Recherche (expérimentale) du boson de Higgs et mesure de ses propriétés

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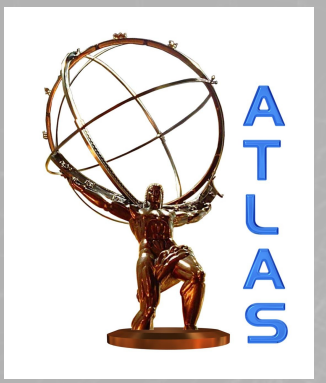
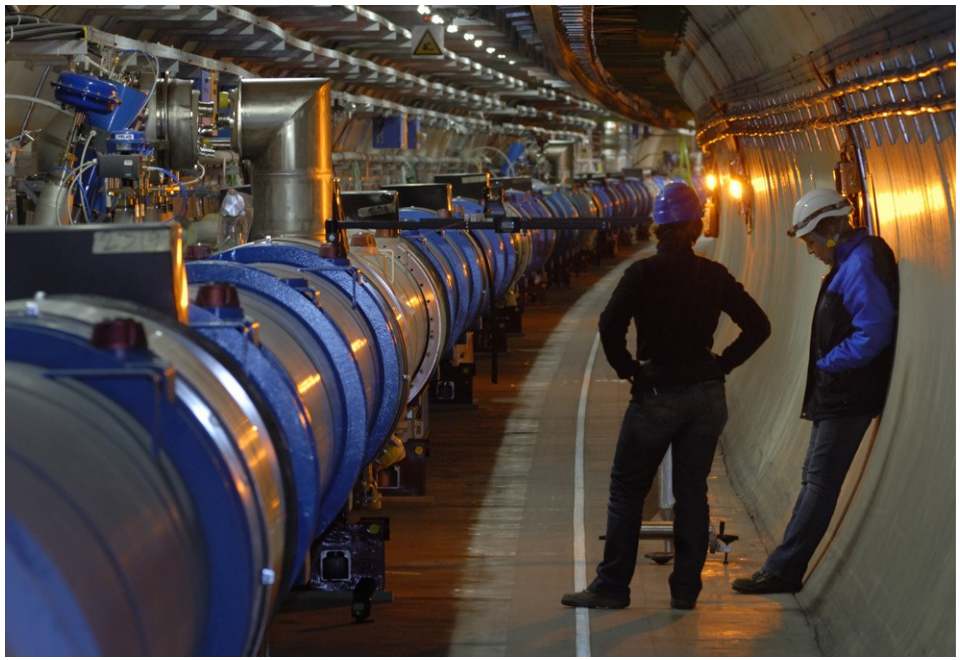
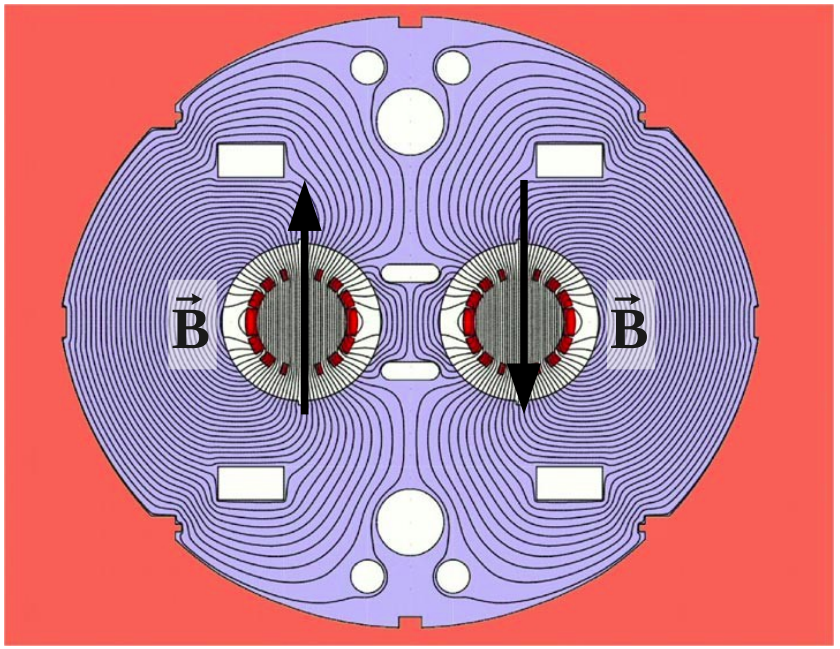
22ème Congrès général de la SFP
1er juillet 2013



Le LHC (1)

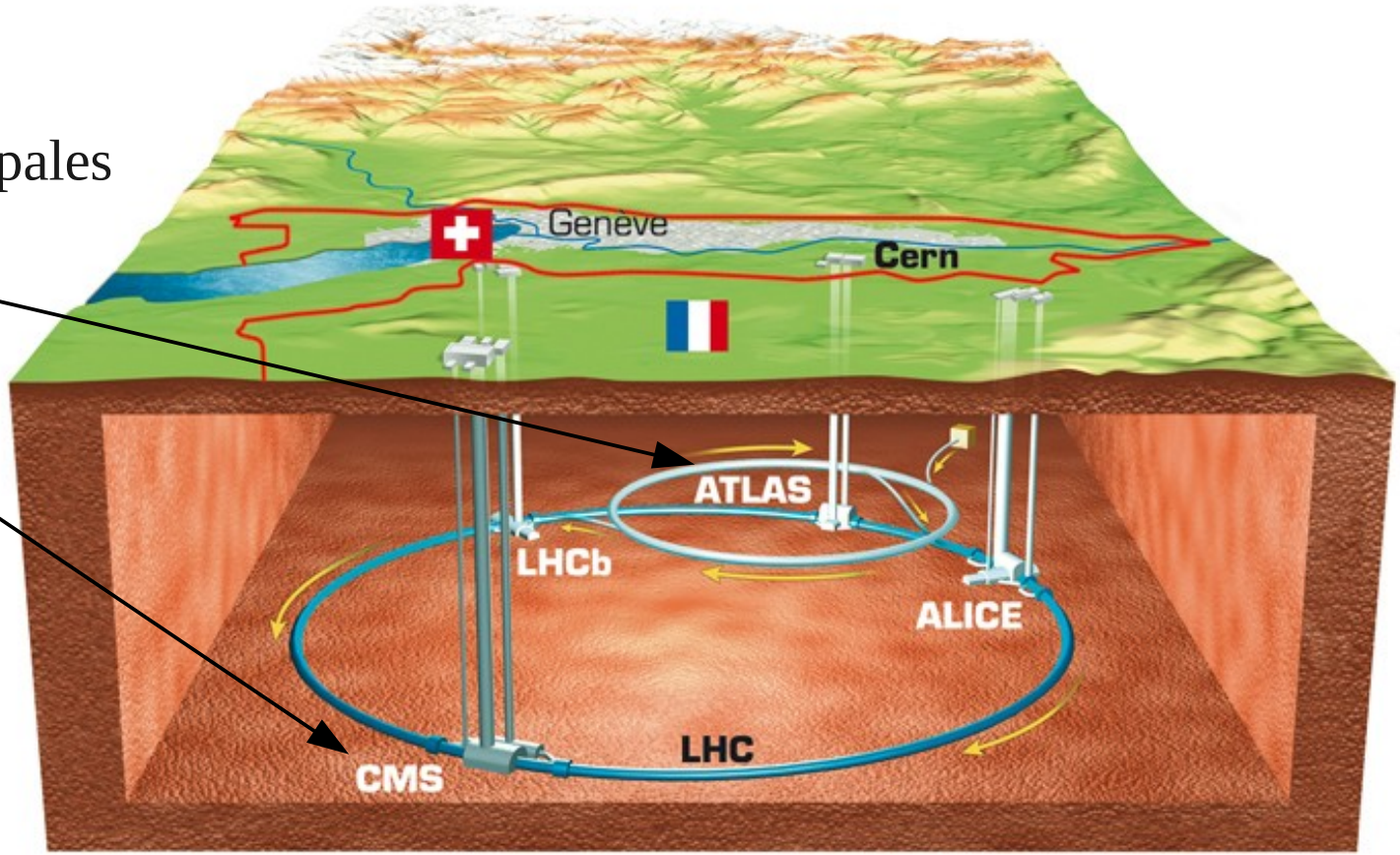
- Collisionneur p-p
- ~9000 aimants supraconducteurs
- ~1000 paquets de 100 milliards de protons
- Protons accélérés à 8 TeV dans le centre de masse
  - ~ énergie d'un moustique en vol concentrée dans une tête d'épingle





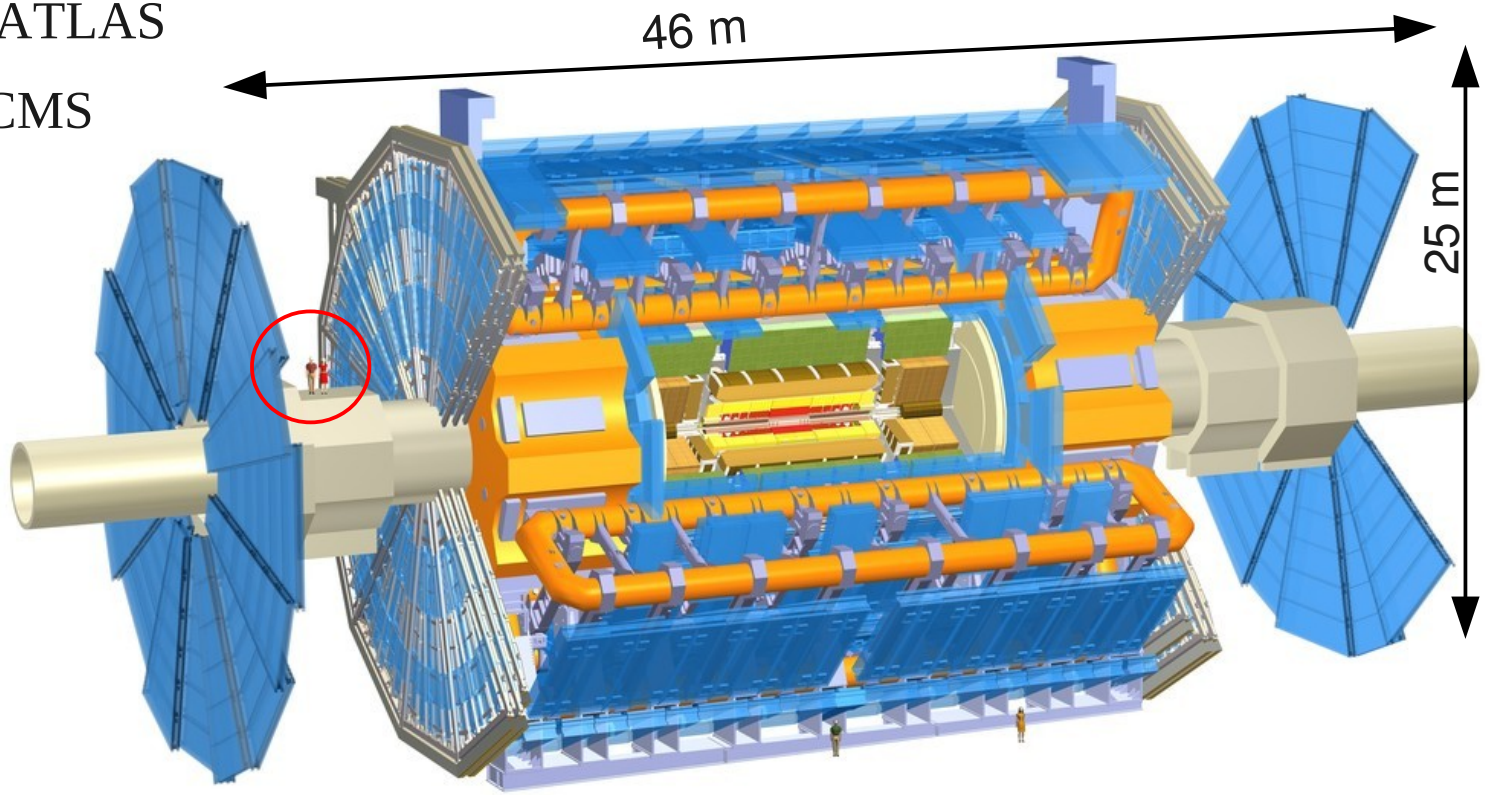
Le LHC (2)

- 27 km de circonférence
- 4 expériences principales
  - ATLAS
  - CMS
  - LHCb
  - ALICE



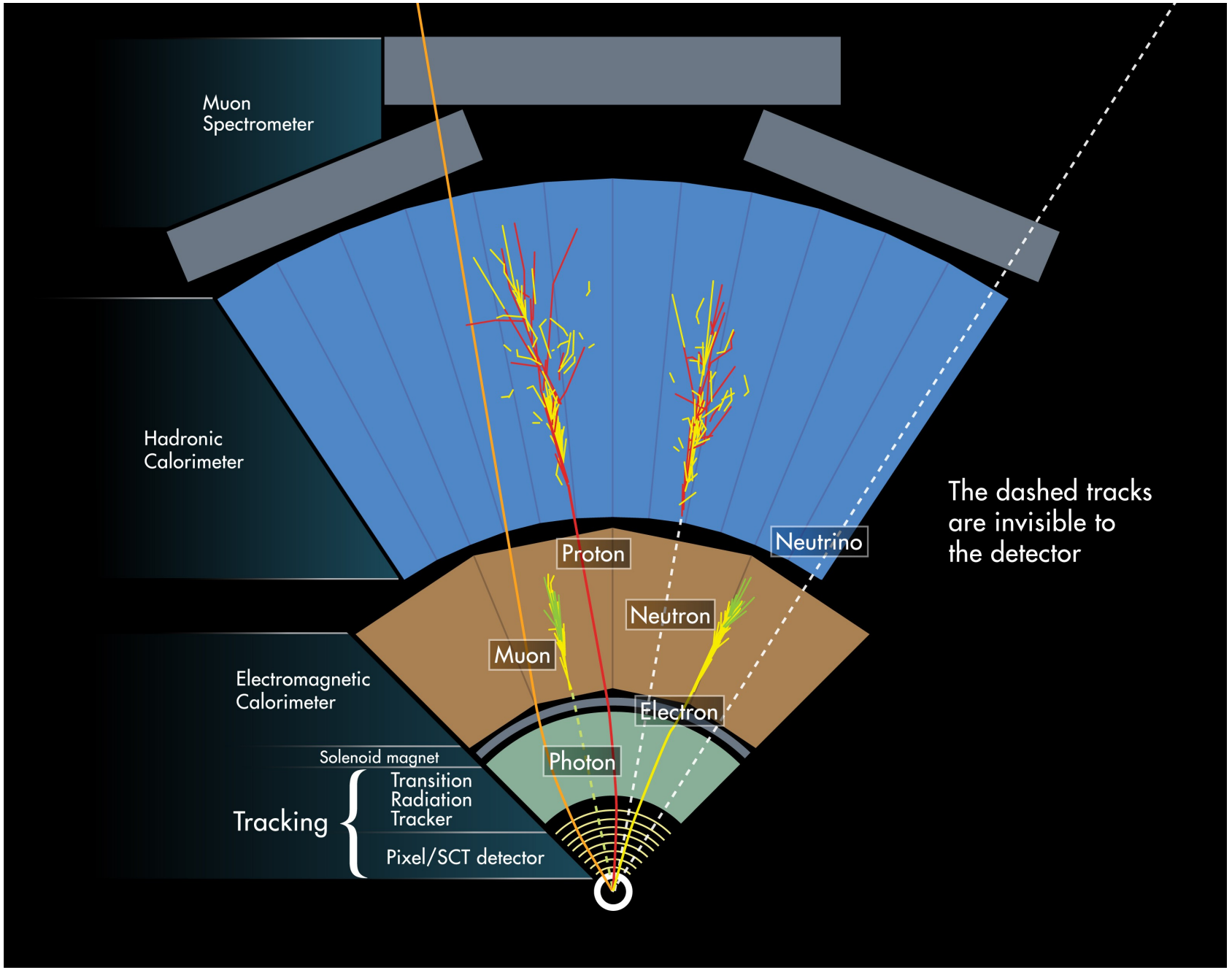
ATLAS et CMS

- Expériences géantes
  - 46x25m pour ATLAS
  - 13800 t pour CMS



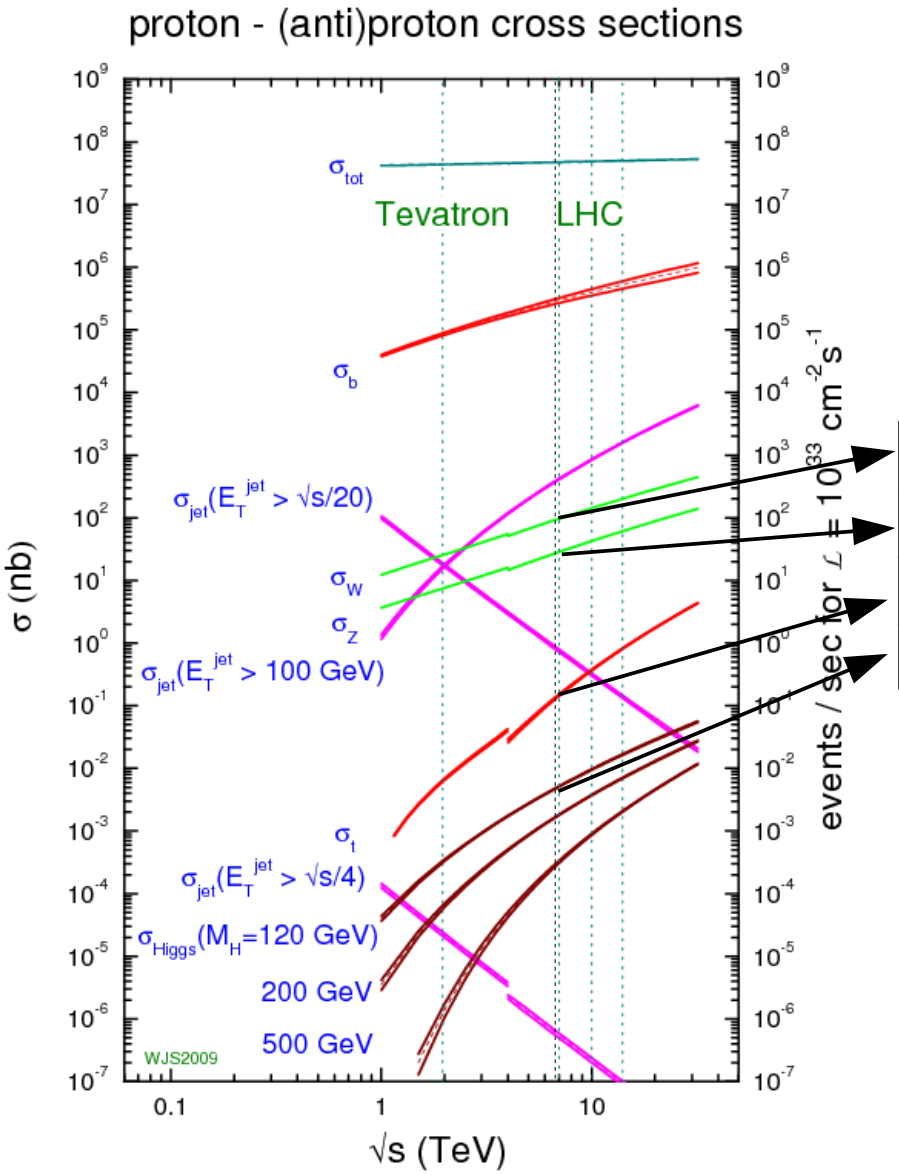
- > 3000 physiciens /expérience
- > 200 instituts

