Search for non-SM Higgs at the CMS

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FH Fellow meeting, 29 November 2016

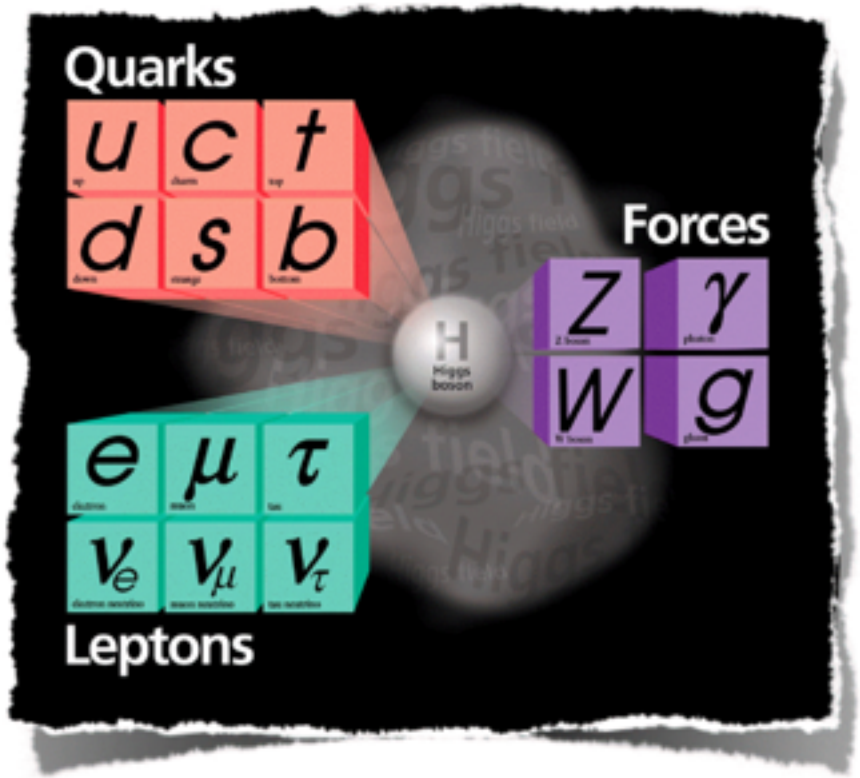
About me

> Born in Bangkok, Thailand
> After 18 years old, I started my studying abroad in China
> Finished my PhD from Peking University, Beijing China (2015)
  - based at CERN from 2012 - 2014
> Started DESY Fellowship in February 2016

Outline

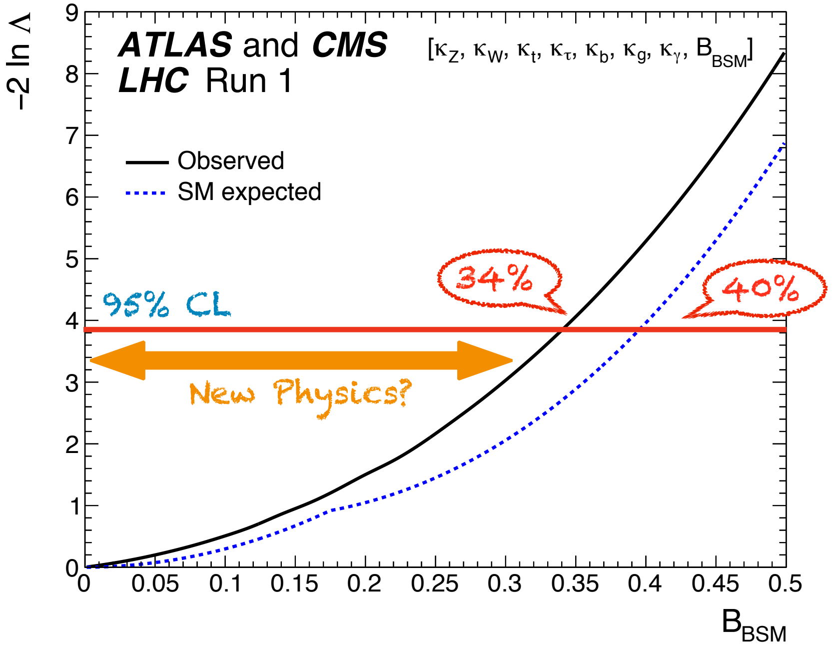
- Introduction
- Higgs → Invisible
- MSSM Higgs → $b\bar{b}$
- Summary

The Standard Model of Particle Physics



Why non-SM Higgs?

