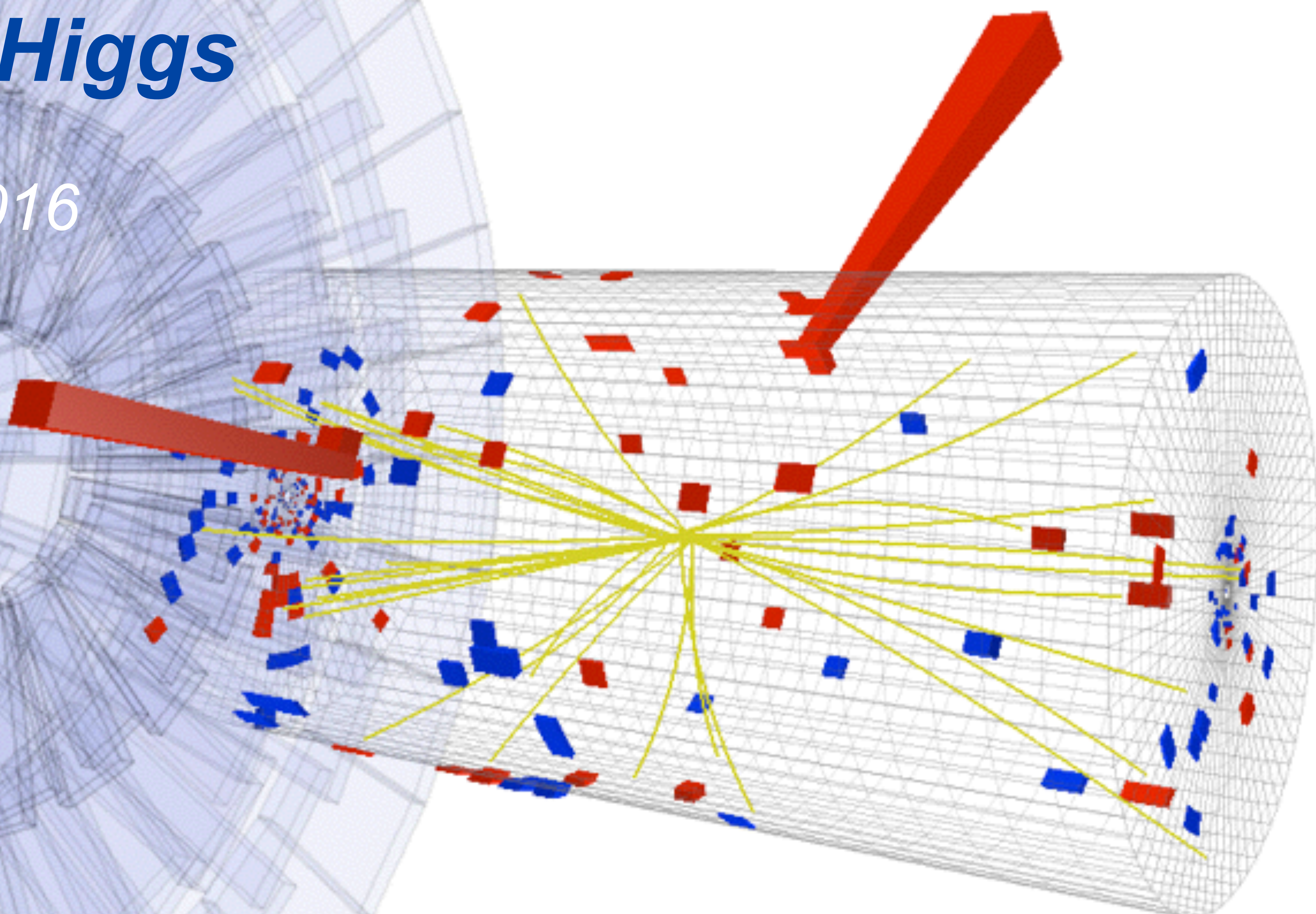
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Higgs couplings and BSM Higgs

SWHEPPS 2016



Mauro Donegà

Outline

- ATLAS-CMS combined:
  Signal strengths
  Coupling modifiers (k-framework)
  Rare decays

- Fiducial and Differential cross sections

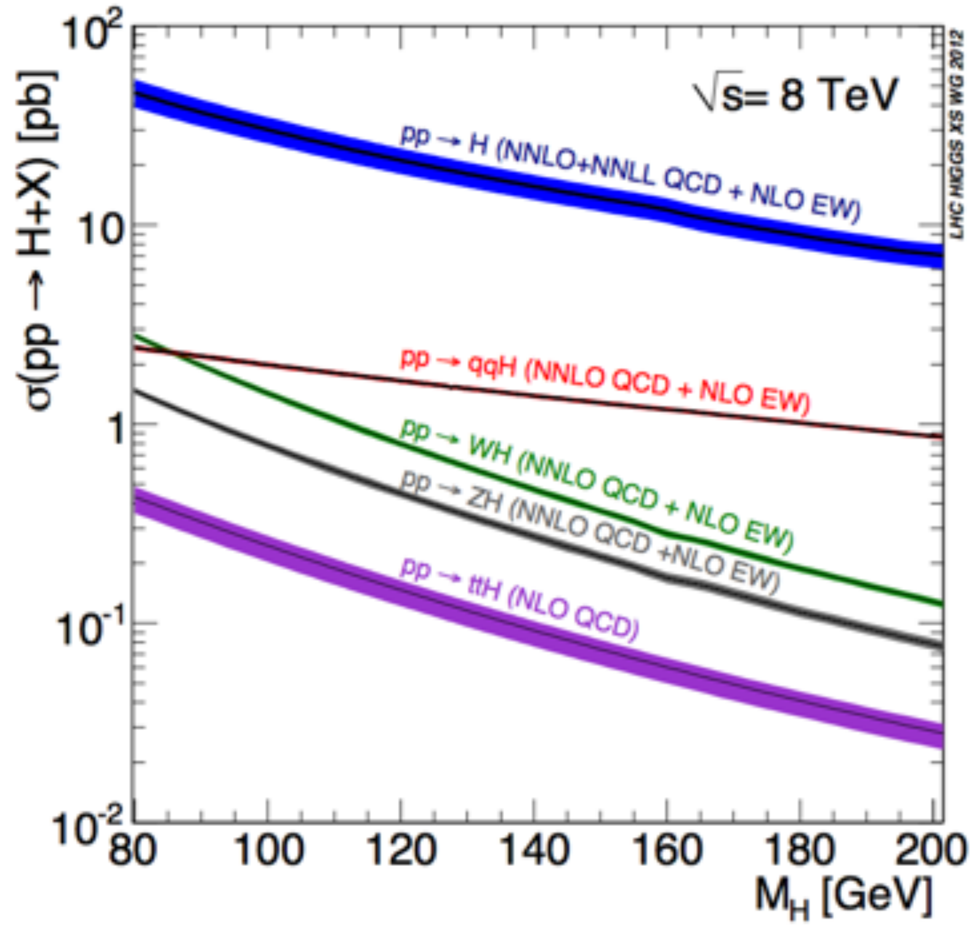
- BSM Higgs
  - High mass diphoton

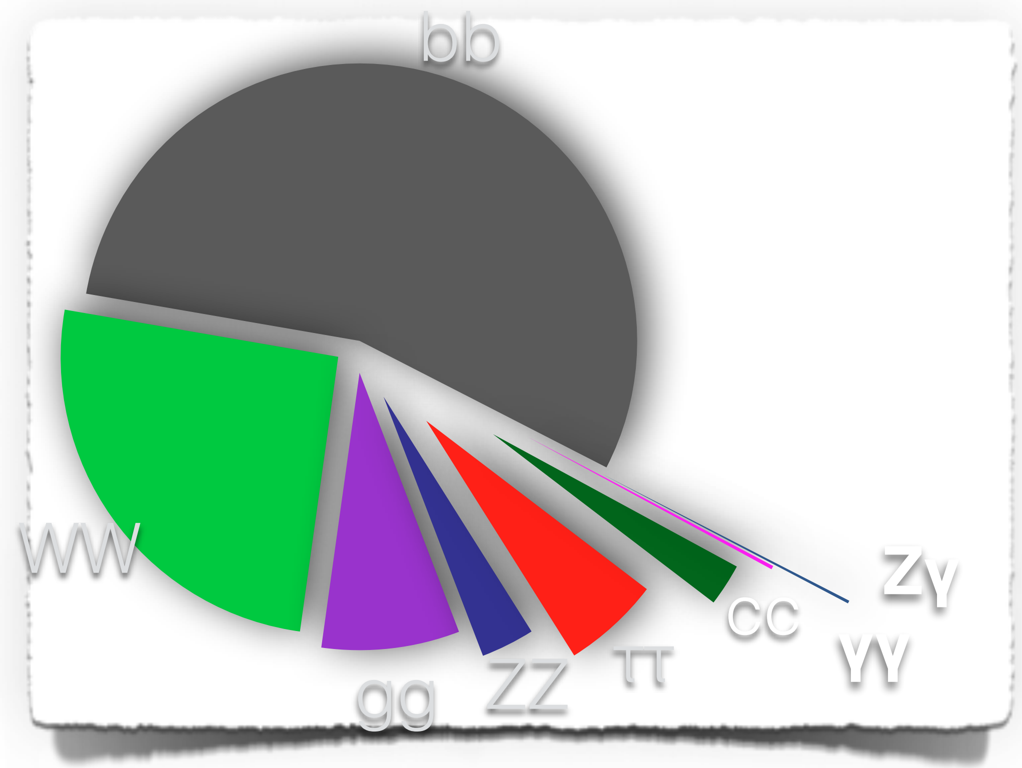
Run 1 datasets:
~5 fb^{-1} at 7 TeV (2011)
~20 fb^{-1} at 8 TeV (2012)

Run 2 dataset: ~3 fb^{-1}

ATLAS+CMS
Combined measurements

Production and decay





SM ggF, ttH, bbH theory uncertainty: ~10% VBF, VH: 2-3%

Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+APP.NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.357 ± 0.015	0.446 ± 0.019	NNLO(QCD)+NLO(EW)
ZH: $gg \to ZH$			LO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

BR uncertainty ~5% on leading channels

Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

Combination framework

General assumptions:

1) the signal comes from only 1 particle
2) SM Higgs boson hypothesis 0^+ and in terms of its production and decay kinematics
3) narrow width approximation is valid (production/decay decoupled)

$$(\sigma \cdot BR)(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

i = production mode ; f = decay channel ; Γ_H = total width = sum of all partial widths

All analyses use categories to optimize sensitivity

The signal yield in category k, $n_{signal}(k)$ is computed as:

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{\sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f\right\},$$

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \quad \text{and} \quad \mu^f = \frac{\text{BR}^f}{\text{BR}^f_{\text{SM}}}.$$

$$= \underbrace{\mathcal{L}(k)}_{\text{Luminosity}} \times \sum_i \sum_f \underbrace{\mu_i \mu^f}_{\text{production/decay modifiers}} \left\{\sigma_i^{\text{SM}} \times \underbrace{A_i^f(k)}_{\text{Acceptance}} \times \underbrace{\varepsilon_i^f(k)}_{\text{Efficiency}} \times \text{BR}^f_{\text{SM}}\right\}$$

Basically all experimental systematics between the experiments are assumed uncorrelated (impact tested). Main correlations through theory uncertainties on production σ and BR.

In total we combine ~100 categories per experiment with ~4200 nuisance parameters.

Signal strength measurements

We combine {ggF, VBF, VH, ttH} ⊗ {H→γγ, H→ZZ, H→WW, H→bb, H→μμ, H→ττ}

(not included ggF/VBF for H→bb and VH/ttH for H→μμ)

All remaining production ⊗ decay modes end up in other channels (e.g. tHq in ttH)

The most constrained model used is to use only one overall μ (same also for 7 and 8 TeV)

$$\mu = 1.09^{+0.11}_{-0.10} \quad = 1.09^{+0.07}_{-0.07}\,(\text{stat})\;^{+0.04}_{-0.04}\,(\text{expt})\;^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

stat = statistical uncertainty
thsig = theory uncertainty on the signal model
thbgd = theory uncertainty on the background predictions
expt = all other experimental uncertainties (+finite MC statistics)

⇒ Compatible with SM : the most precise test so far o(10%)

VERY model dependent and there could be all sorts of compensations acting

Combined significances

Because results on single channels are dominated by (uncorrelated) statistical uncertainties,
combining ATLAS+CMS increases by √2 the sensitivity

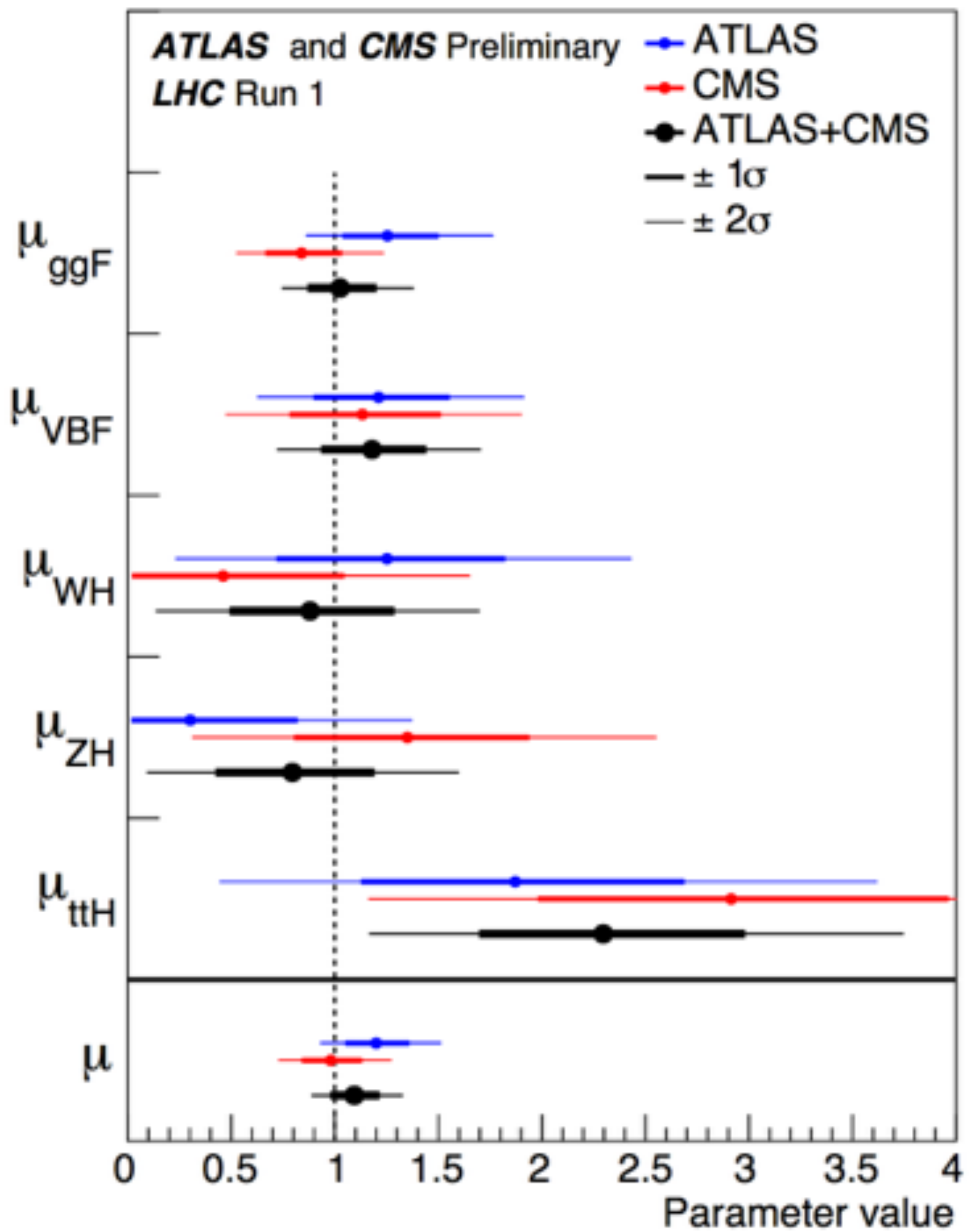
ggF production, H → ZZ, H → WW, and H → γγ decay channels
already above 5σ separately for each experiment

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Production processes

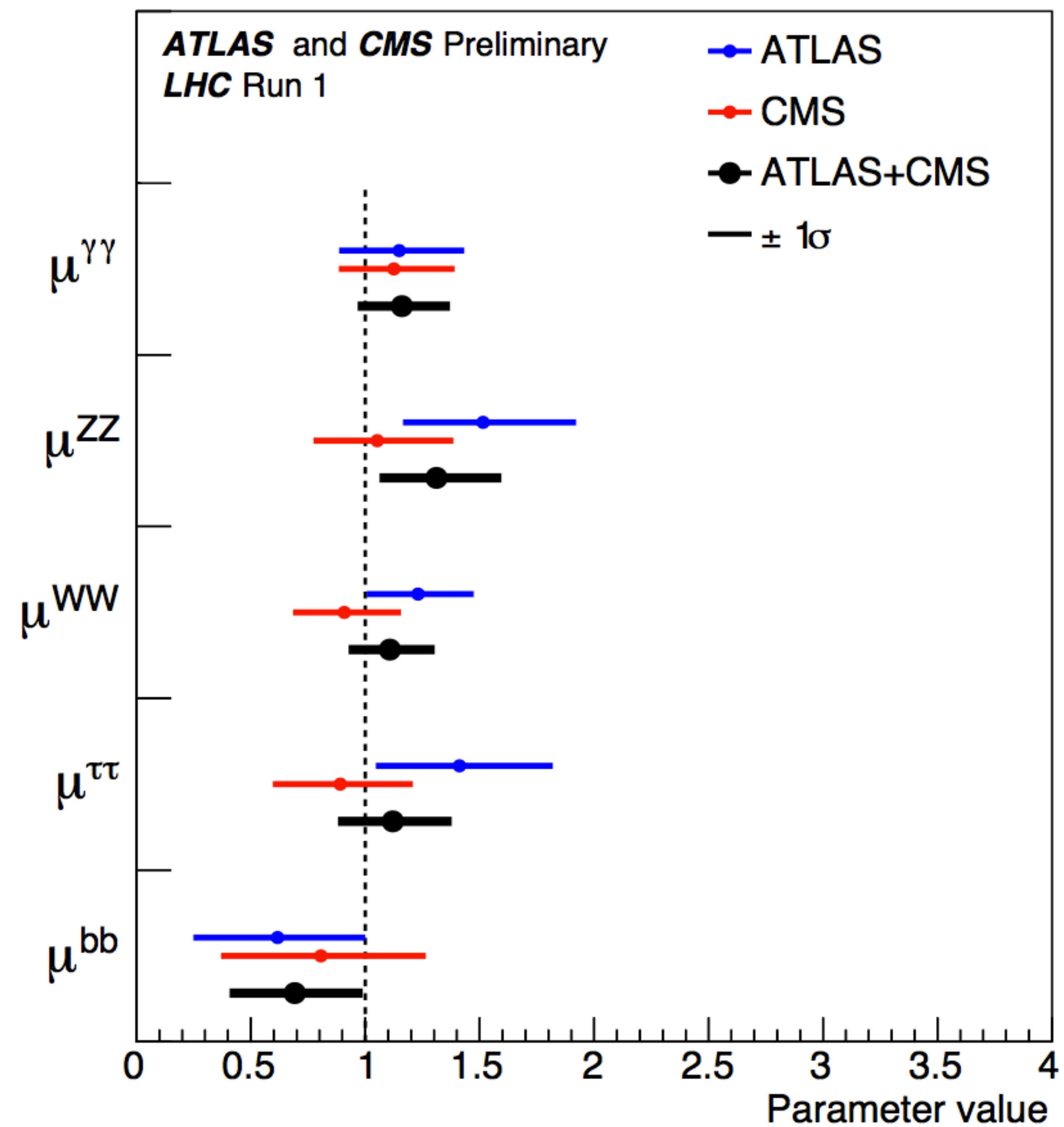
Assume all BR as in the SM ($\mu^f = 1$) and test the production mechanisms

p-value = 24%



Assume all production cross section as in the SM ($\mu^i = 1$) and test the decays

p-value = 60%



largest deviation: ttH ~2.3σ wrt SM

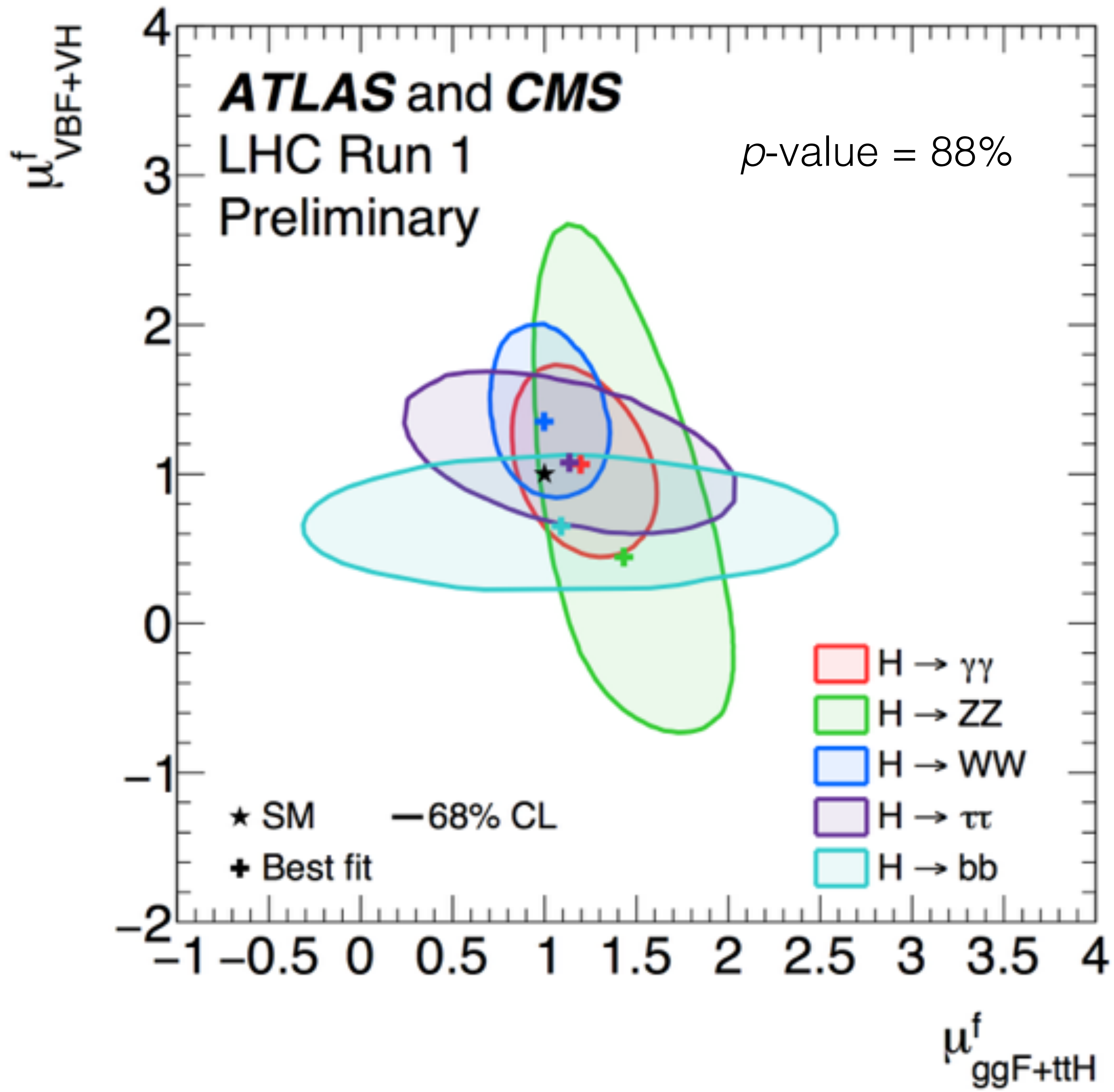
downward fluctuation Hbb

Production processes

μ^f_{VBF+VH} coupling to bosons VBF + VH
$\mu^f_{ggF+ttH}$ coupling to fermions ggF + ttH

5 x 2 parameters

Combination of contours would require additional hypothesis on BR



k-framework

Parametrization defined by the LHC Higgs Cross Section Working Group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

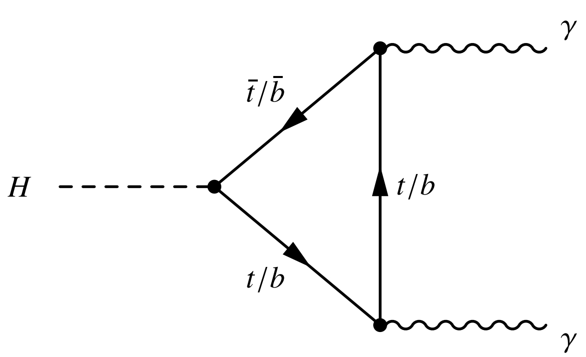
Coupling modifiers: "k-framework" (kappa-framework) = multipliers at amplitude level introduced to parametrise possible deviation from SM. They are defined as

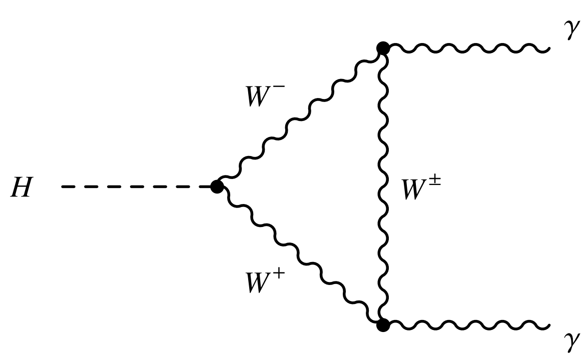
$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$

$$\kappa_H^2 = \textstyle\sum_j \mathrm{BR}^j_{\mathrm{SM}} \kappa_j^2 \qquad \Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

Sensitive to interference effect in loops

e.g. negative interference between:





Fermion/Vector couplings

Assume no new particles in the loops and $BR_{BSM} = 0$

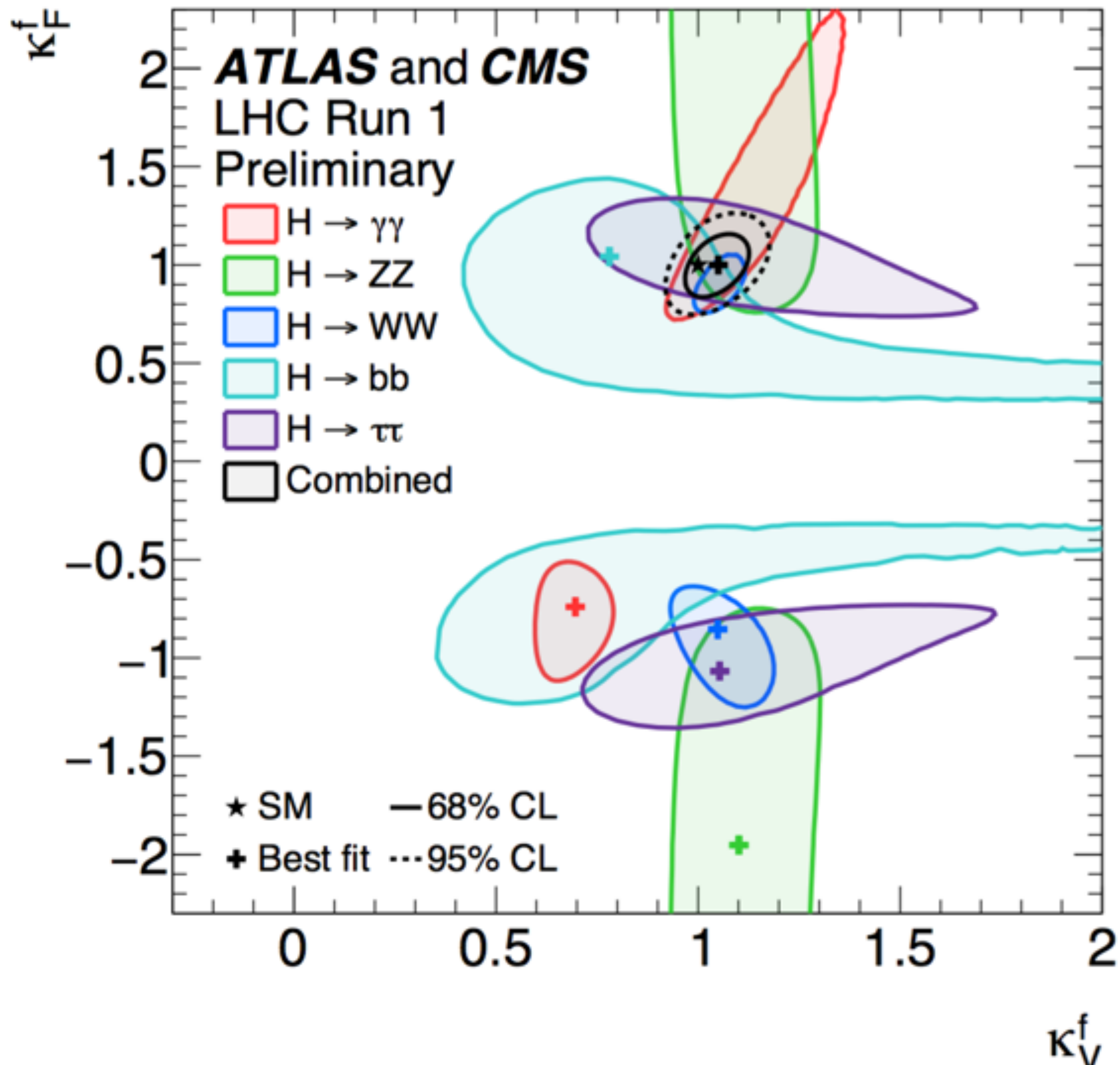
Define:

$\kappa_V = \kappa_Z = \kappa_W$

$\kappa_F = \kappa_t = \kappa_\tau = \kappa_b$

Total 2 x 5 parameters

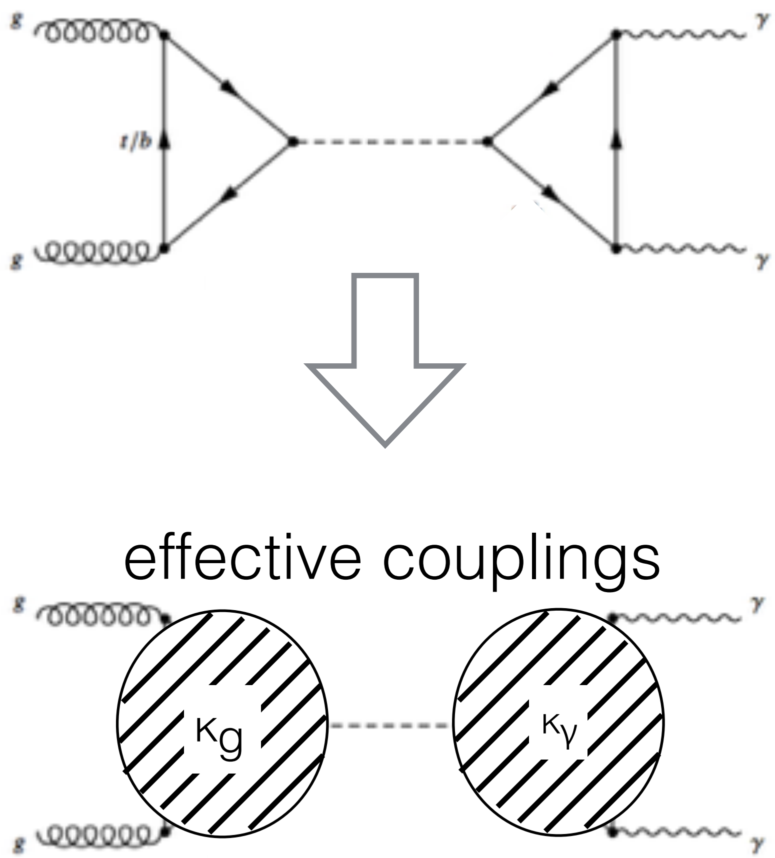
(the other two quadrants are symmetric wrt (0,0) because we're only sensitive to products of two kappas)

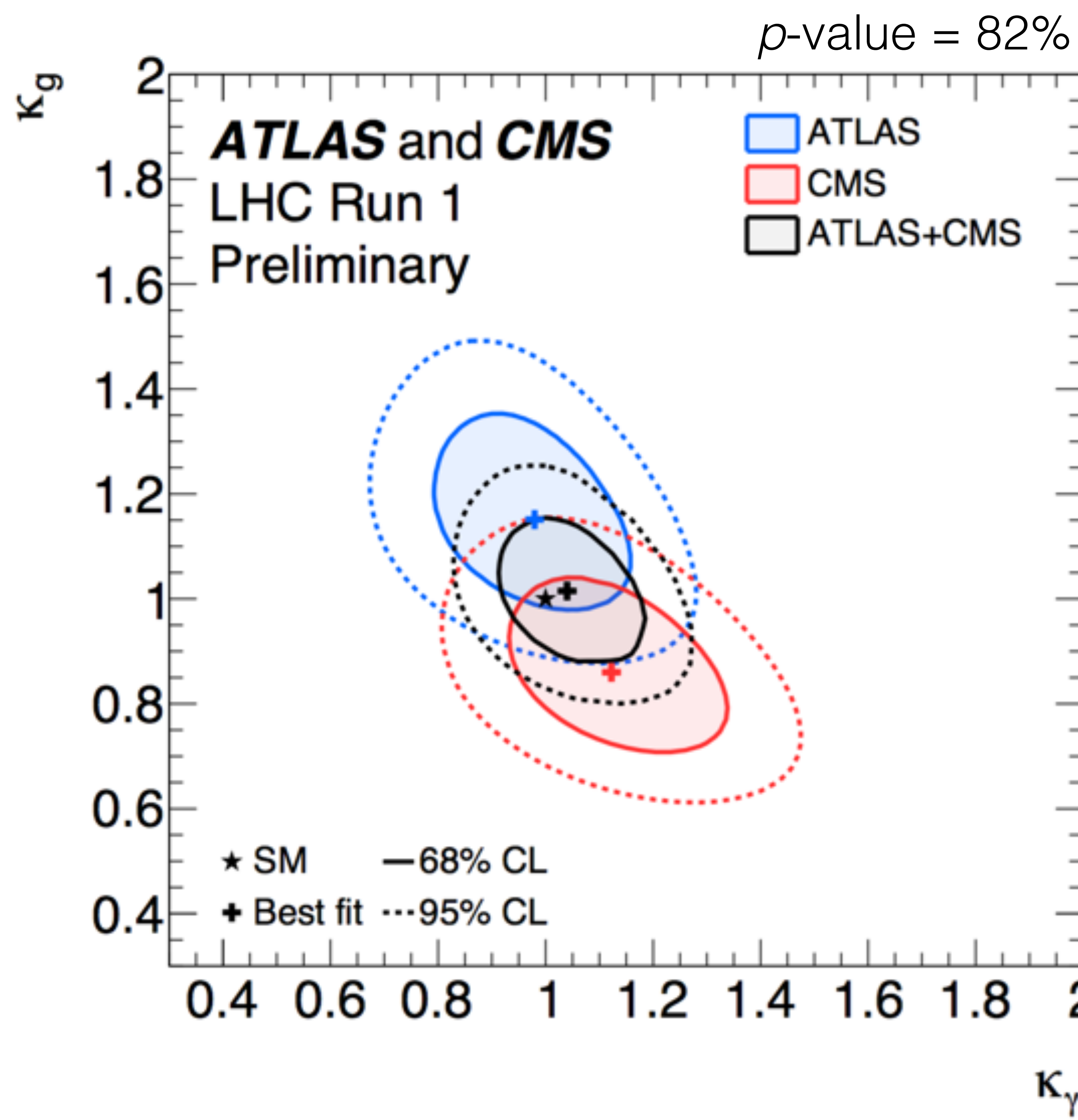


~5σ exclusion of k_F<0

κ_g, κ_γ

Test effective couplings for κ_γ, κ_g





Suppose all tree level decays are SM, test BSM in production/decay "loops":

