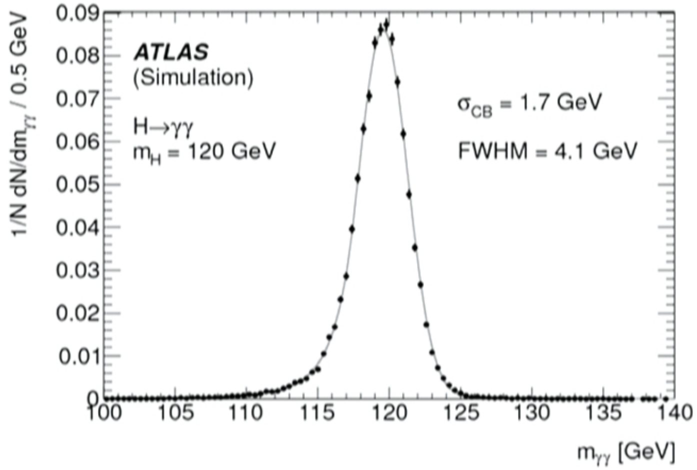
- Small signal and very large backgrounds: need excellent rejection and mass resolution
  - Signal is 0.04 pb
  - $\gamma\gamma$ continuum ~30 pb
  - γ+jet background ~$2\text{x}10^5$ pb
  - Jet-jet background ~$5\text{x}10^8$ pb
- Photon ID takes advantage of the lateral and longitudinal segmentation of the EM calorimeter and hadron calorimeter

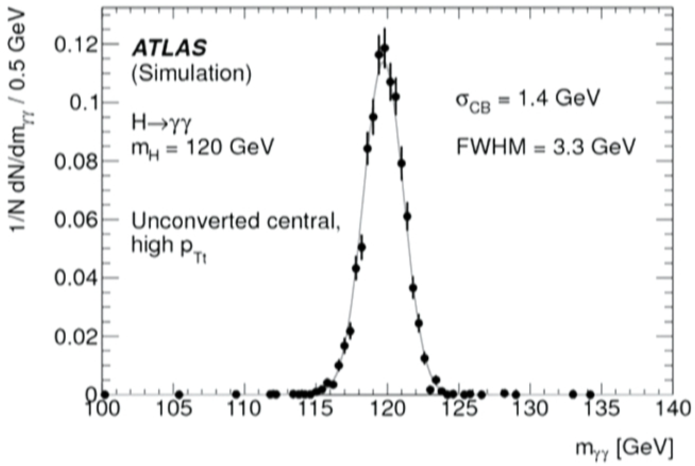


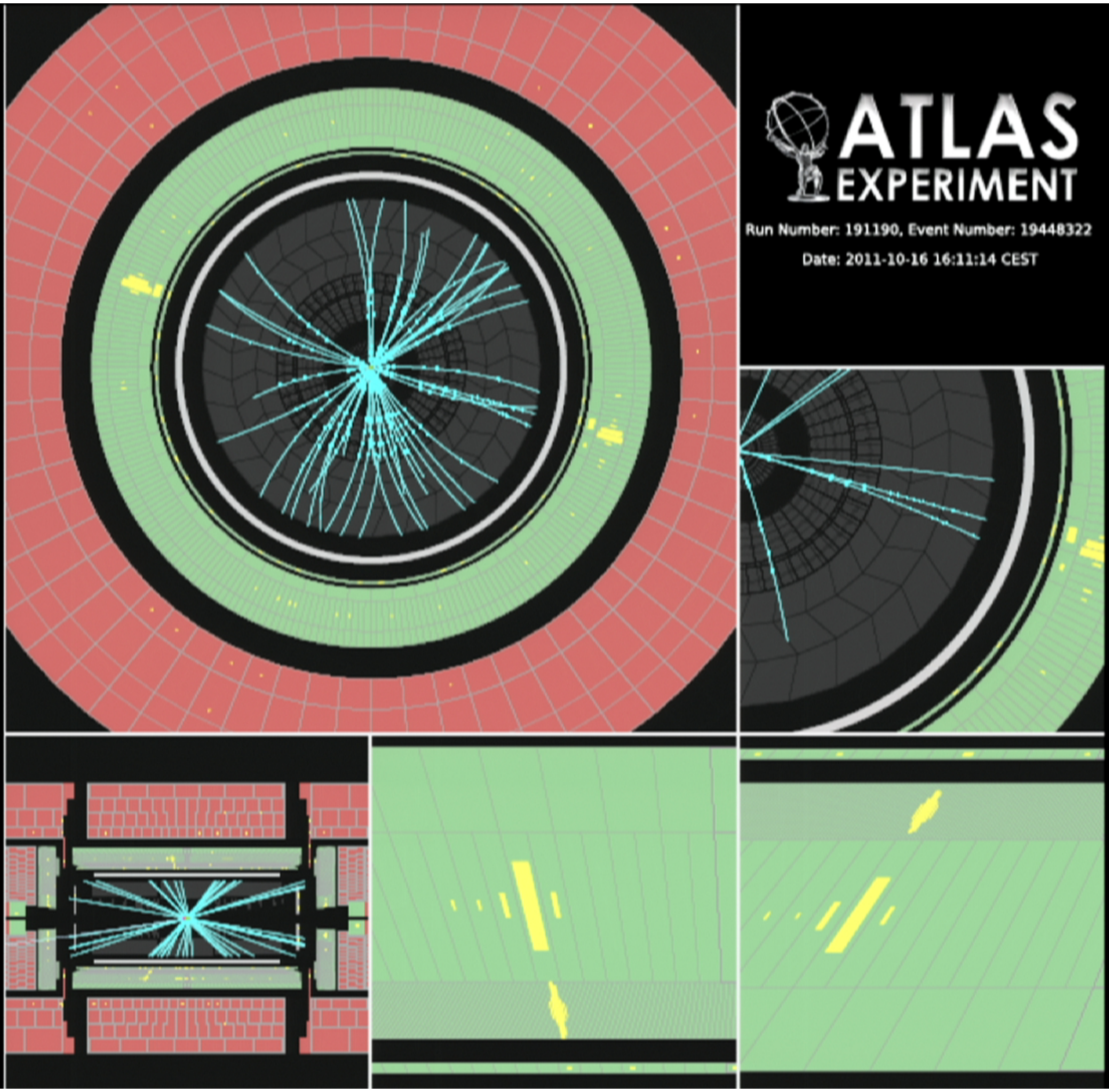
$H \rightarrow \gamma\gamma$ (2)

- Improve mass resolution by using pointing information: allows identification of primary vertex (resolution: 1.5 cm)
- Mass resolution varies from 1.4 to 2.3 GeV for M_H = 120 GeV
  - Depends on calorimeter region
  - Depends on whether photon was converted or not
- To maximize sensitivity, sample divided in 9 categories:
  - Central region vs non-central
  - Converted vs non-converted
  - P_{Tt} cut



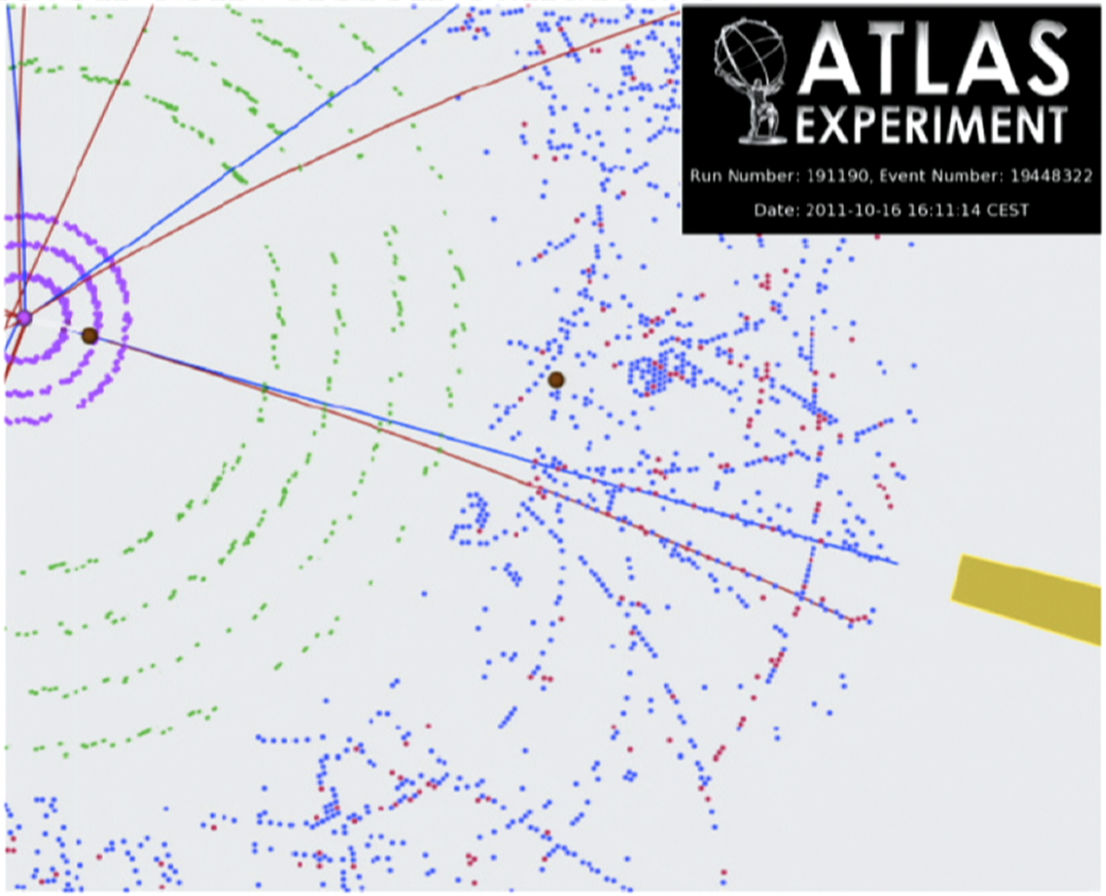





ATLAS EXPERIMENT
Run Number: 191190, Event Number: 19448322
Date: 2011-10-16 16:11:14 CEST

