BSM Higgs Searches in ATLAS and CMS (part 2)

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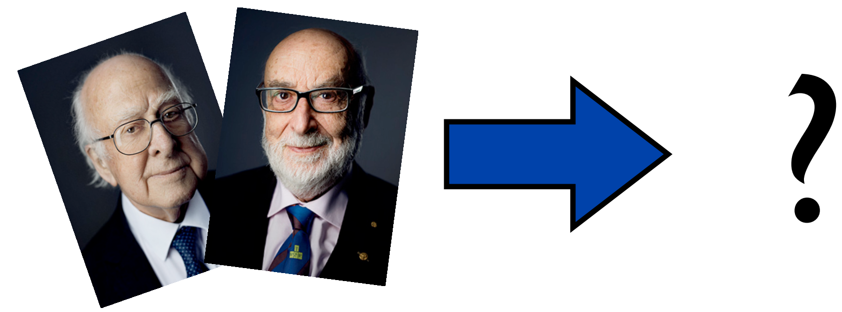
On Behalf of the ATLAS and CMS Collaborations

Overview

- Vital question: **Is it in fact the discovered Higgs boson from the SM or part of an extended sector?**

- Space to probe any **non-SM property**



- **Additional Higgs** bosons still a possibility

- **Indirect searches** from observed Higgs couplings measurement (not in this talk)

Outline

- Talk focuses on results from **ATLAS and CMS**

Many new results from ICHEP and after:

Non-SM property

- Rare Higgs Decays
- Invisible Higgs Decays
- Higgs Decays to Long-Lived NEW
- Lepton Flavour Violation NEW

Additional Higgs bosons

- Additional Higgs in multilepton and photons channels
- MultiHiggs in cascade
- Di-Higgs production in diphoton and di b-jets channels NEW
- New diphoton resonances NEW

Rare decays

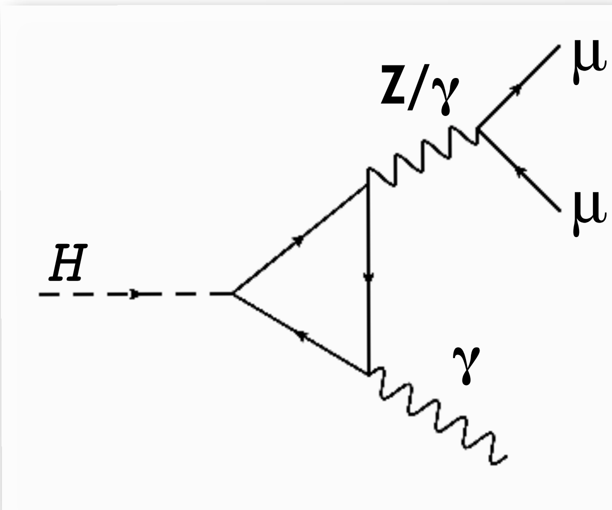
CMS: Phys. Lett. B 726(2013) 587

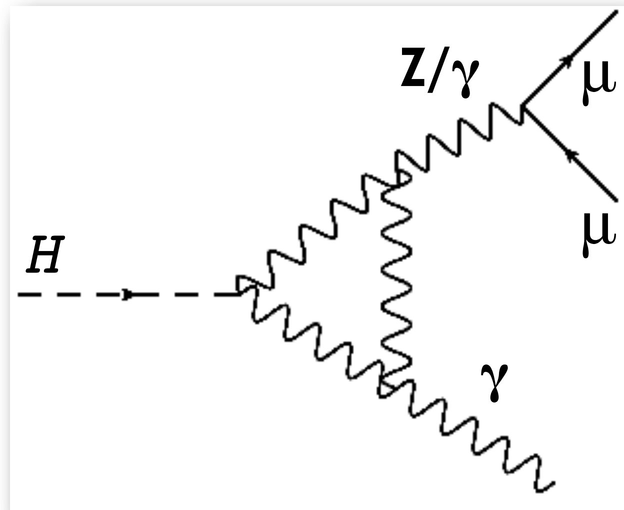
ATLAS: arXiv:1402.3051

CMS PAS HIG-14-003

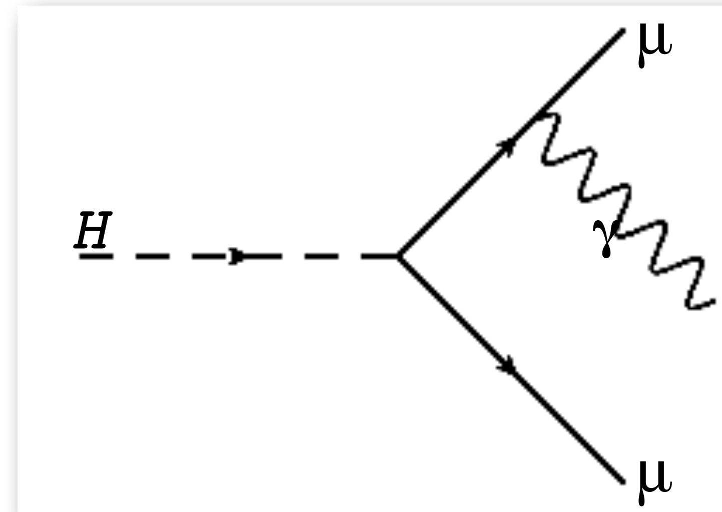
Search for $H \to \gamma^* \gamma \to \mu\mu\gamma$

- **Rare Higgs decays** as probes of **new couplings** and **SM extensions**
- Loop and tree level processes contribute to **$\mu\mu\gamma$ final state**





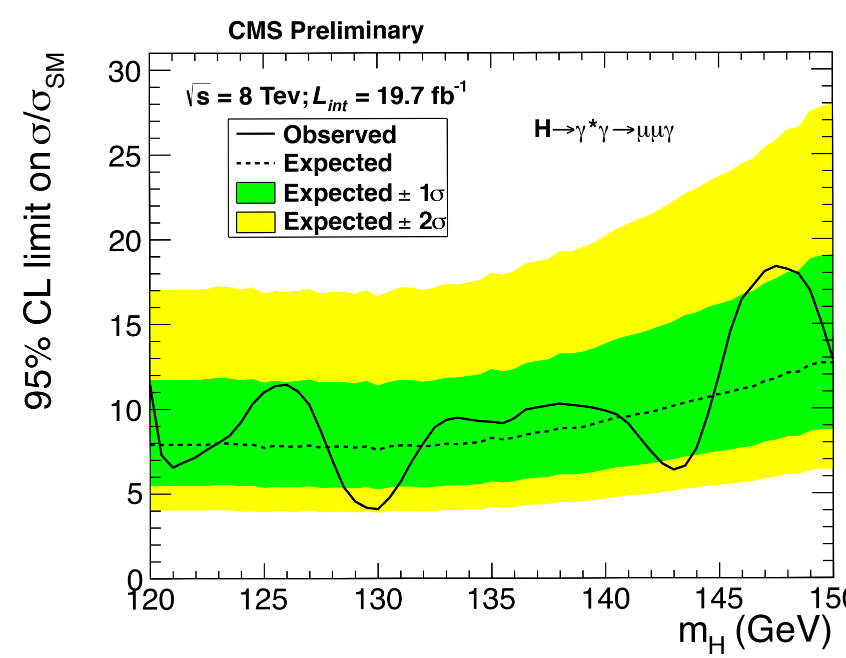
$m_{\mu\mu}$< 100 GeV



Higher $m_{\mu\mu}$

- **First CMS search for Dalitz decays** with **γ^* internal conversion in $\mu\mu$**
  - $m_{\mu\mu}$ < 20 GeV to separate $\gamma^* \gamma$ and Z γ

@125 GeV	CMS	ATLAS
Z γ	9.5X SM	11X SM
γ* γ	10X SM	



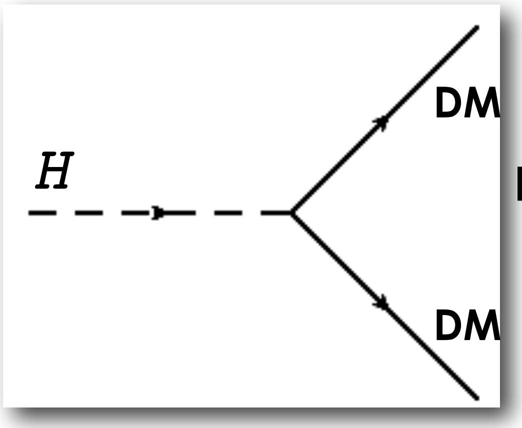
Invisible decays

ATLAS-CONF-2014-011

CMS PAPER HIG-13-030

Higgs decay to invisible particles

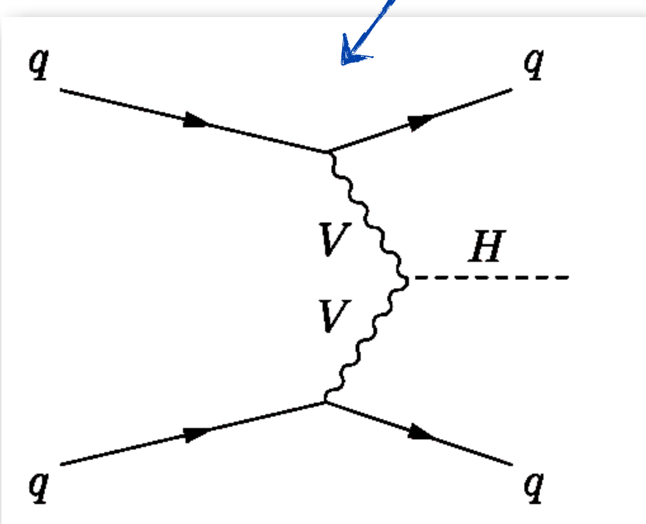
- What if Higgs couples to **something invisible**?

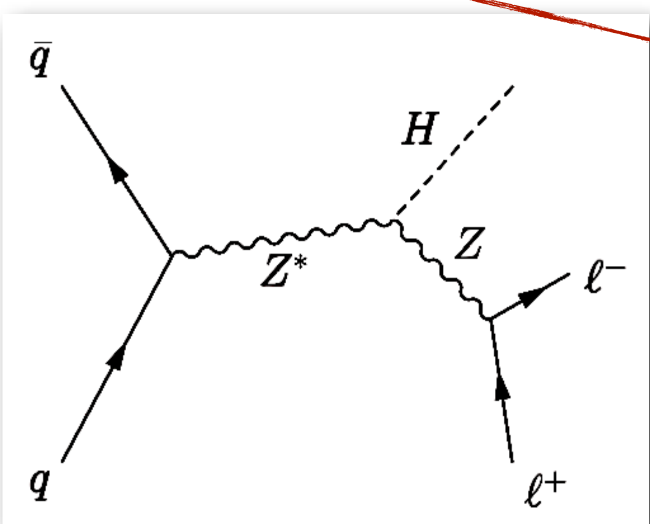


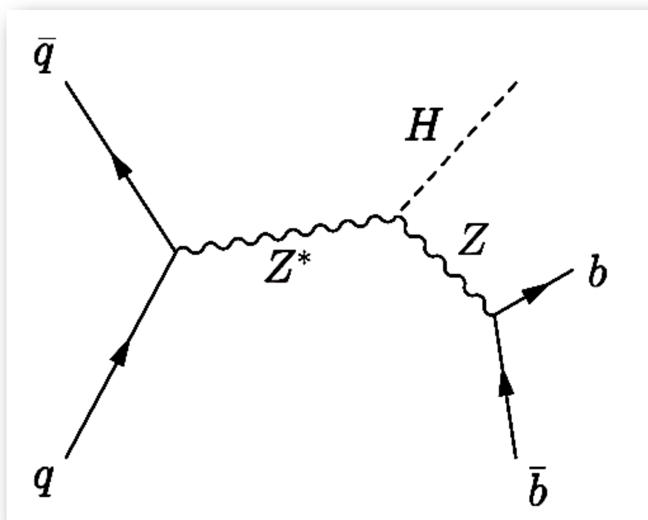
$m_{DM} < m_H/2$

- One possibility: Higgs portal of DM interaction
  - **Higgs mediator between SM and DM particles**

- Search in the **VBF** and **ZH (Z →ll; Z →bbar)** modes







Large cross-section
Large SM background
reduced by VBF jet topology

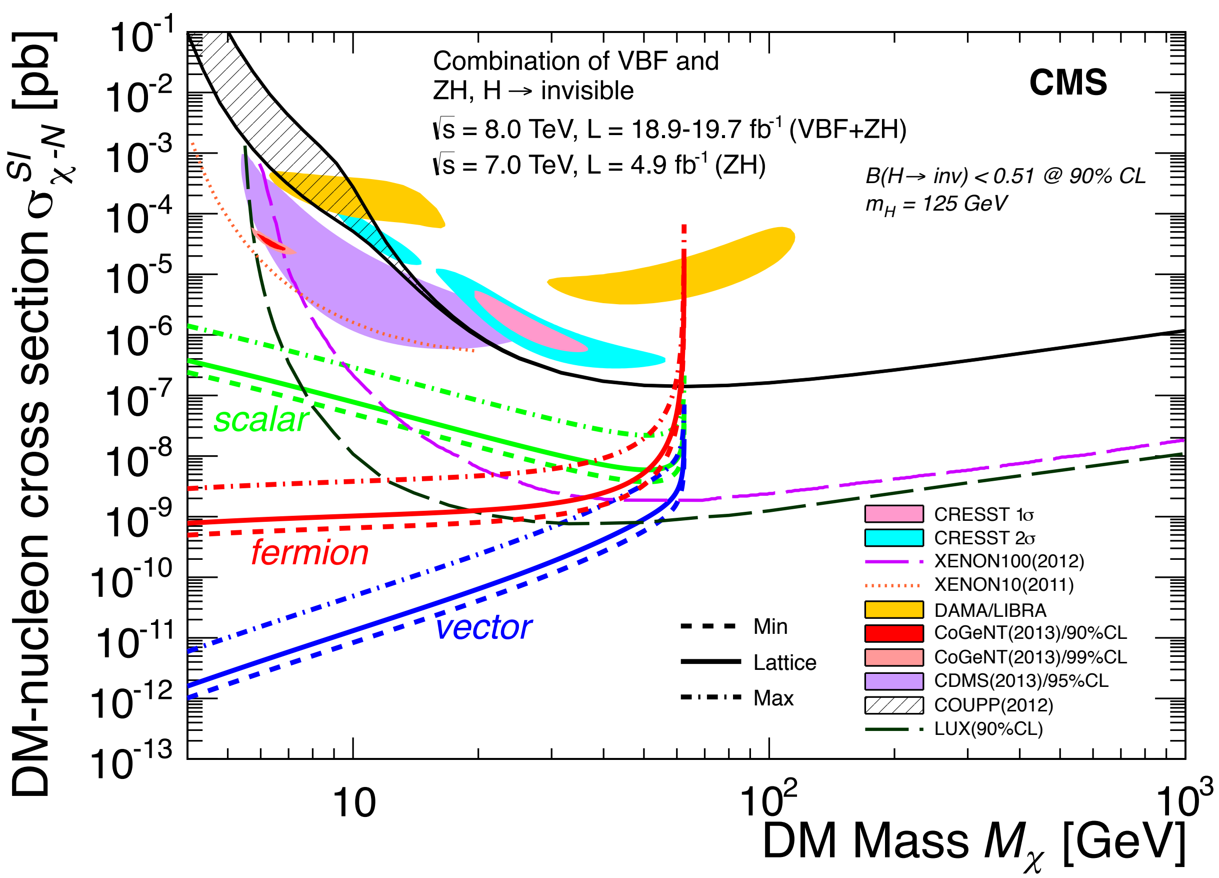
Lower cross-section
Clear topology
Sensitivity increase by the leptons an bs

Results

- No evidence for signal observed in any of the three searches
- 95% CL **Upper Limits on $\sigma \cdot$B(H → inv)**
- **CMS combination paper** just accepted for **publication.**

@125 GeV	CMS	ATLAS
Z(→ll)H	0.75XSM	0.75X SM
Z(→bb)H	1.82X SM	-
VBF	0.69X SM	-
COMB	0.58X SM	-

- Results interpreted in the **Higgs portal of DM interaction** model
- Upper limit on BR(H → inv) : **constrain the DM mass and its elastic cross section on nucleons**



Decays to long-lived particles

ATLAS-CONF-2014-041 NEW

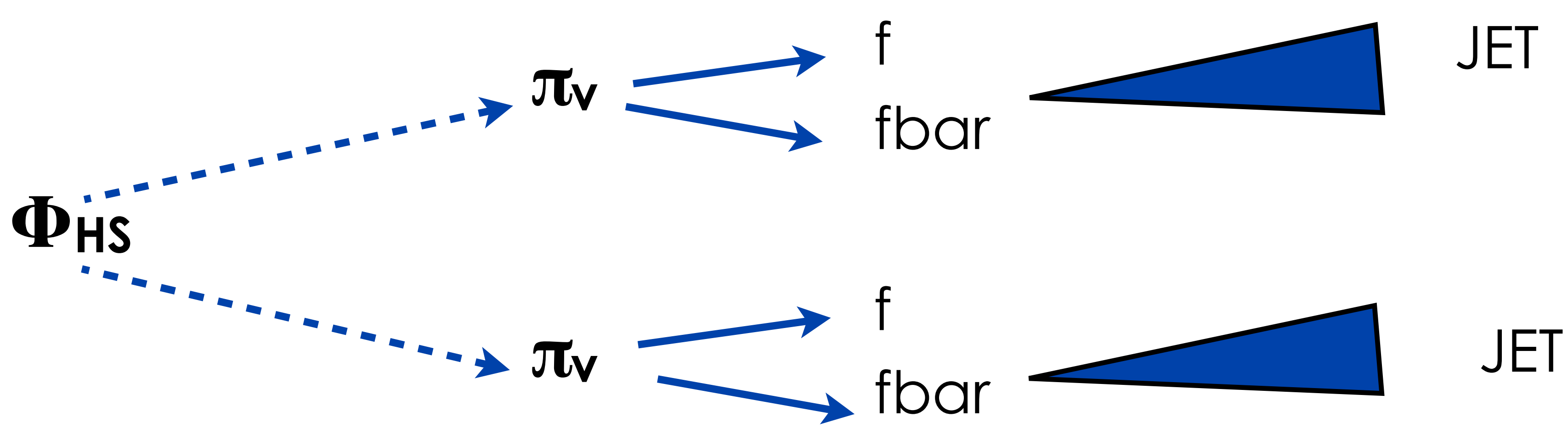
Scalar boson decay to long-lived particles

- What if Higgs couples to **Long-Lived particles**?

