Latest results on Higgs final-states with photons in ATLAS

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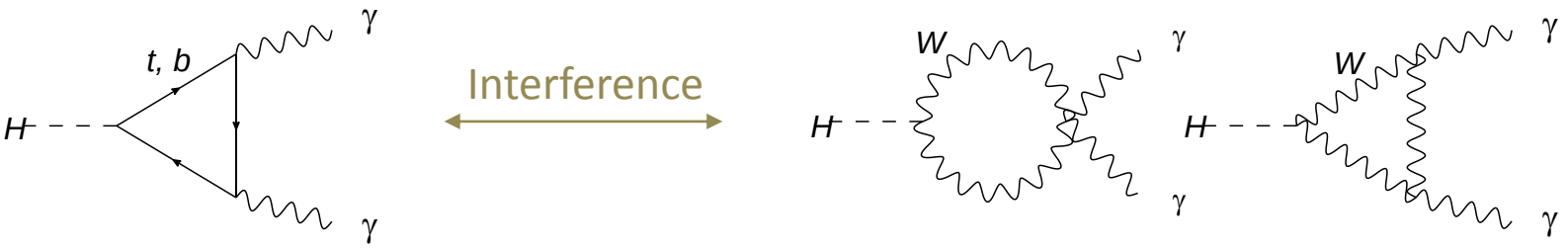
Outline

- Introduction
- Photon reconstruction with ATLAS detector
- Higgs boson property measurements with $H \to \gamma\gamma$ channel
  - mass: Phys. Rev. D. 90, 052004 (2014)
    arXiv:1503.07589
  - coupling: Phys. Rev. D. 90, 112015 (2014)
    Physics Letters B 740 (2015) 222-242
  - spin: ATLAS-CONF-2015-008
  - total and differential cross section: arXiv:1504.05833
- BSM search using $H \to \gamma\gamma$
  - $hh \to \gamma\gamma b\bar{b}$: Phys. Rev. Lett. 114, 081802 (2015)
  - $H \to \gamma\gamma$ + $E_{\mathrm{T}}^{\mathrm{miss}}$: arXiv:1506.01081
  - SUSY + $h \to \gamma\gamma$: Eur. Phys. J. C (2015) 75:208
  - FCNC: JHEP06(2014)008
  - Higgs boson to SUSY: ATLAS-CONF-2015-001

$H \rightarrow \gamma\gamma$

- Significant contribution to discovery of the Standard Model (SM) like Higgs boson
- has great advantages of Higgs boson property measurements
  - coupling, mass, spin, …
- Higgs boson decays to di-photon through top/W loop

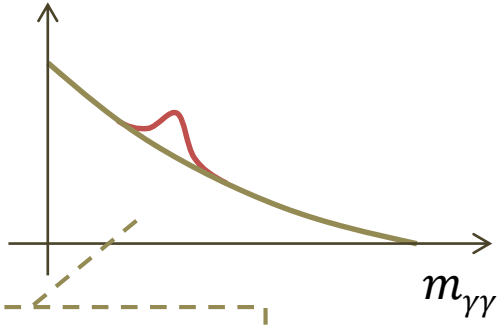


- Sensitive to relative sign of top-Higgs Yukawa coupling with respect to HWW gauge coupling because of interference between loop terms

- $H \rightarrow \gamma\gamma$ + X: Direct search of Beyond the SM (BSM)
  - di-higgs
  - SUSY
  - dark matter
  - …

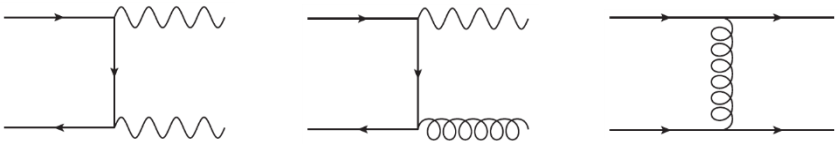
$H \rightarrow \gamma\gamma$ analysis

- Challenge: small branching ratio BR($H \rightarrow \gamma\gamma$) = 2.28 x 10^{-3}
- $m_{\gamma\gamma}$ distribution has peak at Higgs boson mass
- Peak is narrow owing to excellent mass resolution
  - natural width: 4 MeV



Smoothly falling QCD background

Process	γγ	γ-jet	jet-jet
Relative cross section	1	10^4	10^7

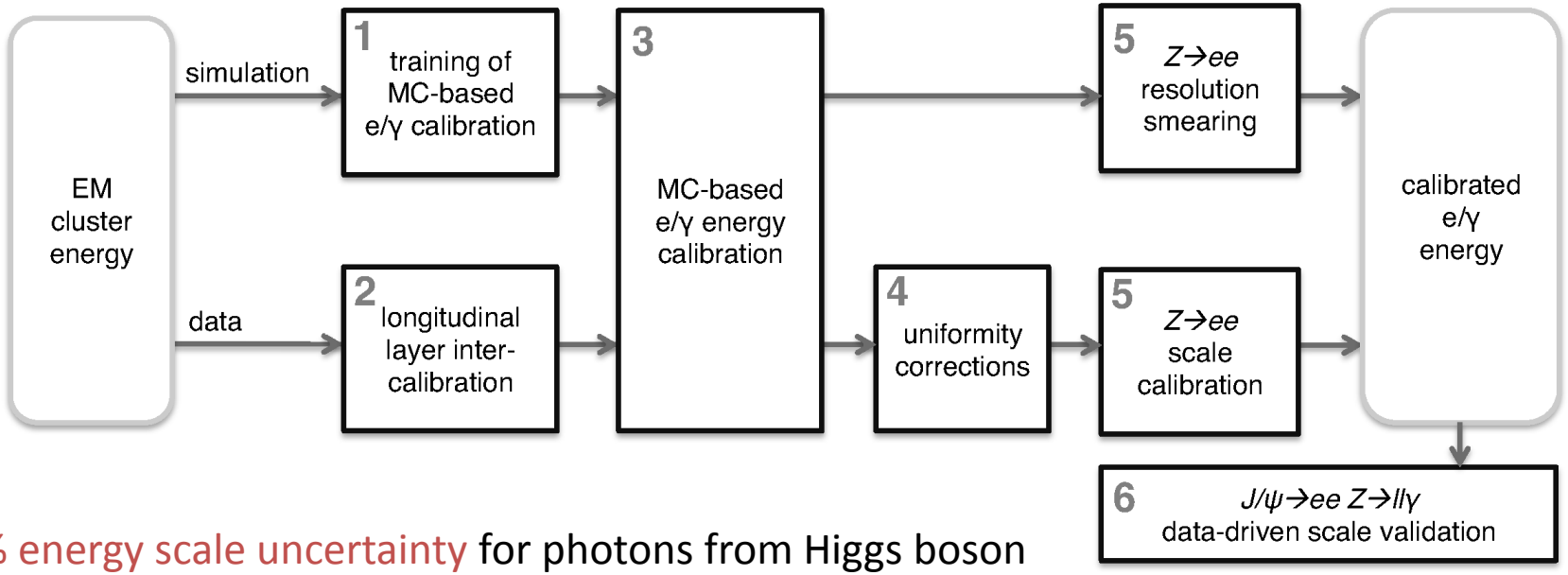


Requirements

- Good photon-jet separation
- High photon reconstruction efficiency
- Good photon energy resolution

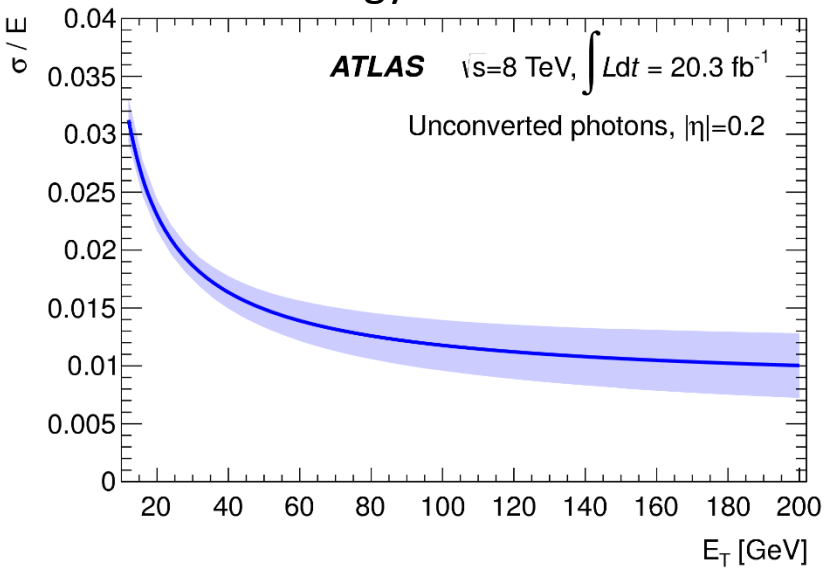
Photon energy calibration

Eur. Phys. J. C (2014) 74: 3071

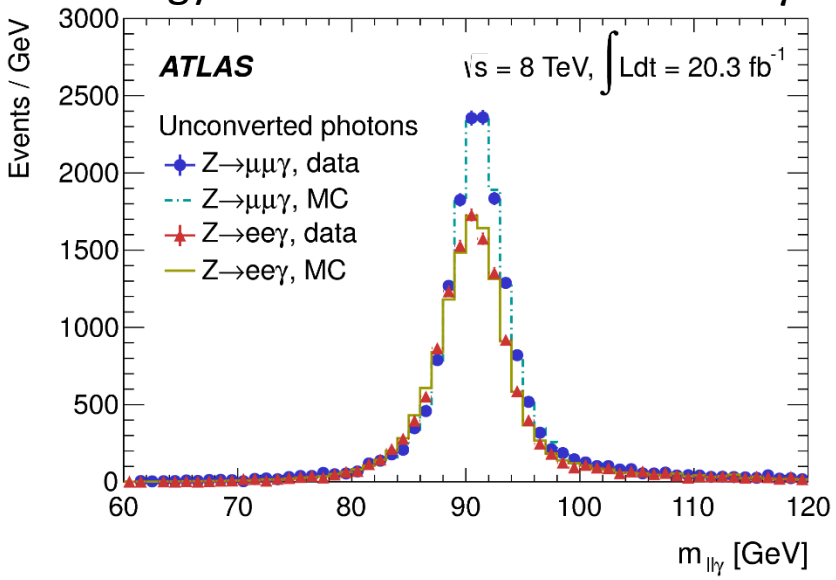


0.3 % energy scale uncertainty for photons from Higgs boson

energy resolution



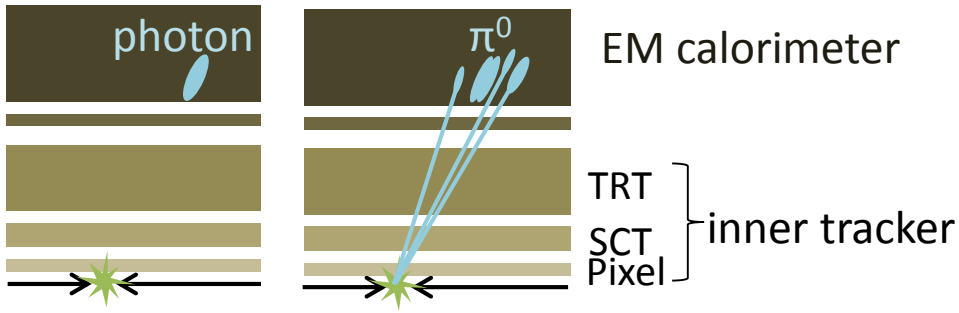
energy scale validation with $Z \to \ell\ell\gamma$



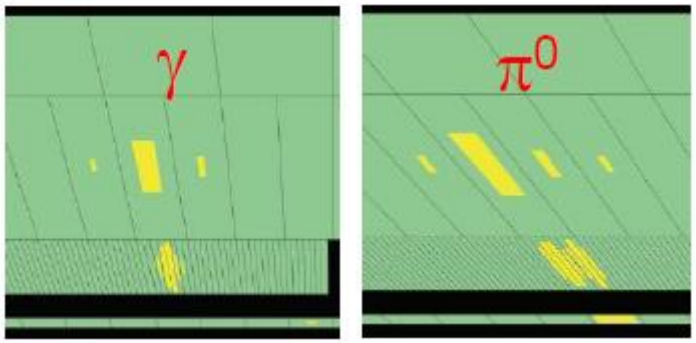
Photon-jet separation

- π^0 ($\rightarrow \gamma\gamma$) in jets: fake photon

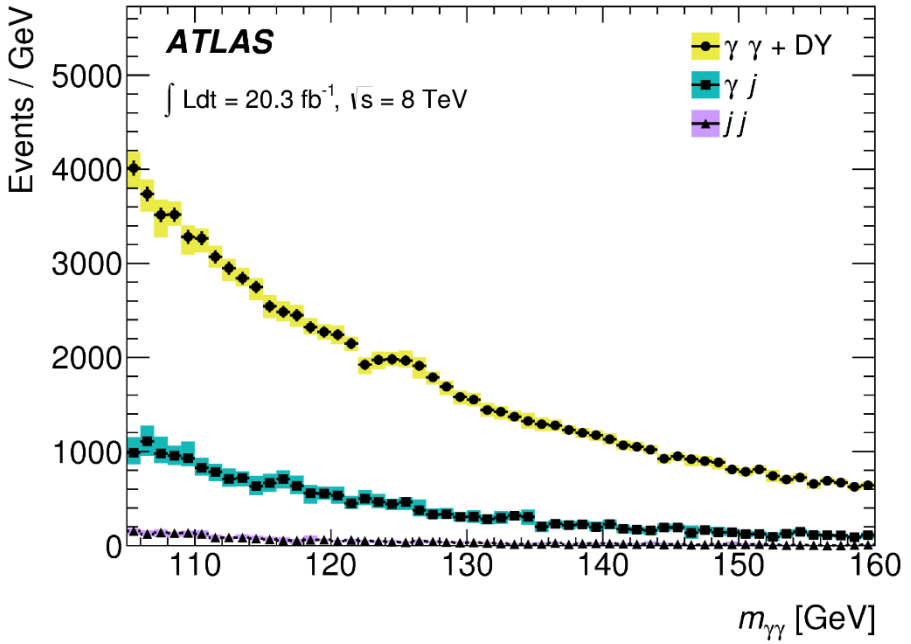
- Isolation
  - Signal photon is isolated
  - π^0 which fakes photon has jet constituents around



