Measurements of the properties of the Higgs boson-like resonance in the di-photon channel using the ATLAS detector

Outline

- Introduction
- Analysis strategy
- Couplings, mass and spin
- Differential cross-sections
- Prospects

ATLAS EXPERIMENT

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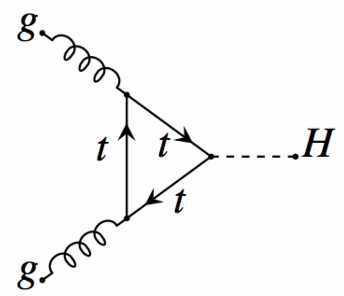
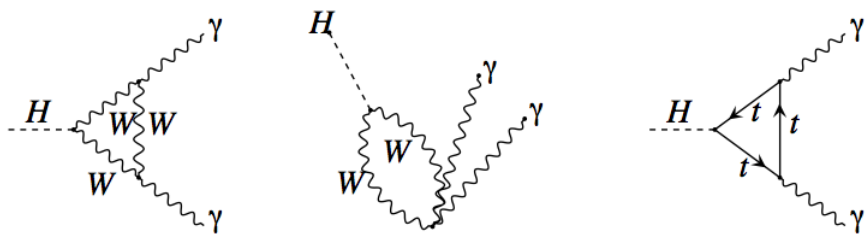
on behalf of the ATLAS Collaboration

See poster D. Gillberg

The relevance of the γγ channel

- Main production processes and decay through loops : good probe for new physics





$$\sim 1.56\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$

Sensitivity to relative sign of couplings to fermion and boson through interference

- Small branching ratio, but still relatively high yield : expect
  ~ 1175 produced events in the 7 + 8 TeV (4.7 + 20.3 fb^{-1}) data sets
  ~ 400 selected events

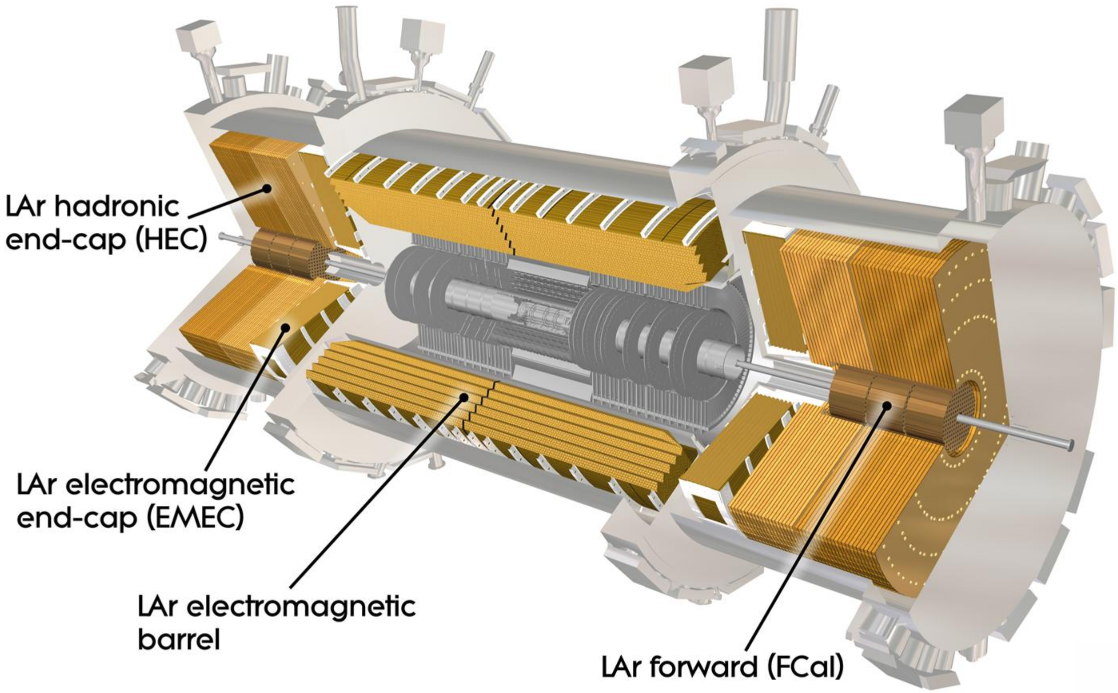
- Excellent mass resolution : ~ 1.8 GeV/c^2 ⇒ mass measurement

- Exclude a spin 1 resonance (on-shell)

- Determine Charge Conjugation quantum number : C = + 1

- Start to probe the underlying QCD dynamics

The main tool : ATLAS Liquid Argon calorimeter

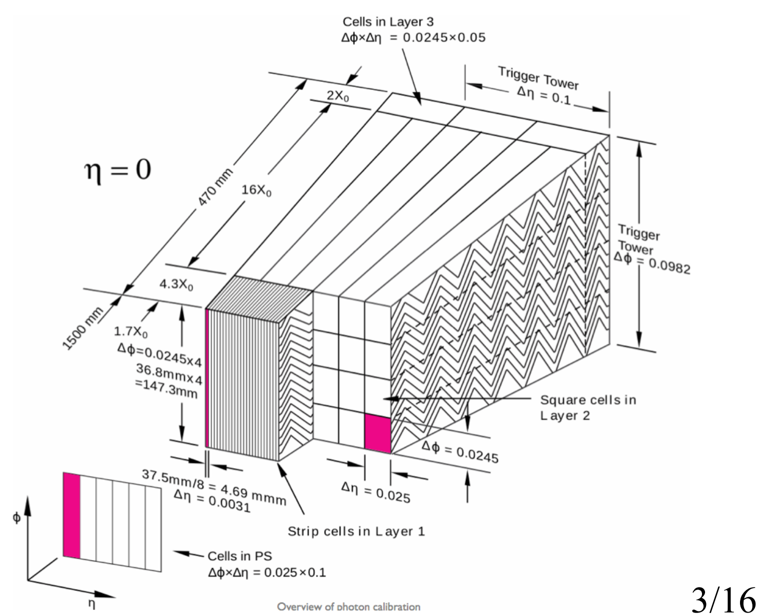


- Crack-less accordion geometry
- Uniform by construction
- Very stable operation

- ~ 200K channels

$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 0.007$$

(0.7% nominal constant term : not there yet)



✓ longitudinal segmentation (pointing)
✓ Fine η granularity in first layer (γ/jet separation)

Very simple analysis selection :

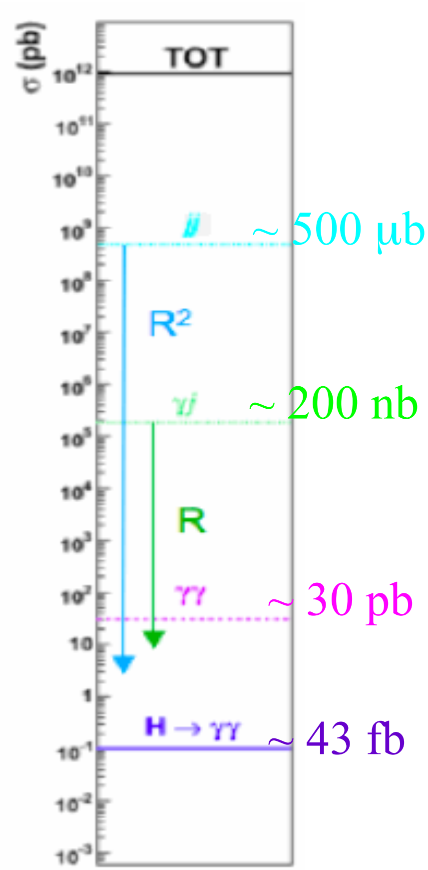
Trigger : di-photon (threshold (8 TeV) 35/25 GeV, loose shower shape requirements)

Selection : 2 tightly identified photons, $p_T > 40$ / 30 GeV/c, $|\eta| < 1.37$ or $1.56 < |\eta| < 2.37$

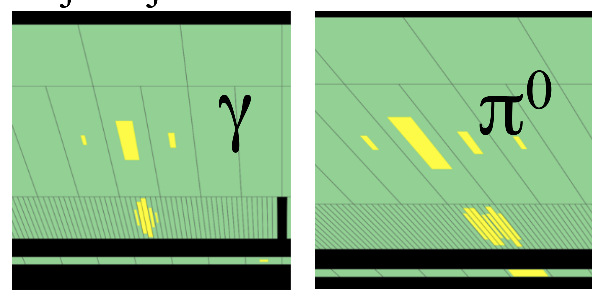
142681 candidate events, 14025 in window around 126.5 GeV/c^2

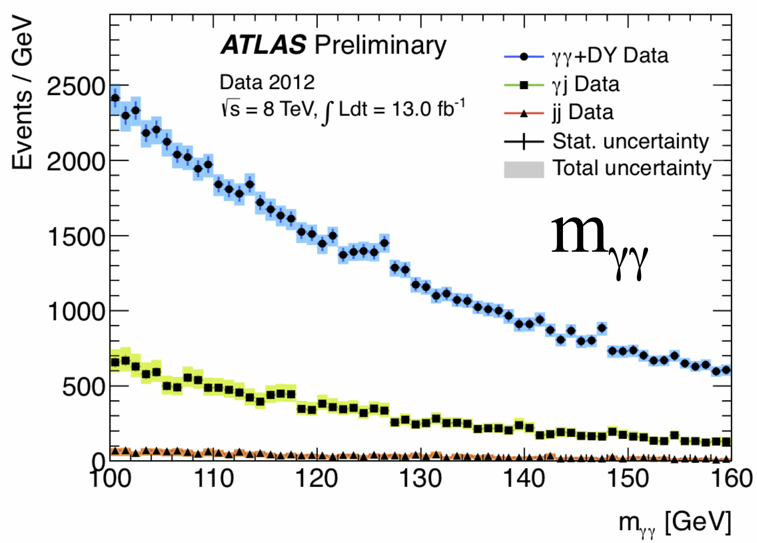
Large background but narrow mass peak : key ingredients

- Understand fake photon rejection
- Precise photon energy and direction measurements for $m_{\gamma\gamma}$ estimation



Benefiting from the highly granular EM calorimeter :
jet rejection ~ 8000





~ 75 % irreducible $\gamma\gamma$
~ 25 % γ-jet, di-jet

(just shown to illustrate the good understanding of the bkg composition, not used in the final results)

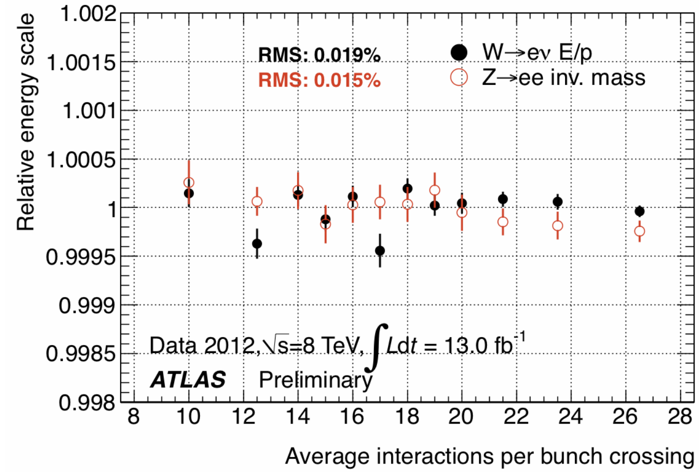
$m_{\gamma\gamma}$ estimation

$$m_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{12})$$

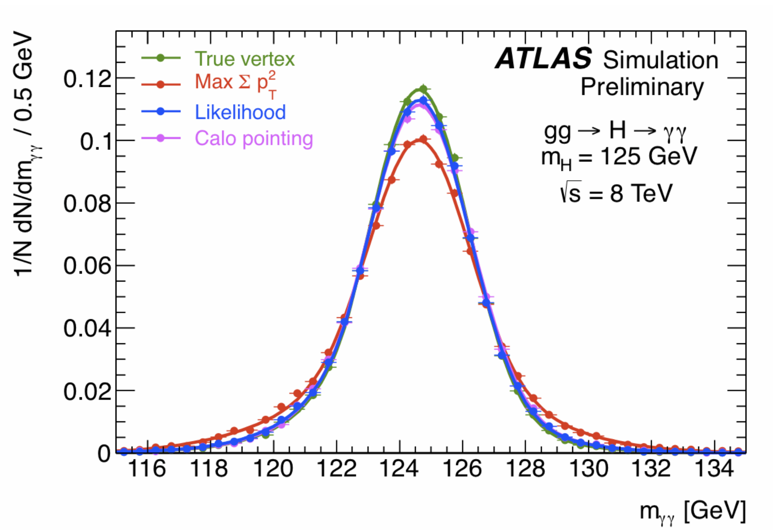
→ accurate photon energy scale : from Z → e^+e^- data and extrapolation e → γ
require excellent material budget knowledge