Principe de détection des particules



Particules produites

- ~20 millions de collisions /s

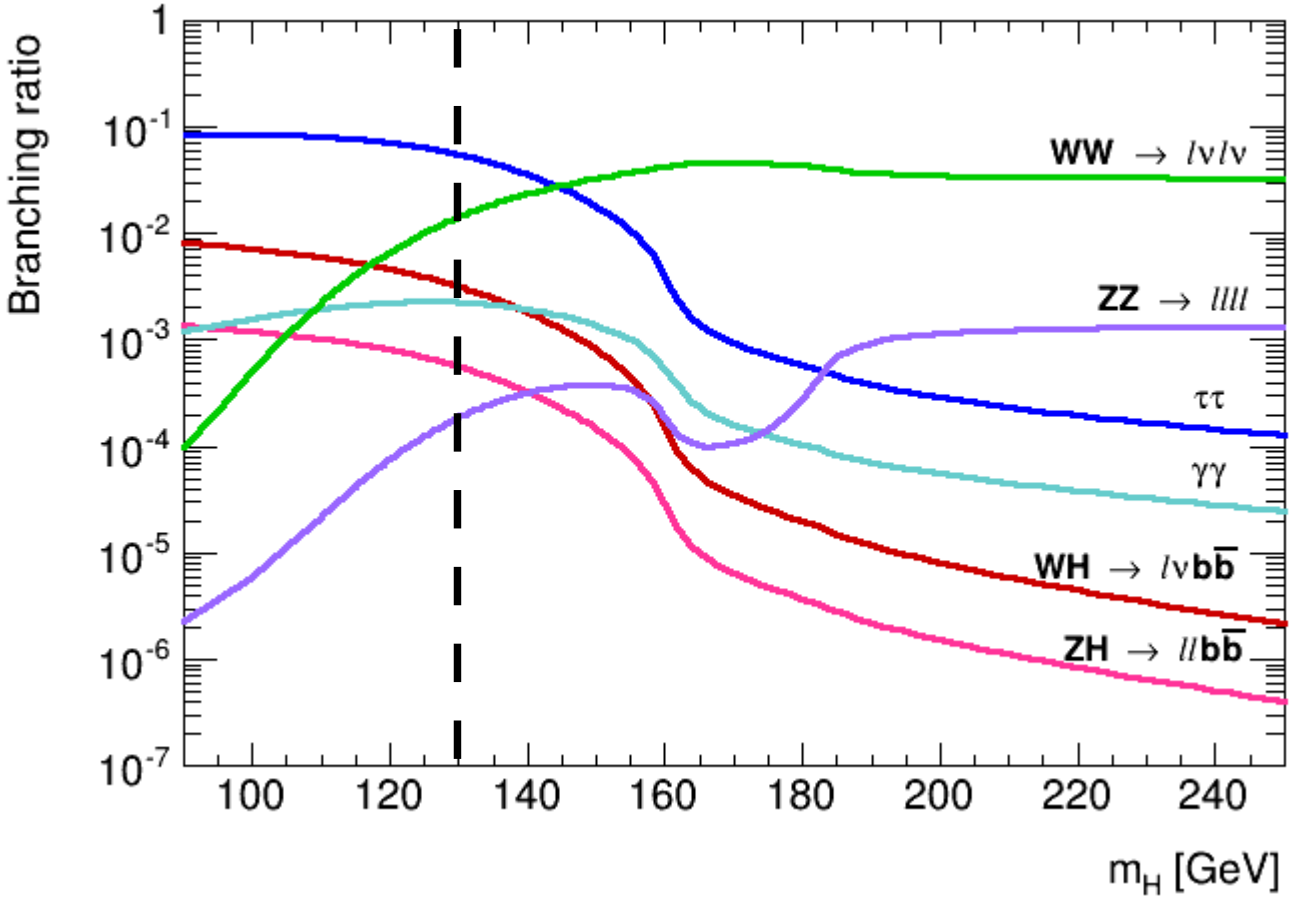


	masse (GeV)	section efficace	Événements (millions)
W→lν	80.4	10 nb	300
Z→ll	91.2	0.9 nb	30
$t\bar{t}$	173.1	165 pb	5
Higgs	125	22 pb	0.7

1b = 10^{-24}cm^2

Canaux de désintégration du boson de Higgs

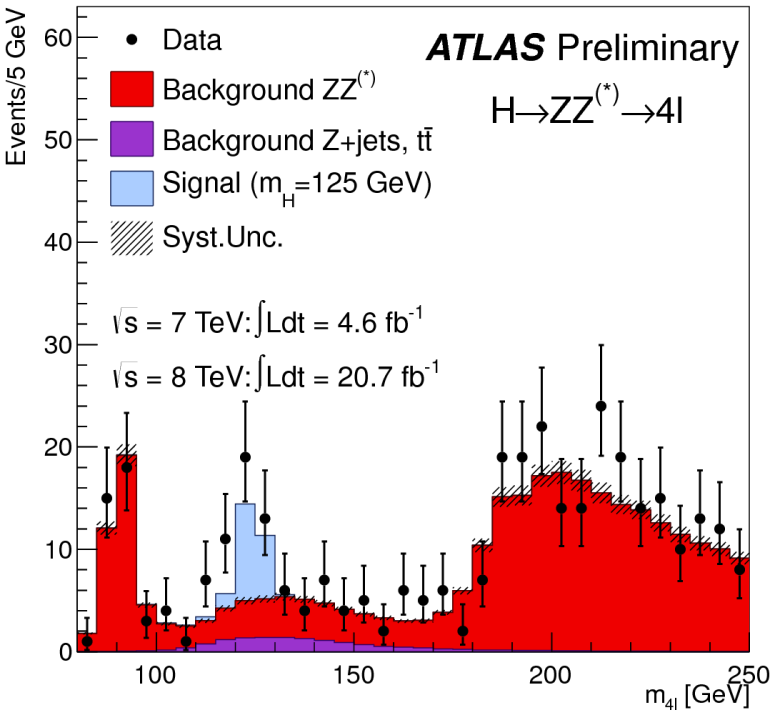
- Rapports de branchement:



- 1 Higgs toutes les 10 s
- 1 H → γγ toutes les 1.5 h
- 1 H → ZZ → 4ℓ tous les 2 jours

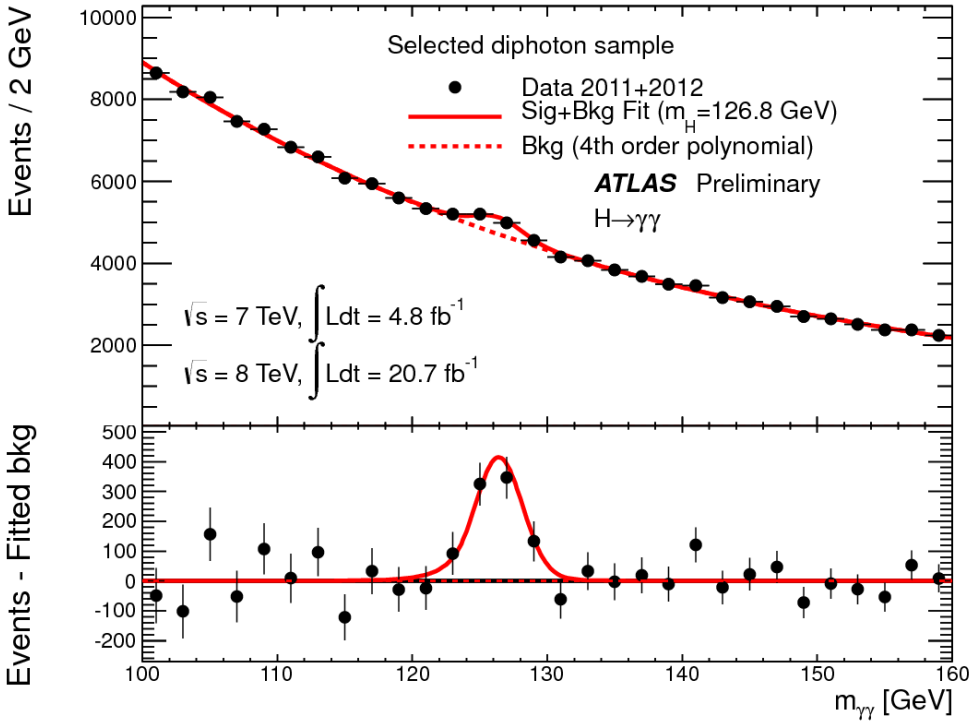
Canaux de désintégration

- $H \rightarrow ZZ^* \rightarrow 4$ leptons (e, μ)



- Signal ≃ 20
- S/B ~ 1

- $H \rightarrow \gamma\gamma$



- Signal ≃ 400
- S/B ~ 1%

Exemple : recherche dans le canal WW*

- Désintégrations W → eν et W → μν
- Sélection des événements (énergie, qualité des objets reconstruits, etc)
- Bruit de fond
  - réductible: tt, WZ, Z+jets, ...
  - irréductible: WW
- Estimation du bruit de fond:
  - avec des simulations
  - à partir des données

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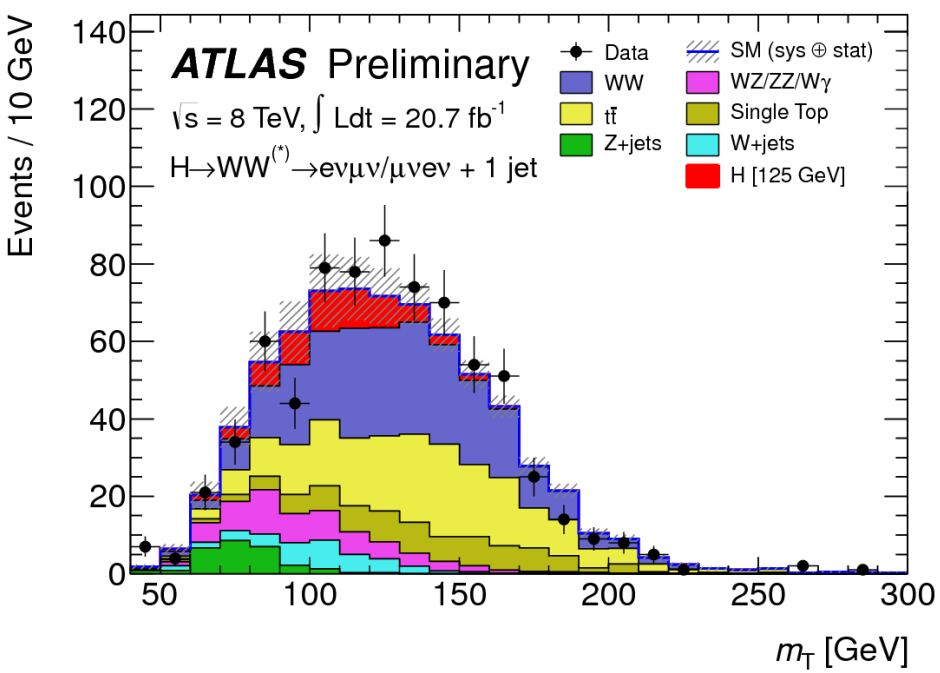
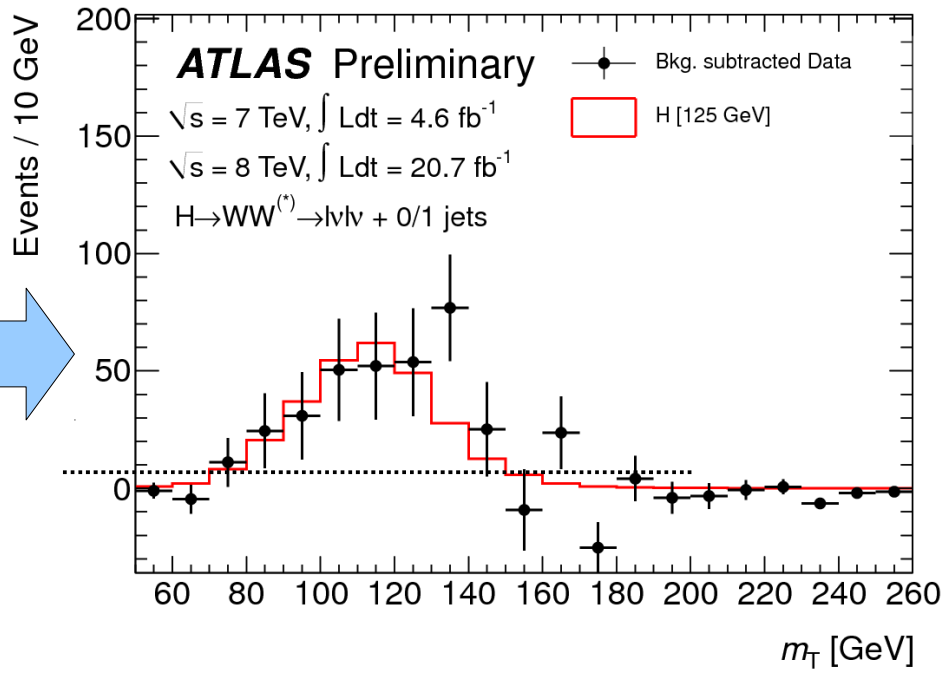
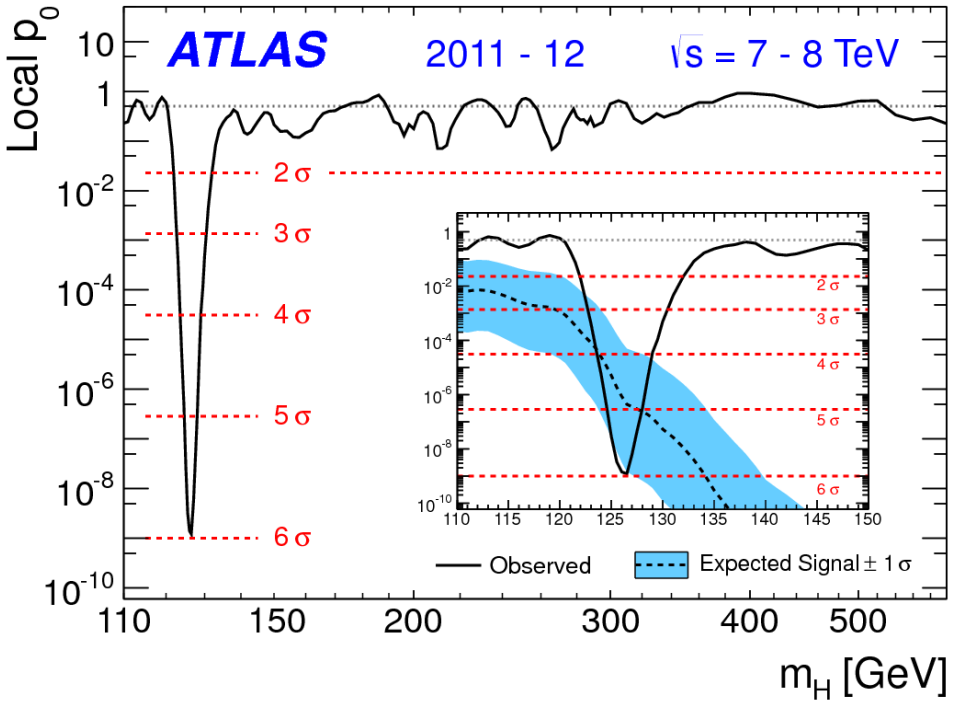
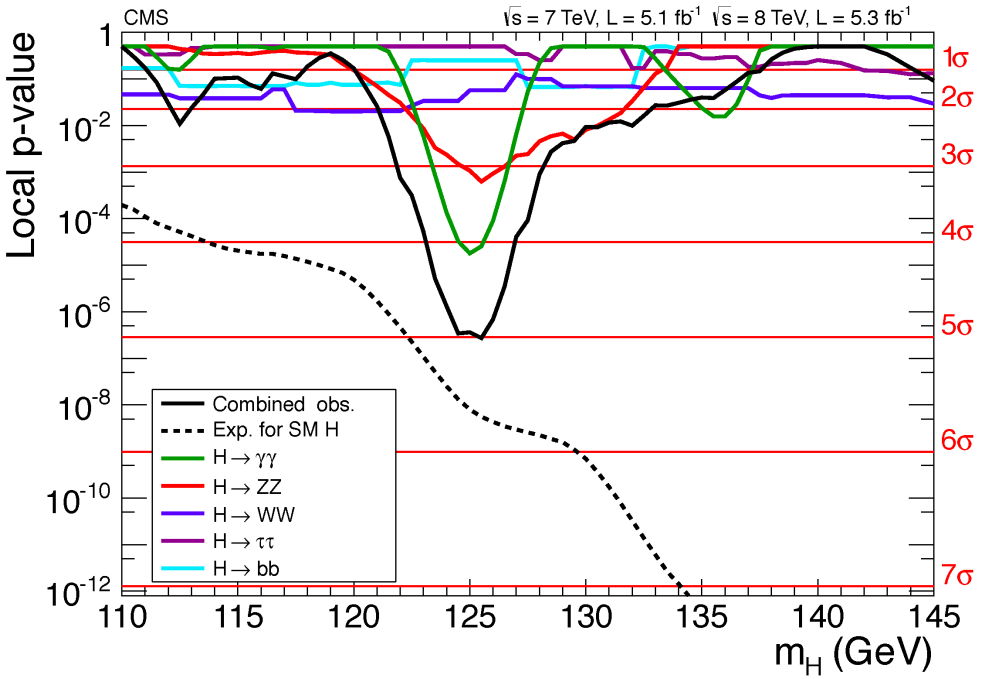




Découverte (1)

- p0: compatibilité des événements sélectionnés avec l'hypothèse du bruit de fond
- Significance: $Z \sim S/\sqrt{B}$





- Plus de 5σ dans chaque expérience !
  - degré de confiance > 99.999994 %

Phys. Lett. B 716, Sep 2012

- Maintenant découverte dans canaux γγ, ZZ* et WW* seuls

Découverte (2)

- 4 juillet 2012 au CERN

Et après ?

- Est-ce bien le boson de Higgs du Modèle Standard ?
- Mesure de la masse
  - valeur non prédite
- Taux de production et couplages
- Spin

Mesure de la masse

ATLAS

- $H \rightarrow ZZ^* \rightarrow 4$ leptons
  - $124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\,\text{GeV}$
- $H \rightarrow \gamma\gamma$
  - 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
- Combined mass:

  124.3 ± 0.2 (stat) $^{+0.6}_{-0.5}$ (syst) GeV

CMS

- $H \rightarrow ZZ^* \rightarrow 4$ leptons
  - 125.8 ± 0.5 (stat) ± 0.2 (syst) GeV
- $H \rightarrow \gamma\gamma$
  - 125.4 ± 0.5 (stat) ± 0.6 (syst) GeV
- Combined mass:

  125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

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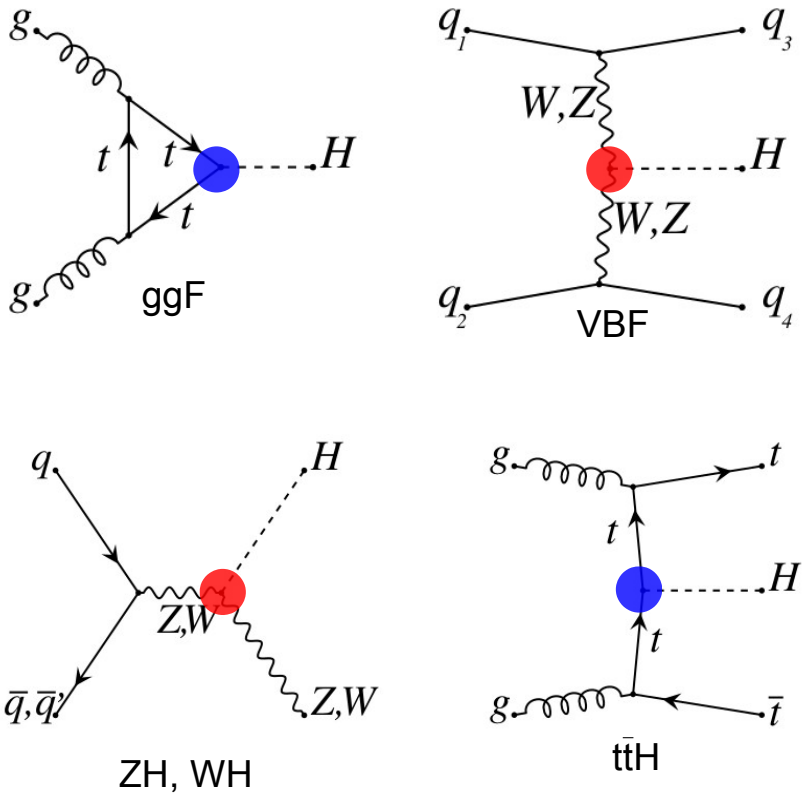
CMS-PAS-HIG-13-005