- Identification with EM shower shape



Phys. Rev. D. 90, 112015 (2014)



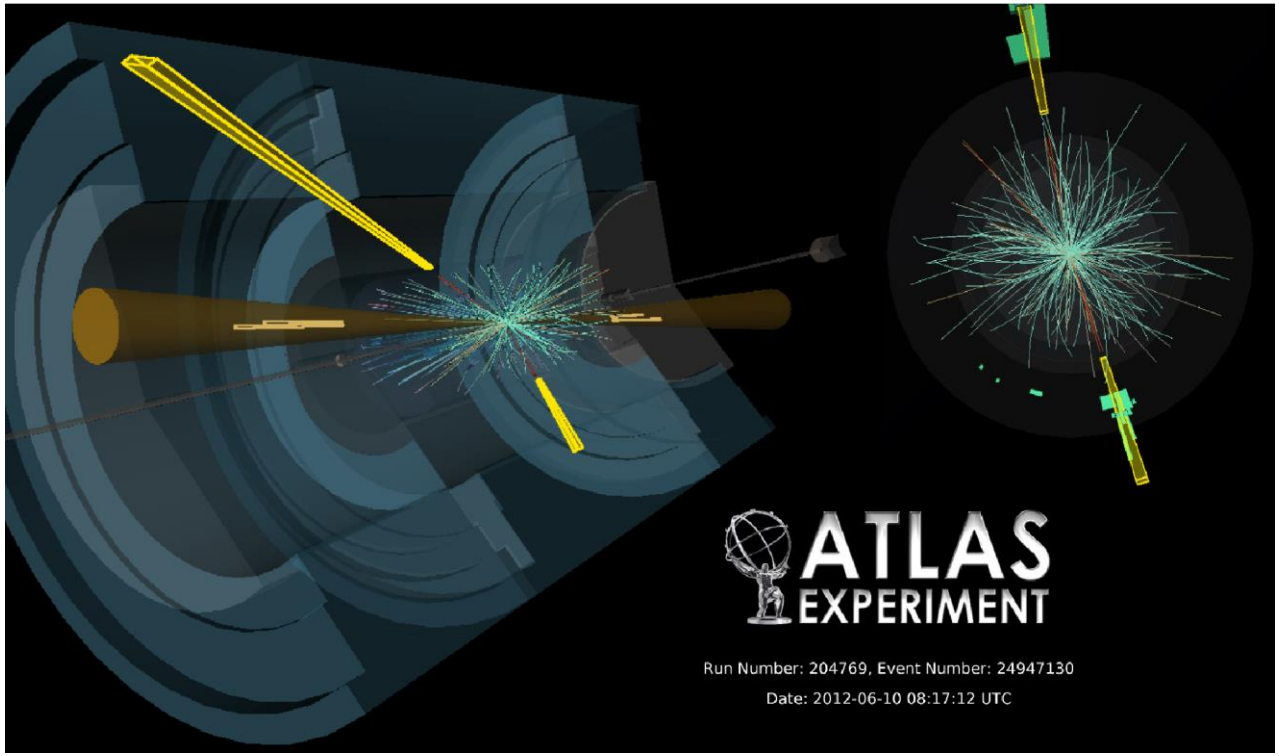
- High efficiency (> 90 %) for photons from Higgs boson
- Good jet rejection
  - γ-γ : γ-jet : jet-jet = 1 : ~10^4 : ~10^7 $\xrightarrow{\text{ID + isolation}}$ 1 : 0.18 : 0.01

—Higgs boson property measurements with $H \rightarrow \gamma\gamma$ channel—

Data sample / $H \rightarrow \gamma\gamma$ candidates

- Data sample: 4.5 fb^{-1} at $\sqrt{s}$ = 7 TeV, 20.3 fb^{-1} at $\sqrt{s}$ = 8 TeV
- Selection: isolated 2 photons $p_T/m_{\gamma\gamma} > 0.35, 0.25$
- Total selected events in $m_{\gamma\gamma}$ [105 : 160] GeV: 1.1 x 10^5 evt
- Total expected signal events: 468 evt for m_H = 125.4 GeV

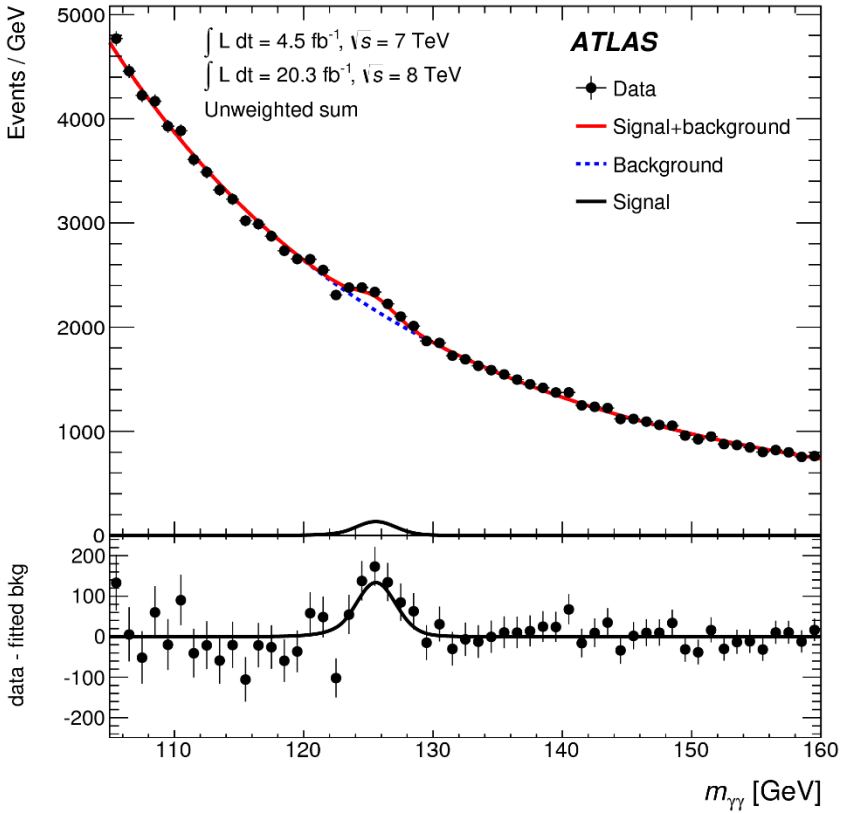
- Vector Boson Fusion (VBF) $H \rightarrow \gamma\gamma$ candidate
- di-photon + forwards 2 jets

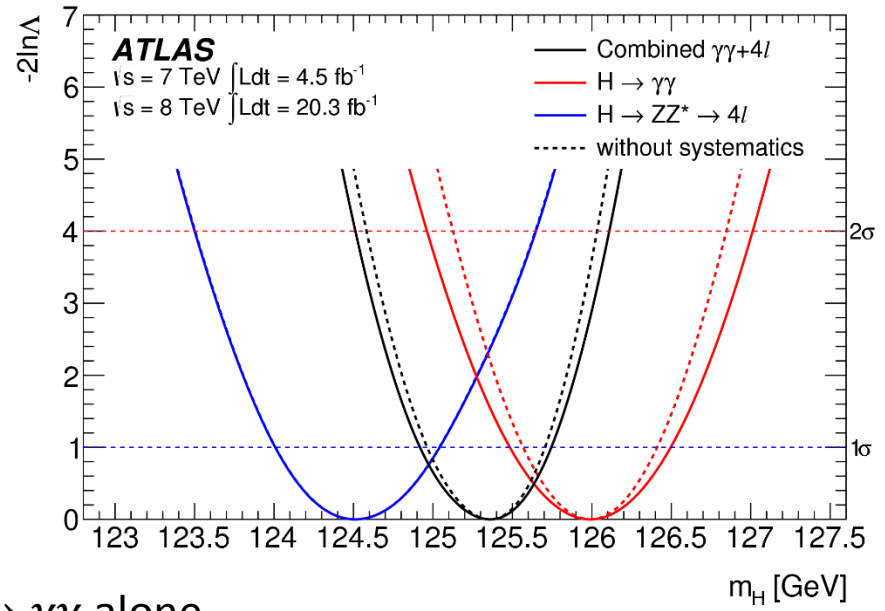


Mass measurement

Phys. Rev. D. 90, 052004 (2014)
arXiv:1503.07589

- Higgs boson mass: input parameter of SM
  - determined by experiments to complete SM
- $H \to \gamma\gamma$: most precise measurement
  - mass resolution: 1.65 GeV





$H \to \gamma\gamma$ alone

$$m_H = 125.98 \pm 0.42\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{GeV}$$

combine with $H \to ZZ \to 4\ell$ analysis

$$m_H = 125.36 \pm 0.37\,(\text{stat.}) \pm 0.18\,(\text{syst.})\ \text{GeV}$$

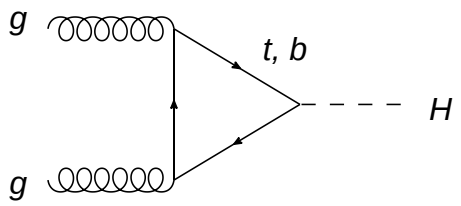
- Dominant systematic uncertainty: energy scale uncertainty due to material amount uncertainty in front of EM calorimeter
- combining ATLAS and CMS: $m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$

Coupling measurement

Phys. Rev. D. 90, 112015 (2014)
Physics Letters B 740 (2015) 222-242

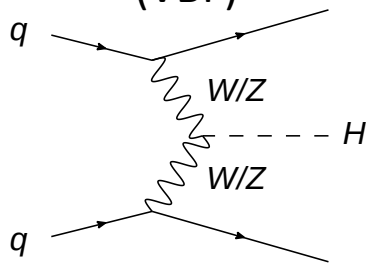
- To measure gauge coupling and Yukawa coupling individually, events are categorized based on event signature of production process

gluon-gluon fusion (ggF)



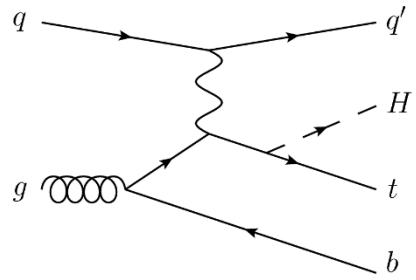
Largest cross section (87 % of Higgs boson production)

vector boson fusion (VBF)



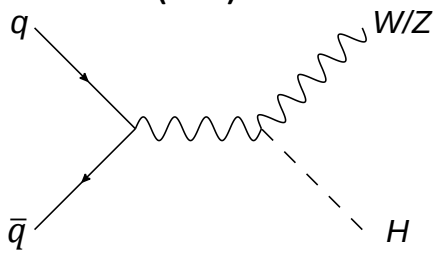
Forwards high p_T 2 jets

tH production



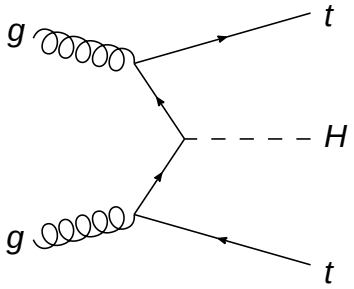
b-jets/W bosons

associated production (VH)



Leptons/jets/Missing E_T from W/Z boson

associated production with $t\bar{t}$ (ttH)



b-jets/W bosons from top-quarks

gauge coupling g_{HWW}, g_{HZZ}: VBF, VH

top-Higgs Yukawa Y_t: ggF, ttH, tH

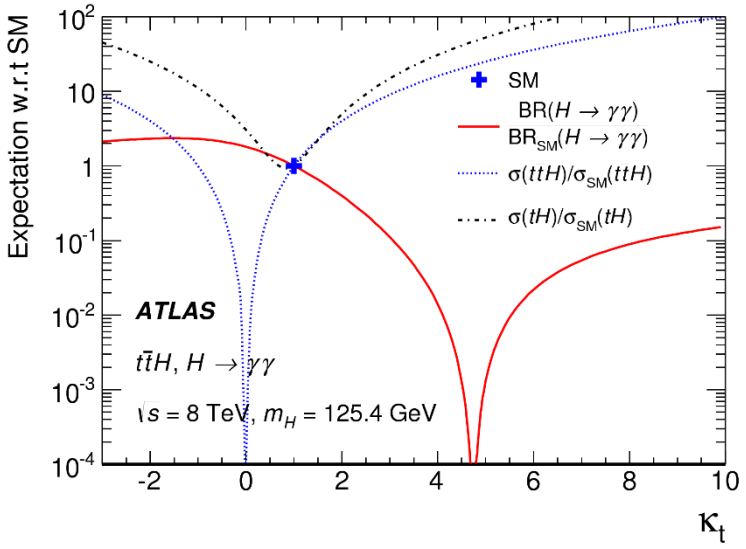
ttH, tH: direct Y_t measurement

Coupling measurement

Phys. Rev. D. 90, 112015 (2014)
Physics Letters B 740 (2015) 222-242

tH cross section is sensitive to relative sign between Y_t and g_{HWW} as well as BR($H \rightarrow \gamma\gamma$) because of interference

Dependence of ttH and tH cross sections and BR($H \rightarrow \gamma\gamma$) on κ_t



$\kappa_t = Y_t / Y_t^{SM}$

$\kappa_t = 0$ means

- turn off ttH process
- remove top quark contribution to tH and to $H \rightarrow \gamma\gamma$

$\kappa_t < 0$ enhances tH cross section and BR($H \rightarrow \gamma\gamma$)