(+ control from radiative decays Z → $e^+e^-\gamma$,
limited by statistics and to low energy)

Also very good stability w.r.t.
Number of interactions / bunch crossing



→ accurate direction : choice of primary vertex with a NN combining
calorimeter pointing (longitudinal segmentation) +
photon conversion (if any) + information from recoiling tracks

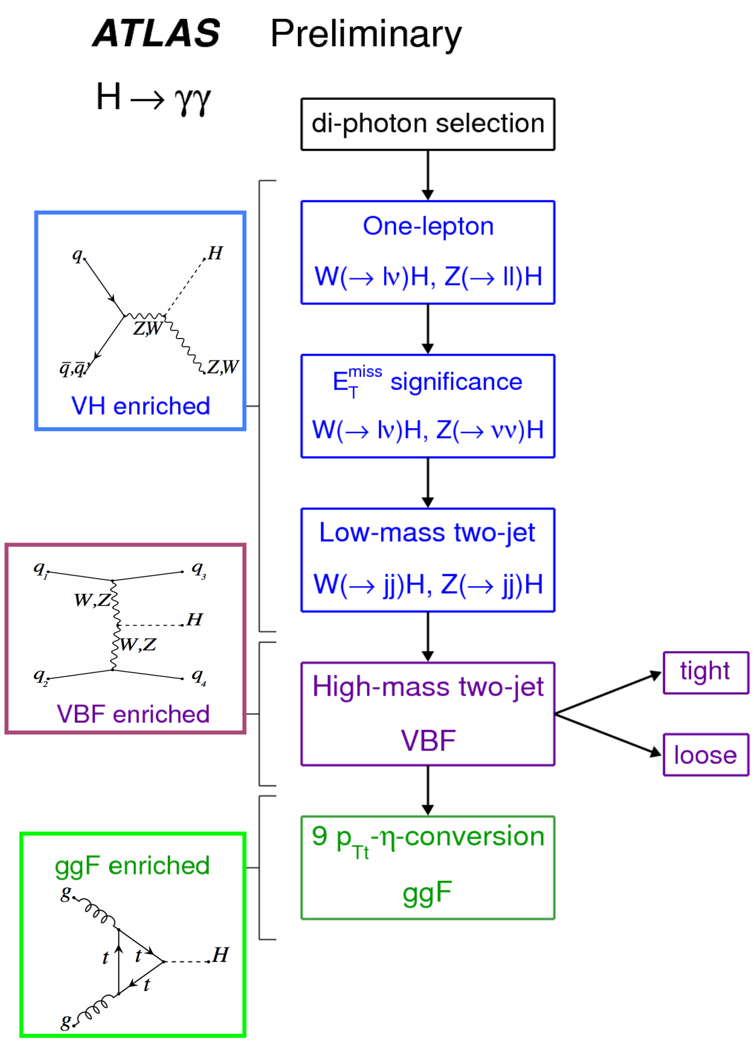


If no measured PV, would add ~ 1.3 GeV/c^2 to the mass resolution
instead : negligible contribution from direction to mass resolution
driven by energy resolution
(sampling term ~ 10%/√E +
constant term ~ 1% not at design yet)

Signal shape used everywhere : *Crystal Ball + Gaussian*

Strategy : from discovery to property measurements

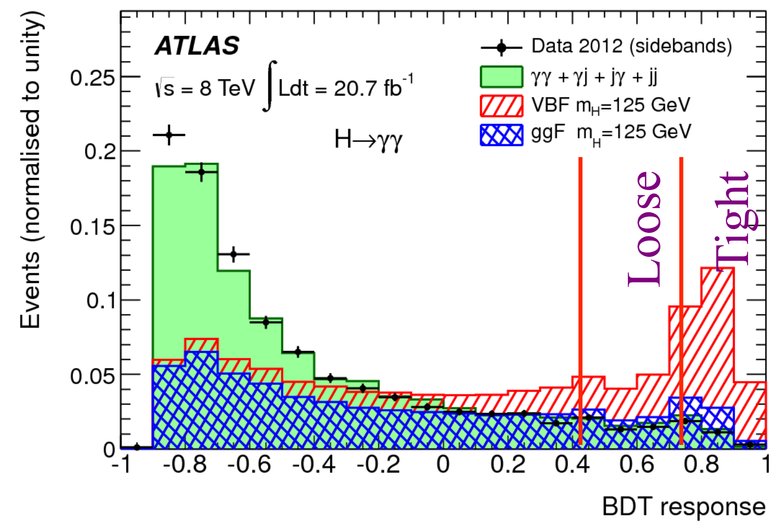
Events with rather different purity are mixed together
⇒ Categories can increase the sensitivity and disentangle production modes

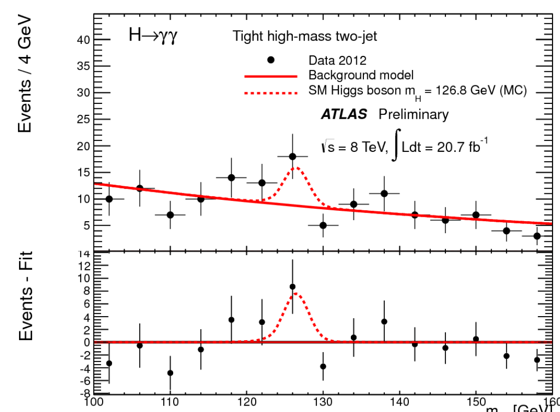


Purest category : high mass two-jet tight

Boosted Decision Tree $\eta_j, m_{jj}, \Delta\eta_{jj}, p_{Tt}$

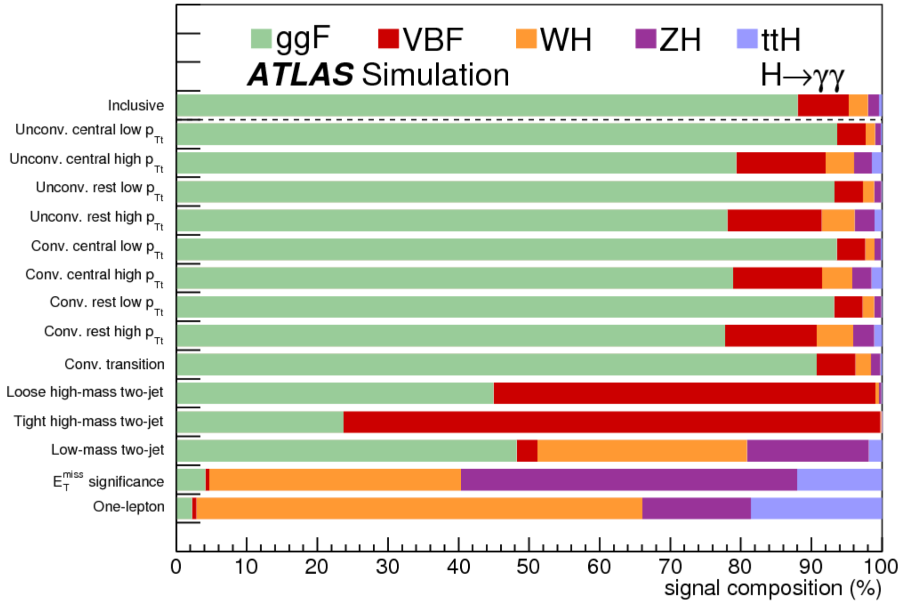
$$\Delta\phi_{\gamma\gamma,jj}, \eta^* = \eta_{\gamma\gamma} - \frac{\eta_{j_1} + \eta_{j_2}}{2}, \Delta R^{\gamma j}_{min}$$



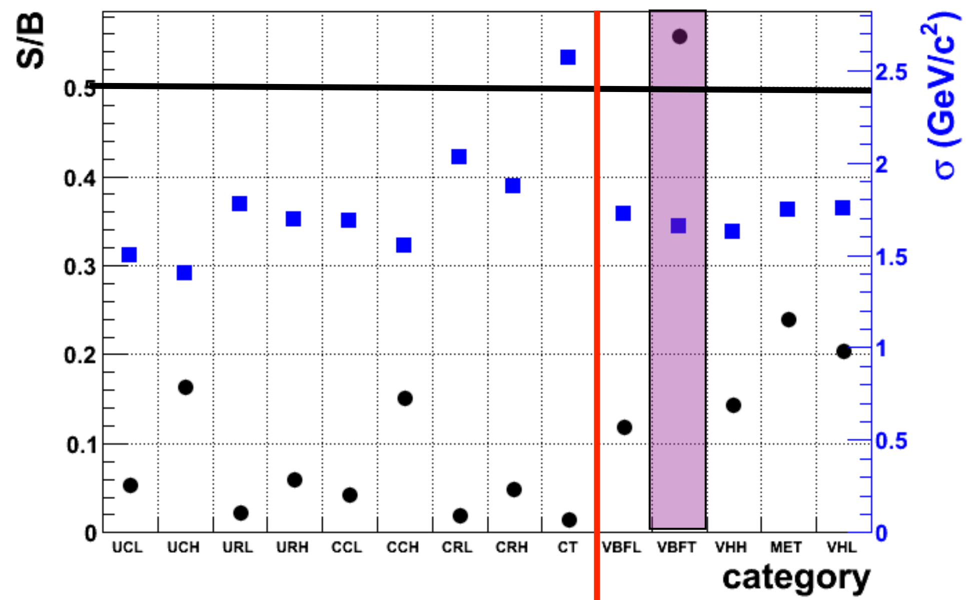


S(exp) ~ 8.5, S(fit) ~ 13.2
B(window) ~ 13
VBF-purity ~ 76%

Expected signal composition in each category

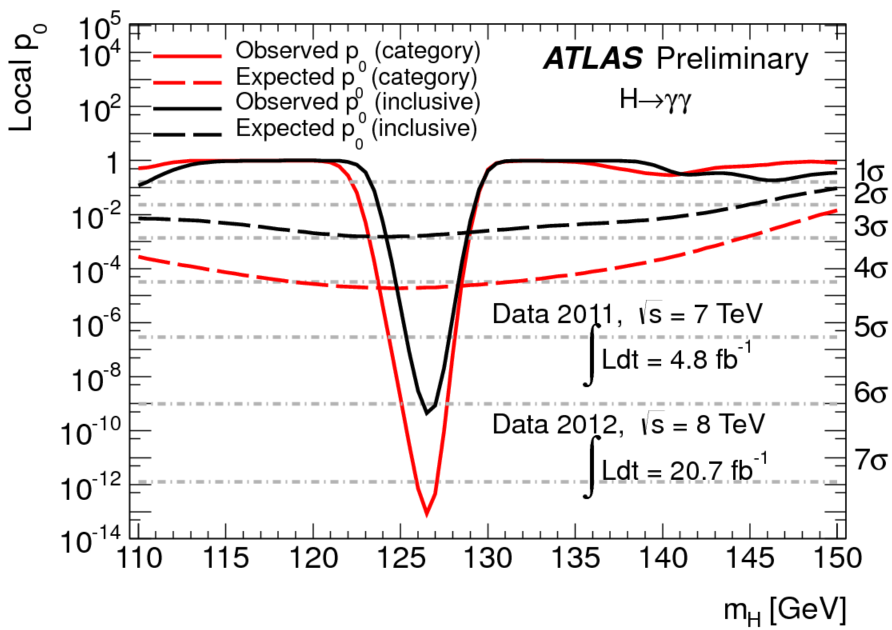


Expected S/B and resolutions



ggF dedicated ←

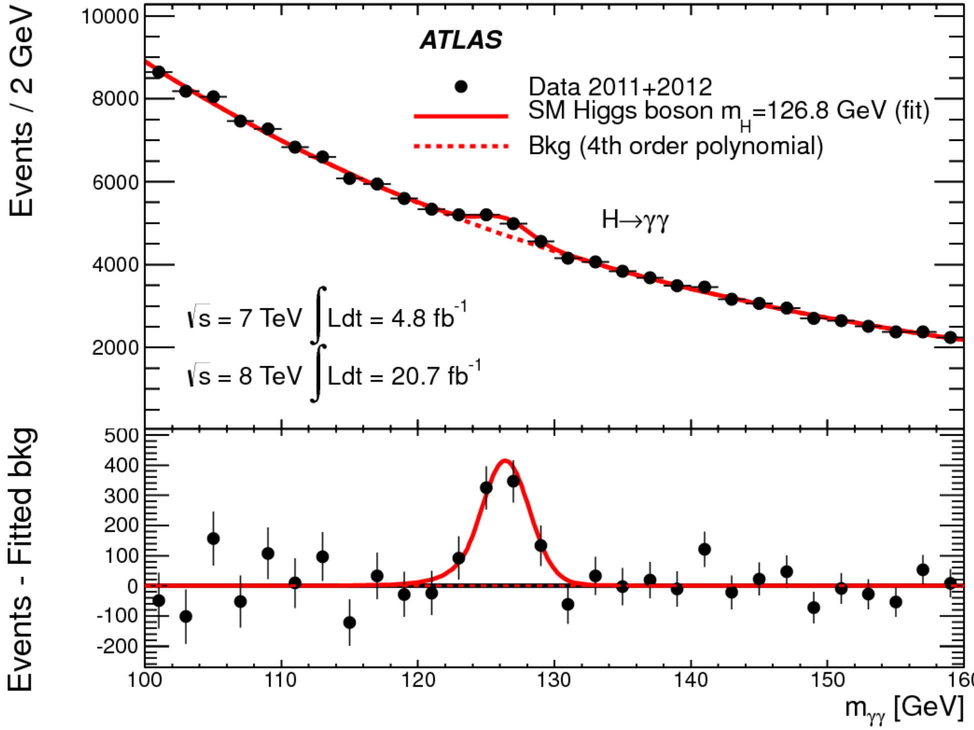
→ Associated prod.



