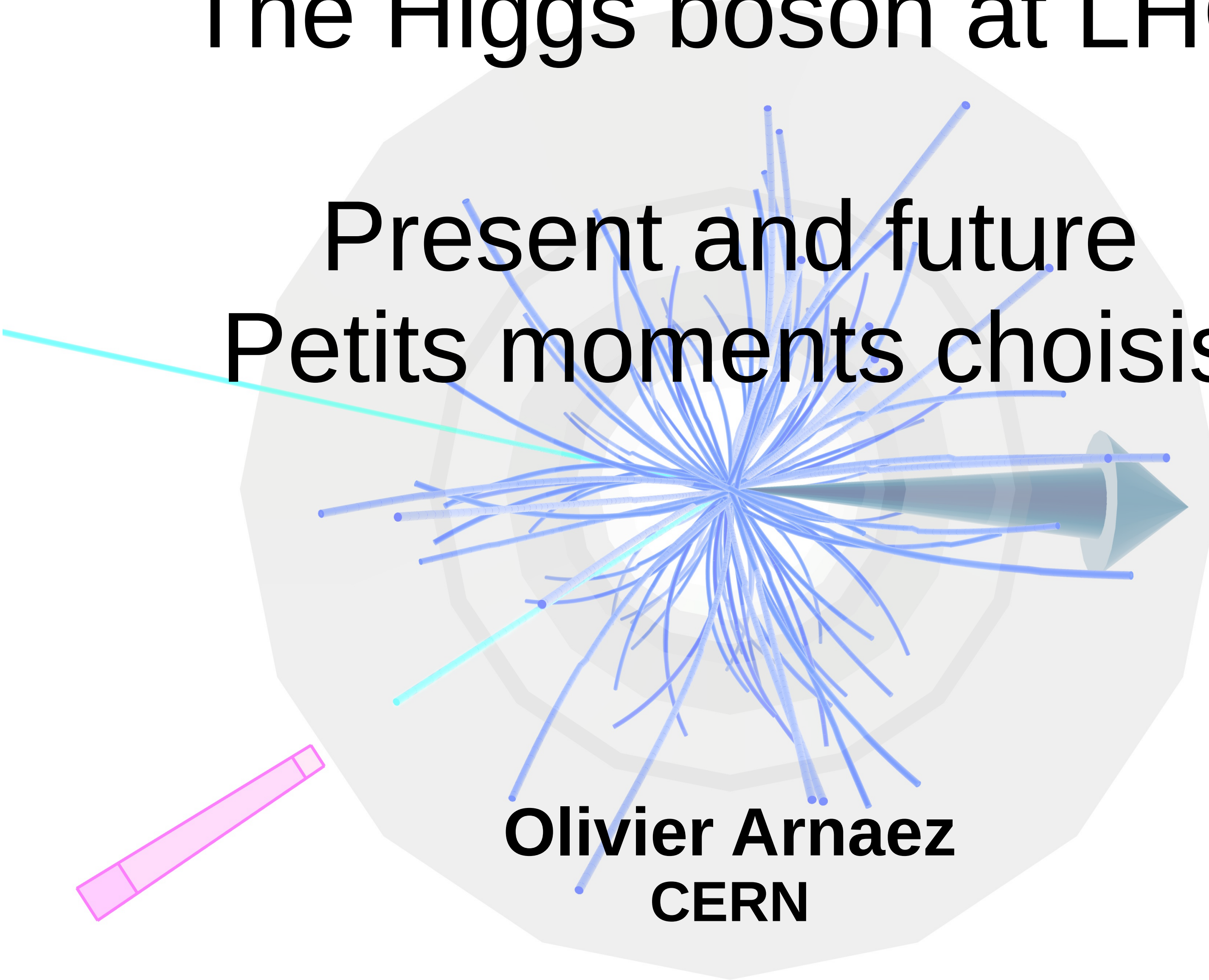
The Higgs boson at LHC

Present and future
Petits moments choisis



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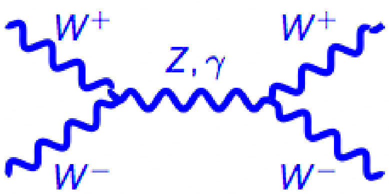
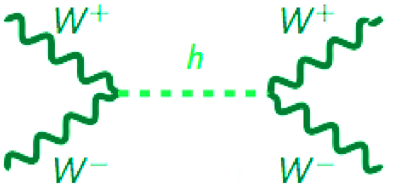
Why the Higgs ?

- Discovery of neutral currents (Gargamelle, 1973) → prediction of W et Z bosons
- Observation of the massive W and Z bosons (UA1/UA2, 1983)
  - Not really an issue to give the W and Z bosons masses in the equations describing the particle fields, their kinematics and interactions ("Lagrangian")
- Interactions can be represented with Feynman diagrams such as : each diagram representing some ~probability that a process (here WW → WW) happens



- Many more diagrams, involving more particles or loops, to describe this process but bottom-line is that the probability associated to this process keeps growing and growing with the energy so that we'd get probabilities >100 %…
  (actually the theory enters a « non-perturbative » case where more and more diagrams introduce large corrections so that computations don't converge)



- ...sane longitudinal gauge boson scattering is restored adding :
- That's the reason why we need, on top of the W, Z and γ bosons, an additional particle in the electroweak sector of the Standard Model
  - We call it the « Higgs boson »

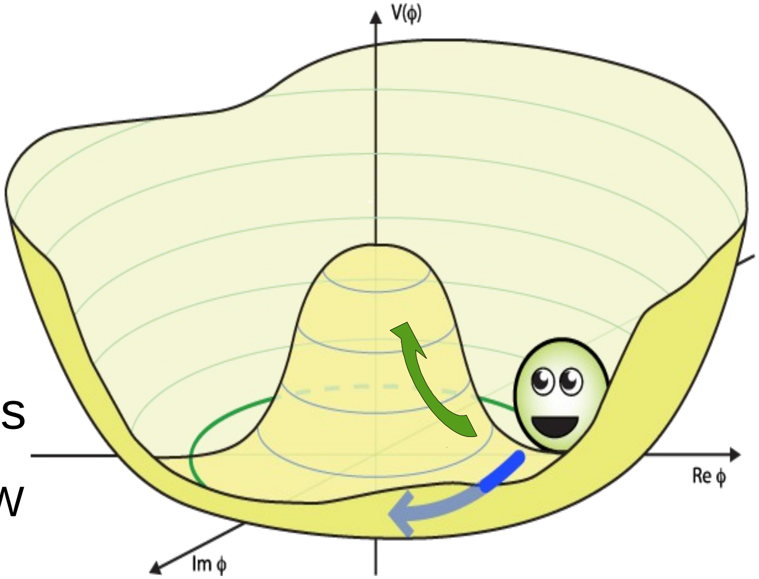
How the Higgs ?

- A bit of this…

...and a lot of this

Physicists' steroids

lead to a great potential



  - For $|\phi|>0$, fermions get massive
  - Excitations along the circle are Goldstone bosons
  - Excitations in non-flat direction are the Higgs boson
- Transforming the previous 3 massive W/Z bosons into 3 pairs of massless boson+massless Goldstone particles
  - At low energies each pair behaves like (previously) a massive W
  - At high energies the pair behaves like two different particles
  - But the combination of the W/Z bosons with 3 Goldstone + Higgs particles ensures the good behaviour of the model at high energies

How the Higgs ? (2)

- Let's go through this famous Lagrangian :

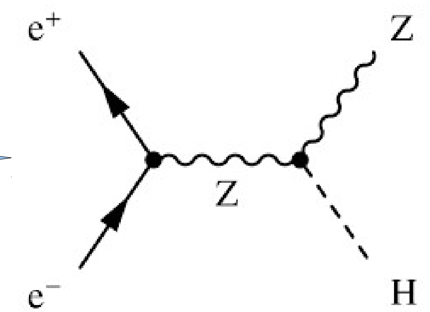
$$
\begin{aligned}
&\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac12 \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac12 \partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
&igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)) - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
&Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac12 \partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac12 \partial_\mu \phi^0 \partial_\mu \phi^0 - \\
&\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac12 (H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
&g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
&\tfrac18 g^2 \alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right) - \\
&gMW^+_\mu W^-_\mu H - \tfrac12 g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
&\tfrac12 ig \left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
&\tfrac12 g \left(W^+_\mu (H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac12 g \tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
&M\left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu \partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac14 g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac18 g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-\right) - \\
&\tfrac12 g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac12 ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu \phi^0 (W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac12 ig^2 s_w A_\mu H (W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1) Z^0_\mu A_\mu \phi^+\phi^- - \\
&g^2 s_w^2 A_\mu A_\mu \phi^+\phi^- + \tfrac12 ig_s \lambda^a_{ij}(\bar q^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar e^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial + \\
&m^\lambda_u) u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu \left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar u^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
&\tfrac{ig}{4c_w} Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar d^\lambda_j \gamma^\mu(\tfrac43 s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
&(\bar u^\lambda_j\gamma^\mu(1 - \tfrac83 s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt2} W^+_\mu \left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar u^\lambda_j \gamma^\mu(1+\gamma^5)C_{\lambda\kappa} d^\kappa_j)\right) + \\
&\tfrac{ig}{2\sqrt2} W^-_\mu \left((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
&\tfrac{ig}{2M\sqrt2}\phi^+ \left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
&\tfrac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M} H(\bar\nu^\lambda\nu^\lambda) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M} H(\bar e^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \tfrac14 \bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa - \\
&\tfrac14 \bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa + \tfrac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
&\tfrac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac g2 \tfrac{m^\lambda_u}{M} H(\bar u^\lambda_j u^\lambda_j) - \\
&\tfrac g2 \tfrac{m^\lambda_d}{M} H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar G^a G^b g^c_\mu + \\
&\bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2 - M^2)X^- + \bar X^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar X^0 X^- - \\
&\partial_\mu\bar X^+ X^0) + igs_w W^+_\mu(\partial_\mu \bar Y X^- - \partial_\mu \bar X^+ Y) + igc_w W^-_\mu(\partial_\mu\bar X^- X^0 - \\
&\partial_\mu \bar X^0 X^+) + igs_w W^-_\mu(\partial_\mu \bar X^- Y - \partial_\mu \bar Y X^+) + igc_w Z^0_\mu(\partial_\mu \bar X^+ X^+ - \\
&\partial_\mu \bar X^- X^-) + igs_w A_\mu(\partial_\mu \bar X^+ X^+ - \\
&\partial_\mu \bar X^- X^-) - \tfrac12 gM\left(\bar X^+ X^+ H + \bar X^- X^- H + \tfrac{1}{c_w^2}\bar X^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w} igM\left(\bar X^+ X^0\phi^+ - \bar X^- X^0\phi^-\right) + \\
&\tfrac{1}{2c_w} igM\left(\bar X^0 X^-\phi^+ - \bar X^0 X^+\phi^-\right) + igMs_w\left(\bar X^0 X^-\phi^+ - \bar X^0 X^+\phi^-\right) + \\
&\tfrac12 igM\left(\bar X^+ X^+\phi^0 - \bar X^- X^-\phi^0\right).
\end{aligned}
$$

one minute per line...

The search for the Higgs boson

- Higgs boson mass is/was a free parameter in the Standard Model
- LEP collided e^+e^-
  - H-$e^{\pm}$ coupling too small to produce Higgs directly

    (Total integrated luminosity ~ 3 fb^{-1})
  - Higgs searched in Higgsstrahlung

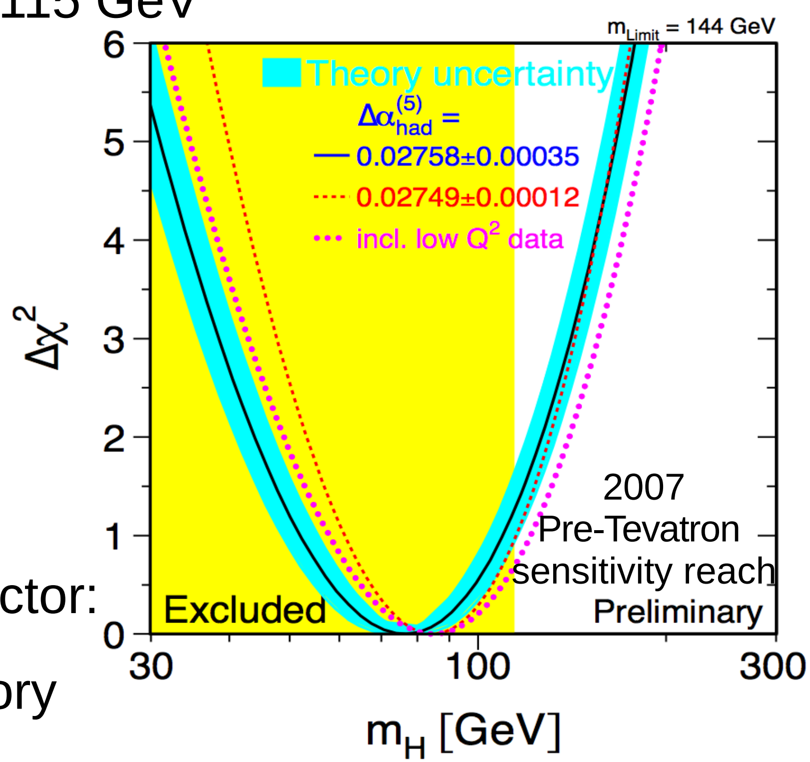


  - Center-of-mass energy ~>206 GeV (in 2000)
    - Search sensitivity up to ~$\sqrt{s}$-M_Z ~ 206 – 91 ~ 115 GeV
  - In this reach, Higgs expected to decay mainly to $b\bar{b}$ pairs, searches into

$(Z\rightarrow q\bar{q})(H\rightarrow b\bar{b})$, $(Z\rightarrow \nu\bar{\nu})(H\rightarrow b\bar{b})$, $(Z\rightarrow ll)(H\rightarrow b\bar{b})$, $(Z\rightarrow \tau\tau)(H\rightarrow b\bar{b})$ but also $(Z\rightarrow qq)(H\rightarrow \tau\tau)$

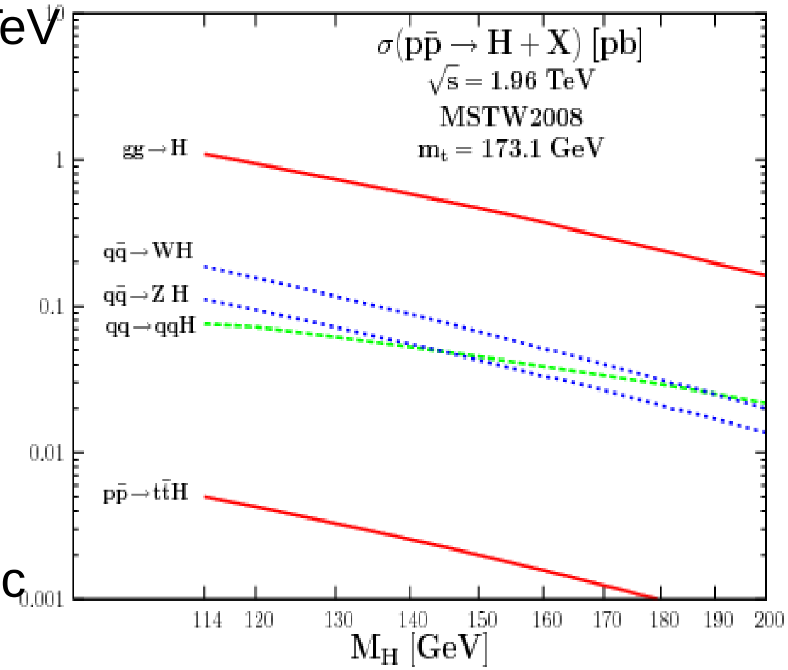
  - ALEPH observing excess at ~115 GeV, not confirmed by L3, OPAL and DELPHI
    → m_H>114.4 GeV at 95 % CL
- But LEP provided wonderful insight into the Higgs sector:

  precision measurements on other aspects of the theory indirectly constraining the Higgs mass

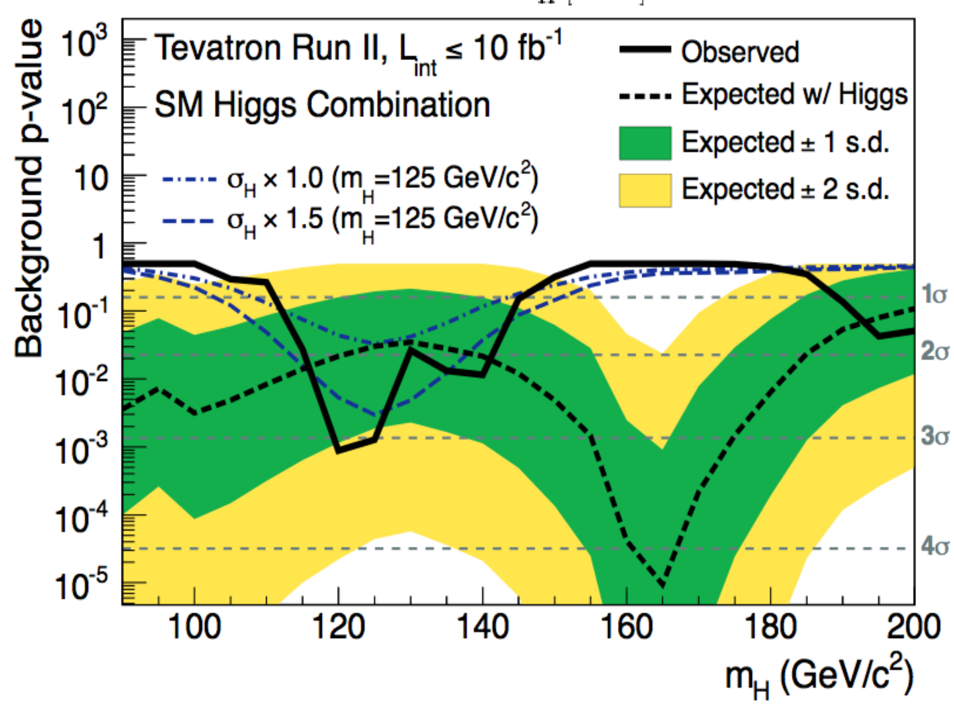


The search for the Higgs boson (2)

- Tevatron (US) collided protons-antiprotons at √s=1.96 TeV
  - “partons” carrying only part of the protons' energy → involved energy not-known event by event → need good detector coverage / precise missing transverse energy measurements for decays with ν
  - Hadronic environment → signatures less clean than LEP
- For mH>~130 GeV, $H \rightarrow W^+W^-$ is expected to contribute the most . For lower masses tagging $H \rightarrow bb$ with leptonic decays of a W or Z boson produced in association
- Many multivariate analyses (MVA) employed
- Tried hard, excluded >149 GeV, reached just 3σ

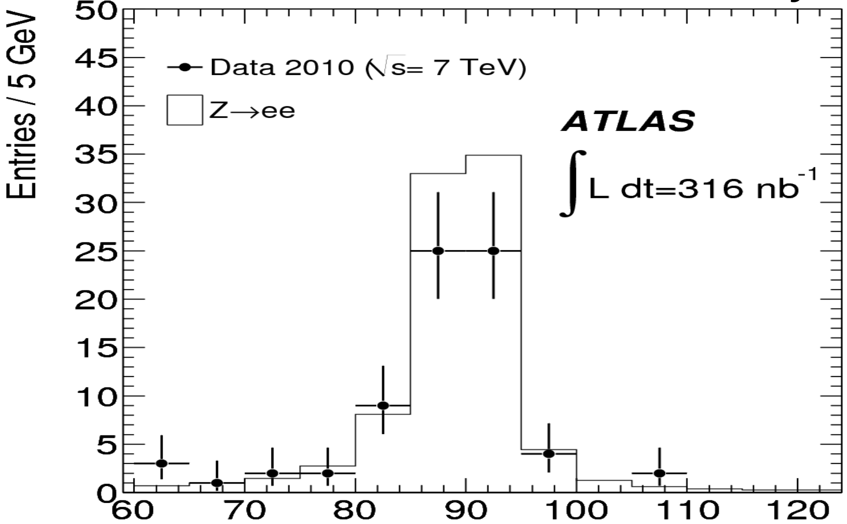


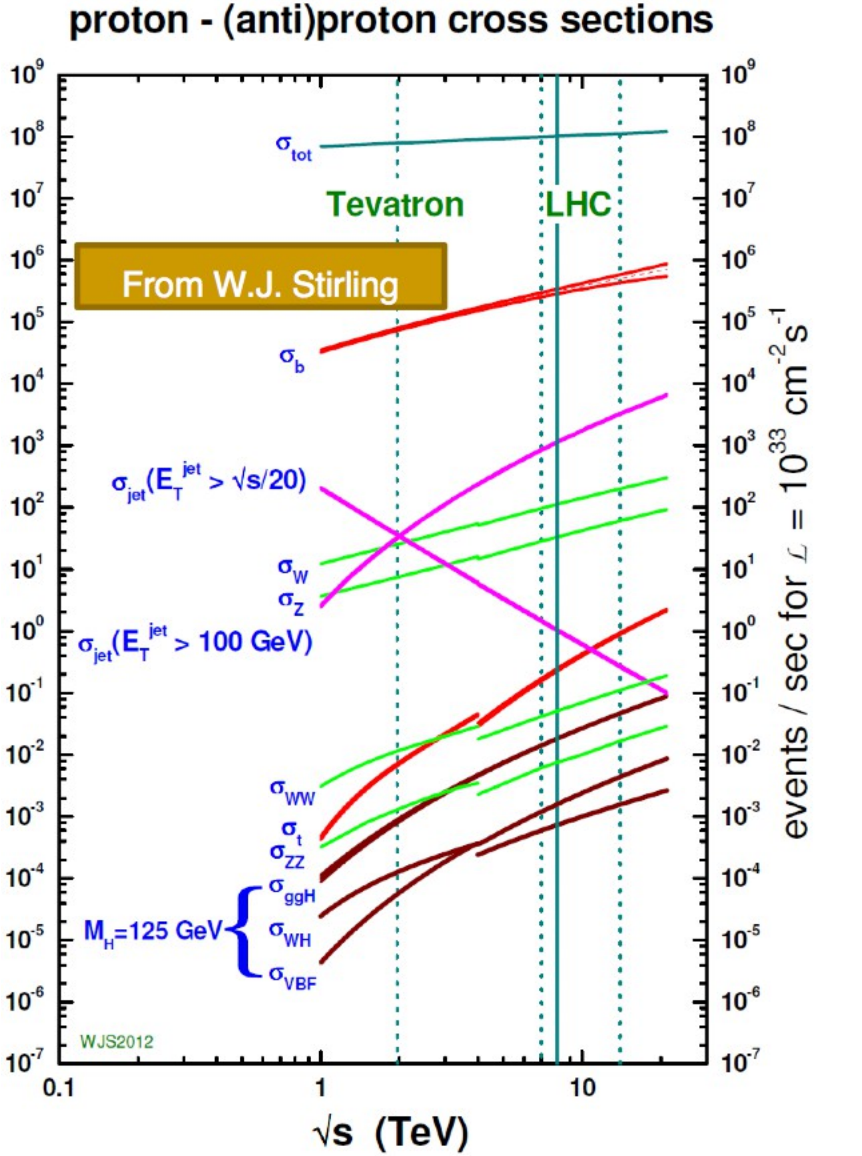
Channel		m_H range (GeV/c^2)
$WH \rightarrow \ell\nu b\bar{b}$ 2-jet channels 4×(5 b-tag categories)	$H \rightarrow b\bar{b}$	90–150
$WH \rightarrow \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)		90–150
$ZH \rightarrow \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)		90–150
$ZH \rightarrow \ell^+\ell^- b\bar{b}$ 2-jet channels 2×(4 b-tag categories)		90–150
$ZH \rightarrow \ell^+\ell^- b\bar{b}$ 3-jet channels 2×(4 b-tag categories)		90–150
$WH+ZH \rightarrow jjb\bar{b}$ (2 b-tag categories)		100–150
$t\bar{t}H \rightarrow W^+bW^-\bar{b}b\bar{b}$ (4 jets,5 jets,≥6 jets)×(5 b-tag categories)		100–150
$H \rightarrow W^+W^-$ 2×(0 jets)+2×(1 jet)+1×(≥2 jets)+1×(low-$m_{\ell\ell}$)	$H \rightarrow W^+W^-$	110–200
$H \rightarrow W^+W^-$ (e-τ_{had})+(μ-τ_{had})		130–200
$WH \rightarrow WW^+W^-$ (same-sign leptons)+(tri-leptons)		110–200
$WH \rightarrow WW^+W^-$ (tri-leptons with 1 τ_{had})		130–200
$ZH \rightarrow ZW^+W^-$ (tri-leptons with 1 jet,≥2 jets)		110–200
$H \rightarrow \tau^+\tau^-$ (1 jet)+(≥2 jets)	$H \rightarrow \tau^+\tau^-$	100–150
$H \rightarrow \gamma\gamma$ 1×(0 jet)+1×(≥1 jet)+3×(all jets)	$H \rightarrow \gamma\gamma$	100–150
$H \rightarrow ZZ$ (four leptons)	$H \rightarrow ZZ$	120–200



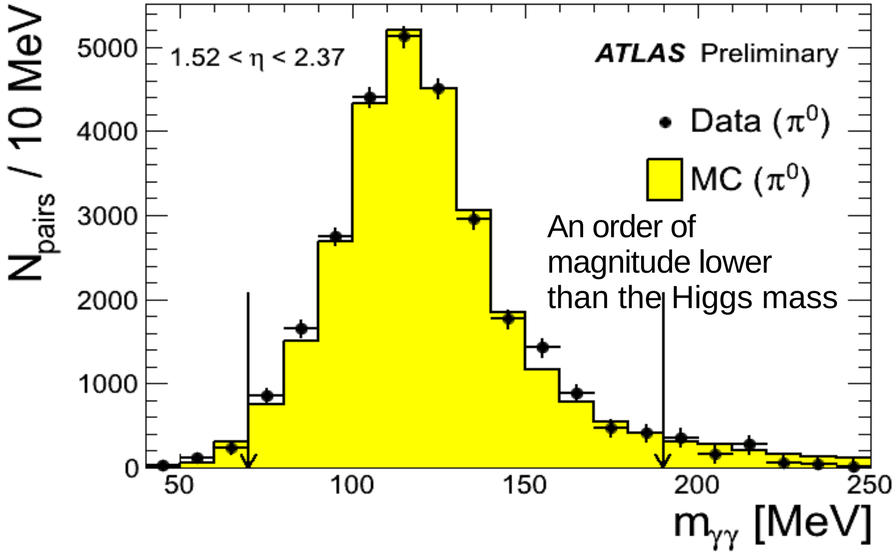
The rise of LHC

- First LHC measurements, rediscovery of the (known) SM





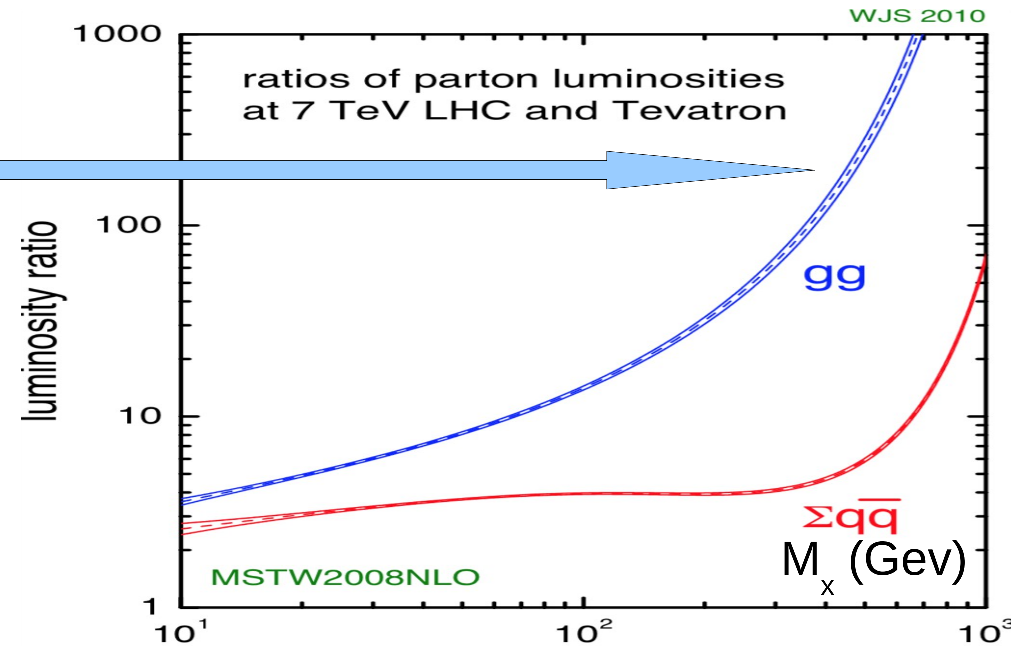
- Calibration of the detectors

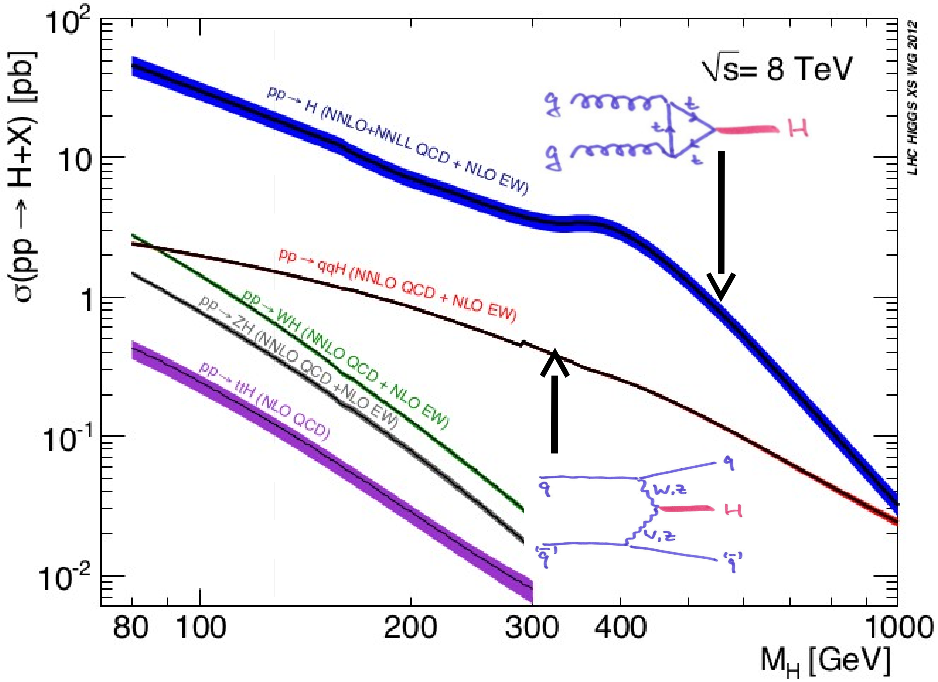


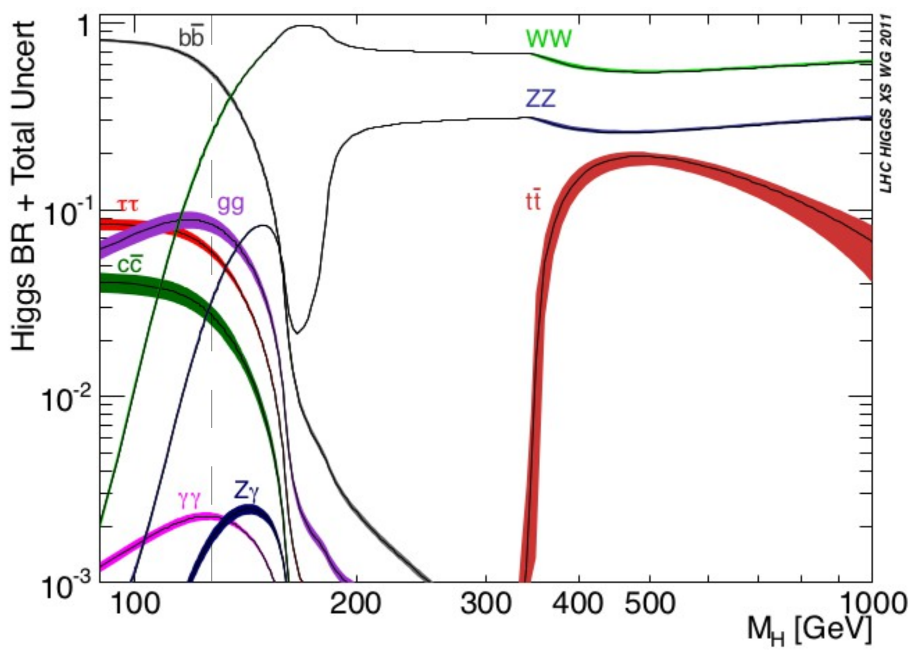
- Large increase of cross-sections: advantage to the LHC in the quest for the Higgs boson
  - But also large background processes to domesticate

Where to find the Higgs ?

