Searches for Beyond SM Higgs bosons

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on behalf of ATLAS and CMS Collaborations

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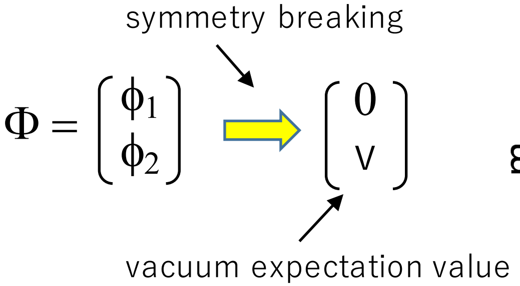
Introduction

[JHEP08(2016)045]

Recent Higgs boson study tell us :

- **symmetry breaking does exists**

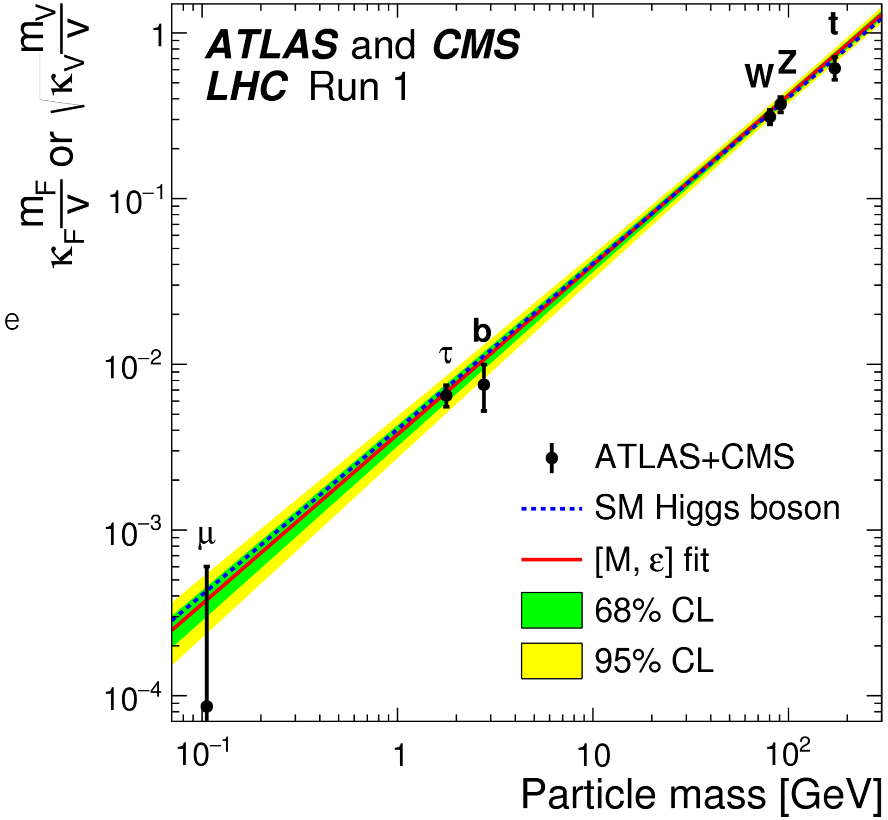
  (mass generation through scalar field)



$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \Rightarrow \begin{pmatrix} 0 \\ v \end{pmatrix}$$

But need to know how it does happen?

- precise measurements (previous talks),
- **searches for another scalar particles**. <= **this talk**



The extension of the Standard Model has many attractive features:

- solve fine tune problem (naturalness),
- give an insight of hierarchy problem,
- even predicts dart matter candidates.

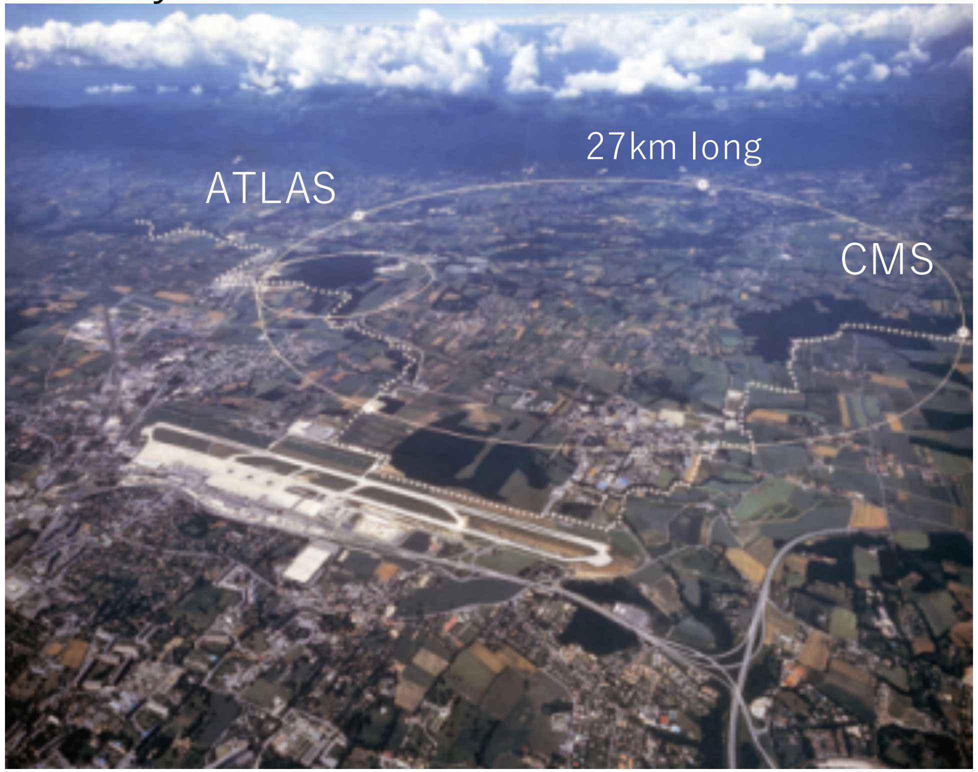
Discovery of the Higgs boson also opens a new opportunity to new physics.

- **Higgs as a probe to the new physics beyond the SM** <= **this talk**

Contents

1. **Search for another Higgs sector :** - MSSM Higgs bosons
2. **Higgs as a probe to new physics :** - Heavy resonance $X \rightarrow VH$ or HH
3. **Anomalous Higgs couplings :** - Flavor violation, Rare decay
4. **Summary**

CERN, Geneve



Not cover everything:

Visit **ATLAS:** https://atlas.cern

CMS: http://cms.cern

Search for another Higgs sectors

- MSSM Higgs bosons

MSSM Higgs searches

Minimum extension of the SM :

2 Higgs Doublet Model : 2HDM

$$\Phi_1 = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} , \quad \Phi_2 = \begin{pmatrix} \phi_3 \\ \phi_4 \end{pmatrix}$$

can be observed H boson.

results in

- 5 Higgs bosons : (h, H, A, H^+, H^-)
- 2 mixing parameters : (α, β)

α : mixing angle of CP even h/H

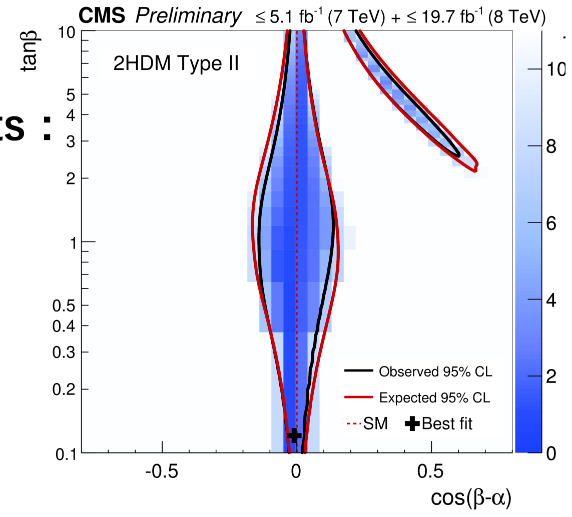
$\tan\beta$: ratio of v_u / v_d

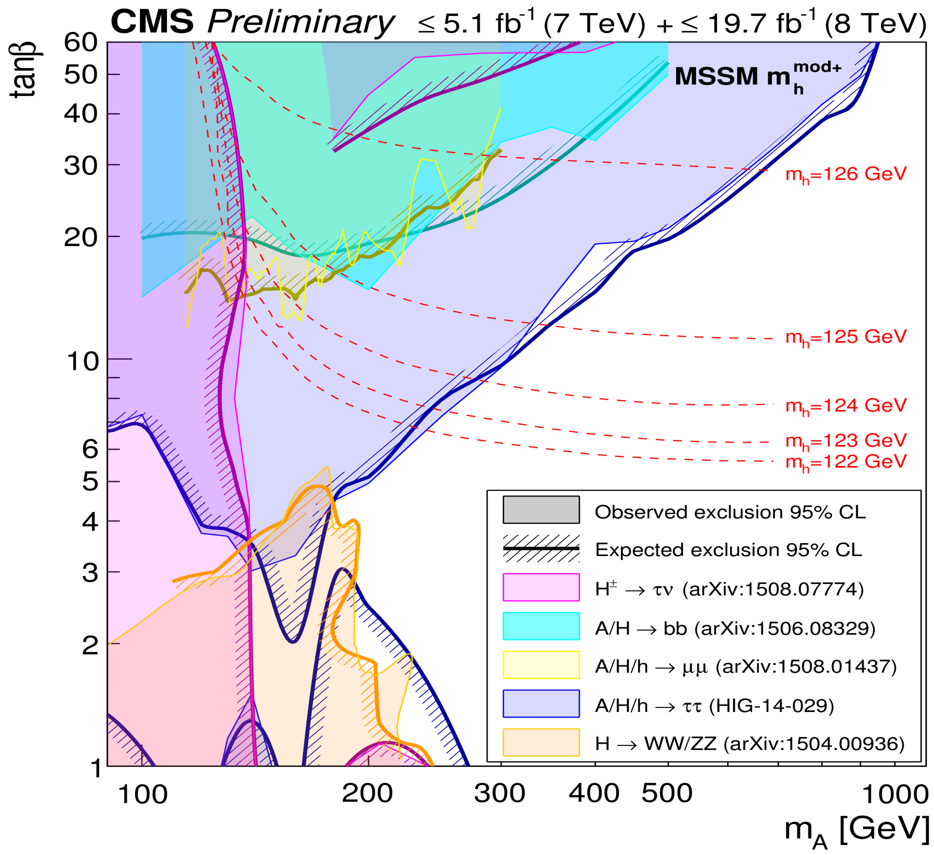
Constraint from the measurements :

$\cos(\beta-\alpha)$ is very close to "zero".

⇨ consistent with SM.

(alignment limit)





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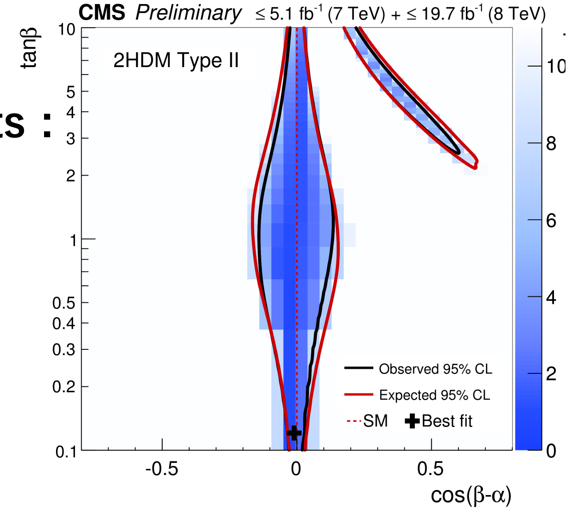