Largest significance @ 126.5 GeV/c^2

7.4 sigmas (4.1σ exp)
Standalone discovery !

Signal strength and cross-section

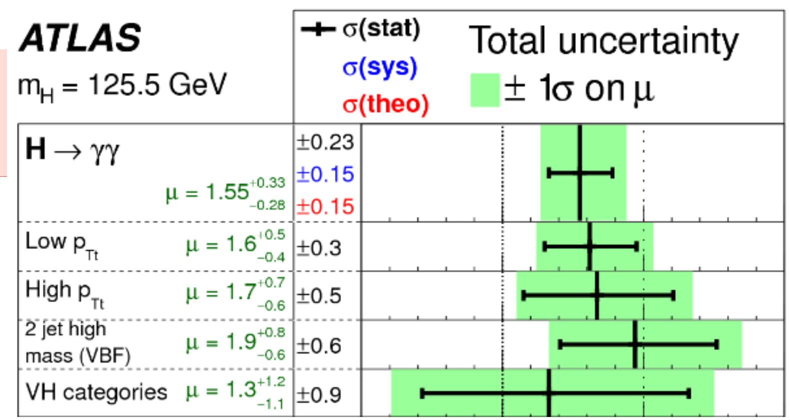


<u>Signal strength</u> (m_H = 125.5 GeV/c^2)

$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}} = 1.55 \pm 0.23_{stat} \pm 0.15_{sys} \pm 0.15_{theo}$$

(slight decrease w.r.t. Moriond2013 due to $H \rightarrow \gamma f\bar{f}$ Dalitz decay treatment)

Compatibility with SM Higgs hypothesis ~ 2σ



<u>Fiducial cross-section</u>

for |η| < 2.37, $p_T(\gamma)$ > 30/40 GeV/c

(inclusive analysis to reduce model dependency) :

σ . BR = 56.2 ± 12.5 fb (including Dalitz contribution)

Coupling measurements

Sensitivity to VBF and VH production modes thanks to the dedicated categories

(VH : lepton, E_t^{miss} significance, low mass two jets

VBF : high mass two jets)

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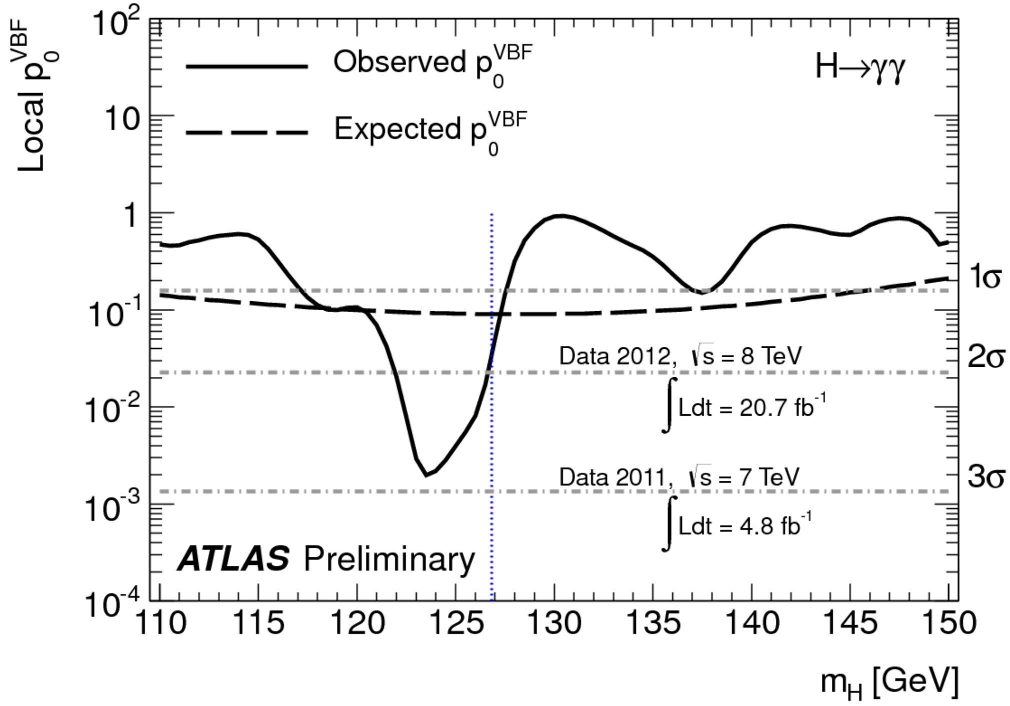
(VH : lepton, E_t^{miss} significance, low mass two jets
VBF : high mass two jets)

VBF significance
Z(126.8) ~ 2.0σ



Coupling measurements

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(VH : lepton, E_t^{miss} significance, low mass two jets
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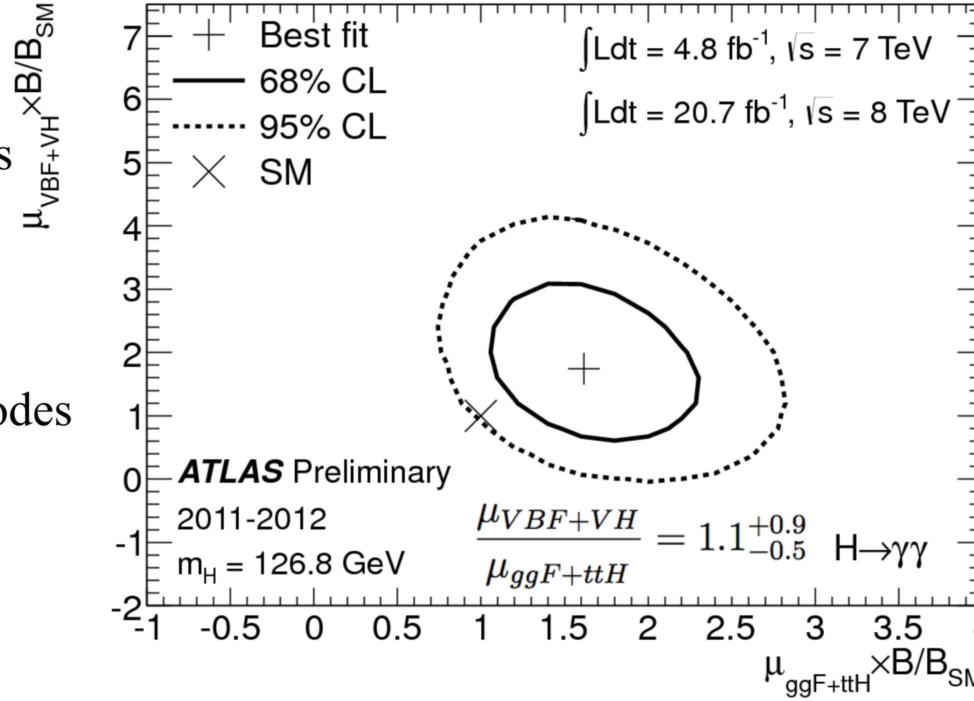
⇒ signal model separated in production modes



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(VH : lepton, E_t^{miss} significance, low mass two jets
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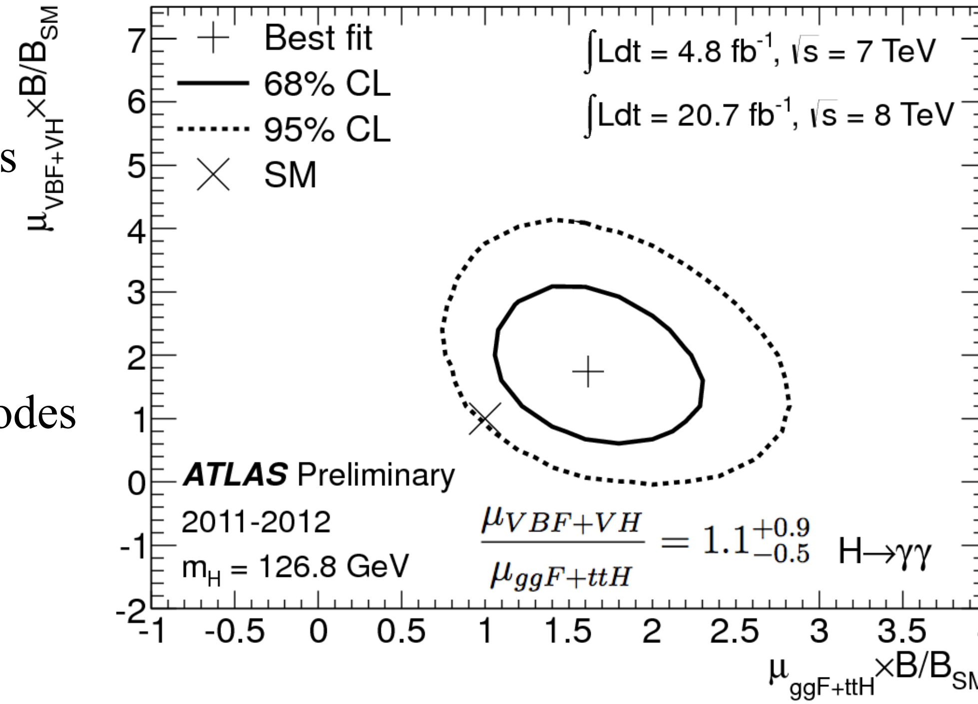
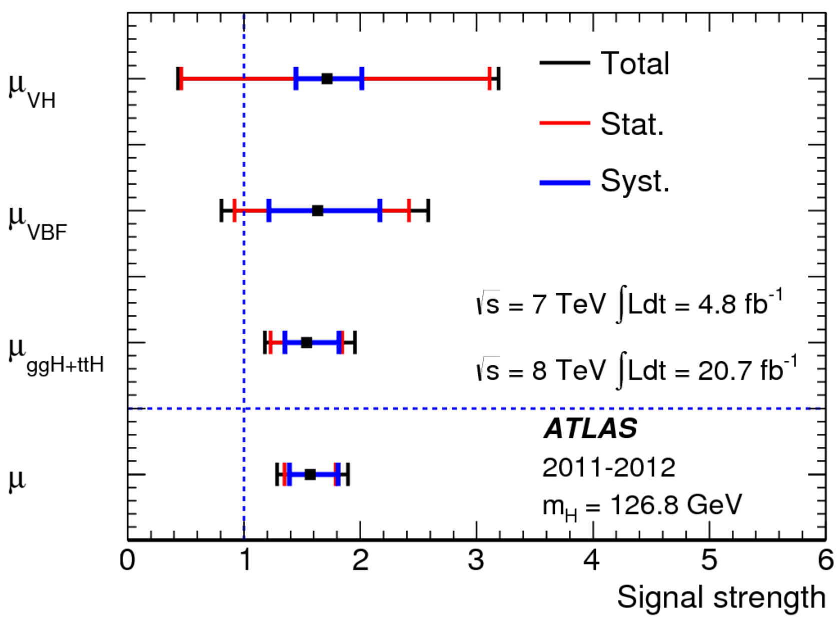