CMS: search for displaced vertex using tracks

ATLAS:Decays in HCal/ECal NEW

- **Hidden Valley Benchmark Model**: coupling via a heavy scalar particle, Φ_{HS}



- π_V **neutral and long-lived**
- Lifetime of the π_V is free parameter → π_V decays result as **displaced vertex**

Both π_V decay in the **hadronic calorimeter** or near the **outer edge of the electromagnetic calorimeter**

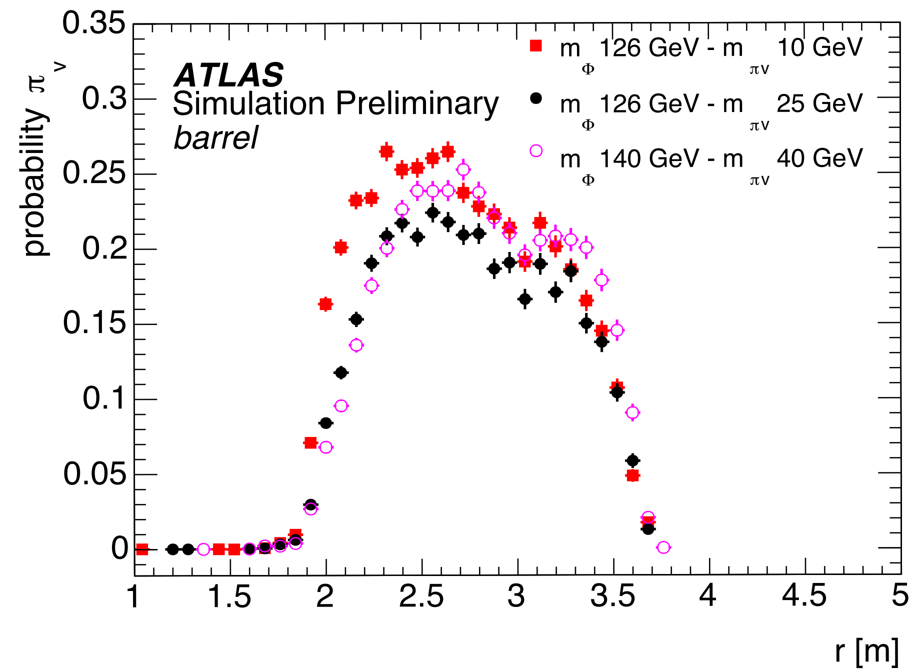
Analysis Strategy

- **Dedicated trigger**:

  At least **one narrow jet with no charged tracks associated**

  Requirement on the $\mathbf{E_H/E_{EM}}$

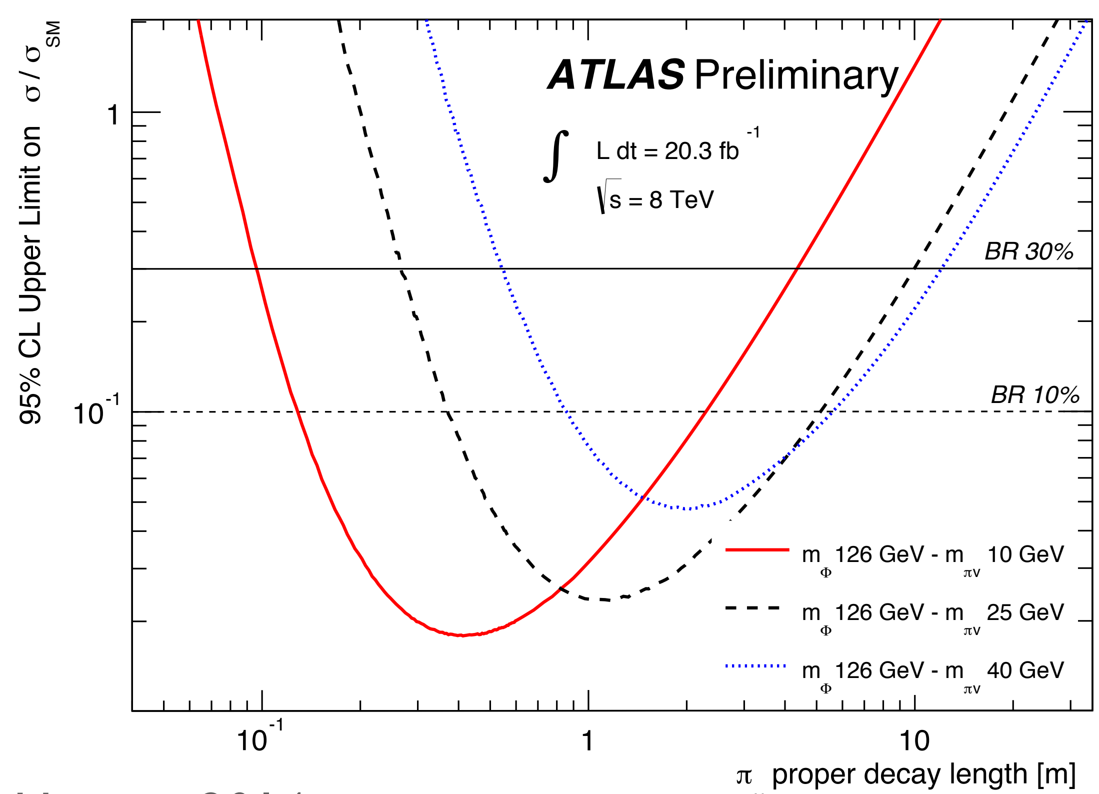
  Average probability to fire the trigger **~ 20% in EB and 6% in EE**



- <u>Non collision background:</u> **Timing of the jet** used to discard out-of-time background

- 95% CL Upper Limits on **cross-section times BR vs π_v proper decay length**

MC sample $m_\Phi, m_{\pi v}$ [GeV]	excluded range 30% BR $\Phi_{HS} \to \pi_v\pi_v$ [m]	excluded range 10% BR $\Phi_{HS} \to \pi_v\pi_v$ [m]
126, 10	0.10 - 4.38	0.13 - 2.30
126, 25	0.27 - 10.01	0.37 - 5.12
126, 40	0.54 - 12.11	0.86 - 5.62

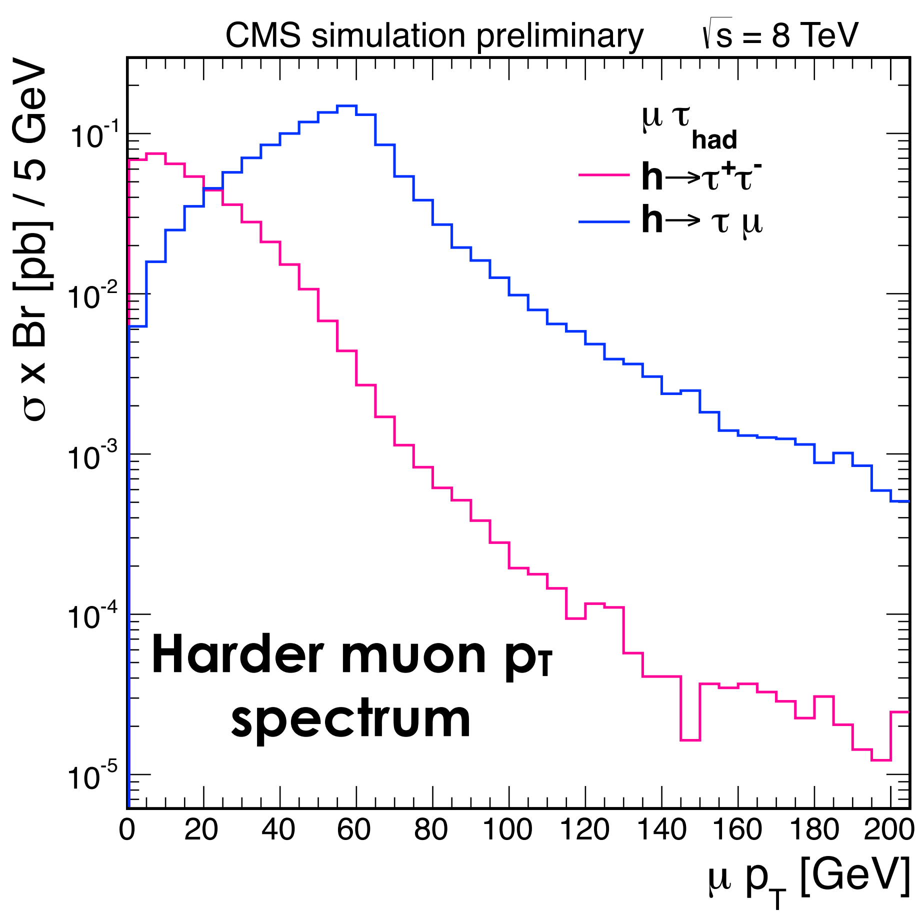


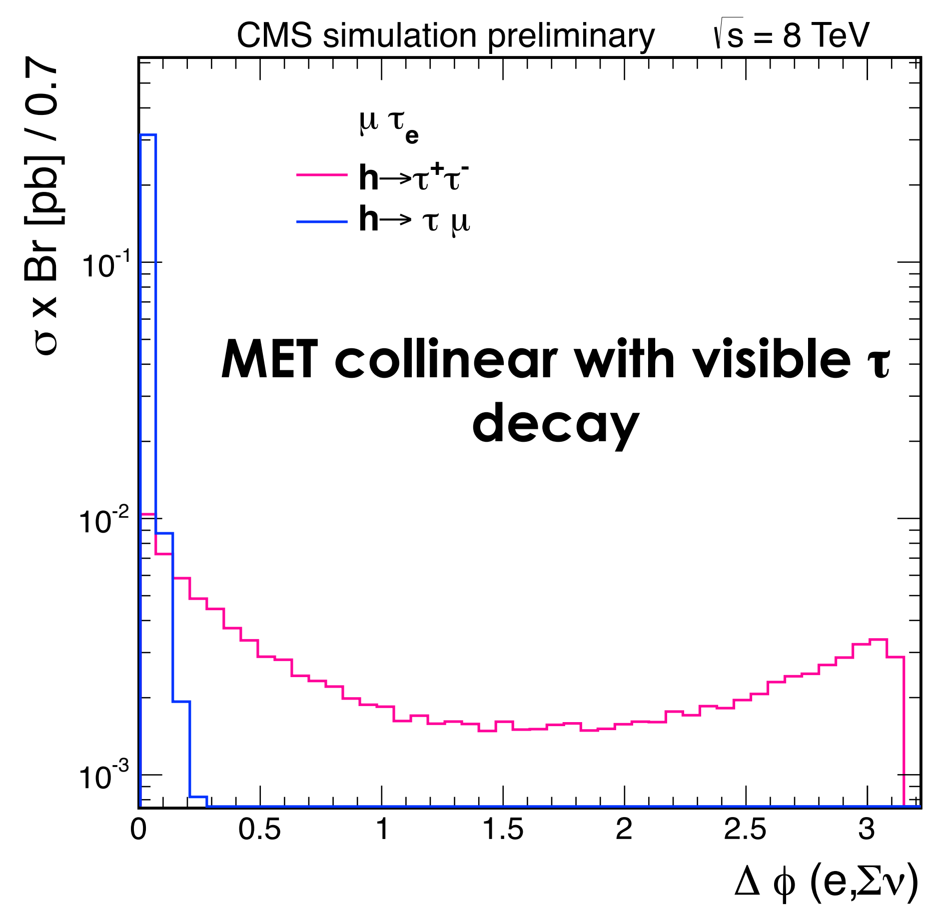
Lepton Flavor Violation

CMS PAS HIG-14-005 NEW

LFV at LHC

- What if we observe an **unexpected decay** of the new boson? **$H \rightarrow \mu\tau$**
  - **LFV** decays occur naturally in 2HDM, composite Higgs, models with flavor symmetries and Randall-Sundrum
- Constraints from **indirect searches:** $B(H \rightarrow \mu\tau) < O(0.1)$, $B(H \rightarrow e\tau) < O(0.1)$
- First dedicated search for **$H \rightarrow \mu\tau_e$** and **$H \rightarrow \mu\tau_{had}$** at LHC
- W.r. t. $H \rightarrow \tau_\mu\tau_{had}$ and $H \rightarrow \tau_\mu\tau_e$:

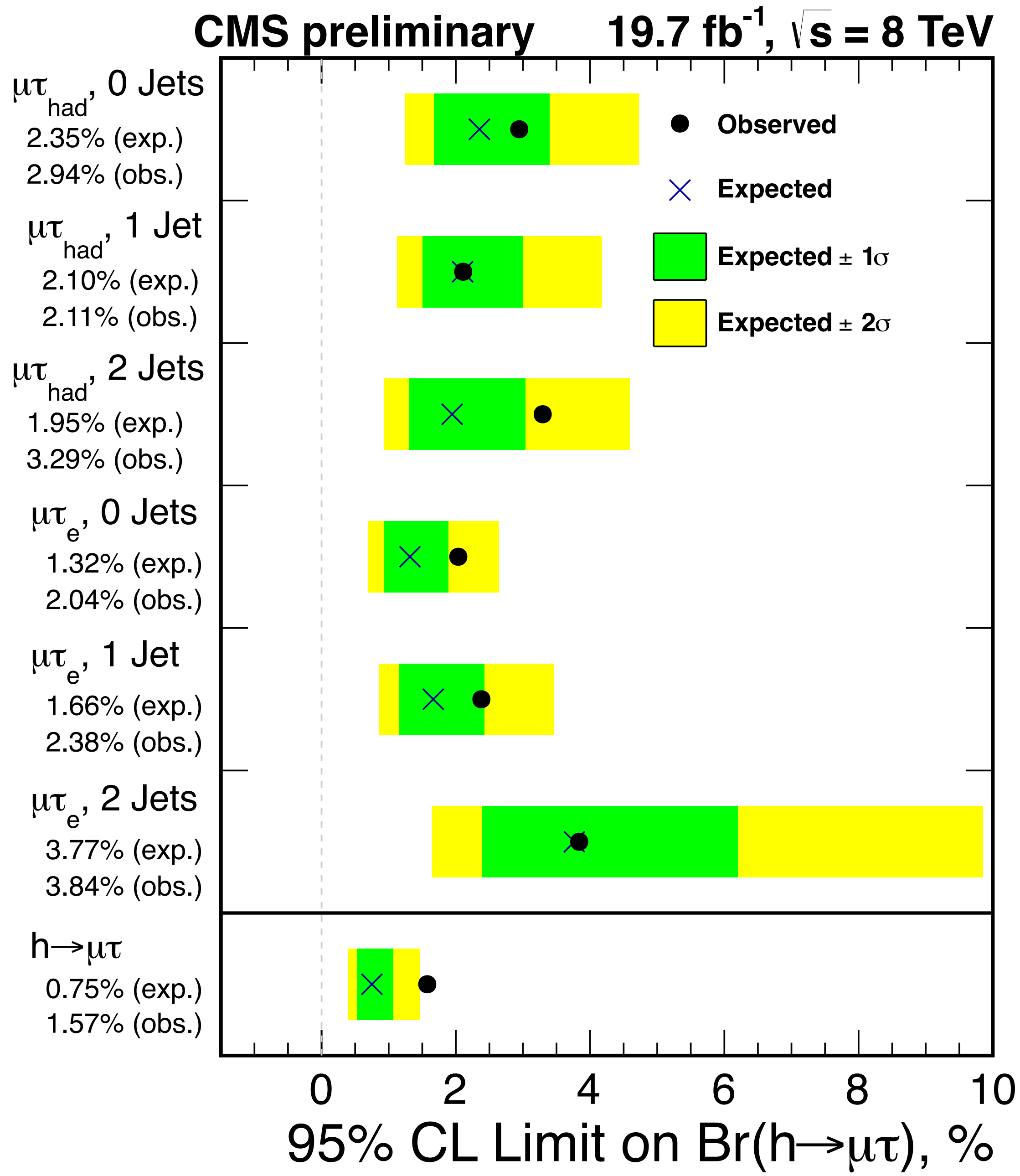




Results

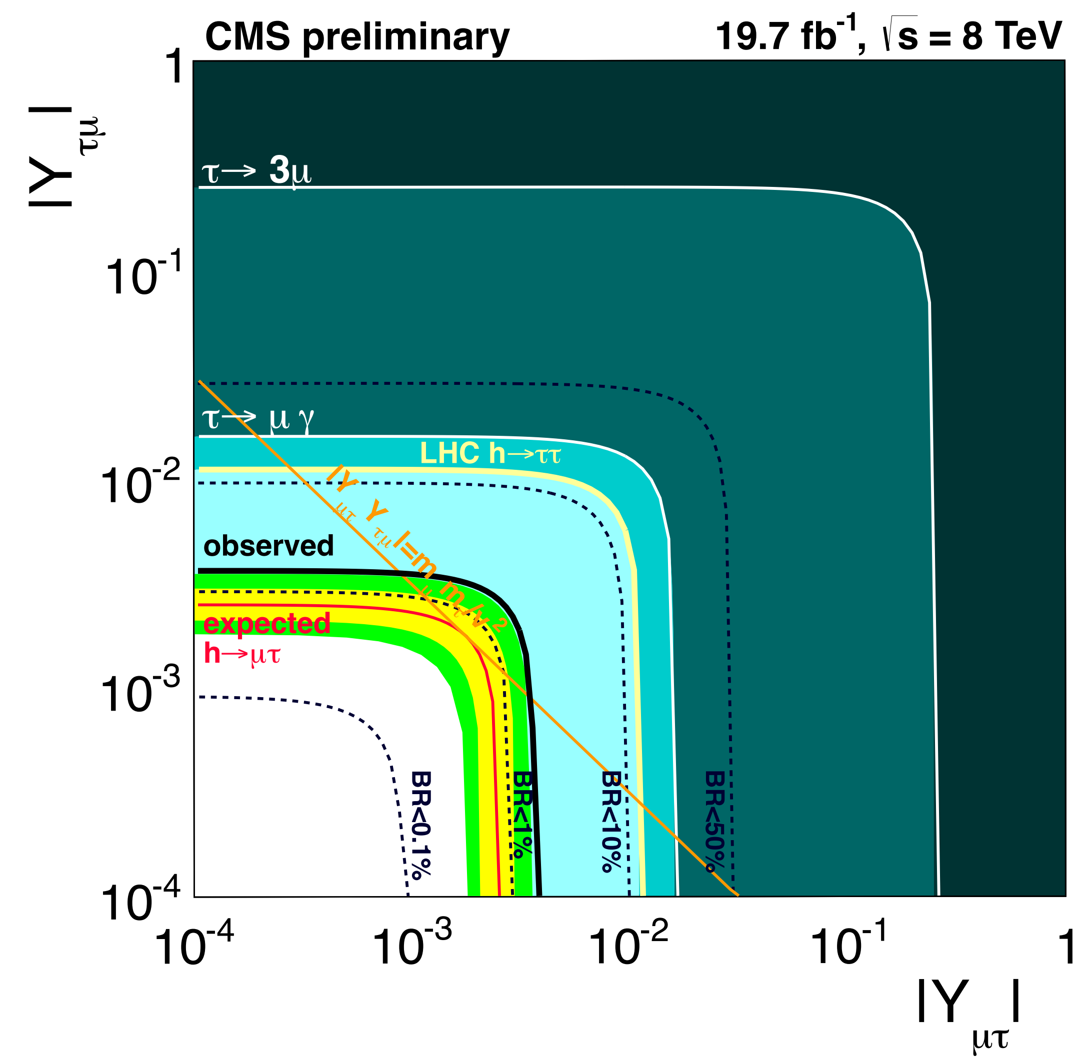
- **expected** upper limit: **B(H → μτ) < (0.75 ± 0.38)%**
- **observed** upper limit: **B(H → μτ) < 1.57%**

slight excess of observed number of events



Best fit: **B(H → μτ) = (0.89+0.40)%**

Constraint on B(H → μτ) interpreted in terms of LFV Higgs Yukawa couplings



Summary of Higgs decay modes

@125 GeV	CMS			ATLAS		
	Dataset	***Status***	***Results***	***Dataset***	***Status***	***Results***
Favoured decay modes						
H(ZZ)	5.1 + 19.7 fb^{-1}	HIG-14-009	**μ= 1.00 +/- 0.09 (stat) +0.08-0.07 (theo) +/-0.07(syst)**	4.8 + 20.3 fb^{-1}	ATLAS-CONF-2014-009	**μ= 1.30 +/- 0.12 (stat) +0.14-0.11(syst)**
H(WW)						
H($\gamma\ \gamma$)						
H(tau tau)						
V-H(bb)						
ttH(bb)				20.3 fb^{-1}	ATLAS-CONF-2014-011	**μ< 4.1(3.4)**
VBF-H(bb)	19.0 fb^{-1}	HIG-13-011	**μ< 3.6(3.0)**	4.7 + 13.0 fb^{-1}	ATLAS-CONF-2012-161	**μ< 1.8(1.9)**
Rare decay modes						
H(mu mu)	5.0+ 19.7 fb^{-1}	HIG-13-007	**μ< 7.4**	24.8 fb^{-1}	arXiv:1406.7663	**μ< 7.2**
H(Z γ)	5.0+ 19.6 fb^{-1}	arXiv:1307.5515	**μ< 10**	4.5 + 20.3 fb^{-1}	arXiv:1402.3051	**μ< 10**
H($\gamma^*\ \gamma$)	19.7 fb^{-1}	HIG-14-003		-	-	-
Invisible decay modes						
Z(ll)-H(inv)	4.9 + 19.7 fb^{-1}	arXiv:1404.1344	**BR< 58(46)%**	4.5 + 20.3 fb^{-1}	arXiv:1402.3244	**BR< 75(62)%**
Z(bb)-H(inv)				-	-	-
VBF-H(inv)				-	-	-
Exotic decay modes						
H(tau mu)	19.7 fb^{-1}	HIG-14-005	**BR<1.57%**	-	-	-
H(long-lived)	-	-	-	20.3 fb^{-1}	ATLAS-CONF-2014-041	**UL vs ctau**