- Larger cross-section than Tevatron in particular due to larger fraction of the proton energy carried by gluons
  - But can also be produced from fusion of W/Z bosons
  - Looking for peaks (in the $\gamma\gamma$ or ZZ mass spectra) or broad excesses (WW for instance)

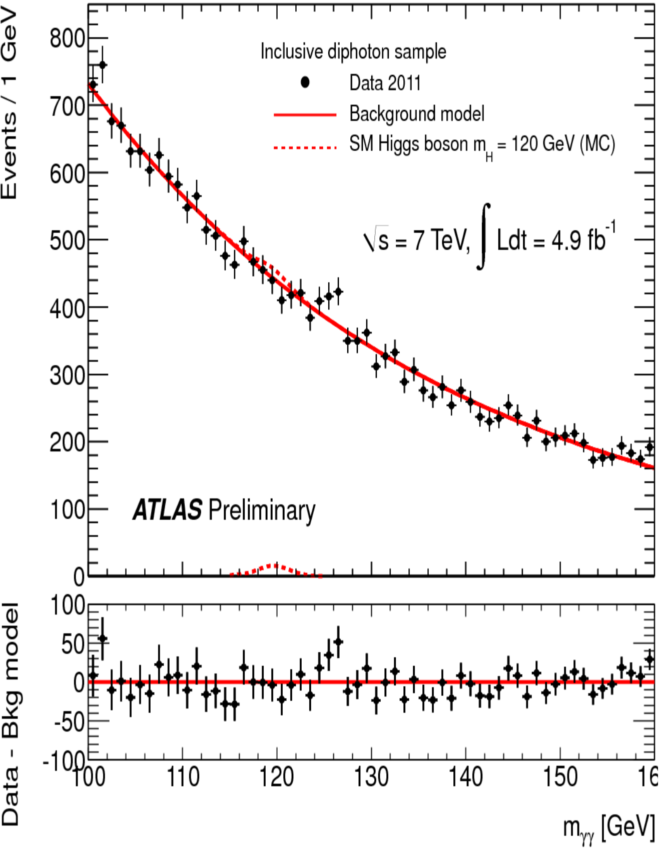


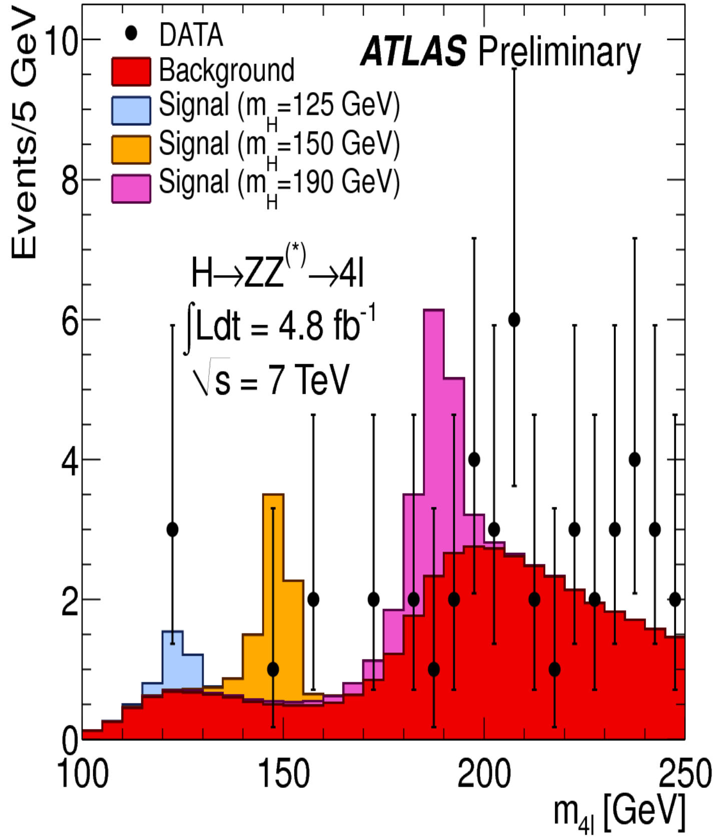


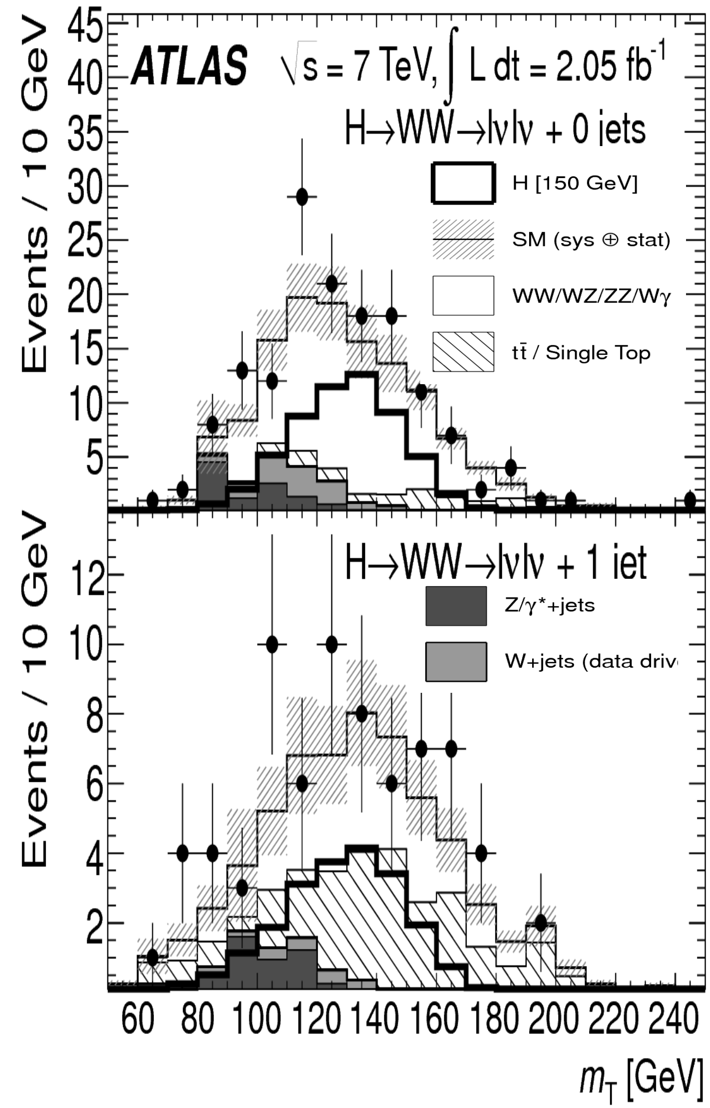


arXiv:1201.3084

2011 searches at 7 TeV





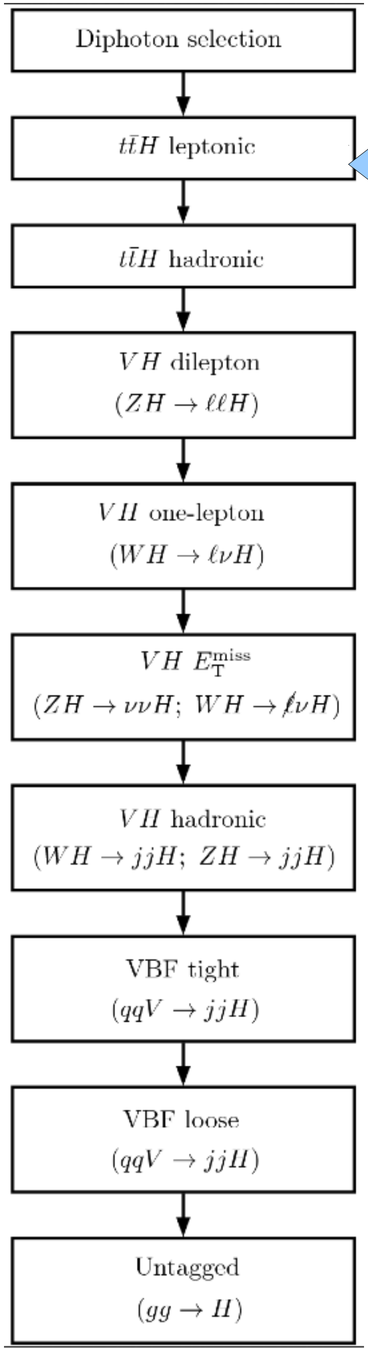


- Exclusion of Higgs masses down to 131 GeV
  → Higgs cornered !
- No convincing excess at this time…

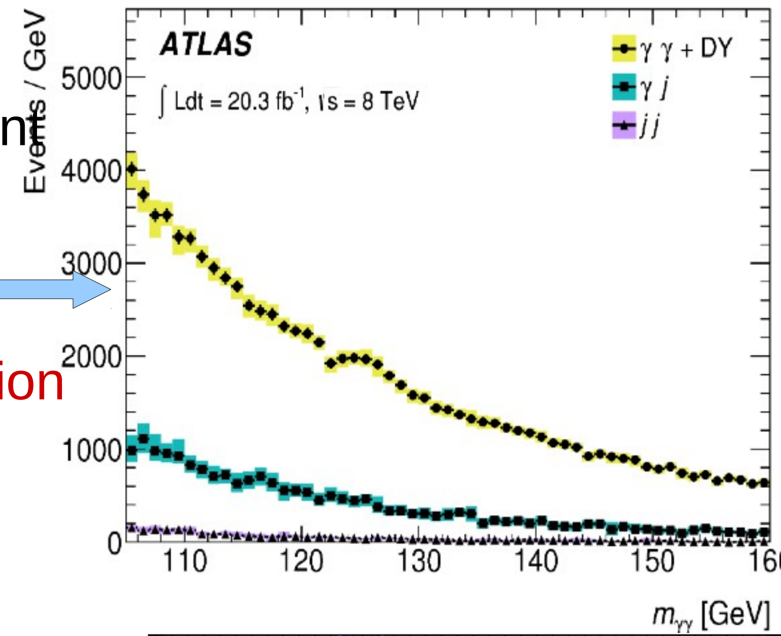
  ...but some interesting « fluctuations » around 125 GeV !
- Spent some time in 2012 on optimizing the analyses targeting for the mass hypotheses around 125 GeV

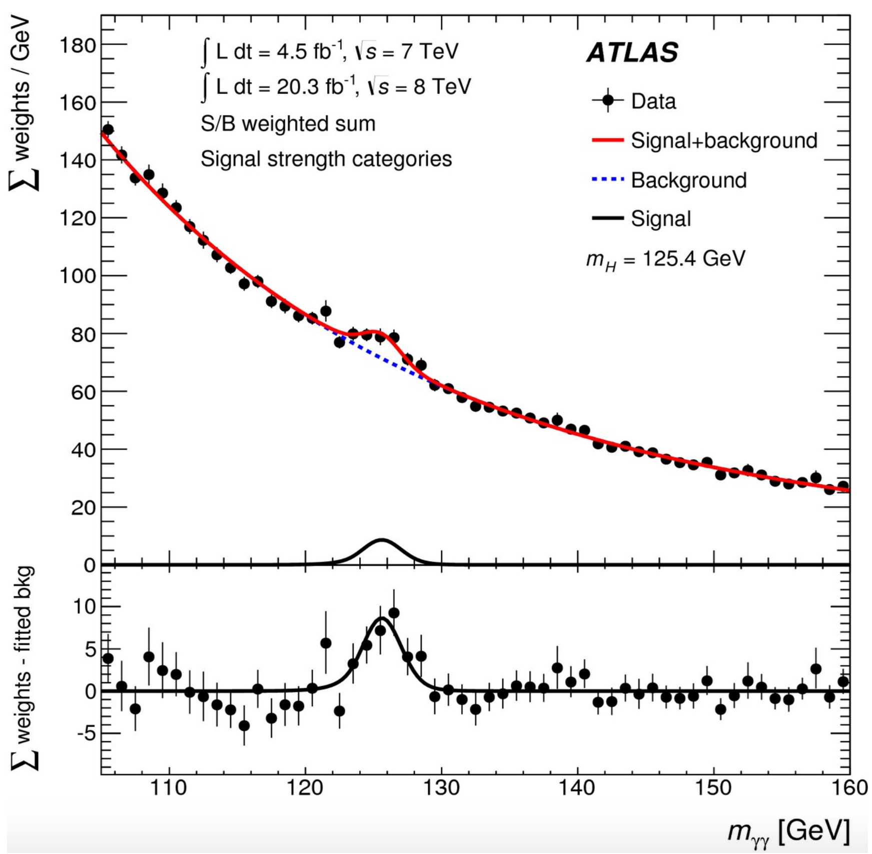
Also learning how to use the ROOT palette...

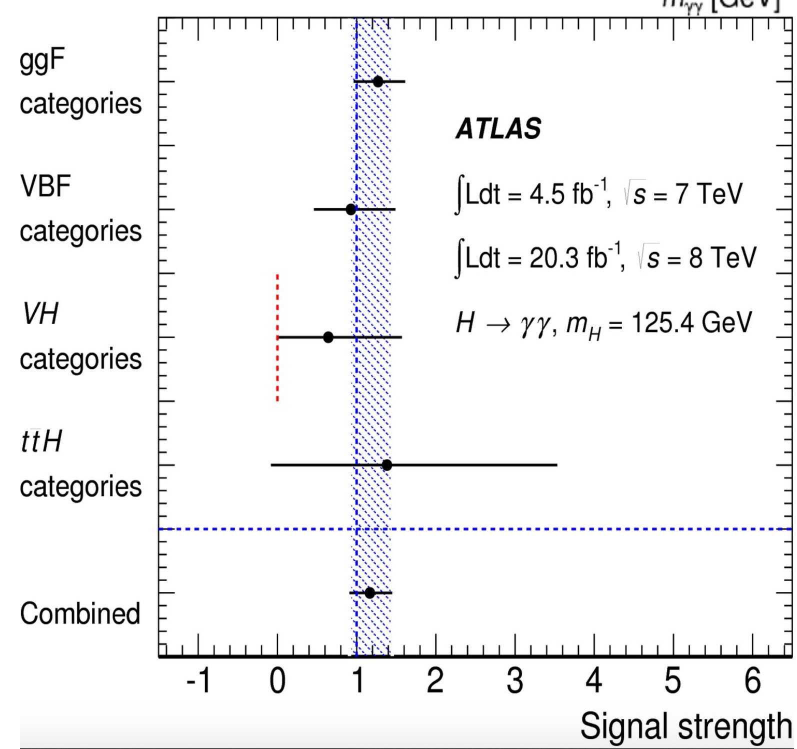
H → γγ in one slide



- Selecting two high-pT « isolated » γ
- Using 12 categories targeting different production modes
- Extracting backgrounds from CRs
- Need accurate energy scale calibration (mainly from Z decay events)

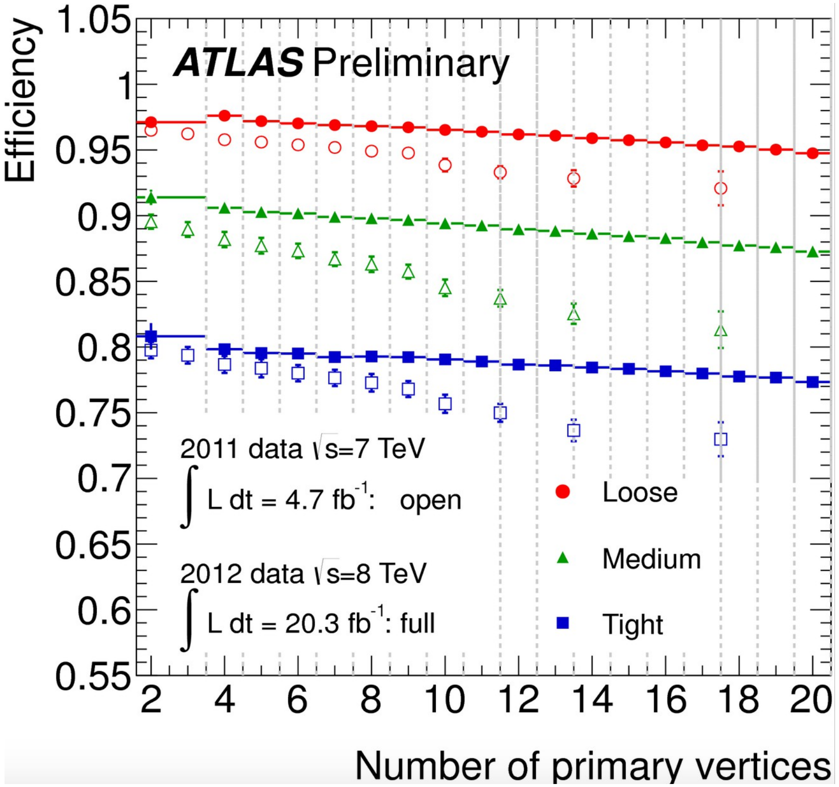


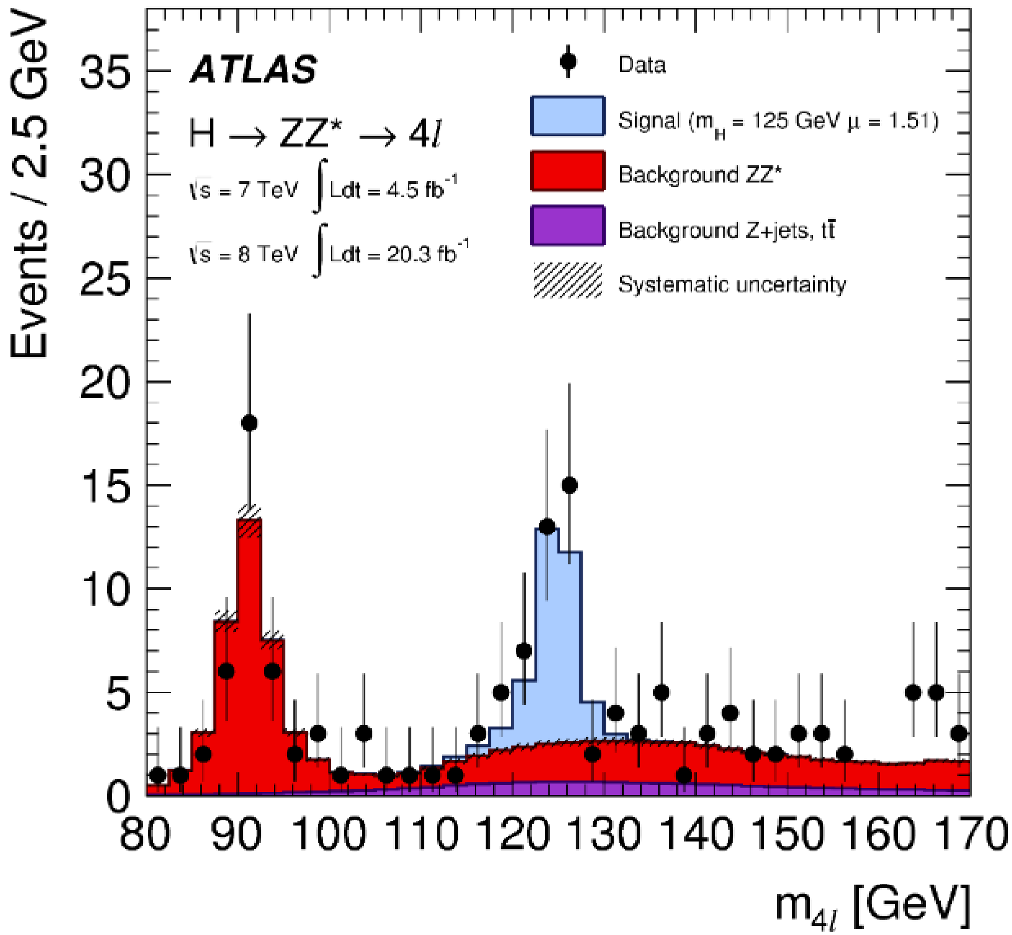




H → ZZ in one slide

- Expecting small signal rates
- But small background rates
  - → Clean 4-leptons signature
  - → Lepton selection efficiencies crucial

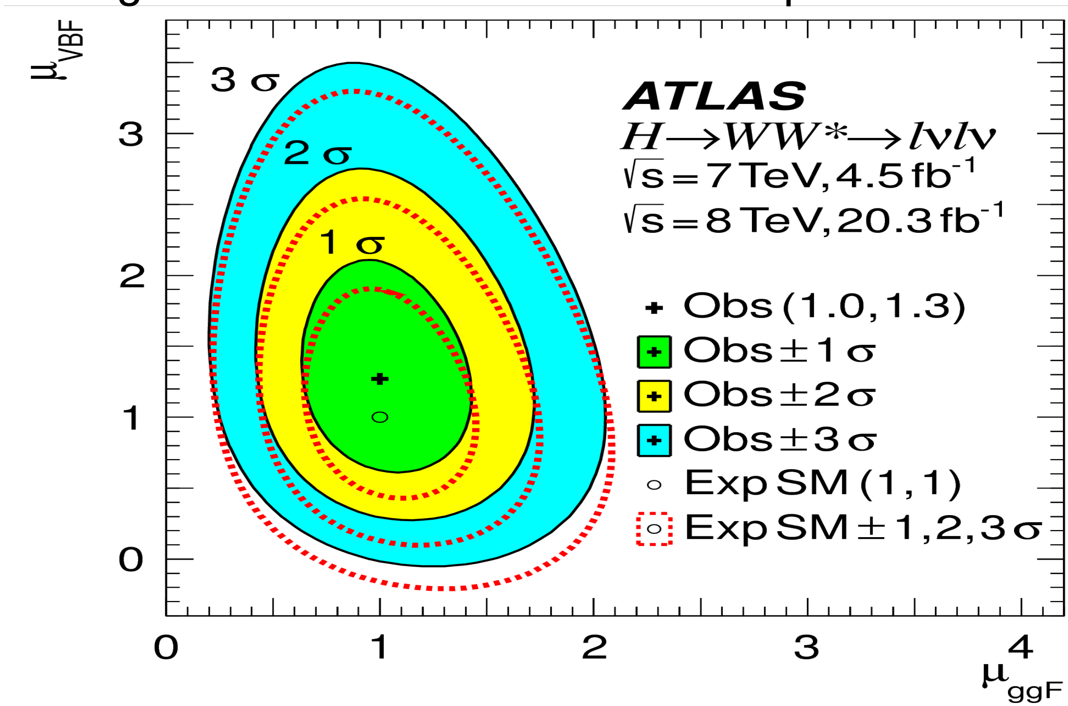


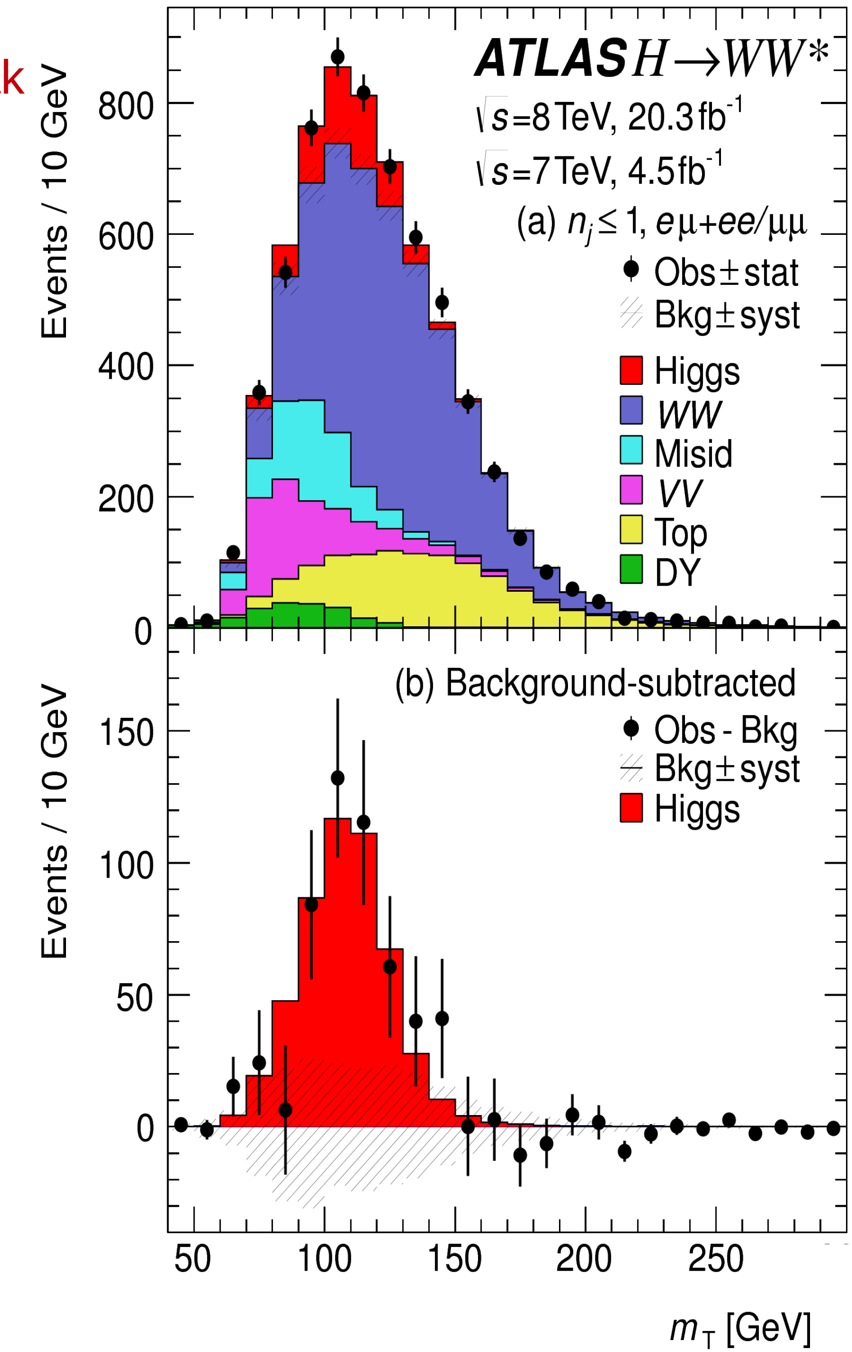


- Control of the energy scale and radiation
  - Precise in-situ measurements
  - Refined electron-track fitting
  - FSR corrections
- Not enough statistics to split the production modes here

H → WW → lνlν in one slide

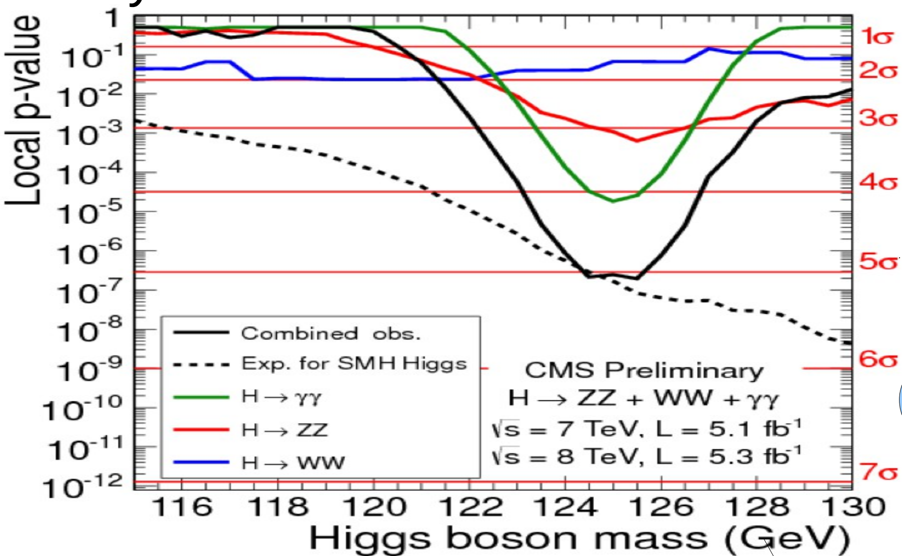
- Complicated signature involving leptons, jets, missing transverse energy (escaping neutrinos) → No mass peak
- Large complicated background processes (WW continuum, top, W+jets/multijets with fake leptons,…)
- But large signal event rates thanks to the BR
- Scalar Higgs transmitting some spin correlation to the leptonic decays of the W pair
    - Discriminant against WW continuum
- Enough statistics to discriminate the production modes