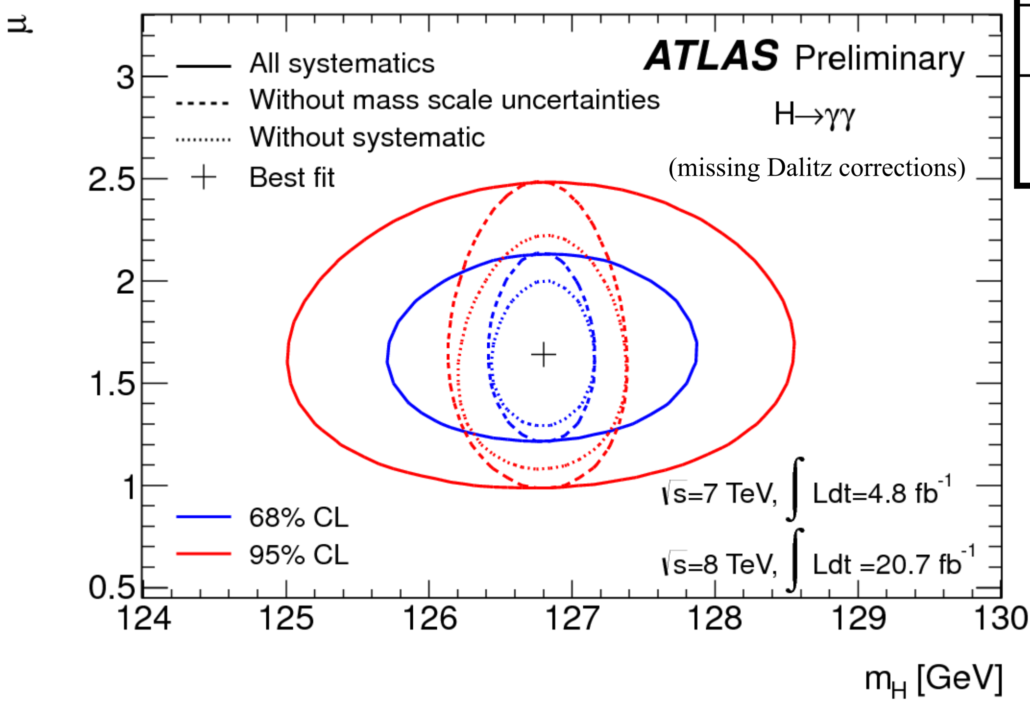


$$\mu_{VH} \cdot B/B_{SM} = 1.7^{+1.5}_{-1.3}(stat) \pm 0.3(syst)$$

$$\mu_{VBF} \cdot B/B_{SM} = 1.6 \pm 0.8(stat)^{+0.5}_{-0.4}(syst)$$

$$\mu_{ggF+ttH} \cdot B/B_{SM} = 1.5 \pm 0.3(stat)^{+0.3}_{-0.2}(syst)$$

Mass measurement



Systematic uncertainties	(%)
Absolute energy scale ($Z \to e^+e^-$)	±0.3
Upstream material simulation accuracies	±0.3
Presampler scale	±0.1
Additional (relative layer calibration, non linearity, etc…)	±0.32

$\Rightarrow \sim 0.7$ GeV/c^2

$m_H = 126.8 \pm 0.2_{stat} \pm 0.7_{syst}$ GeV/c^2

Mass resolution uncertainty ~ 20 %, with Gaussian constrain in the fit
Removing the constraint, the *"measured"* resolution is better by ~ 30%, and the signal strength decreases by ~ 10% : $\mu = 1.49 \pm 0.33$

dedicated investigations revealed no obvious problem
might be a statistical effect from background fluctuation…

Spin studies

Sensitivity through (cosine of) photon production angle in di-photon (Collins Soper) rest frame

Try to disentangle the SM Higgs boson from a singly produced spin J resonance

→ Only J = 2 (J = 1 highly disfavoured from Landau/Yang, higher J not very reasonable 😉)

→ Only *(pseudo-)minimal* model for the time being, no assumption on signal yield

Expected distributions before cuts : SM Higgs boson → flat cosθ* distribution

minimal spin 2 :

$$dN/d\cos\theta^*(gg \to X_2) \sim 1 + 6\cos^2\theta^* + \cos^4\theta^*$$

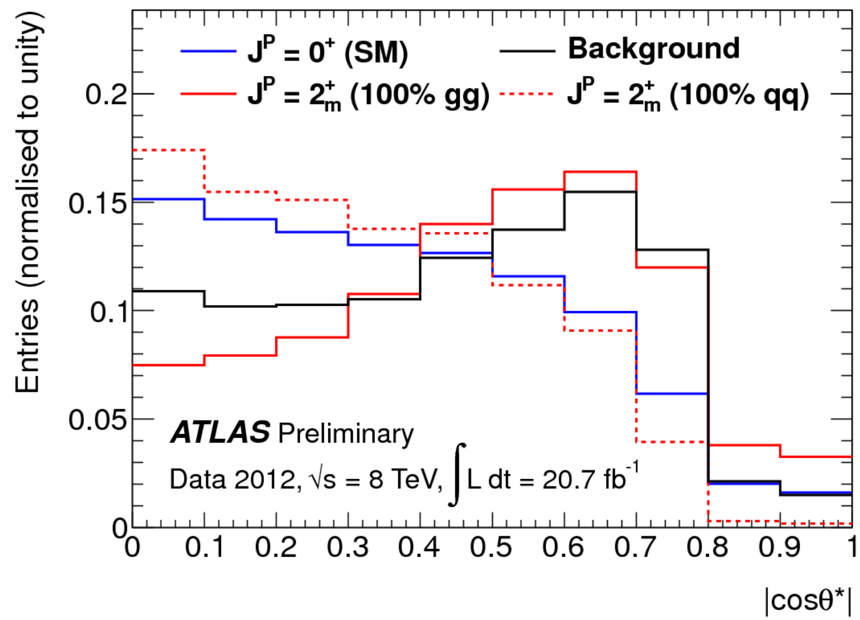
$$dN/d\cos\theta^*(q\bar{q} \to X_2) \sim 1 - \cos^4\theta^*$$

(gg / q$\bar{q}$ = 96 / 4 % for minimal model at LO)

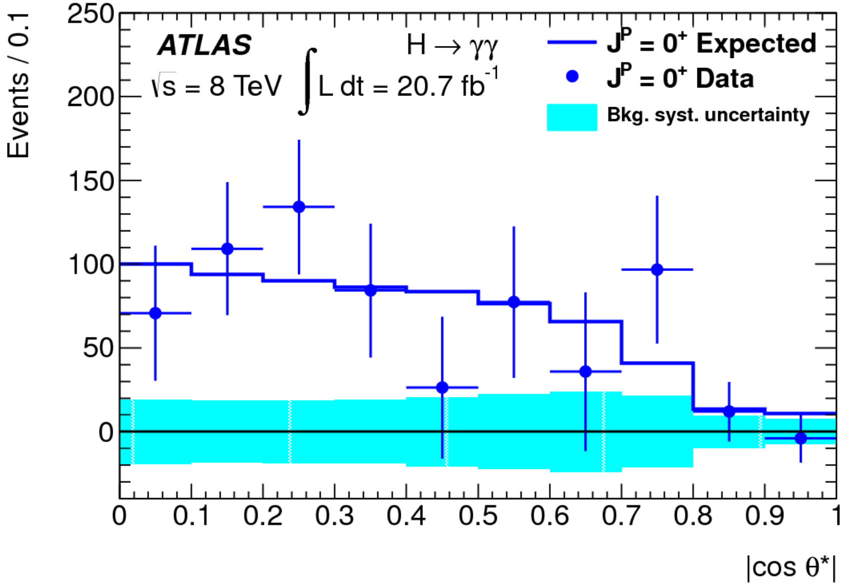
Use inclusive analysis with modified p_T cuts : $p_T^{1,2}/m_{\gamma\gamma}$ > 0.35 / 0.25

⇒ better handling on background shape
cosθ* and $m_{\gamma\gamma}$ almost decorrelated
shape from side band

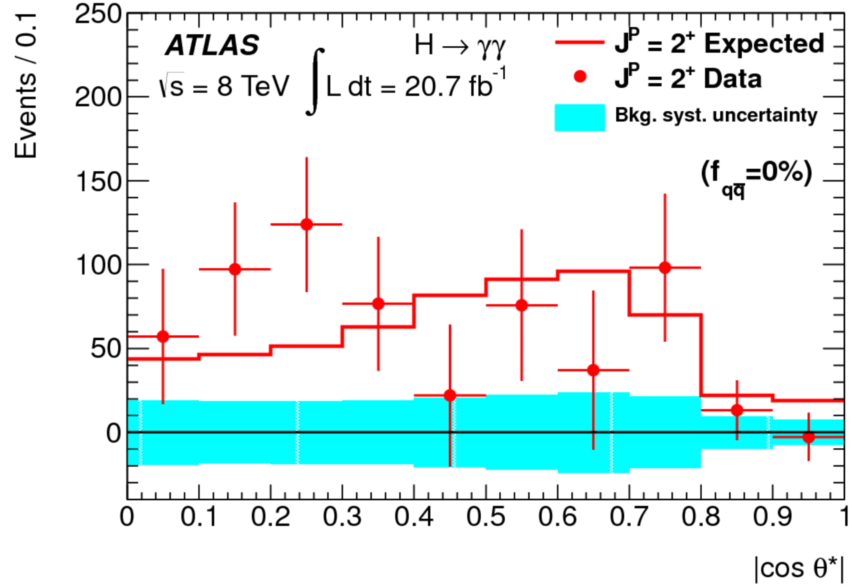
cosθ* shape highly distorted by p_T cuts



Fit assuming SM



Fit assuming spin 2, 100% gg



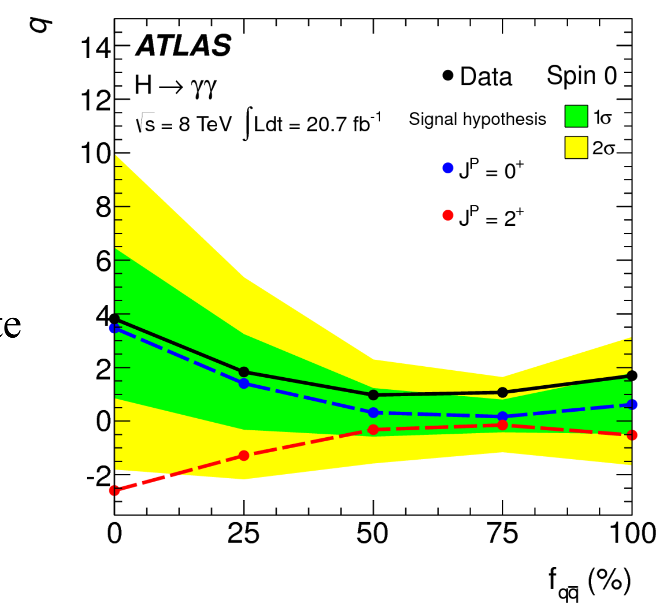
@ spin 2 100% gluon fusion production :

✓ compatibility data / SM : 58.8% (0.5% expected if spin 2 true)

✓ spin 2 model p-value : 0.3% (1.2% expected if SM)

⇒ *minimal* spin 2 strongly disfavoured

Large decrease of sensitivity for
large quark annihilation fraction in initial state
⇒ recovered with WW channel



Differential cross-sections

See poster J. Saxon

Relatively high signal yield (~ 400 expected, ~ 620 fitted)

⇒ can be used to probe the underlying kinematic properties of production and decay

Inclusive	$p_T^{\gamma\gamma}$	Fundamental kinematics, H.O.
	$\|y^{\gamma\gamma}\|$	Fundamental kinematics, pdf
	N_{jets}	VH, VBF, $t\bar{t}H$ vs ggH, H.O.
	$\sigma_i/\sigma_{\geq i}$	H.O.
	$\|\cos\theta^*\|$	Spin
1-jet	$p_T^{leading\ jet}$	H.O.
2-jet	$\Delta\phi_{jj}$	Spin-Parity, VBF, H.O.
	$p_T^{\gamma\gamma jj}$	VBF, H.O.