Coupling measurement

Phys. Rev. D. 90, 112015 (2014)
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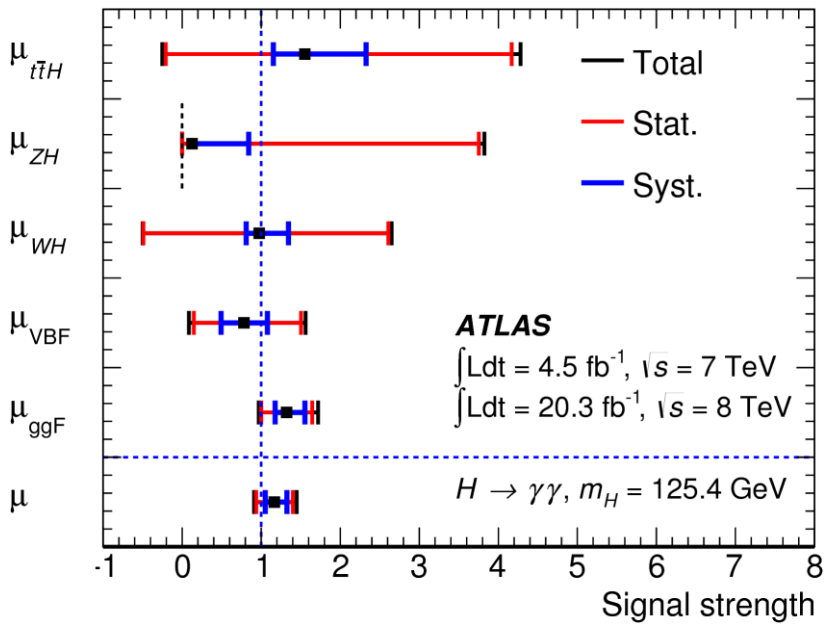
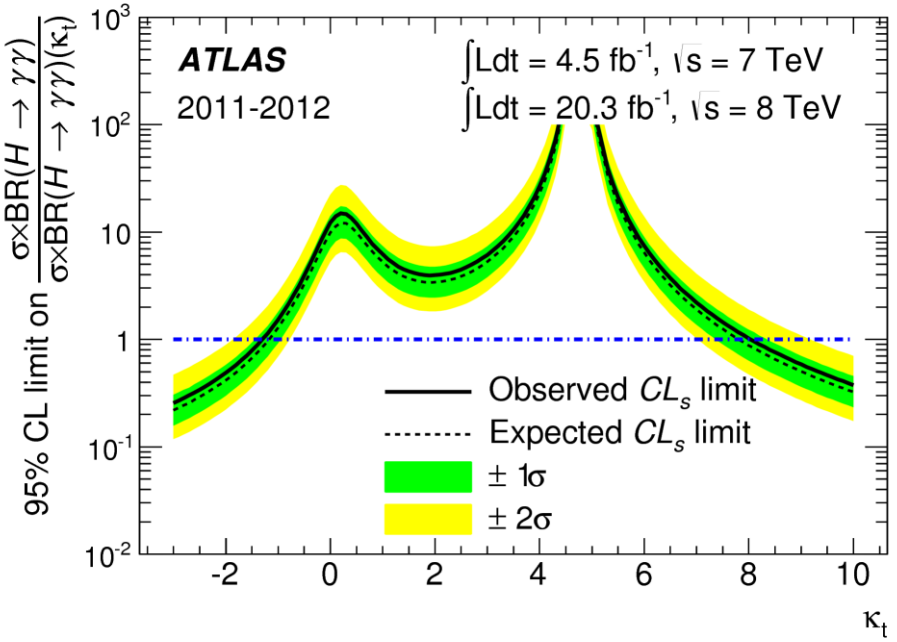
$$\mu = \frac{\sigma \times \mathrm{BR}(H \to \gamma\gamma)}{\sigma_{SM} \times \mathrm{BR}_{SM}(H \to \gamma\gamma)}$$



95 % CL on κ_t



$$\mu = 1.17 \pm 0.23\,(\text{stat.})\ ^{+0.10}_{-0.08}\,(\text{syst.})\ ^{+0.12}_{-0.08}\,(\text{theory})$$

- One of dominant systematic uncertainties is photon energy resolution

μ_{ggF}	μ_{VBF}	μ_{WH}	μ_{ZH}	μ_{ttH}
1.32 ± 0.38	0.8 ± 0.7	1.0 ± 1.6	$0.1\ ^{+3.7}_{-0.1}$	$1.6\ ^{+2.7}_{-1.8}$

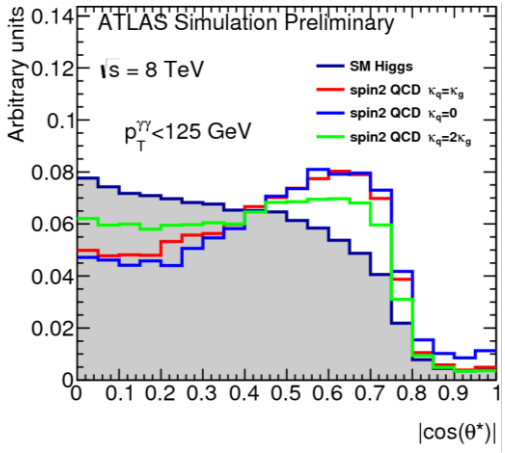
- lower limit: -1.3
- upper limit: 8.0

- Combined measurement of coupling
  ATLAS-CONF-2015-007
- ttH search in other channels
  ATLAS-CONF-2015-006
  arXiv:1503.05066

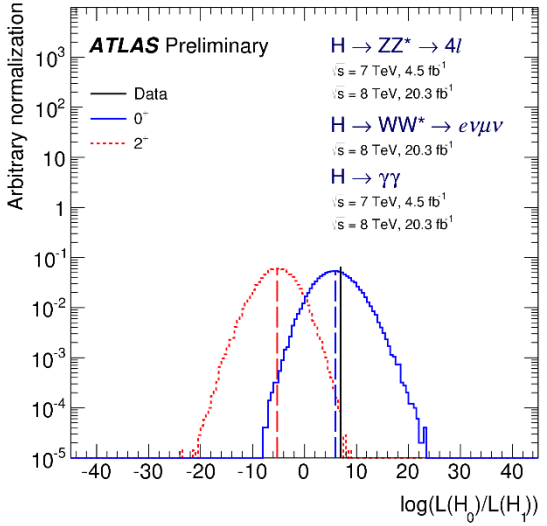
Other property measurements

ATLAS-CONF-2015-008
arXiv:1504.05833

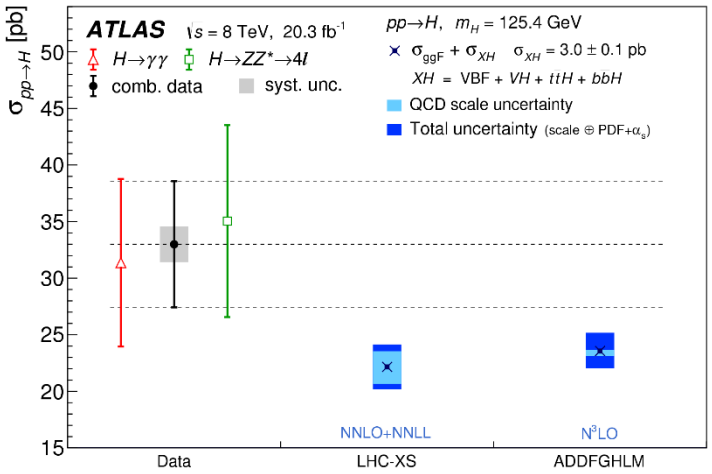
- Spin measurement
  - spin 0 and 2 can be distinguished by angular distribution of 2 photons

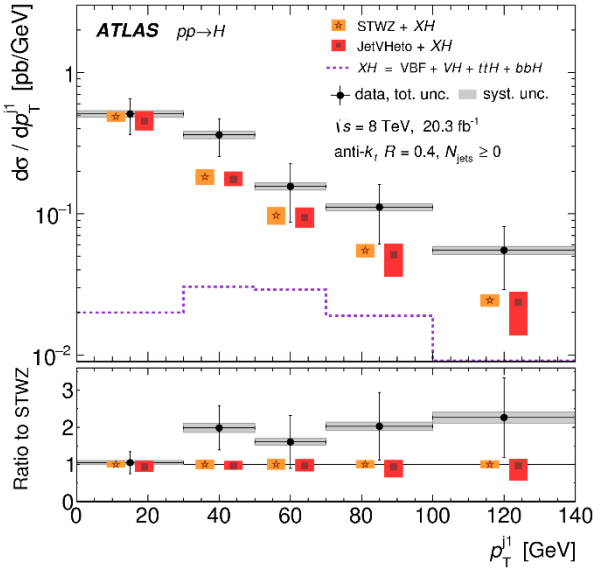


spin 2 model with Universal couplings



- Total and differential cross section measurement
  - $\sigma_{pp\to H} = 33.0 \pm 5.3\ (\text{stat}) \pm 1.6\ (\text{sys})$ pb





BSM search using $H \rightarrow \gamma\gamma$

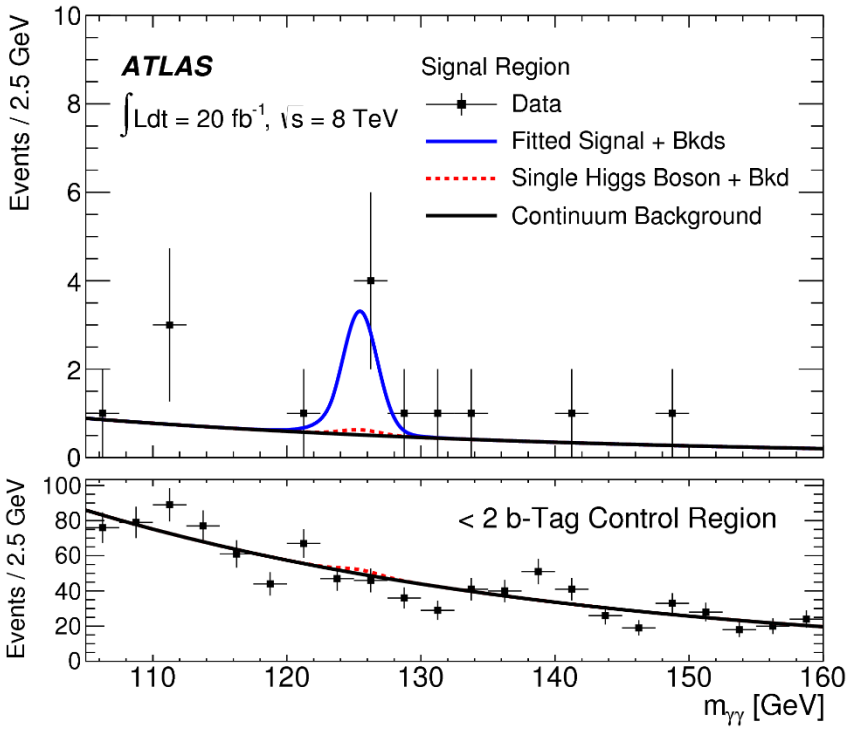
- In search of BSM with Higgs boson, Higgs can be tagged with some final states ($\gamma\gamma$, WW, ZZ, bb, $\tau\tau$, …)
- $H \rightarrow \gamma\gamma$ is excellent final state because of good diphoton mass resolution, and low backgrounds

$hh \rightarrow \gamma\gamma b\bar{b}$

Phys. Rev. Lett. 114, 081802 (2015)

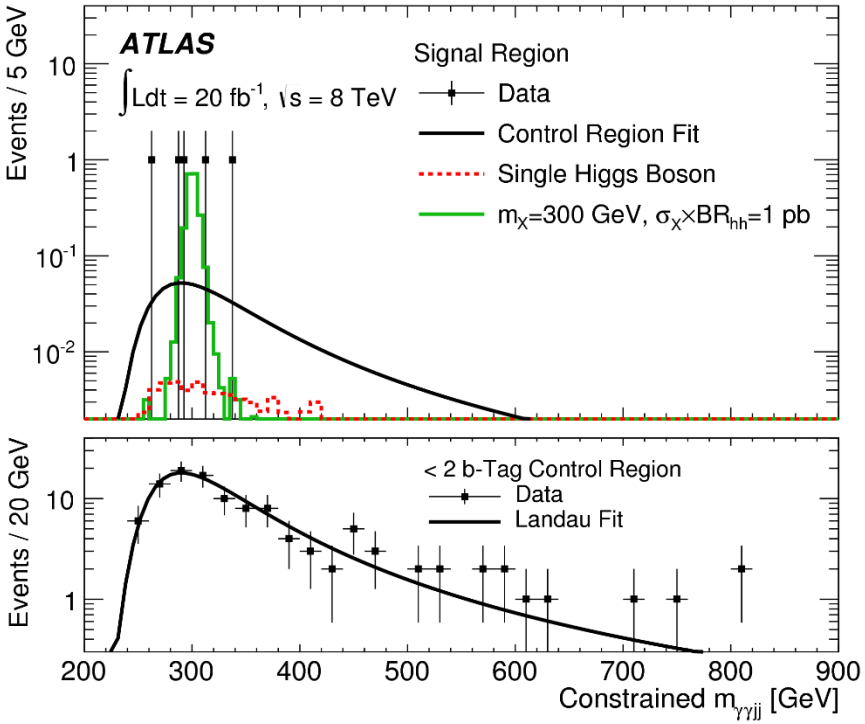
- Predicted cross section for di-higgs production in SM
  - ~ 10 fb at $\sqrt{s} =$ 8 TeV (NNLO)
- various BSM models (i.e. 2HDM) predict large di-higgs production
- Selection:
  - 2 photons + 2 b-jets
  - 95 < m_{bb} < 135 GeV
- Dominant BG: QCD *γγbb*, ttH and (Z→bb)H in SM

non-resonant search



- Signal is extracted from fit in $m_{\gamma\gamma}$

resonant search ($X \rightarrow hh$)



- Counting on $m_{\gamma\gamma}$ and $m_{\gamma\gamma bb}$ plane

$hh \rightarrow \gamma\gamma b\bar{b}$

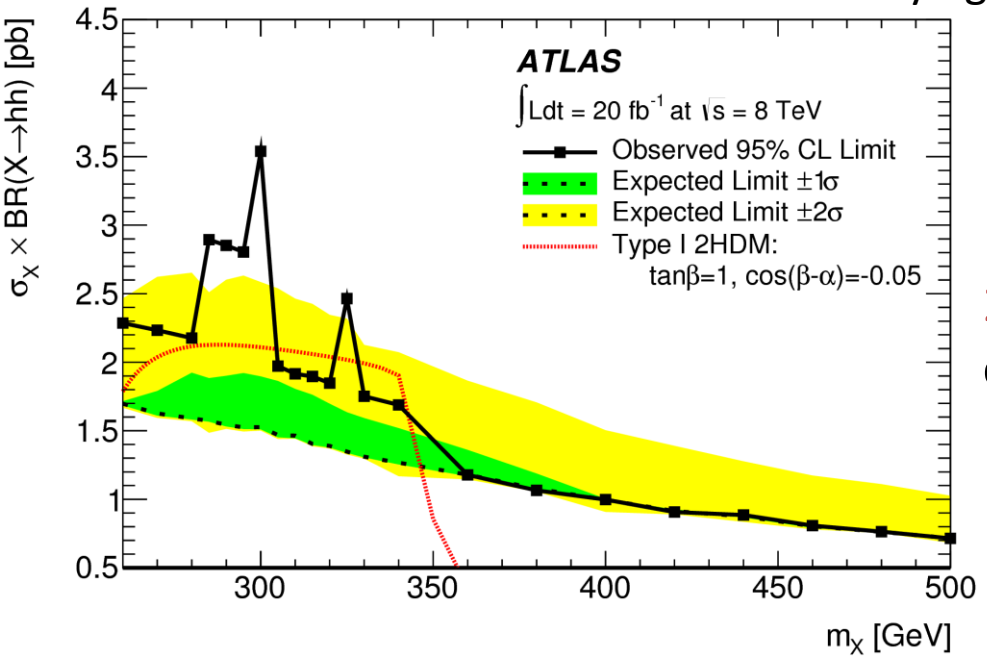
Phys. Rev. Lett. 114, 081802 (2015)