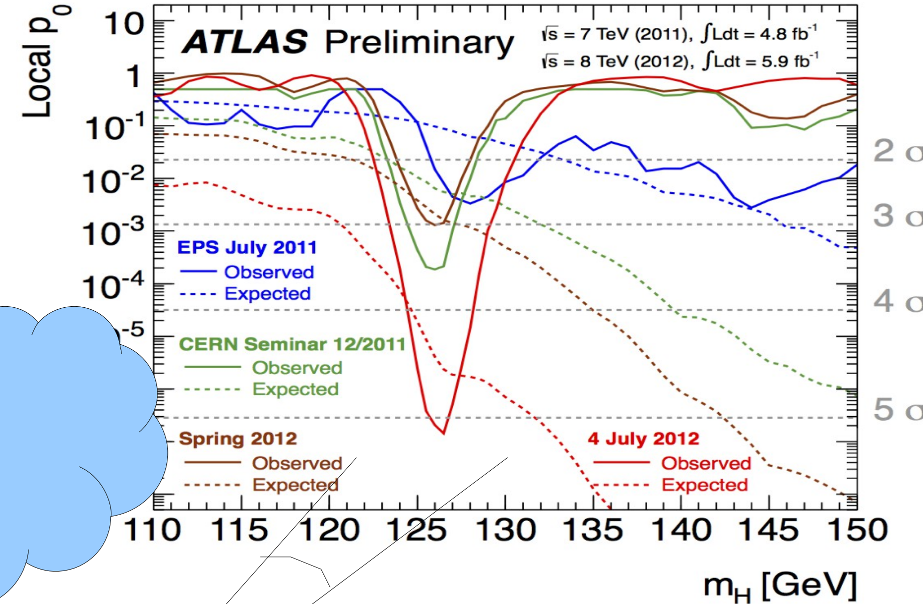




The Higgs discovery

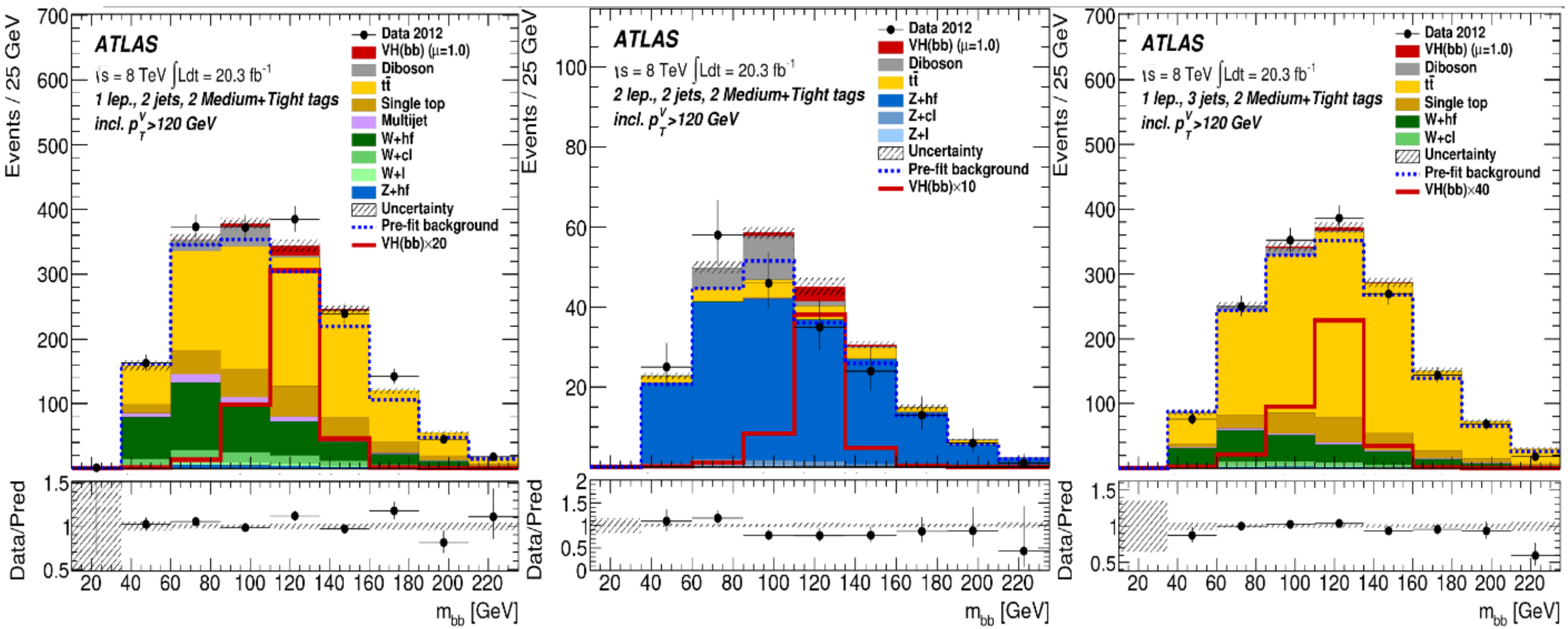
- Combining these three channels, presence of some SM-like Higgs is observed by both ATLAS and CMS around 125 GeV



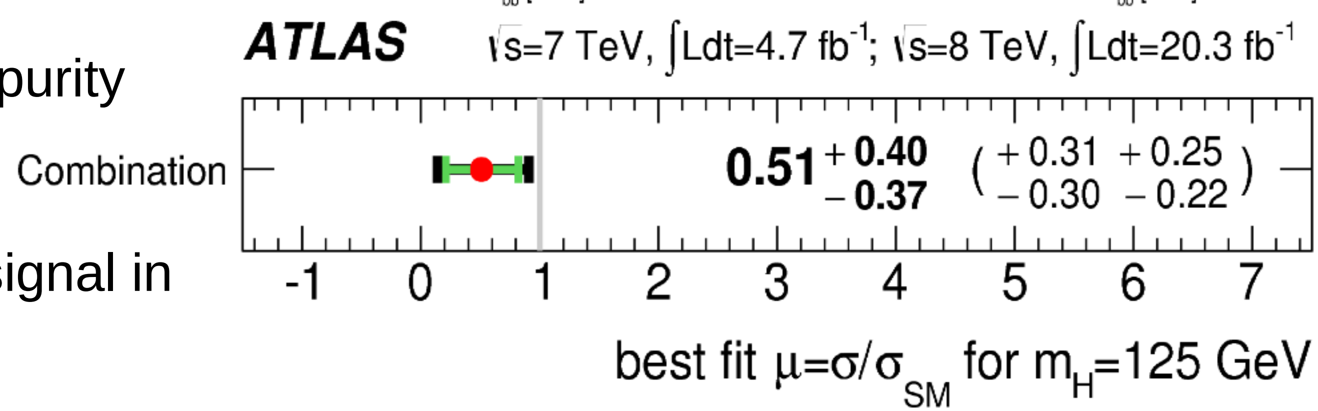


Then b$\bar{b}$

- Using 0/1/2-lepton VH tagging similar as Tevatron analyses
- Huge top and Z+heavy-flavour background to deal with



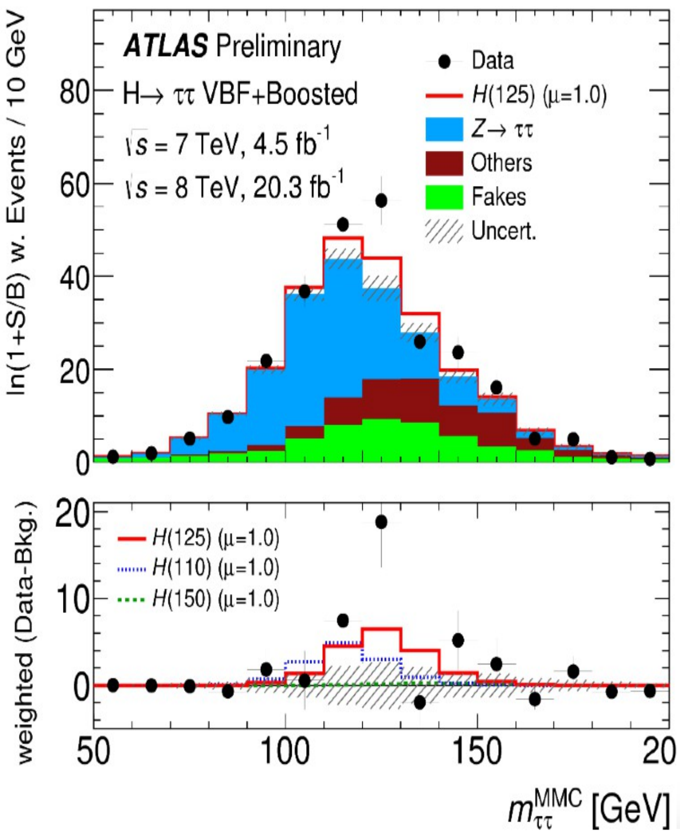
- pT(V) categories to increase purity
- Still quite statistics-limited
- Not yet seen any significant signal in ATLAS nor CMS

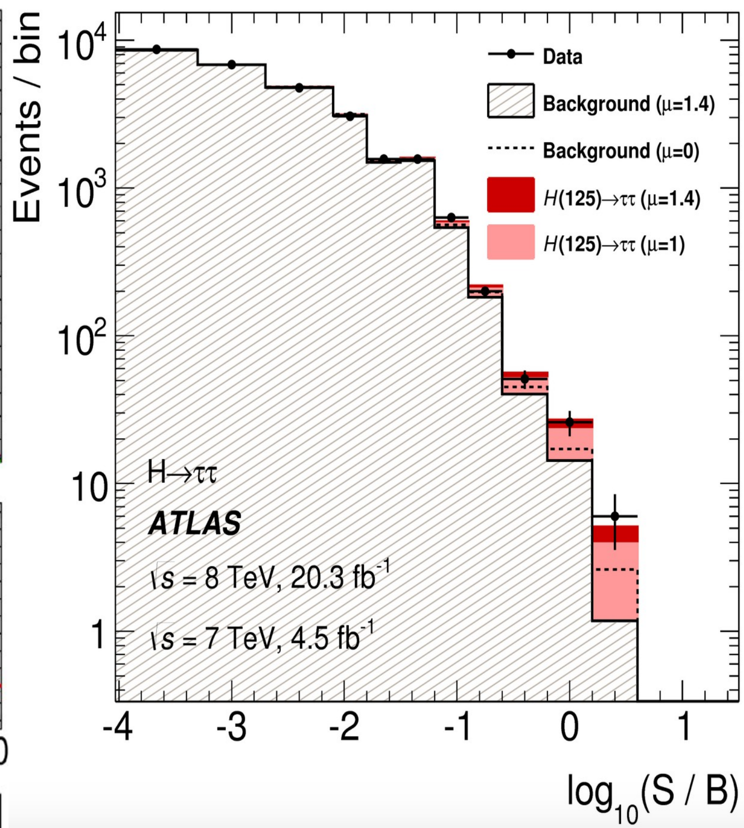


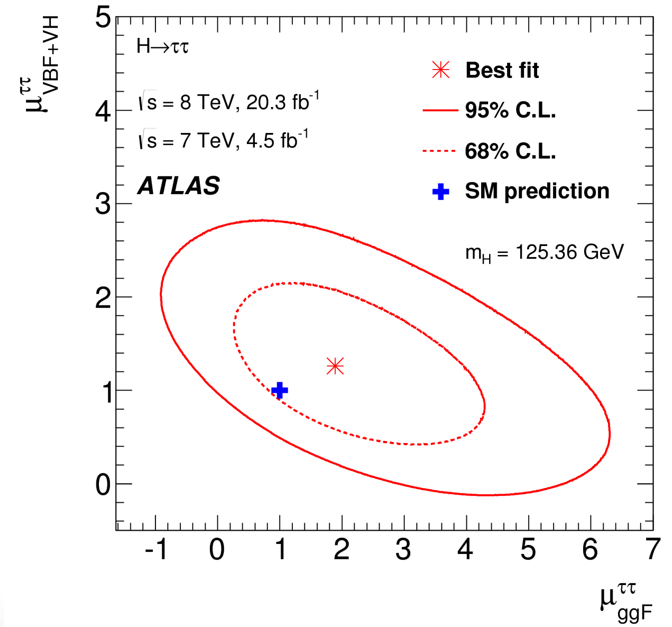
Finally $H \to \tau\tau$

- As the previous one, probes the couplings of the Higgs to fermions
- Need good identification of hadronic taus
- Good control of the Z/DY $\to \tau\tau$ background relies on « embedding » techniques
- This channel too can address the different production modes

	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
physics backgrounds			
$Z/\gamma^* \to \tau\tau$	•	•	•
$t\bar{t}$ (VBF, boosted)	•	•	
$Z/\gamma^* \to ee,\mu\mu$	•		
instrumental backgrounds			
multi-jets	•	•	•
$Z/\gamma^* \to ee$ ($e \to \tau_{had}$)		•	
$Z/\gamma^*(\to ee,\mu\mu)$+jet (jet$\to\tau_{had}$)		•	
$W(\to l\nu)$+jet (jet$\to\tau_{had}$)		•	
$W(\to l\nu)$+jet (jet$\to e,\mu$)	•		

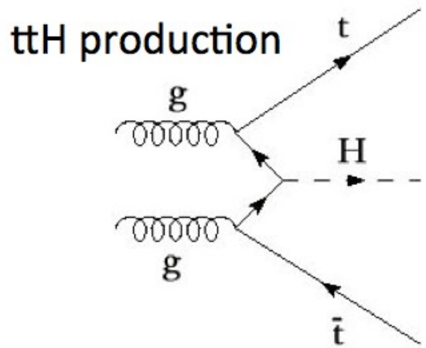


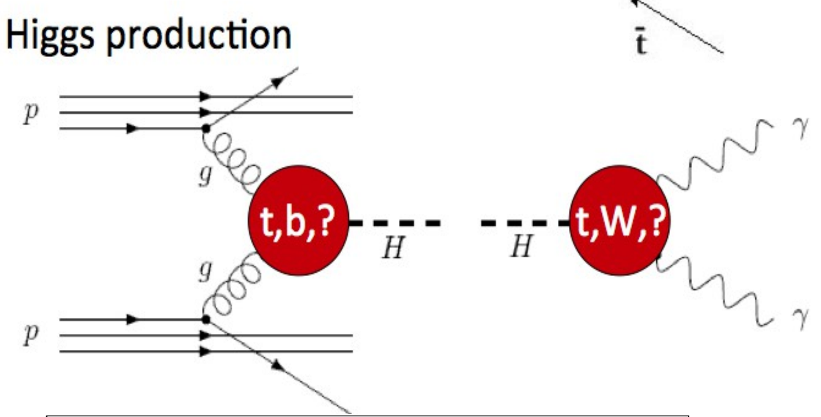


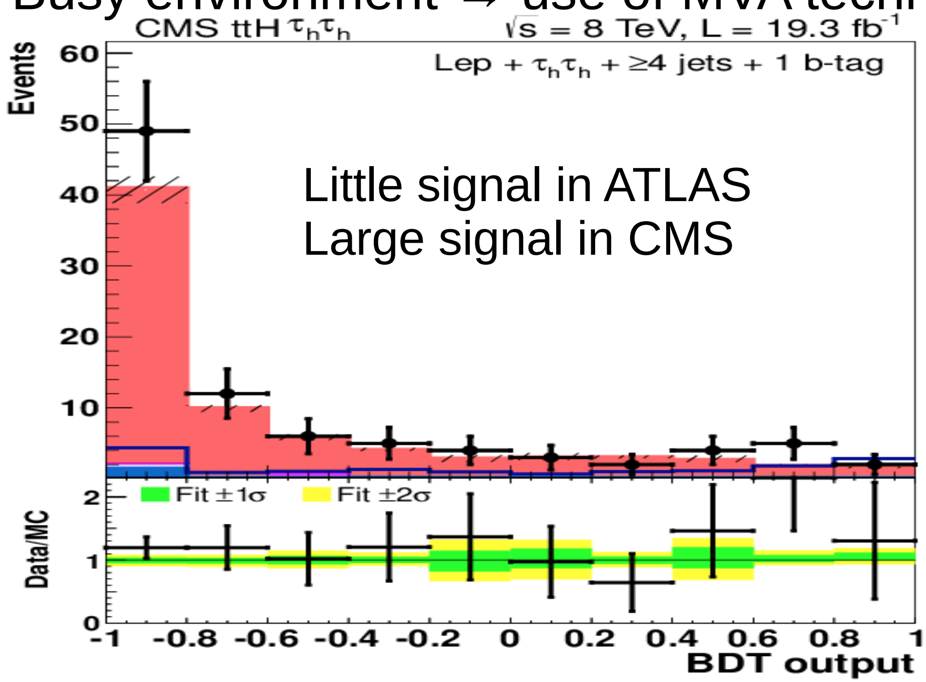


And now ttH

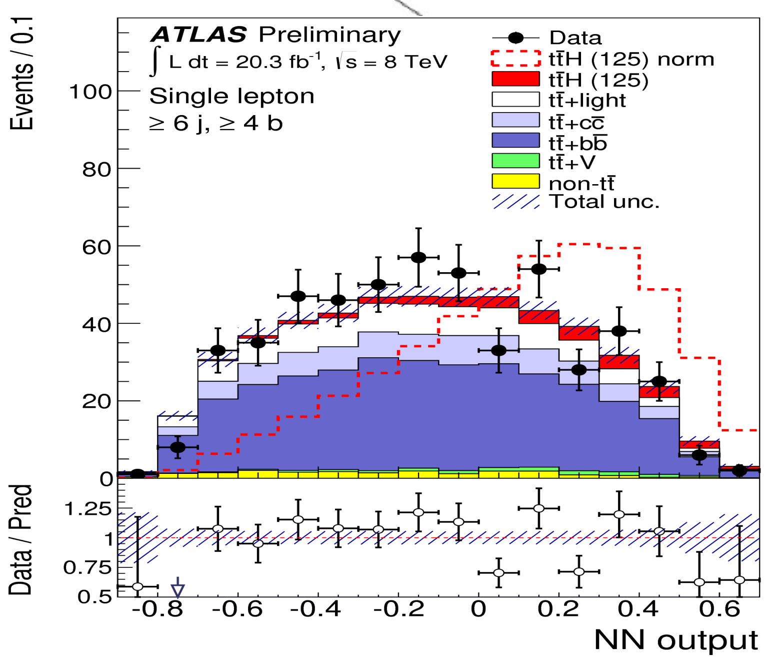
- t is the most strongly-coupled particle to the Higgs
  - By measuring the ttH production and doing the ratio with the $\gamma\gamma$ production one probes the presence of new particles in loops in the ggF production or $H \rightarrow \gamma\gamma$ decay vertices
- Signal rates 2000 times smaller than tt+X
  - Large background systematic uncertainties
- Searches in b-pair and γ-pair Higgs decays or multilepton (WW or $\tau\tau$ decays) signatures
  - Busy environment $\rightarrow$ use of MVA techniques





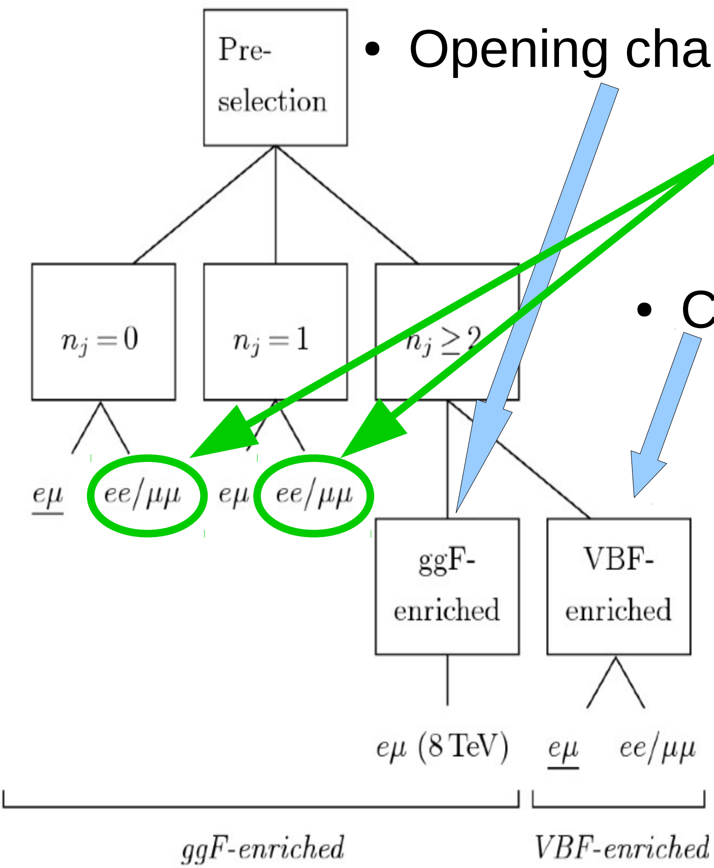


Little signal in ATLAS
Large signal in CMS

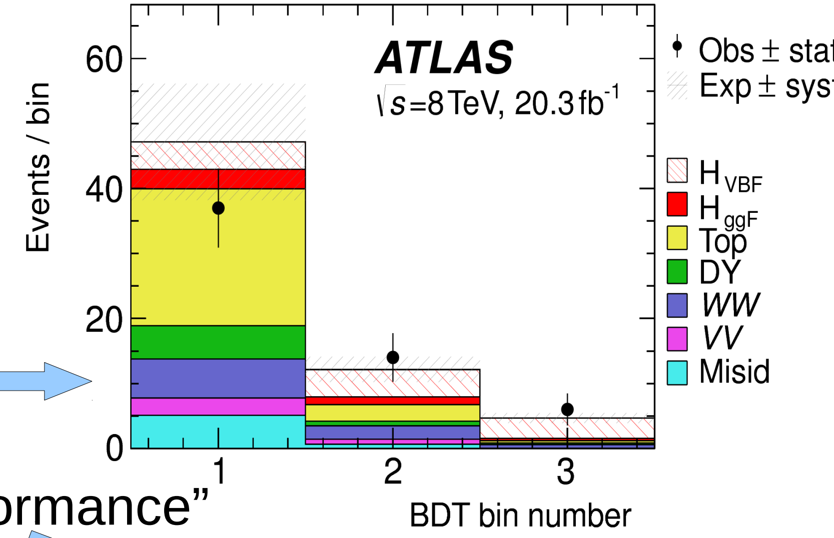


How working hard pays

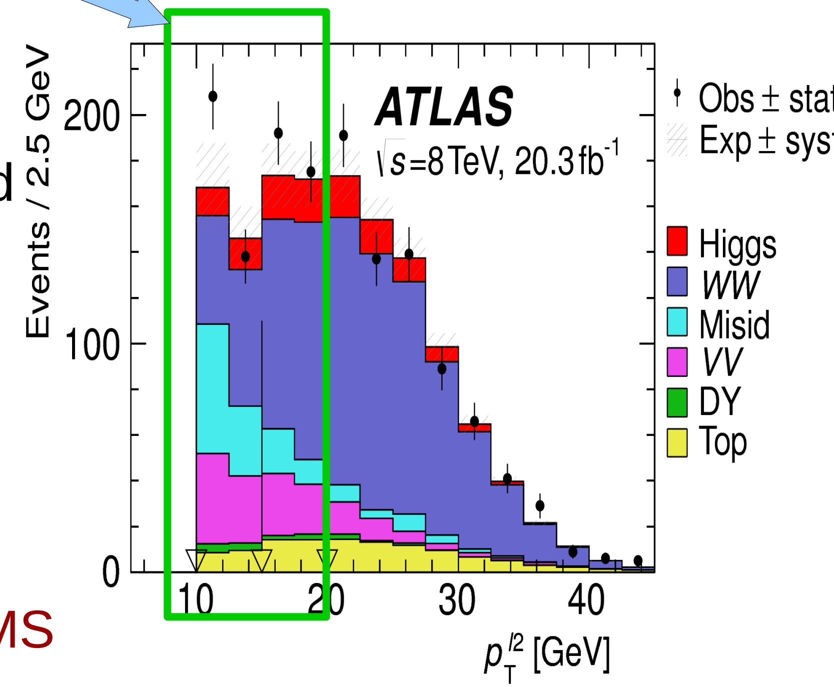
- The example of HWW : from the 2012 discovery to the most precise Higgs channel



- Opening channels
  - Developing new techniques
- Changing paradigm
  (cut-based → MVA)



- Working on the “performance”
- Generator studies to reduce the systs on dominant background

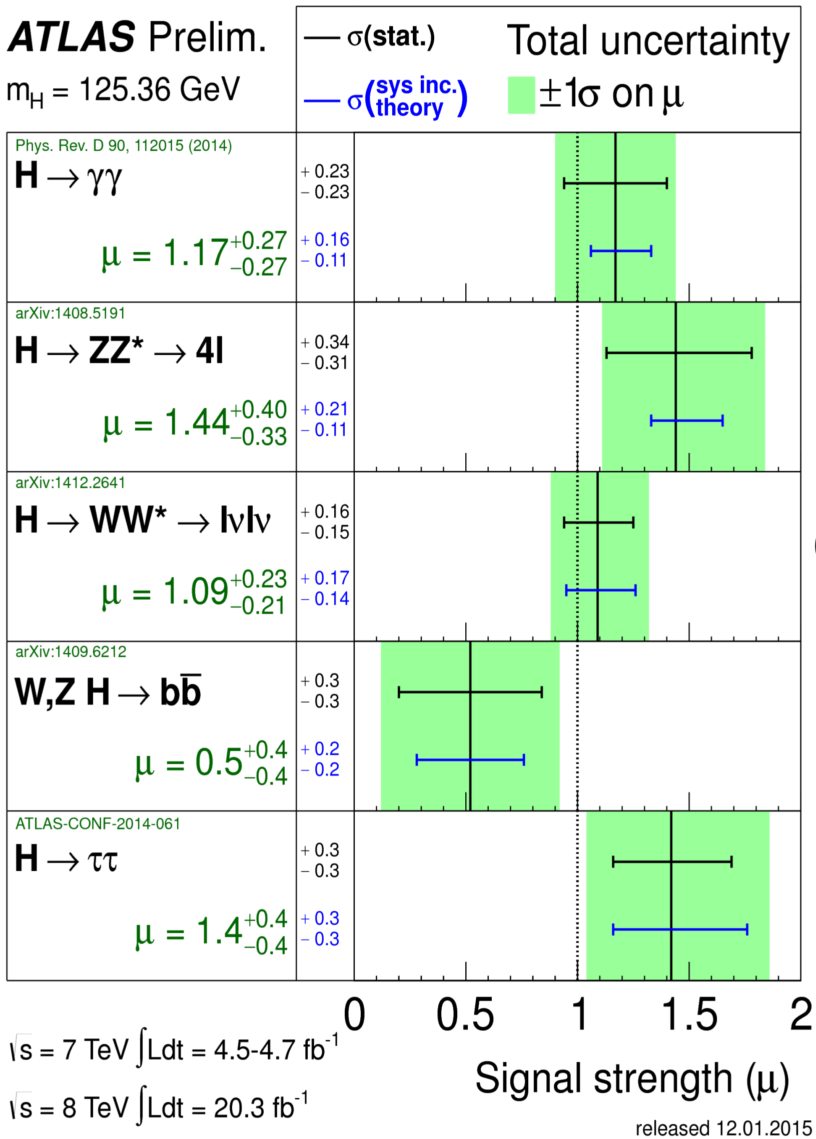


- Results:
  - 2013: 3.8σ
  - 2014: 6.1σ
  - Paper submitted one year after CMS

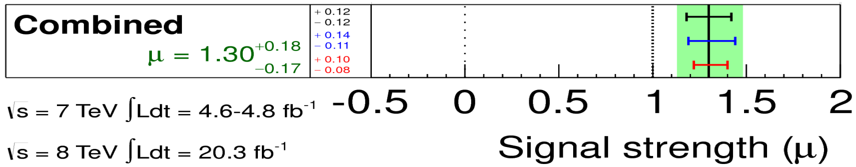
- 2013: μ = 1.01 ±0.31 (31%)
- 2014: μ = 1.08 ±0.22 (20%)
- CMS: μ = 0.72 ±0.19 (26%) (including the VH categories)