Methodology :

✓ Choose a binning for variable X

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- ✓ For each bin, extract signal yield from fit to $m_{\gamma\gamma}$ distribution

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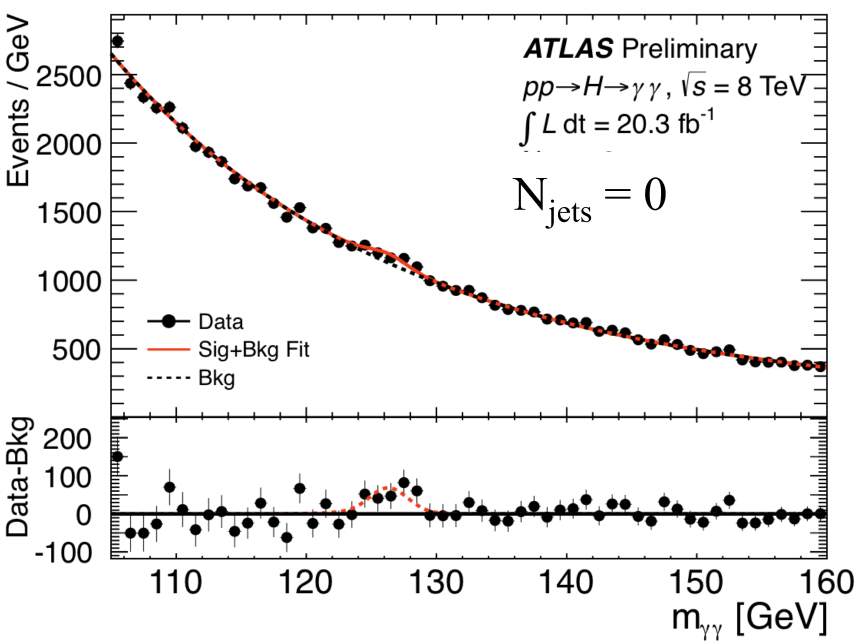
Example for N_{jets}



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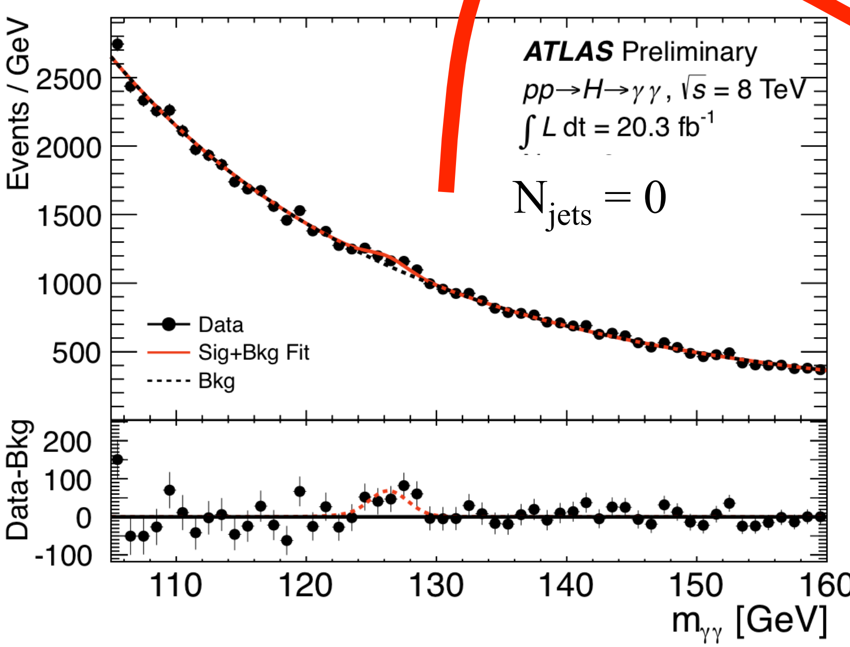

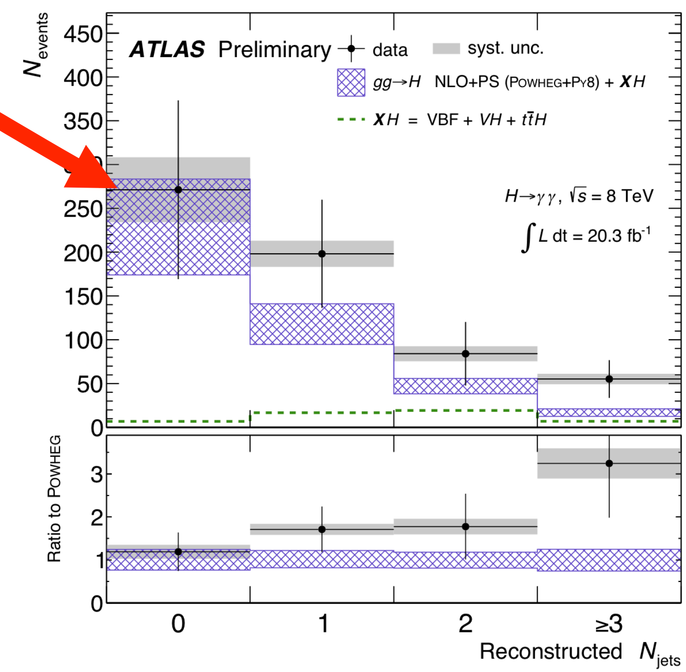

Differential cross-sections

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Relatively high signal yield (~ 400 expected, ~ 620 fitted)
$\Rightarrow$ can be used to probe the underlying kinematic properties of production and decay

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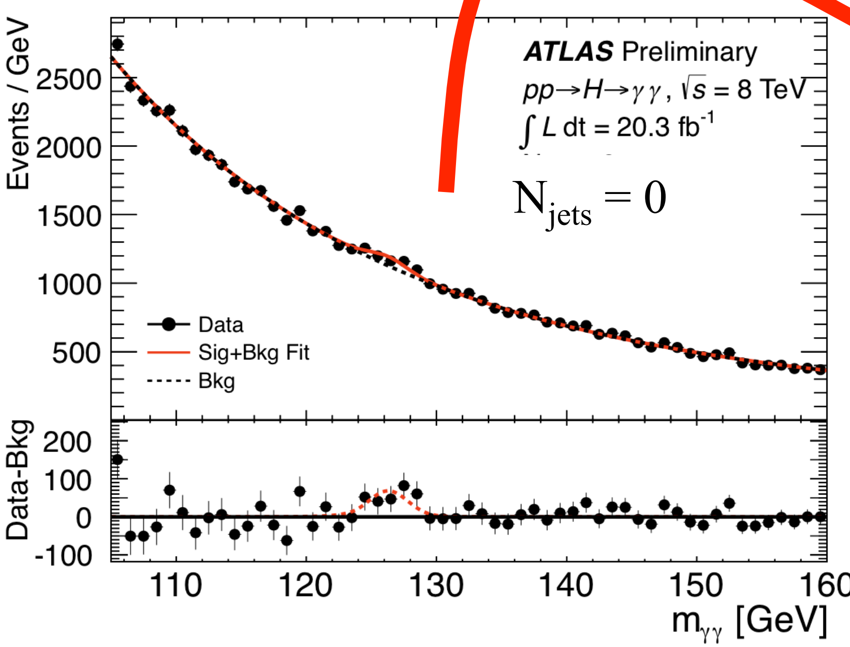
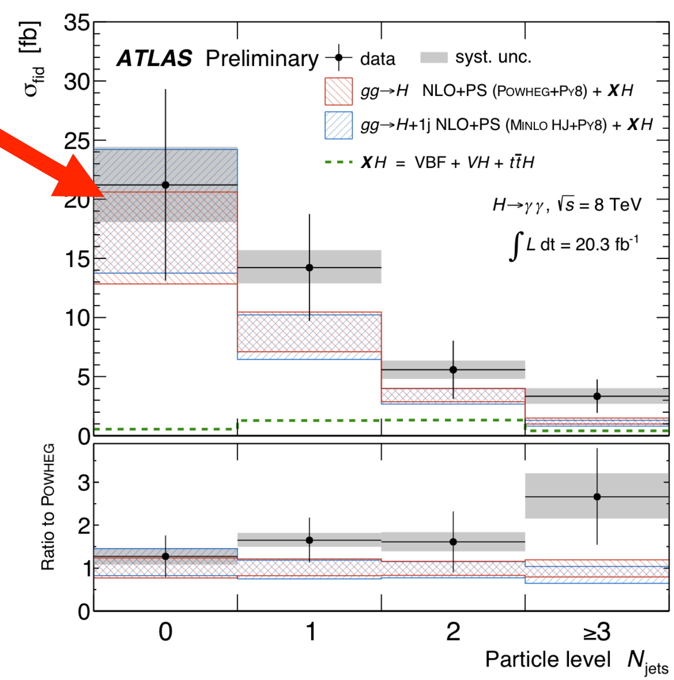
Methodology :

- ✓ Choose a binning for variable X
- ✓ For each bin, extract signal yield from fit to $m_{\gamma\gamma}$ distribution
- ✓ Correct raw yields for acceptance, efficiency, resolution : bin-by-bin unfolding

$\Rightarrow d\sigma/dX$

Example for N_{jets}





➢ Same inclusive selection as spin analysis +
jet definition : anti-k_t, $\Delta R = 0.4$, $p_T > 30$ GeV/c, $|y| < 4.4$ (same definition at *particle level* μ and ν excluded from clusterisation)

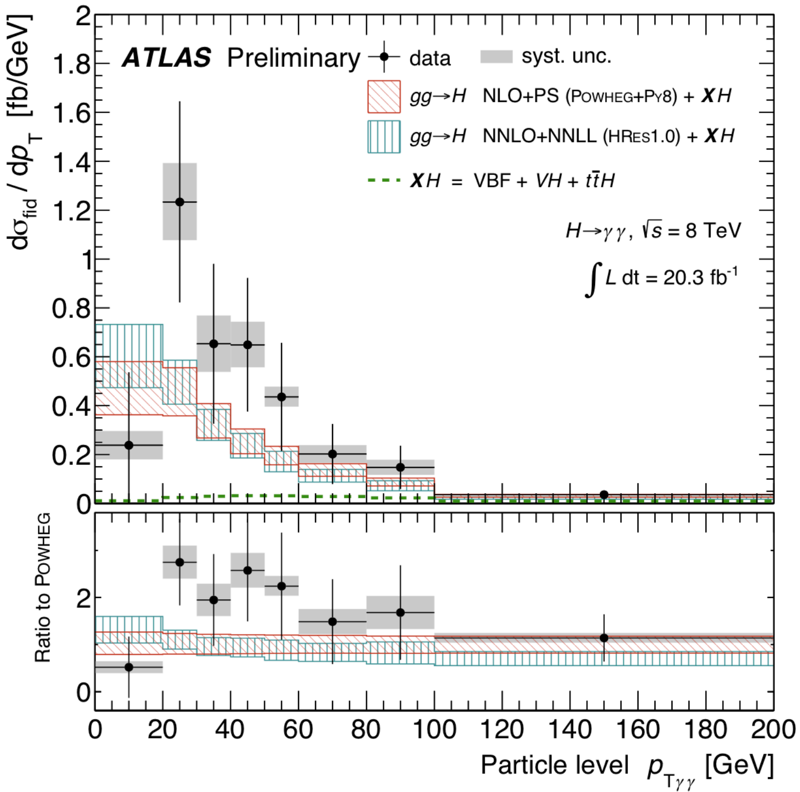
➢ Unfolding to *particle level* : 2 isolated photons with $p_T/m_{\gamma\gamma} > 0.35/0.25$, $|\eta| < 2.37$

photon isolation : $\sum_{\Delta R(\gamma,p)<0.4} p_T < 14\text{GeV}$ (sum over stable particles but μ and ν)

⇒ Statically limited but yet already valuable
No significant deviation from SM predictions

(beyond overall slight excess)

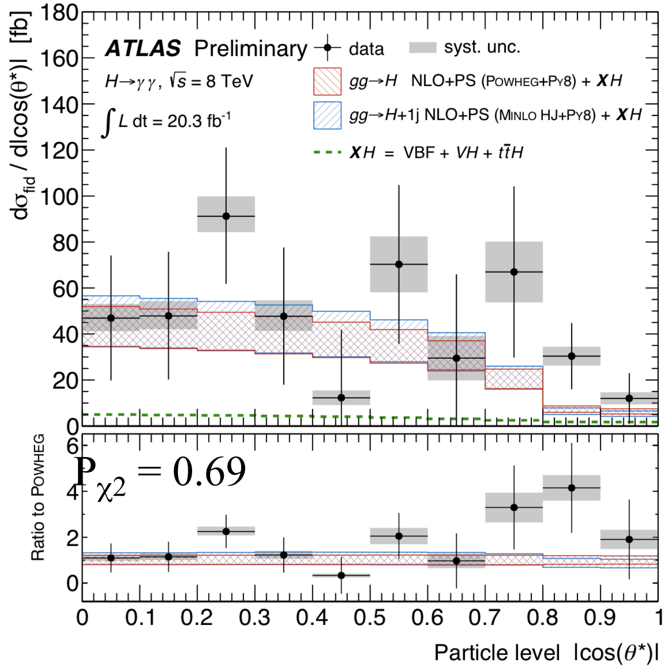
Di-photon p_T spectrum :