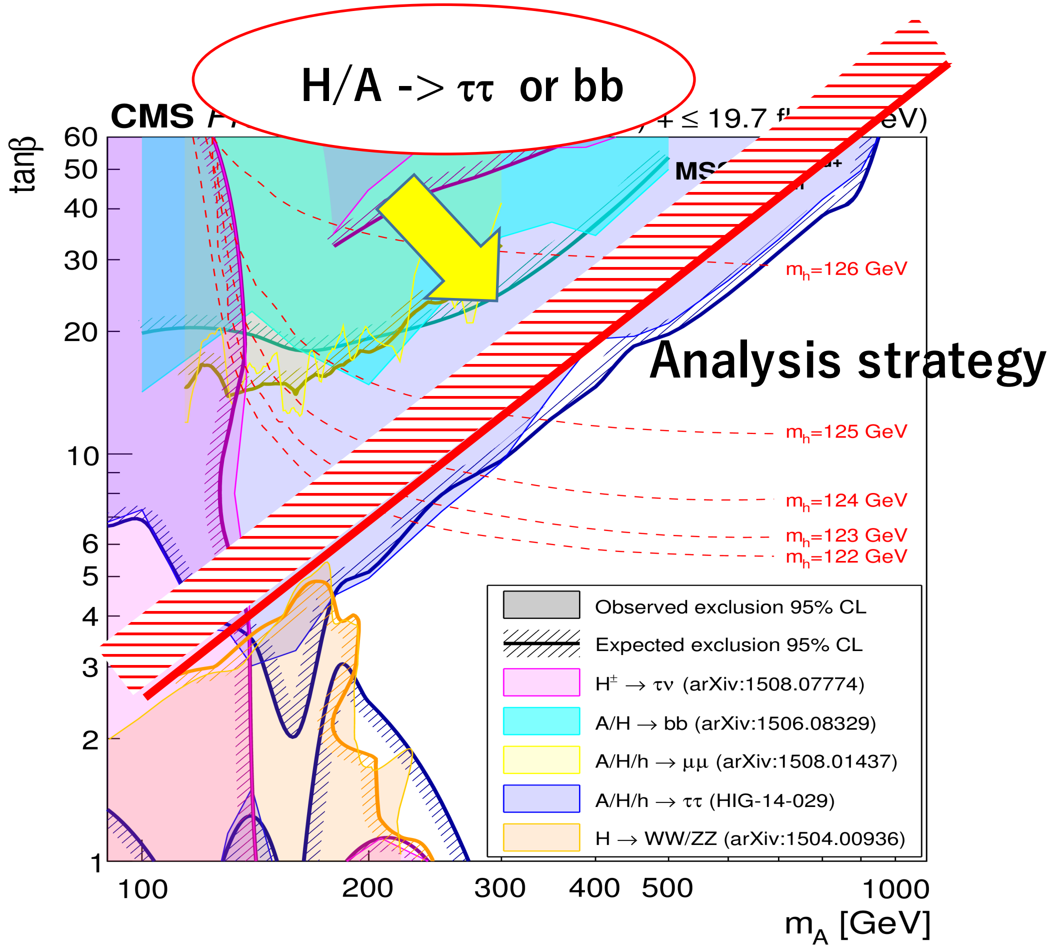

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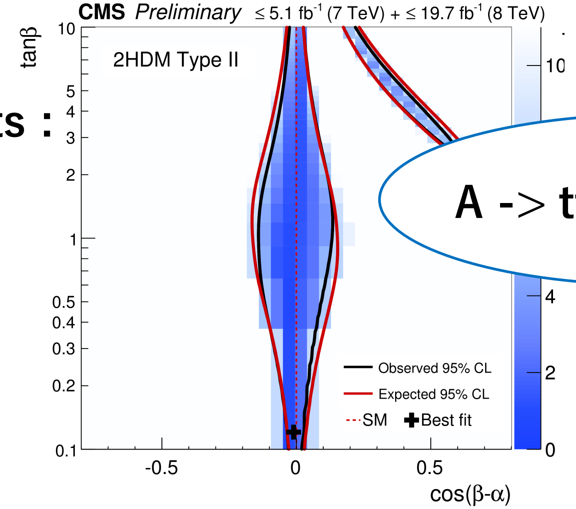

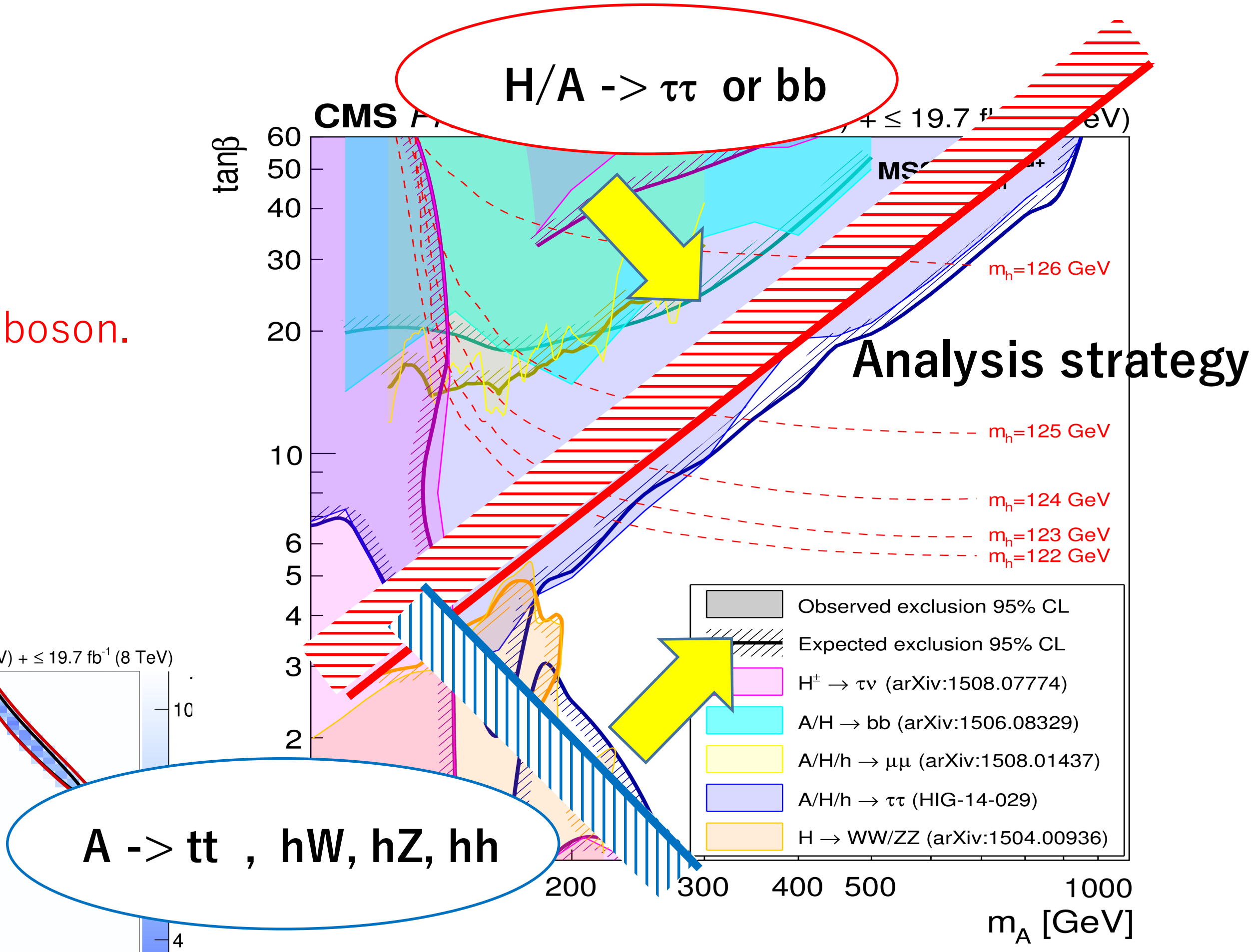

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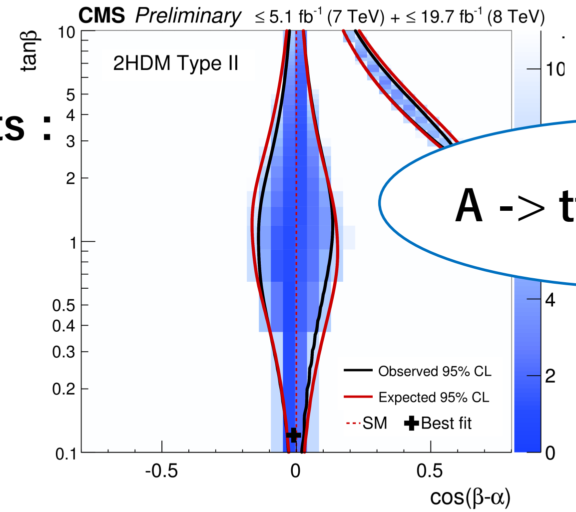
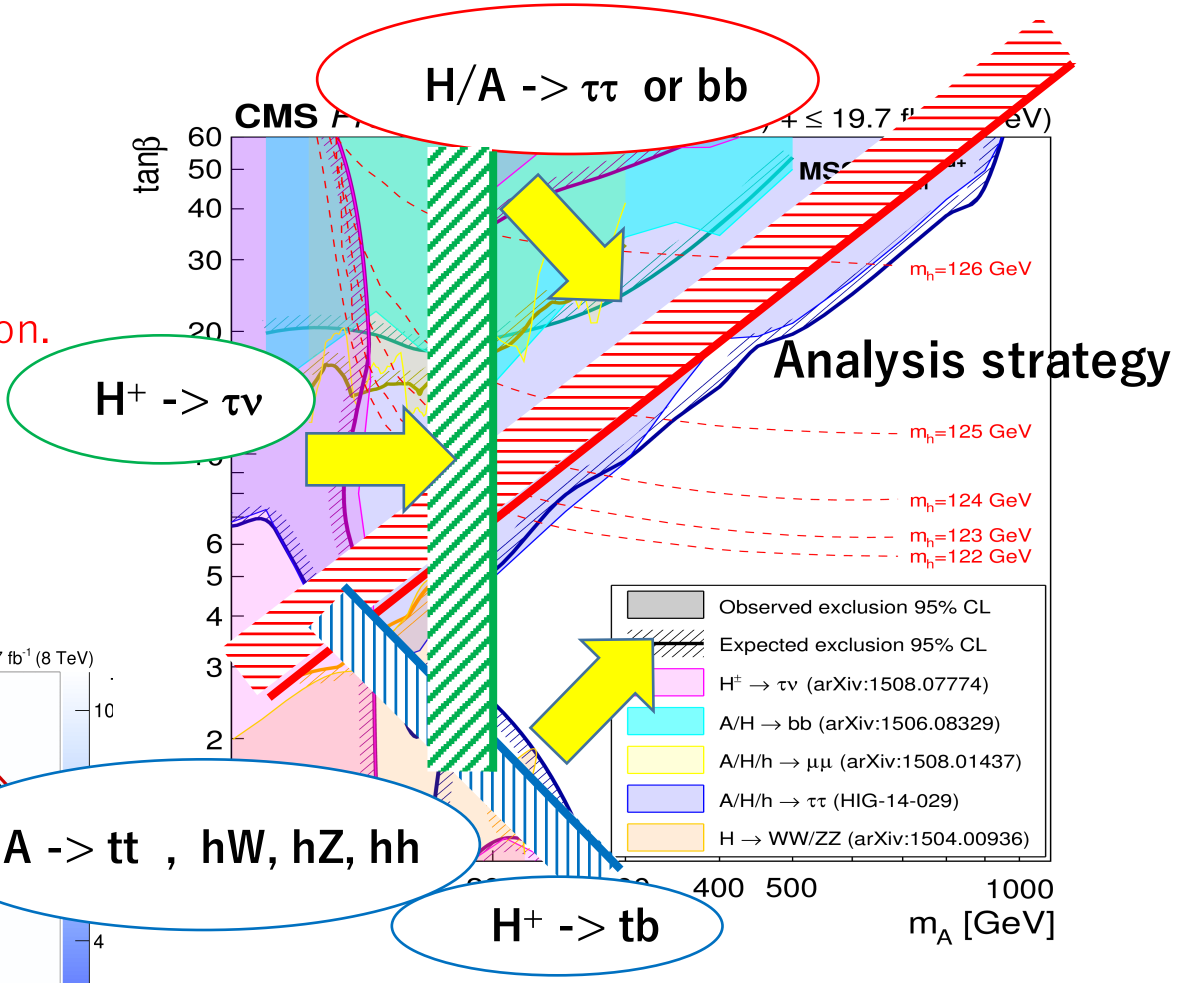
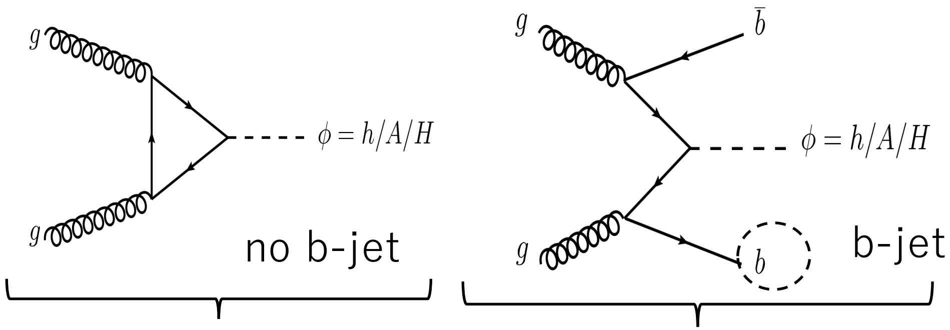




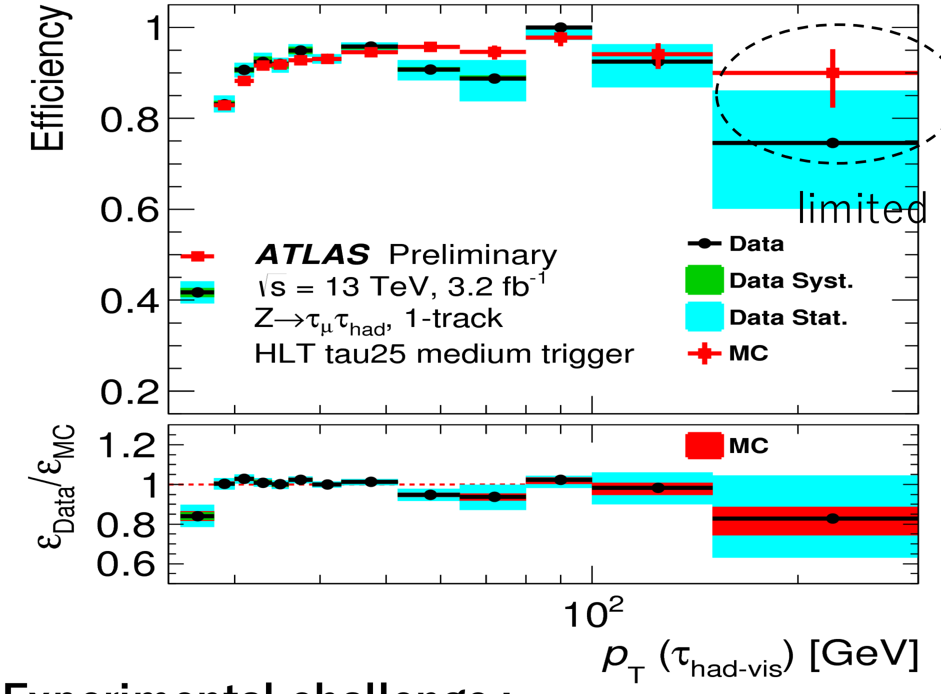
H/A → ττ search

Sensitive to high tanβ region :



gluon fusion (ggH)

b-associated production (bbH)



Analysis :

- Since production mode depends on the size of tanβ , enhance high p_T tau **without b-jet** (ggH) or **with b-jet** (bbH).
- Dominant background is a jet events mis-identified as tau. (W+jets, top, multi-jet process) They are estimated by data.