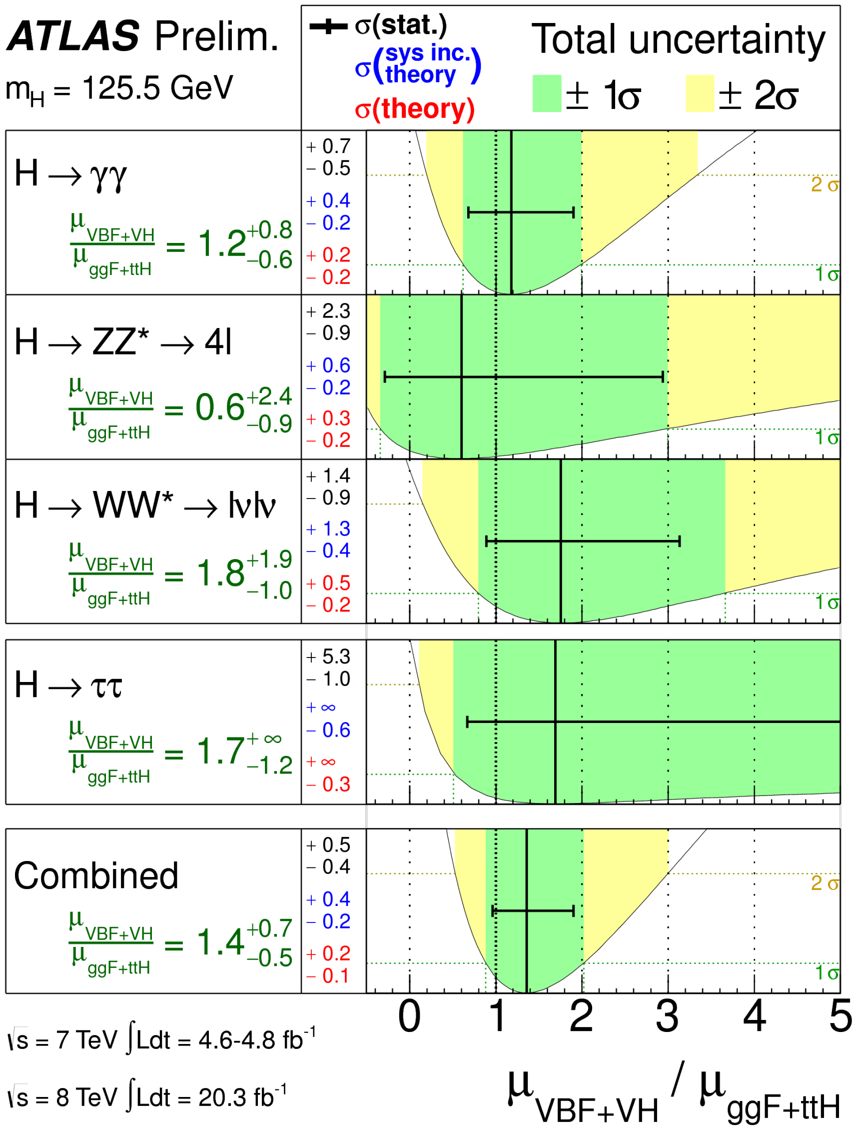
Combined couplings measurements

- Now one can take all these channels and subcategories and combine them to measure Higgs properties



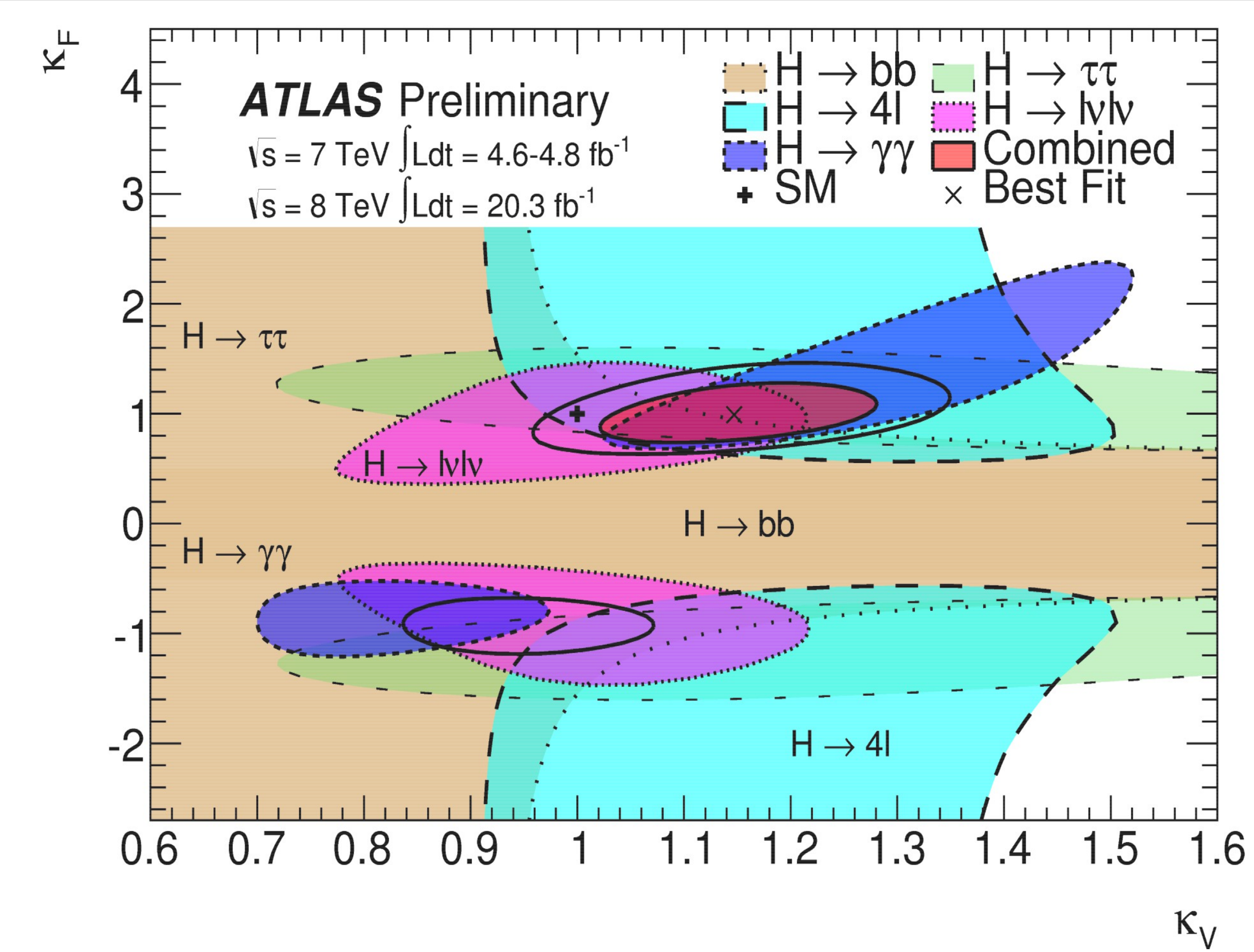
(combined results soon outdated)





Simple models

- Using the information from the different categories targetting different production modes and decay, one can then fit his/her favorite model to the data
- One simple example is the one in which the couplings of the Higgs to fermions all scale with a common factor κ_F and similarly for the bosons κ_V :



- But many more complicated models used to interpret our data...

Simple models

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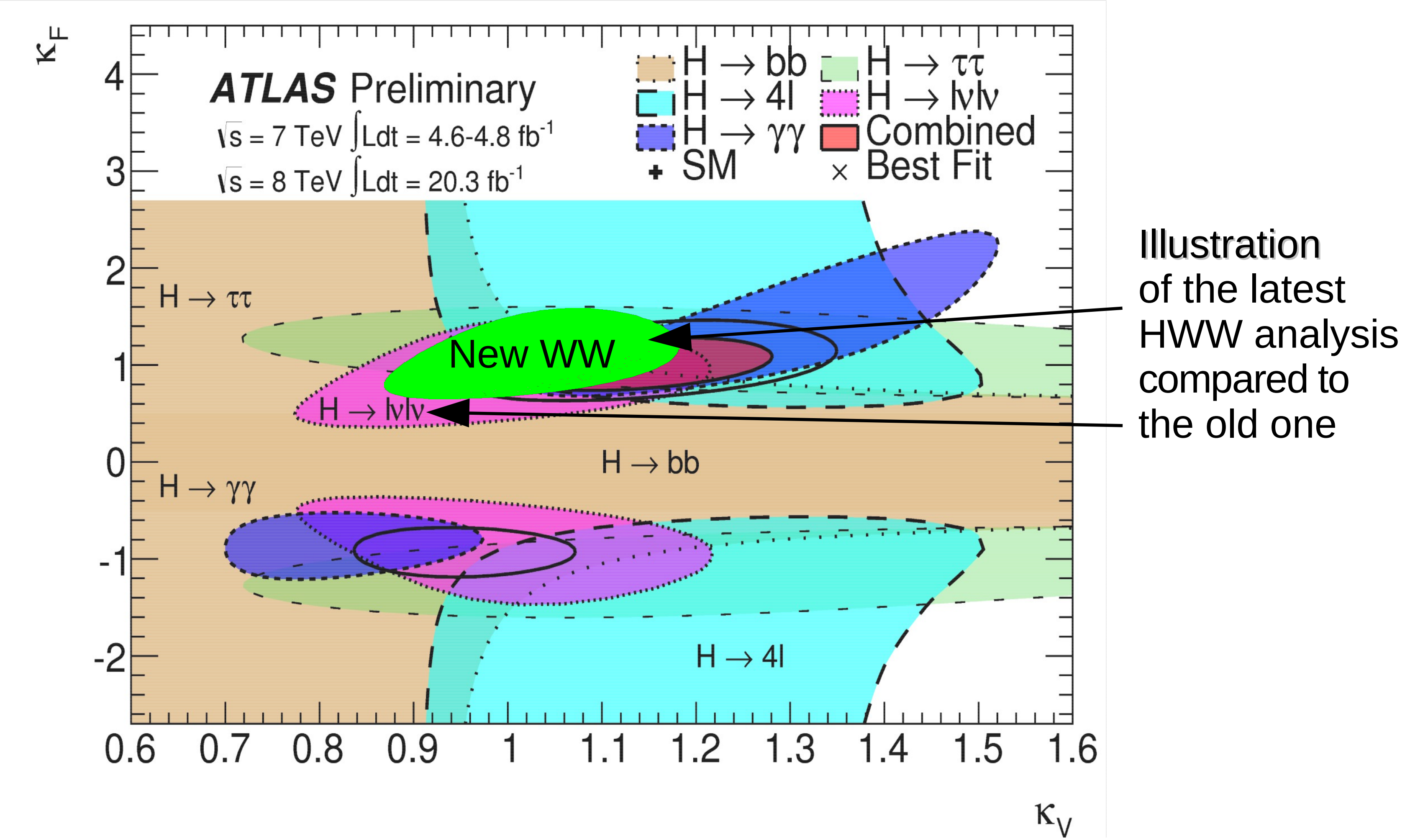
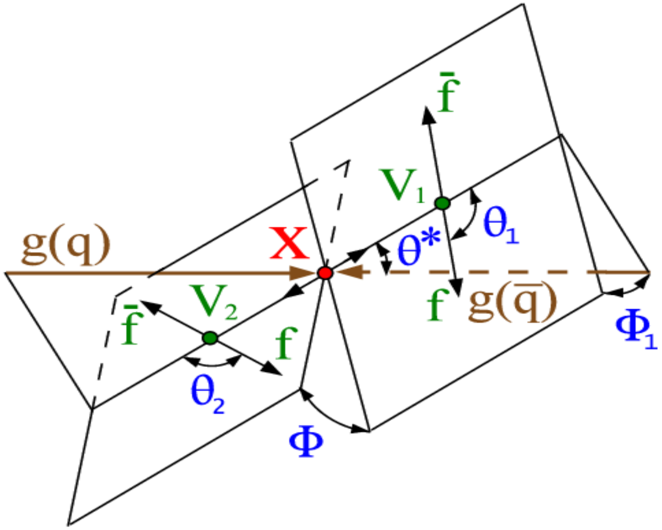


- But many more complicated models used to interpret our data...

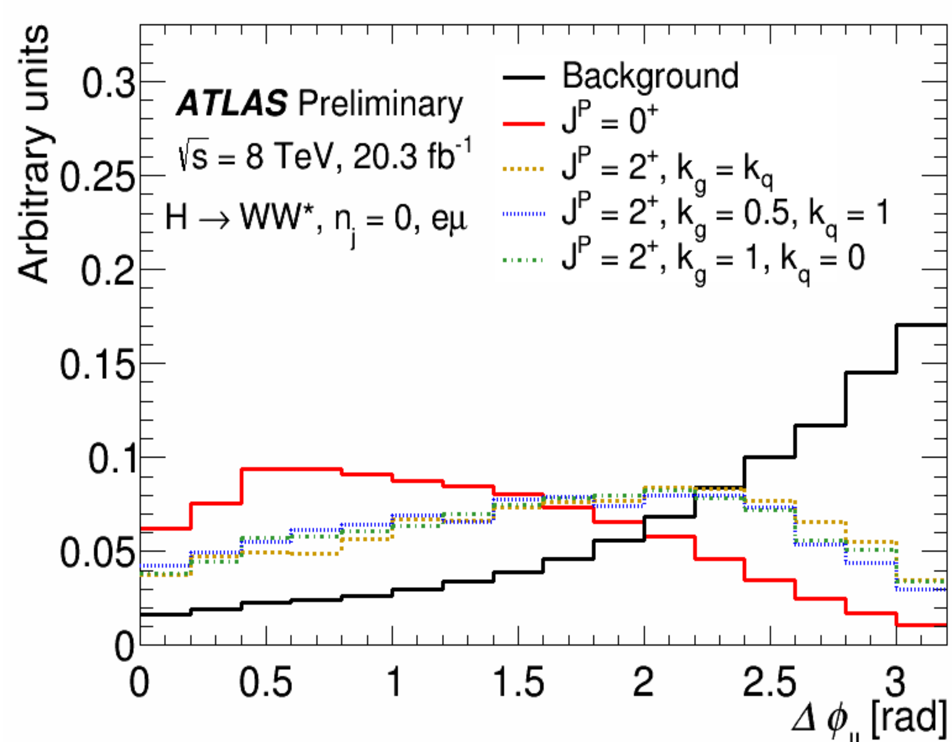
Properties measurements

- The discovered particle can be characterized by J^{PC}:
  J=spin, P=parity, C=charge conjugation
  - SM Higgs is scalar particle (0^+).
  - No CP-mixing/violation in spin-0 in SM but could be small in some BSM models



- Spin1: Observation of $H \rightarrow \gamma\gamma$
  → C=1 (no C violating effects in the Higgs sector)
  → Landau-Yang theorem forbids direct decay of on-shell spin-1 particles into pair of massless particles
- Spin2: graviton-like
  - This new particle would likely not be responsible for EW symmetry breaking
  - Would/could have discovered Kaluza-Klein excitations of SM gauge bosons?
- Shape of decay products can be used to discriminate spin 0/1/2

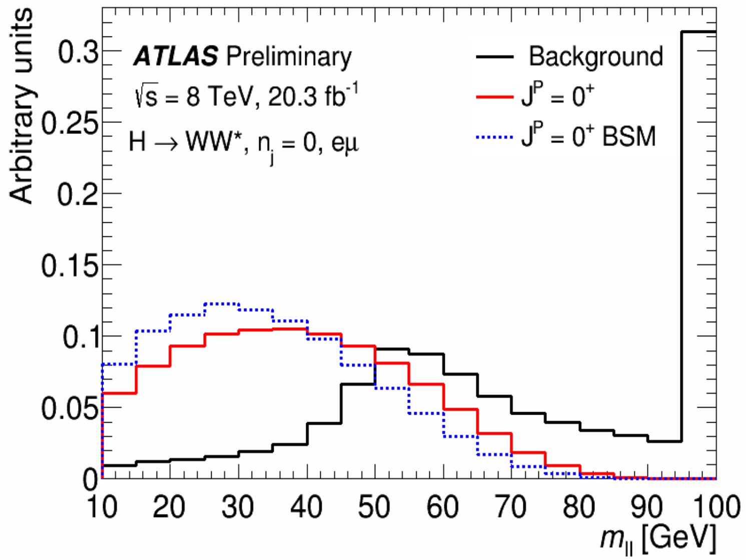
  → Evidence for spin 0 of the new "Higgs"

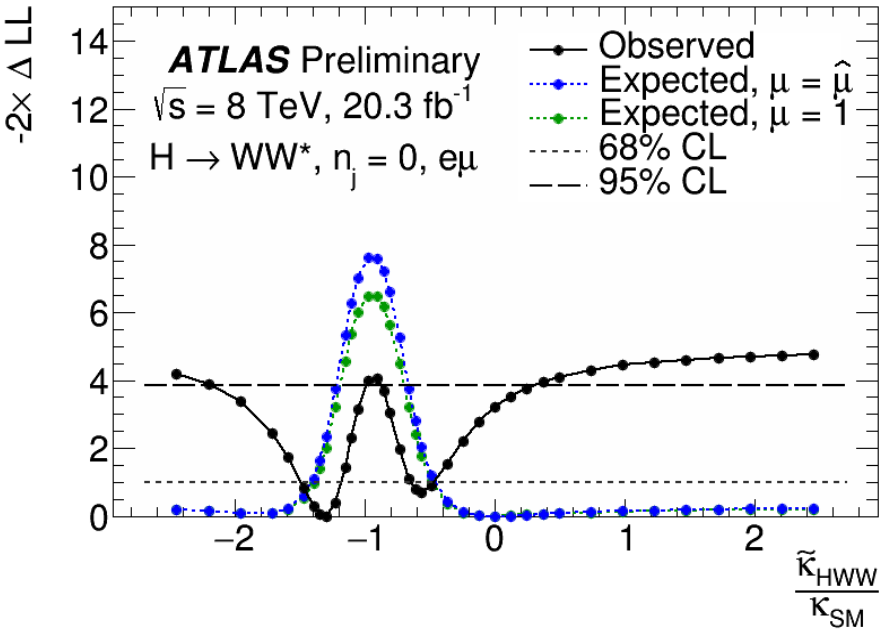


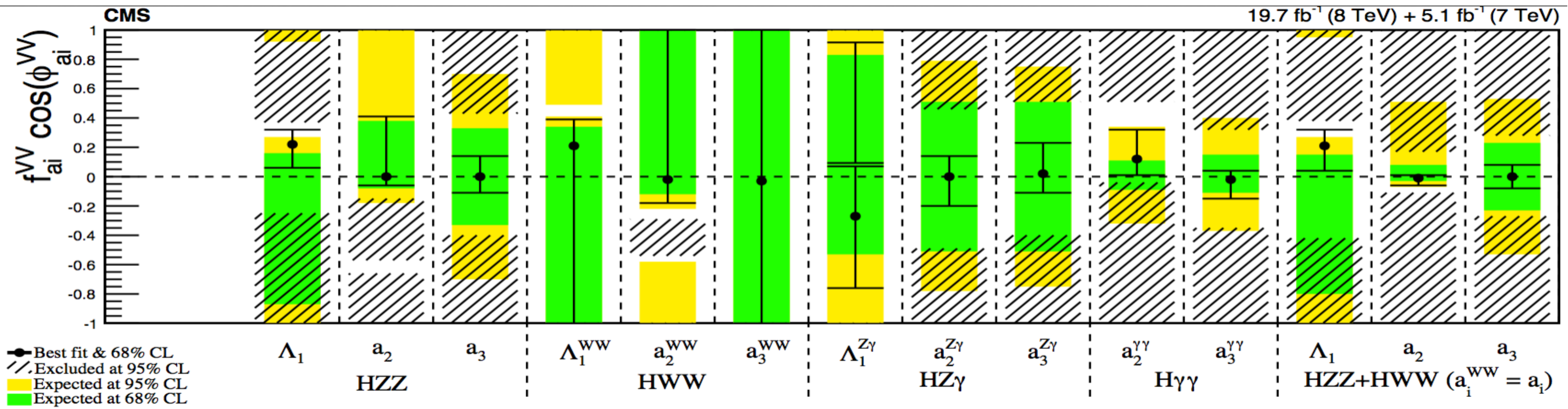
Properties measurements (2)

- Tensor structure of the H→VV couplings can be tested by adding new operators to the Lagrangian (à la anomalous coupling) :

$$\mathcal{L}_0^W = \Big\{ c_\alpha \kappa_{SM} \big[\tfrac{1}{2} g_{HWW} W^+_\mu W^{-\mu}\big] - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\big]\Big\} X_0$$







Differential measurements

- Higgs transverse momentum pT(H) is an important probe for new physics (additional particles in loops for instance)
- Can use the clean signatures to measure the Higgs production differentially (eventually the large rates for other channels will be used)

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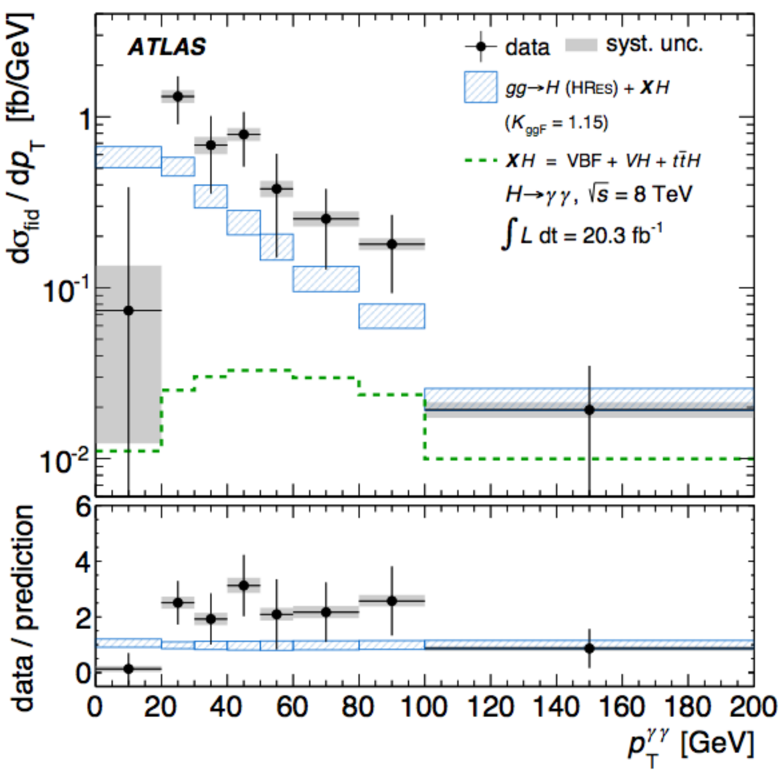

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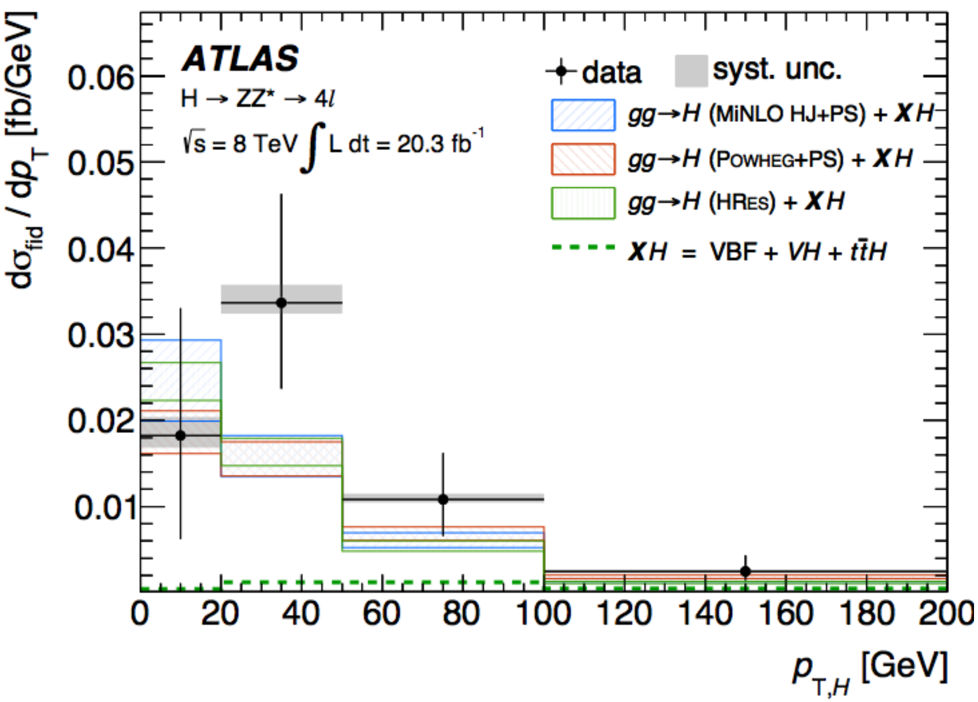
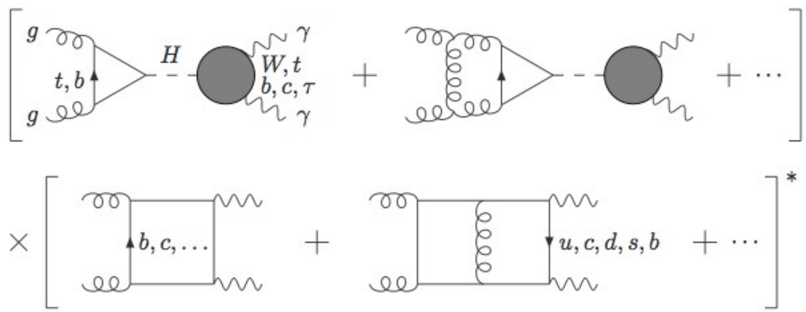
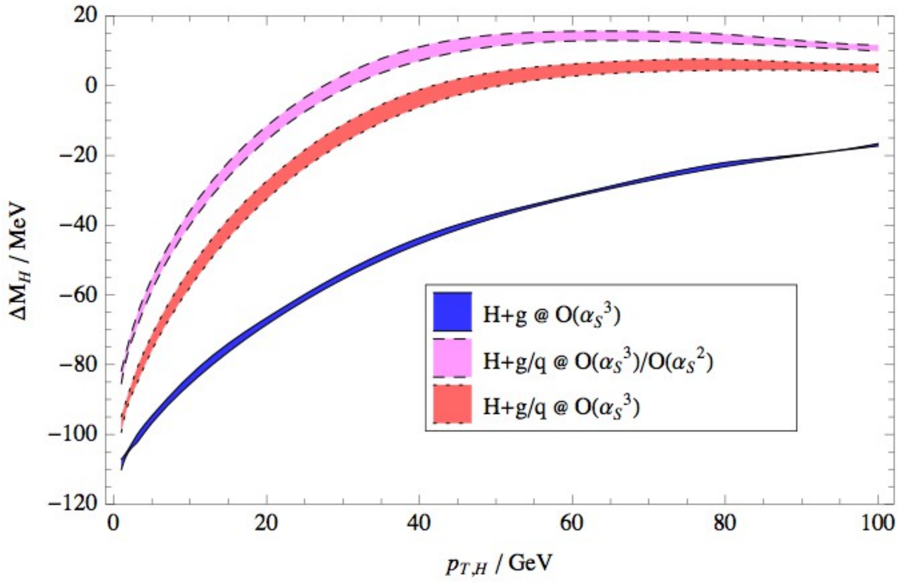


Higgs total width

- Challenging to measure it (~4 MeV) at hadronic colliders
  - Direct measurements in $\gamma\gamma$ and ZZ spectra indeed set limits at <~2 GeV
  - Limits on the branching ratio of H$\rightarrow$invisible decays of O(<50%), i.e. Γ_{SM}<~2Γ_{SM}
- But accessible also through interferometry in $\gamma\gamma$
  - Destructive interference between Higgs signal and gg$\rightarrow$VV continuum bkg
  - Mass-peak shifted with a dependence on pT(H)
  - Could reach Γ_{SM}<~ O(100) MeV

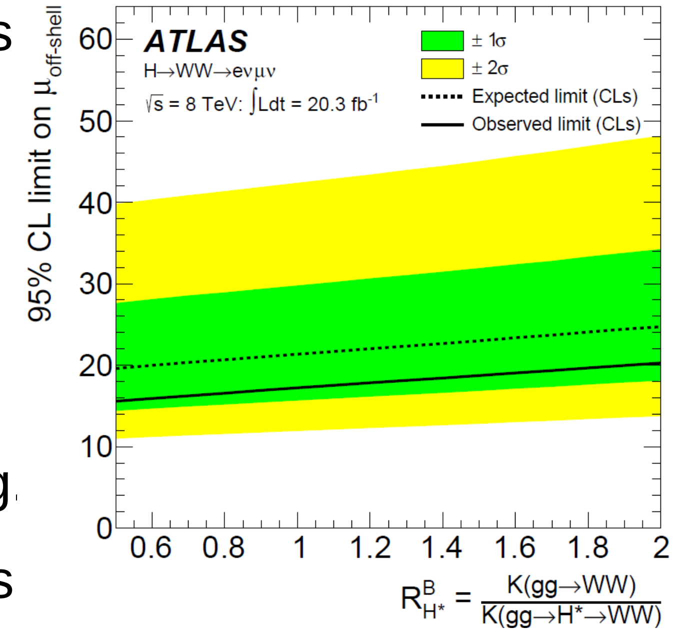


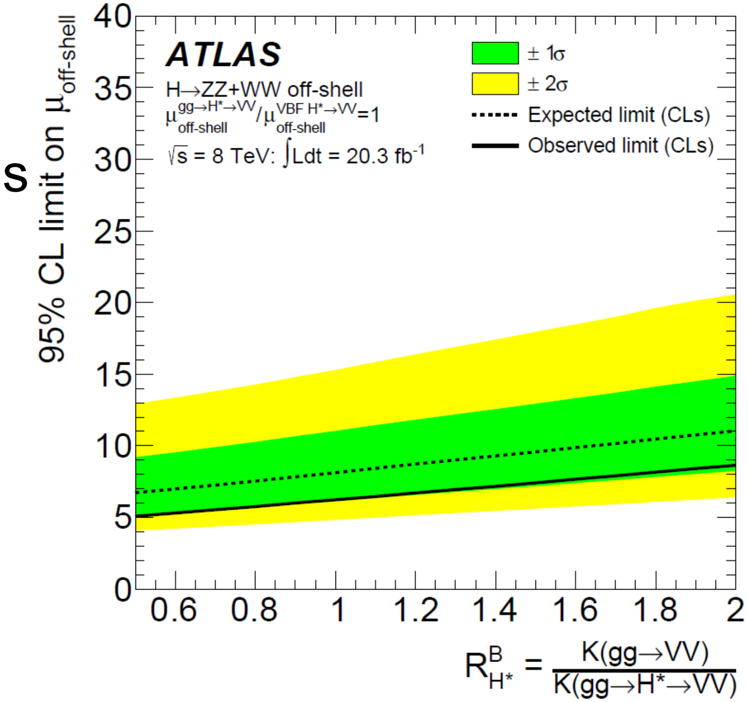


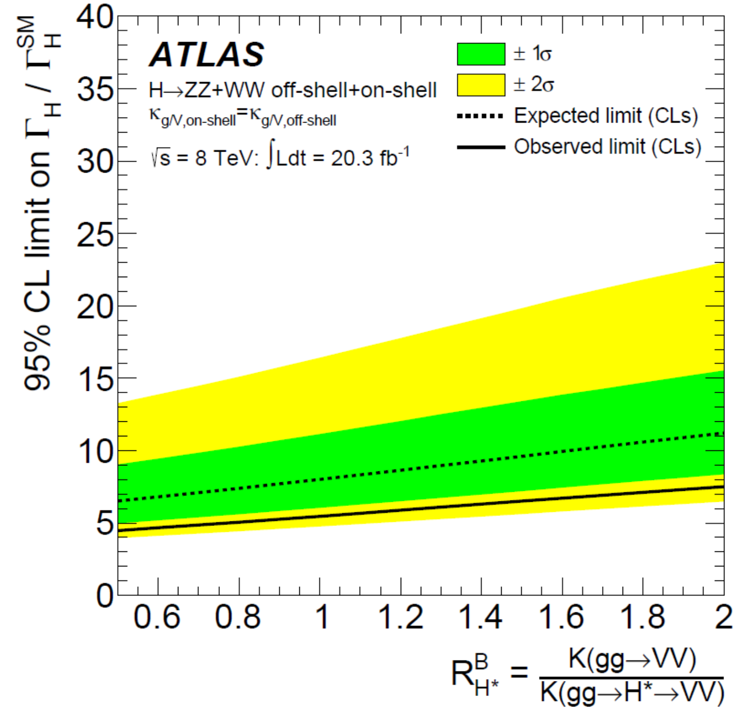
Higgs total width (2)