= published

= preliminary

Extended Higgs Sector Introduction

		CMS	ATLAS
EWK Singlet Model		Future	V
2HDM	MSSM H(tau tau)	V	V
	MSSM H(bb)	V	-
	H^+(tau nu)	V	V
	H^+(tau jet)	-	V
	H^+(csbar)	V	-
	H(hh),A(Zh)	V	V
	H(multi γ)	-	Future
	H(ttbar)	Future	-
	Heavy H cascade	-	V
NSSM	h1->a1->2mu	V	Future
	h1->a1a1->4mu	V	-
	h2->h1h1->4tau	Future	-
	h2->h1h1->2tau2mu	-	Future
	h2->h1h1->2tau2b	Future	-
	H^+(Wa1)	-	Future
Resonant searches	***Low Mass H(γ γ)***	-	V
	HighMass H(γ γ)	V	V
	HighMass H(γ γbb)	V	V
	HighMass H(bbbb)	-	V
	HighMass WW	V	V
	HighMass ZZ	V	V

Heavy Higgs decays to h

CMS PAS HIG-13-025

ATLAS: CERN-PH-EP-2013-173

2HDM Overview

- **Five physical Higgs sector particles** survive EWSB with **masses < TeV** and accessible at LHC (h, H,A, H^{+-})

- If m_H and $m_A > 2m_h$ **H → hh and A → Zh** promising avenues for discovery even when the couplings of the light Higgs within a few percent of SM predictions.

Multilepton signature with **unusual kinematics characteristics**

Resonant decay of the SM-Higgs *h* to two photons

- ***h*** has a nominal mass of **126 GeV** and **Brs to WW, ZZ, ττ, bb and γγ** channels appropriate to SM

$$H \to hh$$

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to bb$	$h \to \gamma\gamma$
$h \to WW^*$	✓	✓	✓	X	✓
$h \to ZZ^*$	-	✓	✓	✓	✓
$h \to \tau\tau$	-	-	✓	X	✓
$h \to bb$	-	-	-	X	X
$h \to \gamma\gamma$	-	-	-	-	X

$$A \to Zh$$

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to \gamma\gamma$
$Z \to ll$	✓	✓	✓	✓
$Z \to qq$	X	✓	X	X
$Z \to \nu\nu$	X	✓	X	X

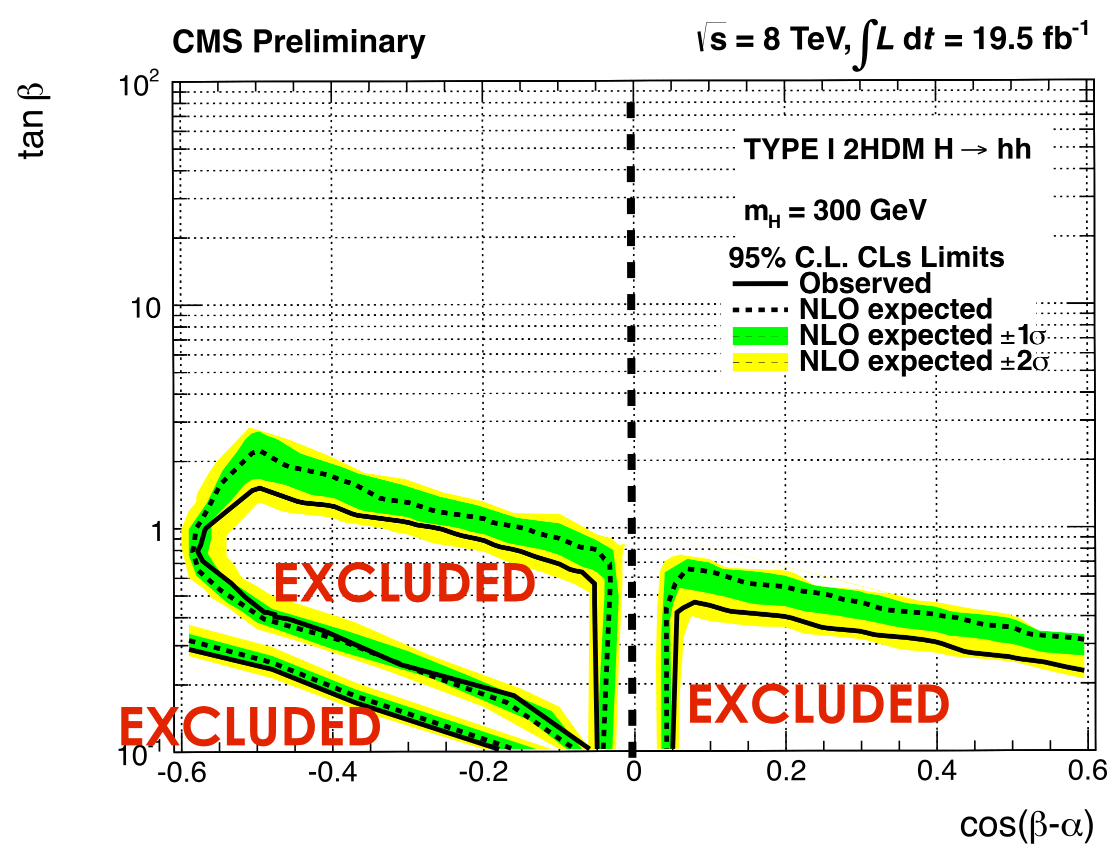
Interpretation in 2HDM

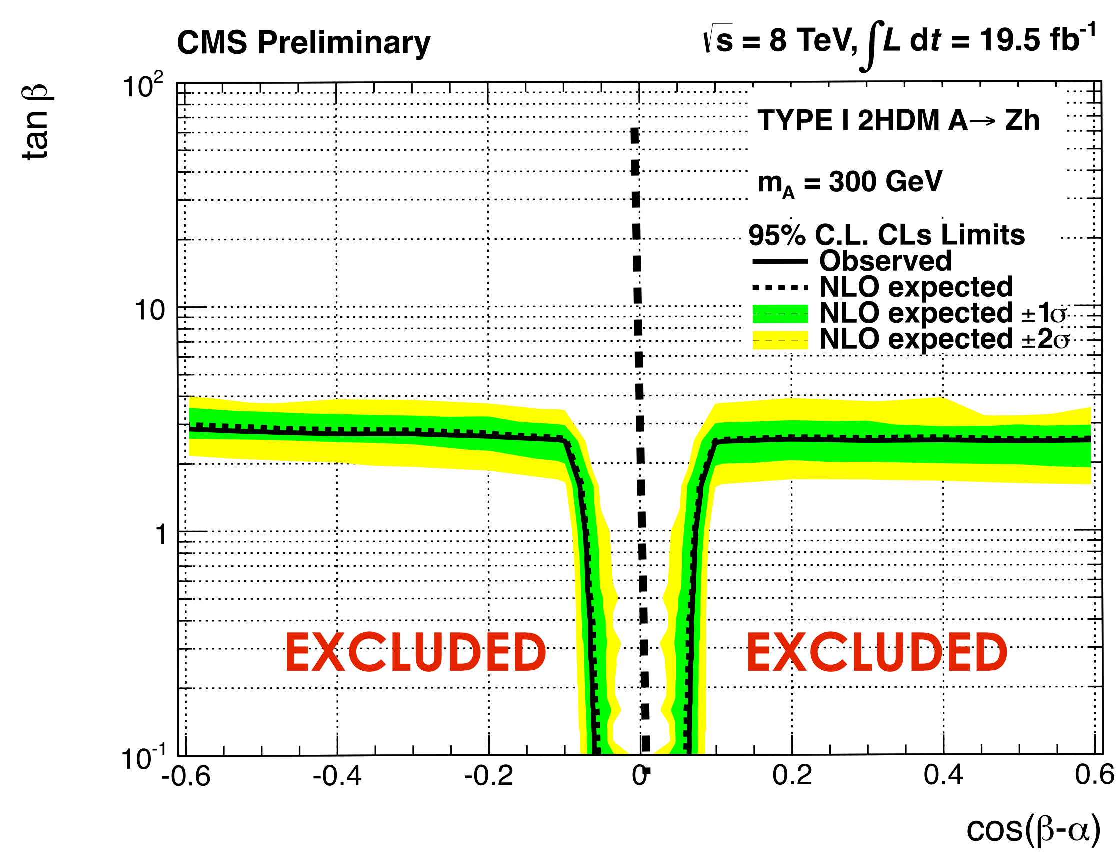
- Search procedure in **exclusive channels depending upon the number of flavor of leptons, hadronic taus, photons, jet flavors and missing energy.**

- Observed and expected limits in the 2HDM for masses in the range **[260-360] GeV**

- **α and β determine cross-section and BRs for H and A production and decays**

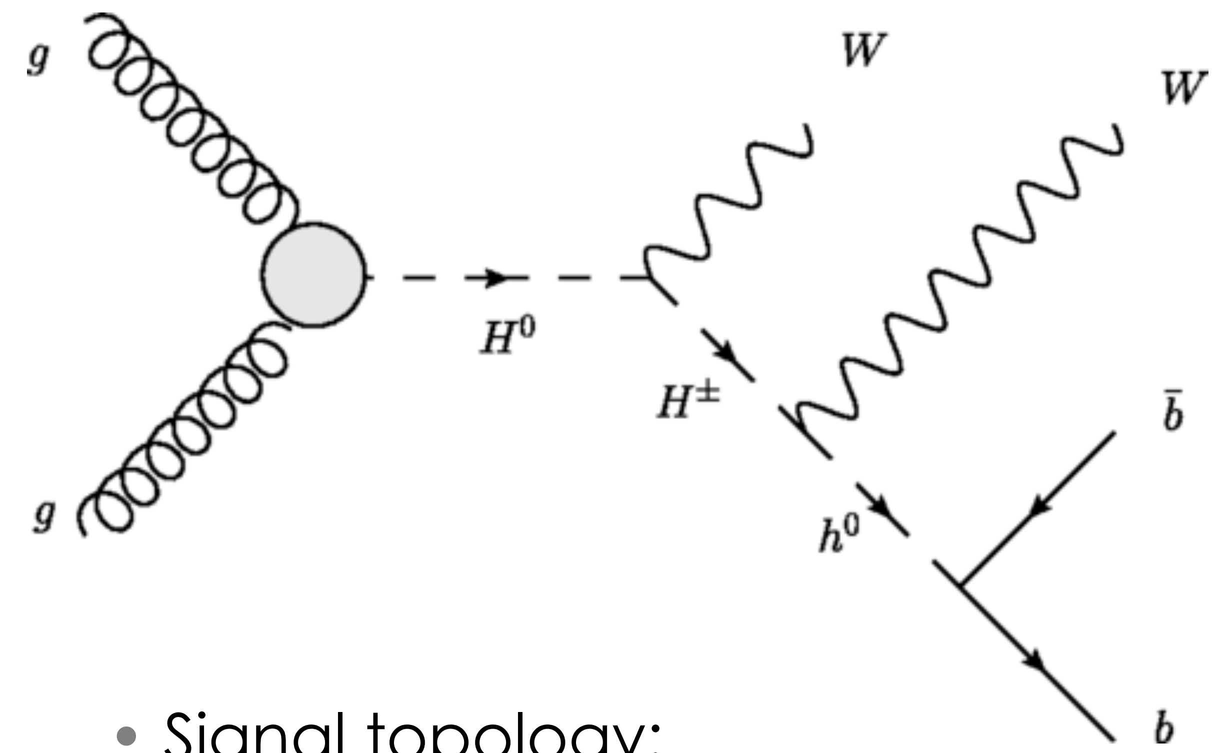
$\cos(\beta - \alpha) = 0$: Decoupling limit: h behaves exactly like in SM





ATLAS search for multi-Higgs sector

- Single heavy neutral **H** decays to charged **H^{+-}** and a **W**.
  H^{+-} decaying to W and ***h*** and *h* to **bbar pair**.



- One W assumed to decay **hadronically** and the other **leptonically**

- Signal topology:
  1. One lepton + MET
  2. At least 4 jets - 2 b-tagged

- **MultiHiggs Cascade** relevant for m_H > 800 GeV

- Main background contributions:
  1. ttbar (~90%)
  2. V+ jets

  → Estimated from simulation and validated in control regions

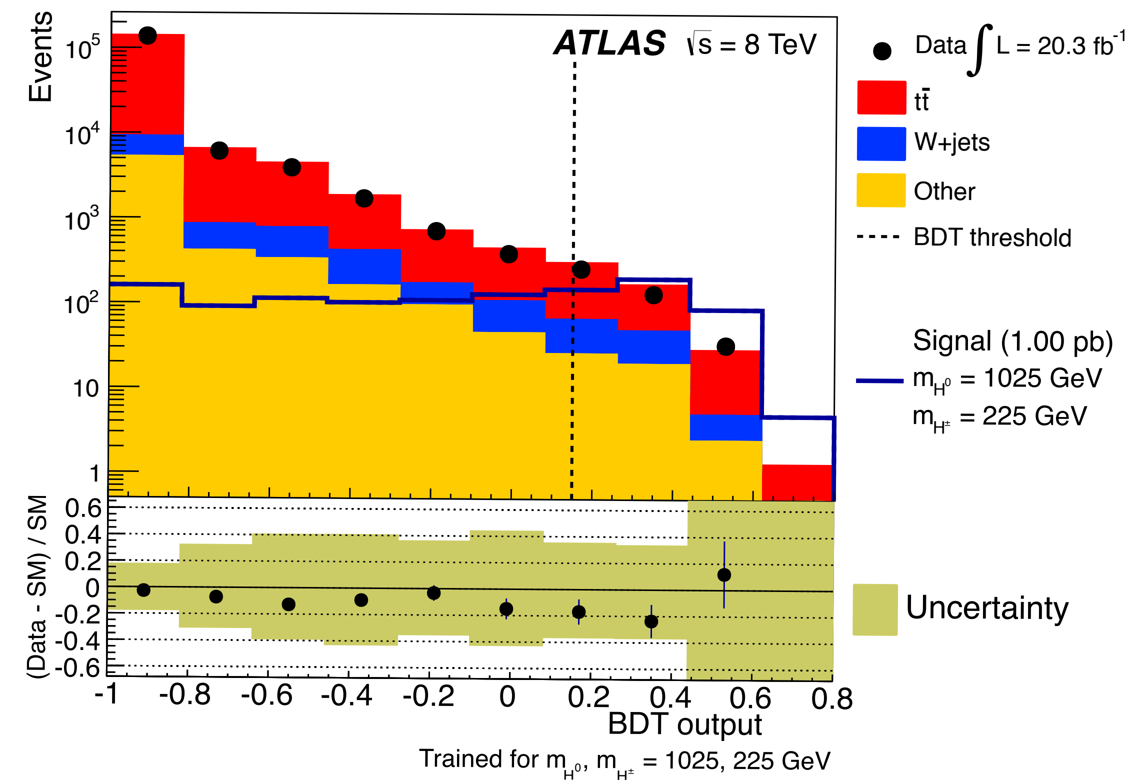
  3. Multi-jets

  → Small. Estimated from data

Results

- **Multivariate analysis** to discriminate signal and main bkg ttbar

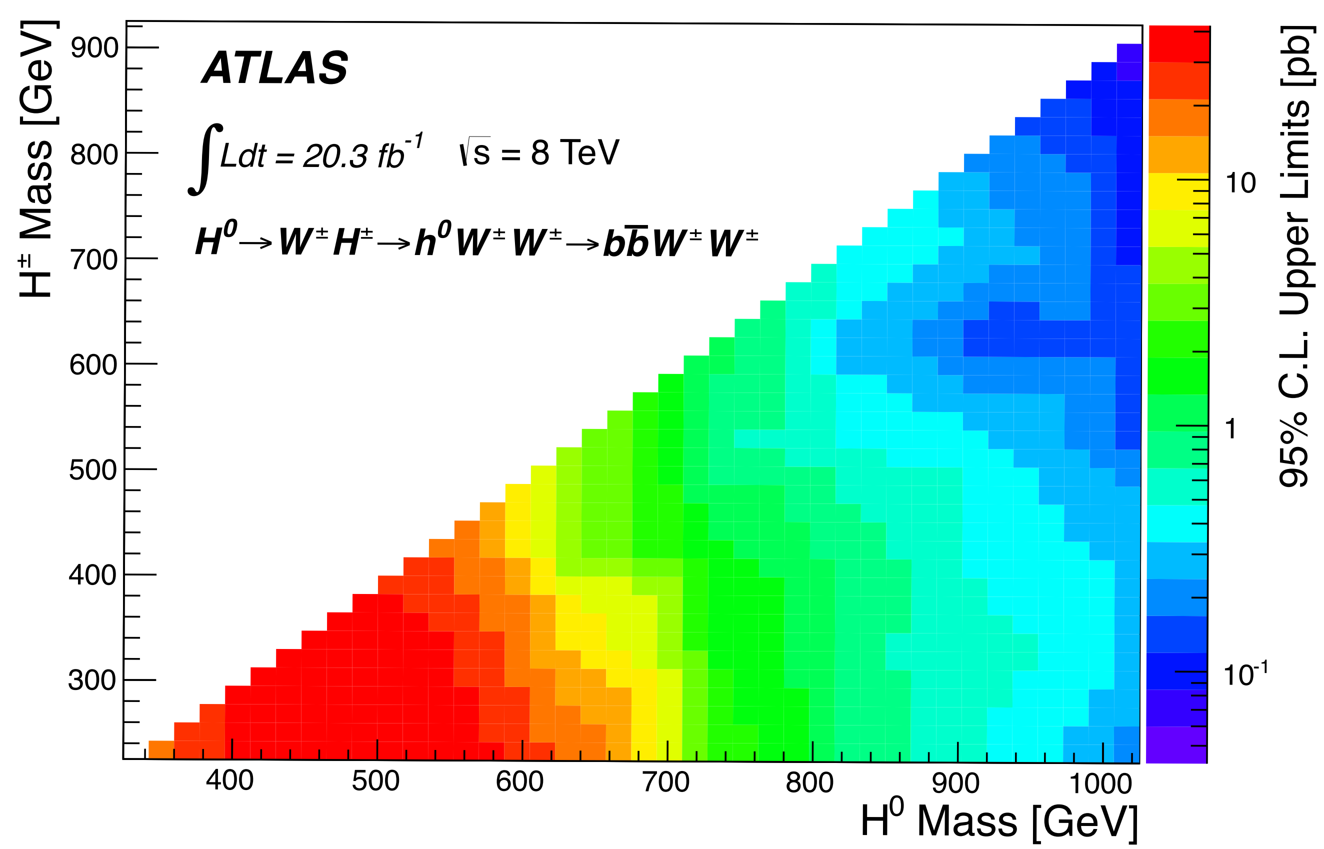
- **Counting experiment** with events passing the BDT output threshold