- Non-resonant di-higgs production
  - Upper limit on anomalous non-resonant di-higgs production

    2.2 pb (observed)
    1.0 pb (expected)
  - 2.4 σ deviations from BG only hypothesis

- Resonant search

cross section x BR of narrow resonance decaying to di-higgs



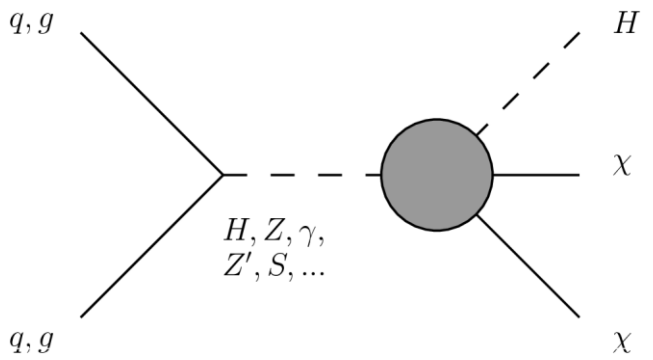
2.1 σ deviation at m_X = 300 GeV with considering look-elsewhere effect

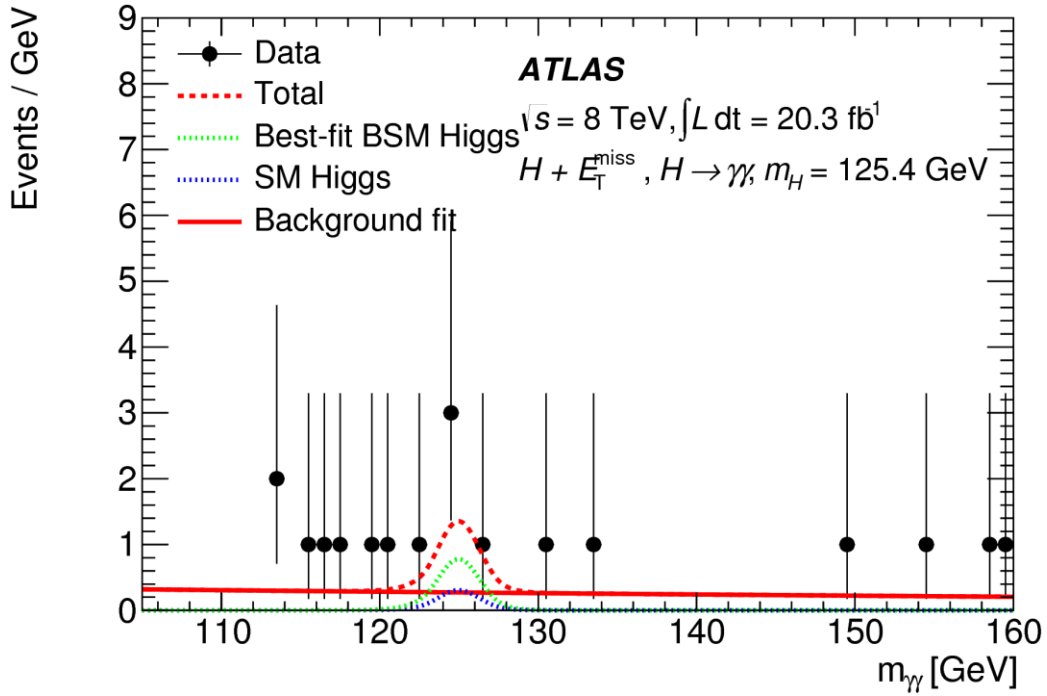
di-higgs search for *hh* → *bbbb*: arXiv:1506.00285

$H \rightarrow \gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$

arXiv:1506.01081

- Motivated by dark matter (DM)
- Higgs boson is unlikely to be radiated with initial state radiation
  - sensitive to structure of effective DM-SM coupling
- Selection:
  - 2 photons + $p_{\mathrm{T}}^{\gamma\gamma}$ > 90 GeV + $E_{\mathrm{T}}^{\mathrm{miss}}$ > 90 GeV

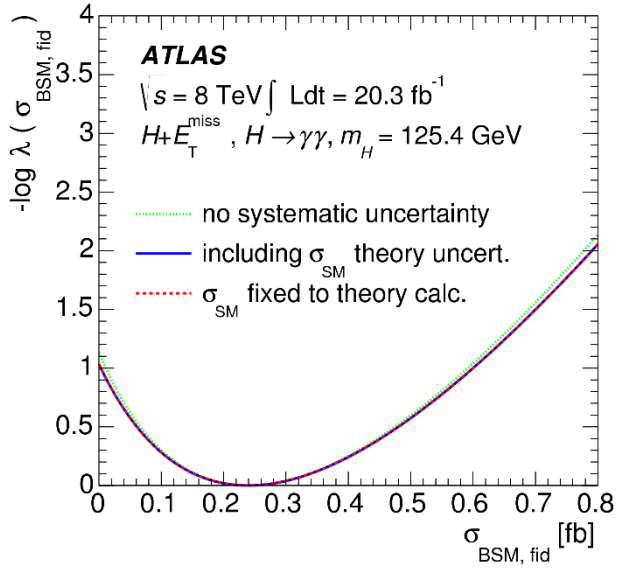




- SM Higgs boson BG
  - $(Z \rightarrow \nu\nu)$H
  - $(W \rightarrow \ell\nu)$H
- non-resonant BG
  - QCD
  - Wγγ, γ + jet
  - Zγγ, γ + jet

$H \rightarrow \gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$

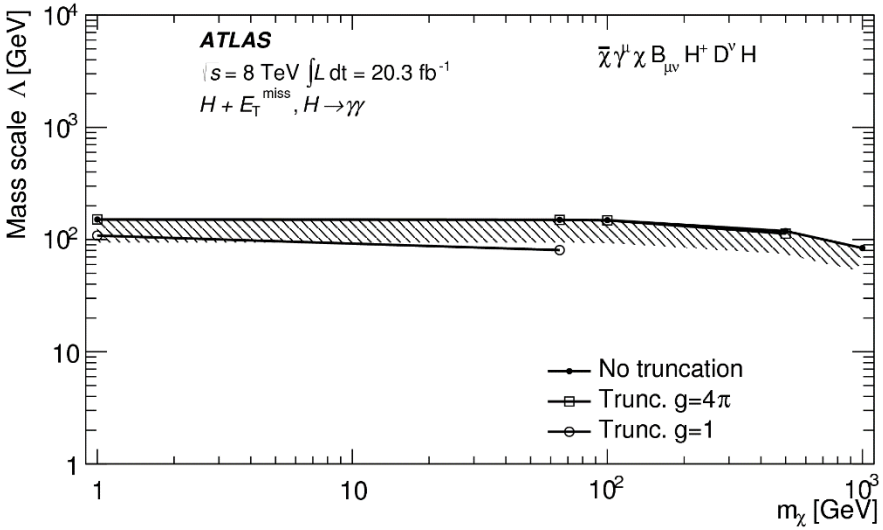
arXiv:1506.01081

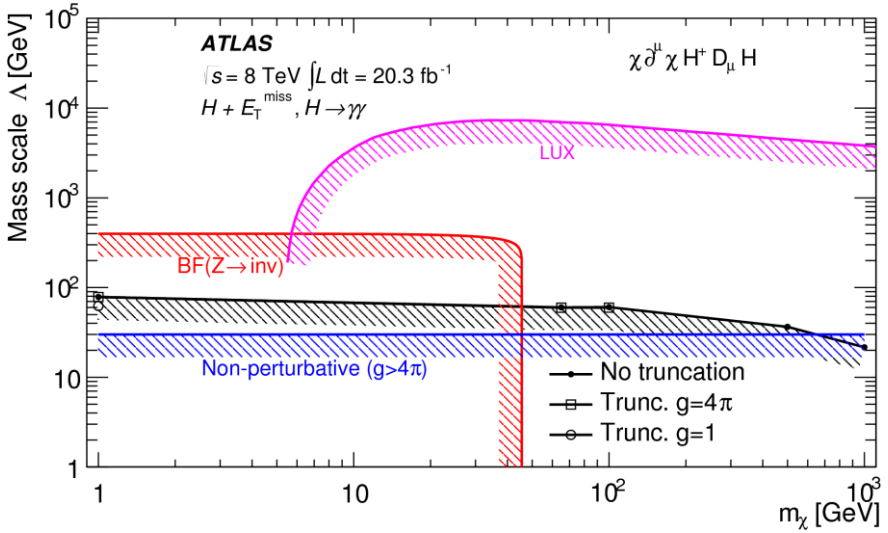


- Likelihood ratio as a function of fiducial cross section of BSM Higgs boson + DM production
- Highly model independent

- Small deviations from BG only hypothesis
- Observed upper limit: 0.70 fb
- Expected upper limit: 0.43 fb

- Interpretation to limits on DM production in Effective Field Theory (EFT)



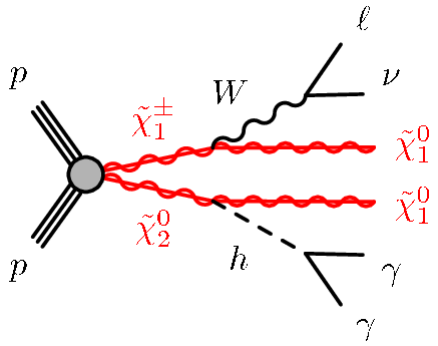


- m_χ: DM mass

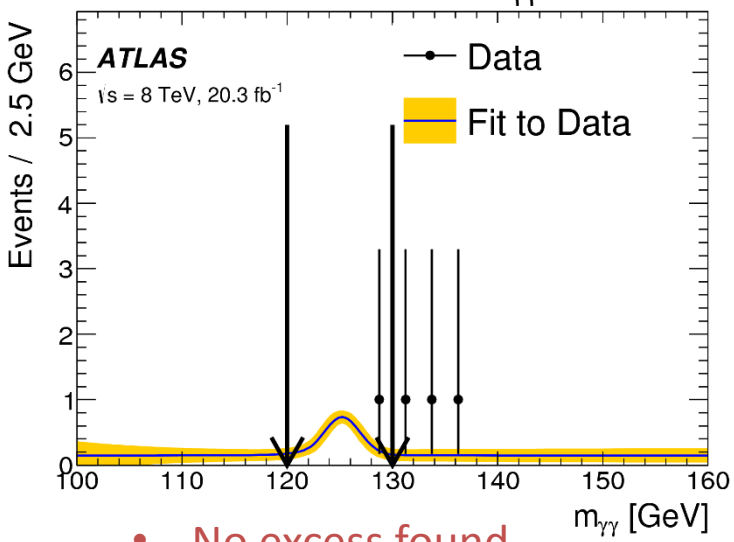
SUSY + $h \rightarrow \gamma\gamma$

Eur. Phys. J. C (2015) 75:208

- Direct pair production of chargino $\tilde{\chi}_1^{\pm}$ and neutralino $\tilde{\chi}_2^0$
- Scenario:
  - masses of pseudo-scalar Higgs boson and sleptons > $m_{\tilde{\chi}_1^{\pm}}$ and $m_{\tilde{\chi}_2^0}$
  - $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > m_{\mathrm{H}}$
  - $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ wino-like and degenerate
- $\tilde{\chi}_1^{\pm} \rightarrow (W \rightarrow \ell\nu)\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$
- SM Higgs boson BG: *WH*, *ZH*, ttH
- Continuous BG: Wγ, Zγ

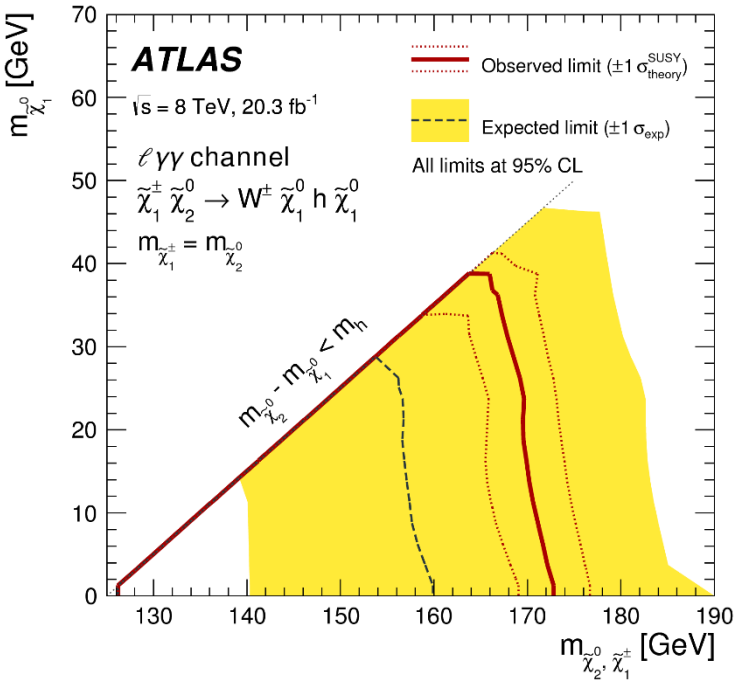


BG only fit to $m_{\gamma\gamma}$



- No excess found

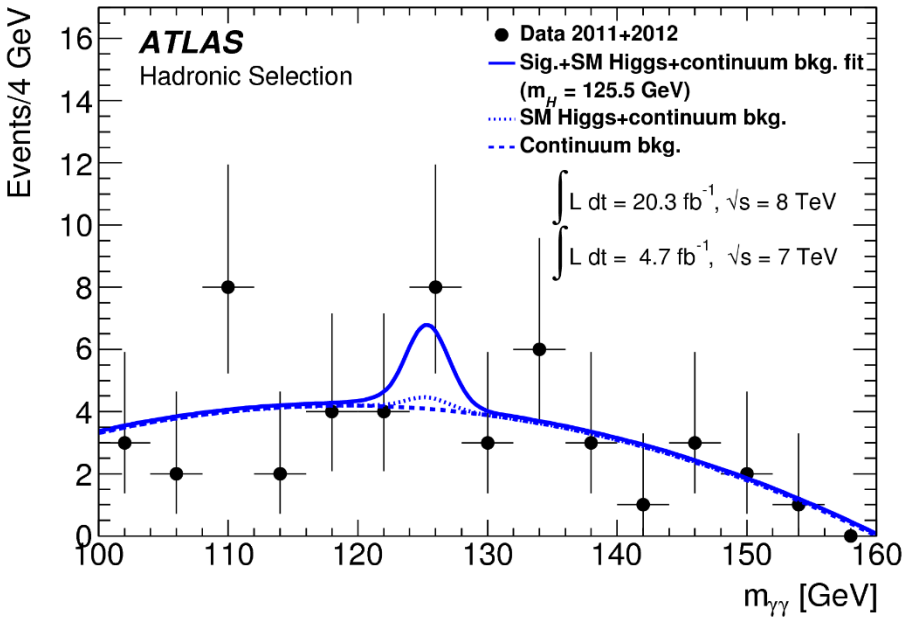
Limits on exclusion regions in $m_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$ mass plane