$$\kappa_W = \kappa_Z = \kappa_b = \kappa_t = \kappa_\tau = 1$$

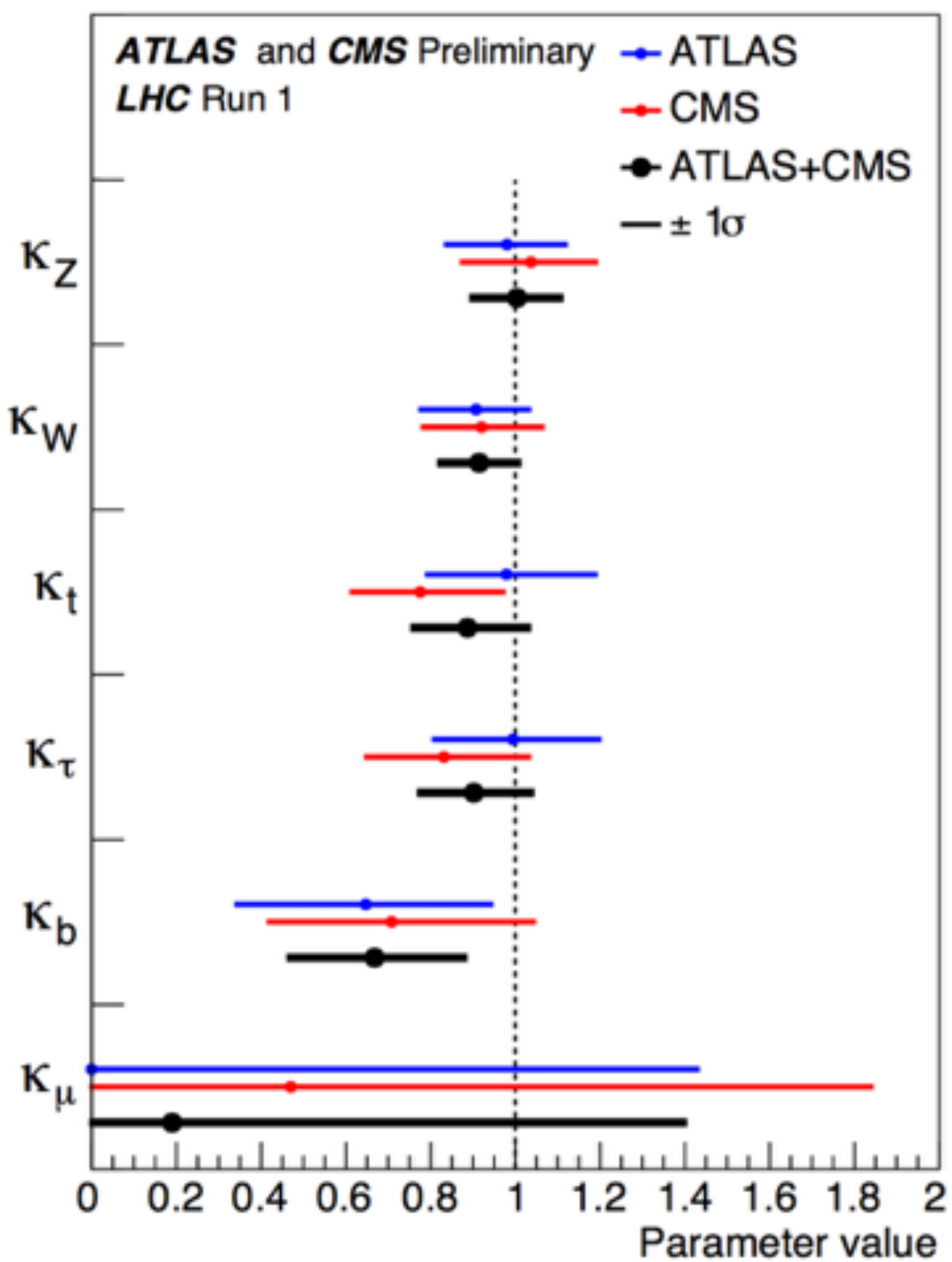
test κ_γ, κ_g

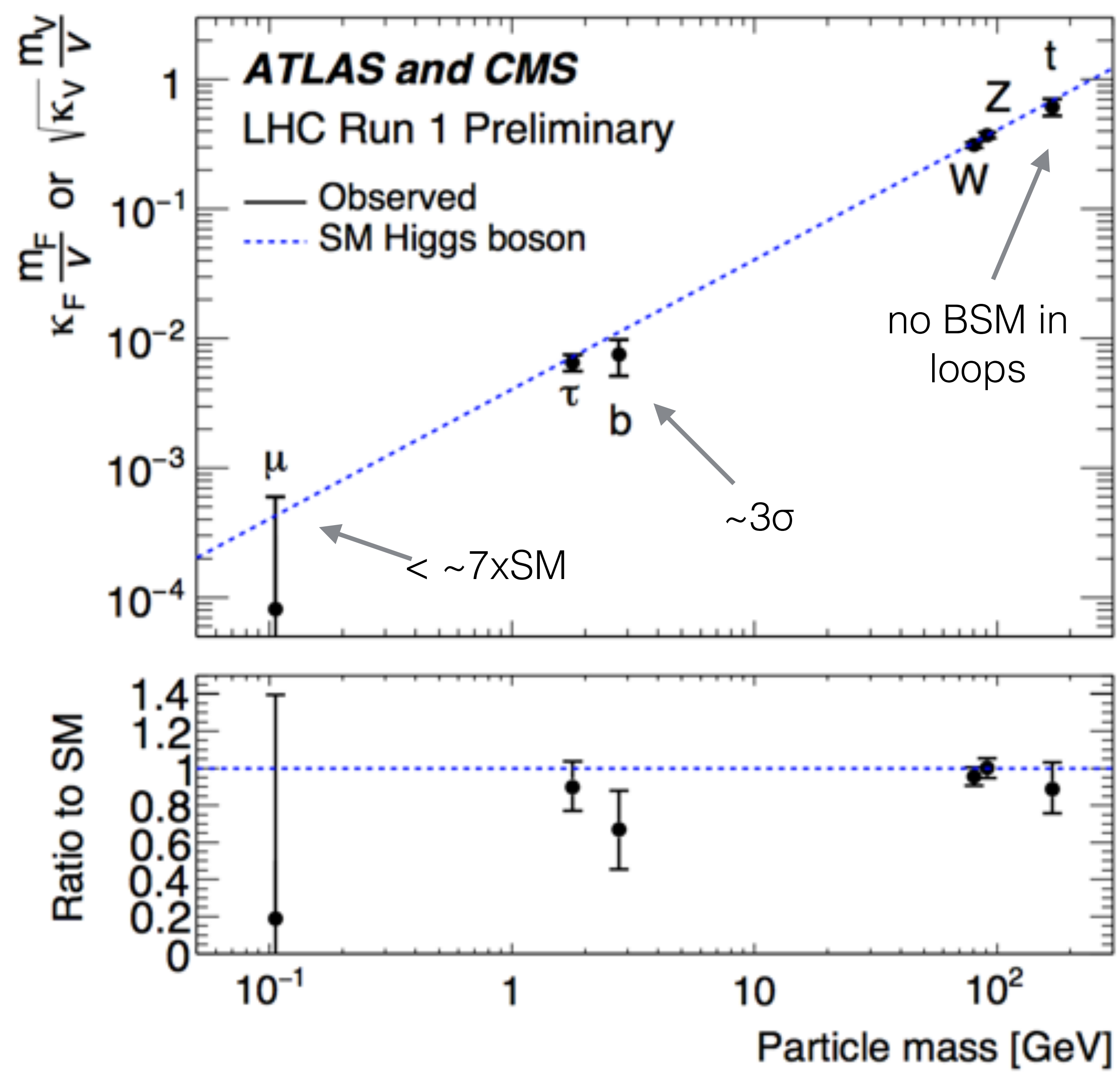
κ_Z, κ_W, κ_t, κ_τ, κ_b, κ_μ

Because $\kappa_\gamma \sim 1$ and $\kappa_g \sim 1$, assume no BSM in loops and fit all the other coupling modifiers:

κ_Z, κ_W, κ_t, κ_τ, κ_b, κ_μ

p-value = 65%



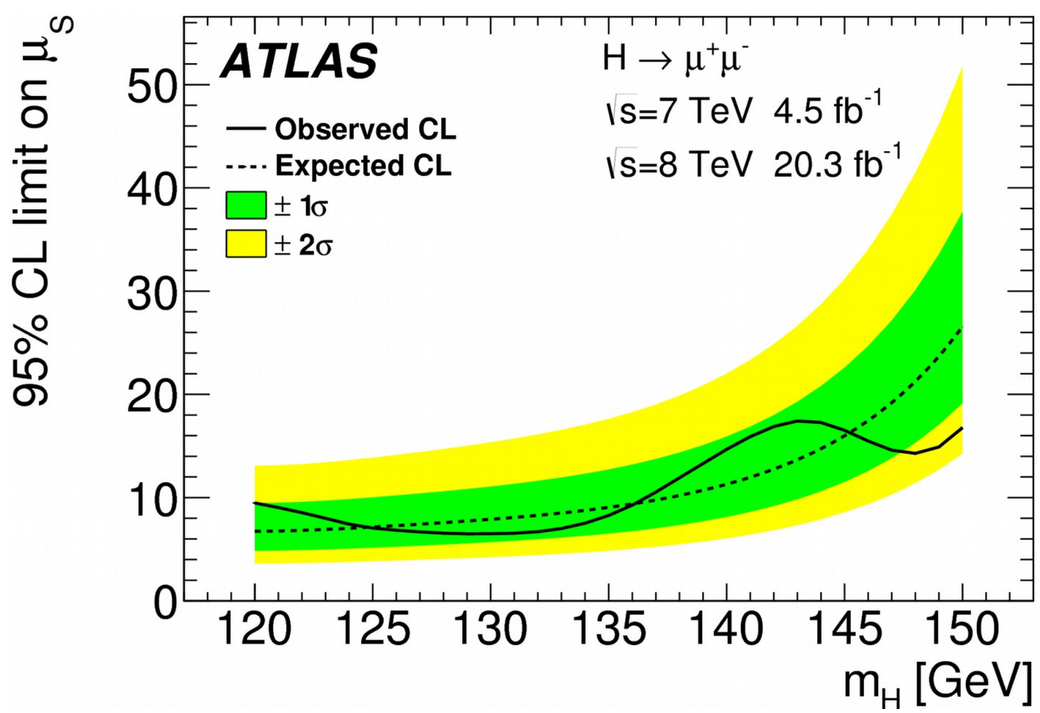


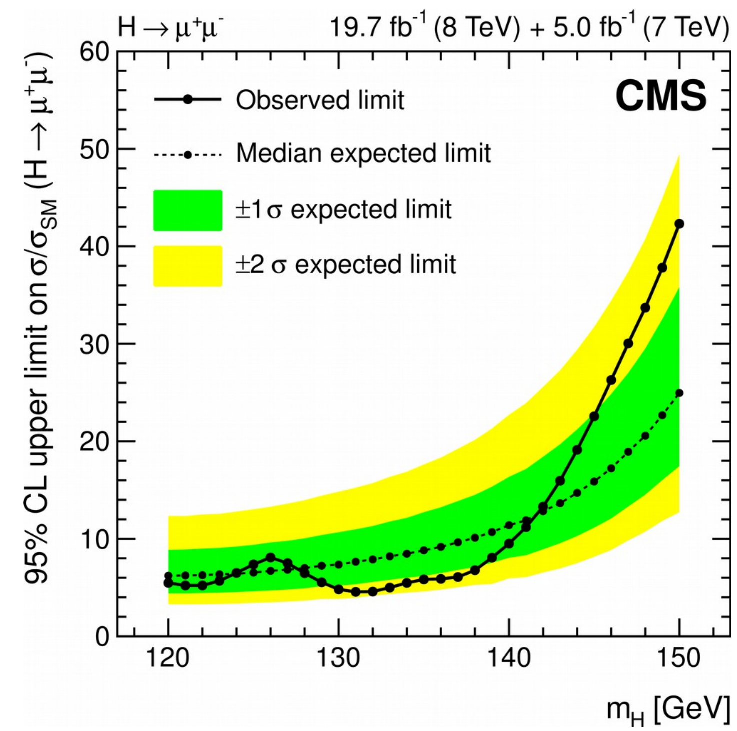
Both ATLAS and CMS measure a low κ_b, Γ is dominated by Γ_{bb}
and remembering that $\mu = 1.09 \pm 0.11$ pulls down all the BRs

Rare decays

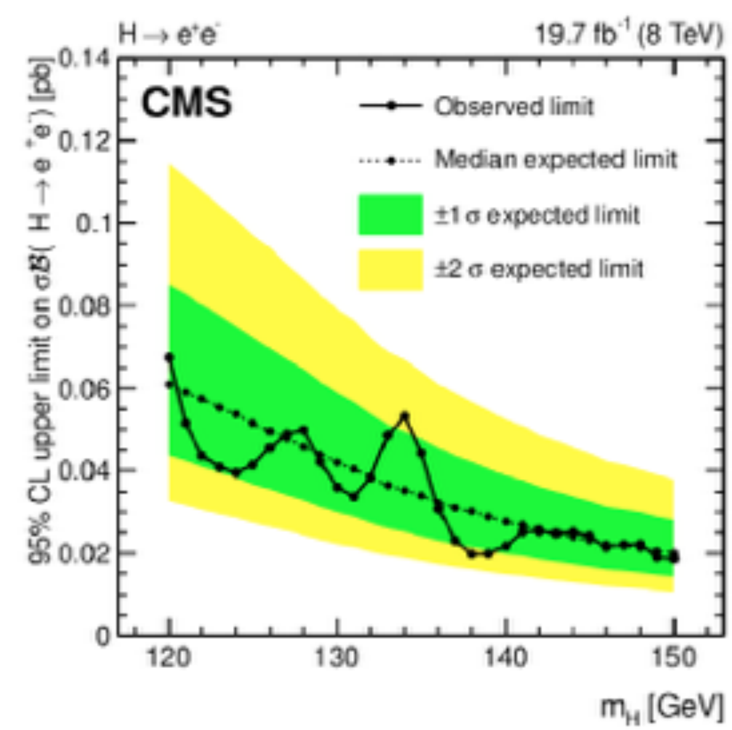
Rare decays

BR(H→μμ) ~ 2 10^{-4} ; UL (σ/σ_{SM})~7 x SM (5σ discovery with 1000 fb^{-1})



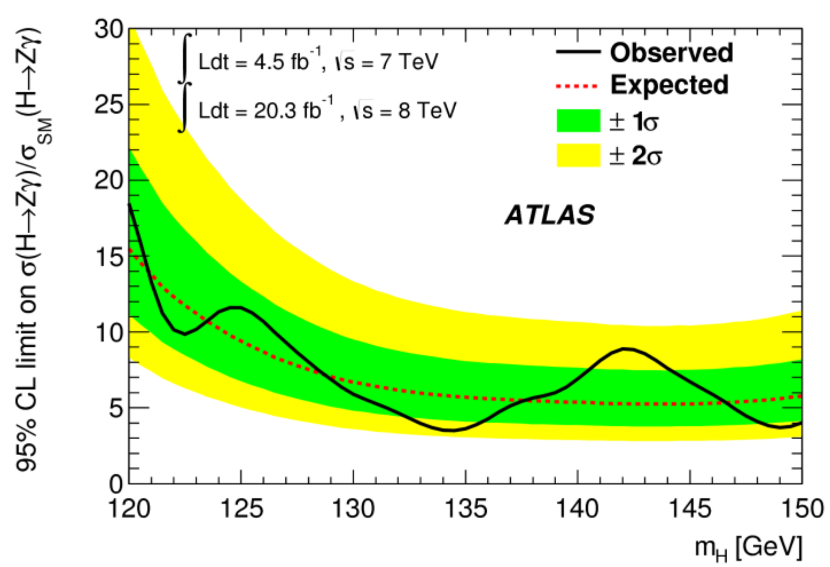


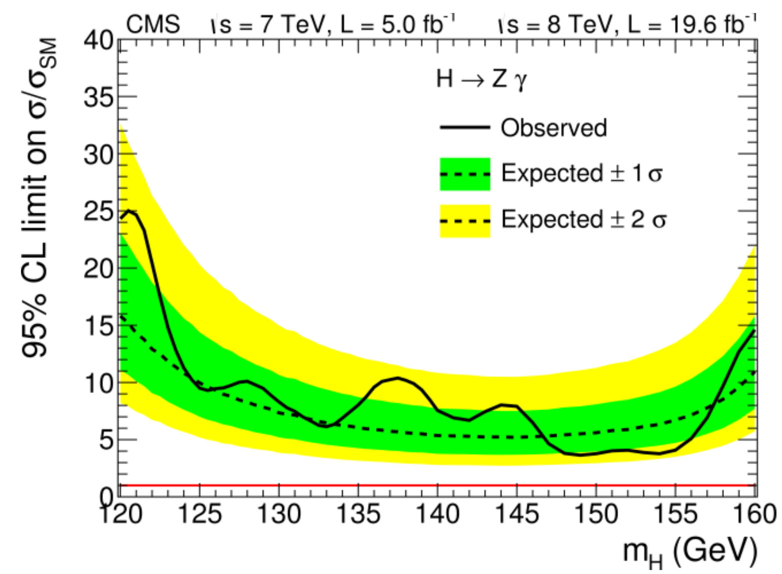
BR(H→ee) ~ 5 10^{-9} ;
UL on BR ~ 3.7 10^{5} x SM

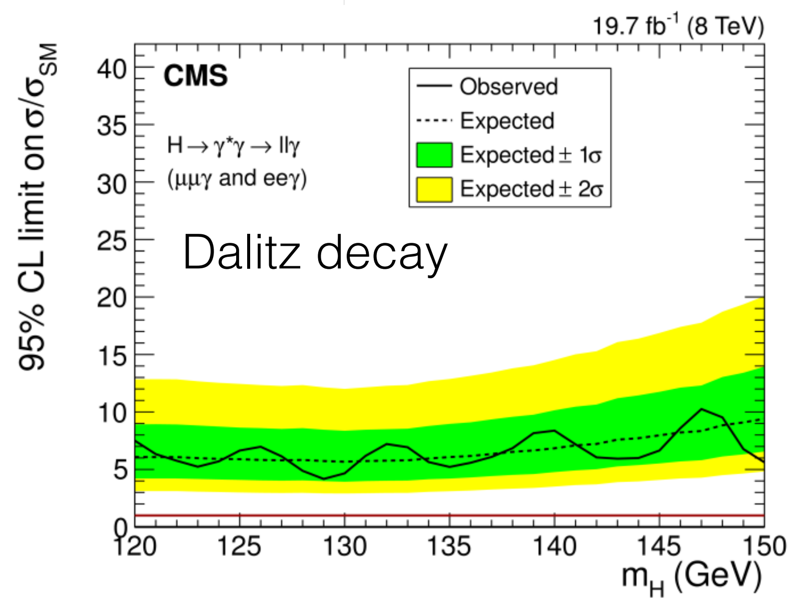


Rare decays

SM BR(H→Zγ) ~ 1.5 10^{-3} ; UL (σ/σ_{SM})~10 x SM

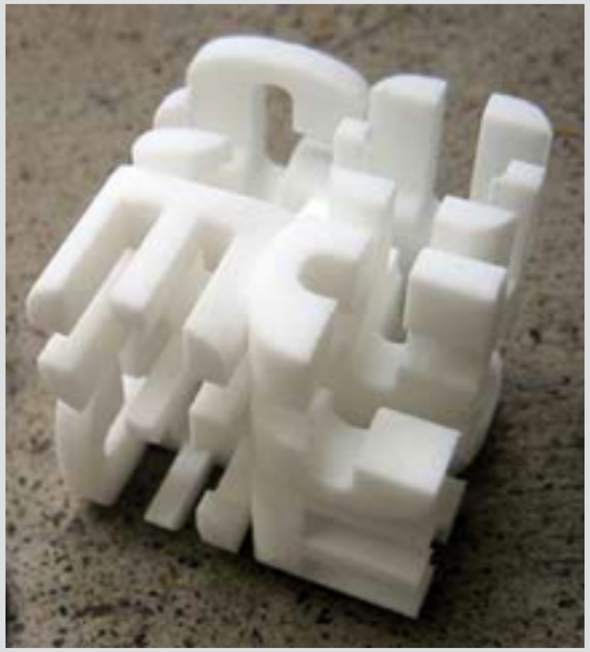






SM BR(H→(J/ψ)γ) = 2.8 10^{-6} for the 125 GeV Higgs

UL on BR(H→(J/ψ)γ) = 1.5 10^{-3}



Fiducial and Differential cross sections

Towards precision

Fiducial cross sections: reduce model dependence
(remove acceptance corrections measuring in a fiducial region)

Differential cross sections: compare differentially theoretical predictions

Measurement structure

For each differential observable:
- define a fiducial phase space at generator level to match analysis acceptance
- extract signal for each bin of the observable (repeat the analysis for each bin)
- unfold the measurement from reconstructed to generator level quantities
  (ATLAS bin-by-bin / iterative, CMS combined with the signal extraction / regularization)
- compare the SM/BSM theoretical prediction

Different observables are sensitive to different parameters of the Higgs sector, e.g.:

p_T^H, y^H	production process, QCD radiation, proton PDF
N_{jets}, p_T^j, y^j	QCD radiation
$\cos\vartheta^*$, $\Delta\phi_{jj}$	spin CP
$\Delta\phi_{\gamma\gamma,jj}$, Zeppenfeld	VBF production

Decay channels studied so far: **$H\rightarrow\gamma\gamma$, $H\rightarrow ZZ\rightarrow 4$ leptons, $H\rightarrow WW$ leptonic**

H→γγ

Large background but clean signal because of high mass resolution

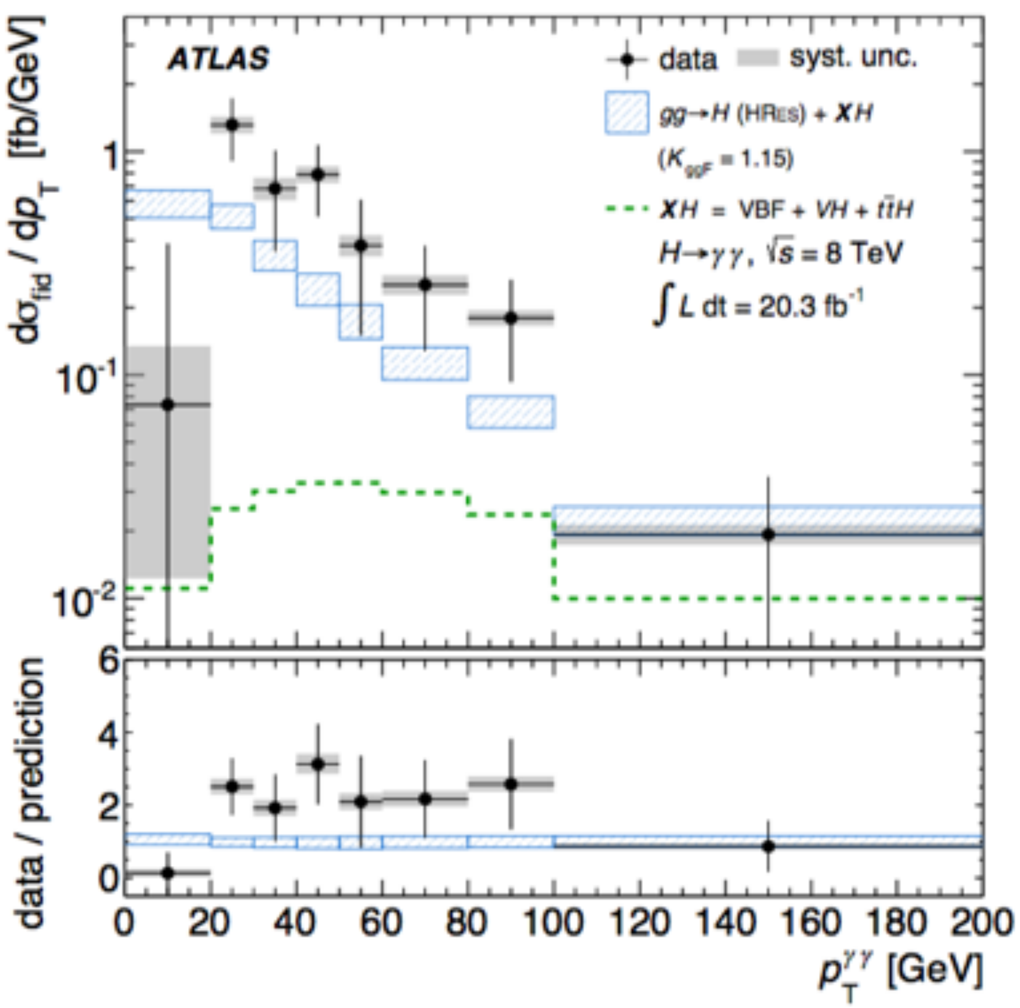
Fiducial cross sections:

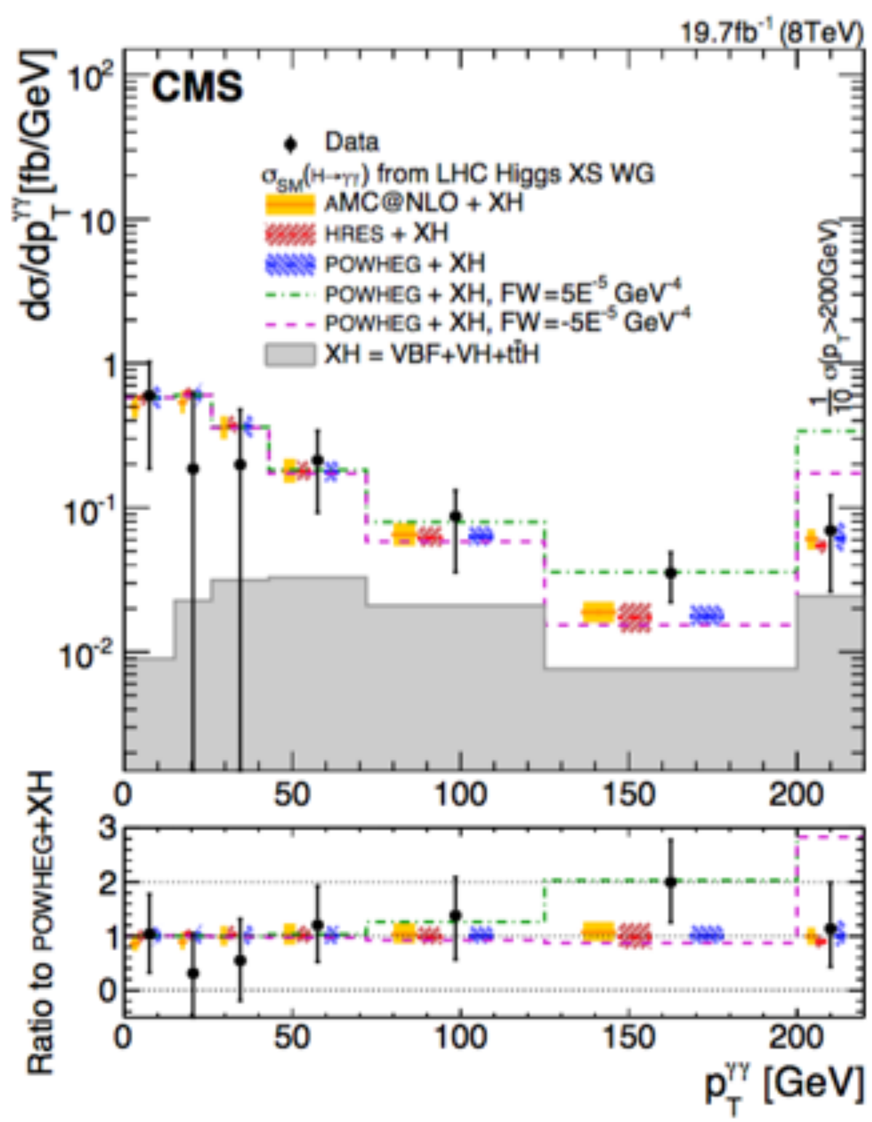
ATLAS measured: $\sigma_{\rm fid}(pp \to H \to \gamma\gamma) = 43.2 \pm 9.4\,(\text{stat.})\,^{+3.2}_{-2.9}\,(\text{syst.}) \pm 1.2\,(\text{lumi})\ \text{fb}$

theory: $30.5 \pm 3.3\ \text{fb}$

CMS measured: $\sigma_{\rm obs} = 32^{+10}_{-10}\,(\text{stat})^{+3}_{-3}\,(\text{syst})\,\text{fb}$

theory: $\sigma_{\rm HRES+XH} = 31^{+4}_{-3}\ \text{fb}$





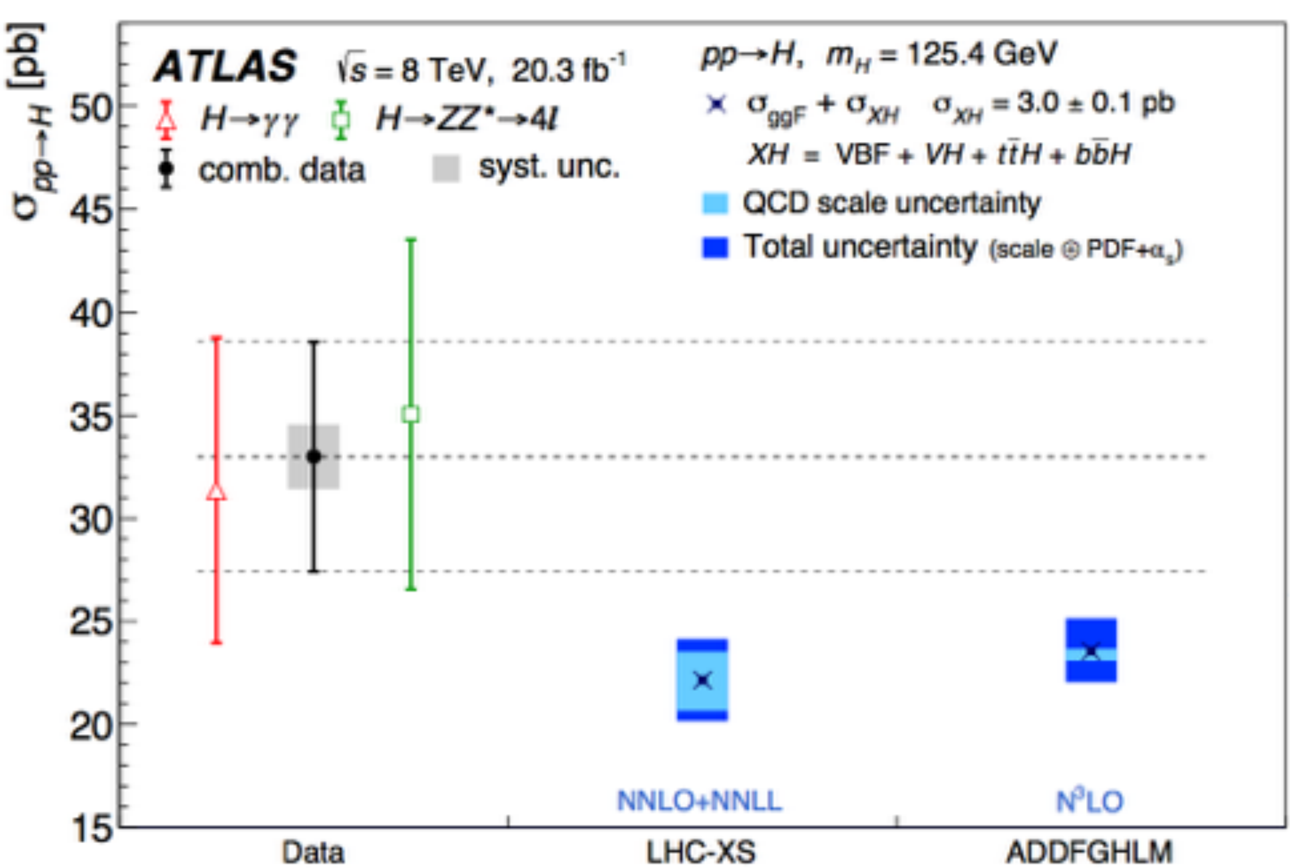
Combination H→γγ,H→ZZ

Statistical uncertainty reduced by ~30% on average

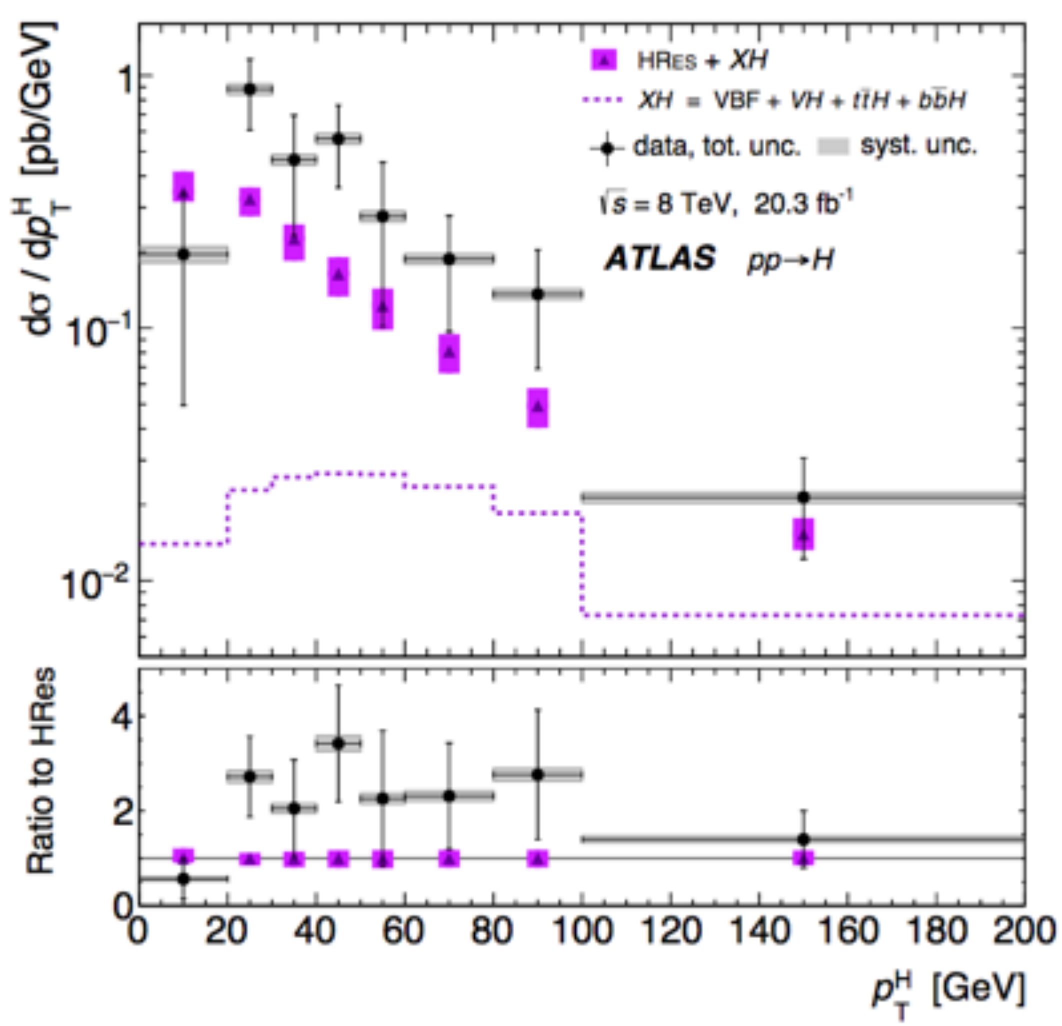
Measurements extrapolated to total cross section: acceptances

56-62% ($H \to \gamma\gamma$) 44-53% ($H \to ZZ^* \to 4l$)

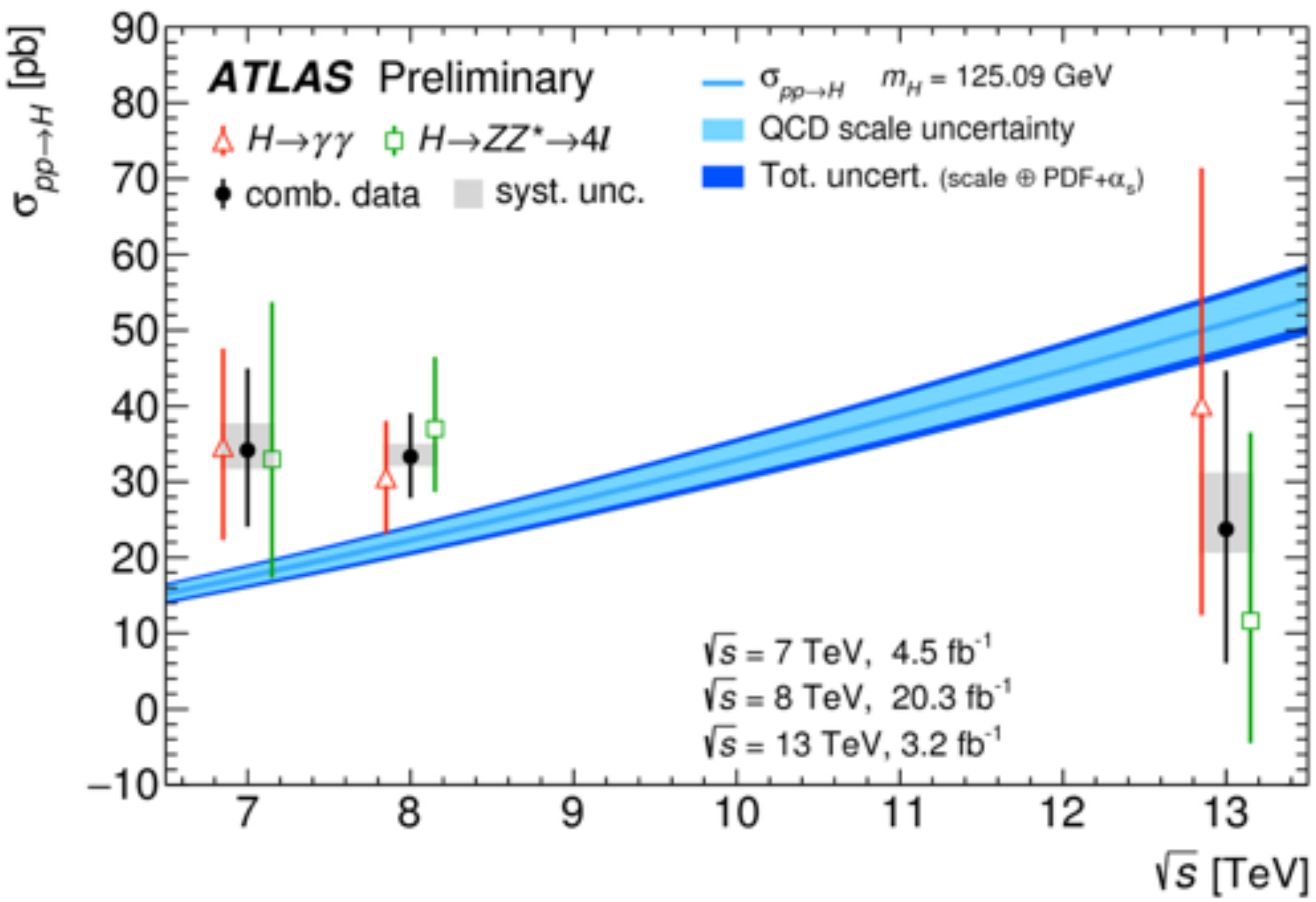
Four variables are studied: p_T^H, y^H, N_{jets}, p_T^{j1}



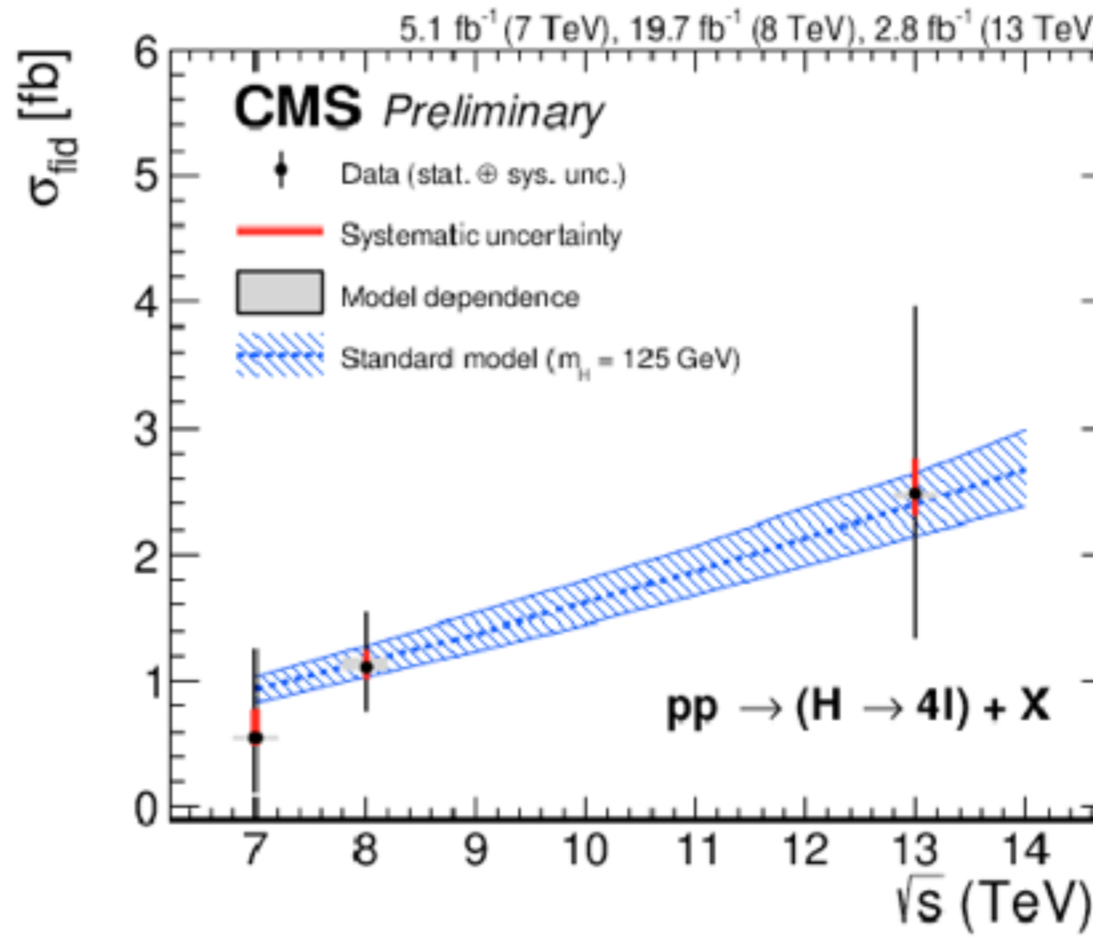
p-value = 5.5% p-value = 9%



Fiducial cross sections



ATLAS: combined H→ZZ and H→γγ channels



CMS: H→γγ channel

BSM Higgs

A map of BSM Higgs searches

Additional Higgs bosons or BSM decays of the Higgs

2HDM

indirect contraints from H couplings

MSSM/hMSSM

$H \to \tau\tau$
$H \to bb$
$H \to \mu\mu$
$H \to \gamma\gamma$
$H^+ \to \tau^+\nu$
$A \to Zh$
...

resonant $X \to hh$

non resonant HH

2HDM + S

NMSSM

BSM decay
$h \to aa$
$h \to ss$

$h \to 4\mu$
$h \to \mu\mu\tau\tau$
$h \to \mu\mu bb$
$h \to bb\tau\tau$
$h \to 4\gamma$
$h \to 4b$

low mass
$h \to \gamma\gamma$
$h \to bb$

$bb + a \to \tau\tau$

Invisible

VBF, ZH
mono jet
mono V
ttH
$h \to \chi\chi \to \gamma MET$

LFV

$H \to \mu\tau$
$H \to e\tau$
$H \to e\mu$

Higgs triplet

H^{++}

etc..