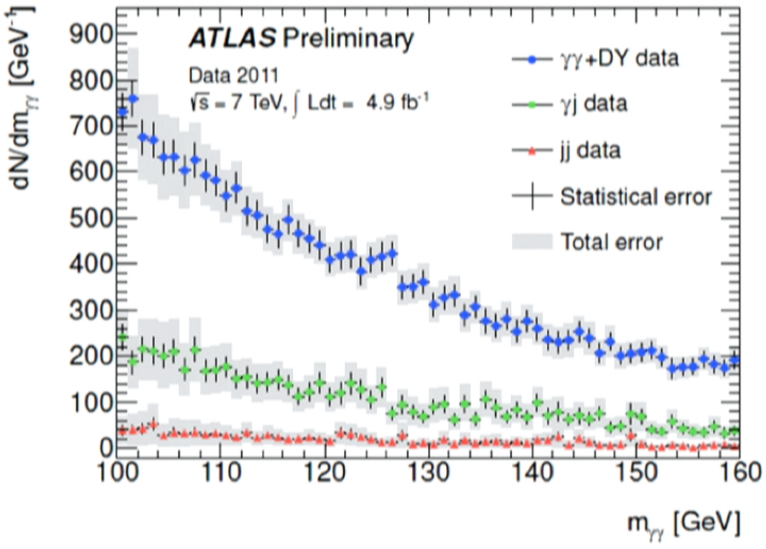
H➡γγ (4)

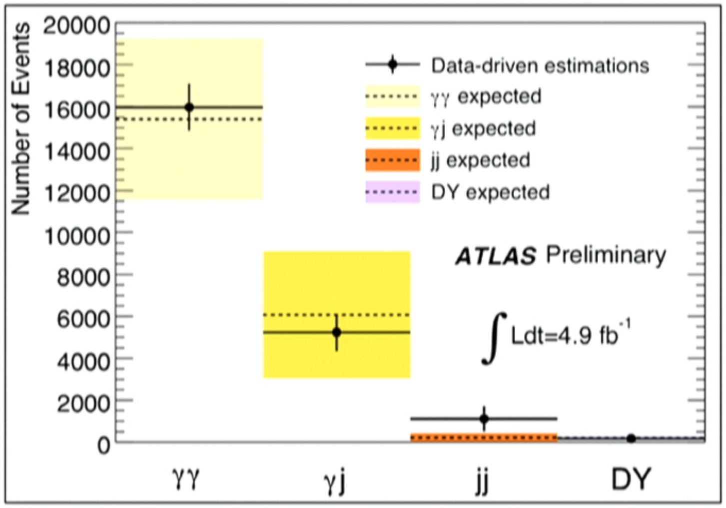
Photon conversion candidate

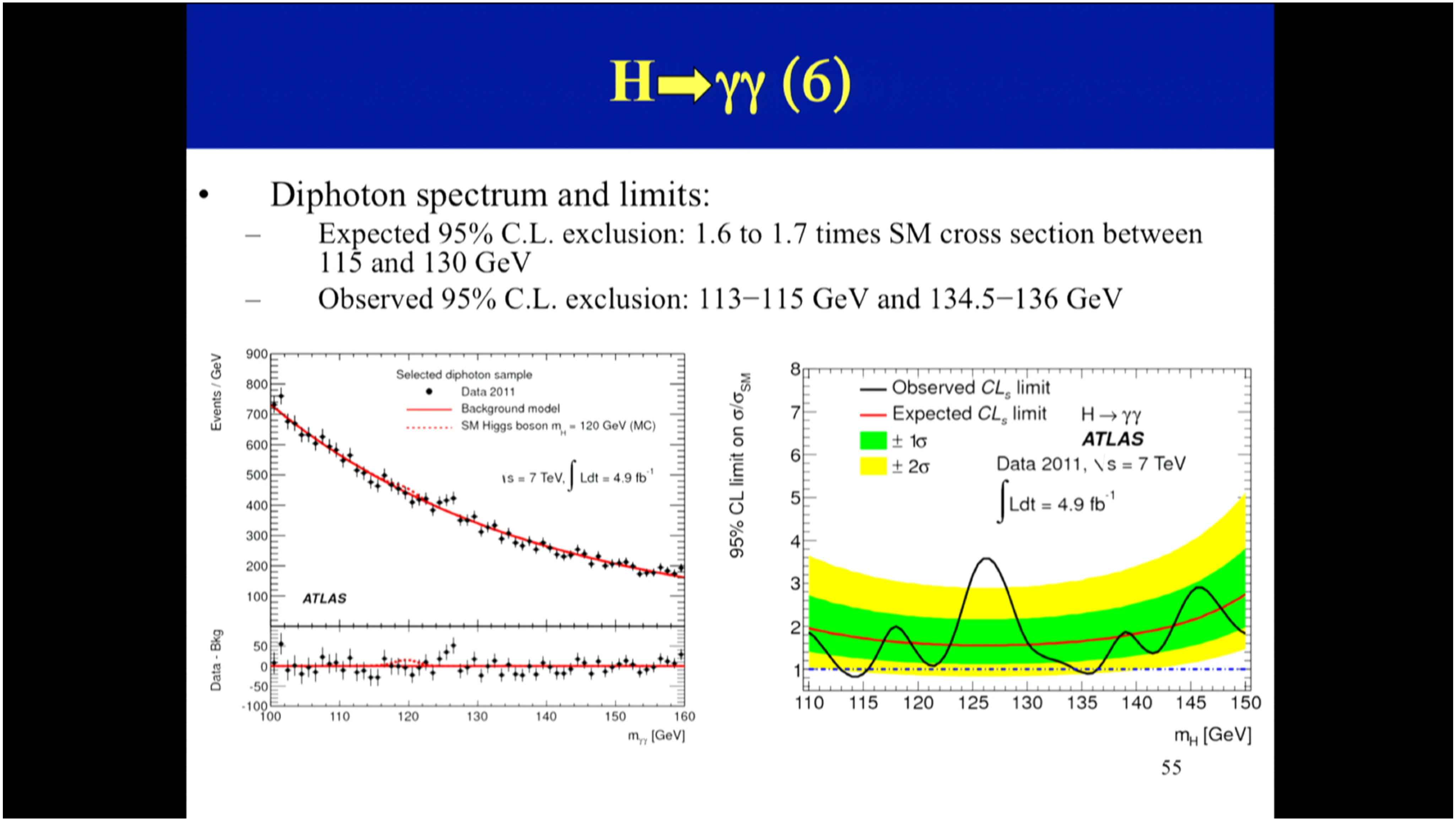


H→γγ (5)

- Systematic uncertainties: signal yield (20%), mass resolution (14%), background modeling (depends on category)
- Estimated background composition (not used in results):





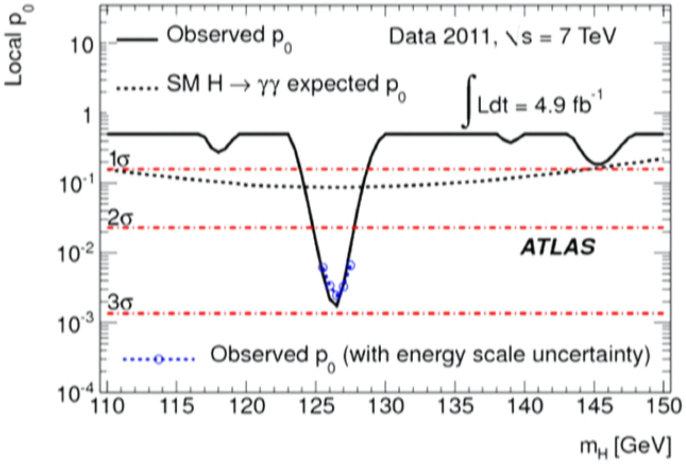


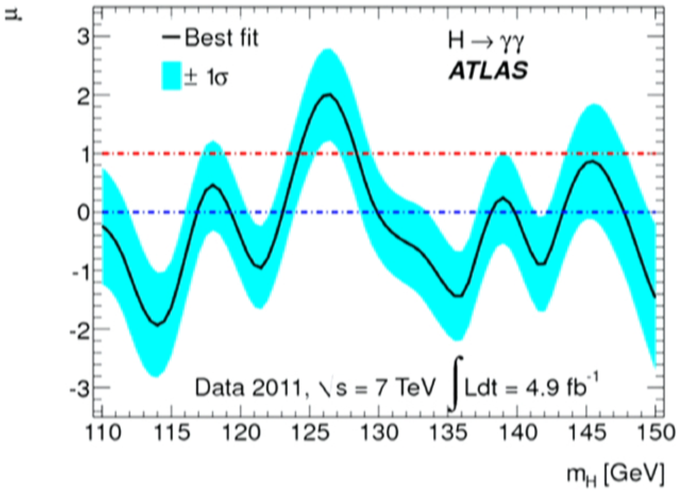
H→γγ (6)

- Diphoton spectrum and limits:
  - Expected 95% C.L. exclusion: 1.6 to 1.7 times SM cross section between 115 and 130 GeV
  - Observed 95% C.L. exclusion: 113−115 GeV and 134.5−136 GeV

H➡γγ (7)