- Standard Model (SM) successfully describe particles and interactions but doesn't address the hierarchy problem, fine tuning, dark matter … ➜ **need to go beyond the SM (BSM)**
  - The discovered Higgs at 125 GeV can play a crucial role in probing BSM physics
- Combined ATLAS and CMS couplings measurements constrains **BR(H → BSM) < 34% (40%)** at 95% CL from Run-1 data (7 and 8 TeV)
  - **Still room for "New Physics"!**



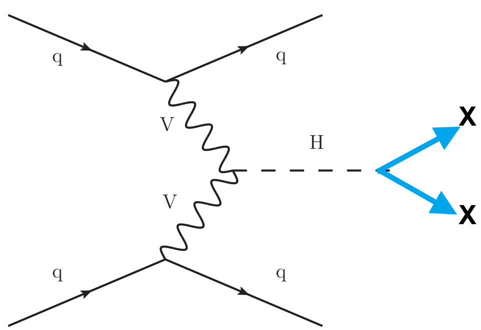
- Many BSM theories such as SUSY, Two Higgs Doublet Models, predict such decays, e.g.
  - Higgs → invisible particles
  - MSSM Higgs searches
- CMS and ATLAS experiments are actively working on the full Run-2 data to cover large number of BSM Higgs searches

JHEP 08 (2016) 045

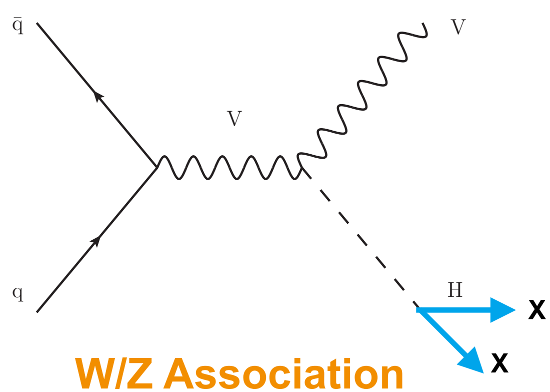
Higgs → Invisible

- Any excess of **BR(H → invisible)** might be
  - a strong sign of physics in the BSM
  - a hint of Dark Matter
- **Direct searches** must be performed in channels where the Higgs recoils against a visible system

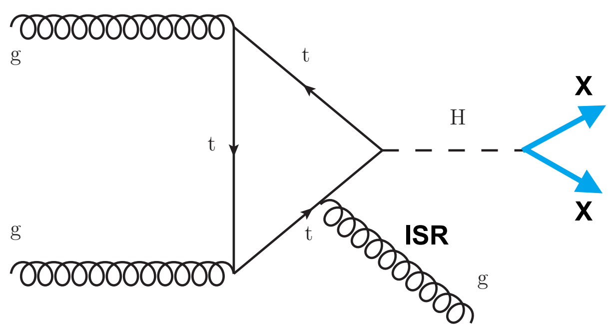
In proton-proton collision at the LHC the following channels are possible



Vector boson fusion (VBF)



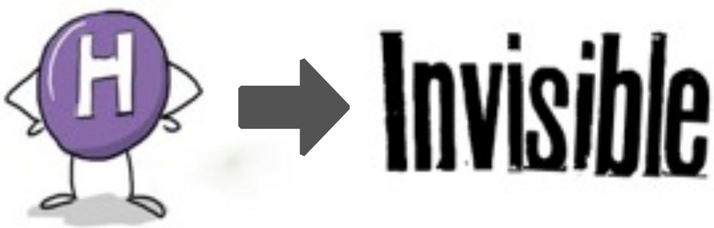
W/Z Association (VH)



Gluon-Gluon fusion (ggH)

