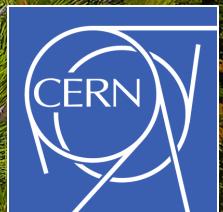


# BSM Scalar Searches at the LHC

Tristan du Pree (CERN)

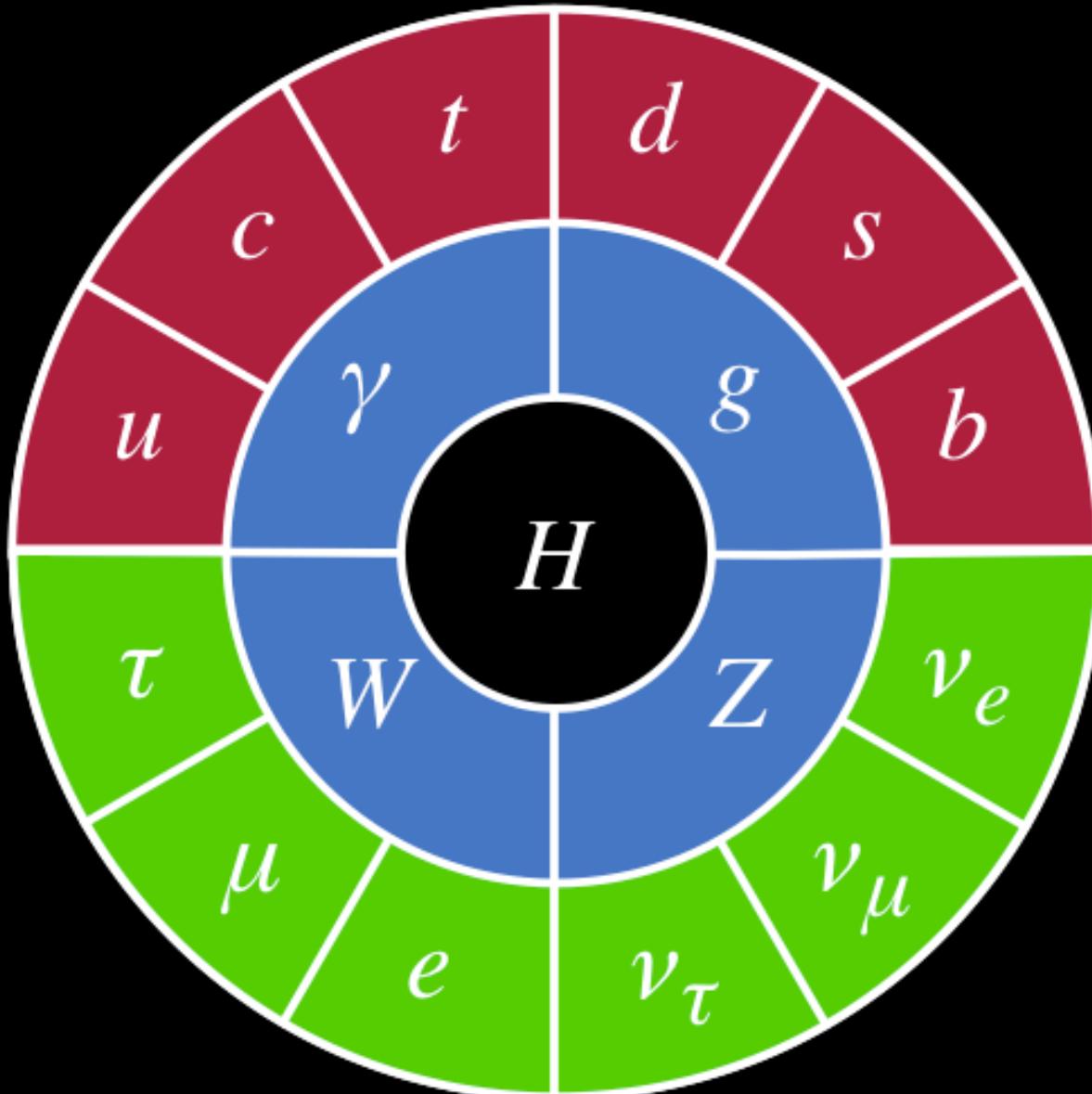
*on behalf of the ATLAS+CMS Collaborations*



SUSY 2015

23 – 29 August 2015, Lake Tahoe

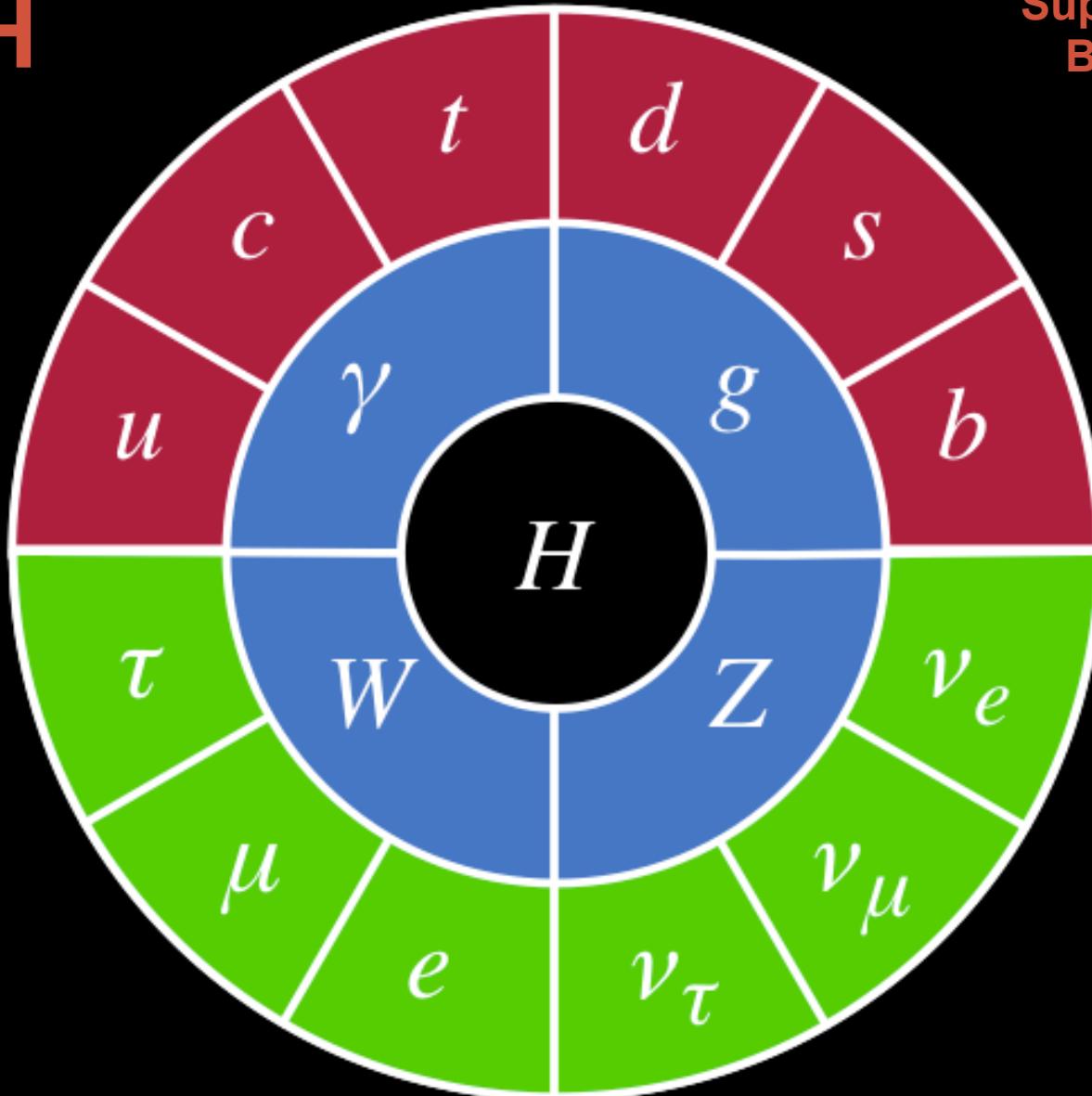
**SM**



# BSM H

See also Jessie Shelton (Tuesday)

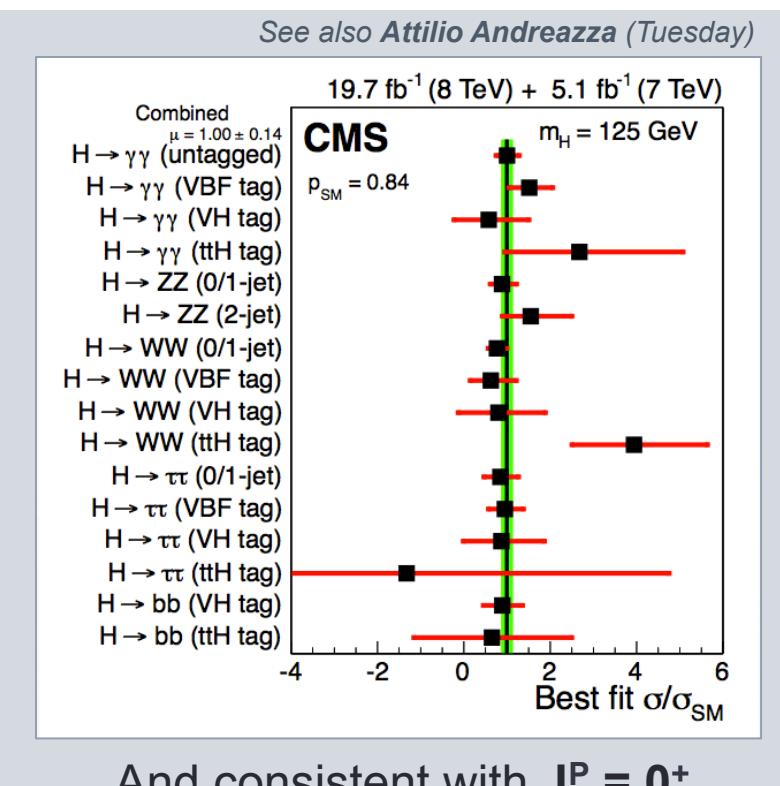
Supersymmetry  
Baryogenesis  
Dark Matter  
Hierarchy  
Flavour  
Gravity  
...



Wide range of BSM predictions related to H boson and new scalar bosons

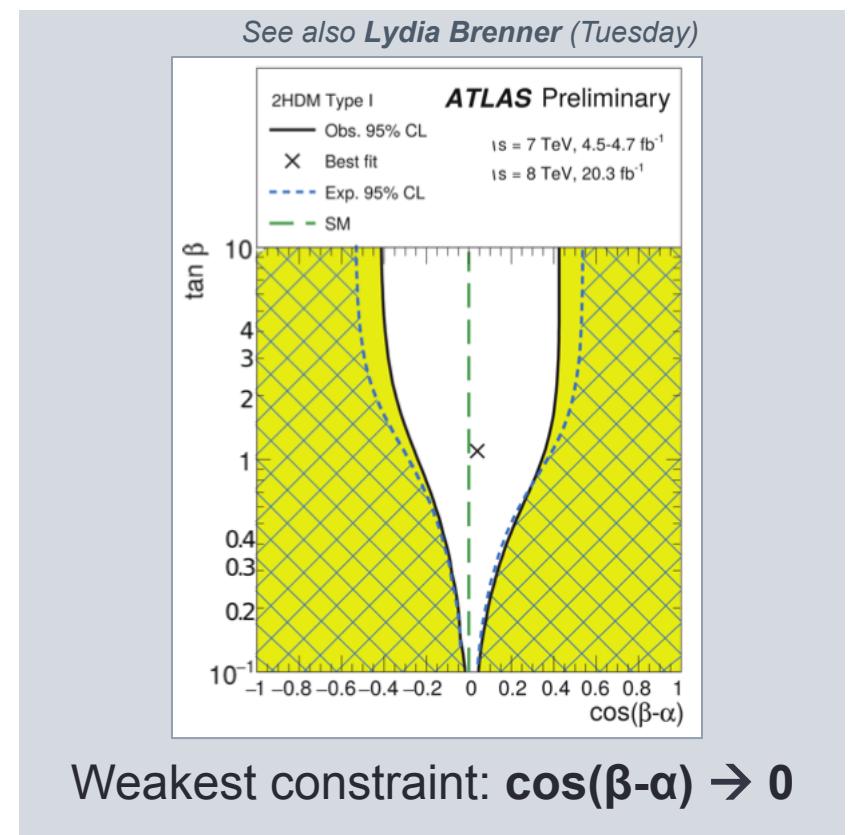
# Indirect H

## H properties



And consistent with  $J^P = 0^+$

## Indirect constraints



Weakest constraint:  $\cos(\beta - \alpha) \rightarrow 0$

Still some room for direct searches

# Direct searches

New scalar bosons:

- MSSM
- NMSSM
- 2HDMs

- Heavy H
  - SM-like H: ZZ + WW +  $\gamma\gamma$
- Di-H
  - X → hh: WW + bb + tt +  $\gamma\gamma$

à la  
125 GeV discovery

- Exotic decays
  - Rare&LFV [see Hideki Okawa]
  - H → MET: invisible + pseudo-invisible

Exotic final states

- 2HDMs & SUSY
  - A → Zh & H → ZA: bb + tt
  - Charged H $^\pm$ : tb + tv + cs
  - MSSM  $\Phi$ : bb + tt +  $\mu\mu$
  - NMSSM light a: tt +  $\mu\mu$  +  $\gamma\gamma$

Couplings  
to lighter fermions

- A full SUSY2015 week of BSM electroweak afternoon sessions!



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354

# Heavy H

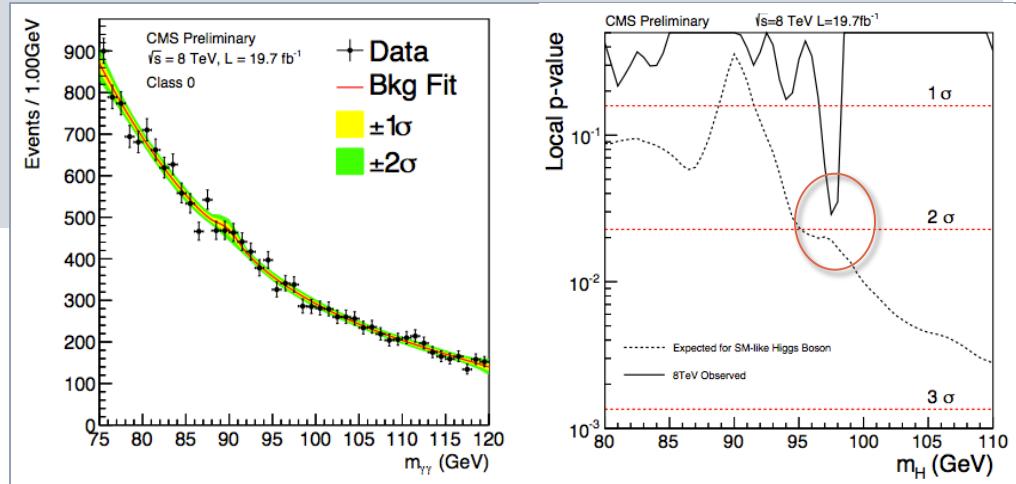
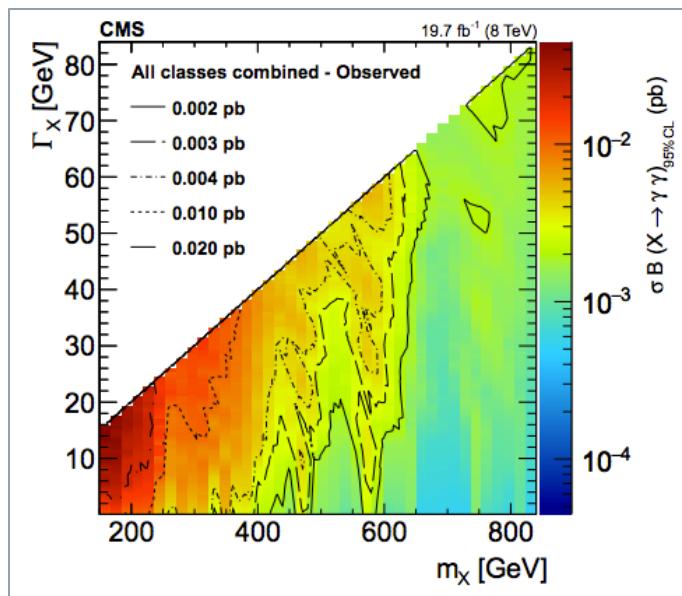
SM-like final states  
**ZZ/WW/ $\gamma\gamma$**

# H $\rightarrow$ $\gamma\gamma$

ATLAS: PRL113(2014)171801  
 CMS: arXiv:1506.02301  
 CMS HIG-14-037

See also Petra Merkel (Thursday) & Graham Cree (Friday)

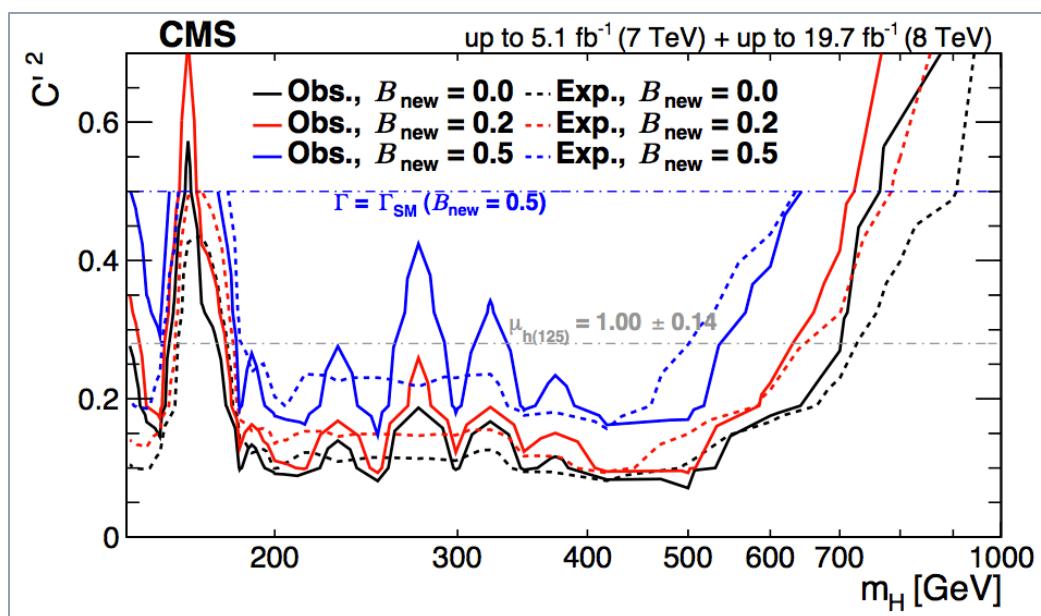
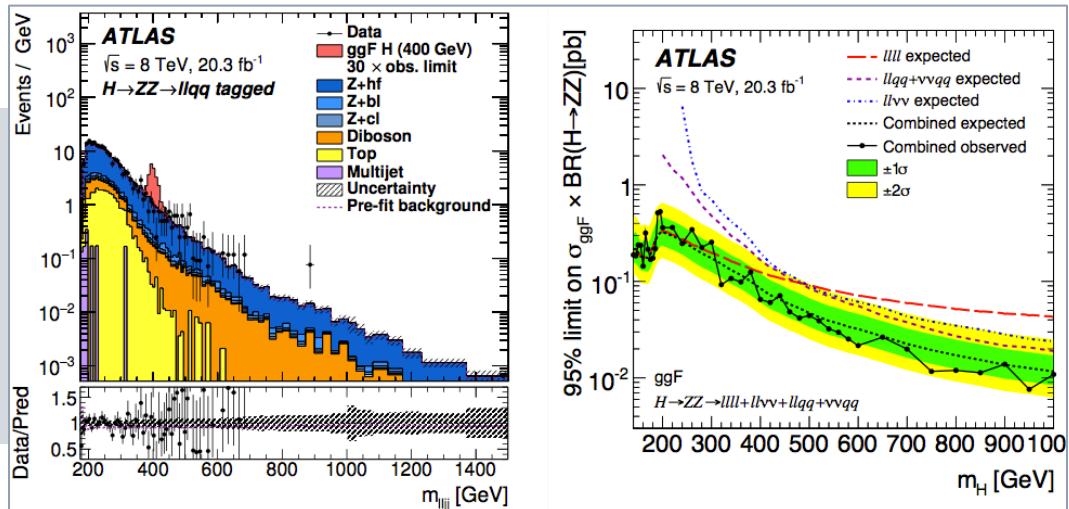
- **BSM mass ranges**
  - **Low mass:** 80-110 GeV
  - **High mass:** 150-850 GeV



- **Interpretation**
  - Spin-0 & spin-2 & 2HDM
- **Model-independent scan**
  - **M<sub>X</sub> vs  $\Gamma_X$**

# H $\rightarrow$ VV

- WW+ZZ
  - I<sub>1</sub>I<sub>1</sub>, I<sub>1</sub>qq, 4I, IIqq, IIvv  
(CMS) qqvv (Atlas)
- Assume SM-like production & decay



CMS arXiv:1504.00936

- Reinterpretation:  
**EW singlet scalar**
- **B<sub>new</sub>**: non-SM decay modes
- **C'**: coupling scale factor

$$\Gamma' = \Gamma_{SM} \frac{C'^2}{1 - B_{new}}$$

# Dark H



- $H \rightarrow \text{invisible}$
- $H \rightarrow \text{light} + \text{dark}$
- $\text{Mono-}H + \text{Dark Matter}$

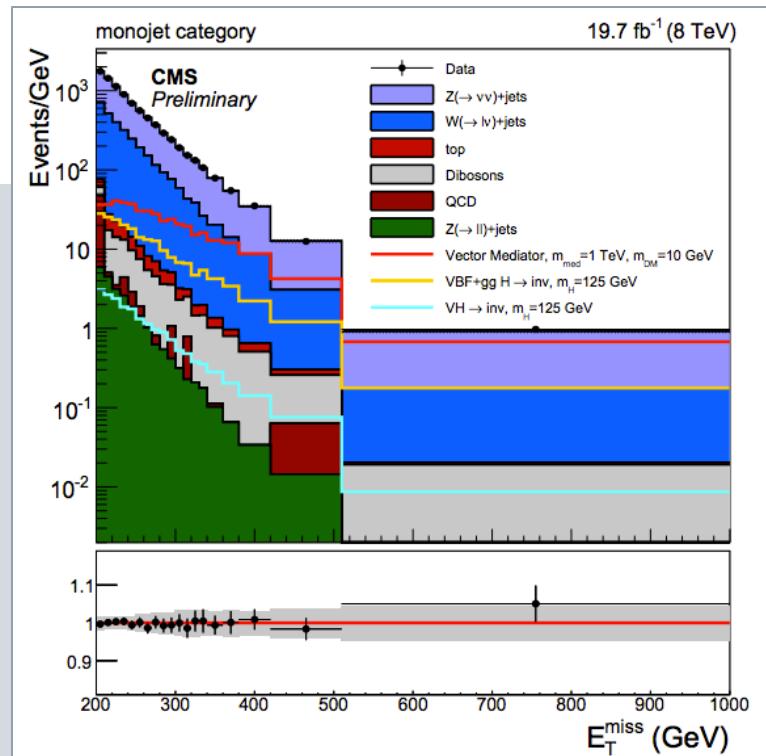
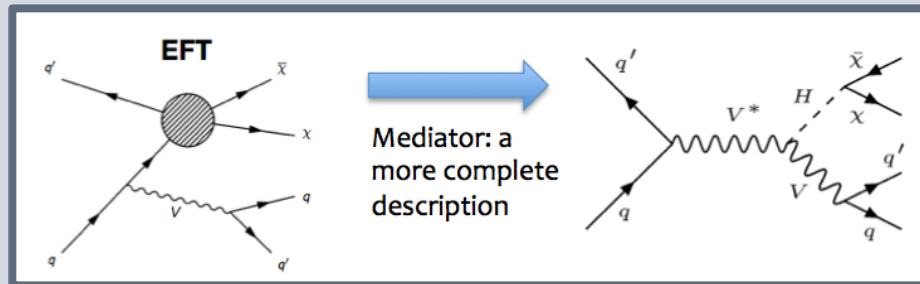
# DM

See also *Priscilla Pani* (Monday)

- **New Dark Matter search**

- Mono-jet & mono- $V_{\text{had}}$
- Boosted & resolved

CMS PAS  
EXO-12-055



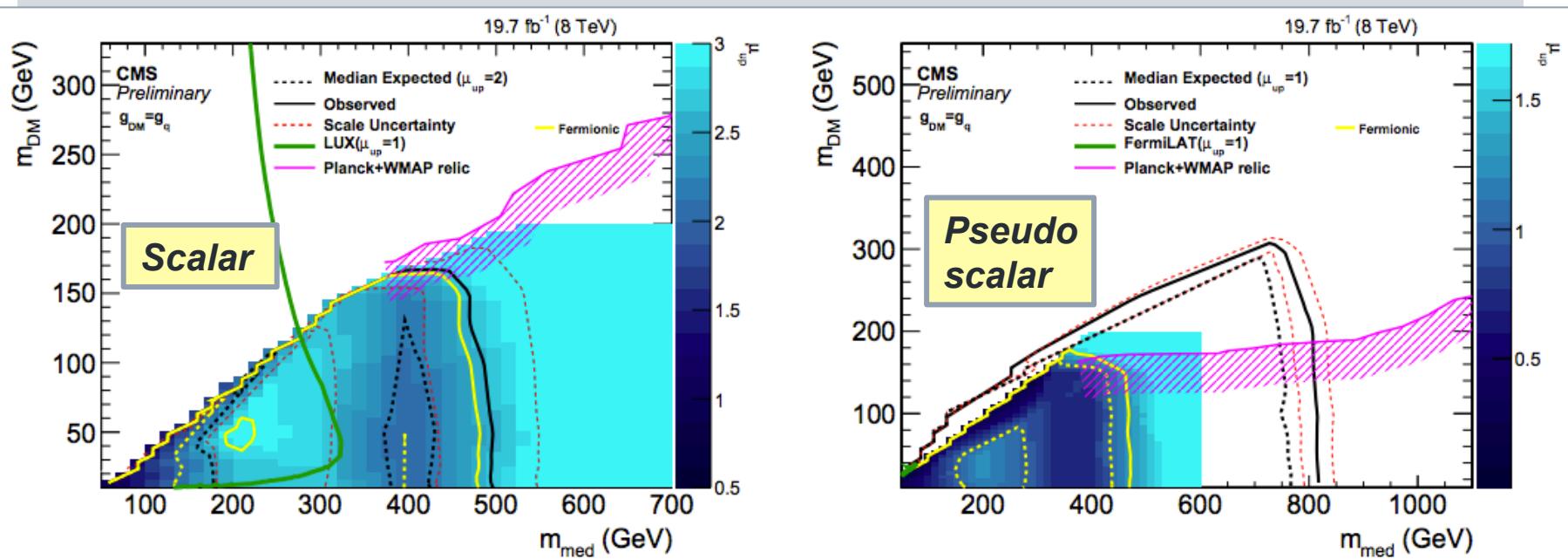
- **Generic DM mediator models**
  - **Vector & Axial & Scalar & Pseudo**
  - **LHC ‘Dark Matter Forum’ [arXiv/1507.00966]**

# DM

- **New Dark Matter search**
  - Mono-jet & mono- $V_{had}$
  - Boosted & resolved

**CMS PAS EXO-12-055**

See also **CERN LPCC Seminar (Phil Harris)** <https://indico.cern.ch/event/388149/>

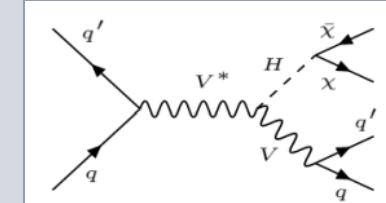
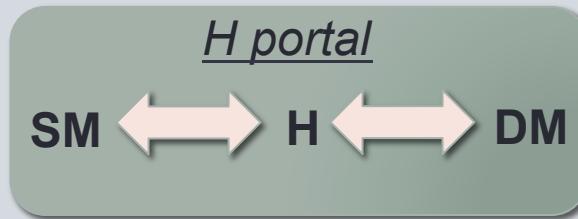


- **Constraints (M<sub>DM</sub>, M<sub>Med</sub>) for V&A&S&P mediators**
  - Also sensitive to  $V_{had}H$  & ggH

# H $\rightarrow$ inv

**H $\rightarrow$ inv interpretation**

- Dark Matter in  
**H-portal models**



## Summary of direct LHC searches for H $\rightarrow$ inv

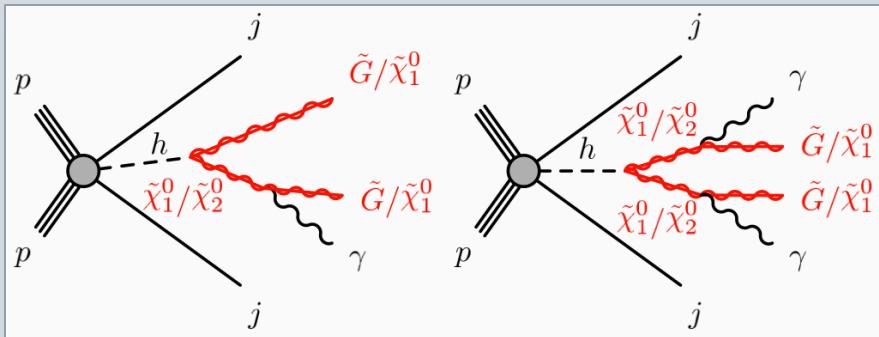
BR(H $\rightarrow$ inv) upper limits at 95% C.L.	ATLAS	CMS
ZH	75% (62%) arXiv/1402.3244	81% (83%) arXiv/1404.1344
V <sub>had</sub> H (+ggH)	78% (86%) arxiv/1504.04324	53% (62%) CMS PAS EXO-12-055
VBF	28% (31%) ATLAS-CONF-2015-004 <a href="#">link to EPS</a>	57% (40%) CMS PAS HIG-14-038

New Atlas VBF+VH combination: H $\rightarrow$ inv < 25% (27%) [\[link to EPS\]](#)

