

CosPA 2016



Sydney, Australia
Nov 30, 2016

Invisible Higgs decays, SUSY searches and BSM Higgs at the LHC

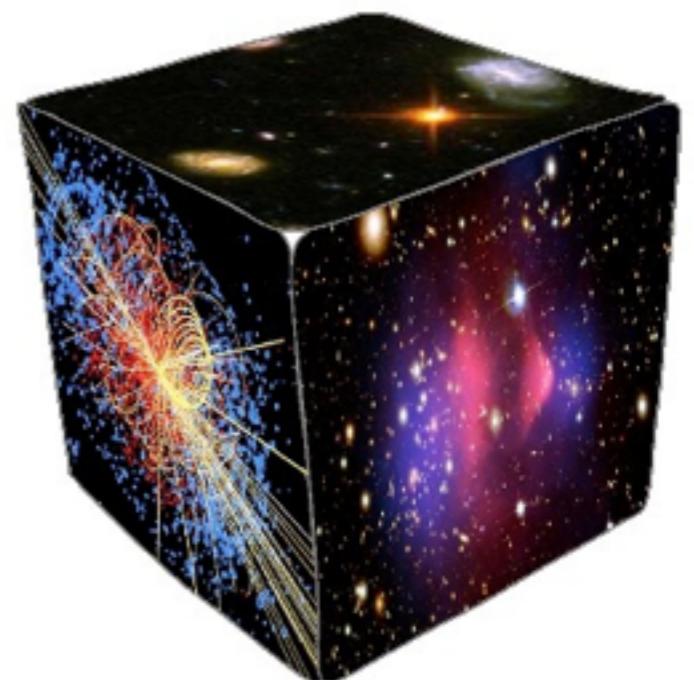
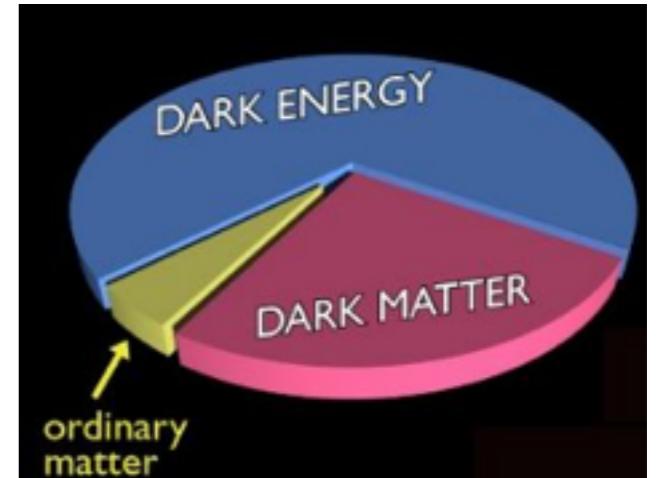
Chia Ming, Kuo
National Central University, Taiwan



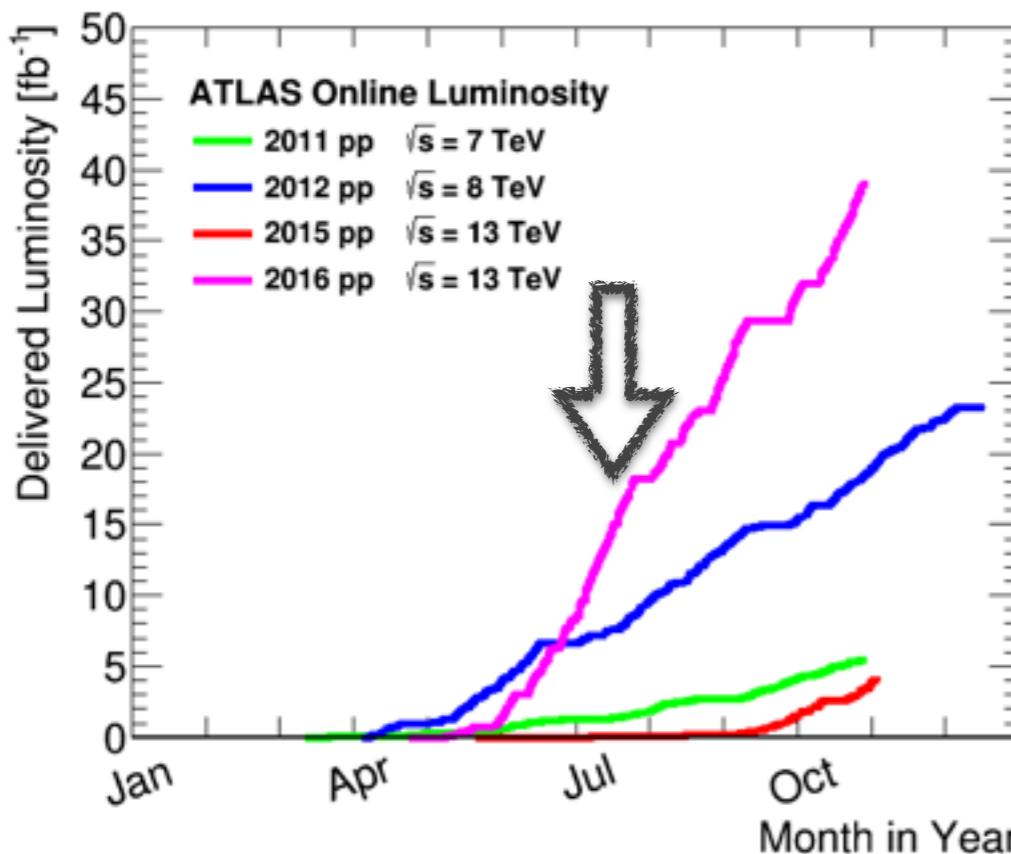
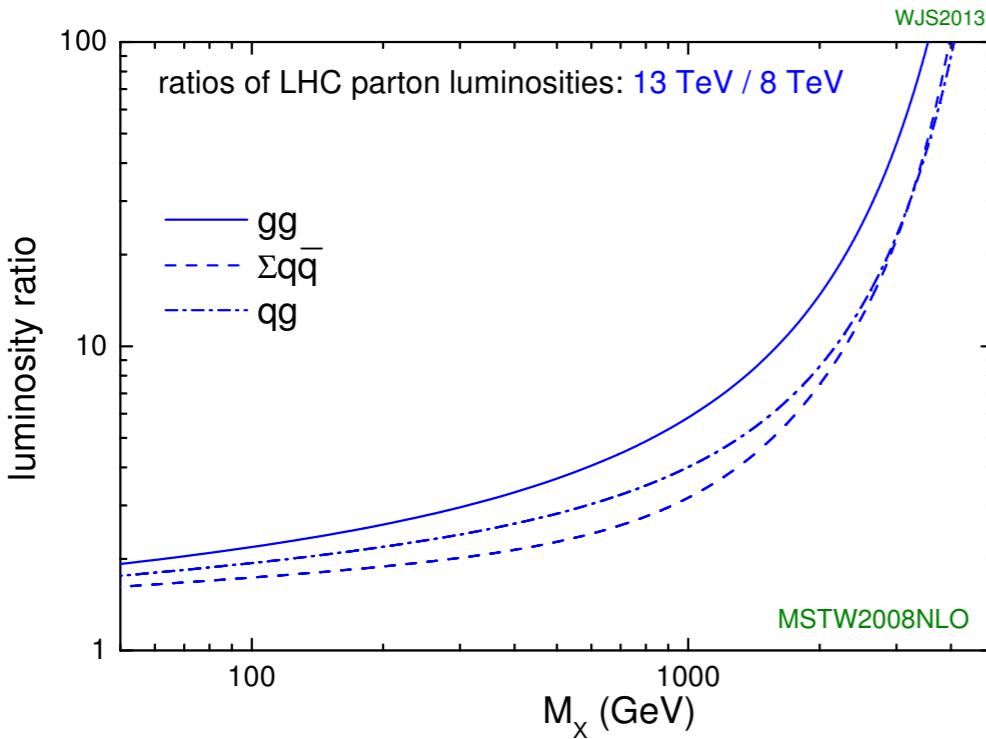
DM and LHC



- There is strong evidence for the existence of DM
- DM outnumbers visible matter : 27% vs 5%
 - detect through gravitational effects
- DM : one of important unsolved problems of the Universe
- one of the important physics programs after the discovery of the Higgs boson at the LHC
- At the LHC, we try to create it ourselves !
- Complementary to other DM experiments
- The searches of DM at the LHC can be more sensitive in some cases
 - if DM is light or if interactions are spin-dependent



LHC and DM signatures



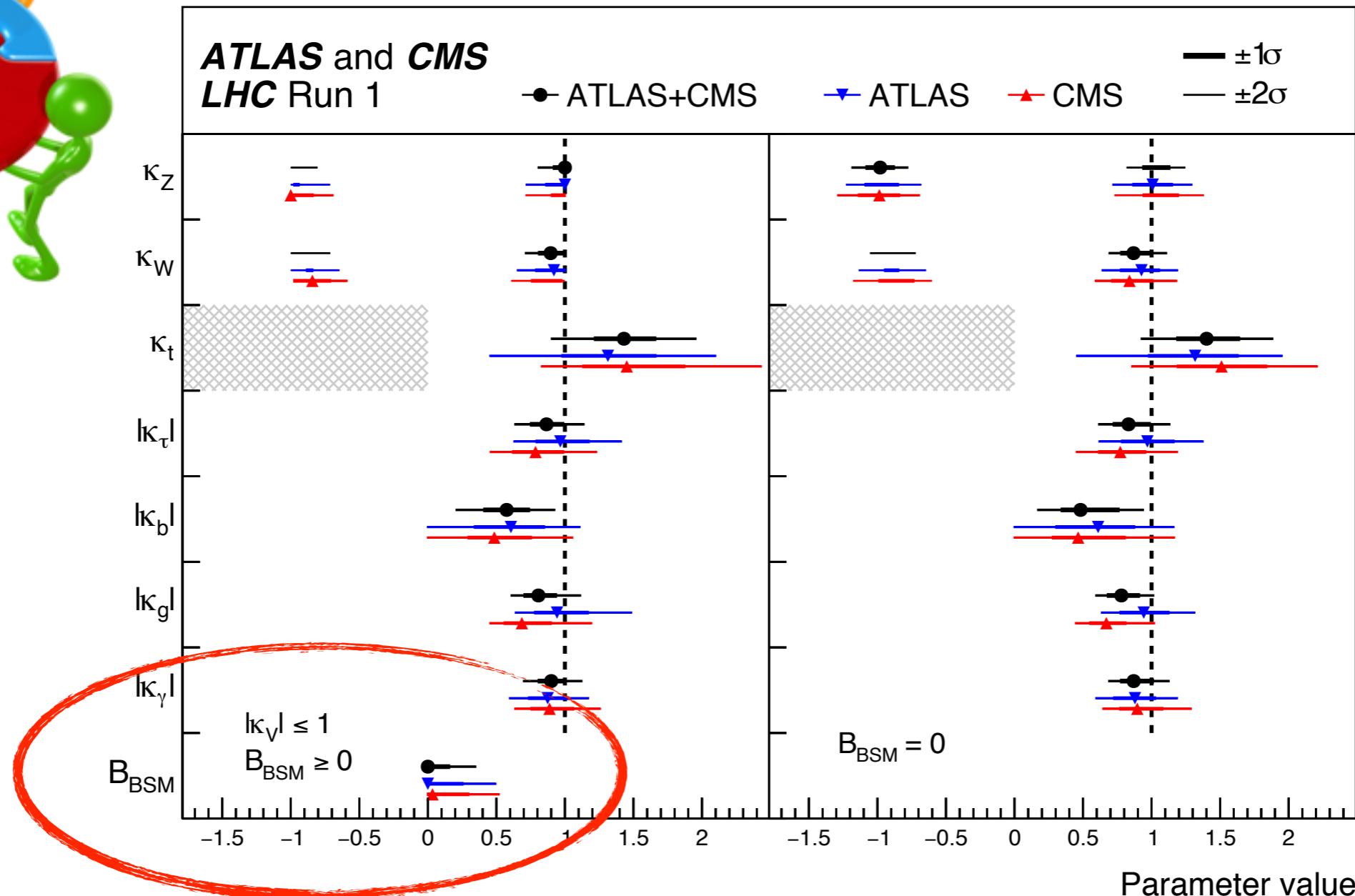
- DM signatures :
 - mono-X
 - mono-Z, mono-H, mono- γ ,
 - dijet
 - long-lived particles
 - invisible Higgs decays
 - SUSY
 - BSM Higgs
- higher \sqrt{s} gives better sensitivity to BSM physics in the high mass region

See the talk by
Millie McDonald

Higgs couplings : currently allowed BSM BR



ATLAS + CMS : JHEP 06 (2016) 045
 5/fb @ 7 TeV + 20/fb @ 8 TeV

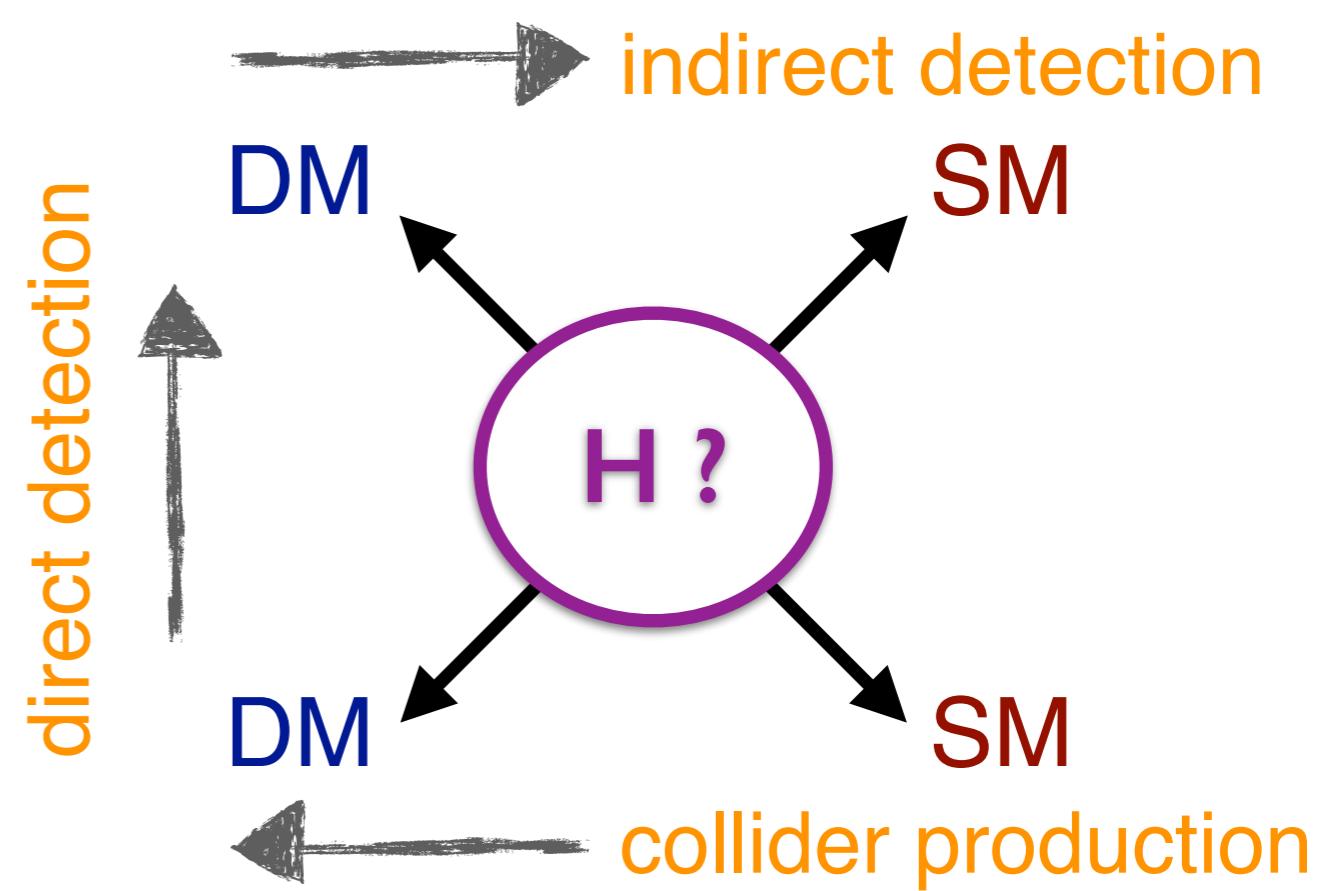
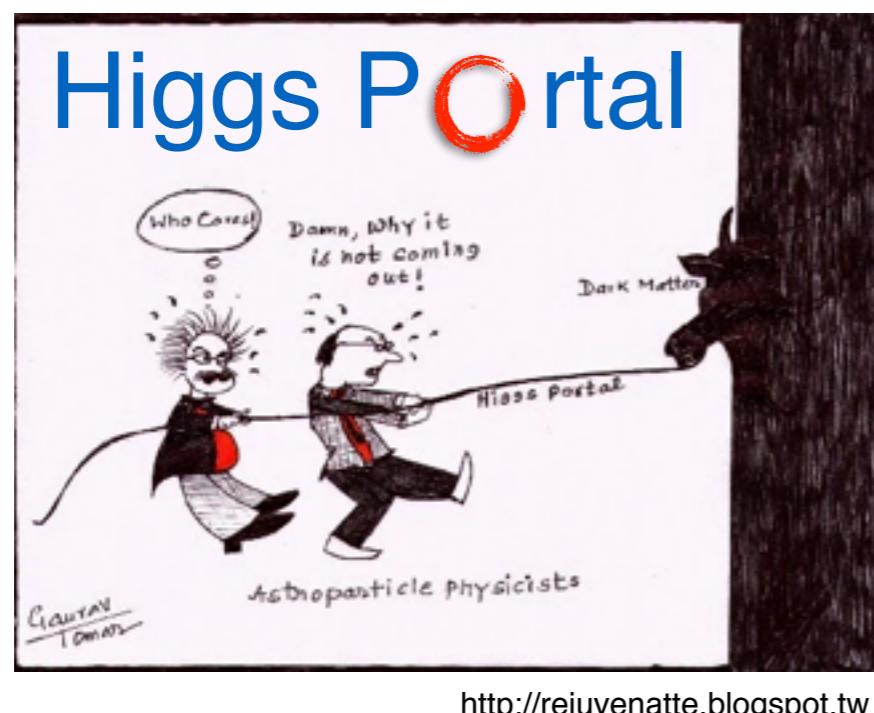


potential invisible or undetectable $B_{BSM} < 34\%$ (39% exp.) @ 95% C.L.
 → still allow ample space to look for BSM Higgs decays

Invisible Higgs decay



- a number of BSM models allow for this
 - decays to neutralinos in SUSY
 - graviscalars in models with extra spatial dimensions
 - interactions between the Higgs and DM
 - complementary to direct detection
 - DM mass $< m_H/2$

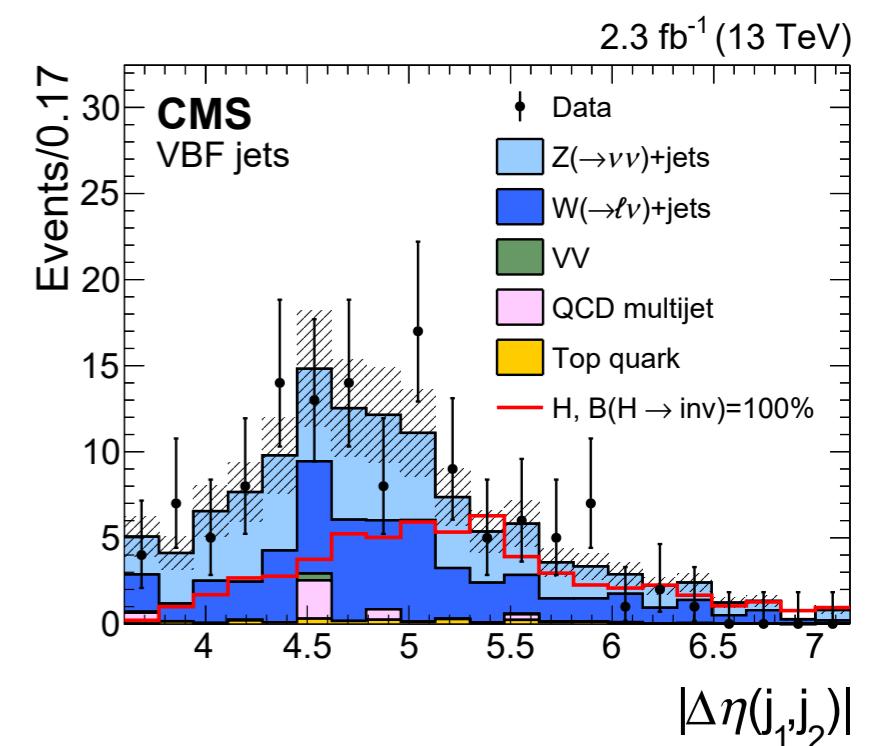
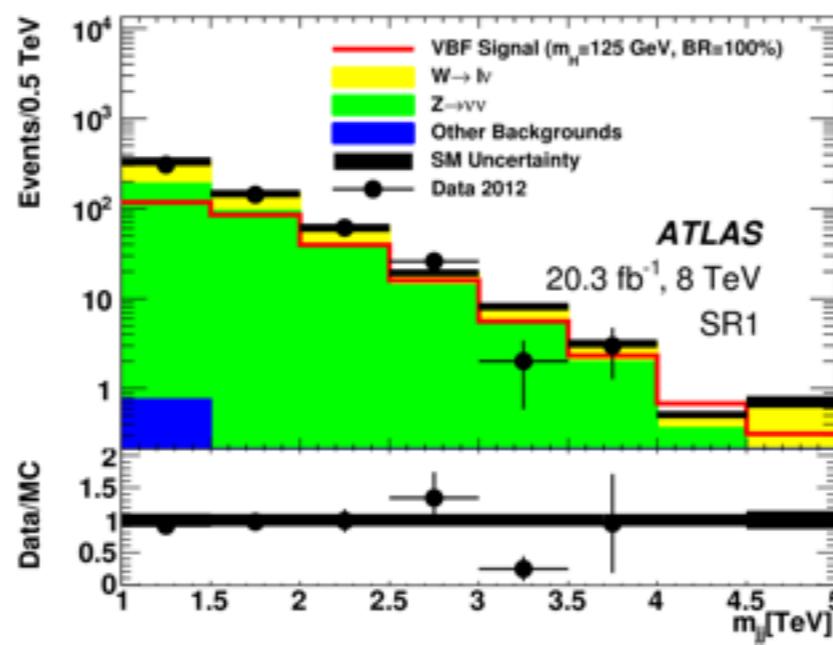
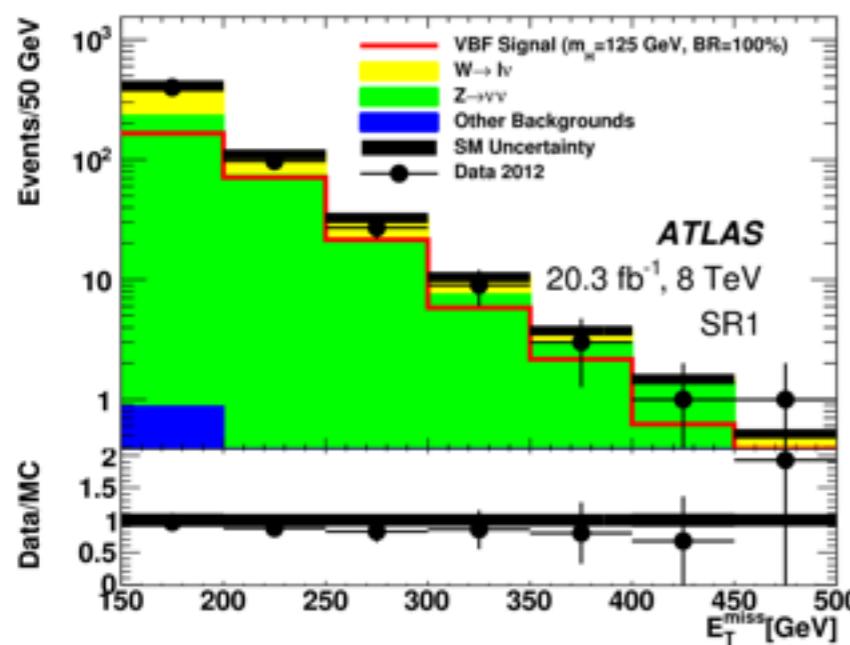
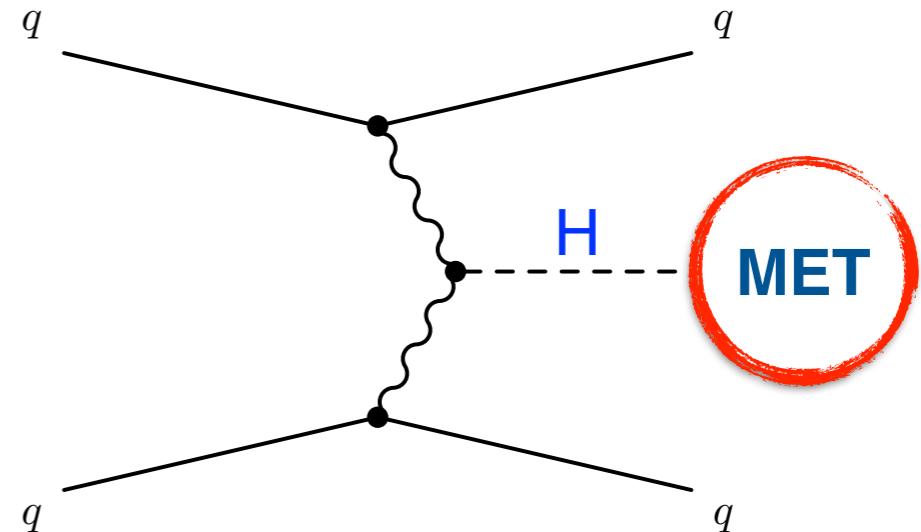