- Observed and expected 95% CL model independent upper limits on cross-section

- Analysis performed for any **combination of m_H and m_{H+-}**

- Gain sensitivity for **Very High Masses**



X->hh

CMS PAS HIG-13-032 NEW

ATLAS: CERN-PH-EP-2014-113

ATLAS-CONF-2014-005 NEW

Overview

- **Heavy H resonant** search performed in channels which allow **full reconstruction of the decay chain**

$$X \rightarrow hh \rightarrow ?$$

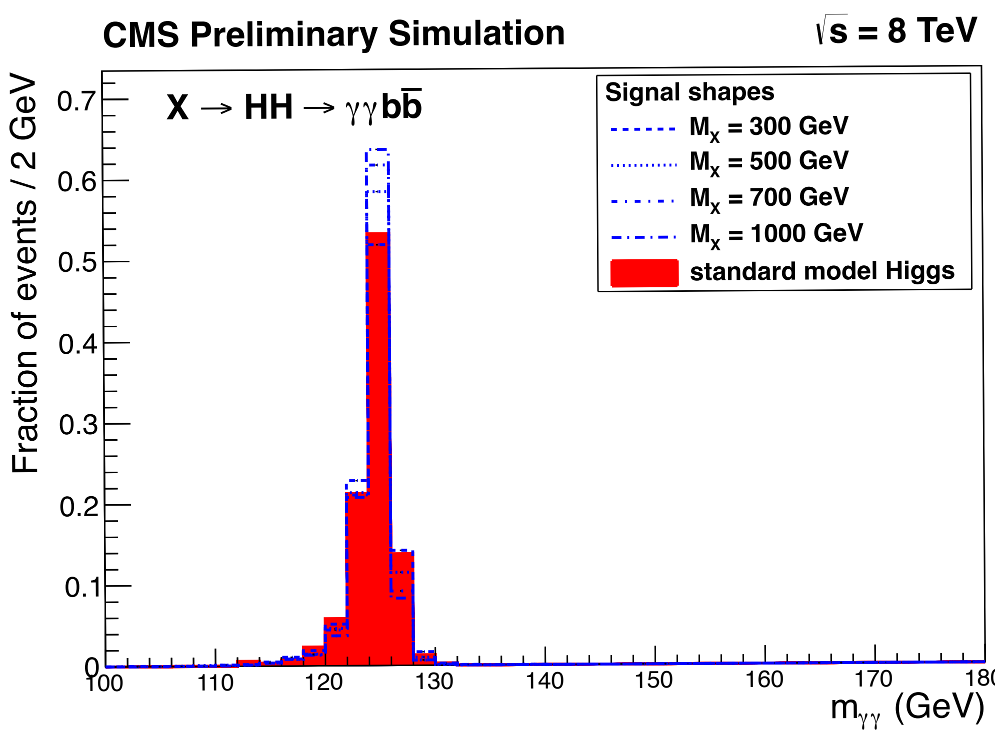
- Non Resonant SM Higgs pair production not expected to be observable at LHC 8 TeV

	CMS	ATLAS
$\gamma\,\gamma$ bb	V	V
$\gamma\,\gamma$ bb non resonant		V
bbbb		V

- **Model independent** analyses: Results interpreted in terms of **Graviscalars or Radion** production

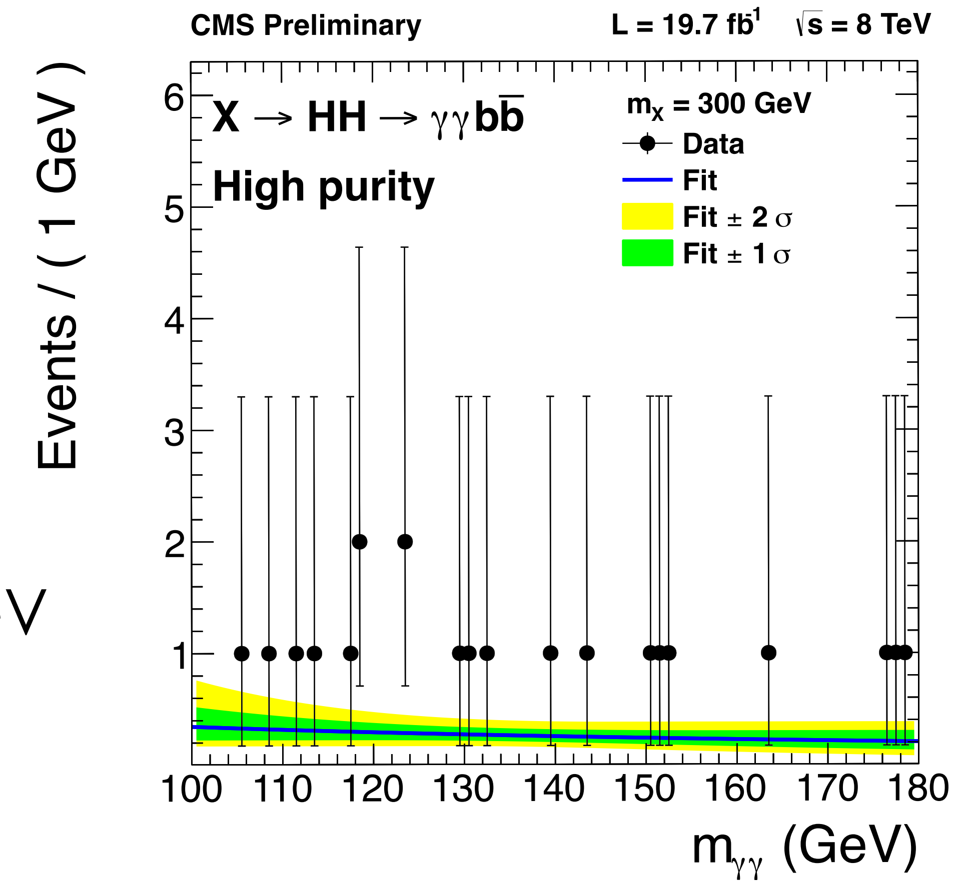
- $\gamma\,\gamma$ bb: **Large BR of the H → bbar** and the **low background and good resolution of the H → $\gamma\gamma$ channel**

- bbbb: **More sensitive at high mass**



$\gamma\,\gamma$ bb Analysis Strategy

- **CMS[260-1100]GeV**: Analysis performed in **two ranges: m_X<400 GeV and m_X > 400 GeV**
  - Low mass: signal extracted from a **fit to the $m_{\gamma\gamma}$ data spectrum**
  - High mass: similar procedure with a **fit to the $m_{\gamma\gamma jj}$**

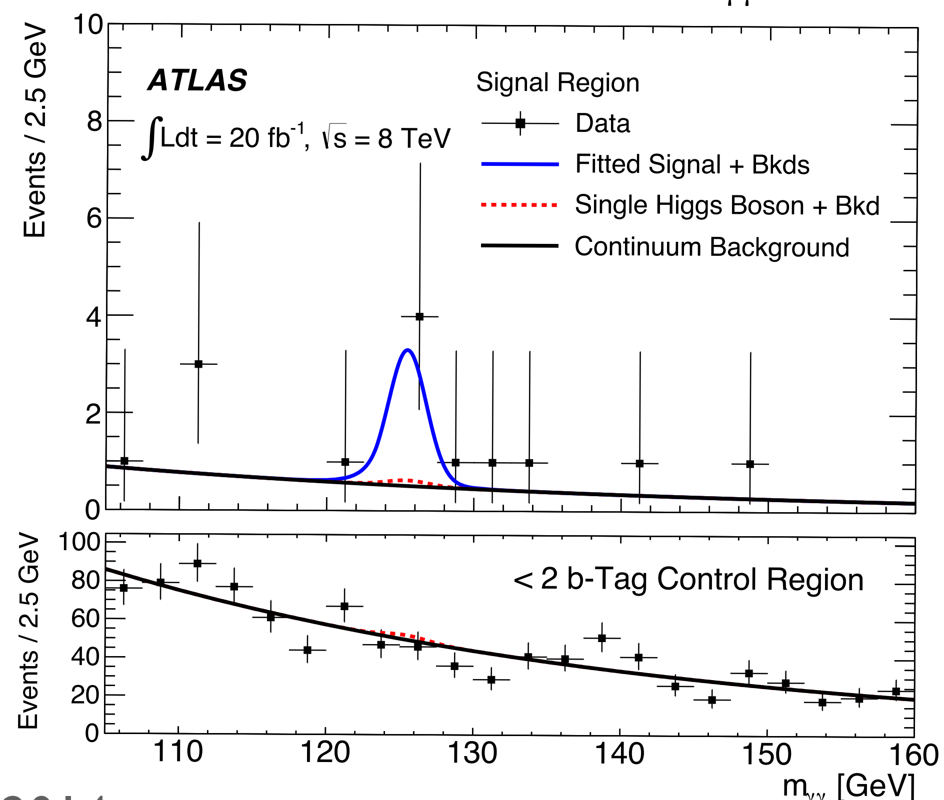


Not possible to fit a bump in the $m_{\gamma\gamma jj}$ below 400 GeV
$m_{\gamma\gamma jj}$ has **kinematic peak ~300 GeV**

- **ATLAS [260-550]GeV**:
  - Non resonant search:

    Fit to the unbinned $m_{\gamma\gamma}$ spectrum
  - Resonant production search:

    Counting experiment due to small number of expected events



bbbb Analysis Strategy

- 4-tag selection: **4 b-tagged high energy jets**

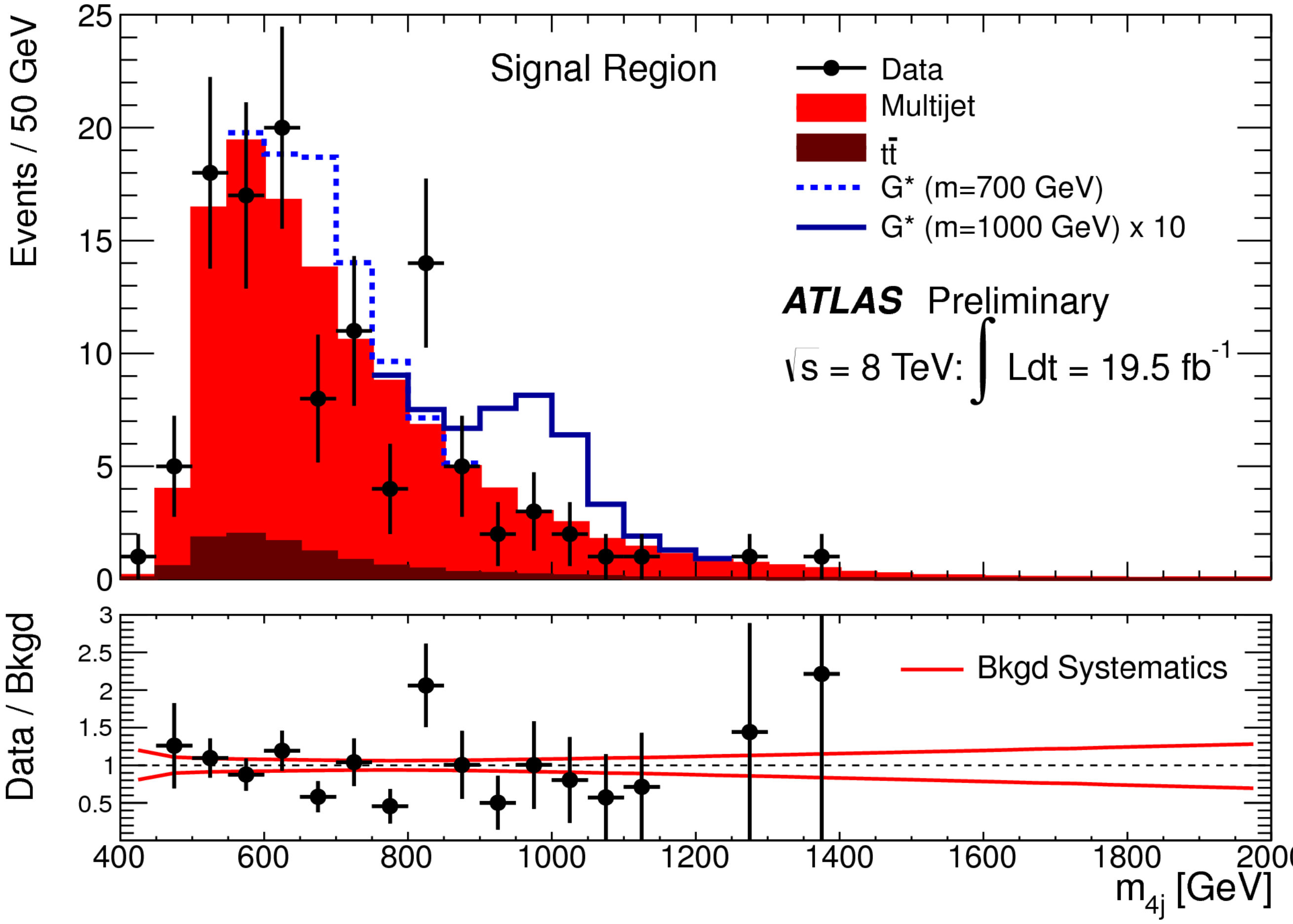
- Kinematics requirement on dijet system to **veto ttbar events**

- **Elliptical cut in the plane of the leading and the subleading dijet invariant mass**

$$X_{HH} = \sqrt{\left(\frac{m^1_{jj} - \tilde{m}^1_{jj}}{\sigma_{m^1_{jj}}}\right)^2 + \left(\frac{m^2_{jj} - \tilde{m}^2_{jj}}{\sigma_{m^2_{jj}}}\right)^2}$$

- >90% background in the signal region from **multijet events** + 10% **ttbar**

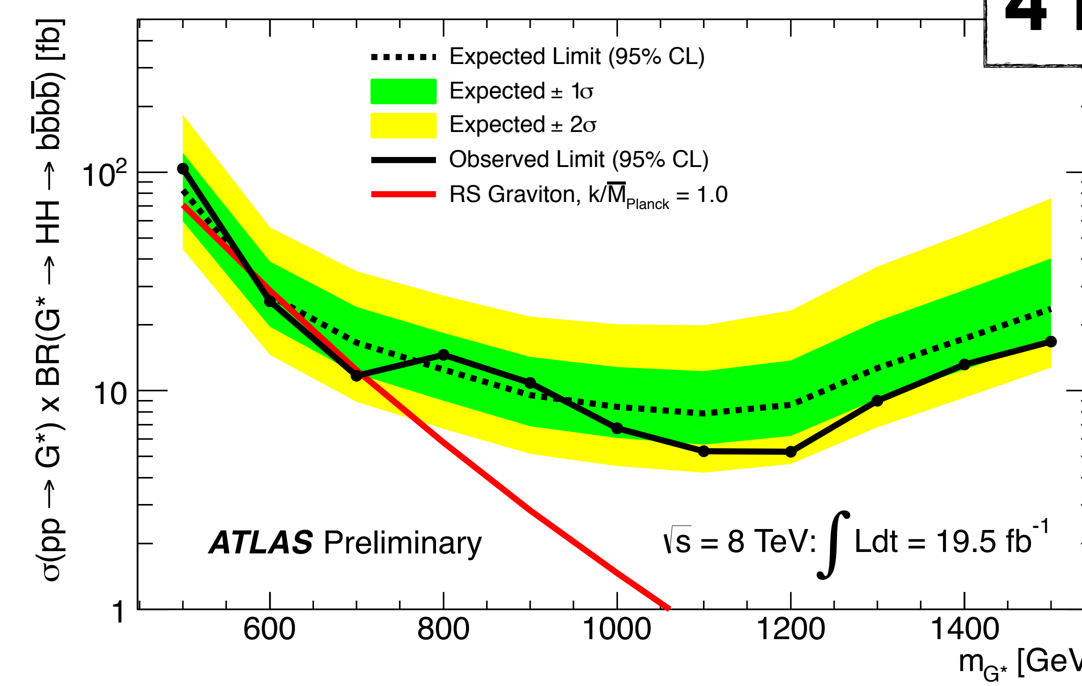
<u>Multijet</u>: m_{4j} shape and normalization from data
<u>ttbar:</u> m_{4j} shape from MC and normalization from data



Results

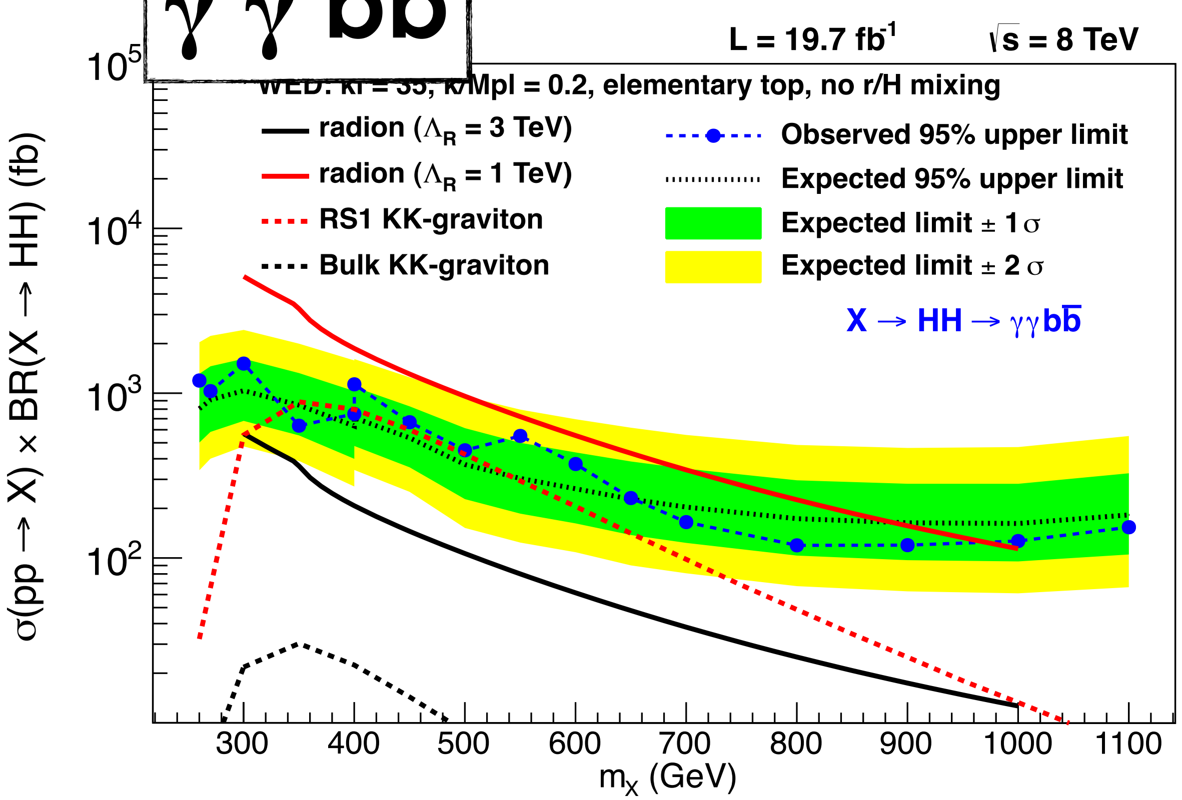
- 95% CL Upper Limits set on the cross-section times BR of the process
- <u>Non Resonant Search</u> assuming SM BR(hh): **Exp (Obs) 1.0 (2.2) pb**