Experimental challenge :

- High p_T τ reconstruction

  There is no control data for such high p_T τ.

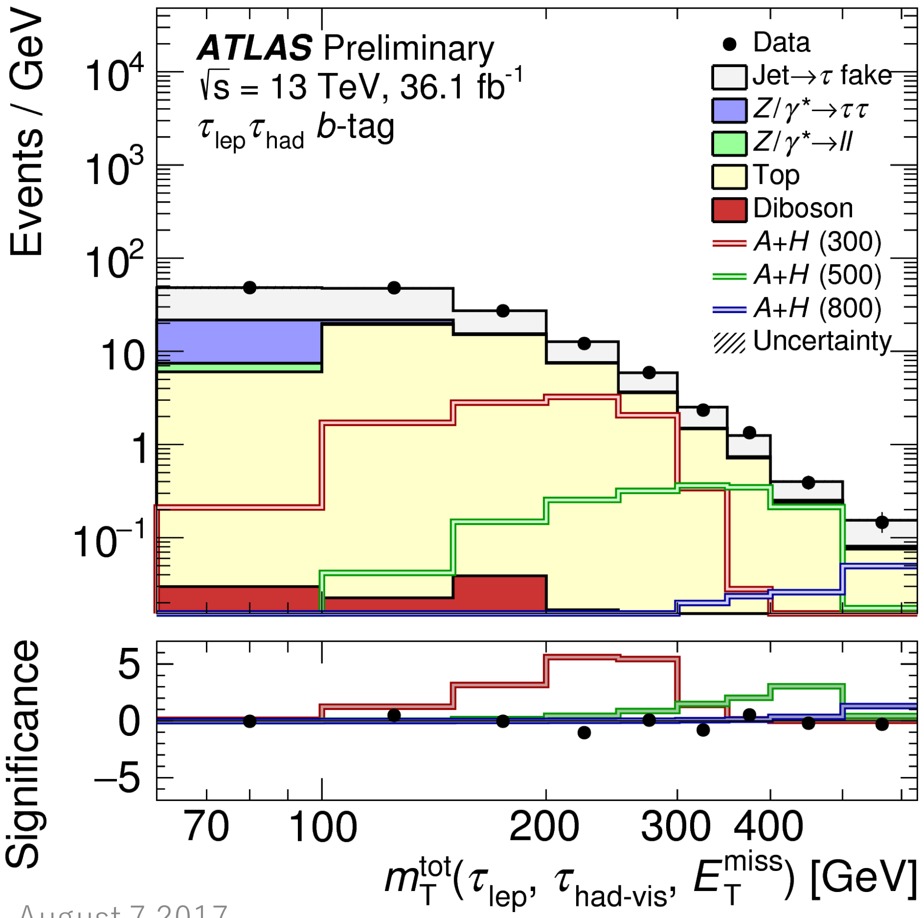
  Extra ~20% uncertainties using di-jet events are added on the top of the tau ID (5%).

- Theory uncertainty: the treatment of b-quark in the initial state.

H/A → ττ search con't

Reconstruct mass :

$$m_T^{tot} \equiv \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{miss})^2}$$

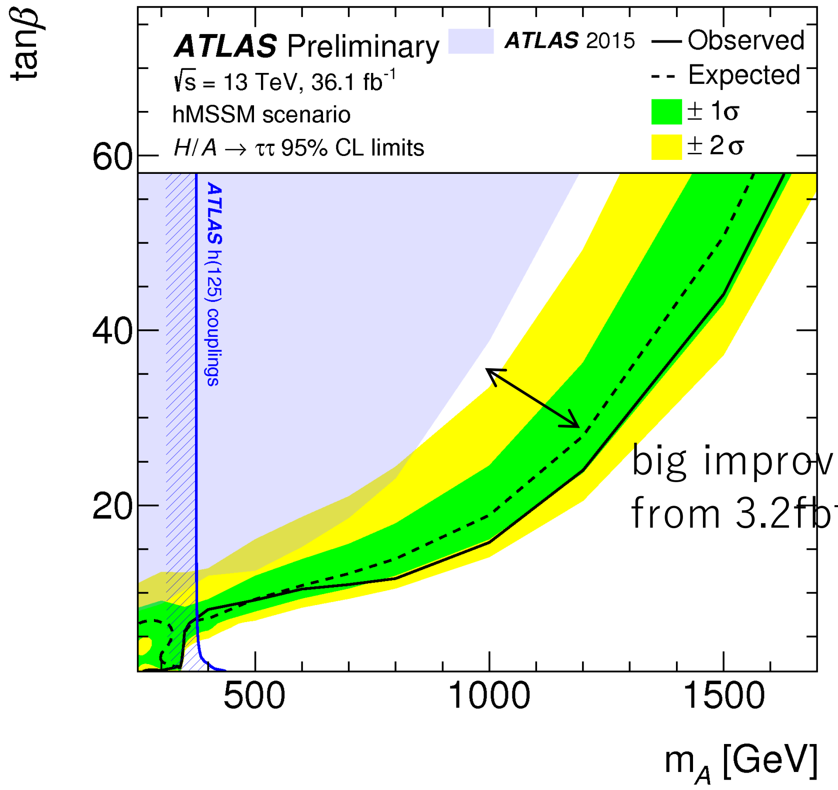


Model independent limits are obtained :

σ x Br : 0.85 – 0.0058pb for ggH,

0.95 – 0.0041pb for bbH.

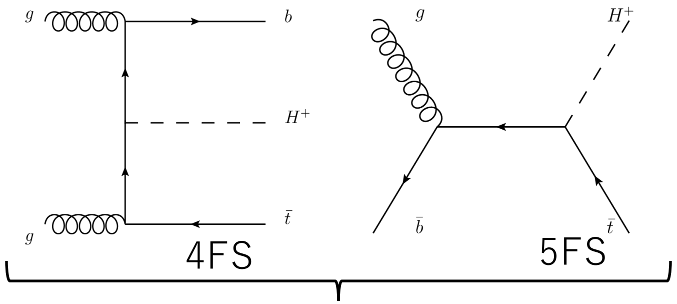
Interpretation to typical MSSM benchmark scenario :



big improvement from 3.2fb^{-1} analysis.

Charged Higgs searches

Direct production: Synergy with Belle exp.
(indirect search)



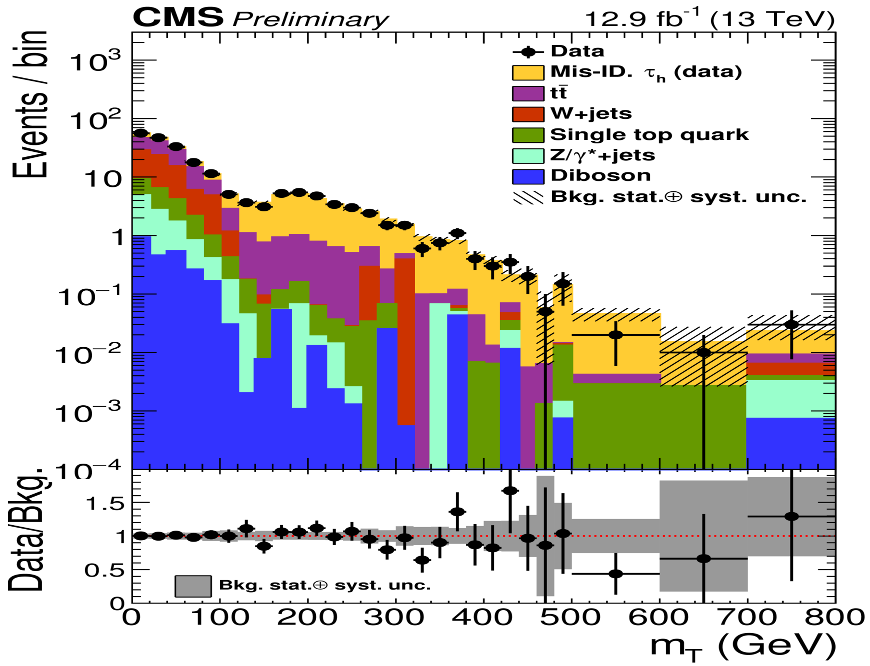
top associated production (tbH+)

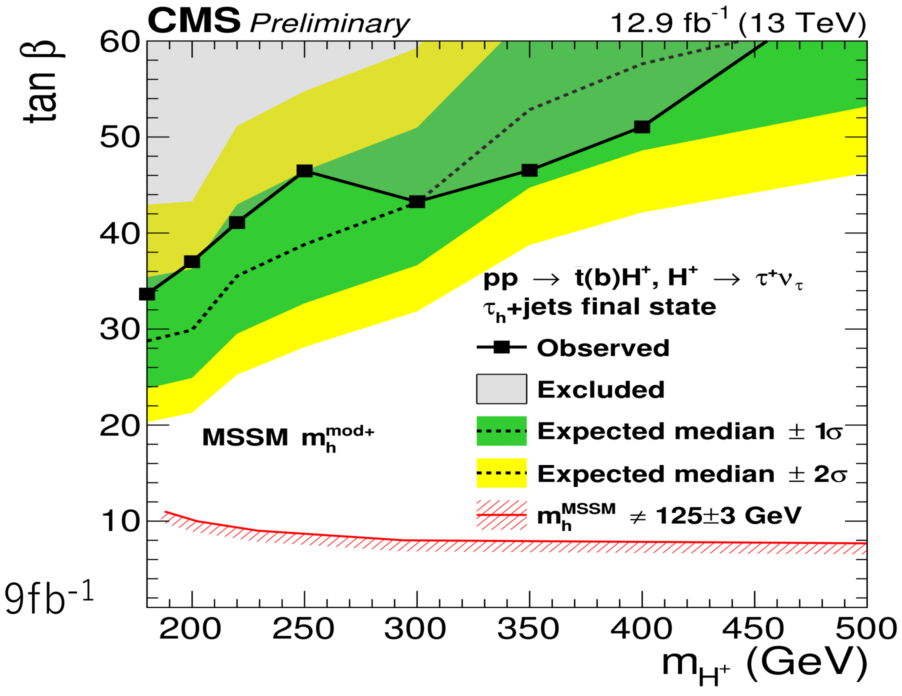
<u>High tanβ</u> <u>region:</u>

- $H^+ \to \tau\nu$ decay mode is more sensitive.
- Final discriminant m_T :

$$m_T^2 = 2 \cdot p_T^{\tau h} |\vec{\not{E}}_T| \left(1 - \cos\Delta\phi(\not{E}_T, \tau^h)\right)$$

- Dominant background are fakes from top, W+jets and multijet.



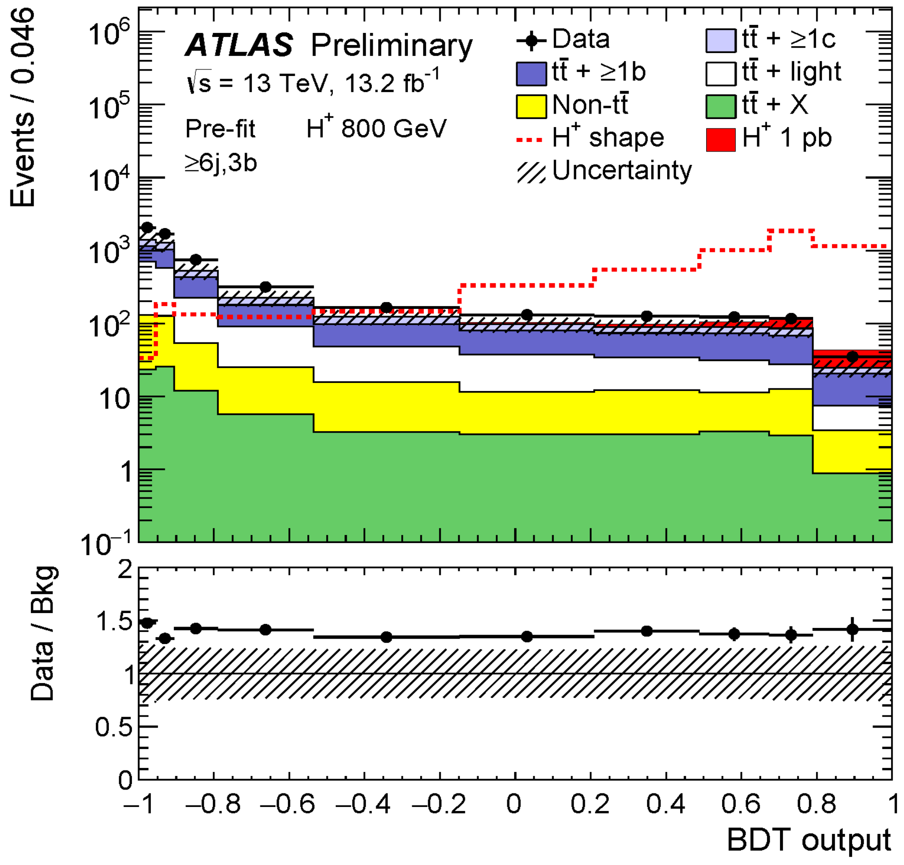


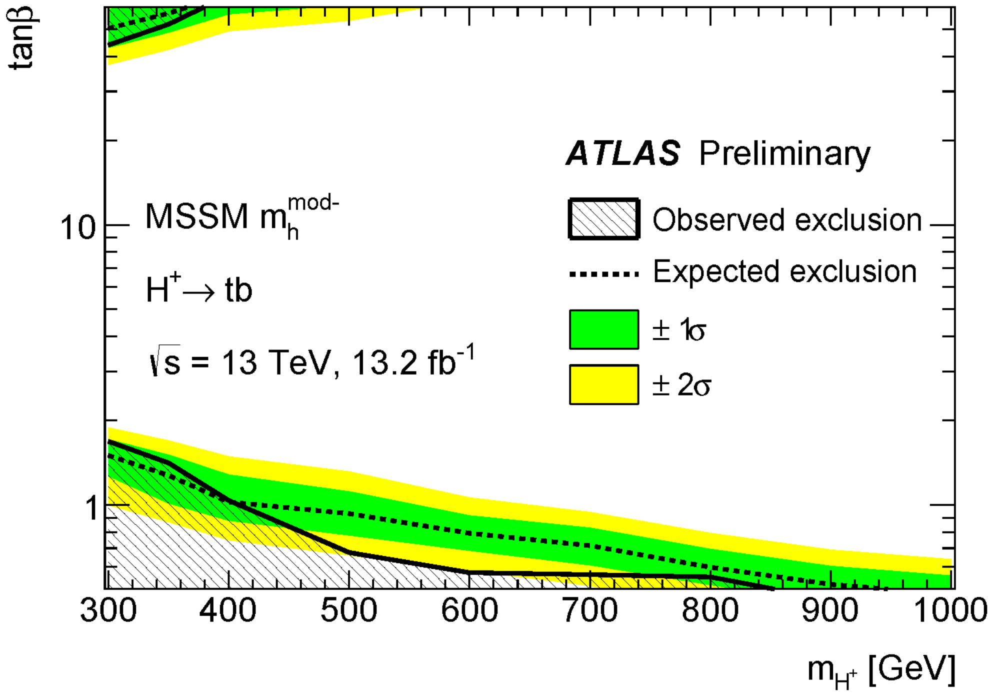
CMS-PAS-HIG-16-031 12.9fb^{-1}

Charged Higgs searches con't

Low tanβ region:

- Use $H^+ \to tb$ decay mode.
- Multivariate analysis (BDT) dividing jets and b-jets.





- Significant systematics is tt + jets modeling (theory). NLO precision (Sherpa+OneLoops) is used with 50% uncertainty in multiple interaction (MPI).

ATLAS-CONF-2016-089 $13.2 fb^{-1}$

Higgs as a probe to new physics

- Heavy resonance X $\rightarrow$ VH or HH

Many di-boson channels

X $\rightarrow$ di-bosons (**W/Z/H/γ**) $\rightarrow$ 4 or 6-fermions

Access m_X ~ a few TeV

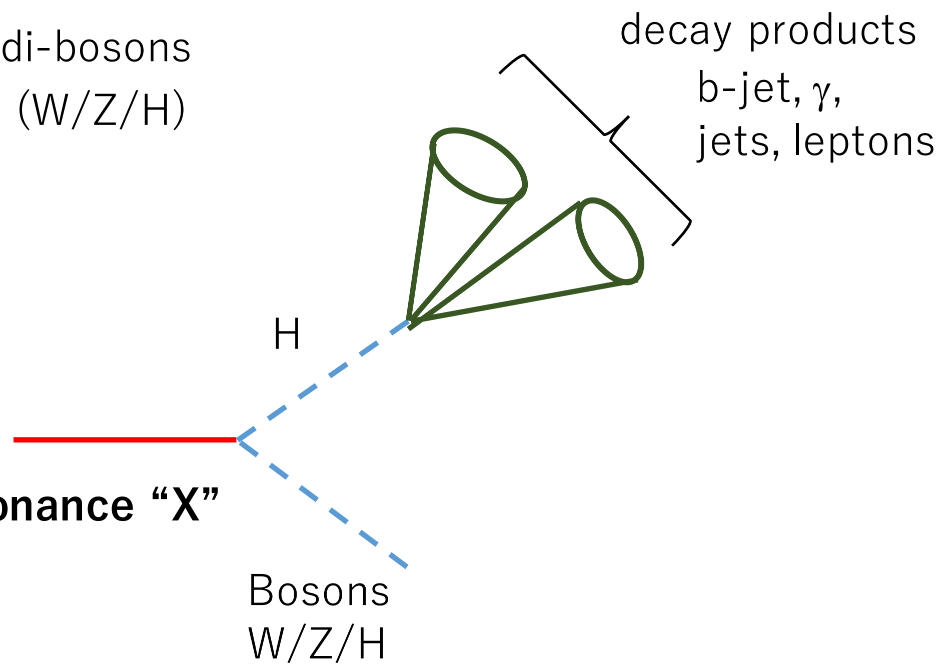
Only cover VH, HH.

Final state	ATLAS	CMS
$\gamma\gamma$, Zγ	submit to Phys.Lett.B.,36.7fb^{-1} arXiv:1707.04147 arXiv:1708.00212	Run1(19.7fb-1) + Run2(16.2fb^{-1}) Phys.Lett.B.767(2017)147 arXiv:1610.02960
ZZ (llll, ll$\nu\nu$, llqq, $\nu\nu$qq)	L =36.1fb^{-1} ATLAS-CONF-2017-058 ATLAS-CONF-2016-082	L = 2.3fb^{-1} CMS-PAS-HIG-16-001 CMS-PAS-HIG-16-033
WW (lνlν, lνqq, qqqq)	L = 36.1fb^{-1} ATLAS-CONF-2017-051 ATLAS-CONF-2016-074	L = 2.3fb^{-1} CMS-PAS-HIG-16-023
HV (bbll, bb$\nu\nu$, bblν, bbqq)	NEW L = 36.1fb^{-1} ATLAS-CONF-2017-018 ATLAS-CONF-2017-055	L = 2.2-2.5fb^{-1} Phys.Lett.B768(2016)137
HH (bbbb, bblνlν, bb$\tau\tau$, bb$\gamma\gamma$)	NEW L = 13.3fb^{-1} ATLAS-CONF-2016-049 ATLAS-CONF-2016-071 ATLAS-CONF-2016-004	NEW L = 35.9fb^{-1} CMS-PAS-HIG-17-008 CMS-PAS-HIG-17-006 CMS-PAS-HIG-16-029 CMS-PAS-HIG-16-002

High mass resonance searches (X → di-bosons including Higgs)

Production mode :

X → di-bosons (W/Z/H)

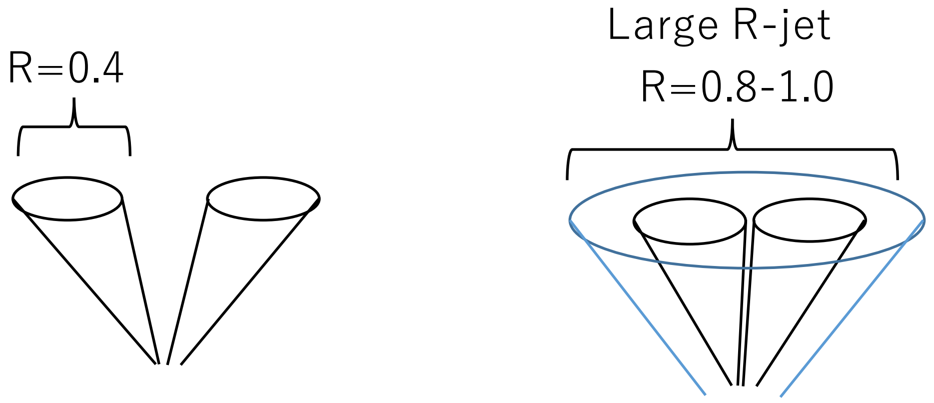


The "X" might be another Higgs.

If the final state is Higgs, decaying to bb or $\gamma\gamma$ mode is a good handle of the background.

Analysis strategy :

According to the mass of the resonance particle, m_X



"Resolved" category

$m_X < \sim 1\text{TeV}$

"Merged" category

$m_X > \sim 1\text{TeV}$

High mass X → HV

Exploit all possible combination :

- H → bb
- V (W or Z) → ll, lν, jj, νν

Reconstruct mass :

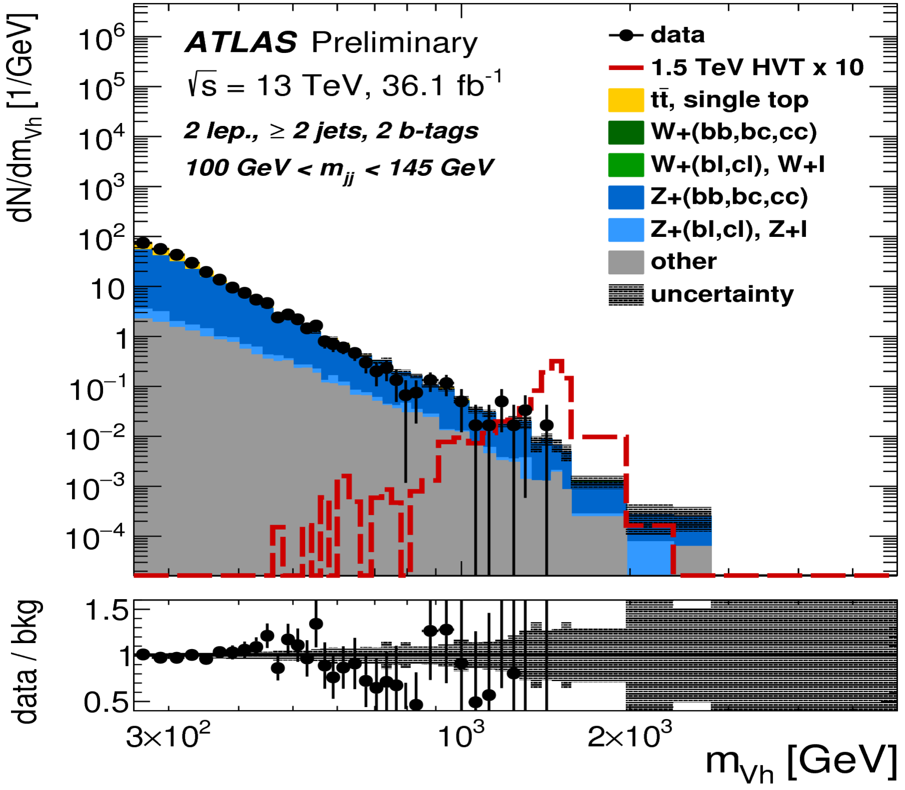
- 4-fermion invariant mass if all "visible".
- Or in case neutrino in the final state, use

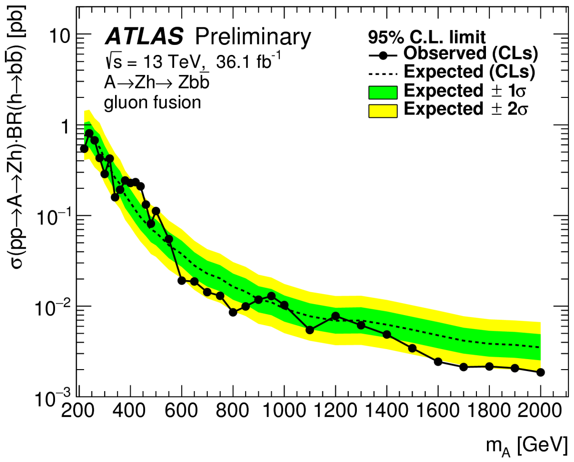
$$m_{\mathrm{T},Vh} = \sqrt{(E_{\mathrm{T}}^{h} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T}}^{h} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2},$$

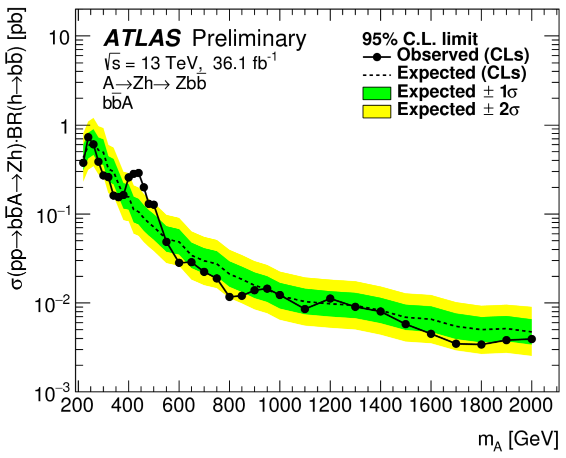
Experimental challenge :

- B-jet performance is a key. ~5-10% ID syst.
- Mass resolution ~30-40%.

Cross section limit : ~1.0x10^{-2} pb @ m_A=1TeV



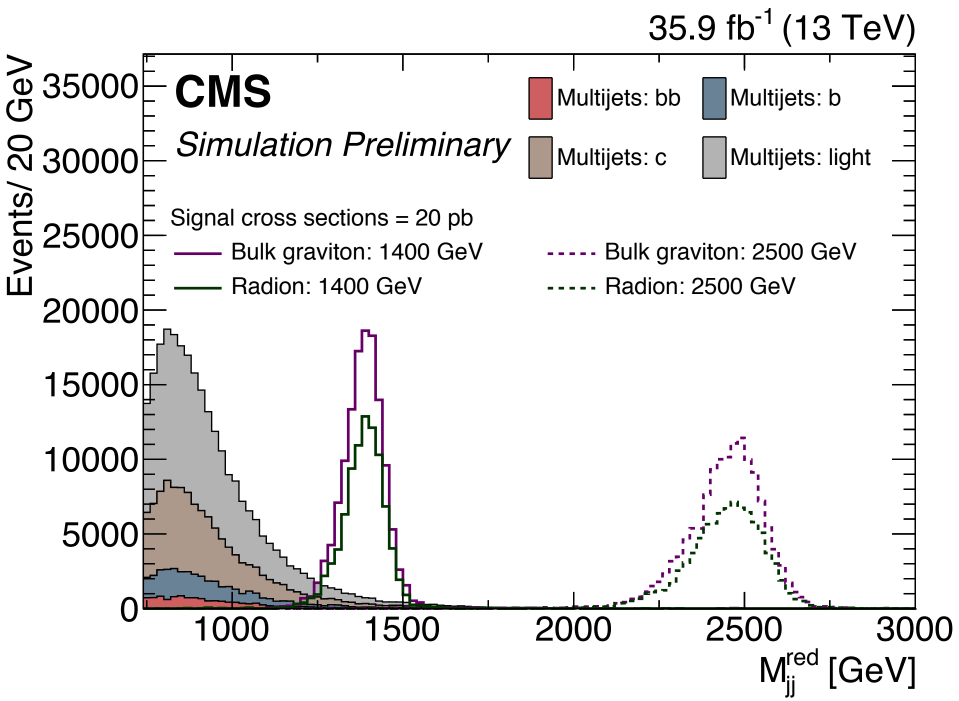




High mass X → HH → bbbb

Analysis :

- Both H → bb is reconstructed as single jet,
- Sub-jets are identified as b-jets,
- Reconstruct M_{jj} mass as HH resonance.