qqH

ATLAS JHEP 01 (2016) 172
CMS HIG-16-016



- most sensitive mode
- VBF topology
- reject extra leptons

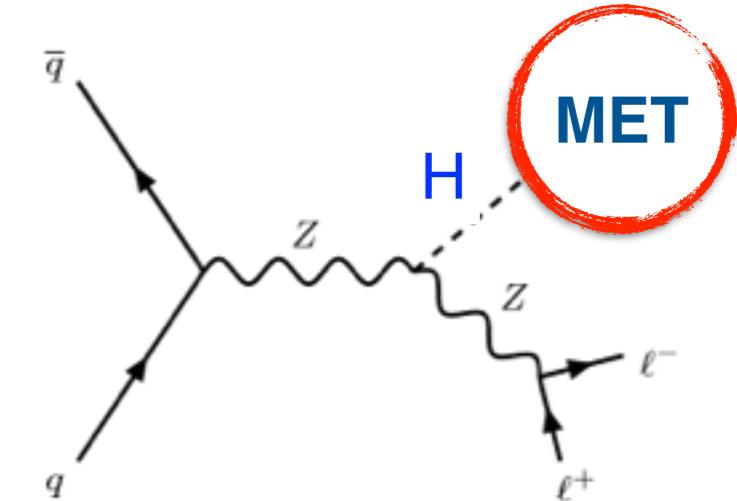
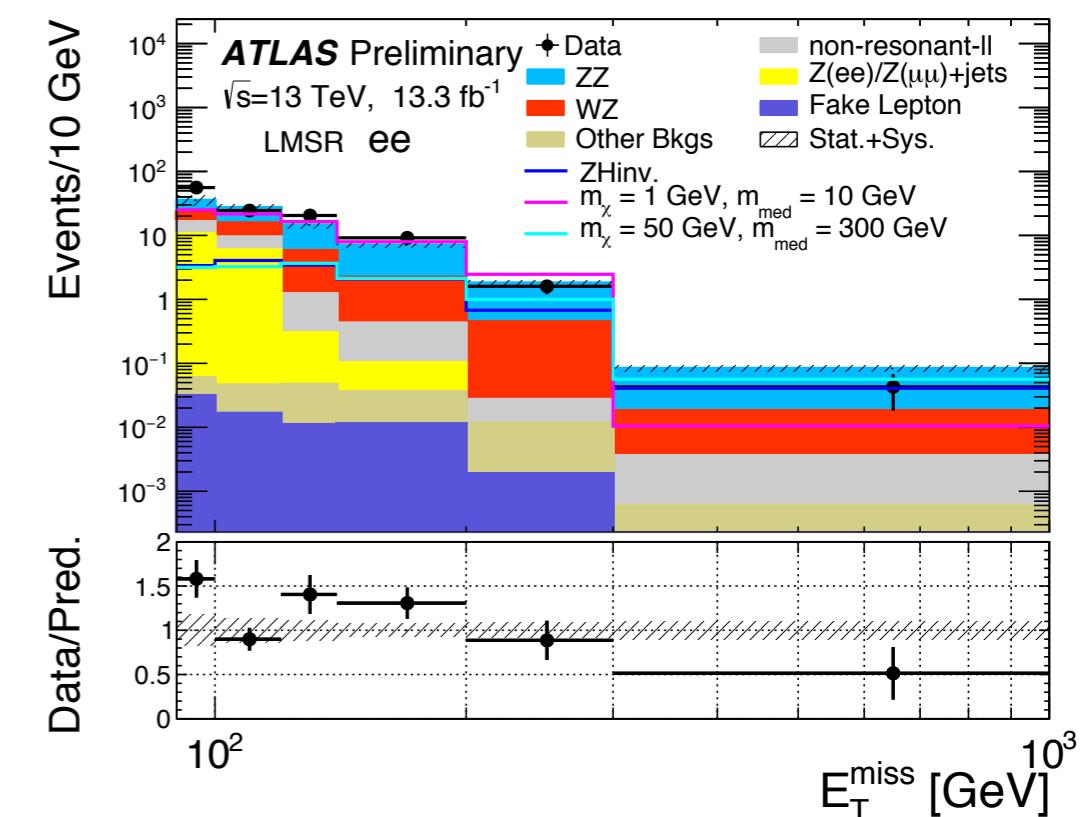
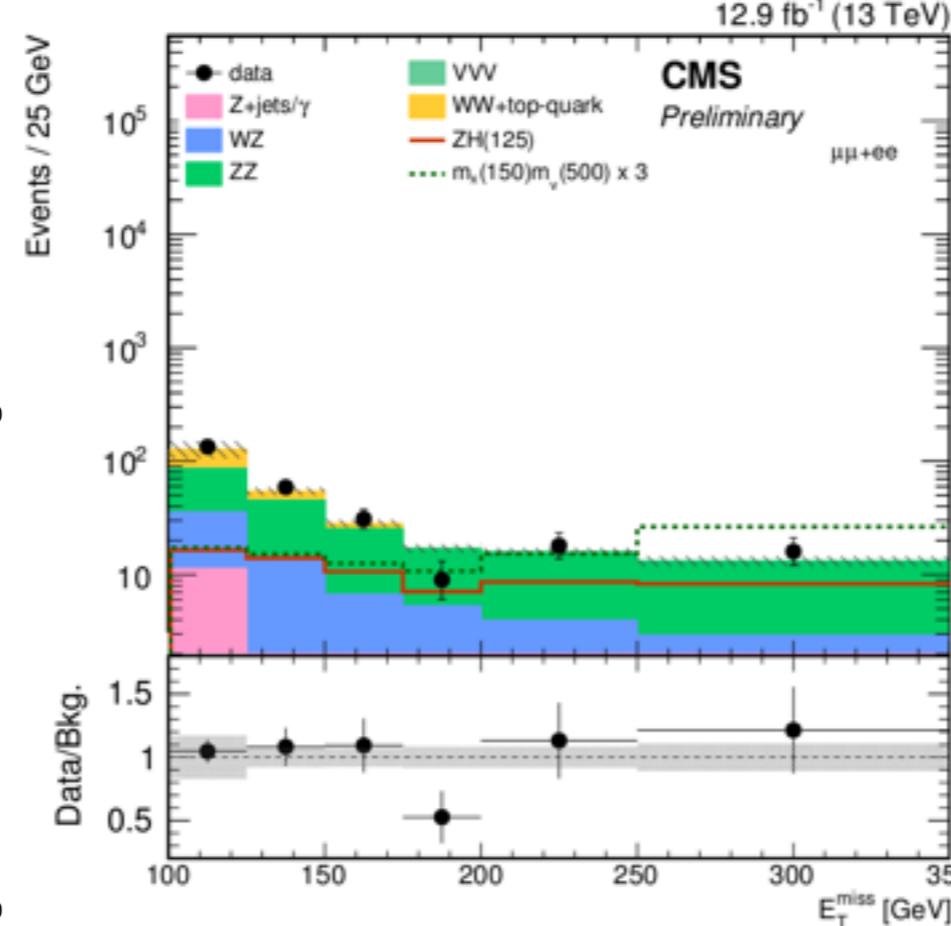
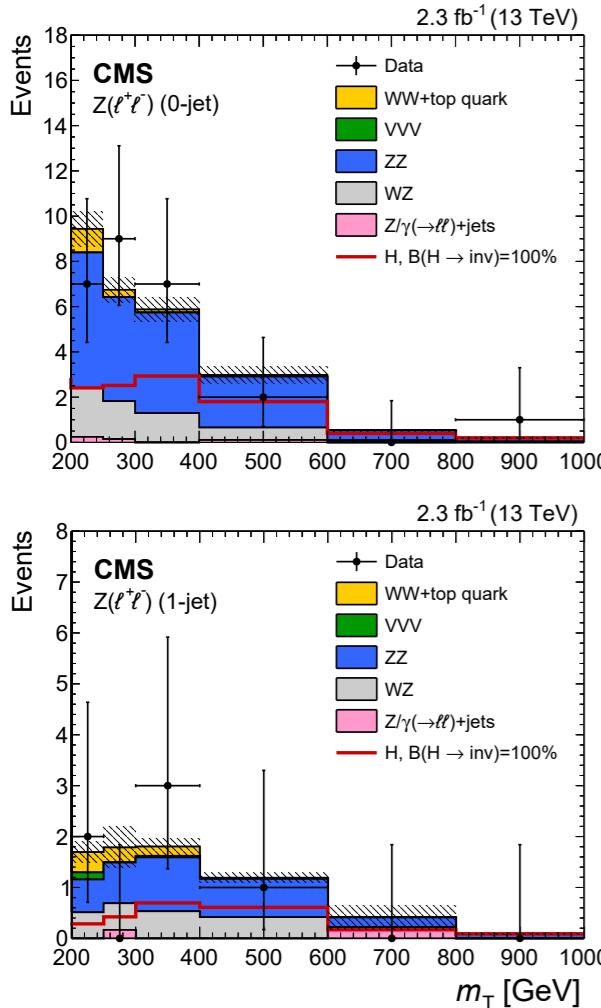


Z($\rightarrow ll$)H

ATLAS PRL 112 (2014) 201802
 ATLAS CONF-2016-056
 CMS HIG-16-016
 CMS EXO-16-038



- smaller cross section than VBF
- clean final state with low background
- select good Z bosons back-to-back with MET



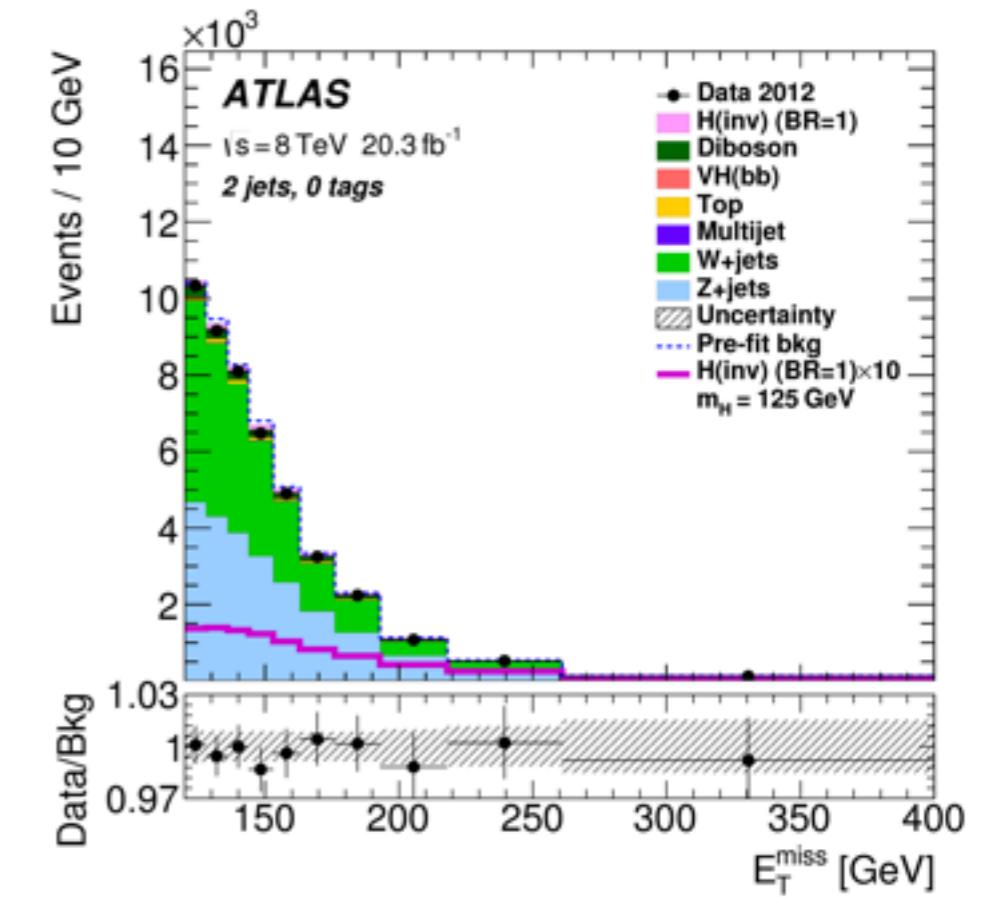
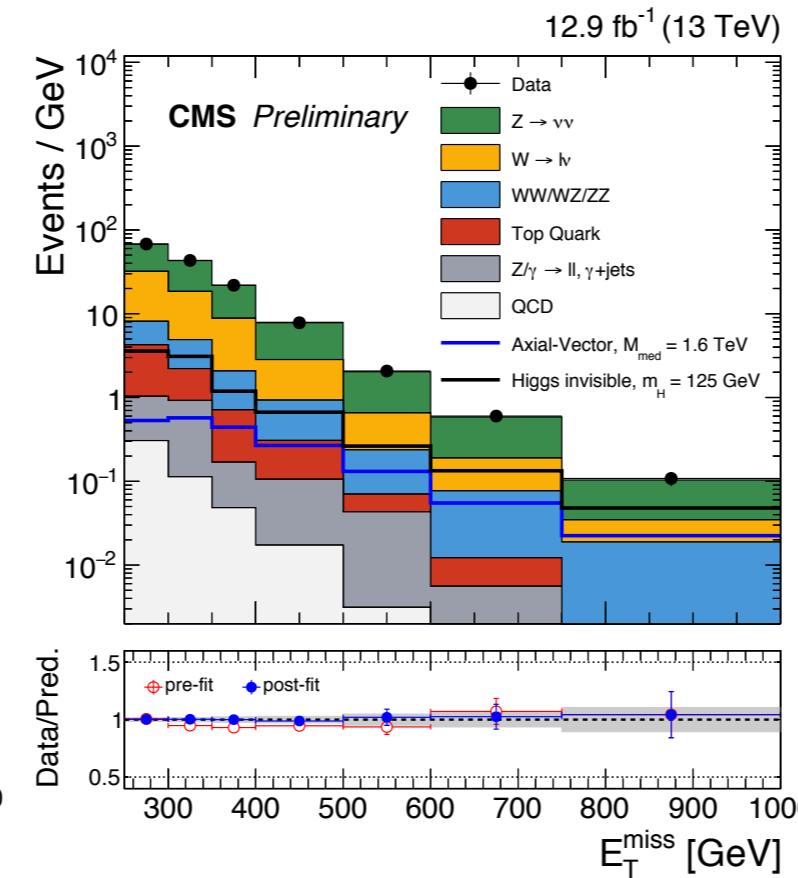
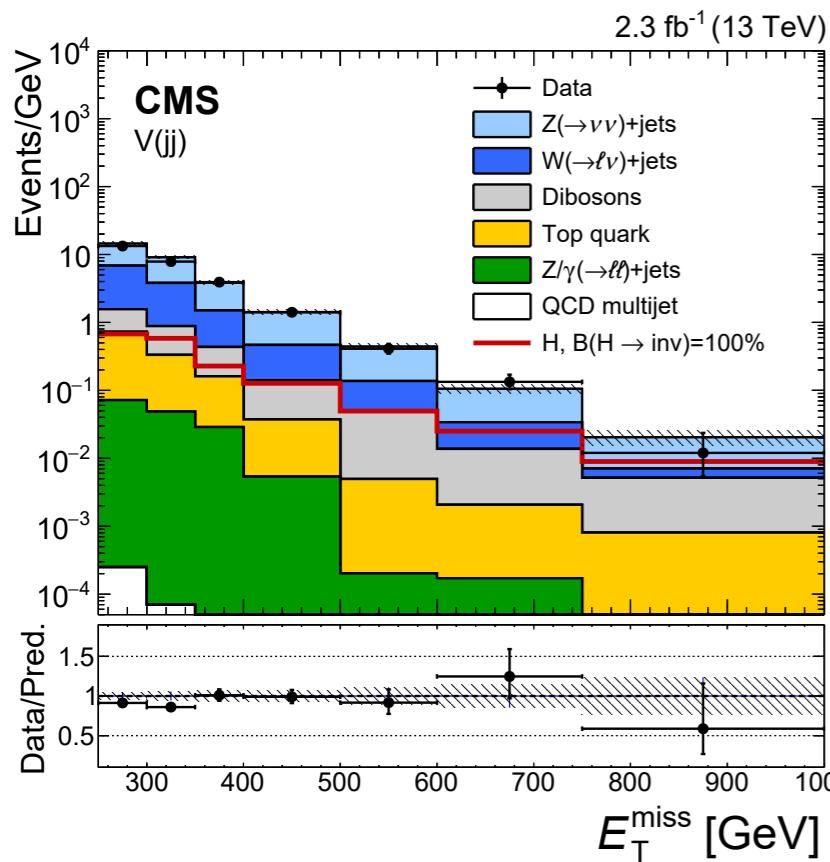
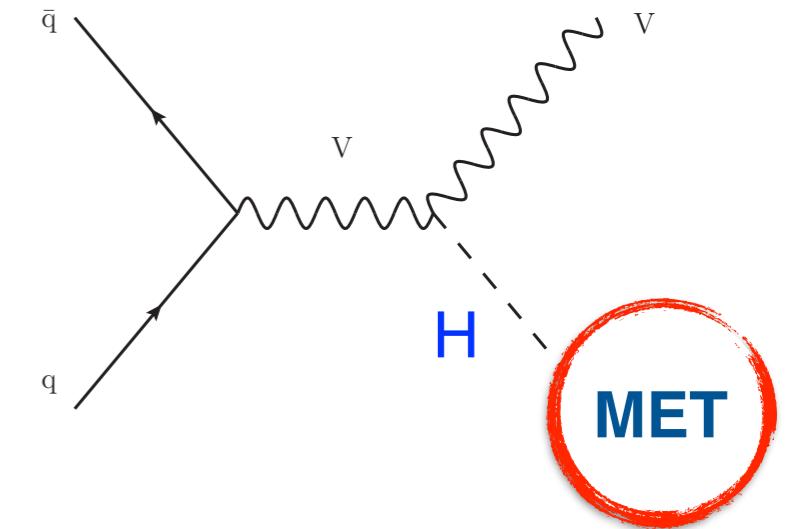
$$m_T = \sqrt{2p_T^{\ell\ell}E_T^{\text{miss}} [1 - \cos \Delta\phi(\ell\ell, \vec{p}_T^{\text{miss}})]},$$

$V(\rightarrow qq)H$

ATLAS EPJC (2015) 75:337
 CMS arXiv:1610.09218
 CMS EXO-16-037

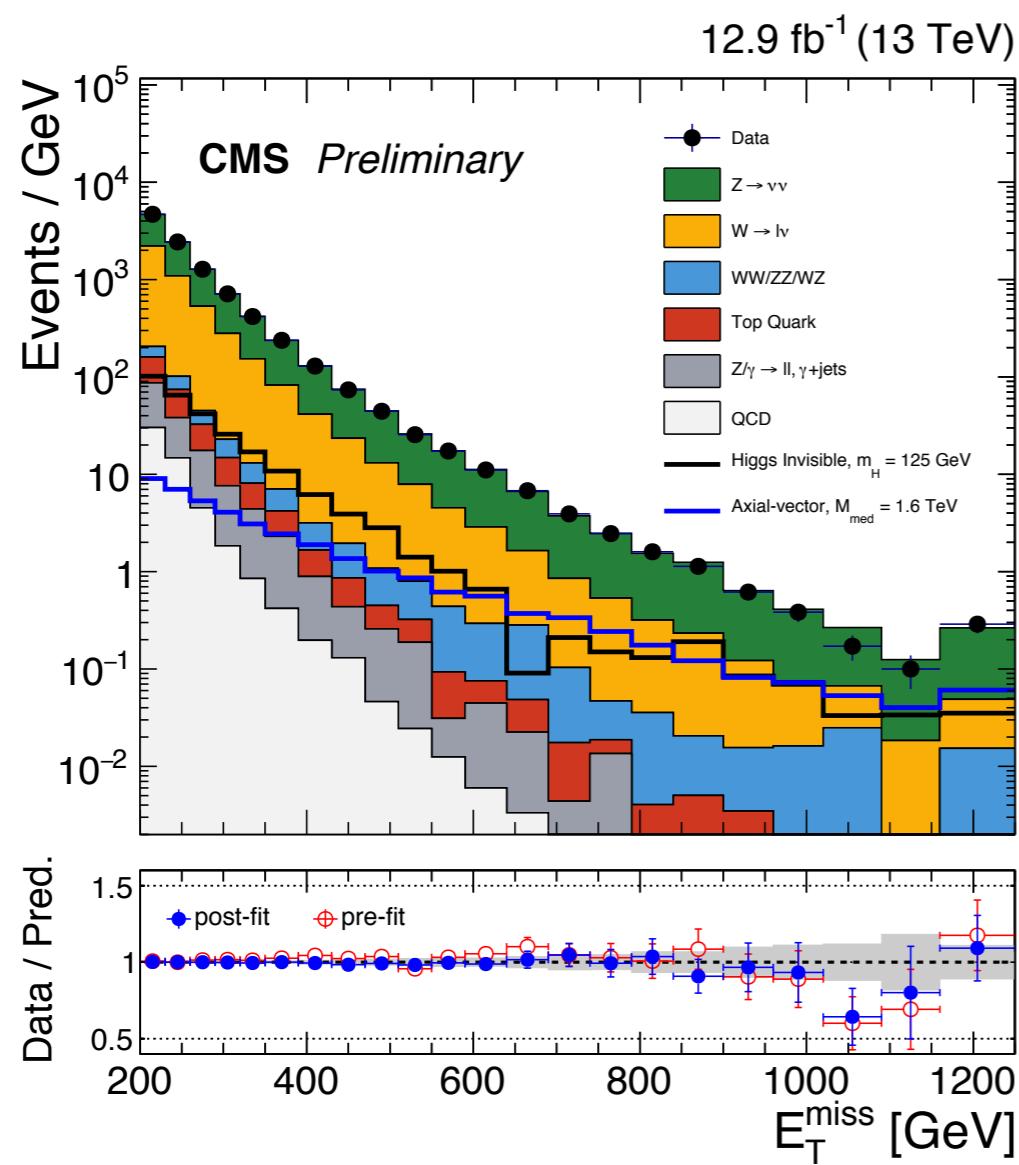


- large background but relatively larger signal contribution
- ATLAS : 2 & 3 jets & b-tags (leading $p_T > 45$ GeV)
- CMS : large radius jet ($R = 0.8$), $p_T > 200/250$ GeV for 8/13 TeV
 - rely on jet substructure techniques

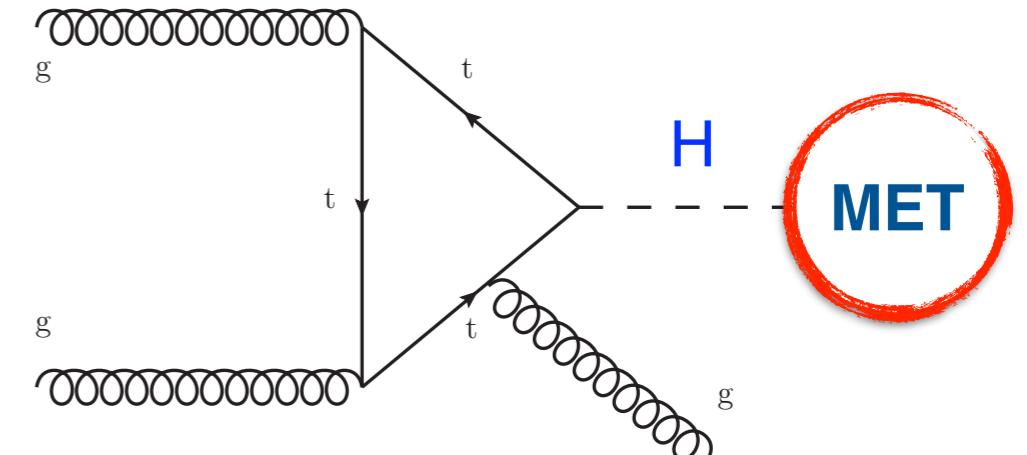


Monojet + H

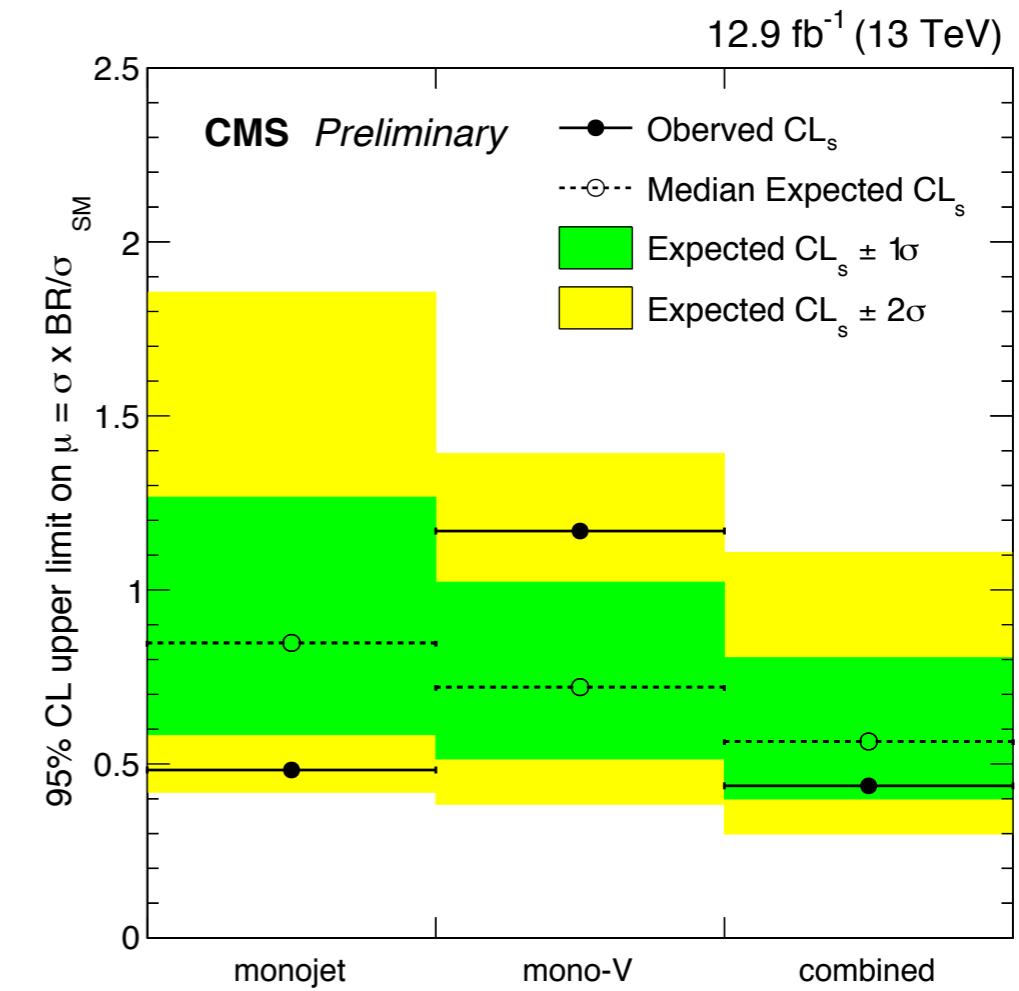
- events failing V(jj)-tagging but satisfying jet $p_T > 150/100$ GeV ($R = 0.5/0.4$) for 8/13 TeV are included
- large background
- improve V(jj)H sensitivity by $\sim 15\%$ after adding this mode