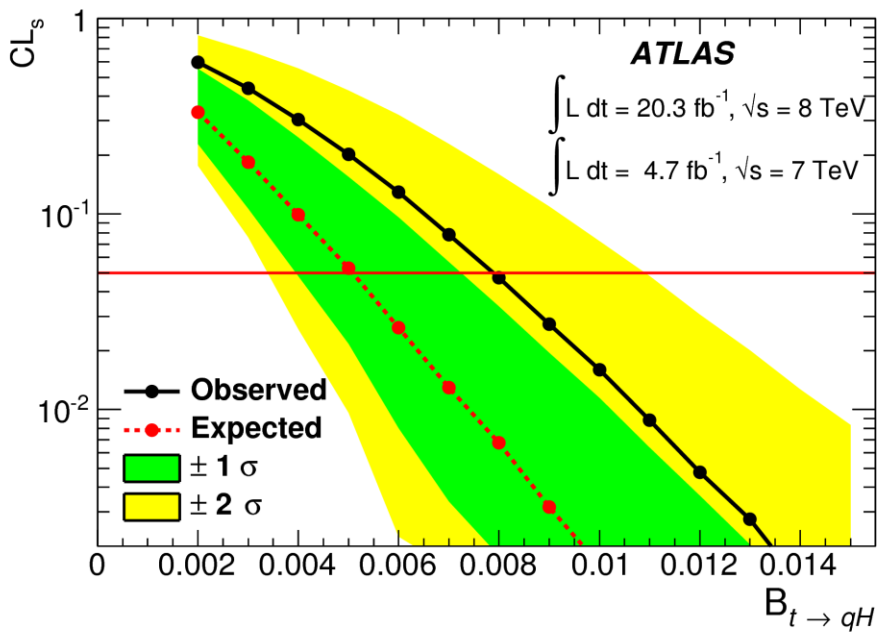
JHEP06(2014)008

Other BSM searches

- Flavor-changing neutral current
  - top quark decays to up-type (c, u) quark and Higgs boson
  - much suppressed in SM
    - BR($t \to cH$) ~ 3 x 10^{-15}
  - $pp \to t\bar{t} \to bW + qH(\to \gamma\gamma)$



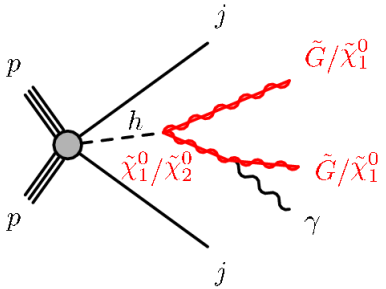
no significant signal is observed

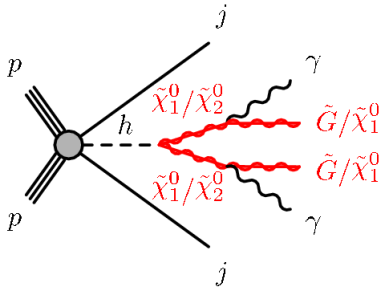


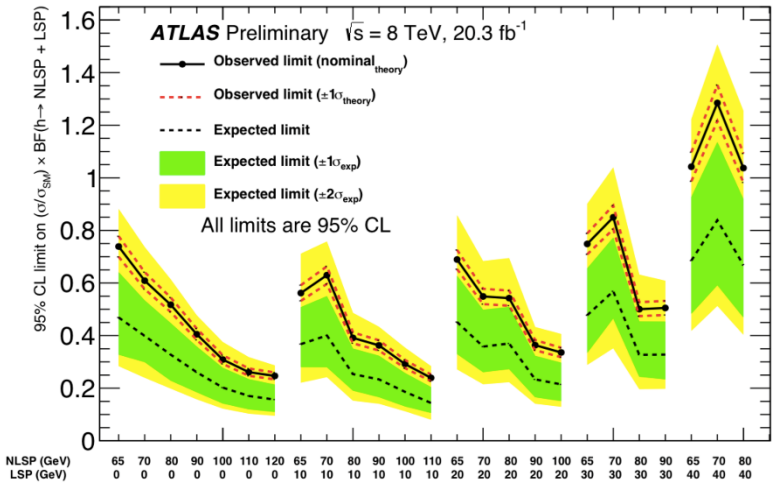
upper limit on $t \to qH$ branching ratio: 0.79 %

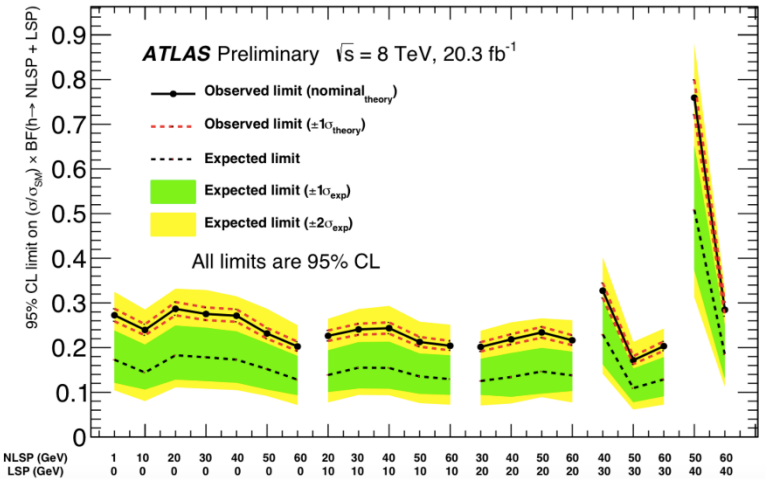
Other BSM searches

- Higgs boson to BSM
  - Higgs boson decays to neutralinos and/or gravitinos
  - $h \to \gamma(\text{or } 2\gamma)+ E_{\mathrm{T}}^{\mathrm{miss}} + 2$ forward jets
  - predicted GMSB and NMSSM models in SUSY
    - GMSB: $h \to \tilde{G}\tilde{\chi}^0 \to \tilde{G}\tilde{G}\gamma$ or $h \to \tilde{\chi}^0\tilde{\chi}^0 \to \tilde{G}\gamma\tilde{G}\gamma$
    - NMSSM: $h \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$ or $h \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma\tilde{\chi}_1^0\gamma$
  - not using $h \to \gamma\gamma$ but using Higgs boson final-states with photons









Conclusions

- $H \rightarrow \gamma\gamma$ analysis has great advantages of Higgs boson property measurements
  - one of the most accurate Higgs boson mass measurement
  - sensitive to Y_t and g_{HWW} as well as their relative sign
- $H \rightarrow \gamma\gamma + X$ is a tool for BSM discovery
  - di-higgs
  - SUSY
  - dark matter

- LHC started physics at 13 TeV in 3rd June
  - The discovery of Higgs boson was a great achievement in 7 TeV and 8 TeV run
  - We are excited for 13 TeV Higgs boson analysis

$H \to Z\gamma$

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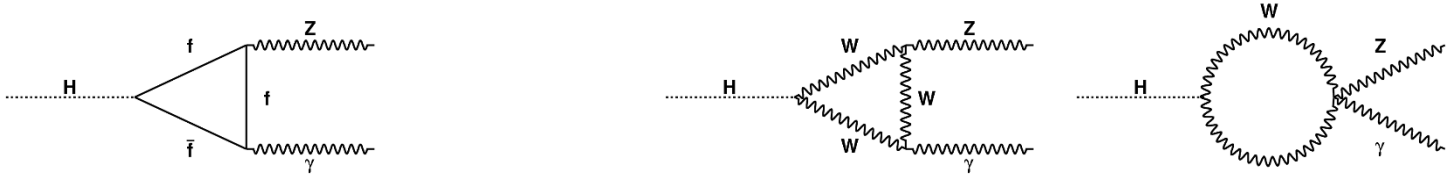
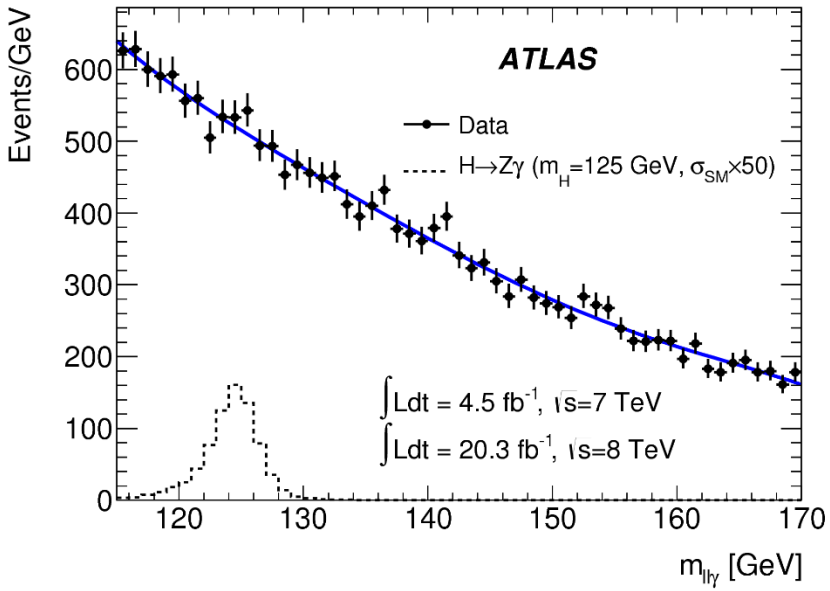
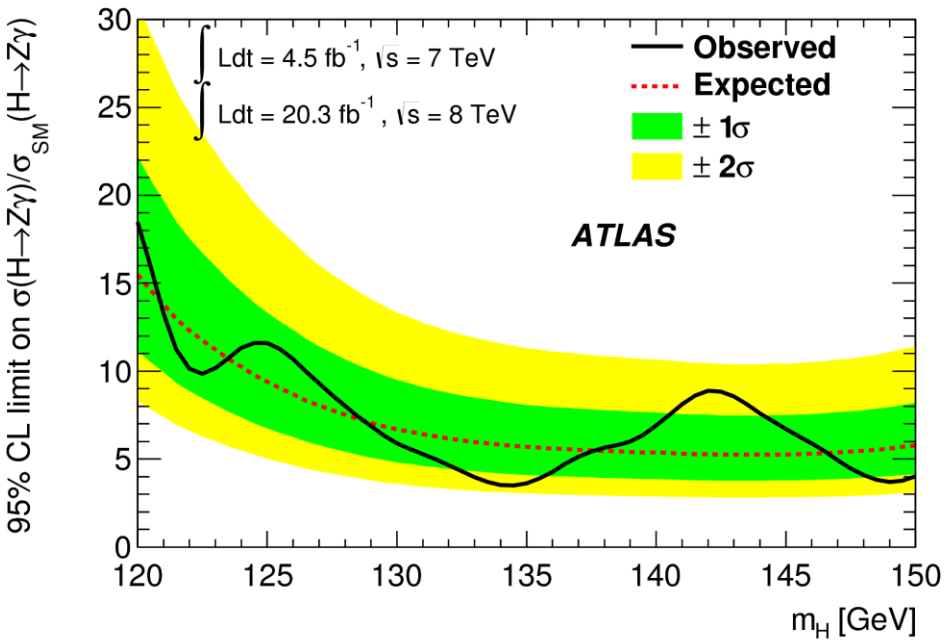
- $H \to Z\gamma$
  - rare process in SM
  - corss section ($pp \to H \to Z\gamma \to \ell\ell\gamma$) = 2.3 fb at 8 TeV
  - sensitive to new heavy particles in loops
  - Ratio BF($H \to Z\gamma$)/BF($H \to \gamma\gamma$) permits assessment