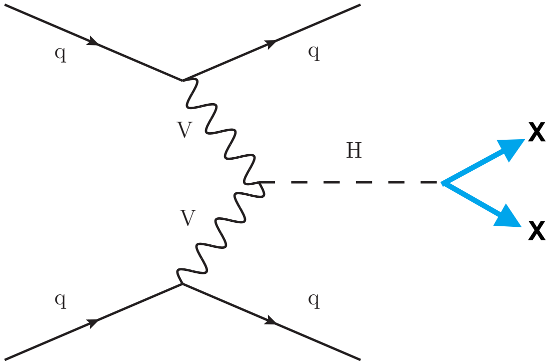
VBF H → Invisible

> Why **Vector Boson Fusion** (VBF)?
  - larger cross-section, better sensitivity



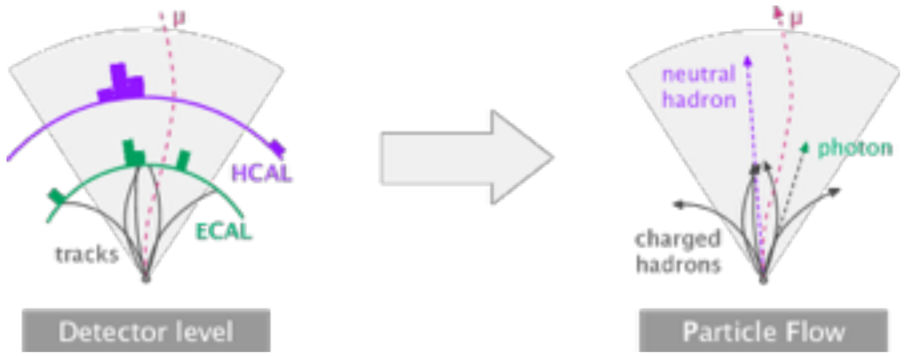
> Events with **two well-separated tag jets** and **large missing transverse energy**
  - absence of particle decay products = simple counting experiment
  - require well modeled missing energy response and resolution

> **Backgrounds with data-driven estimations**
  - irreducible Z(→νν)+jets
  - W(→lν)+jets where lepton is unidentified
  - QCD multijet process



E_T^{miss} Reconstruction

- **Particle Flow (PF) Algorithm**
  - optimal combination of information from all sub-detectors
  - to improve energy resolution and particles identification
  - photon, charged/neutral hadron, **μ**, e

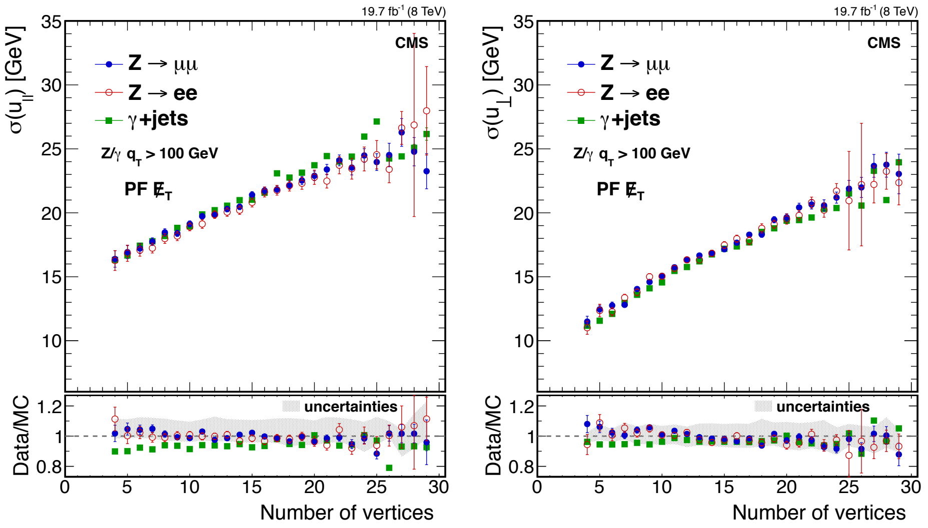


- **Particle Flow Missing Transverse Energy (PF E_T^{miss})**

$$\mathrm{PF}\,\vec{\not{E}}_{\mathrm{T}}^{\mathrm{raw}} = - \sum_{\mathrm{PF\ candidates}} \vec{p}_{\mathrm{T}}$$