CMS arXiv:1610.09218
CMS EXO-16-037



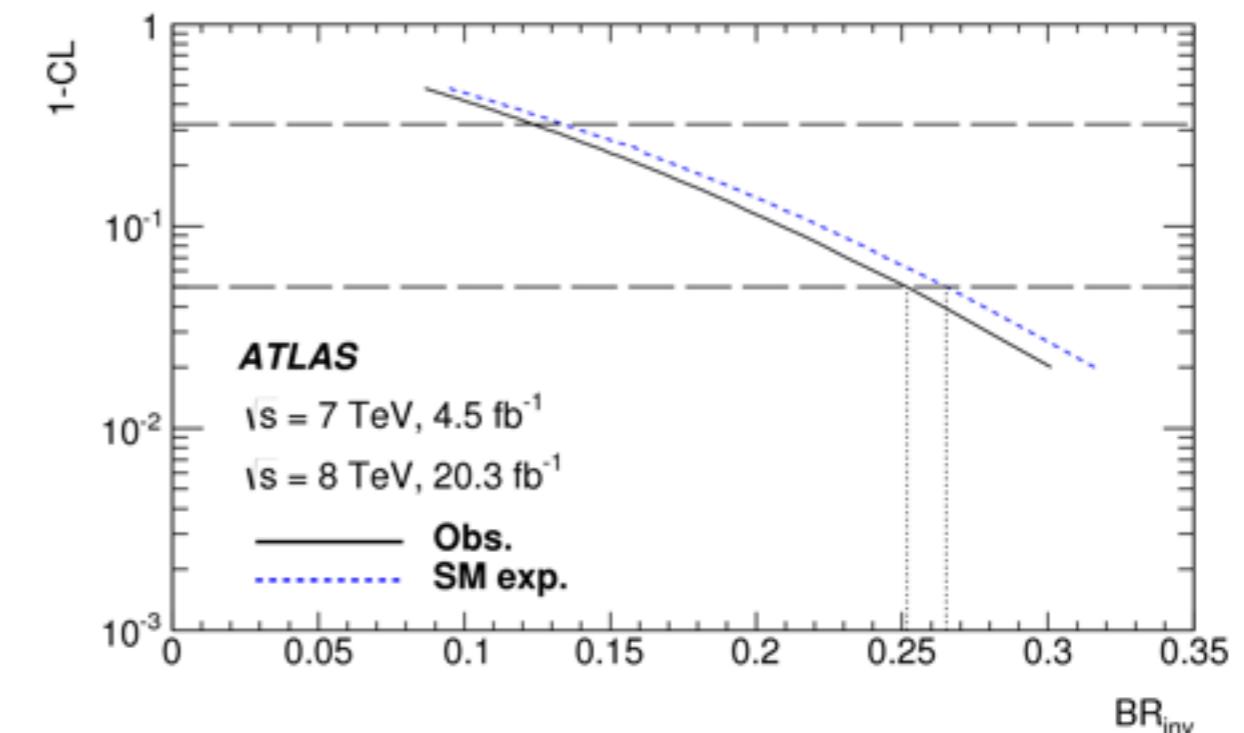
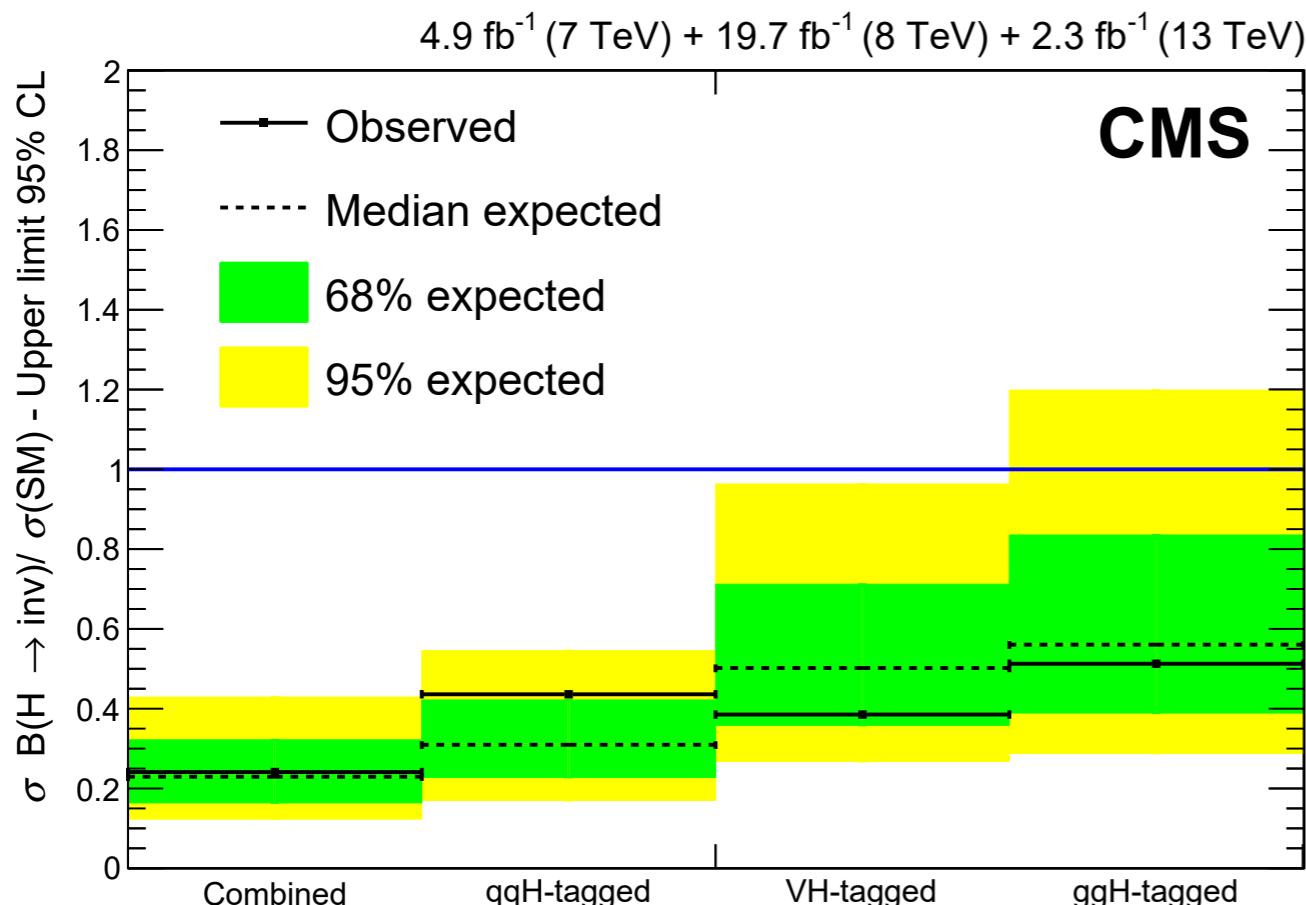
Combination of V(qq)H and gH



Combined $H \rightarrow$ invisible limits



- No significant deviations from SM expectation are observed in any search mode
- ATLAS : Run-1 dataset
- CMS : Run-1 + 2015 dataset



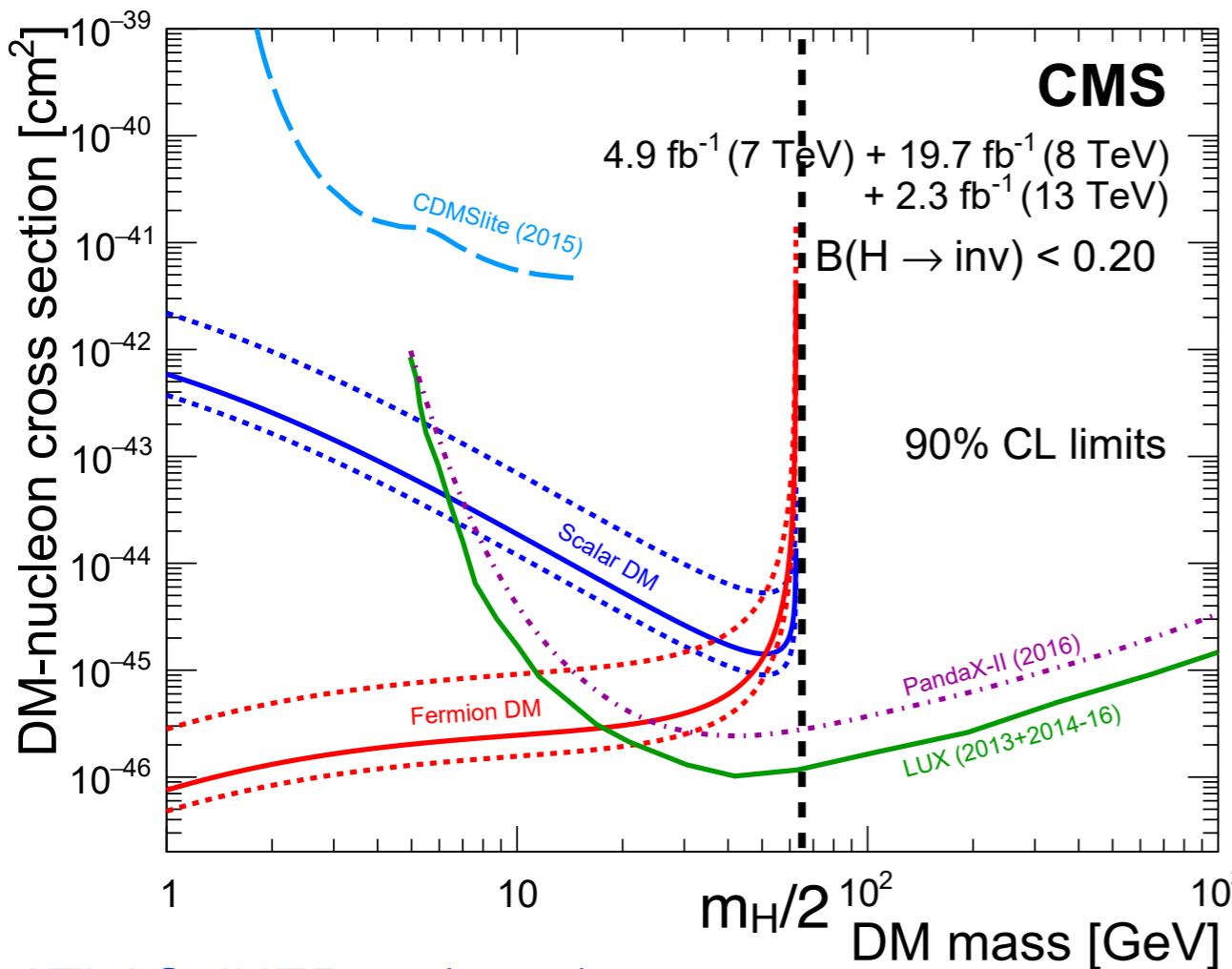
- Direct search increases the sensitivity beyond indirect constraints

| | ATLAS | VBF H | Z(II)H | V(qq)H | Combined |
|------|-------|-------------|-------------|-------------|-------------|
| Exp. | | 0.31 | 0.62 | 0.86 | 0.27 |
| Obs. | | 0.28 | 0.75 | 0.78 | 0.25 |

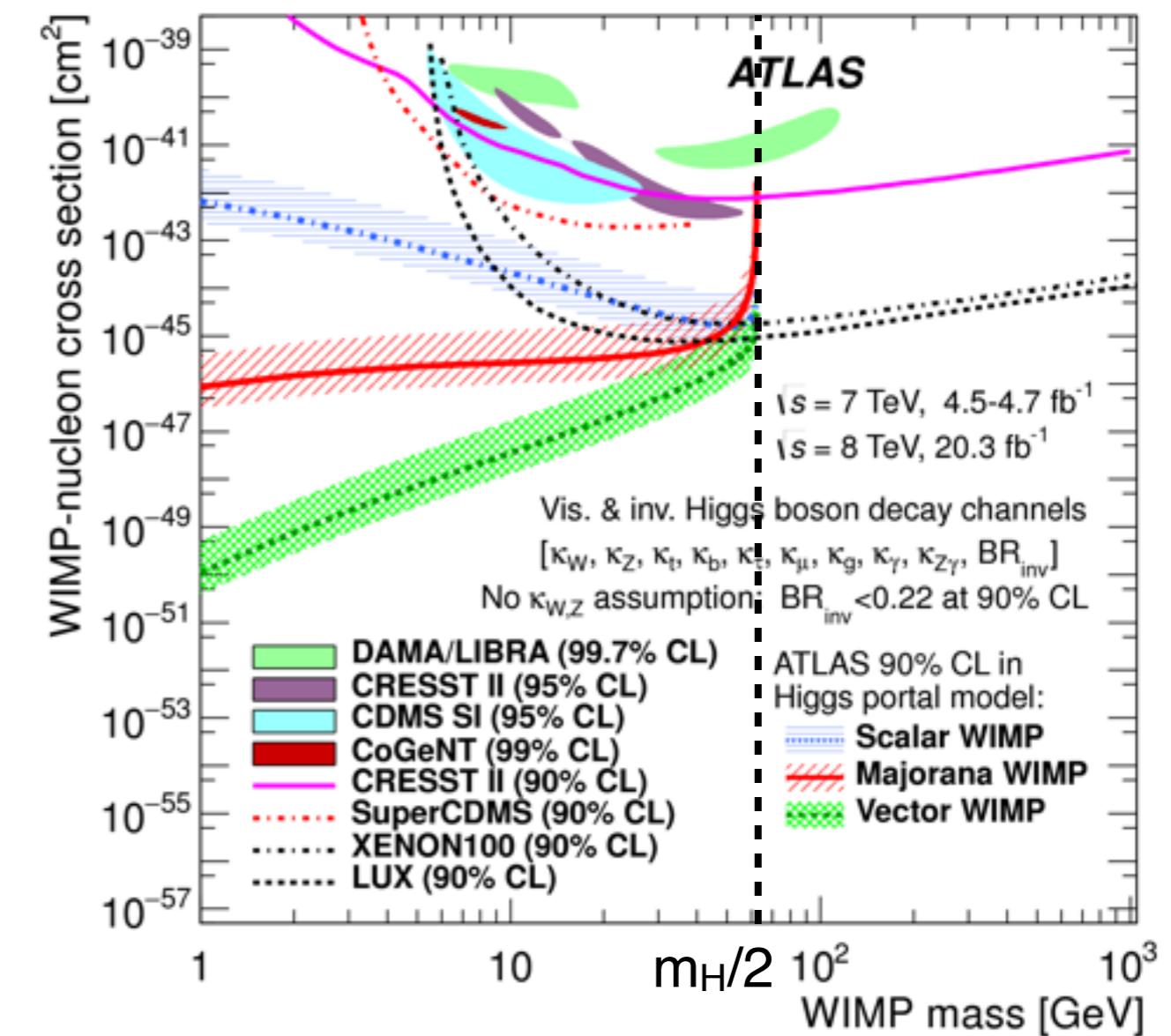
Comparison to direct DM detection



- Direct detection : sensitive to elastic interactions between DM and nuclei via H
 - nuclear recoil signatures → interpreted in terms of DM-nucleon interaction cross section
- the invisible Higgs decay width is translated into the spin-independent DM-nucleon elastic cross section if DM mass $< m_H/2$
- LHC results : complementary phase space



ATLAS JHEP 11 (2015) 206
CMS HIG-16-016

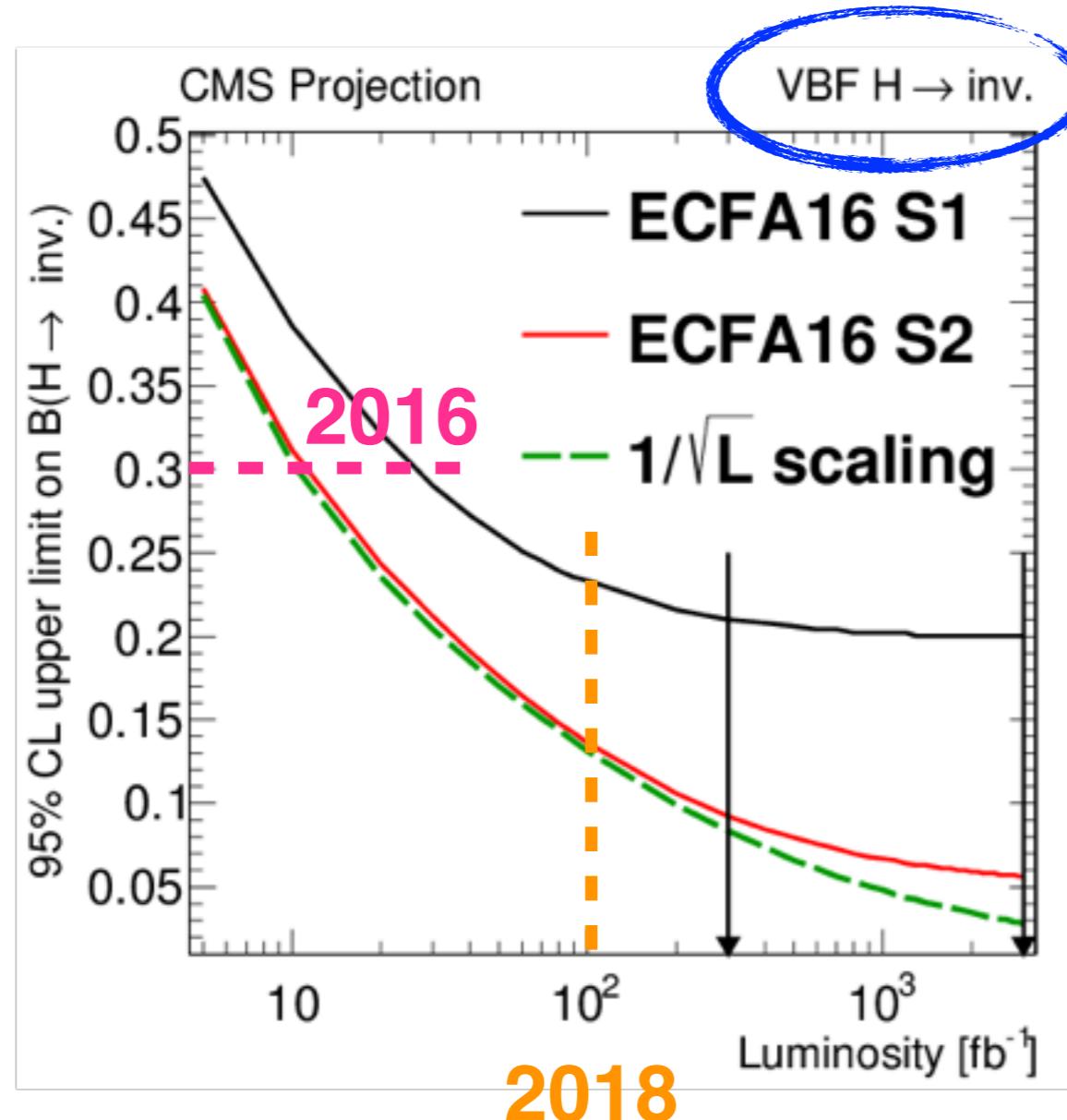


Outlook of $H \rightarrow \text{invisible}$

CMS DP-2016-064



- SM $\text{BR}(H \rightarrow \text{inv.}) = 0.001$



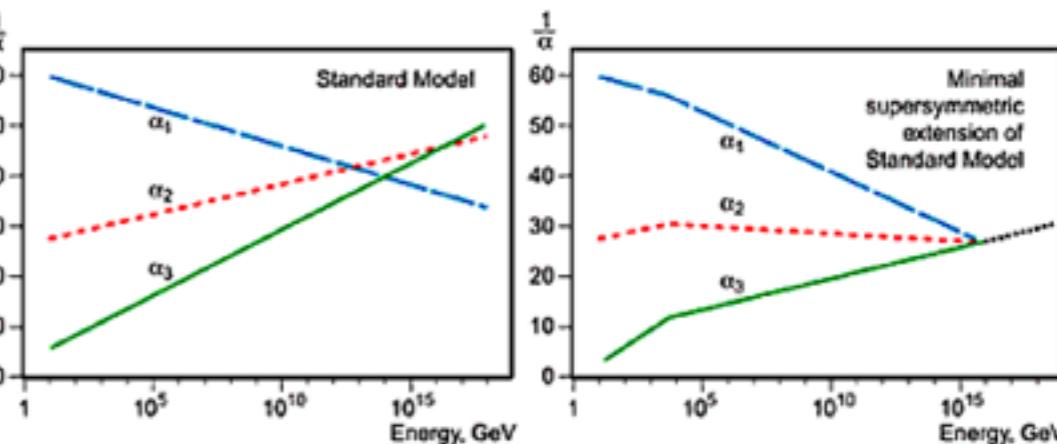
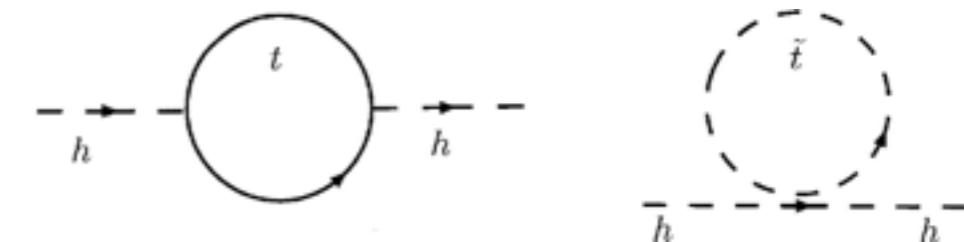
S1 : all systematic uncertainties are fixed to 2015 values

S2 : experimental systematic uncertainties decrease with L and theoretical ones are scaled by 1/2
→ improved by a factor of 2 by the end of 2018 and 5 at HL-LHC

SUSY searches



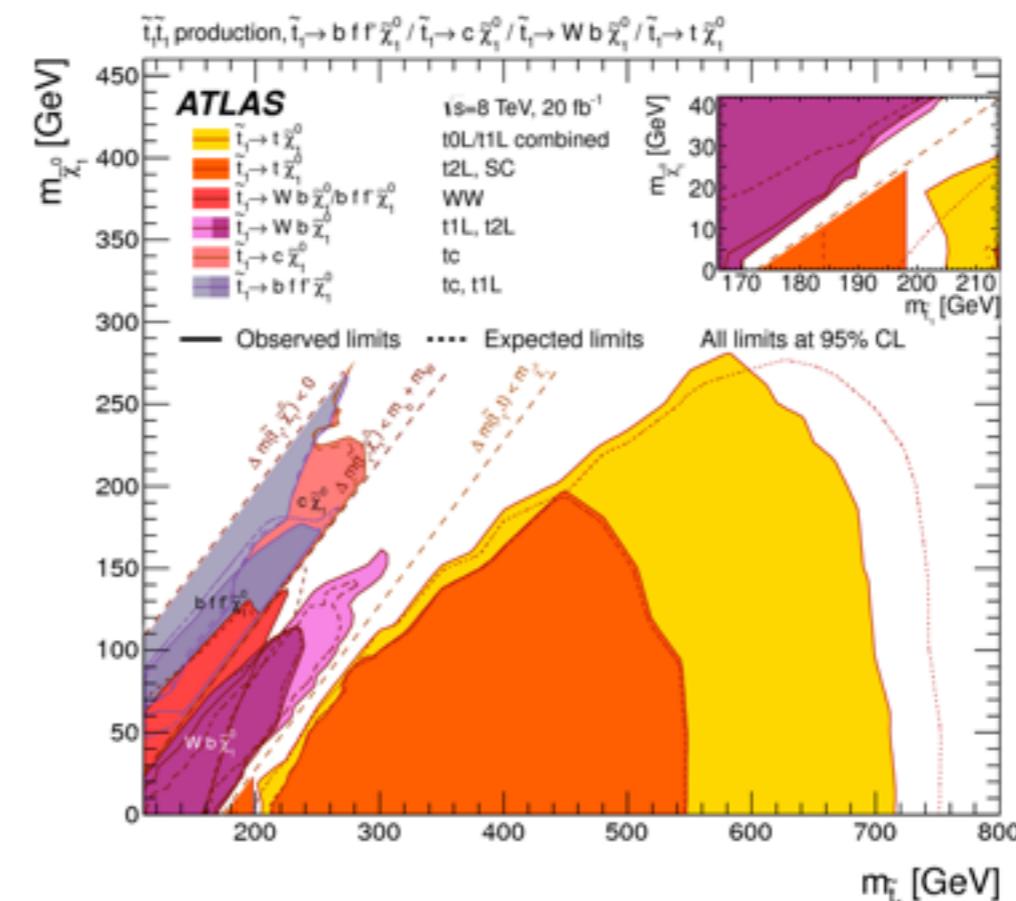
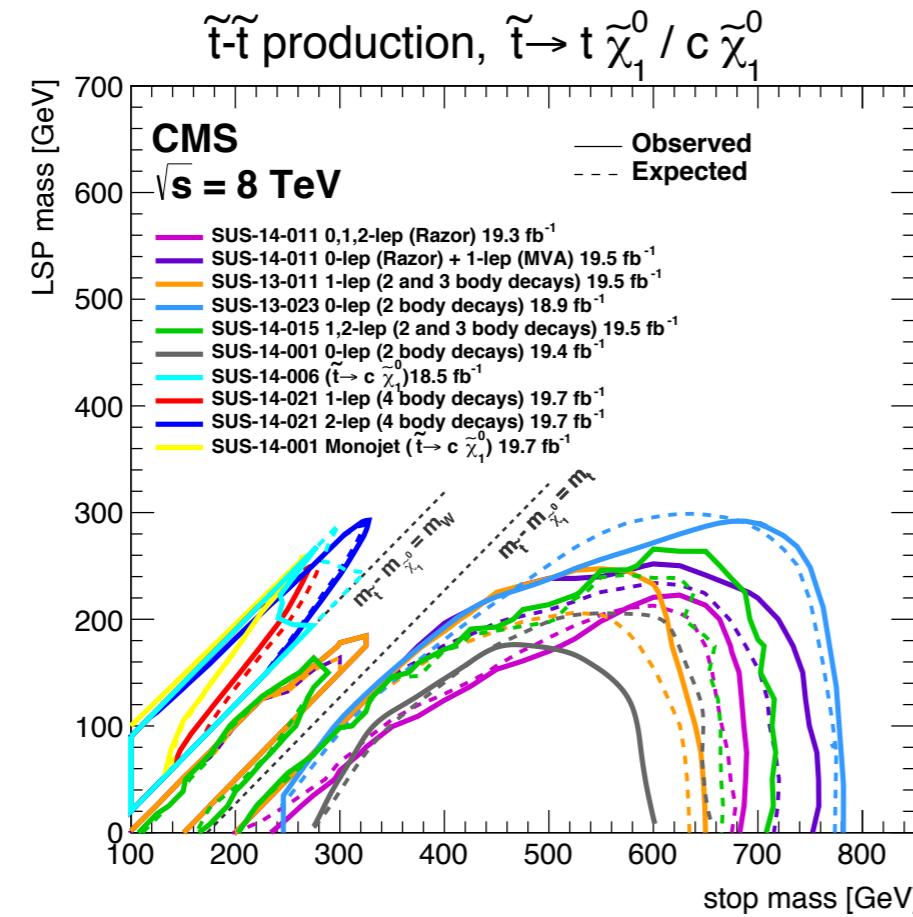
- Solution to the hierarchy problem
- Unification of gauge couplings
- Dark Matter in the Universe
 - LSP : stable, electrically neutral, interact weakly with the SM particles
 - may be an excellent DM candidate
- the known fundamental particles have superparticle partners : quark \rightarrow squark, gluon \rightarrow gluino



Selected Run I SUSY results



- A large number of searches were done with Run-1 data
- No significant signals consistent with SUSY have yet been observed
 - constrain the allowed SUSY model space