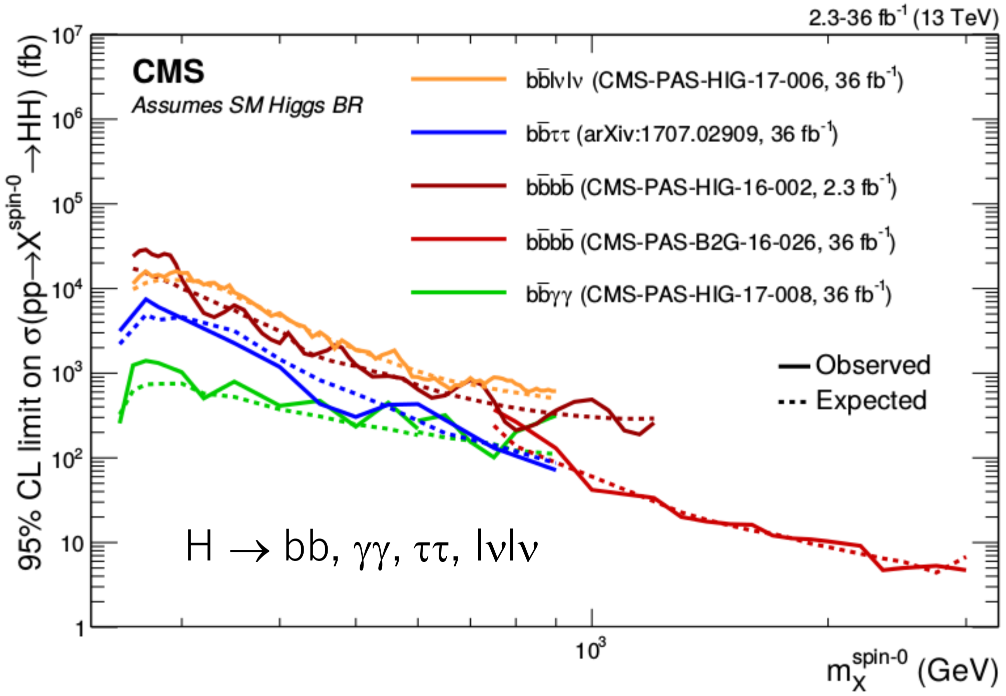


Experimental challenge :

- Trigger :

  Combination of H_T>800(900)GeV
  and H_T >680+ di-jet topology M_{jj} + $\Delta\eta$

[CMS-PAS-B2G-16-026]



Anomalous Higgs couplings

- Flavor violation, Rare decay

Search for flavor violating decay

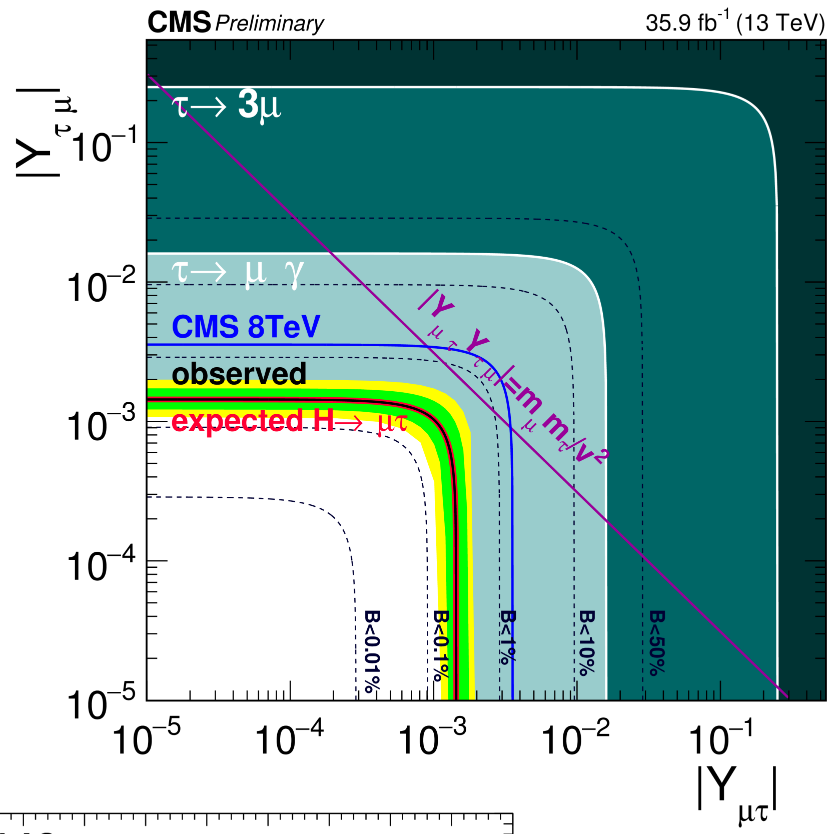
Lepton flavor violating decay:

- Many interesting physics connecting to neutrino flavor mystery.

⇨ FCNC is forbidden in SM. But how about Higgs?

$H \to \mu\tau$, $e\tau$ search: CMS-PAS-HIG-17-001 NEW

- Strong constraint Br(H→eμ)~2x10^{-8} from μ→eγ or μ→3e experiments. But tau decay mode is rather weakly constraint.



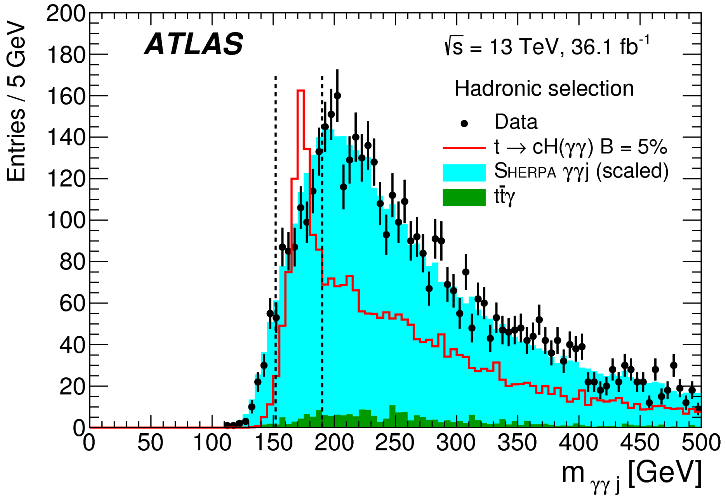
Flavor violation in quark sector:

$t \to qH$, $H \to \gamma\gamma$ search : arXiv:1707.01404 NEW

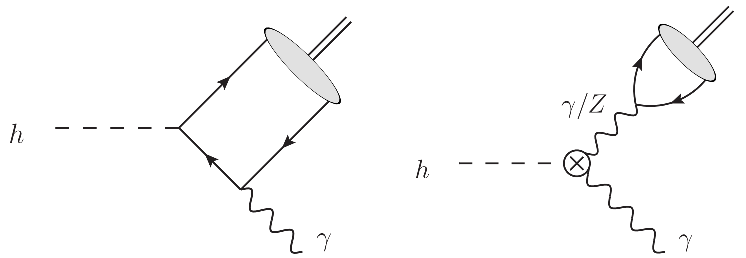
- SM prediction: Br(t→qH)=3x10^{-15}

- Use top-pair samples with two photons, construct top mass, $m_{\gamma\gamma j}$.

- Limit obtained: Br(t→uH) < 2.4x10^{-3}



Search for "new" exclusive decay mode



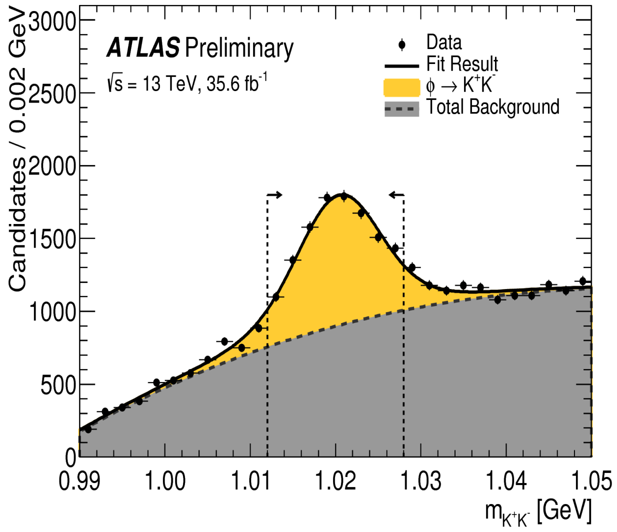
H → ργ , ϕγ search : ATLAS-CONF-2017-057 NEW

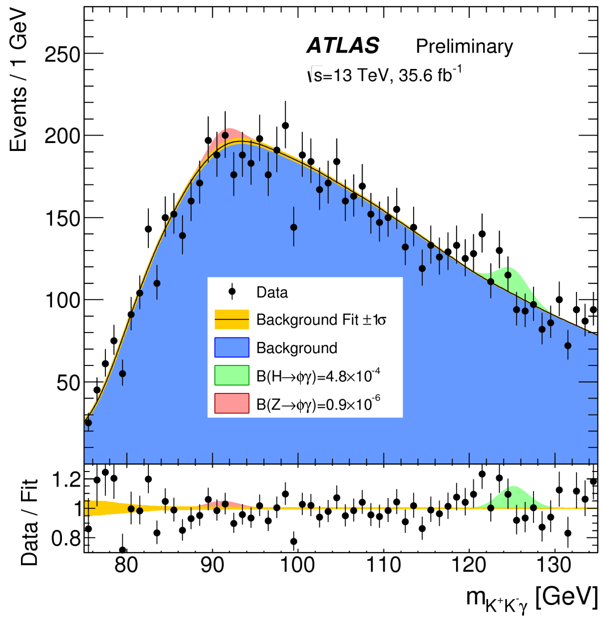
- Use $\phi \to K^+K^-$ and $\rho \to \pi^+\pi^-$
- Mass resolution ~4MeV
- Dominant background is γ + jets, side-band fit.

Experimental challenge :

- Huge improvement in trigger: 35GeV photon + 2 tracks with $p_T > 15$GeV.

Mode / Method	Branching Fraction $[10^{-6}]$ NRQCD [1487]	LCDA LO [1486]	LCDA NLO [1489]
$\mathrm{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$





Limit on Br :

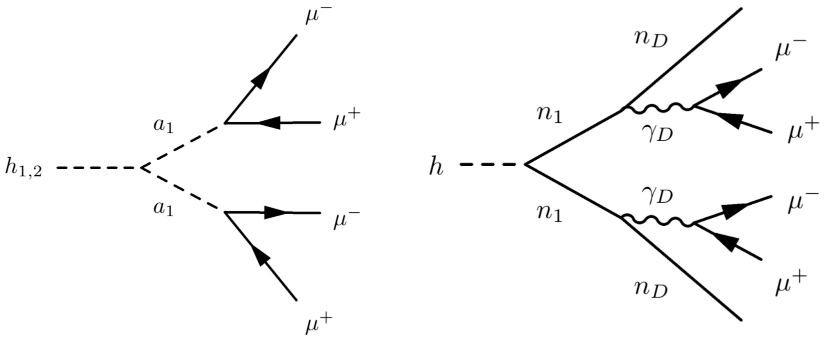
$\mathrm{Br}(H \to \phi\gamma) < 4.8 \times 10^{-4}$

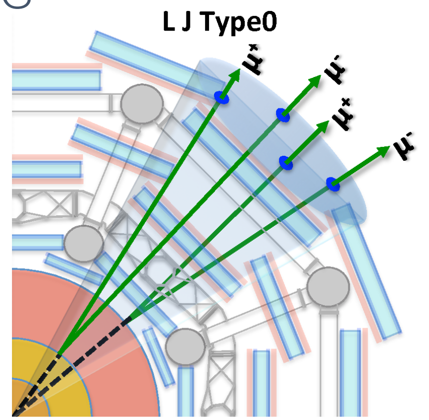
$\mathrm{Br}(H \to \rho\gamma) < 8.8 \times 10^{-4}$

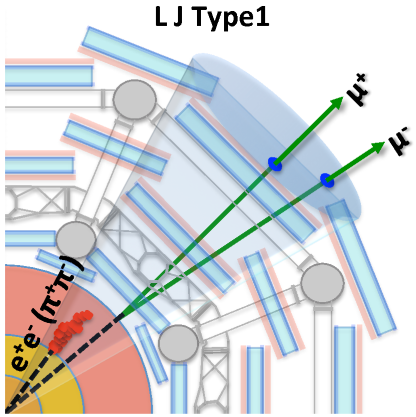
(SM prediction Br ~10^{-6})