# H $\rightarrow$ inv+ $\gamma(\gamma)$

ATLAS-CONF-2015-001  
CMS arXiv:1507.00359

- Production: ggH & VH & VBF



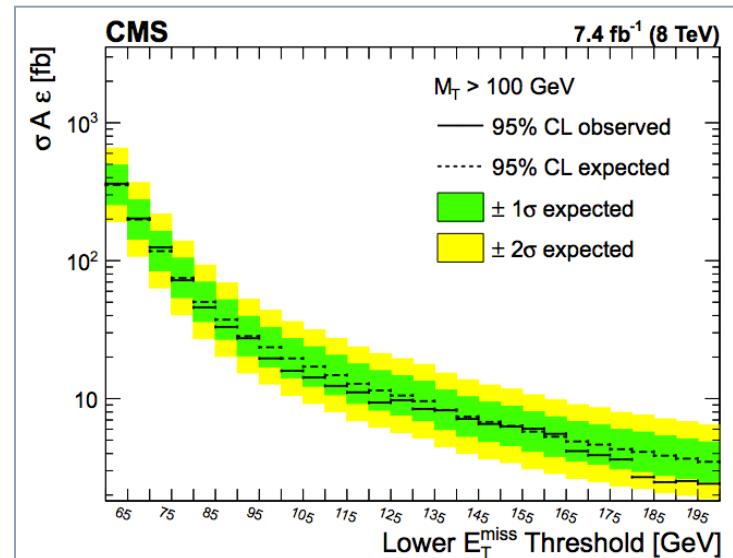
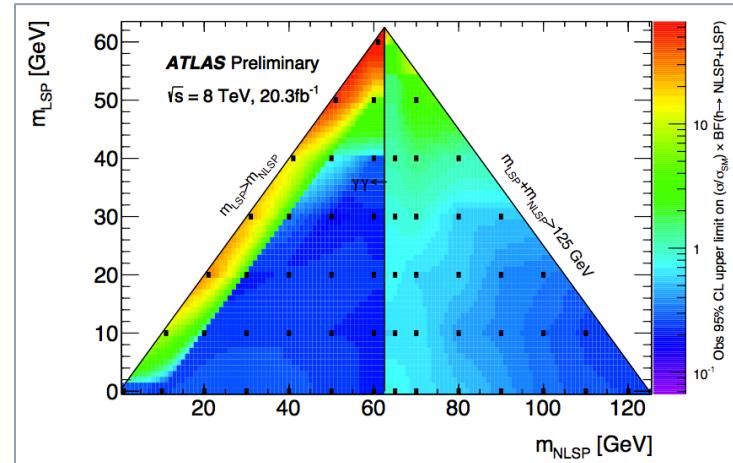
Atlas Trigger  
 $E_T(\gamma) > 40$  GeV  
 $MET > 60$  GeV

CMS ['data parking']  
 $E_T(\gamma) > 30$  GeV  
 $MET > 25$  GeV

## ➤ Model-specific interpretations

- GMSB:  $h \rightarrow \tilde{G}\tilde{\chi}^0 \rightarrow \tilde{G}\tilde{G}\gamma$
- NMSSM:  $h \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$
- NMSSM:  $h \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma\gamma$

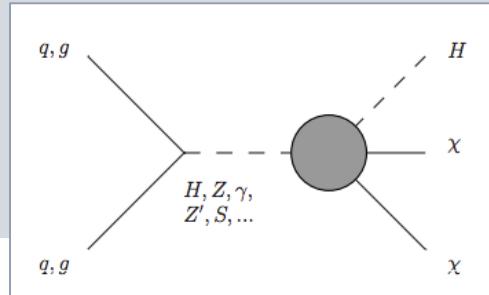
## ➤ Model-independent results



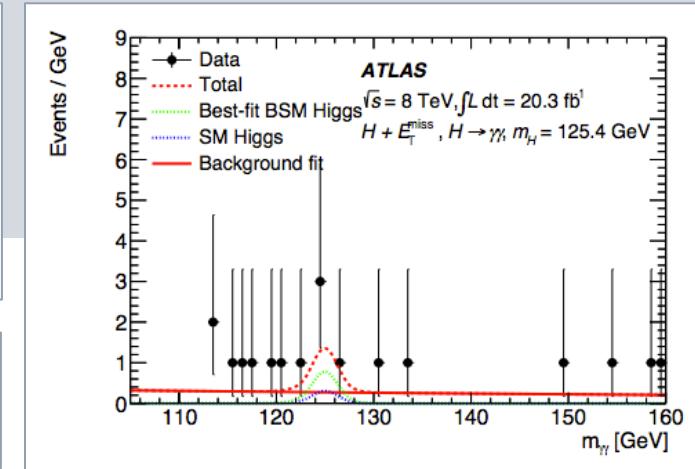
# Mono-H

See also *Florian Bernlochner* (Tuesday)

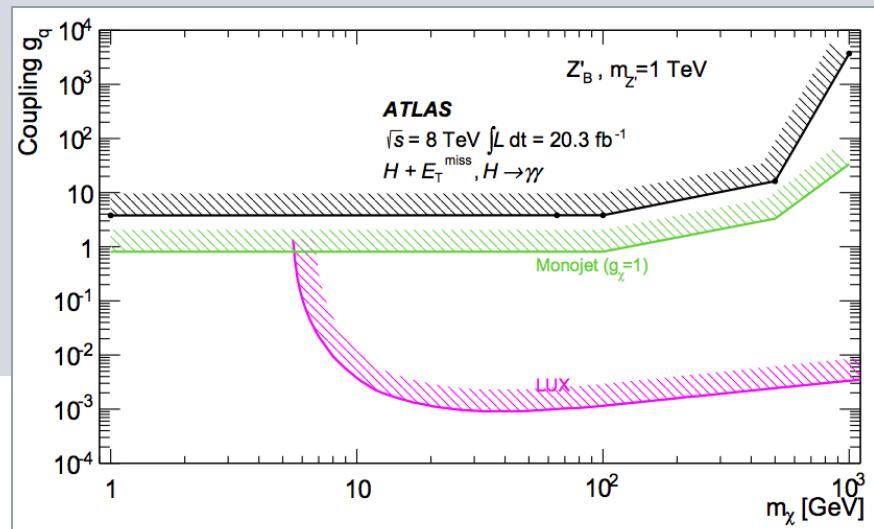
- $H(\gamma\gamma) + \text{MET}$ 
  - $p_T(\gamma\gamma) > 90 \text{ GeV}$
  - $\text{MET} > 90 \text{ GeV}$



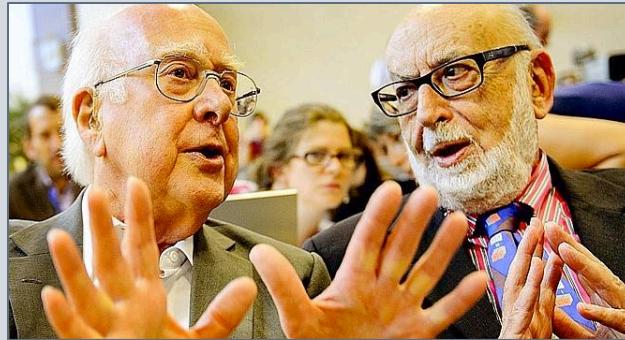
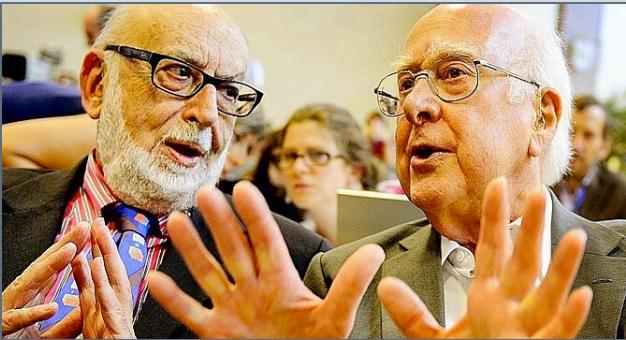
[arXiv/1506.01081](https://arxiv.org/abs/1506.01081)  
→ PRL



- Different interpretations
  - EFT
  - Simplified mediator models
- Constraints also low DM mass
  - Still statistically limited



# 2HDMs



# 2HDMs

- Two complex Higgs doublets:  $\Phi_{1,2}$
- 5 states: **h**, **H** (CP-even), **H $\pm$**  (charged), **A** (CP-odd)
  - SM h = 125 GeV
- 2HDM parameters
  - Masses **M<sub>H</sub>**, vev ratio **tan $\beta$  = v<sub>1</sub>/v<sub>2</sub>**, mixing angle  **$\alpha$**
- Four types
  1. **Type I**: all fermions couple to  $\Phi_2$  [*"fermiophobic"*]
  2. **Type II**: up-type  $\Phi_2$ , down-type  $\Phi_1$  [*"MSSM"*]
  3. **Type III**: quarks Type-I, leptons Type-II [*"lepton-specific"*]
  4. **Type IV**: quarks Type-II, leptons Type-I [*"flipped"*]

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
$\kappa_V$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
$\kappa_u$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$
$\kappa_d$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$
$\kappa_l$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$

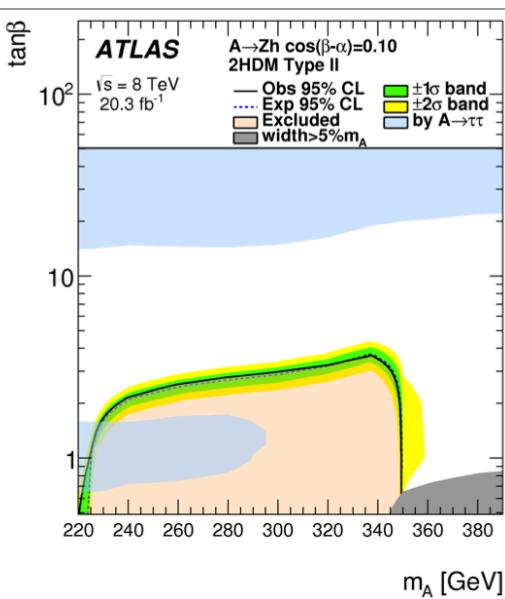
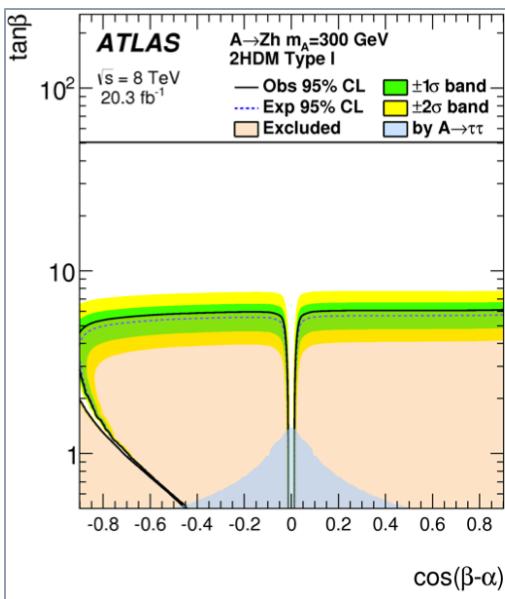
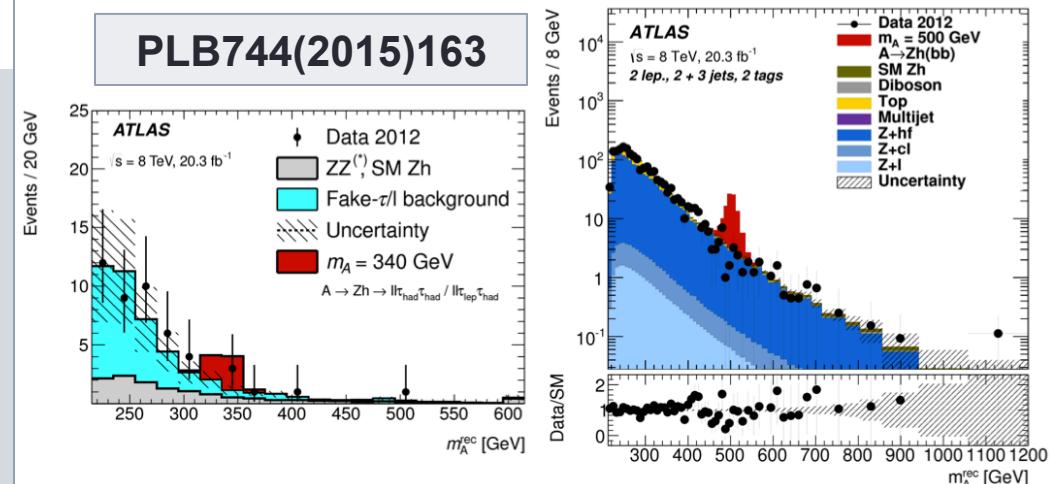
# A $\rightarrow$ Zh

See also [Matteo Bauce \(Monday\)](#)

- A $\rightarrow$ Z(II)h( $\tau\tau$ )
  - Three  $\tau\tau$  channels
- A $\rightarrow$ Z(II)h(bb)
  - Two tags,  $M_h$  constraint
- A $\rightarrow$ Z(vv)h(bb)
  - Transverse mass

CMS arXiv/1504.04710

PLB744(2015)163



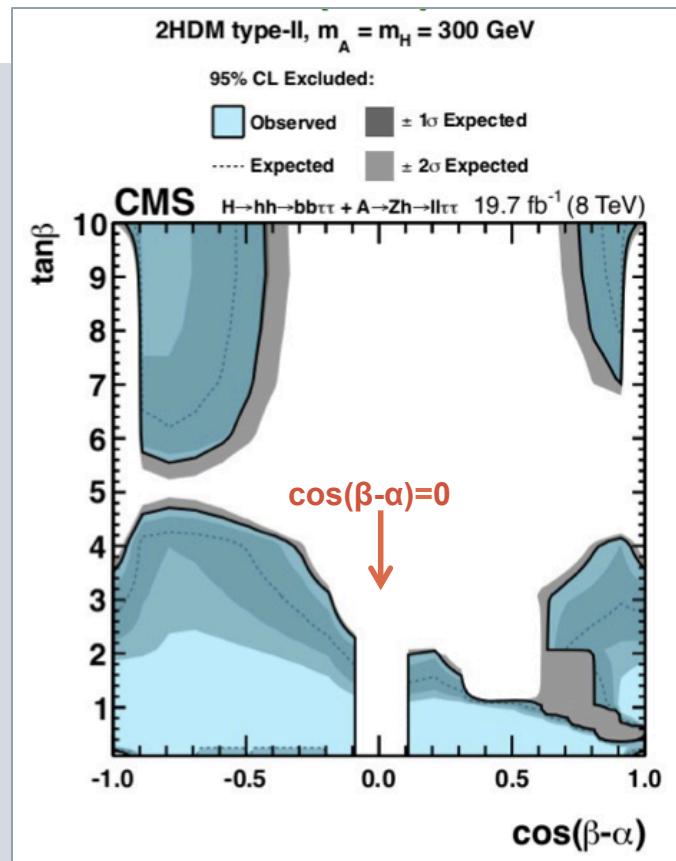
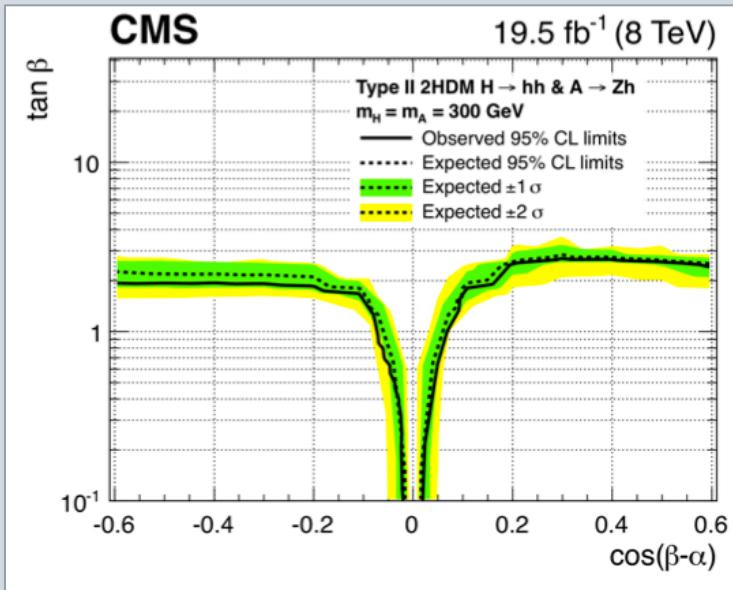
## Interpretation:

- **Exclude small  $\tan\beta$** 
  - Type-I up to 5
  - Type-II up to 3

# A $\rightarrow$ Zh + H $\rightarrow$ hh

PRD90(2014)112013  
CMS PAS HIG-14-034

- Multi-lepton & lepton+photons [left]
- bb $\tau\tau$  & ll $\tau\tau$  [NEW!]



- These combinations leave room for cos( $\beta-\alpha$ ) $\rightarrow$ 0 and large tan $\beta$

# H $\rightarrow$ Z $\alpha$

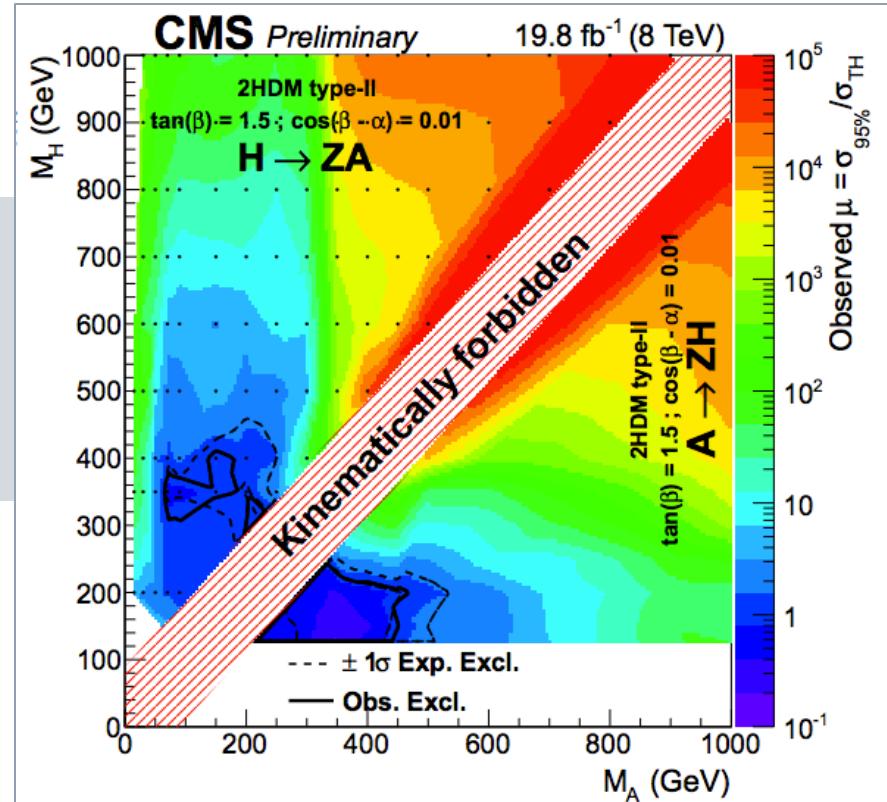
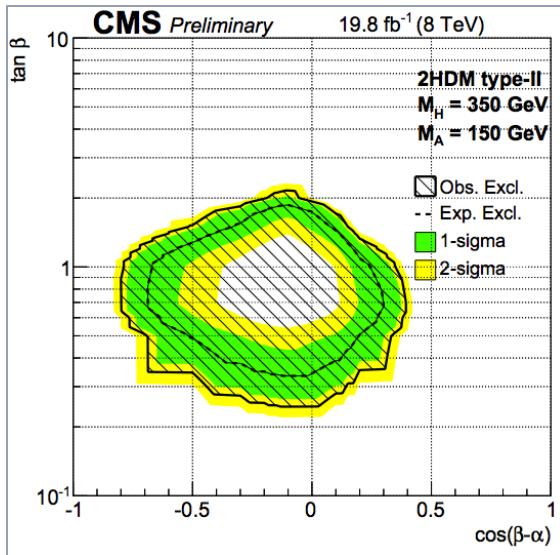
See also Roberto Castello (Monday)

## H $\rightarrow$ Z(II)A( $\tau\tau$ )

- Invariant mass  $M_{\tau\tau}$ 
  - Small background

## Model-independent limits

CMS PAS HIG-15-001



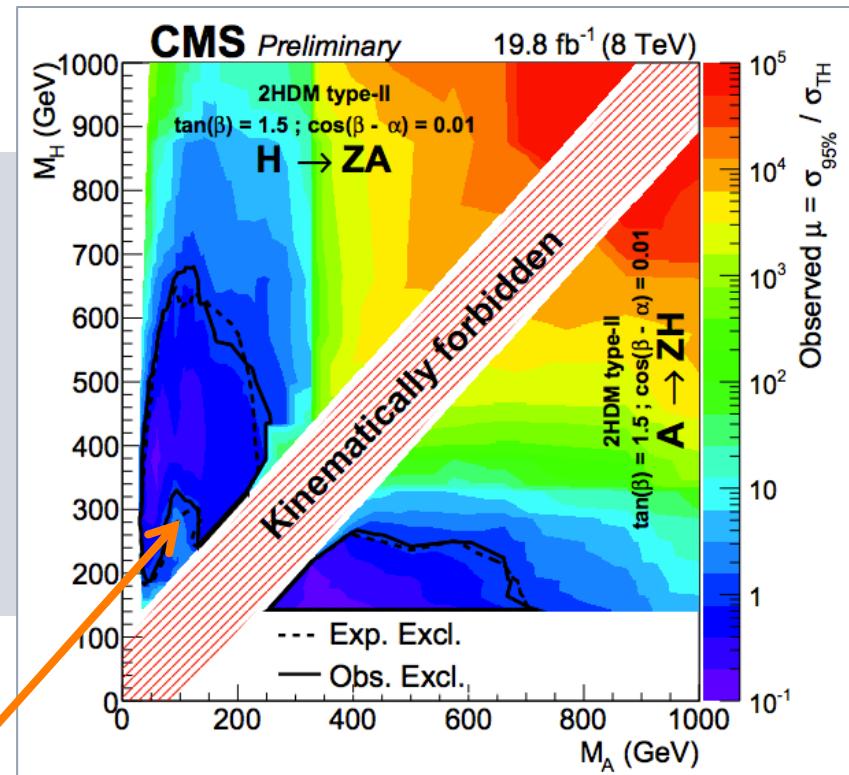
## Interpretation in type-II 2HDM

- Exclude in terms of
  - ( $M_A, M_H$ )
  - ( $\cos(\beta-\alpha), \tan\beta$ )
- Sensitive for  $[\cos(\beta-\alpha), \tan\beta] = [0, 1]$

# H $\rightarrow$ ZA excess

## H $\rightarrow$ Z(II)A(bb)

- Invariant masses ( $M_{bb}$ ,  $M_{Zbb}$ )
  - More background
  - Larger b coupling
  - Model-independent constraints
- Exclude larger ( $M_A$ ,  $M_H$ )



- Two excesses observed. ( $M_{bb}$ ,  $M_{Zbb}$ ) = (93, 286) GeV
  - **1.6  $\sigma$  global** (2.6  $\sigma$  local)
- Run-1  $\rightarrow$  only covered by CMS
  - To be studied in Run-2

CMS PAS HIG-15-001

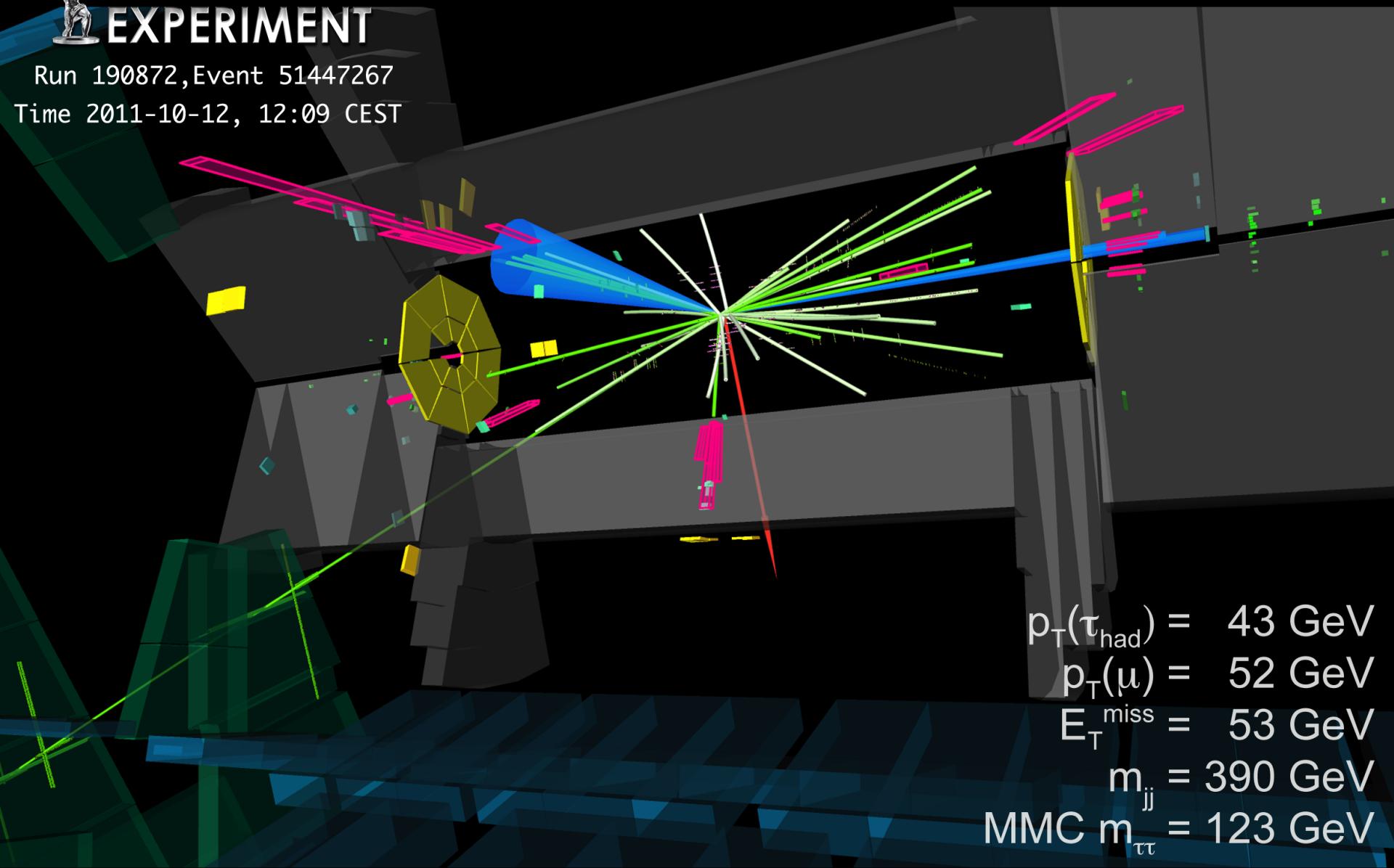


# ATLAS EXPERIMENT

Run 190872, Event 51447267

Time 2011-10-12, 12:09 CEST

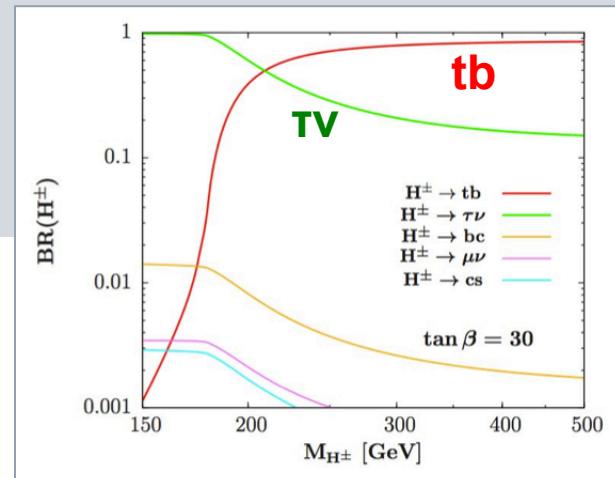
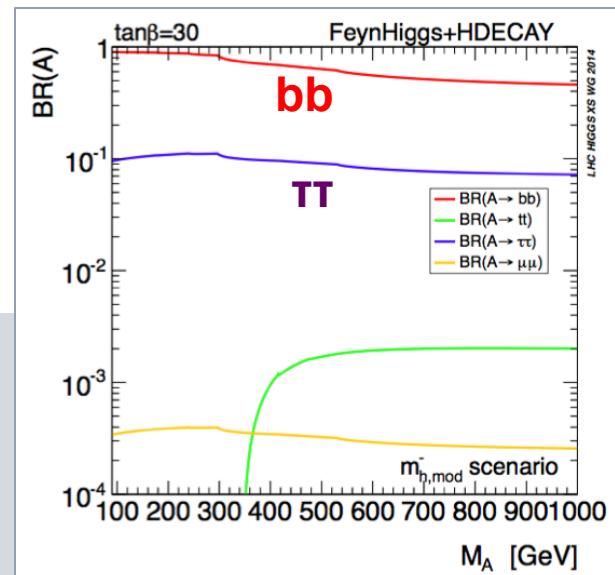
# SUSY $\Phi$



# MSSM

- **MSSM:** constrained **Type-II 2HDM**
  - Two main parameters:  $M_A$  &  $\tan\beta$

1. **Neutral H**
  - **Large  $\tan\beta$ :** Enhanced coupling to **b&t**
2. **Charged H:** **tv, tb**
  - Above/below mass threshold
3. **NMSSM:** MSSM + singlet
  - **Additional light pseudo-scalar**

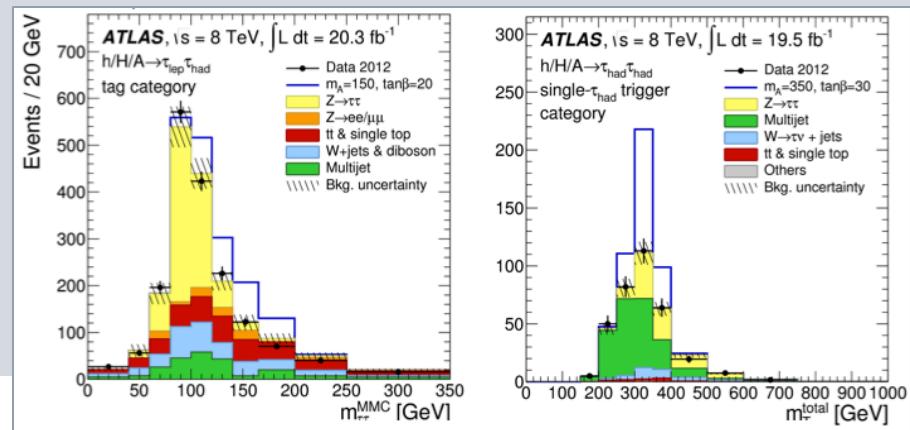
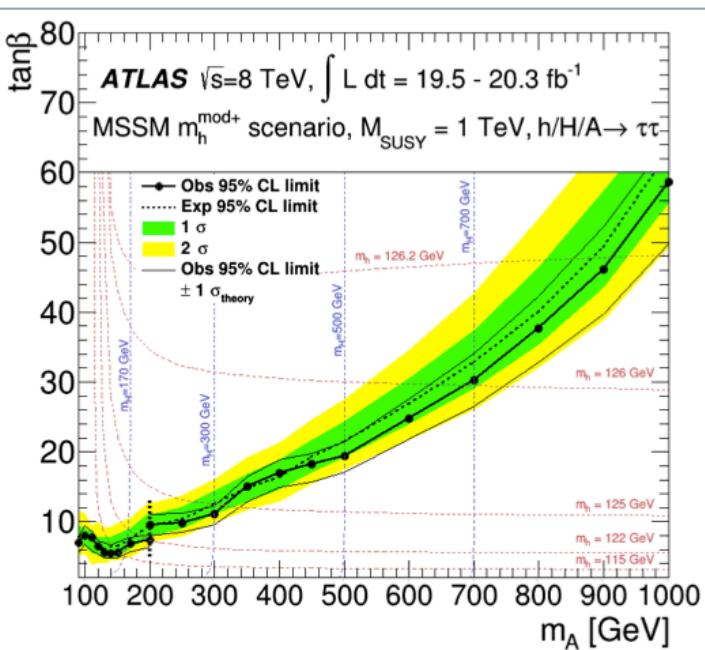