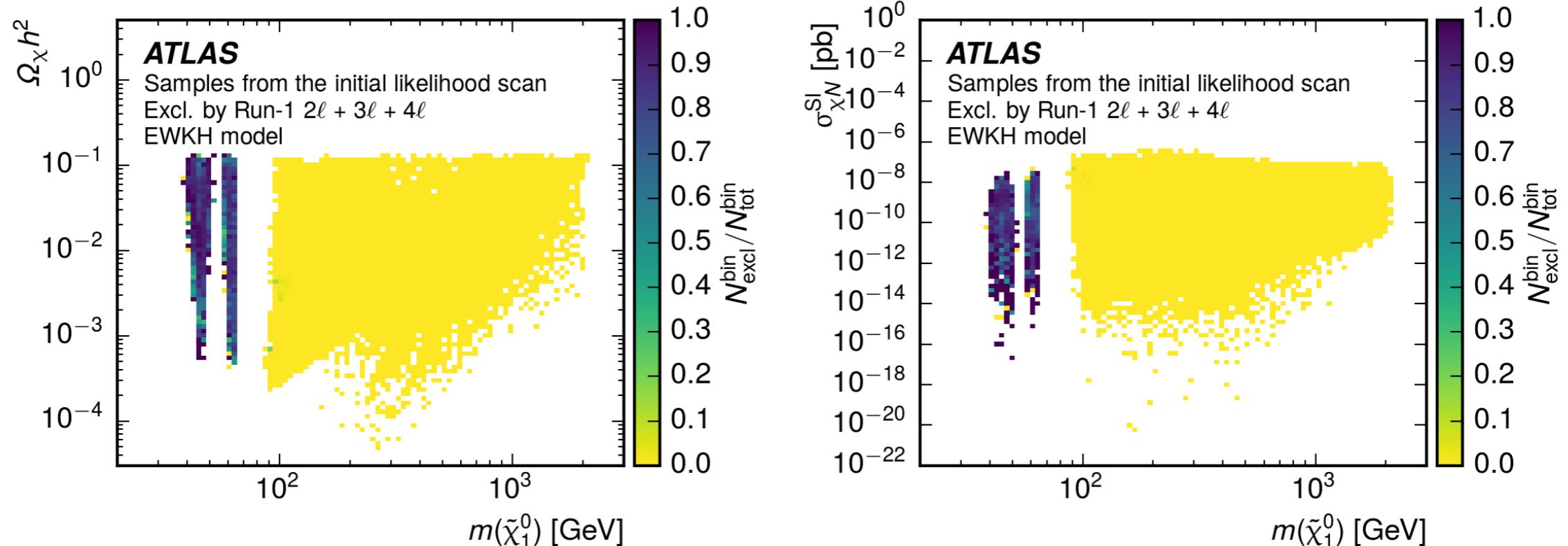


Atlas summary plots : <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/>
 CMS summary plots : <https://twiki.cern.ch/twiki/bin/view/CMSPublic/SUSYSMSSummaryPlots8TeV>

pMSSM interpretations



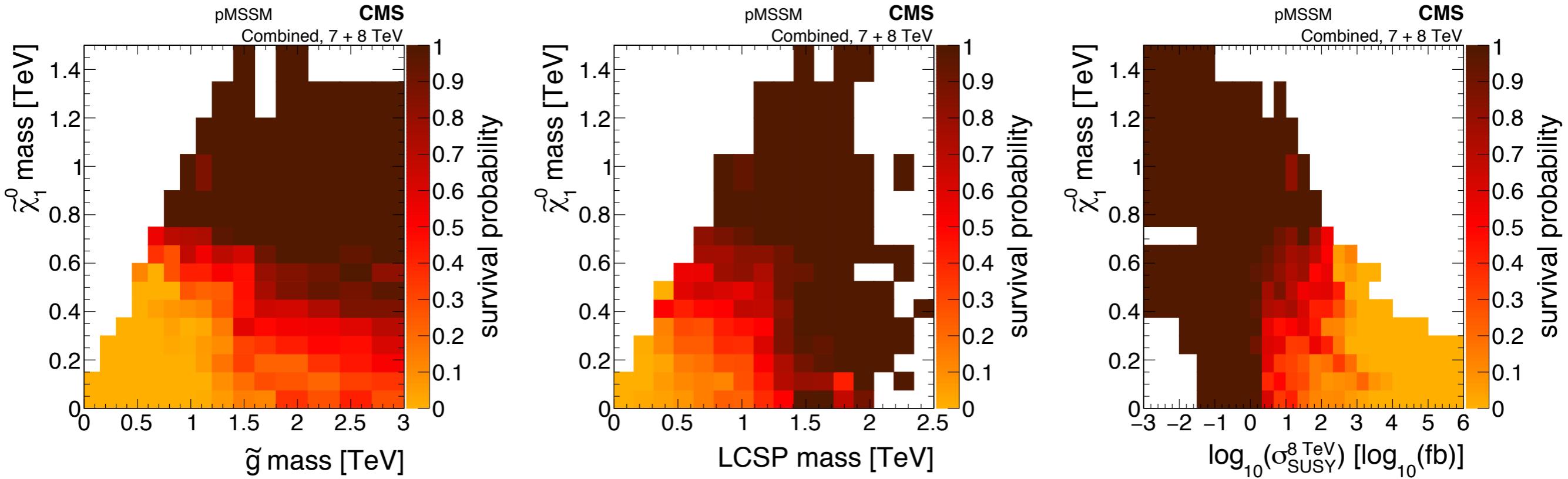
ATLAS JHEP 09 (2016) 175



- more than 20 EWK SUSY results → the impact on the constraints on DM
- interpreted with 19 independent weak-scale parameters (phenomenological MSSM)
 - considered model : EWKH → described by 5 parameters
 - the results can be assessed in a relatively straightforward way
- probe regions of the parameter space that are difficult to reach with direct-detection dark matter experiments

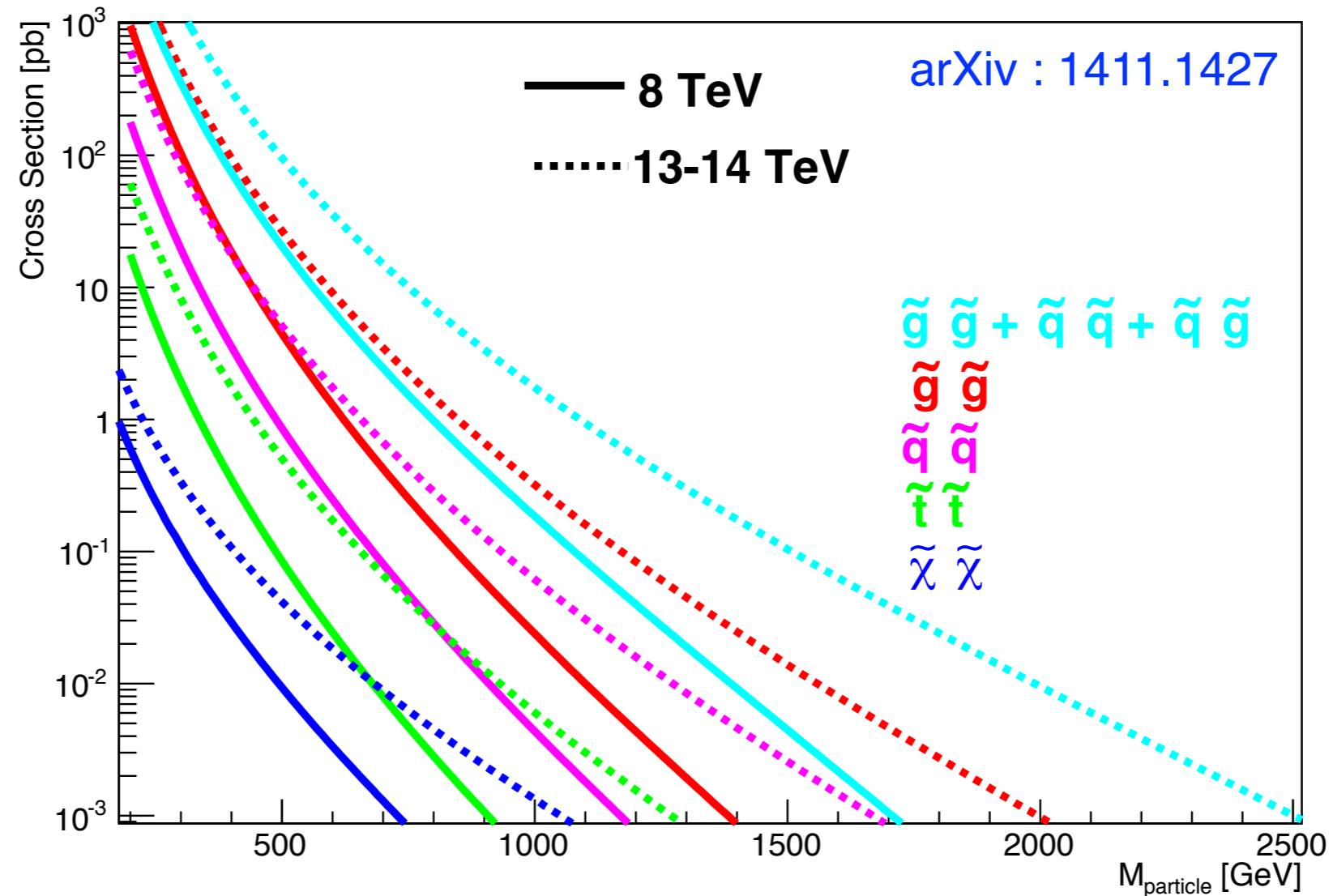
pMSSM interpretations

CMS JHEP 10 (2016) 129



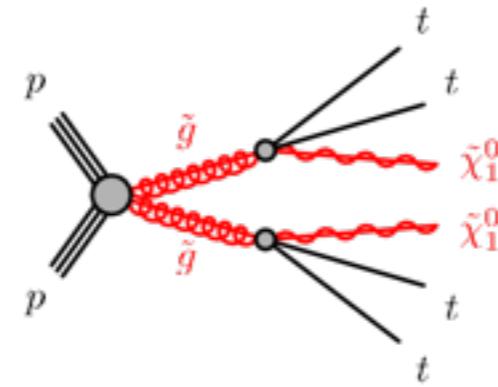
- CMS results from Run-1 started to test the most interesting region with LSP masses below about 400-500 GeV
- Neutralino mass is strongly correlated with the gluino and LCSP mass
- Neutralino mass is correlated most strongly with the cross section
 - a light neutralino is disfavored

SUSY production cross section : 8 vs 13 TeV



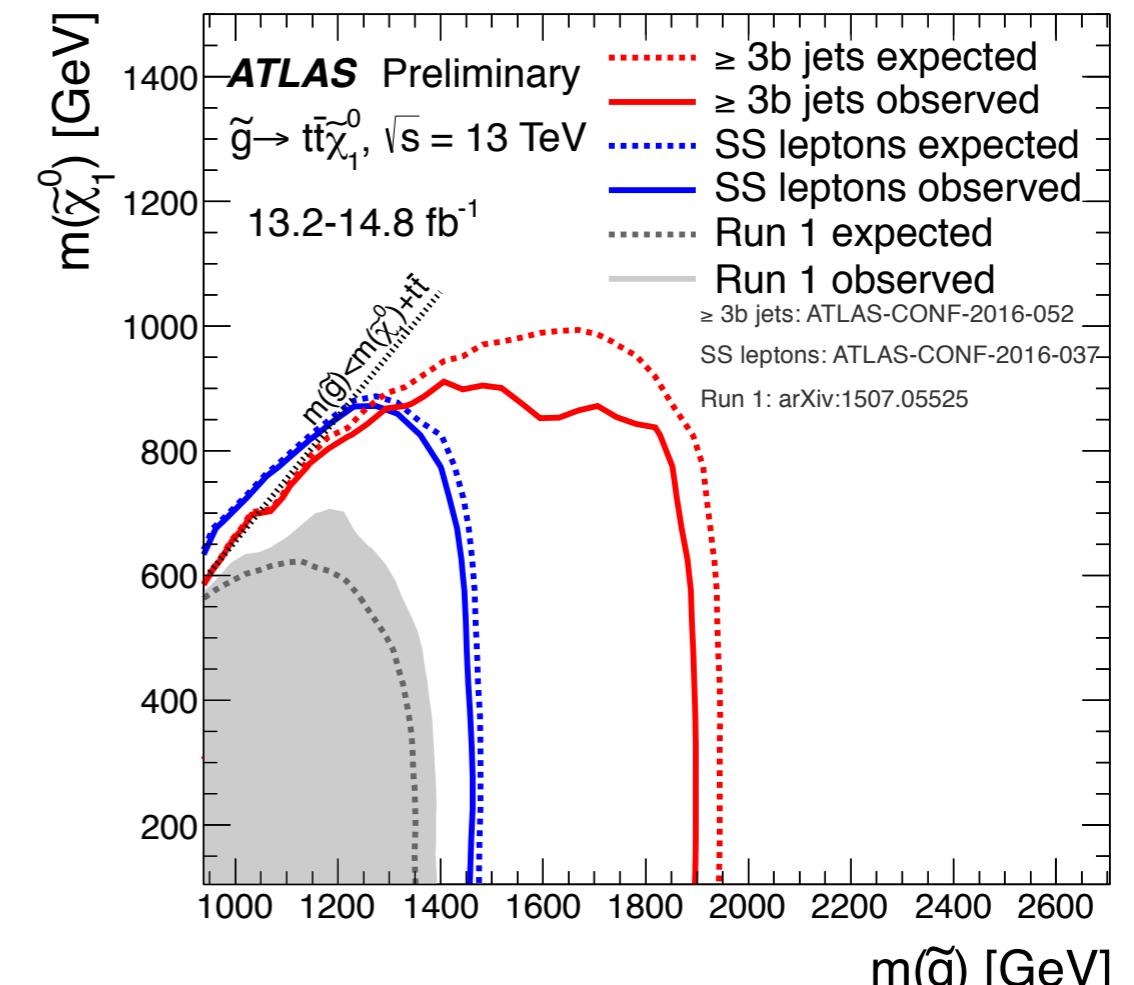
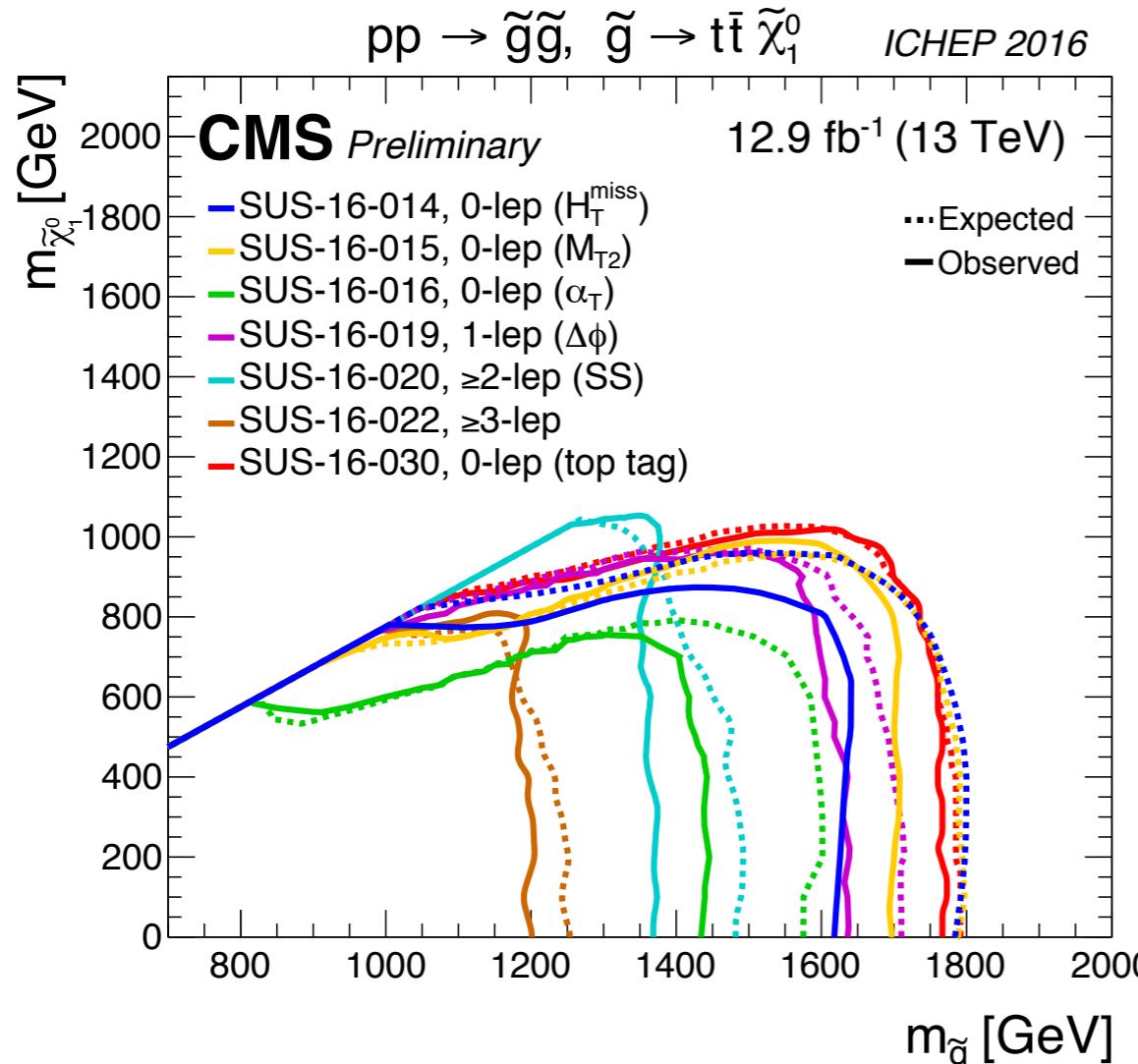
- Cross section ratio (13TeV/8TeV)
 - gluino for mass = 1.4 TeV : ~ 25
 - stop/sbottom for mass = 750 GeV : ~ 10
 - $t\bar{t}$: $\sim 3.3 \rightarrow$ S/B boosts

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$



ATLAS CONF-2016-052
ATLAS CONF-2016-037
arXiv:1507.05525

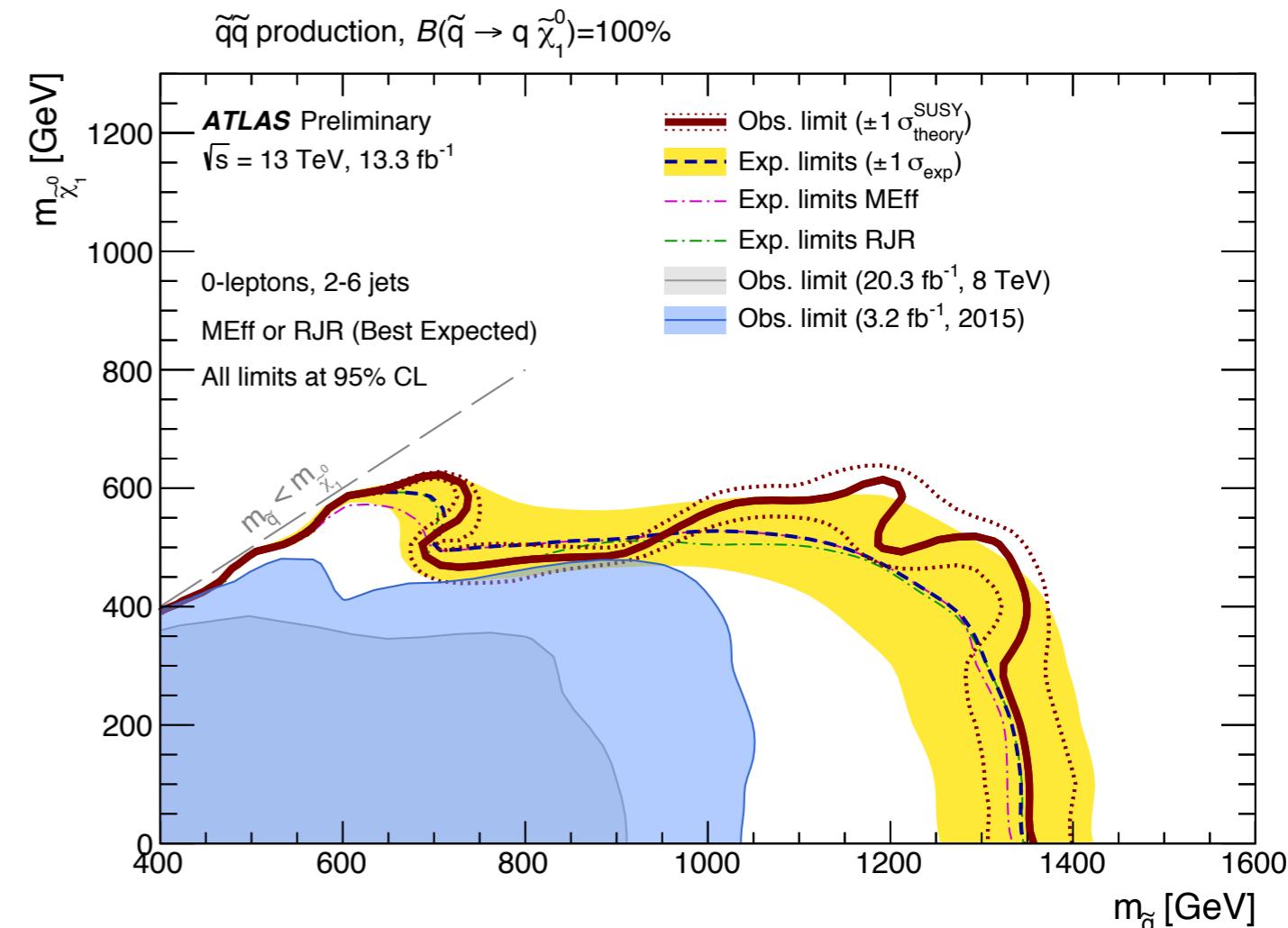
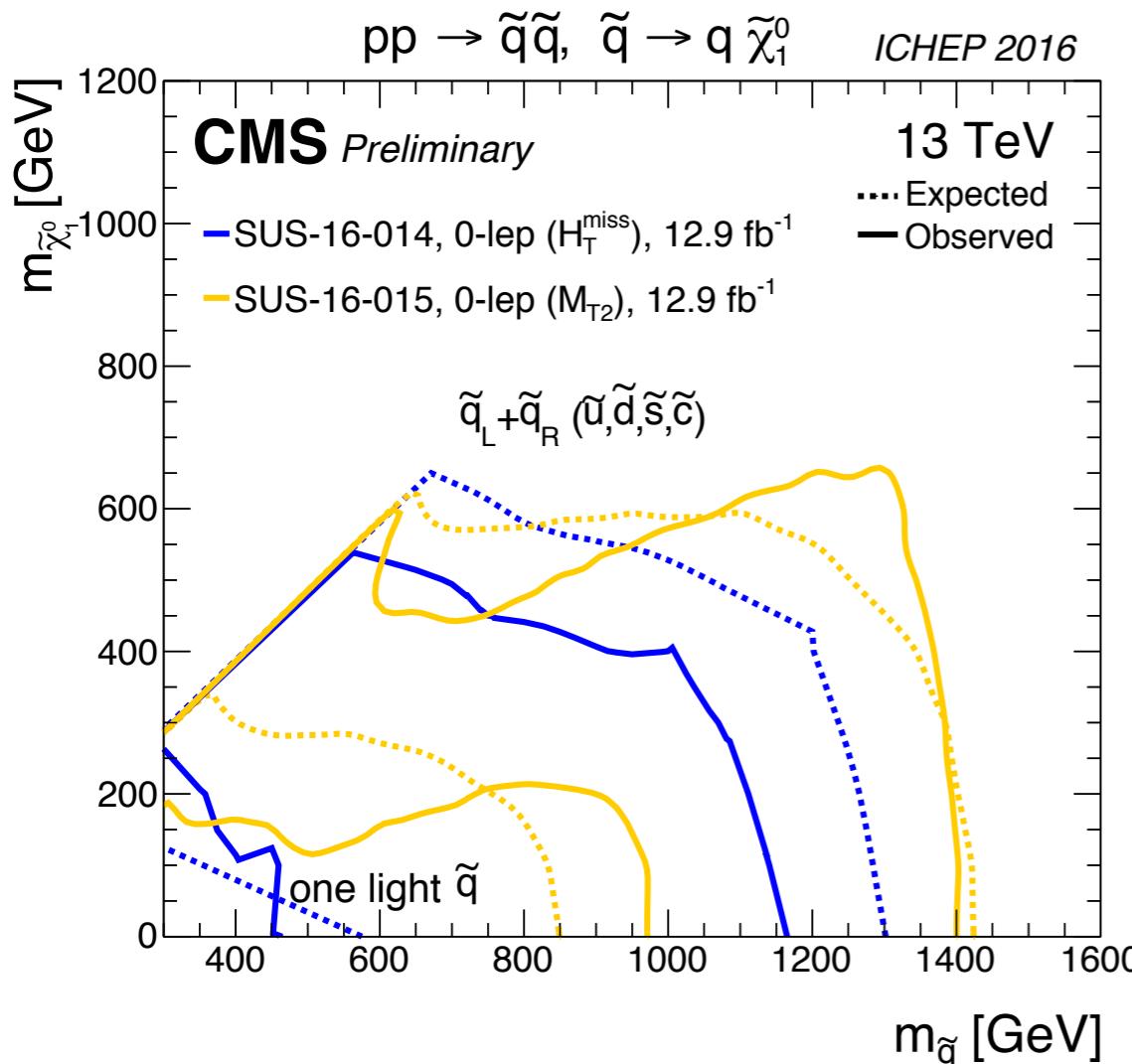
CMS SUS-016-014
CMS SUS-016-015
CMS SUS-016-016
CMS SUS-016-019
CMS SUS-016-020
CMS SUS-016-022
CMS SUS-016-030



- highly motivated decay channel due to natural SUSY scenarios
- the strongest limits is about 1.9 TeV