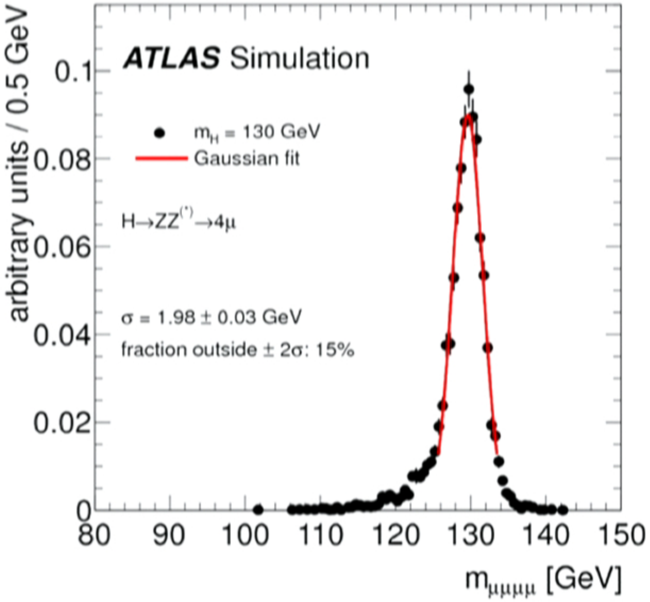
- Consistency of data with background-only expectation (left)
  - Observed local significance 2.8σ at 126.5 GeV including energy uncertainty
  - Including look elsewhere effect in 110-150 range, significance is: 1.5σ
- Best-fit signal strength (right)

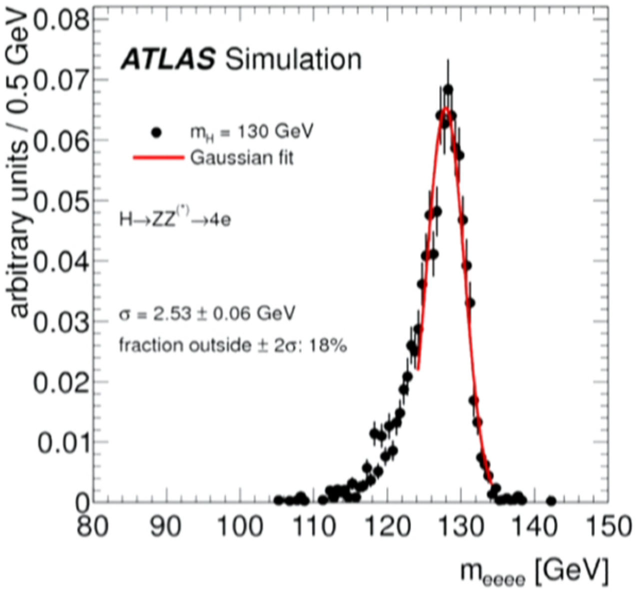




$H \rightarrow ZZ^{(*)} \rightarrow llll$ (1)

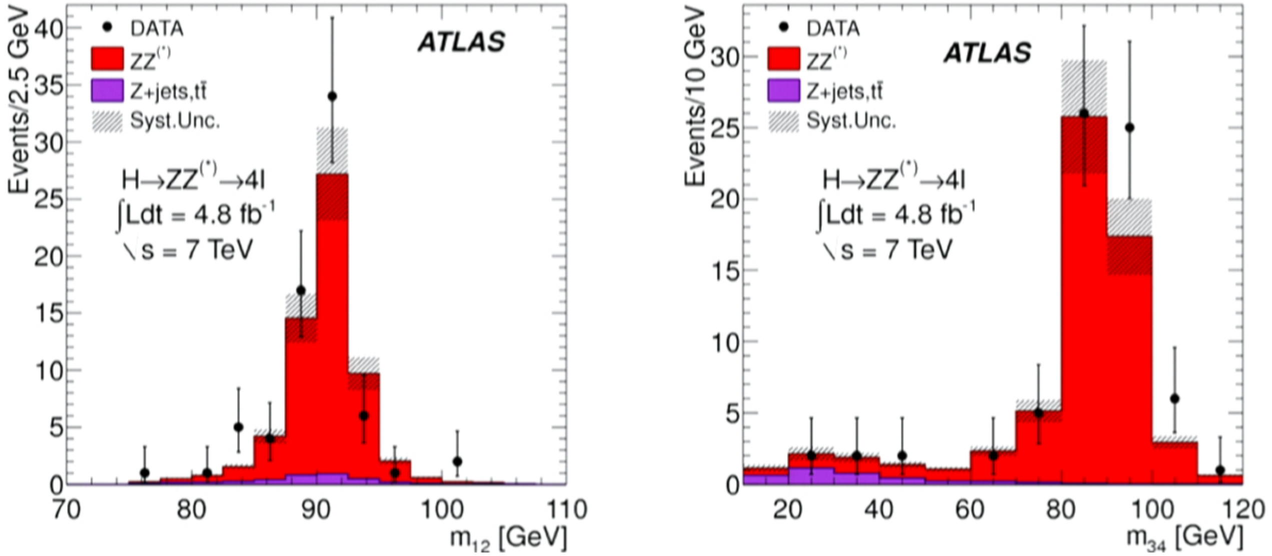
- Clean signal
  - Use isolation, dilepton masses to reduce Z+jets and top backgrounds
- Low rate: need to keep efficiencies high
- Main backgrounds from SM ZZ production
- Good 4-lepton mass resolution helps to enhance signal





$H \rightarrow ZZ^{(*)} \rightarrow llll$ (2)

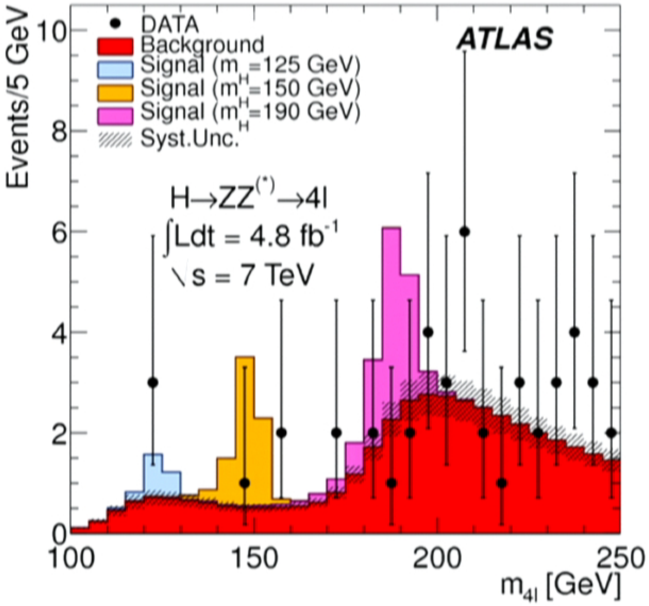
- Selections:
  - 4 leptons with $p_T > 20,20,7,7$ GeV
  - Pair same-flavour, opposite charge leptons. M_{12}:pair with mass closest to Z
  - M_{12} within 15 GeV of Z mass, minimum M_{34} depends on mass
- Signal efficiency ~15% for M_H of 125 GeV
- M_{12} and M_{34} of candidates:

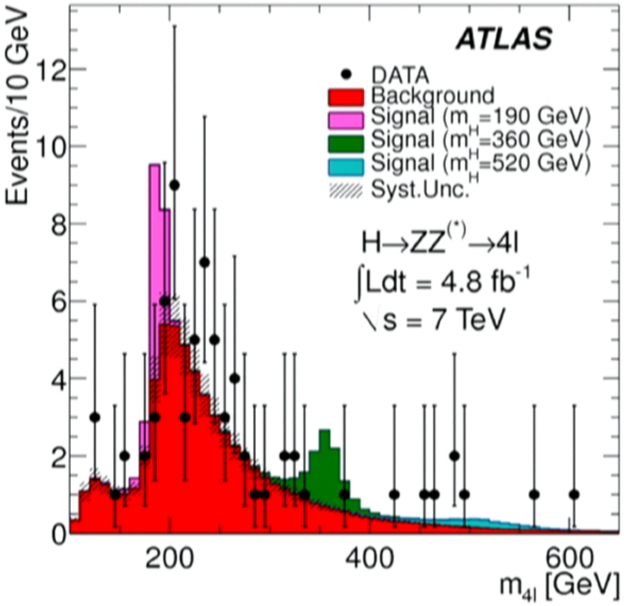


$H \rightarrow ZZ^{(*)} \rightarrow llll$ (3)

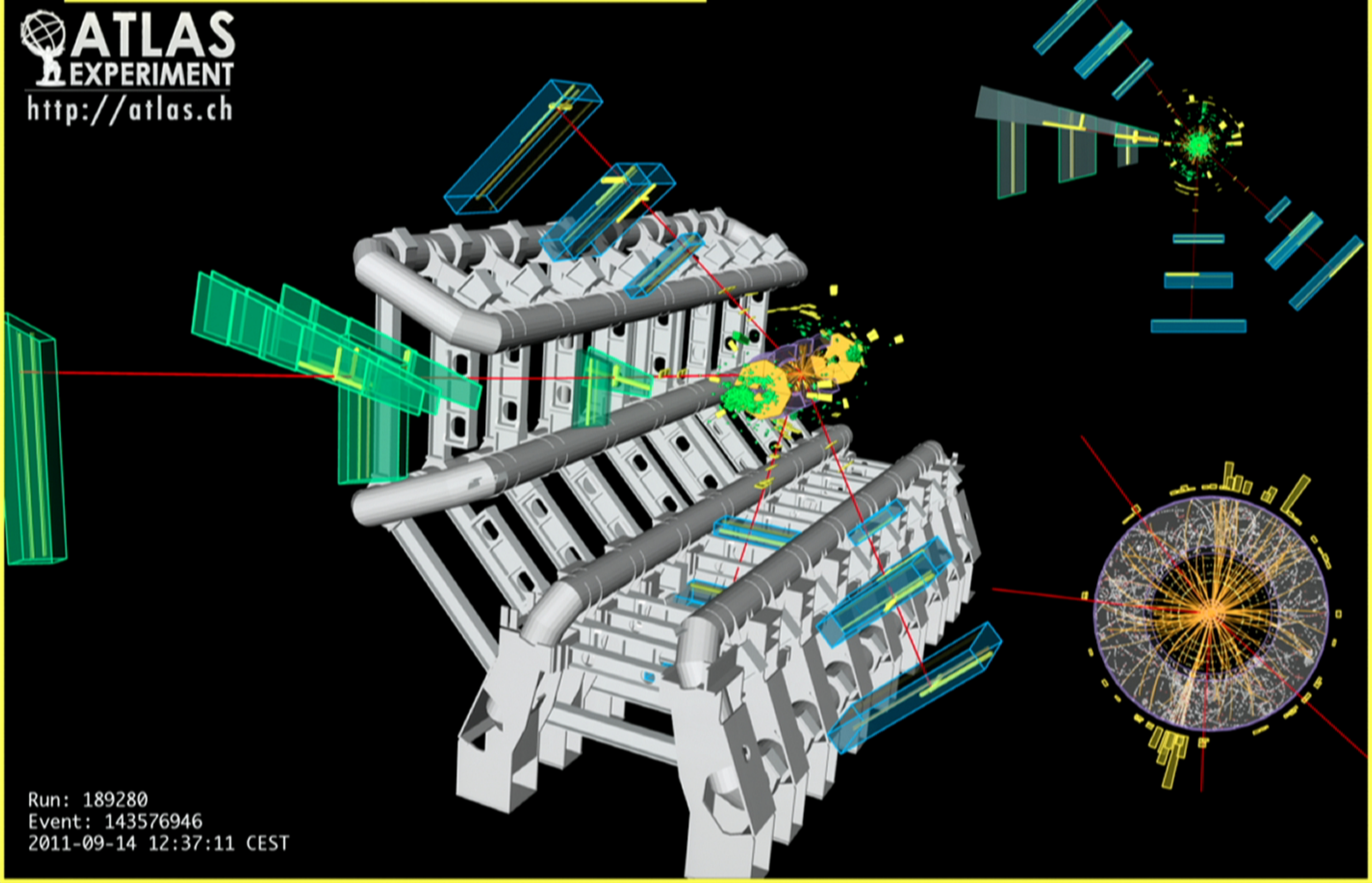
Candidate events: 71 observed, 62 +/- 9 predicted