- Higgs off-shell analysis searches for large Higgs couplings for the off-shell Higgs at large virtualities (mass) m_{VV}
- Use high mass channels $H^* \rightarrow ZZ \rightarrow 4l$, $H^* \rightarrow ZZ \rightarrow 2l2n$ and $H^* \rightarrow WW \rightarrow l\nu l\nu$
- Unknown QCD effects
  → all analysis done inclusive in jets
  → depending on the unknown K-factor for the $gg \rightarrow VV$ bkg.
- Combination with on-shell analysis allows interpretation as measurement of Γ_H
- Assumes same on- & off-shell couplings
- $\Gamma_H < 22$ MeV

(95%CL limit on $\mu_{\text{off-shell}}$ between 5.1-8.6)

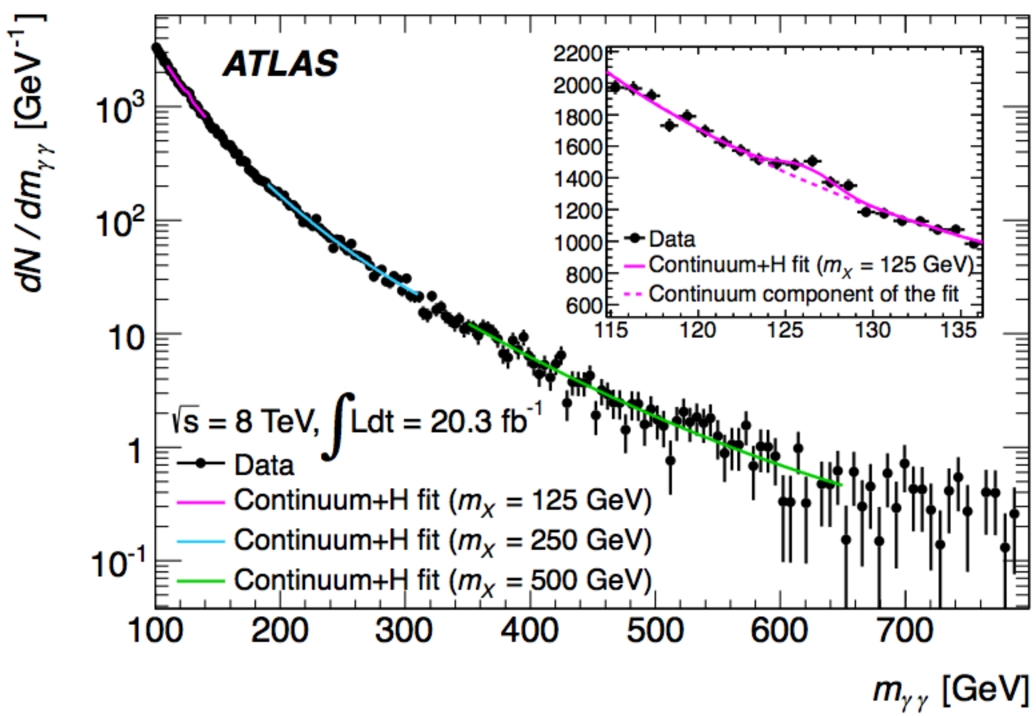


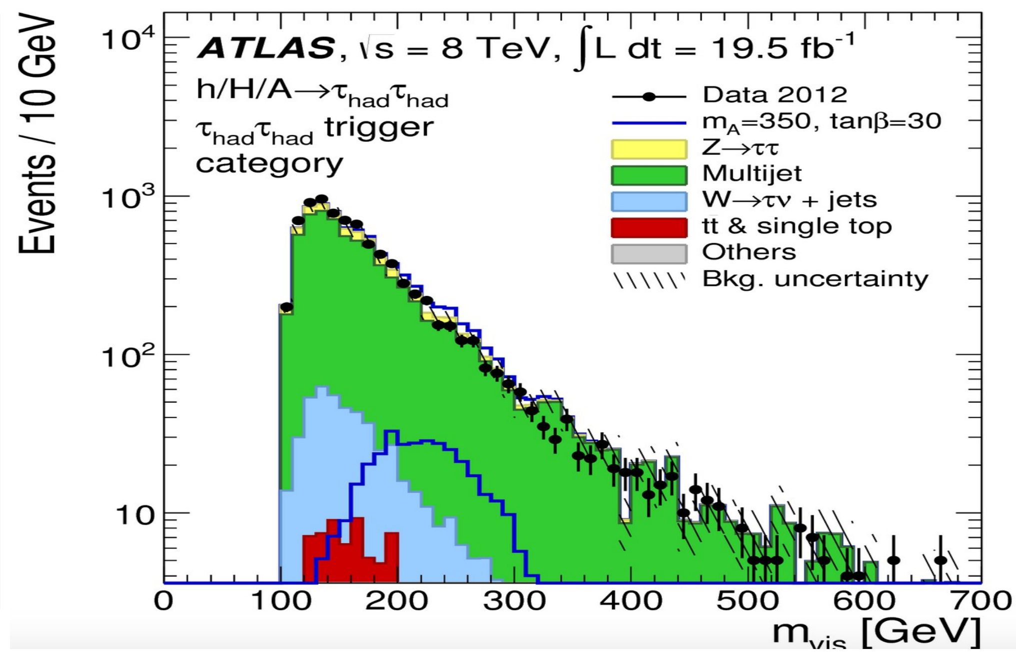




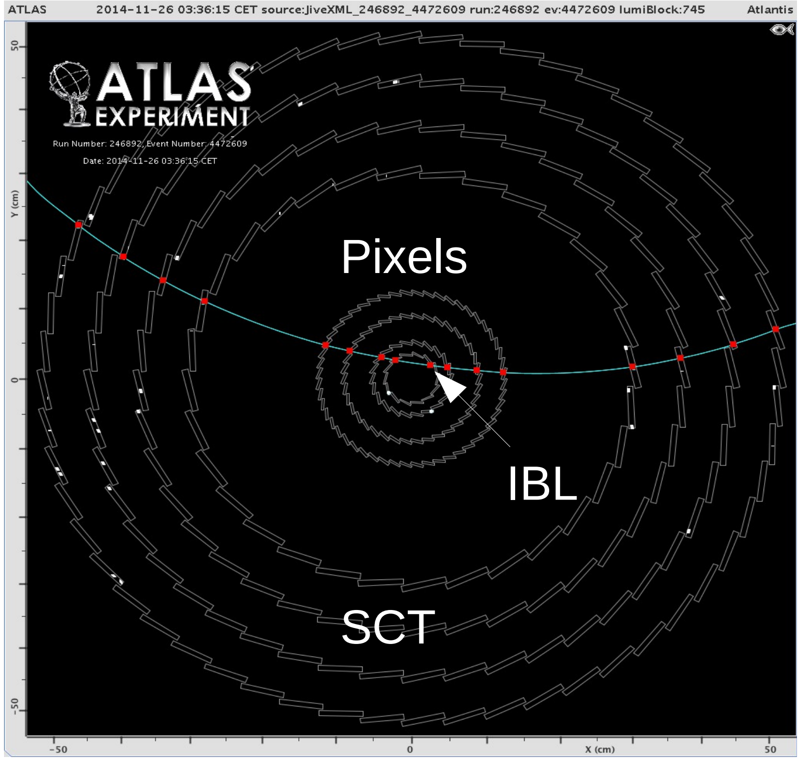
Additional « Higgs » searches

- Is the found "Higgs" part of an extended scalar sector ?
  - 2 Higgs Doublets (2HDM) with 5 (2 neutral CP-even, 1 neutral CP-odd and 2 charged) physical Higgs bosons after EW symmetry breaking for instance ?
    - 2 additional parameters to describe the MSSM 2HDM (mass of CP-odd A, ratio of vev) at tree level
  - Electroweak singlet (EWS) predicting one additional Higgs (both Higgs sharing the SM couplings)
- All previous signatures (+others) are reused to search for a new mass resonance





Towards Run-II



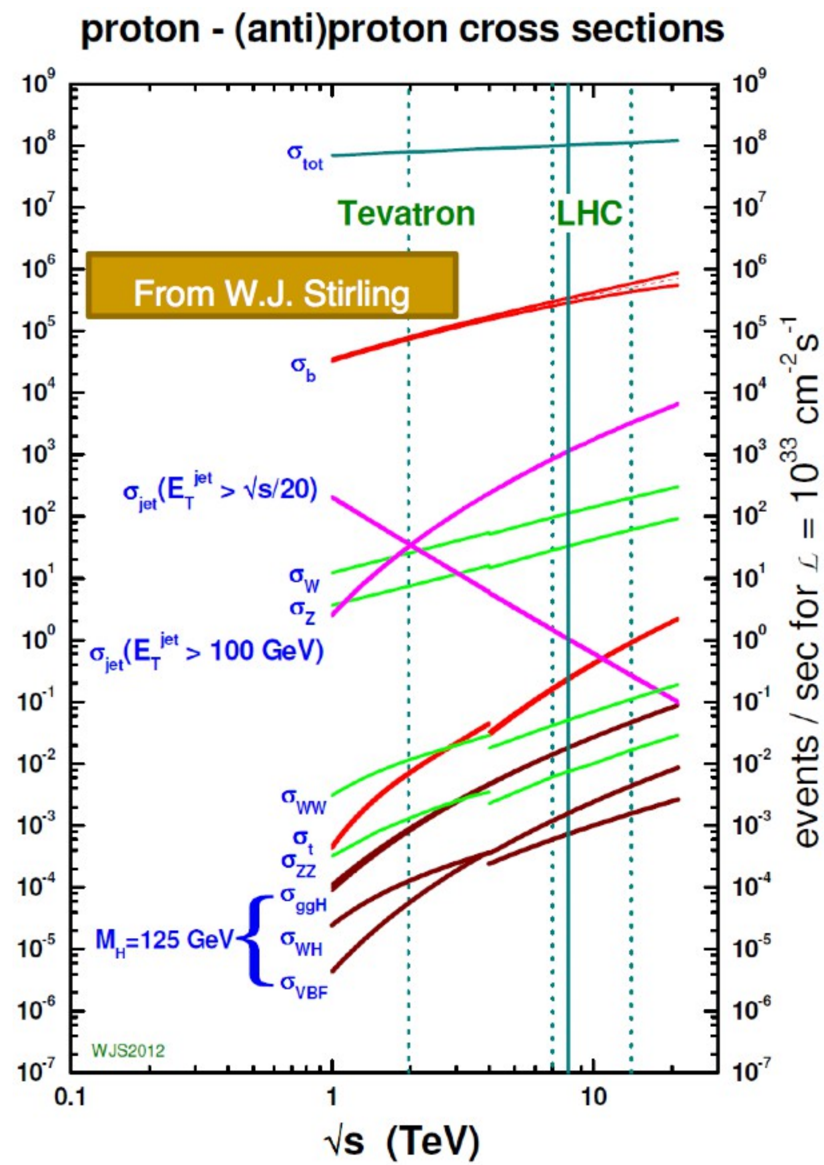
- First of all, need to rediscover our (ATLAS) detector and machine
  - 25 ns vs 50 ns bunch-spacing
    - Level of pile-up, calorimeter response
  - New precision tracking layer: IBL close to the interaction point

    → Multiple scattering reduced, better impact parameter resolution

    → Improves conversion reconstruction, rejection of jets faking electron/photon, pile-up jets recognition, b-jets tagging (3 times larger rejection at low pT),...
- Increase of √s → increase of backgrounds too
  - Are our Monte Carlo simulation tunings Ok ? Minimum bias measurements will tell us
  - Most of Higgs analyses have to be reoptimized to cope with different background composition

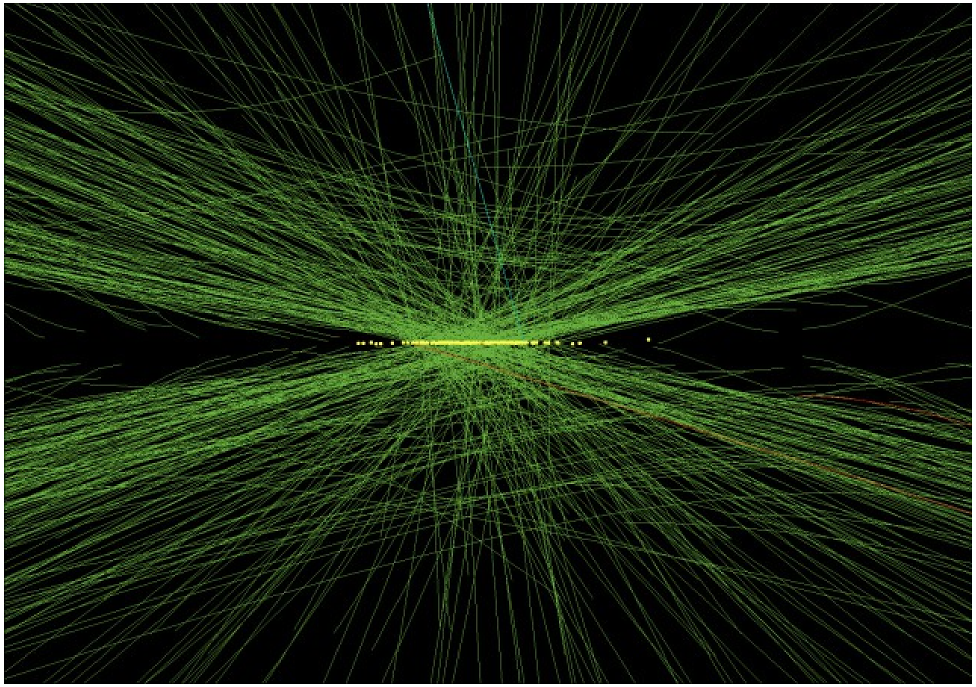
Run-II Higgs physics program

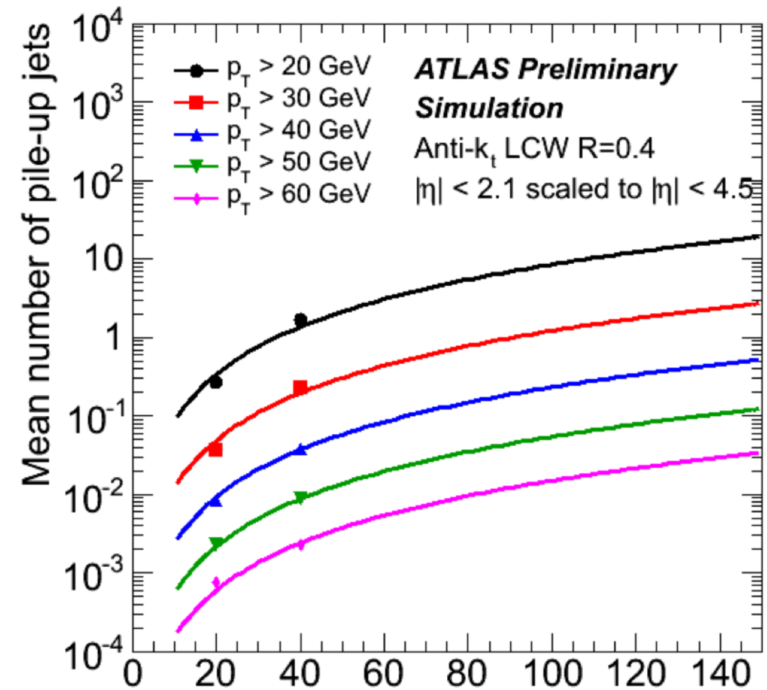
- Rediscover the Higgs, like we rediscovered the rest of the SM at 7/8 TeV
  - after a ~year ?
- Look for additional Higgs-like particles or partners at high masses
- First 13 TeV cross-section measurements
- Higgs property measurements
  - Integrating all previous properties measurements together
  - Adding many more operators to probe in the Lagrangian
  - Extension to the Higgs Effective Field Theory
    - Major change of paradigm
      → Analyses not designed only for signal but also for pseudo-observables
      → Our understanding of backgrounds will change too
      → Including LEP data ?

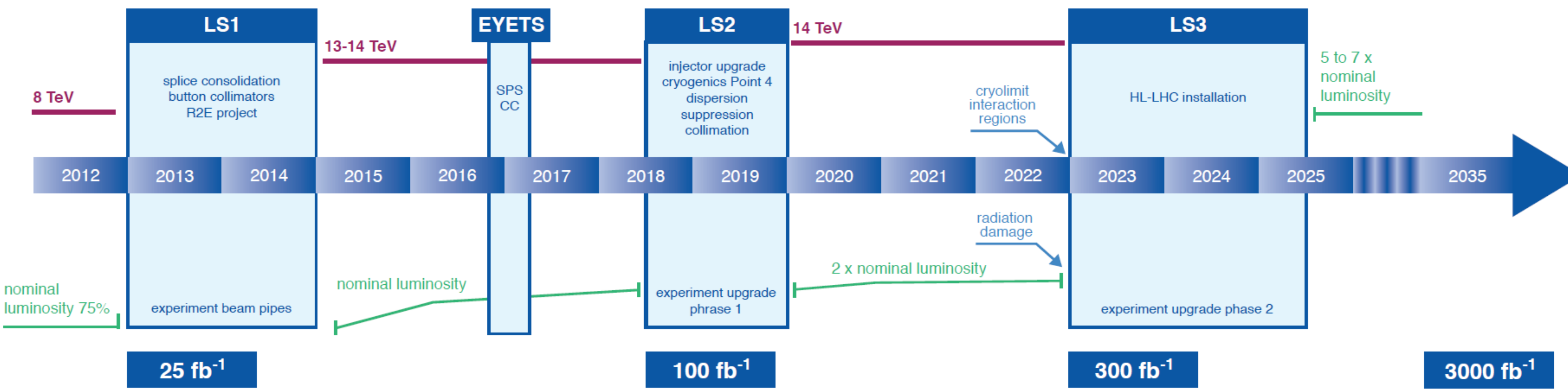


Prospects for long-term measurements

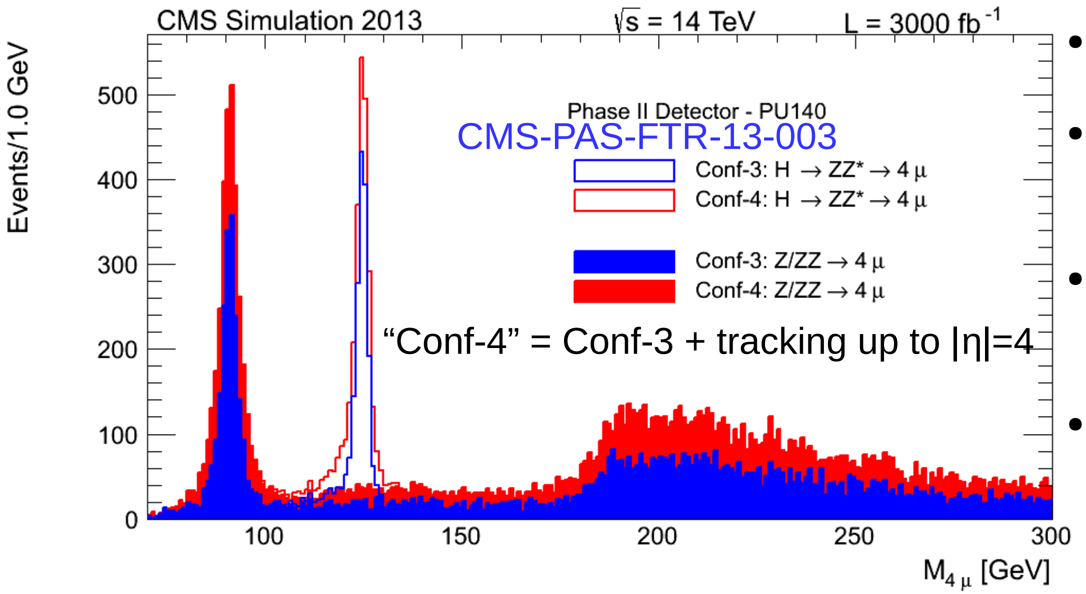
- LHC (and its detectors) will eventually upgrade for higher number of interactions per bunch-crossing μ → degraded experimental environmental at HL-LHC



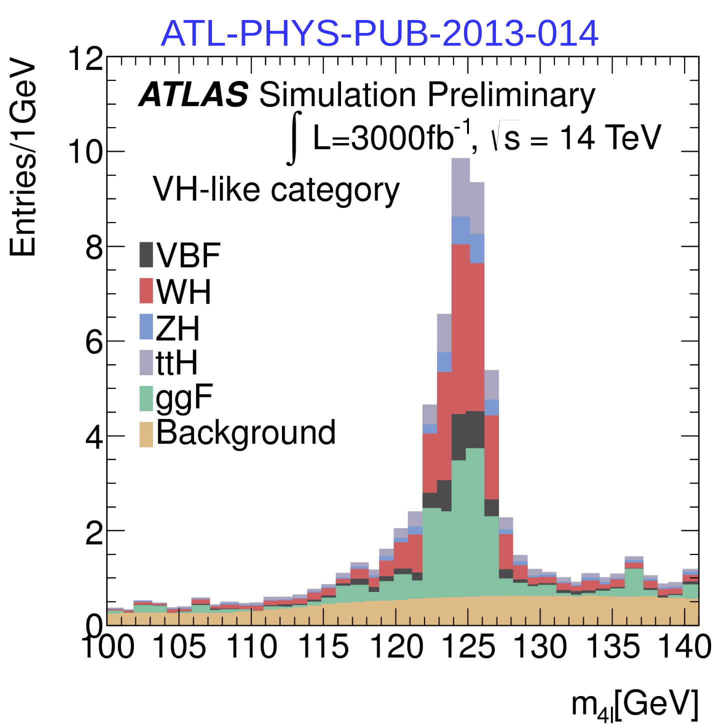




H → ZZ : A peak, a cape, it's a peninsula !



- ZZ final states remain very clear channels
- The statistics allow to probe many production modes
- Total H production cross-section uncertainty can be constrained by ZZ events at O(few %)
- CMS showed that these channels could also benefit from a tracking system extended in rapidity (increase of acceptance)



$\mu=\sigma/\sigma_{SM}$

$\Delta\mu/\mu$ ATLAS	Total	Stat.	Expt. syst.	Theory
Production mode	300 fb^{-1}			
ggF	0.152	0.066	0.053	0.124
VBF	0.625	0.545	0.233	0.226
WH	1.074	1.064	0.061	0.085
$t\bar{t}$H	0.535	0.516	0.038	0.120
Combined	0.125	0.042	0.044	0.108
	3000 fb^{-1}			
ggF	0.131	0.025	0.040	0.124
VBF	0.371	0.187	0.225	0.226
WH	0.390	0.375	0.061	0.085
ZH	0.532	0.526	0.038	0.073
$t\bar{t}$H	0.224	0.184	0.034	0.120
Combined	0.100	0.016	0.036	0.093

Diphoton channels

- Similarly, significance in $\gamma\gamma$ decay channels grows up with clear peaks on top of smooth background shapes

ATLAS	$t\bar{t}H$	WH	ZH	VBF
Significance	8.2	4.2	3.7	3.8

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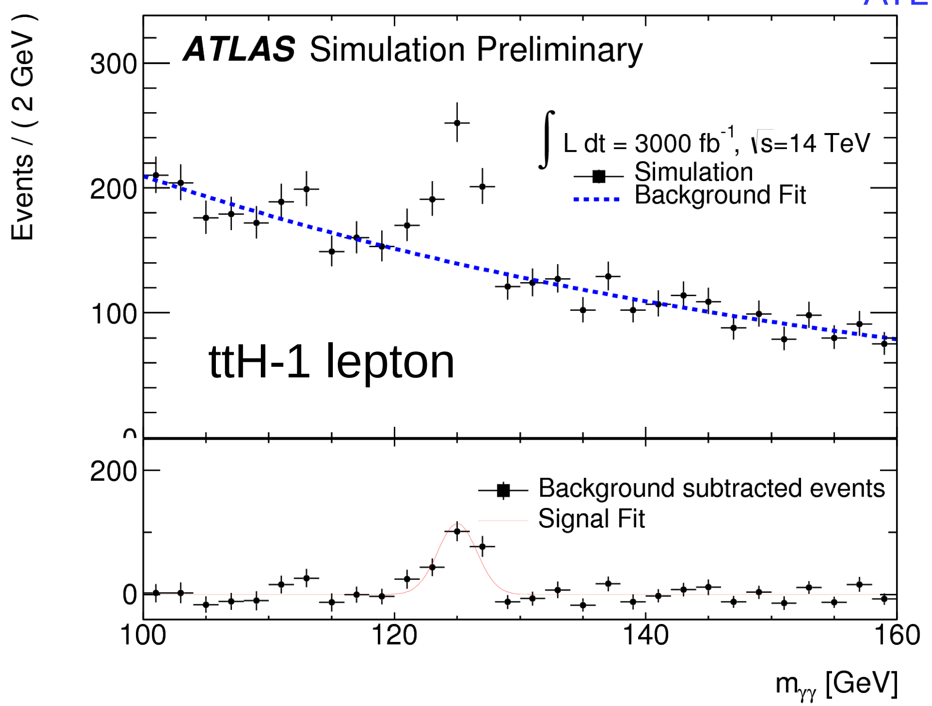
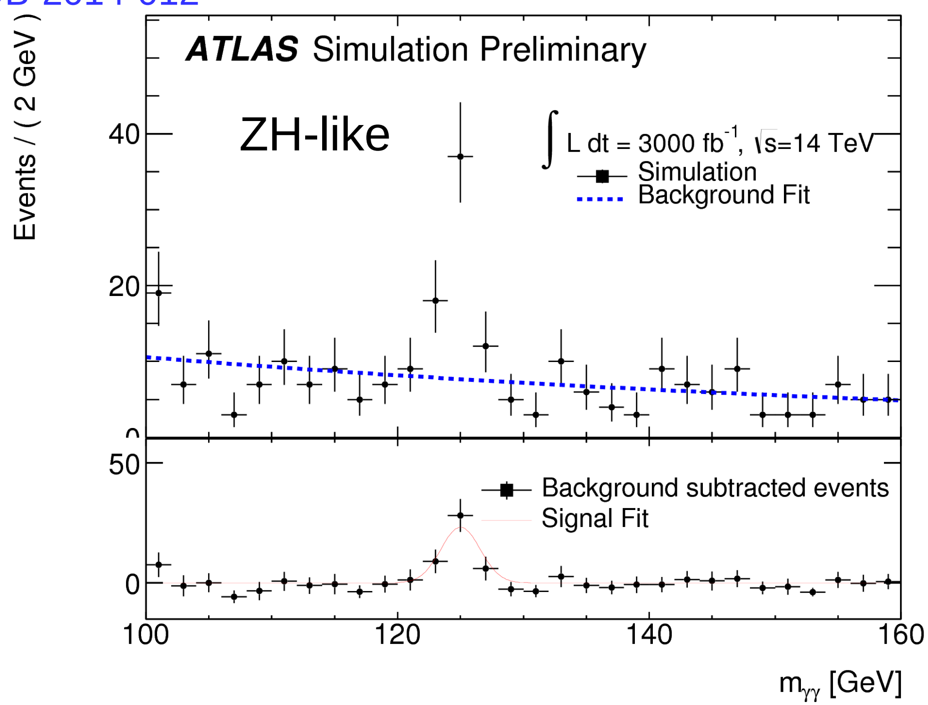


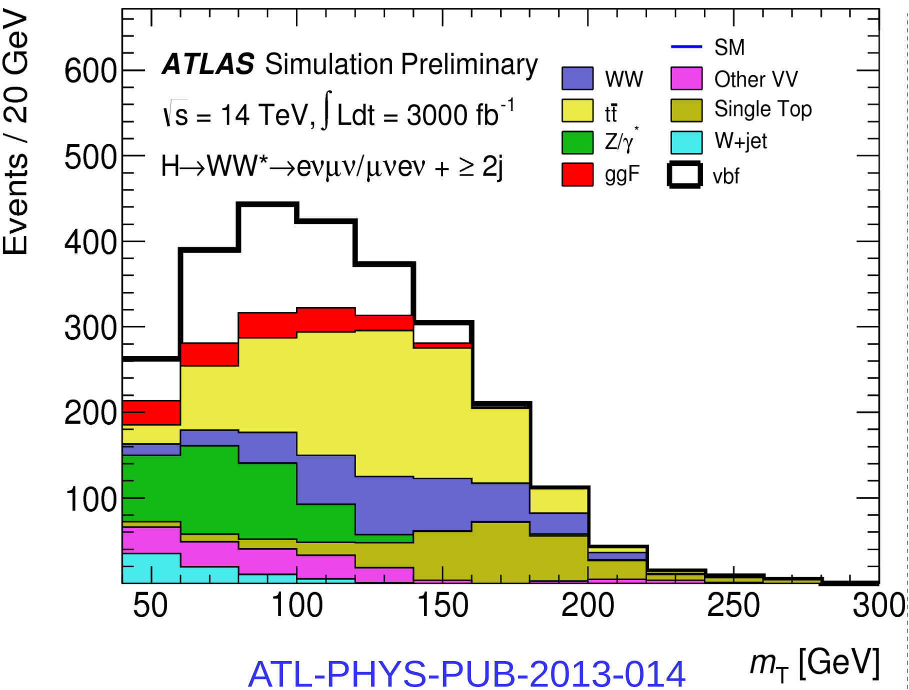


- Diphoton channels is powerful for H-t Yukawa coupling measurements
- Measurements limited by current signal uncertainties
- Reaching the ~3.5% level of precision on the combined signal strength (without th. uncertainties)