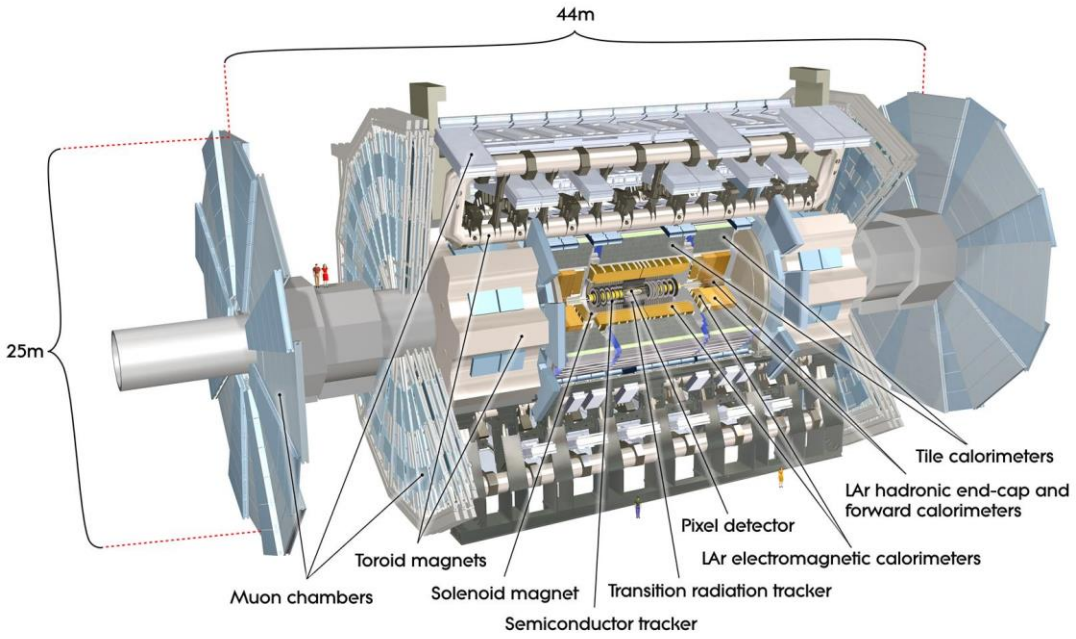


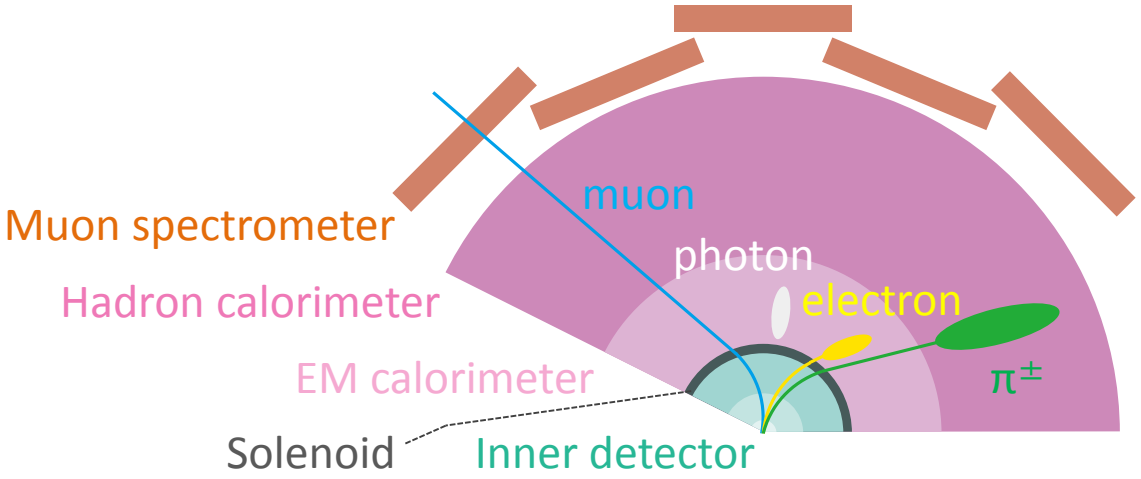




Number of signal { expected = 9.0
observed = 11.3

ATLAS detector

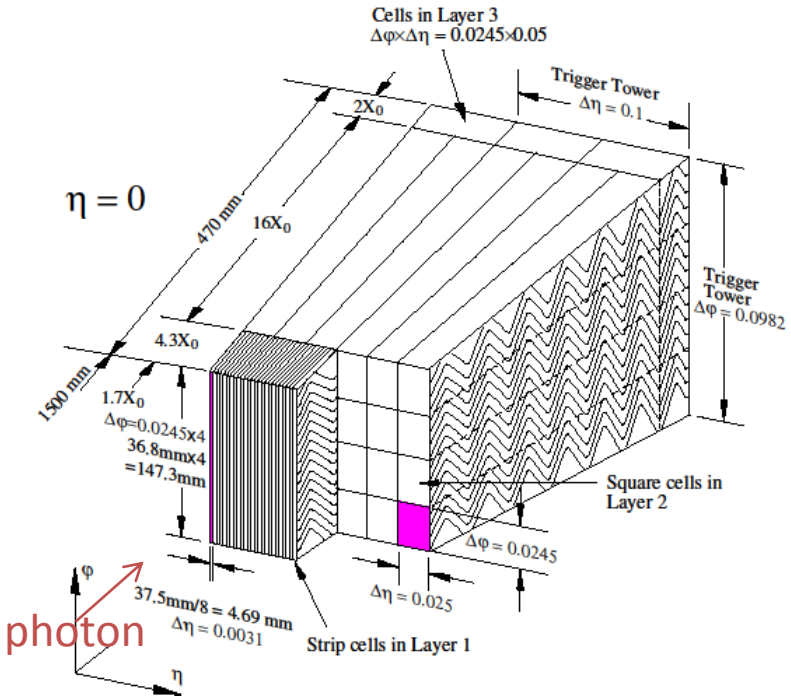




- Solenoid magnet
  - supply 2T magnetic field to inner detector
  - very thin (0.66 X_0)
- Toroid magnet
  - bend charged particle for η
- Inner tracker
- Calorimeter
  - EM calorimeter
  - Hadron calorimeter
- Muon spectrometer
- Luminosity detector

ATLAS EM calorimeter

- Accordion structure Pb absorber
  - develop EM shower
  - cover full φ region + great φ uniformity
- Ionization in Liquid Ar
- 4 layers → 3D shower reconstruction
  - photon direction reconstruction
  - energy calibration with shower shape



pre-sampler: no absorber, correction for energy loss in inner detector

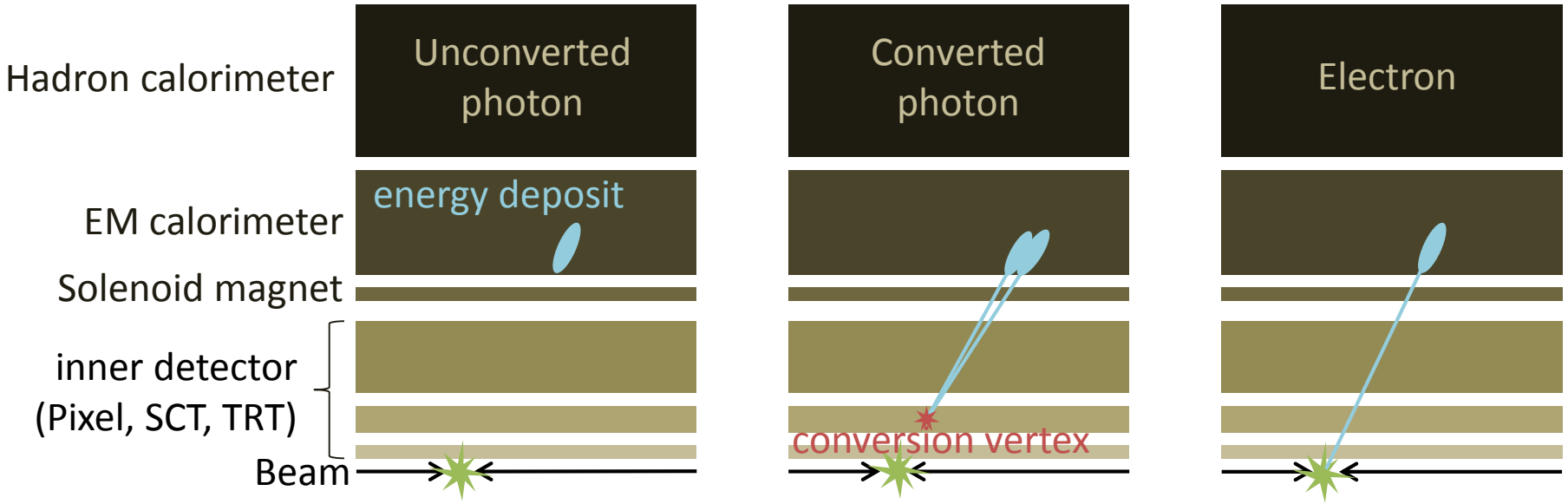
1st layer: high granularity along η → separation of incoming particles

2nd layer: deposit most of energy

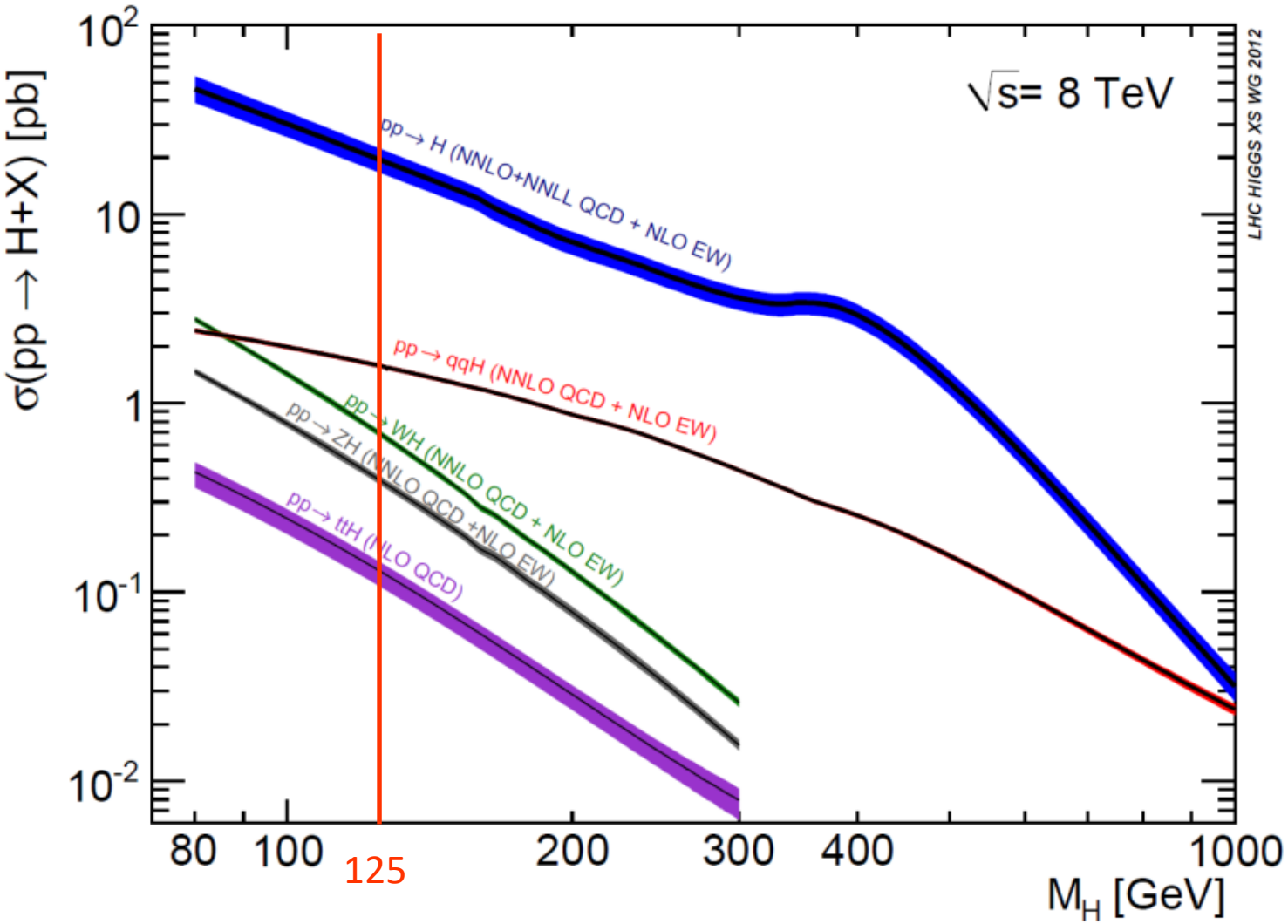
3rd layer: correction for high energy

Photon reconstruction

- Energy clustering in EM calorimeter with fixed size window
- Photon-electron separation with track matching
  - Conversion vertex reconstruction
  - Unconverted photon / Converted photon / Electron separation



SM Higgs production



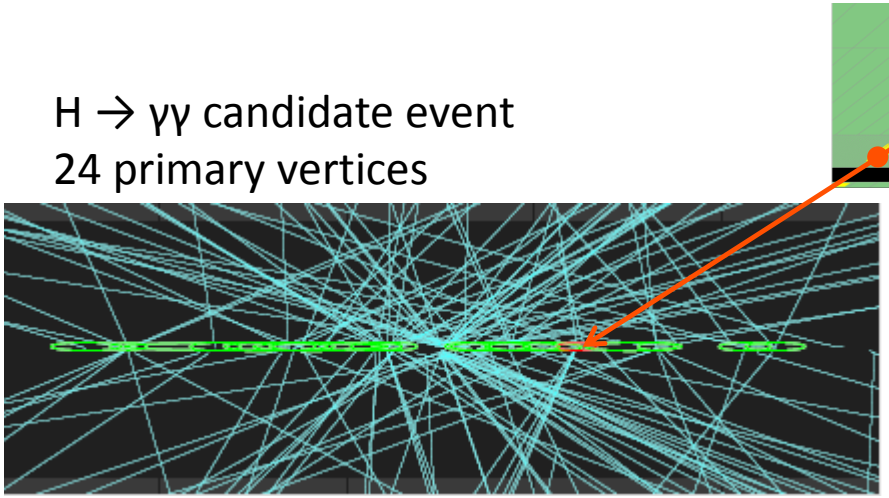
tH:

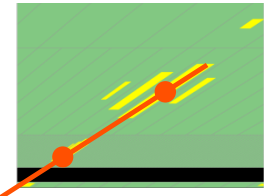
- *tHqb*: 0.0172 pb
- *WtH*: 0.0047 pb

Vertex of photon pairs

- High peak luminosity of LHC → many inelastic proton-proton interactions
- Many pileup vertices in addition to primary vertex where Higgs is produced
- Photons don't have tracks → a bit difficult to select primary vertex in $H \to \gamma\gamma$ analysis