- Systematic uncertainties:
  - Higgs cross-section : ~ 15%, Electron efficiency : ~ 2-8%
  - Zbb, +jets backgrounds : ~ 40%, ZZ* background : ~ 15%

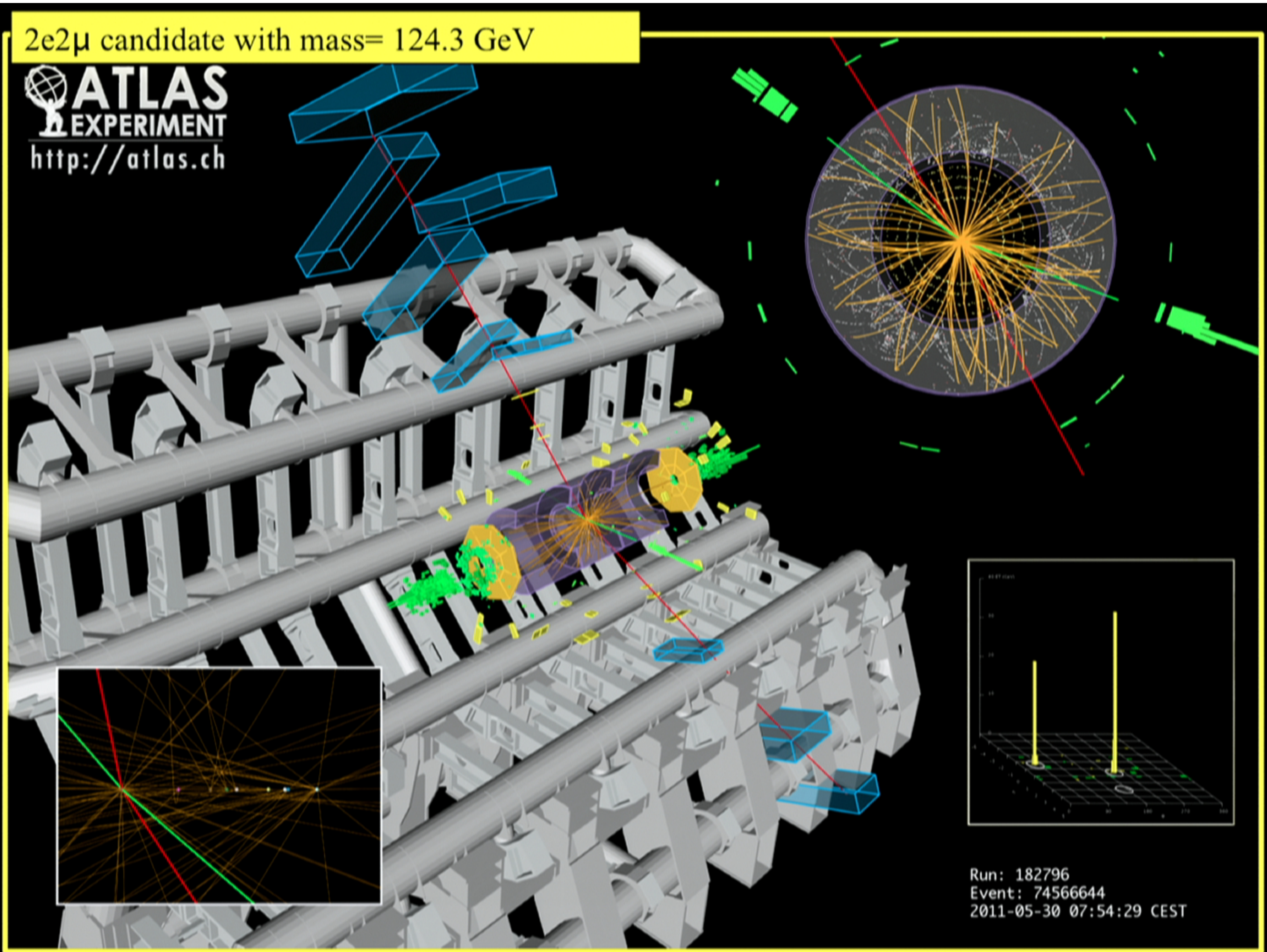




4μ candidate with mass = 124.6 GeV



2e2μ candidate with mass= 124.3 GeV

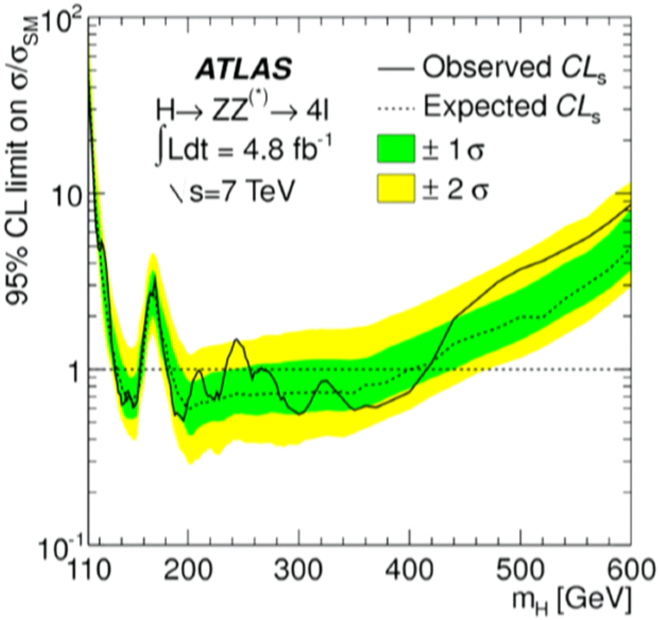


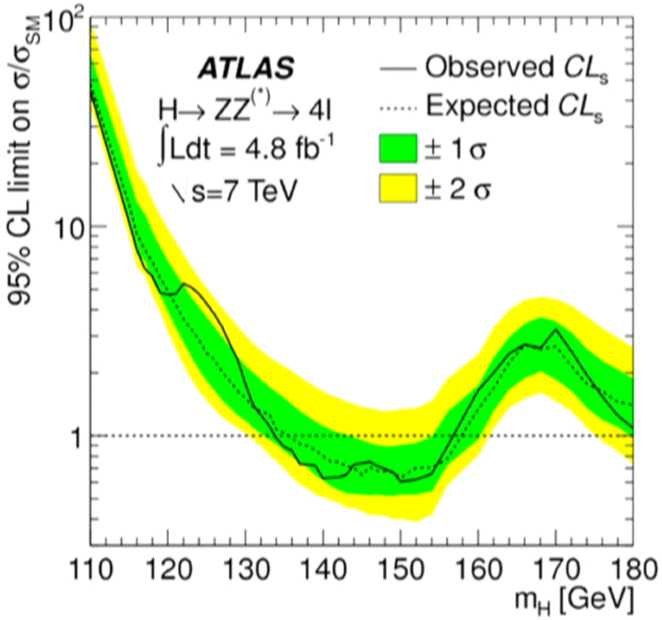
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

$H \rightarrow ZZ^{(*)} \rightarrow llll$ (7)

- Limits:

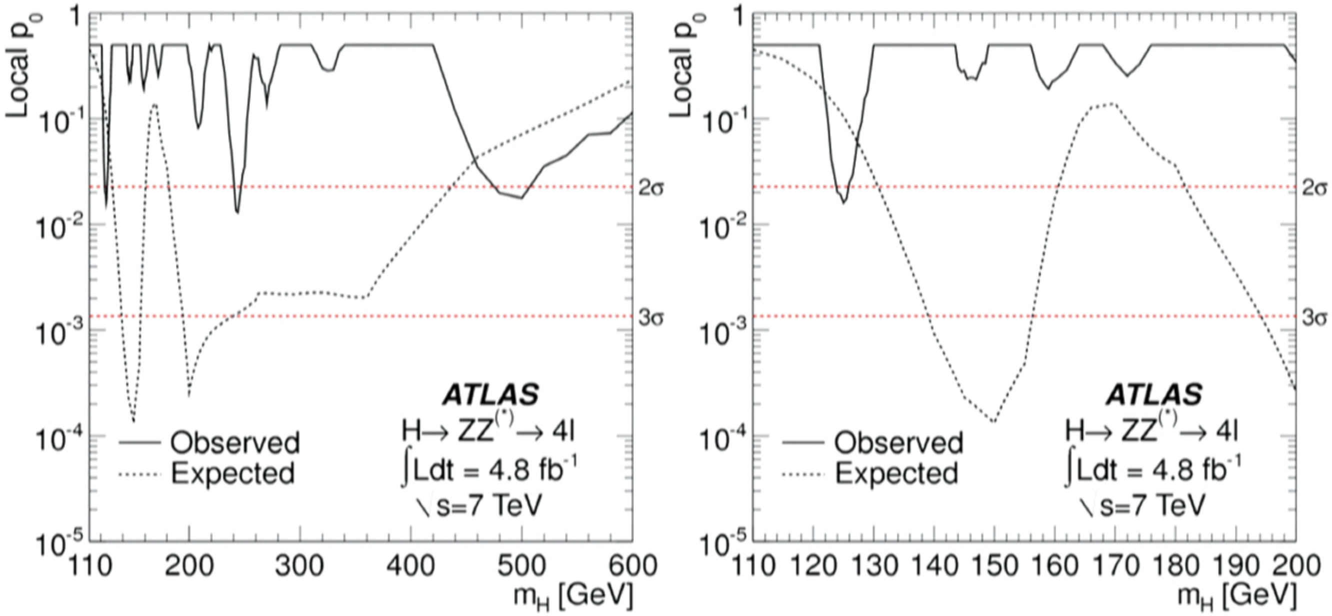
Excluded (95% CL): **134 < mH < 156 GeV and 182 < mH < 415 GeV (except 234-255 GeV)**
Expected (95% CL): **136 < mH < 157 GeV and 184 < mH < 400 GeV**





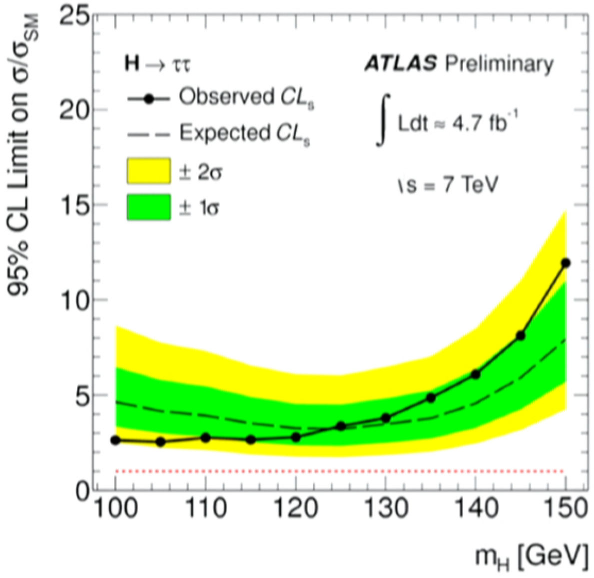
$H \to ZZ^{(*)} \to llll$ (8)

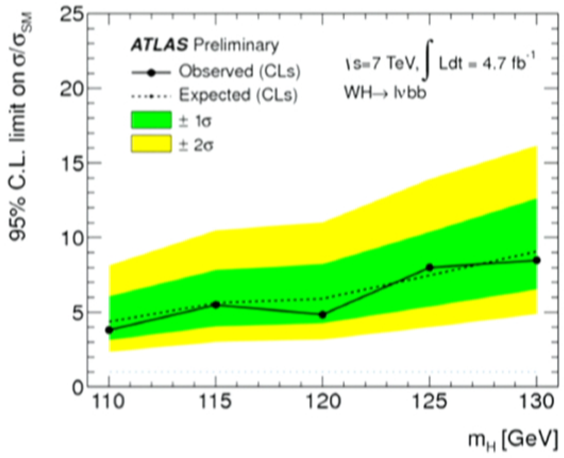
- Consistency of data with background-only expectation
- Local significances below 2 σ:
  - at ~125 GeV
  - at ~245 GeV (excluded by ATLAS-CMS combination)
  - at ~480 GeV

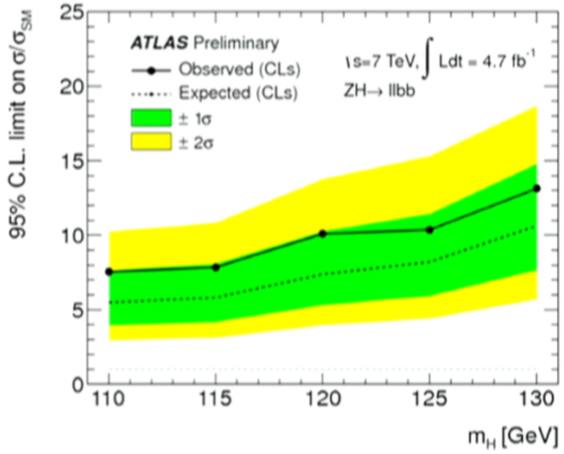


H➡ττ and H➡bb

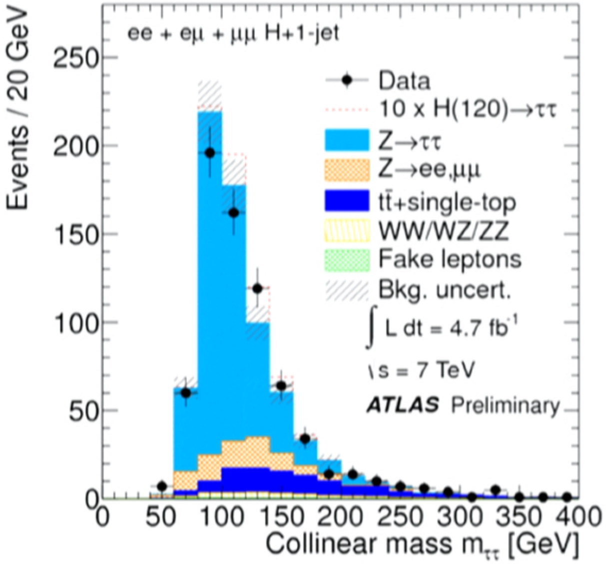
- Not sensitive enough for set exclusion limits yet but these channels do make an impact on combined limits



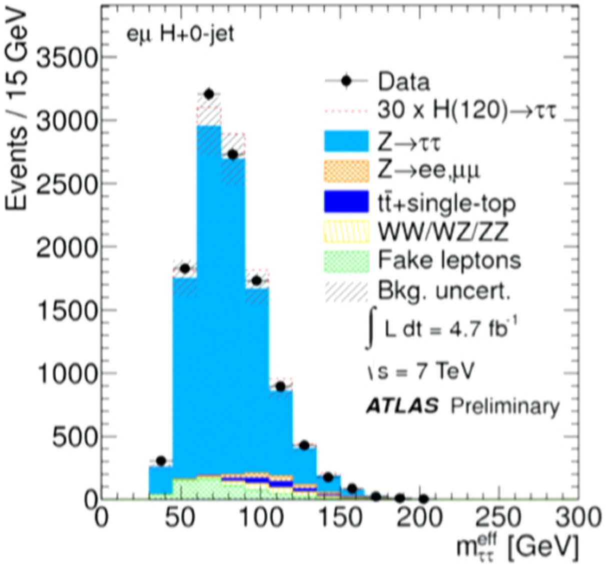




H⇒ττ and H⇒bb

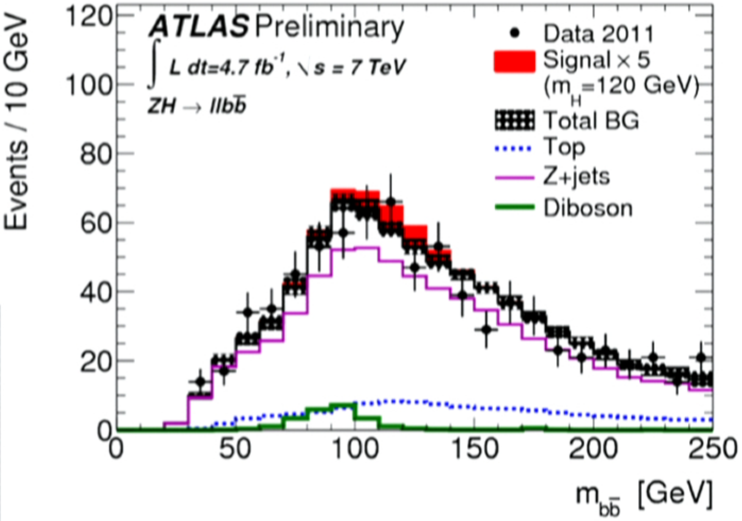


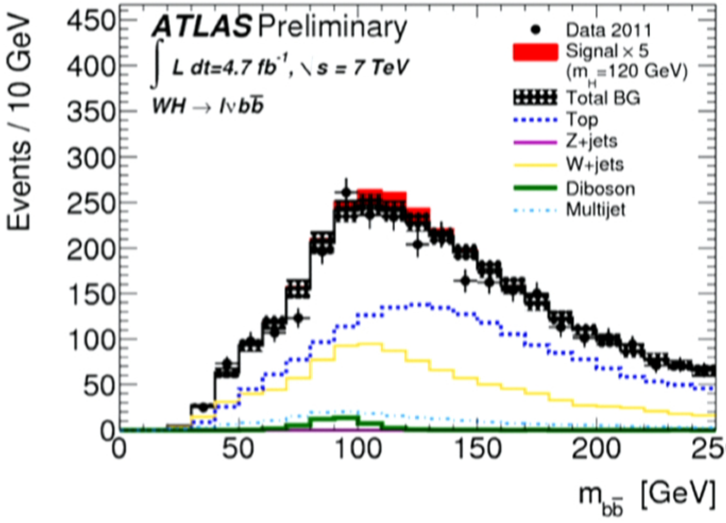
ee + eμ + μμ H+1-jet
Data
10 x H(120)→ττ
Z→ττ
Z→ee,μμ
tt̄+single-top
WW/WZ/ZZ
Fake leptons
Bkg. uncert.
∫ L dt = 4.7 fb⁻¹
√s = 7 TeV
ATLAS Preliminary
Events / 20 GeV
0
50
100
150
200
250
0
50
100
150
200
250
300
350
400
Collinear mass m_ττ [GeV]