Compatibility with SM predictions (shape)
- $P_{\chi 2} = 0.55$ (POWHEG)
- $P_{\chi 2} = 0.39$ (Hres 1.0)

→ Still very large uncertainties (125% in first bin)
→ Nothing fancy (beyond the overall slight excess)

$|\cos\theta^*|$



$P_{\chi^2} = 0.69$

Difference w.r.t. spin analysis :

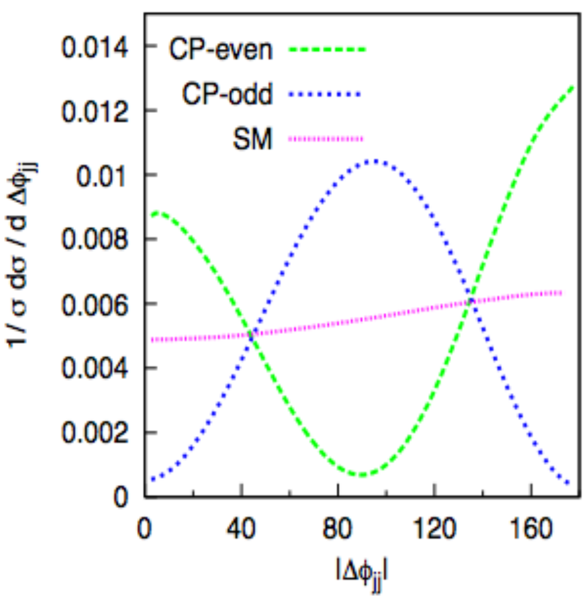
(almost-) *model-independent*

(whereas spin hypothesis folded in in spin fit)

$\Delta\phi_{jj}$

Sensitive to parity (and spin)

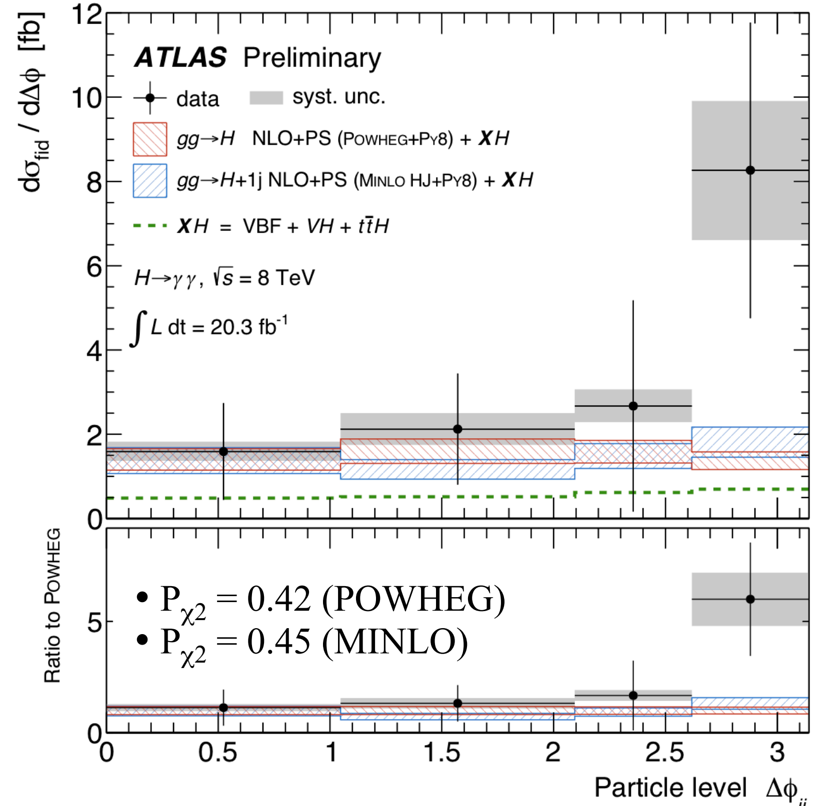
(e.g. Figy et al, hep-ph/0609075)



Anomal CP-even, $A \sim q_1 q_2\, \eta_{\mu\nu} - q_{1\mu} q_{2\nu}$

SM, $A \sim \eta_{\mu\nu}$

Anomal CP-odd, $A \sim \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$



- $P_{\chi^2} = 0.42$ (POWHEG)
- $P_{\chi^2} = 0.45$ (MINLO)

→ Slight excess for back-to-back topology but nothing significant and predictions not easy…

Conclusions

Signal strength evolution with integrated luminosity :

	Lumi (fb^{-1})	m_H (GeV/c^2)	$\hat{\mu}$	SM compatibility (σ)
ICHEP 2012	4.8 + 5.9	126.5	1.9 ± 0.5	-
Council 2012	4.8 + 13.0	126.6	$1.80 \pm 0.30(stat)^{+0.21}_{-0.15}(sys)^{+0.20}_{-0.14}(theo)$	2.4
Moriond 2013	4.8 + 20.7	126.8	$1.65 \pm 0.24(stat)^{+0.25}_{-0.18}(allsys)$	2.3
July 2013	4.8 + 20.7	125.5 (combined)	$1.55 \pm 0.23(stat) \pm 0.15(sys) \pm 0.15(theo)$	1.9

Prospects

Waiting final calibration for final LHC-runI mass measurement

Coming soon : limits on ttH, resonance width,
additional resonances with mass in [70,600] GeV/c2 decaying to $\gamma\gamma$

Search for new physics, e.g. FCNC in top quark decay $t \to cH$, $H \to \gamma\gamma$

After shutdown : Improved mass and coupling precision
CP asymmetries in VBF
approaching ttH, constraint on tH

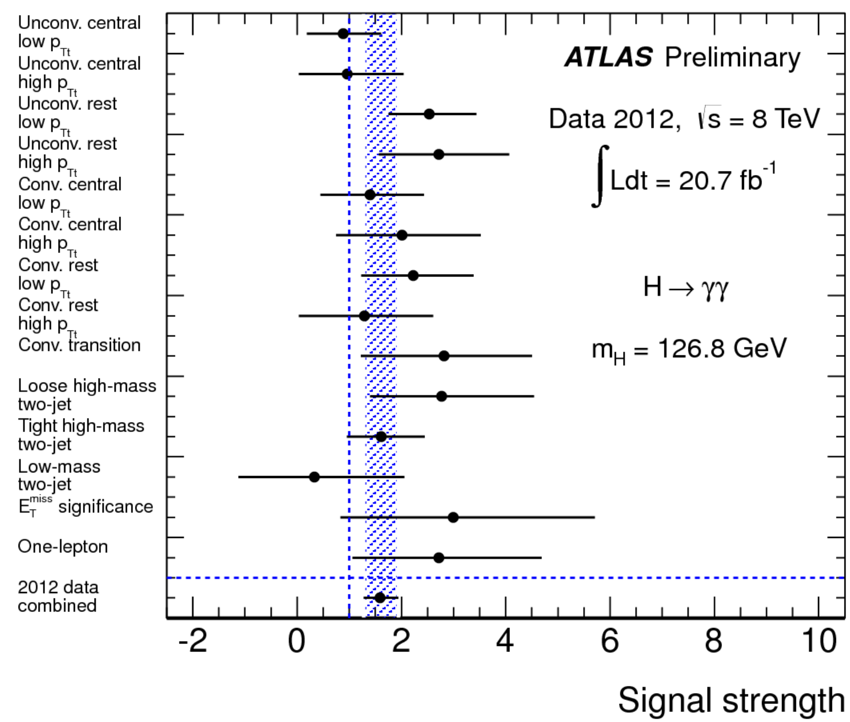
Entering the real era of precision Higgs physics !

References

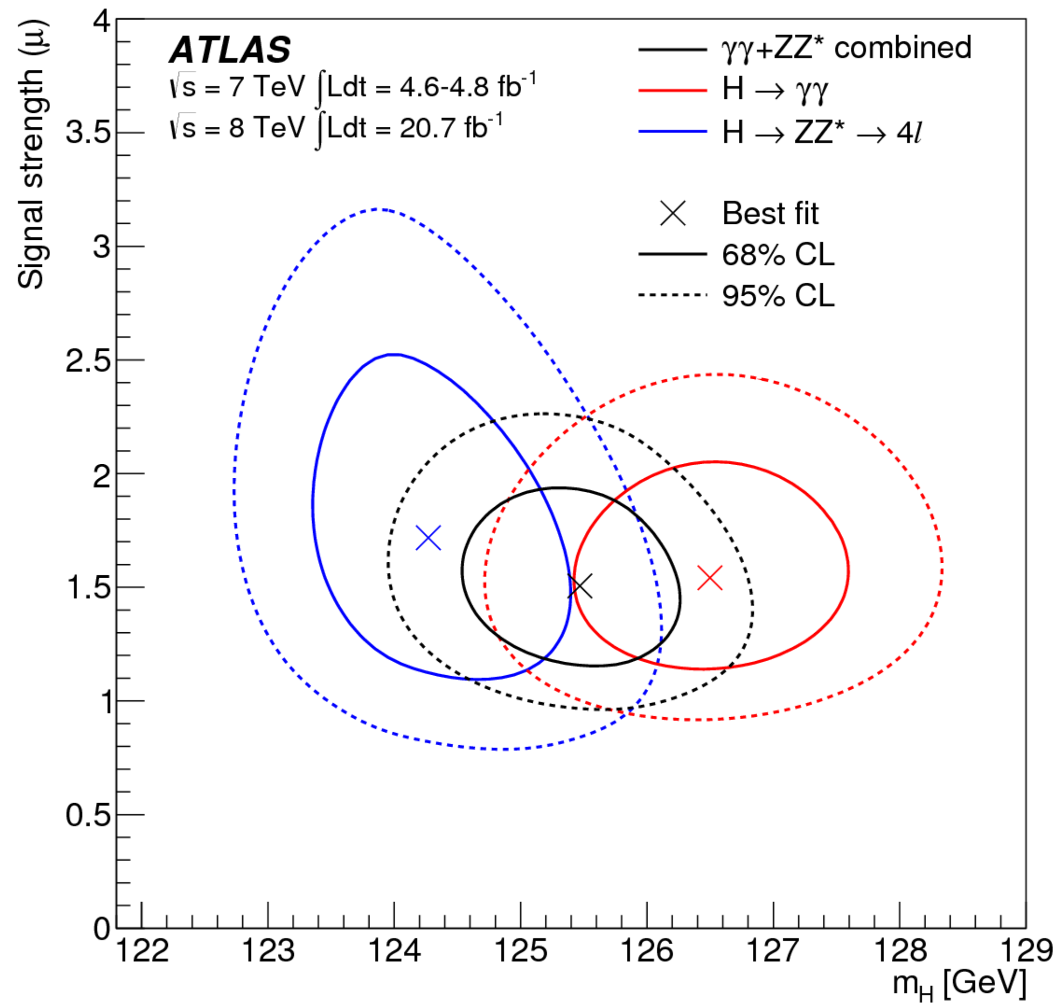
Couplings : http://inspirehep.net/record/1241574 1307.1427 [hep-ex]
Spin combination : http://inspirehep.net/record/1241575 1307.1432 [hep-ex]

Di-photon Moriond 2013 :
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-012
Di-photon spin Moriond 2013 :
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-029
Di-photon differential cross-sections EPS 2013 :
To be updated…