$\tilde{q} \rightarrow q \tilde{\chi}_1^0$

ATLAS CONF-2016-078
CMS SUS-016-014
CMS SUS-016-015

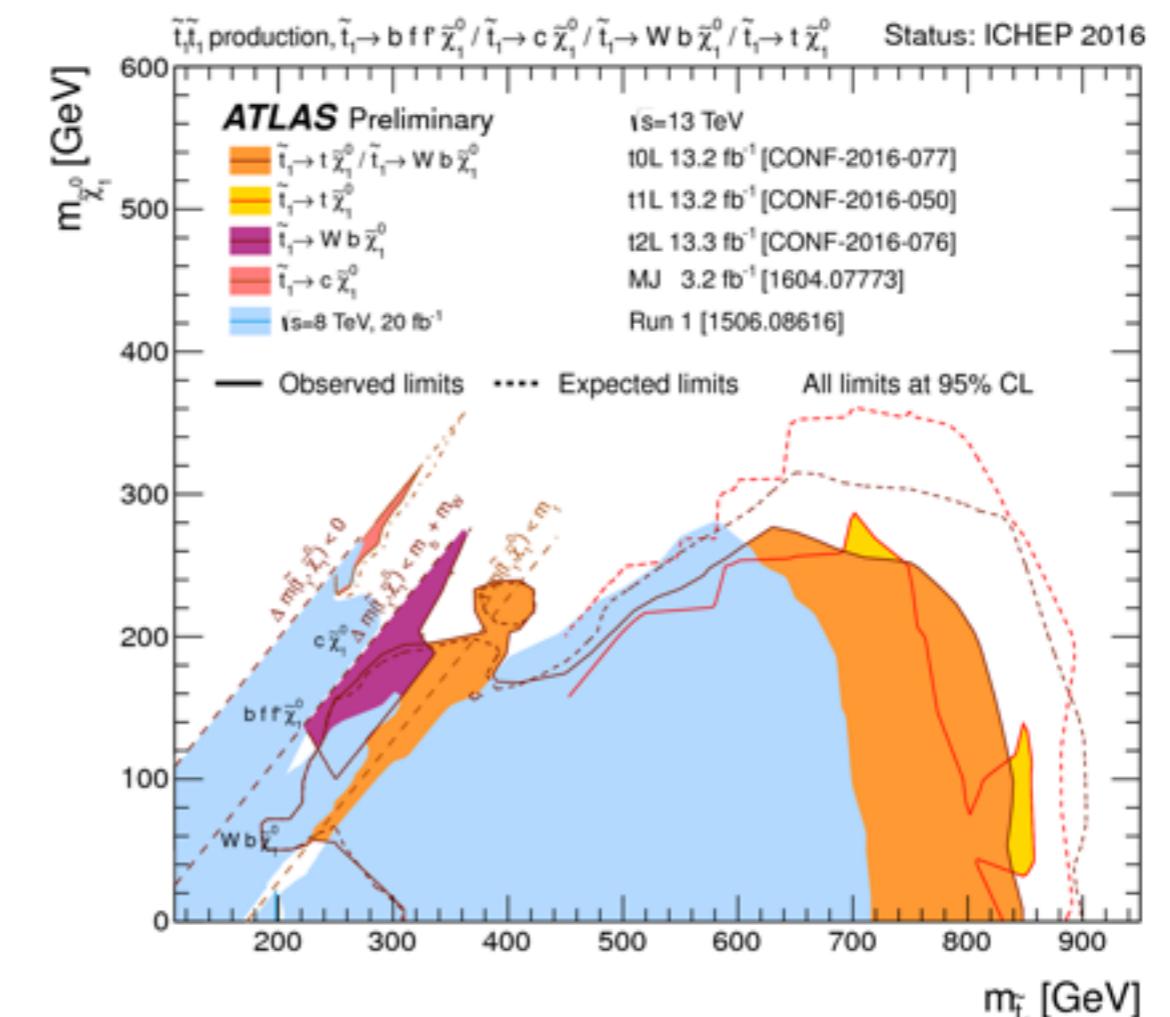
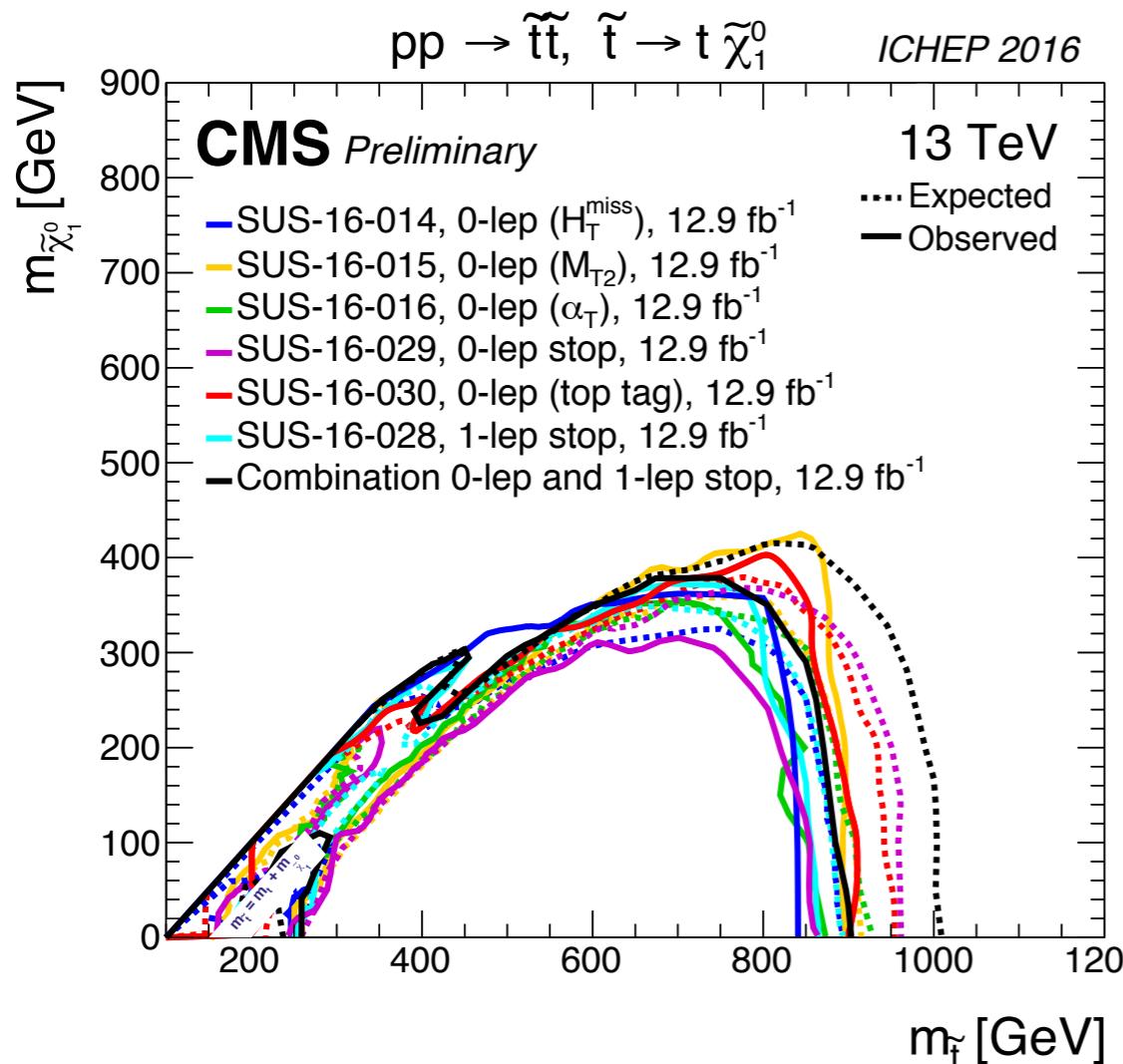


- large production cross section \rightarrow primary target for early SUSY searches
- squark masses below ~ 1.4 TeV are excluded for a massless lightest neutralino

$\tilde{t} \rightarrow t\tilde{\chi}_1^0$

ATLAS CONF-2016-050
ATLAS CONF-2016-076
ATLAS CONF-2016-077

CMS SUS-016-014
CMS SUS-016-015
CMS SUS-016-016
CMS SUS-016-028
CMS SUS-016-029
CMS SUS-016-030



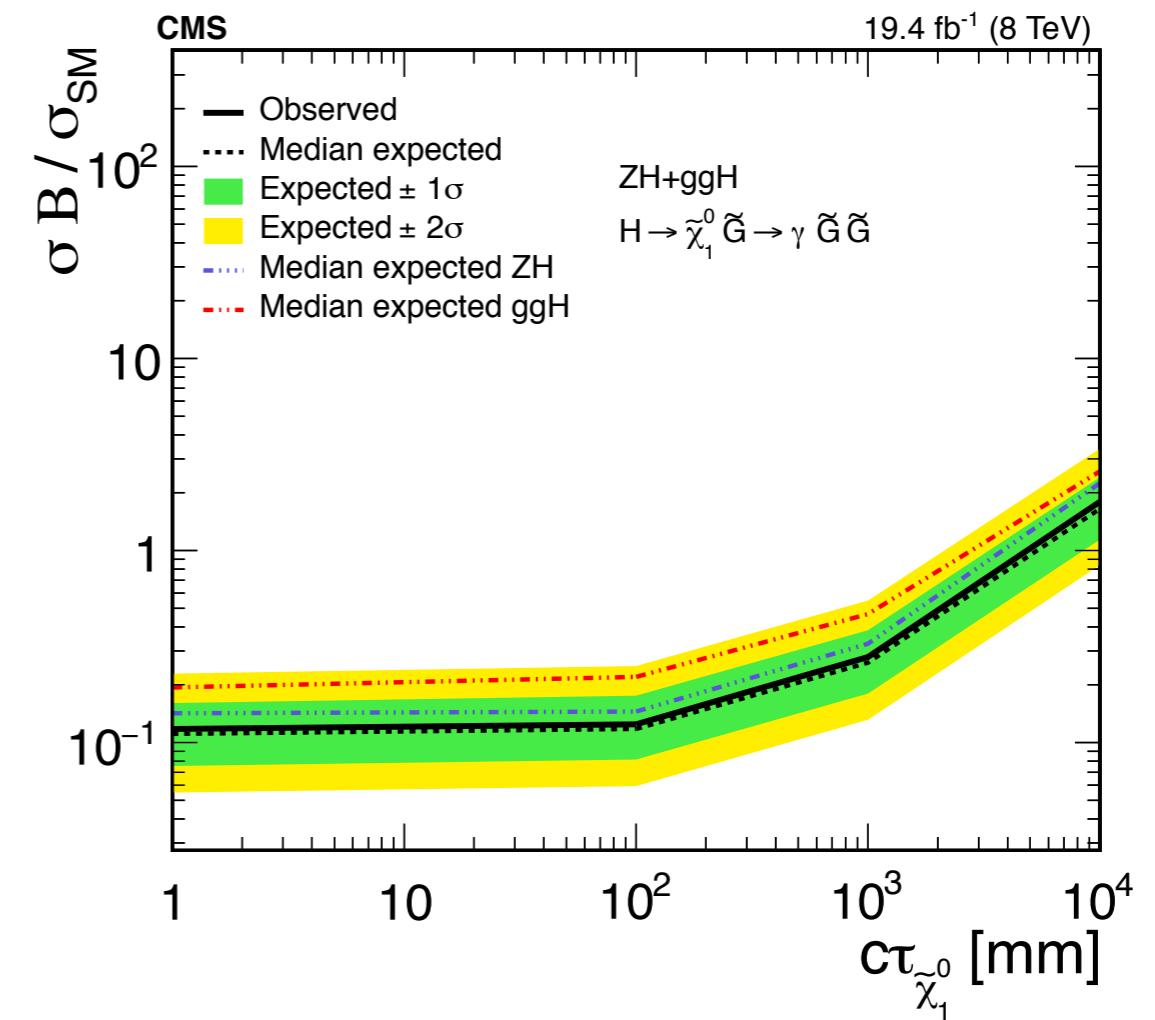
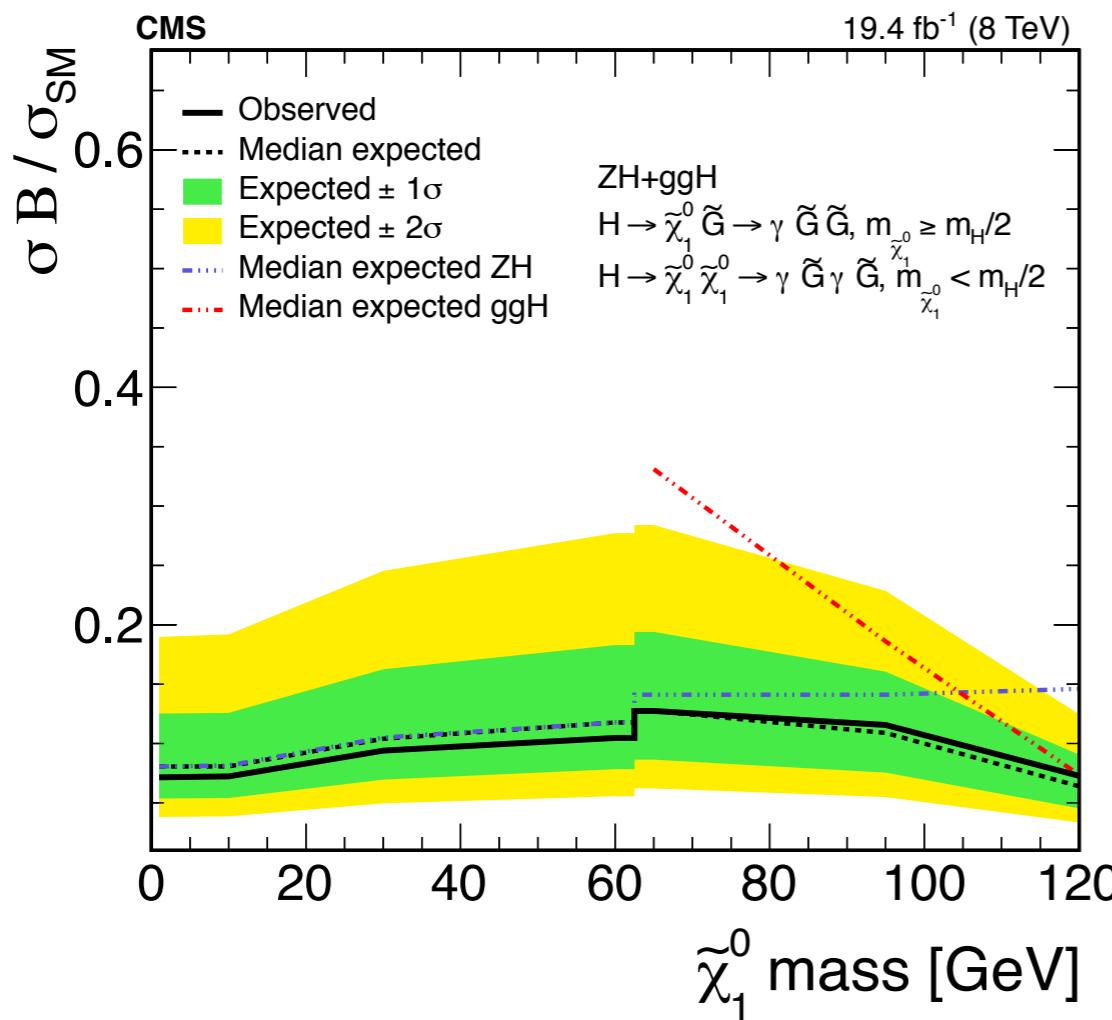
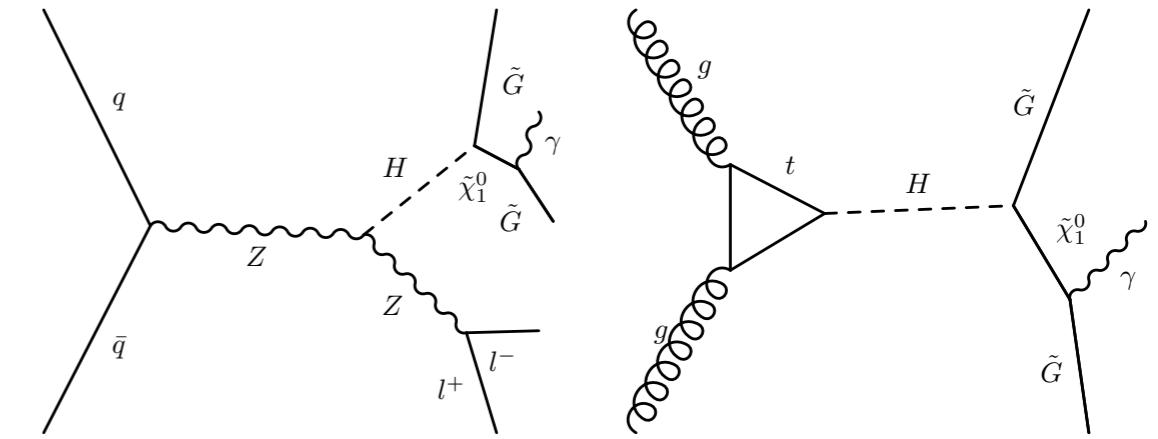
- stop plays an important role in cancelling the dominant top loop diagram contributions to the divergence of the Higgs mass
- LHC starts having sensitivity with 0.9-1 TeV for stop
- new results from ATLAS fill in the regions unfilled in Run-1

$H \rightarrow \text{undetectable} + \gamma$

CMS PLB 753 (2016) 363



- several BSM models predict this final state
- In certain low-scale SUSY models, $H \rightarrow$ a gravitino + a neutralino or a pair of neutralinos

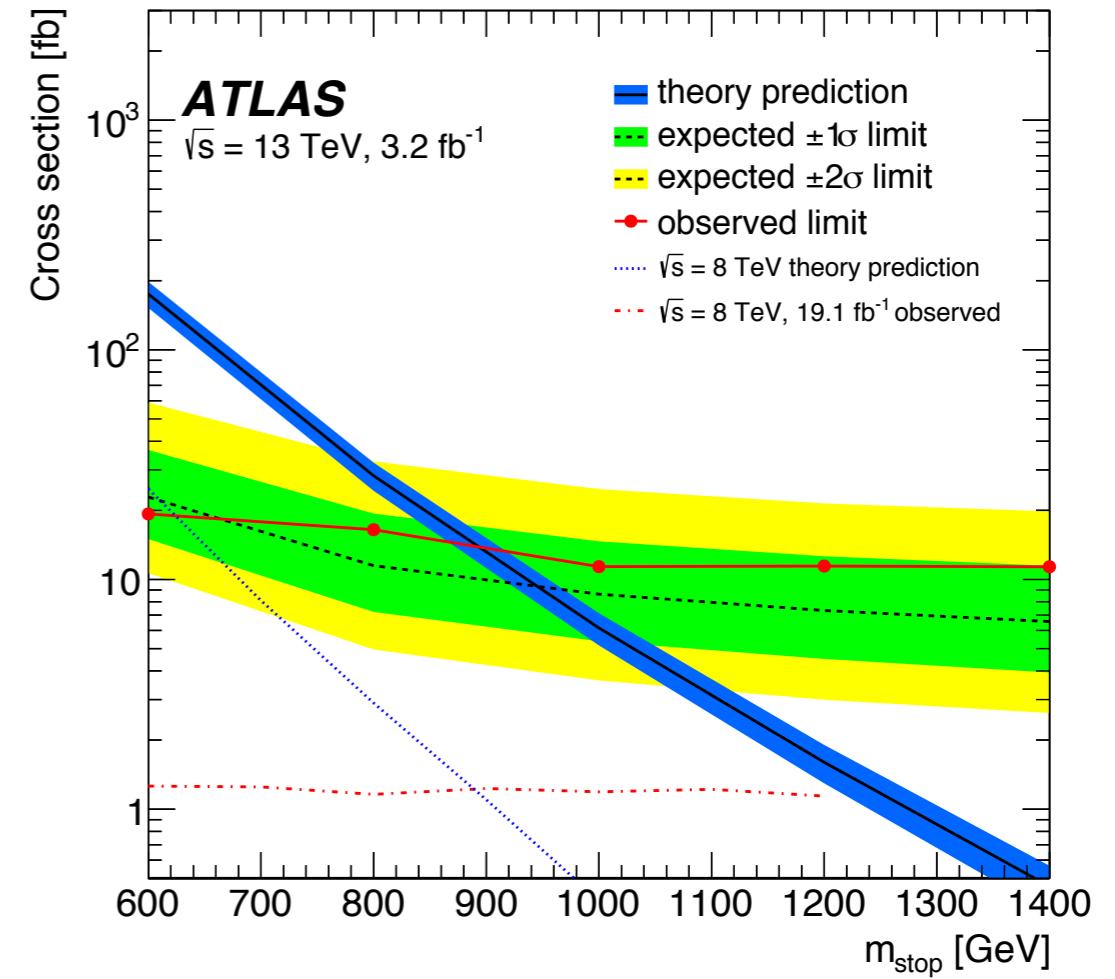
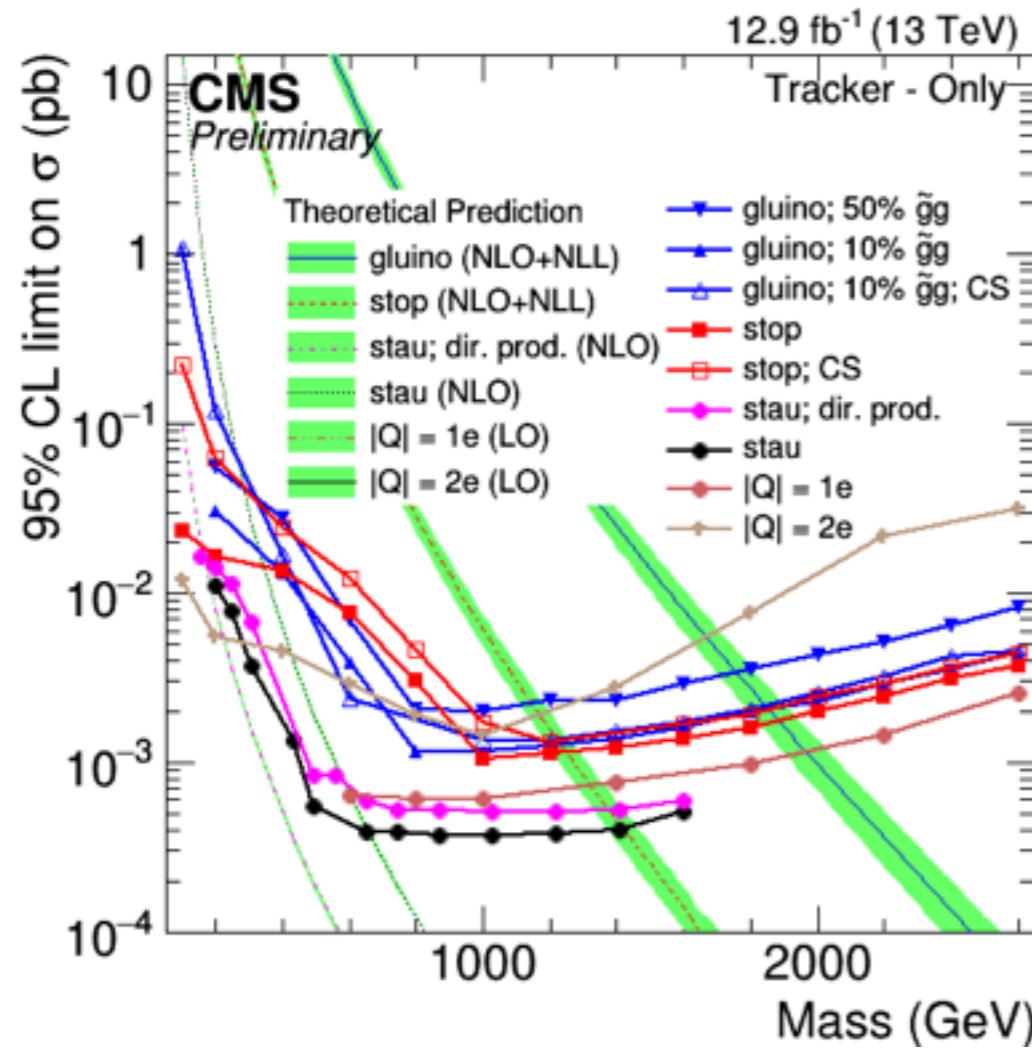


Heavy Long-Lived Particles



- an attempt to address the hierarchy problem
- SUSY allows for long-lived sparticles
- new results improve the previous limits from the LHC

ATLAS PLB 760 (2016) 647
CMS EXO-16-036

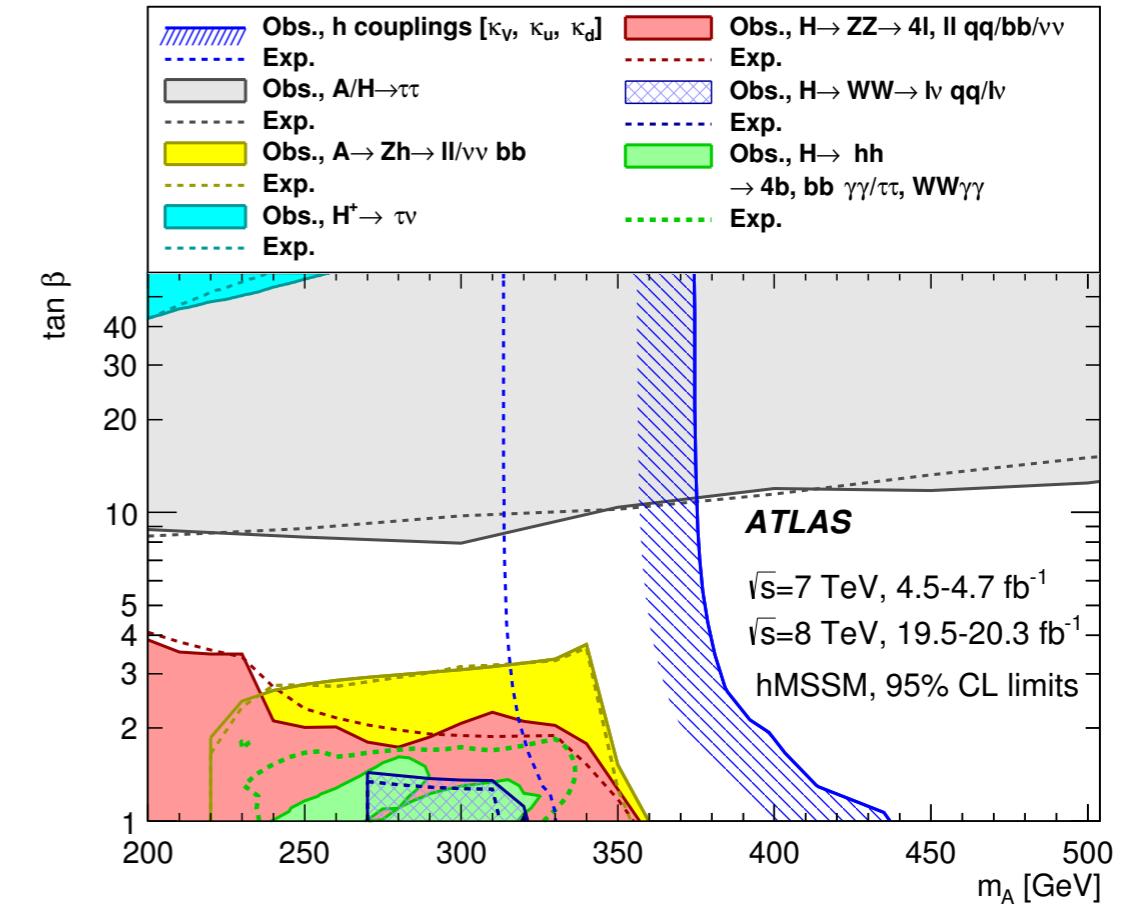
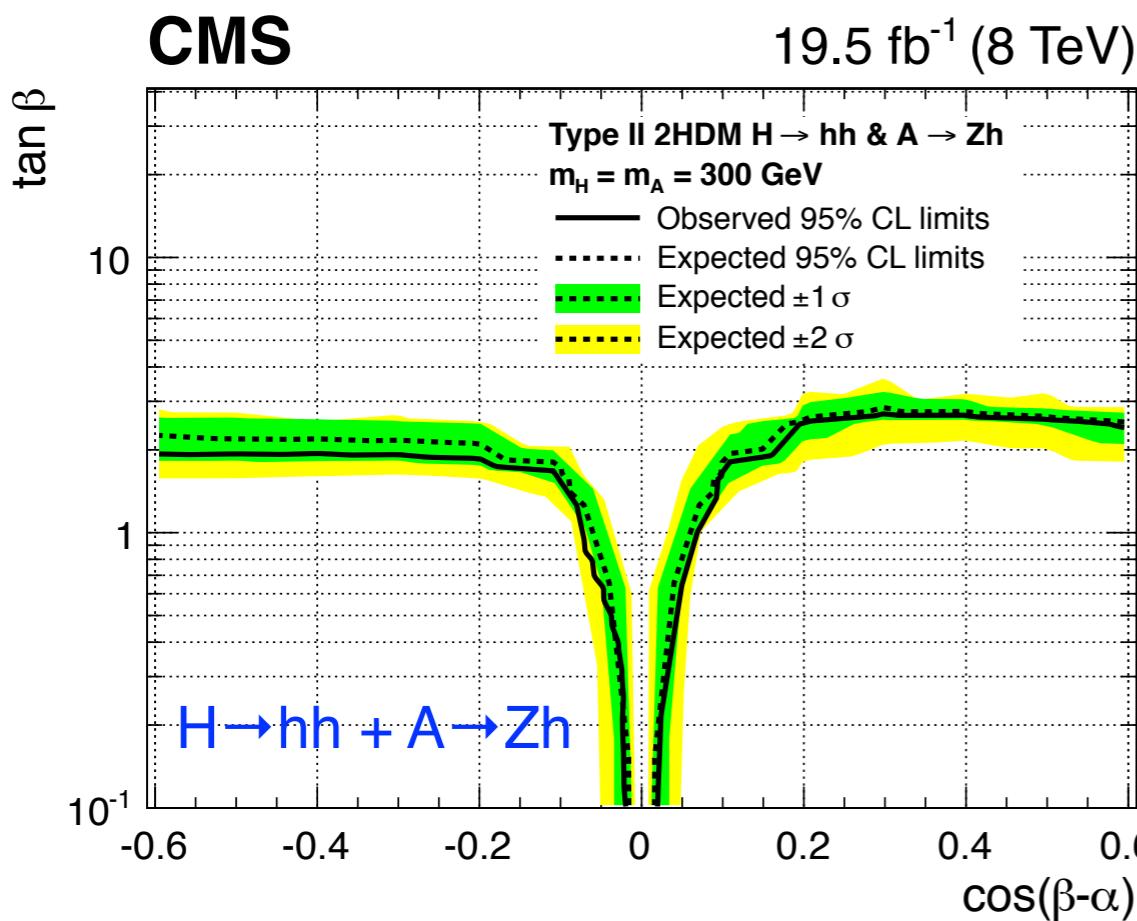