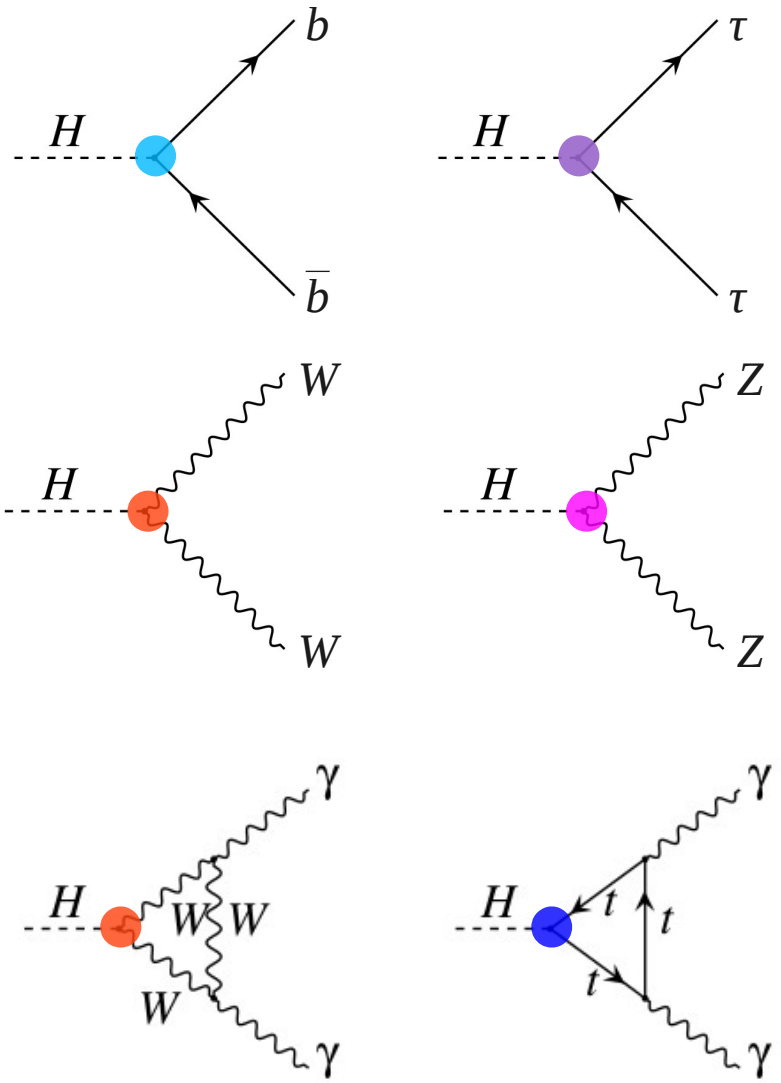
Couplages du boson de Higgs

♦ Modes de production :



: fermions (t, b, τ)
: bosons vecteurs (W, Z)

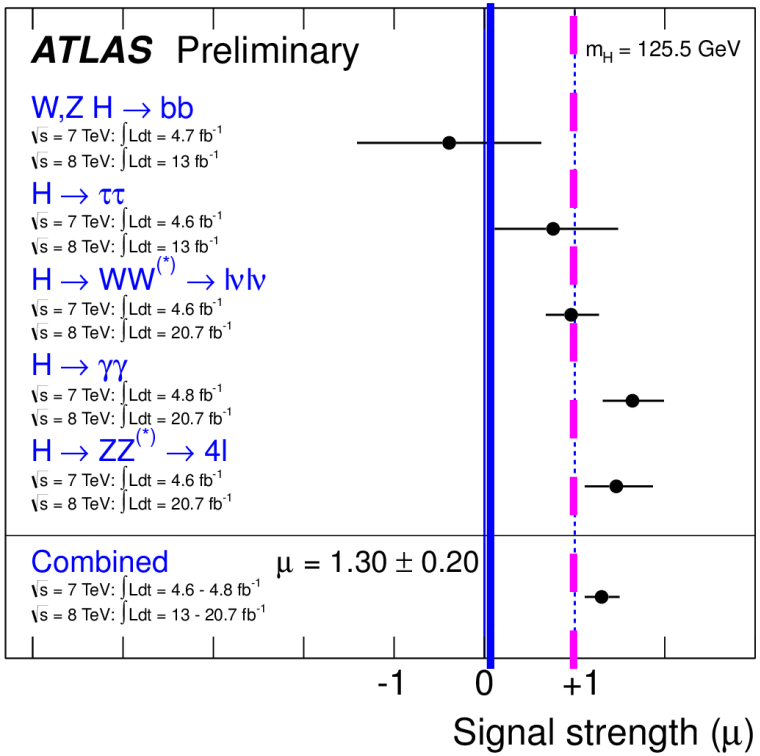
♦ Canaux de désintégration :

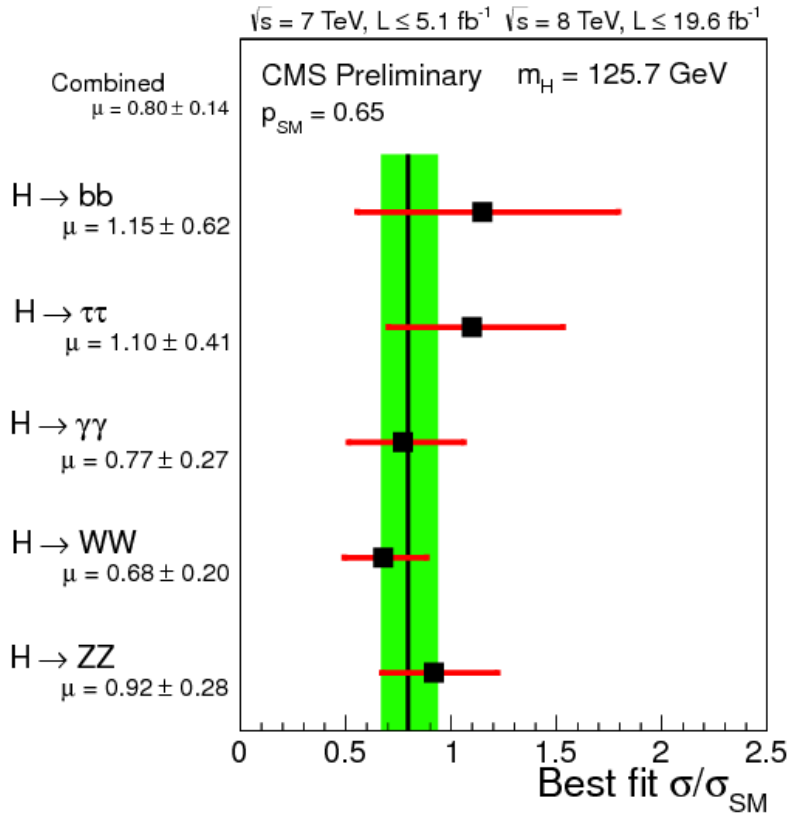


♦ Mesures des sections efficaces et largeurs partielles de désintégration
⇒ remonter aux couplages

Taux de désintégration

- Force du signal: $\mu = \frac{N_{observé}}{N_{SM\ Higgs}}$
  - = 0: bruit de fond uniquement
  - = 1: boson de Higgs du Modèle Standard





combinaison : 0.80 ± 0.14

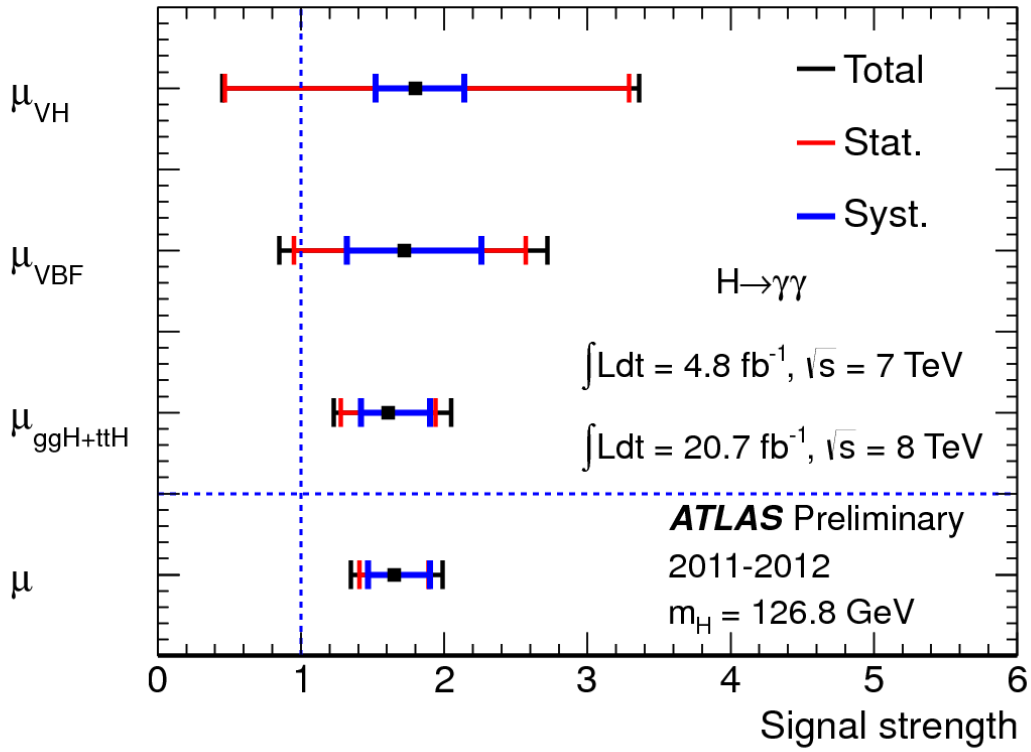
- Toutes mesures compatibles avec 1
  - déviation max : 2.4σ (H→γγ ATLAS)

Séparation des modes de production

- Analyses dédiées aux modes de production:

channel	mH (GeV)	ggF	VBF	VH	ttH
H→ZZ→4l	110-600	✓	✓	✓	
H→γγ	110-150	✓	✓	✓	
H→WW→lvlv	110-600	✓	✓	✓	
H→ττ	110-145	✓	✓	✓	
H→$b\bar{b}$	110-130			✓	✓

- Example H→γγ:



$$\mu = \frac{N_{observé}}{N_{SM\ Higgs}}$$

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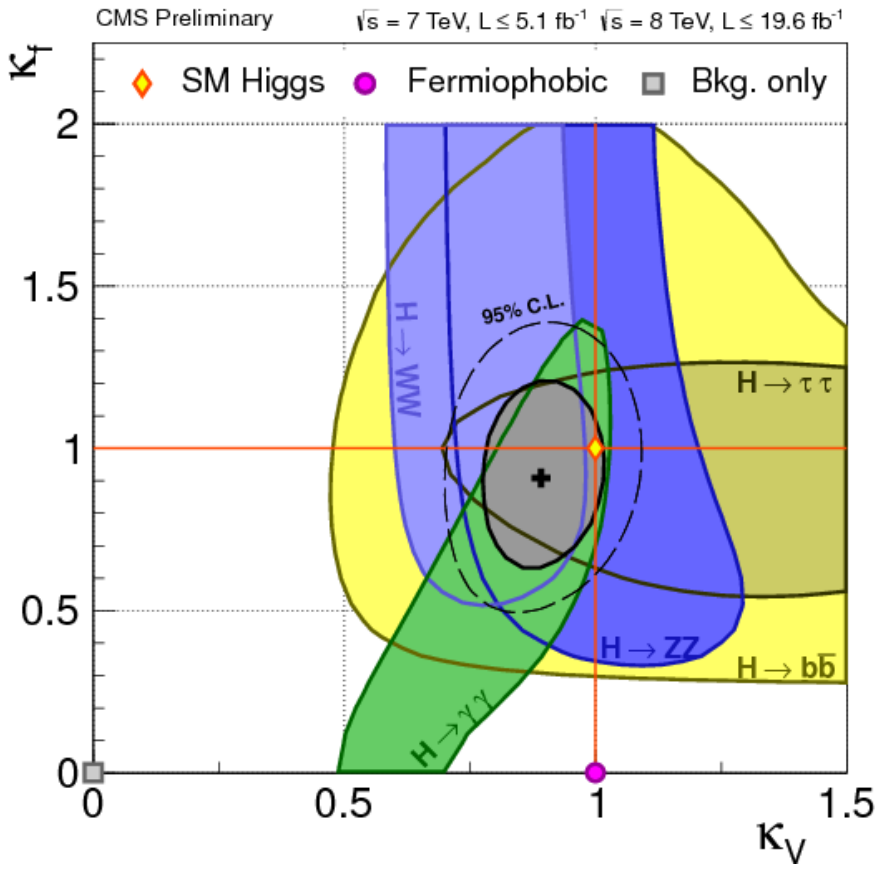
Premières mesures de couplages (1)

- Comparaison aux couplages prédits par le Modèle Standard
  - κ_V : couplages aux bosons vecteurs
  - κ_F : couplages aux fermions

  } ratio par rapport au Modèle Standard

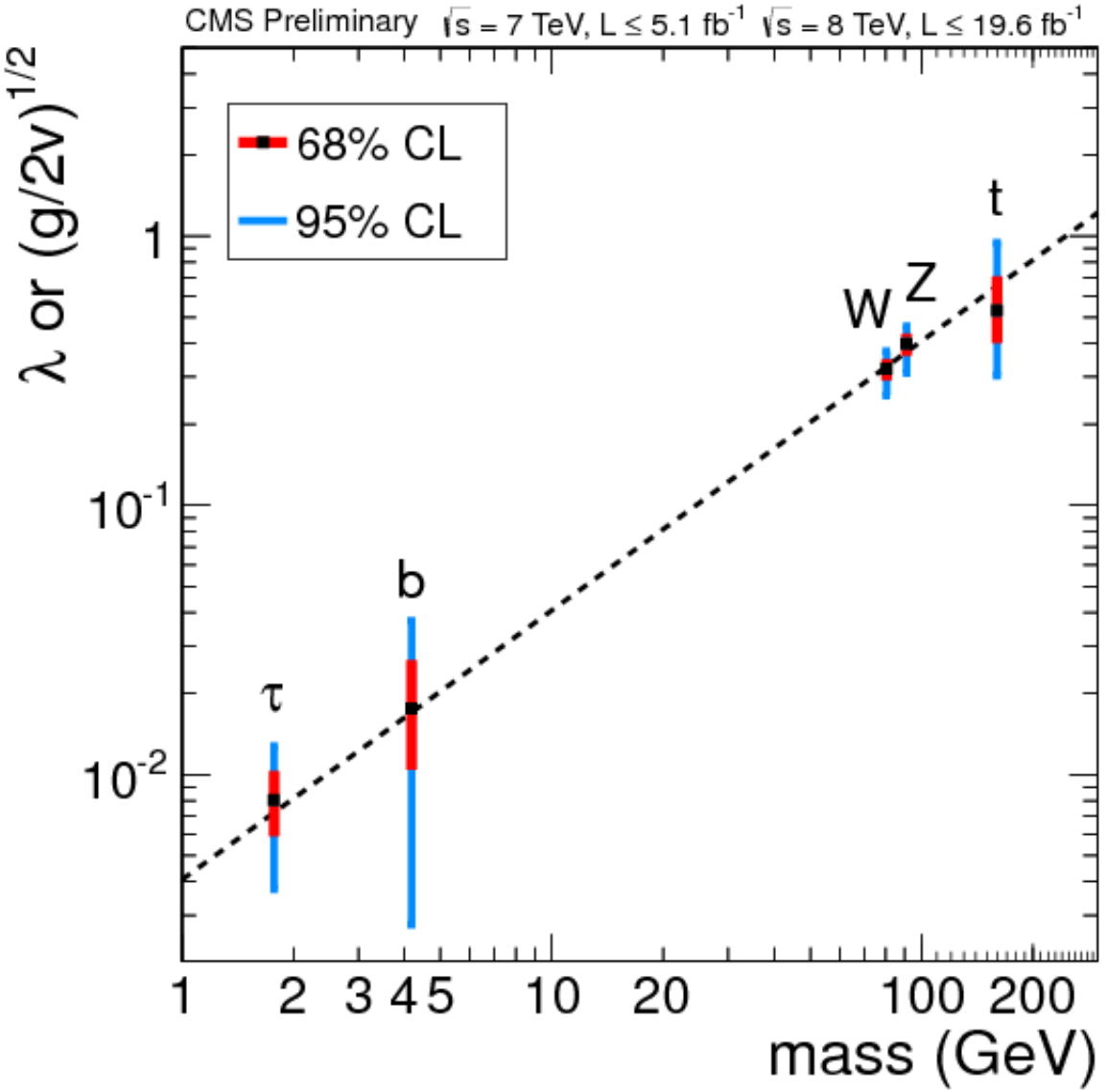


CMS-PAS-HIG-13-005

- Pour l'instant, couplages compatibles avec les prédictions

Premières mesures de couplages (2)

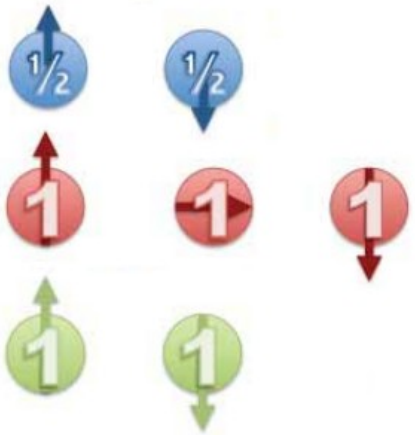
- Couplage du boson de Higgs aux particules ∝ leur masse



CMS-PAS-HIG-13-005

Mesure de spin (1)

- Boson de Higgs de spin 0
- Spin des autres particules :
  - leptons, quarks : +1/2, -1/2
  - W, Z : +1, 0, -1
  - γ : +1, -1

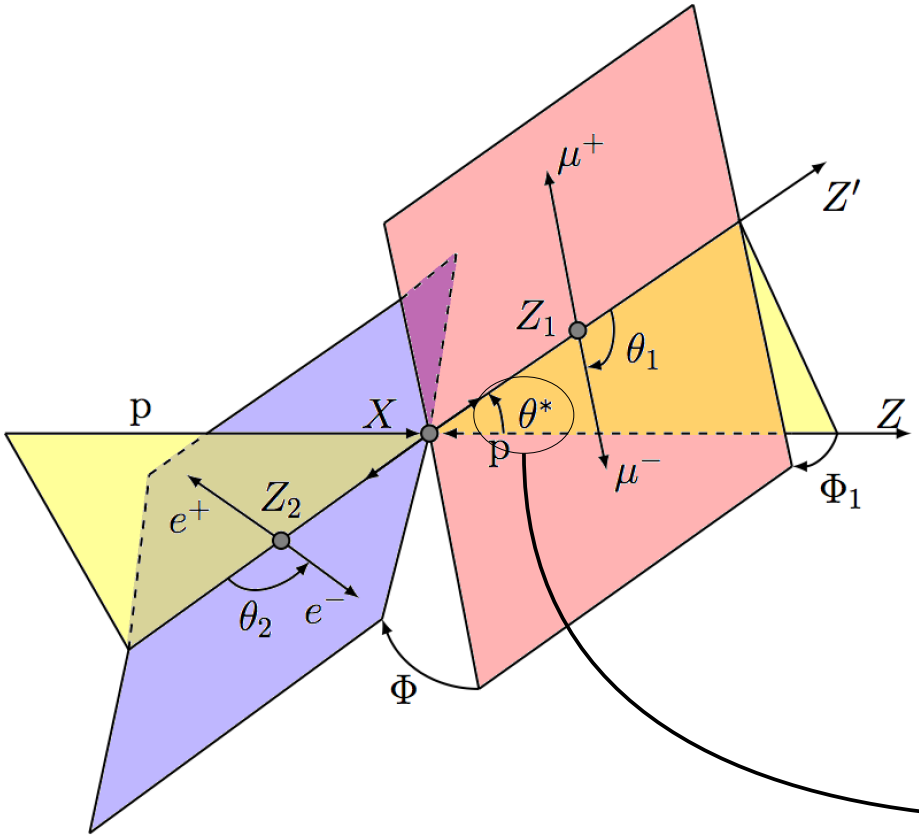


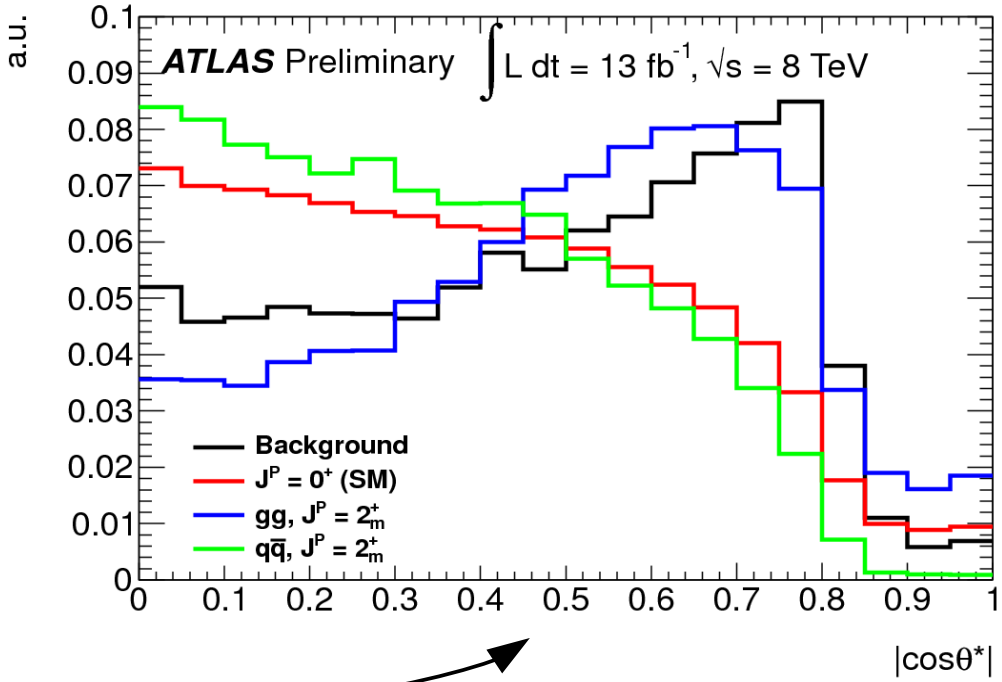
- Valeurs autorisées selon le mode de désintégration :

	spin 0	spin 1	spin 2
$H \to WW, H \to ZZ$	✔	✔	✔
$\gamma\gamma$	✔	✘	✔
$H \to \tau\tau, H \to b\bar{b}$	✔	✔	✘ ← pas encore observé