"negative of the vector sum over all transverse momentum of PF-candidates with energy correction and pile-up effect reduction"

JINST 10 P02006 (2015)



Background Estimation

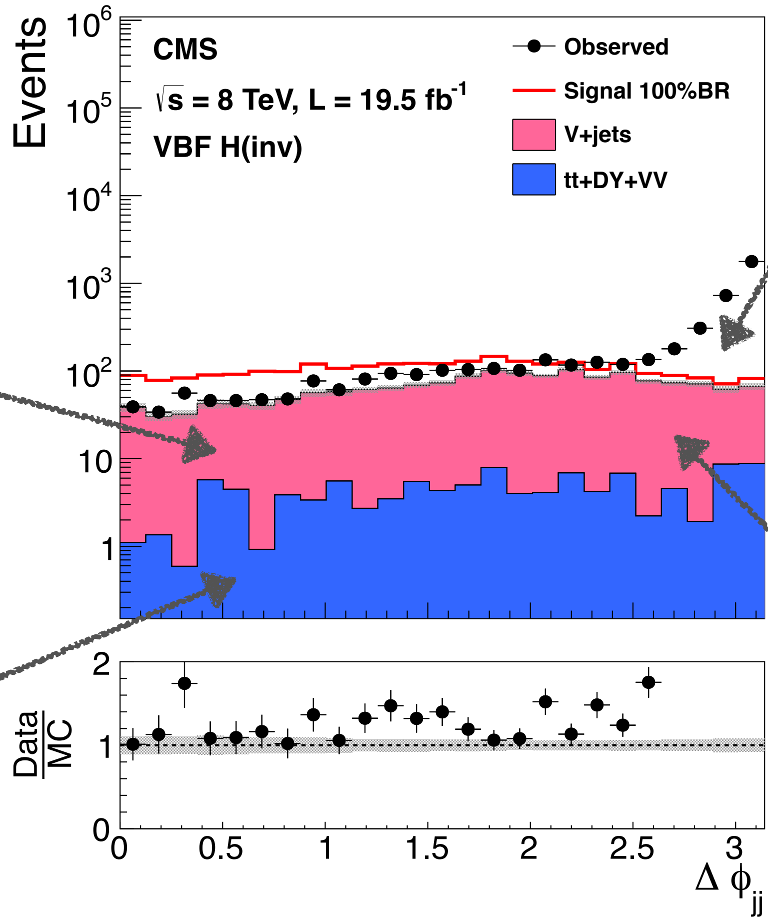
W(lν)+jets (l = e,μ,τ)

caused background when leptons misidentified

estimated from visible W(→lν)+jets control sample using data-driven method and corrected the efficiencies difference between two regions using MC

tt+DY+VV process

minor backgrounds estimated from Monte Carlo simulations



QCD multi-jet

estimated from data due to lack of statistics and mis-modeled

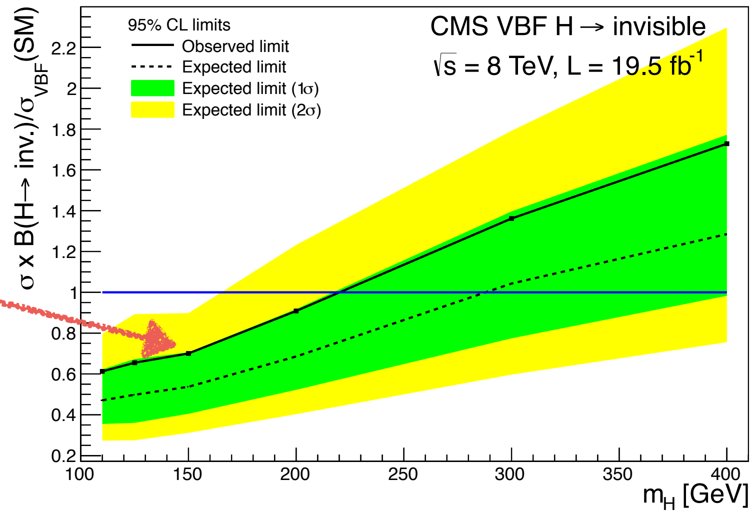
extrapolated from control region to signal region (ABCD method)