# MSSM: $\Phi \rightarrow \tau\tau$

See also *Cecile Caillol* (Thursday)

## Event categorisation

- Tau decay modes
  - $\tau_1 \tau_1$ ,  $\tau_1 \tau_{\text{had}}$ ,  $\tau_{\text{had}} \tau_{\text{had}}$
- B-jet categorization
  - b-tags, b-veto
- Discriminating observable:  $M_{\tau\tau}$



## Interpretation

JHEP11(2014)056

- Production
  - Gluon fusion
  - b-associated
- Constrain large  $\tan\beta$ 
  - For  $M_A$  up to 1 TeV
- Still unexcluded phase space
  - Compatible with  $M_h = 125$  GeV

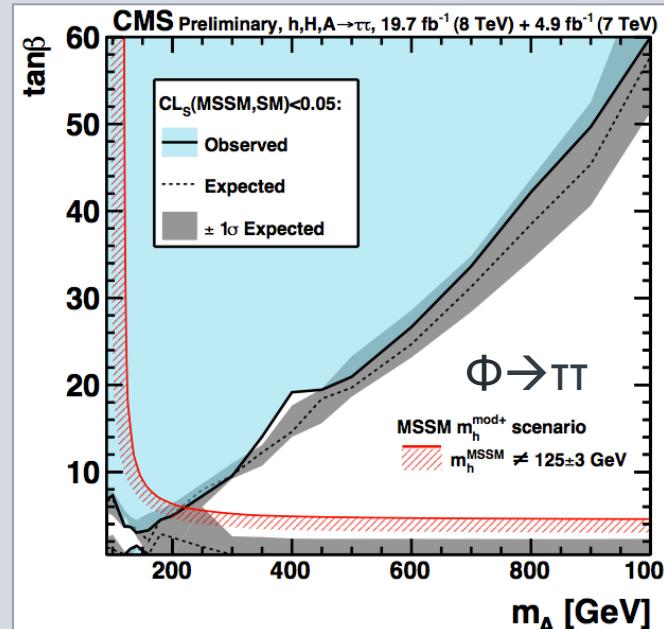
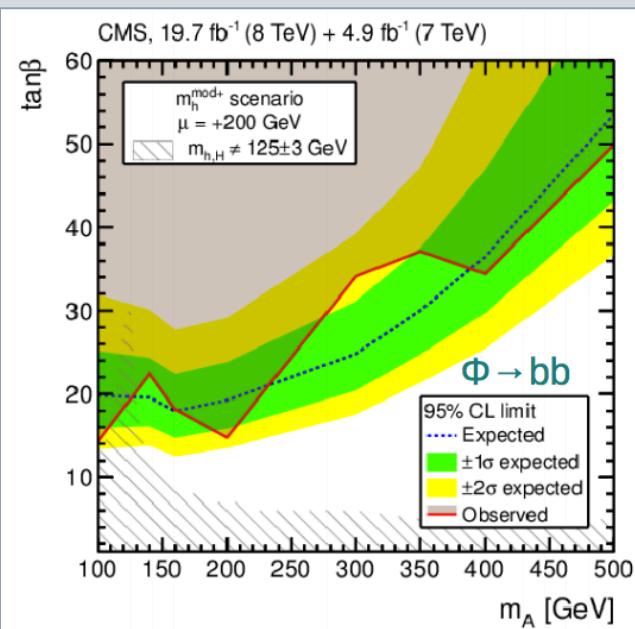
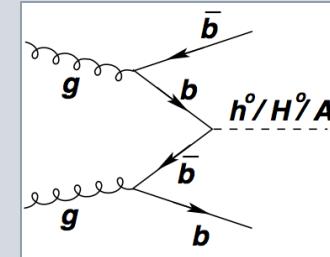
# $\Phi \rightarrow bb/\tau\tau$

arXiv:1506.08329  
CMS PAS HIG-14-029

See also Sara Alderweireldt (Tuesday)

MSSM:  $bb/\tau\tau$  resonances

- $\Phi \rightarrow bb$  : production with extra b's
  - Also sensitive to **large  $\tan\beta$**
- $\Phi \rightarrow \tau\tau$  also consider  $gg\Phi$ 
  - **Various scenarios:**  $m_h^{\max}$ ,  $m_h^{\text{mod}}$ , light-stop/stau,  $\tau$ -phobic, low-mass  $M_H$

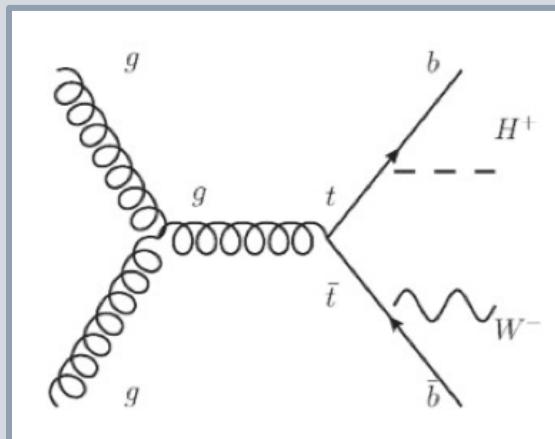


# $H^\pm \rightarrow TV$

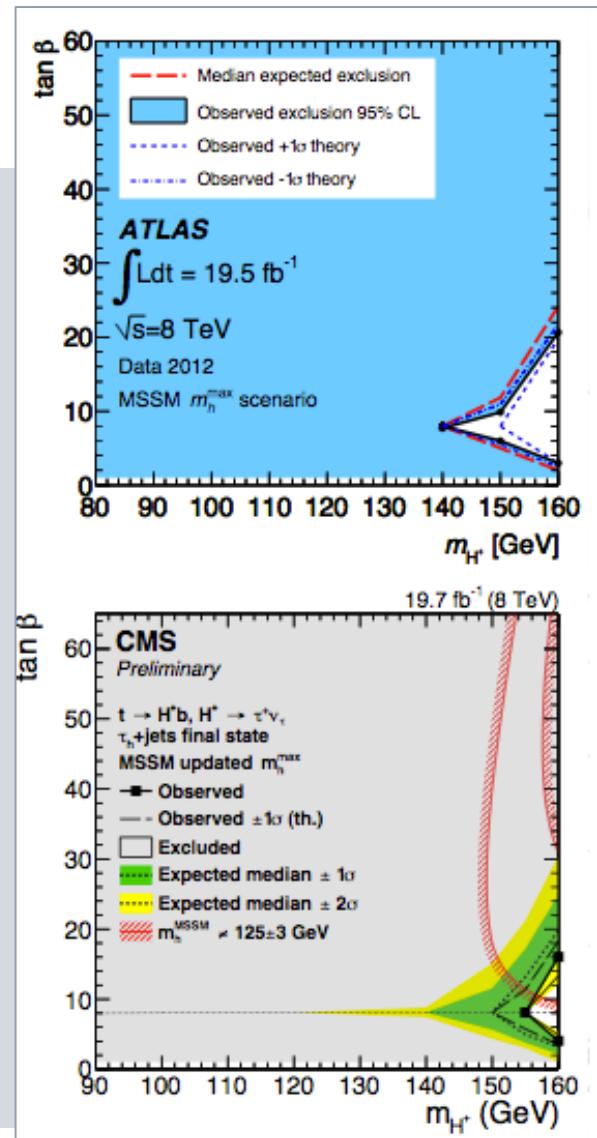
See Geoffrey Gille & Gourange Kole (Thursday)

Light: dominant  $H^\pm \rightarrow TV$

- $M(H^\pm) < 200$  GeV
  - $\tan\beta > 2$
  - ttbar production



CMS-PAS-HIG-14-020  
Atlas JHEP03 (2015) 088



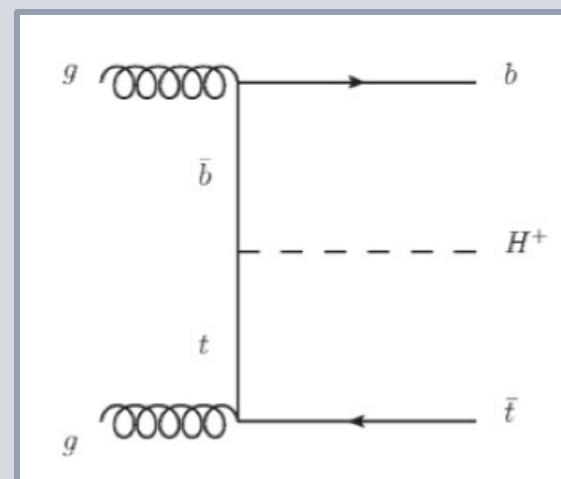
# H $\pm$

See Geoffrey Gille & Gourange Kole (Thursday)

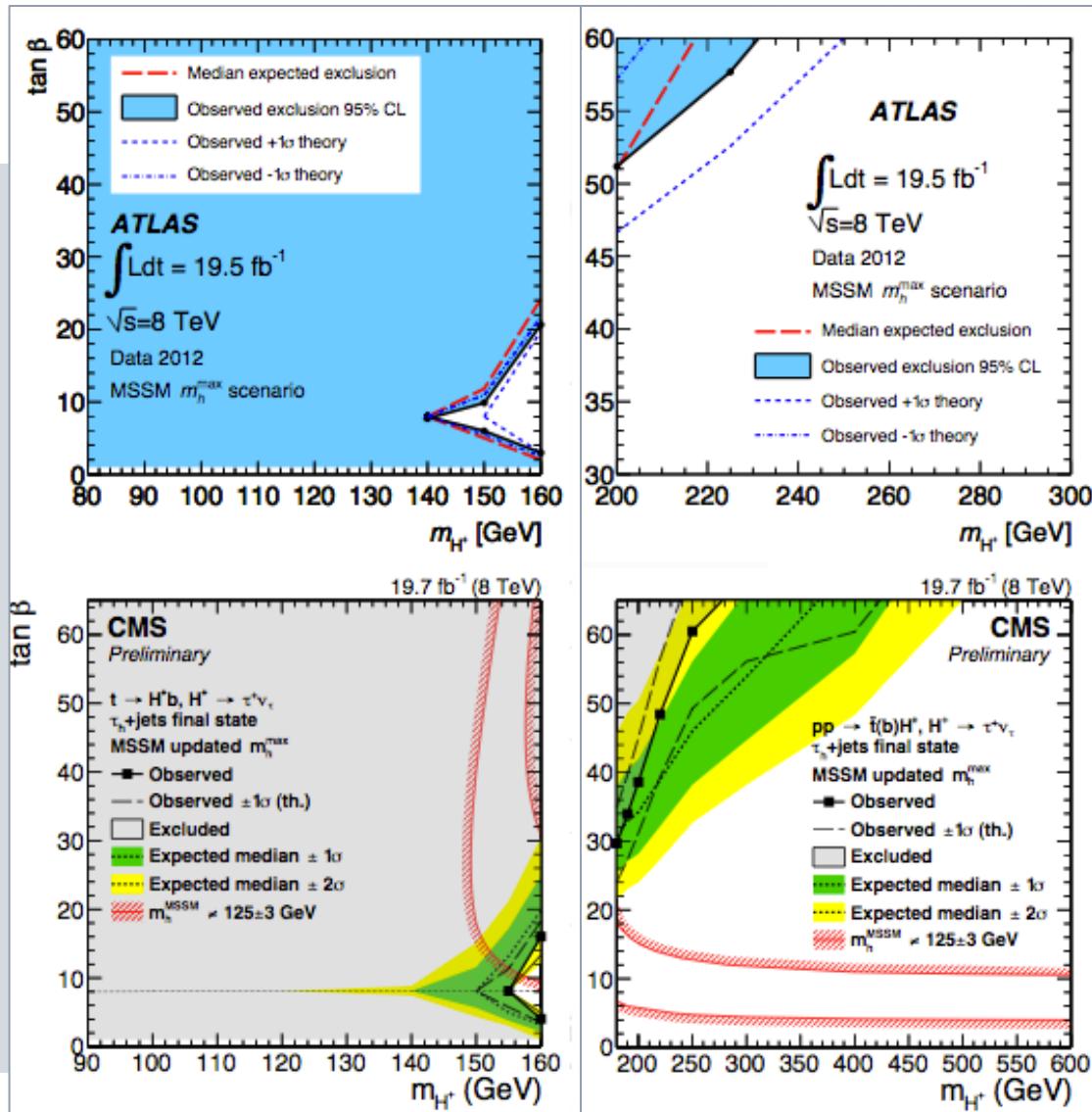
Light: dominant H $\pm$   $\rightarrow \tau\nu$

Heavy: dominant H $\pm$   $\rightarrow tb$

- M(H $\pm$ ) > 200 GeV



CMS-PAS-HIG-14-020  
Atlas JHEP03 (2015) 088

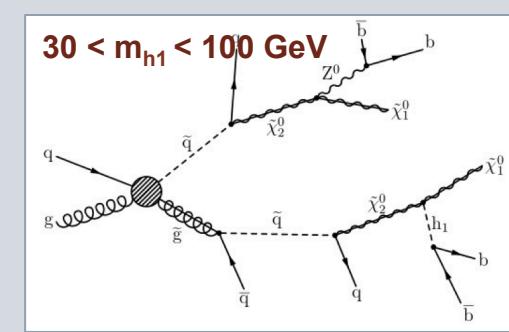
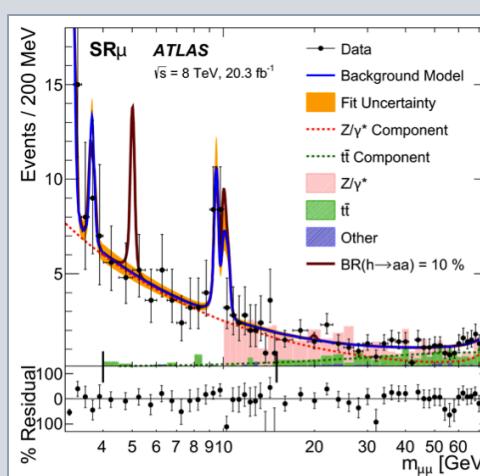


# Light NMSSM

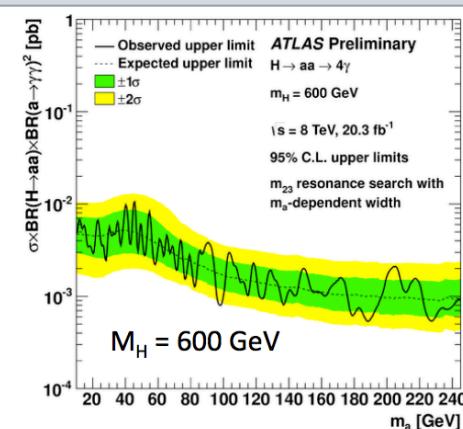
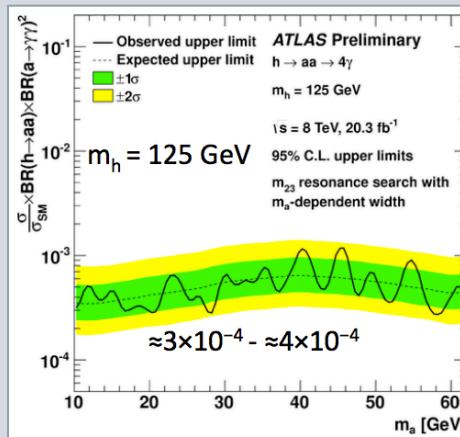
See also *Kristina Looper & Francesca Ricci-Tam* (Friday)

- $h \rightarrow aa \rightarrow \mu\mu\tau\tau$ 
  - Collimated **boosted** final state objects
- $h \rightarrow aa + X \rightarrow \mu\mu\mu\mu + X$ 
  - **$0.25 < m_a < 3.55$  GeV**
  - **$90 < m_{h12} < 150$  GeV**
- $h + X \rightarrow bb + X$ 
  - h part of **cascade**
  - 2 energetic jets
  - **large MET**
- $h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$ 
  - **$300 < M_H < 900$  GeV**
  - **$10 \text{ GeV} < M_a < M_H/2$**
  - Search for light & heavy resonances

CMS arXiv/1506.00424  
ATLAS-HIGG-2014-02  
CMS PAS HIG-14-030



NEW Atlas-EXOT-2013-24

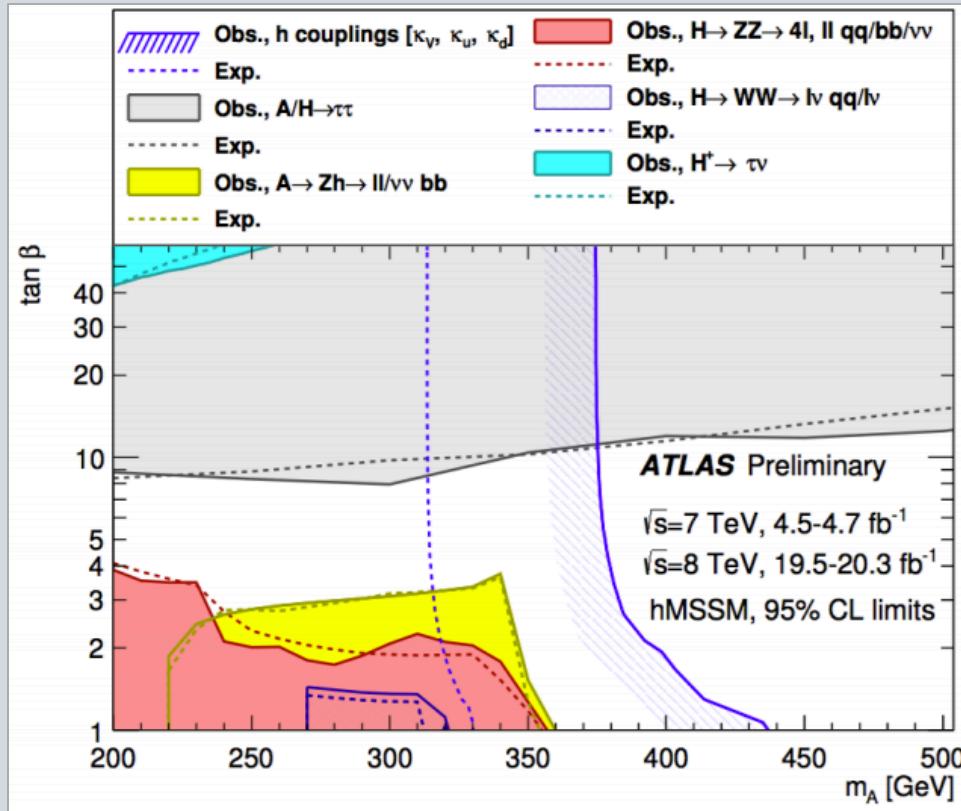


➤ Rich program of searches for light scalar bosons

# SUSY combined

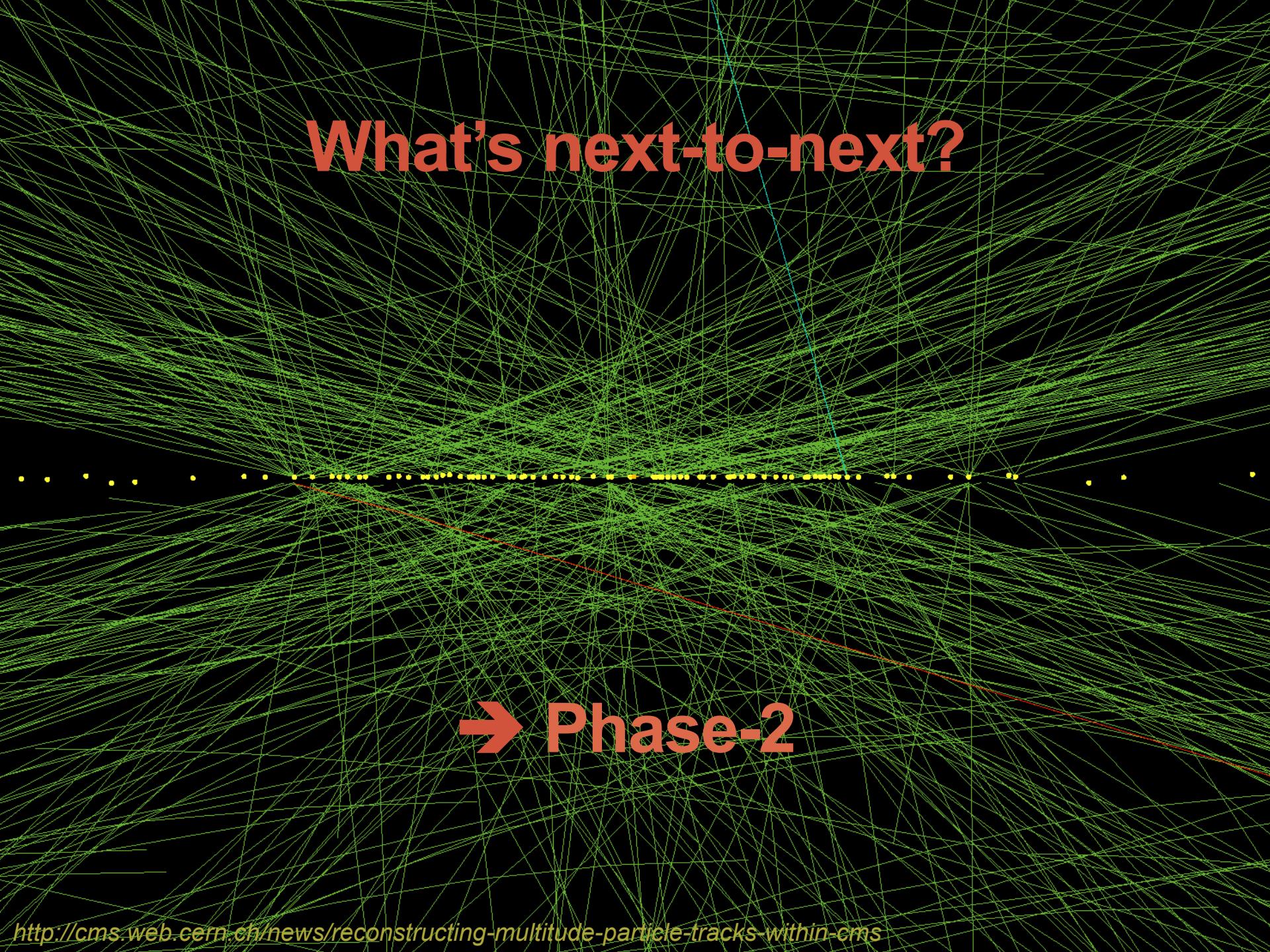
*to be submitted as  
CERN-PH-EP-2015-191*

- Direct+indirect tightly constrain hMSSM at low mass



Large  $\tan \beta$   
 → Fermionic  
Small  $\tan \beta$   
 → Bosonic  
 $M_A \rightarrow 2xM_t$   
 → Indirect

- Room for **high mass and alternative interpretations**
- Weakest constraints from direct searches at **intermediate  $\tan \beta$**



# What's next-to-next?

→ Phase-2

# X $\rightarrow$ hh

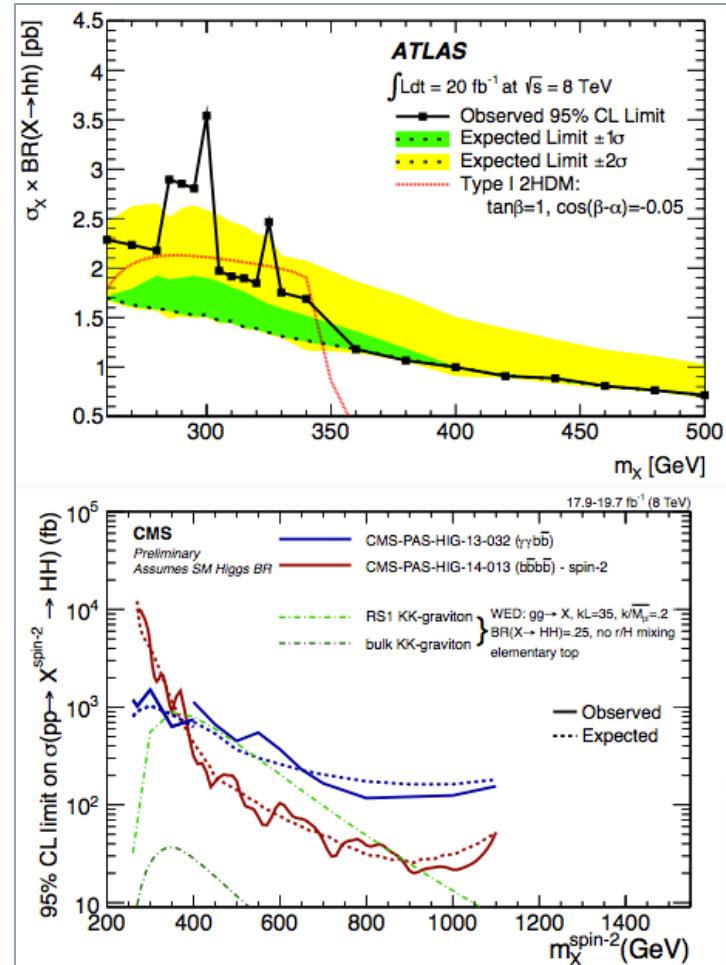
## Motivation

1. Prepare long-term SM hh
  - HL-LHC: test self coupling
2. Search X $\rightarrow$ hh resonances
  - bb $\gamma\gamma$ , bb $\tau\tau$ , bbbb,multilepton, l+ $\gamma$

## Results

1. Intermediate mass
  - Atlas excess: **2.4 $\sigma$**  [global!]
2. High mass  $\rightarrow$  boosted
  - Interpretation:  
**warped extra dimensions**

CMS-PAS-HIG-13-032  
arXiv/1503.04114  
PRL114(2015)081802

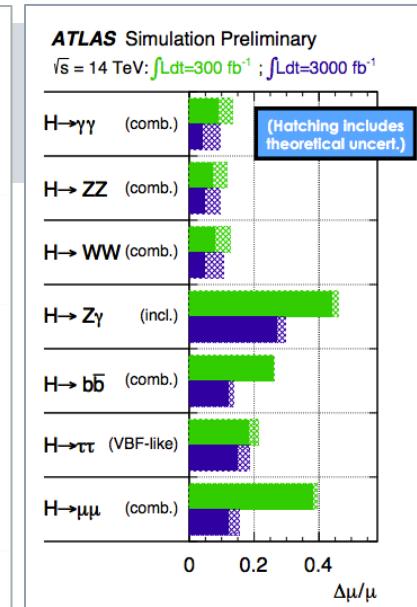
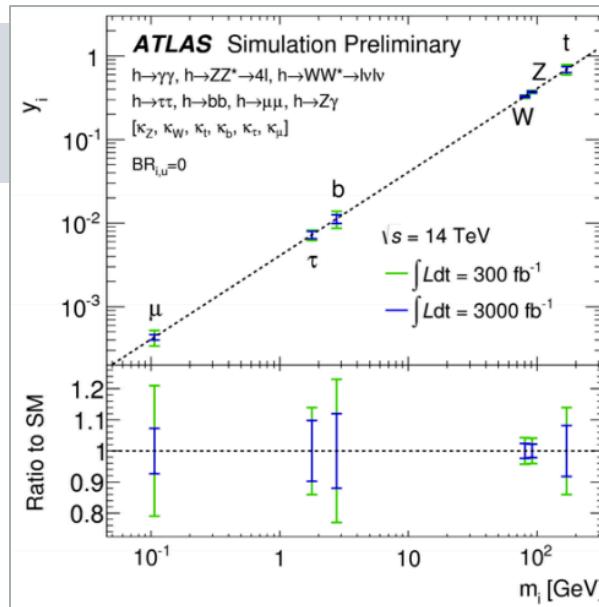
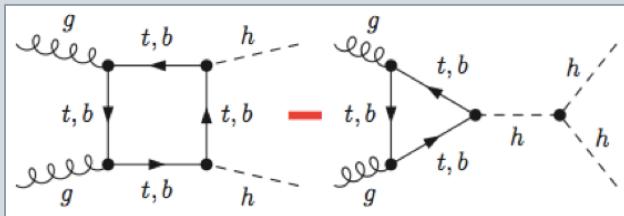


# Phase-2

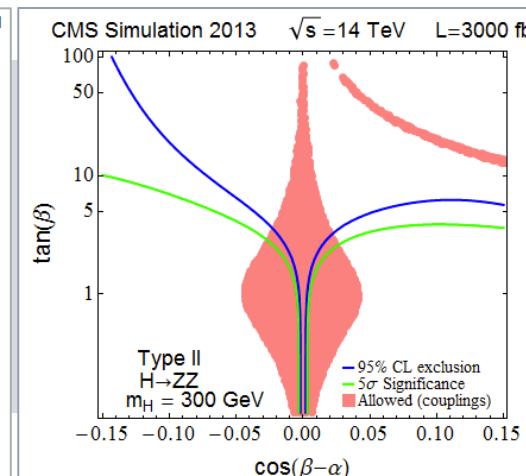
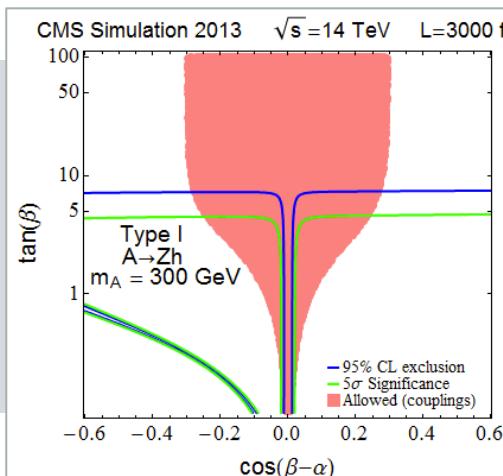
See also Adrian Perieanu (Thursday)

- H-boson beyond RunII
  - HL-LHC:  $3000 \text{ fb}^{-1}$  at 14TeV

- Standard Model: HH
  - Challenging for SM



- 2HDMs
    - indirect constraints
    - direct searches
- $\cos(\beta-\alpha) \rightarrow 0$
- $\tan\beta \rightarrow \text{intermediate}$