H → γγ candidate event
24 primary vertices





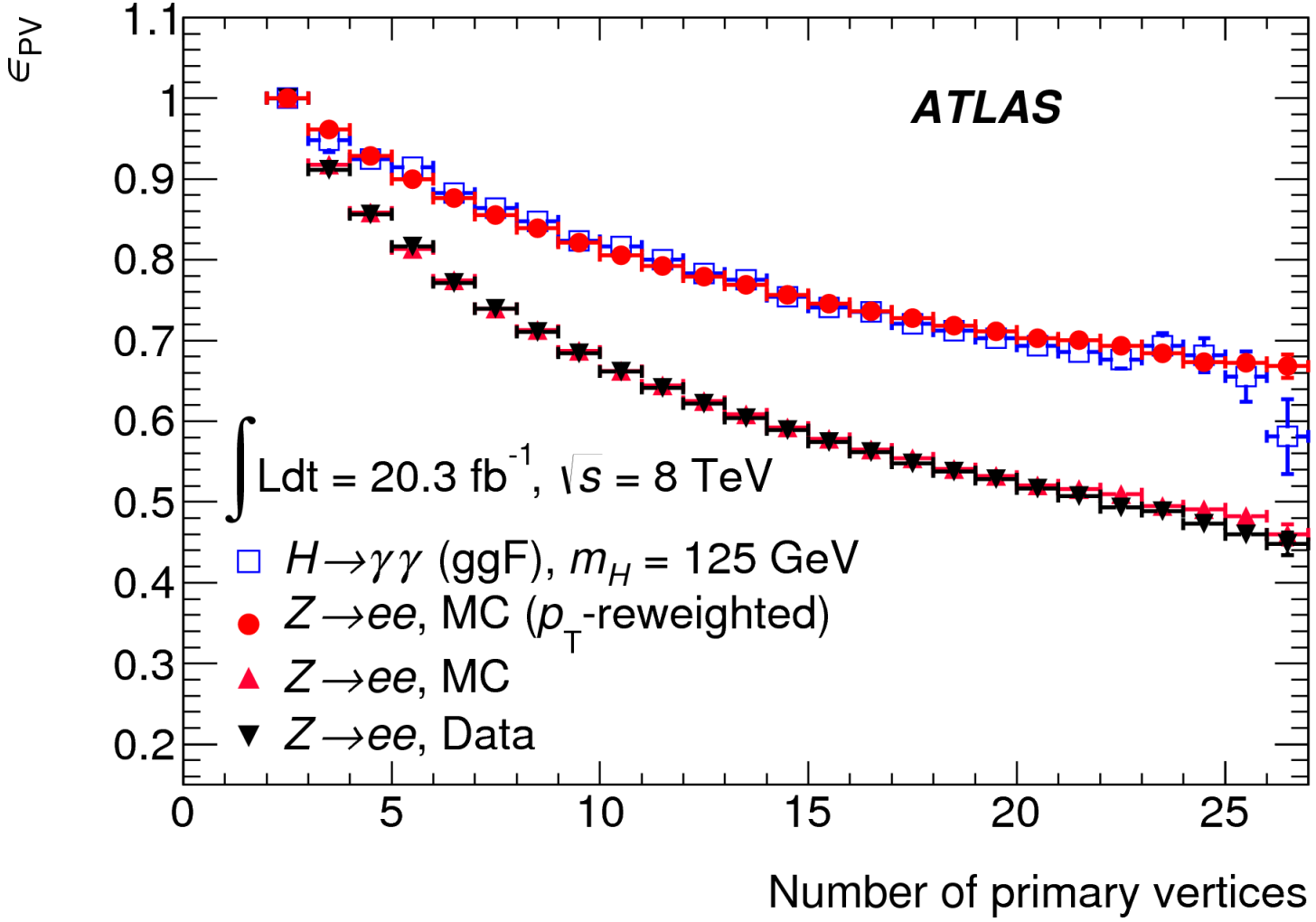
A. calo-pointing
extrapolate from barycenters of energy deposits in EM calorimeter layers

B. Σp^2_T
Primary vertex tends to have high p_T tracks from underlying events
→ primary vertex has higher Σp^2_T of tracks

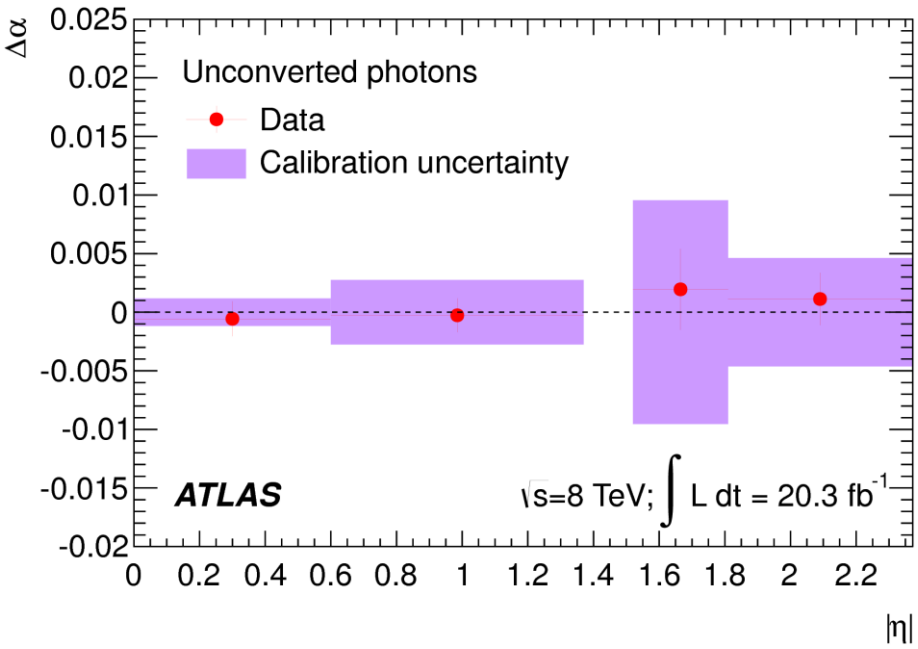
C. conversion vertex
Converted photons have e^+e^- tracks
→ extrapolate tracks to beam line

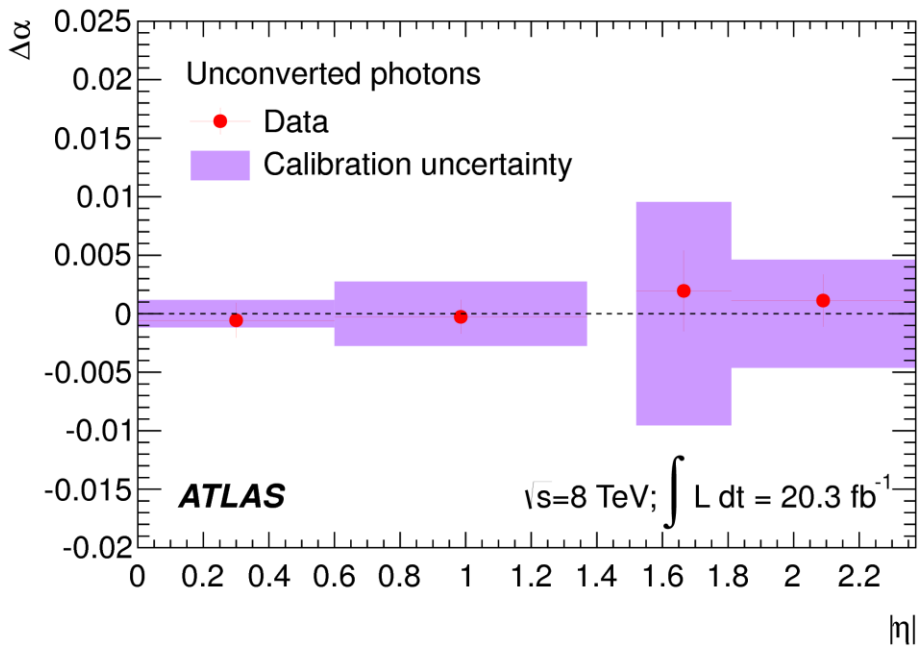
Vertex selection efficiency is 85 % with combining A, B and C,