BSM Higgs searches

CMS PRD 90 (2014) 112013

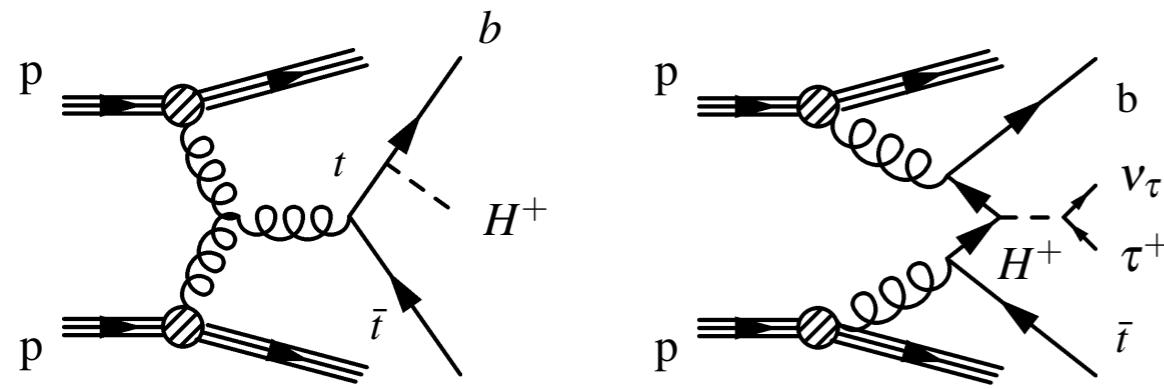


- Two-Higgs Doublet Models (2HDM)
 - simplest possible extensions of the SM
 - MSSM, axion, baryogenesis models
 - five “Higgs” bosons : h , H , H^+ , H^- , A

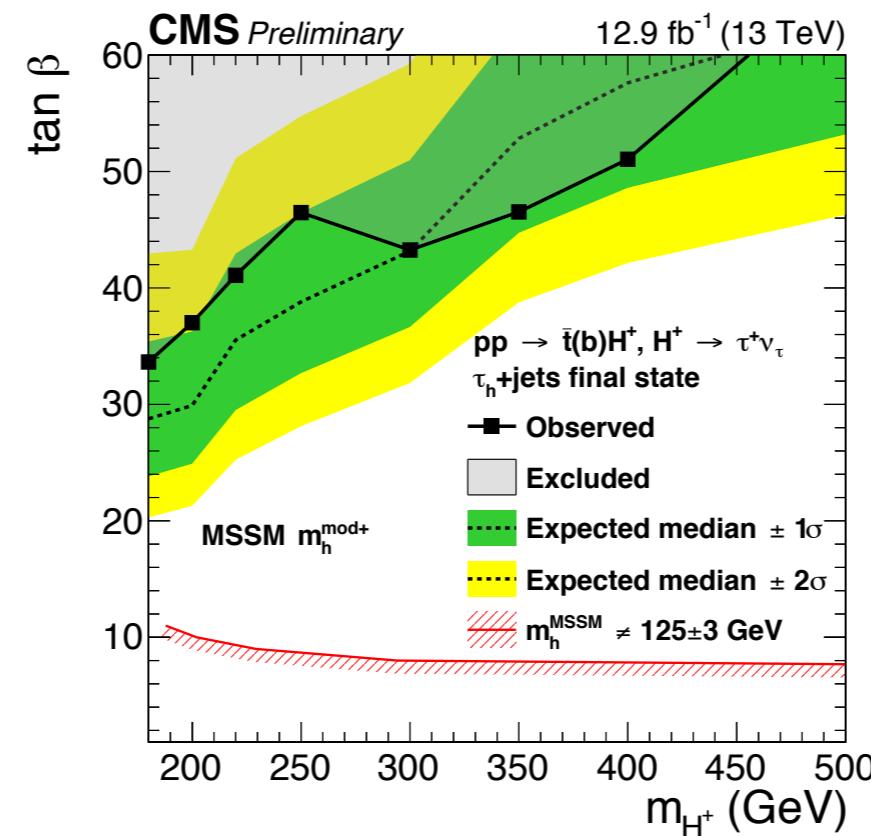
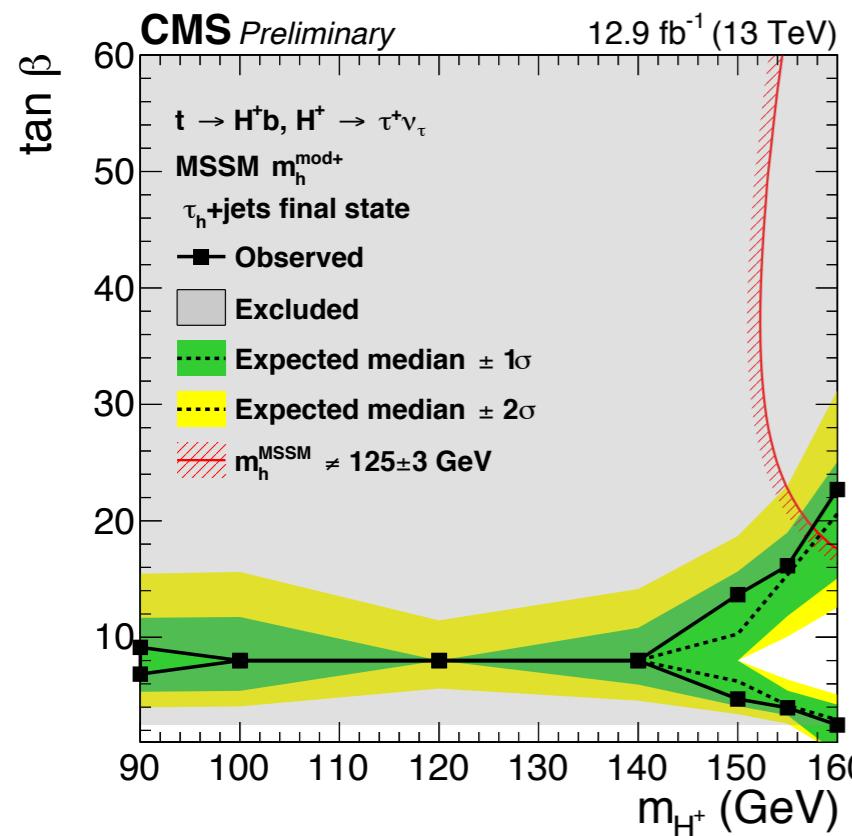


$H^\pm \rightarrow \tau^\pm V_\tau$

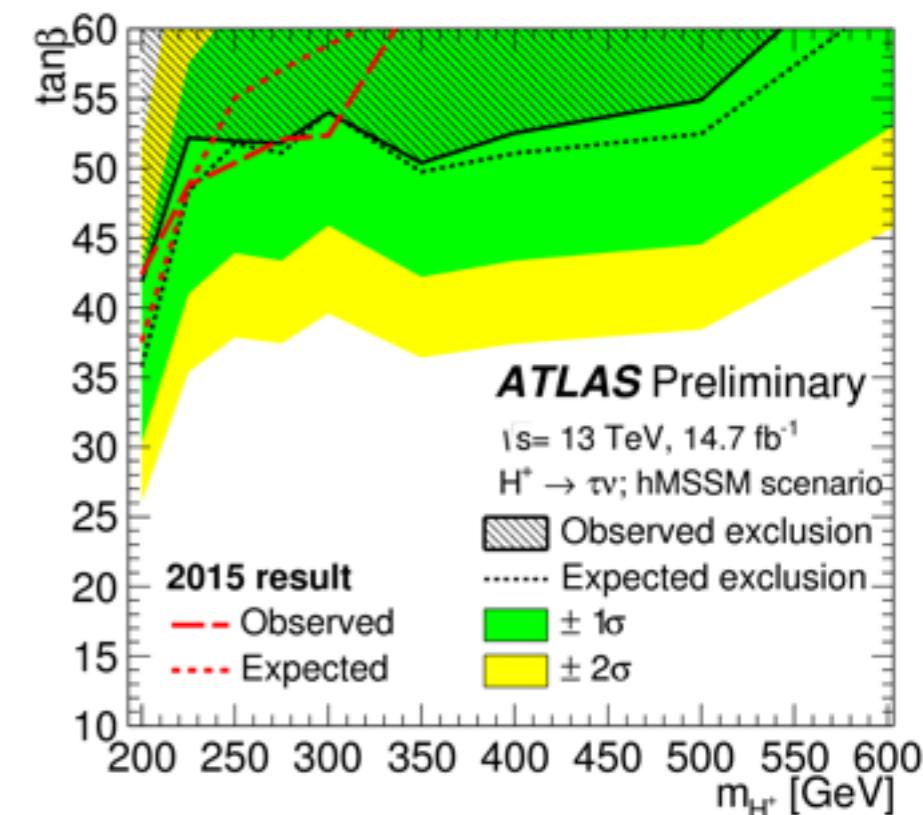
ATLAS CONF-16-088
CMS HIG-16-031



- ATLAS : $pp \rightarrow H^+ t$ ($m_{H^+} > m_{top}$)
- CMS : $pp \rightarrow H^+ tb$ ($m_{H^+} > m_{top}$),
 $pp \rightarrow H^+ W^- bb$ ($m_{H^+} < m_{top}$)



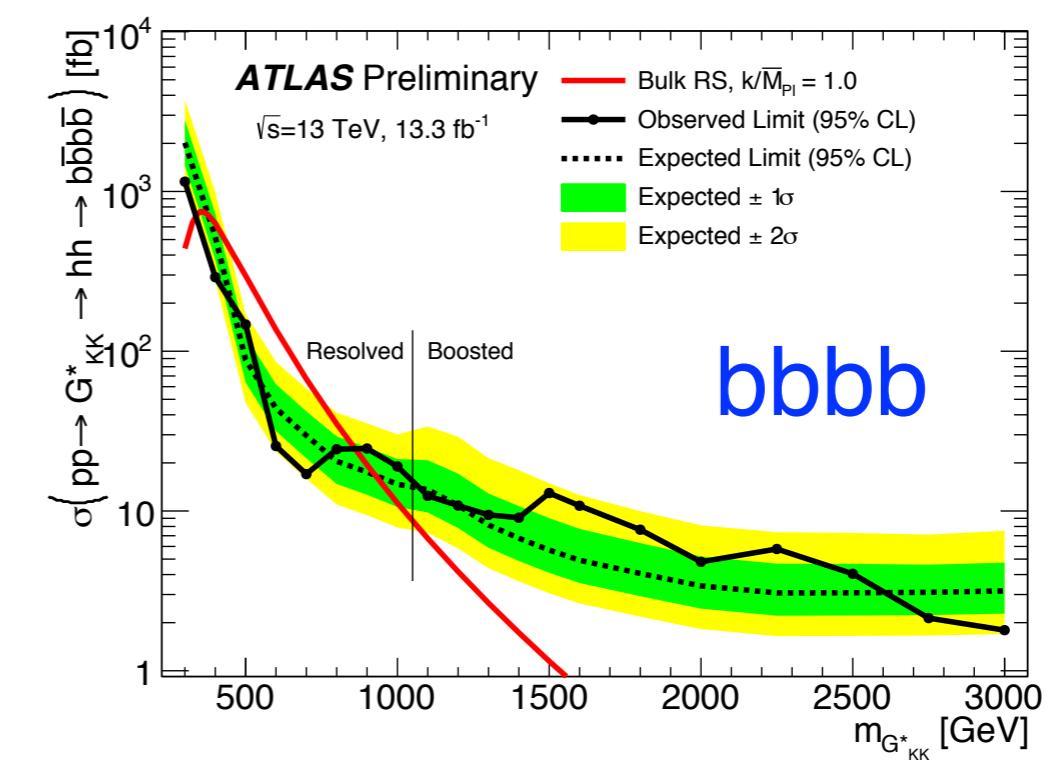
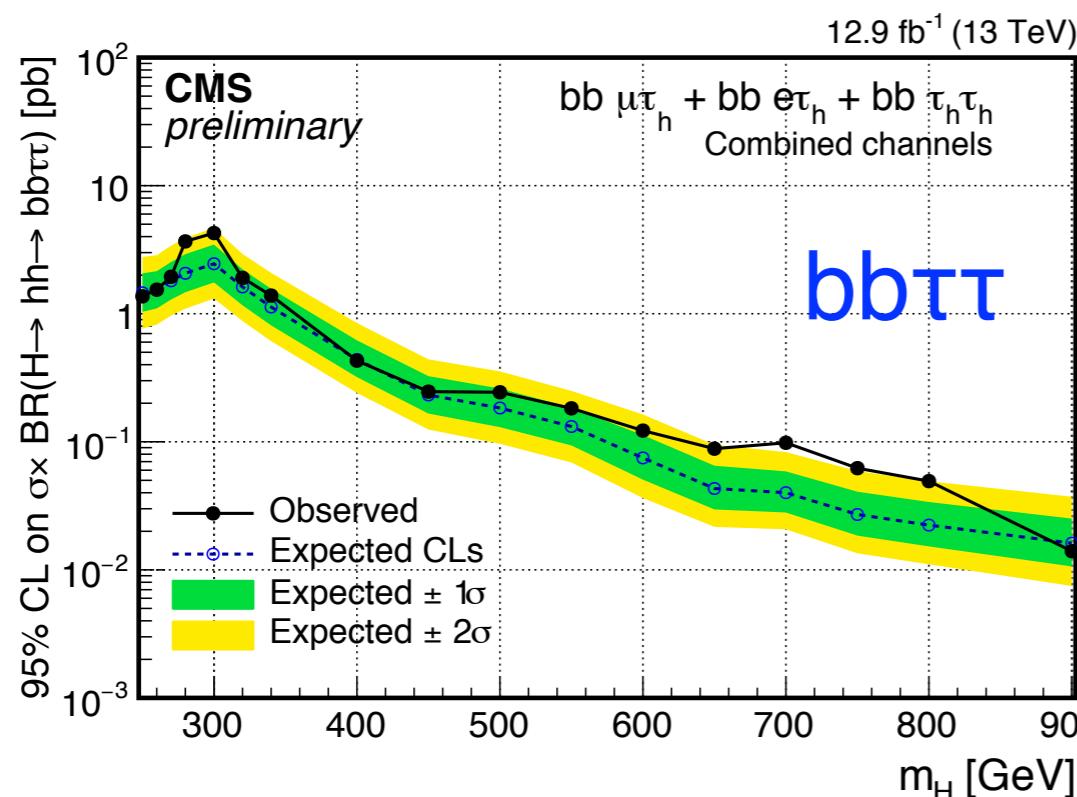
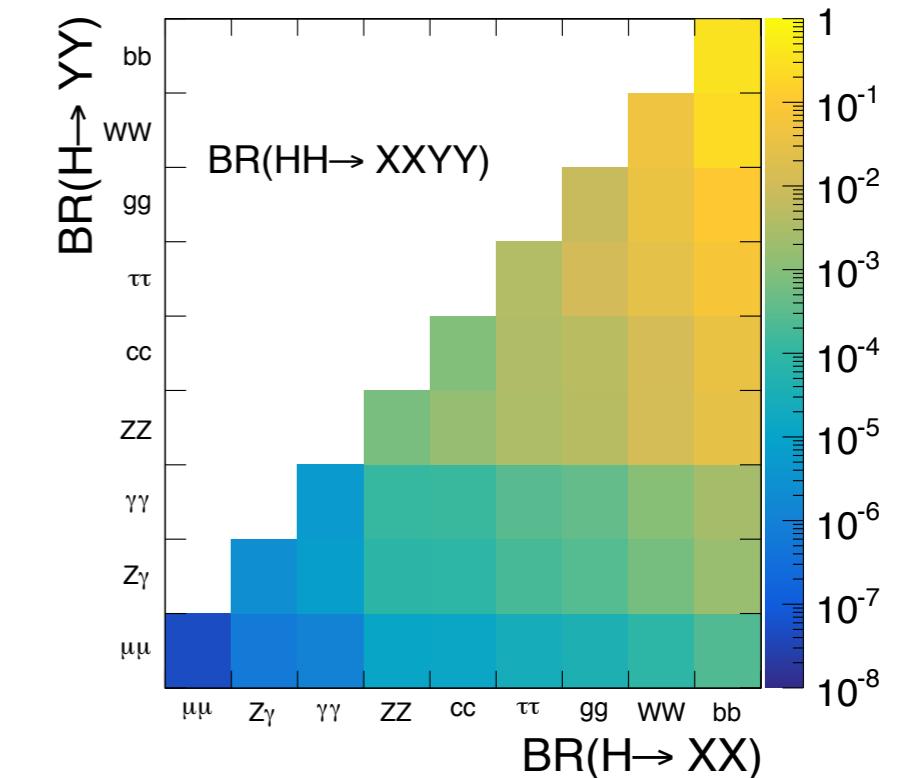
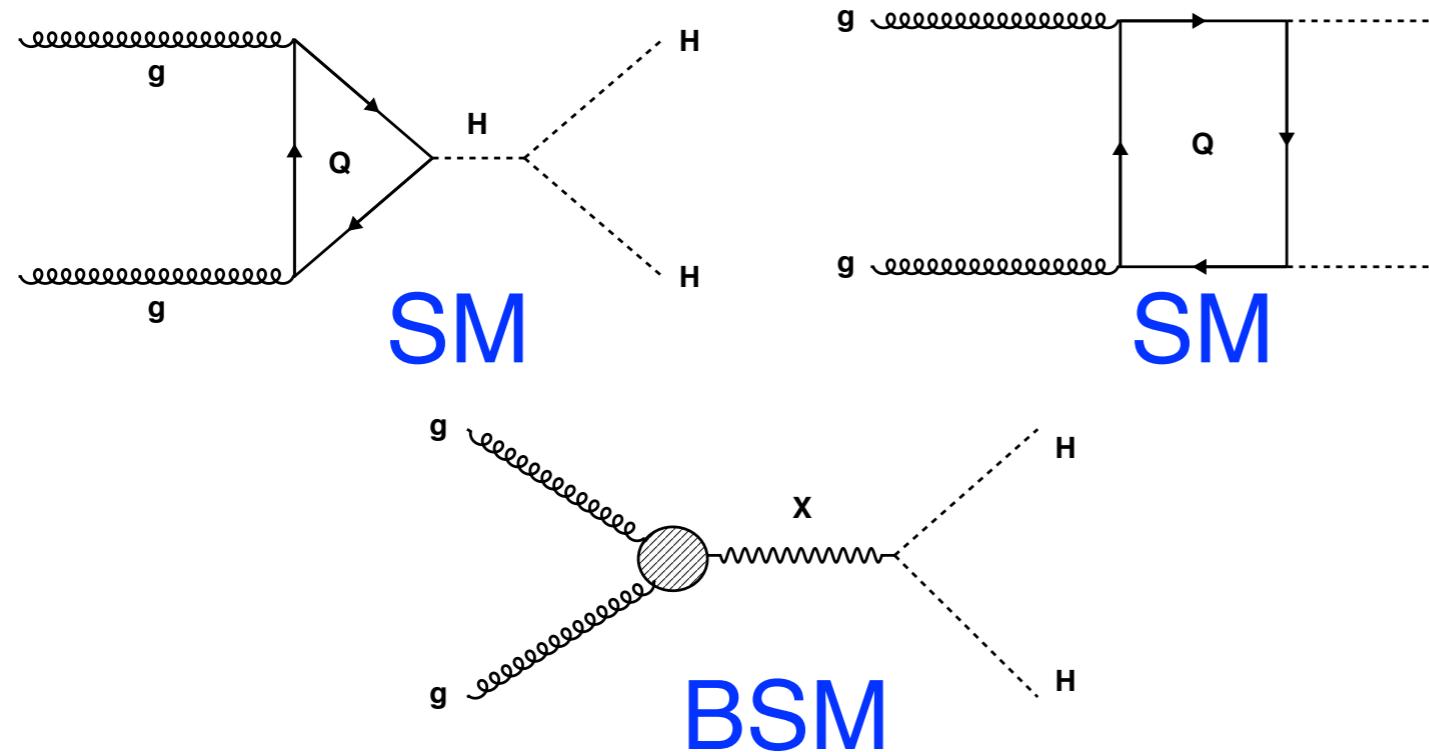
$\sigma \times BR$ enhanced at large $\tan \beta$
 \rightarrow large $\tan \beta$ is excluded



significantly improve the limit
for high mass region

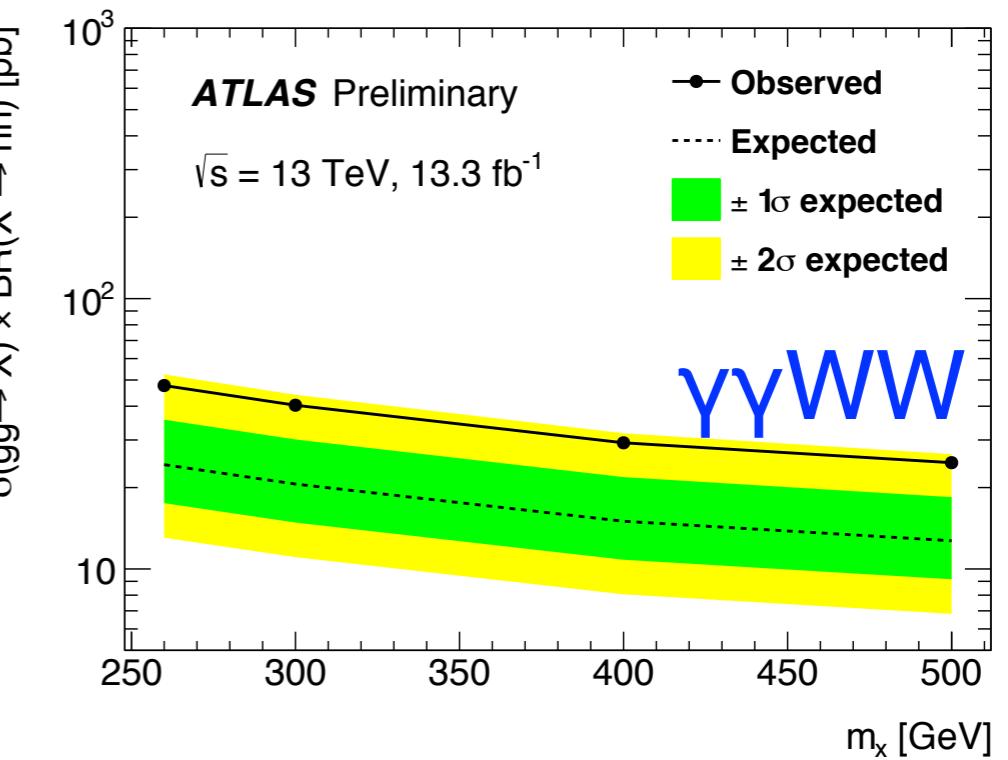
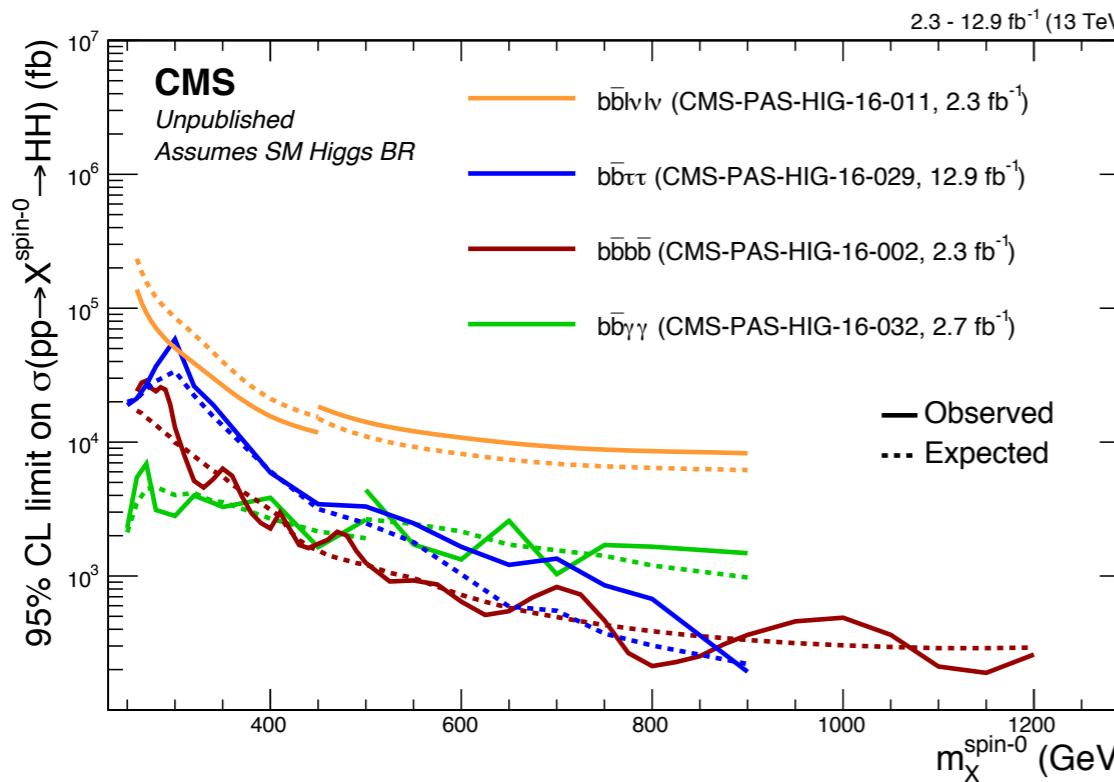
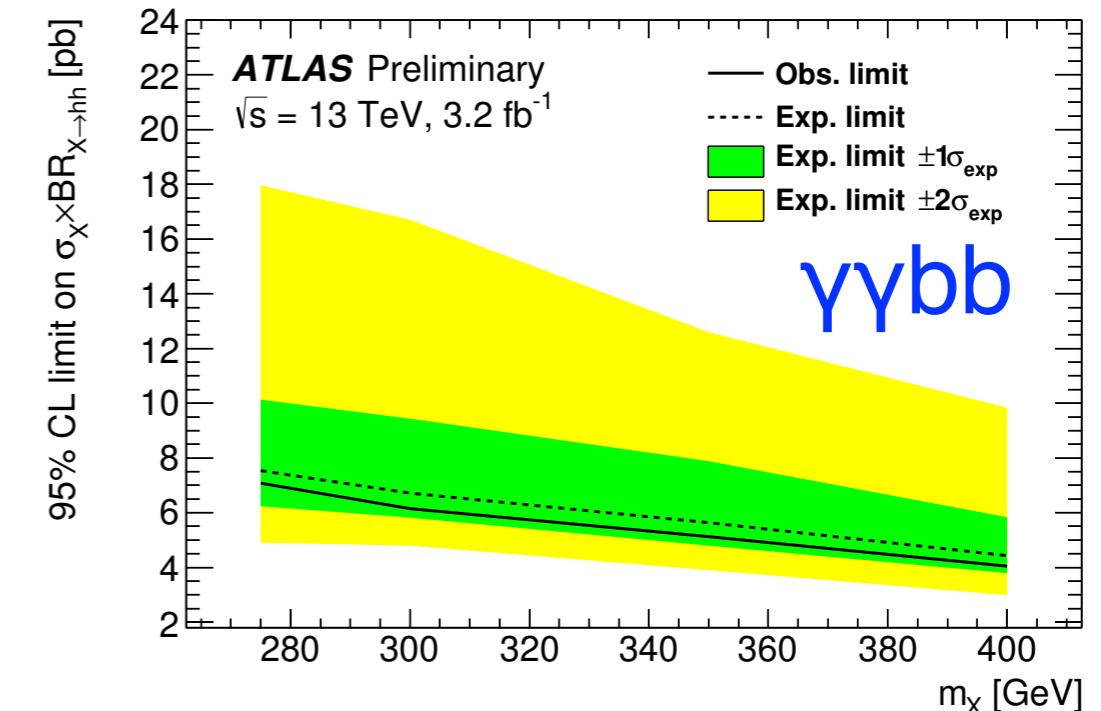
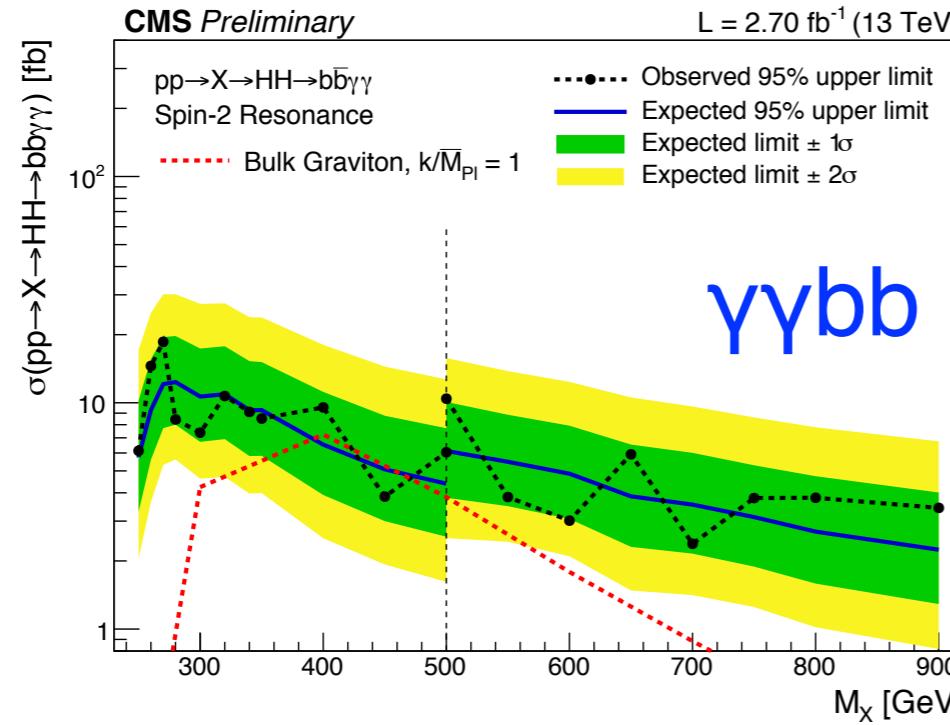
Di-Higgs production