Mesure de spin (2)

- Tests des hypothèses de spin avec variables angulaires :





- Résultats:
  - spin 2 exclu à >99.9%
  - compatible avec spin 0

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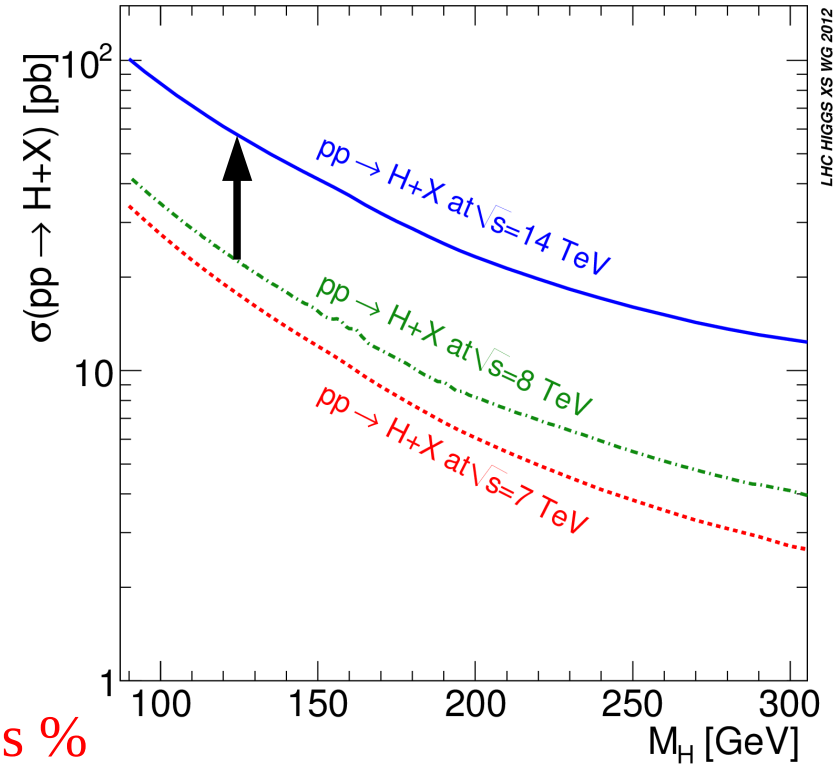
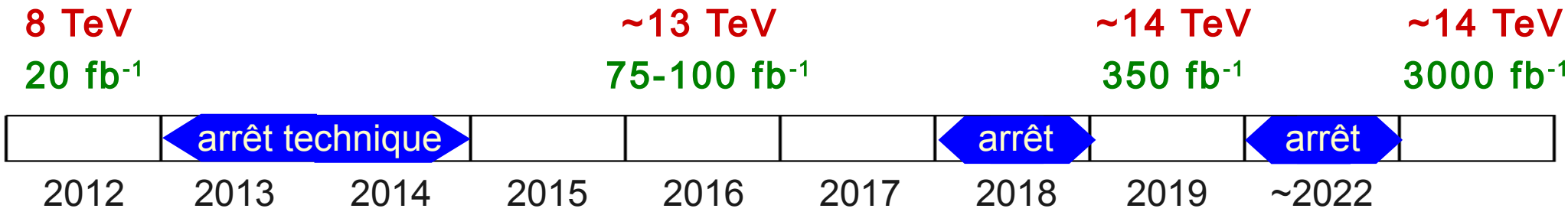
CMS-PAS-HIG-13-002

Conclusion

- Découverte en juin 2012 d'un boson de Higgs
  - 48 ans après sa prédiction !
- Masse ~125 GeV
- Couplages compatibles avec prédictions
- Spin compatible avec 0
- En 2015: √s = 13 TeV
  - σ(Higgs) x 2.5
- A la fin du LHC, mesures couplages à quelques %



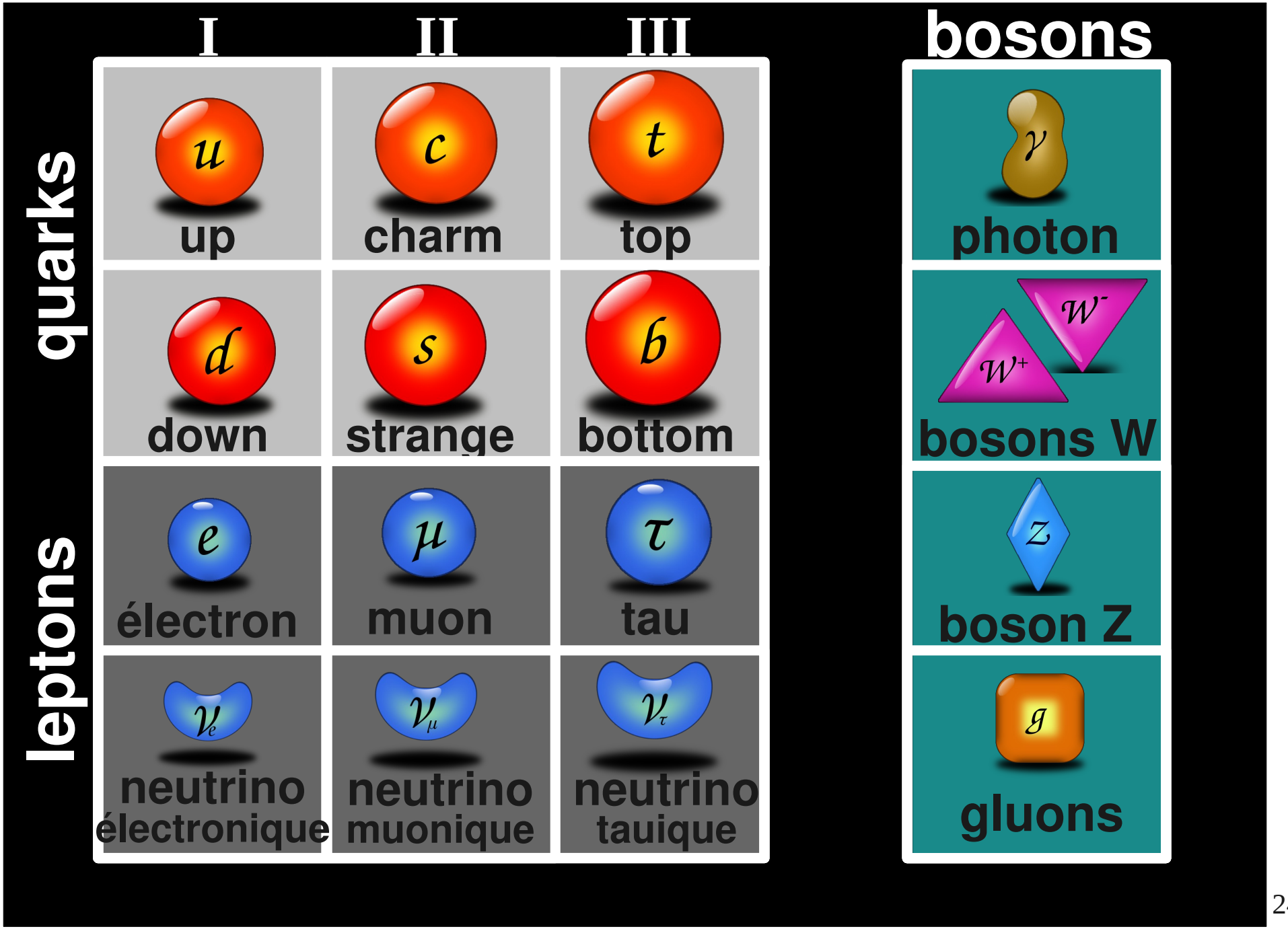


Back-up slides

"Take a look at this everyone - it just could be the signature we've been looking for!"

image : http://www.lhc-france.fr

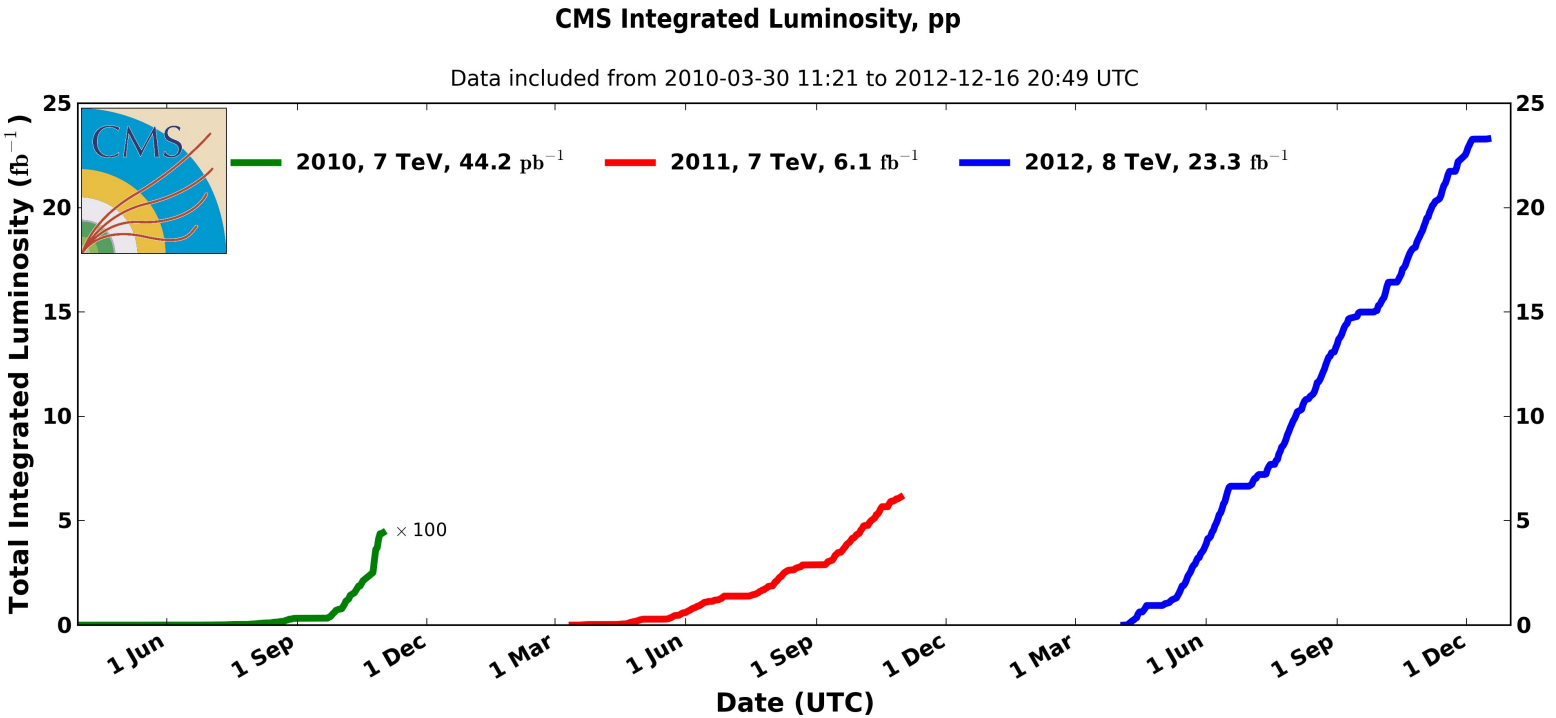
Le modèle standard de la physique des particules



Le LHC (3)

- Luminosité instantanée : $L_{inst} = \frac{f.N^2}{4\pi.\sigma_x.\sigma_y}$
  - f: fréquence de révolution
  - N: nombre de paquets
  - σ: taille transverse des faisceaux

- Luminosité intégrée : $L_{tot} = \int L_{inst}\, dt$



Collaborations

CMS
collaboration

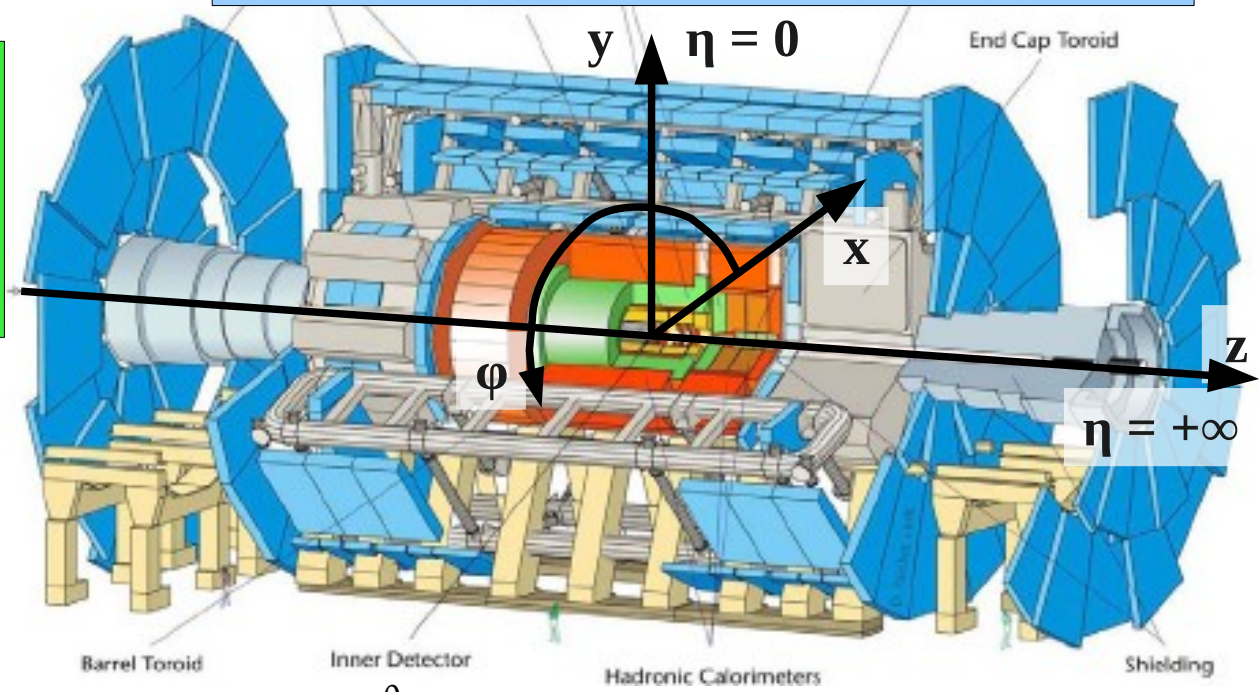
The ATLAS experiment

Inner detector (2 T)
$|\eta| < 2.5$
Si Pixel et SCT, TRT
tracks, vertex
$\sigma/p_T \sim 0.05\% \; p_T$ (GeV) $\oplus$ 1%

Electromagnetic calorimeter
$|\eta| < 3.2$
Pb + LAr
electrons, photons, trigger
$\sigma/E \sim 10\%/\sqrt{E}$ (GeV) $\oplus$ 0.7%

Hadronic calorimeter
$|\eta| < 4.9$
Fe/Tile (central)
Cu/W + LAr (forward)
jets, E_T^{miss}, trigger
$\sigma/E \sim 50\%/\sqrt{E}$ (GeV) $\oplus$ 3%

Muon spectrometer (0.5 T)
$|\eta| < 2.7$
gas chamber in toroidal magnetic field
tracks, trigger
$\sigma/p_T < 10\%$ up to 1 TeV



$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- > 96% operating channels
- > 90% of data used for physics

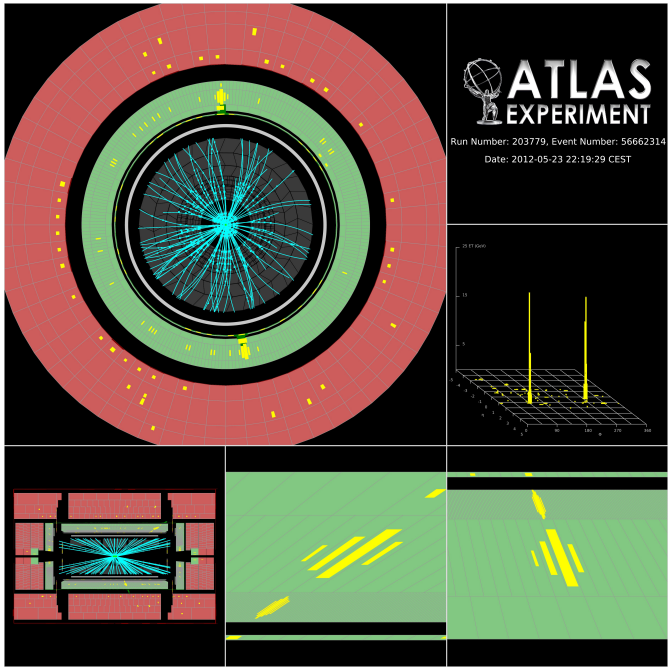
➔ Very good behaviour of all sub-detector

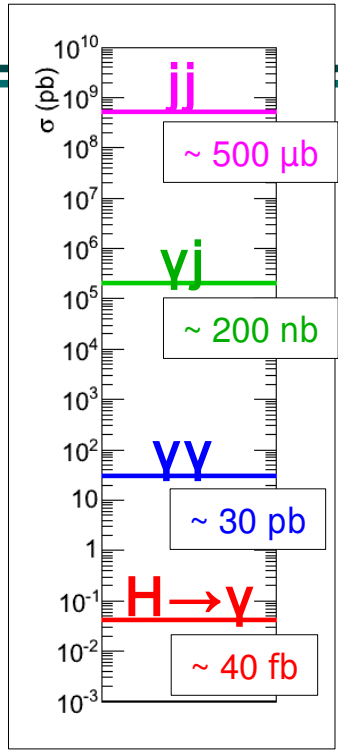
38 countries
~ 3000 members

Recherche dans le canal di-photons

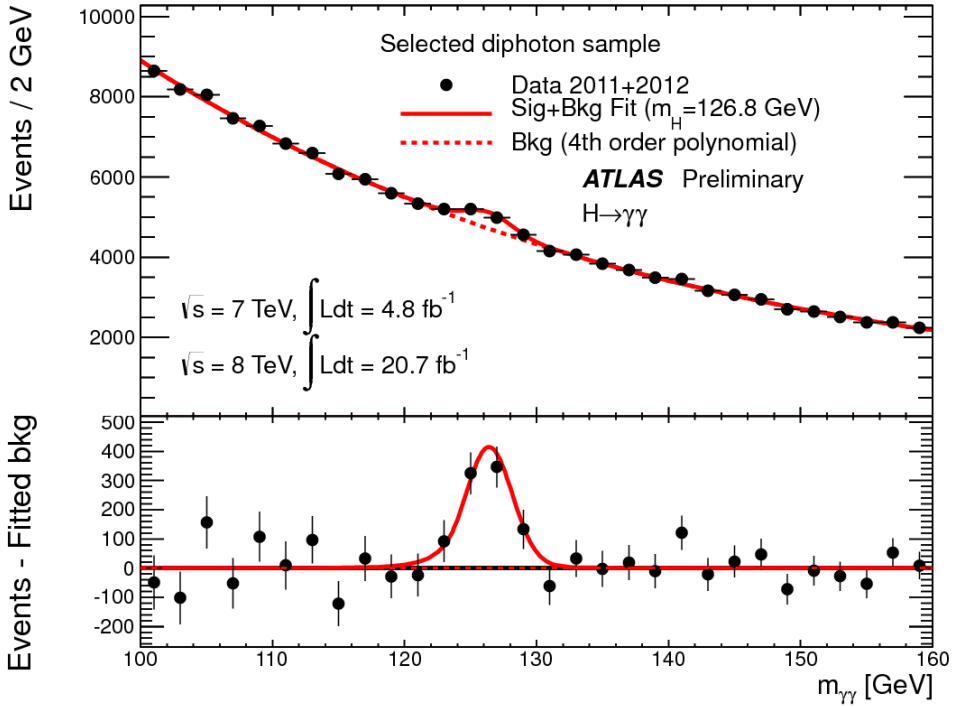
- Sélection des évenements
  - 2 photons isolés
  - $E_T^1 > 40$ GeV, $E_T^2 > 30$ GeV
  - identification photons / jets