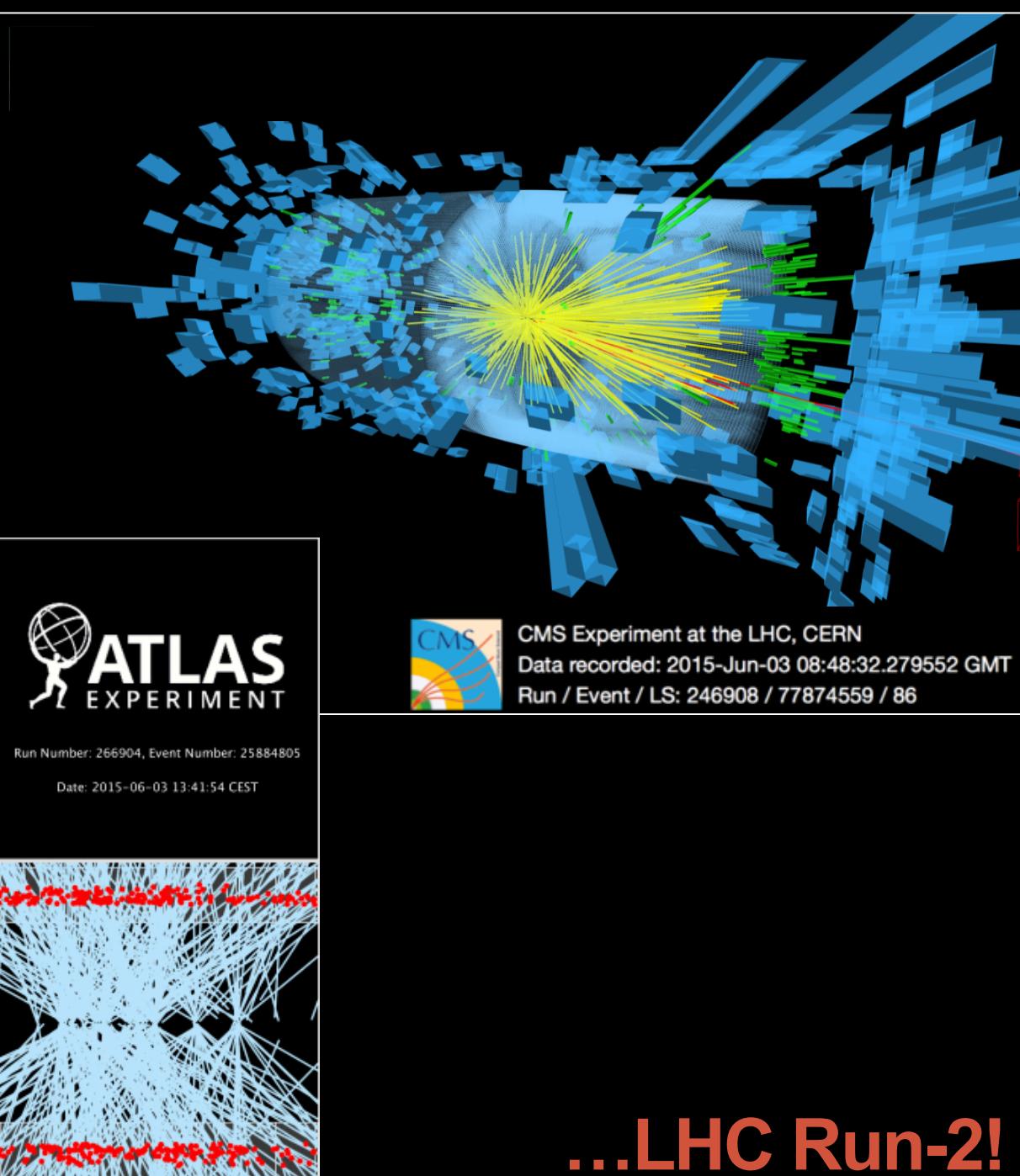
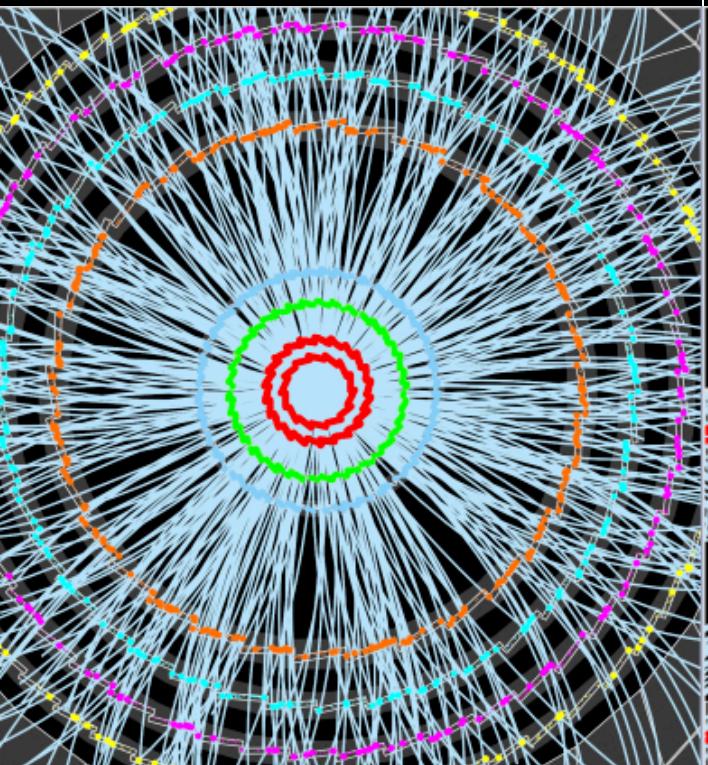
# Conclusions



- **H related to various BSM**
  - Motivate search for non-standard scalar bosons
- **Various final states**
  - SM-like: ZZ, WW,  $\gamma\gamma$  & BSM couplings: b,  $\tau$ ,  $\mu$ , etc
- **Various searches**
  - Light+heavy+charged scalars & exotic decays & indirect
- **Various interpretations**
  - Singlet, MSSM, NMSSM, 2HDM & model independent limits

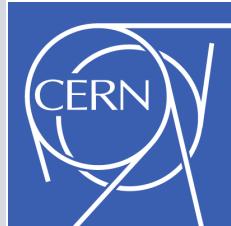
- **Run-1 has provided tight constraints**
  - **Run-2 will allow to enter uncovered parameter space!**

# It's time for...



# BACKUP

---



# Motivation in 2014

After the discovery of the 125 GeV boson...  
search for BSM processes in the scalar sector

- **Precision studies of properties**
  - **Couplings:** production & decays
    - CMS-HIG-13-005, see presentation by Linda Finco
  - **Rare decays:**  $Z\gamma$ ,  $\gamma^*\gamma$ ,  $\mu\mu$
  - **Invisible decays:** Dark Matter
- **Direct searches for extended scalar sector**
  - **Extra singlets/doublets**
    - 2HDMs
    - MSSM
    - NMSSM

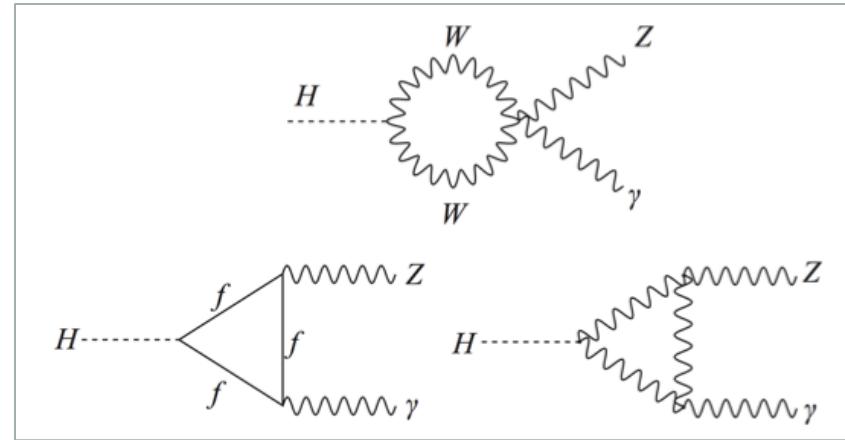
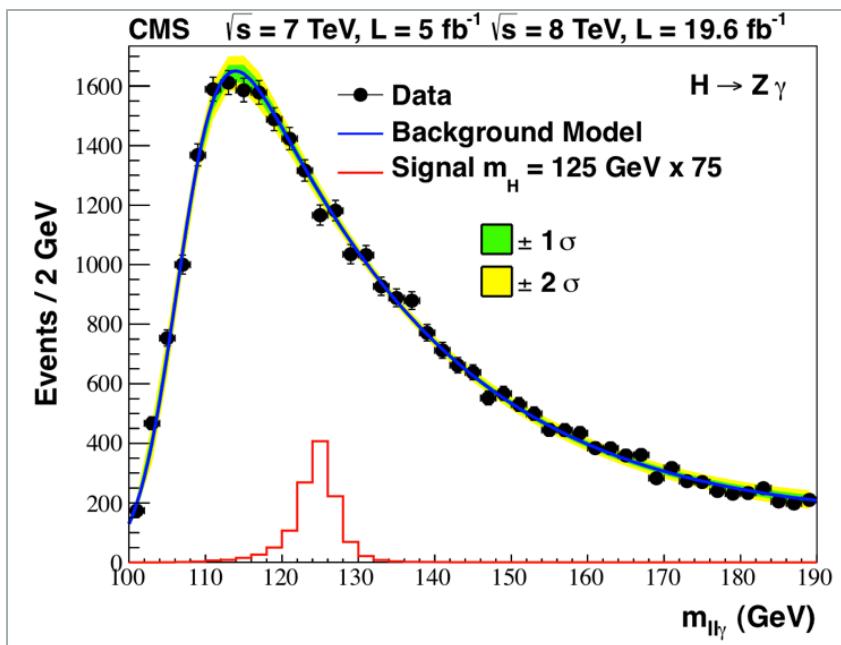
- **Interplay between direct & indirect searches**
- **Today's focus:** recent results on direct searches

Phys.Lett.B726(2013)587

# H $\rightarrow$ Z $\gamma$

## Rare decay

- Small BR in SM: 0.1%
- Loops: sensitive to undiscovered processes
  - E.g. composite Higgs



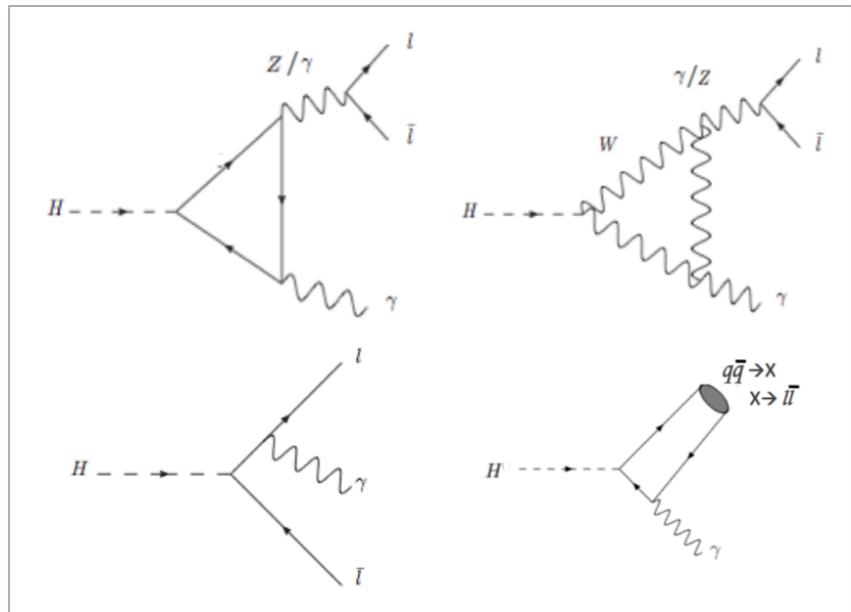
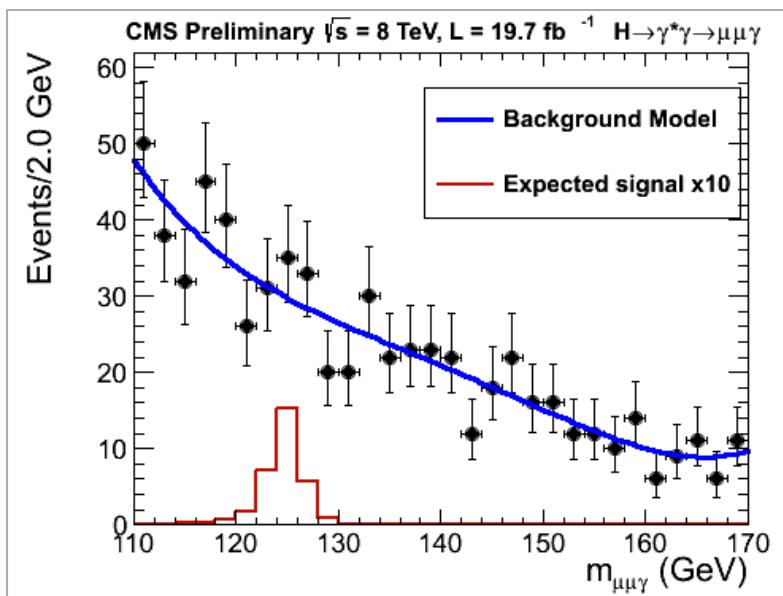
## 7+8 TeV (24.6 fb $^{-1}$ )

- Search in  $Z(ee) + \gamma$  and  $Z(\mu\mu) + \gamma$  final states
  - 5 event cat's (jets, leptons, photon)
  - Use invariant mass  $m_{ll\gamma}$
- Exclusion limit at 125 GeV
  - Observed:  $> 9.5 \times \text{BR}_{\text{SM}}$  @95%CL
  - Expected:  $> 10 \times \text{BR}_{\text{SM}}$

CMS-HIG-14-003

# $H \rightarrow \gamma^* \gamma \rightarrow \mu\mu\gamma$

- Rare Dalitz decay
  - Various contributions to same final state
  - Sensitive to e.g. new resonances
  - Selection w.r.t.  $Z\gamma$ :  $m_{\mu\mu} < 20$  GeV



## 8 TeV (19.7 fb-1)

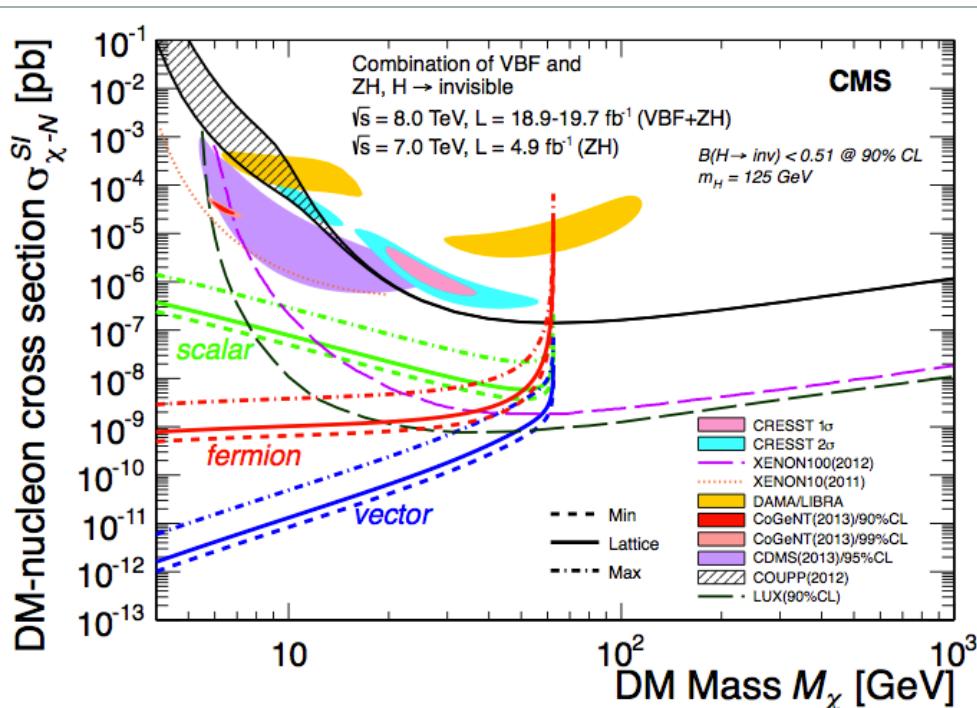
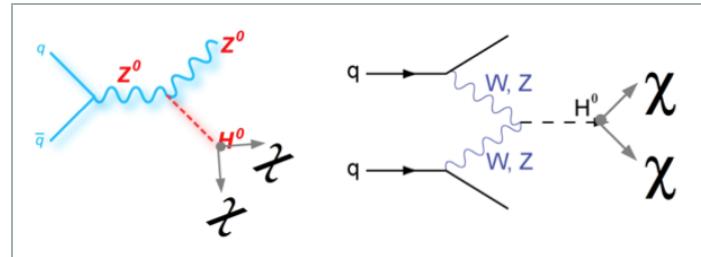
- Use invariant mass  $m_{\mu\mu\gamma}$
- Limit at 125 GeV
  - Exclude  $> 11$  (7)  $\times \text{BR}_{\text{SM}}$  @95%CL

CMS-HIG-13-030

# H $\rightarrow$ XX

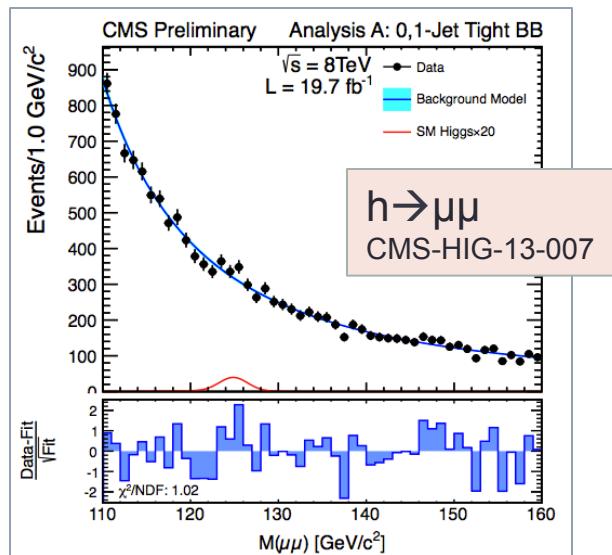
## Direct search for invisible decays

- Exploit associated production in VBF and VH final states

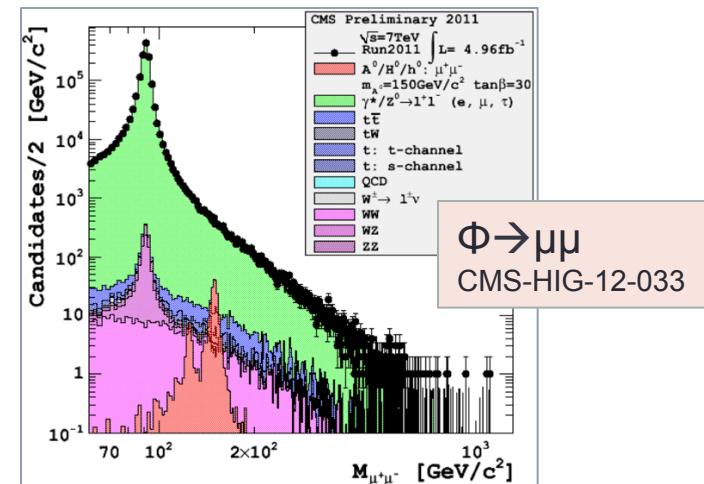


## Limits on $\text{BR}_{\text{inv}}$

- Combine searches
  - VBF,  $Z(\text{ll})H$ ,  $Z(\text{bb})H$
- **Direct exclusion limit:**  $\text{BR}_{\text{inv}} > 58\% (46\%)$ 
  - Indirect (width):  $> 52\% (56\%)$
  - CMS-HIG-13-005
- **Interpret as DM limits**  
Higgs-portal models
  - Scalar, vector, fermion DM



# PROPERTIES → SEARCHES

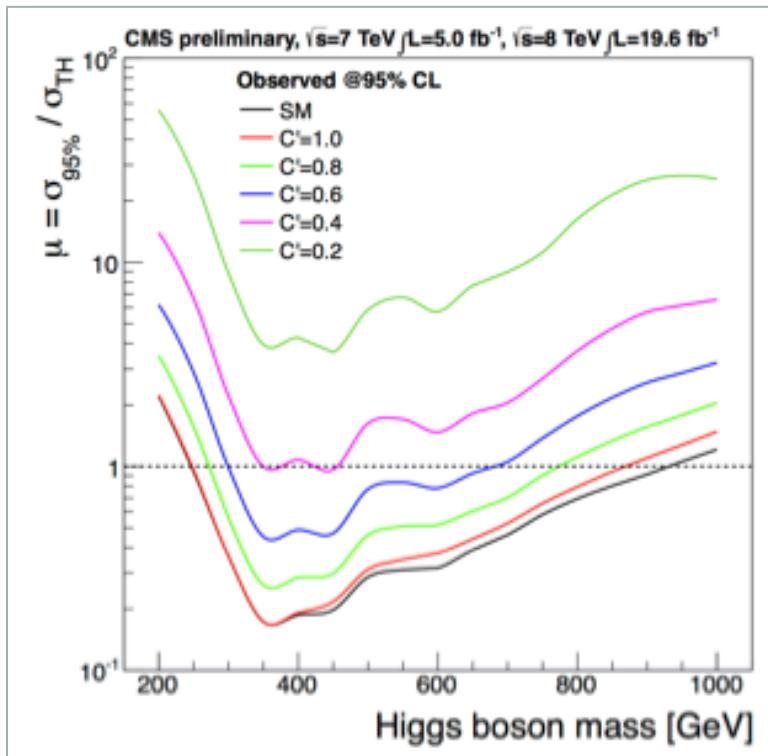


CMS-HIG-13-014

# Singlet

## SM+EW singlet field

- Mixing → heavy Higgs with SM Higgs-like couplings



Rescale light h couplings:

$$\mu_h = \frac{\sigma_h \times \text{BR}_h}{(\sigma_h \times \text{BR}_h)_{\text{SM}}} = C^2$$

Heavy H:

- $\mu_H = C'^2(1 - \text{BR}_{H,\text{new}})$
- $C'^2 = 1 - \mu_h$
  - unitarity

## Results

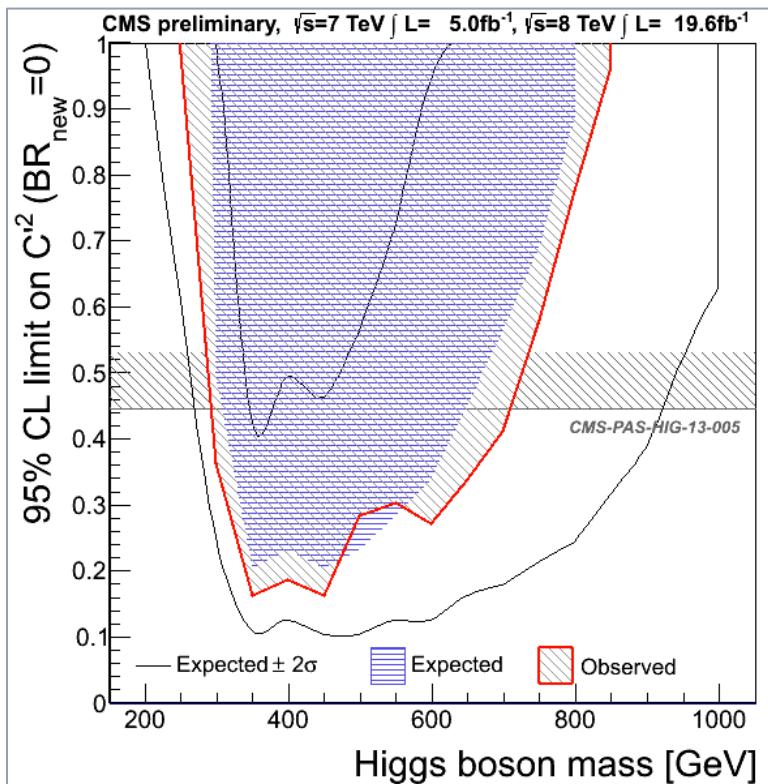
- Exclude SM-like heavy Higgs up to 1 TeV
  - With  $H \rightarrow ZZ \rightarrow llvv$  alone
- Exclude large  $C'$ 
  - Assuming  $\text{BR}_{\text{new}}=0$
- Room left for smaller  $C'$

CMS-HIG-13-014

# Singlet

## SM+EW singlet field

- Mixing → heavy Higgs with SM Higgs-like couplings



Rescale light h couplings:

$$\mu_h = \frac{\sigma_h \times BR_h}{(\sigma_h \times BR_h)_{SM}} = C^2$$

Heavy H:

- $$\mu_H = C'^2(1 - BR_{H,new})$$
- $C'^2 = 1 - \mu_h$
  - unitarity

## Results

- Exclude SM-like heavy Higgs up to 1 TeV
  - With  $H \rightarrow ZZ \rightarrow llvv$  alone
- Exclude large  $C'$ 
  - Assuming  $BR_{new}=0$
- Room left for smaller  $C'$

# 2HDMs

- **Effective theory with two complex scalar doublets**
  - 5 physical scalar fields after EWSB
    - 3 neutral: **h**, **H** (CP-even), **A** (CP-odd)
    - 2 charged: **H $\pm$**
- **Couplings described by 2 mixing angles**
  - $\tan\beta = v_1/v_2$
  - $\alpha$  mixing angle h/H

Coupling strength	Type I	Type II
$\kappa_V$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
$\kappa_u$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
$\kappa_d$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
$\kappa_l$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$

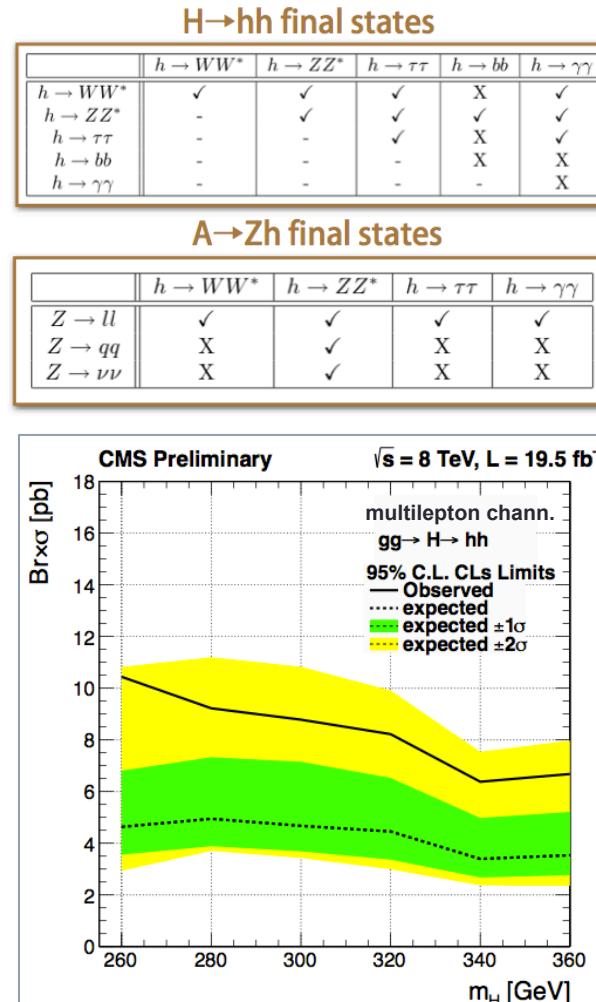
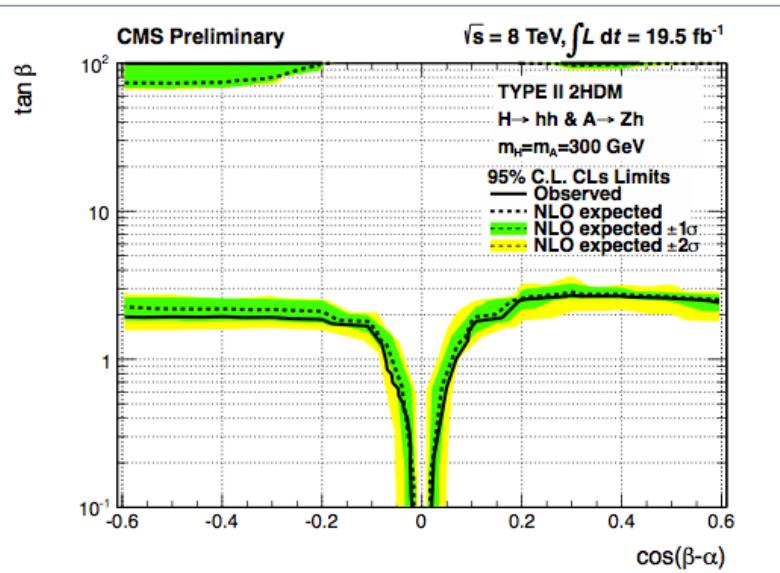
- Type 1  
 $\Phi_1$  coupled to V,  $\Phi_2$  to f
- Type 2  
 $\Phi_1$  coupled to u-type,  
 $\Phi_2$  to d-type quarks

- Using measurements of h(125), indirect limits can already be set
  - See e.g. ATLAS-CONF-2014-010

# H $\rightarrow$ hh & A $\rightarrow$ Zh

CMS-HIG-13-025

- Direct 2HDM searches
  - H $\rightarrow$ hh ( $2m_h < m_H < 2m_t$ )
  - A $\rightarrow$ Zh ( $m_h + m_Z < m_A < 2m_t$ )
- Various final states
  - Leptons/photons/etc



- Direct constraints on 2HDMs of Type I and Type II

CMS-HIG-13-025

# H $\rightarrow$ hh & A $\rightarrow$ Zh

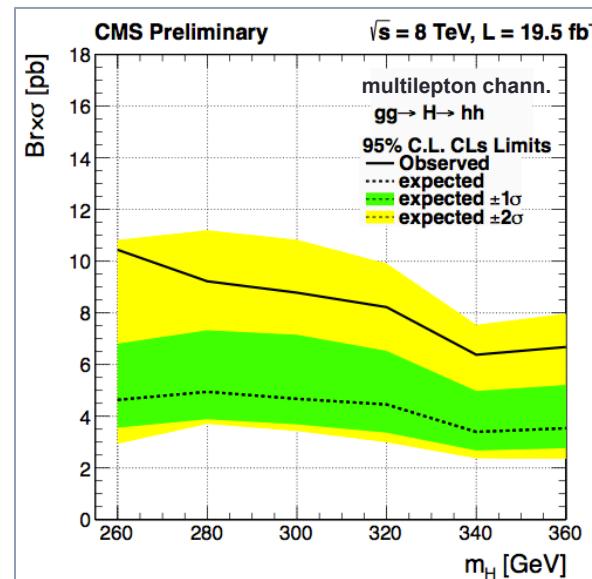
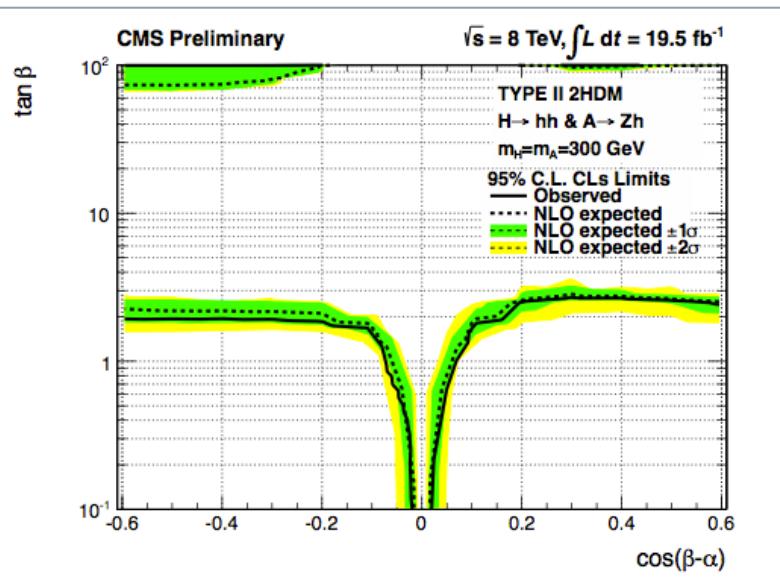
- Direct 2HDM searches
  - H $\rightarrow$ hh ( $2m_h < m_H < 2m_t$ )
  - A $\rightarrow$ Zh ( $m_h + m_Z < m_A < 2m_t$ )
- Various final states
  - Leptons/photons/etc

## H $\rightarrow$ hh final states

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

## A $\rightarrow$ Zh final states

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



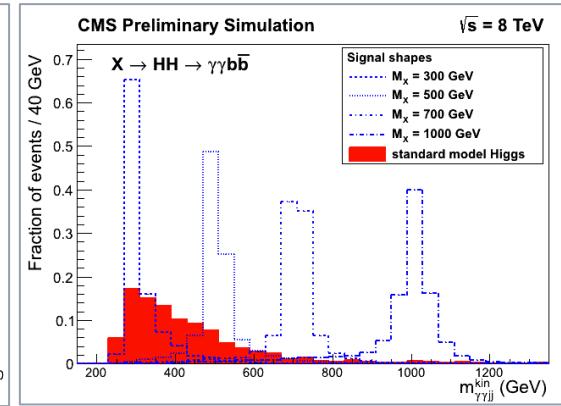
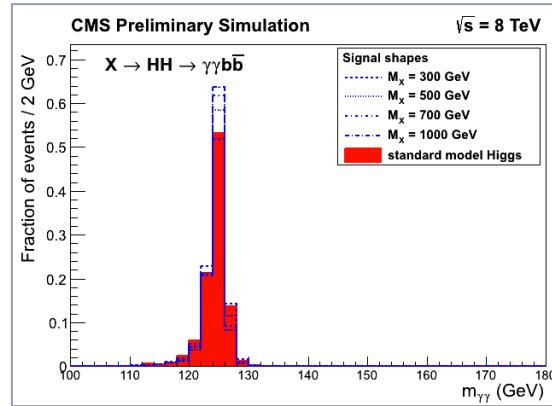
- Direct constraints on 2HDMs of Type I and Type II

# X → h(γγ)h(bb)

## Search hh resonance

- $m_X = [260, 1100]$  GeV
  - 2 γ
  - 1/2 b-tagged jets
- Public since Monday!