Selected examples

Byproducts of SM-like analysis:

Indirect constraints on BSM from couplings

Extending SM analysis to high masses: $H \to \tau^+\tau^-$, $H \to ZZ$

Double Higgs resonant / non resonant (self coupling)

Link with low energy LFV experiments

$H \to e\tau$ $H \to \mu\tau$ $H \to e\mu$

Link with DM searches:

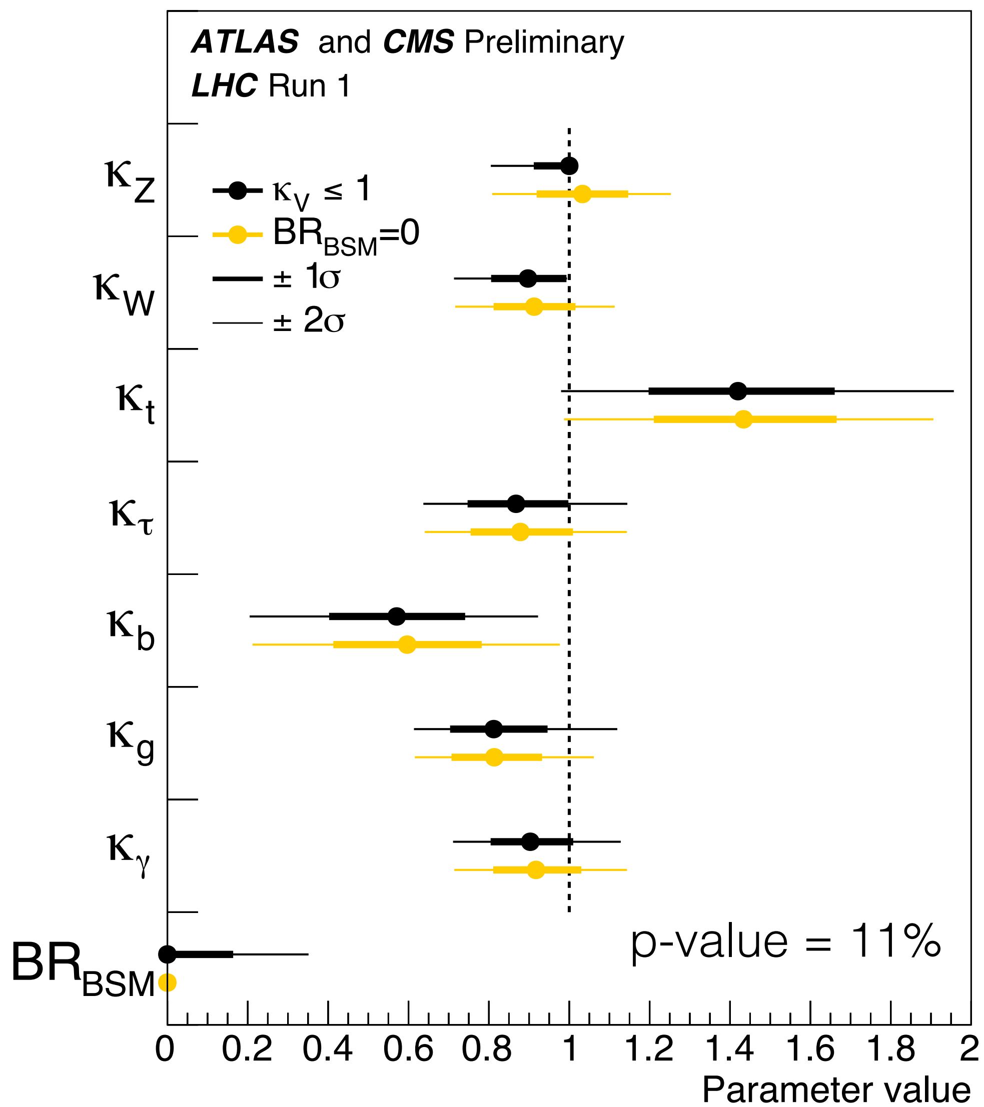
Invisible Higgs

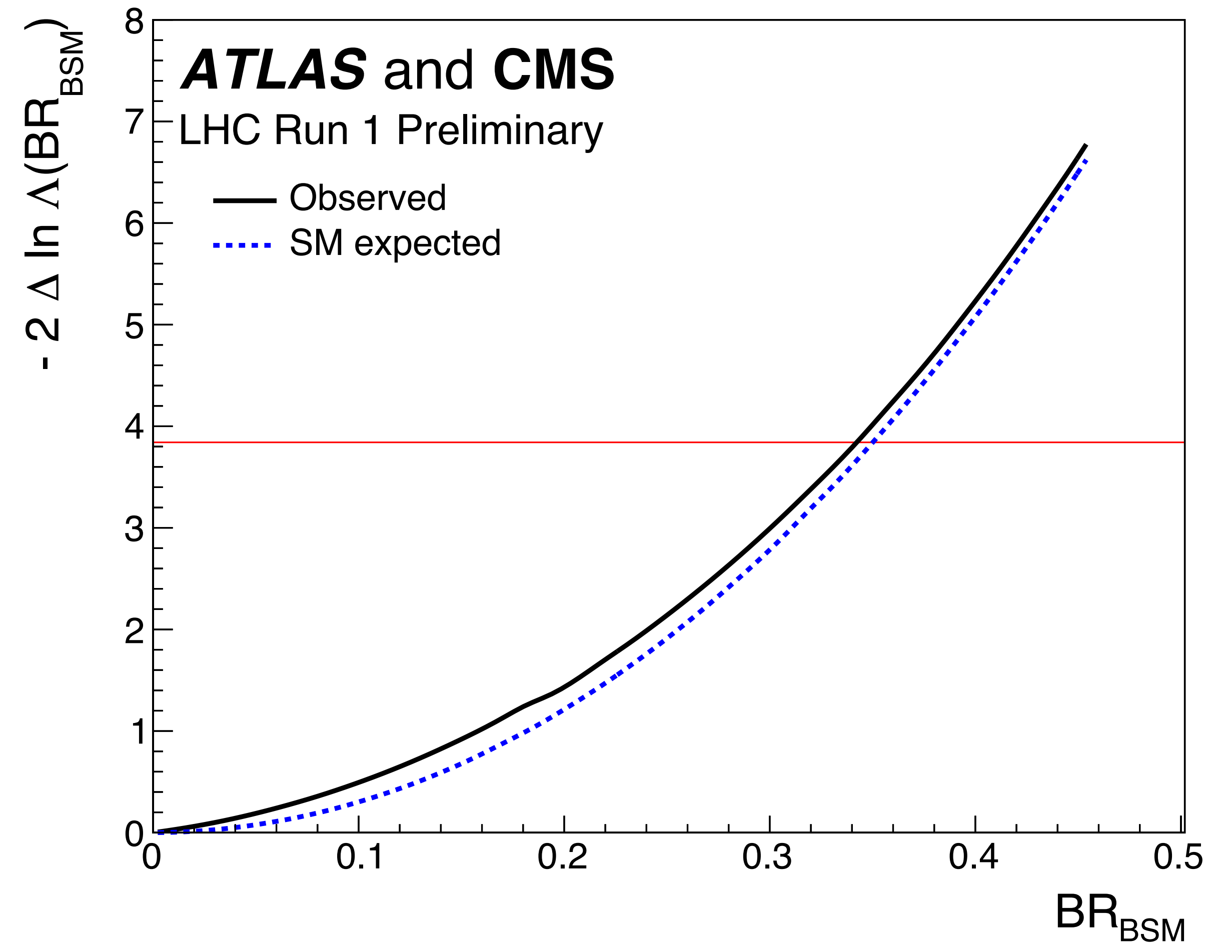
Indirect constrains from Run 1 on BR_{BSM}

BR in the various decay modes are sensitive to the H-width (which includes invisible decays)
⇒ to measure individual couplings need assumptions on the H-width.

Two scenarios:

- $BR_{BSM} = 0$
- $BR_{BSM} \geq 0$, constrain $K_W \leq 1$, $K_Z \leq 1$ ($K_V \leq 1$)



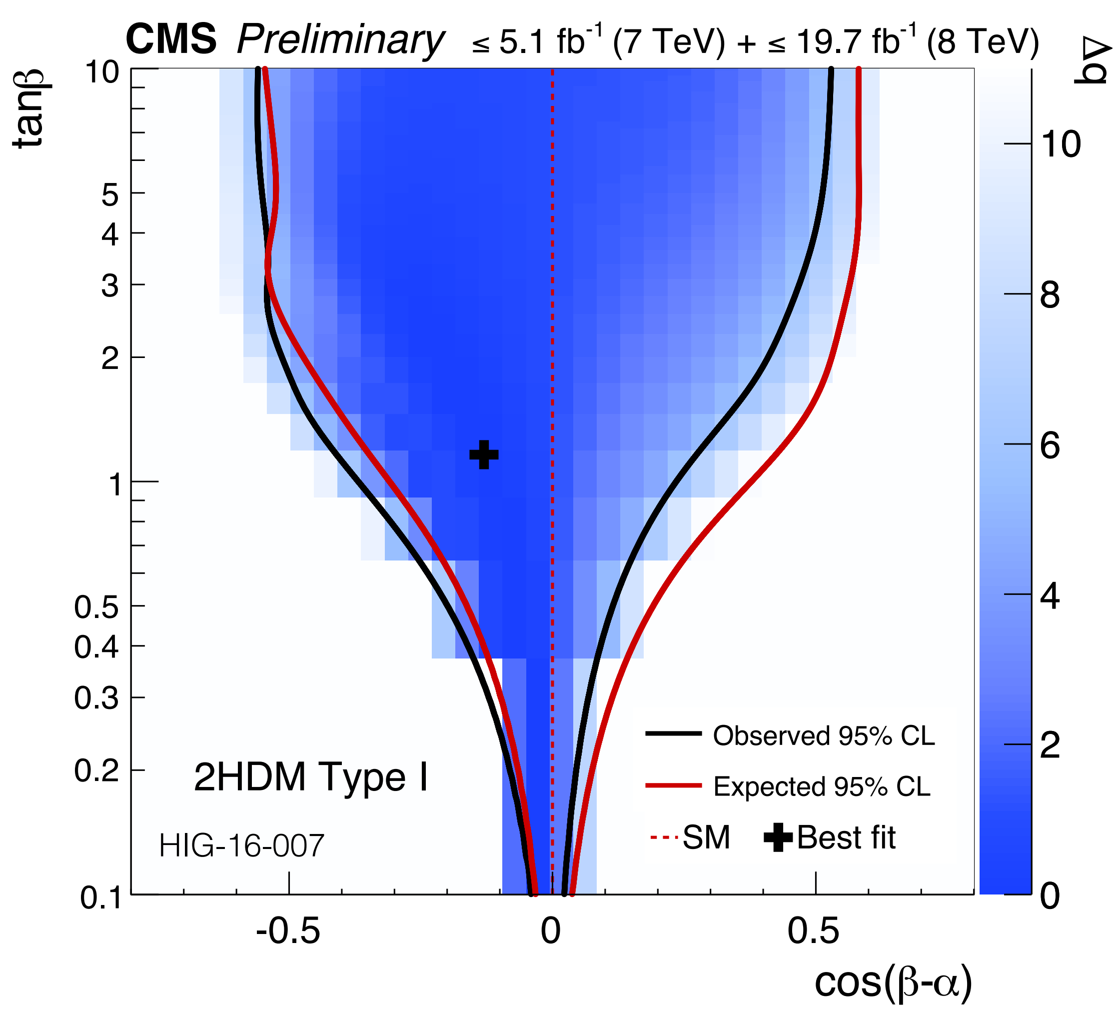


$BR_{BSM} < 0.34$ @ 95%CL

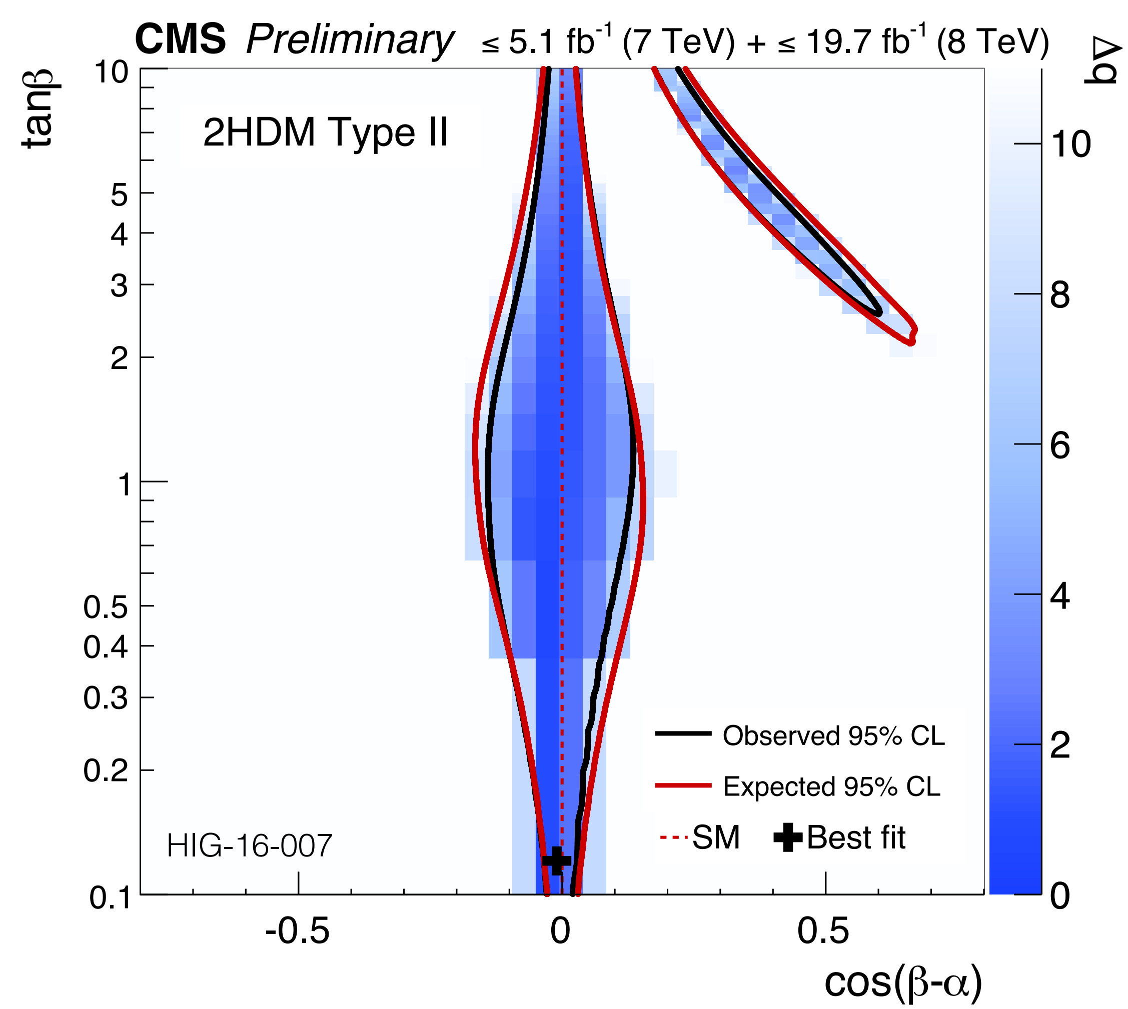
Indirect constrains from Run 1on 2HDM

2 doublets, 5 Higgs bosons (CP-even h (SM-like), H; CP-odd A, charged H^+, H^-)
Physical basis: 7 variables (m_h,m_H,m_A,$m_{H\pm}$,mixing angle α of the mixing matrix M^2, tan(β) ratio of Higgs vevs, soft Z_2-breaking mass parameter m_{12})

Reinterpret constrains on k_u,k_d,k_V:
assume h is the 125 GeV and put constraints on tan(β) - cos(α-β).
Data favours the "alignment" limit cos(β−α) → 0, i.e. h couplings close to SM Higgs boson



type-I: $SU(2)_L$ doublets couple to both up- and down-type fermions equally

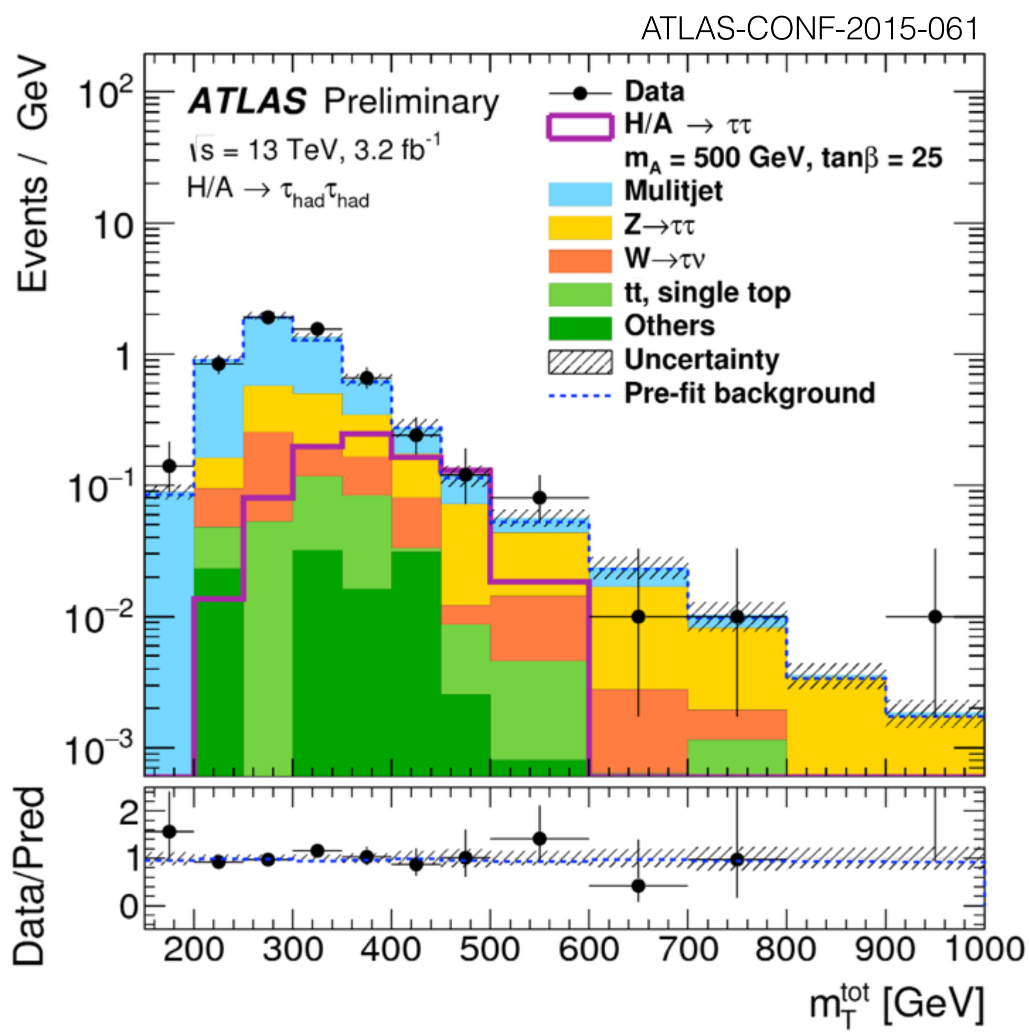


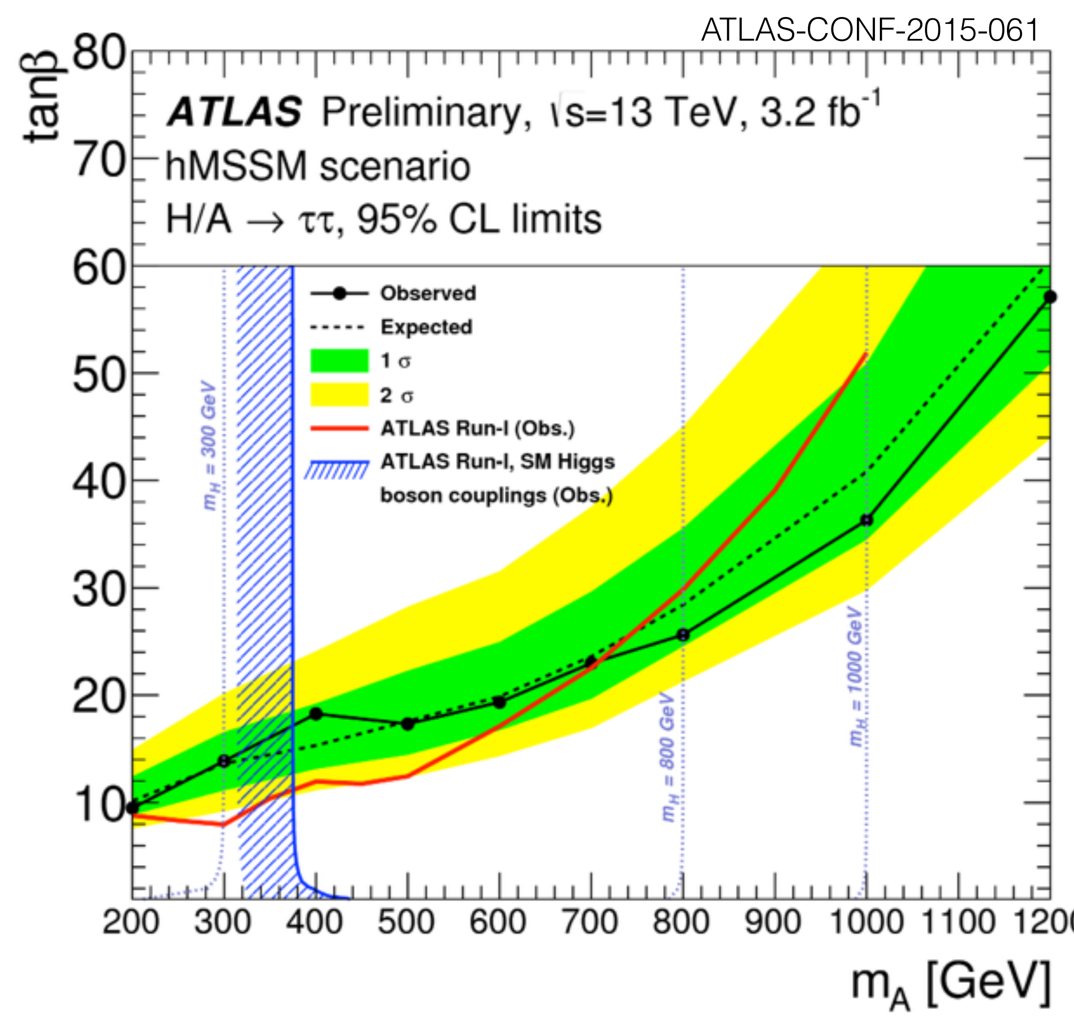
type-II: one doublet couples exclusively to up-type and the other exclusively to down-type fermions

Extension to high mass: $H\rightarrow\tau^+\tau^-$

Clear signature, discriminating variable: $$m_T(\ell, E_T^{miss}) \equiv \sqrt{2p_T(\ell)E_T^{miss}(1-\cos\Delta\phi(\ell, E_T^{miss}))}$$

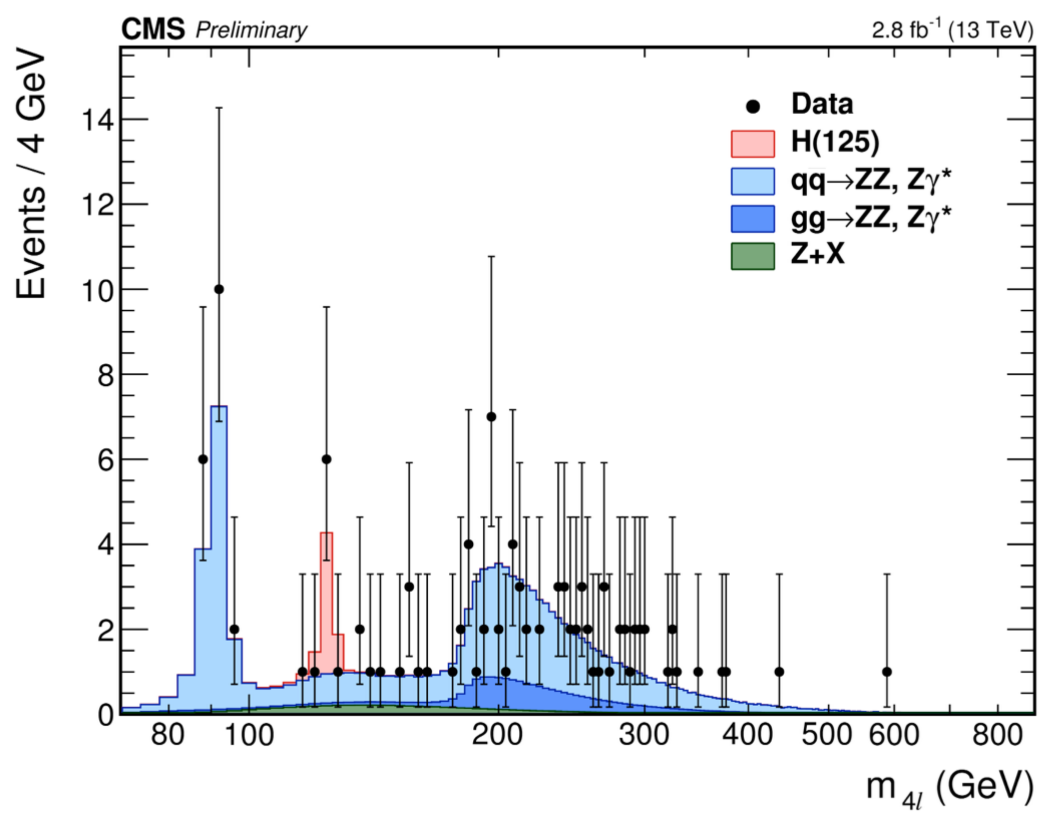
Interpretation: model independent (σxBR($\phi\rightarrow\tau\tau$)) and several MSSM benchmark
Sensitivity already exceeds ATLAS Run-1 for m_A>700 GeV.