	$\Delta\hat{\mu}/\hat{\mu}$ (%)			
Production mode	Total	Statistical	Experimental	Theoretical
$t\bar{t}H$	$^{+21}_{-17}$	$^{+13}_{-12}$	$^{+5}_{-4}$	$^{+17}_{-11}$
WH	$^{+26}_{-25}$	$^{+21}_{-20}$	$^{+13}_{-12}$	$^{+10}_{-8}$
ZH	$^{+35}_{-31}$	$^{+32}_{-29}$	$^{+7}_{-7}$	$^{+12}_{-8}$
ggF	$^{+19}_{-14}$	$^{+3}_{-3}$	$^{+1}_{-1}$	$^{+19}_{-14}$
VBF	$^{+29}_{-29}$	$^{+18}_{-18}$	$^{+1}_{-1}$	$^{+23}_{-23}$

WW, $b\bar{b}$ and ττ

- Going from 8 to 14 TeV, $t\bar{t}$ increases ~1.7x faster than the signal ; jet counting affected by pile-up conditions → in general, current categories have a largely degraded S/B → HL-LHC studies require dedicated optimizations



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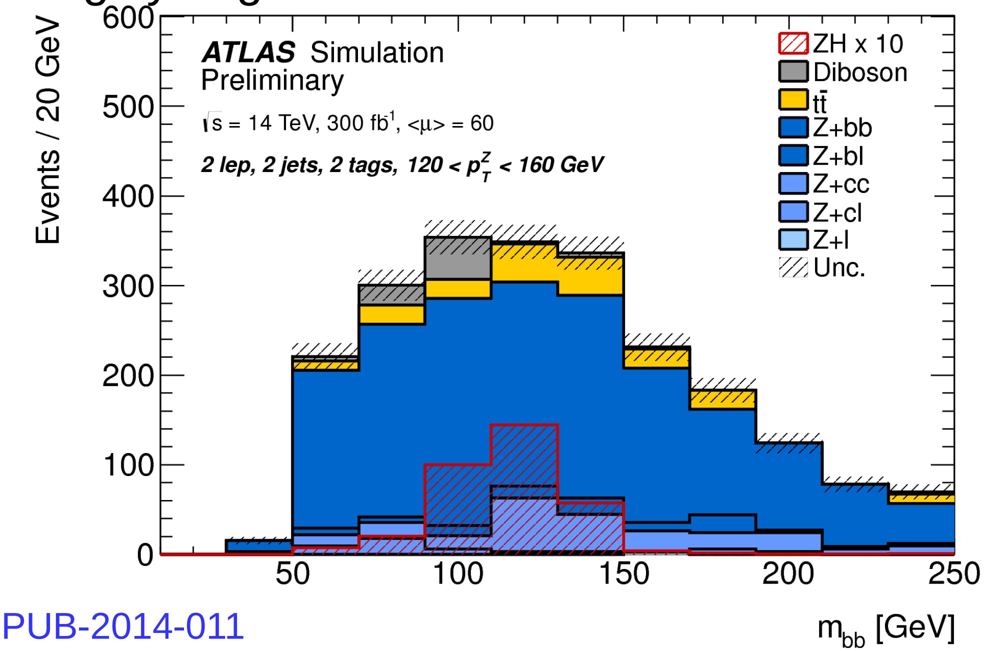
	μ_{ggF}	μ_{VBF}	$\mu_{ggF+VBF}$
300 fb^{-1}	$1^{+0.18}_{-0.15}$	$1^{+0.25}_{-0.22}$	$1^{+0.14}_{-0.13}$
3000 fb^{-1}	$1^{+0.16}_{-0.14}$	$1^{+0.15}_{-0.15}$	$1^{+0.10}_{-0.09}$



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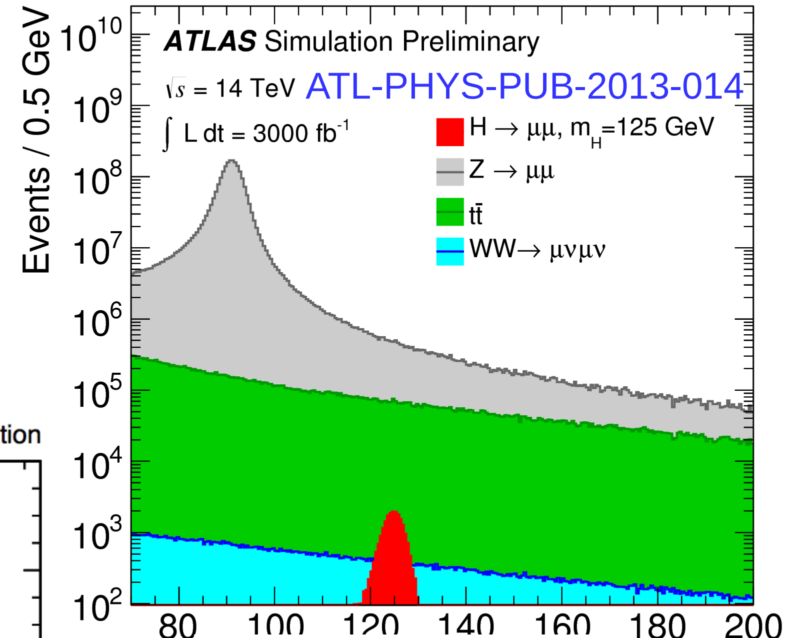
		One-lepton	Two-lepton	One+Two-lepton
Stat-only	Significance	15.4	11.3	19.1
	$\hat{\mu}_{Stats}$ error	+0.07 −0.06	+0.09 −0.09	+0.05 −0.05
Theory-only	$\hat{\mu}_{Theory}$ error	+0.09 −0.07	+0.07 −0.08	+0.07 −007
Scenario I	Significance	2.7	8.4	8.8
	$\hat{\mu}_{w/Theory}$ error	+0.37 −0.36	+0.15 −0.15	+0.14 −0.14
	$\hat{\mu}_{wo/Theory}$ error	+0.36 −0.36	+0.14 −0.12	+0.12 −0.12
Scenario II	Significance	4.7	-	9.6
	$\hat{\mu}_{w/Theory}$ error	+0.23 −0.22	-	+0.13 −0.13
	$\hat{\mu}_{wo/Theory}$ error	+0.21 −0.21	-	+0.11 −0.11

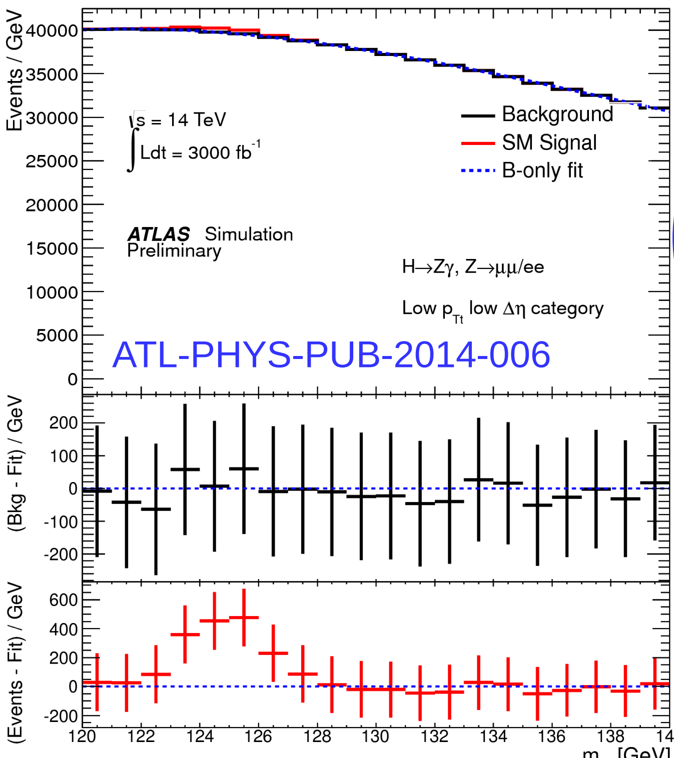
- Large stat → diff measurements, EFT ?
- ττ expectations on the signal strength precision are 8(5)% with current (/2) theory uncertainties

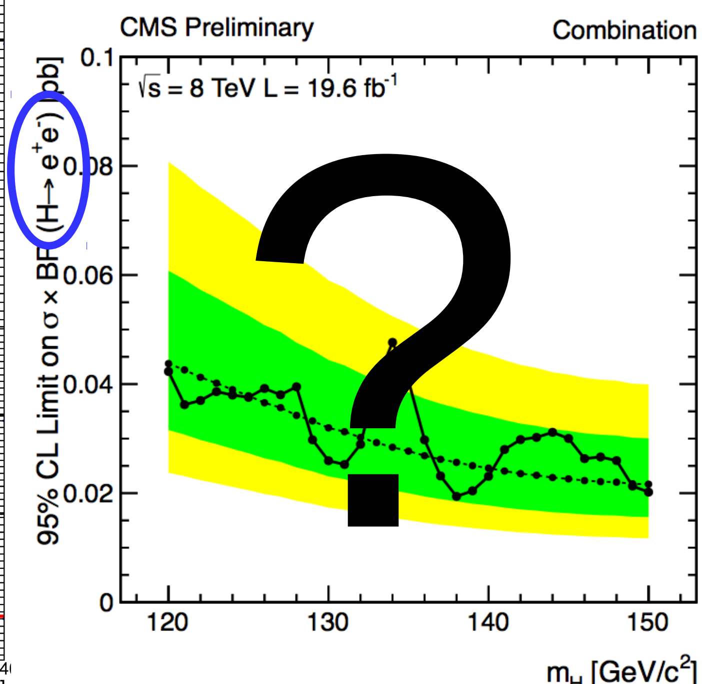
Rare channels

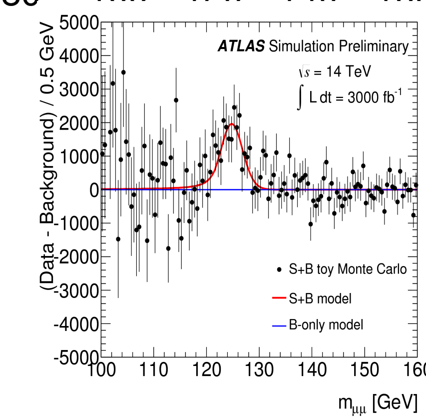
- Rare decays are the ones benefitting the most from the large HL-LHC dataset
- $Z\gamma$ sensitive to potential new particles in loop
  - ~20-30% precision on signal strength (~4σ) expected by CMS/ATLAS

    (Currently limits are at ~10x the SM prediction)
- μμ sensitive to the 2[nd] generation couplings
  - 7-8σ and Δμ/μ~20% expected, ttH(μμ) observable
- H→e+e-, H→cc decays and bbH productions observable ?

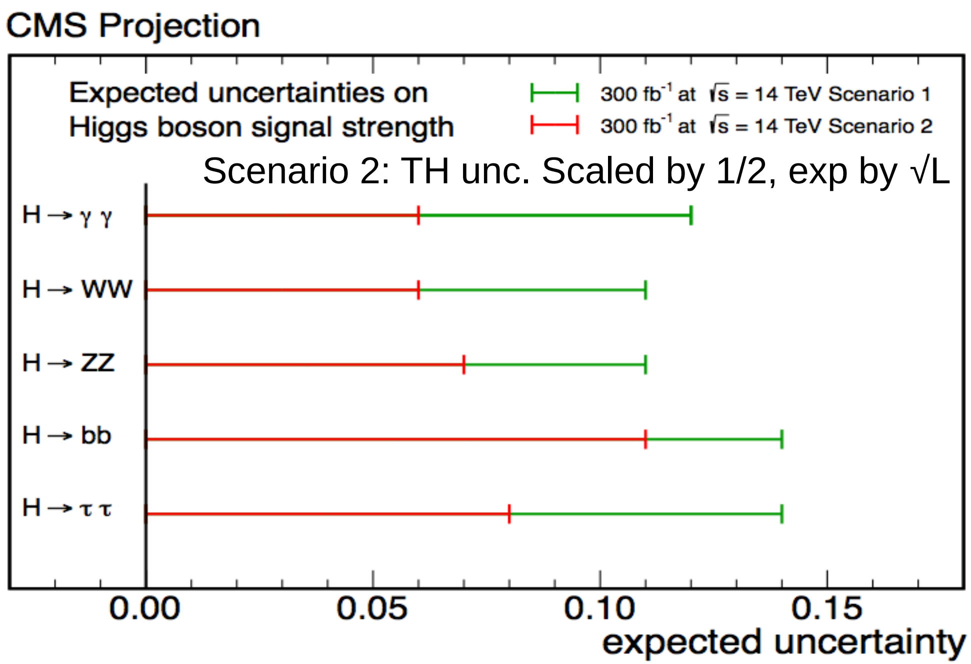


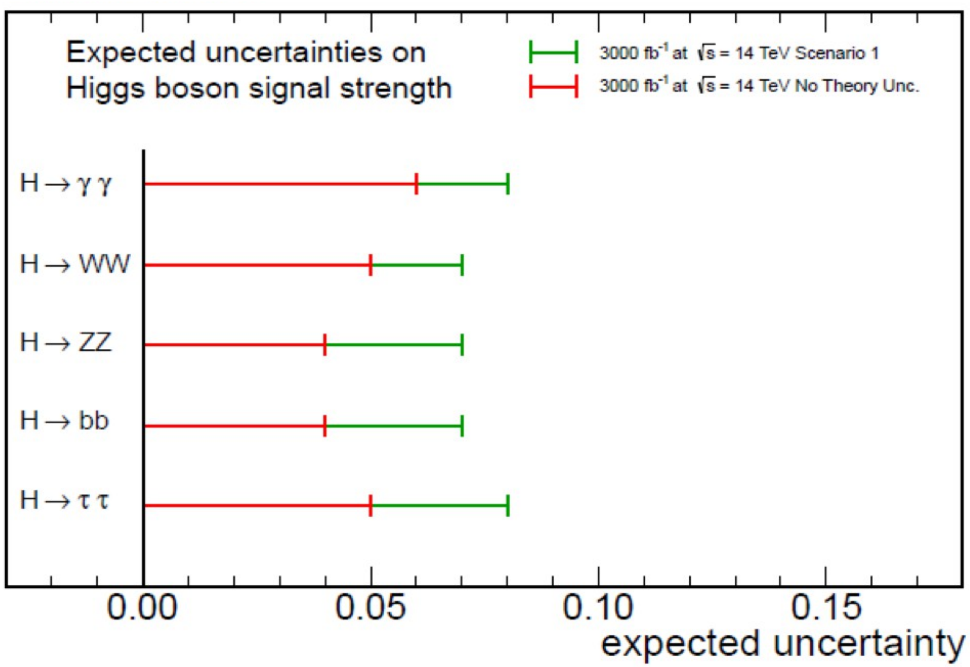


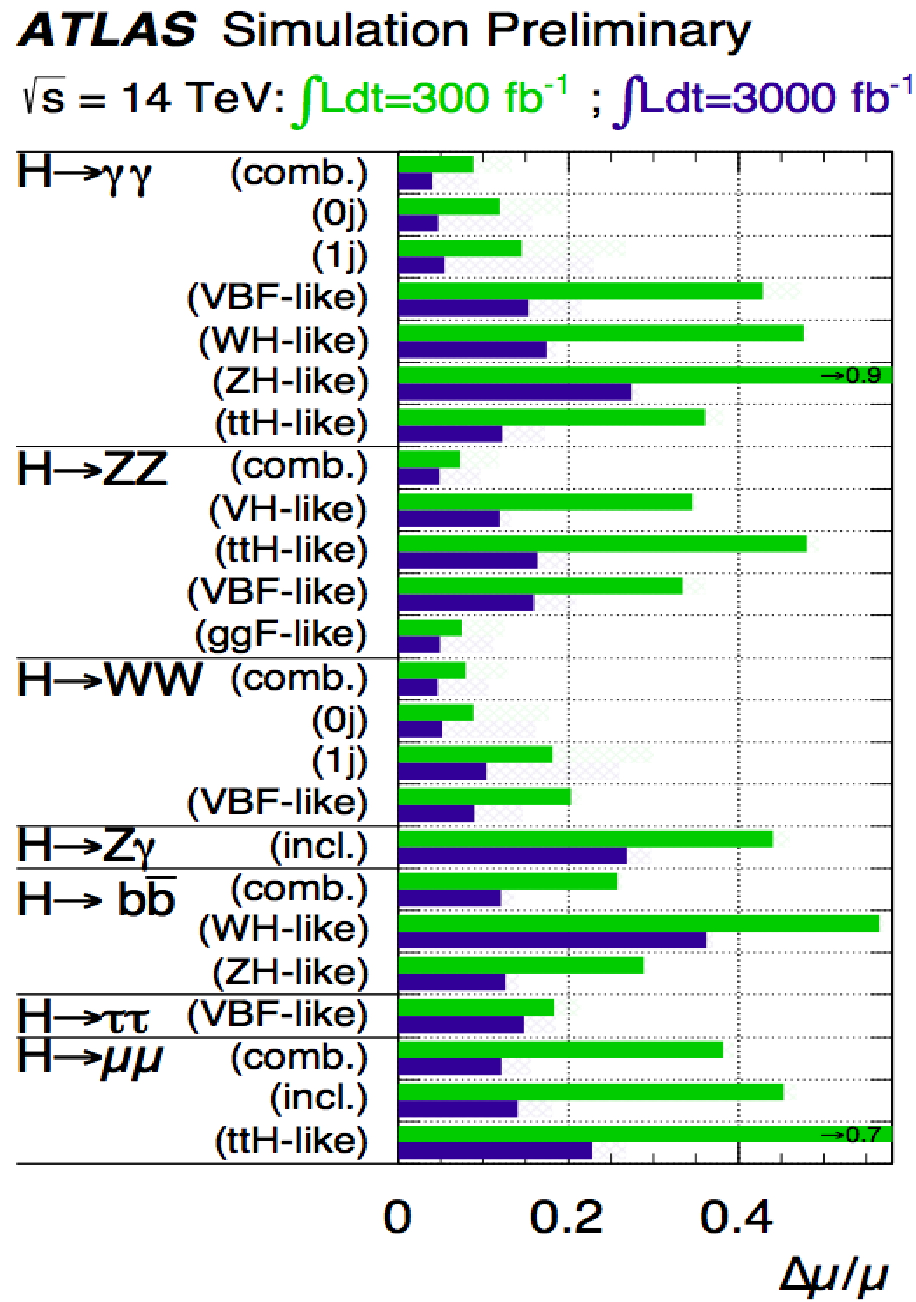




Channels summary





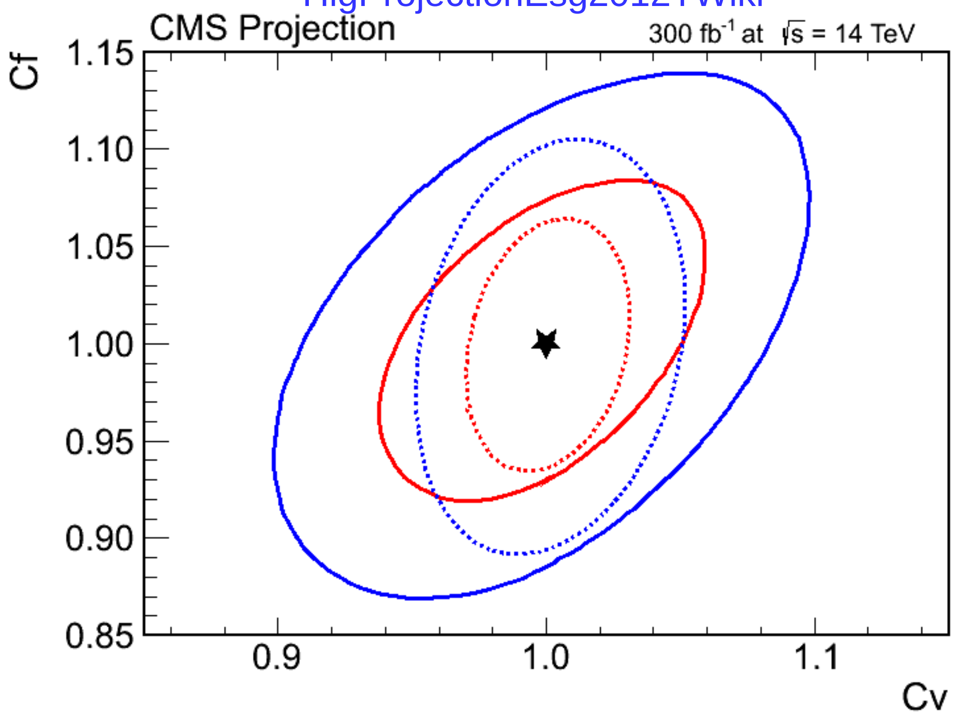


Dashed band = adding current theo. unc.

Combination

- Inputs from ATLAS and CMS concerning the individual channels are very similar although techniques to obtain those prospects are quite different
- As for run-I data, those channels prospects can be combined to obtain precision on couplings measurements
- One very simple model consists in fitting scale factors for fermions on one hand and bosons on the other hand:

HigProjectionEsg2012TWiki



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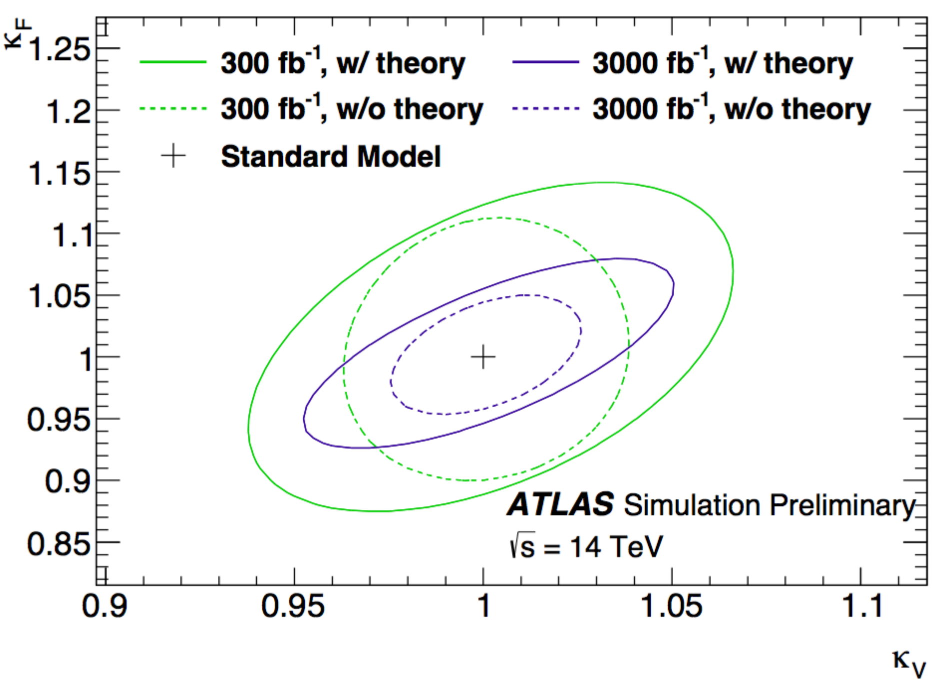
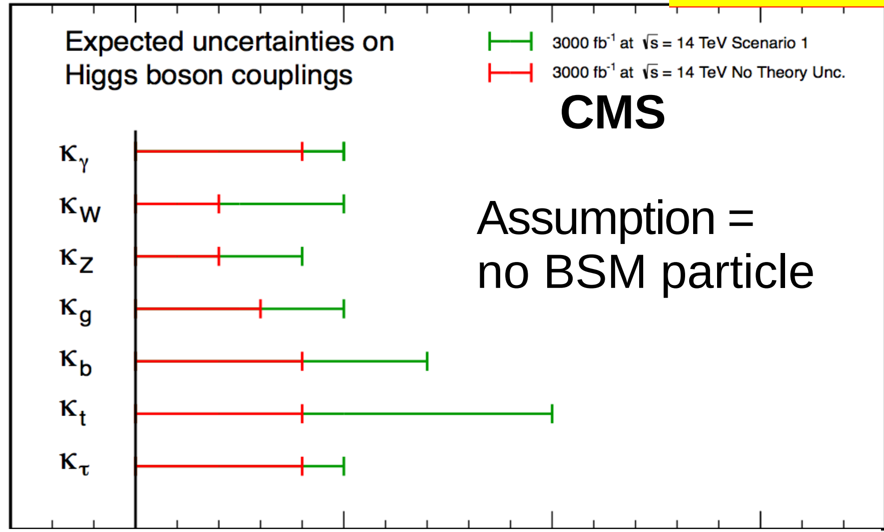


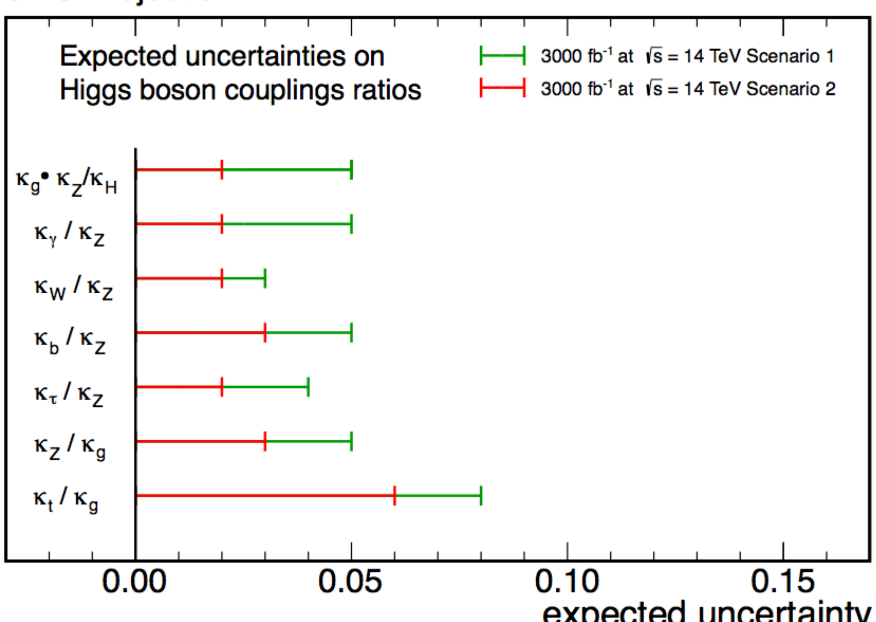
- Comparable to today's Run-I plot shown earlier

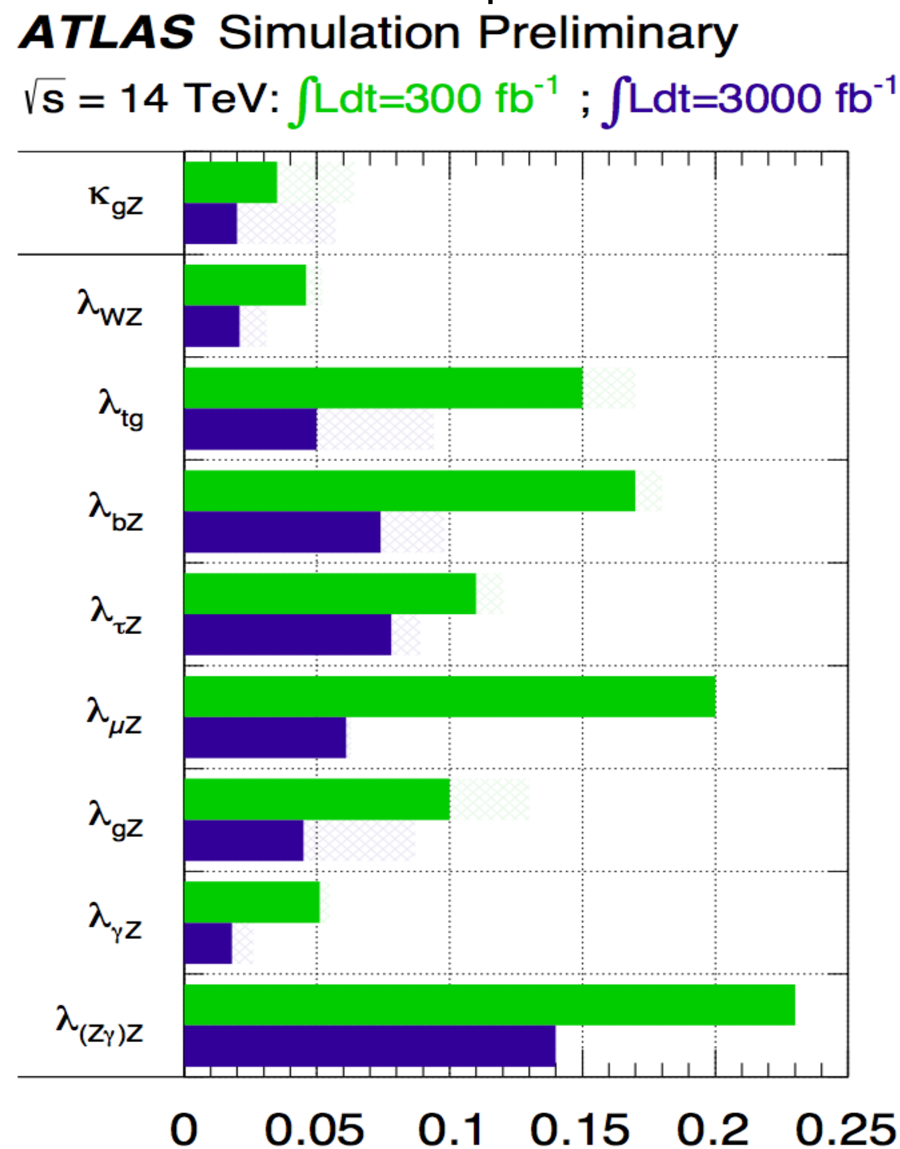
Couplings fit

- κ-framework to scale couplings or their ratios to get rid of total width assumptions
  Which precision do we need to go? $5\% \times \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$



CMS Projection





ATLAS combined results do not include yet the new information for Zγ, VH(γγ), ttH(γγ) and VH(bb)

$$\Delta\lambda_{XY} = \Delta\left(\frac{\kappa_X}{\kappa_Y}\right)$$

- In the future, use of EFT for more general model fits

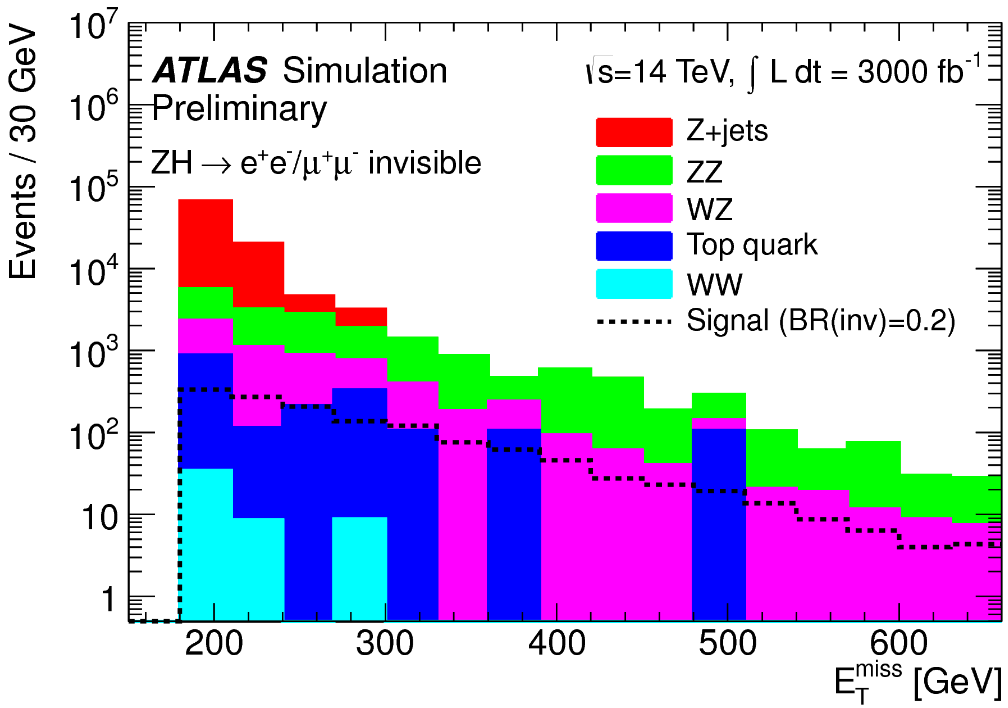
Missing partial decay width ?