**NEW CMS-HIG-13-032**



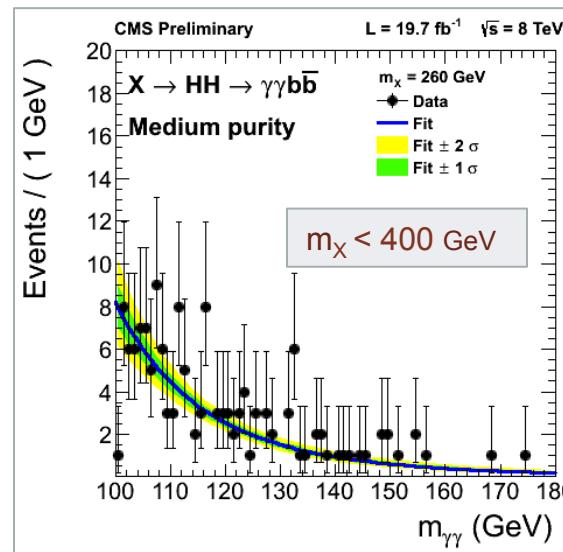
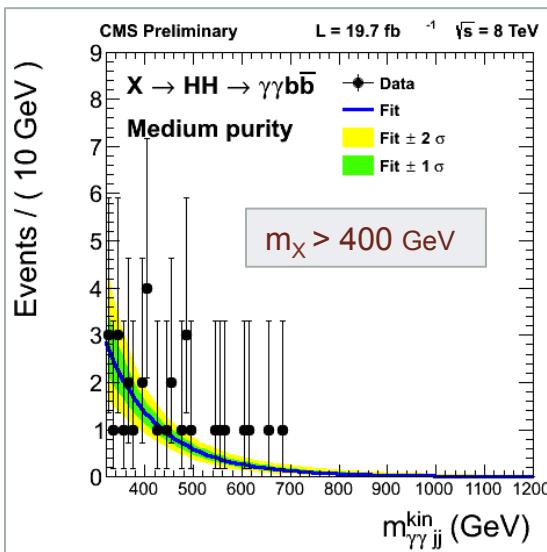
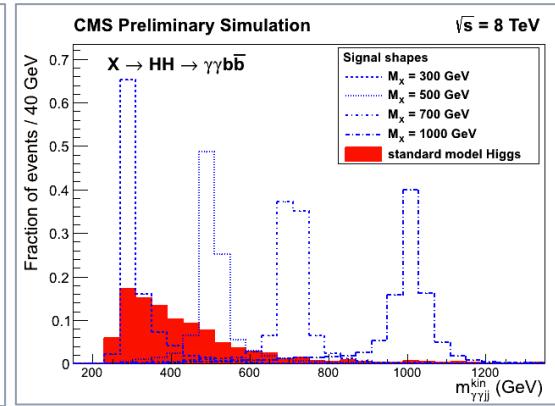
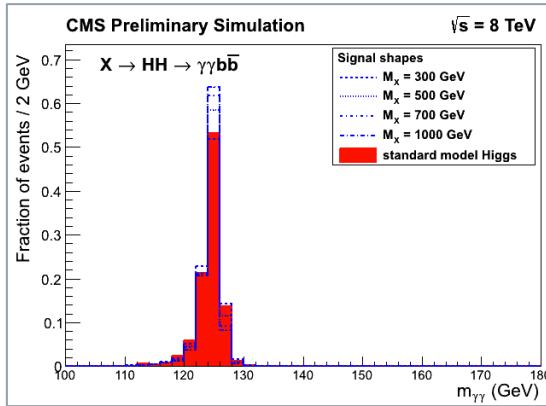
- See presentation by M.Gouzevitch for details on photon reconstruction

# X → h(γγ)h(bb)

## Search hh resonance

- $m_X = [260, 1100]$  GeV
  - 2 γ
  - 1/2 b-tagged jets
- Public since Monday!

**NEW CMS-HIG-13-032**



## Fits

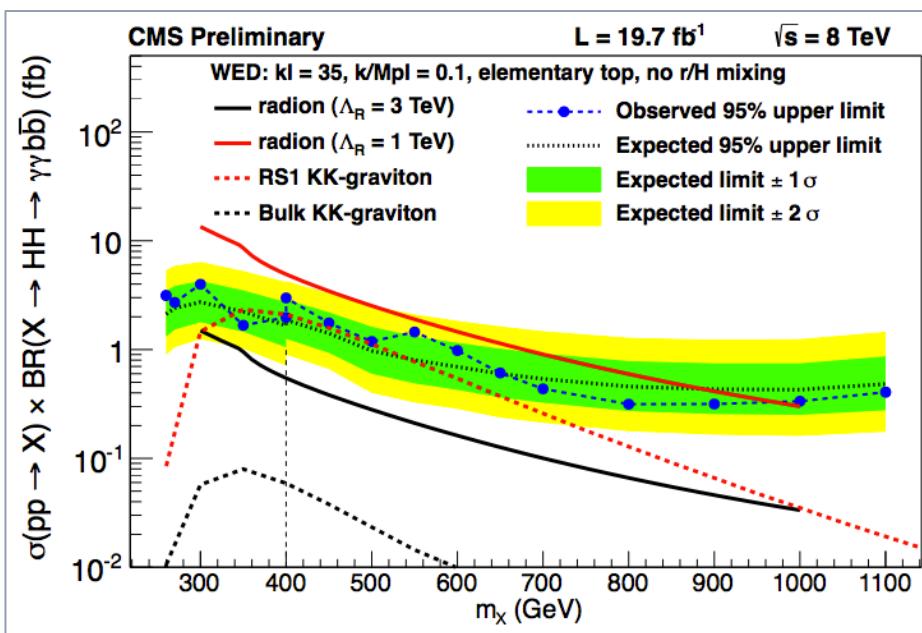
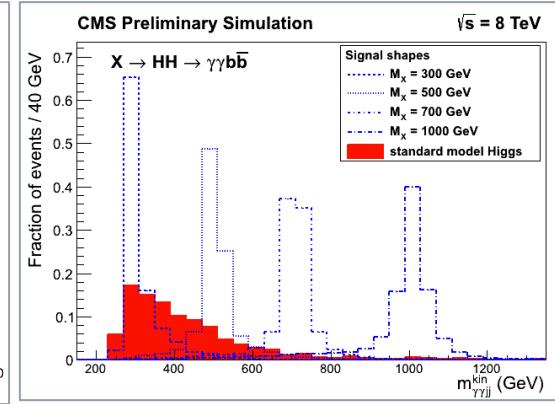
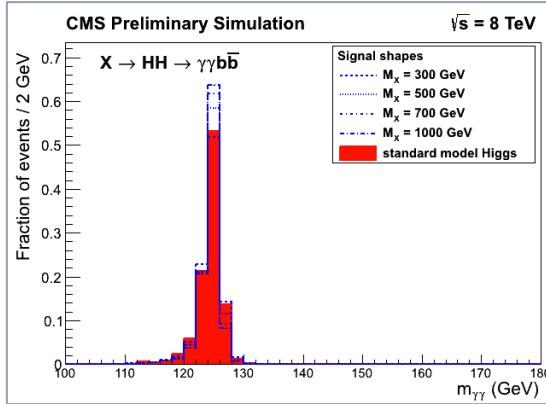
- Polynom. background
- 1.  $m(\gamma\gamma jj)$ 
  - $m_X > 400$  GeV
  - Kinematic fit
- 2.  $m(\gamma\gamma)$ 
  - $m_X < 400$  GeV

# X → h(γγ)h(bb)

**NEW CMS-HIG-13-032**

## Search hh resonance

- $m_X = [260, 1100]$  GeV
  - 2 γ & 1/2 b-tagged jets
  - >400GeV: **kinematic fit**
- Public since Monday!



## Spin hypothesis

- Test spin-0 and spin-2 models
- Selection minimally sensitive

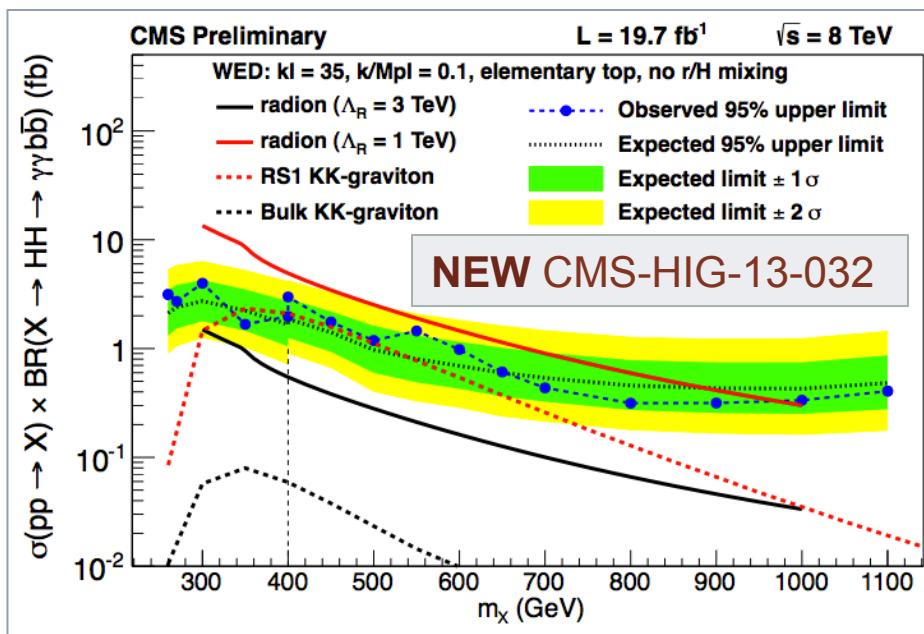
## Limits

- Warped extra dimensions
  - Radion scale  $\Lambda_R = 1$  TeV
  - **Radion mass exclusion:**  $M_X < 970$  GeV

# X $\rightarrow$ h( $\gamma\gamma$ )h(bb)

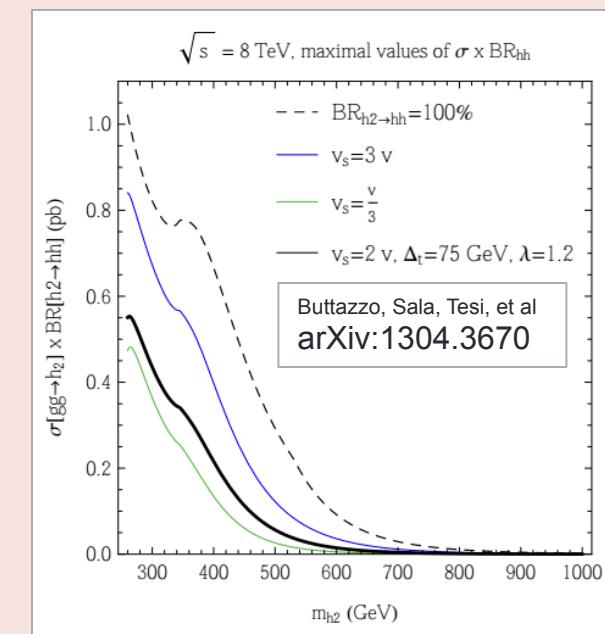
## Search hh resonance

- $m_X = [260, 1100]$  GeV
  - 2  $\gamma$  & 2 b-tagged jets
  - >400GeV: **kinematic fit**
- Public since a week!



## Plan:

- 2HDM interpretation
- H $\rightarrow$ h( $\gamma\gamma$ )h(bb)
- Example: (N)MSSM



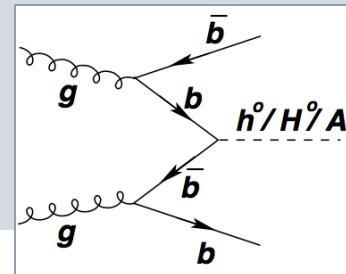
# MSSM

- **MSSM scalar sector**
  - A particular 2HDM Type II model
  - Phenomenology described in  $\tan\beta$  vs  $m_A$
- **Indirect exclusion** from  $h(125)$  on  $m_A$ 
  - Simplified MSSM (arXiv:1305.2172)
- **Direct searches**
  - **Neutral scalars**
  - **Charged Higgses**

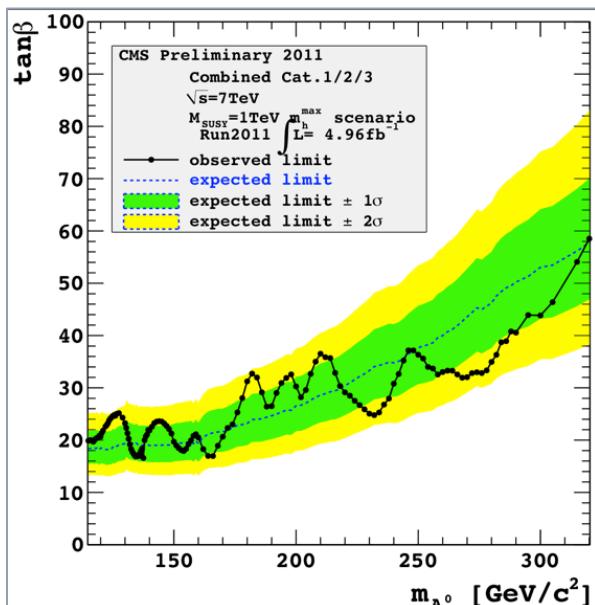
# $\Phi \rightarrow b\bar{b}$ and $\Phi \rightarrow \mu\mu$

## Various direct MSSM searches

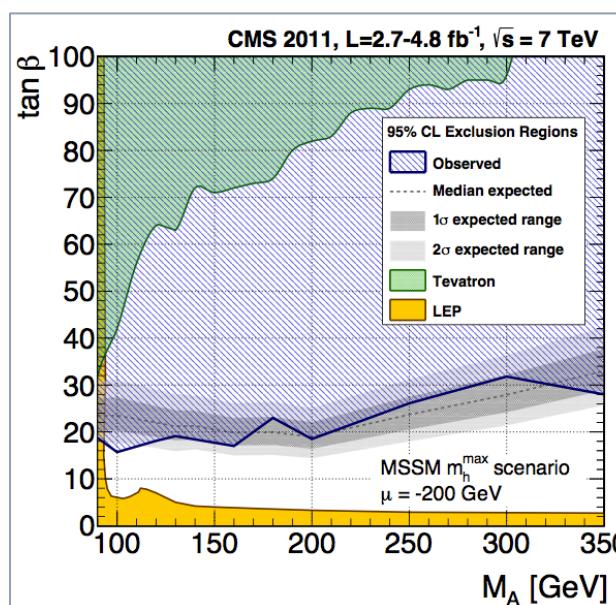
- $\Phi \rightarrow b\bar{b}$  and  $\Phi \rightarrow \mu\mu$ 
  - Possibly with b's in final state



CMS-HIG-12-033

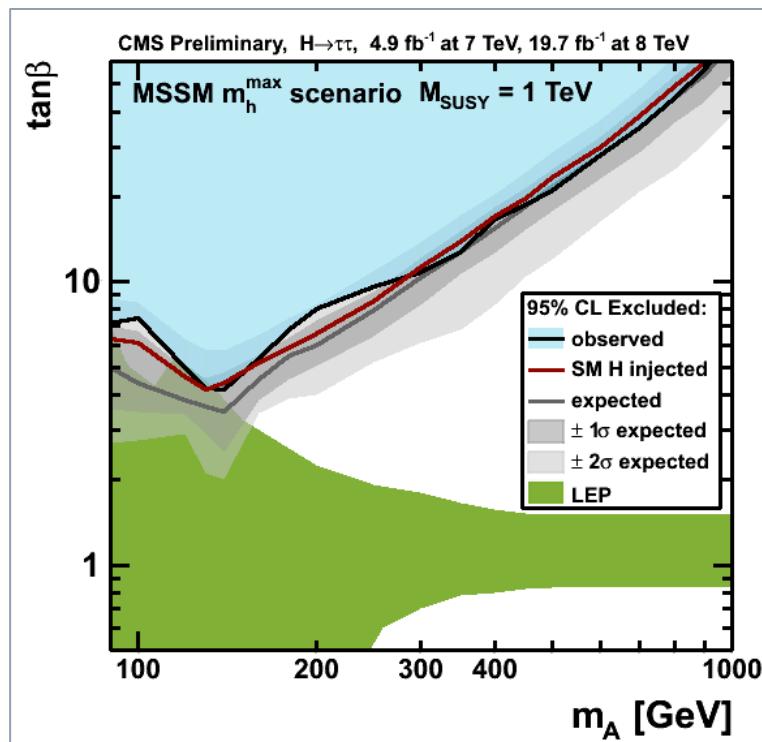


CMS-HIG-12-033

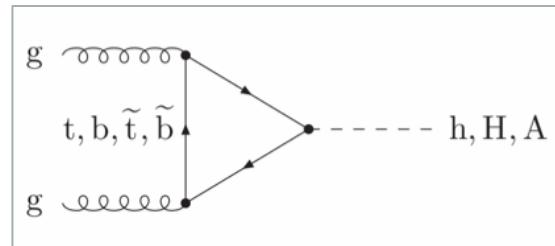


# $\Phi \rightarrow \tau\tau$

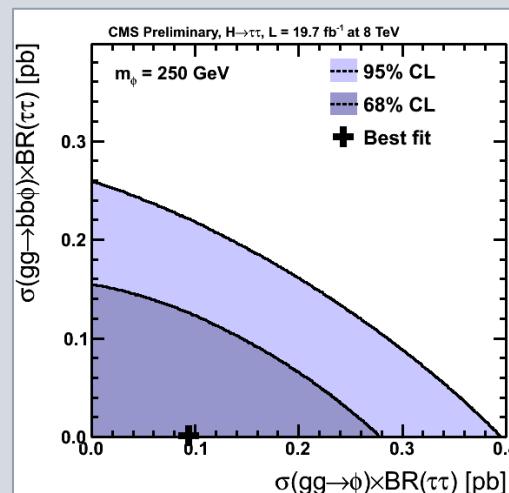
- Direct search for MSSM neutral Higgs with  $\Phi \rightarrow \tau\tau$
- $m_A < 140$  GeV almost excluded
  - $\Phi \rightarrow \tau\tau + \text{LEP}$



CMS-HIG-13-021



- Split b-tag multiplicity
- Model-independent limits:

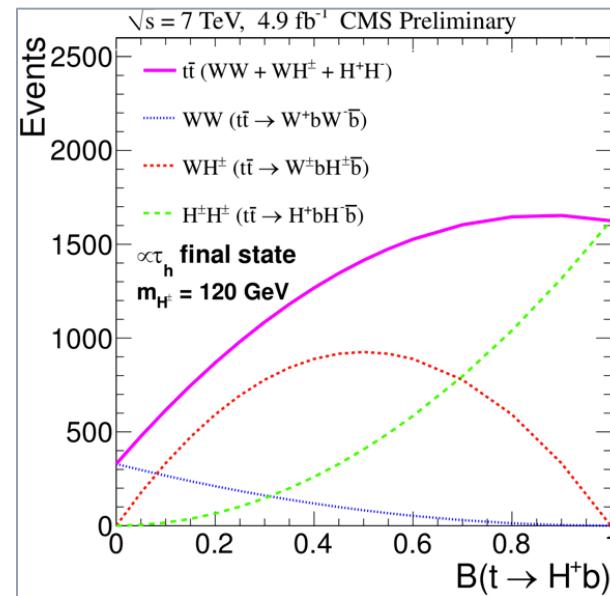
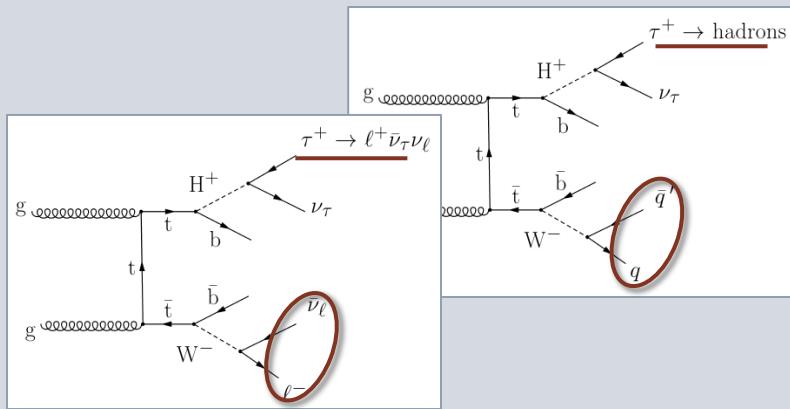


CMS-HIG-11-019

# H $^\pm \rightarrow \tau\nu$

## MSSM H $^\pm \rightarrow \tau\nu$

- $m_{H^\pm} < m_t$ : ttbar decay
  - $t\bar{t} \rightarrow H b W b$
- $H^\pm \rightarrow \tau^\pm \nu$  significant
  - Also for small  $\tan\beta$
- Combining various channels
  - Fully hadronic, e-tau, e-mu



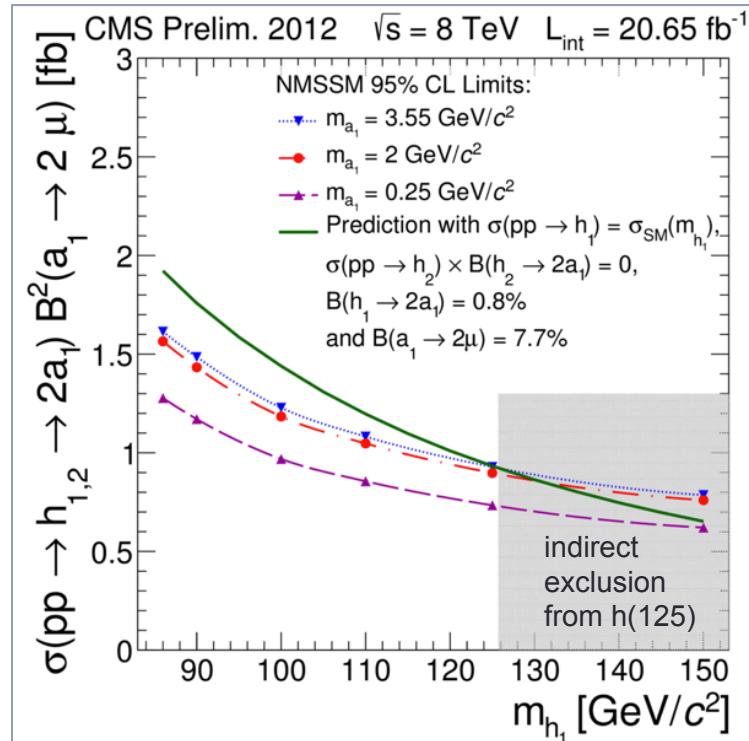
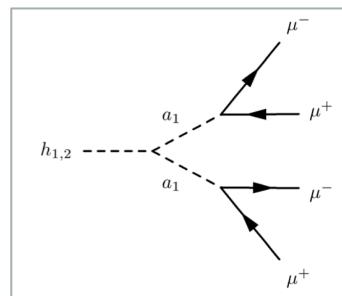
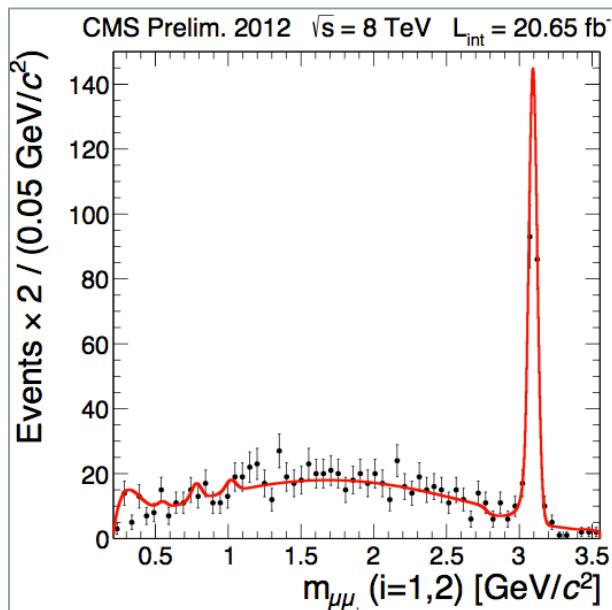
Limits (4.9fb $^{-1}$  @ 7TeV)

- **BR( $t\bar{t} \rightarrow H^+ b$ ) > 2-4 %**
  - $80 < m_H < 160 \text{ GeV}$
  - Assuming  $\text{BR}(H^+ \rightarrow \tau\nu) = 1$

# NMSSM

CMS-HIG-13-010

- Beyond MSSM: NMSSM
  - Additional gauge singlet
- Further extend Higgs sector
  - Additional **CP-even & CP-odd**
- Larger phenomenology
  - Neutral scalars with  **$m < 125$**  not excluded in NMSSM

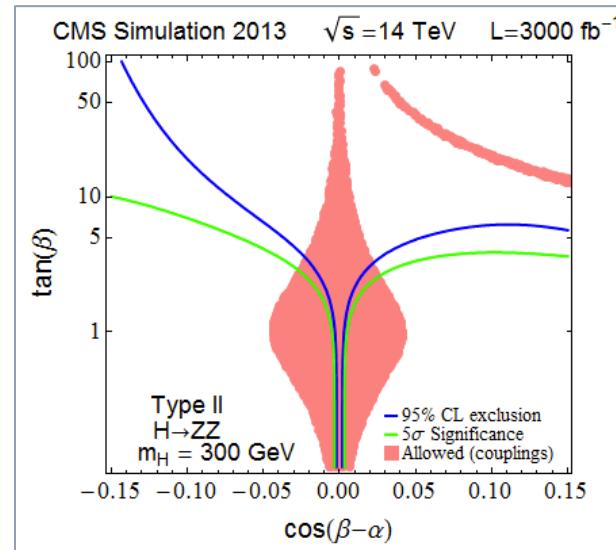
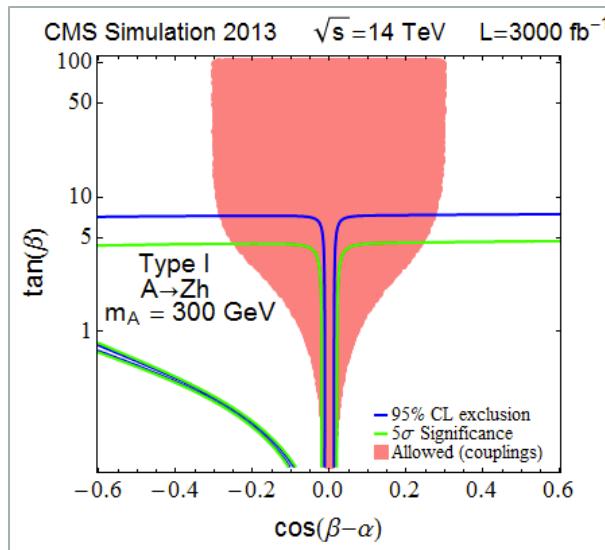


- Most recent search:  $h_{1,2} \rightarrow a_1 a_1 \rightarrow 4\mu$ 
  - $2m_\mu < m_a < 2m_\tau$
- Limits on various BSM models