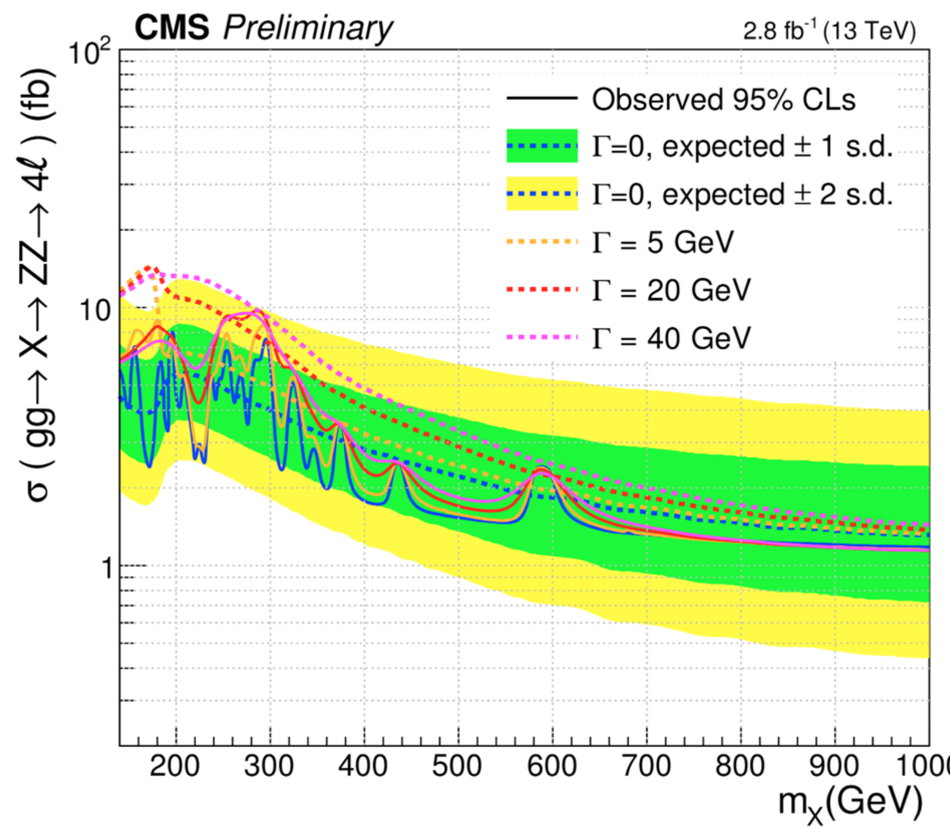


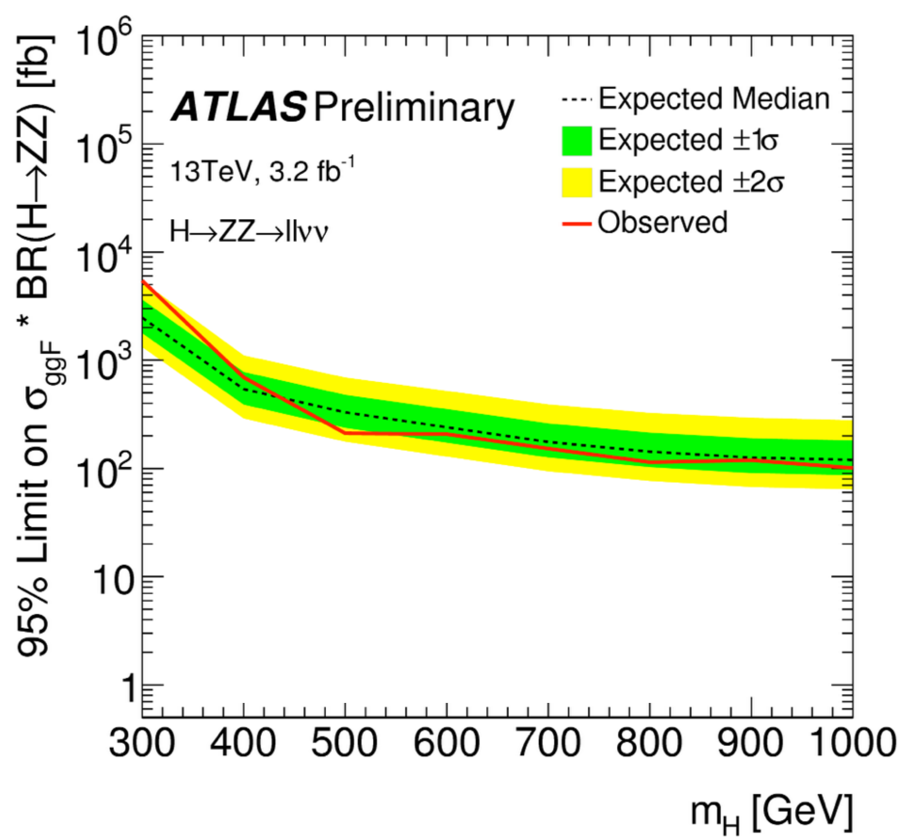


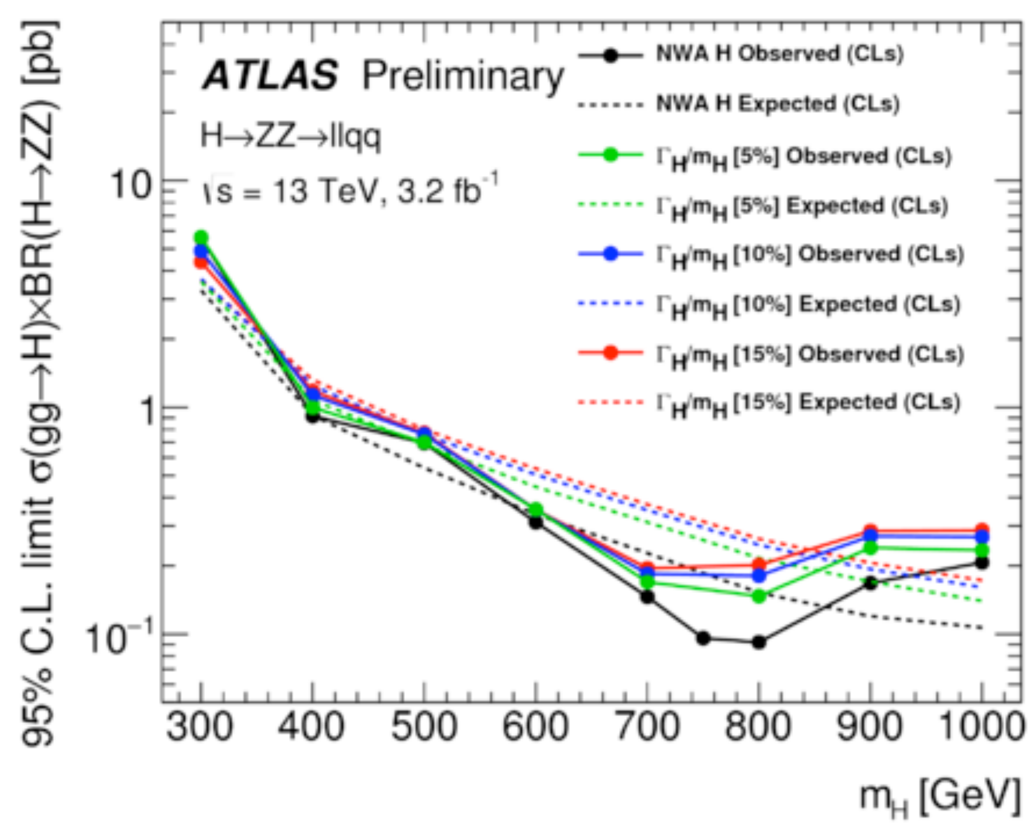
Extension to high mass: H→ZZ

Various decay channels: 4l, 2l2nu, 2l2q







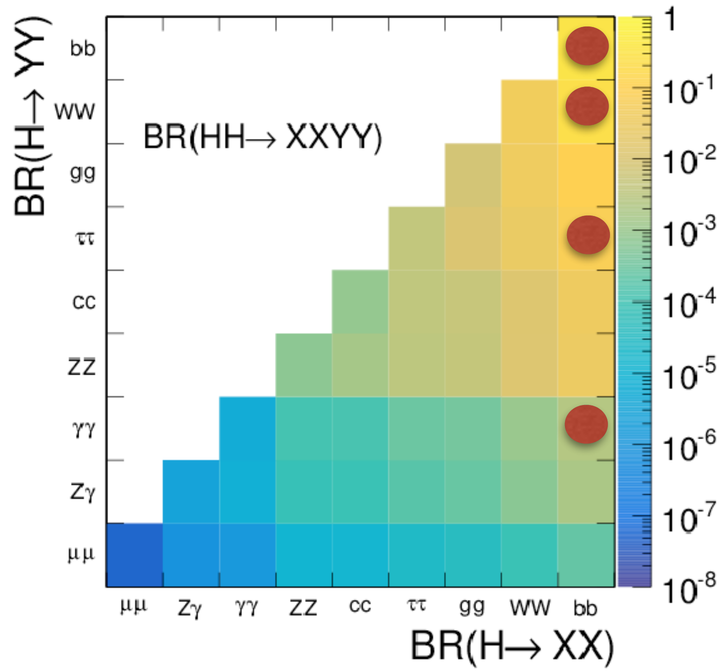


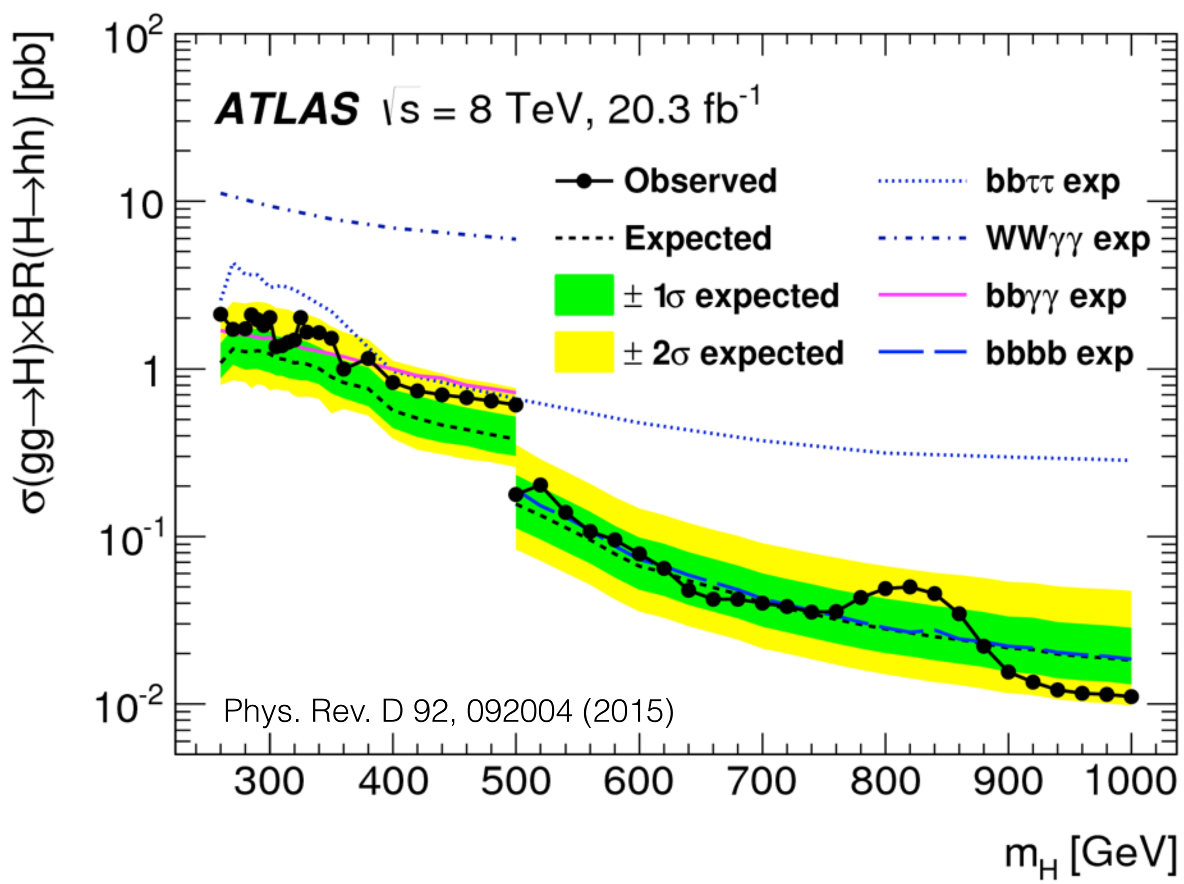
Resonant HH searches

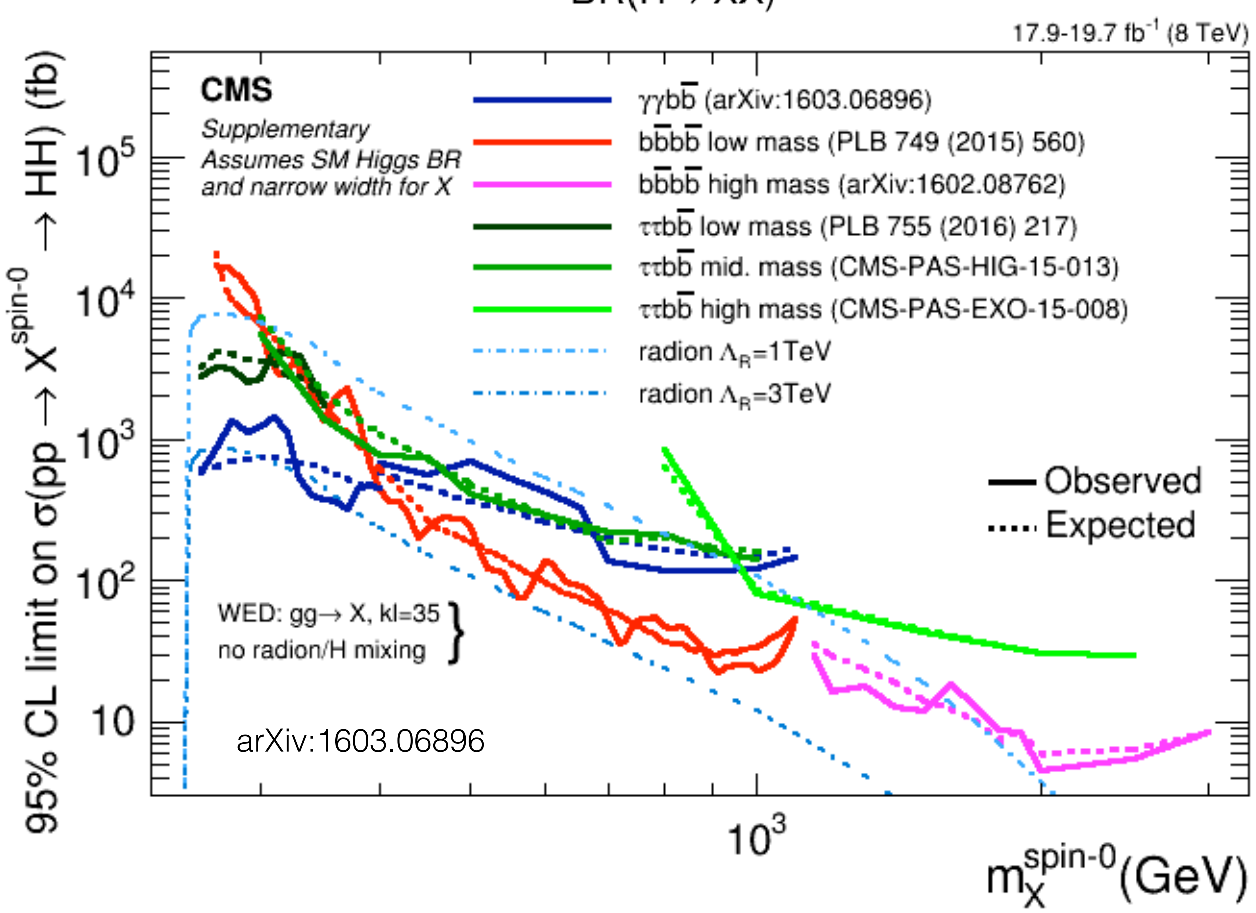
(Non resonant also studied, look in "prospects slides" for *self-coupling*)

Most promising channels are being probed:

- bb bb : resolved regime (boosted >1TeV)
- bb WW : leptonic final states
- bb $\tau\tau$: $bb\tau_e\tau_h$, $bb\tau_\mu\tau_h$, $bb\tau_h\tau_h$
- bb $\gamma\gamma$: mass resolution, low stat







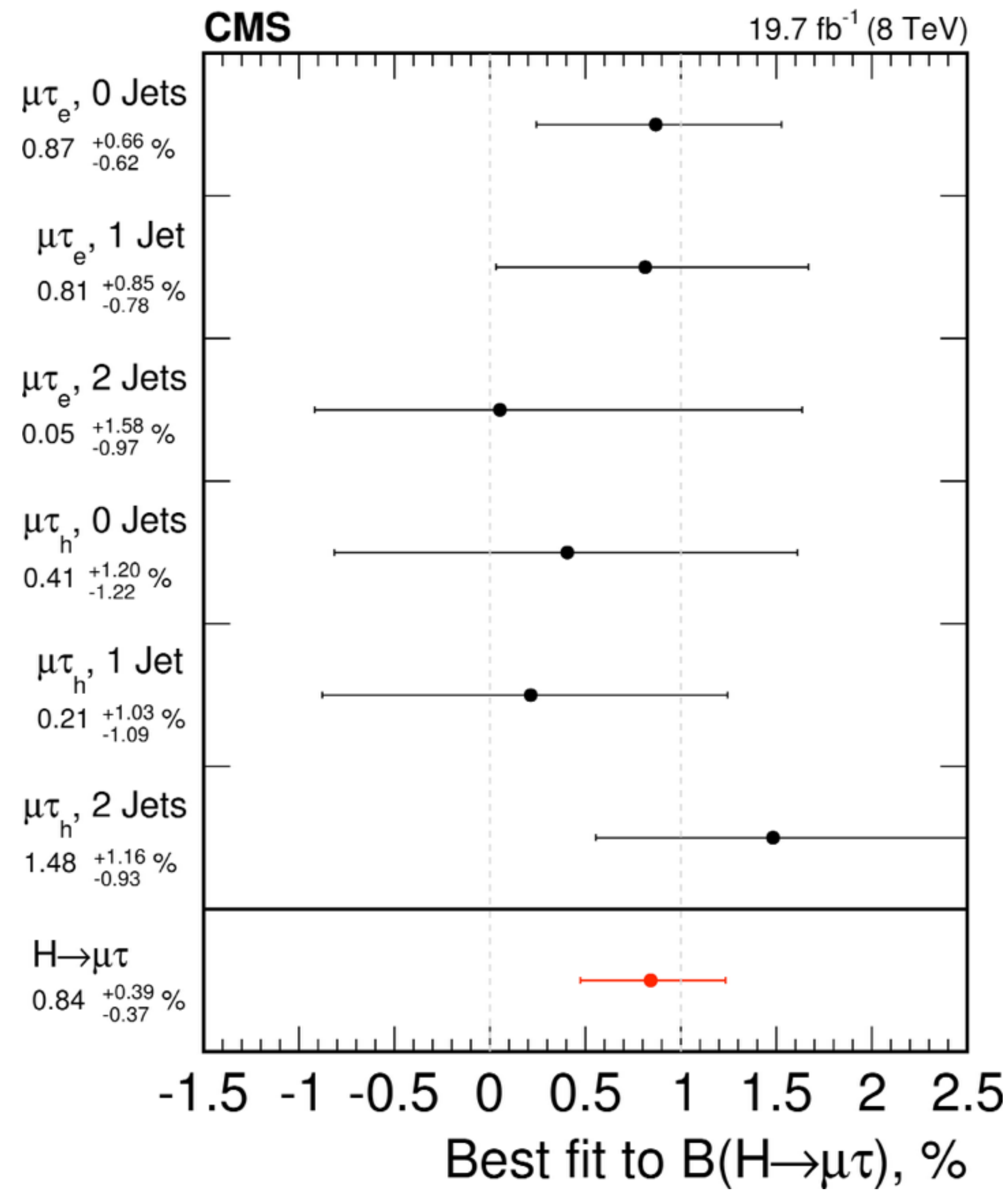
LFV: H→eτ H→μτ H→eμ

H→eτ

ATLAS: Br(H→eτ) < 1.04% (exp. 1.21%) at 95% CL

CMS: Br(H→eτ) < 0.69% (exp. 0.75%) at 95% CL

(Indirect limits are at 10% from τ→eγ)



H→μτ

CMS: 2.4σ excess in Run 1. No excess found in Run 2, but not enough to exclude Run 1.

ATLAS: no significant excess

H→eμ

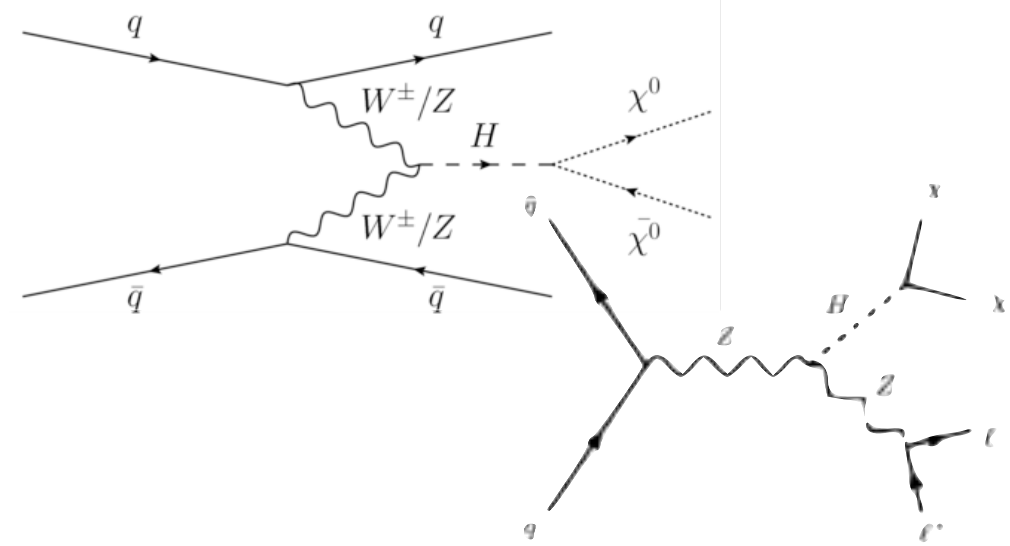
no excess observed. Limits:

Br(H→eμ) < 0.36 10^{-3} (exp. 0.48 10^{-3}) at 95% CL

Invisible Higgs

Combine all the visible and invisible Higgs boson decay channels.

Use VBF or VH production modes to tag the events
Main challenge: model bkg (QCD, Wjets, DY)

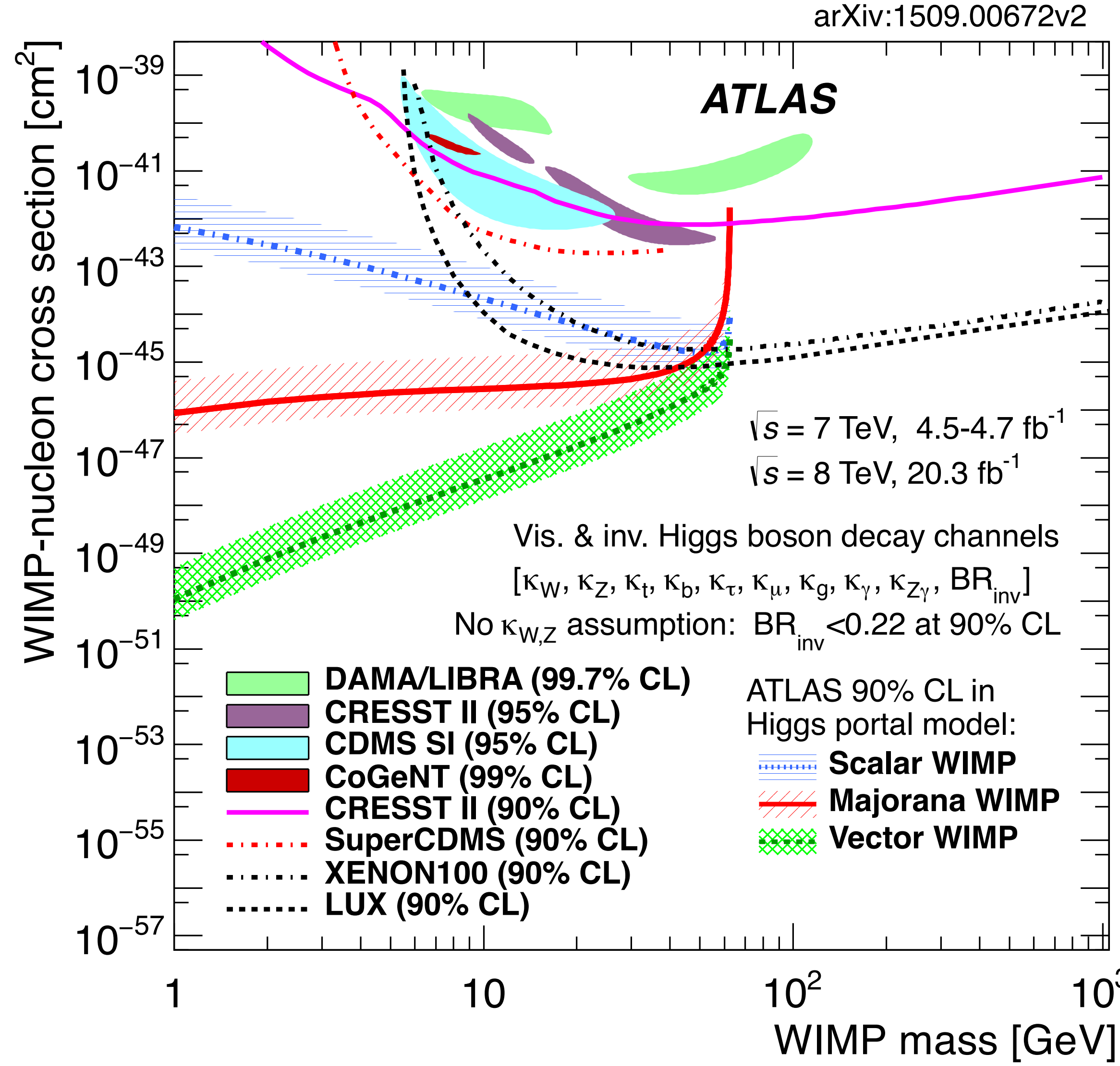


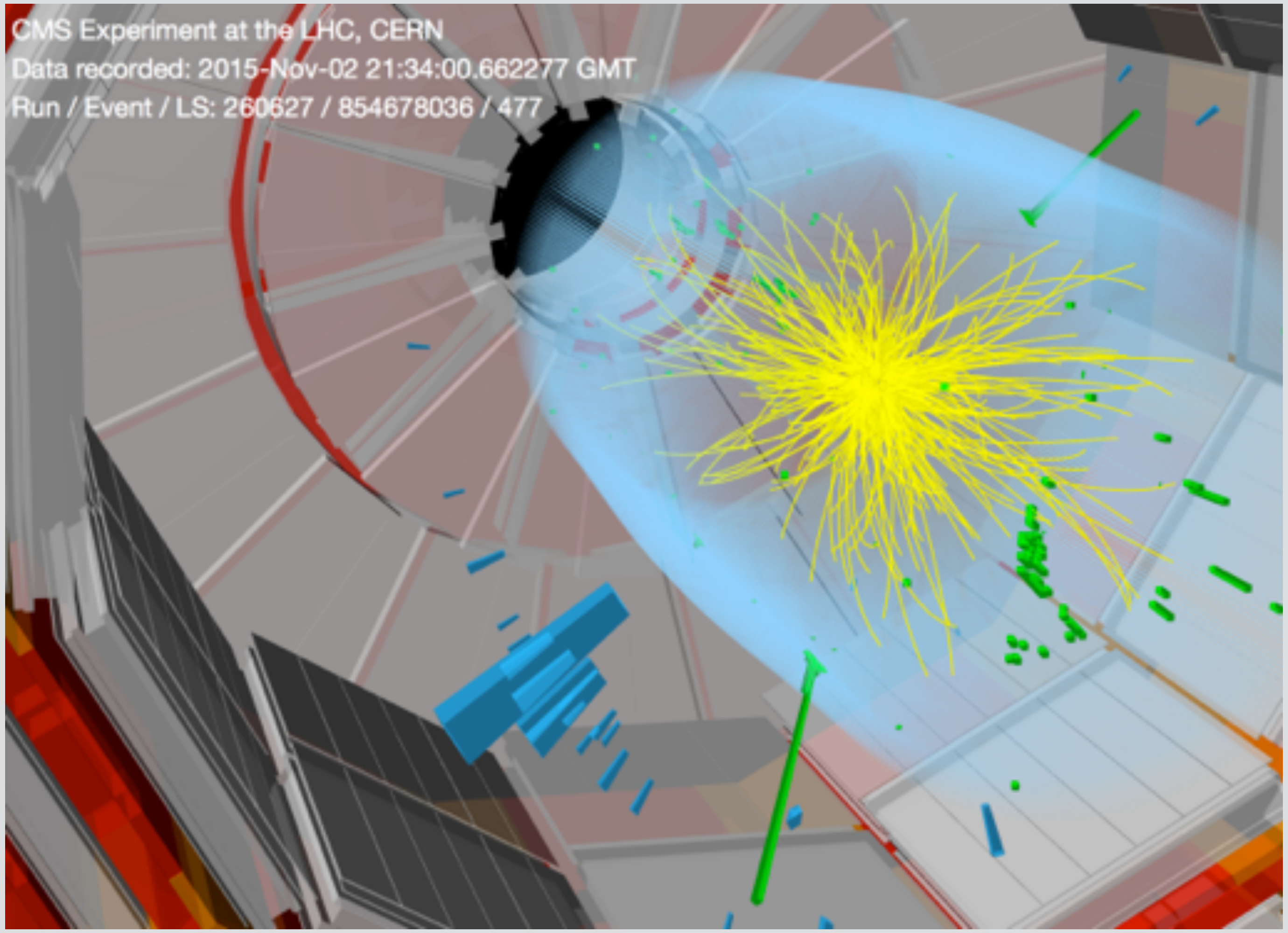
“Higgs portal”: Higgs is the only mediator (assume WIMP weak interacting with all other SM particles)

Couplings parameterised as σ(WIMP-nucleon) via Higgs boson exchange

WIMP mass < $m_H/2$

arXiv:1509.00672v2





High mass diphoton

Analysis strategy

The analysis is extremely simple !

- 2 isolated high pT photons (easy to trigger on, easy to reconstruct)
- categorize events on S/B to maximize sensitivity

- Energy scale, resolution and efficiencies from data

- Find a suitable background parametrization
- Hp test on bkg only hypothesis (bump hunt)

Spin 0 / 2:

CMS:

one analysis reinterpreted with the two hypothesis

- bkg parametrization on MC

$$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$$

ATLAS:

Two analysis:

different selection

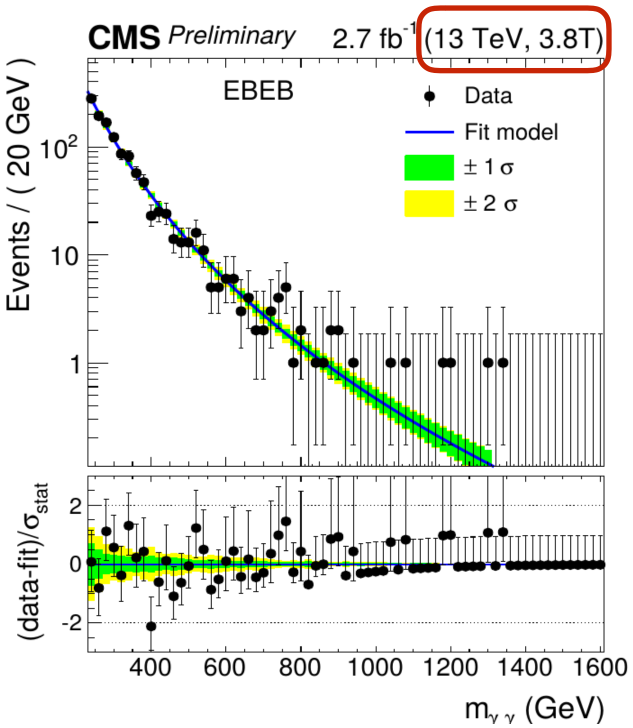
- spin 0: $p_{T\gamma} / M_{\gamma\gamma} > 0.4$ (0.3)
- spin 2: $pT\gamma > 55$GeV

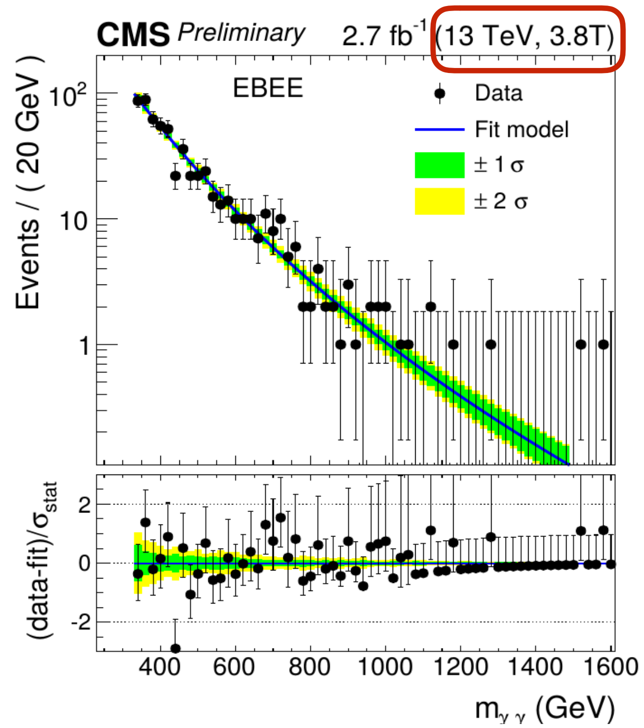
different bkg parametrization

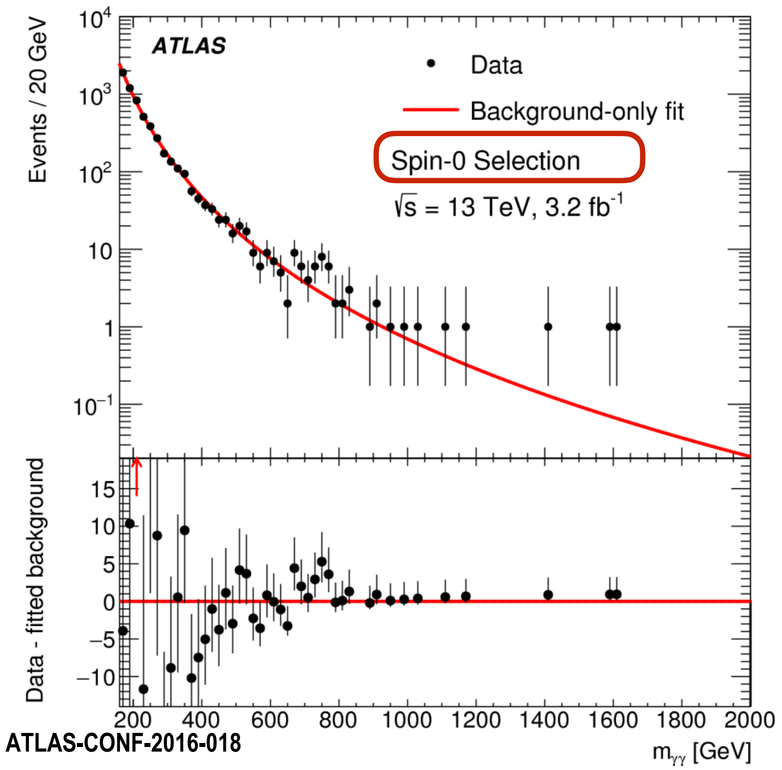
- spin 0: parametrization from data
- spin 2: MC-γγ + Data γj,jj ; mixed on data driven purity

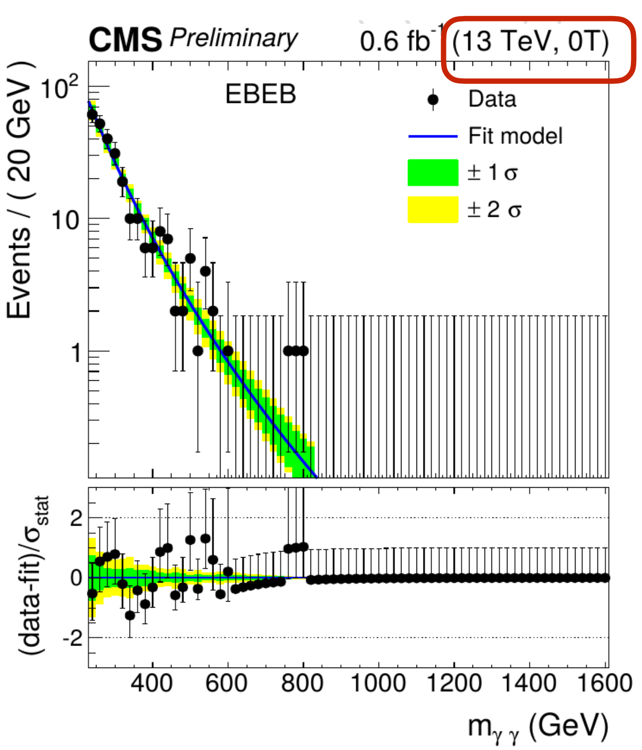
$$f_{(k)}(x; b, \{a_k\}) = N(1 - x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j}$$

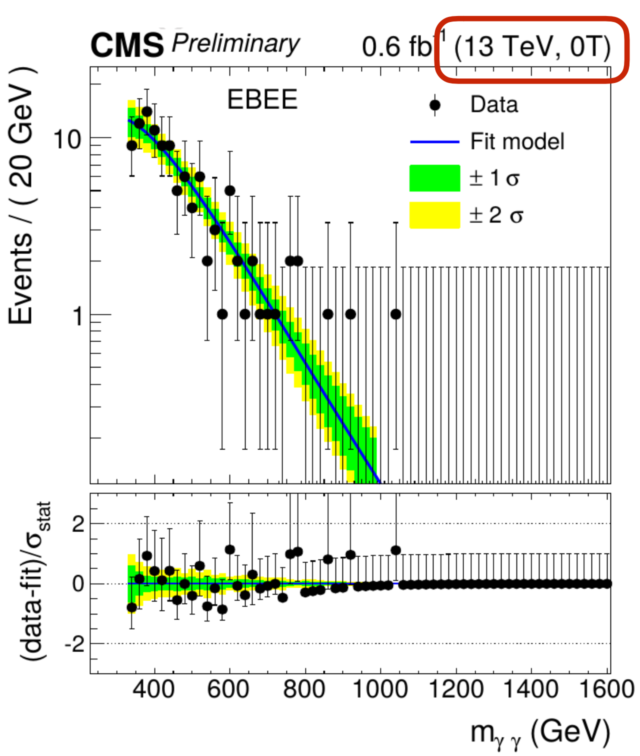
Mass spectra

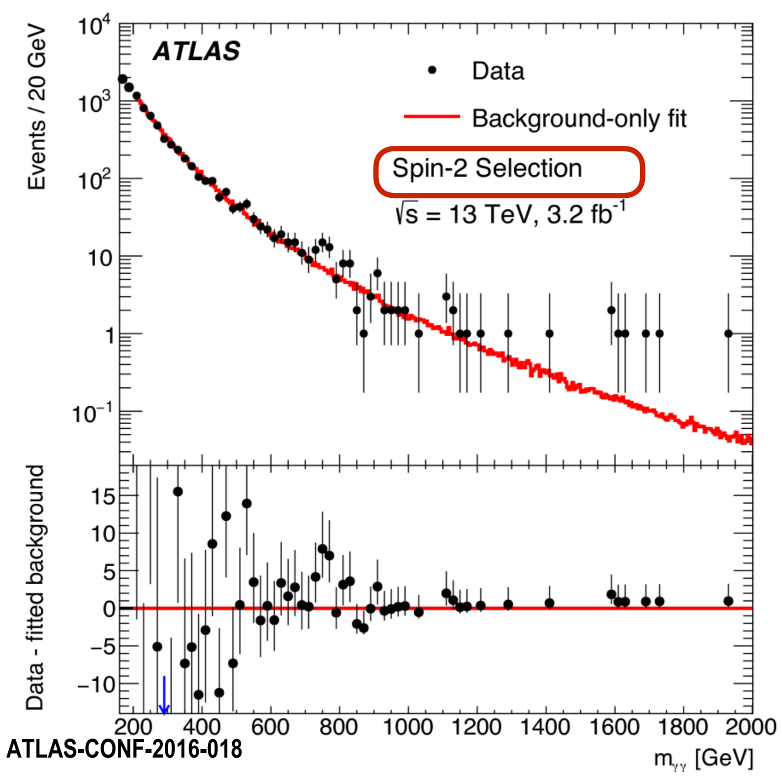






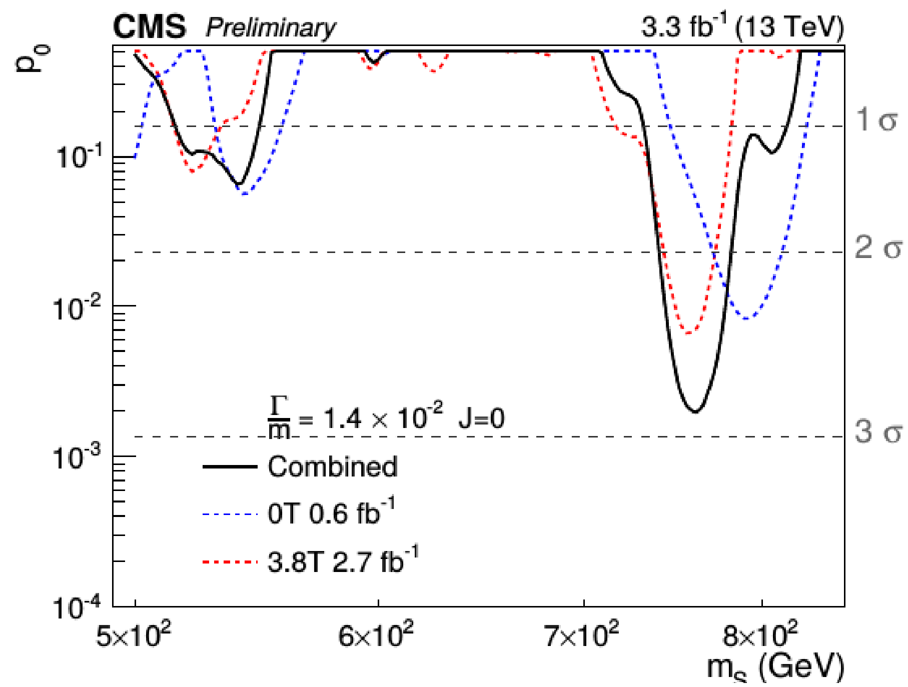


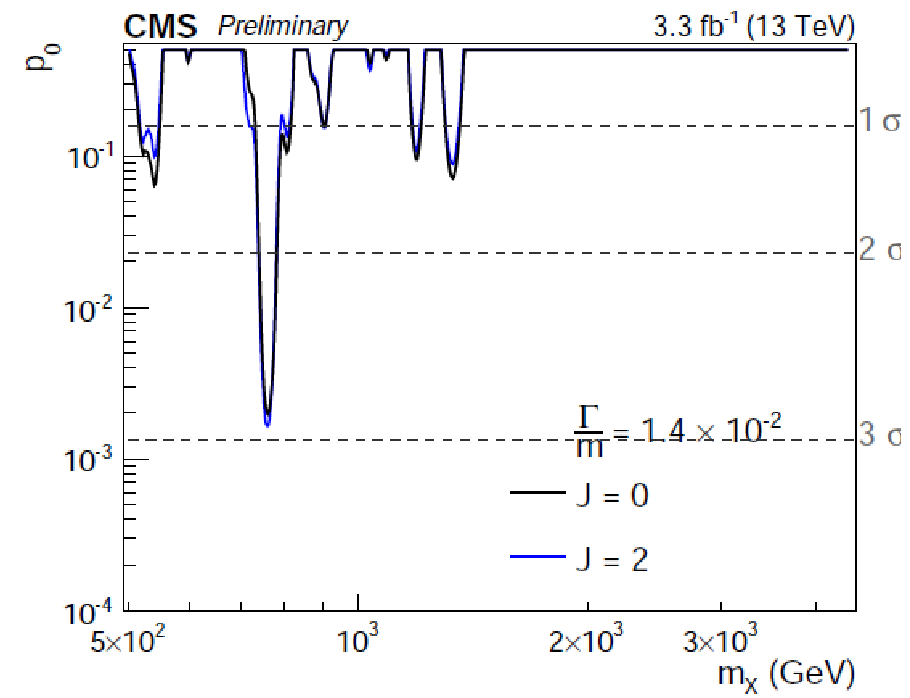




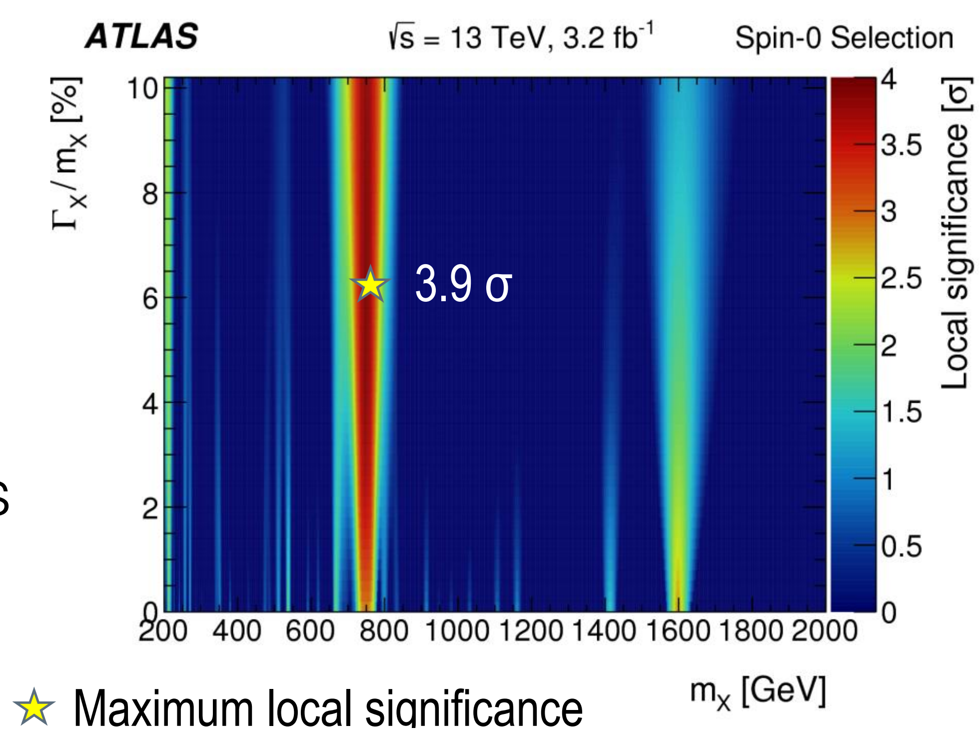
Largest *p*-values

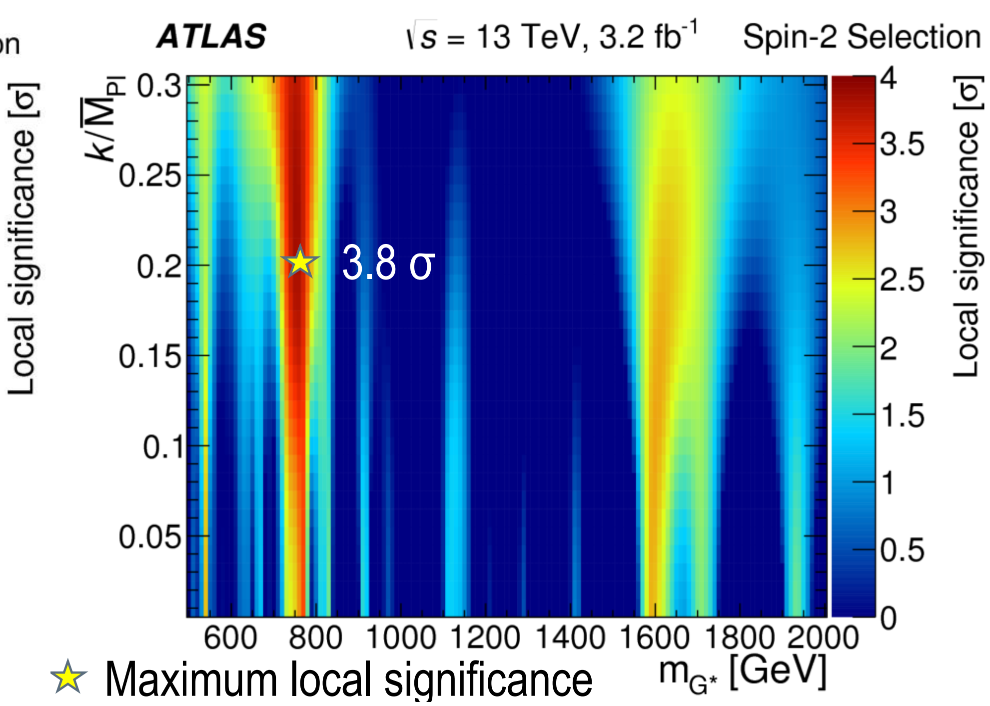
CMS:
local *p*-value 2.8σ (2.9σ)
spin 0 (2) hypothesis.
global *p*-value < 1σ