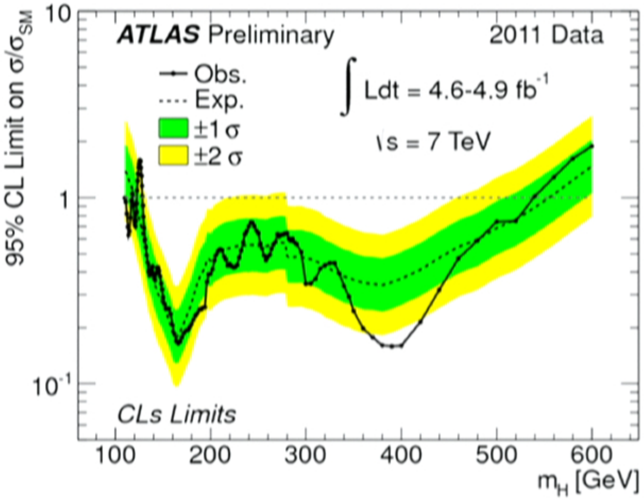
eμ H+0-jet
Data
30 x H(120)→ττ
Z→ττ
Z→ee,μμ
tt̄+single-top
WW/WZ/ZZ
Fake leptons
Bkg. uncert.
∫ L dt = 4.7 fb⁻¹
√s = 7 TeV
ATLAS Preliminary
Events / 15 GeV
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
200
250
300
m_ττ^eff [GeV]

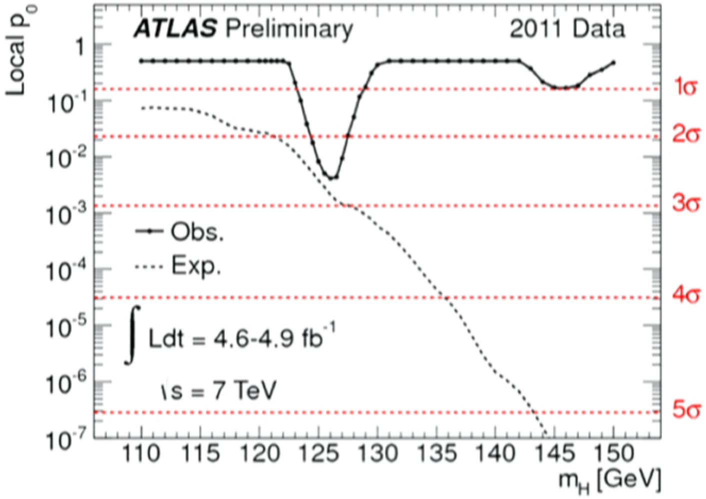
H➡ττ and H➡bb

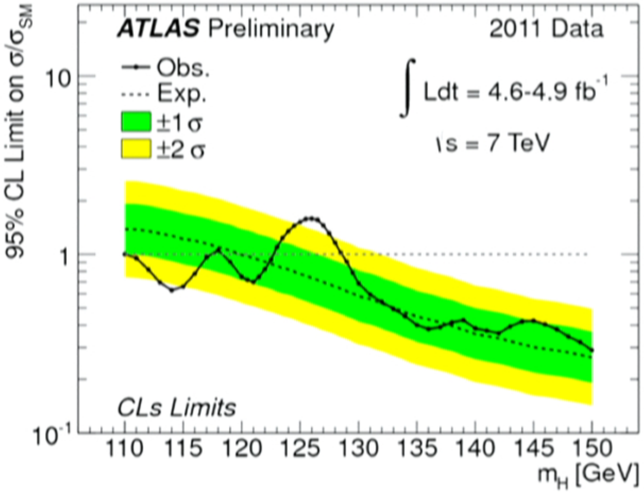

ATLAS Preliminary
$\int L\,dt = 4.7\ \mathrm{fb}^{-1}$, $\sqrt{s}$ = 7 TeV
$ZH \to llb\bar{b}$
● Data 2011
Signal × 5
(m_H=120 GeV)
Total BG
Top
Z+jets
Diboson
Events / 10 GeV
0
20
40
60
80
100
120
0
50
100
150
200
250
$m_{b\bar{b}}$ [GeV]

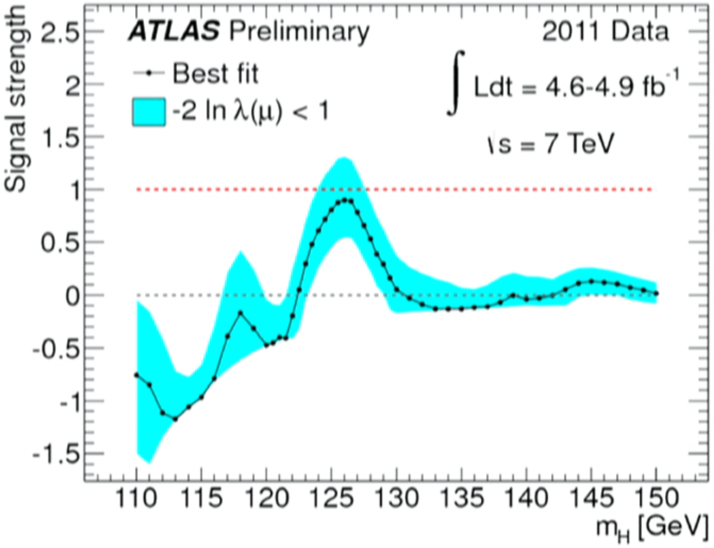

ATLAS Preliminary
$\int L\,dt = 4.7\ \mathrm{fb}^{-1}$, $\sqrt{s}$ = 7 TeV
$WH \to l\nu b\bar{b}$
● Data 2011
Signal × 5
(m_H=120 GeV)
Total BG
Top
Z+jets
W+jets
Diboson
Multijet
Events / 10 GeV
0
50
100
150
200
250
300
350
400
450
0
50
100
150
200
250
$m_{b\bar{b}}$ [GeV]