- Using Z-tagging, direct search for invisible branching fraction in ZH events can be carried out

BR($H \rightarrow$inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)

ATLAS

- Through the coupling fit, CMS expects to constrain the BR(inv) to better than 11%
- Limits on the invisible branching fraction can be interpreted as bounds on the strength of the interaction between the dark matter (WIMP) and the Higgs boson



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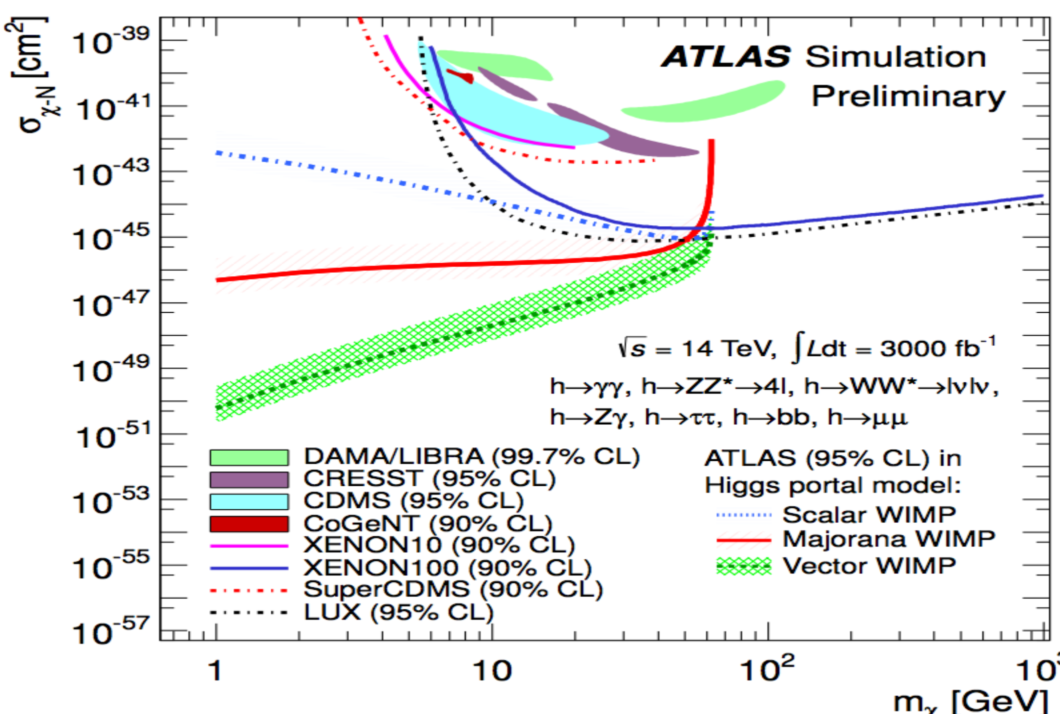
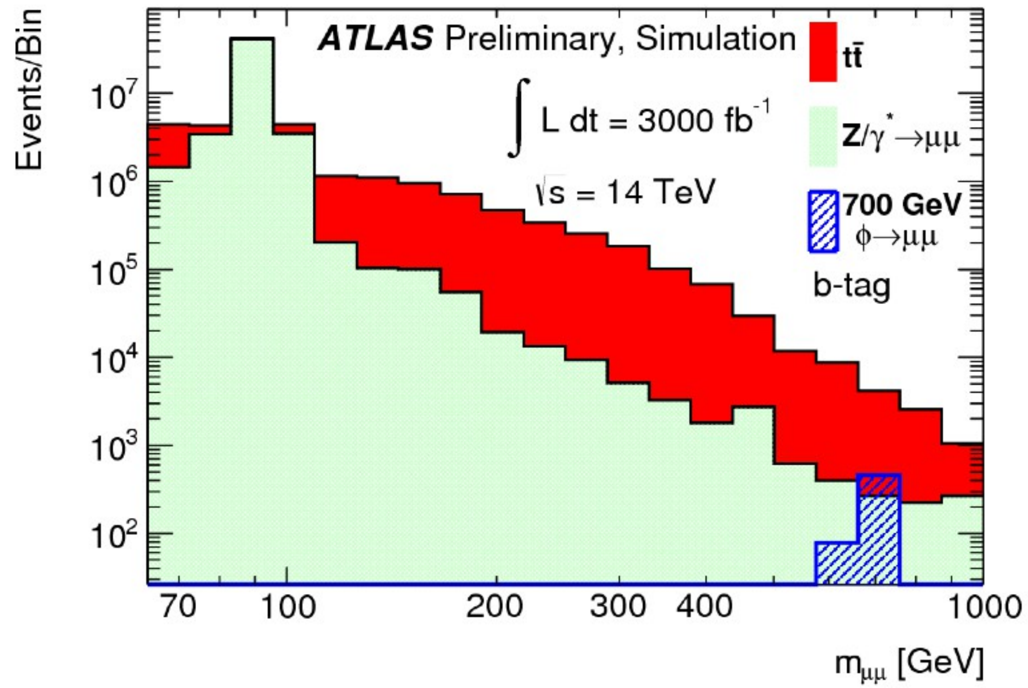
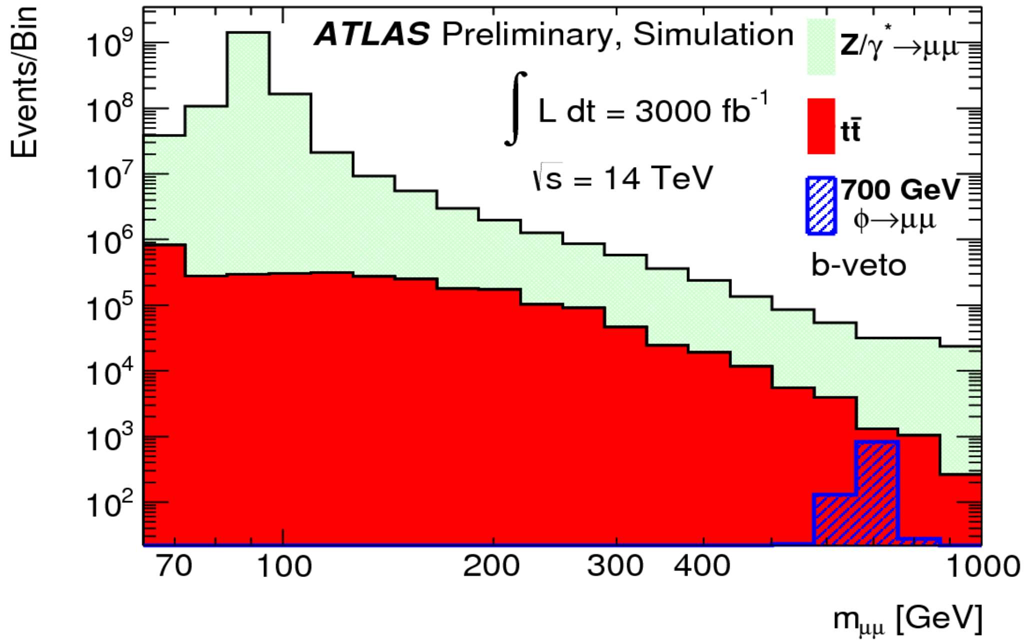


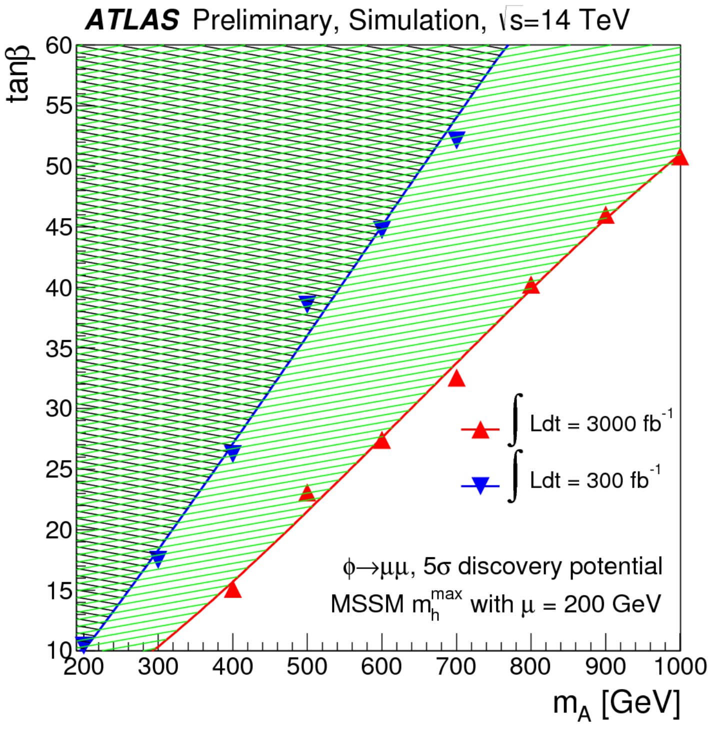
arXiv:hep-ph0605188 arXiv:1109.4398
arXiv:1112.3299 arXiv:1203.2064

MSSM μμ limits



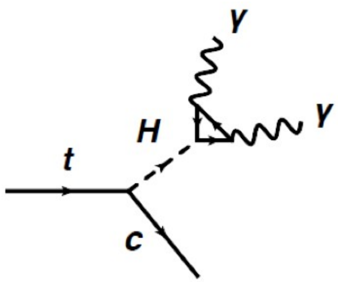


- high tan β region complementary to A → Zh for MSSM constraints
- High mass resolution at high dimuon mass
- Search for two production modes
  - gluon fusion
  - b associated production



FCNC top to Higgs

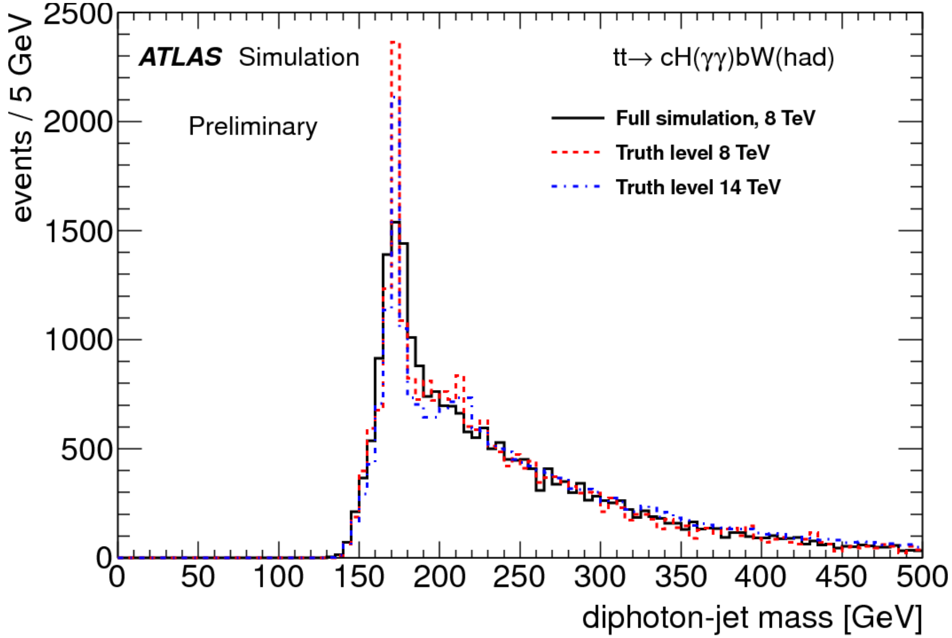
- FCNC processes are forbidden at tree level in the SM
- t→cH observation in ttbar events would certainly be a sign of new physics

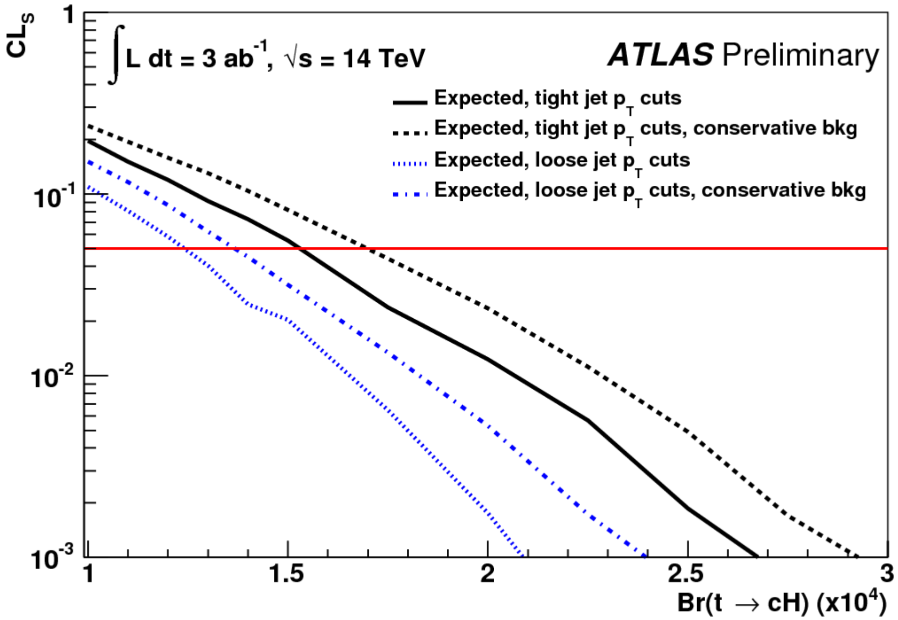


Typical BRs of EW FCNC-top decays:

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

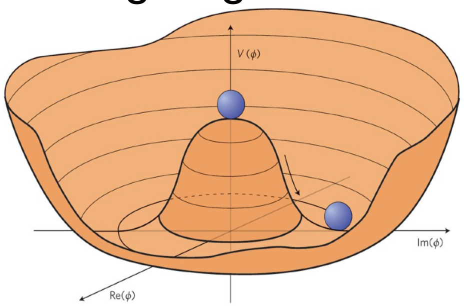
- Event selection relies on diphoton Higgs decay for its clear signature





Self-coupling & di-Higgs production

- The Higgs mechanism and the shape of its potential rely on the self-coupling term of the Lagrangian



$$V(|\phi|^2) = \mu^2|\phi|^2 + \lambda|\phi|^4 \longrightarrow$$

$$V(H^0) = 2\lambda v^2\frac{(H^0)^2}{2} + 6\lambda v\frac{(H^0)^3}{3!} + 6\lambda\frac{(H^0)^4}{4!} - \frac{v^4\lambda}{4}$$
$$\equiv m_H^2\frac{(H^0)^2}{2} + \lambda_{3H}\frac{(H^0)^3}{3!} + \lambda_{4H}\frac{(H^0)^4}{4!} - \frac{v^4\lambda}{4}.$$

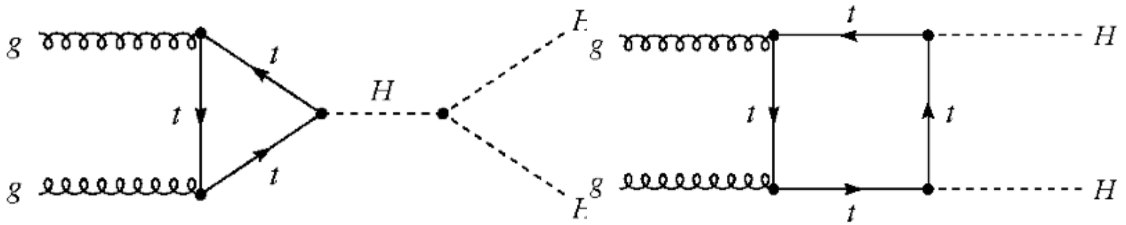
- Origin of matter relies in baryon/anti-baryon asymmetry
- Electroweak baryogenesis: generate baryon asymmetry with particle mass generation at EW scale, under some conditions on the way the EWSB happens
- Inflation of the Universe usually modeled using a scalar field (inflaton) : could this be related to the Higgs boson ?
- All this may happen in some extended Higgs sector in which the trilinear coupling

$\lambda_{3H} = \frac{3m_H^2}{v}$ is modified

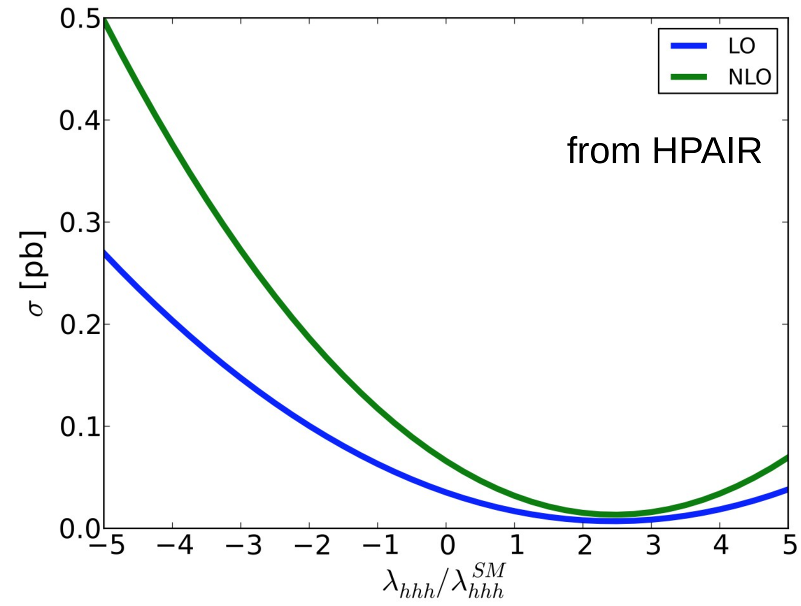
Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of $\%$
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

Di-Higgs boson production

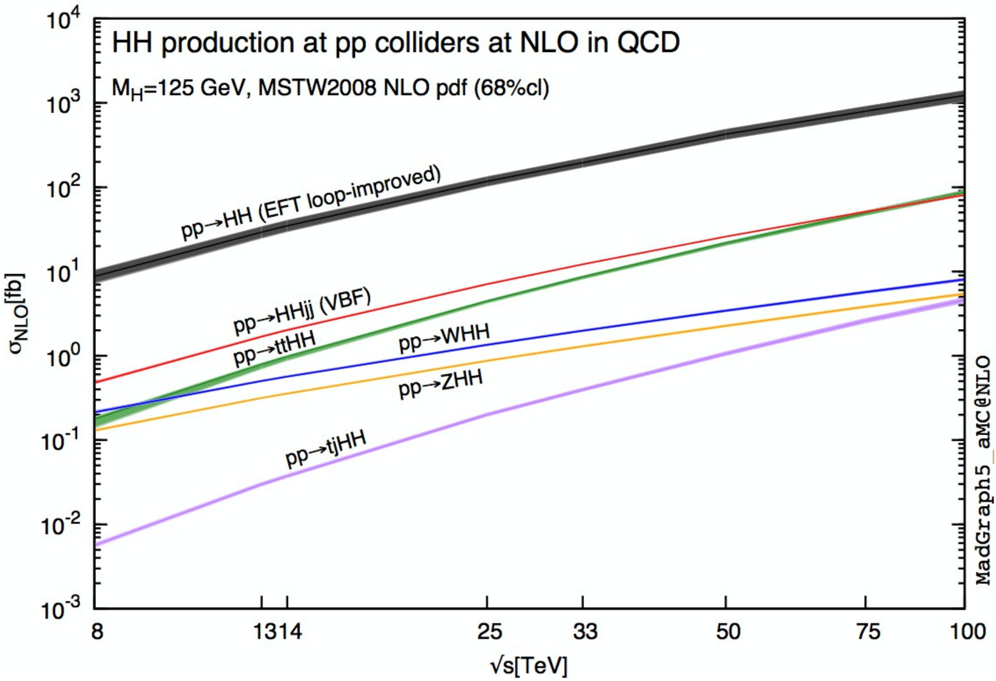
- Di-Higgs boson production dominated by box diagram
- Negative interference with self-coupling diagrams



- Low cross-section
- Currently large theoretical uncertainties for the signal

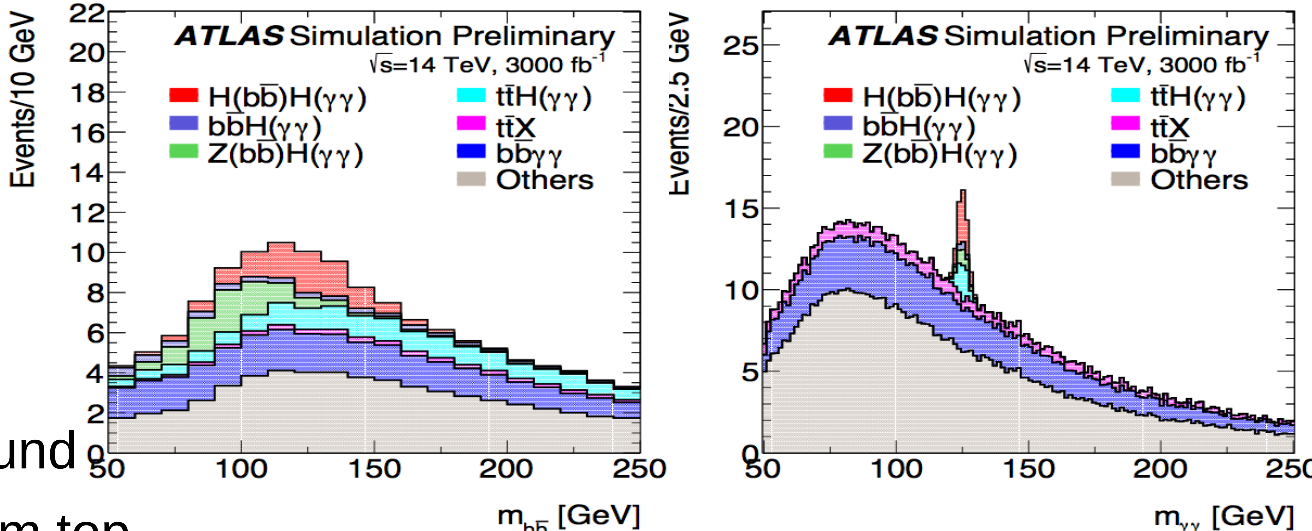


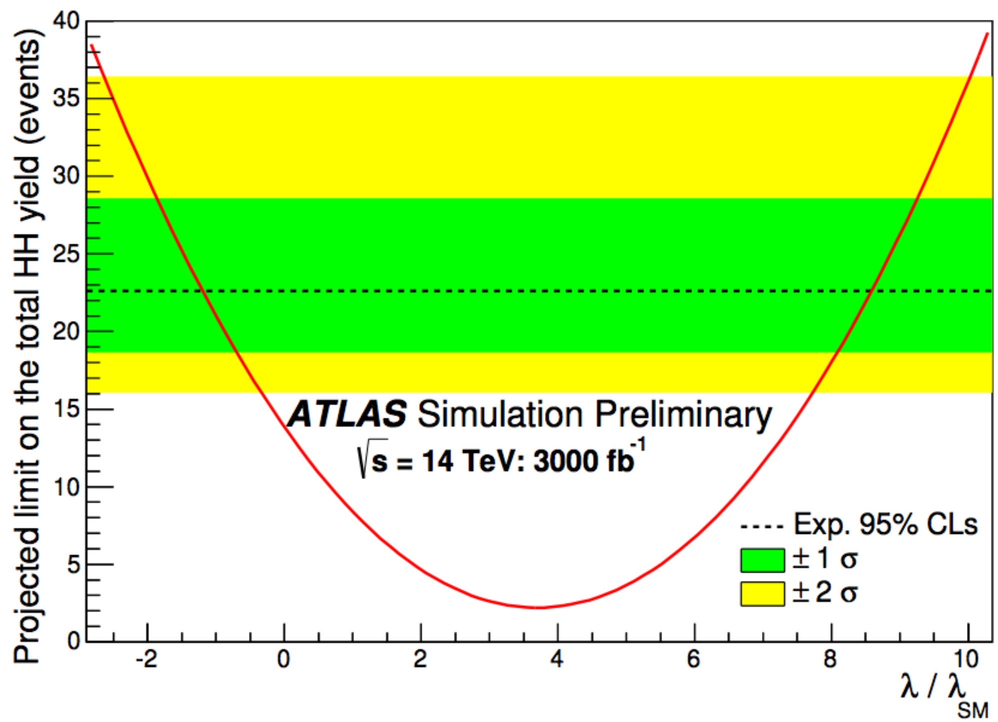
- Many channels are now being explored in order to assess the potential for the di-Higgs boson observation and the sensitivity to the self-coupling at the HL-LHC
  - The simplest (ggF with decays into b pairs) might not be the most powerful
- Difficult (new!) analyses to develop



Self-coupling measurements ?

- ATLAS and CMS have documented some prospects for the di-Higgs production measurements
- Here the example of the -so far- “golden” channel : $bb\gamma\gamma$
- Very complicated analyses
    - Often large background
        - Higgs its own background
        - Large contributions from top and/or fakes processes
        - Currently no good prediction for the continua ($bb\gamma\gamma$, bbjj,...)
    - Working in busy environment (high pile-up for hadrons colliders) where triggering will be an issue too
- So far, barely able to see with 3000 fb^{-1} the total HH production
- Measuring precisely the trilinear coupling will be very challenging !



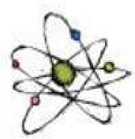


Other machines ?