ATLAS:
local *p*-value 3.89 (3.8σ)
spin 0 (2) hypothesis
global *p*-value < 2.1σ
both spin hypothesis

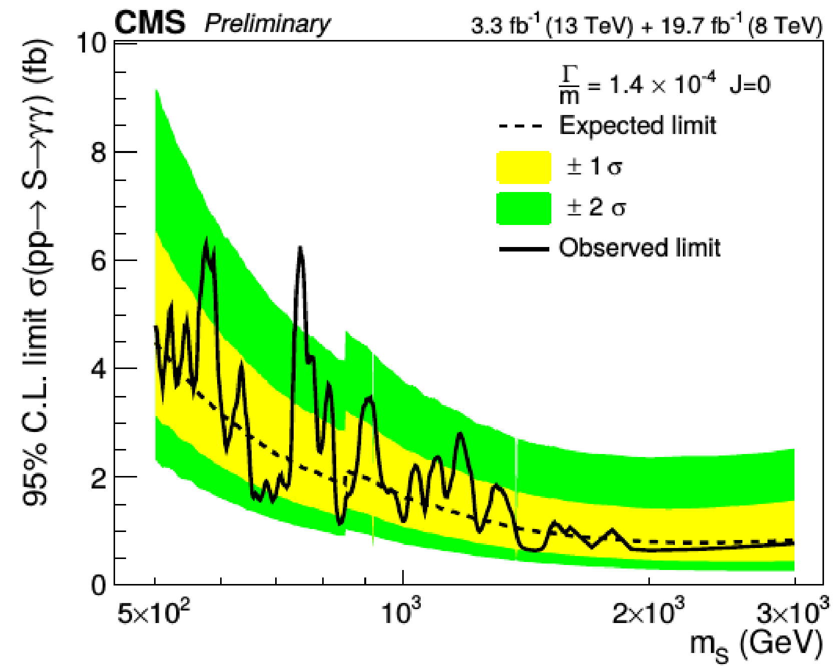


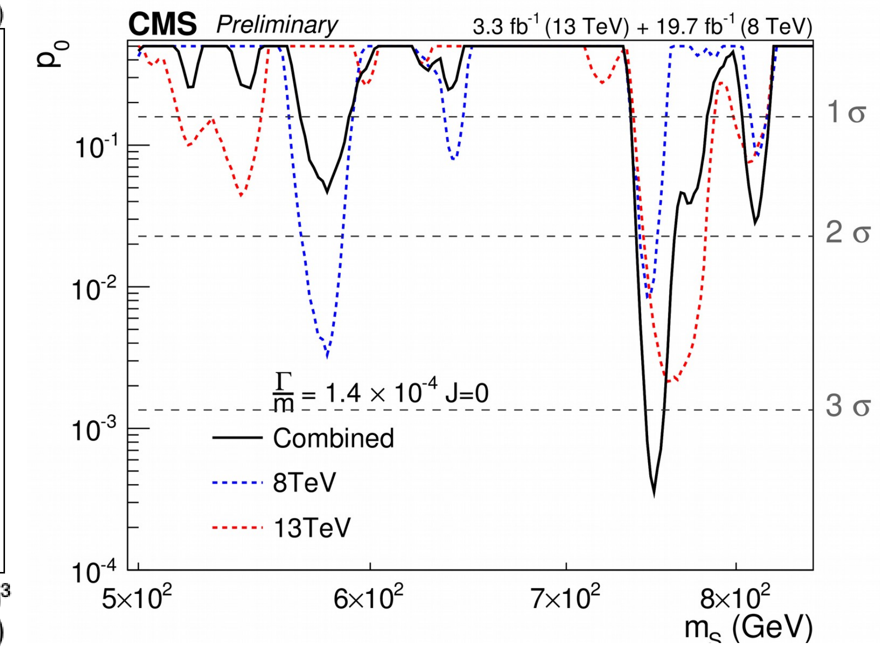


Combined 8 + 13 TeV

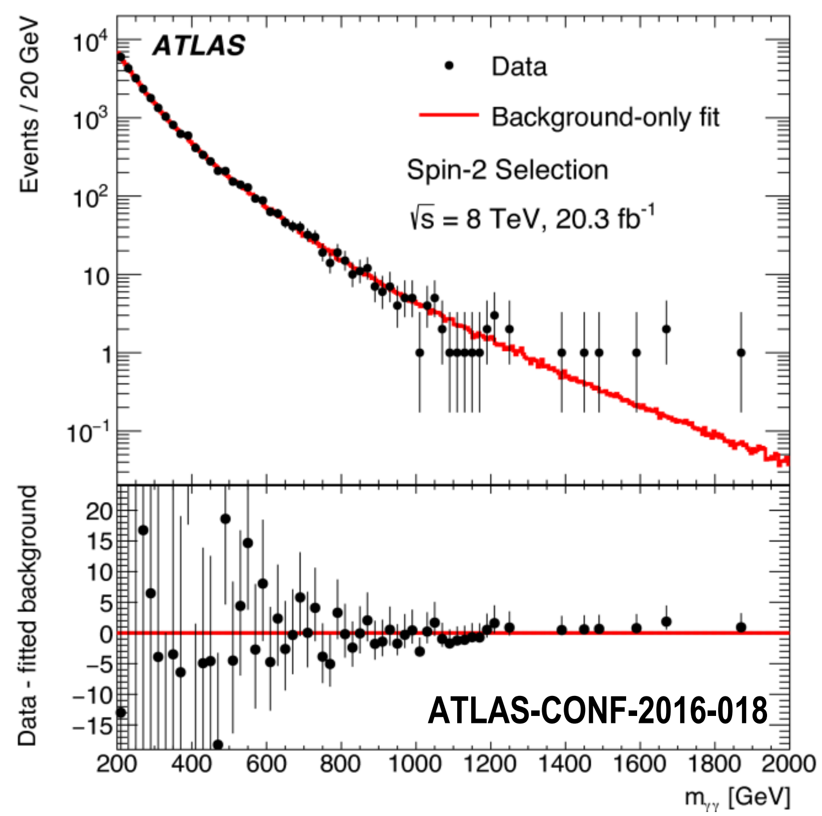
(combined cross sections using Pythia ggF 8TeV/13TeV 0.22 @ 750GeV)

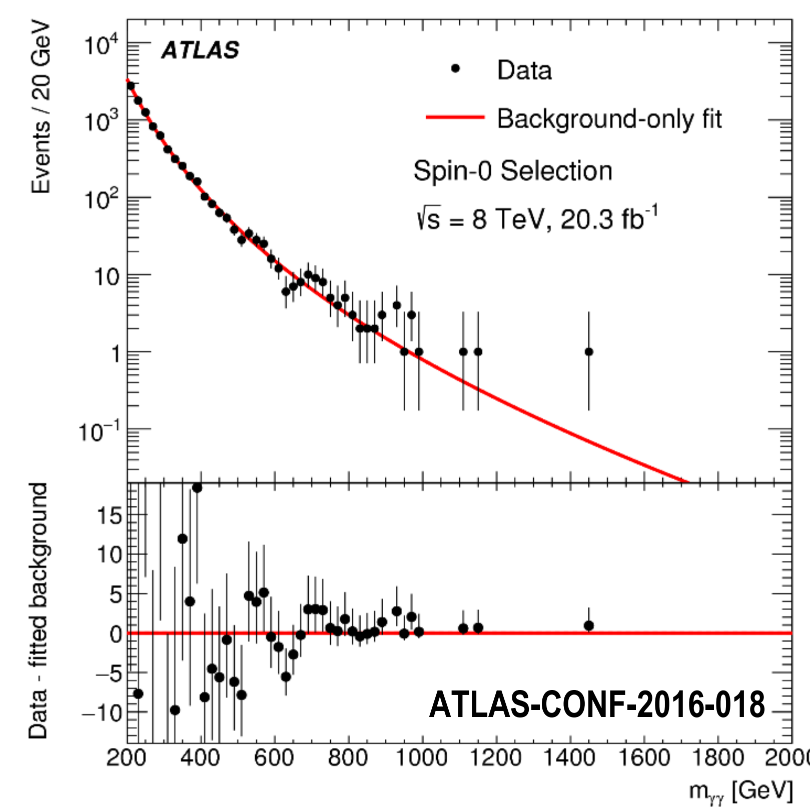
CMS
local p-value: 3.4σ
global p-value: 1.6σ
m∈[500, 3500] GeV,
all signal hypotheses





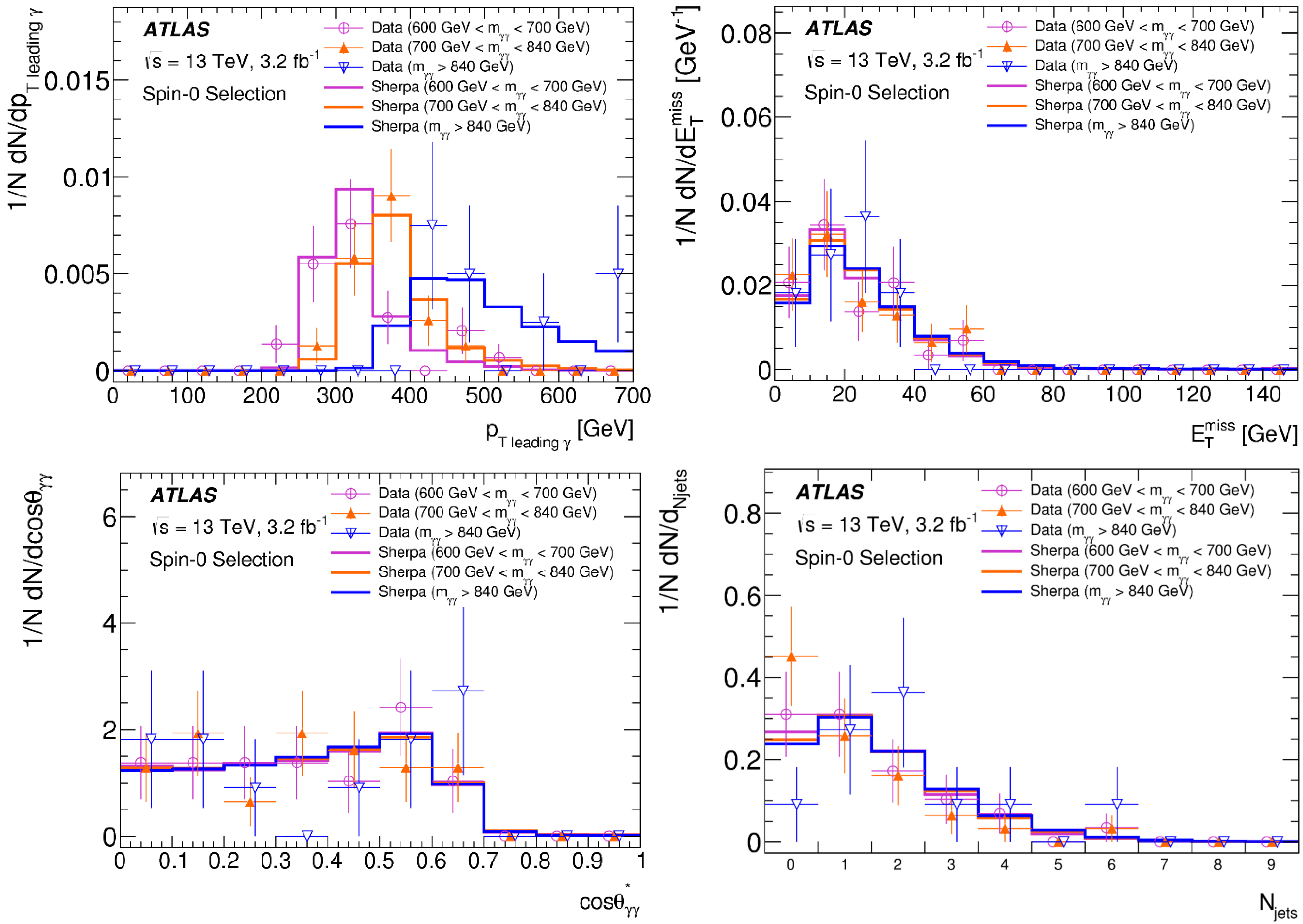
ATLAS:
local p-values:
spin 0 : ~2 σ
spin 2 : no excess





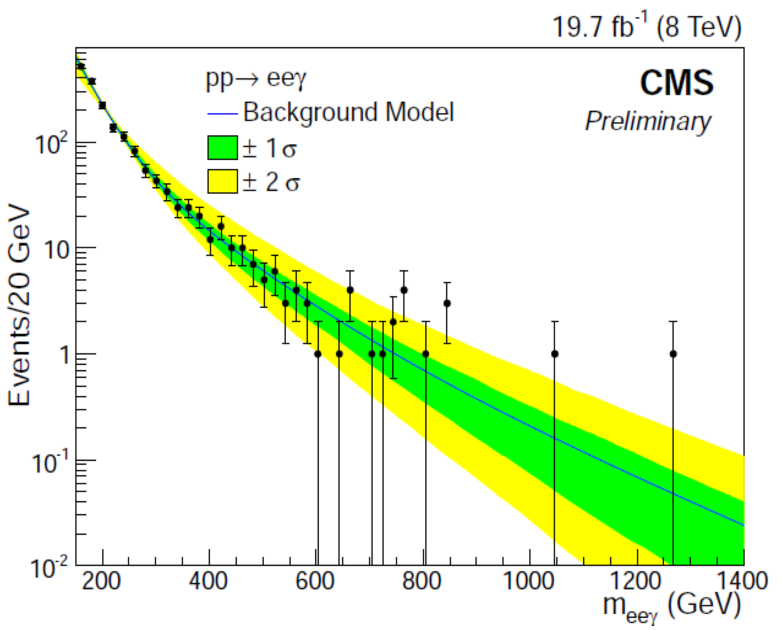
Compatibility Run 1/ Run 2
Spin 2 : ggF: 2.7 σ, qq 3.3 σ
Spin 0 : ggF: 1.2 σ, qq 2.1 σ

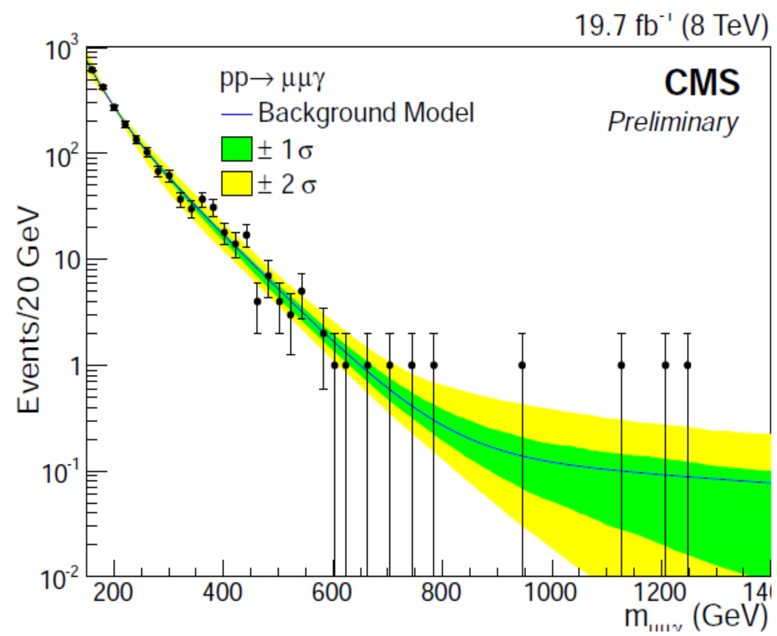
Sideband comparisons

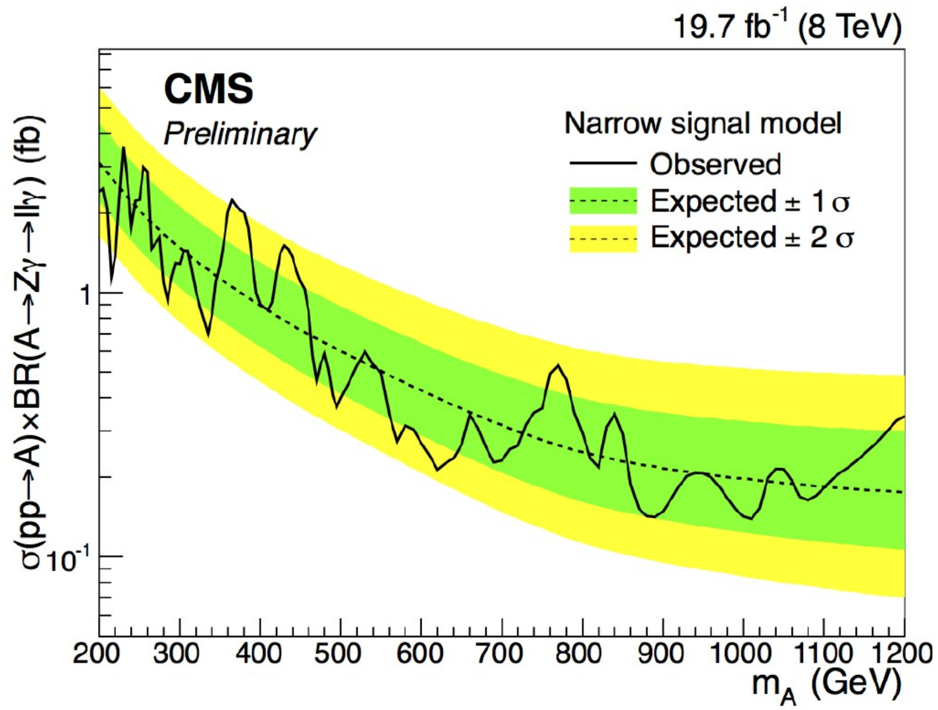


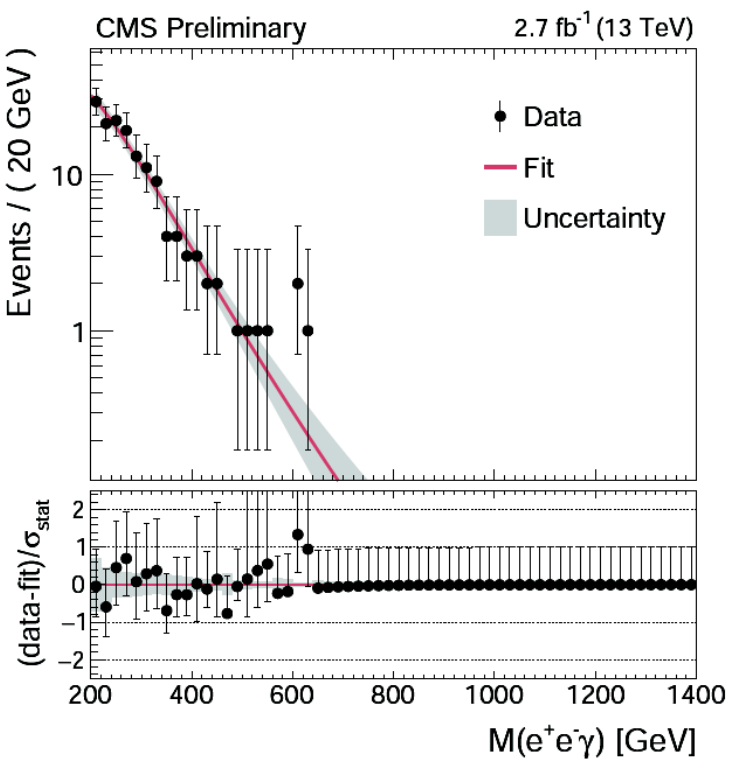
No pattern is observed

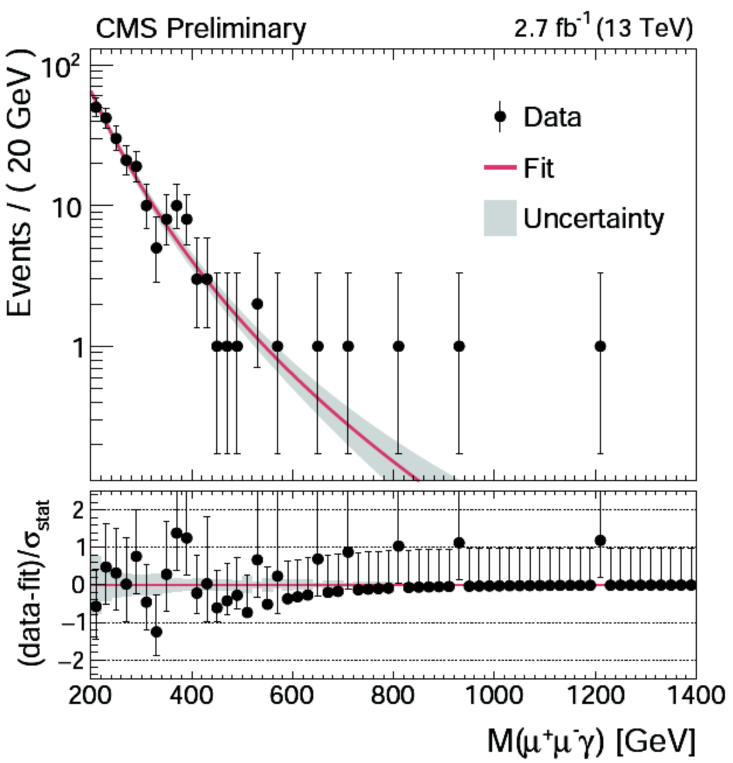
Spin off analysis Zγ

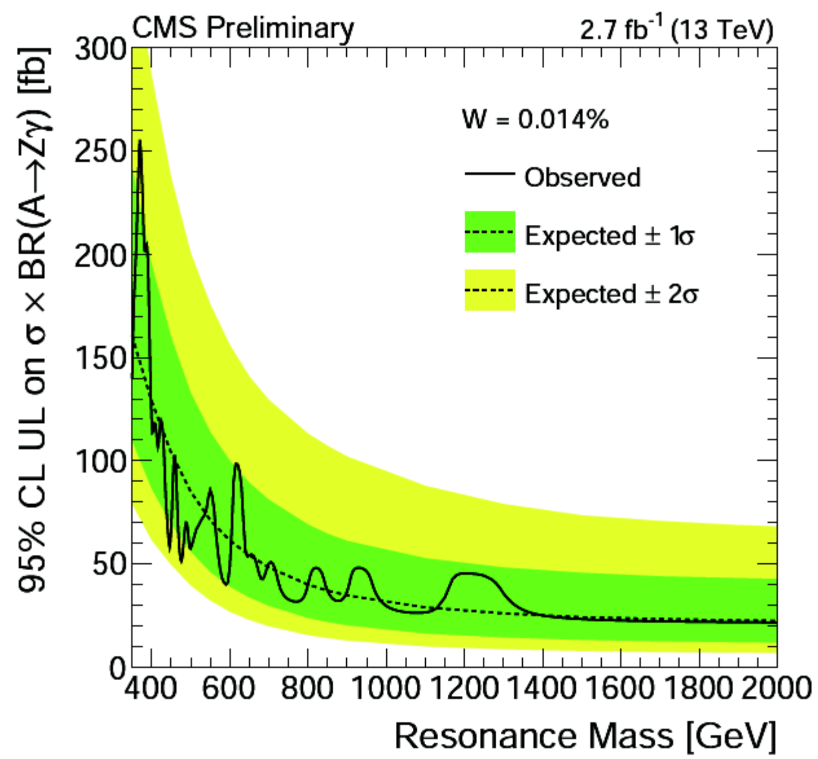












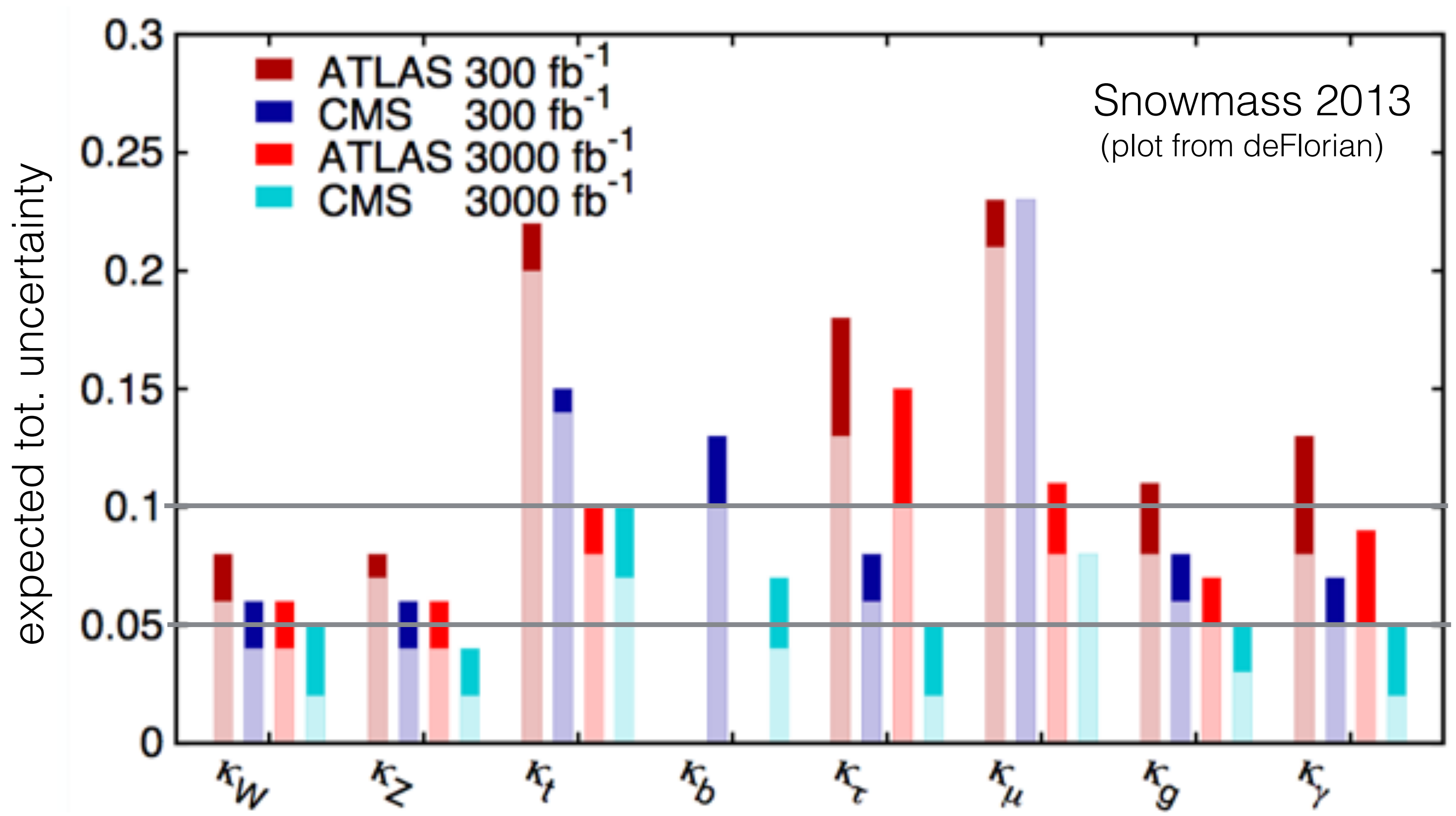
No excess observed. Combination ongoing

Projections

SM Higgs couplings

Two scenarios considered:

- systematic unc. as Run1/sqrt(N) and theory/2
- systematic unc. as in Run1



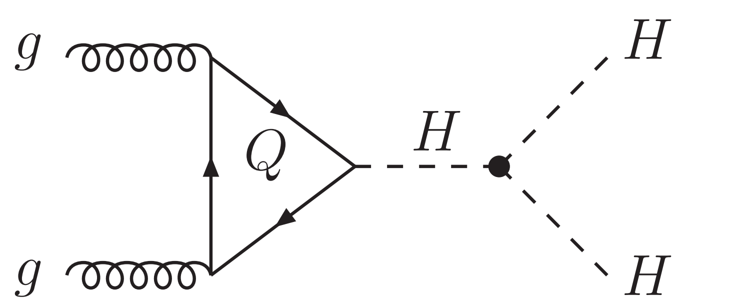
BR$_{BSM}$ Extrapolations (K_V<1):

L (fb^{-1})	BR_{SM}
300	[14, 18]
3000	[7, 11]

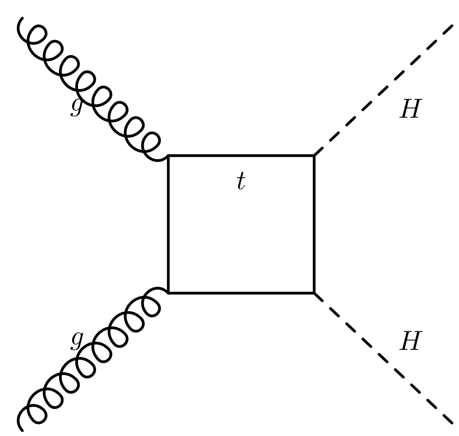
SM Higgs self-coupling

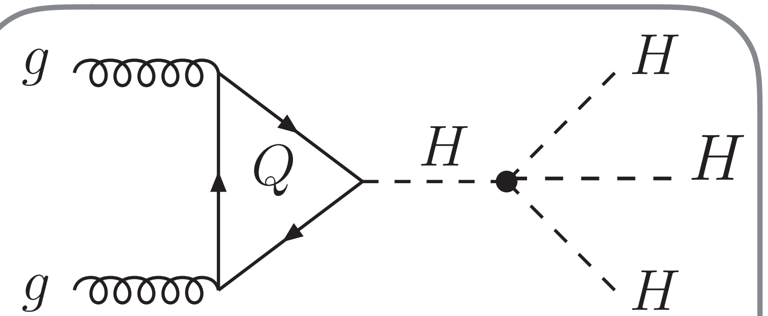
Reduced by 3 orders of magnitude every extra Higgs in the final state:

~50 pb single Higgs



~40 fb @14TeV





~0.05 fb @14TeV

Destructive interference btw trilinear and box.

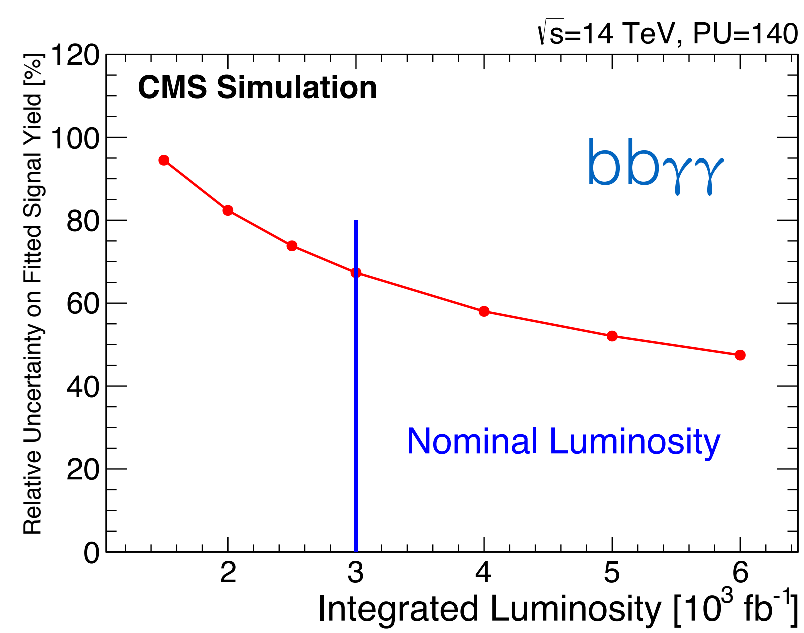
If trilinear coupling =0 cross section increases by 2.