Combination



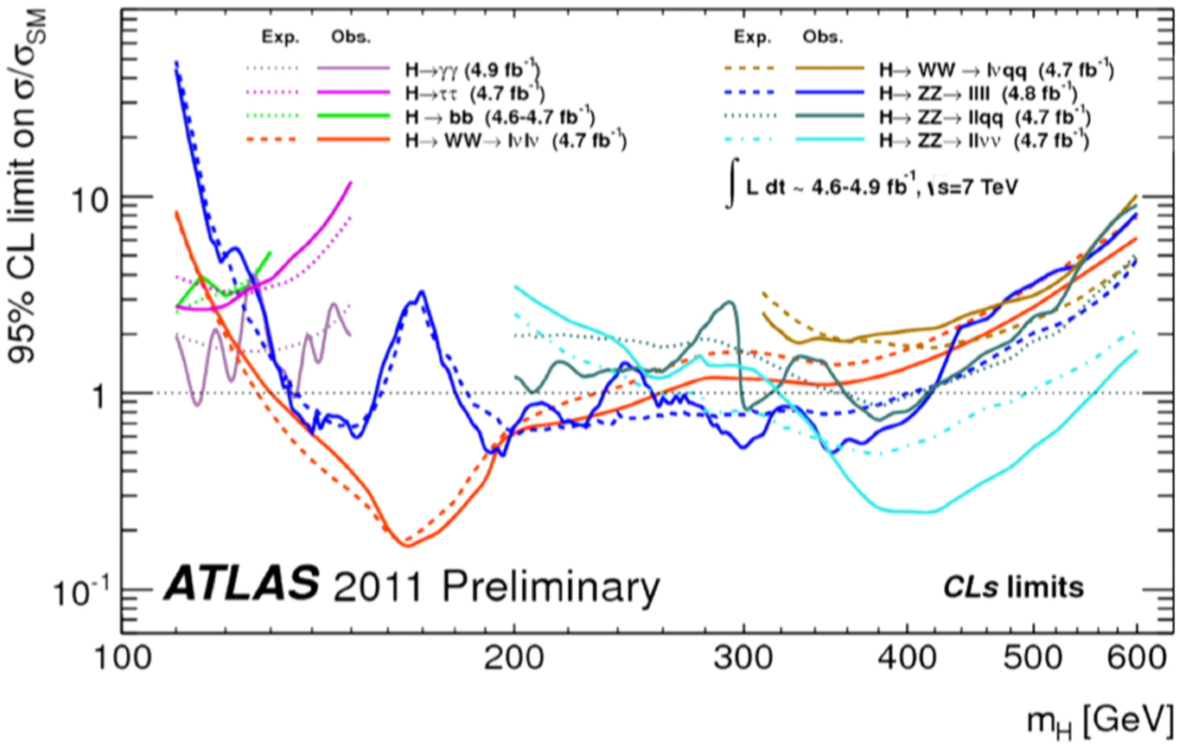






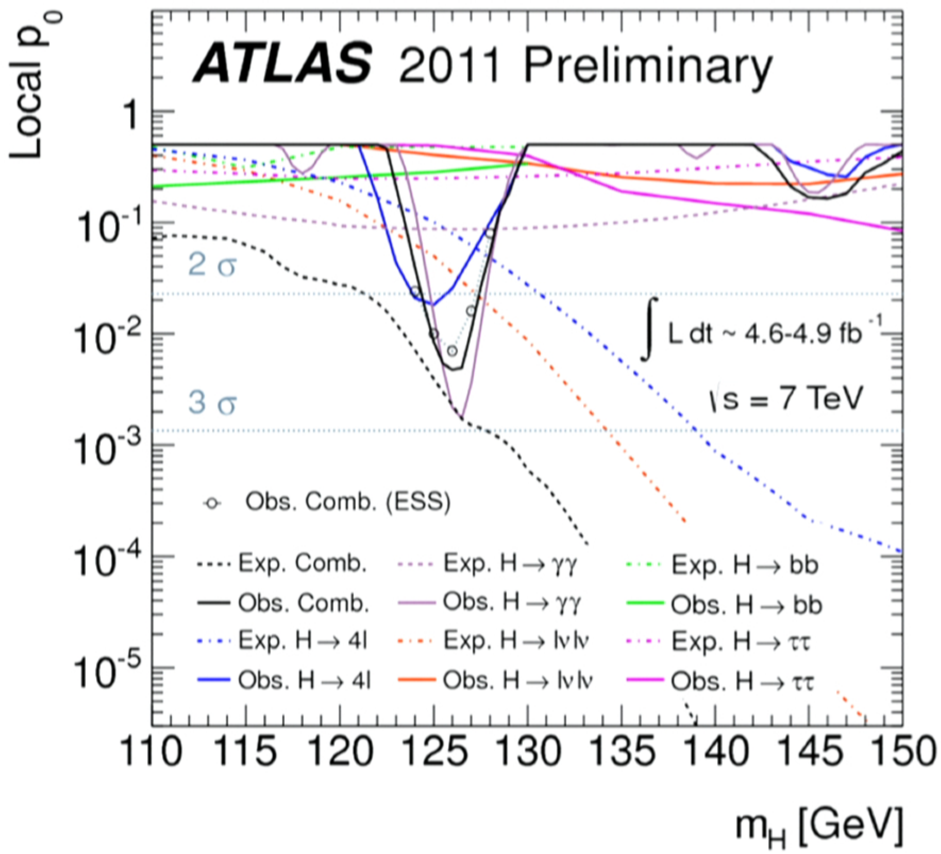
Combination

- Observed exclusion 95% CL: 110.0 GeV to 117.5 GeV, 118.5 GeV to 122.5 GeV, and 129 GeV to 539 GeV (99% CL: 130-486 GeV)
- Expected exclusion: 120 to 155 GeV



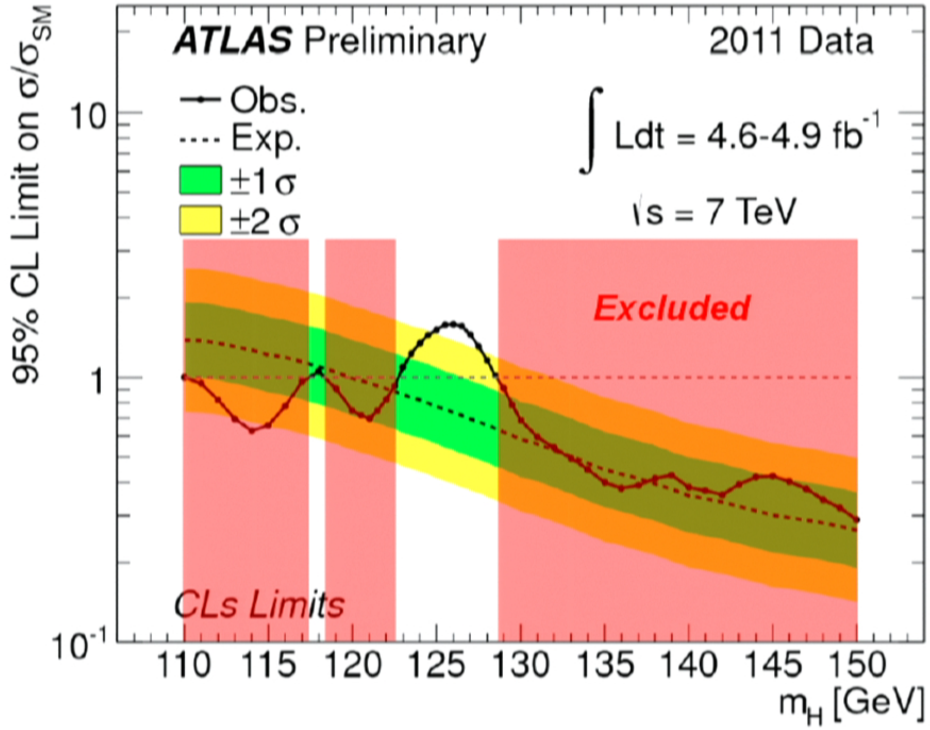
Combination

- Local p-value at minimum is 2.5 σ
- Global probability for full mass range: 30% and 10% for 110-146 GeV

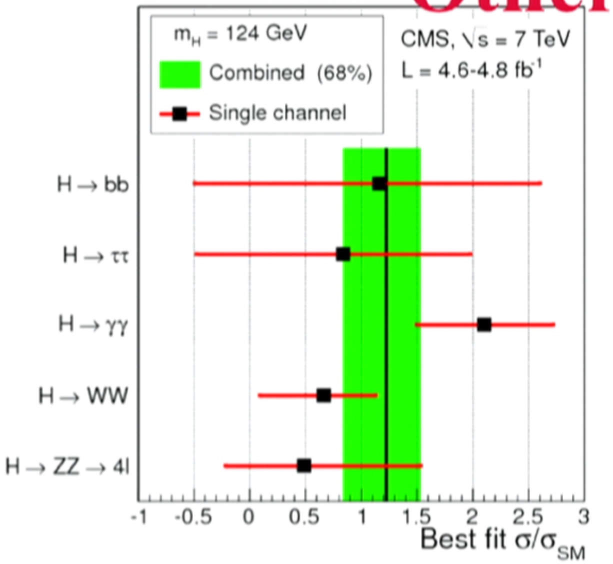


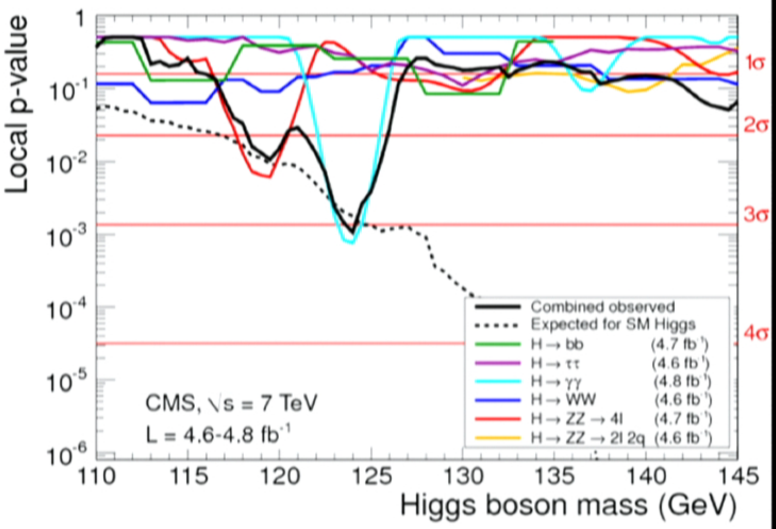
Where is the SM Higgs?

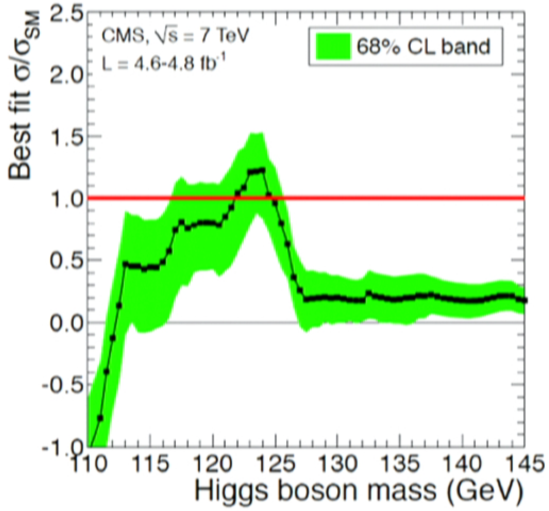
- From ATLAS limits: there is ~6 GeV left in the allowed mass range (< 5 GeV with CMS)