4 b-jets

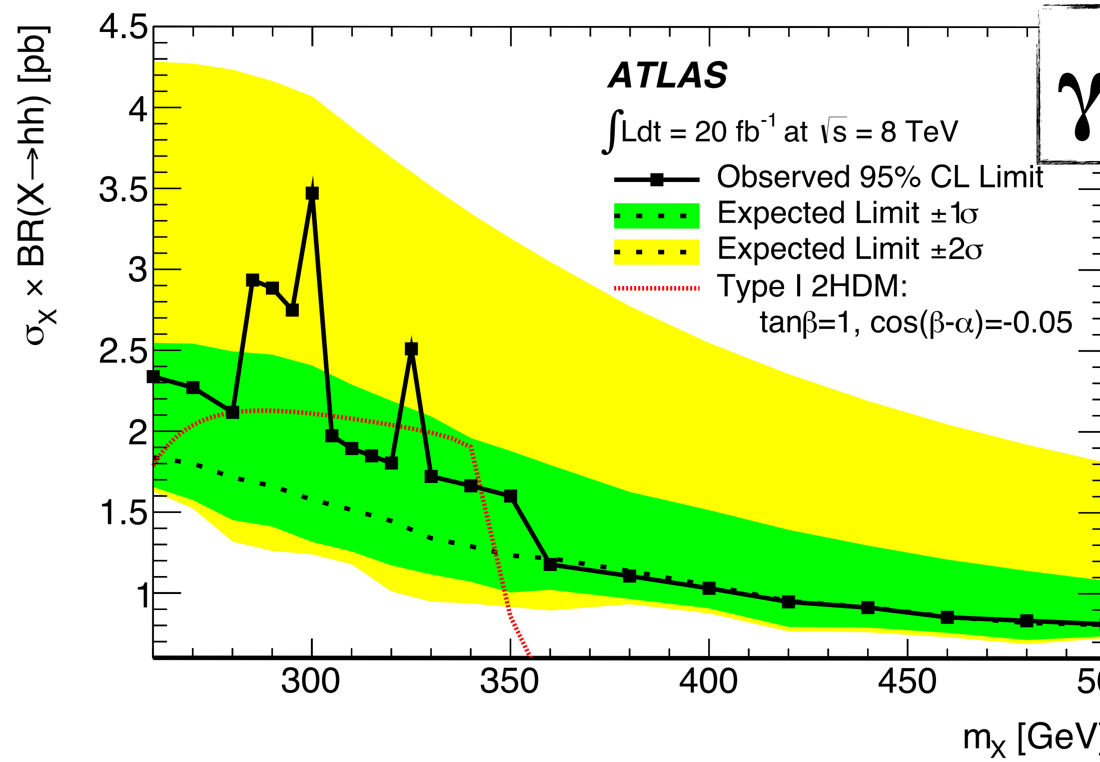


- <u>Resonant Searches:</u> Results interpreted in terms of **KK-graviton, radion and 2HDM models**

γ γ bb



γ γ bb



$X \to \gamma\gamma$

CMS PAS HIG-14-006 NEW

ATLAS-CONF-2014-031

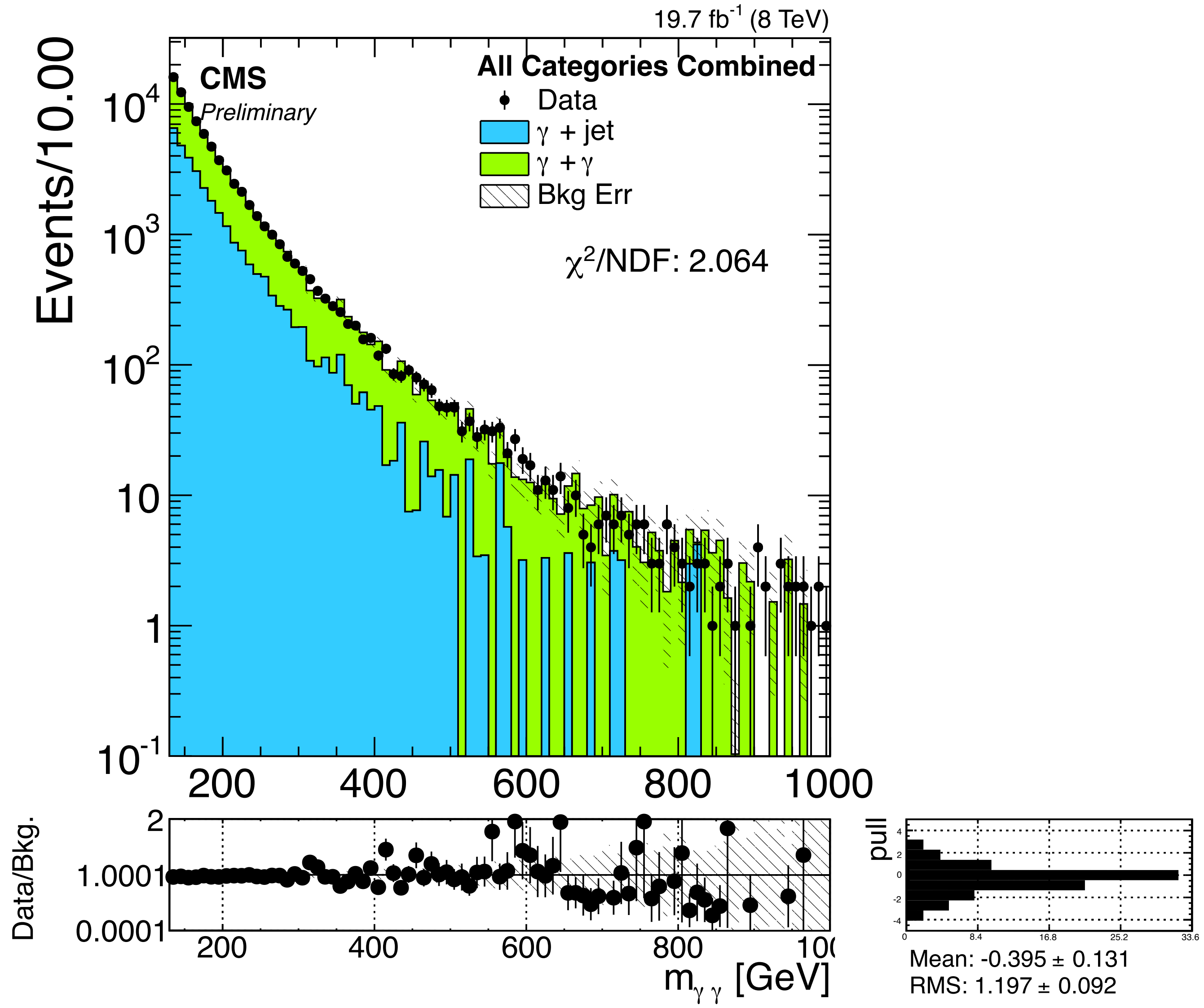
Overview

- **Model Independent search for local excesses in the diphoton spectrum exploiting a fit technique**

  H $\rightarrow \gamma\gamma$ interesting in 2HDM in the **decoupling limit**

- Method developed for the **SM H** $\rightarrow \gamma\gamma$ **channel extended to search for diphoton resonances in a wider mass range**

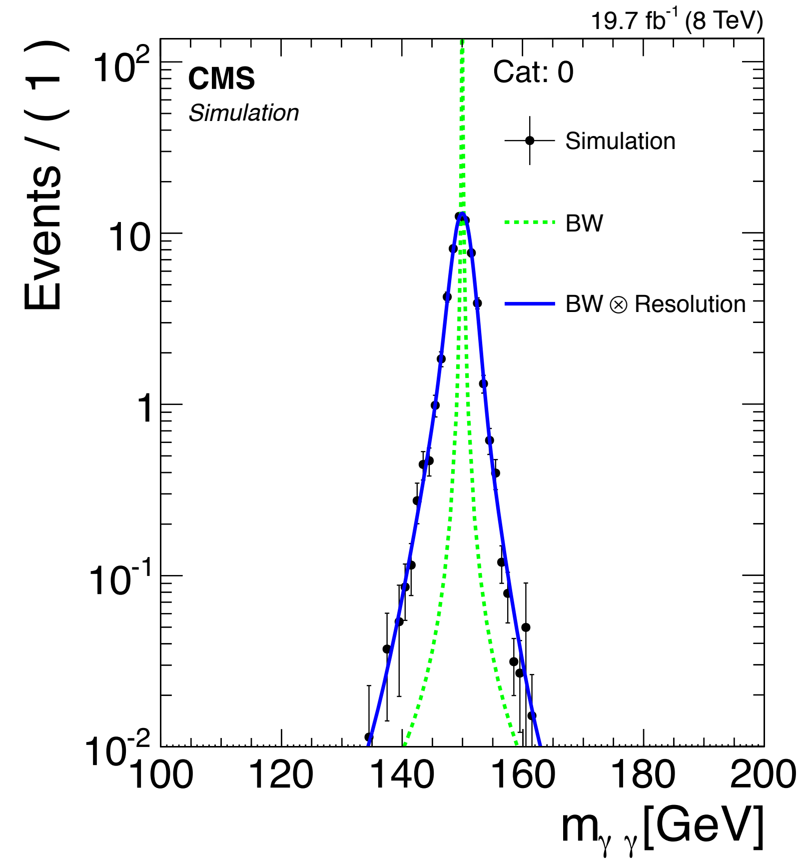
	CMS	**ATLAS**
Mass Range [GeV]	150-850	65-600
Width Range [GeV]	0-85	0
Spin	0,2	0



CMS Analysis

- **High Mass** analysis performed in **four classes** according to the two photons kinematics properties to increase the search sensitivity

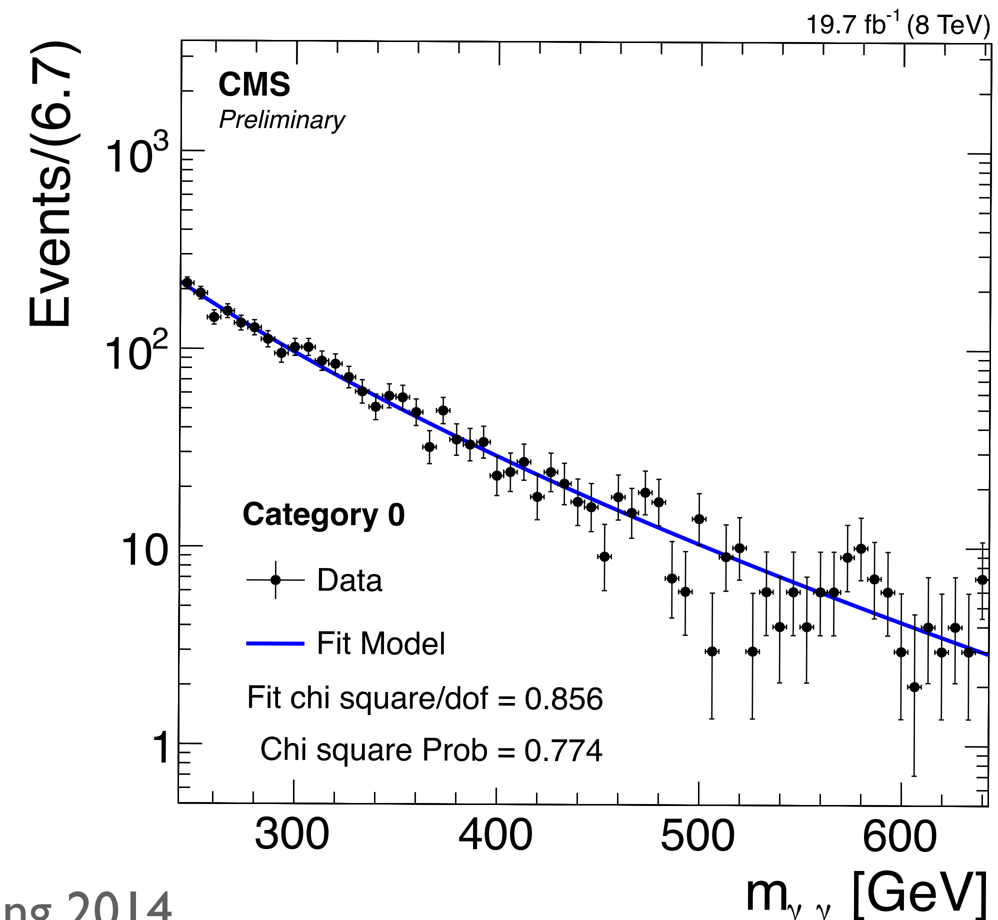
- **Parametrized signal** model through analytic function with **two free parameters: m_X and Γ_X**



- **Background** estimated **fitting directly data** assuming negligible signal

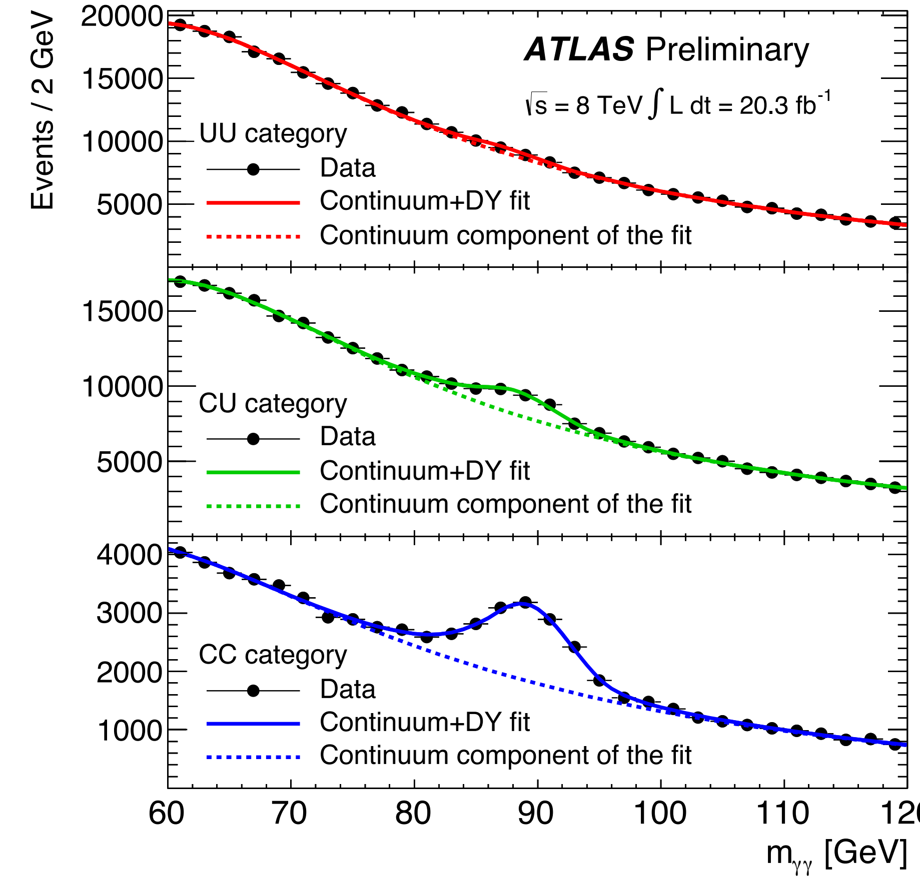
Sliding window fit range

Bias Study to validate the fit technique



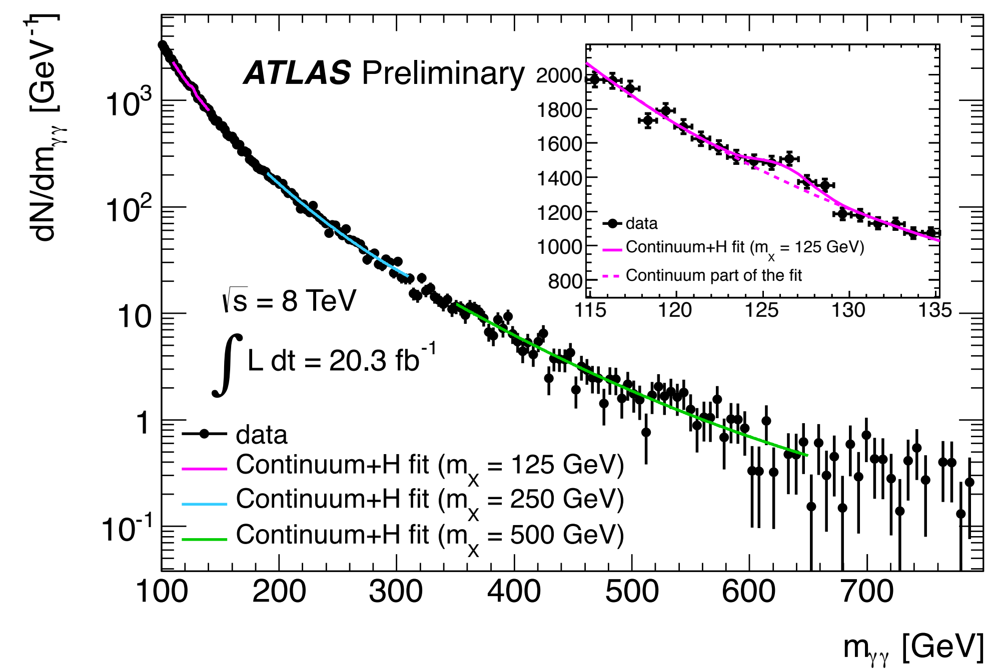
ATLAS Analysis

- Search split into a **categorized low-mass [65-110] GeV** and a **inclusive high mass [110-600] GeV analysis**



- Low-mass: Main background from Drell-Yan production estimated from data.