Z(νν)+jets process

estimated from visible Z(→μμ)+jets control sample using data-driven method and corrected efficiencies difference between two regions using MC

Limits H → Invisible

- VBF H→invisible results
  - No excess of signal : observed **390 events** compatible with **332 ± 36 ± 45** events SM prediction
  - 95% CL observed (expected) limit on B(H→inv) for m_H = 125 GeV is **65% (49%)**
- Combination of VBF and ZH productions
  - most sensitive results at the LHC Run-1



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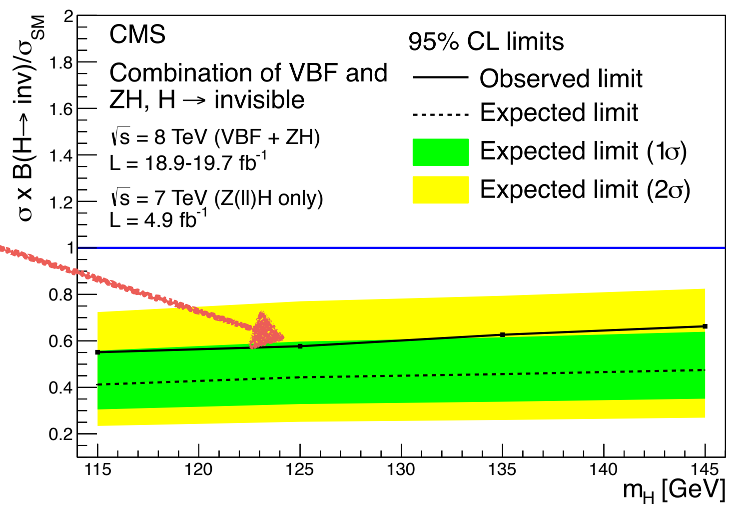
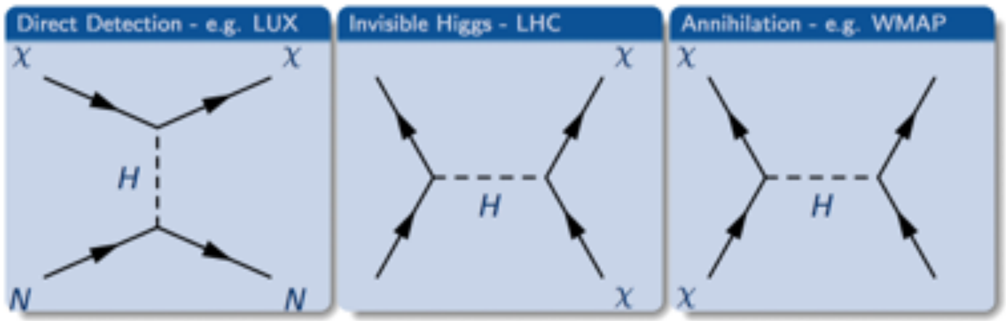
observed 58% at m_H = 125 GeV (44% expected)



m_H (GeV)	Observed (expected) upper limits on $\sigma \cdot B(H \to inv)/\sigma_{SM}$		
	VBF	ZH	VBF+ZH
115	0.63 (0.48)	0.76 (0.72)	0.55 (0.41)
125	0.65 (0.49)	0.81 (0.83)	0.58 (0.44)
135	0.67 (0.50)	1.00 (0.88)	0.63 (0.46)
145	0.69 (0.51)	1.10 (0.95)	0.66 (0.47)
200	0.91 (0.69)	-	-
300	1.31 (1.04)	-	-