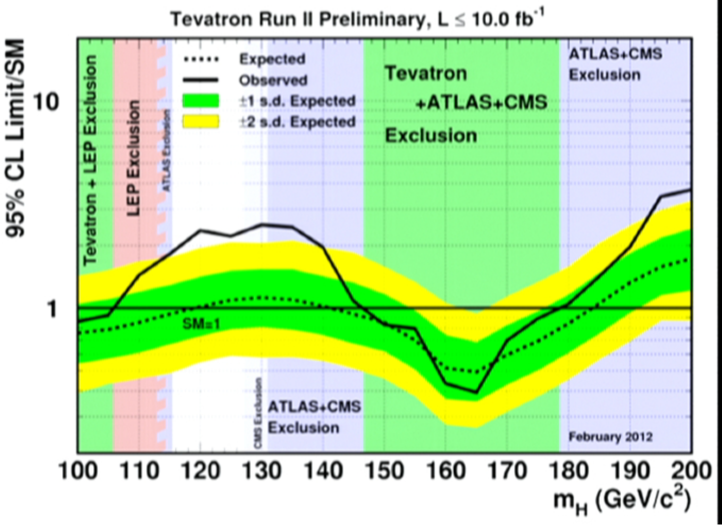


Other Experiments



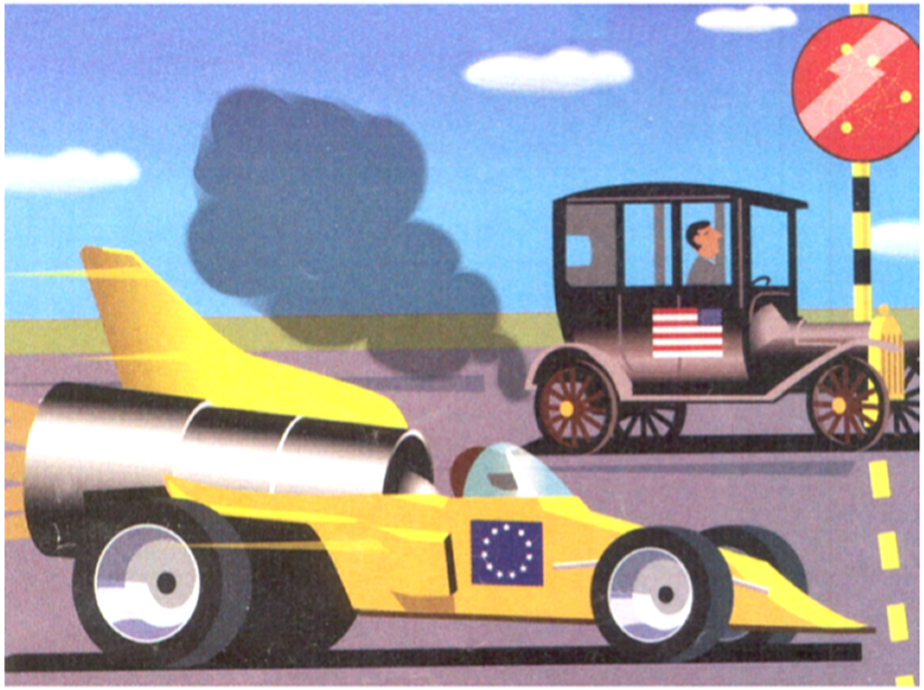




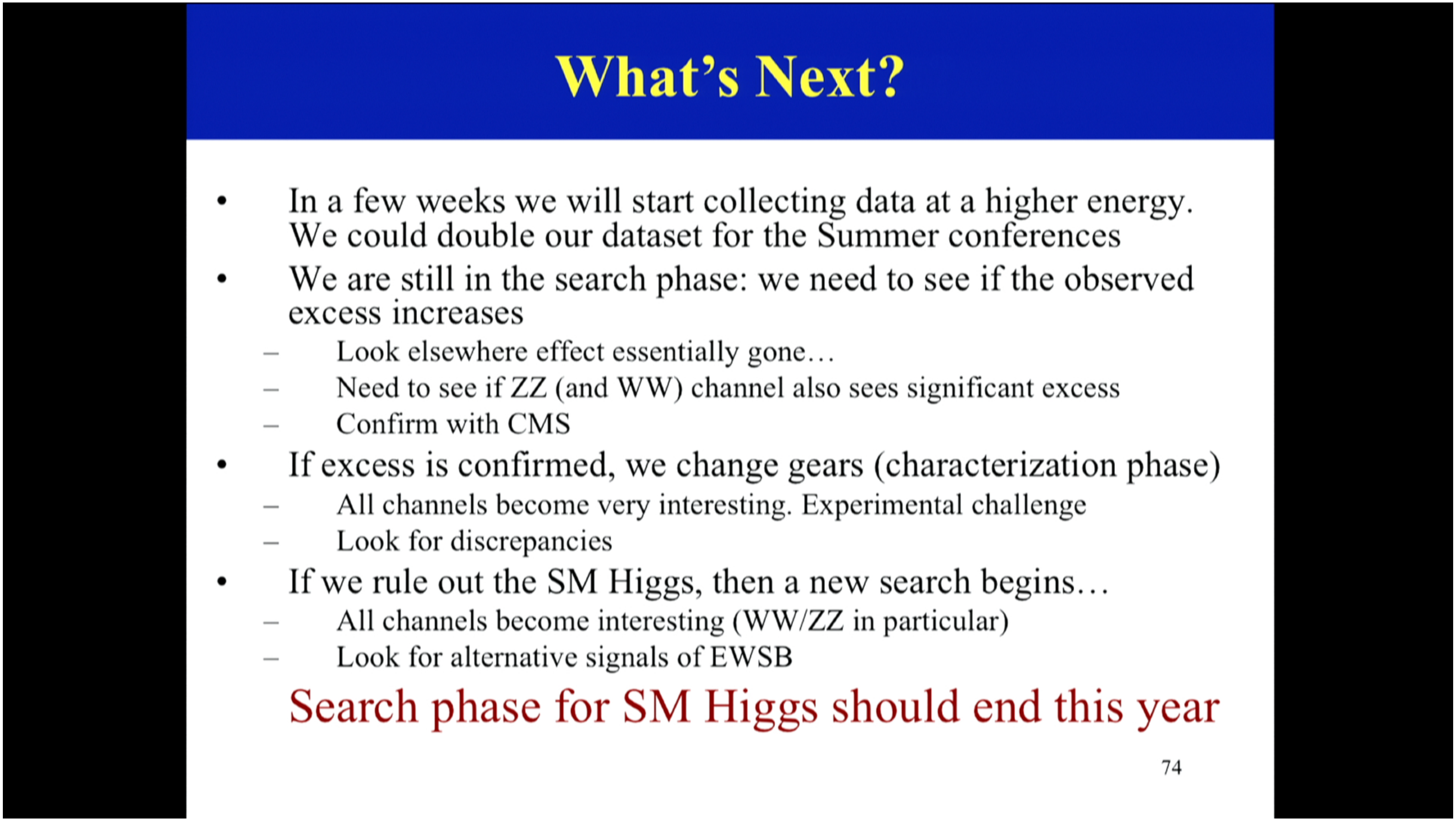


The LHC and Tevatron in the News…

From The Economist, March 2007:



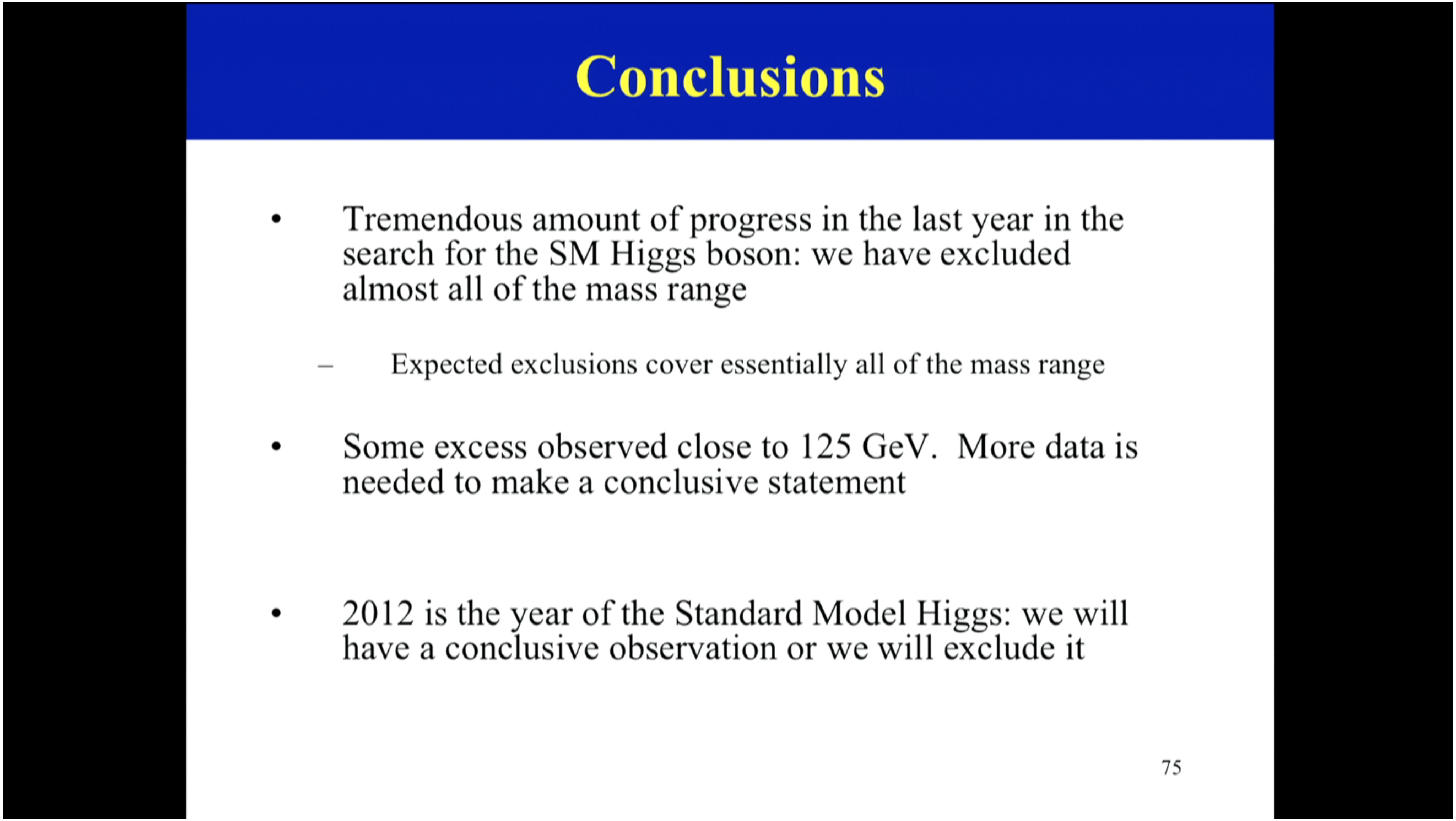
Jet engine car (LHC) will not lose the race after all but
Tevatron (Model T) contributed to low mass combination



What’s Next?

- In a few weeks we will start collecting data at a higher energy. We could double our dataset for the Summer conferences
- We are still in the search phase: we need to see if the observed excess increases
  - Look elsewhere effect essentially gone…
  - Need to see if ZZ (and WW) channel also sees significant excess
  - Confirm with CMS
- If excess is confirmed, we change gears (characterization phase)
  - All channels become very interesting. Experimental challenge
  - Look for discrepancies
- If we rule out the SM Higgs, then a new search begins…
  - All channels become interesting (WW/ZZ in particular)
  - Look for alternative signals of EWSB

Search phase for SM Higgs should end this year



Conclusions

- Tremendous amount of progress in the last year in the search for the SM Higgs boson: we have excluded almost all of the mass range
  - Expected exclusions cover essentially all of the mass range
- Some excess observed close to 125 GeV. More data is needed to make a conclusive statement
- 2012 is the year of the Standard Model Higgs: we will have a conclusive observation or we will exclude it