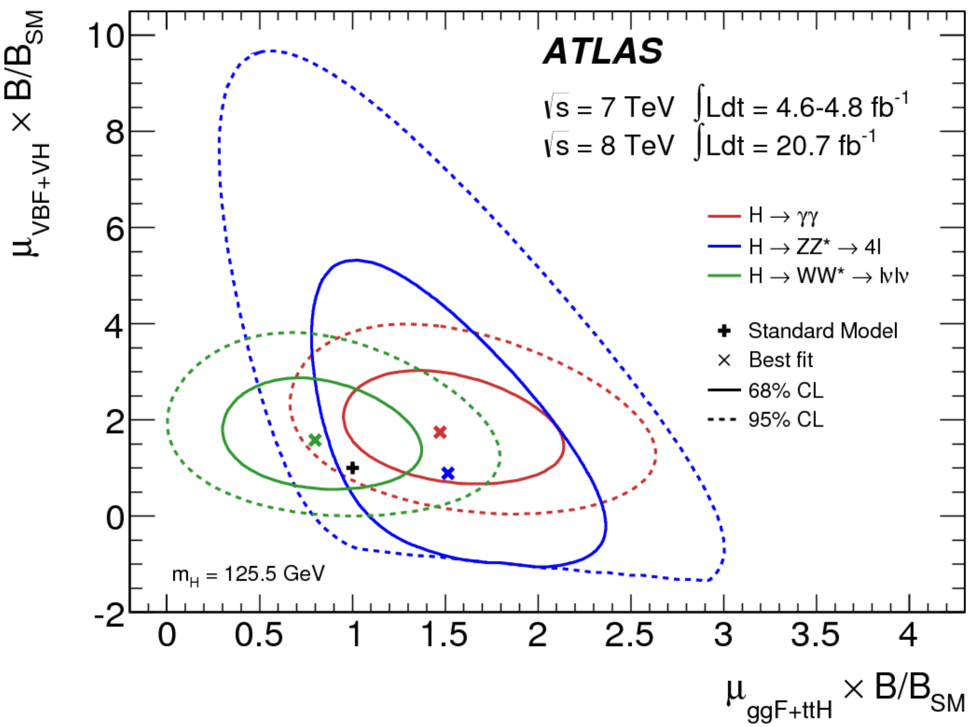
backup



Unconv. central low p_{Tt}
Unconv. central high p_{Tt}
Unconv. rest low p_{Tt}
Unconv. rest high p_{Tt}
Conv. central low p_{Tt}
Conv. central high p_{Tt}
Conv. rest low p_{Tt}
Conv. rest high p_{Tt}
Conv. transition
Loose high-mass two-jet
Tight high-mass two-jet
Low-mass two-jet
E_T^{miss} significance
One-lepton
2012 data combined
ATLAS Preliminary
Data 2012, $\sqrt{s}$ = 8 TeV
$\int Ldt = 20.7\ fb^{-1}$
$H \rightarrow \gamma\gamma$
m_H = 126.8 GeV
-2 0 2 4 6 8 10
Signal strength

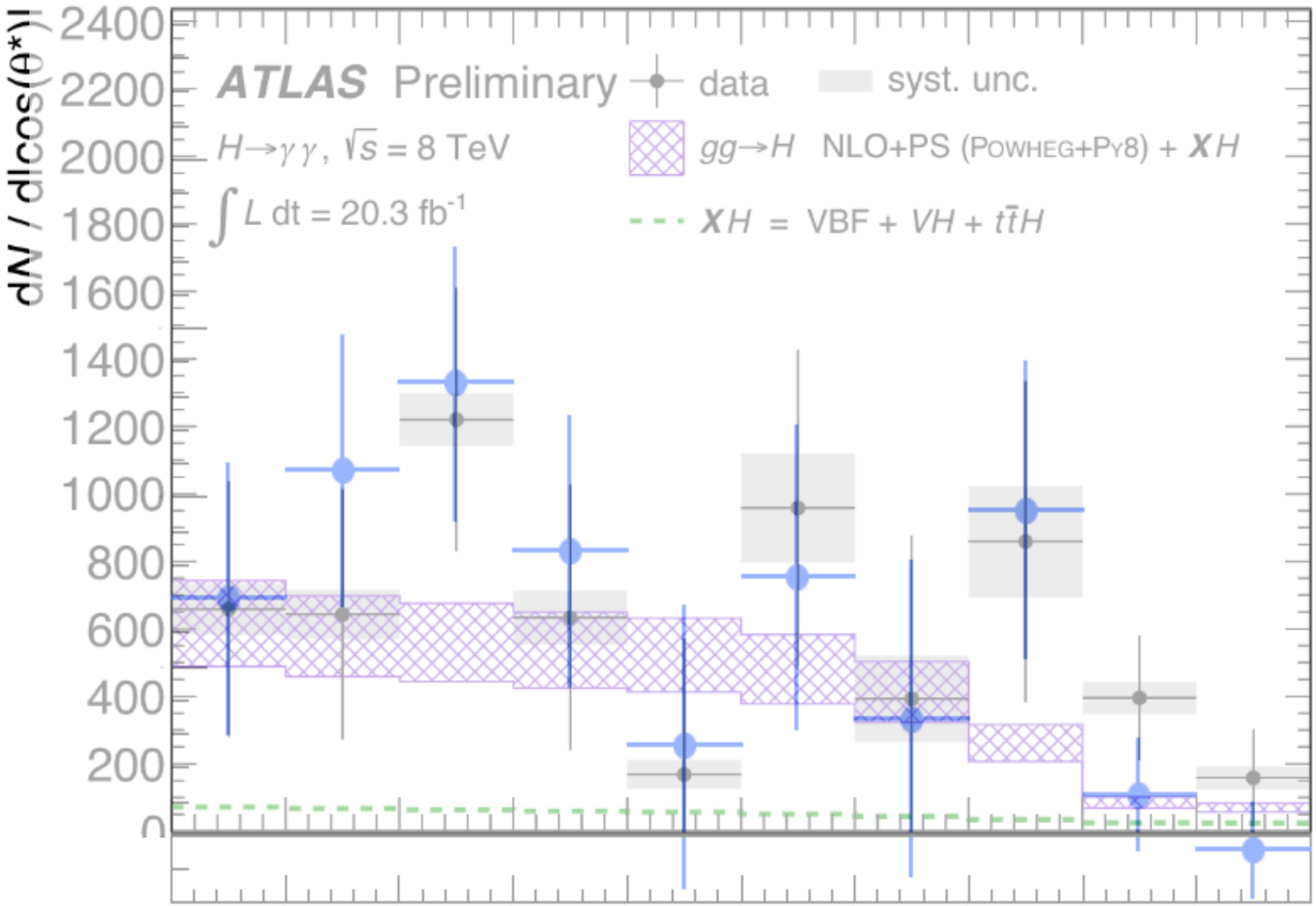


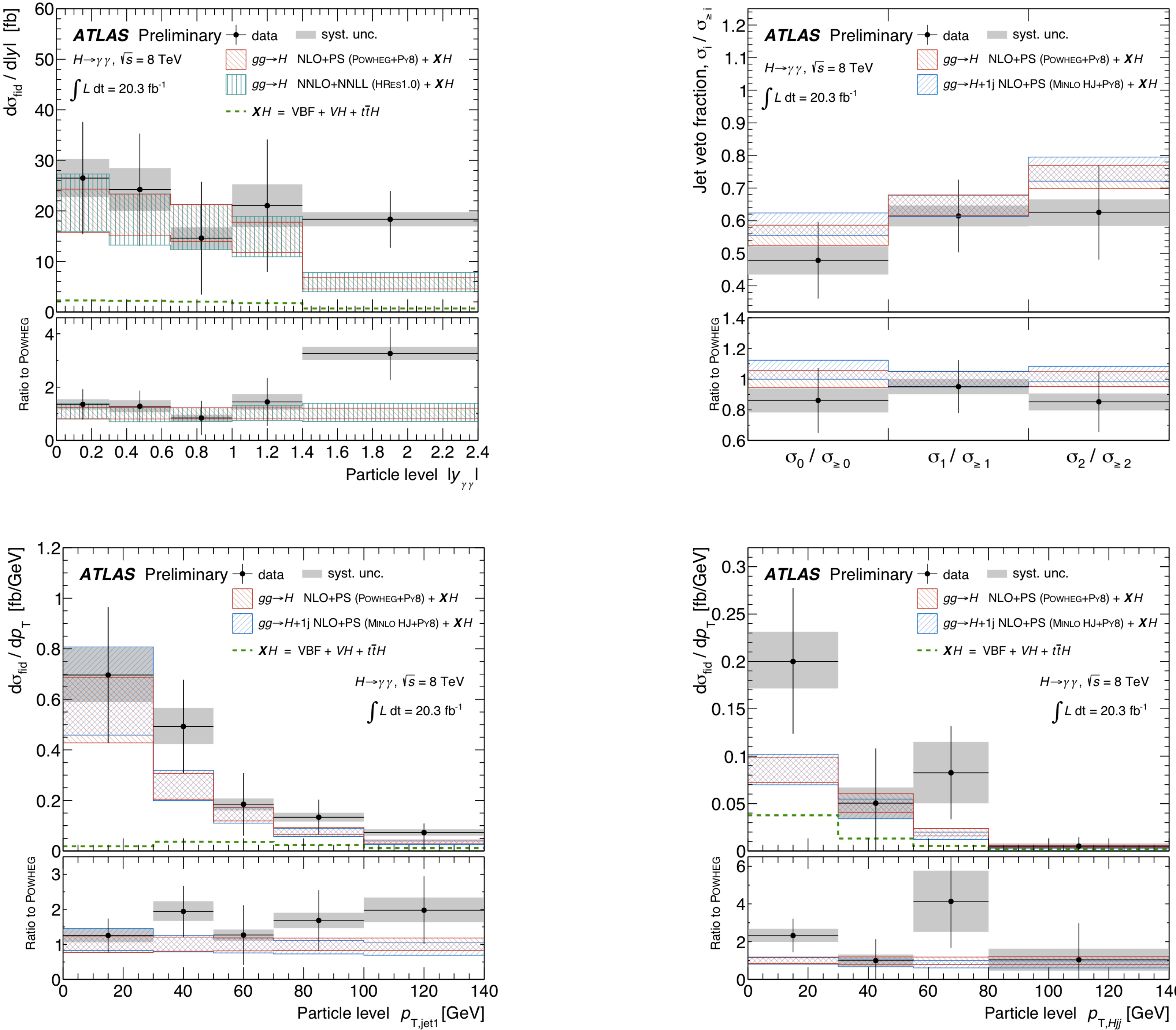
ATLAS
$\sqrt{s}$ = 7 TeV $\int$Ldt = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int$Ldt = 20.7 fb^{-1}
γγ+ZZ* combined
H → γγ
H → ZZ* → 4l
Best fit
68% CL
95% CL
Signal strength (μ)
m_H [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
122
123
124
125
126
127
128
129



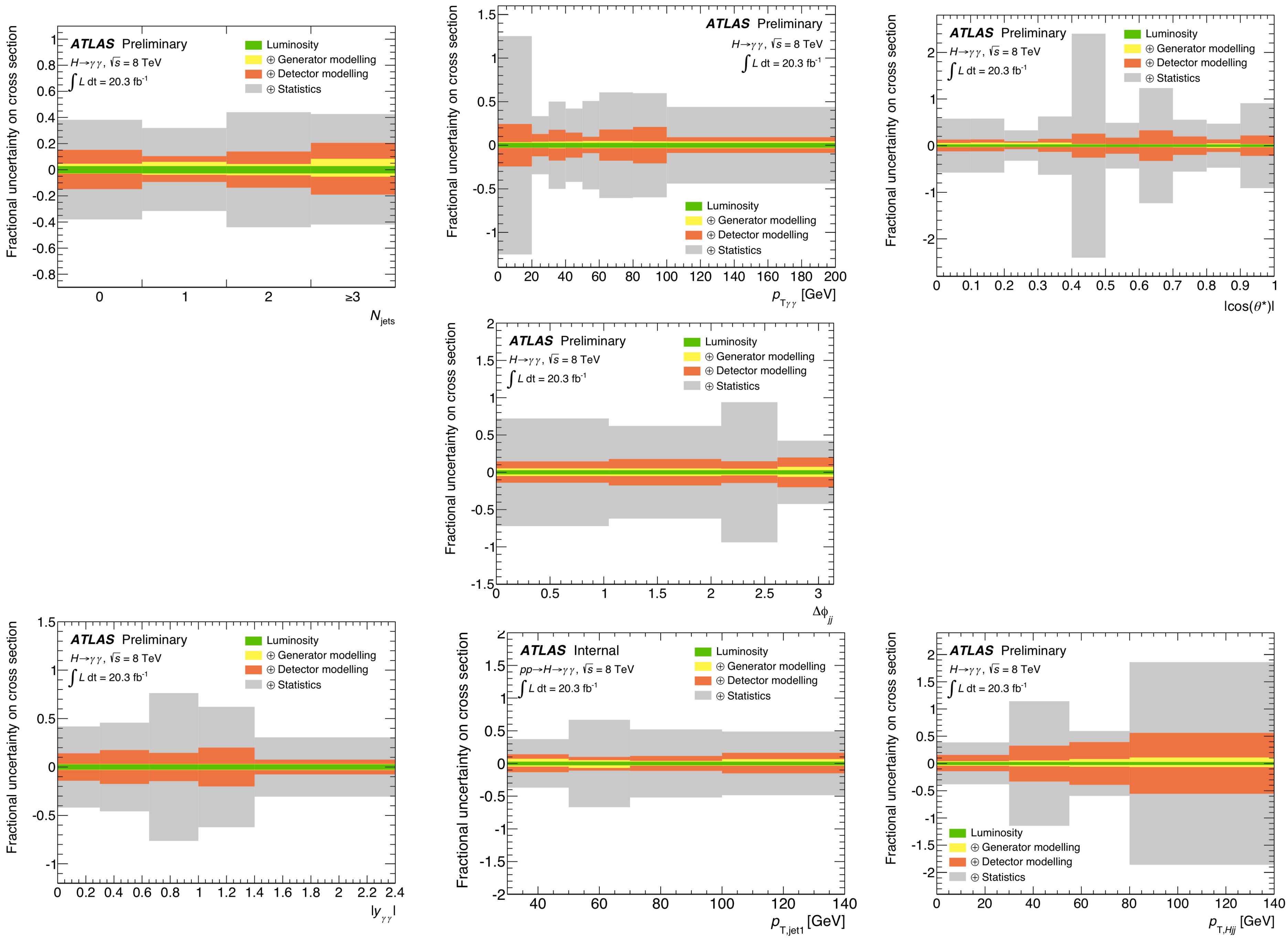
ATLAS
√s = 7 TeV ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
H → γγ
H → ZZ* → 4l
H → WW* → lνlν
Standard Model
Best fit
68% CL
95% CL
m_H = 125.5 GeV
μ_VBF+VH × B/B_SM
μ_ggF+ttH × B/B_SM