Dark Matter Interpretation

- If Dark Matter couples to the Higgs, the following diagrams are possible



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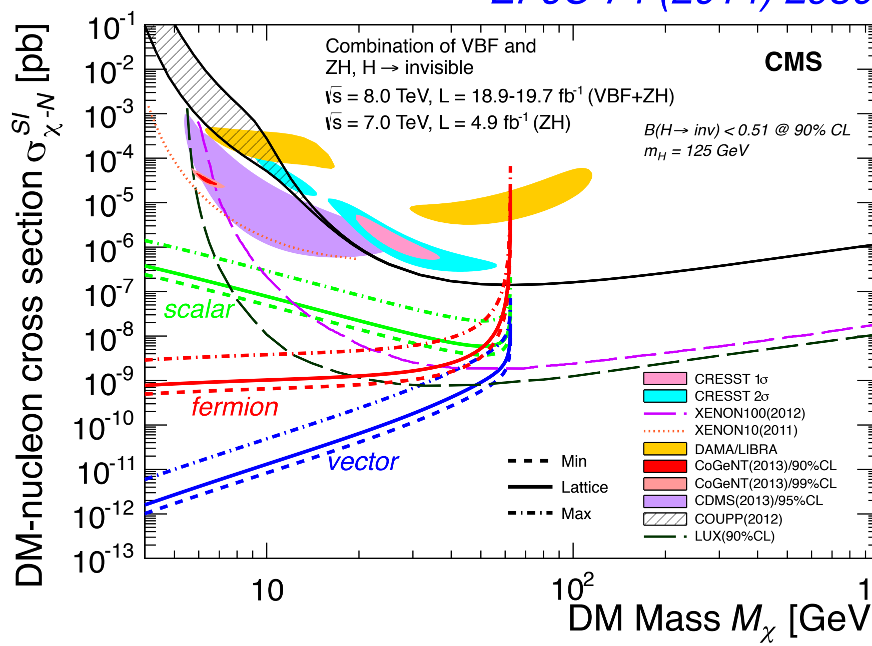
- Limits on B(H→inv) therefore constrain Higgs Portal DM models
- Using effective field theory (EFT) Higgs Portal model which translates into a DM-nucleon cross-section*
  - At 90% CL the combined limit on B(H→inv) is 0.51 for a 125 GeV Higgs
  - Consider three DM spin scenarios : ***scalar***, ***vector***, ***Majorana fermion***

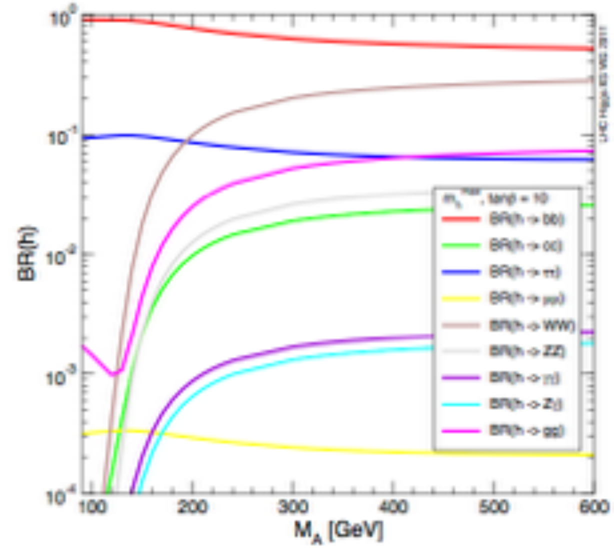


*A. Djouadi et al, Phys. Lett. B 709 (2012)

MSSM $\Phi \to b\bar{b}$

> MSSM extends beyond the SM Higgs sector by including two complex Higgs doublets which, after symmetry breaking, lead to five physical states

- **3 neutral Higgs : Φ = *A* (CP-odd), *H*, *h* (CP-even)**
- **2 charged Higgs : H^+, H^-**