CMS-FTR-13-024

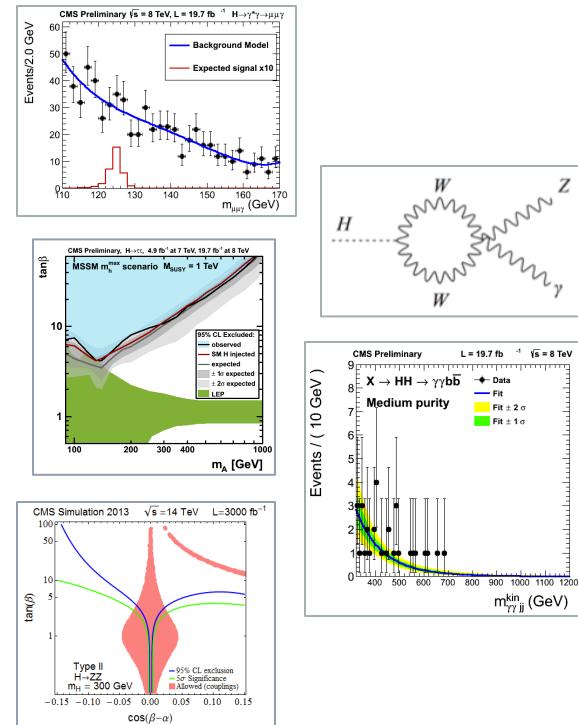
# Prospects

- **Outlook beyond RunII**
  - 3000  $\text{fb}^{-1}$  at 14 TeV
- **Direct searches**
  - $H \rightarrow ZZ$ ,  $A \rightarrow Zh$ , ...
- Cover regions of phasespace not excluded by indirect constraints

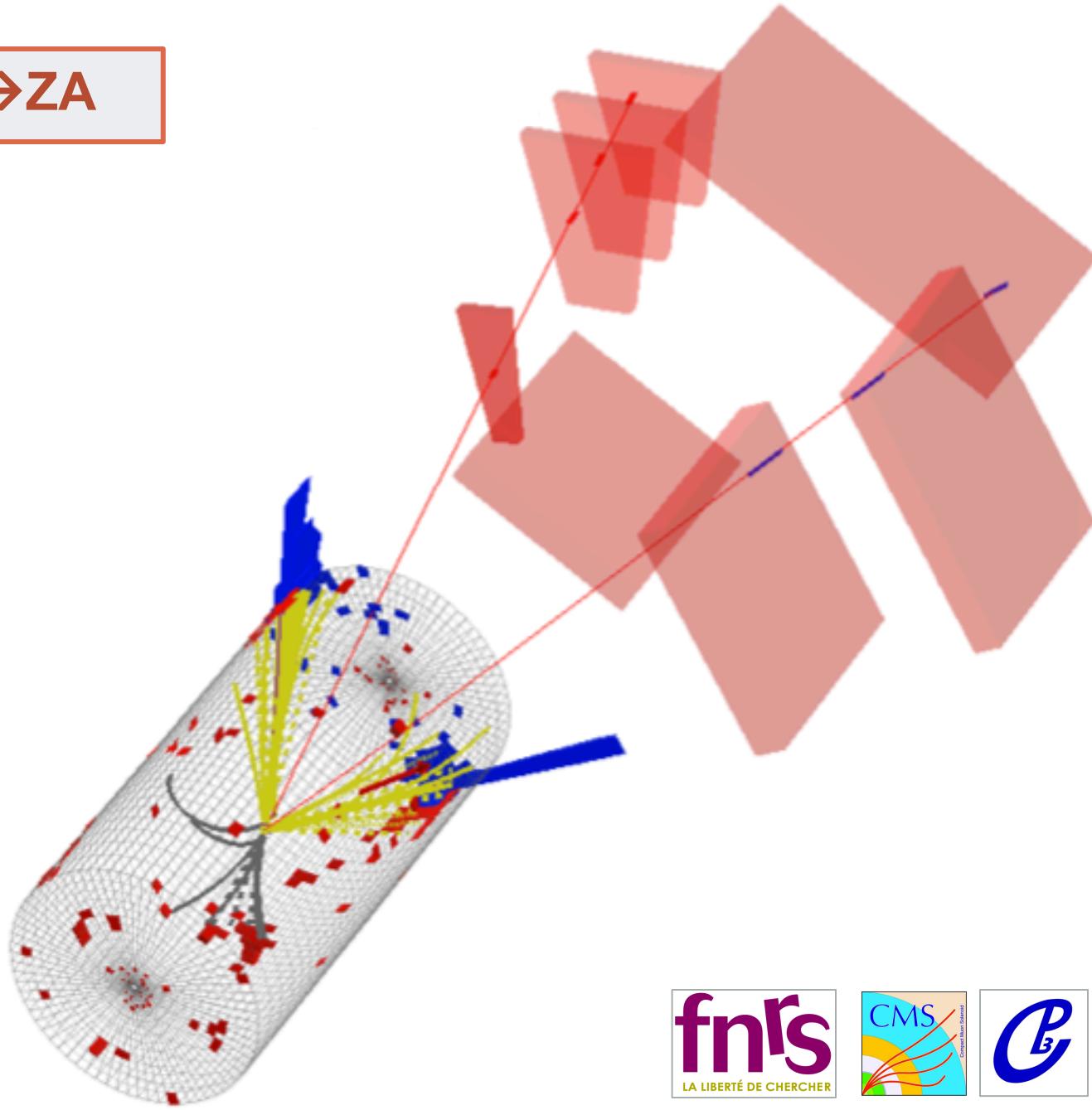


# Conclusions in 2014

- After  $h(125)$  discovery
  - Now entering domain of precision physics
  - No deviation from SM expectations
    - Indirect constraints of BSM phase space
- Variety of direct searches being conducted
  - Rare decays, invisible decays,  
2HDM, (N)MSSM, etc..
- Plan: further extend scope  
of direct BSM searches in scalar sector
  - Probe uncovered phasespace

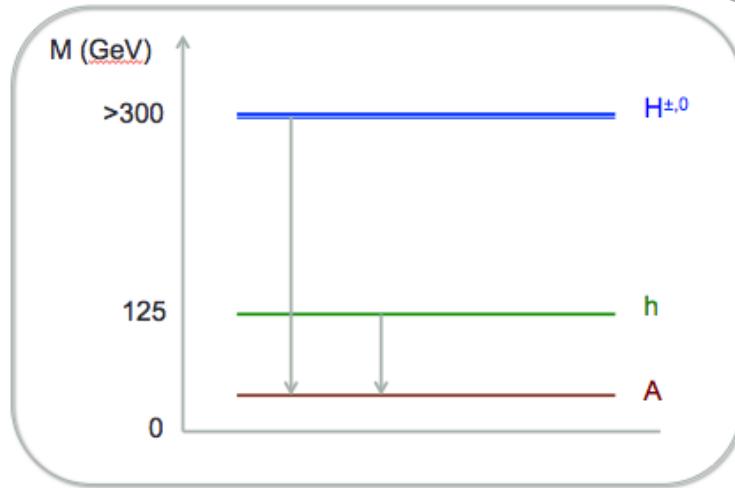
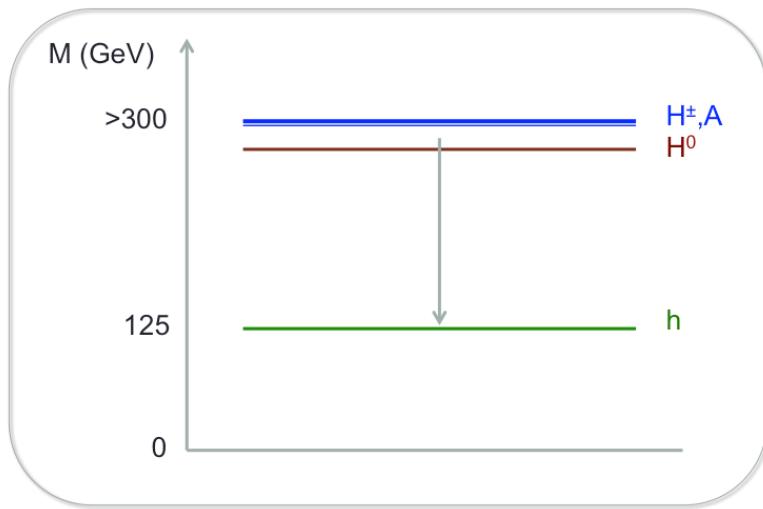


$H \rightarrow ZA$



# Hierarchy sketches

Illustrations similar to  
<http://arxiv.org/abs/hep-ph/0703051>

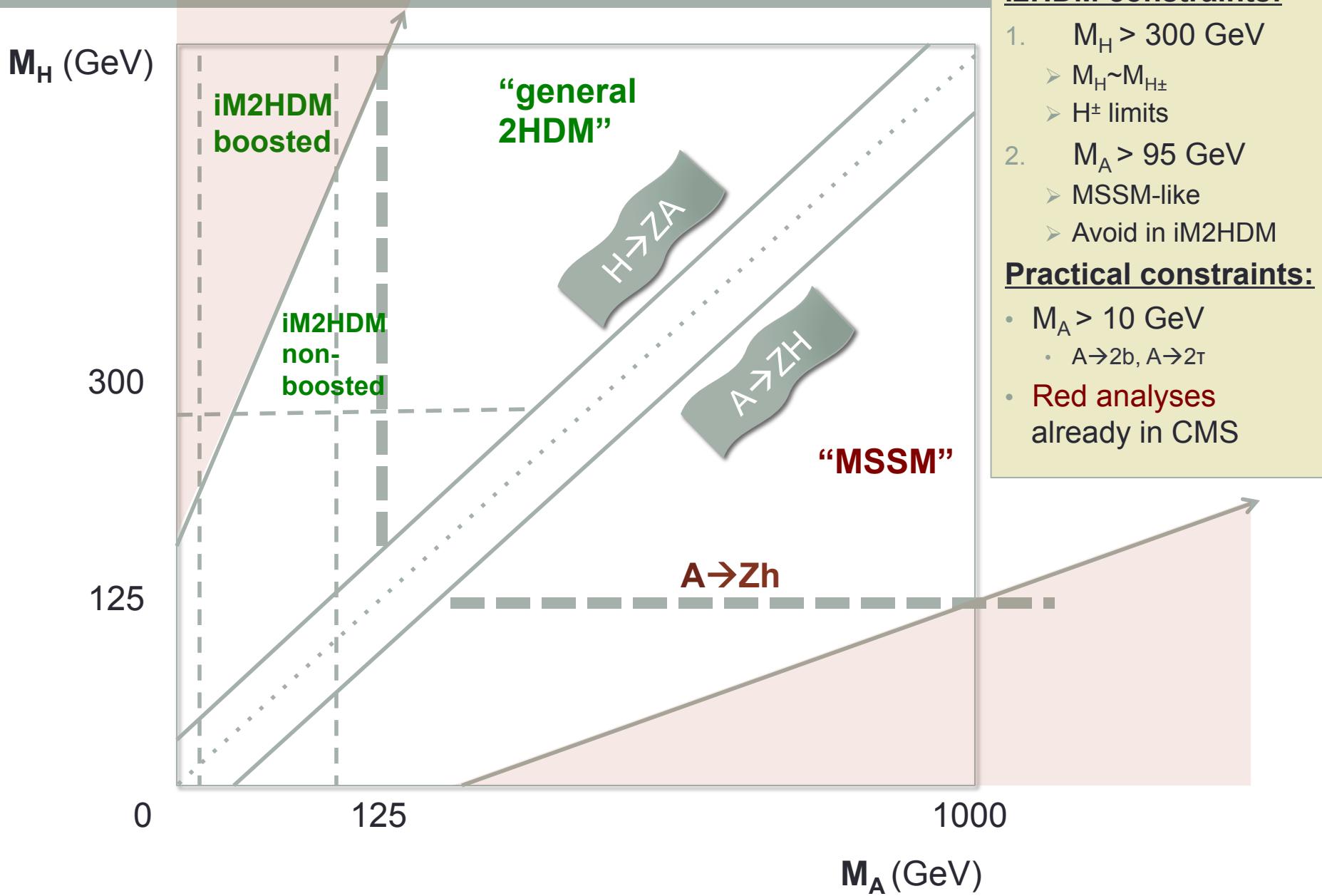


## 1. Usual hierarchy

- Example: MSSM
  - SM-like Higgs boson lightest
    - Heavy susy Higgses
  - Ongoing CMS search for  $A \rightarrow Z h$ 
    - Final state:  $A \rightarrow Z(l\bar{l}) h(bb)$   
with 125 GeV  $h \rightarrow bb$

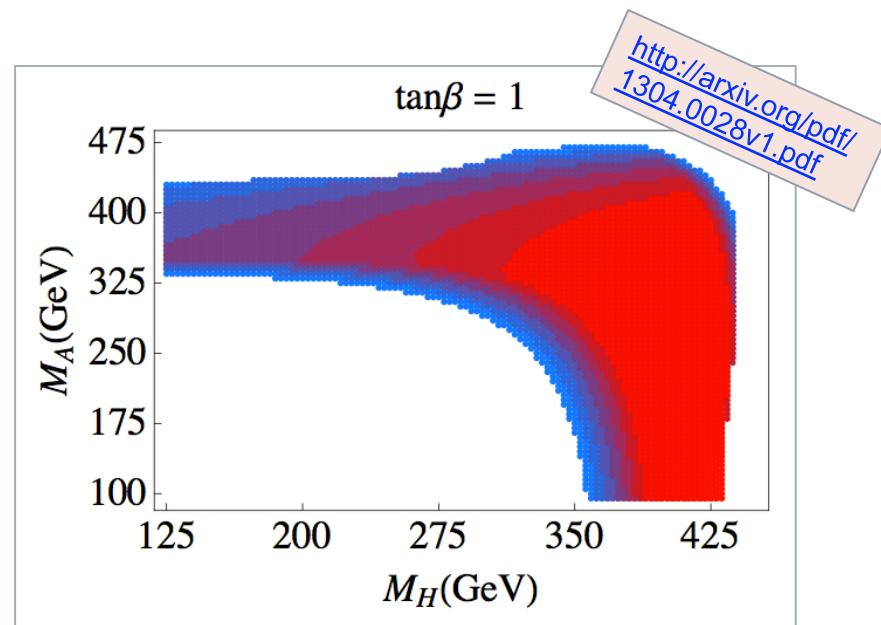
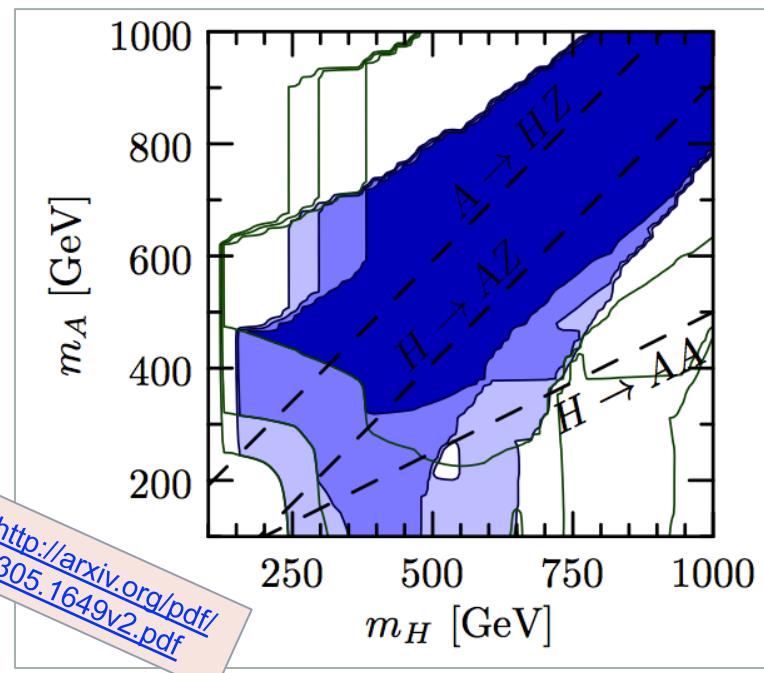
## 2. Alternative: inverted hierarchy

- From “A Twisted Custodial Symmetry in the Two-Higgs-Doublet Model”
  - <http://arxiv.org/abs/hep-ph/0703051>
- Light pseudoscalar  $A$ 
  - $M_A$ : few GeV (NMSSM) or more
  - Possibility:  $H \rightarrow ZA$



# Recent constraints

- **Examples.** NB: these papers use the MSSM-like constraint from LEP
  - $M_A > 95$  GeV
- Even then still **much room remaining**
  - Also with inverted hierarchy



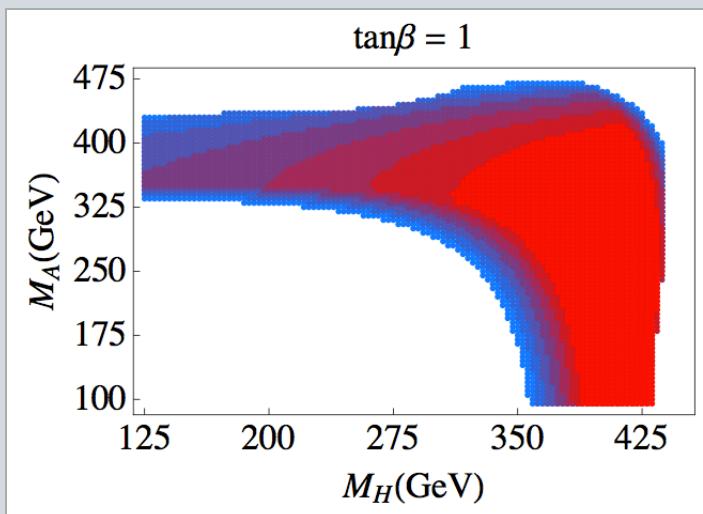
Top plot ( $\tan\beta=1$ ) favors

- **Heavy  $M_H$**  ( $\sim 400$  GeV)
- **Lighter  $M_A$**  (95-400 GeV)

# Limits & couplings

<http://arxiv.org/pdf/1304.0028v1.pdf>

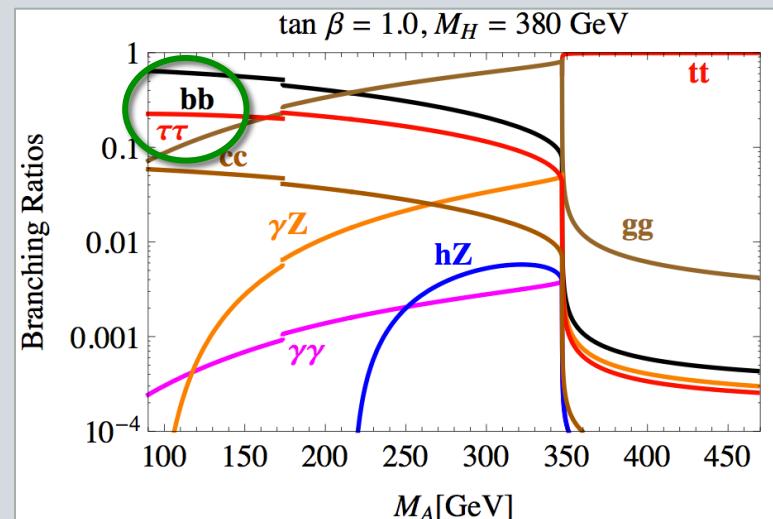
- Recent limits



This plot ( $\tan\beta=1$ ) favors

- Heavy  $M_H$  ( $\sim 400$  GeV)
- Lighter  $M_A$  (95-400 GeV)

- BRs

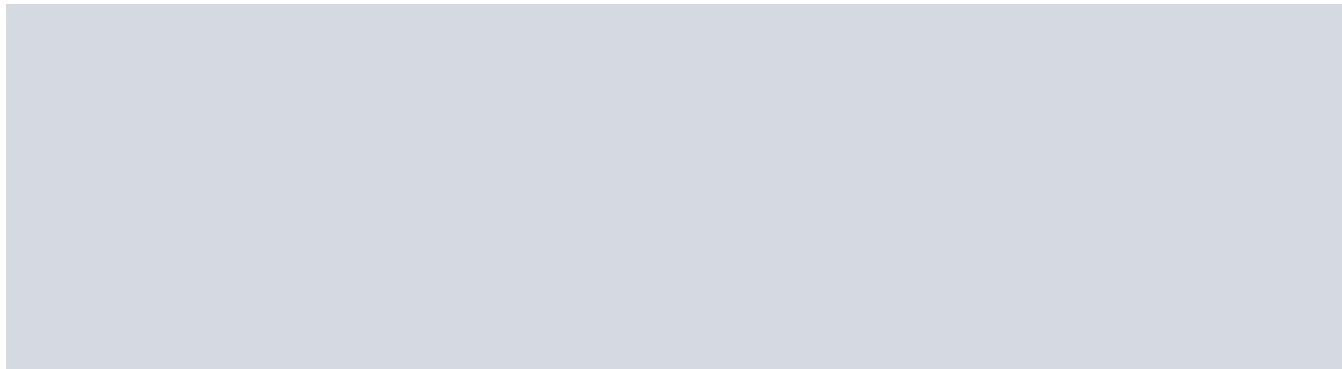


If  $M_A$  small  $\rightarrow$  dominant decays:

- $A \rightarrow bb$
- $A \rightarrow \tau\tau$
- $H \rightarrow Z(l\bar{l})A(bb)$  and  $H \rightarrow Z(l\bar{l})A(\tau\tau)$

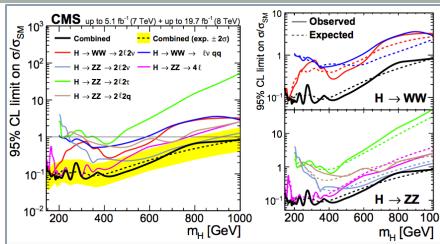
# HEAVY H

---

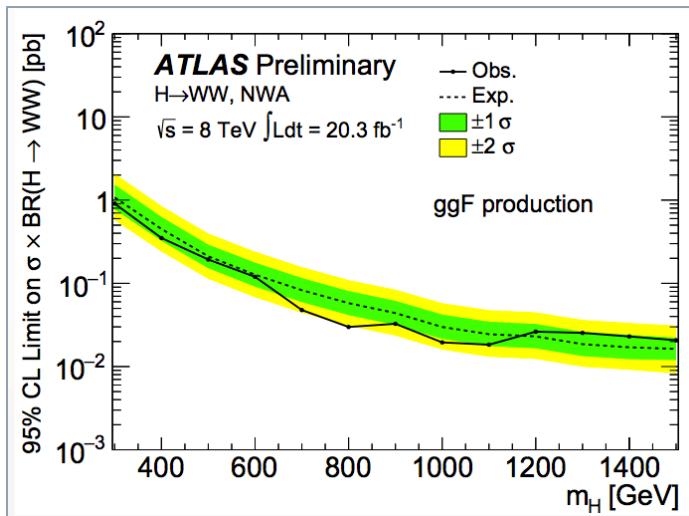
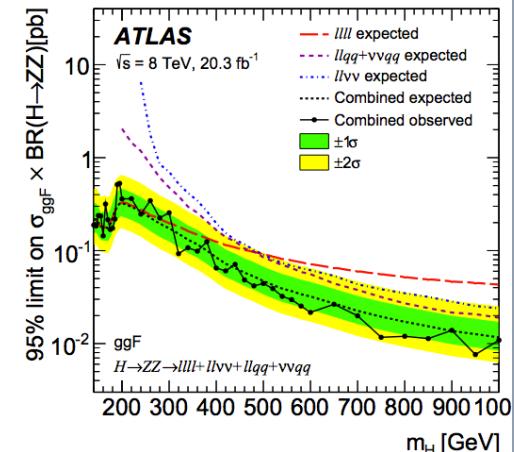
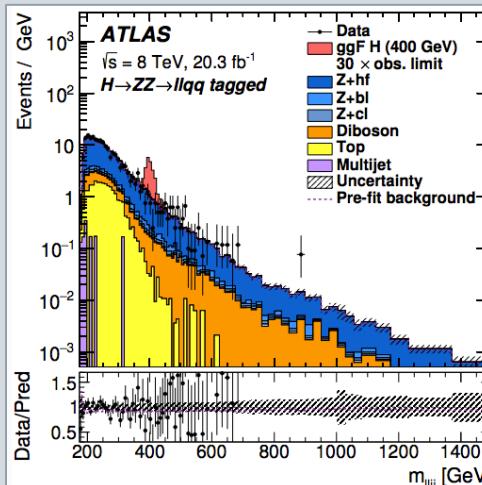


# H $\rightarrow$ WW

- H $\rightarrow$ ZZ (4 channels)
  - 4l, llqq, llvv, **qqvv**
- Discrimination
  - 4-object **mass**
  - **M<sub>T</sub>** (neutrinos)
- Interpretation: **2HDM**
  - Narrow width



ATLAS-HIGG-2013-19  
ATLAS-HIGG-2013-20



- H $\rightarrow$ WW: (2 channels)
  - lqqq, llvv
- Discrimination
  - Mass definition
- Limits
  - Narrow width
  - SM-like width

# H $\rightarrow$ $\gamma\gamma$

- Interpretations

<http://arxiv.org/pdf/1506.02301v1.pdf>

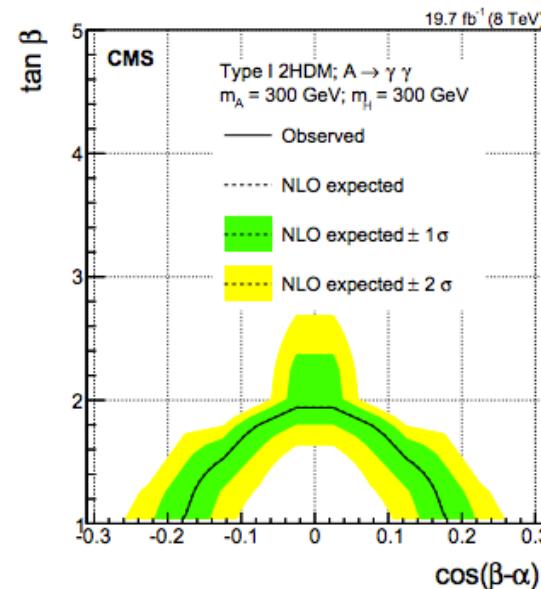
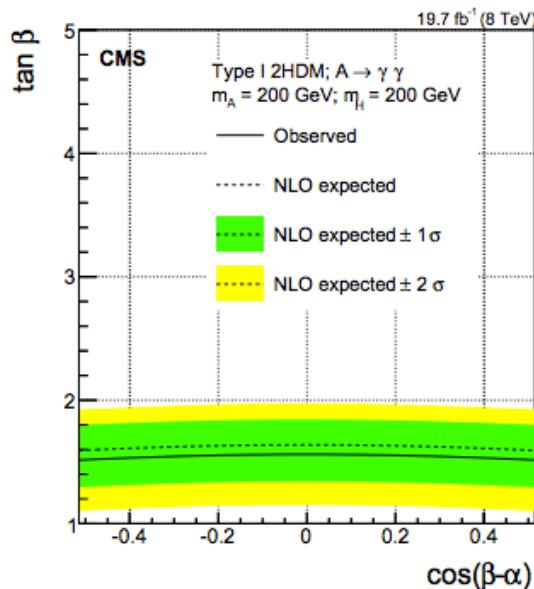
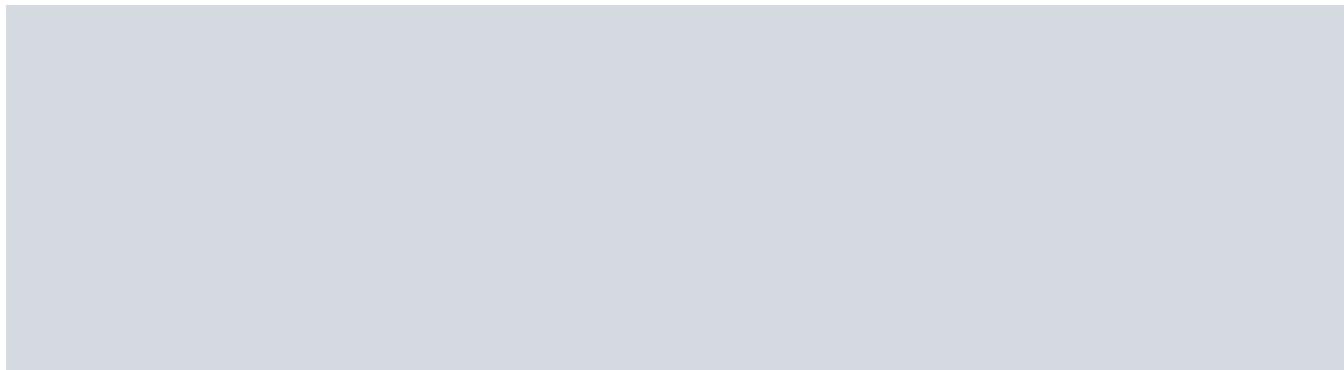


Figure 10: Observed and expected 95% CL exclusion regions for gluon-fusion production of a heavy Higgs boson A of mass 200 GeV (left) and 300 GeV (right) in the  $\tan \beta$  versus  $\cos(\beta - \alpha)$  plane for the Type I 2HDM, assuming the H boson to be degenerate in mass with A. The regions below the curves are excluded.