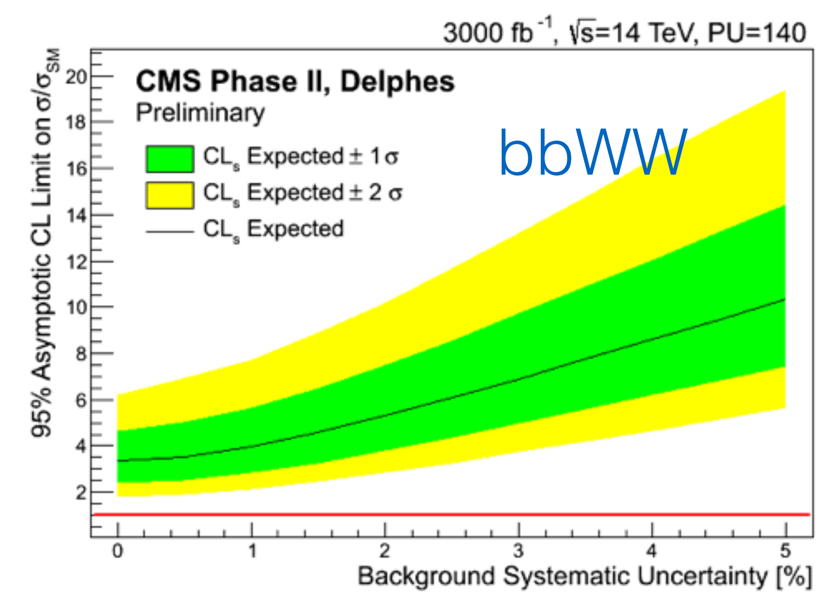
Expected N_{evts} for 3000/fb:

320 $bb\gamma\gamma$, 9000 $bb\tau\tau$, and 1500 bbWW(leptonic)

Expected significance for the HH :

- 0.5σ $bb\tau_\mu\tau_h$ and 0.7σ $bb\tau_h\tau_h$
- 1.9σ combining $bb\tau\tau$ and $bb\gamma\gamma$





data driven estimate on tt expected at 1%

Summary

ATLAS and CMS combined results allow to exploit the full LHC potential on Higgs Physics:

- $\sqrt{2}$ improvement on sensitivity from combination
- o(0.2%) mass precision $m_H = 125.09 \pm 0.24$ GeV
- o(10%) coupling precision $\mu = 1.09^{+0.11}_{-0.10}$ (most constrained model)
- In less constrained models couplings are also in agreement within SM predictions

First differential cross sections measurements were performed and found in agreement with SM prediction (within the large statistical uncertainty)

Searches for BSM Higgs are continuing on several fronts.
Important links with other HEP fields

Diphoton excess at 750 GeV could be confirmed for ICHEP:

- If still there: *It would be just amazing !!*
  - width / spin / differentials
  - associate production
  - correlated final states: $Z\gamma$, WW, tt, VV,

References

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

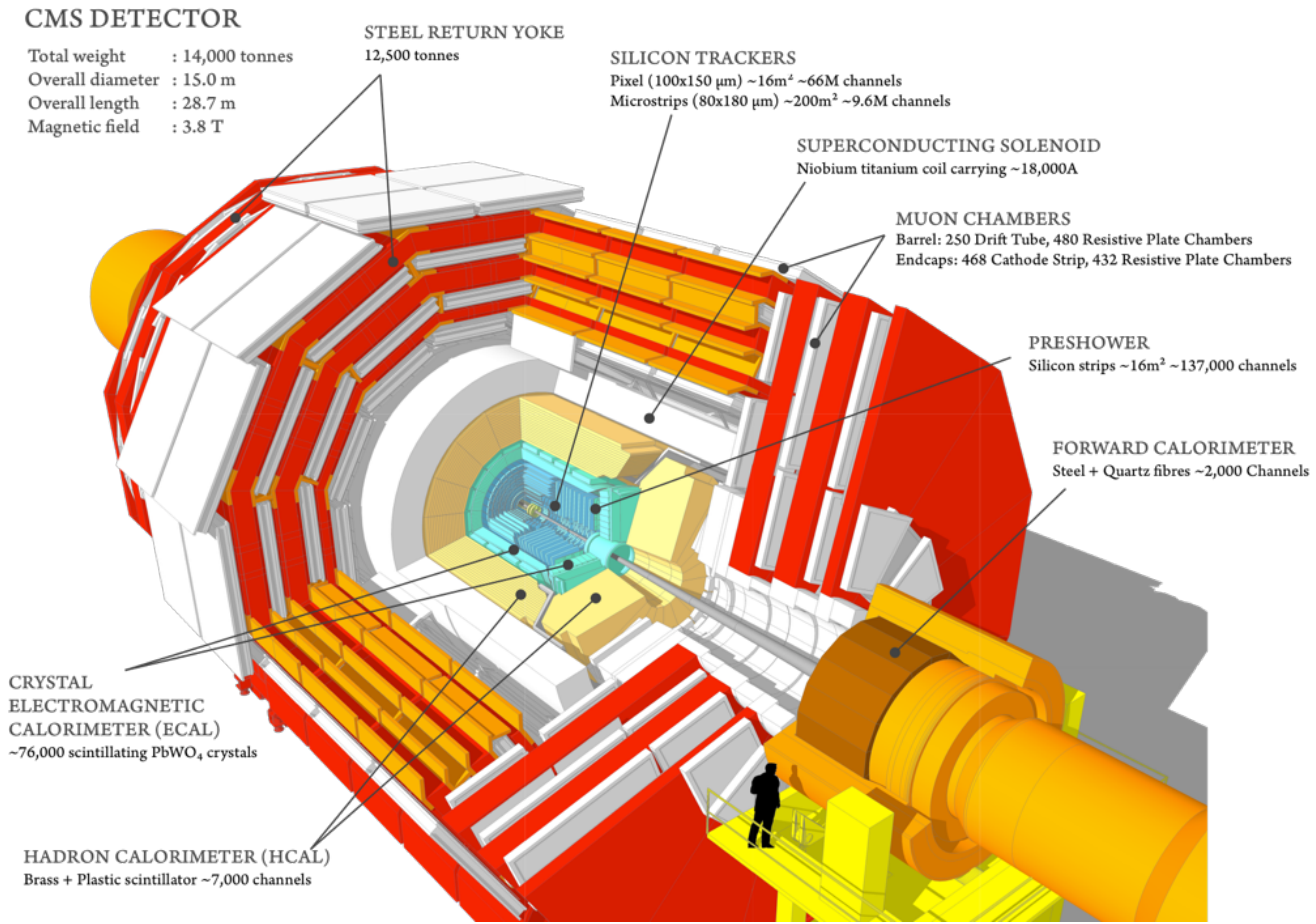
- ATLAS/CMS Combination:
- https://cds.cern.ch/record/2053103 (ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002)
- http://arxiv.org/abs/1503.07589 (Phys. Rev. Lett. 114, 191803 (2015))

- Differentials CMS:
- http://arxiv.org/abs/1508.07819 (Hgg - EPJC 76 (2016) 13)
- http://arxiv.org/abs/1512.08377 (HZZ - JHEP 04 (2016) 005)
- https://cds.cern.ch/record/2116452 (HWW - HIG-15-010)

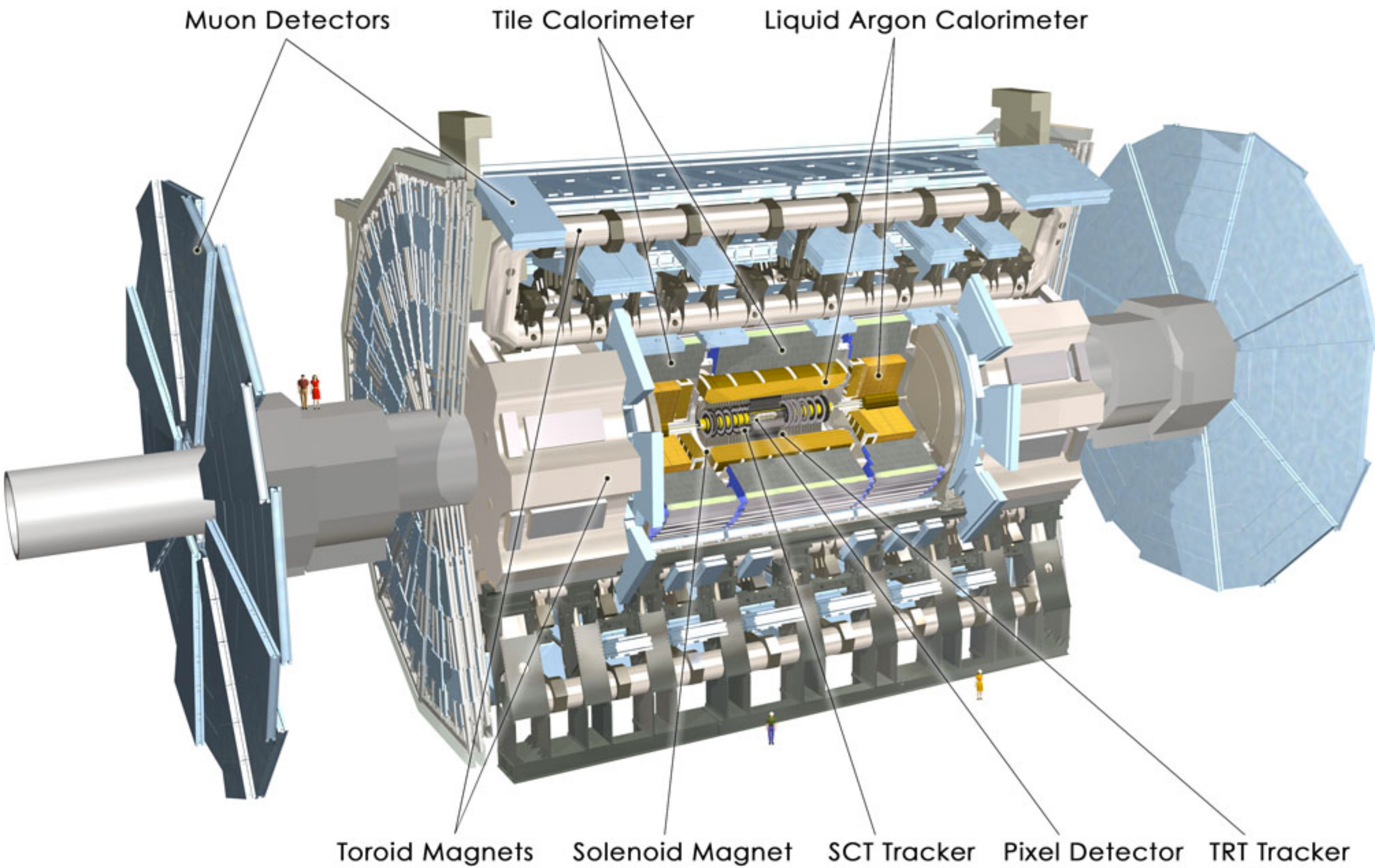
- Differentials ATLAS:
- http://arxiv.org/abs/1407.4222 (Hgg - JHEP09(2014)112)
- http://arxiv.org/abs/1408.3226 (HZZ - Physics Letters B 738 (2014) 234-253)
- http://arxiv.org/abs/1504.05833 (combined Hgg HZZ - Phys. Rev. Lett. 115 (2015) 091801)
- http://arxiv.org/abs/1604.02997 (HWW - HIGG-2015-04 - submitted JHEP)

Projections: Snowmass 2013 / 2nd ECFA workshop:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

More material


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

ATLAS


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

Loops

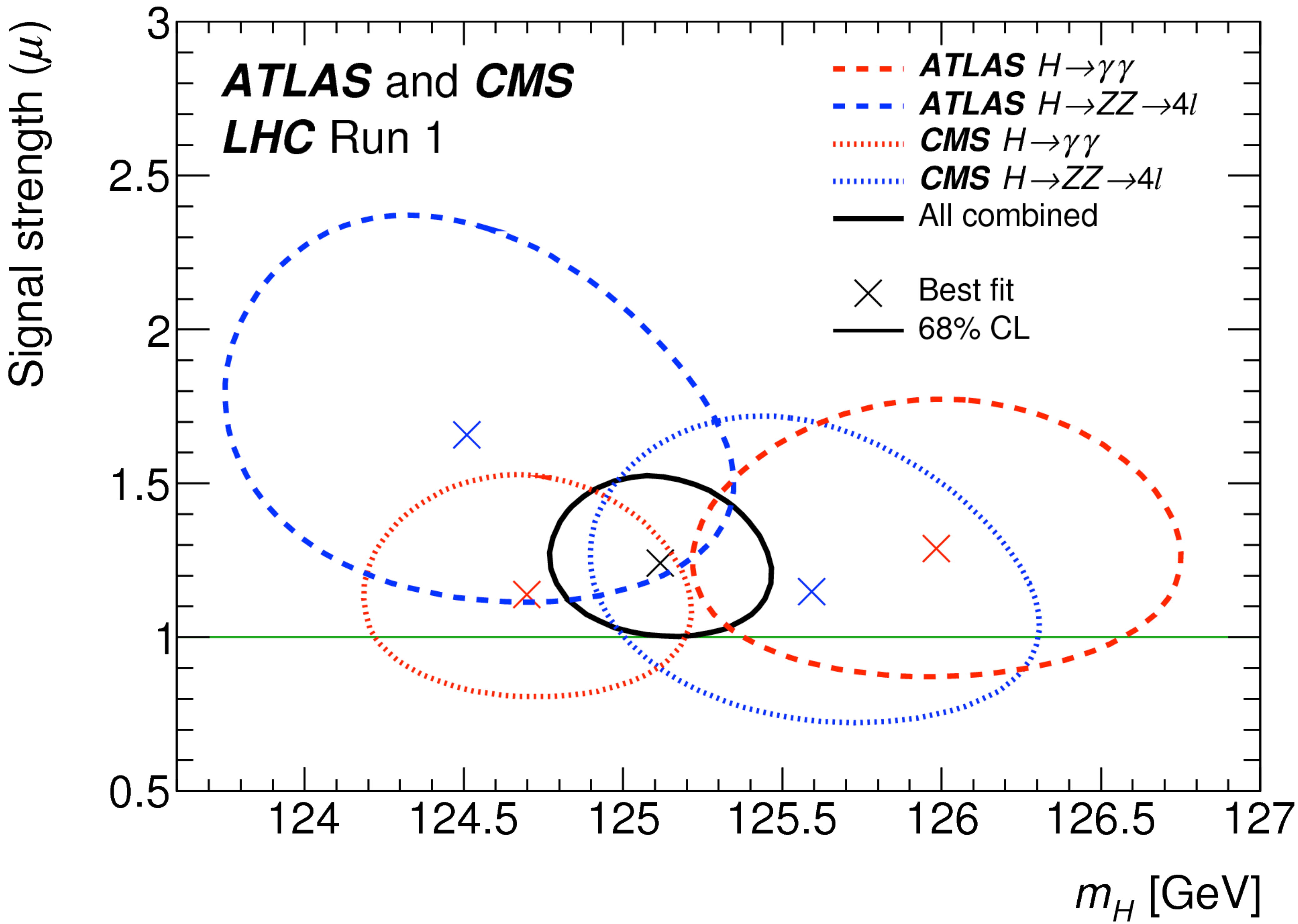
Production	Loops	Interference	Multiplicative factor
$\sigma(\mathrm{ggF})$	✓	$b-t$	$\kappa_\mathrm{g}^2 \sim 1.06\cdot\kappa_\mathrm{t}^2 + 0.01\cdot\kappa_\mathrm{b}^2 - 0.07\cdot\kappa_\mathrm{t}\kappa_\mathrm{b}$
$\sigma(\mathrm{VBF})$	–	–	$\sim 0.74\cdot\kappa_\mathrm{W}^2 + 0.26\cdot\kappa_\mathrm{Z}^2$
$\sigma(WH)$	–	–	$\sim \kappa_\mathrm{W}^2$
$\sigma(q\bar{q}\to ZH)$	–	–	$\sim \kappa_\mathrm{Z}^2$
$\sigma(gg\to ZH)$	✓	$Z-t$	$\sim 2.27\cdot\kappa_\mathrm{Z}^2 + 0.37\cdot\kappa_\mathrm{t}^2 - 1.64\cdot\kappa_\mathrm{Z}\kappa_\mathrm{t}$
$\sigma(bbH)$	–	–	$\sim \kappa_\mathrm{b}^2$
$\sigma(ttH)$	–	–	$\sim \kappa_\mathrm{t}^2$
$\sigma(gb\to WtH)$	–	$W-t$	$\sim 1.84\cdot\kappa_\mathrm{t}^2 + 1.57\cdot\kappa_\mathrm{W}^2 - 2.41\cdot\kappa_\mathrm{t}\kappa_\mathrm{W}$
$\sigma(qb\to tHq')$	–	$W-t$	$\sim 3.4\cdot\kappa_\mathrm{t}^2 + 3.56\cdot\kappa_\mathrm{W}^2 - 5.96\cdot\kappa_\mathrm{t}\kappa_\mathrm{W}$
Partial decay width			
$\Gamma_{b\bar{b}}$	–	–	$\sim \kappa_\mathrm{b}^2$
Γ_{WW}	–	–	$\sim \kappa_\mathrm{W}^2$
Γ_{ZZ}	–	–	$\sim \kappa_\mathrm{Z}^2$
$\Gamma_{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59\cdot\kappa_\mathrm{W}^2 + 0.07\cdot\kappa_\mathrm{t}^2 - 0.66\cdot\kappa_\mathrm{W}\kappa_\mathrm{t}$
Total width for $\mathrm{BR}_\mathrm{BSM}=0$			
Γ_H	✓	–	$\kappa_\mathrm{H}^2 \sim 0.57\cdot\kappa_\mathrm{b}^2 + 0.22\cdot\kappa_\mathrm{W}^2 + 0.09\cdot\kappa_\mathrm{g}^2 + 0.06\cdot\kappa_\tau^2 + 0.03\cdot\kappa_\mathrm{Z}^2 + 0.03\cdot\kappa_\mathrm{c}^2 + 0.0023\cdot\kappa_\gamma^2 + 0.0016\cdot\kappa_{\mathrm{Z}\gamma}^2 + 0.0001\cdot\kappa_\mathrm{s}^2 + 0.00022\cdot\kappa_\mu^2$

Computed for 8 TeV at m_H=125.09 GeV

Input analyses

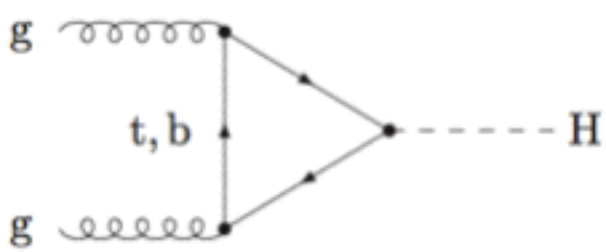
Channel	Signal strength [μ]		Signal significance [σ]	
	from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	5.0	5.6
	$\left(^{+0.26}_{-0.24}\right)$	$\left(^{+0.24}_{-0.22}\right)$	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
	$\left(^{+0.33}_{-0.27}\right)$	$\left(^{+0.31}_{-0.26}\right)$	(5.5)	(6.8)
$H \to WW$	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
	$\left(^{+0.21}_{-0.20}\right)$	$\left(^{+0.23}_{-0.20}\right)$	(5.8)	(5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
	$\left(^{+0.37}_{-0.33}\right)$	$\left(^{+0.31}_{-0.29}\right)$	(3.3)	(3.7)
$H \to bb$	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
	$\left(^{+0.39}_{-0.37}\right)$	$\left(^{+0.45}_{-0.43}\right)$	(2.7)	(2.5)
$H \to \mu\mu$	-0.7 ± 3.6	0.8 ± 3.5		
	(± 3.6)	(± 3.5)		
ttH production	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
	$\left(^{+0.72}_{-0.66}\right)$	$\left(^{+0.88}_{-0.80}\right)$	(1.6)	(1.3)

μ vs. mass

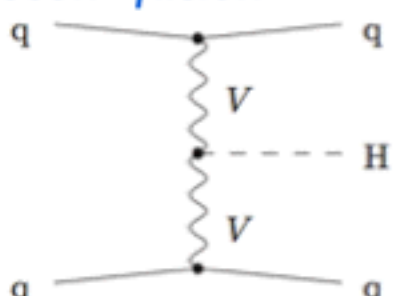

ATLAS and CMS
LHC Run 1
ATLAS H→γγ
ATLAS H→ZZ→4l
CMS H→γγ
CMS H→ZZ→4l
All combined
Best fit
68% CL
Signal strength (μ)
3
2.5
2
1.5
1
0.5
124
124.5
125
125.5
126
126.5
127
m_H [GeV]

Main production processes

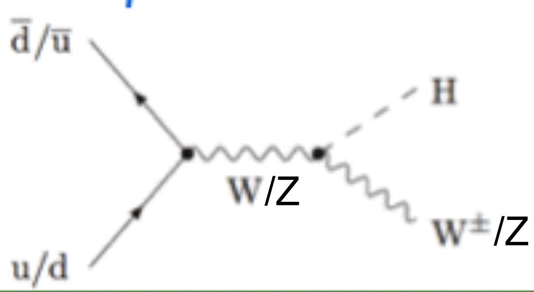
gluon fusion



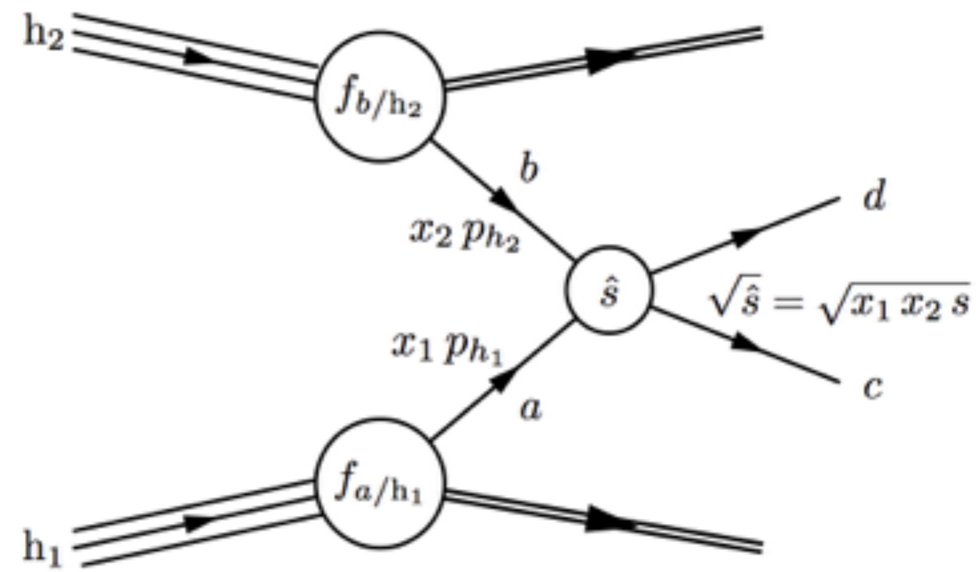
vector boson fusion



associated production



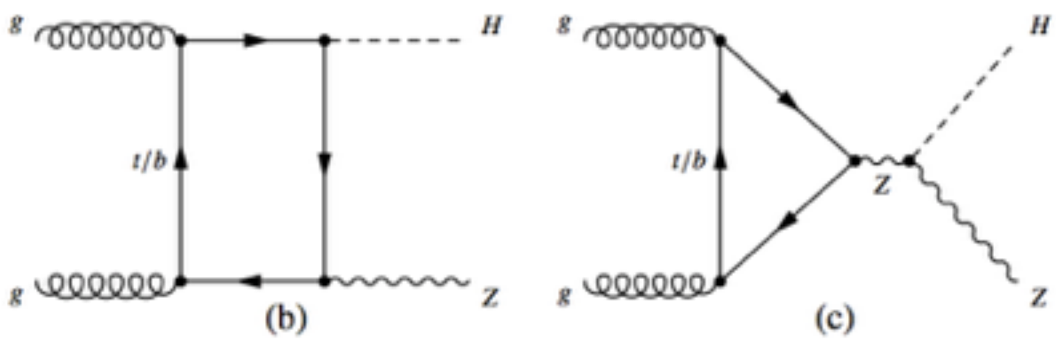
tt̄H



$$d\sigma(h_1 h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) d\hat{\sigma}^{ab\to cd}(Q^2)$$

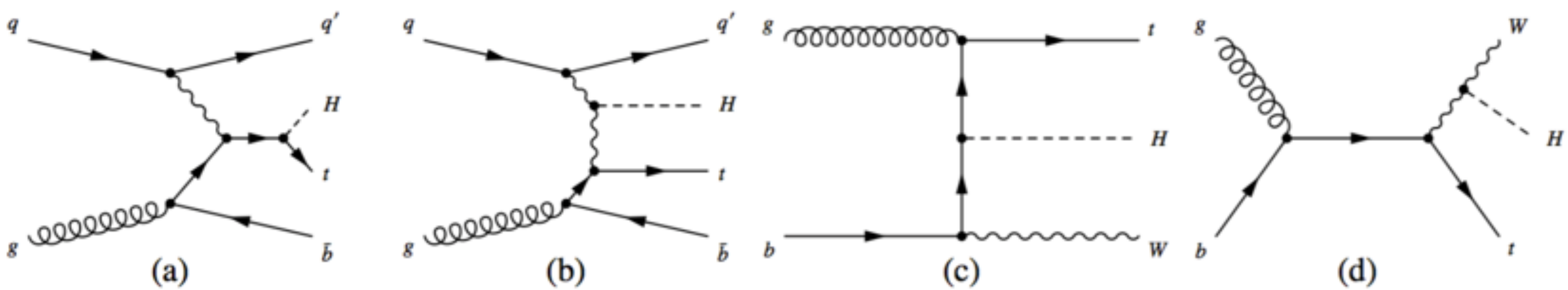
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+APP.NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.357 ± 0.015	0.446 ± 0.019	NNLO(QCD)+NLO(EW)
ZH: $gg \to ZH$			LO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

Main production processes

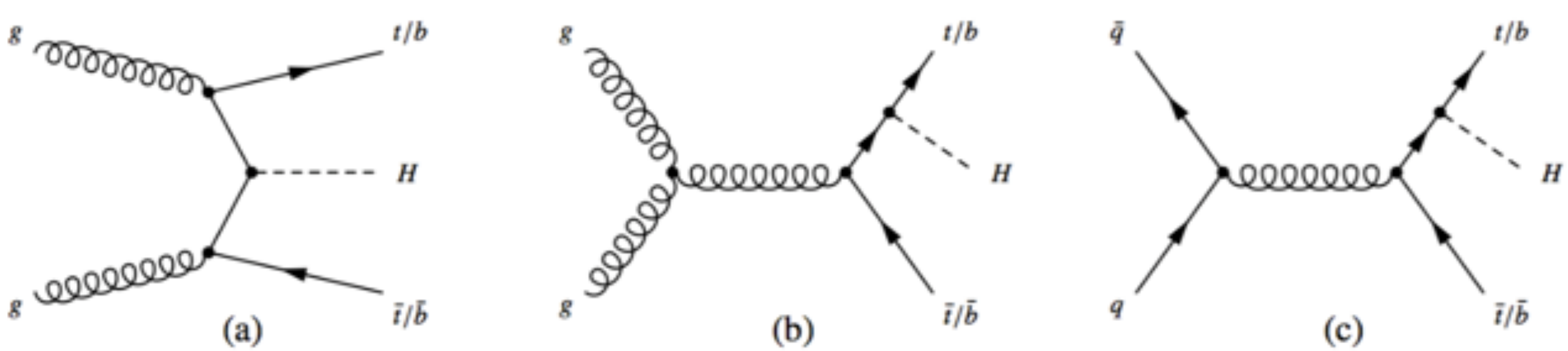


ggZH: O(10%) effect on VHbb in SM, higher p_T than VH

tHq+tHW possible large effect if negative couplings

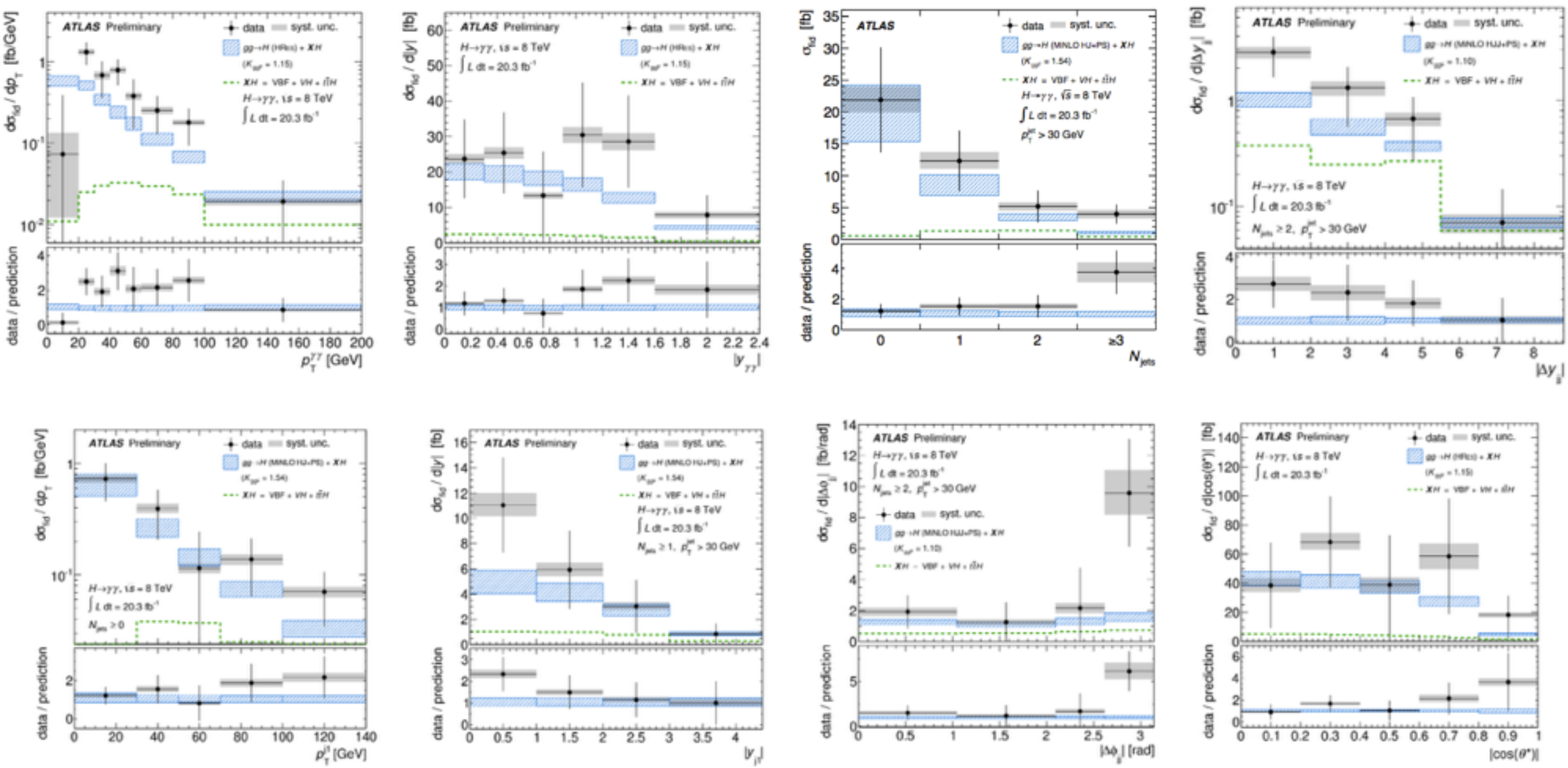


bbH (counter part of ttH) included in ggF



Differential H$\longrightarrow\gamma\gamma$

$$\mathcal{L}(m_{\gamma\gamma}, \nu^{\rm sig}, \nu^{\rm bkg}, m_H) = \prod_i \left\{ \frac{e^{-\nu_i}}{n_i!} \prod_j^{n_i} \left[\nu_i^{\rm sig}\, \mathcal{S}_i(m_{\gamma\gamma}^j; m_H) + \nu_i^{\rm bkg}\, \mathcal{B}_i(m_{\gamma\gamma}^j) \right] \right\} \times \prod_k G_k$$



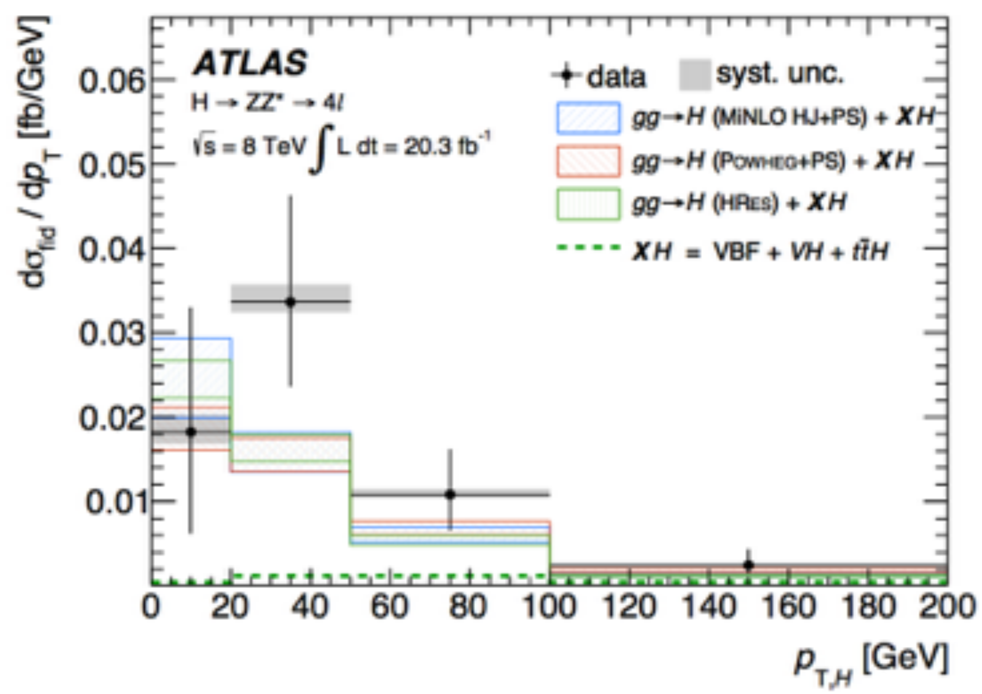
sensitive to CP

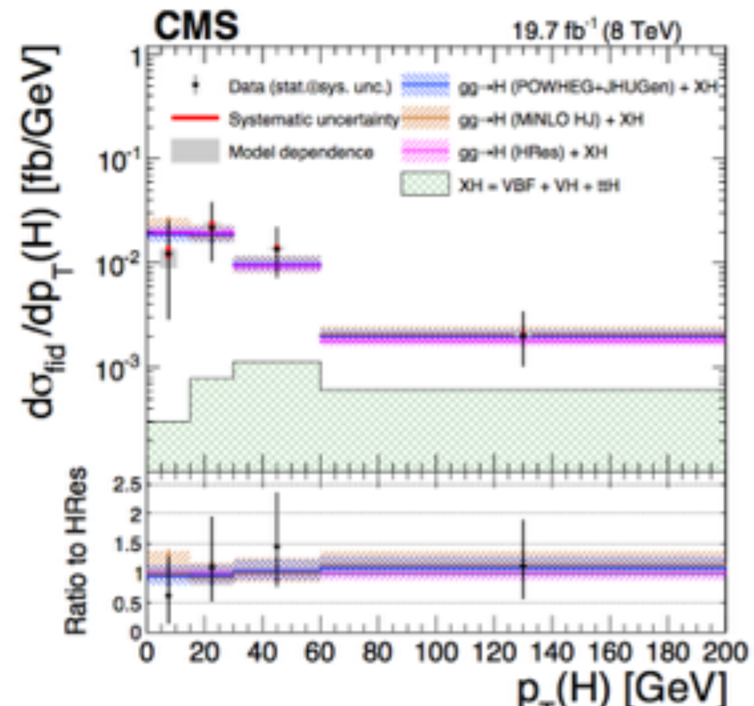
$$A_{\Delta\phi} = 0.72\,^{+0.23}_{-0.29}\,(\text{stat.})\,^{+0.01}_{-0.02}\,(\text{syst.})$$

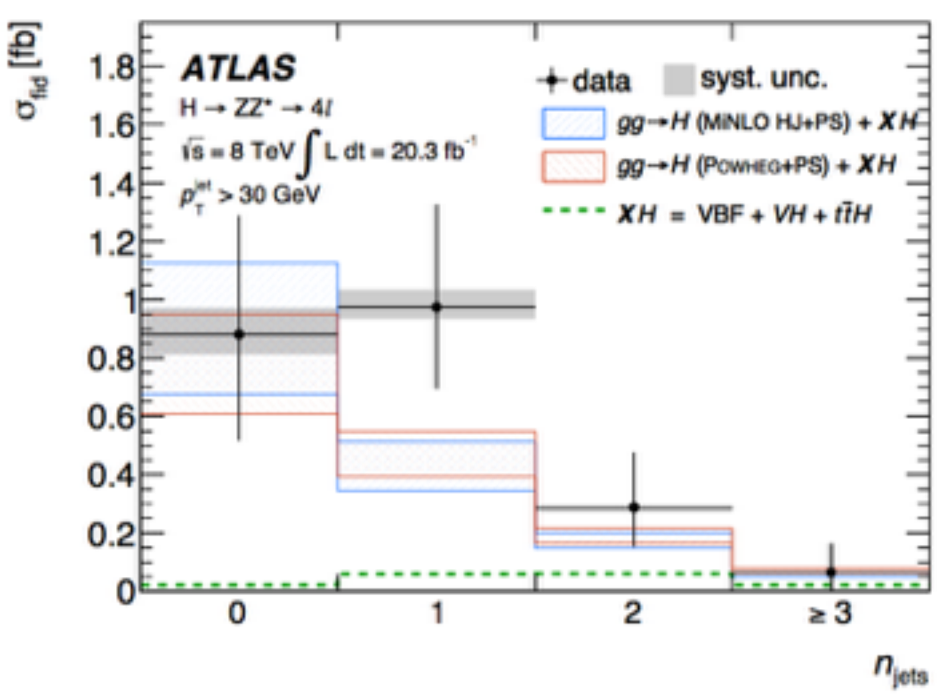
$$A^{\rm SM}_{\Delta\phi} = 0.43 \pm 0.02$$