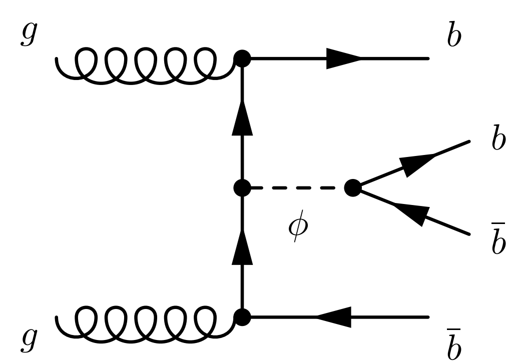


> At tree level, Higgs sector can be determined by only two parameters

- m_A and $\tan\beta = v_u/v_d$

> Search for degenerate H and A in **higher mass region**

- large BR($\Phi \to b\bar{b}$) ~ 90%

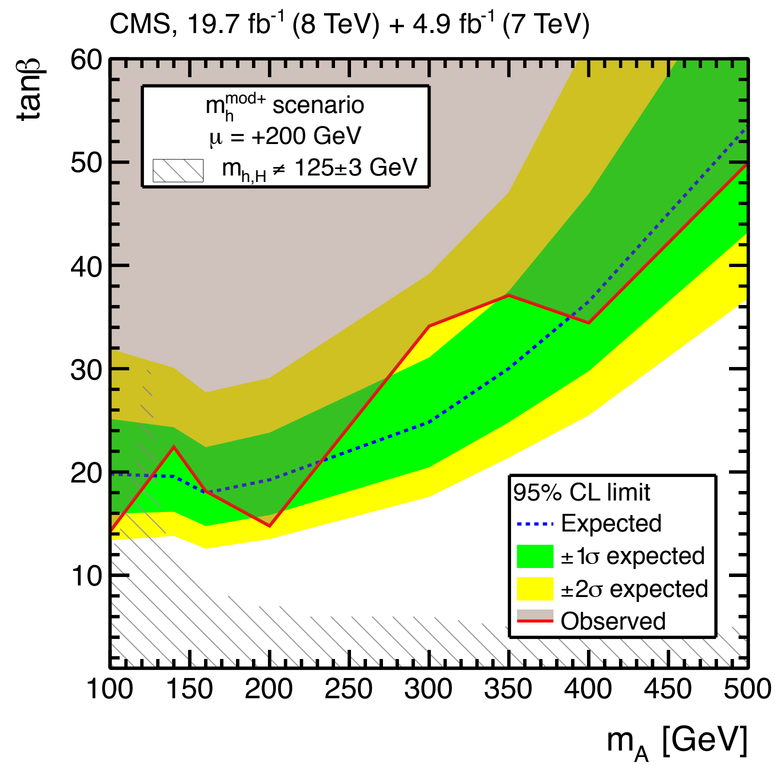


> b-associated production: cross-section enhanced by ~$2\tan^2\beta$, better background control

- require at least 3 b-tagged jets
- dedicated triggers

MSSM $\Phi \rightarrow b\bar{b}$: Run-1

- Search for a peak in the invariant mass distribution of the two b jets with the highest p_T values
- Combination of **4.9 fb^{-1} (7 TeV)** and **19.7 fb^{-1} (8 TeV)**
  - Upper limits at 95% CL are set for the MSSM parameter tanβ versus m_A in m_h^{mod+} scenario



- CMS analysis is unique at the LHC
- 7+8 TeV achieved the best sensitive in this channel to date
  - aim to improve further with 13 TeV data

MSSM $\Phi \rightarrow b\bar{b}$: Run-2

- Search for $\Phi \rightarrow b\bar{b}$ resonances with double up of center-of-mass energy (13 TeV) and integrated luminosity (37 fb^{-1})
- Two dedicated triggers developed in both 2015 and 2016 data (13 TeV)
  - requirement of two jets having strong online b-tagged
- New approach for QCD background using analytical function to model QCD shape from data in signal-like control region and extrapolate the shape to signal region (blinded analysis)
- Limits will be set on σxBR by fitting invariant mass distribution
- Interpretation in MSSM and more general 2HDMs will be achieved

Stay tuned!