# 2HDM

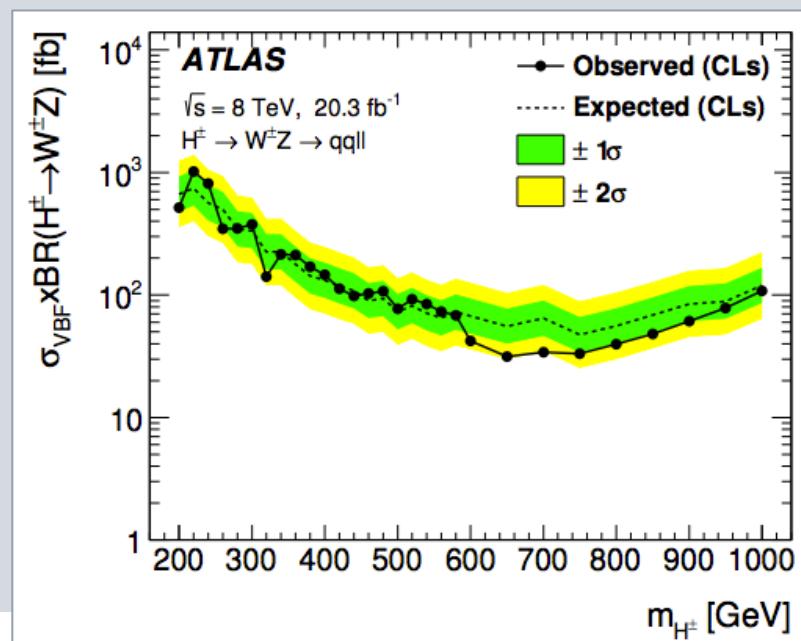
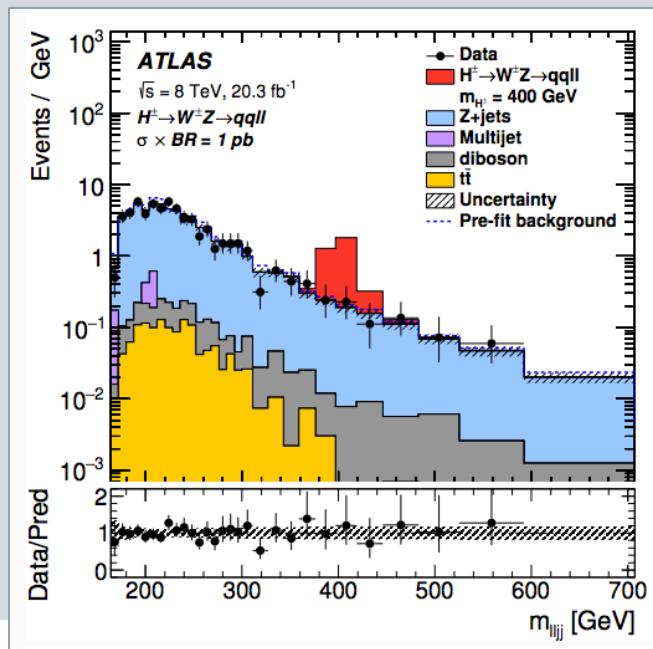
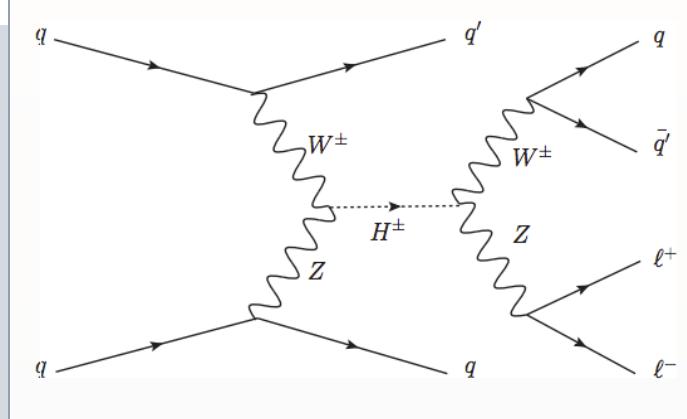
---



# $H^\pm \rightarrow W^\pm Z$

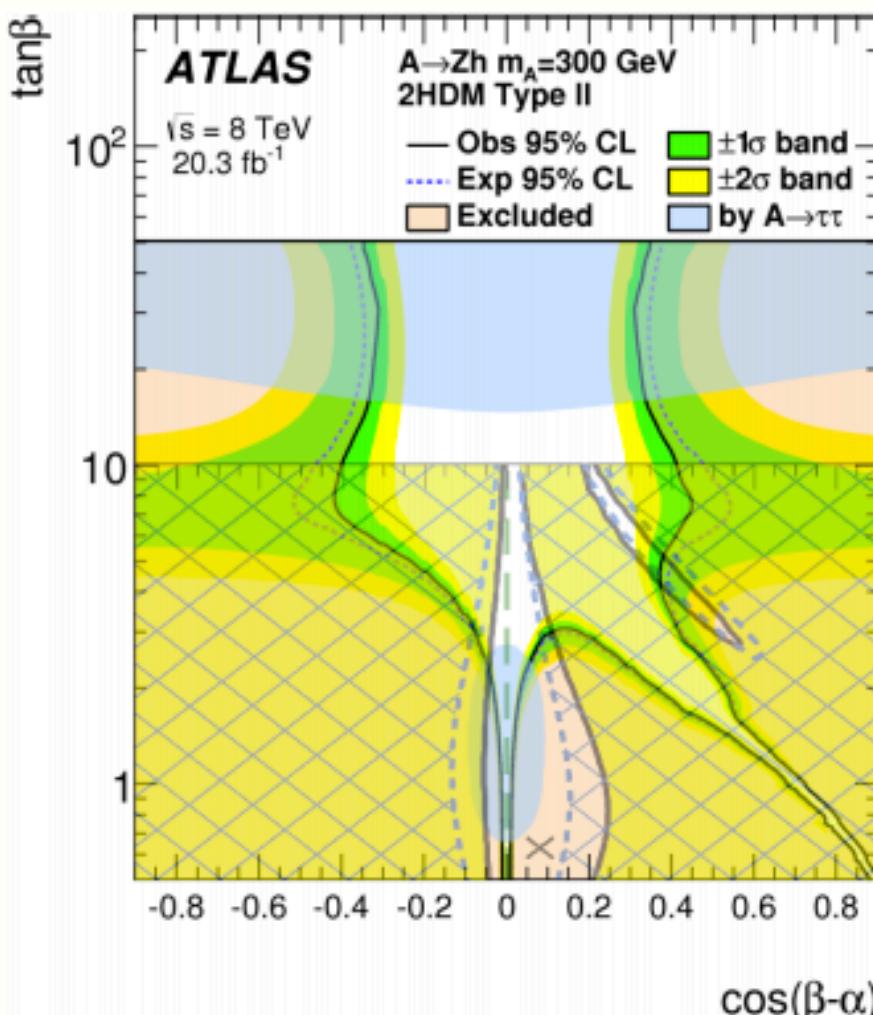
PRL114(2015)231801

- Loop vs tree
  - **Higgs Triplet**: tree level
  - **2HDM**: loop level
- $H^\pm$  reconstructed:  $M_{llqq}$ 
  - **Initial state**: VBF
  - **Final state**:  $W \rightarrow qq$ ,  $Z \rightarrow ee, \mu\mu$



## COMPARISON WITH OTHER RESULTS

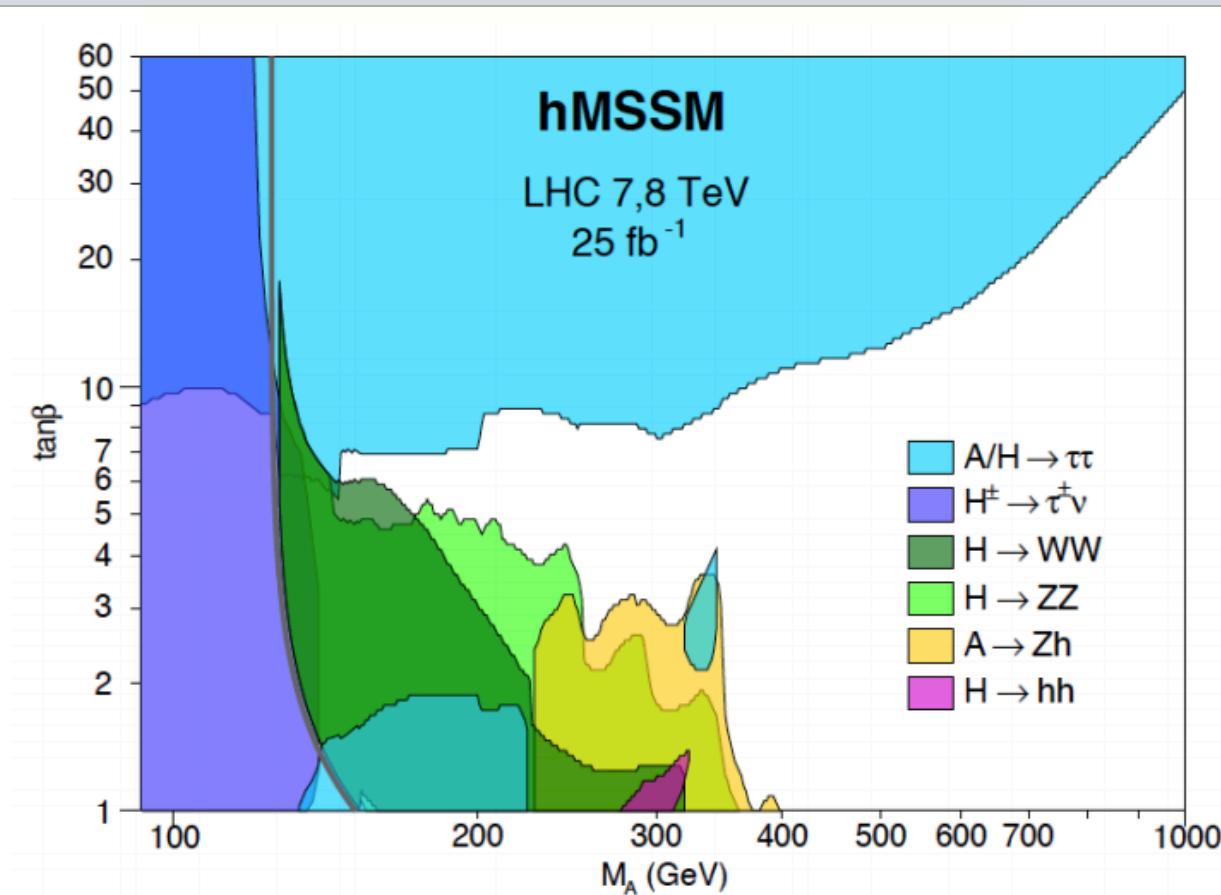
$A \rightarrow Zh$  and  $A \rightarrow \tau\tau$ ,  $m_A = 300$  GeV



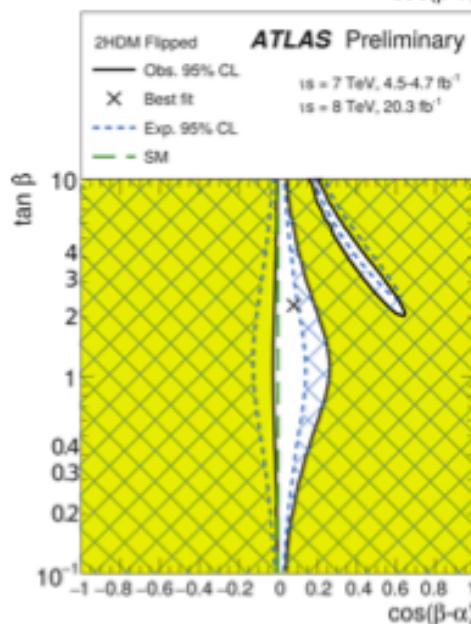
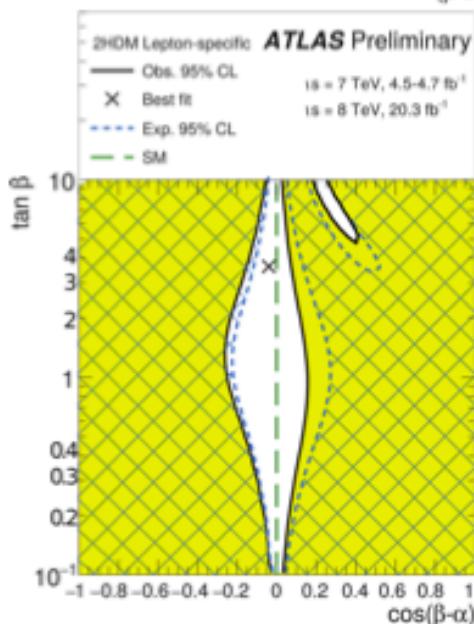
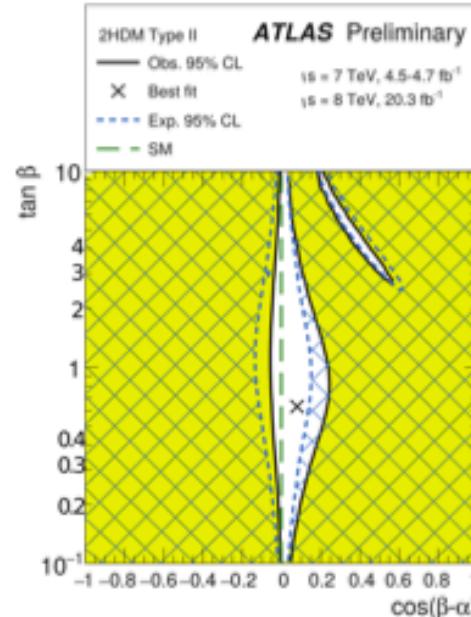
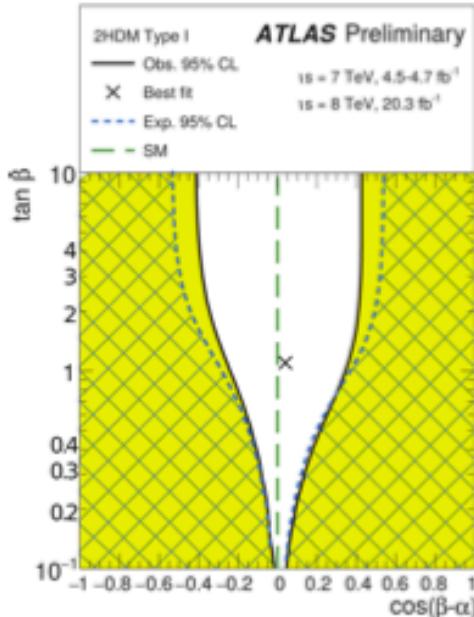
- Here shown a “quick-and-dirty” overlay of the exclusion plot in the  $\tan \beta$  vs  $\cos(\beta - \alpha)$  space of  $A \rightarrow Zh$  and  $A \rightarrow \tau\tau$  searches, assuming  $m_A = 300$  GeV, and the one obtained by indirect constraints produced measuring  $h$  couplings, for 2HDM Type II models

2HDMs with  $m_A \approx 300$  GeV are significantly constrained

# Other combination



# Backup: Coupling Combination



# Simplified MSSM

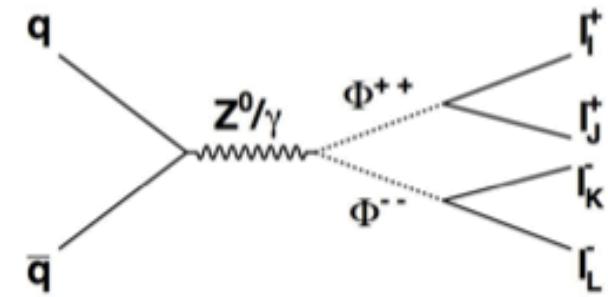
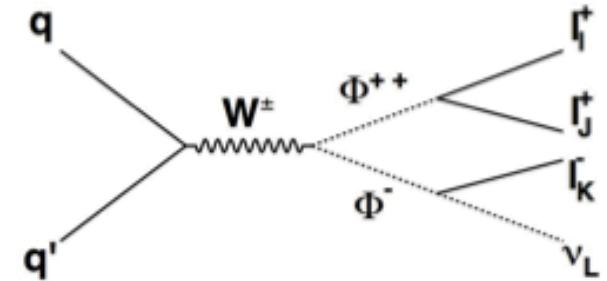
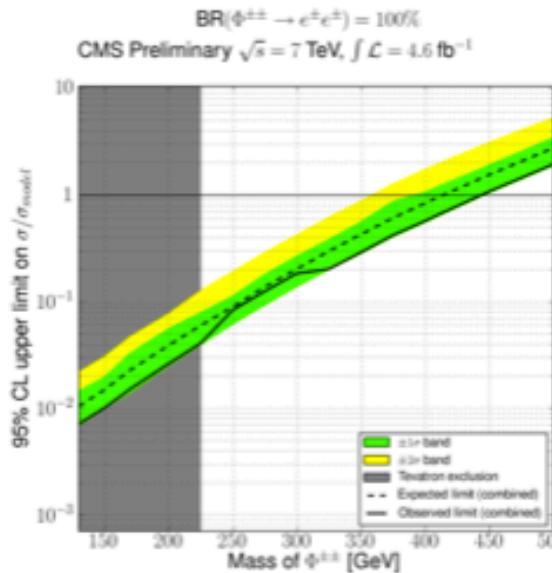
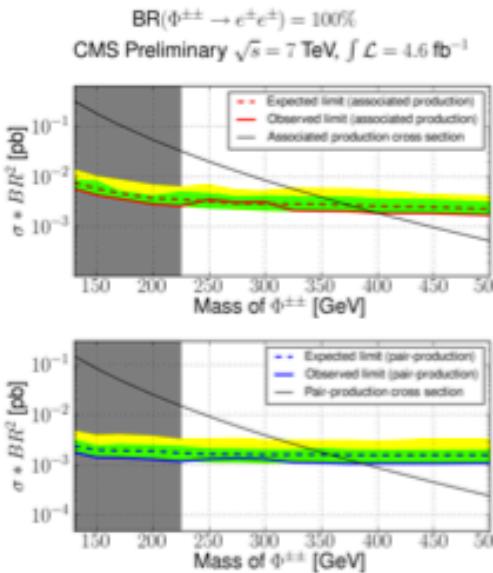
- Supersymmetry provides a natural solution to the hierarchy problem and Dark Matter

The made assumptions are:

- Simplified means the same decay modes as for the SM Higgs boson
  - No Higgs boson decays to supersymmetric particles, heavy Higgs boson decays to lighter ones
- Neglecting loop corrections from stops in gluon fusion production and di-photon decays
- Assume universality of the down-type fermion couplings:  $\kappa_b = \kappa_\tau$
- Measured Higgs mass used to express couplings ( $k_V, k_u, k_d$ ) in terms of  $m_A$  and  $\tan\beta$ :  $\kappa_b = \kappa_\tau = \kappa_\mu$

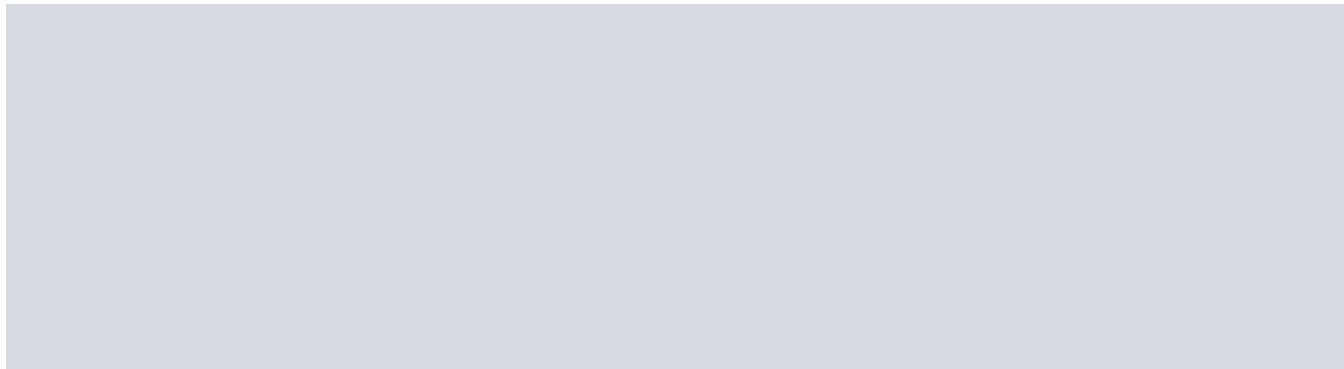
# Doubly charged Higgses $\Phi^{\pm\pm}$

- 6 channels
  - ee,  $\mu\mu$ , e $\mu$ , e $\tau$ ,  $\mu\tau$ ,  $\tau\tau$
- Interpretation for 4 benchmark models



H → INV

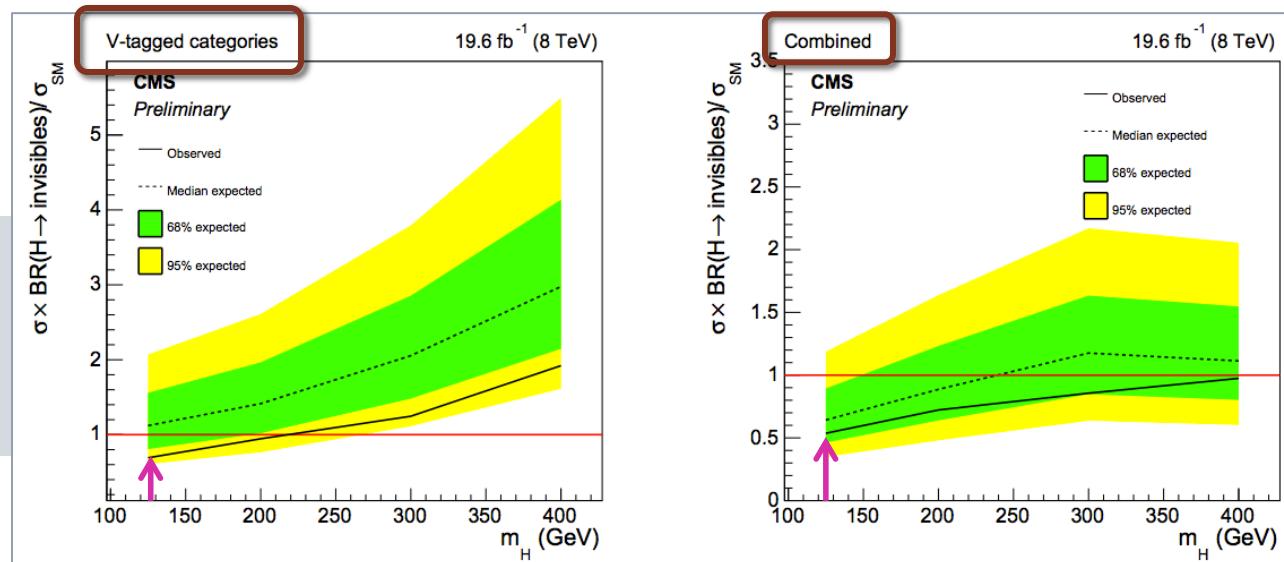
---



# H $\rightarrow$ inv

CMS hadronic limit

- $\text{BR}(\text{H}\rightarrow\text{inv}) < 53\% \text{ (62\%)}$



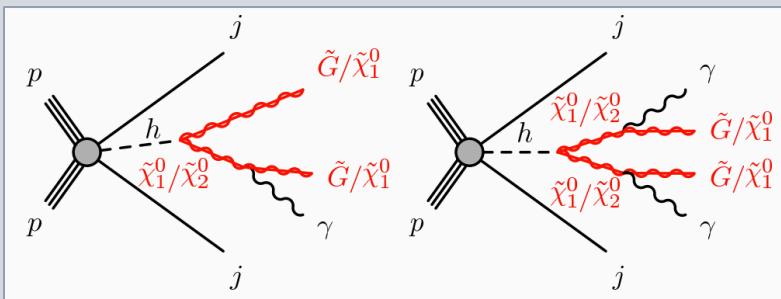
*Monojet* [CMS PAS EXO-12-055]

- Mono-V/j :  $\text{BR}_{\text{H}\rightarrow\text{inv}} < 53\% \text{ (62\%)}$ 
  1. Include V $\rightarrow$ hadronic final state
  2. MET shape
  3. Use  $\gamma+\text{jet}$

# H $\rightarrow$ $\gamma + \text{inv}$

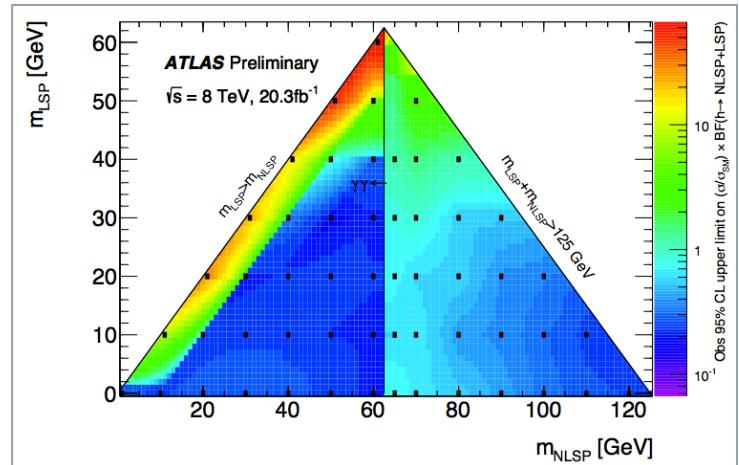
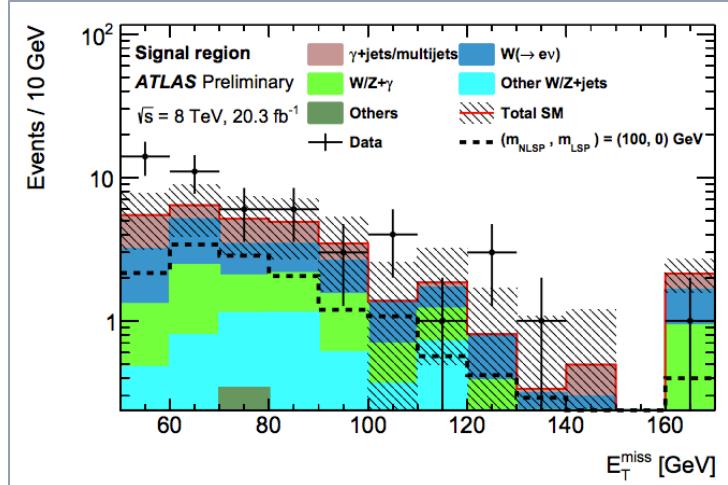
ATLAS-CONF-2015-001

## VBF production



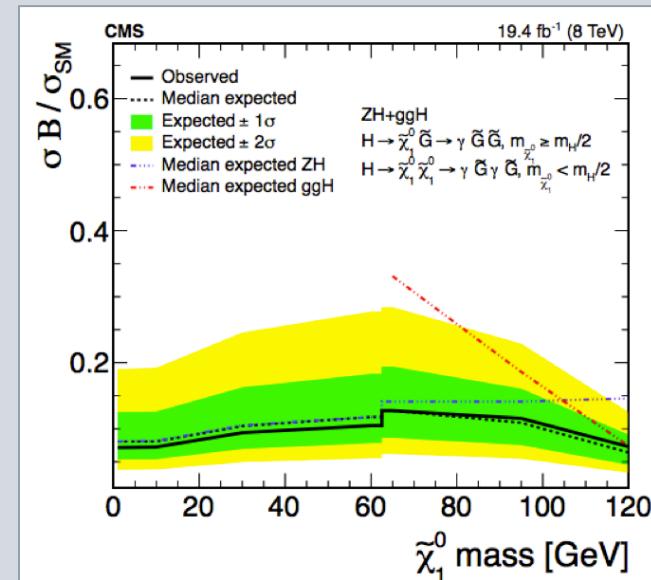
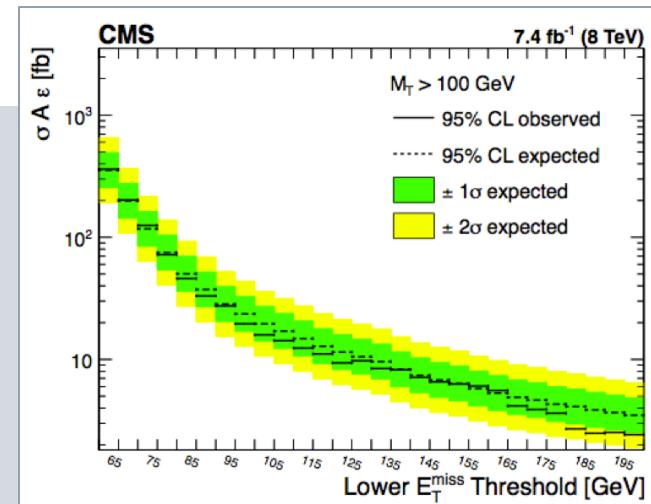
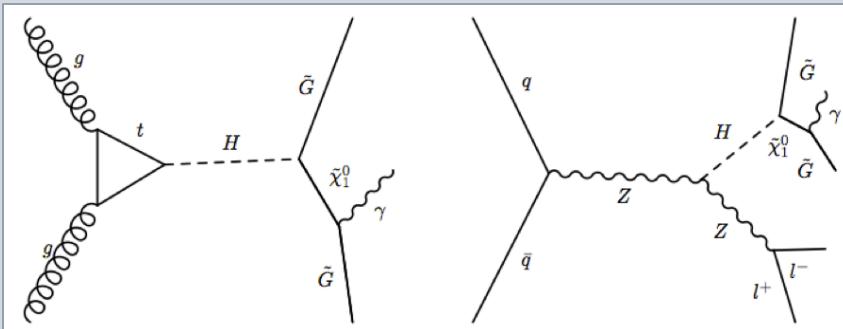
- Trigger
  - $\gg E_T(\gamma) > 40 \text{ GeV}$
  - $\gg \text{MET} > 60 \text{ GeV}$
- Model-specific results

- GMSB:  $h \rightarrow \tilde{G}\tilde{\chi}^0 \rightarrow \tilde{G}\tilde{G}\gamma$
- NMSSM:  $h \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$
- NMSSM:  $h \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma\gamma$



# H $\rightarrow$ $\gamma + \text{inv}$

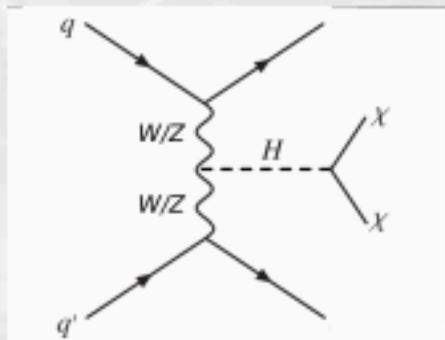
- ggH & VH production



- CMS ‘data parking’
  - $E_T(\gamma) > 30$  GeV
  - $\text{MET} > 25$  GeV
- Model-independent results
- Model-specific
  - GMSB:  $h \rightarrow \tilde{G}\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma$
  - NMSSM:  $h \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$

# Higgs to invisible searches

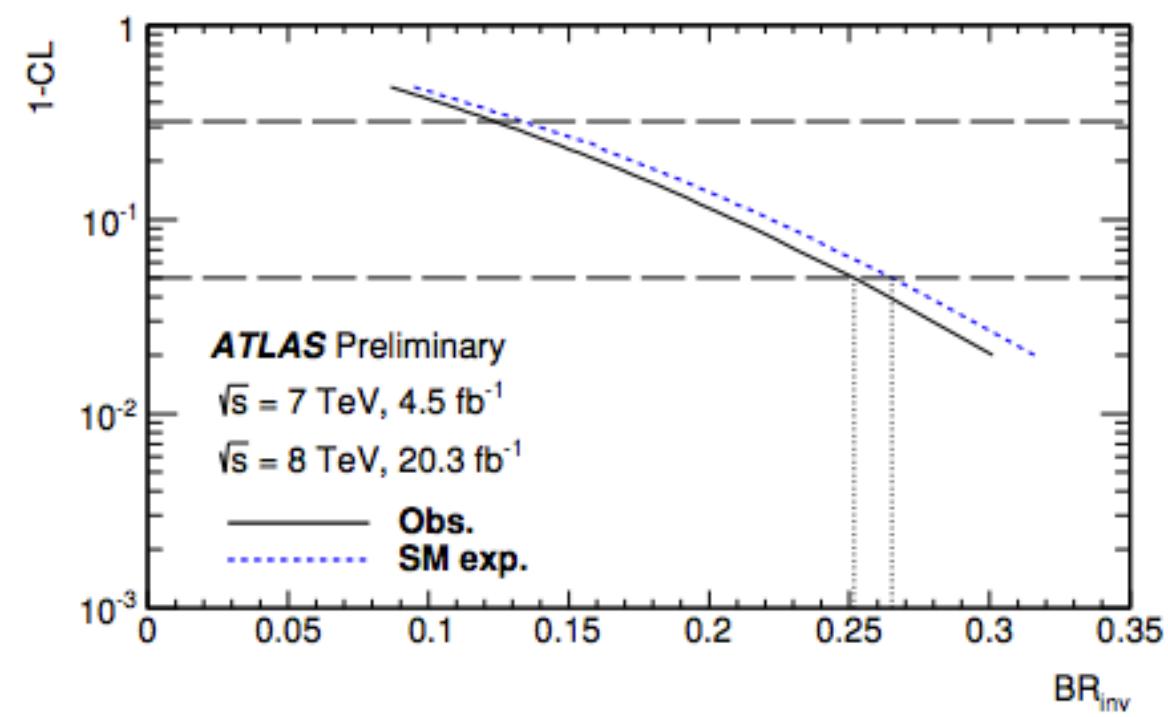
More details in Philippe Calfayan talk!