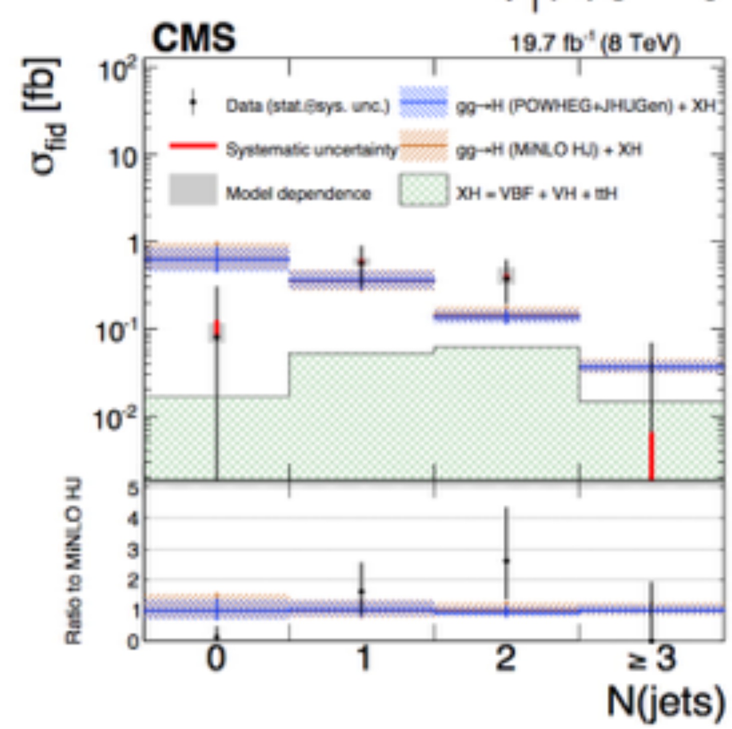
H→ZZ→4 leptons

Low background, high mass resolution, but low statistics









Compatible with SM predictions but very large statistical uncertainties

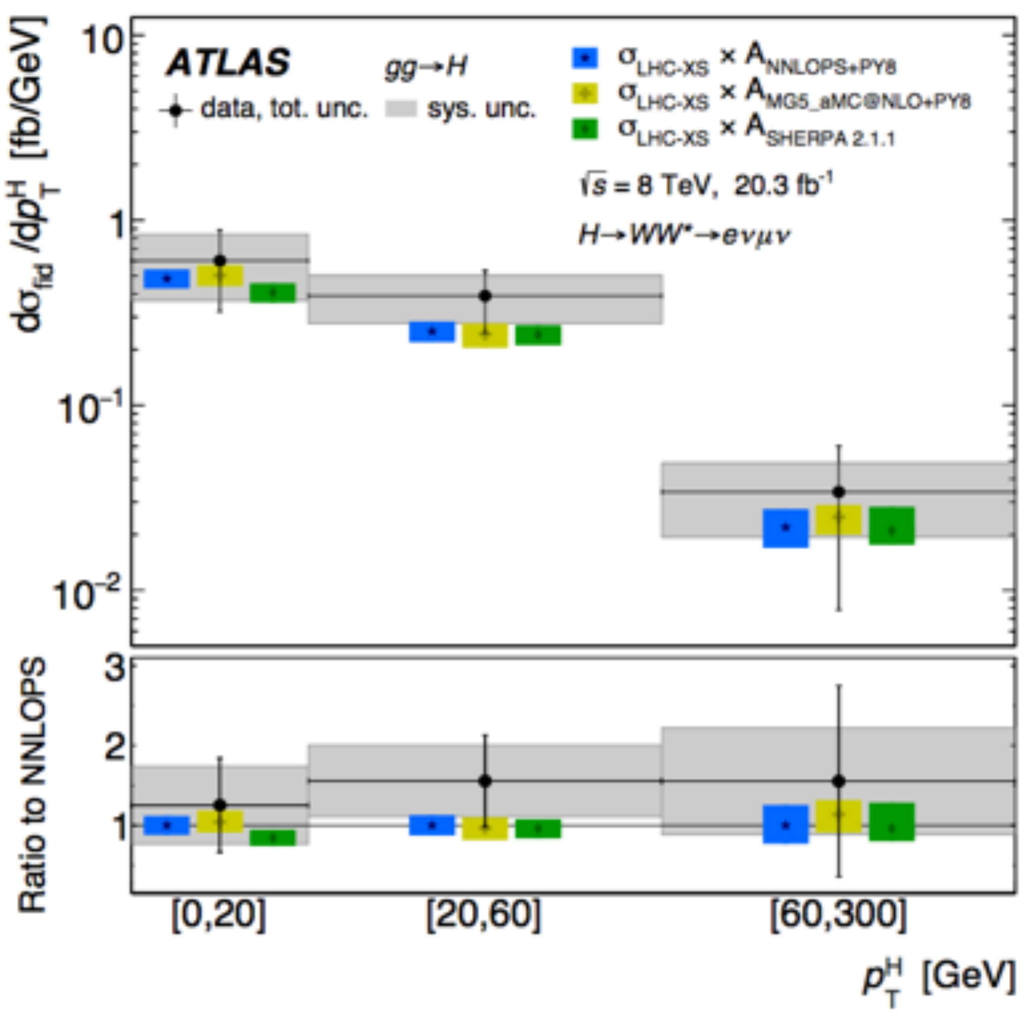
H→WW→ ℓν ℓ'ν'

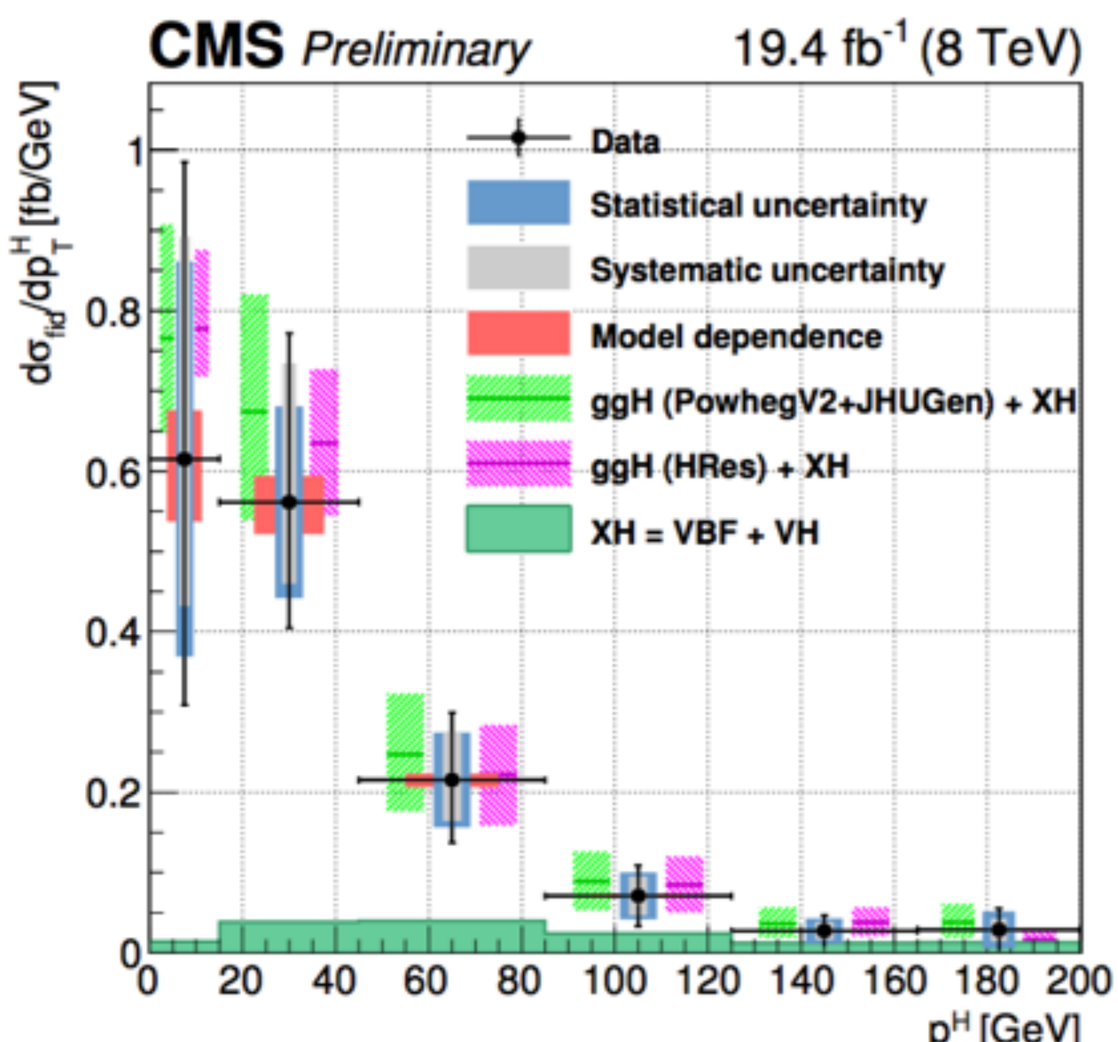
Different flavour and opposite charge. Large σxBR, but low mass (E_T^{miss}) resolution
⇒large off diagonal elements in the unfolding matrix
(ATLAS: iterative bayesian, CMS: Tikhonov regularization)

Fiducial cross sections:

ATLAS (ggF only) σ^{fid}= 36.0 ± 7.2 (stat.) ± 6.4 (syst.) ± 1.0 (lumi) fb
theory : 25.1 ± 2.6 fb

CMS σ_{fid} = 38 ± 8 (stat.) ± 9 (syst.) fb
theory : 48 ± 8 fb





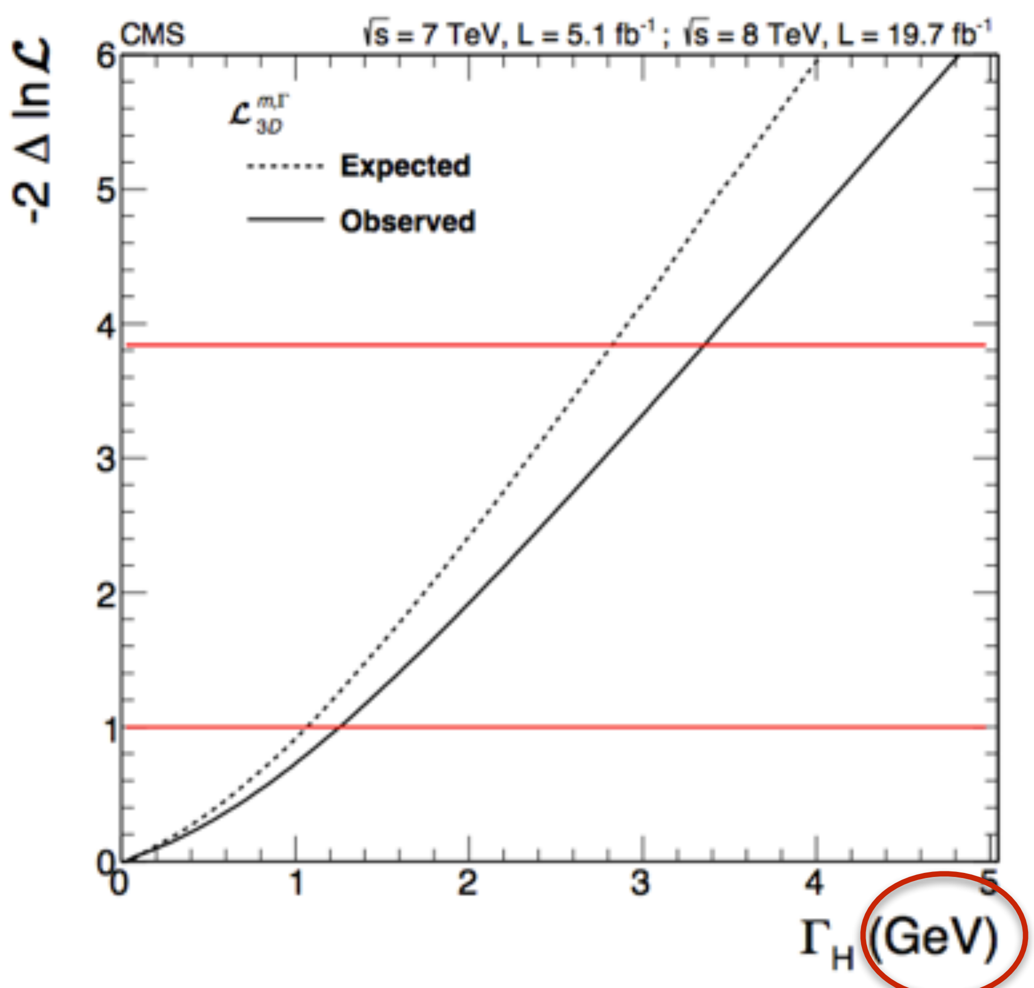
Direct measurement

SM width ~4 MeV

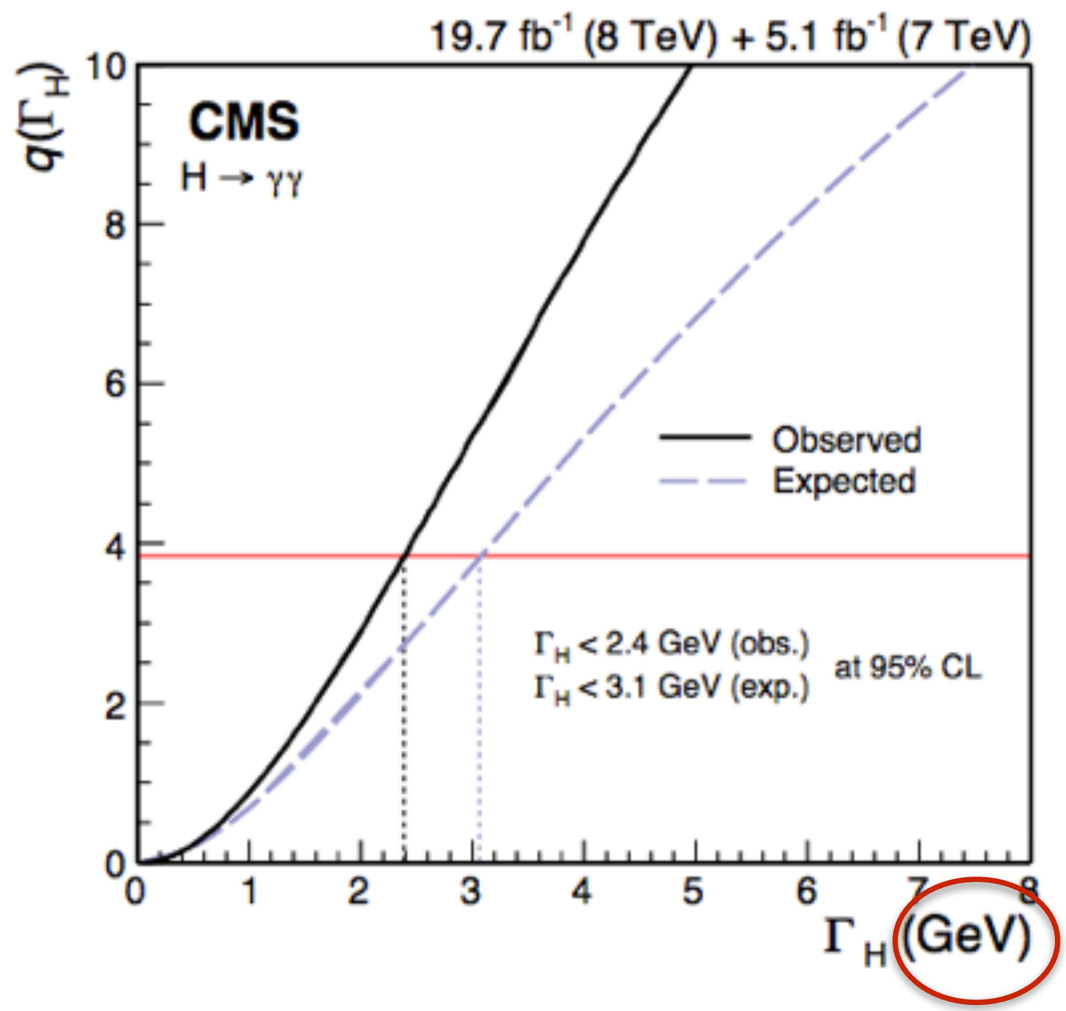
Strongly limited by the mass (energy/momentum) resolution of the detector

Scanning the $\gamma\gamma$, ZZ(3D) likelihood vs. the width parameter

$$\Gamma_H = 0.0^{+1.3}_{-0.0}\,\text{GeV},$$



Upper Limit 3.4 GeV
(exp 2.8 GeV)



off-shell ZZ production: method

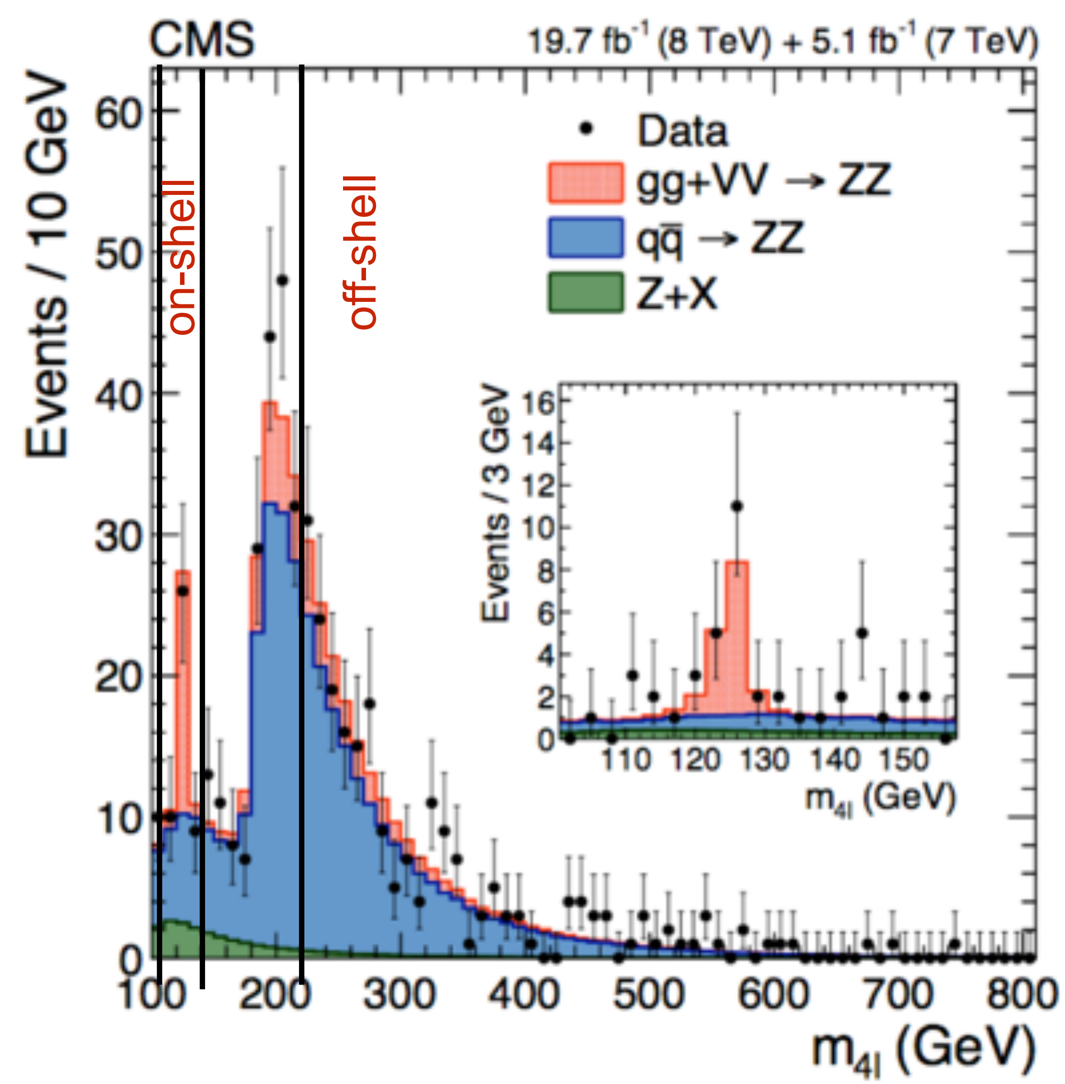
Caola-Melnikov arXiv:1307.4935

In general:

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

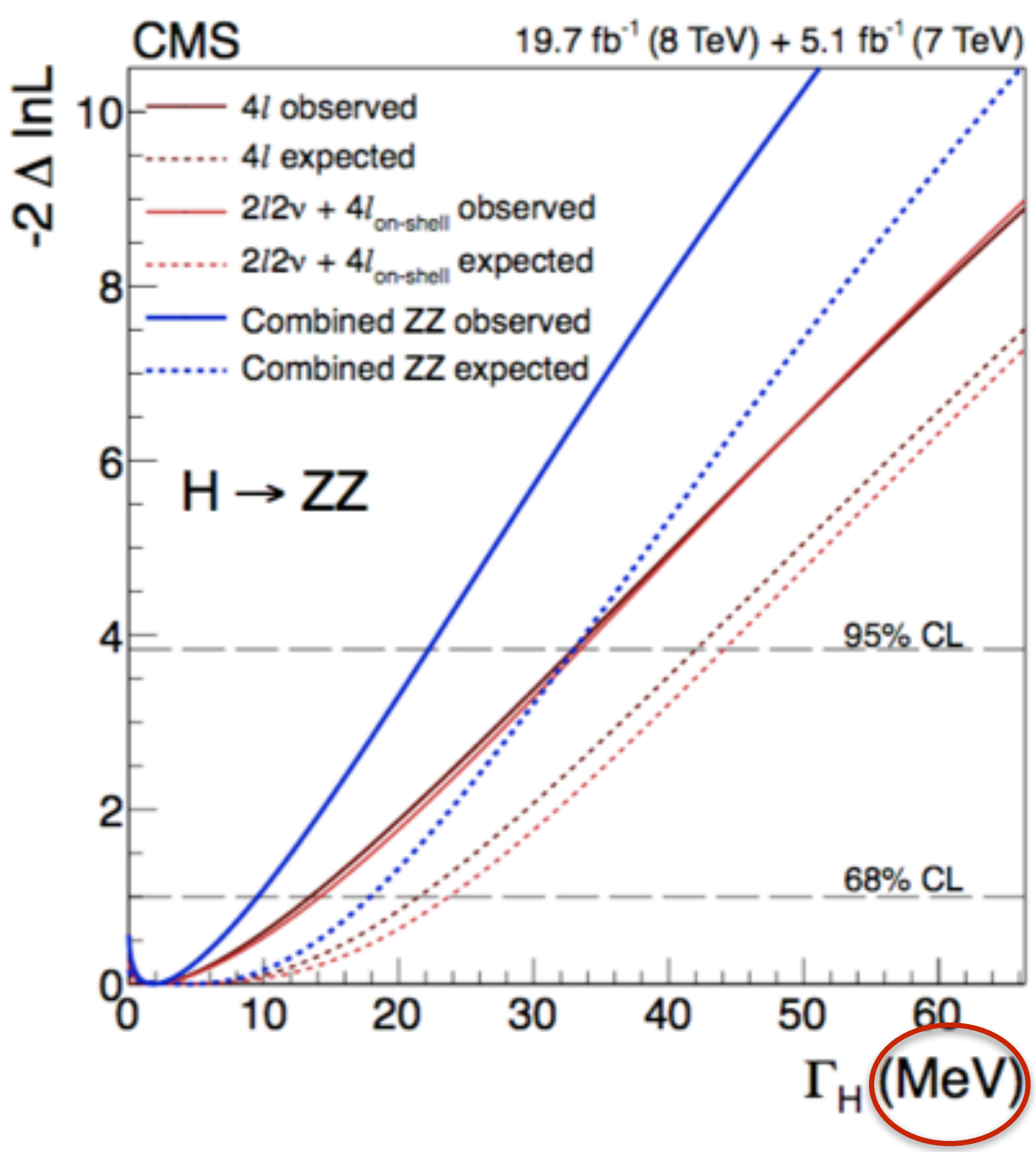
on peak $$\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

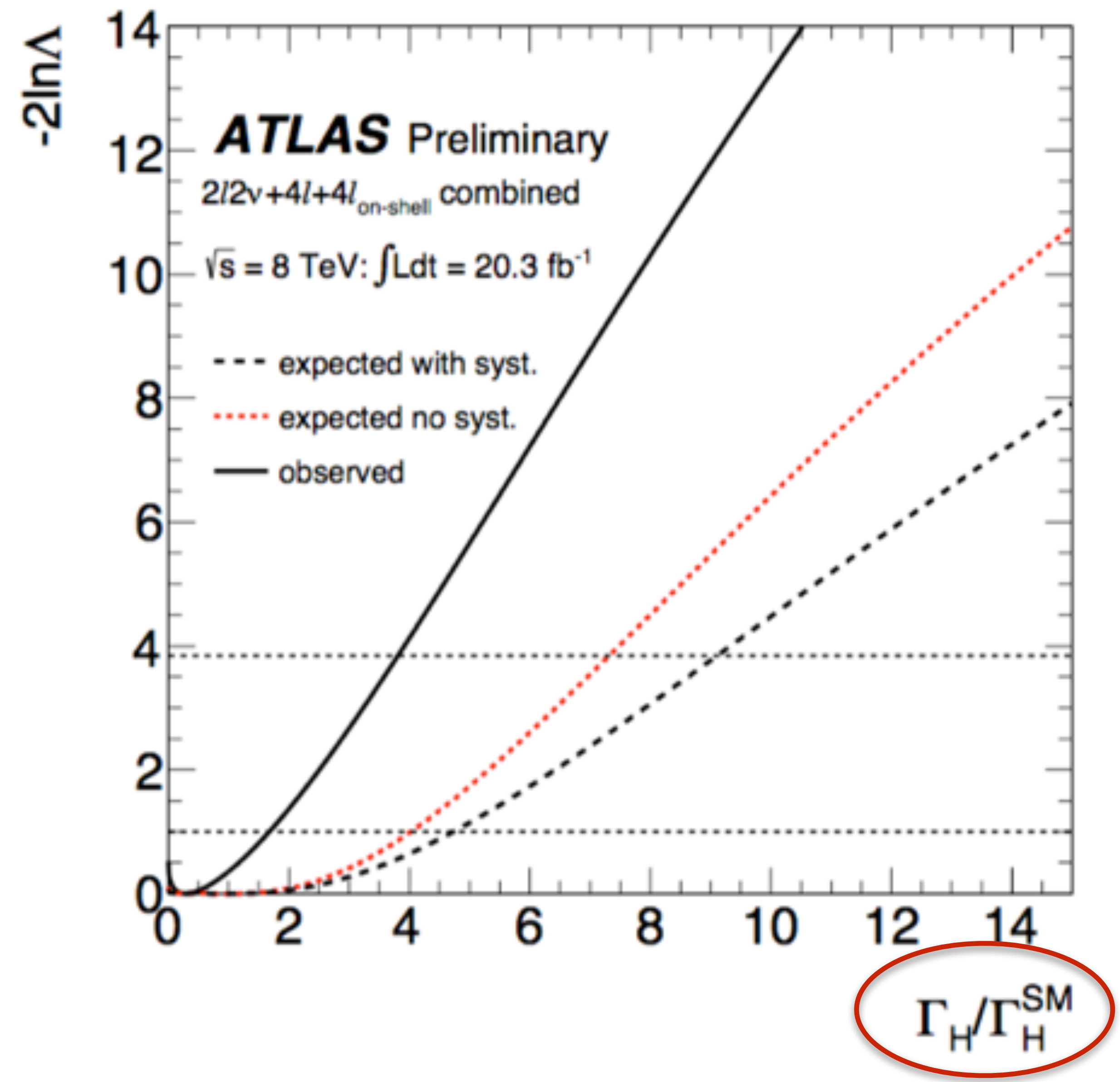
off peak $$\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{M_{4l}^2}$$



From the ratio of the two cross sections we can infer the width

off-shell ZZ production: results



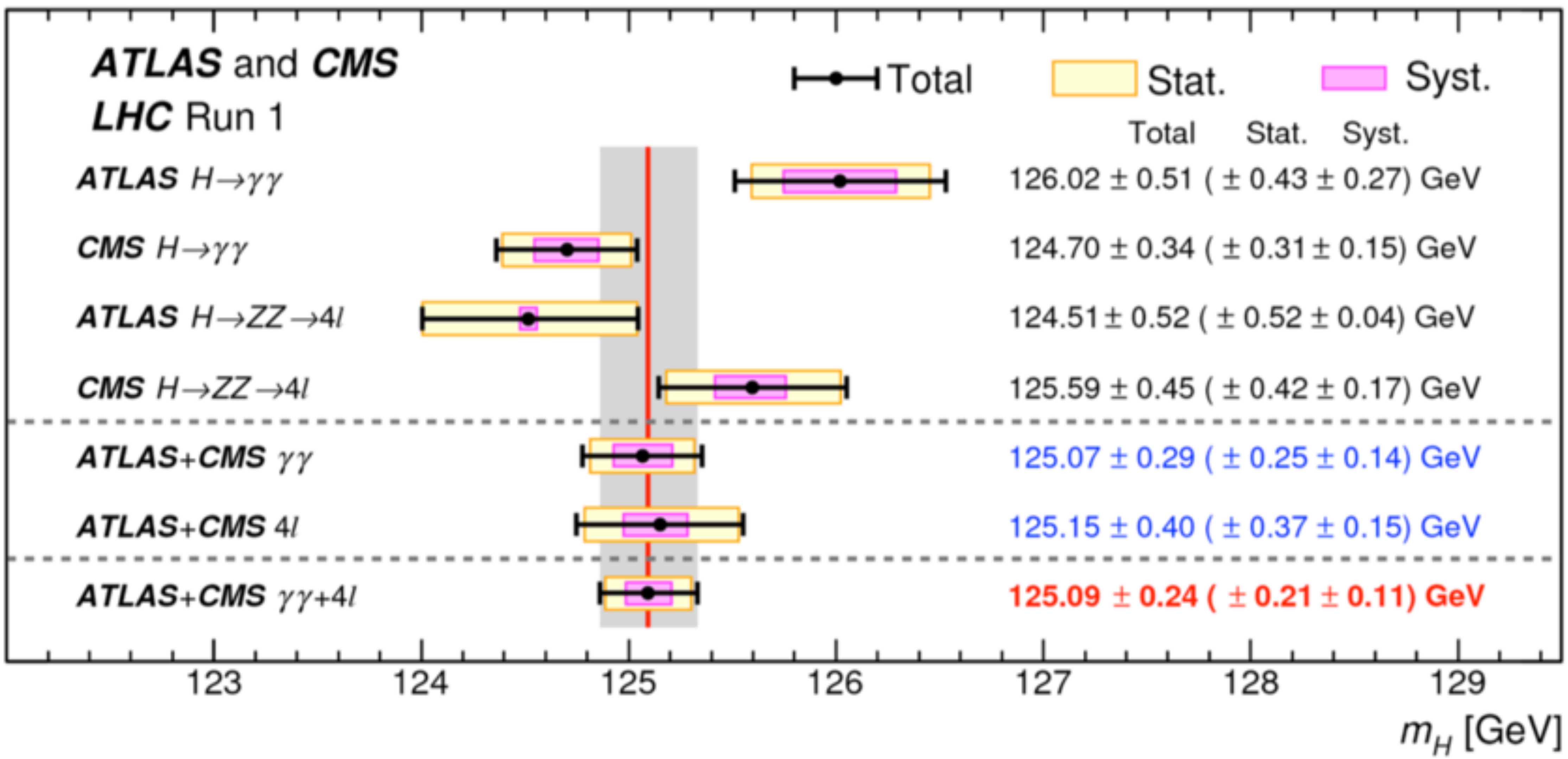


Mass measurement

The Higgs boson mass is the (non-predicted) parameter from which the whole phenomenology of the SM-Higgs sector is derived

High mass resolution channels: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4$ leptons

$M_H = 125.09 \pm 0.24$ GeV $= \pm 0.21$ (stat.) ± 0.11(syst.) GeV



Opposite trends in $H \rightarrow \gamma\gamma$ / $H \rightarrow ZZ$ in ATLAS / CMS: p-value~10%

H→γγ CMS

Source of uncertainty	Uncertainty in $\hat{m}_H$ (GeV)
Imperfect simulation of electron-photon differences	0.10
Linearity of the energy scale	0.10
Energy scale calibration and resolution	0.05
Other	0.04
All systematic uncertainties in the signal model	0.15
Statistical	0.31
Total	0.34

BOOST 90 → 125 (high pT Z)

Z→ee
- Z-scale energy
- Electrons

Systematics:
- energy scale/resolution
- ±50 MeV

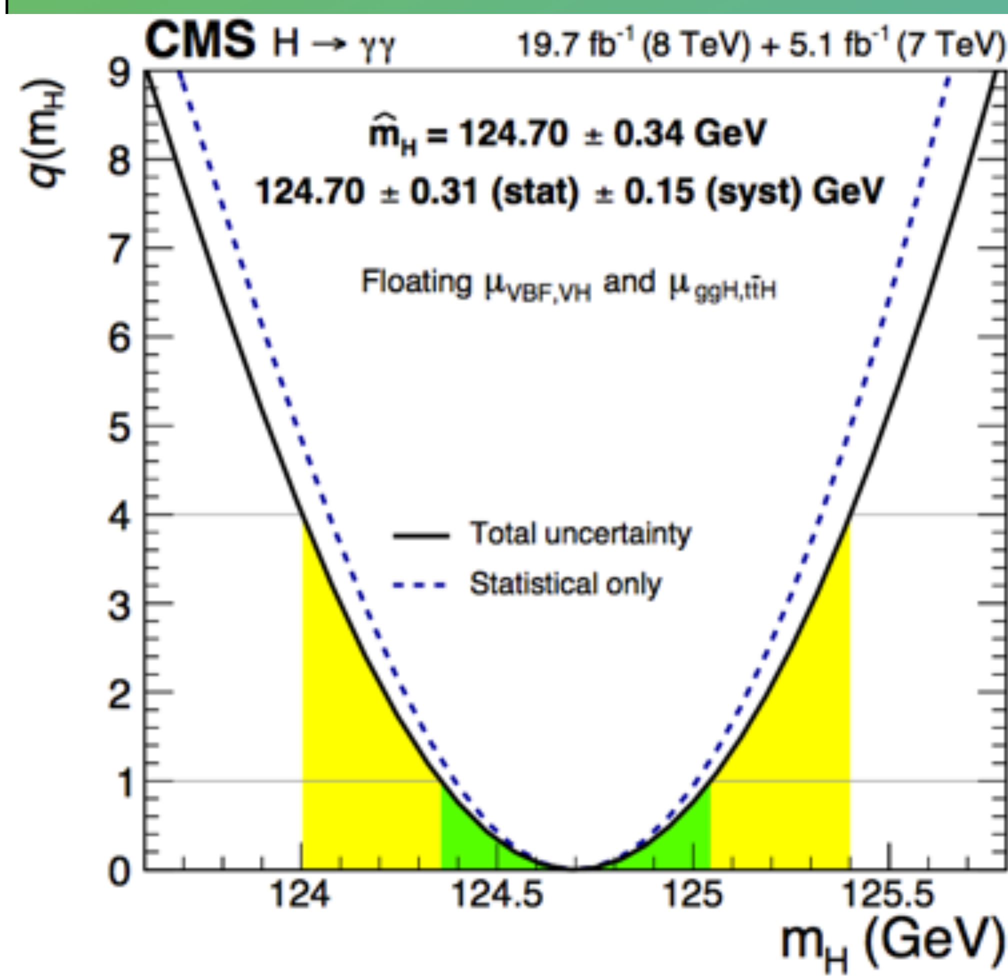
H→ee
- H-scale energy
- Electrons

Systematics:
- Non-linearity
- ±100 MeV

H→γγ
- H-scale energy
- Photons

Systematics:
- Electron/photon differences
- ±100 MeV

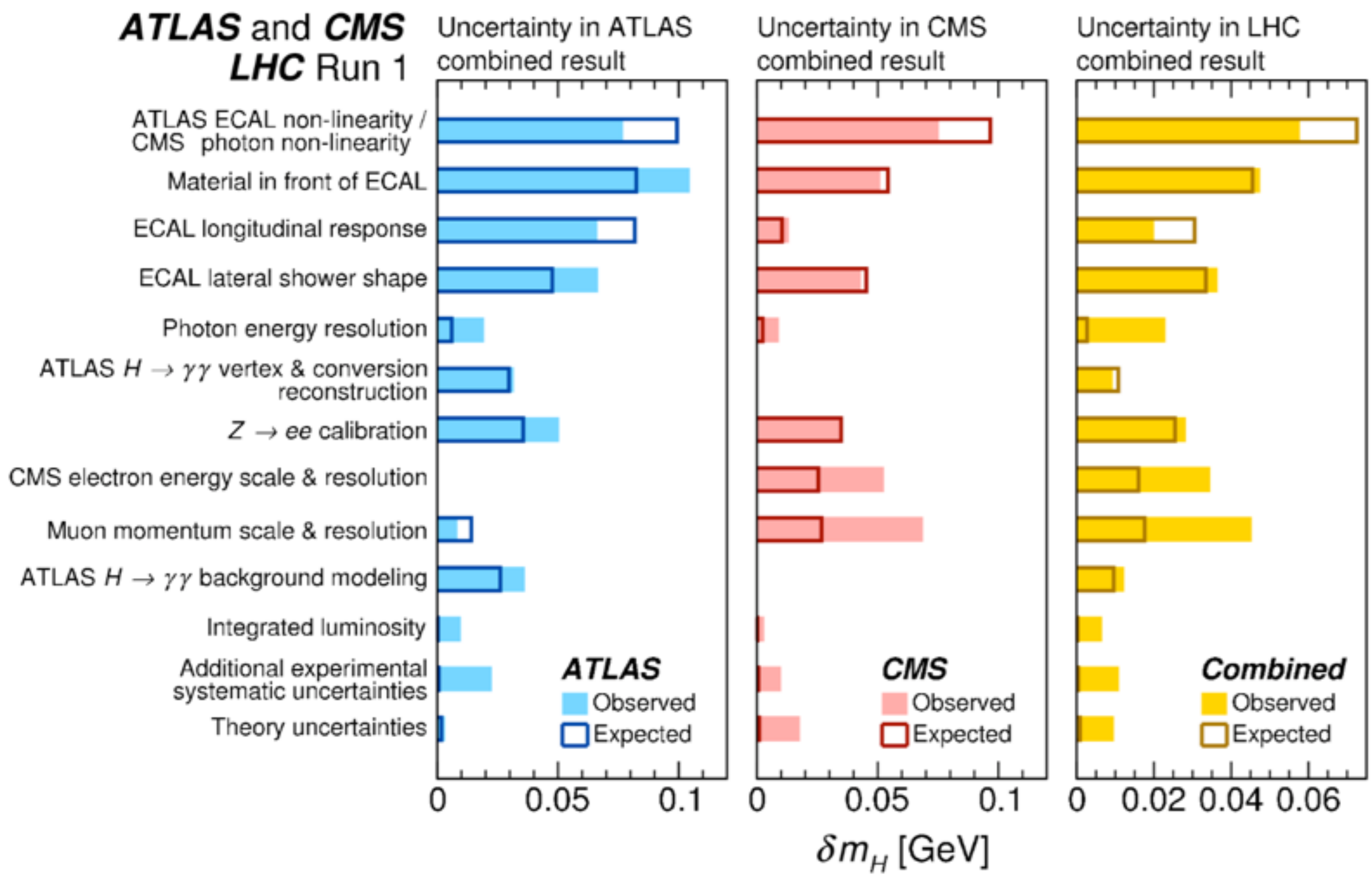
ELECTRONS → PHOTONS (MC)



Get the statistical uncertainty by fixing the nuisance to their best values

Mass measurement

Energy scale systematic uncertainties:
(the mass uncertainty is still statistically dominated)