Summary

- VBF H→invisible analysis provided the most sensitive results at that time of publication
  - the world's first measurement in a challenging and tropical channel
  - the best LHC Run-1 published results when combined with ZH production

- MSSM $\Phi \rightarrow b\bar{b}$ results for Run-2 are on its way

Backup

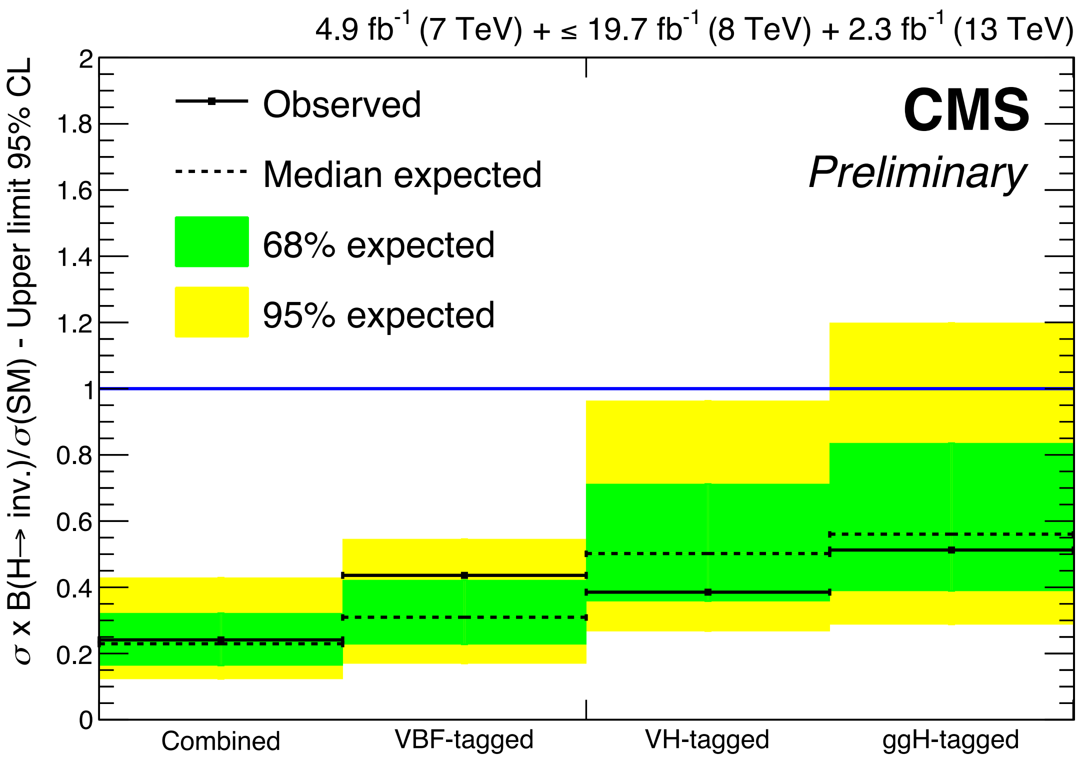
Signal Efficiency

m_H [GeV]	yield POWHEG (VBF)	eff [%] POWHEG (VBF)	yield POWHEG (ggH)	eff [%] POWHEG (ggH)
110	214.0 ± 9.2	0.607 ± 0.026	22.8 ± 8.0	0.0047 ± 0.0017
125	209.5 ± 8.6	0.681 ± 0.028	13.8 ± 5.3	0.0037 ± 0.0014
150	197.1 ± 7.5	0.790 ± 0.030	11.9 ± 4.0	0.0045 ± 0.0015
200	148.5 ± 7.6	0.877 ± 0.045	11.1 ± 3.0	0.0081 ± 0.0021
300	96.2 ± 4.3	1.119 ± 0.050	14.3 ± 2.4	0.0204 ± 0.0034
400	69.3 ± 2.8	1.397 ± 0.056	16.7 ± 2.4	0.0294 ± 0.0041

- Signal yield and efficiency, assuming 100% BR (H→invisible)
- For m_H = 125 GeV
  - VBF production : 210 ± 9 (stat.) events
  - Gluon fusion production : 14 ± 5 (stat.) events

H → Invisible Run-2

- Combination of H→invisible using **Run-1** and **2.3 fb^{-1} of 13 TeV** (2015) data
  - 3 production modes : VBF, VH (Z→ll,Z→bb,V→qq) and ggH
- 95% CL Upper limits on σxBR relative to SM production



- Expected sensitivity dominated by Vector Boson Fusion channel
- Better results comparing with indirect constraint from visible decays (34% observed)

σxB(H→inv) < 24% observed (23% expected)