    (~75% d'événements di-photons)





- Fit des données pour recherche excès



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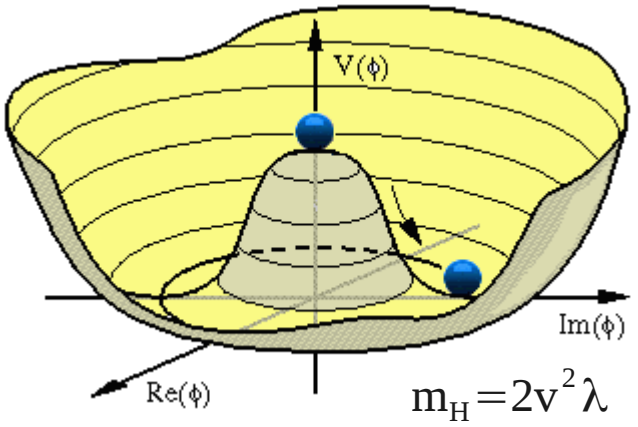
Premières mesures de couplages

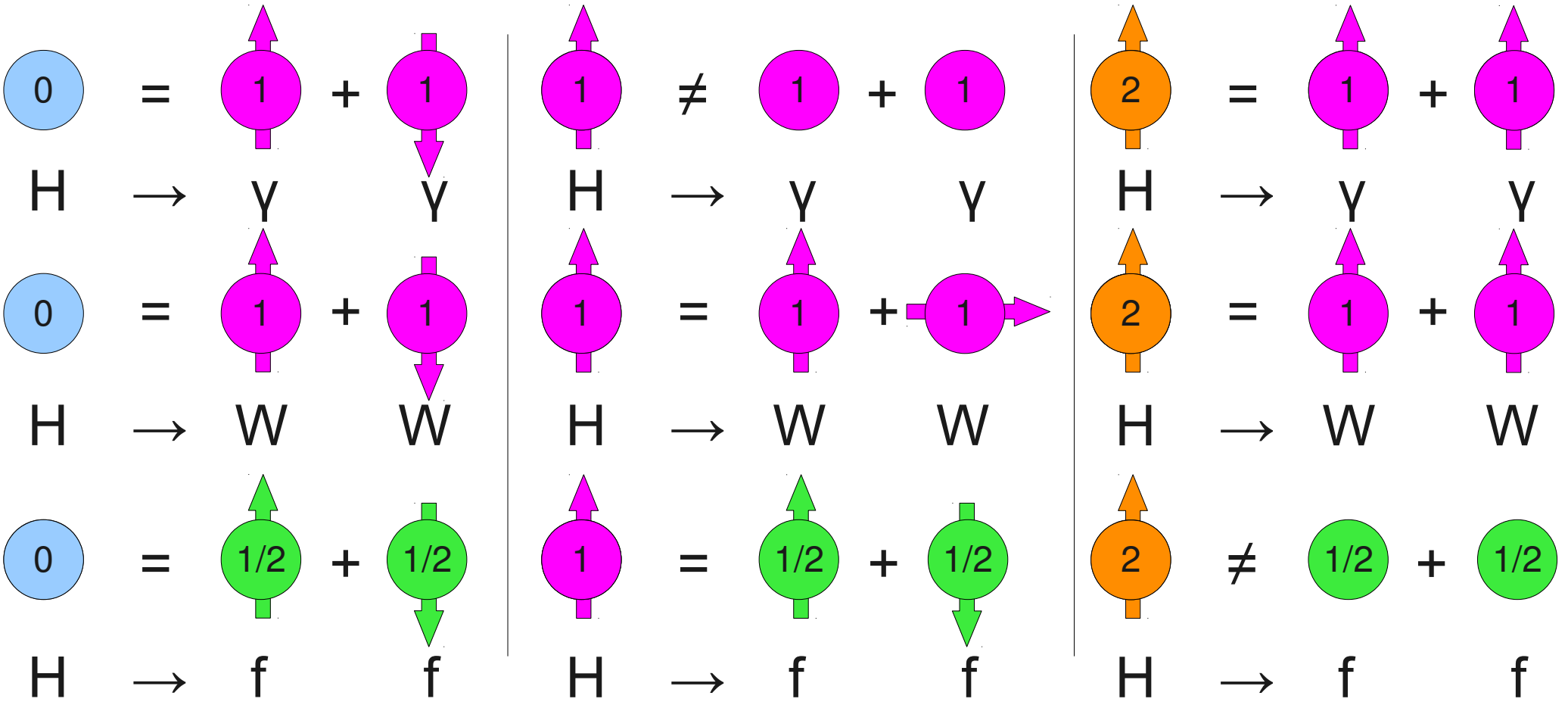
- Couplage du boson de Higgs aux particules $\propto$ leur masse
  - bosons: $g_{HVV} \propto \frac{m_V^2}{v} \propto m_W \propto \frac{m_Z}{2\cos(\theta_W)}$
  - fermions: $g_{Hff} \propto \frac{m_f}{v} \propto \frac{m_f}{2m_W} \propto m_f \cdot \sqrt{\frac{2.\lambda}{m_H}}$
  - v : vacuum expectation value, $v = \frac{1}{(\sqrt{2}\,G_F)^{1/2}} = \frac{2m_W}{g}$



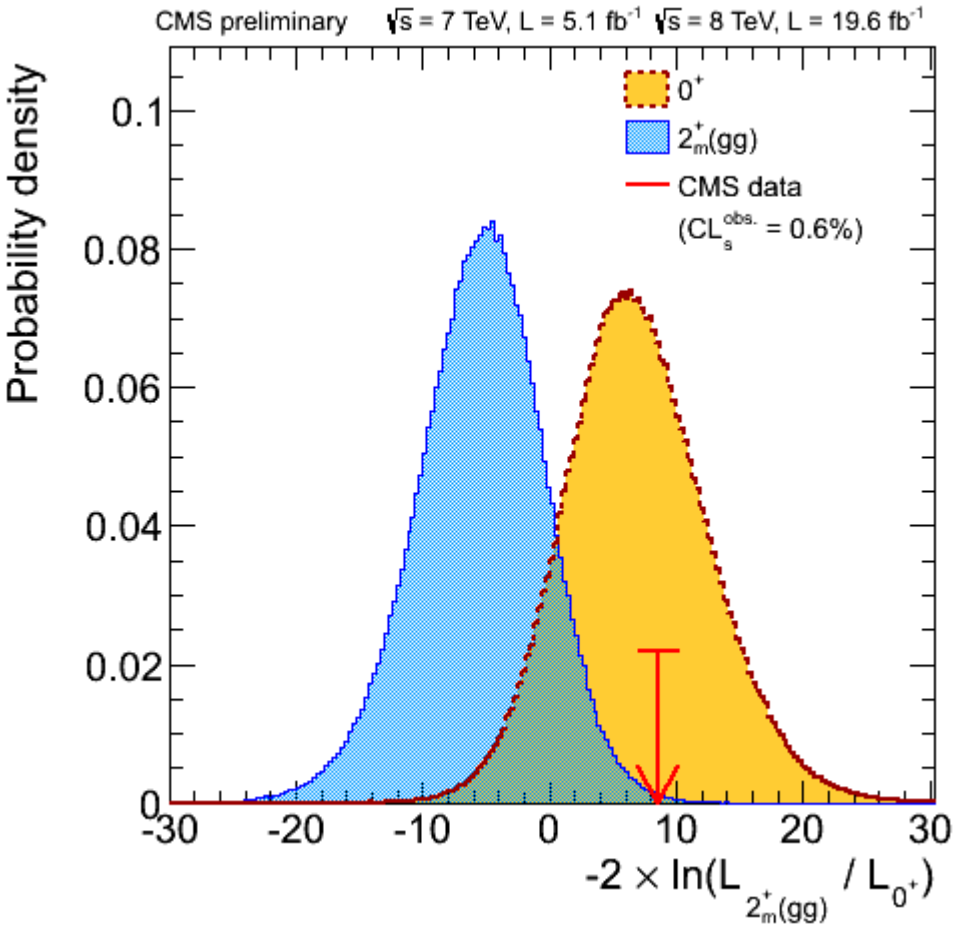
$m_H = 2v^2\lambda$

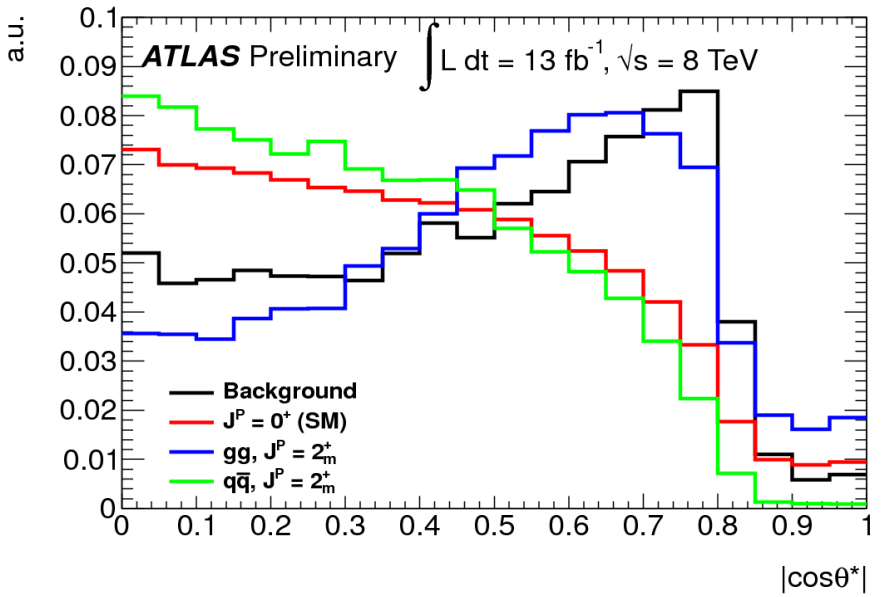
Mesure de spin

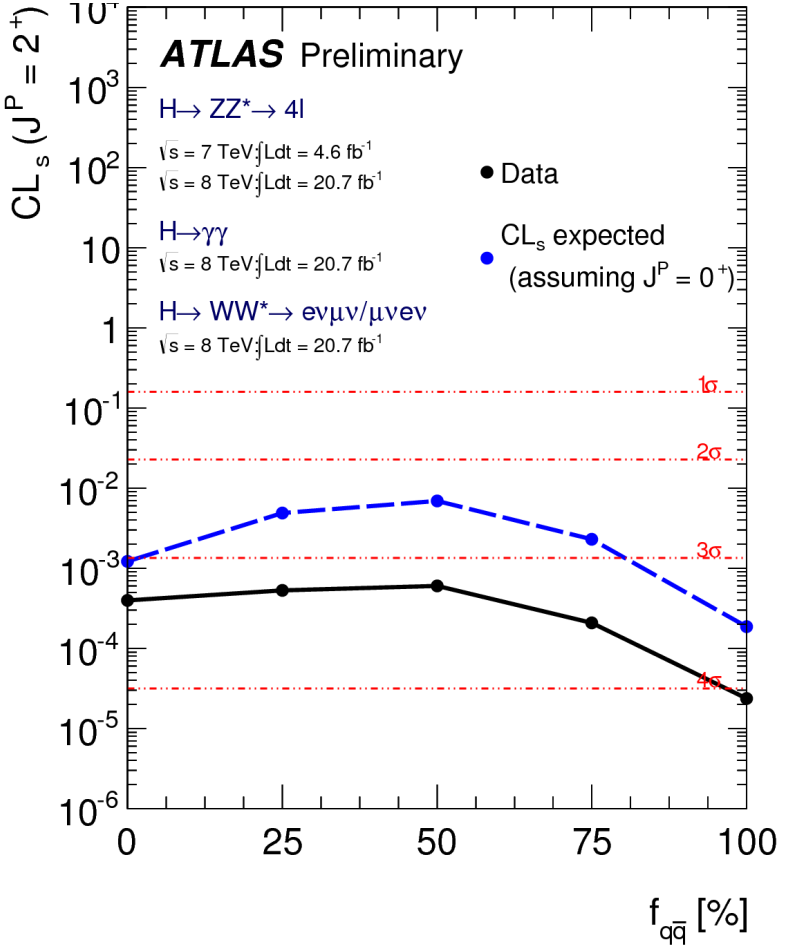
- Boson de Higgs de spin 0
- Valeurs autorisées selon le mode de désintégration :



Spin results

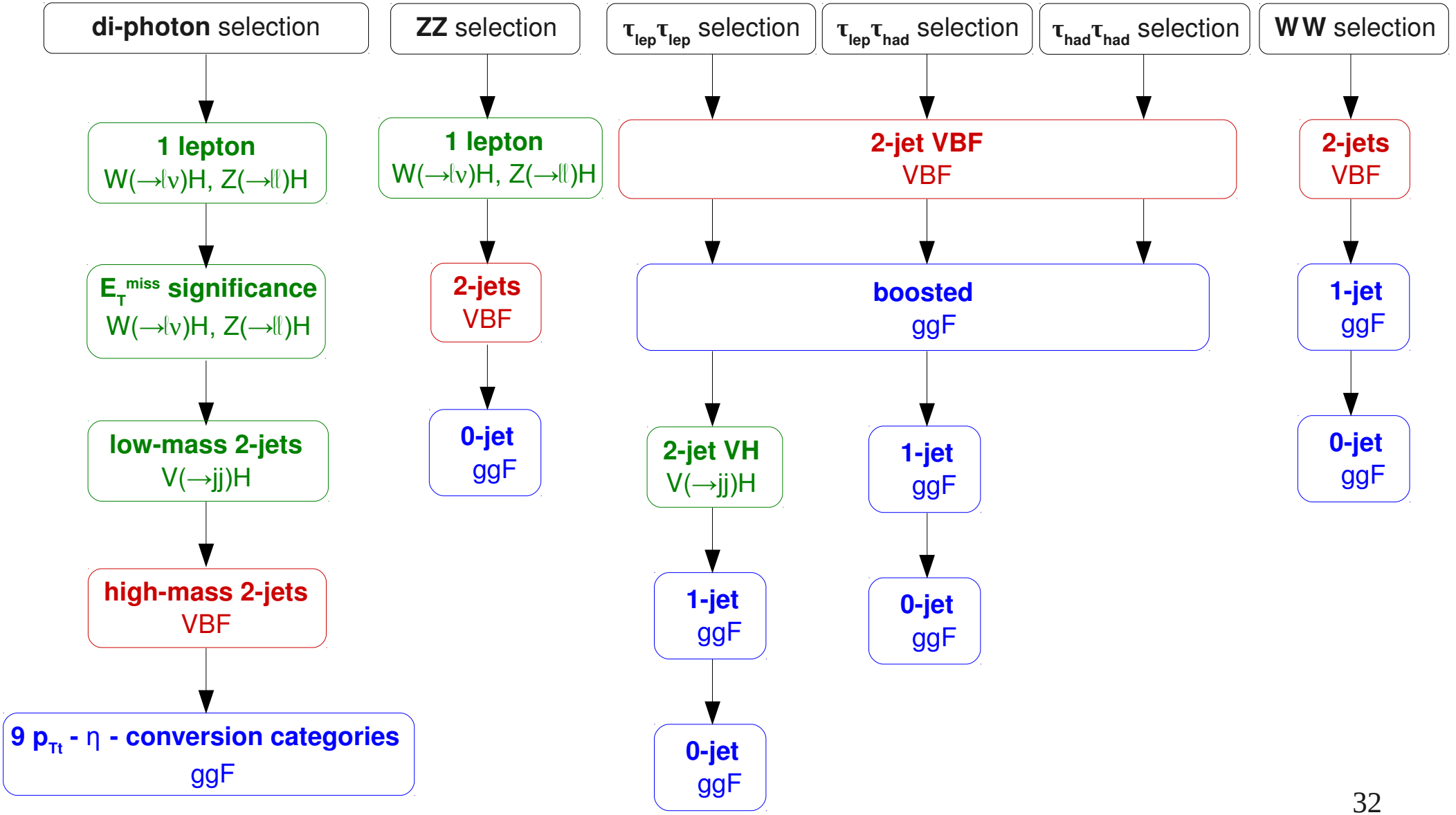






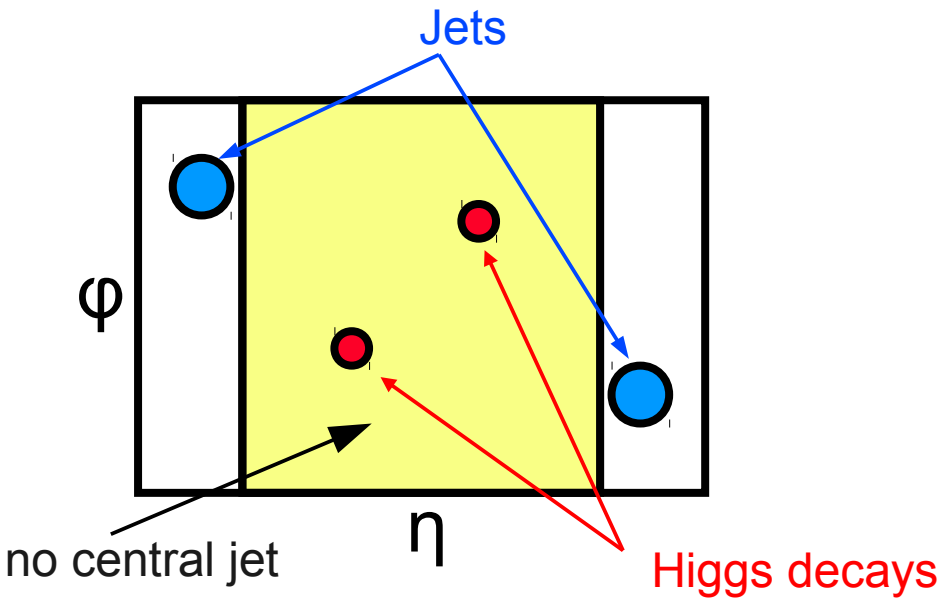
Analyses flow-charts

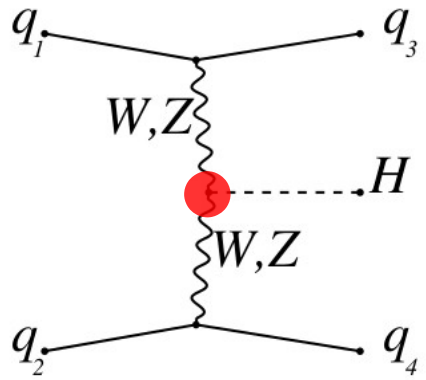
- Datasets divided in exclusive categories

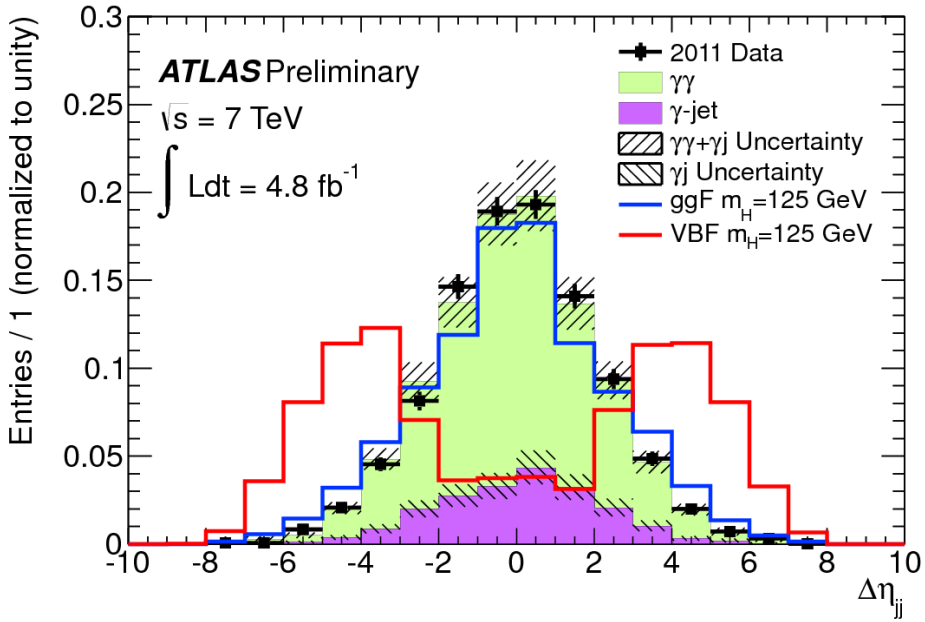


Look for VBF mode

- Cross-section at 125 GeV: 1.578 pb
- Higgs boson produced with 2 forward jets:



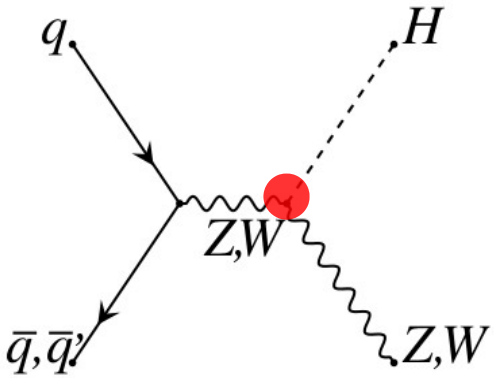




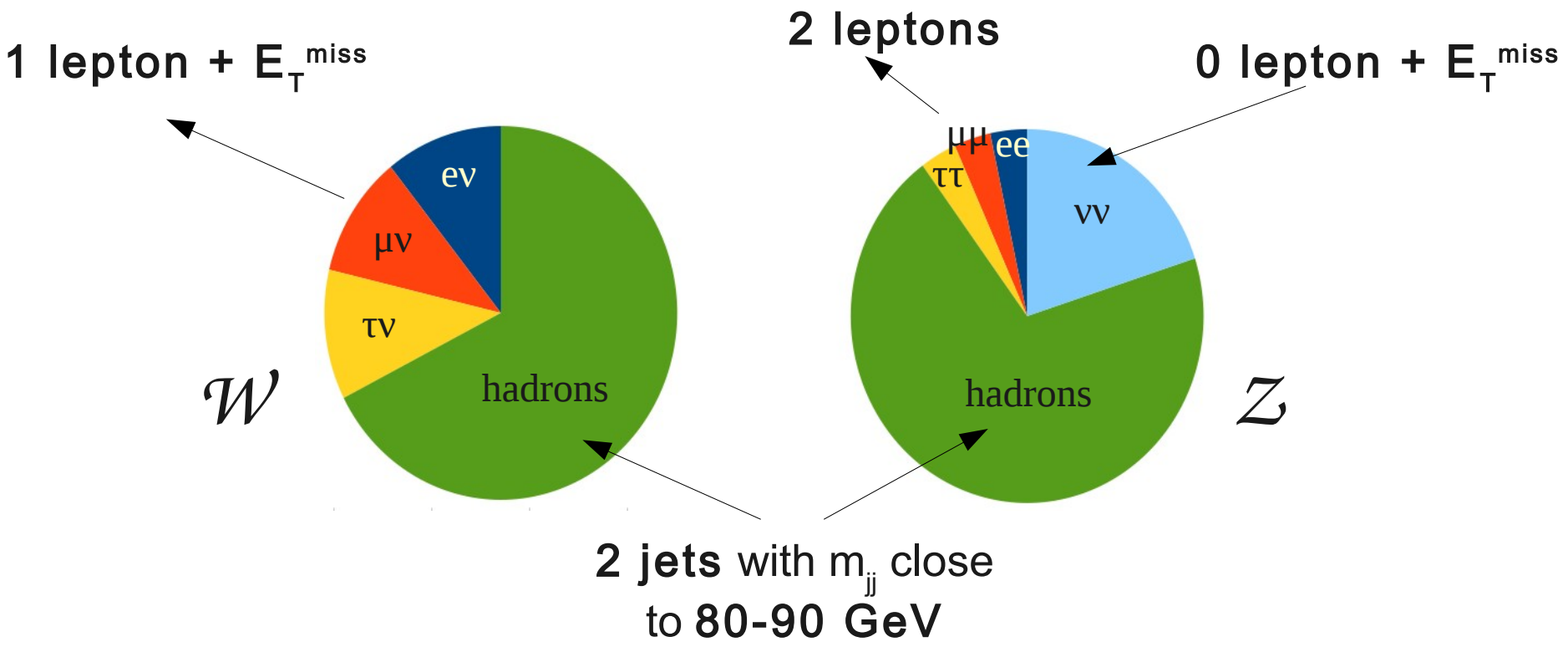
- Usual cuts:
  - $\Delta\eta_{jj}$
  - m_{jj}
  - veto 3rd central jet
- One of main uncertainties: knowledge of ggF + 2 jets
  - 25% to 30%

Look for VH mode

- Cross-section at 125 GeV: 0.6966 + 0.3943 pb

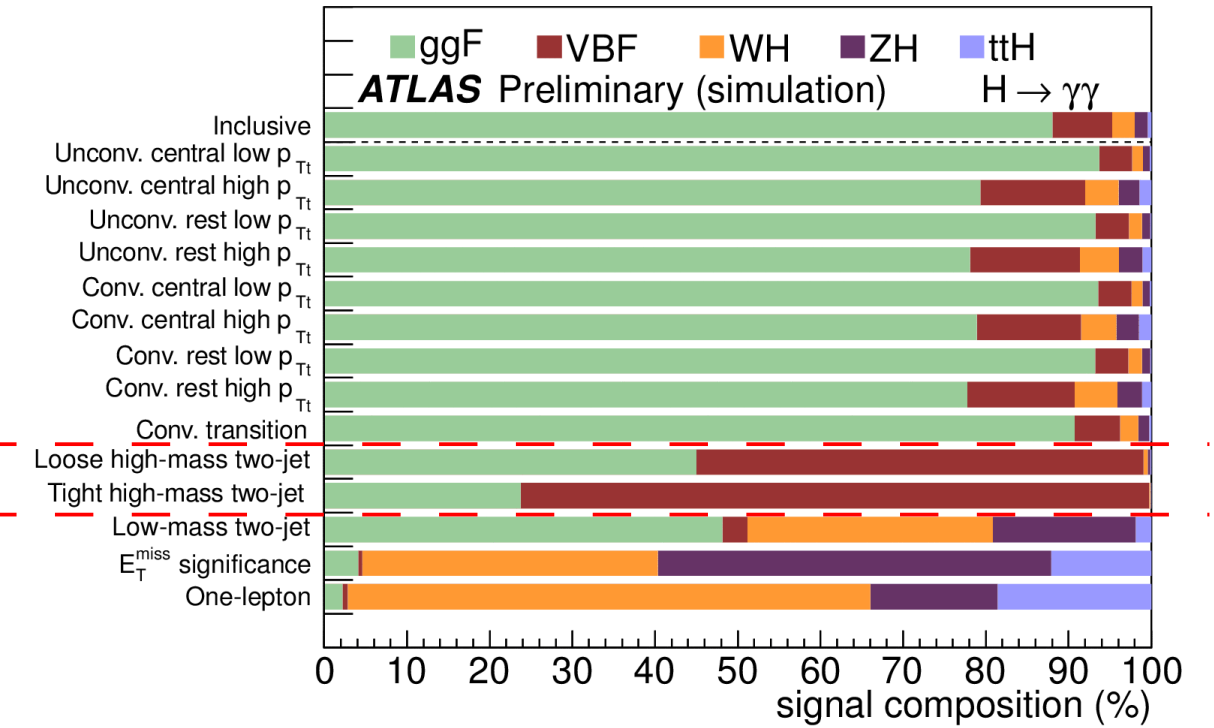


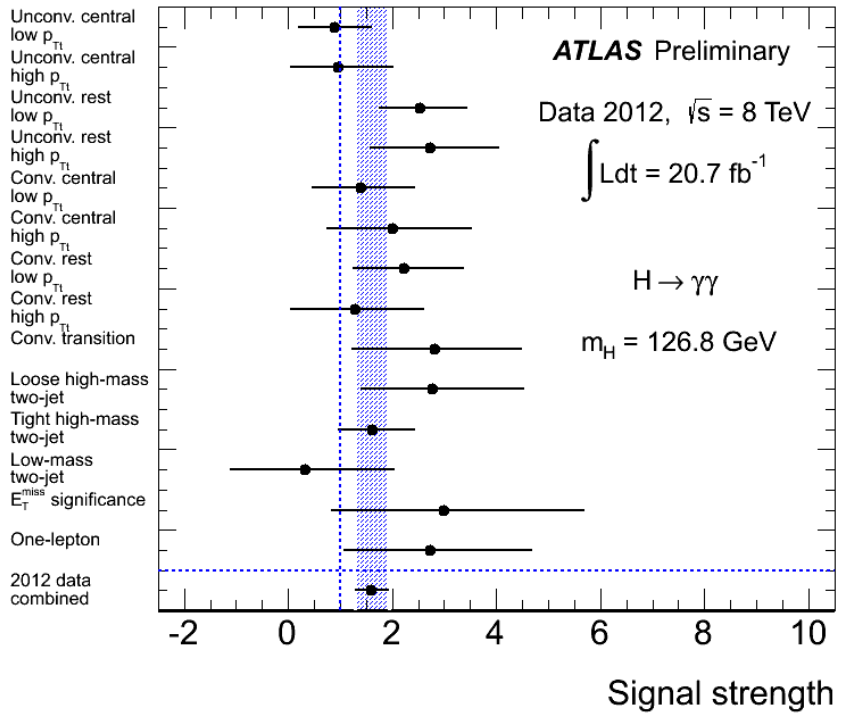
- Divide into categories depending on the W/Z decay



H→γγ: signal strength / category

- Signal composition /category:



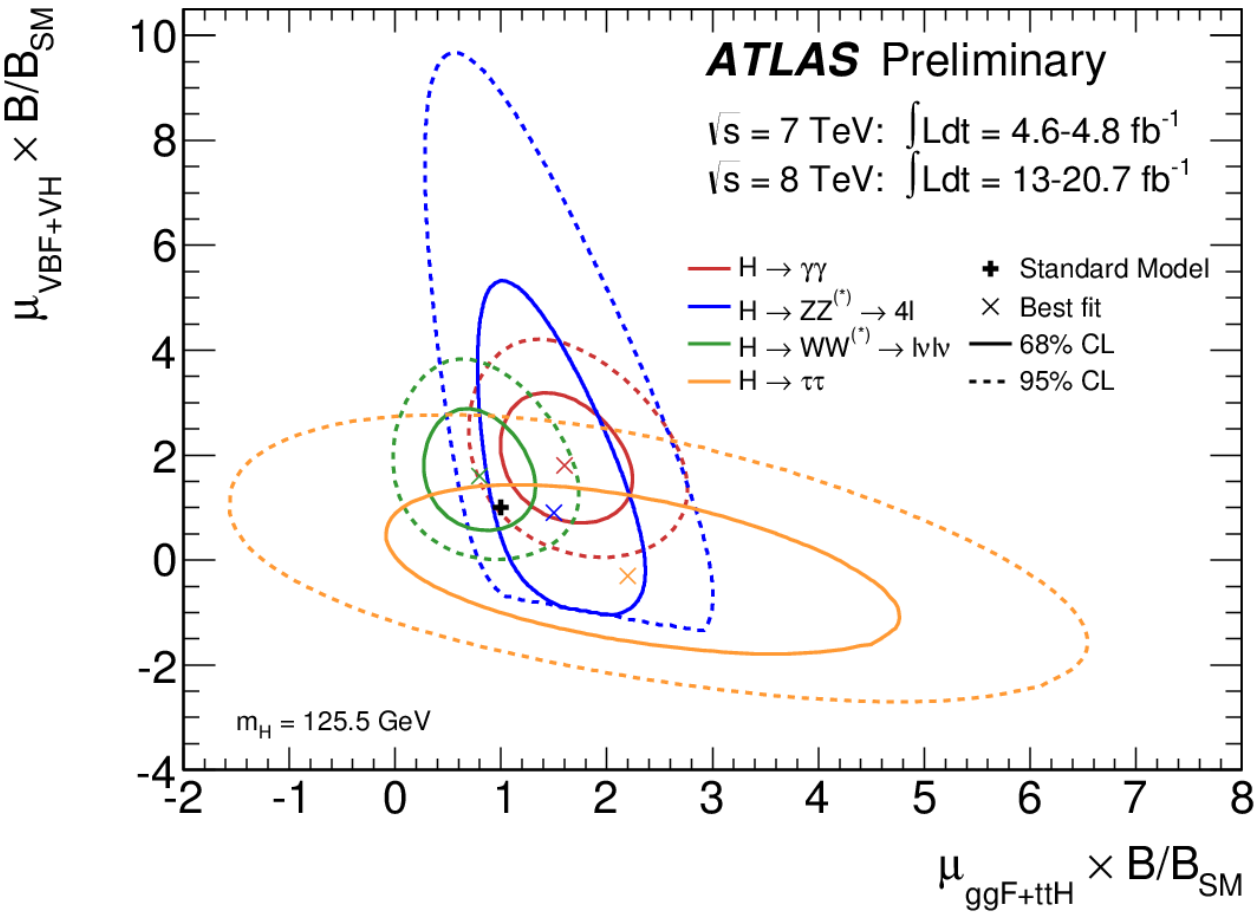


- None of those categories is 100% pure in targeted process

Signal strength / production mode

- Signal strength parameter for each production mode: $\mu_i = \frac{N_i^{observed}}{N_i^{SM\,Higgs}}$
  - i = ggF, VBF, VH, ttH

- For $H \to ZZ$, $H \to \tau\tau$ and $H \to WW$ channels



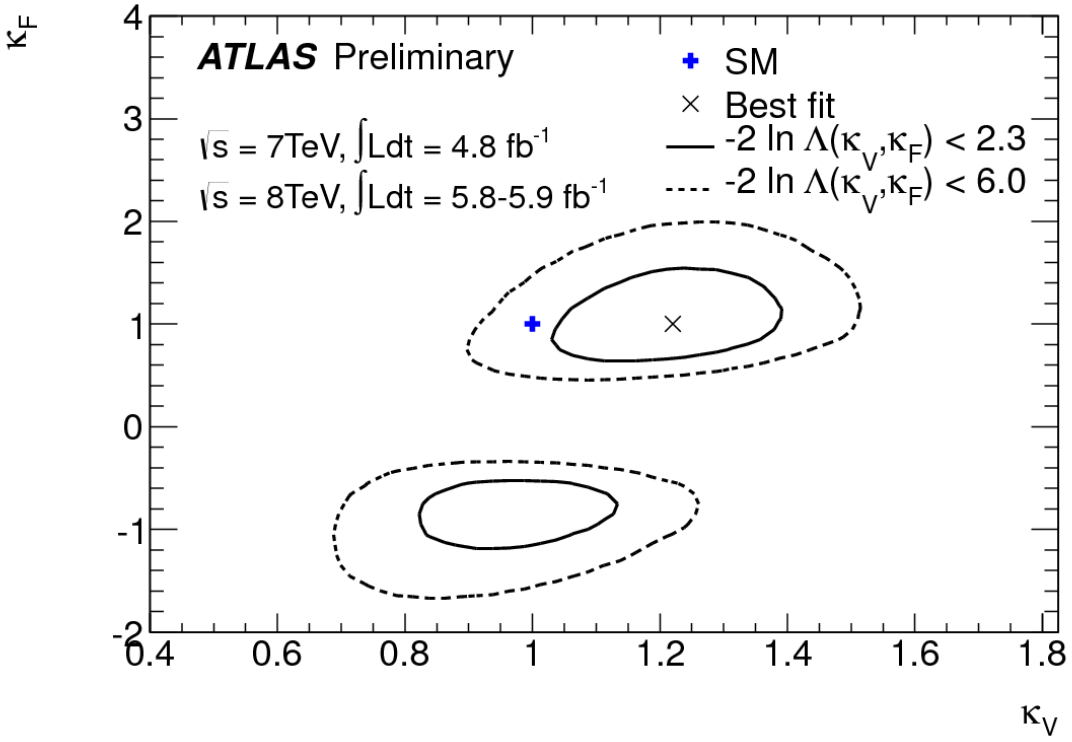
Coupling fits

- 4.8 fb^{-1} $\sqrt{s}$=7 TeV, 5.8 fb^{-1} $\sqrt{s}$=8 TeV
- Global fits with 5 channels
- Hypotheses:
  - single resonance
  - spin 0
  - Higgs boson width negligible
- Cross-section expressed as: $\sigma \cdot BR(ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$

- To compare σ_{ii} and Γ_{ii} to SM predictions, introduce scale factors κ_i
  - example 1 : $\kappa_W^2 = \frac{\sigma_{WH}}{\sigma_{WH}^{SM}}$ and $\kappa_W^2 = \frac{\Gamma_{WW^*}}{\Gamma_{WW^*}^{SM}}$
  - example 2: $\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, \kappa_{BSM\,particule}?, m_H)$

Couplings to fermions and vector bosons

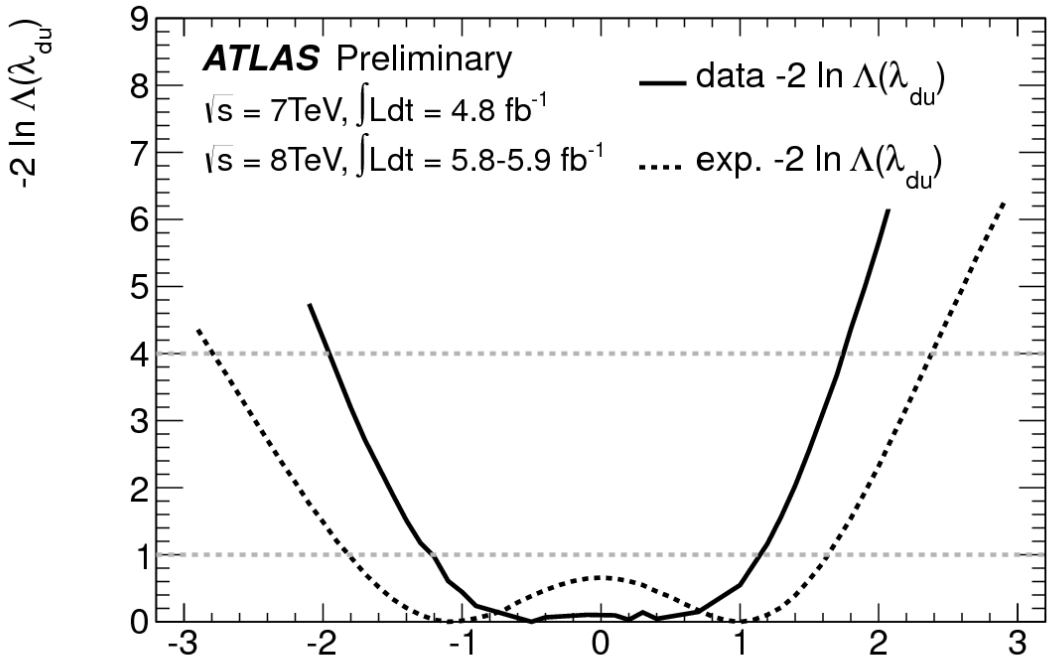
- Assume same scale factors for bosons and fermions
  - $\kappa_V = \kappa_W = \kappa_Z$
  - $\kappa_F = \kappa_\tau = \kappa_b = \kappa_t$
- Assume no BSM contribution to total width or to γγ loop:



- Compatibility of SM with best fit point: 21%

Up/down symmetry

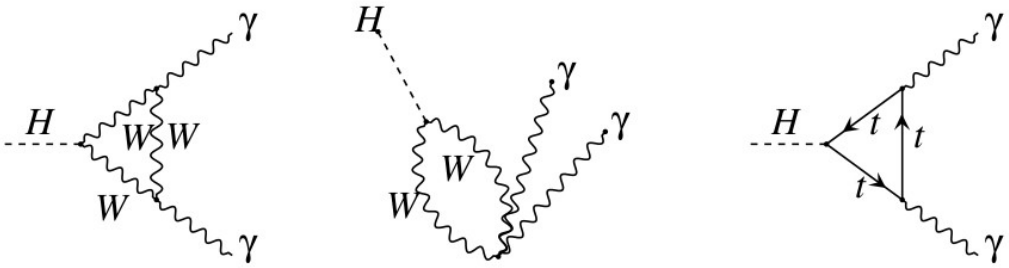
- Some super-symmetry scenarios: different couplings to up and down type quarks
- Define $\lambda_{ud} = \kappa_u/\kappa_d$
  - keep $\kappa_V = \kappa_W = \kappa_Z$