ATLAS CONF-2016-049
CMS HIG-16-029



Di-Higgs production

ATLAS CONF-2016-004
 ATLAS CONF-2016-071
 CMS HIG-16-002
 CMS HIG-16-011
 CMS HIG-16-029
 CMS HIG-16-032

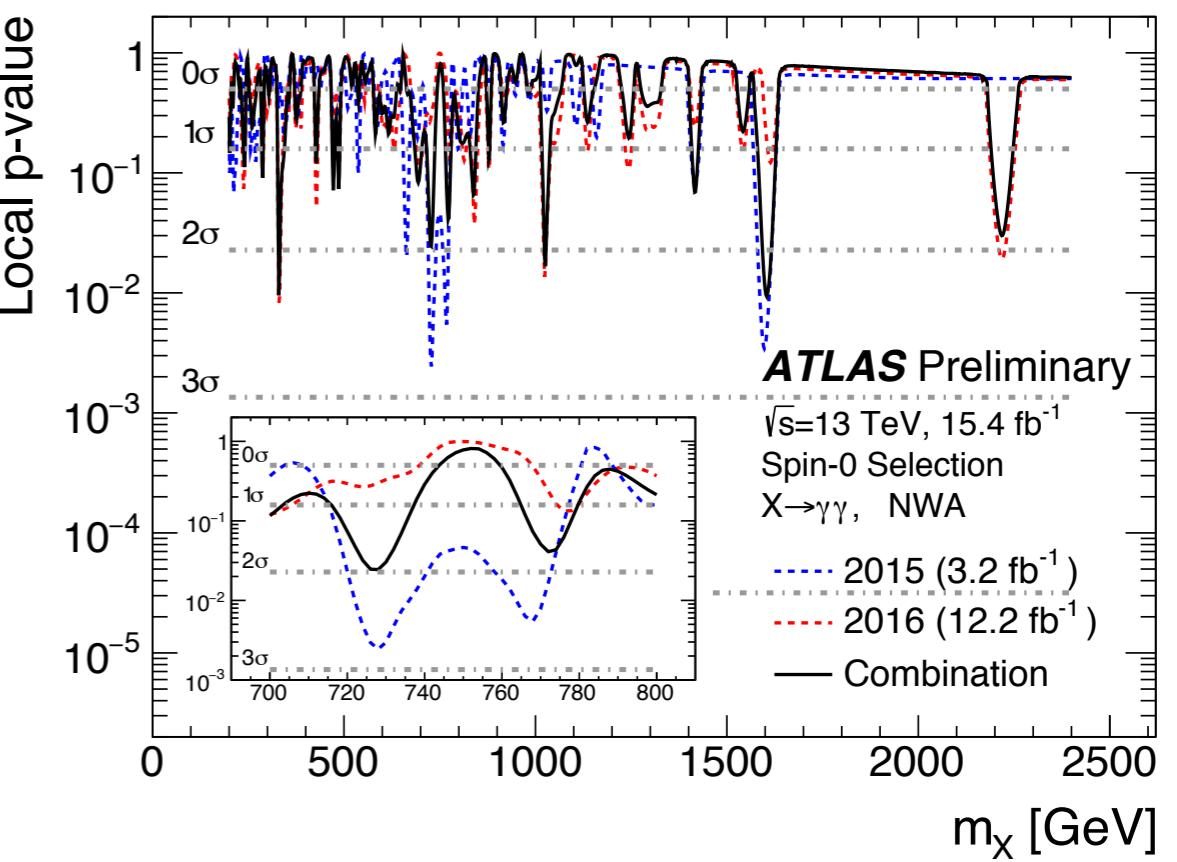
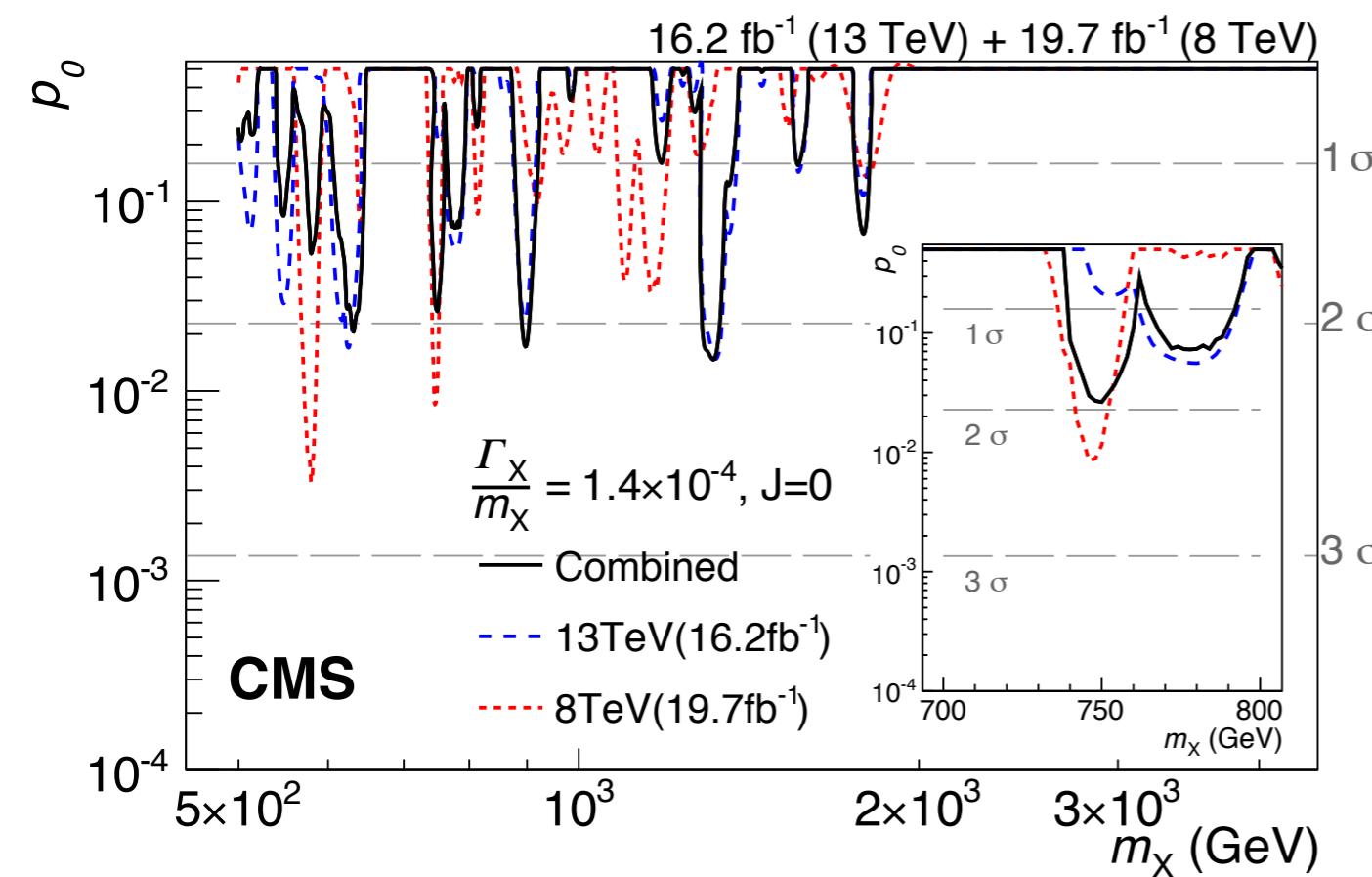


High mass search for $\gamma\gamma$

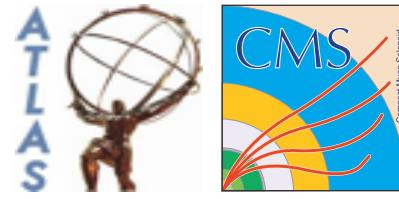


- many extensions to the SM predict new resonances decaying into $\gamma\gamma$
- ATLAS and CMS test both of heavy scalar ($J=0$) and Randall-Sundrum (RS) graviton ($J=2$) models and different widths

ATLAS CONF-2016-059
CMS arXiv:1609.02507

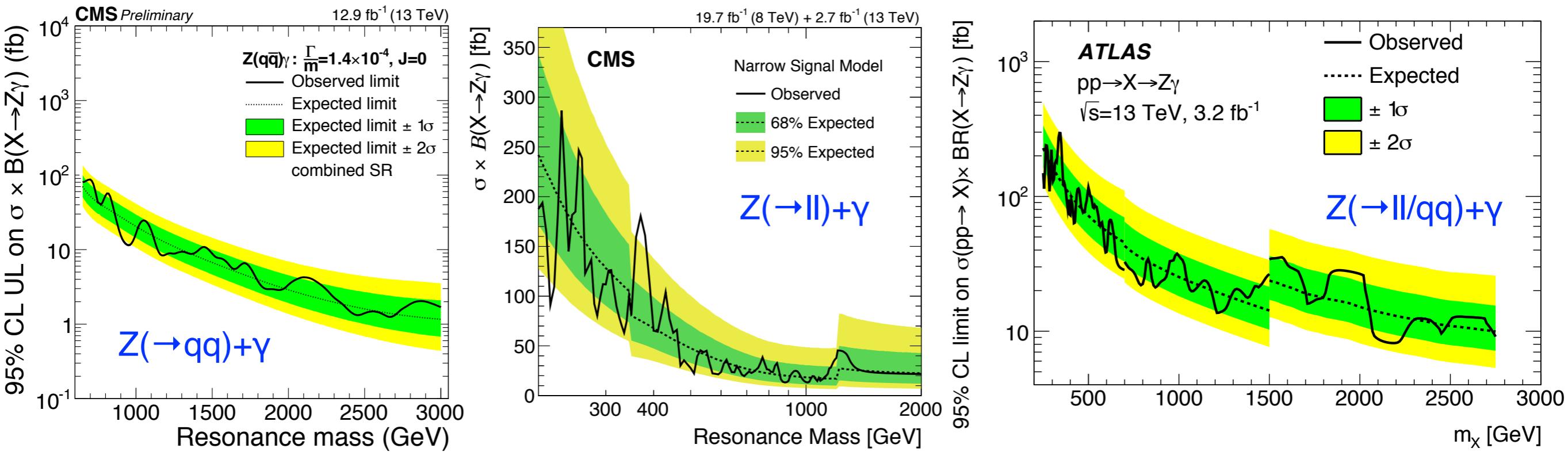


High mass search for $Z\gamma$



- an extended SM incorporating a scalar (or pseudo scalar) decaying to two photons would imply the observation of $Z\gamma$ as well
- ATLAS and CMS look into $Z \rightarrow ll$ and $Z \rightarrow qq$

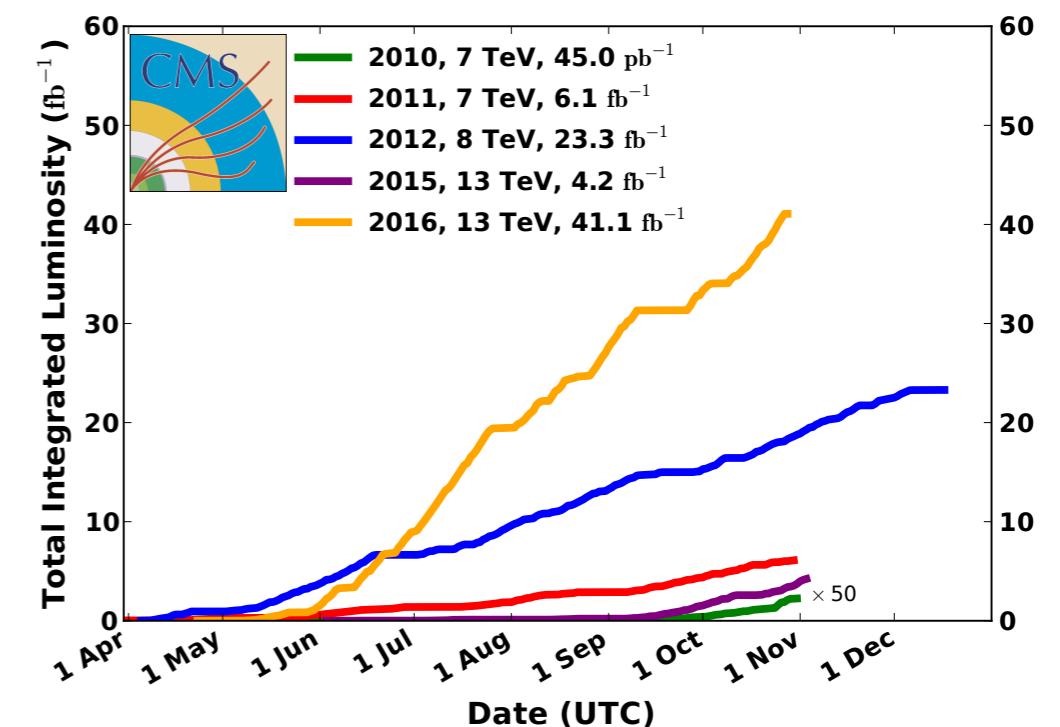
ATLAS PLB 764 (2017) 11
CMS arXiv:1610.02960
CMS EXO-16-035



Summary



- LHC provides alternative, complementary way to search for DM
- Rich DM search programs have been conducted at the LHC since Run-1
 - invisible Higgs decays
 - SUSY
 - BSM Higgs
- Stay tuned with new results updated with full 2016 data

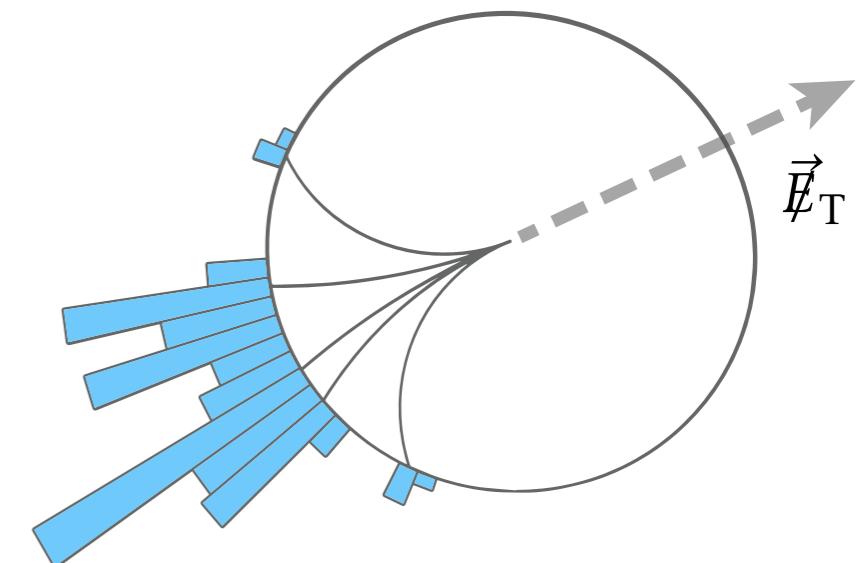


- Backup

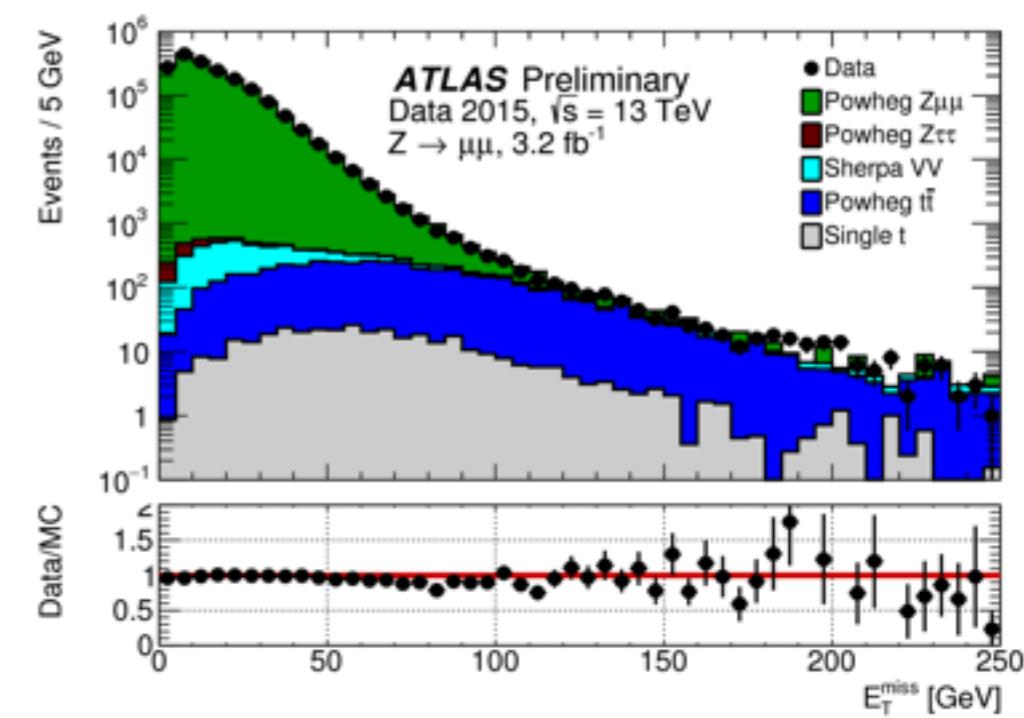
“Invisible” particles in detector



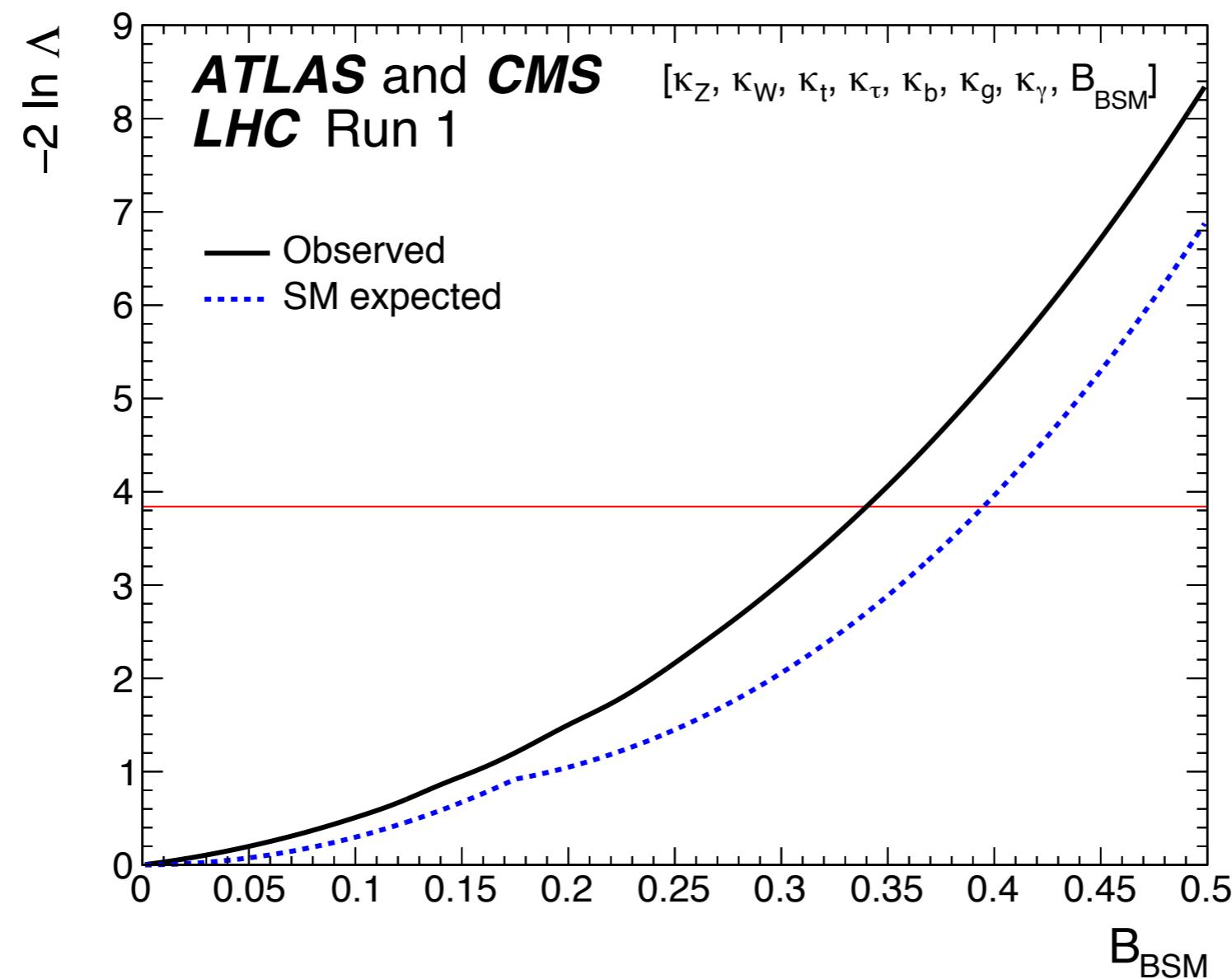
- Particles like neutrinos or DM do not leave signatures in the detector → invisible
 - cause large imbalance in the transverse plane
- Missing transverse energy (MET)
 - a powerful variable to discriminate between signal (e.g. DM) and SM background