Spin vs diff xs



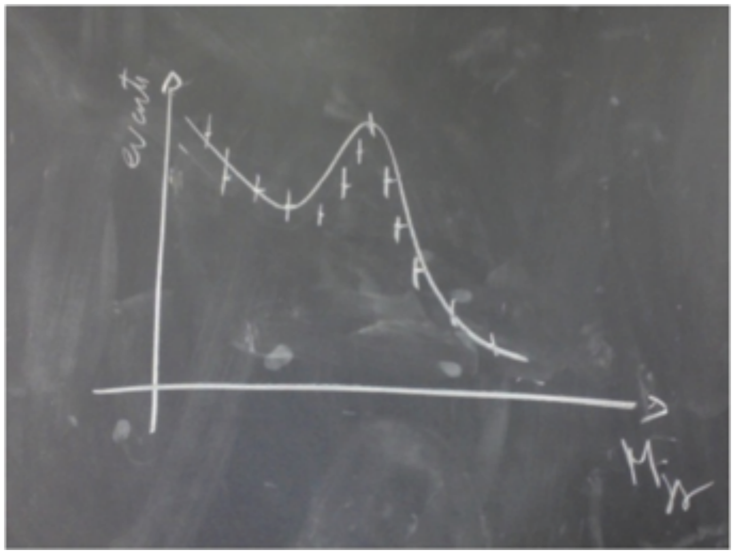


ATLAS Preliminary
data
syst. unc.
gg→H NLO+PS (POWHEG+PY8) + XH
gg→H NNLO+NNLL (HRES1.0) + XH
XH = VBF + VH + ttH
H→γγ, √s = 8 TeV
∫L dt = 20.3 fb-1
dσfid / d|y| [fb]
Ratio to POWHEG
Particle level |yγγ|
ATLAS Preliminary
data
syst. unc.
gg→H NLO+PS (POWHEG+PY8) + XH
gg→H+1j NLO+PS (MINLO HJ+PY8) + XH
H→γγ, √s = 8 TeV
∫L dt = 20.3 fb-1
Jet veto fraction, σi / σ≥i
Ratio to POWHEG
σ0 / σ≥0
σ1 / σ≥1
σ2 / σ≥2
ATLAS Preliminary
data
syst. unc.
gg→H NLO+PS (POWHEG+PY8) + XH
gg→H+1j NLO+PS (MINLO HJ+PY8) + XH
XH = VBF + VH + ttH
H→γγ, √s = 8 TeV
∫L dt = 20.3 fb-1
dσfid / dpT [fb/GeV]
Ratio to POWHEG
Particle level pT,jet1 [GeV]
ATLAS Preliminary
data
syst. unc.
gg→H NLO+PS (POWHEG+PY8) + XH
gg→H+1j NLO+PS (MINLO HJ+PY8) + XH
XH = VBF + VH + ttH
H→γγ, √s = 8 TeV
∫L dt = 20.3 fb-1
dσfid / dpT [fb/GeV]
Ratio to POWHEG
Particle level pT,Hjj [GeV]

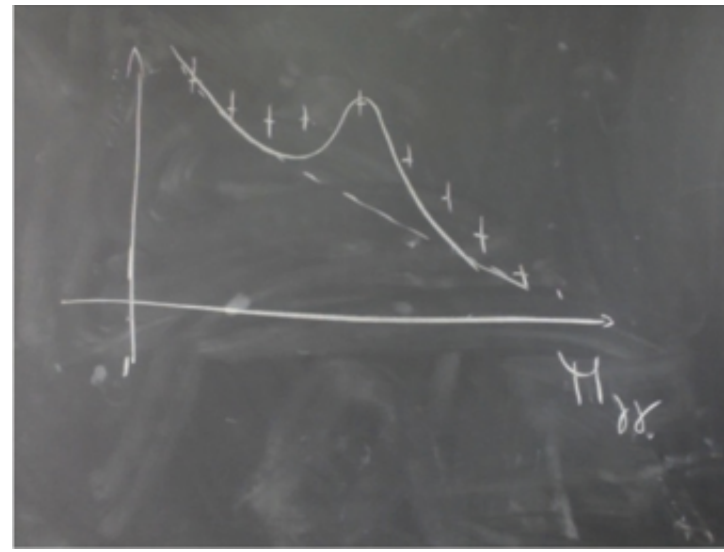


ATLAS Preliminary
H→γγ, √s = 8 TeV
∫ L dt = 20.3 fb-1
Luminosity
⊕ Generator modelling
⊕ Detector modelling
⊕ Statistics
Fractional uncertainty on cross section
N jets
0
1
2
≥3
p T,γγ [GeV]
|cos(θ*)|
Δϕ jj
|y γγ|
ATLAS Internal
pp→H→γγ, √s = 8 TeV
p T,jet1 [GeV]
p T,Hjj [GeV]

Nominal resolution larger than data resolution
⇒ might over-estimate signal strength



Nominal resolution better than data resolution
⇒ might under-estimate signal strength



Parameterising the most general $X_2 \to$ VV decay amplitude :

$$A(X \to V_1 V_2) = \Lambda^{-1} \Big[2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right)$$
$$+ g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
$$+ g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Big] , \quad (18)$$

$q\sim = q_1 - q_2$
$t_{\mu\nu} \sim X_2$ wave function

$\Rightarrow$ 10 complex coupling constants

(in fact using only polarisation vectors, only seven independent terms)

$\Rightarrow$ for the gg $\to X_2 \to \gamma\gamma$ channel : "only" 5 relevant

$\Rightarrow$ For a 2^+ particle, $g_{1\text{-}7}$ ($g_{8\text{-}10}$) are parity conserving (violating)

Parameterising the most general $X_2 \to q\bar{q}$ decay amplitude :

$$A(X_{J=2} \to q\bar{q}) = \frac{1}{\Lambda} t^{\mu\nu} \bar{u}_{q_1} \left(\gamma_\mu \tilde{q}_\nu \left(\rho_1^{(2)} + \rho_2^{(2)} \gamma_5 \right) + \frac{m_q \tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} \left(\rho_3^{(2)} + \rho_4^{(2)} \gamma_5 \right) \right) v_{q_2}$$

Too many degrees of freedom to study spin model-independently :
concentrate on the most simple, well motivated model

a spin 2 particle 2^+_m with minimal coupling, inspired from Gravitation :
→ replacing the Planck scale by the Electroweak scale
→ assigning a mass ~ 126 GeV to the graviton
(e.g. the first graviton KK excitation in Randall-Sundrum type models)

⇒ Keep only the term ∝ g_1/Λ

$$\mathcal{L}_2 = \frac{1}{\Lambda} \sum_{i=V,\gamma,g,\psi} k_i \, \mathcal{T}^i_{\mu\nu} X^{\mu\nu}$$

$T_{\mu\nu}$: energy-momentum tensor
Minimal : all k_i identical

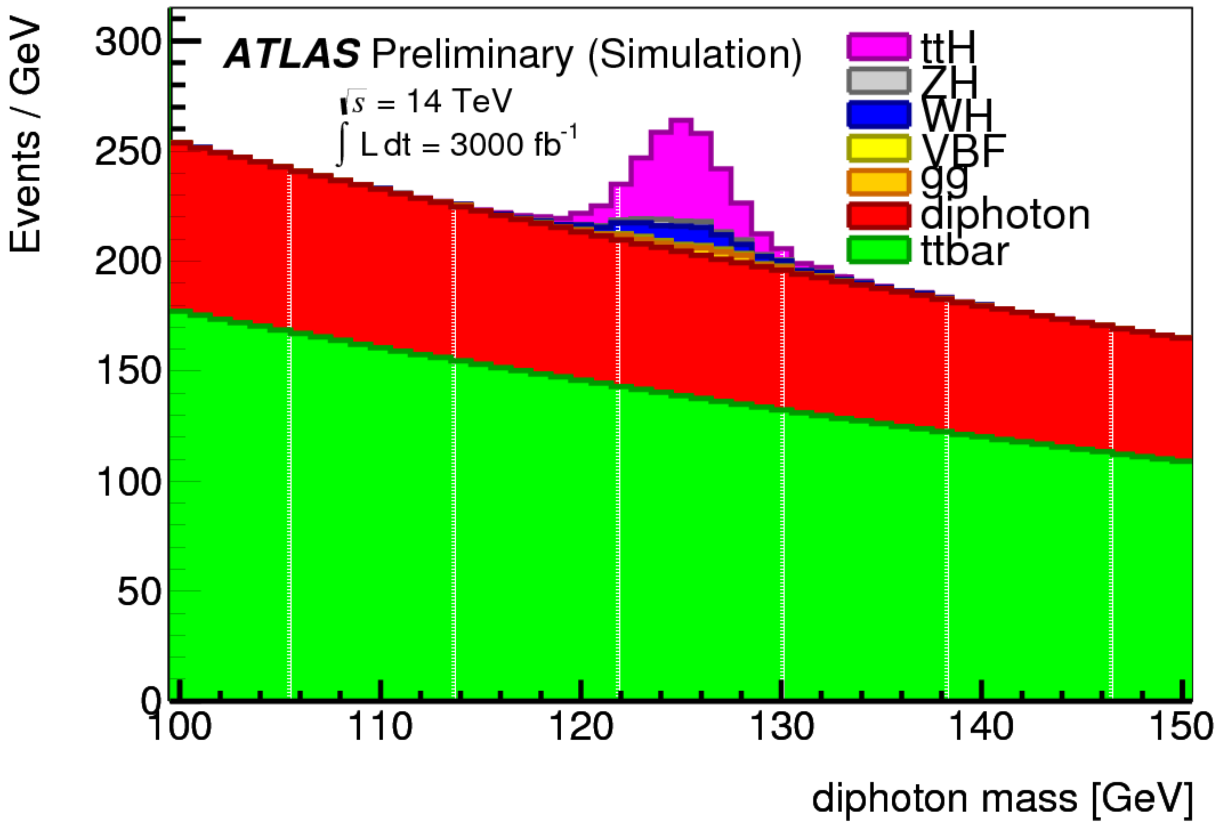
For a "true" minimal model, ρ_1/Λ is fixed once g_1/Λ is (there is a single gravitational constant)
⇒ $\sigma(q\bar{q} \to X_2)/\sigma(gg \to X_2) \sim 0.042$ (@ LO_{QCD} and using CTEQ6L1)

In Atlas, the fraction of events produced via $q\bar{q}$ annihilation has been scanned
(resulting in *a priori* *"bad"* p_T behaviour : not easy to build a consistent Spin 2 model deviating from minimal…)

This *minimal coupling* scenario is in fact already excluded at a high confidence level from the coupling analysis, since it predicts e.g.

✓ $\Gamma(gg) = 8\Gamma(\gamma\gamma)$ whereas HCP data ⇒ $\Gamma(gg) \sim (29\pm13)\, \Gamma(\gamma\gamma)$

✓ $\kappa_V \sim O(35)\, \kappa_\gamma$ whereas HCP data ⇒ $\kappa_V \sim (175\pm25)\, \kappa_\gamma$
(in RS type models)



ATLAS Preliminary (Simulation)
√s = 14 TeV
∫ L dt = 3000 fb-1
ttH
ZH
WH
VBF
gg
diphoton
ttbar
Events / GeV
0
50
100
150
200
250
300
100
110
120
130
140
150
diphoton mass [GeV]