  Events categorized according to the **number of converted photons**



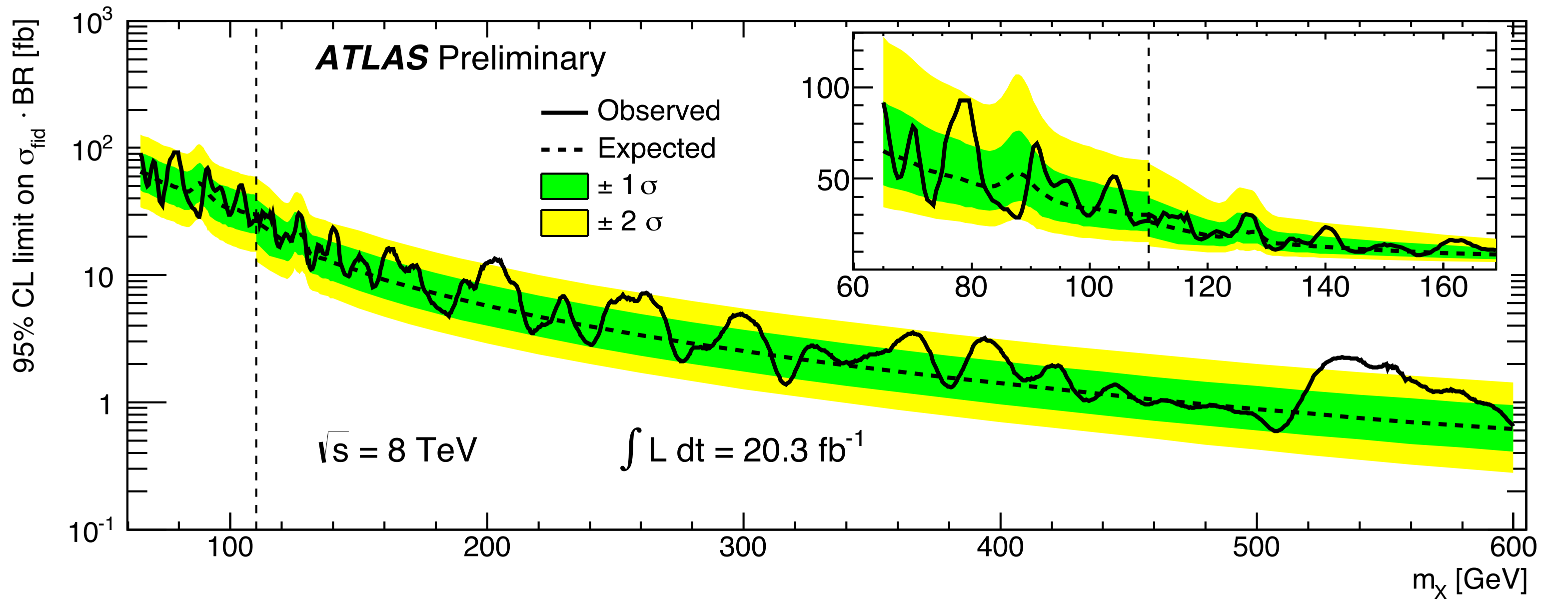
- High-mass: Sliding window fit range using **analytic function**

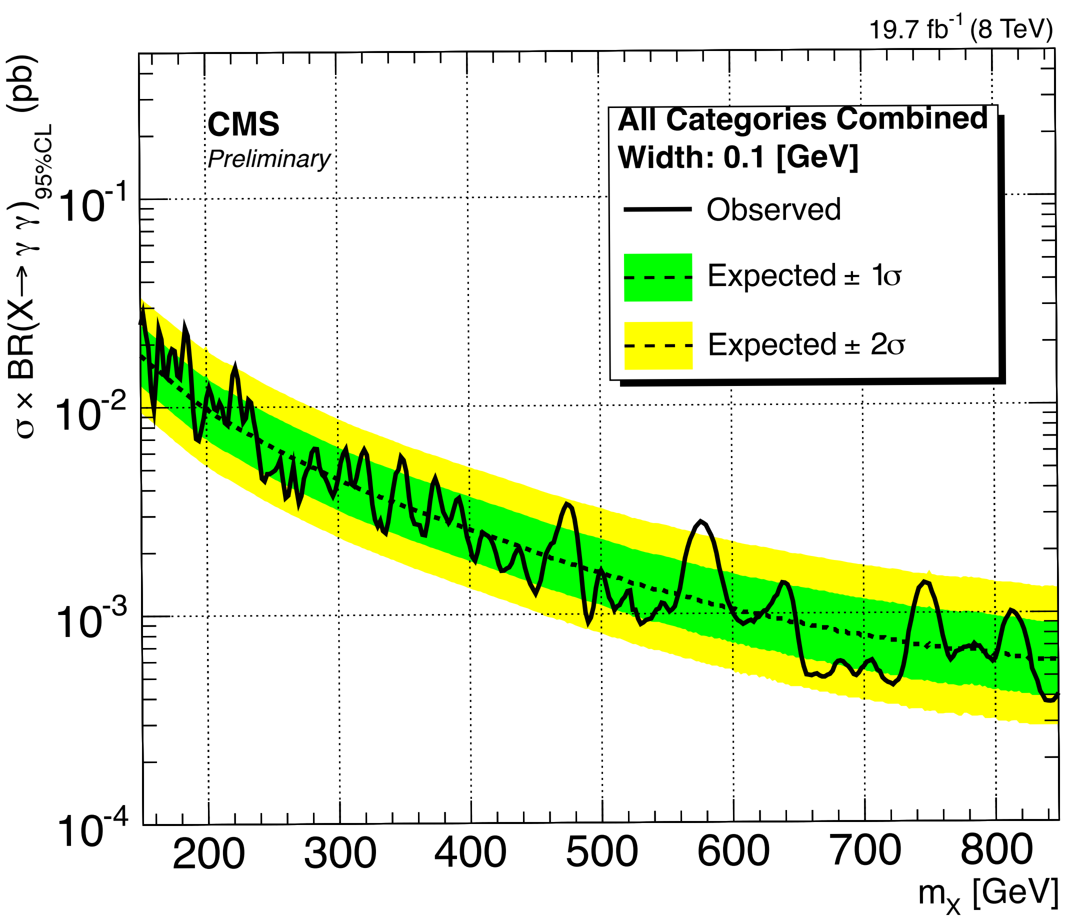
  SM-Higgs production as background

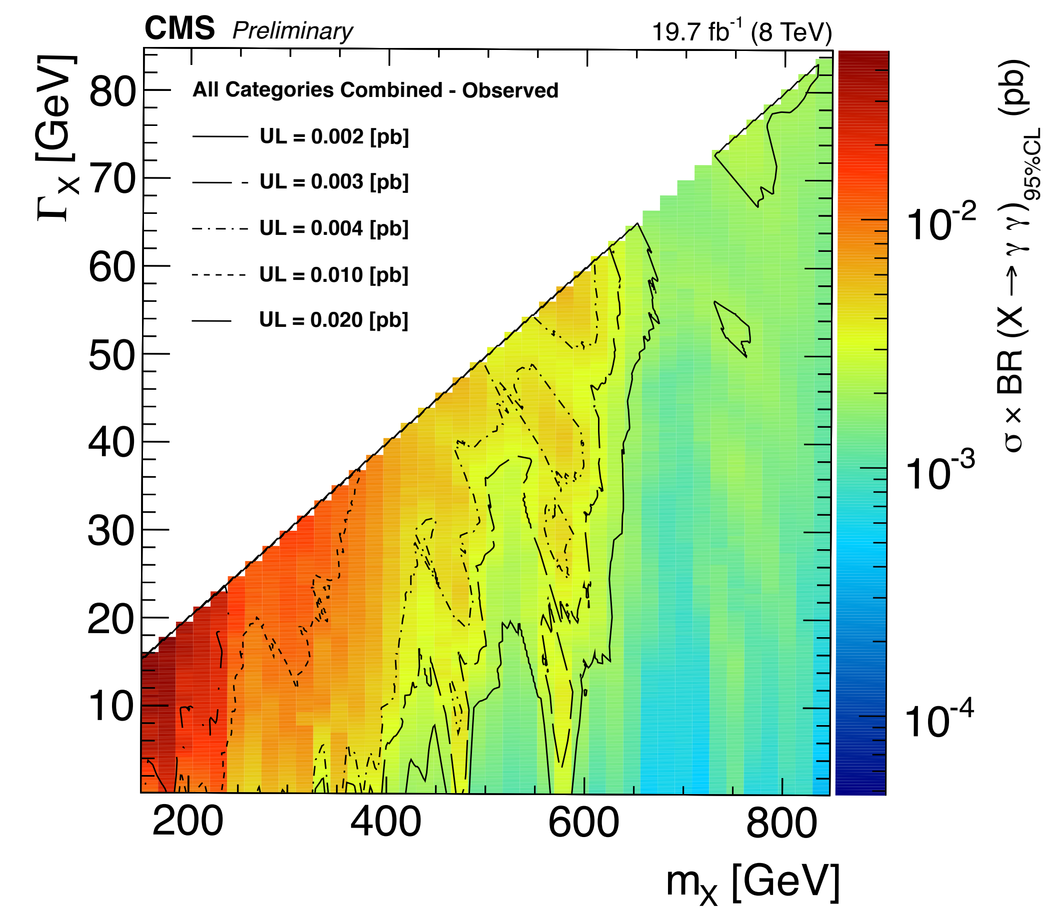
- Parametrized **narrow signal** model with **m_X parameter**

Results

- No excess observed over the full mass range. 95% CL limits set on the fiducial cross-section times BR







Conclusions

- Search for BMS physics in the Higgs sector:

  Directly from **decays of neutral and charged Higgses**

  Indirectly by **interpreting measured properties** of the light Higgs

- Many analyses completed at **ATLAS + CMS** on **full 8 and 7 TeV data**:

  No significant excess observed and various **cross-section limits and exclusion regions for the parameter space of several models** have been provided.

- **2015 and sqrt(s)=13 TeV** will greatly enhance our sensitivity

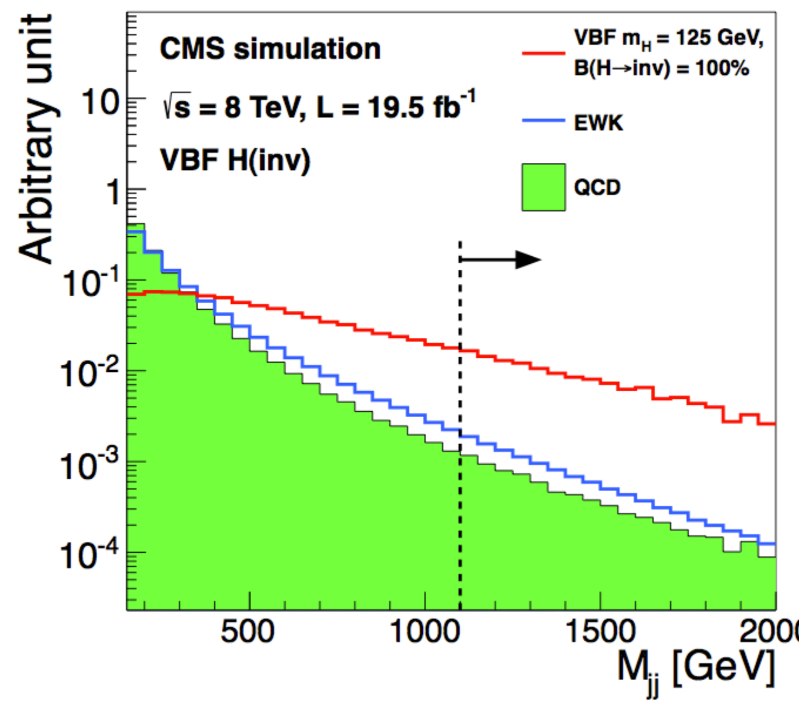
  BSM Higgses might be just around the corner...

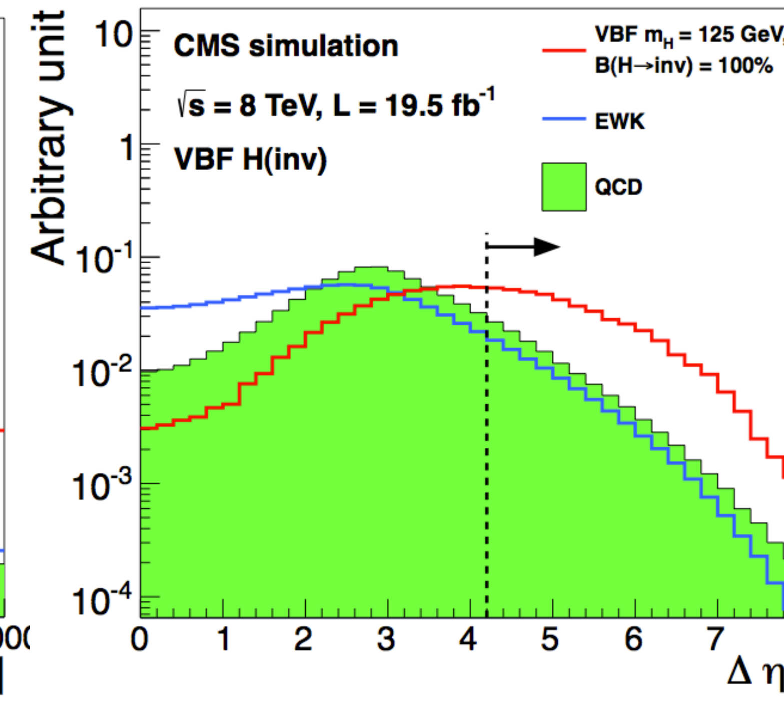
BACKUP

Invisible:Search in VBF and ZH channels

- <u>VBF Signal topology:</u>

  1. Two final state quarks separated by a **large rapidity gap** and with **high invariant mass**
  2. Large **missing energy**



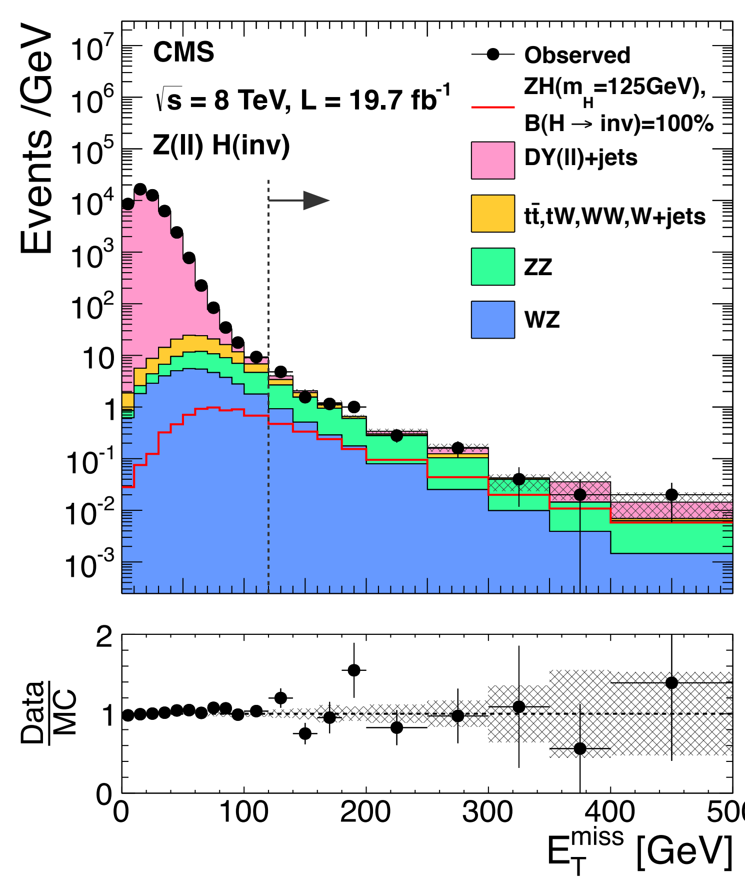


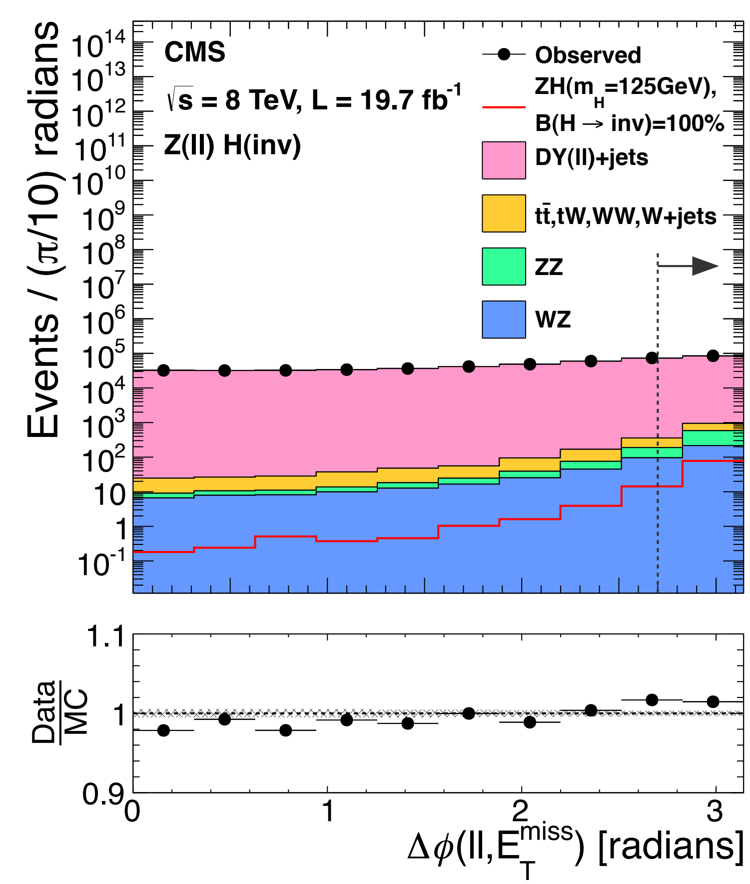
- <u>ZH Signal topology:</u>

1.**Z(ll)H(inv)**: Pair of **isolated leptons** and **High MET** - Limited jet activity

2.**Z(bbar)H(inv)**: **B-tagged jet pair** and High MET (same as Z(νν)H(bbar))

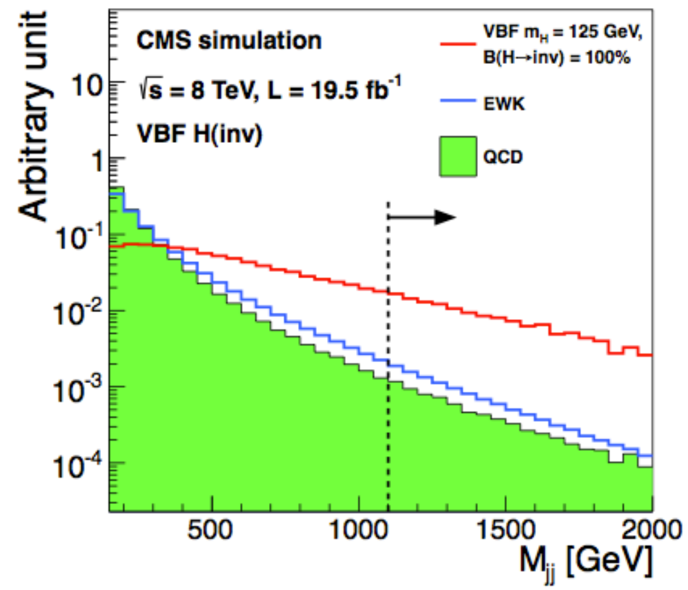
Angular separation MET-Z system

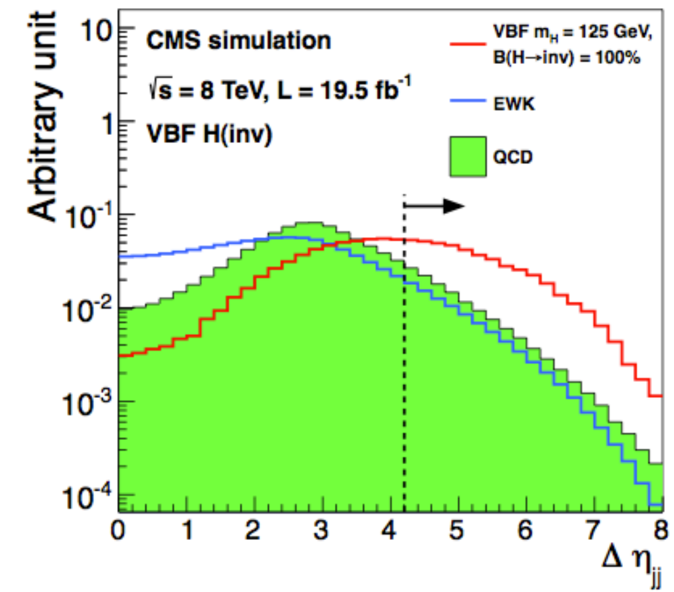




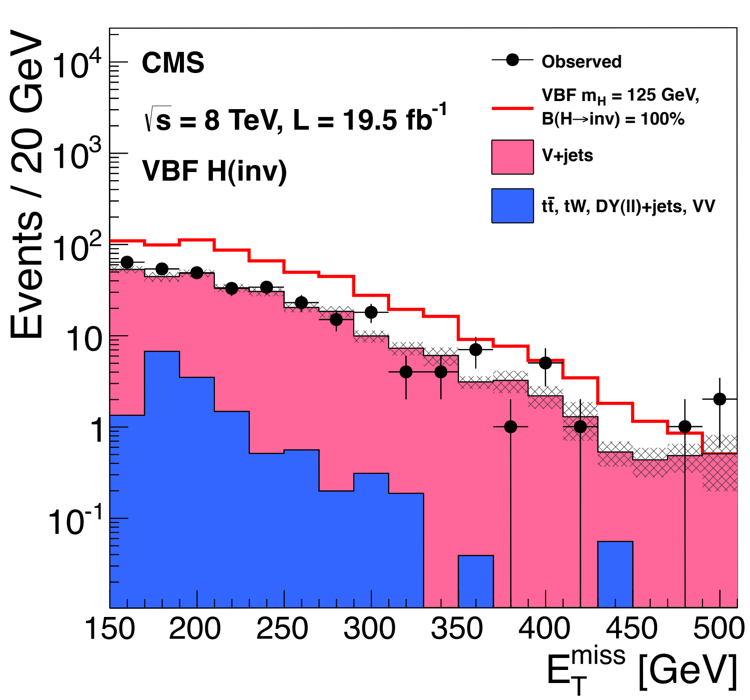
INVISIBLE:Search in vector boson fusion channel