Higgs decays long-lived neutral particles

Higgs decay another exotic (scalar) bosons :

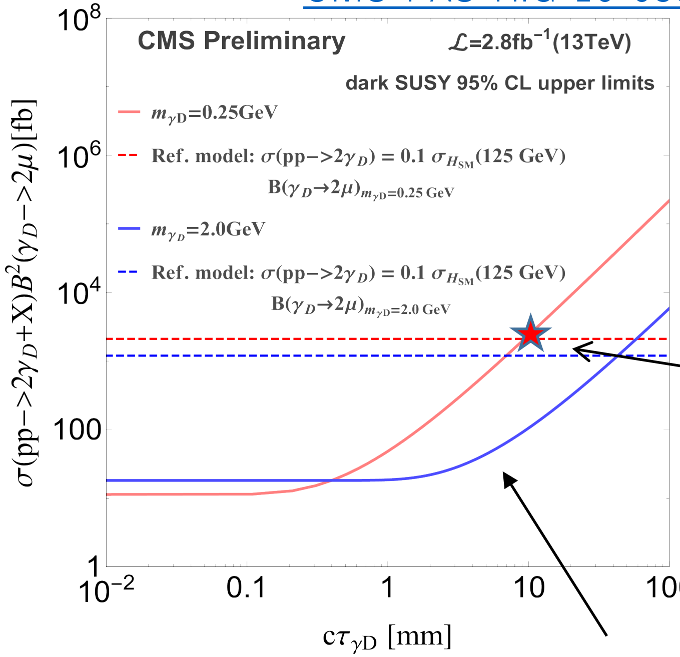






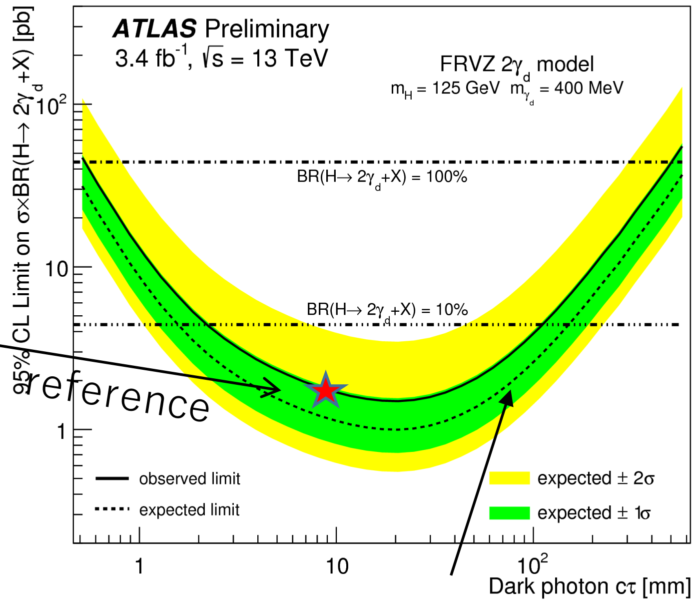
- Results in non-negligible lifetime of the bosons which can decay outside beam pipe.
- Main background : **different target**
  - bb — if lifetime is short, it can decay inside tracking detector.
  - beam-induced bkg — if long lifetime, decays outside tracking detector.

CMS-PAS-HIG-16-035



decays inside pixel detector

ATLAS-CONF-2016-042



decays outside tracker

Summary

1. Search for another Higgs sector :

- MSSM Higgs bosons

Strategic, excludes low and high tanβ regions. ~1TeV@tanβ~20-40

HL-LHC will exploit up to 400 GeV for whole parameter space.

(above 400GeV, tanβ~10 is rather weak..)

2. Higgs as a probe to new physics :

- Heavy resonance $X \rightarrow VH$ or HH

All decay modes (4, 6-fermion) are fully covered.

Accessible to m_X~ a few TeV.

3. Anomalous Higgs couplings :

- Flavor violation, Rare decay

LFV for tau starts limits on theory.

Rare decay limit : ~10^{-4} (SM prediction: ~10^{-6})

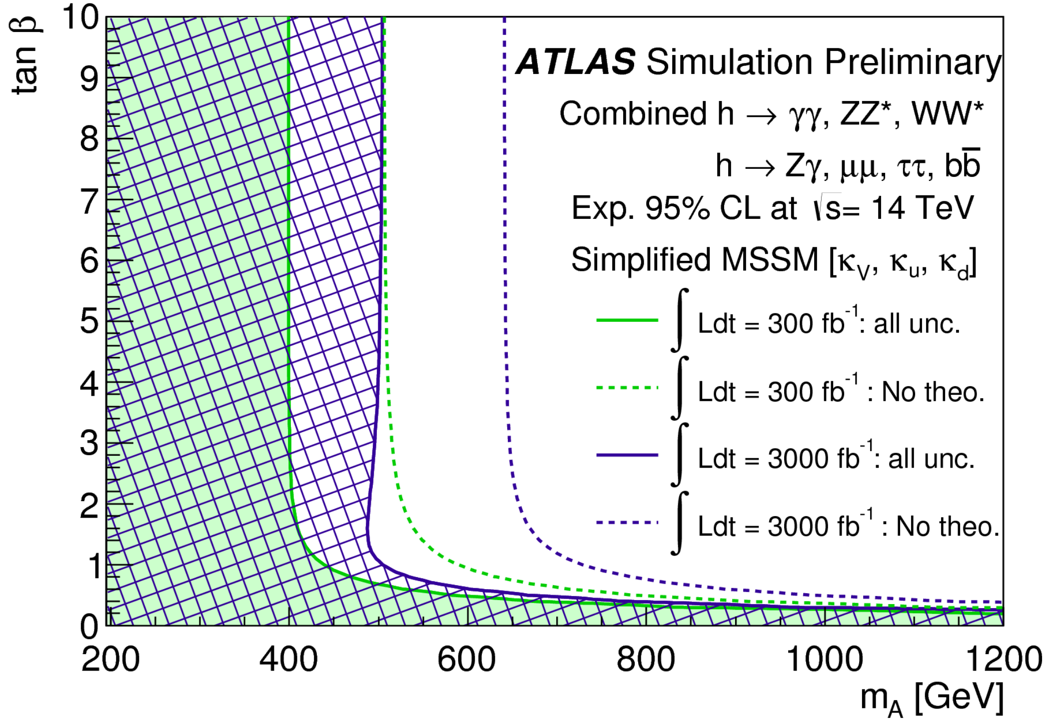
With 3000fb^{-1}, reach to $Br(H \rightarrow J/\psi\,\gamma) < 55 \times 10^{-6}$ accessible to 2nd generation.

Backup

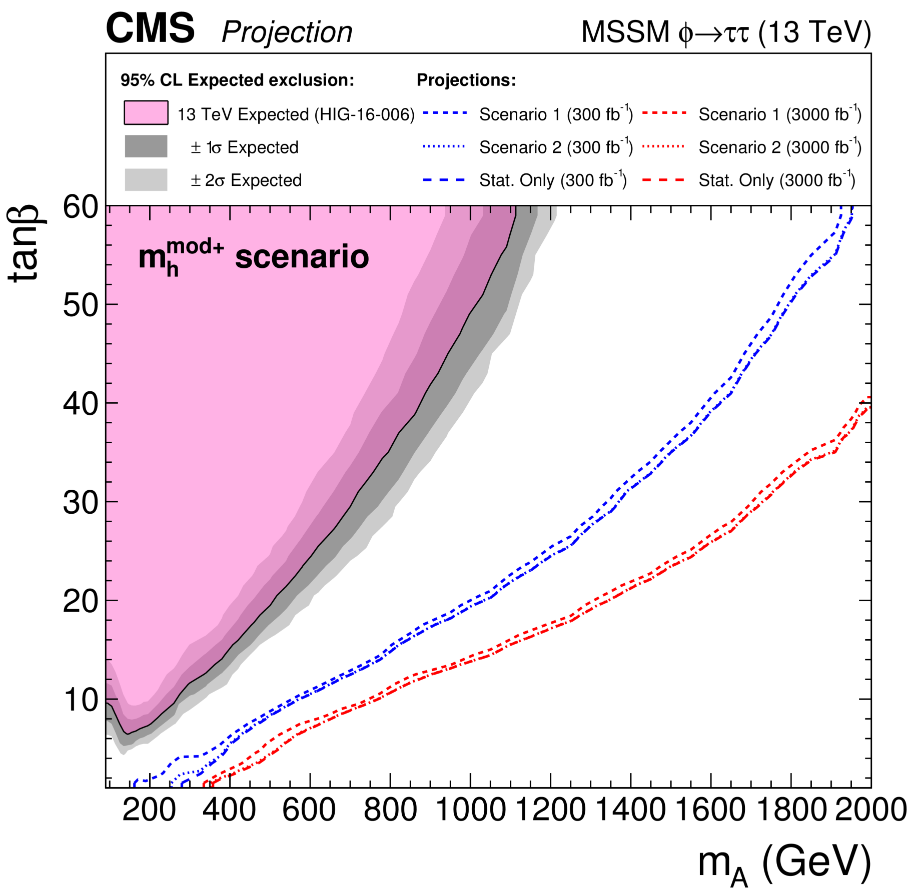
Perspective for HL-LHC

Constraint to SM Higgs measurements:

ATL-PHYS-PUB-2014-017



Direct searches: CMS-PAS-FTR-16-002



Highlight： High-mass diphoton resonance

ATLAS: Update new analysis with full dataset of 2015+2016.

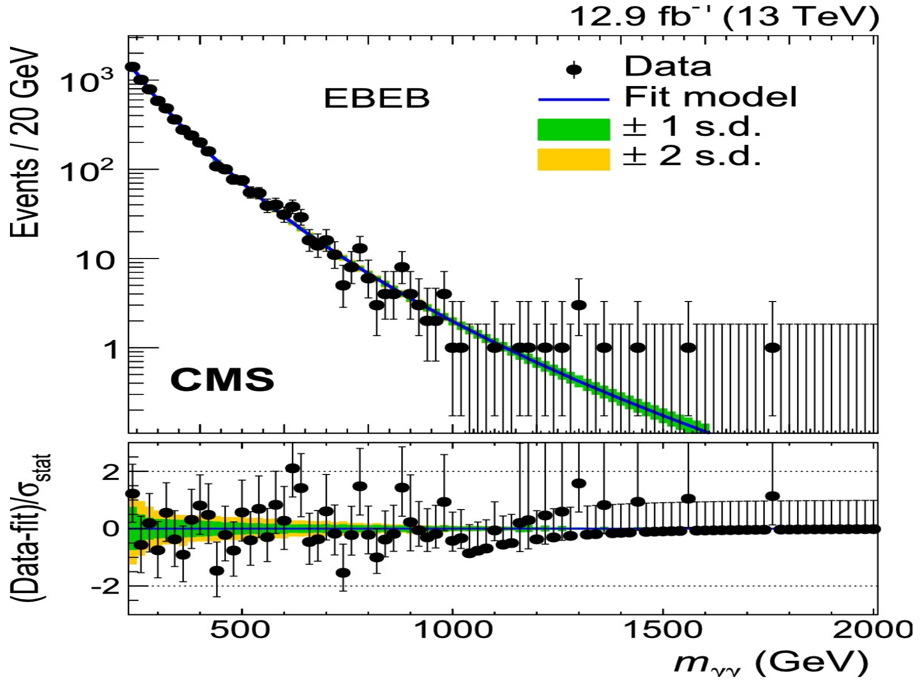
- $L=36.7fb^{-1}$ (2015+2016)
- Improved photon ID (conversion track recovery)
- Re-calibrated with 2016 dataset.

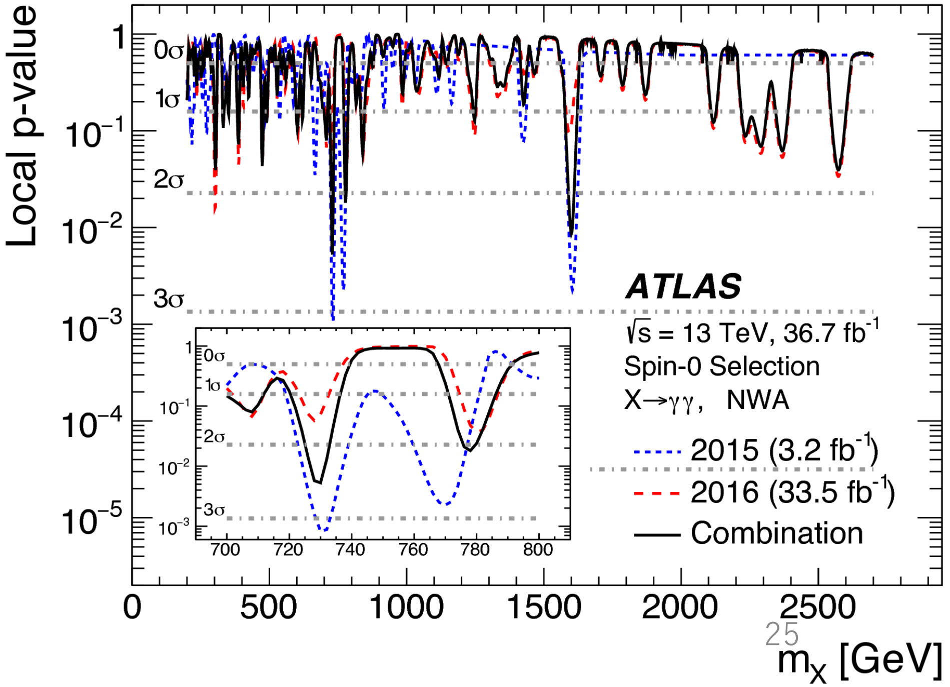
CMS: Last update at Moriond 2017

- paper published in April.