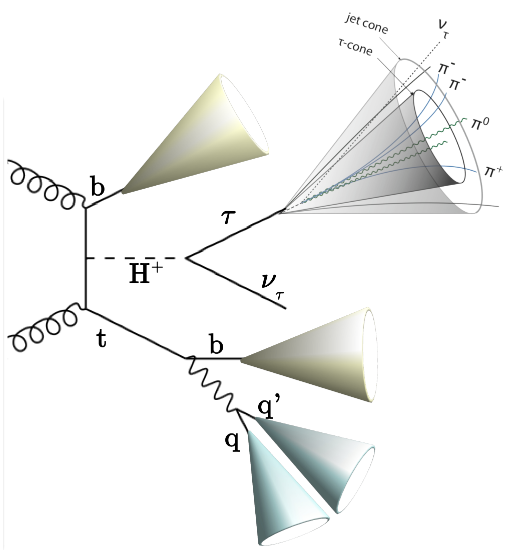


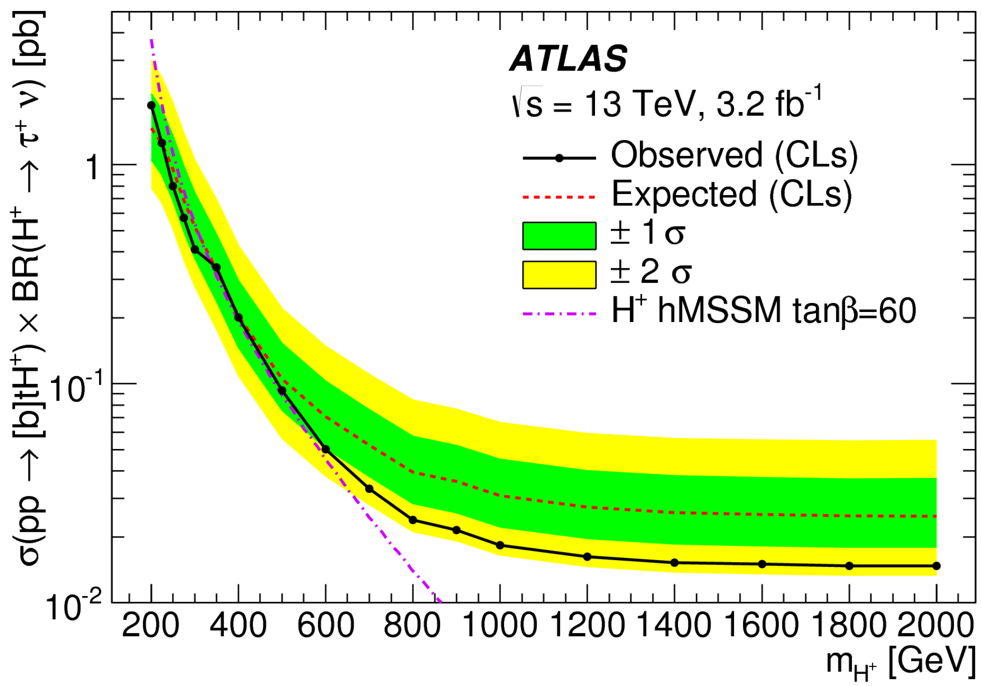
LFV constraints

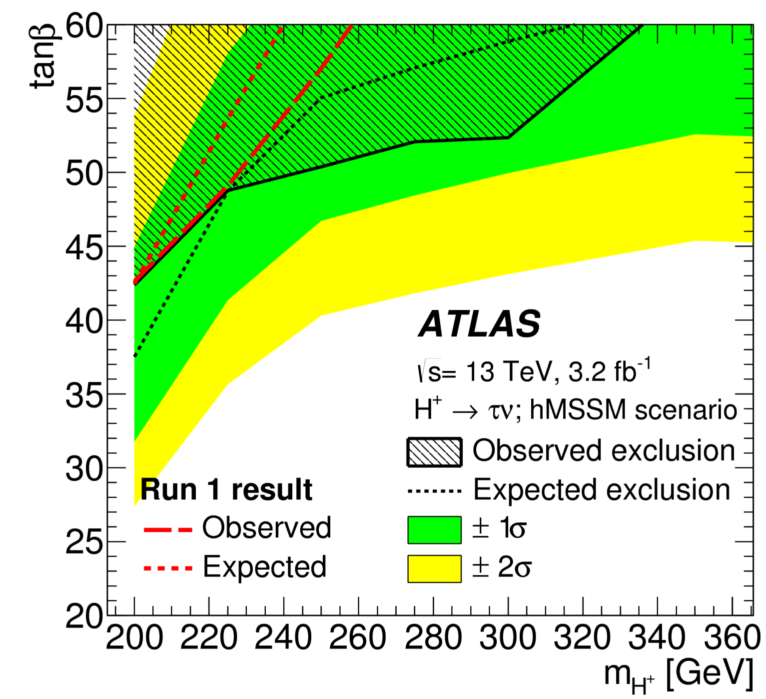
Channel	Coupling	Limit	Higgs Br Limit
$\mu \to e\gamma$	$\sqrt{|Y_{e\mu}|^2+|Y_{\mu e}|^2}$	$3.6\ 10^{-6}$	$Br(H \to e\mu)<10^{-8}$
$\tau \to e\gamma$	$\sqrt{|Y_{e\tau}|^2+|Y_{\tau e}|^2}$	0.016	$Br(H \to e\tau)<10\%$
$\tau \to \mu\gamma$	$\sqrt{|Y_{\mu\tau}|^2+|Y_{\tau\mu}|^2}$	0.014	$Br(H \to \mu\tau)<10\%$

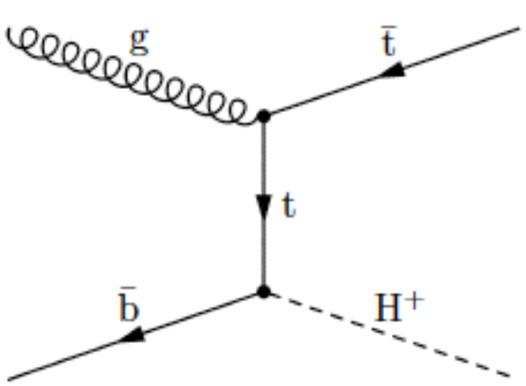
Charged Higgs: $H^+ \to \tau^+\nu$; $H^+ \to tb$

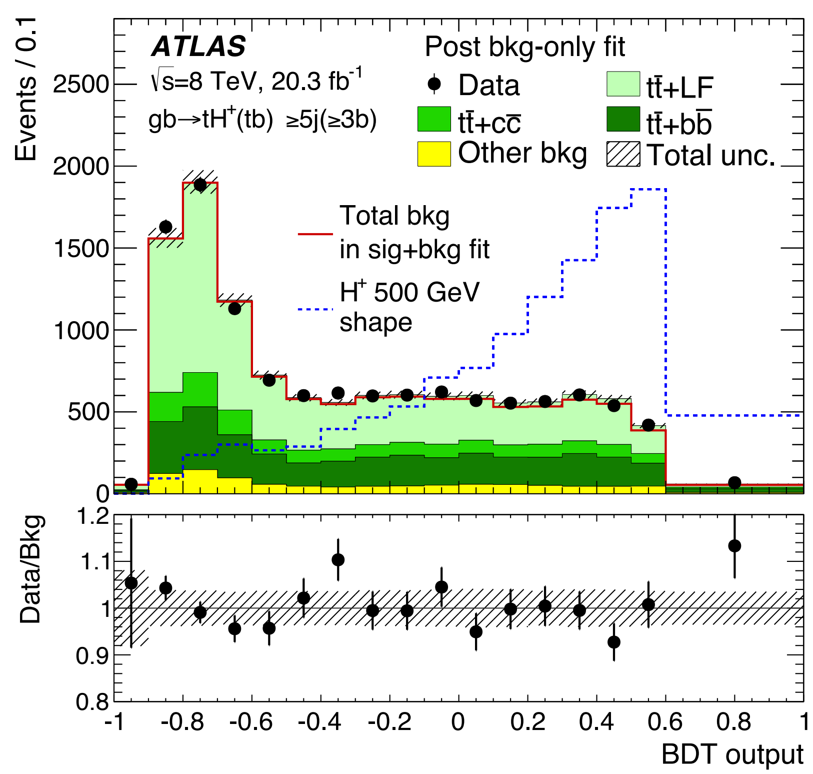
Many $H^\pm$ decays probed in Run 1: tb, cs, τν ; VBF $H^\pm \to W^\pm Z$

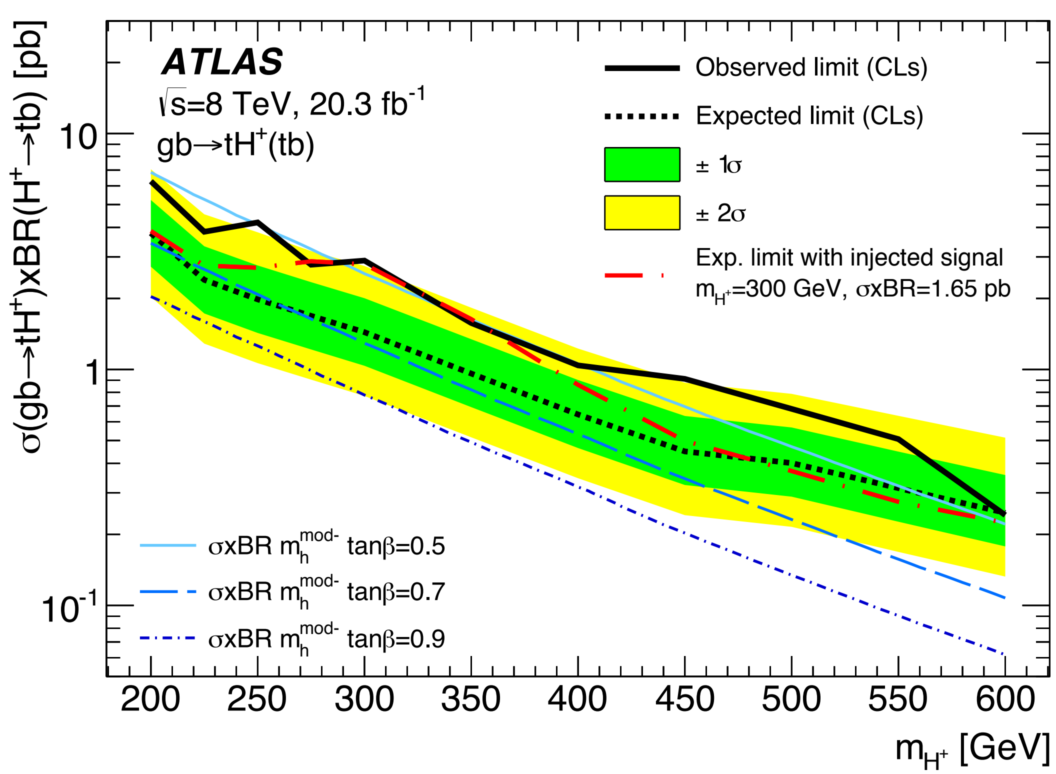






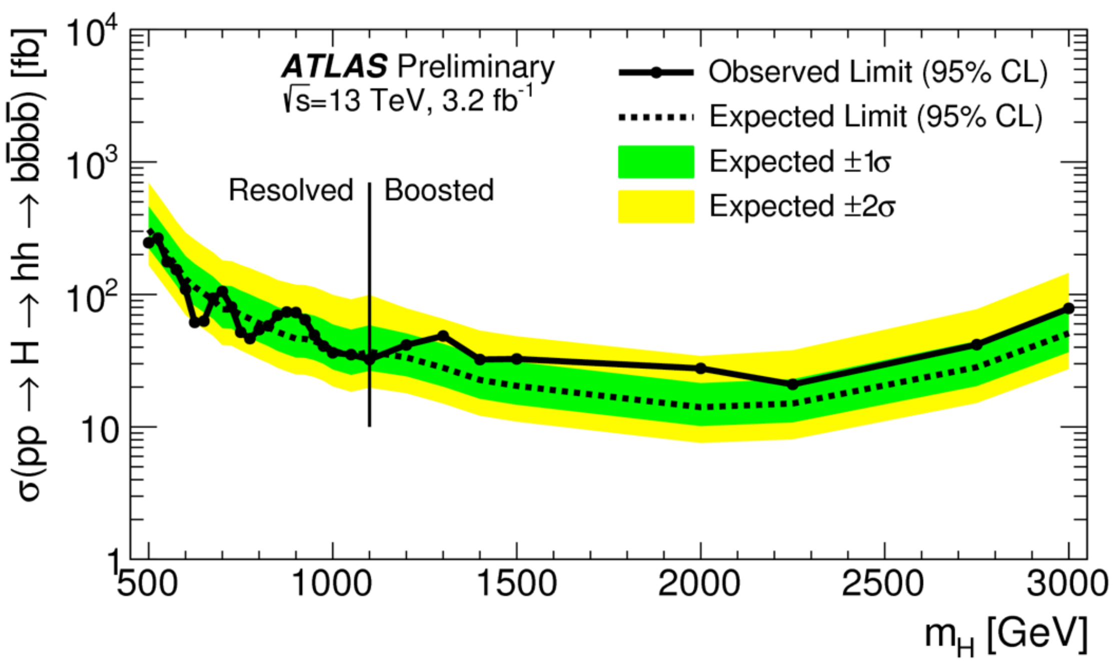




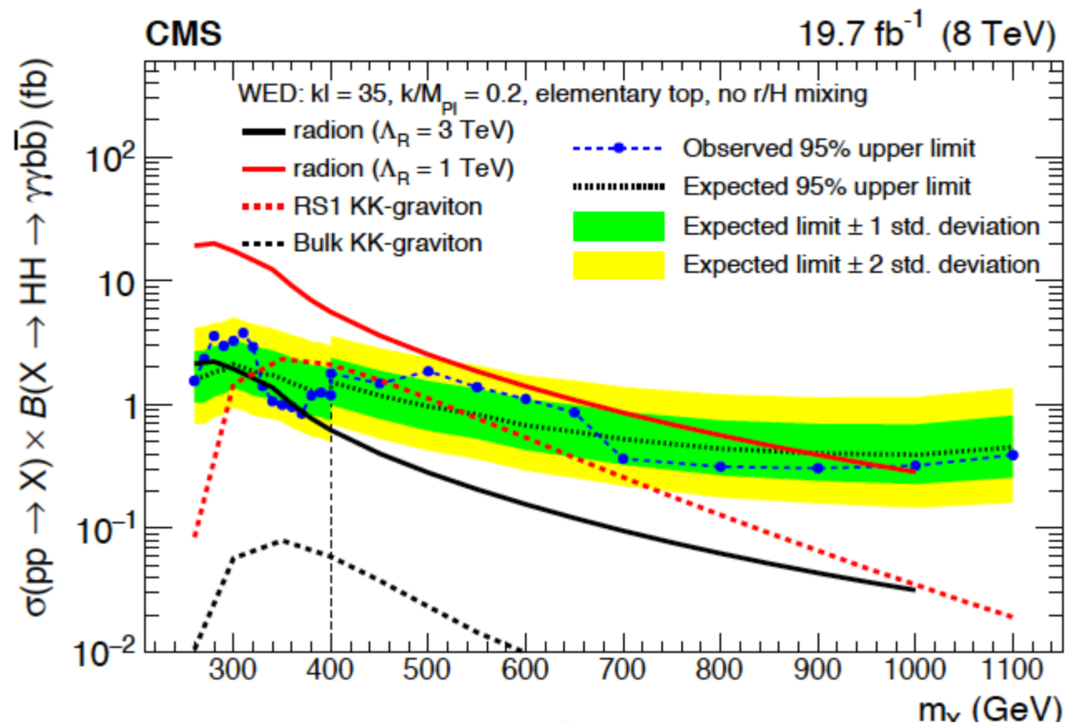


Resonant HH searches

bb bb: resolved/boosted regimes
m(bb) consistent with h-mass

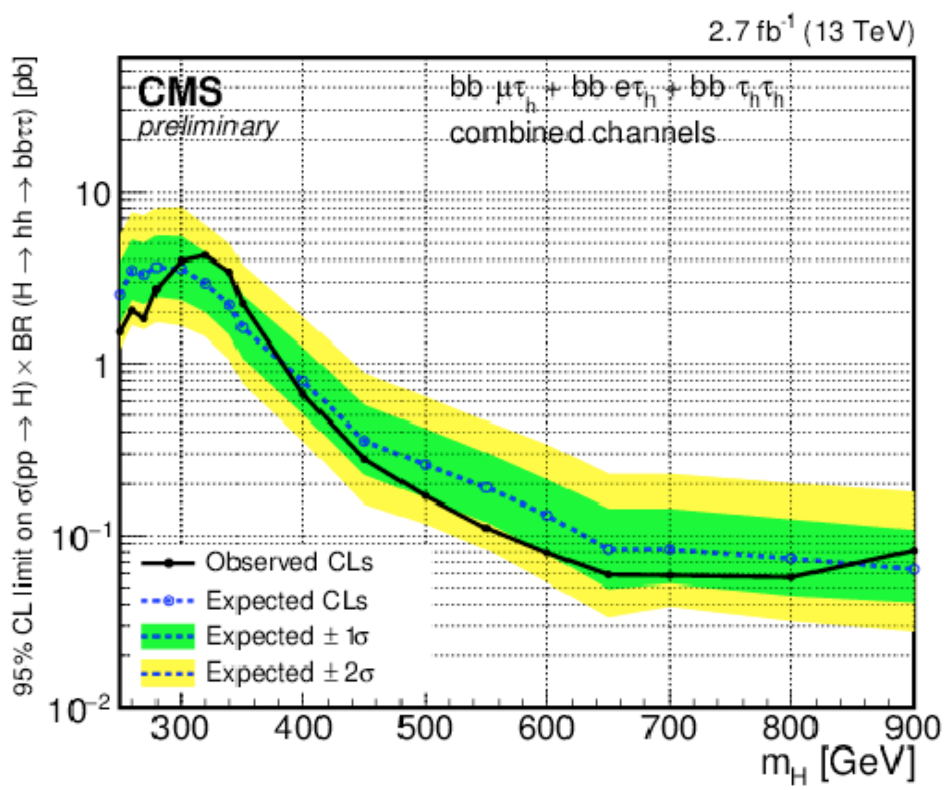


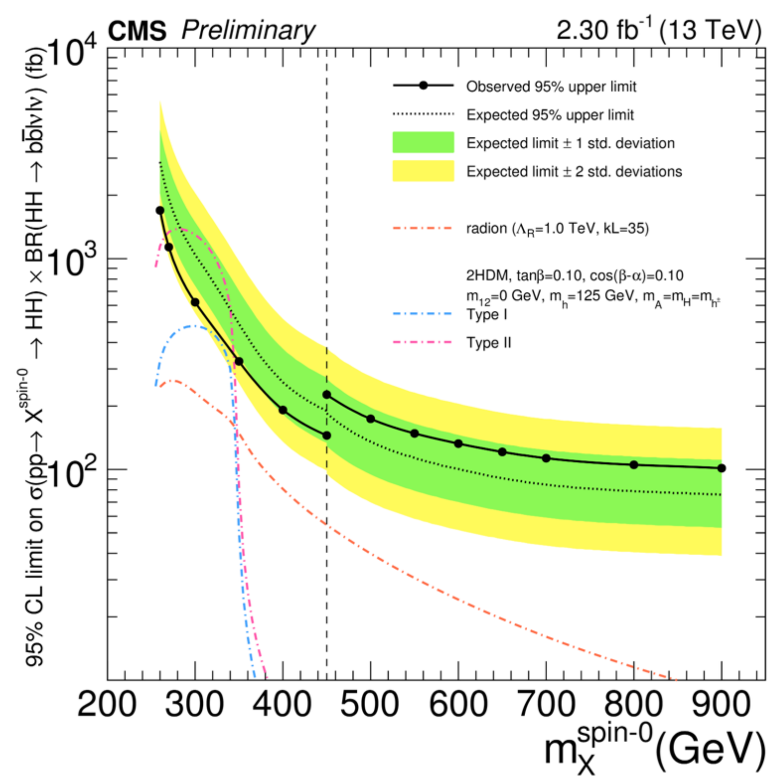
bb $\gamma\gamma$: large bb BR + $\gamma\gamma$ mass resolution

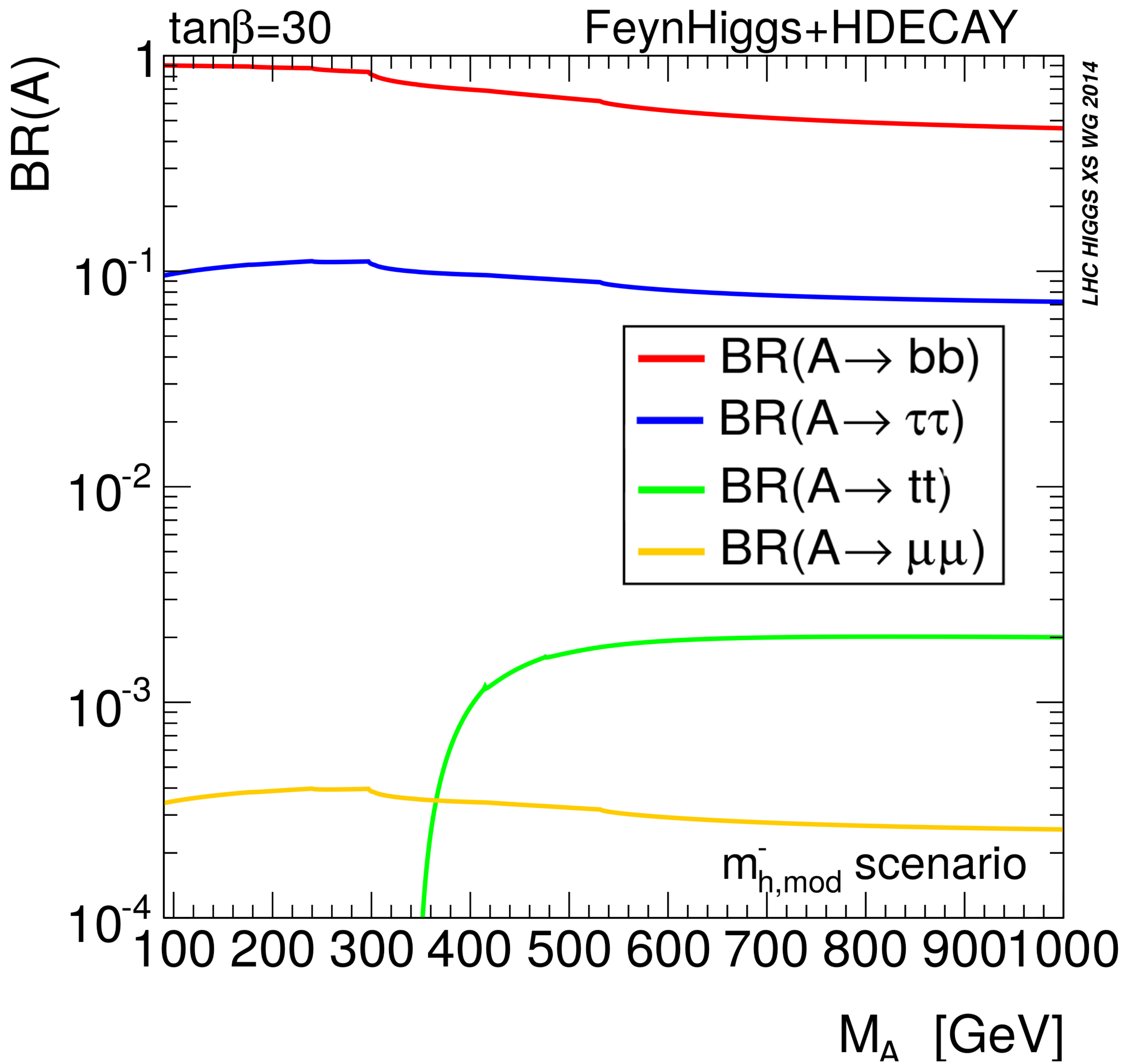


bb WW: leptonic final states
BDT discriminant

bb$\tau_e\tau_h$, bb$\tau_\mu\tau_h$, bb$\tau_h\tau_h$

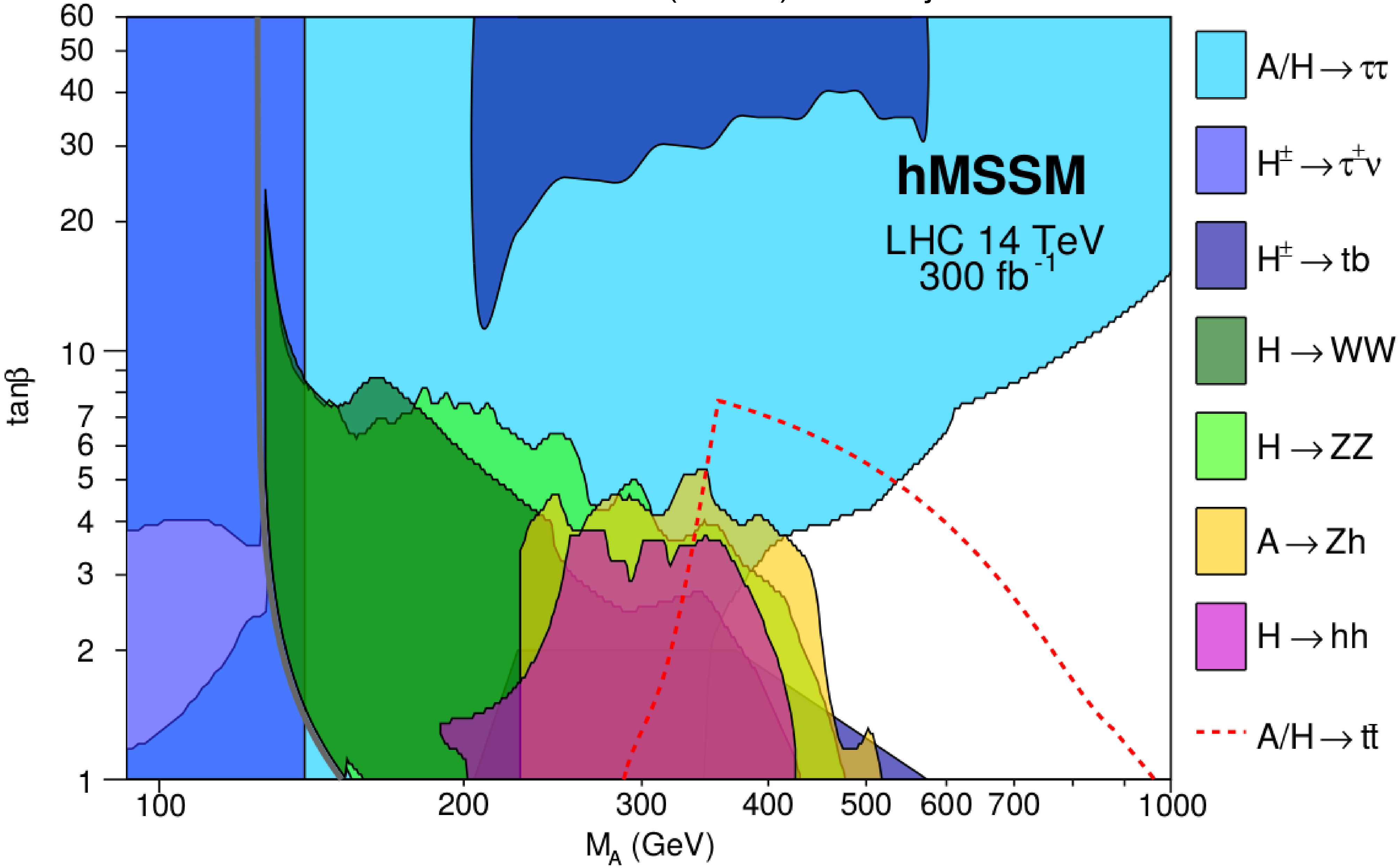





tanβ=30
FeynHiggs+HDECAY
BR(A)
LHC HIGGS XS WG 2014
1
10-1
10-2
10-3
10-4
BR(A→ bb)
BR(A→ ττ)
BR(A→ tt)
BR(A→ μμ)
m-h,mod scenario
100 200 300 400 500 600 700 800 900 1000
M_A [GeV]

hMSSM Projections

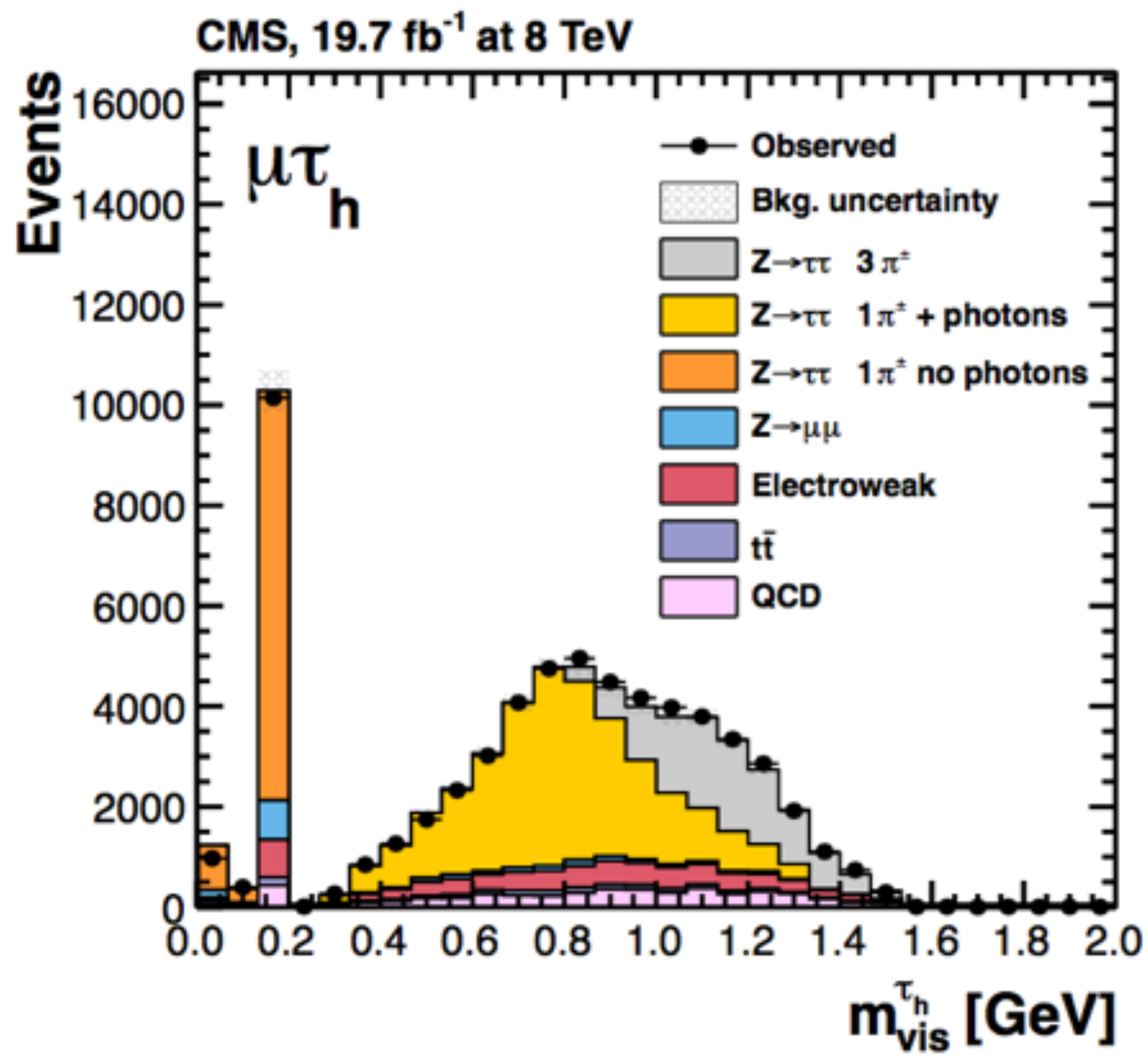
JHEP 06 (2015) 168 Djouadi *et al.*



H→ττ invariant mass

Discriminating variable: invariant mass of the ττ system, but you have 2ν in the final state

Simple approach: ignore the presence of the neutrinos and compute the visible mass m_{vis}



Good Data/MC agreement means both
good daata/MC in τ reco efficiency and E calibrations

H→ττ invariant mass

"collinear approximation": neutrino emission coincide with the tau direction

$$E_{T,x}^{\text{miss}} = p_{\tau_1}^{\nu} \cdot \sin\vartheta_{\tau_1} \cos\varphi_{\tau_1} + p_{\tau_2}^{\nu} \cdot \sin\vartheta_{\tau_2} \cos\varphi_{\tau_2}$$
$$E_{T,y}^{\text{miss}} = p_{\tau_1}^{\nu} \cdot \sin\vartheta_{\tau_1} \sin\varphi_{\tau_1} + p_{\tau_2}^{\nu} \cdot \sin\vartheta_{\tau_2} \sin\varphi_{\tau_2}$$

$$p_{\tau_1}^{\nu} = \frac{E_{T,x}^{\text{miss}} \cdot \sin\varphi_{\tau_2} - E_{T,y}^{\text{miss}} \cdot \cos\varphi_{\tau_2}}{\sin\vartheta_{\tau_1} \sin(\varphi_{\tau_1} - \varphi_{\tau_2})} \qquad p_{\tau_2}^{\nu} = -\frac{E_{T,x}^{\text{miss}} \cdot \sin\varphi_{\tau_1} - E_{T,y}^{\text{miss}} \cdot \cos\varphi_{\tau_1}}{\sin\vartheta_{\tau_2} \sin(\varphi_{\tau_1} - \varphi_{\tau_2})}$$

and $m_{\tau\tau}$ can be calculated as

$$m_{\tau\tau} = \frac{m_{\text{vis}}}{\sqrt{x_{\tau_1} x_{\tau_2}}}, \qquad x_{\tau_i} = \frac{p_{\tau_i}^{\text{vis}}}{p_{\tau_i}^{\text{vis}} + p_{\tau_i}^{\nu}}$$

The collinear approximation works better when the taus are highly boosted.
The system of eq. is degenerate when the taus are back to back

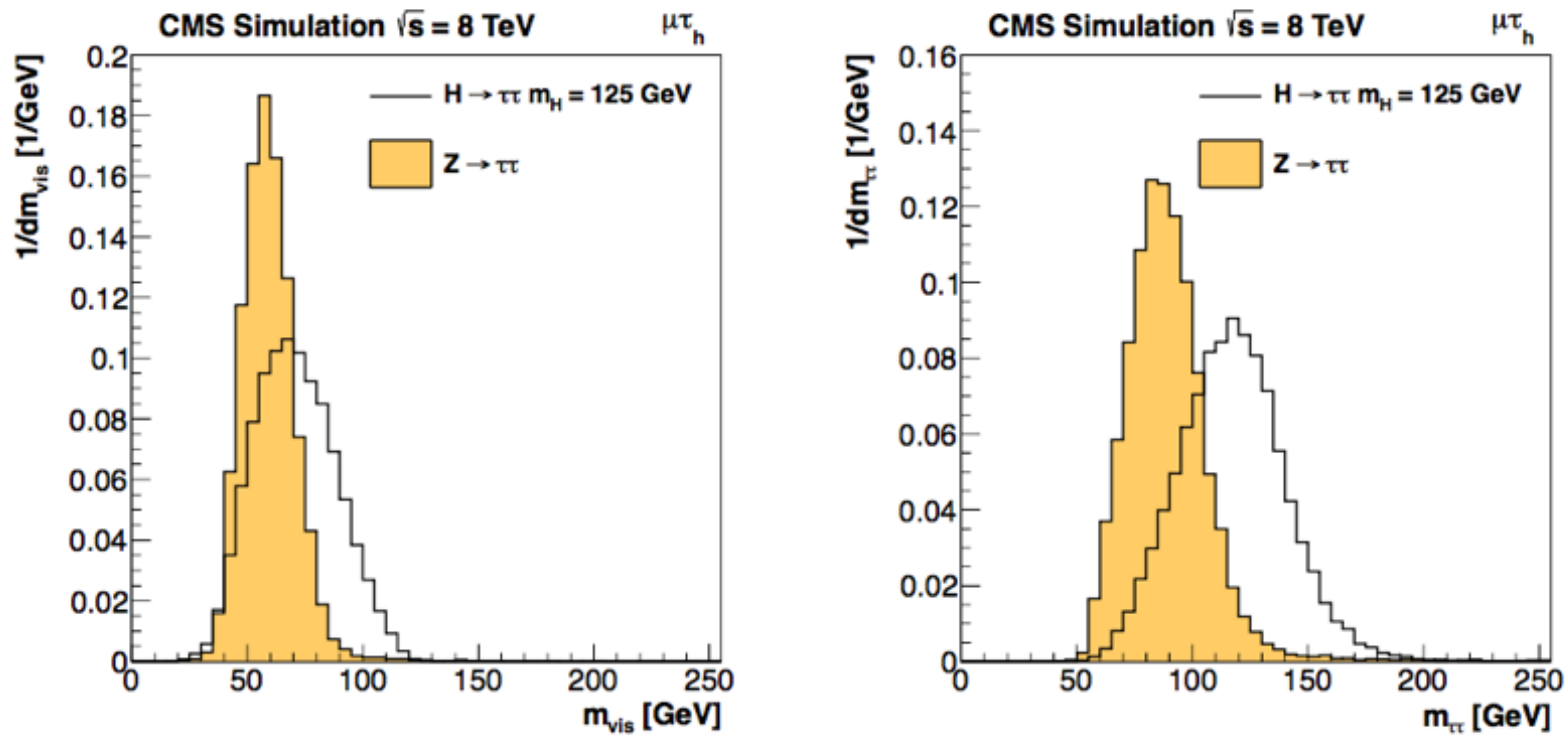
H→ττ invariant mass

Final choice was to use a likelihood fit to get the neutrino momenta:

$$\mathcal{L}_\nu(E_x^{\text{miss}}, E_y^{\text{miss}}) = \frac{1}{2\pi\sqrt{|V|}} \exp\left[-\frac{1}{2}\begin{pmatrix} E_x^{\text{miss}} - \sum p_x^\nu \\ E_y^{\text{miss}} - \sum p_y^\nu \end{pmatrix}^T V^{-1} \begin{pmatrix} E_x^{\text{miss}} - \sum p_x^\nu \\ E_y^{\text{miss}} - \sum p_y^\nu \end{pmatrix}\right]$$

V is the covariance matrix of the MET

Resolution: ~10 /15 / 20 % for $\tau_h\tau_h$ / $l\tau_h$ / ll



WW scattering

Expected significance for the discovery of the longitudinal same-sign WW scattering