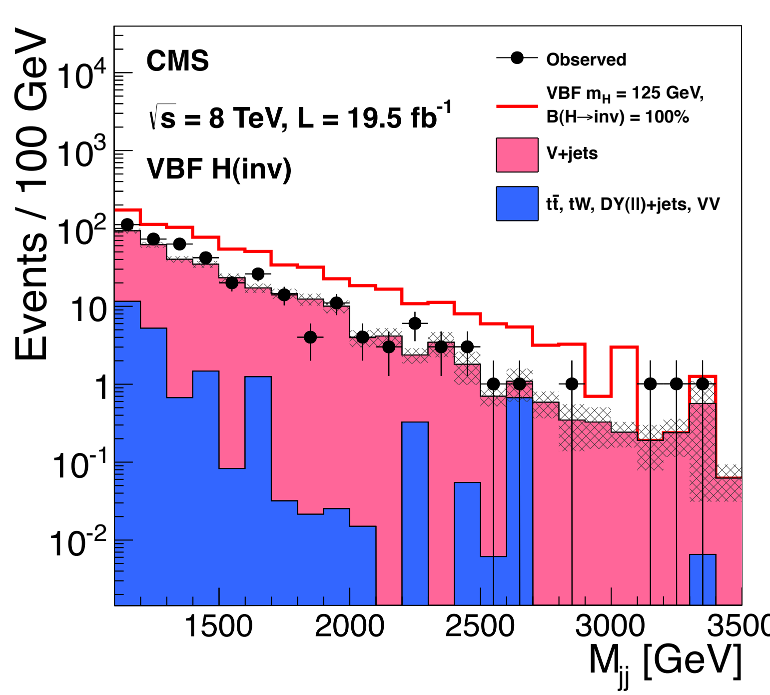
- Signal topology:
  1. Two final state quarks separated by a large rapidity gap and with high invariant mass
  2. Large missing energy





- Main background from V+jets estimated from control regions in data
- Signal region defined: MET > 130 GeV && m_{jj} > 1100 GeV && $\Delta\eta$>4.2





Process	Event yields
$Z(\nu\nu)$+jets	99 ± 29 (stat.) ± 25 (syst.)
$W(\mu\nu)$+jets	67 ± 5 (stat.) ± 16 (syst.)
$W(e\nu)$+jets	63 ± 9 (stat.) ± 18 (syst.)
$W(\tau_h\nu)$+jets	53 ± 18 (stat.) ± 18 (syst.)
QCD multijet	31 ± 2 (stat.) ± 23 (syst.)
Sum ($t\bar{t}$, single top quark, VV, DY)	20.0 ± 8.2 (syst.)
Total background	332 ± 36 (stat.) ± 46 (syst.)
VBF H(inv.)	210 ± 30 (syst.)
ggF H(inv.)	14 ± 11 (syst.)
Observed data	390
S/B (%)	70

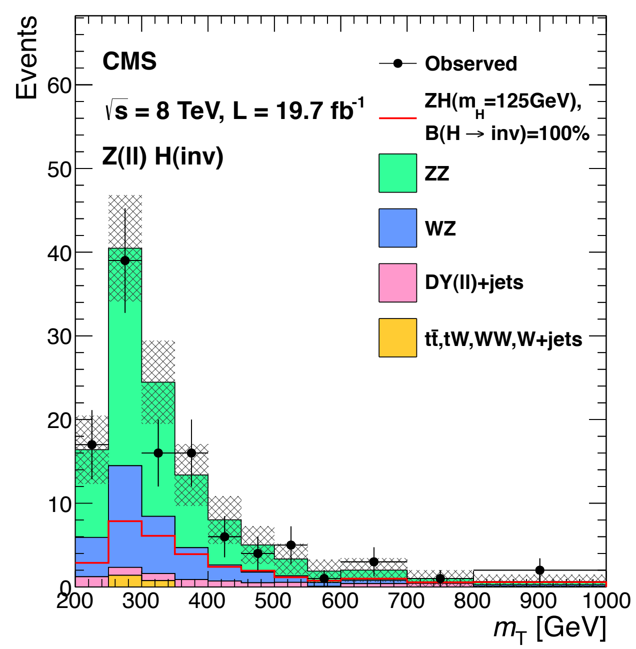
INVISIBLE:Search in associated channel

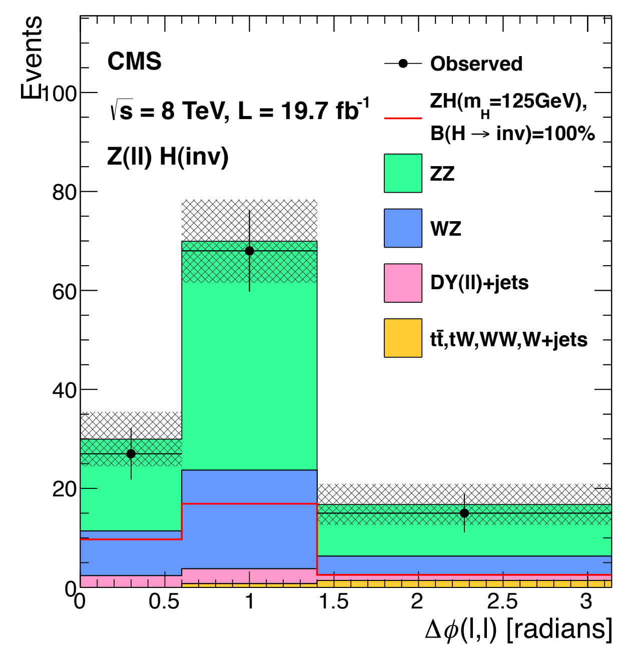
- Signal topology:
  1. Z(ll)H(inv): Pair of isolated leptons and High MET - Limited jet activity
  2. Z(bbar)H(inv): B-tagged jet pair and High MET

- Dominant background from boson and diboson production w/o jets estimated from control regions.

- Signal region 1: MET > 120 GeV, $\Delta\phi$(ll, MET)>2.7, $|\text{MET}-p_{T,ll}|/p_{T,ll}$

Signal extracted with a 2-dimensional fit of $\Delta\phi$ and m_T of the dilepton-MET system





- For the Z(bb)H(inv) a BDT technique is used to select the signal.

LFV: Analysis strategy

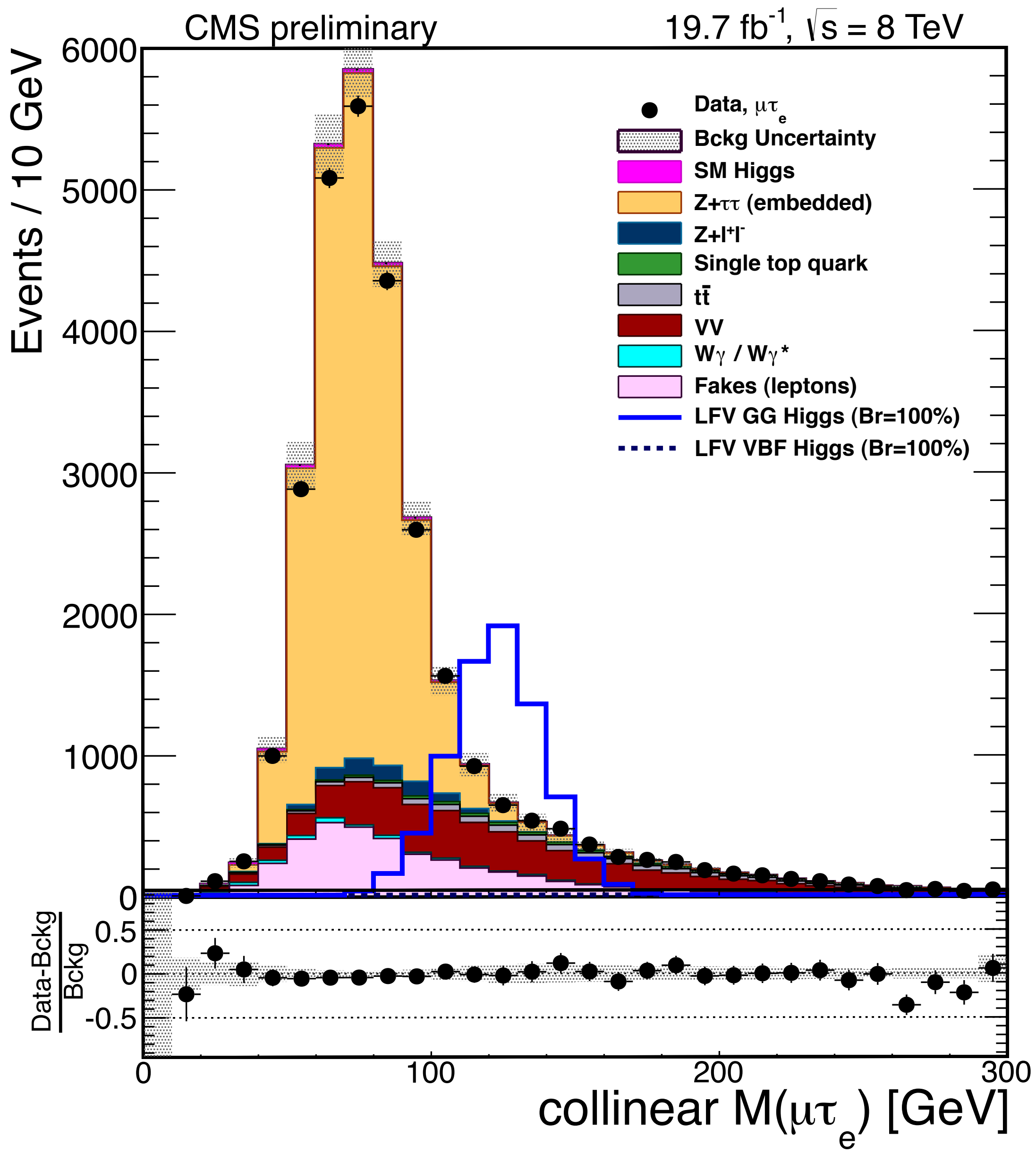
- **$M_{collinear}$** between de decay products as **estimator of the Higgs mass**

  Exploit the kinematics of the boosted τ from H decay

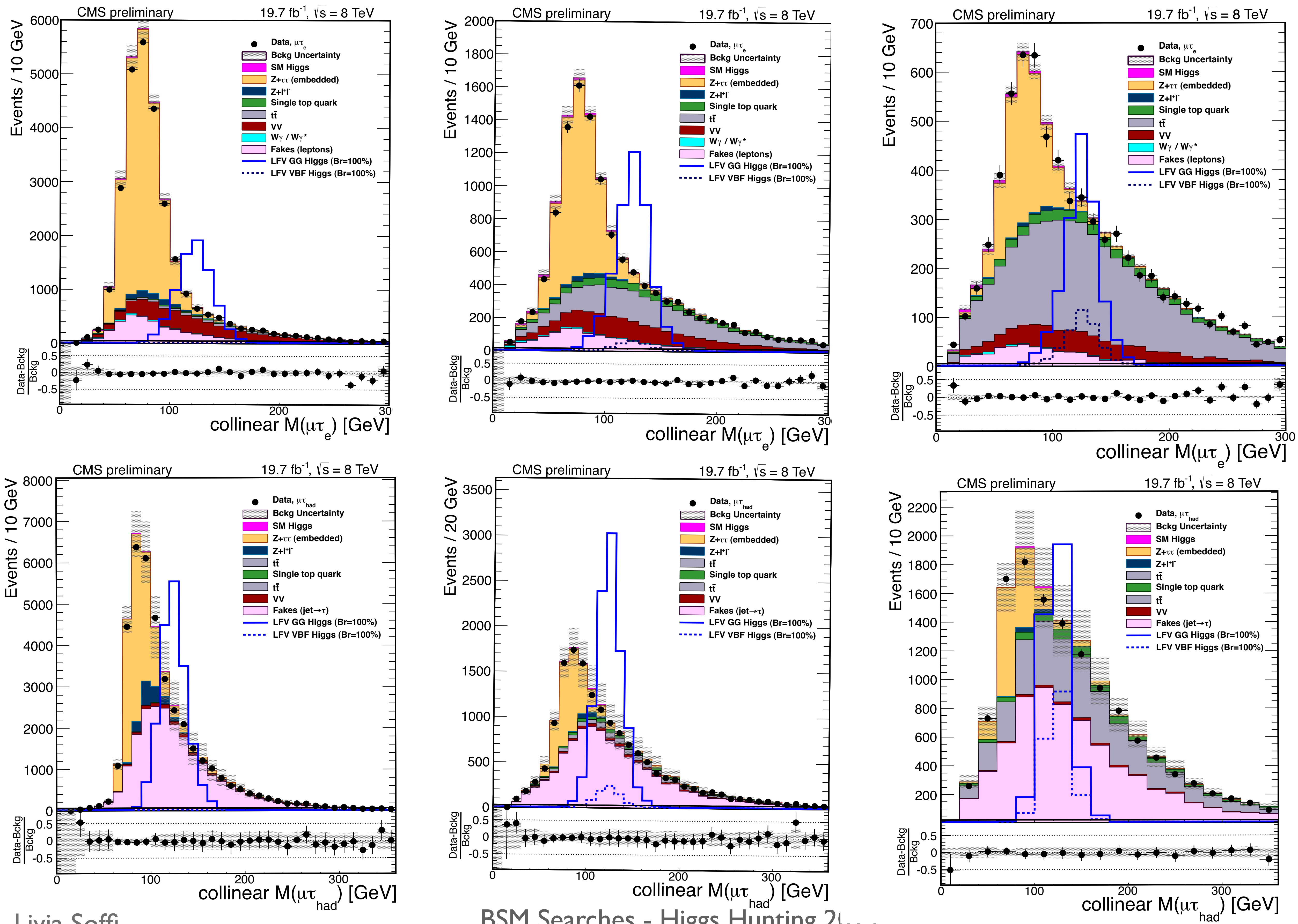
$$M_H = M_{collinear} = \frac{M_{vis}}{\sqrt{x_{\tau_{vis}}}}$$

- Events divided into categories according to the **number of jets** in the event

- $Z \rightarrow \tau\tau$ and misidentified leptons from W+jets and QCD multi-jet from data



LFV: Mass spectra



2HDM: Background estimation

- Multilepton searches allow probing regions of parameter space inaccessible to hadronic searches.
  - Main reducible contributions:

    1. Z+jets, W+jets with bosons decay leptonically and additional *fake* lepton → Estimated from data
    2. ttbar with W's leptonically decays → Evaluated in control regions

  - Irreducible contributions:

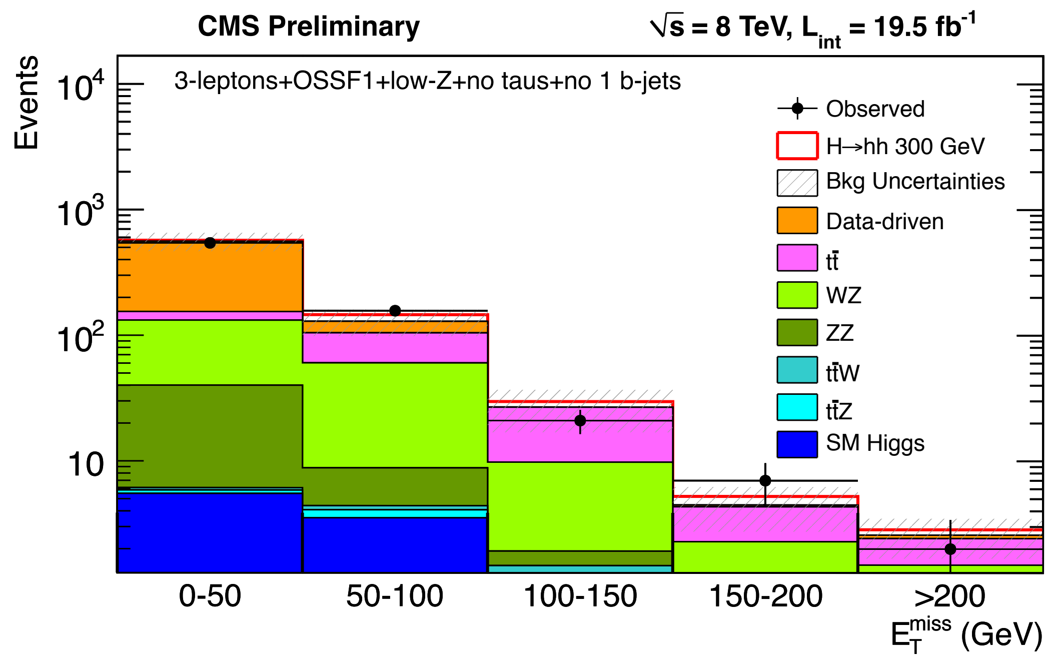
    1. VV+jets with >=3 real leptons
    2. Drell-Yan processes with internal asymmetric conversions