- $ZH \rightarrow (\ell\ell)$  INV:  
[Phys. Rev. Lett. 112, 201802 \(2014\)](#)
- $VH \rightarrow (jj)$  INV:  
[Submitted to EPJC \(2015\)](#)
- VBF  $H \rightarrow$  INV:  
[HIGGS-2015-YY](#)

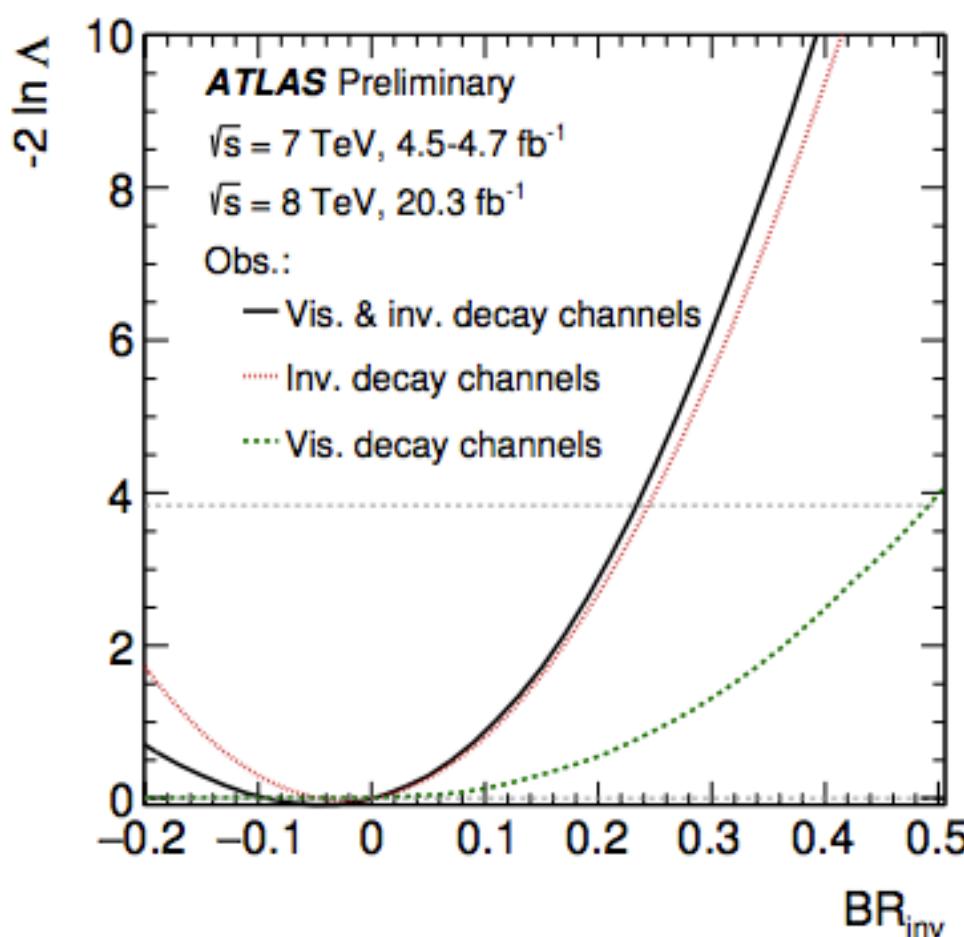
Results	Obs.	Exp.
VBF $h$	0.30	0.35
$Z(\rightarrow \ell\ell)h$	0.75	0.62
$V(\rightarrow jj)h$	0.78	0.86
Combined	<b>0.25</b>	<b>0.27</b>

- Tag events with large missing energy → use particles produced together with the Higgs
- Assume productions (& acceptance) as in SM
- $h \rightarrow ZZ \rightarrow 4\nu$ :  $1.2 \times 10^{-3}$  (no sensitivity)



# Combining indirect (visible channels) & direct (invisible searches)

- The partial widths for Higgs decays to **undetectable** (e.g.  $h \rightarrow gg$ ) assumed to be negligibly
- With the **visible channels** alone (and  $\kappa_V \leq 1$ ):  
 $\text{BR}_{\text{inv}} < 0.49(0.48)$  obs (exp)
- Combination **visible channels** and **invisible searches** one can **remove restrictions of** ( $\kappa_V \leq 1$ )
- Physical boundary  $\text{BR}_{\text{inv}} > 0$
- The most general result with independent parameters:  
 $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma}, \text{BR}_{\text{inv}}$   
 95%CL limit of:  
**0.23 (0.24) obs (exp)**



# Higgs Invisible, alternative parametrisations

95% CL

	Observed	Expected	Assumptions
Direct (invisible searches)	0.25	0.27	Productions as SM ( $\kappa_i = 1$ )
Indirect (visible channels)	0.49	0.48	$\kappa_{Z,W} \leq 1$
<b>Combination<sup>[*]</sup></b>	<b>0.23</b>	<b>0.24</b>	<b>None<sup>[**]</sup></b>

Comb. (alt. parametrisation)	0.23	0.23	$\kappa_{Z,W} \leq 1$
Comb. (alt. parametrisation)	0.18	0.24	one $\kappa_F$ , and one $\kappa_V$
Comb. (alt. parametrisation)	0.16	0.23	one $\kappa_F$ , and one $\kappa_V \leq 1$

90% CL

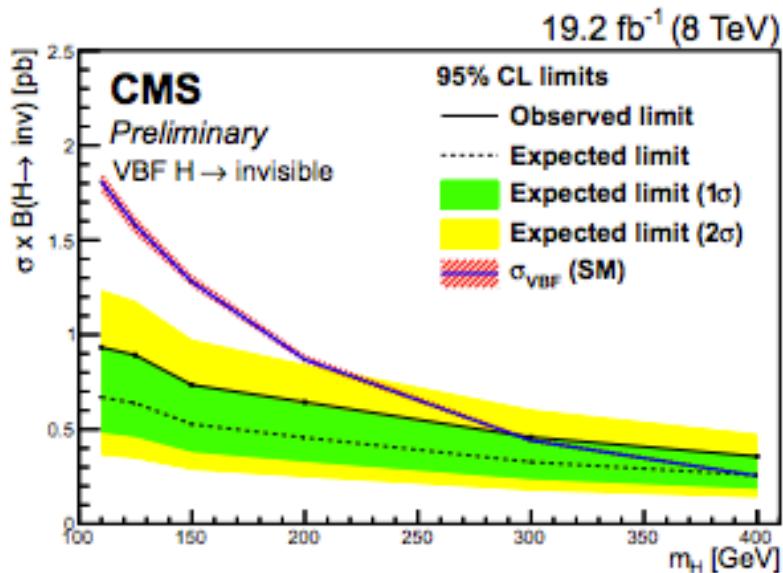
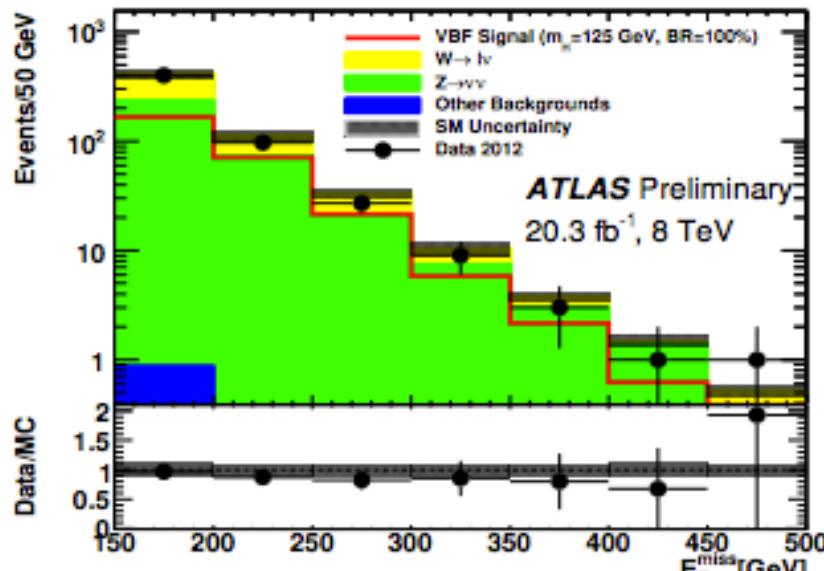
	Observed	Expected	Assumptions
Combination	0.22	0.23	None <sup>[**]</sup>

[\*] Except  $VH \rightarrow (jj)\text{inv}$ , overlapping phase-space

[\*\*] Except for undetectable

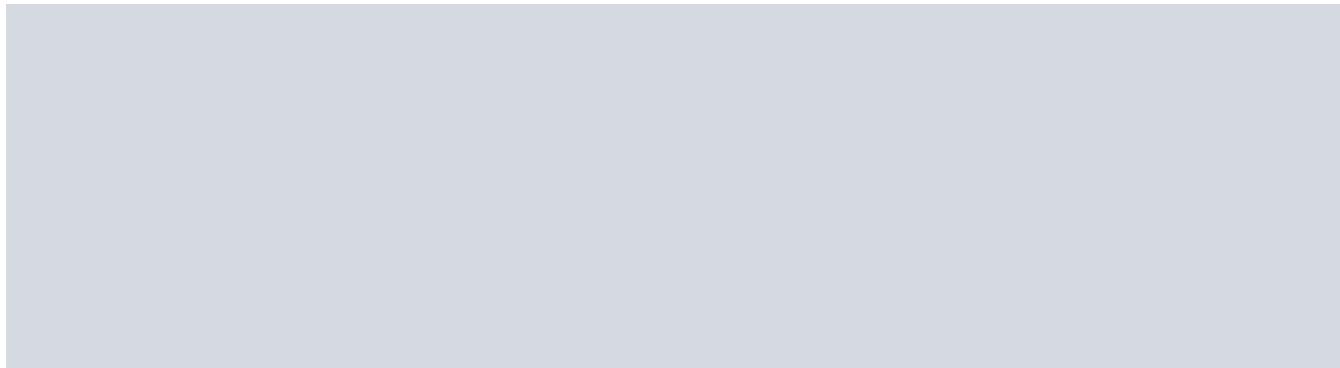
## Search with the **VBF** signature [ATLAS, CMS]

- Total uncertainties on  $Z \rightarrow \nu\nu$ :
  - CMS: 27%, with 23.5% stat.
  - ATLAS: 11%, with < 6.4% stat.
- Observed (expected) upper limits on  $\text{BR}(H \rightarrow \text{inv})$  assuming  $m_H = 125 \text{ GeV}$ :
  - ATLAS: 28% (31%)
  - CMS: 57% (40%)
  - Expected CMS bound is 33% if Z CR had as much stat as a W →  $\mu\nu$  CR
  - VBF is most sensitive channel

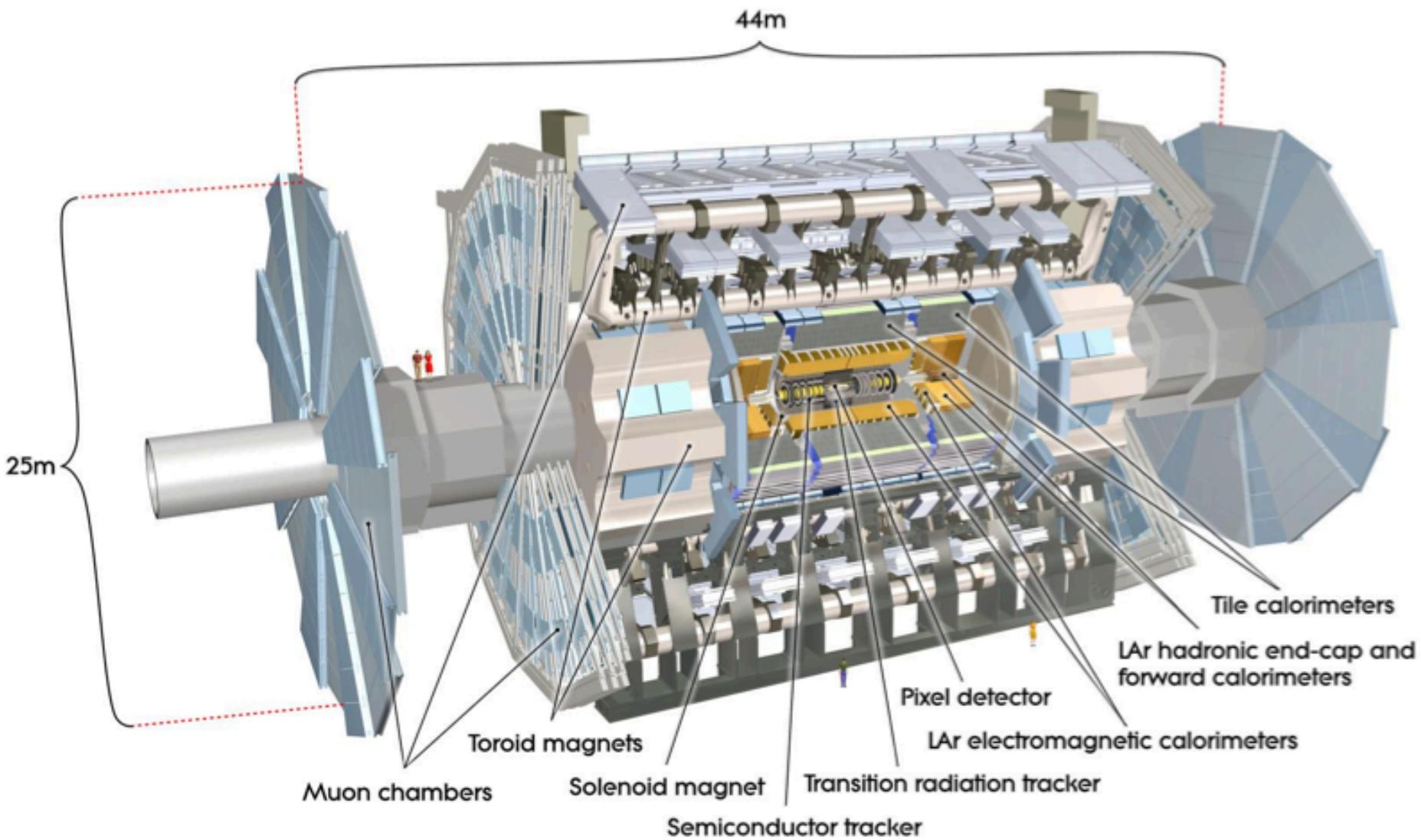


# DETECTORS & UPGRADE

---



# ATLAS detector



# CMS detector

## 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 ( $100 \times 150 \mu\text{m}$ )  $\sim 16\text{m}^2$   $\sim 66\text{M}$  channels  
Microstrips ( $80 \times 180 \mu\text{m}$ )  $\sim 200\text{m}^2$   $\sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
Niobium titanium coil carrying  $\sim 18,000\text{A}$

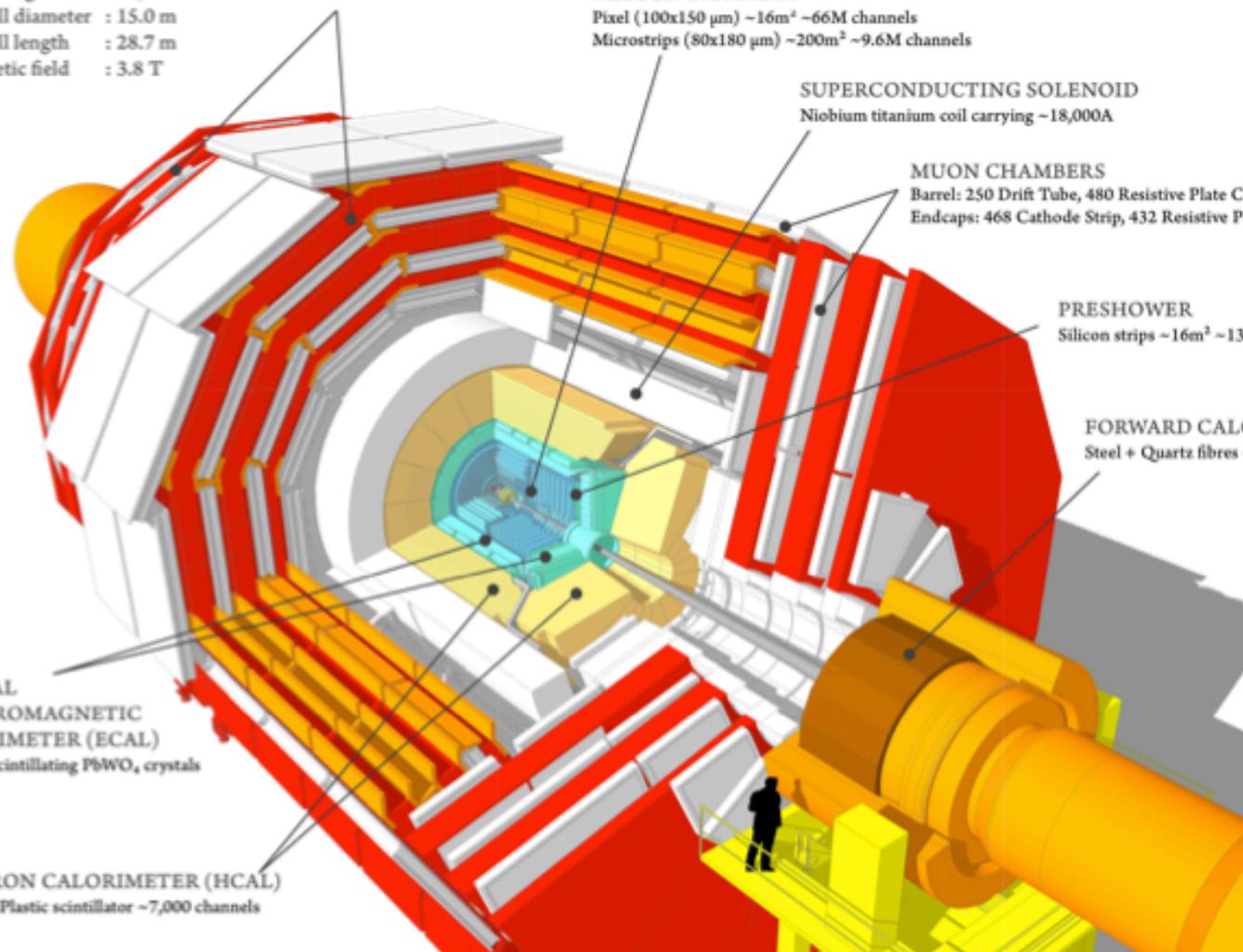
MUON CHAMBERS  
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER  
Silicon strips  $\sim 16\text{m}^2$   $\sim 137,000$  channels

FORWARD CALORIMETER  
Steel + Quartz fibres  $\sim 2,000$  Channels

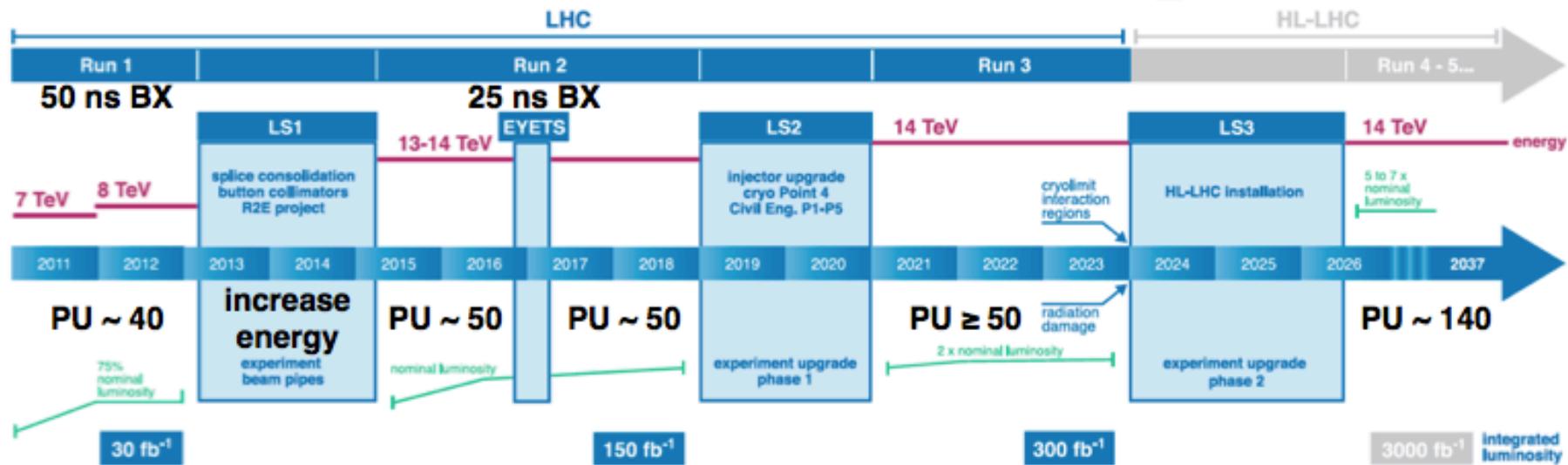
CRYSTAL  
ELECTROMAGNETIC  
CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator  $\sim 7,000$  channels



# High Lumi LHC: time scale

## LHC / HL-LHC Plan

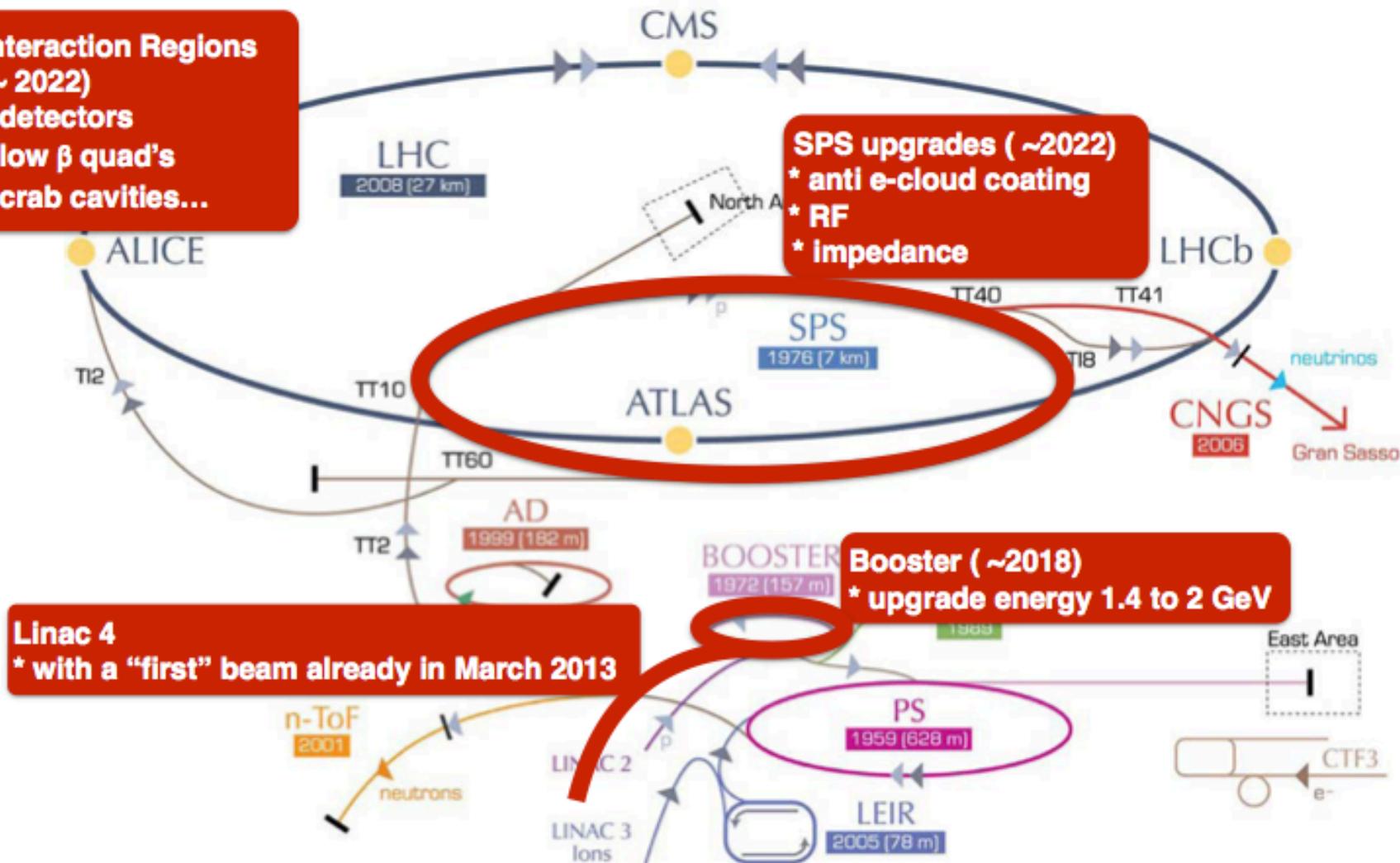


- \* experiments survived Run I and LS 1 without being damaged by their own constructors
- \* new data at 13 TeV start accumulating (slowly, but steadily)
- \* experiments and LHC will have a major upgrade during LS3
- \* from mid 2026 (probably 2027) we can talk about HL-LHC data
- \* goal: deliver 200 to 300 fb<sup>-1</sup> a year
- \* many results that you will see in the next slides are quoting 3000 fb<sup>-1</sup>, nice dream :)

# to HL LHC

**Interaction Regions (~ 2022)**  
\* detectors  
\* low  $\beta$  quad's  
\* crab cavities...

**SPS upgrades (~2022)**  
\* anti e-cloud coating  
\* RF  
\* impedance



# Detector upgrades

ATLAS

- \* Forward Muon Spectrometer:
  - new small wheel (nSW)
- \* L1-trigger: high precision calorimeter
- \* L2-trigger: fast tracking (FTK)
- \* new forward diffractive physics detectors (AFP)

LS 2

- \* new Tracker (Silicon)
- \* Calorimeter electronics upgrade
- \* Muon System upgrade
- \* L0/L1 trigger architecture with L1-Track Trigger
- \* Forward Calorimeter upgrade

LS 3

*they will almost look like twins*

CMS

- \* Pixel detector: add Layer 4 and squeeze Layer 1 radius
- \* HCAL electronics
- \* L1 trigger upgrade
- \* GEM: forward muon

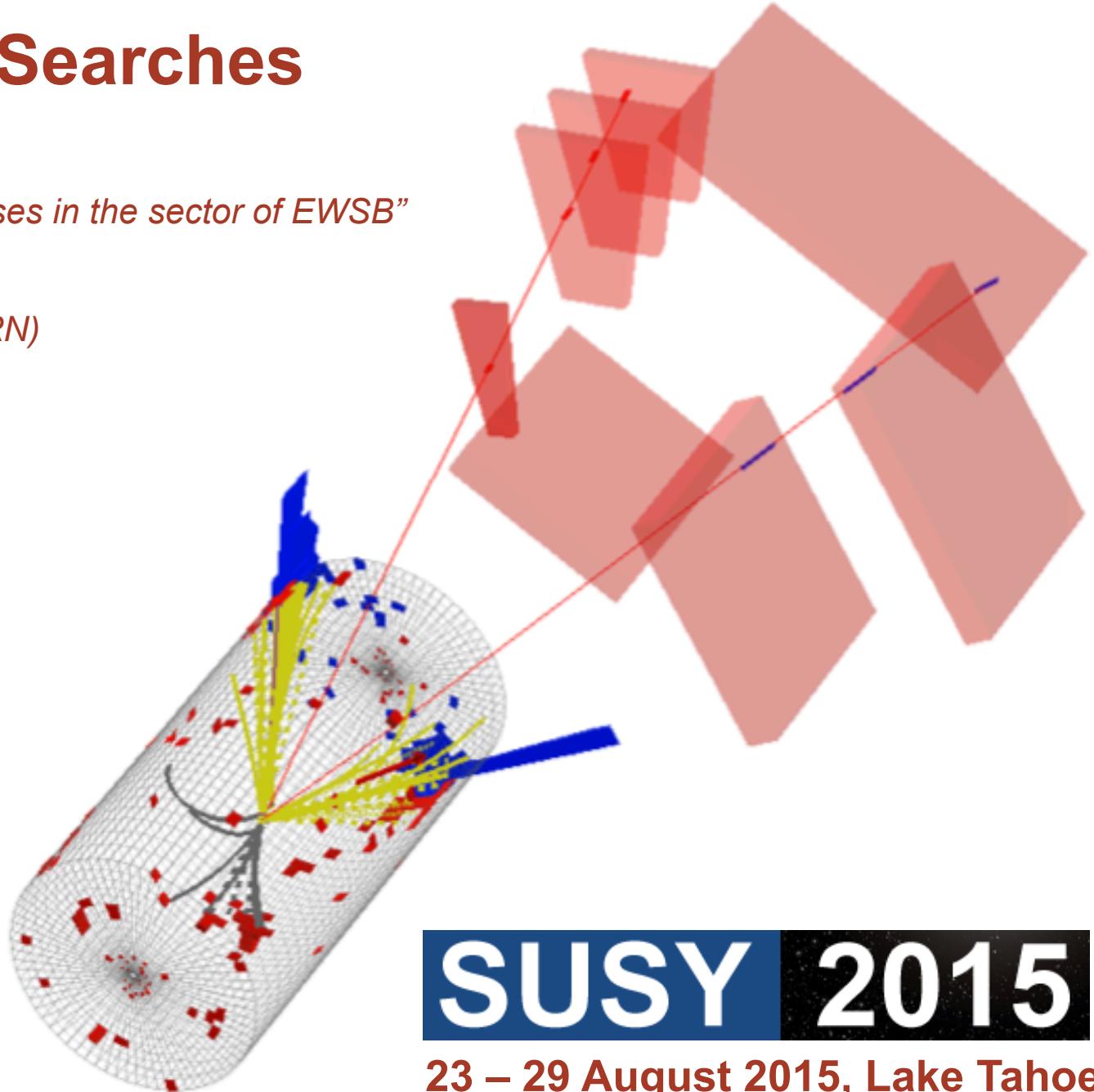
- \* complete Tracker replacement
- \* L1-Track Trigger
- \* forward regions: improve tracking, calorimetry, muon ID
- \* High precision timing for PU mitigation
- \* Trigger upgrade
- \* DAQ upgrade

# BSM Scalar Searches at the LHC

*“Searches for new processes in the sector of EWSB”*

Tristan du Pree (CERN)

on behalf of the  
ATLAS+CMS  
Collaborations



**SUSY 2015**  
23 – 29 August 2015, Lake Tahoe