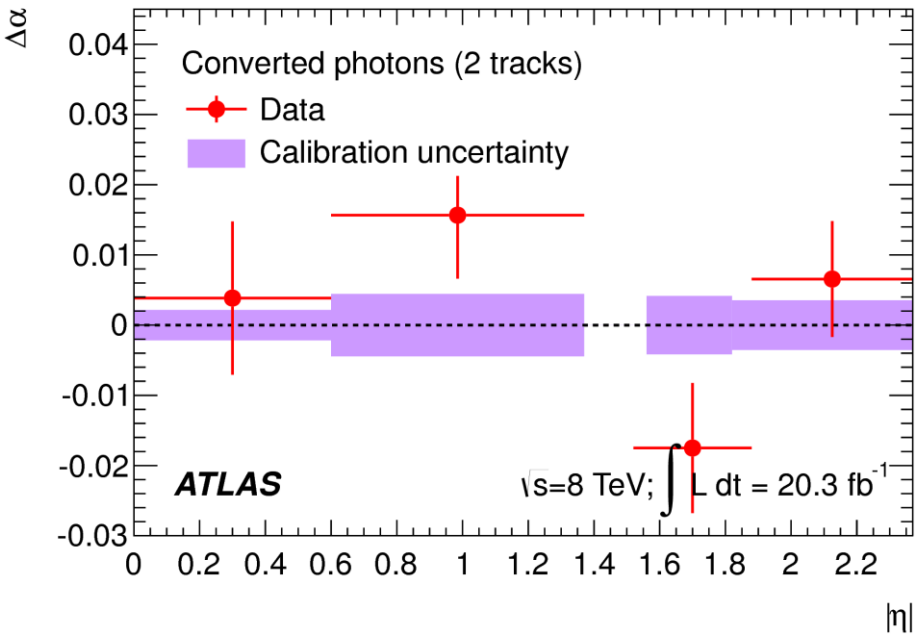
primary vertex selection efficiency



Photon energy scale uncertainty



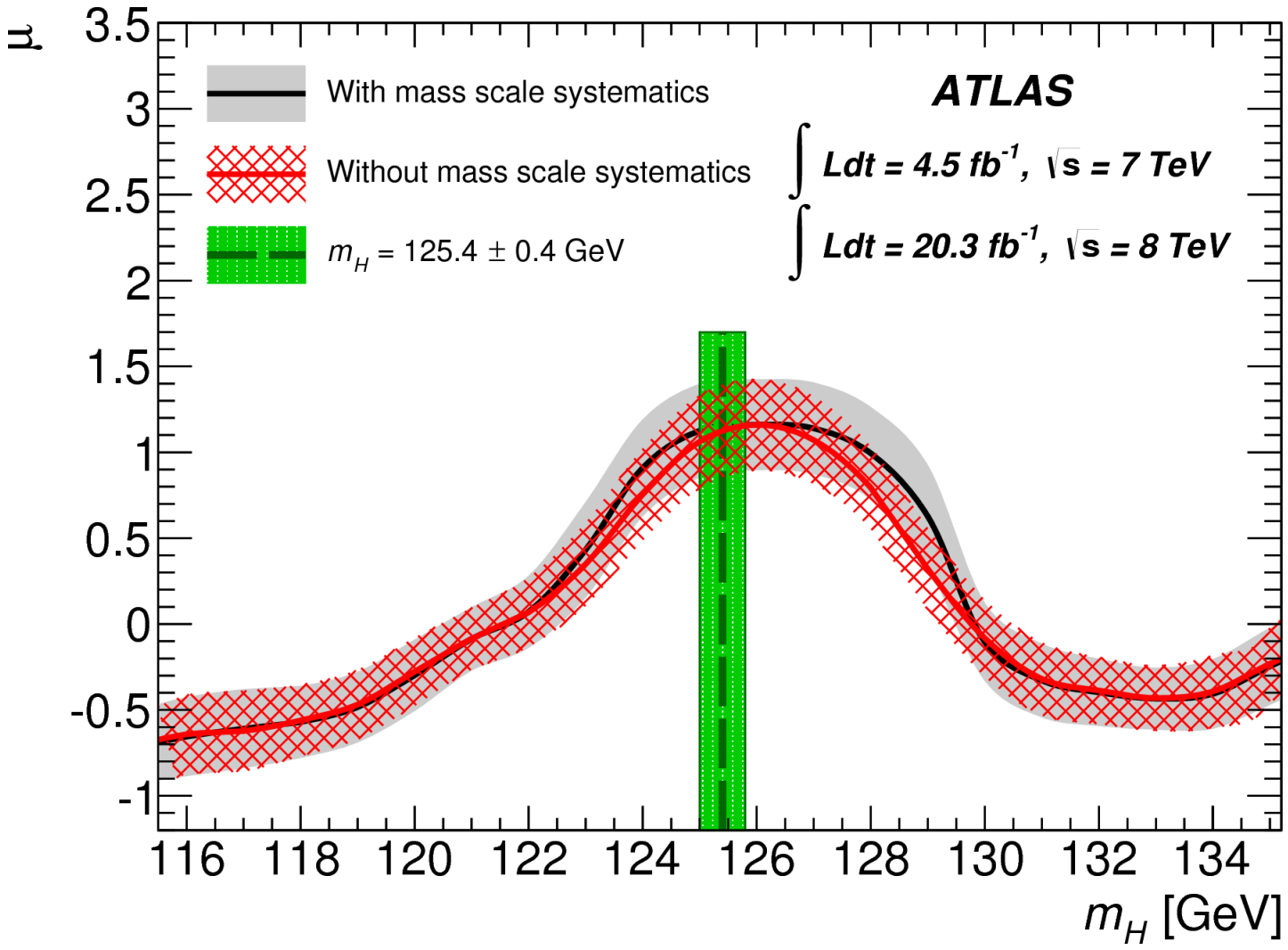




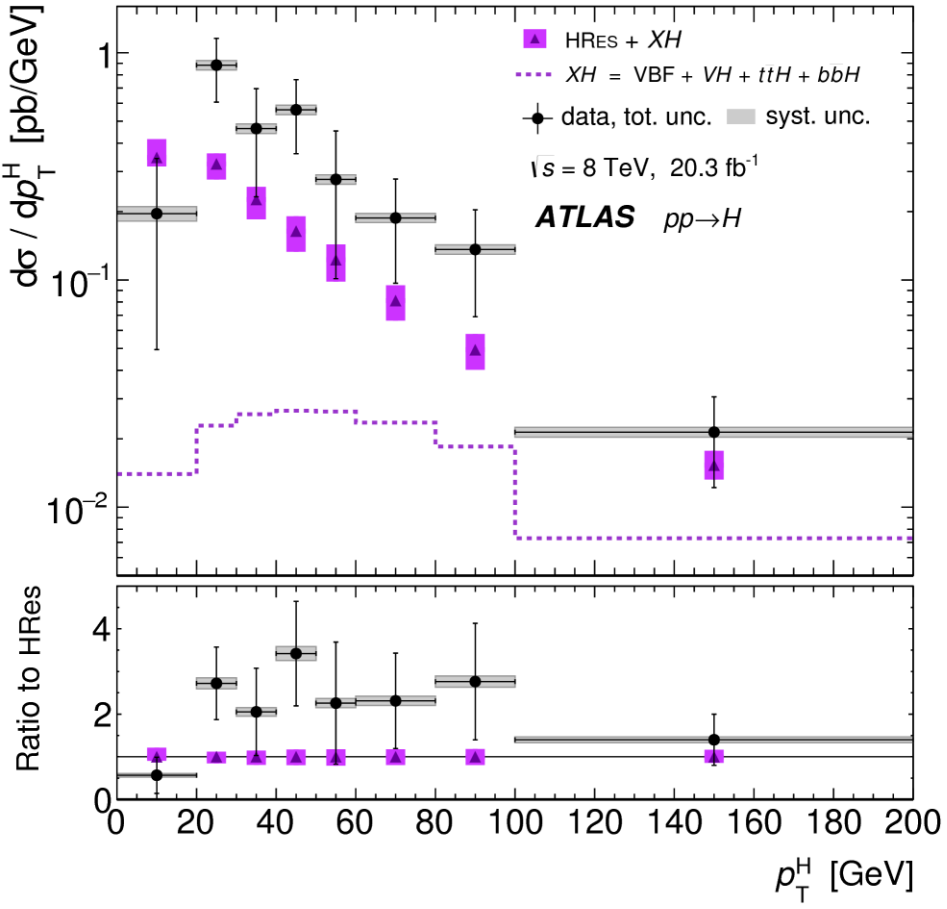
Compatibility of mass measurements

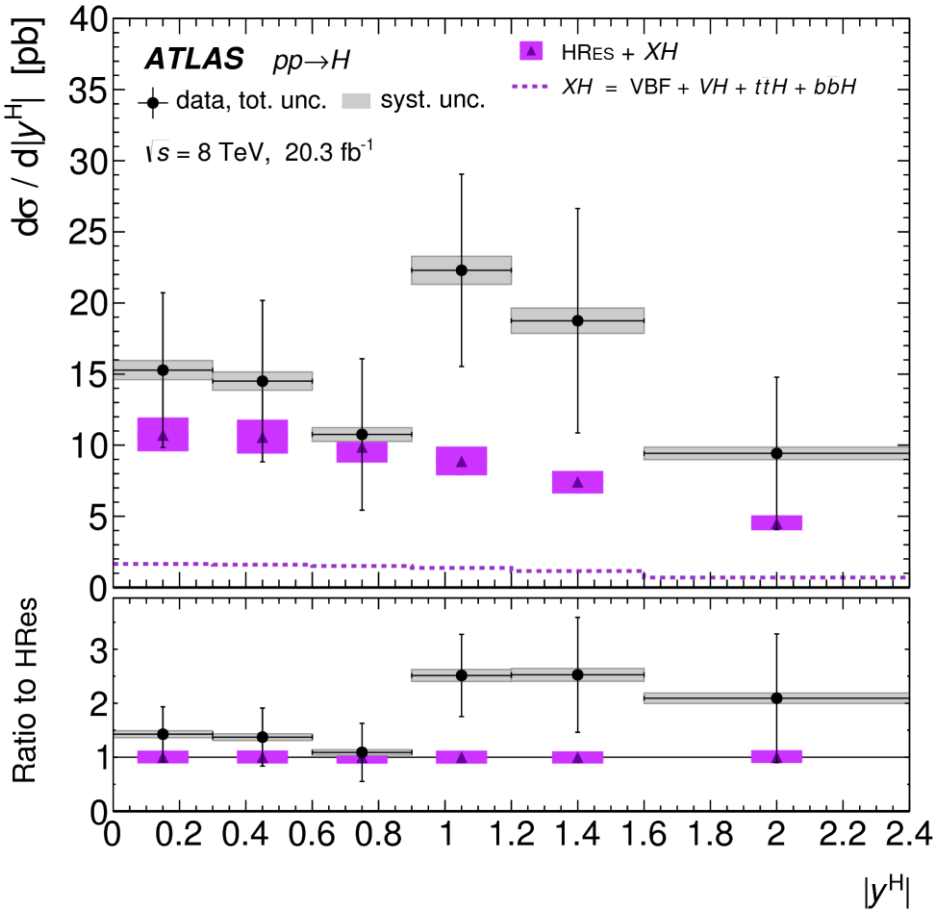
compatibility of mass measurements from H→γγ and H→ZZ
$\Delta m_H = 1.47 \pm 0.72$ GeV
compatibility of 11 % (1.6 σ)

Signal strength vs Higgs mass



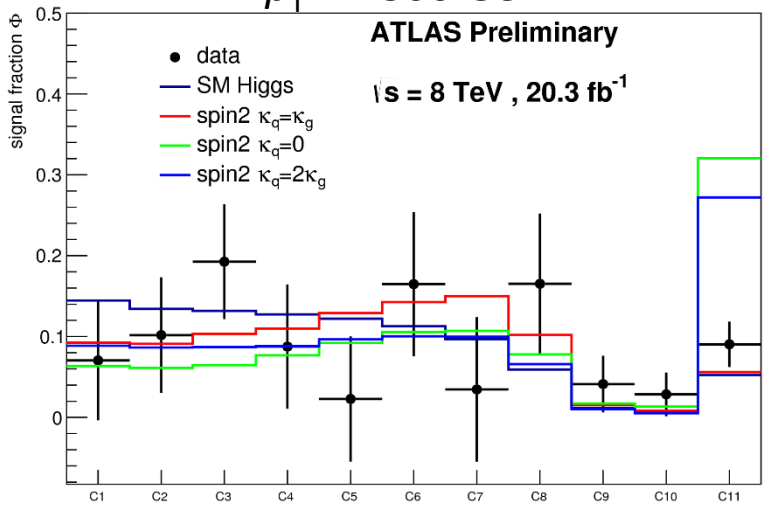
Differential cross section



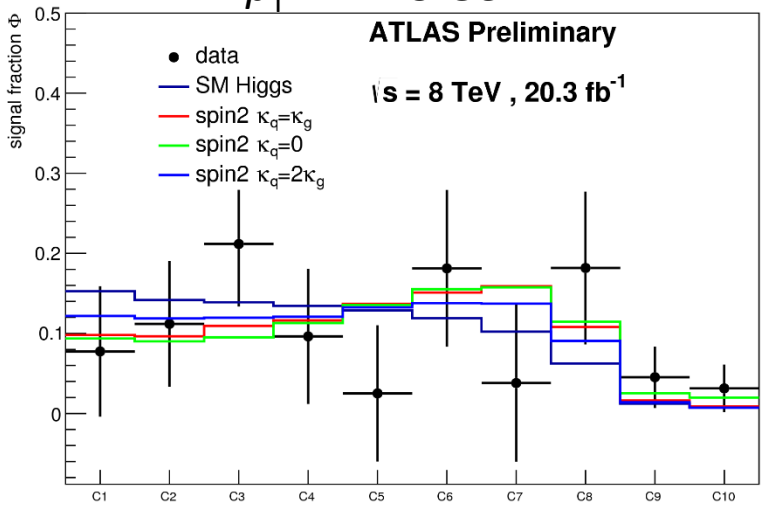


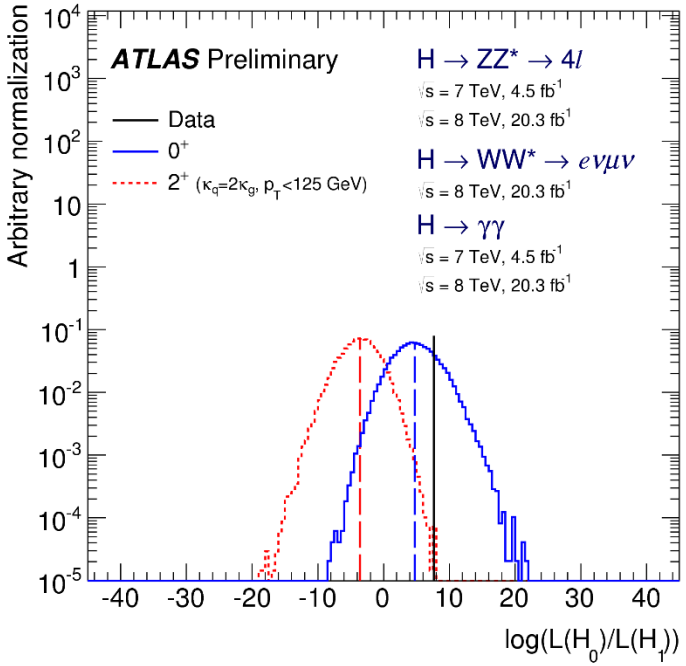
Spin

$p_T^{\gamma\gamma} < 300$ GeV



$p_T^{\gamma\gamma} < 125$ GeV

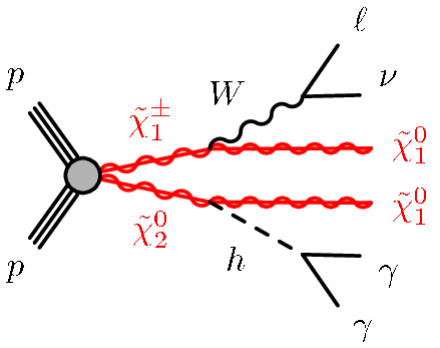




Spin 2 model with low gluon fraction and p_T cut-off at 125 GeV

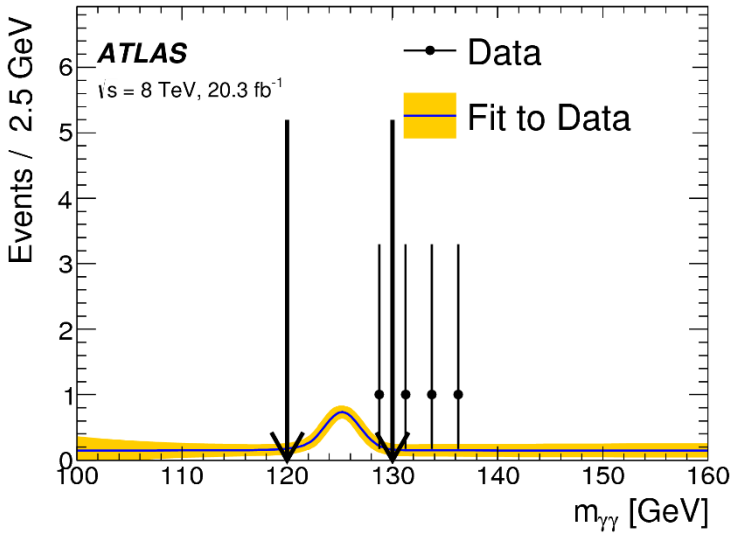
SUSY + $h \to \gamma\gamma$

- Direct pair production of chargino $\tilde{\chi}_1^{\pm}$ and neutralino $\tilde{\chi}_2^0$
- Scenario:
  - masses of pseudo-scalar Higgs and sleptons > $m_{\tilde{\chi}_1^{\pm}}$ and $m_{\tilde{\chi}_2^0}$
  - $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > m_{\mathrm{H}}$
  - $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ degenerate
- $\tilde{\chi}_1^{\pm} \to (W \to \ell\nu)\tilde{\chi}_1^0, \tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$



- Selection
  - 2 photons + 1 electron/muon + $E_{\mathrm{T}}^{\mathrm{miss}}$ > 40 GeV
  - W and Higgs are back-to-back on transverse plane
  - high $m_{\mathrm{T}}^{W\gamma}$
  - $m_{\mathrm{T}}^{W\gamma} = \sqrt{(m_{\mathrm{T}}^{W})^2 + 2E_{\mathrm{T}}^{W}E_{\mathrm{T}}^{\gamma} - 2\boldsymbol{p}_{\mathrm{T}}^{W} \cdot \boldsymbol{p}_{\mathrm{T}}^{\gamma}}$
- BG
  - SM $h \to \gamma\gamma$ (*WH*, *ZH*, ttH)
  - Wγ
  - Zγ

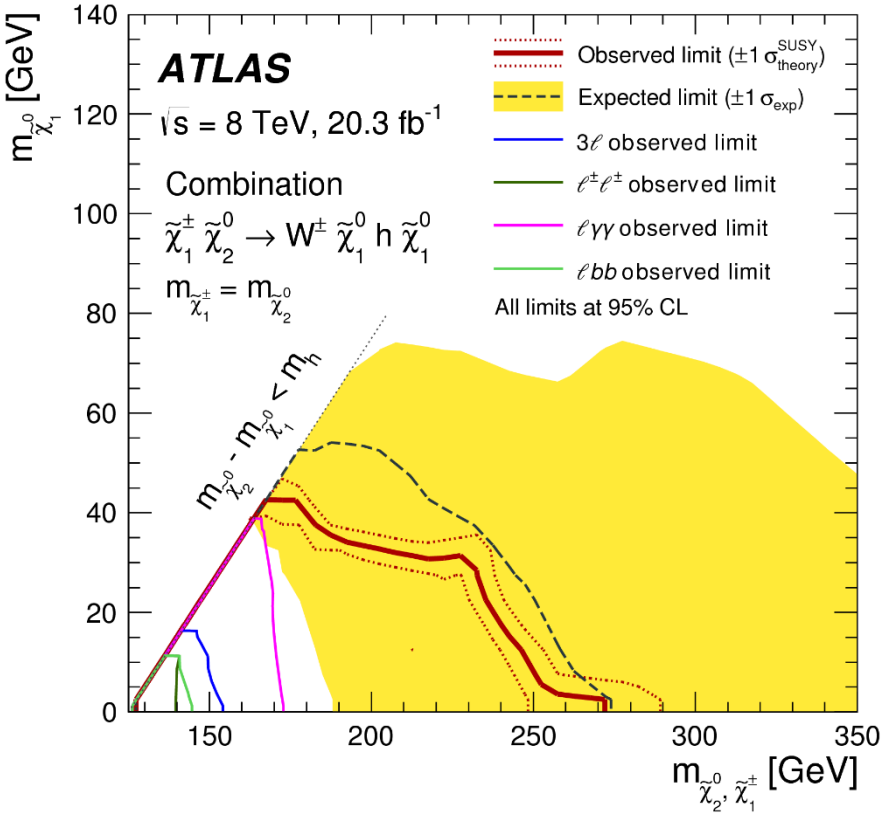
BG only fit to $m_{\gamma\gamma}$



SUSY + $h \to \gamma\gamma$

- Combined with $h \to b\bar{b}$ and $h \to WW$
- No excess found

- Limits on exclusion regions in $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_2^0}$ mass plane



- limits on signal cross section normalized by the simplified-model prediction as a function of $m_{\tilde{\chi}_1^\pm, \tilde{\chi}_2^0}$ for $m_{\tilde{\chi}_1^0} = 0$