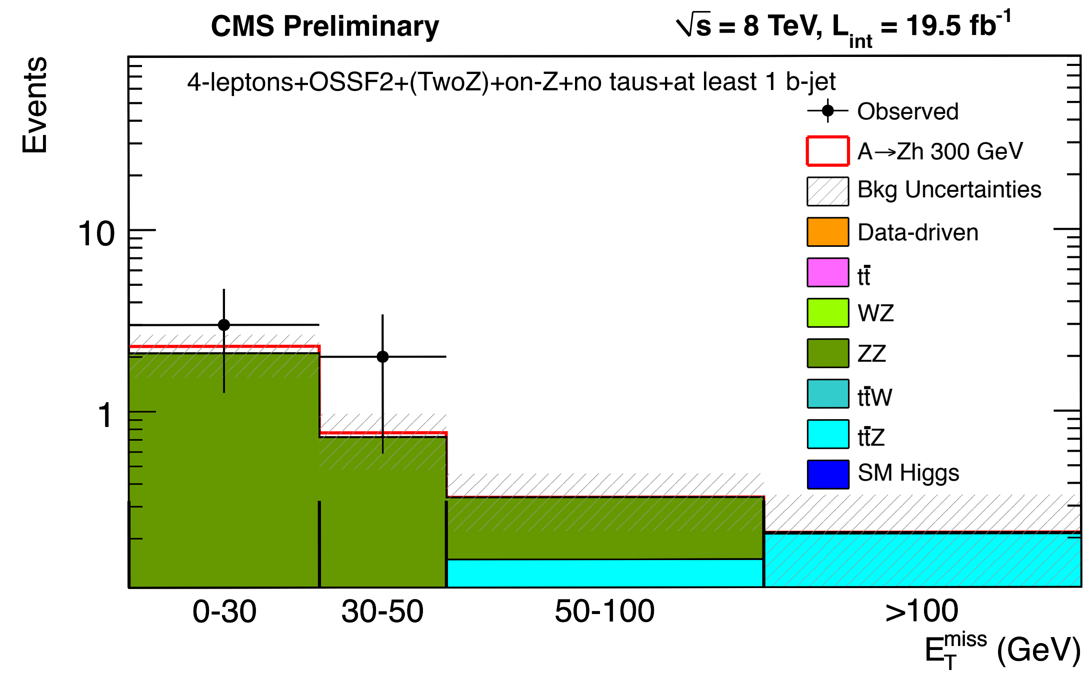
- Diphoton plus lepton searches:

  Main background reduced by the diphoton mass cut around the SM-Higgs observed value → Estimated with sidebands

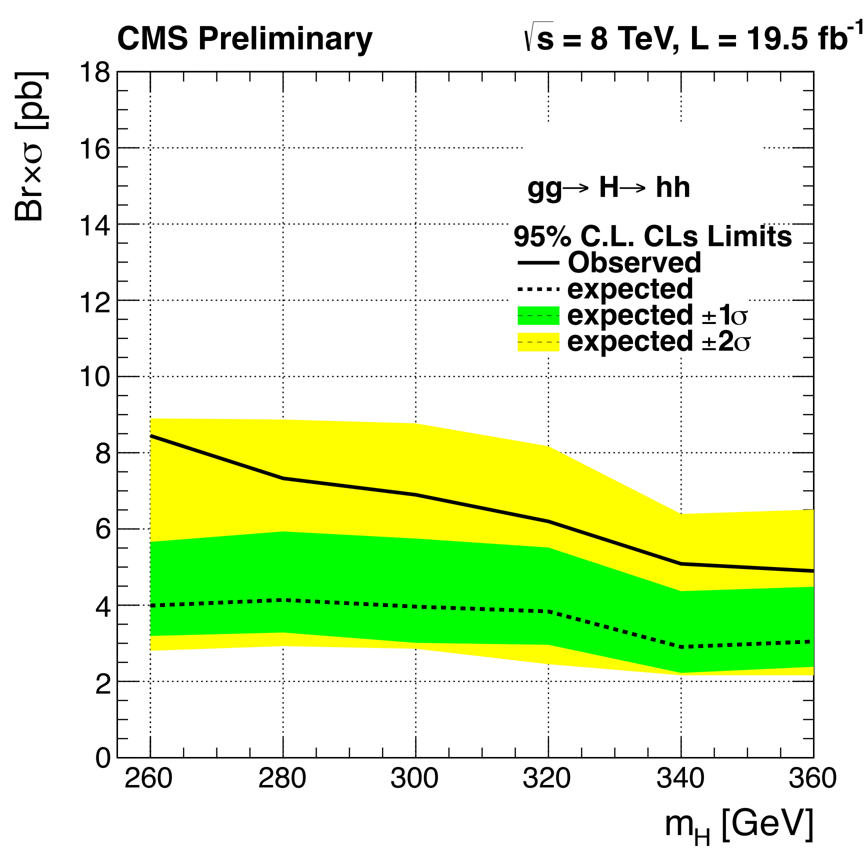
2HDM:Results

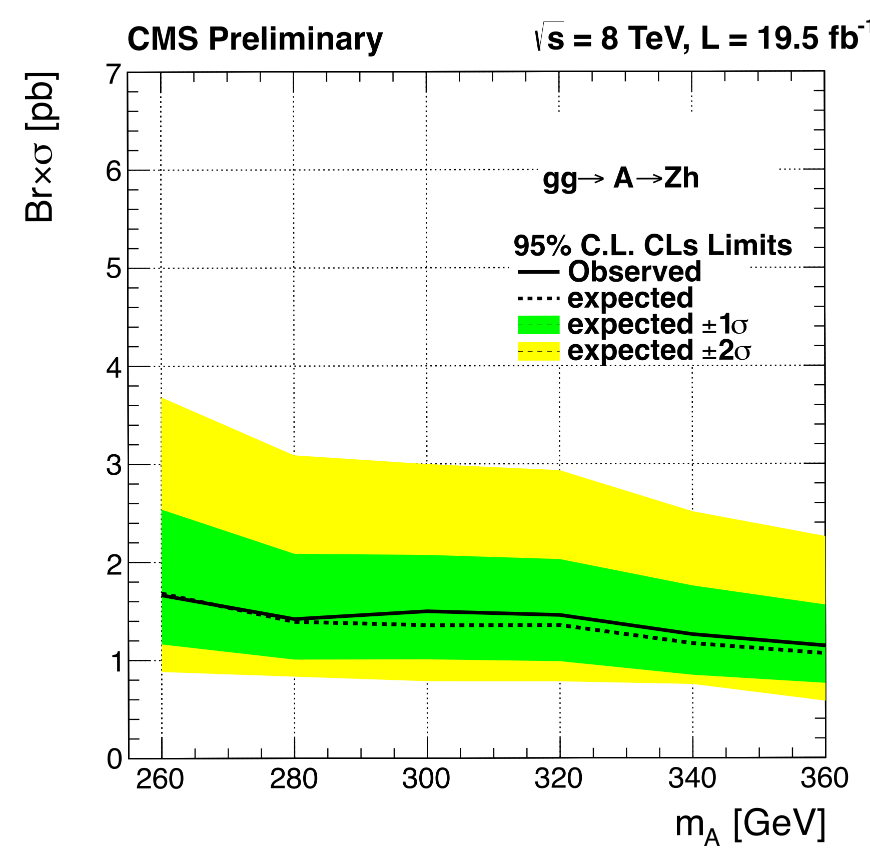
- Most sensitive search channels for a Heavy Higgs search





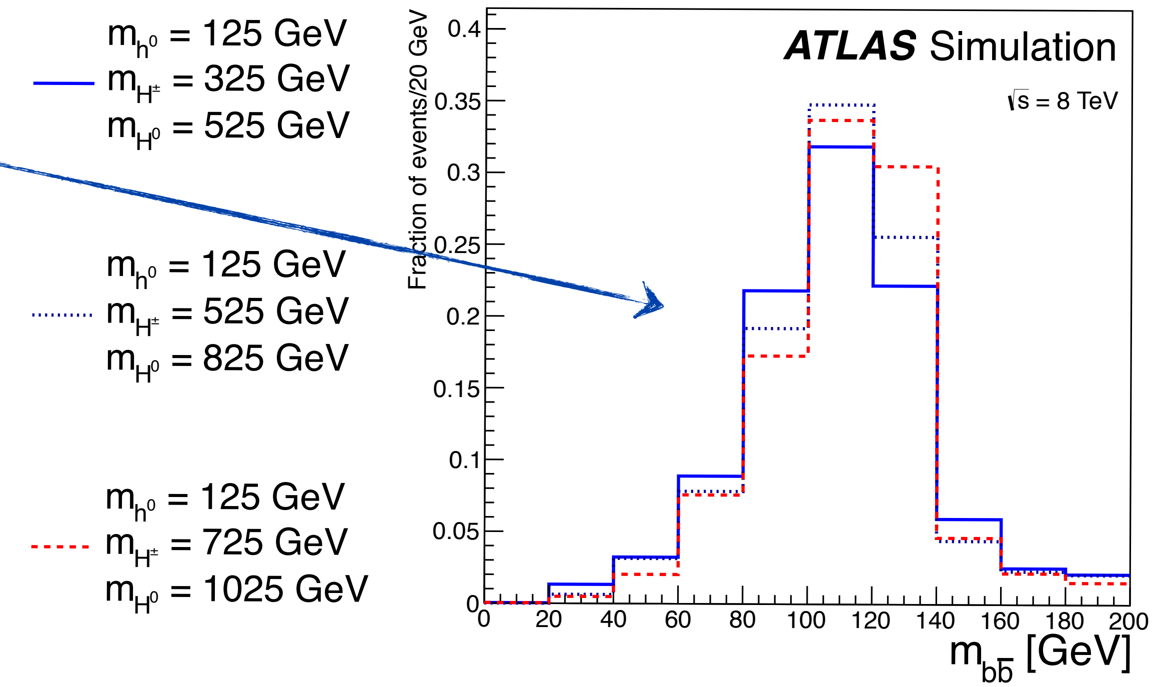
- 95% CL limits on cross-section times Br



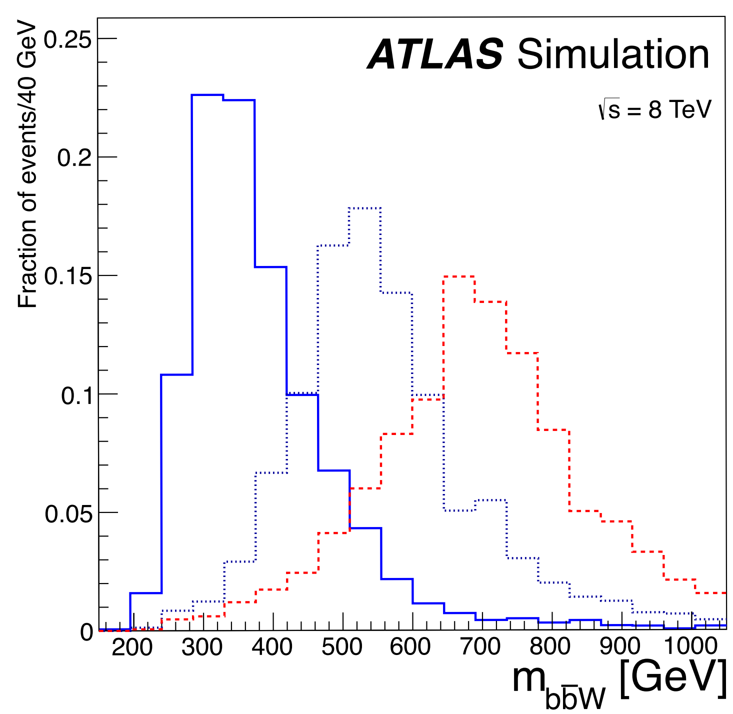


MultiHiggs: Event Reconstruction

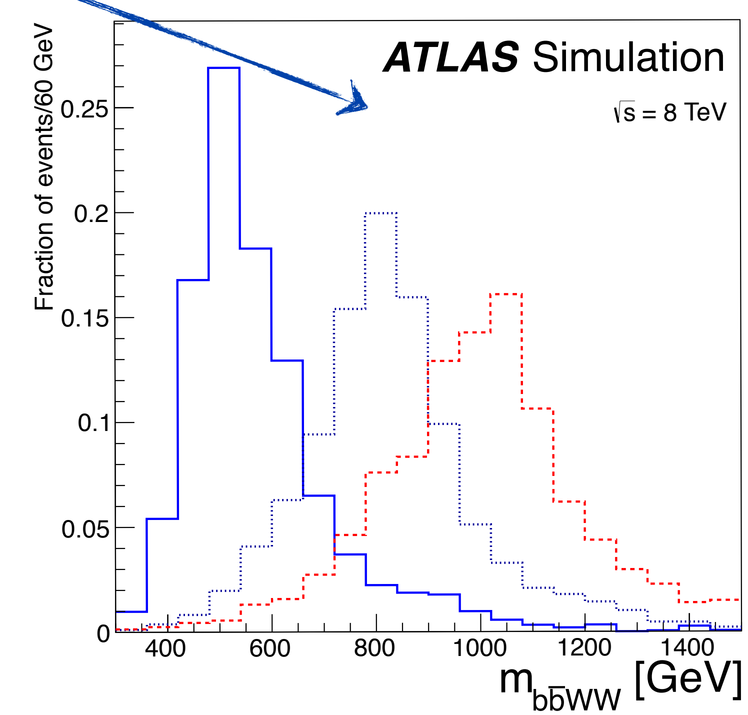
- Identification of the leptonically decaying W
- *h* candidate reconstructed with the two b-tagged jets



- Hadronically decaying W reconstructed from the remaining jets.
- H^{+-} reconstructed from h and the W which gives the highest mass



- H formed with the bbarWW system reconstructed



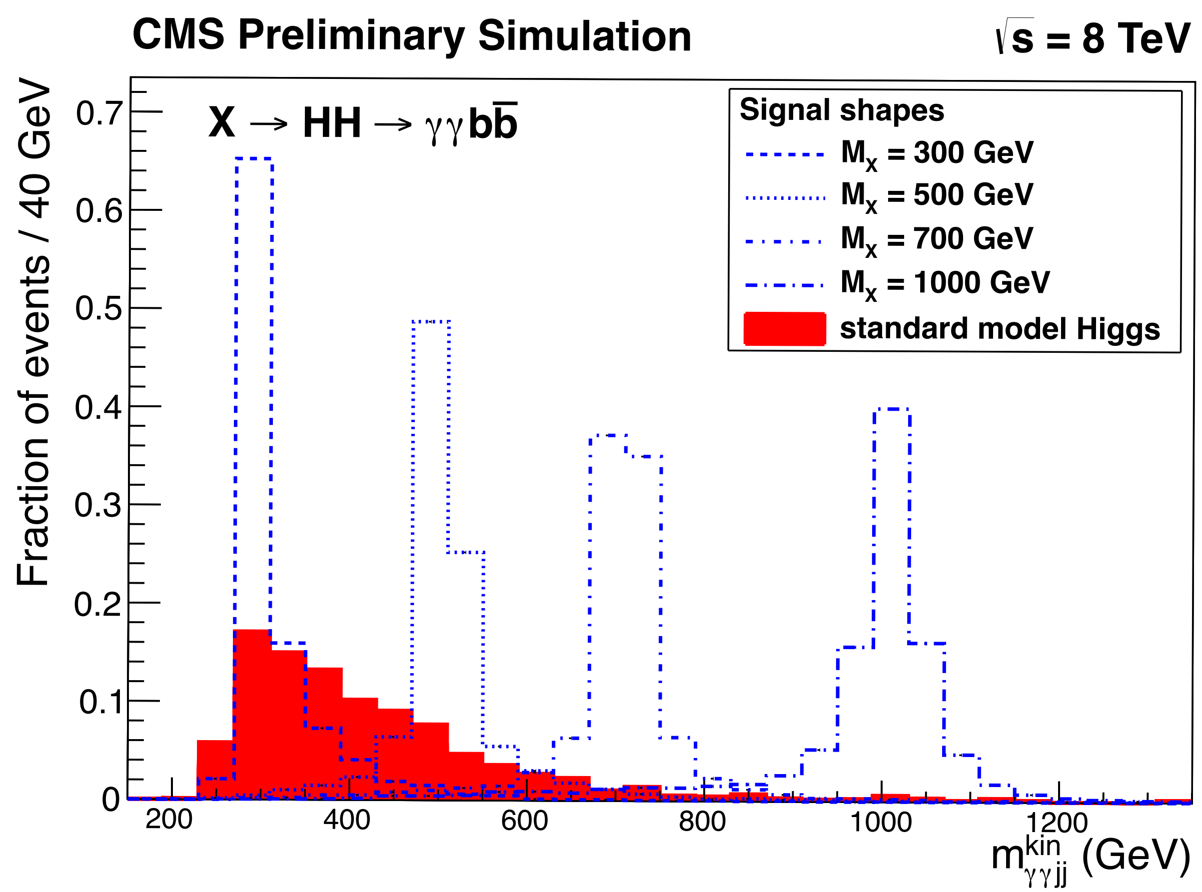
bbgg: Signal Reconstruction

- Di-Higgs system reconstructed from a pair of photons and a pair of jets originating from b-quarks

- Resonant signal topology:

  1. **Peak around m_H (125 GeV)** in diphoton and dijet spectra

  2. **Peak around m_X (unknown) in the 4-body spectrum**



- m_X mass range: ATLAS [260-500] GeV
  CMS [260-1100] GeV

- Narrow resonance signal hypothesis

- Dominant Background: non resonant production of photons and jets (QCD)
  SM-Higgs considered as resonant background

Summary on decay modes

	CMS			ATLAS		
	Dataset	Status	Results	Dataset	Status	Results
Favoured decay modes						
H(ZZ)	5.1 + 19.6 fb^{-1}	arXiv:1312.5353	**μ= 0.93**	4.8 + 20.3 fb^{-1}	**ATLAS-CONF-2014-009**	**μ= 1.44**
H(WW)	5.1 + 19.4 fb^{-1}	arXiv:1312.1129	**μ= 0.72**	4.8 + 20.3 fb^{-1}	**ATLAS-CONF-2014-009**	**μ= 1.00**
H($\gamma\gamma$)	5.1 + 19.7 fb^{-1}	arXiv:1407.0558	**μ= 1.14**	4.8 + 20.3 fb^{-1}	**ATLAS-CONF-2014-009**	**μ= 1.57**
H(tau tau)	4.9 + 19.7 fb^{-1}	arXiv:1401.5041	**μ= 0.78**	4.8 + 20.3 fb^{-1}	**ATLAS-CONF-2014-009**	**μ= 1.44**
V-H(bb)	5.1 + 18.9 fb^{-1}	arXiv:1310.3687	**μ< 1.89(0.95)**	4.7 + 20.3 fb^{-1}	**ATLAS-CONF-2013-079**	**μ< 1.4(1.3)**
VBF-H(bb)	19.0 fb^{-1}	**HIG-13-011**	**μ< 3.6(3.0)**	4.7 + 13.0 fb^{-1}	**ATLAS-CONF-2012-161**	**μ< 1.8(1.9)**
ttH(bb)	19.5 fb^{-1}	**HIG-14-010**	**μ< 2.9(3.3)**	20.3 fb^{-1}	**ATLAS-CONF-2014-011**	**μ< 4.1(3.4)**
Rare decay modes						
H(mu mu)	5.0+ 19.7 fb^{-1}	**HIG-13-007**	**μ< 7.4**	24.8 fb^{-1}	arXiv:1406.7663	**μ< 7.2**
H(Z γ)	5.0+ 19.6 fb^{-1}	arXiv:1307.5515	**μ< 10**	4.5 + 20.3 fb^{-1}	arXiv:1402.3051	**μ< 10**
H($\gamma^*\gamma$)	19.7 fb^{-1}	**HIG-14-003**		-	-	-
Invisible decay modes						
Z(ll)-H(inv)	4.9 + 19.7 fb^{-1}	arXiv:1404.1344	**BR< 58(46)%**	4.5 + 20.3 fb^{-1}	arXiv:1402.3244	**BR< 75(62)%**
Z(bb)-H(inv)				-	-	-
VBF-H(inv)				-	-	-
Exotic decay modes						
H(tau mu)	19.7 fb^{-1}	**HIG-14-005**	**BR<1.57%**	-	-	-
H(long-lived)	-	-	-	20.3 fb^{-1}	**ATLAS-CONF-2014-041**	UL vs proper decay length

= published

= preliminary