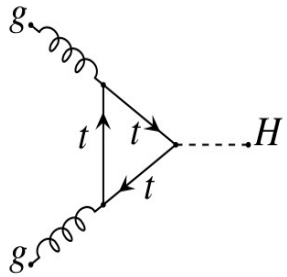
- Best fit: $\lambda_{ud} \in [-2.0\ ;\ 1.8]$ at 95% CL
  - dominated by $H \to \tau\tau$ and $H \to b\bar{b}$

New contributions to gg/γγ loops

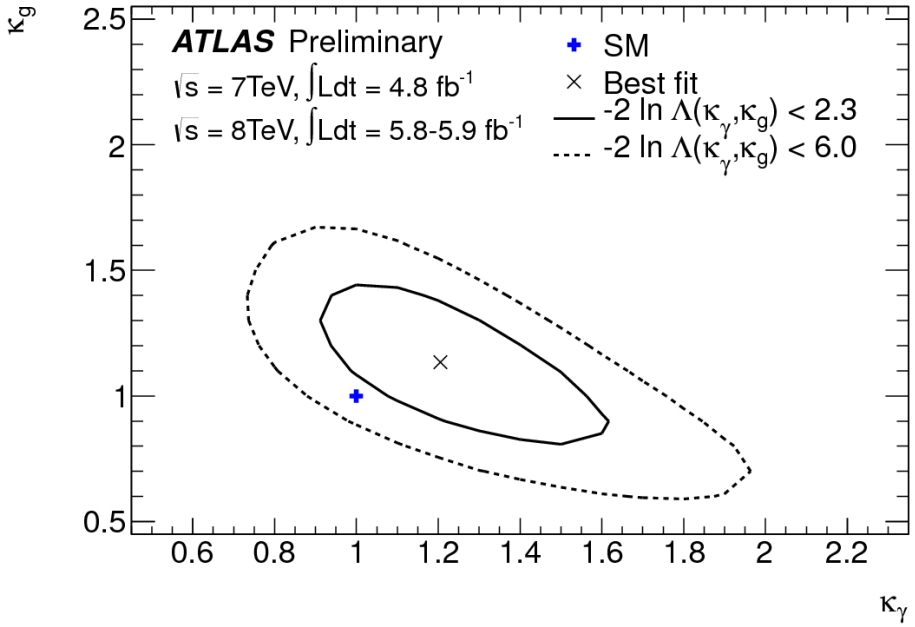
- Main contributions to $H \to \gamma\gamma$ decay:



- Best fit signal strength: $\mu = 1.65^{+0.34}_{-0.30}$
  - one hypothesis: non-SM particles in γγ loop
- Assume no Higgs boson decays into BSM particles



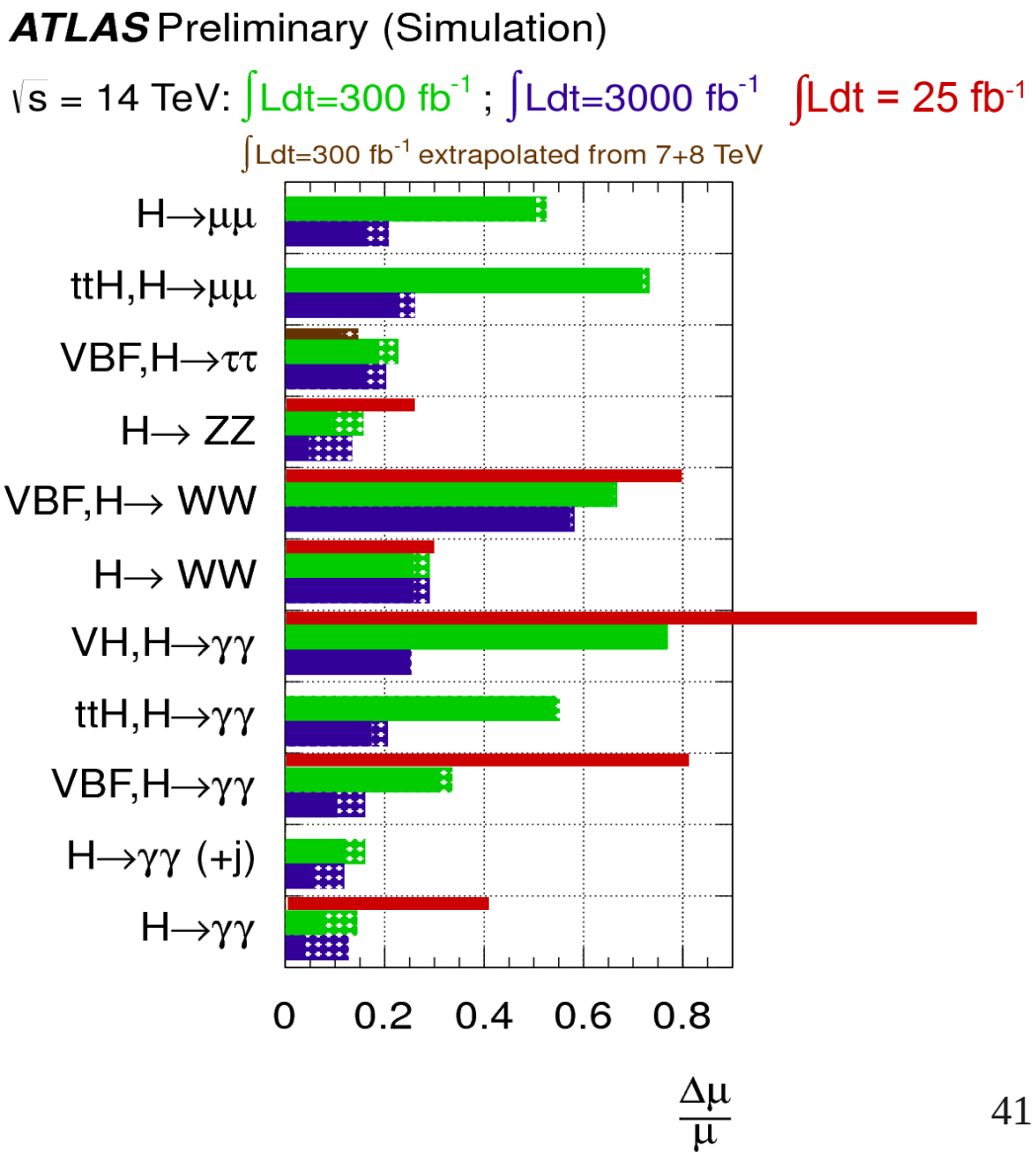
- All $\kappa_i = 1$, except κ_g and κ_γ



- Best fit:
  - $\kappa_g = 1.1^{+0.2}_{-0.3}$
  - $\kappa_\gamma = 1.2^{+0.3}_{-0.2}$
- Compatibility of SM with best fit point: 18%

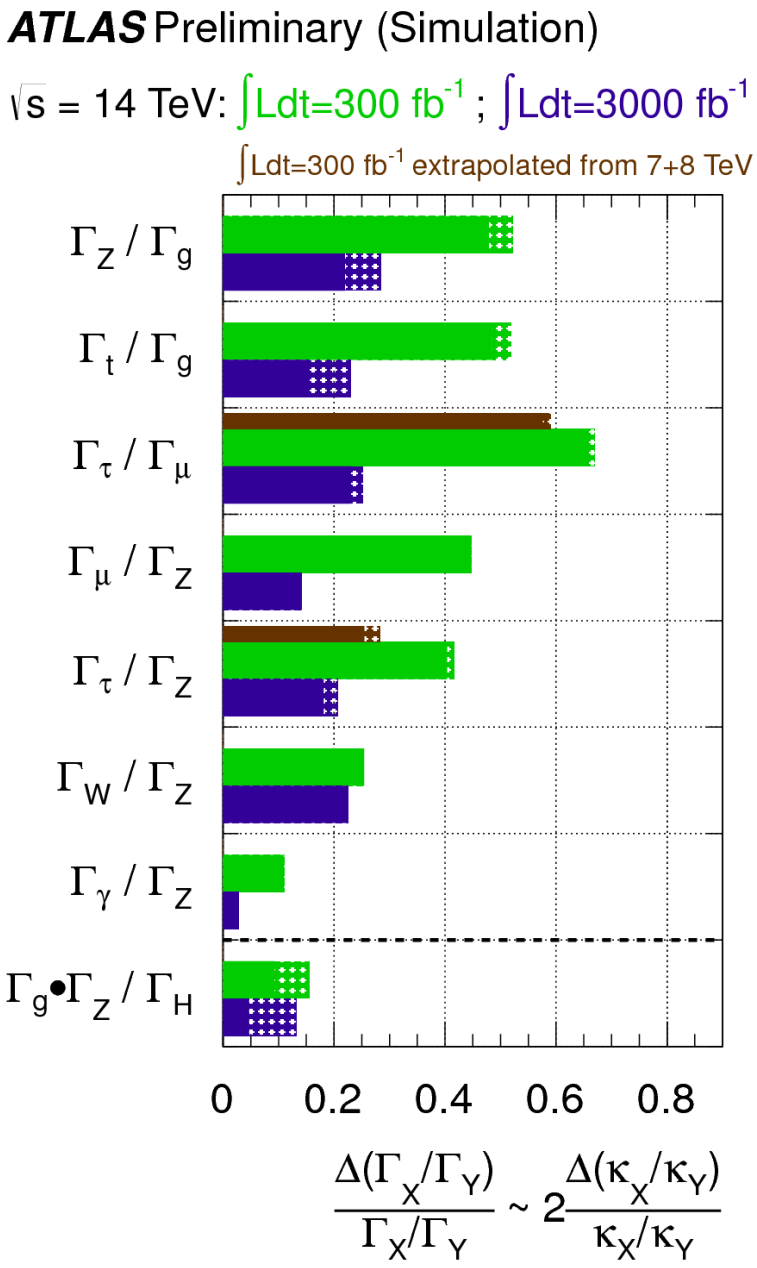
Long term prospects (1)

- With 2011+2012 dataset, possible to have first test of couplings
  - look for deviations due to Beyond SM physics
- Future of LHC
  - ~2018-2022: 300 fb^{-1}
  - > ~2022: HL-LHC: 3000 fb^{-1}
- Signal strengths:



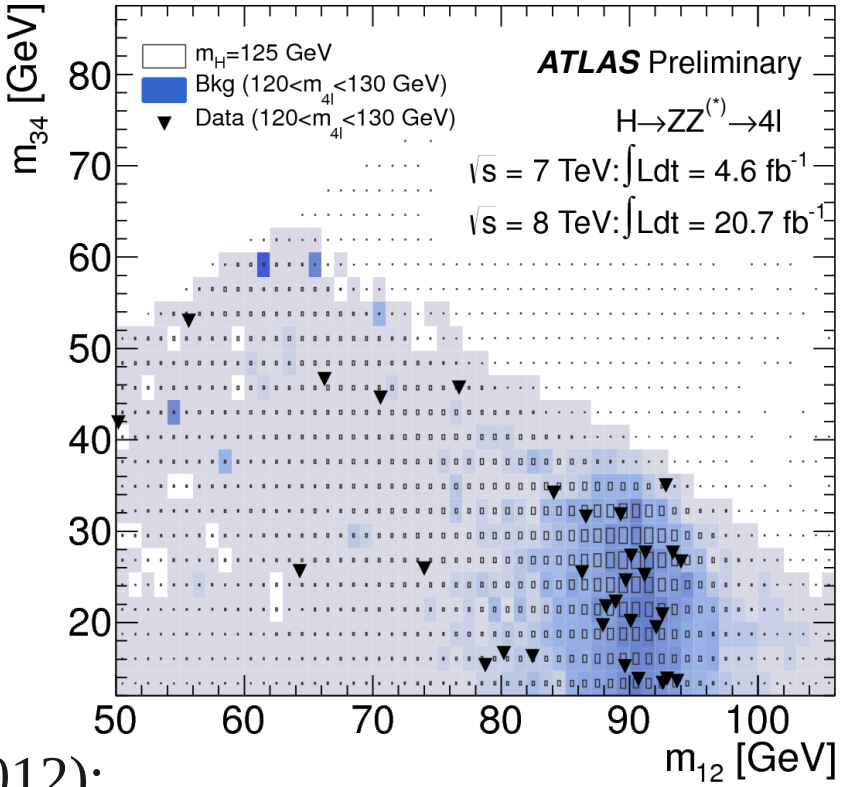
Long term prospects (2)

- Couplings parameters
  - no measurement of total width
  - only ratios: $\frac{\Gamma_i}{\Gamma_j}$
- With 300 fb^{-1}
  - 20-60% precision
- With 3000 fb^{-1}
  - almost all couplings better than 20%
  - at minimum: ~5% uncertainties



H→ZZ* (1)

- Two same flavour, opposite sign lepton pairs
  - well identified and isolated
  - p_T^l > 20-15-10-7/6 GeV



- 50 < m_{12} < 106 GeV
- 12 < m_{34} < 115 GeV for m_{4l} < 145 GeV
- Number of expected signal events (2011+2012):

category	ggF	VBF	VH
ggF-like	15.7	0.93	0.76
VBF-like	0.31	0.49	0.01
VH-like	0.07	-	0.17

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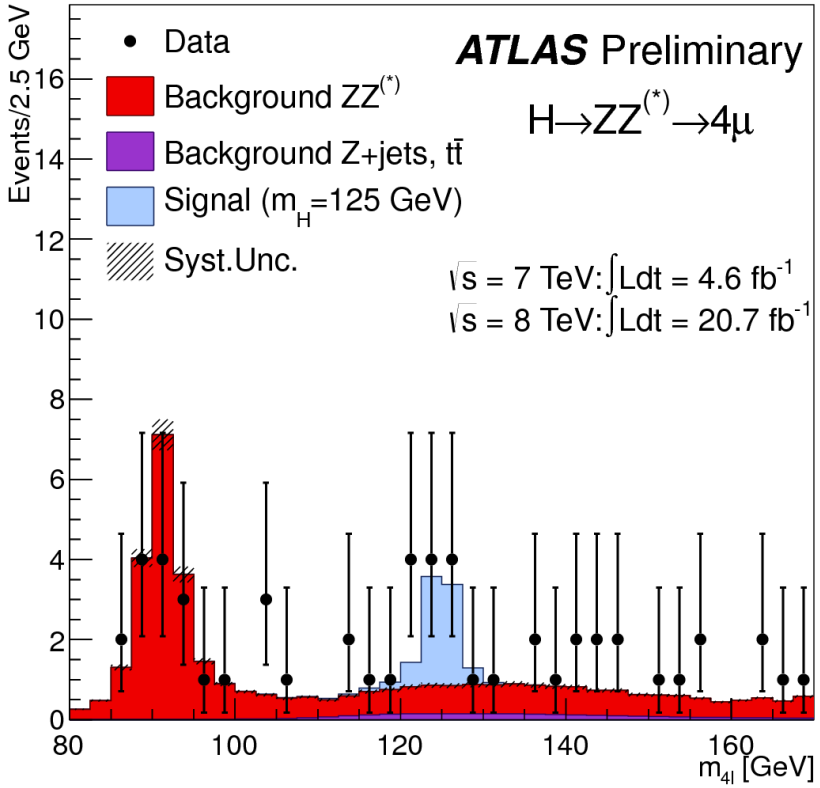
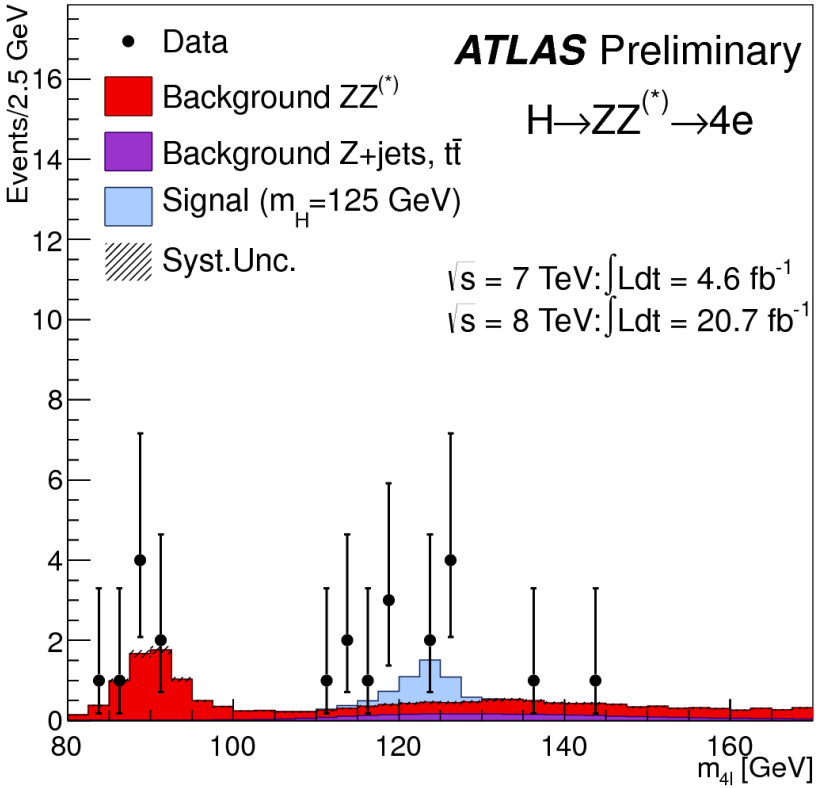
H→ZZ* (2)



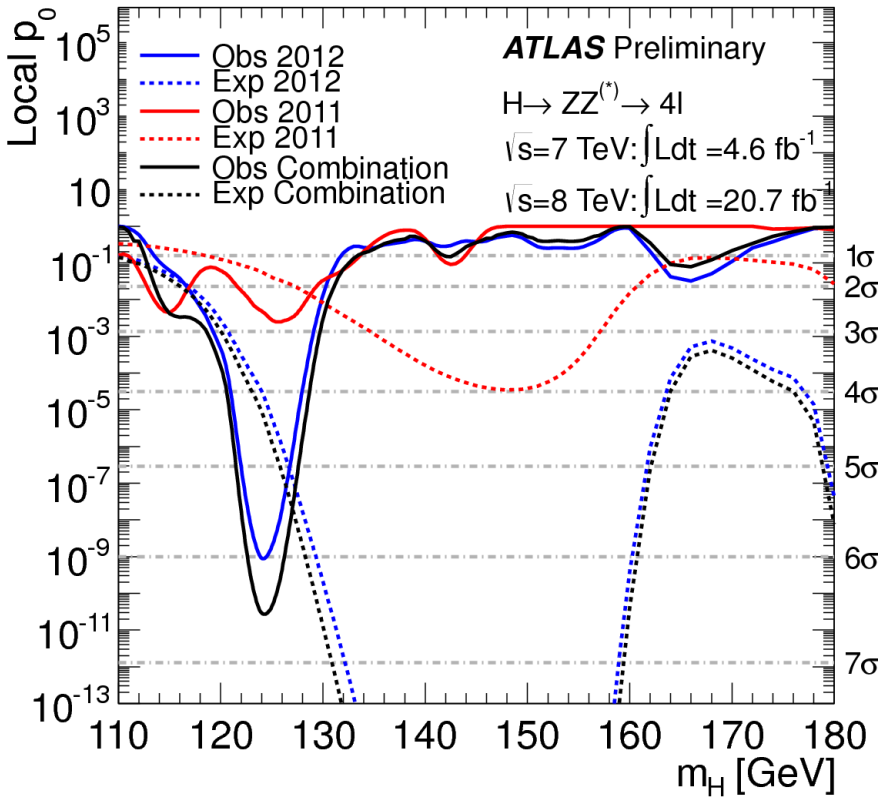


♦ In 120-130 GeV window (7+8 TeV):

	4μ	2e2μ	2μ2e	4e	total
signal	6.3	3.0	4.0	2.6	15.9
ZZ	2.8	1.4	2.1	1.2	7.4
Z, Zbb̄, tt̄	0.55	1.6	0.6	1.1	3.7
observed	13	5	8	6	32

H→ZZ* (3)