Summary： Significance at m_H~750GeV saga

	Old (2015)	New (2015+2016)
ATLAS	**3.9σ** Run2, $L=3.2fb^{-1}$ JHEP09(2016)001	**2.6σ** Run2, $L=36.7fb^{-1}$ Phys.Lett.B. arXiv:1707.04147
CMS	**3.4σ** Run1(19.7fb-1)+Run2($3.3fb^{-1}$) PRL.117(2016)051802	**1.9σ** Run1(19.7fb-1)+Run2($16.2fb^{-1}$) Phys.Lett.B.767(2017)147

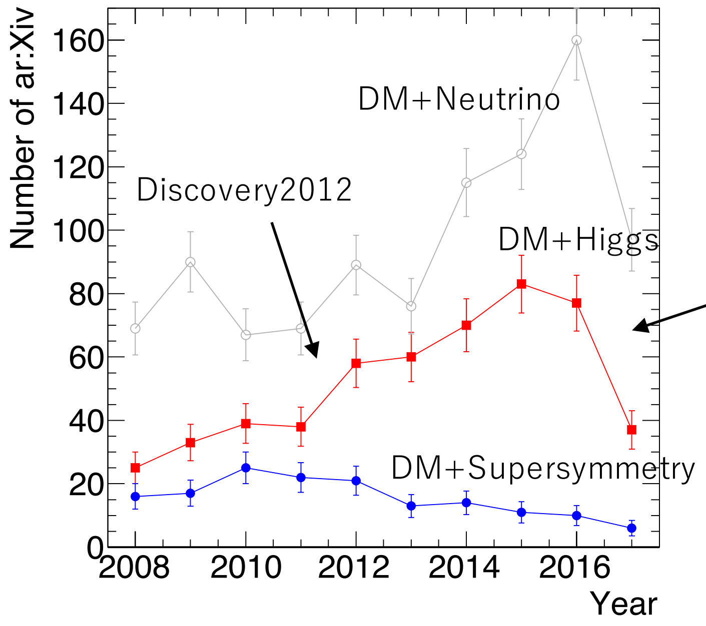




Dark matter with Higgs

Collider experiment: "**Direct production**".

Wide interests of HEP community :



"Dark Matter + Higgs" papers are growing...

paper title

Go to HEP-INSPIRE :

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find t dark matter and t higgs and d 2017
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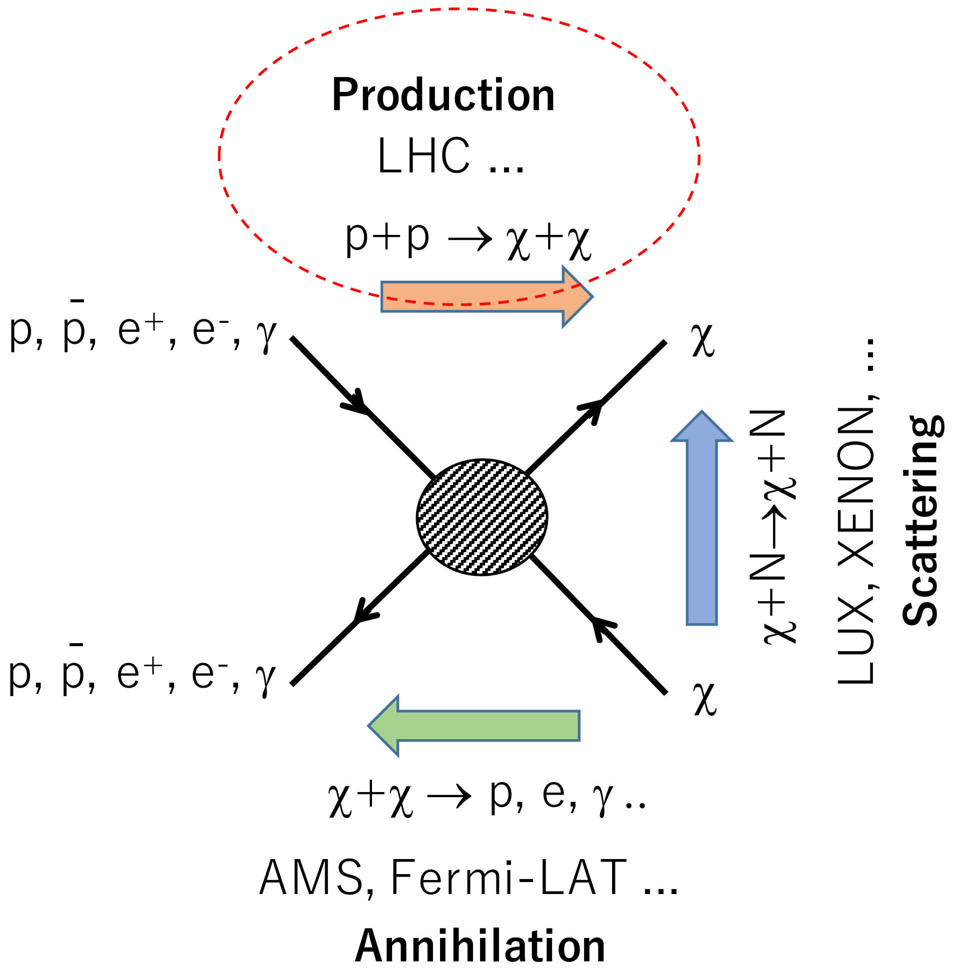
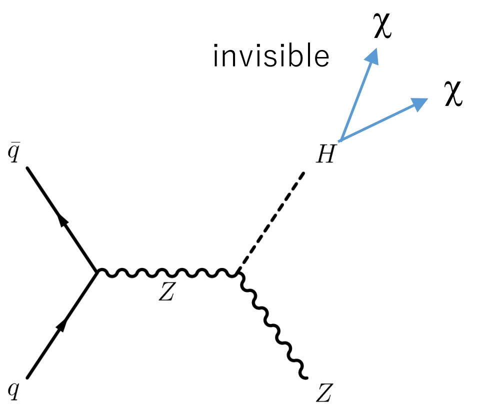


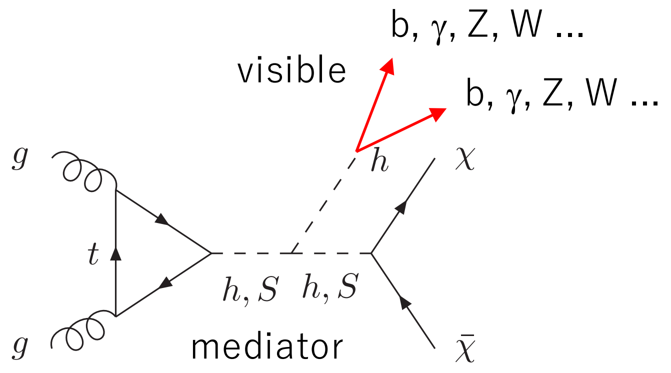
Open a new signature with Higgs

Invisible Higgs decay:

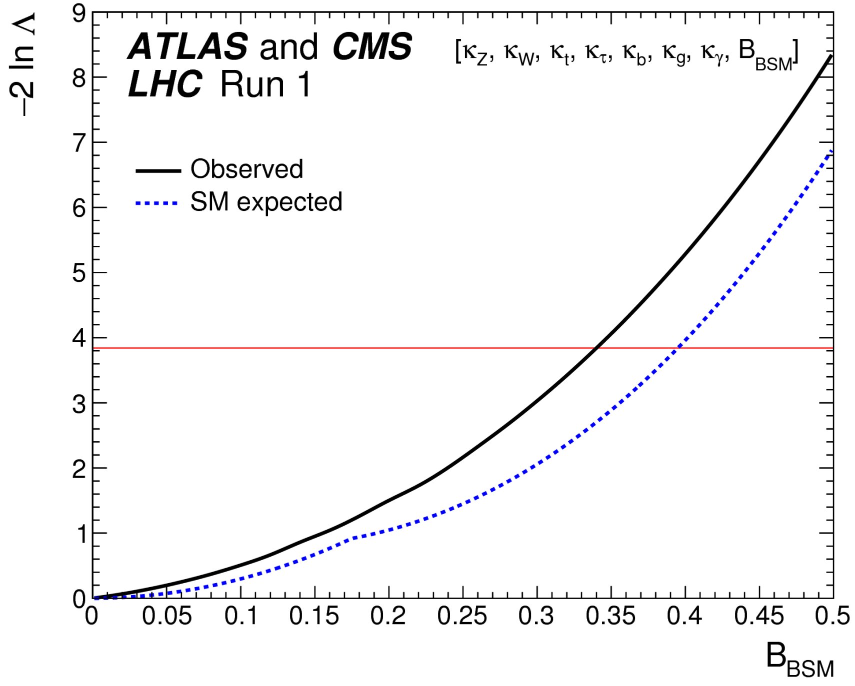


- Mono-X searches (X=Z, jet, γ, ...)
  - SM Br(H→νννν) = 0.1%
  - Current SM measurements weakly constrain **Br(H→BSM)<~30%**

(NEW) Visible Higgs decay:

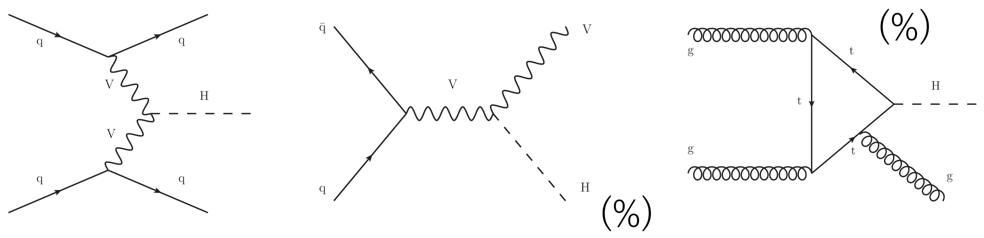


- **Mono-H searches**
  - Search H + MET signature,
  - No initial state radiation.



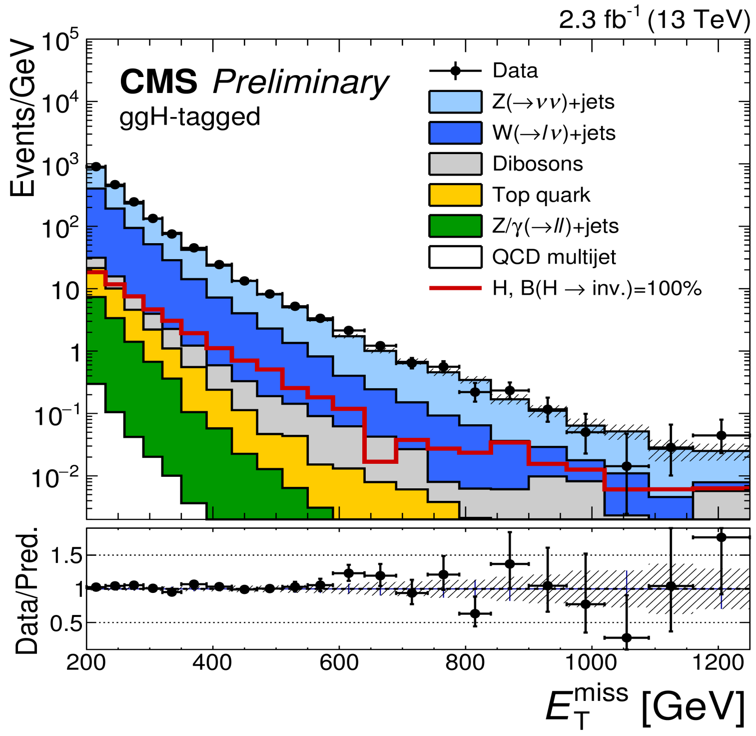
Invisible Higgs searches

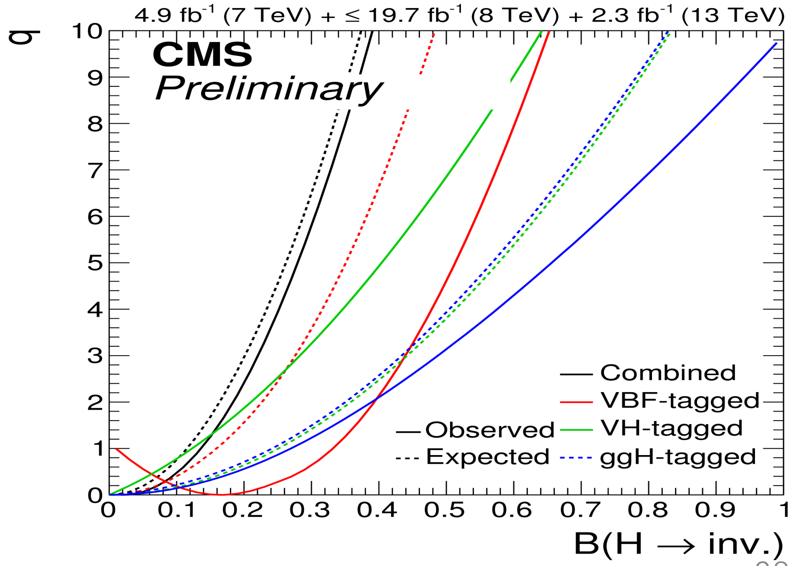
Usual Higgs production, but decays "invisibly".



Experimental challenge :

- VBF trigger, forward/backward jets with large $\Delta\eta_{jj}$ and m_{jj}.
- Better control of the MET reconstruction to suppress multijet background.