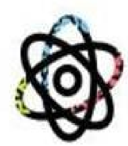
- Which machine ?
  - You've seen the gap between leptons colliders (LEP) and hadrons colliders (Tevatron/LHC)
  - But also the gap between √s~2 TeV and √s~8 TeV (this made the difference for the discovery!)
  - Choice depends on what we find in the near future… cannot answer today...
    - Do we want precision or statistics ?
      - Leptonic vs hadronic
      - Size matters ! Costs (α√L) and geopolitics too…
      - If precision, for which energies ? ttbar threshold ?
    - Have we found something else we want to study? Do we want to focus only on the Higgs ?
      - VBF production in lepton colliders too → limited stat for width measurement, but other couplings measurements would improve
    - Certainly the Higgs self-coupling measurement should be a big part of the physics programme !
      - Difficult at both hadrons and leptons colliders !
- In any case, facing a completely new object -elementary scalar boson- that we need to dissect

Conclusion

- Searched for the Standard Model Higgs boson
  - Found something looking pretty much like it
- Entered a Higgs precision measurements phase
  - Run-II will its “age d'or”
- Also, great potential for direct evidence of new physics in
  - (Not so?) rare decays
  - 2DHM models-like signatures
  - FCNC



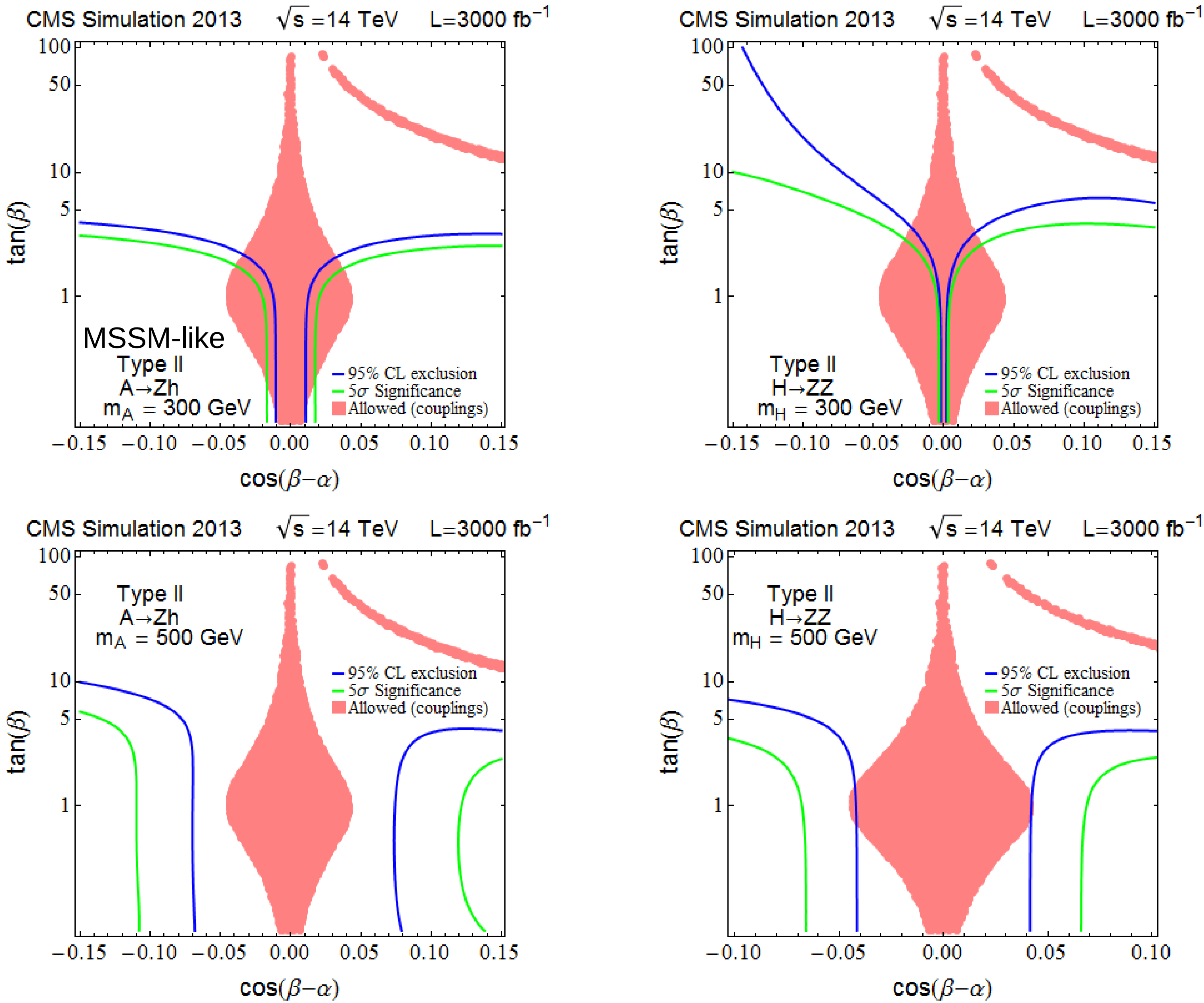
“Two Higgs bosons get into an elevator...’



- Need to continue in parallel working on
  - Establishing the potential for di-Higgs bosons measurements and sensitivity to the self-coupling
  - Consolidating the detector designs and running conditions in order to achieve those goals
  - Writing the developments of this story

Matière additionnelle

2HDM expected sensitivity



A → Zh → 2l2b

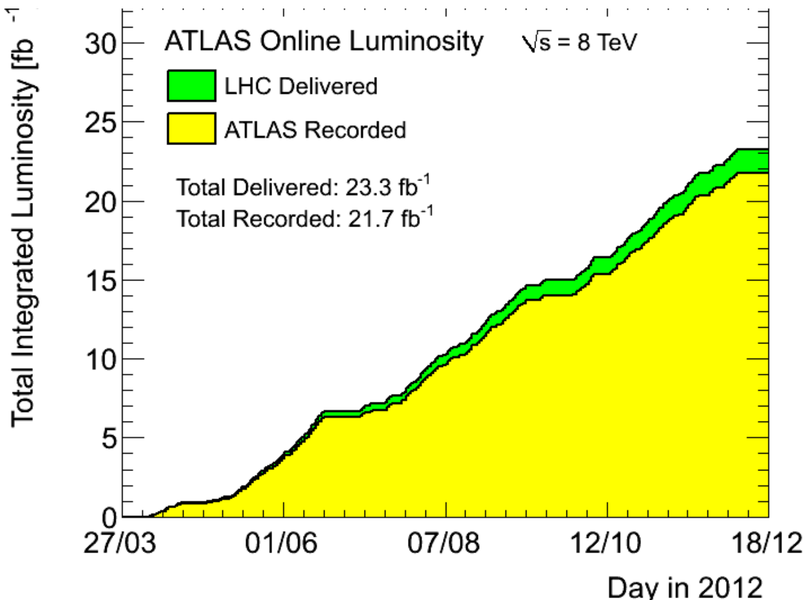
H → ZZ → 4l

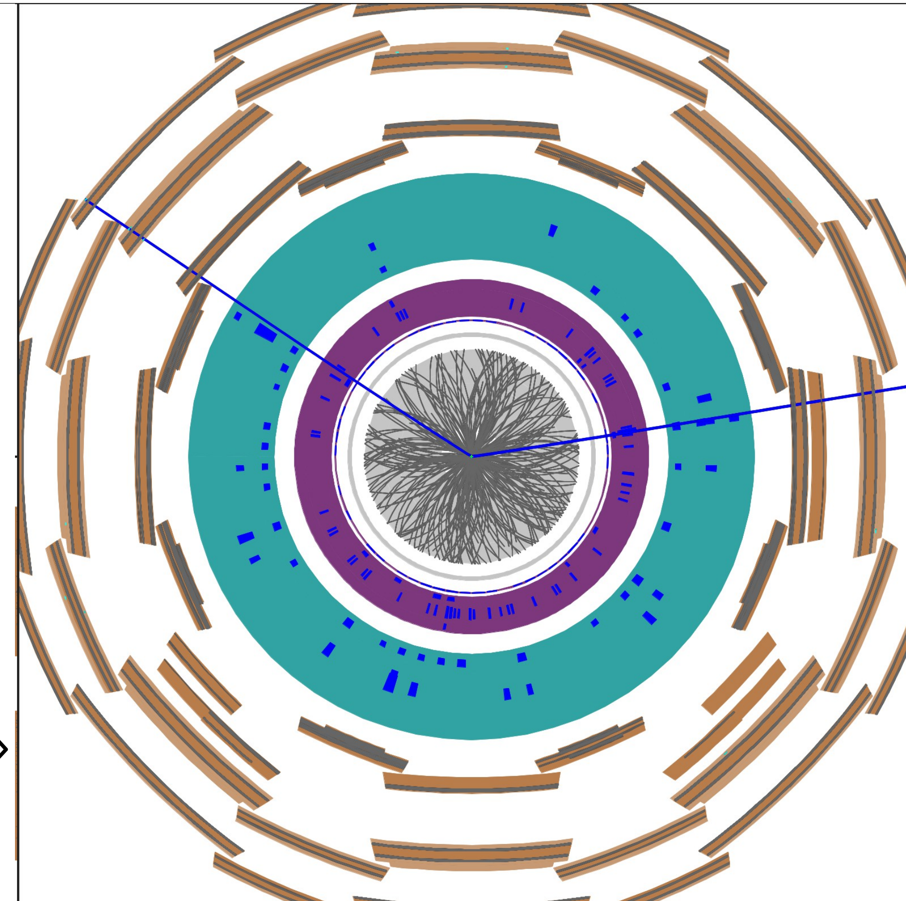
$m_{A/H}$ = 300 GeV

$m_{A/H}$ = 500 GeV

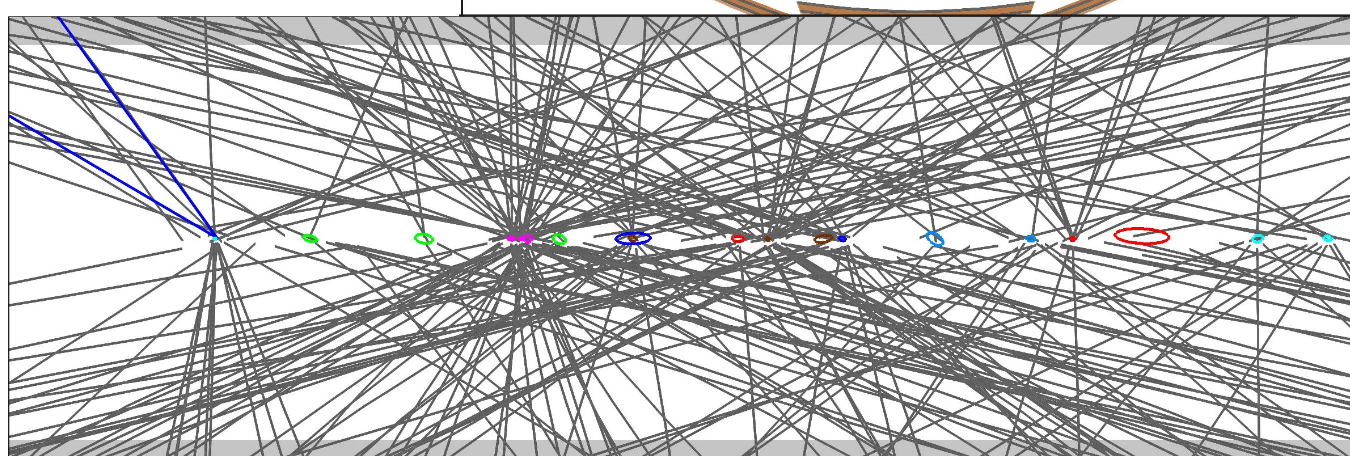
La fin d'un premier run excitant !

- Quelle année riche en physique au LHC ! (~4 fois plus de collisions qu'en 2011)



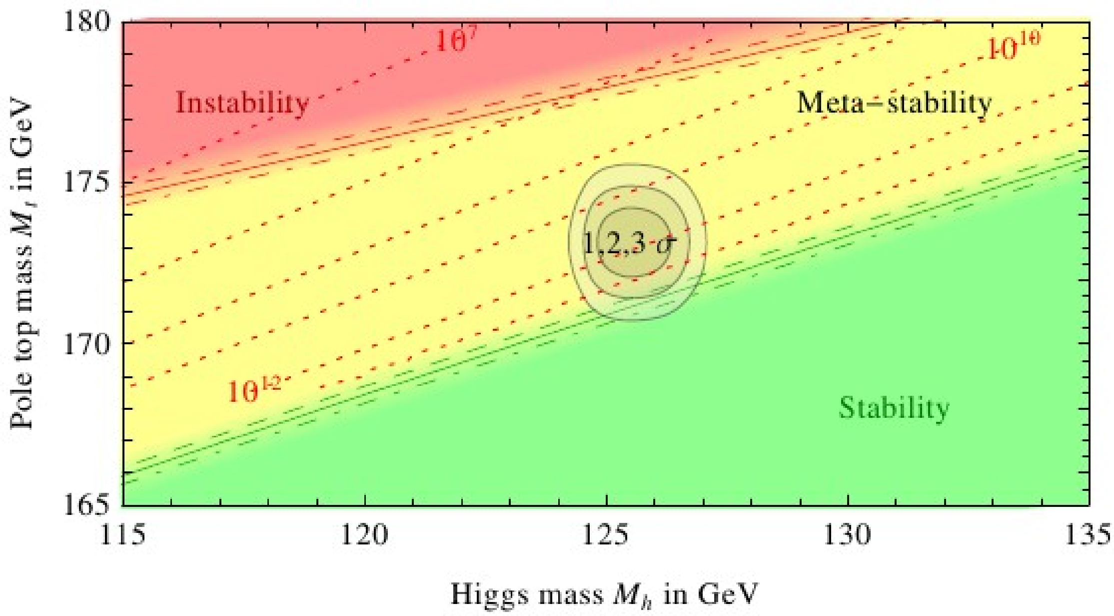


- Le prix à payer est un fort taux « d'empilement »
  - Déclenchement
  - Reconstruction et séparation des objets
  - Résolutions (Etmiss)
  - Ressources informatiques
  - Adéquation de la simulation
- Dur labeur...



Conclusion

- L'année 2012 a été très fructueuse en matière de recherche de Higgs !
  Et ce n'est qu'un début !
- La zone d'exclusion a été largement étendue, spécialement à basse masse, mais surtout, une nouvelle particule a été observée
- L'ensemble des canaux est maintenant mis à profit afin d'étudier ses propriétés (rapports d'embranchement, mass, spin) et vérifier son adéquation avec le boson de Higgs prédit par le Modèle Standard
- Nous rentrons maintenant dans une phase de mesures de précision dans le secteur du Higgs !



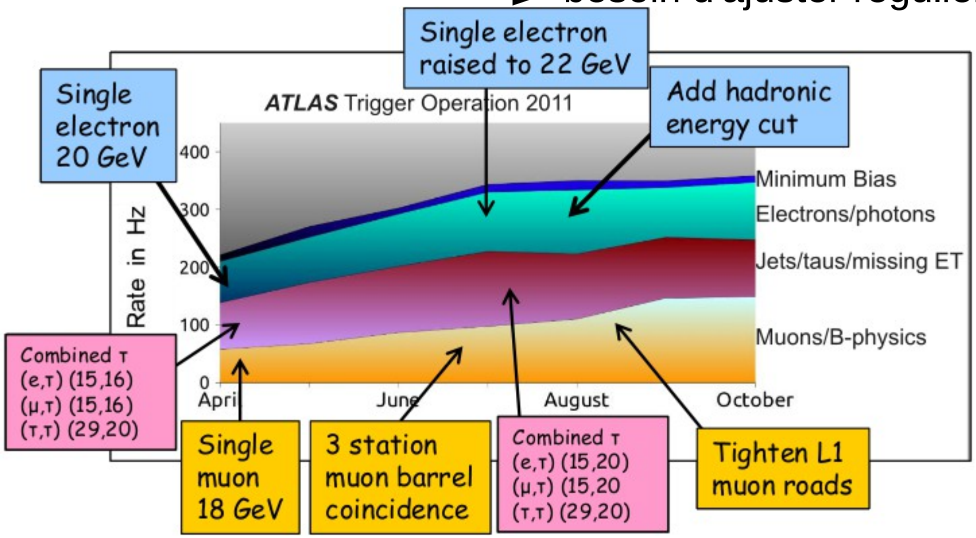
hep-ph/1205.6497

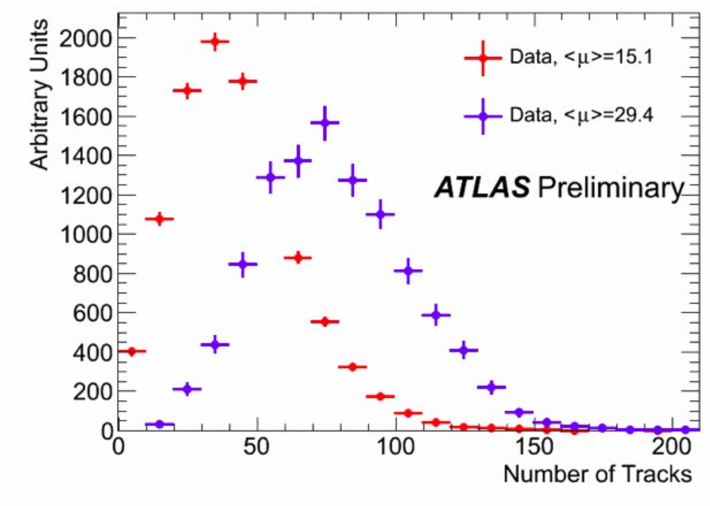
Effet de l'empilement

- Grande occupation du détecteur
- Stratégie d'ATLAS en matière de déclenchement : privilégier les signatures inclusives à un lepton isolé (généralistes)

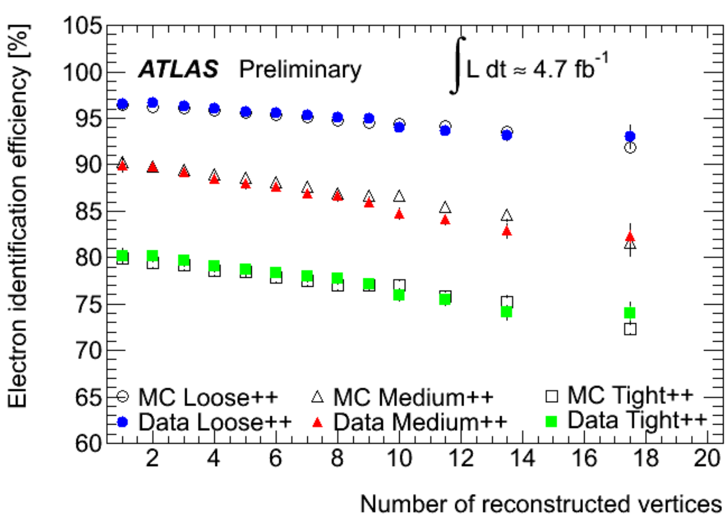
  ⟶ Taux de déclenchement toujours plus haut

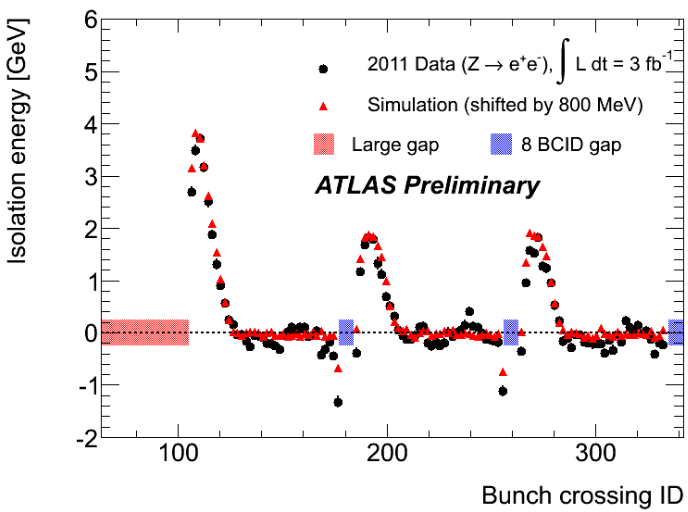
  ⟶ besoin d'ajuster régulièrement les seuils de déclenchement



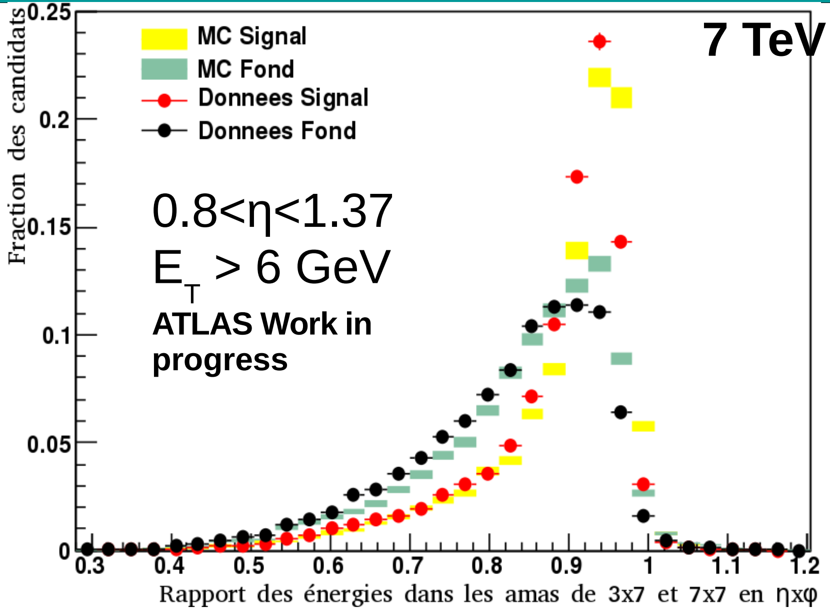


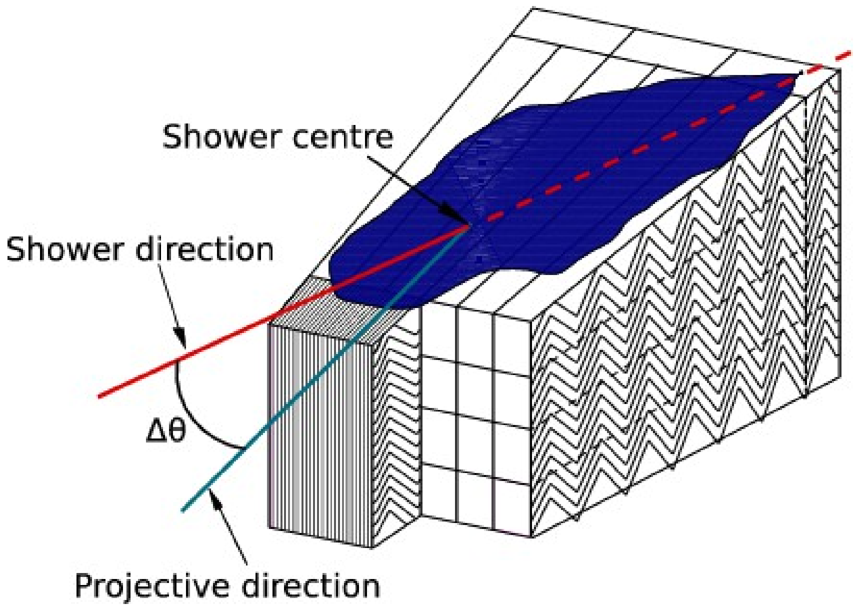
- Dépendance des efficacités de sélection :

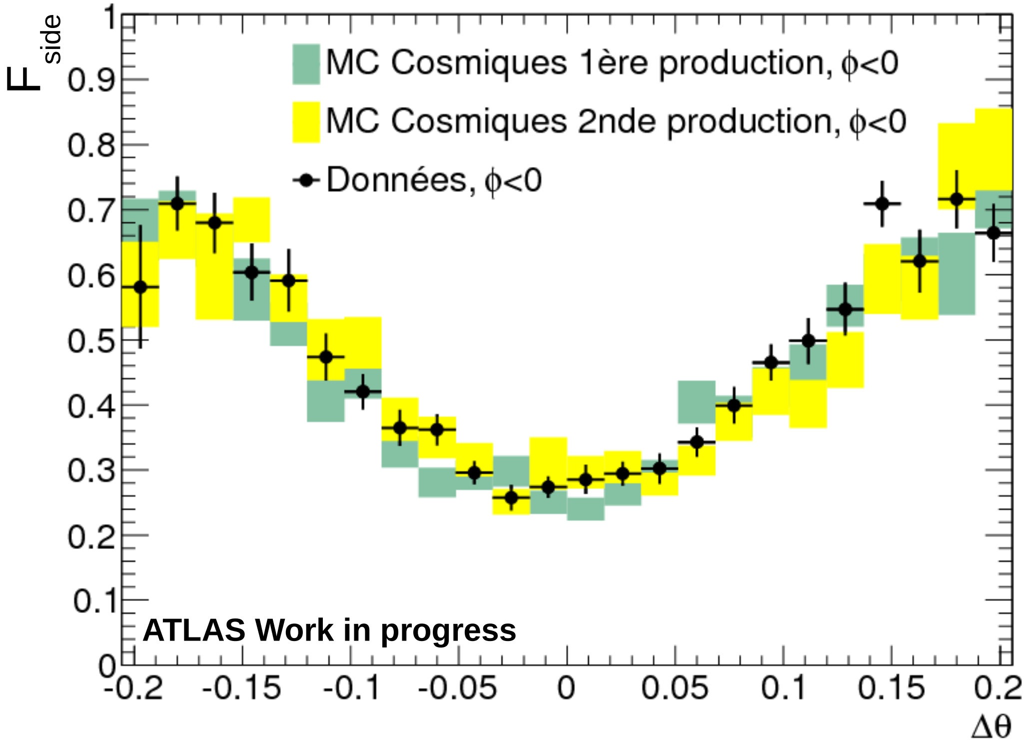




Formes de gerbes EM

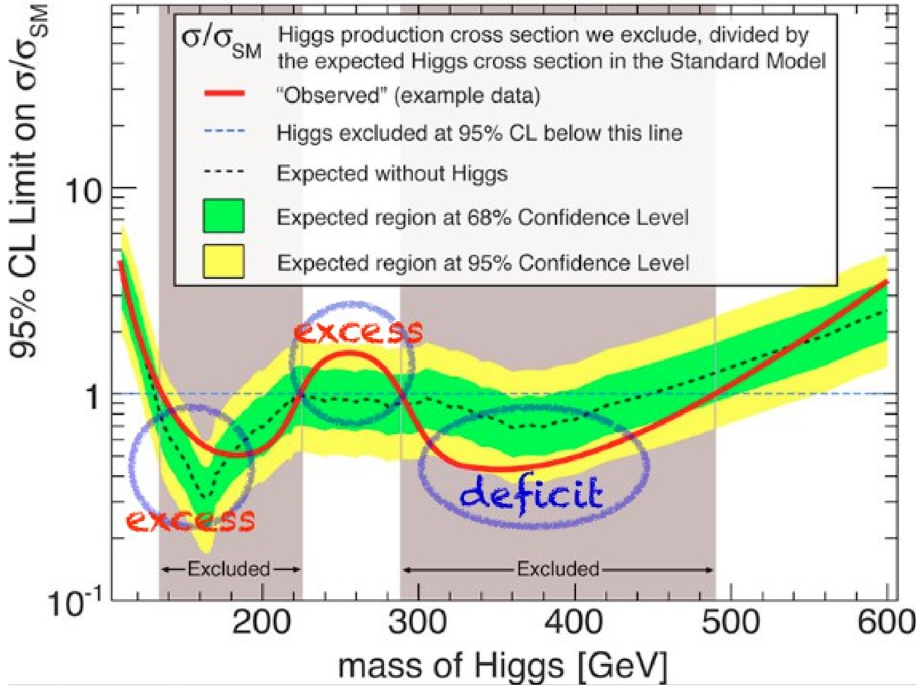






Limites d'exclusion (1)

- Une fonction de vraisemblance permet de calculer la significance du signal ainsi que les limites sur la production du boson de Higgs et de produire des figures synthétiques telles



- Cette fonction est basée sur le produit des probabilités Poisonniennes du nombre d'événements dans la région de signal et les régions de contrôle (WW 0 et 1-jet et top 1-jet) et ce, pour chaque canal de désintégration (e-e, μ-μ, e-μ) et nombre de jets dans l'état final (0 ou 1 jet)

- Les normalisations des sections efficaces de production du fond WW et du top peuvent varier indépendamment dans les régions de contrôle ; les autres composantes sont normalisées en utilisant des paramètres de nuisance de forme gaussienne qui incluent les incertitutes systématiques.

Limites d'exclusion (3)

A likelihood function is constructed that contains a signal region and two control regions for three lepton channels and two jet bins:

$$\mathcal{L}(\mu,\theta) = \prod_{\ell=ee,\mu\mu,e\mu} \prod_{j=0,1} \begin{array}{l} \text{Poisson}(N^{SR}_{\ell j} | \mu s_{\ell j} + \alpha^{WW}_{\ell,j} \dot{b}^{WW}_{e\mu,j} + \delta^1_j \alpha^{top}_{\ell,j} \dot{b}^{top}_{e\mu,j} + \sum_k b_{\ell jk}) \\ \text{Poisson}(N^{WW}_{\ell j} | \mu s_{\ell j} + \beta^{WW}_{\ell,j} \dot{b}^{WW}_{e\mu,j} + \delta^1_j \beta^{top}_{\ell,j} \dot{b}^{top}_{e\mu,j} + \sum_k b_{\ell jk}) \\ \text{Poisson}(N^{top}_{\ell j} | \mu s_{\ell j} + \delta^1_j \dot{b}^{top}_{e\mu,j} + \sum_k b_{\ell jk}) \end{array} \prod_\theta \text{Gaussian}(\theta | 0, 1) \quad (3)$$

Here, μ is the normalized signal strength, the ratio of the cross-section over the SM Higgs boson cross-section, θ represents the full suite of nuisance parameters which are constrained by a Gaussian probability density function (PDF), N represents the number of observed events in each jet and lepton channel region, s represents the expected number of signal events and b the expected number of background events given a particular set of values for the nuisance parameters. The expected number of events in each channel is multiplied by a log-normal response term for each systematic uncertainty that applies to the channel, i.e., $s_{\ell j}$ is the product of the luminosity, cross-section, acceptance, and the product of log-normal functions of each of the systematic uncertainties for the decay channel ℓ and jet multiplicity j.

Additional $\dot{b}$ parameters are introduced without a constraint to normalize the expected number of events in the signal region using the control region. A set of extrapolation factors α (and β), obtained from MC simulation, describe the theoretical knowledge on the ratio of the number of expected events in the signal (or main control) region to the control region.

Profile likelihood : $q_\mu = -2\ln \frac{\mathcal{L}(\mu, \ddot{\theta}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$

$\hat{\mu}$ and $\hat{\theta}$ refer to the global maximum of the likelihood and $\hat{\theta}_\mu$ corresponds to the conditional maximum likelihood of θ given μ and the data. The constraint $0 \leq \hat{\mu} \leq \mu$ is applied; the lower bound since the signal is positive and the upper bound to guarantee a one-sided limit.

$$p_\mu = P(q_\mu \geq q^{obs}_\mu \mid \text{signal+background}) = \int_{q^{obs}_\mu}^{\infty} f(q_\mu \mid \mu, \hat{\theta}^{obs}_\mu) dq_\mu, \quad p_0 = P(q_\mu \geq q^{obs}_\mu \mid \text{background-only}) = \int_{q^{obs}_\mu}^{\infty} f(q_\mu \mid 0, \hat{\theta}^{obs}_0) dq_\mu, \quad CLs(\mu) = \frac{p_\mu}{p_0}$$

For CLs= α the Confidence Level is defined as $(1-\alpha)$. The observed limit at 95% Confidence Level is set by an iterative procedure on μ.