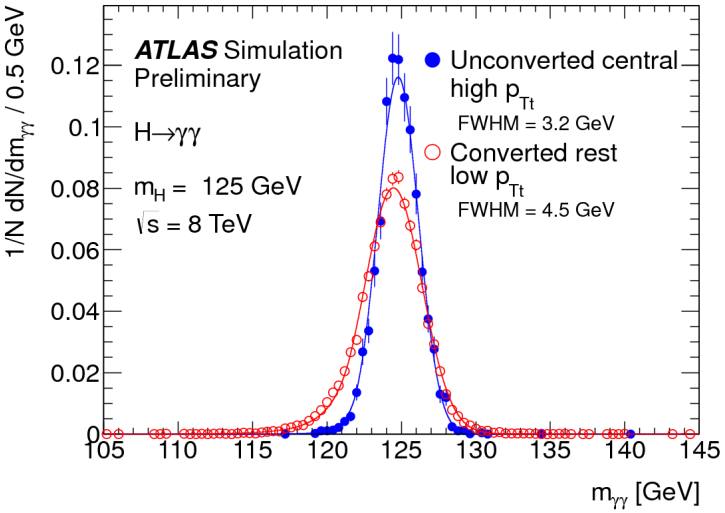
- Excess:
  - expected: 3.1σ
  - observed: 4.1σ

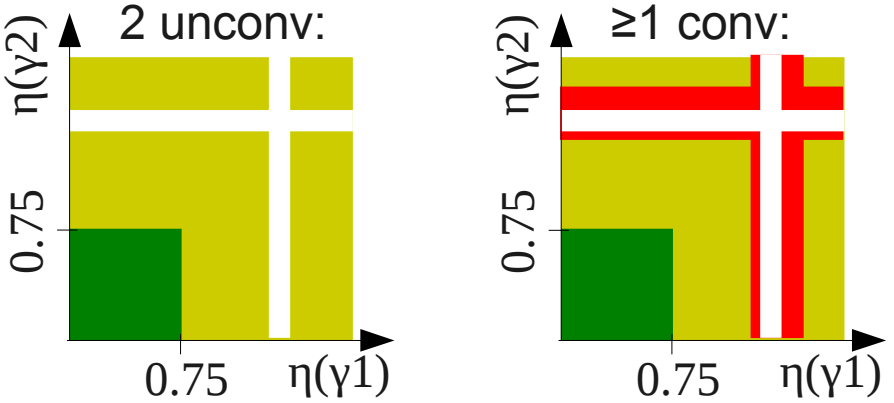


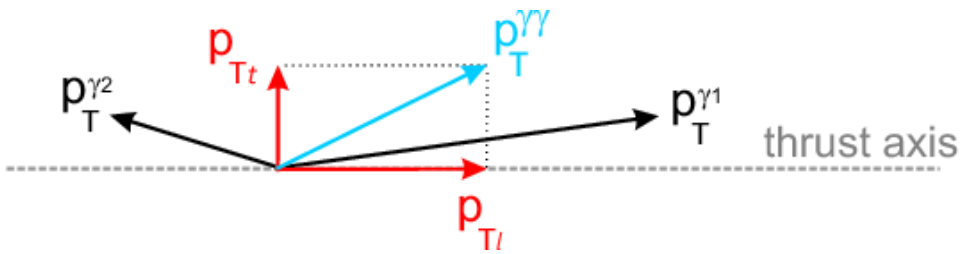
- Best fit for mass:
  $124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\,\text{GeV}$
- Signal strength at 124.3 GeV: $\mu = 1.7^{+0.5}_{-0.4}$

H→γγ (1)

- Two well identified and isolated photons
  - $E_T^{\gamma 1} > 40$ GeV, $E_T^{\gamma 2} > 30$ GeV
  - γγ purity: 75%
- Events divided in 12 exclusive categories
  - with ≠ resolution: 1.4 → 2.5 GeV
  - with ≠ S/B: 0.014 → 0.204
  - with ≠ production modes fractions
    - 9 ggF enriched
    - 1 VBF enriched
    - 2 VH enriched







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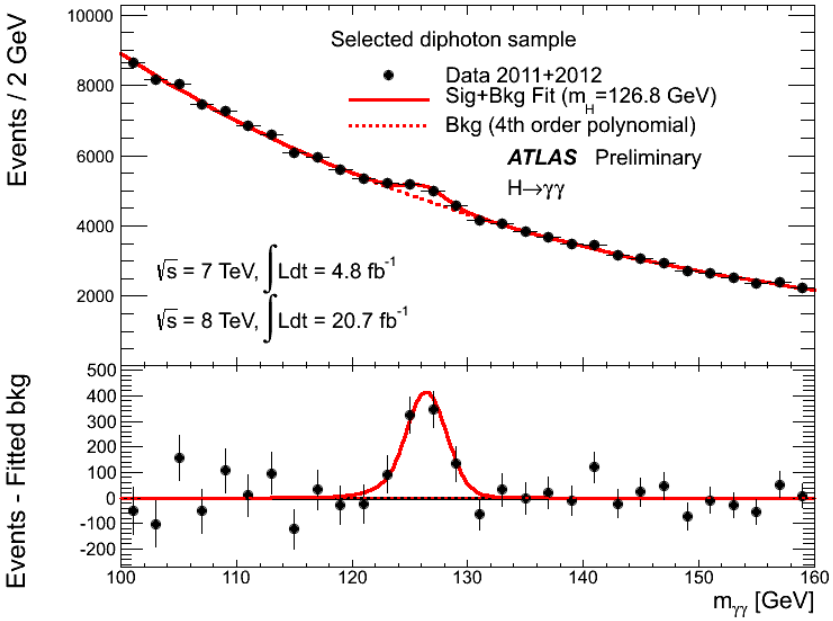
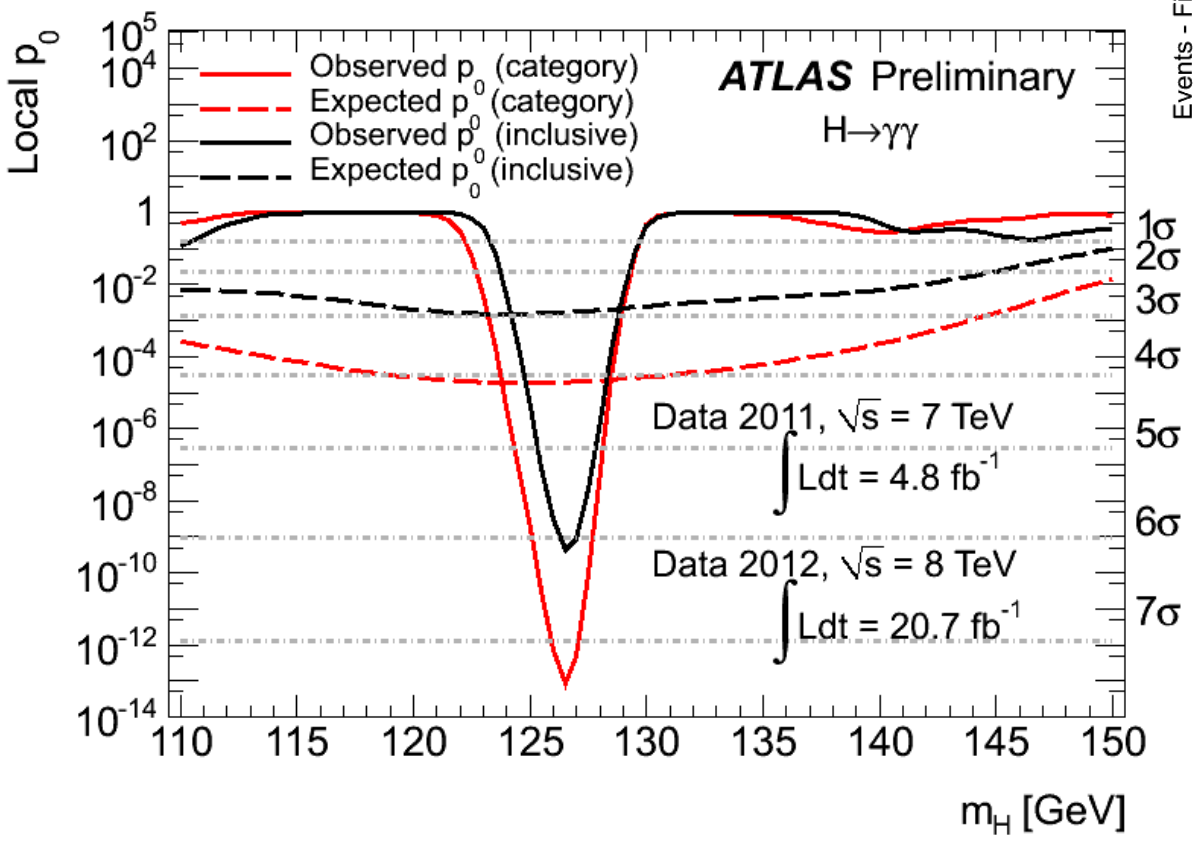
H→γγ (2)

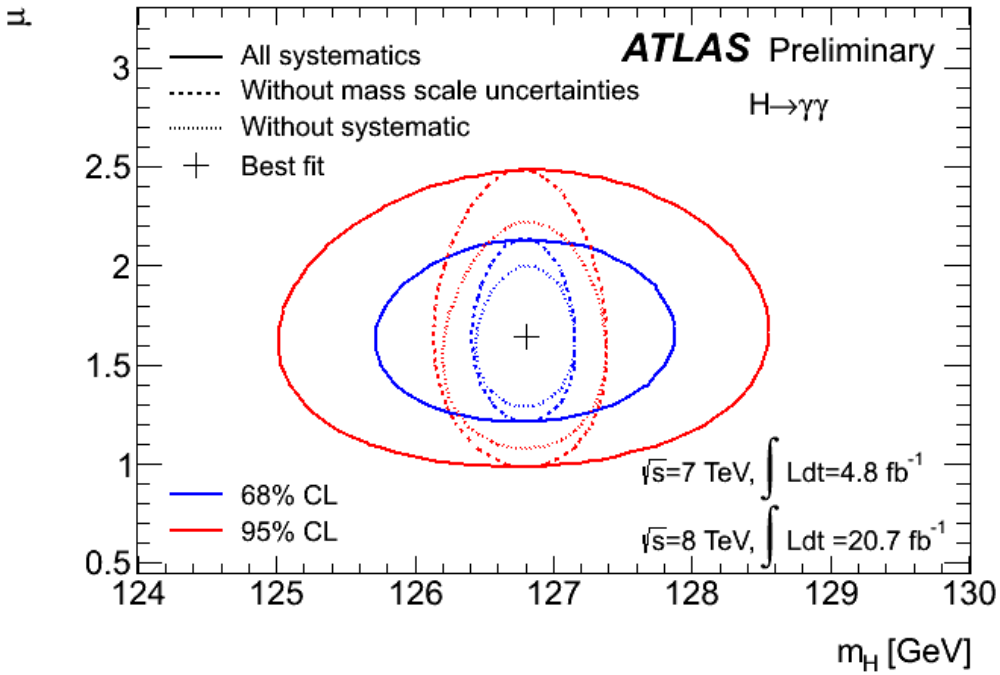
- Observation confirmed for γγ channel
  - observed: 7.4 σ at 126.5 GeV
  - expected: 4.1 σ





H→γγ (3)

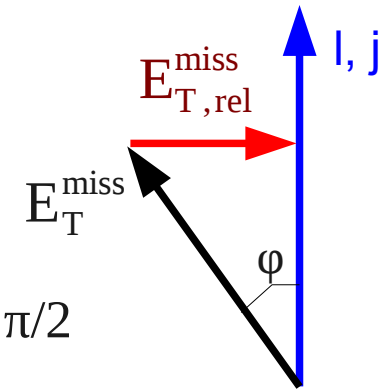
- Best fit for mass:
  - 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

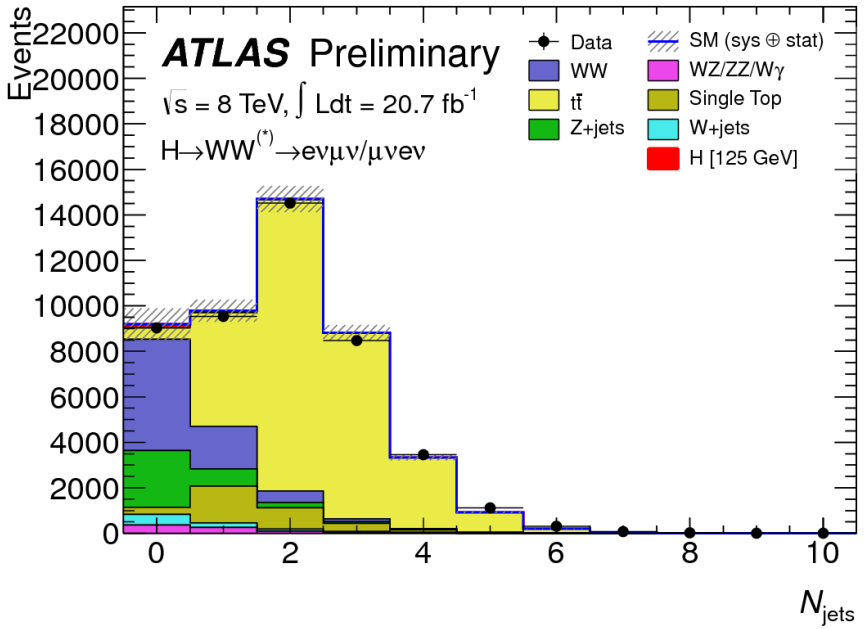


- Best fit signal strength at 126 .8 GeV
  - $\mu = 1.65 \pm 0.24\,(\text{stat})^{+0.25}_{-0.18}(\text{syst})$
  - 2.3 σ from SM hypothesis

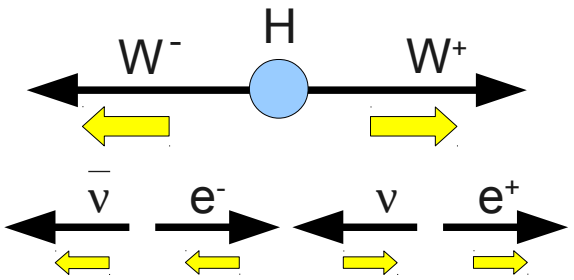
H→WW* (1)

- H → WW* → eνμν only
- isolated leptons with p_T > 25/15 GeV
- $E_T^{miss}{}_{rel}$ > 25 GeV
  - E_T^{miss} if Δφ > π/2
  - E_T^{miss}.sin(Δφ) if Δφ < π/2





- Spin correlations
  - m_{ll} < 50 GeV and $\Delta\varphi_{ll}$ < 1.8



- Divide events in H+0 jet, H+1 jet and H+2 jets

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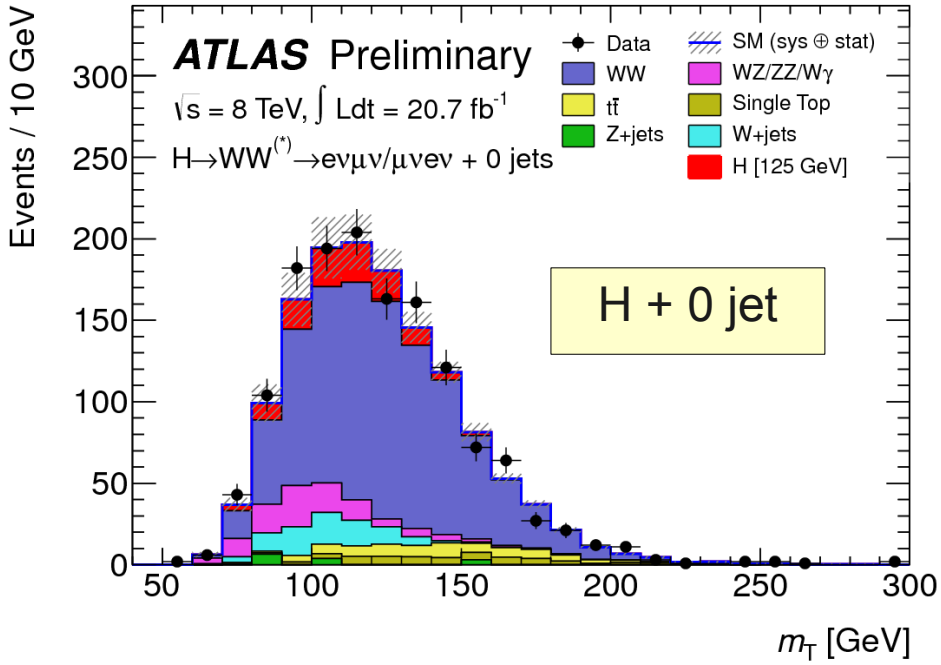
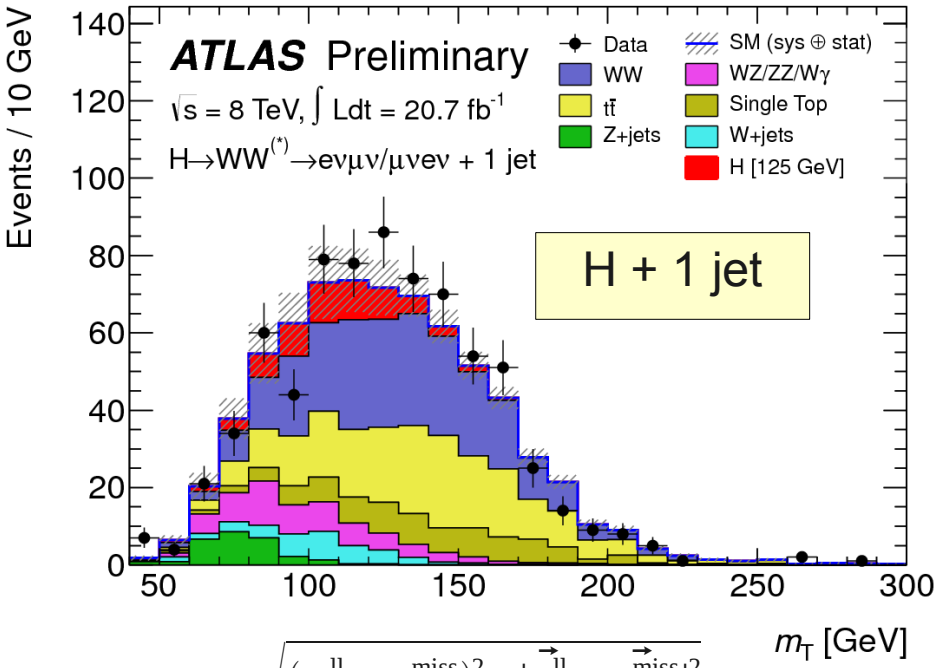
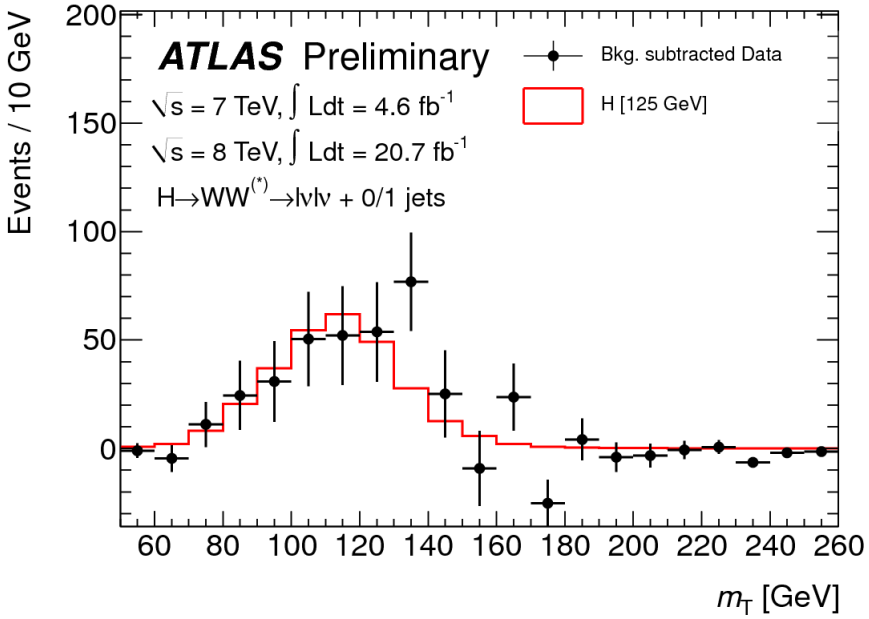
H→WW* (2)







$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - |\vec{p}_T^{\,ll} + \vec{E}_T^{miss}|^2}$$

$$E_T^{ll} = \sqrt{|\vec{p}_T^{\,ll}|^2 + m_{ll}^2}$$

	H + 0 jet	H + 1jet	H + 2jets
signal	97	40	10.6
background	739	261	36
observed	831	309	55

H→WW* (3)

- Excess of events for $m_H < 150$ GeV

- For $m_H = 125$ GeV
  - observed: 3.8 σ
  - expected: 3.7 σ

- Signal strength at 125 GeV:
  - $\mu = 1.01 \pm 0.31$