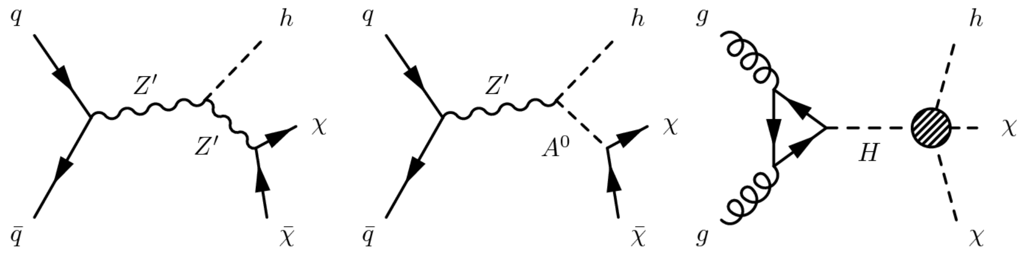




Upper limit on Br(H→inv.)<0.24 @95%C.L. JHEP.02(2017)135

(%) Relatively high p_T regime (Mono-jet, V(jj)) are not considered in this talk.

Mono-Higgs searches



Z'$_B$ model　　Z'-2HDM　　HSB model

H → γγ + MET : arXiv:1706.03948 NEW

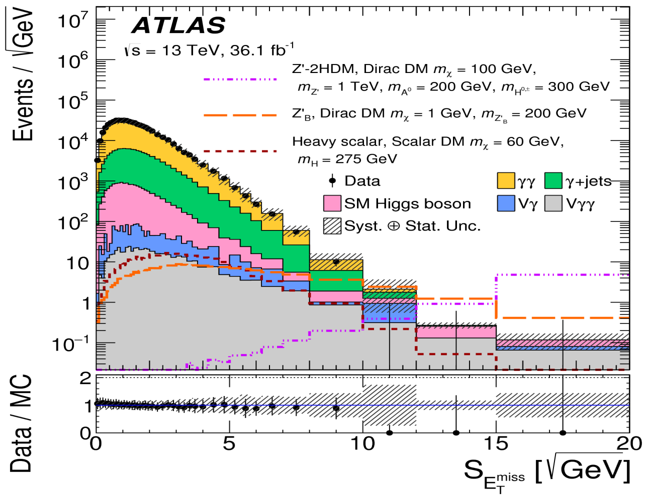
- Use di-photon trigger (35/25GeV)
- MET significance and $p_T(\gamma\gamma)$ is strong parameter.

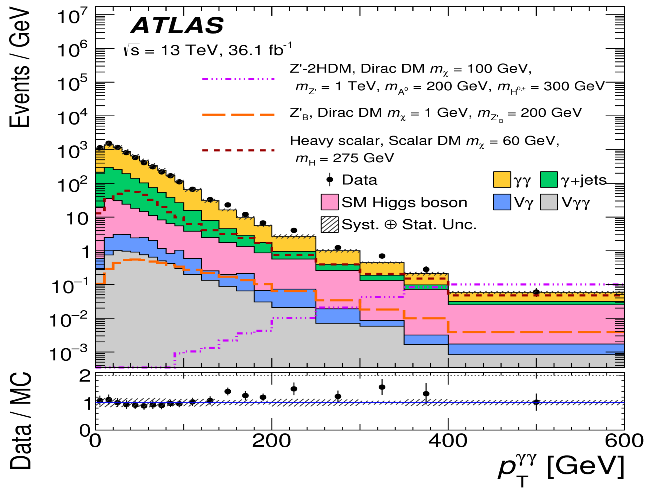
$$S_{E_T^{\mathrm{miss}}} = E_T^{\mathrm{miss}} / \sqrt{\sum E_T}$$

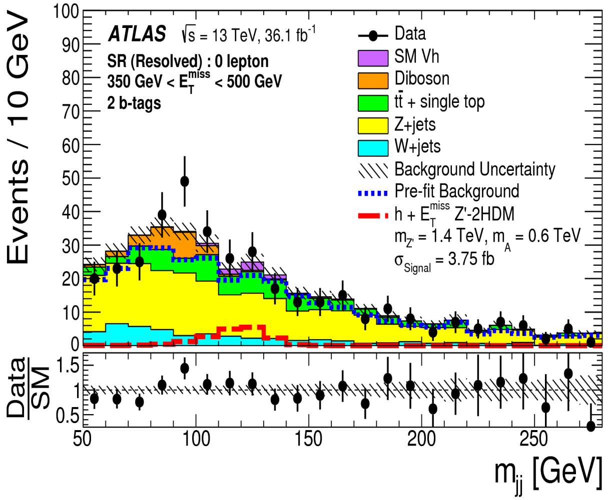
- Final discriminant is $m_{\gamma\gamma}$ by line-shape fit.

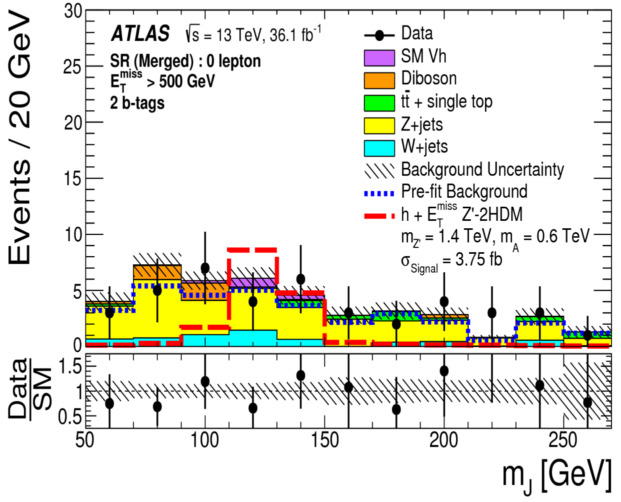
H → bb + MET : arXiv:1707.01302 NEW

- Use MET trigger (70-110GeV)
- 'Resolved' (m_{jj}) and 'Merged' (m_J) categories.
- b-jet uncertainty is dominant (~17%)









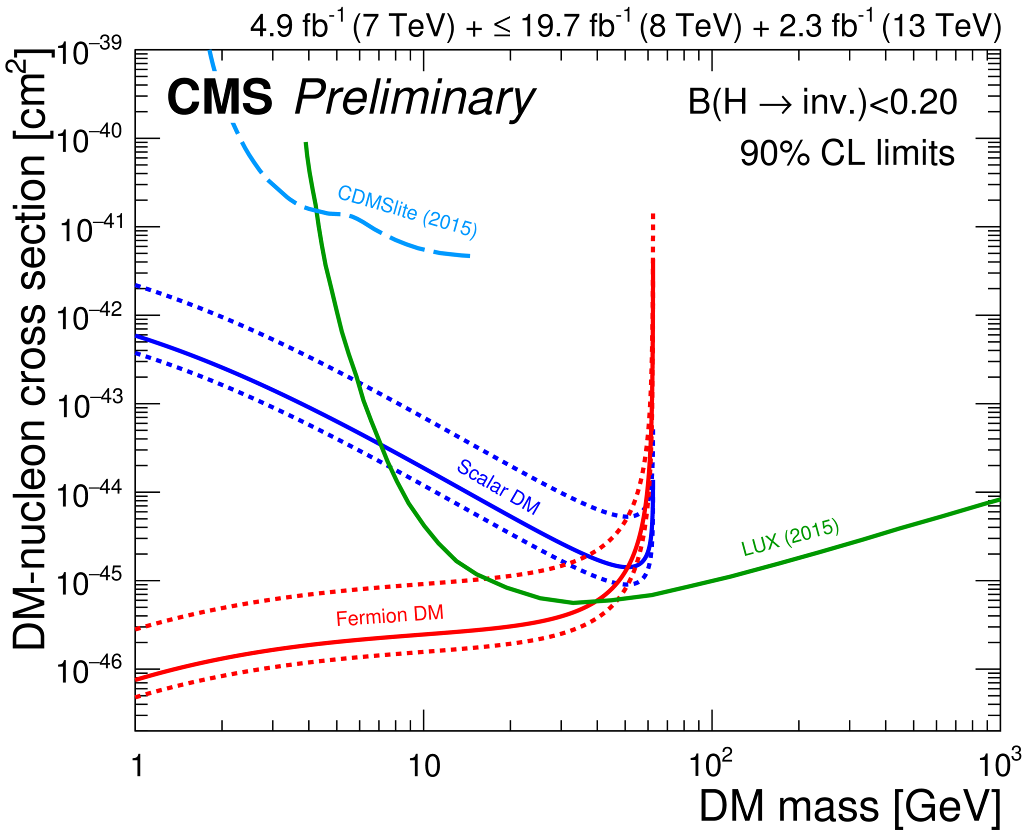
Interpretation to dark matter

Effective Field Theory :

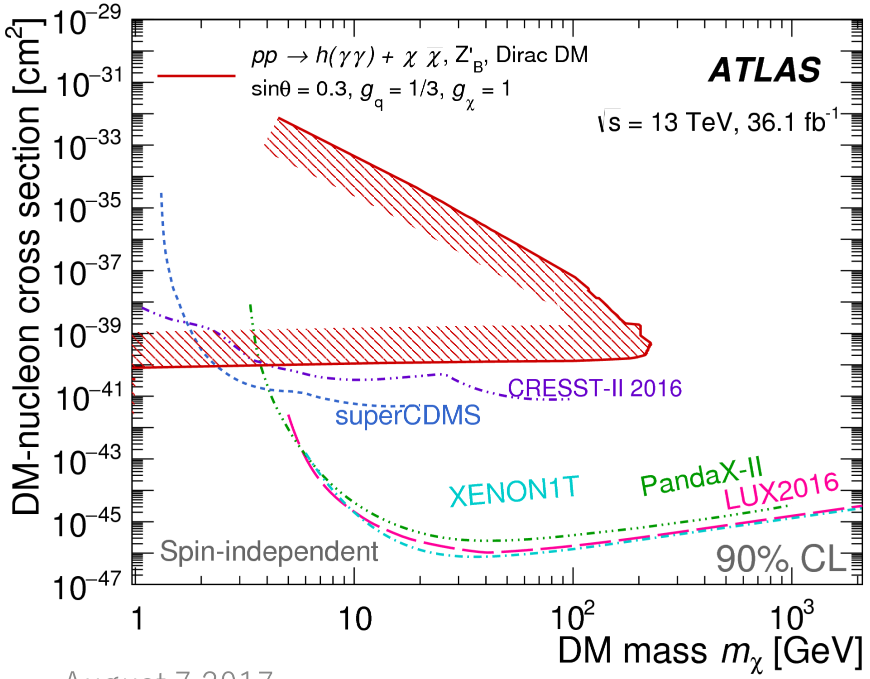
Invisible Higgs: simple formalizm

$$\Gamma(h \to \chi\chi) = \frac{\lambda^2 v^2}{4\pi m_h} \quad \text{scalar } \chi$$

$$\Gamma(h \to \chi\bar{\chi}) = \frac{v^2 m_h}{8\pi\Lambda^2} \quad \text{fermion } \chi$$



Mono-Higgs: Benchmark Models



Collider searches are very powerful tool below Higgs mass.

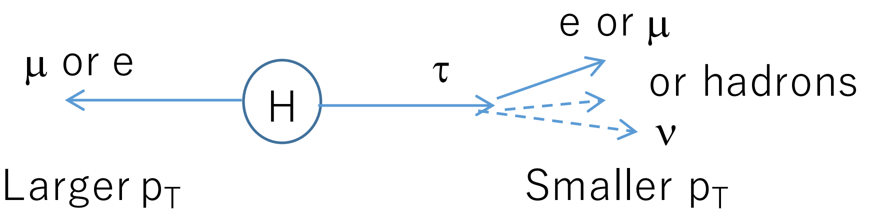
With $3000 fb^{-1}$, reach Br(H→inv.) ~2.8%.

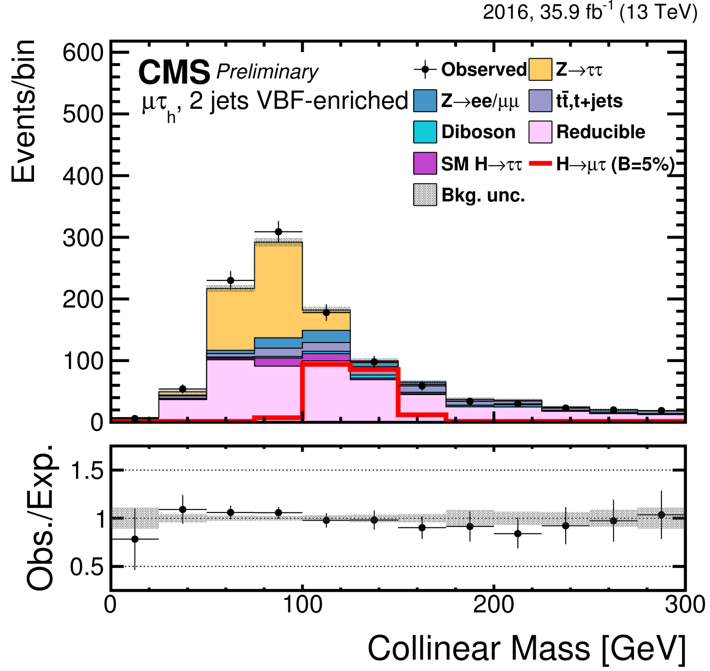
Search for lepton flavor violating decay

H → μτ , eτ search: [CMS-PAS-HIG-17-001](CMS-PAS-HIG-17-001) NEW

Strong constraint Br(H→eμ)~2x10^{-8} from μ→eγ or μ→3e experiments.

But tau decay mode is rather weakly constraint.





Analysis:

- Reconstruct a mass with collinear mass approximation.
- Dominant systematics is jet uncertainty ~10-20%.
- Limits are obtained on the Br(H→μτ) and Br(H→eτ).
- With Br limit, constrain to Yukawa coupling through

$$\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{m_\mathrm{H}}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right)$$