ATLAS JETM-2016-003

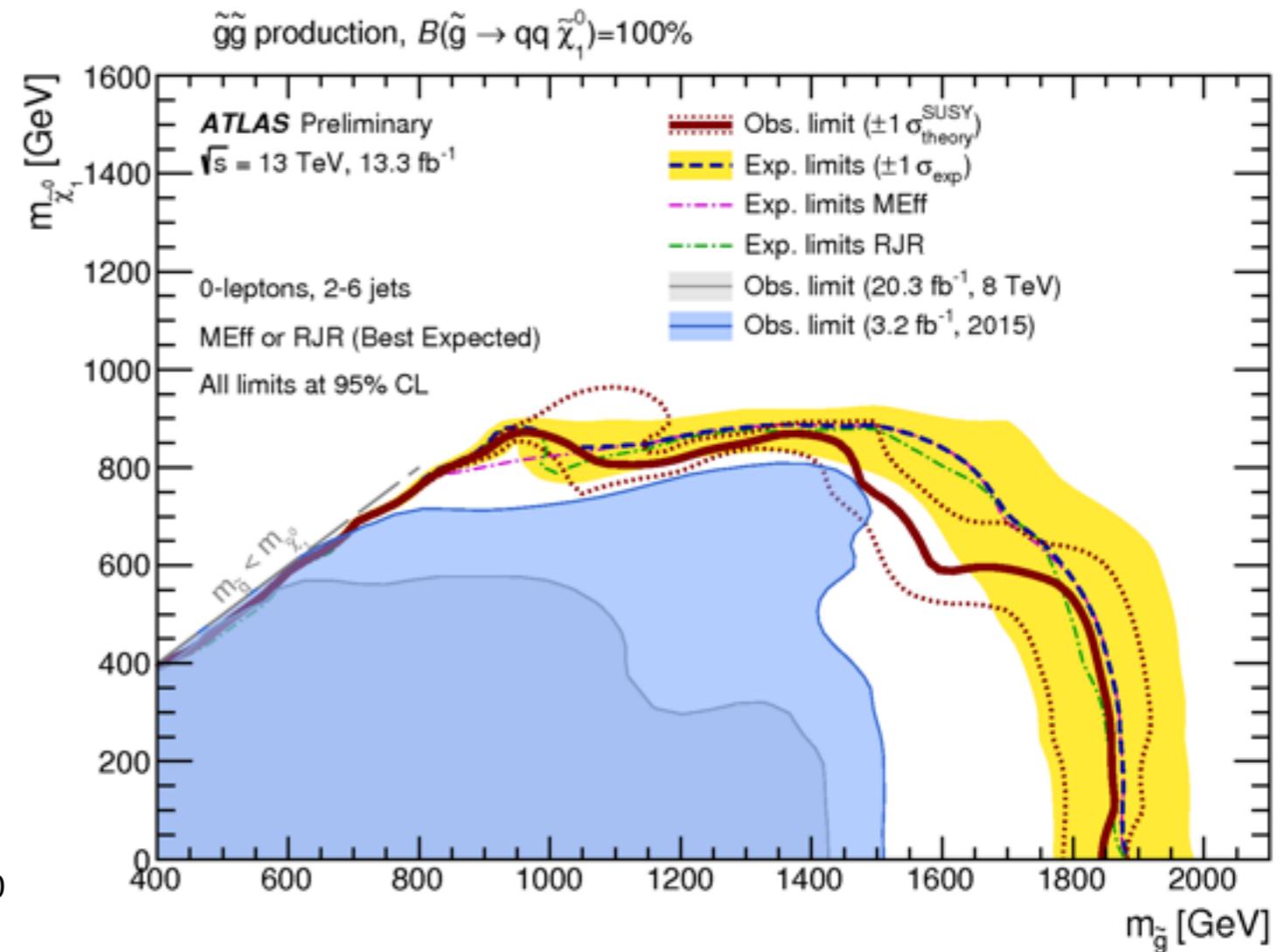
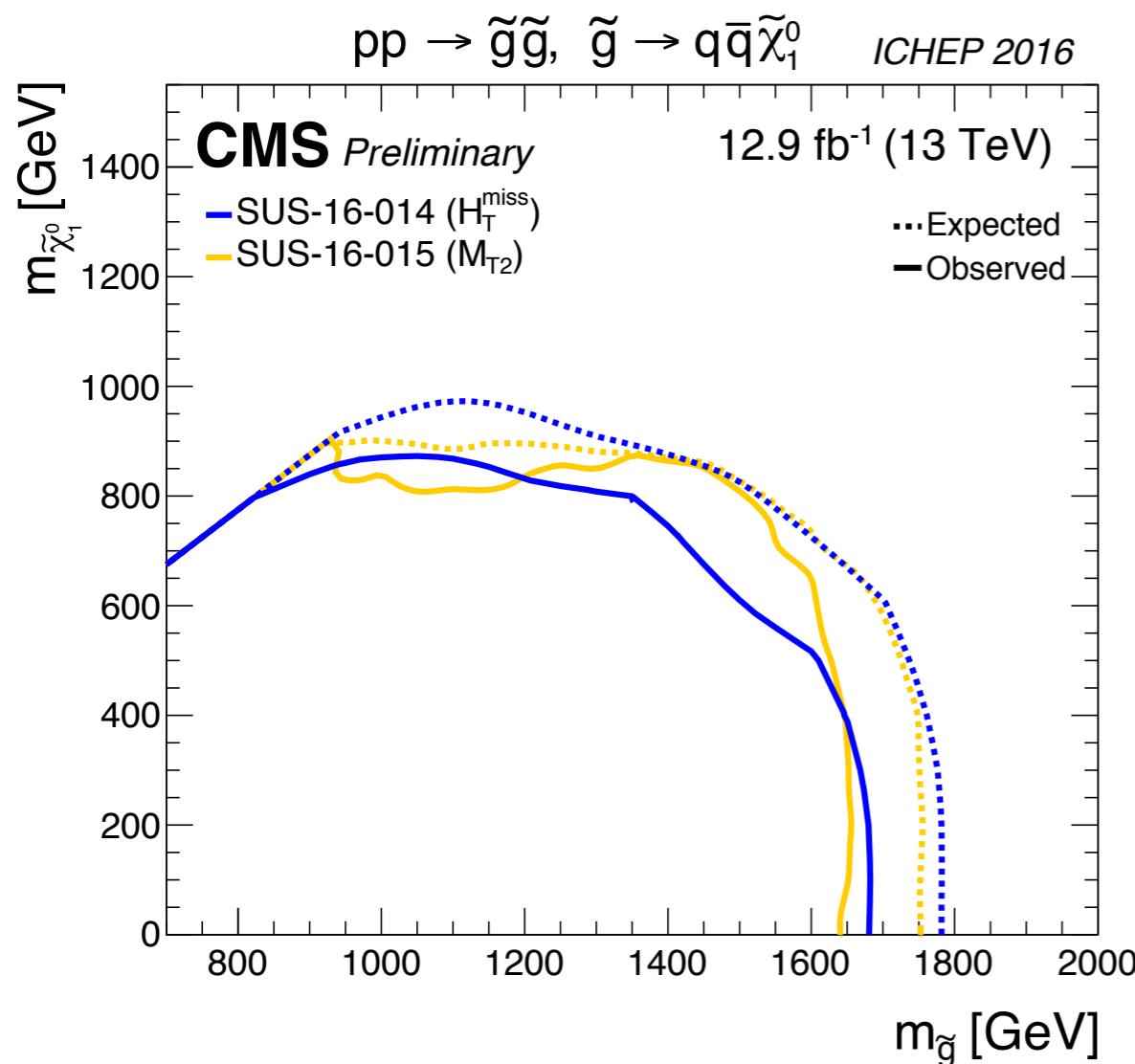


Additional contributions to the Higgs boson width from BSM processes



$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

ATLAS CONF-2016-078
CMS SUS-016-014
CMS SUS-016-015



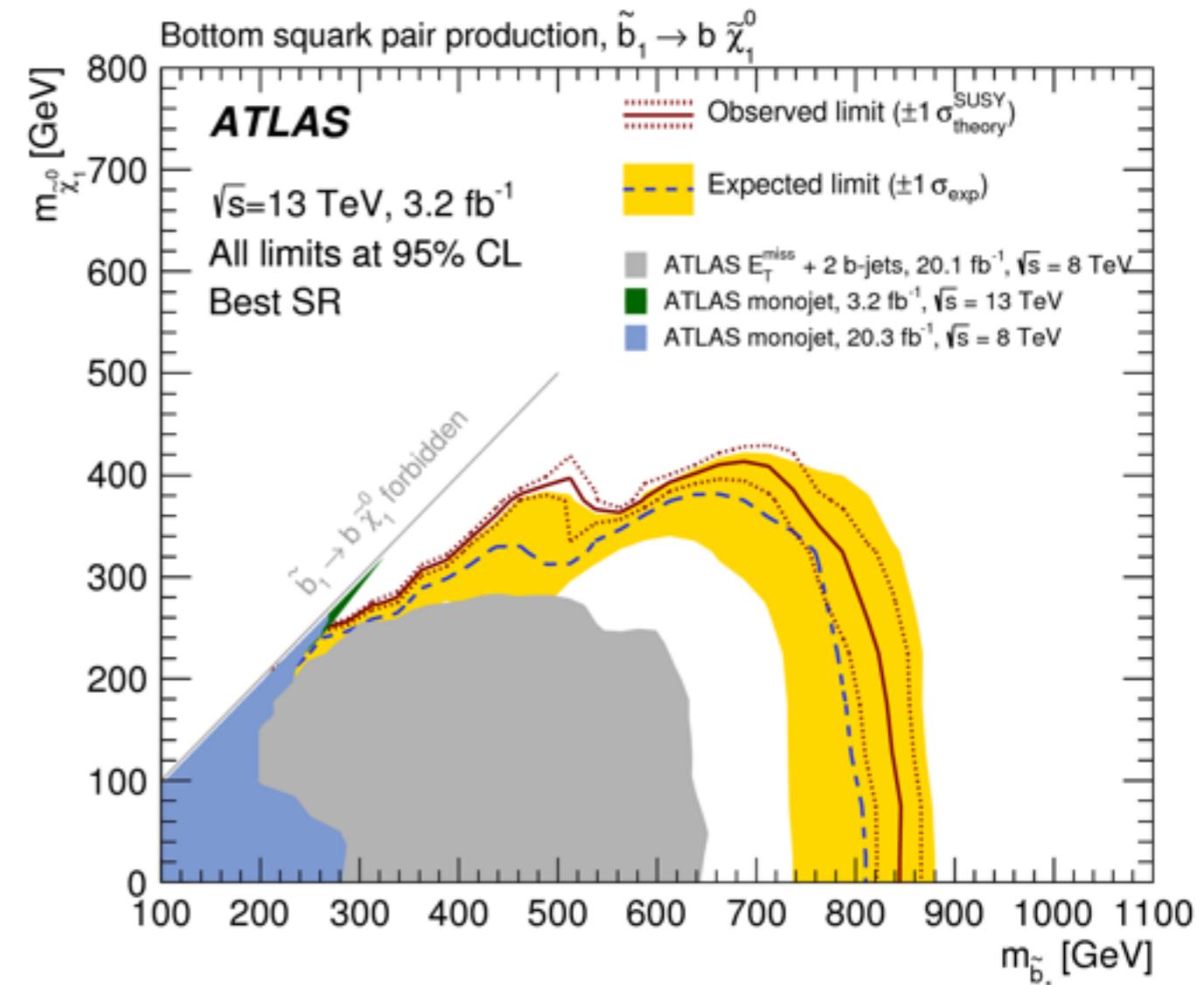
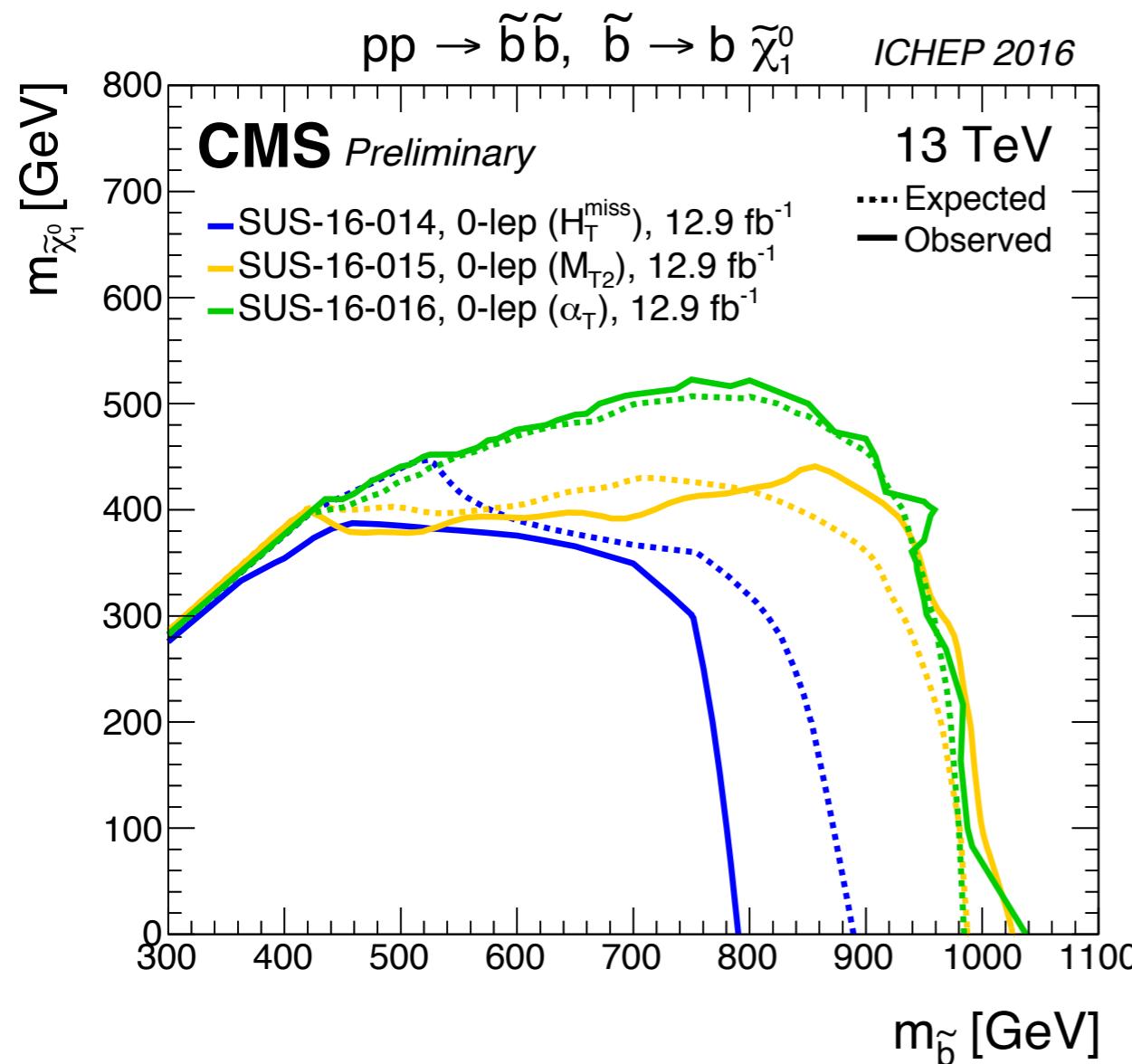
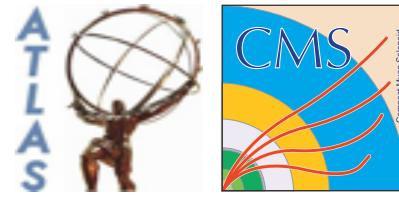
$\tilde{b} \rightarrow b \tilde{\chi}_1^0$

ATLAS EPJC (2016) 76:547

CMS SUS-16-014

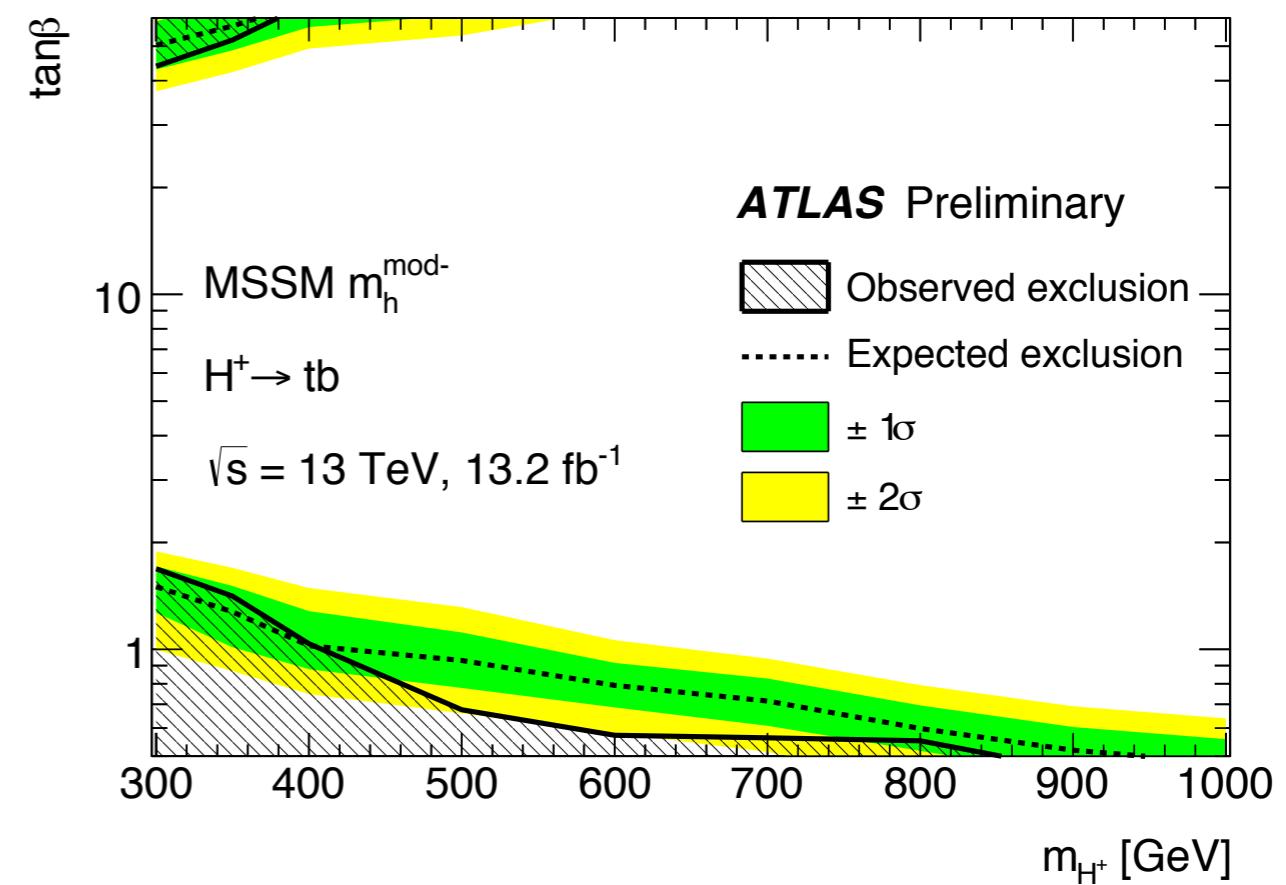
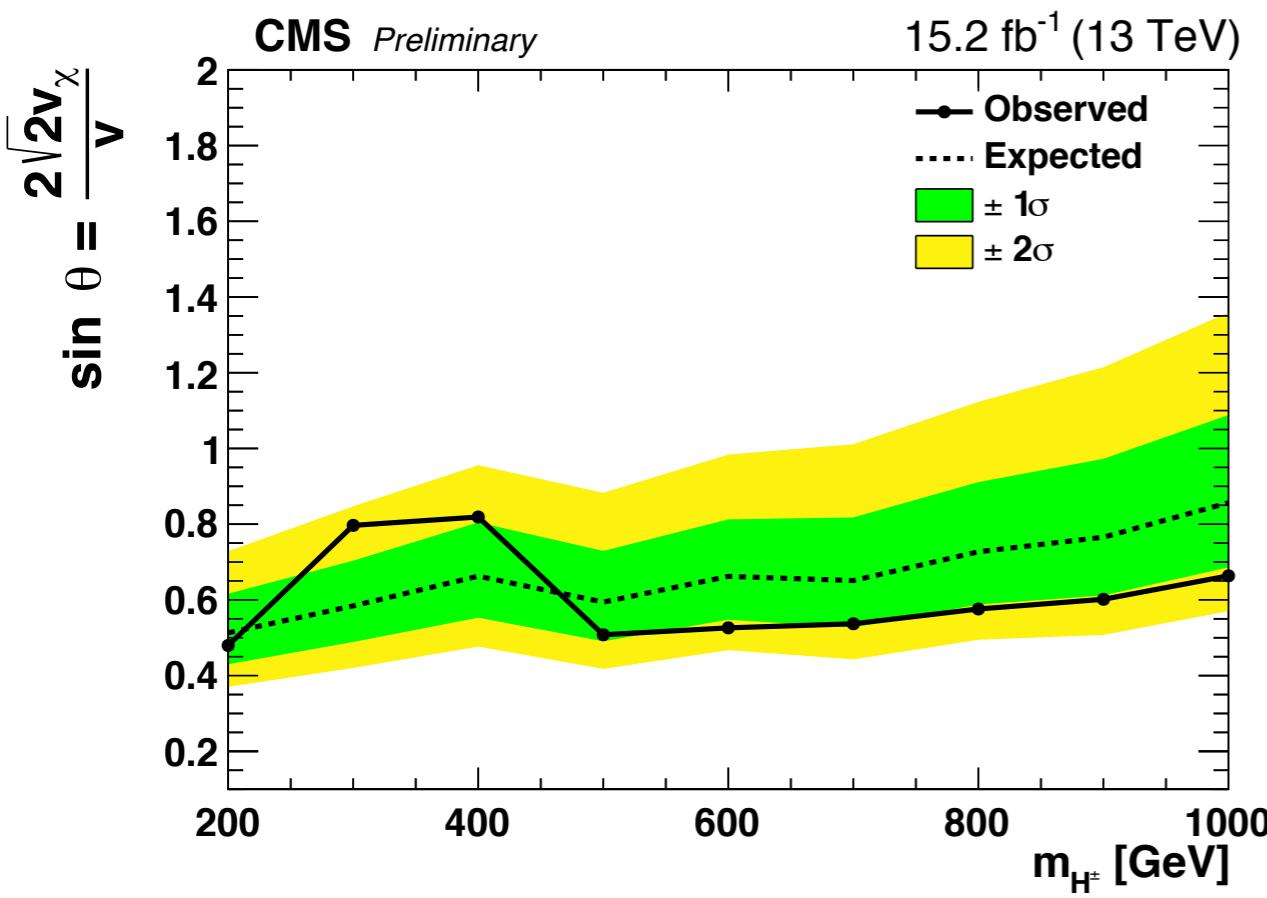
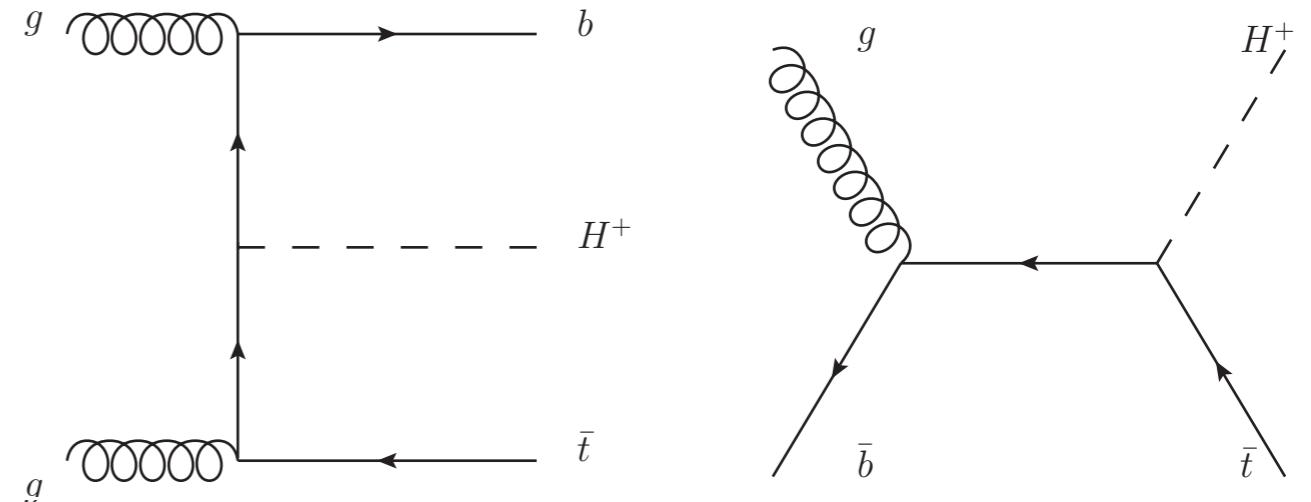
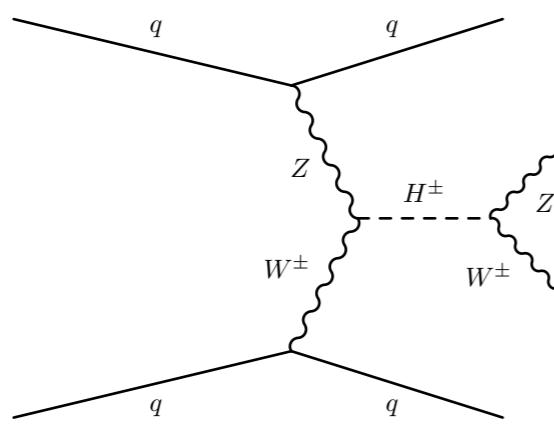
CMS SUS-16-015

CMS SUS-16-016



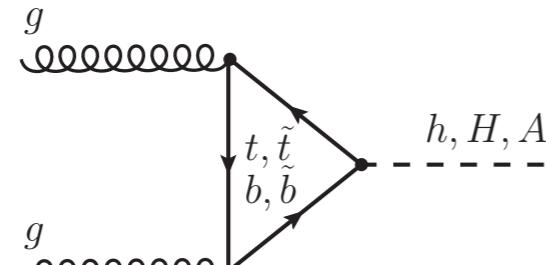
$H^+ \rightarrow WZ$ or tb

ATLAS CONF-16-089
CMS HIG-16-027

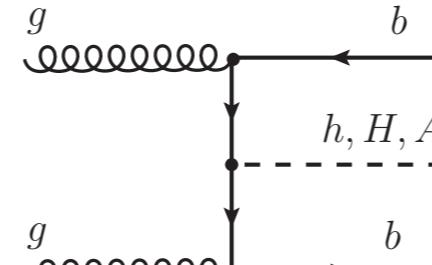


$\Phi \rightarrow \tau\tau$

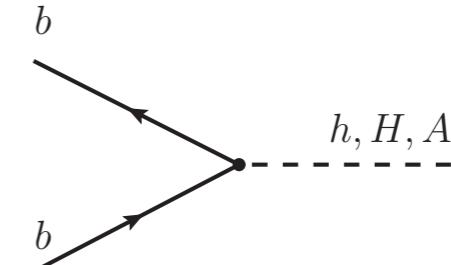
CMS HIG-16-037



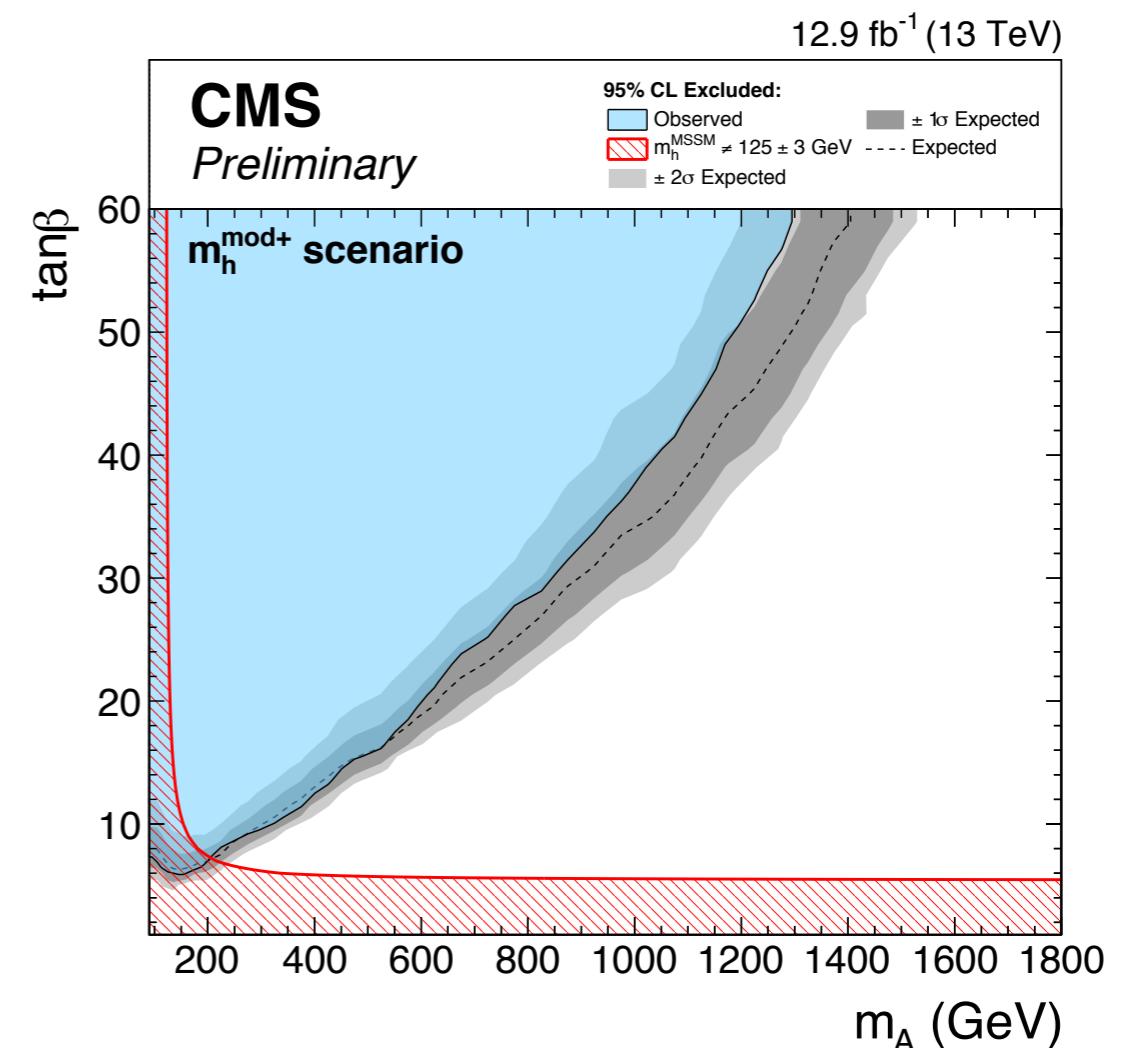
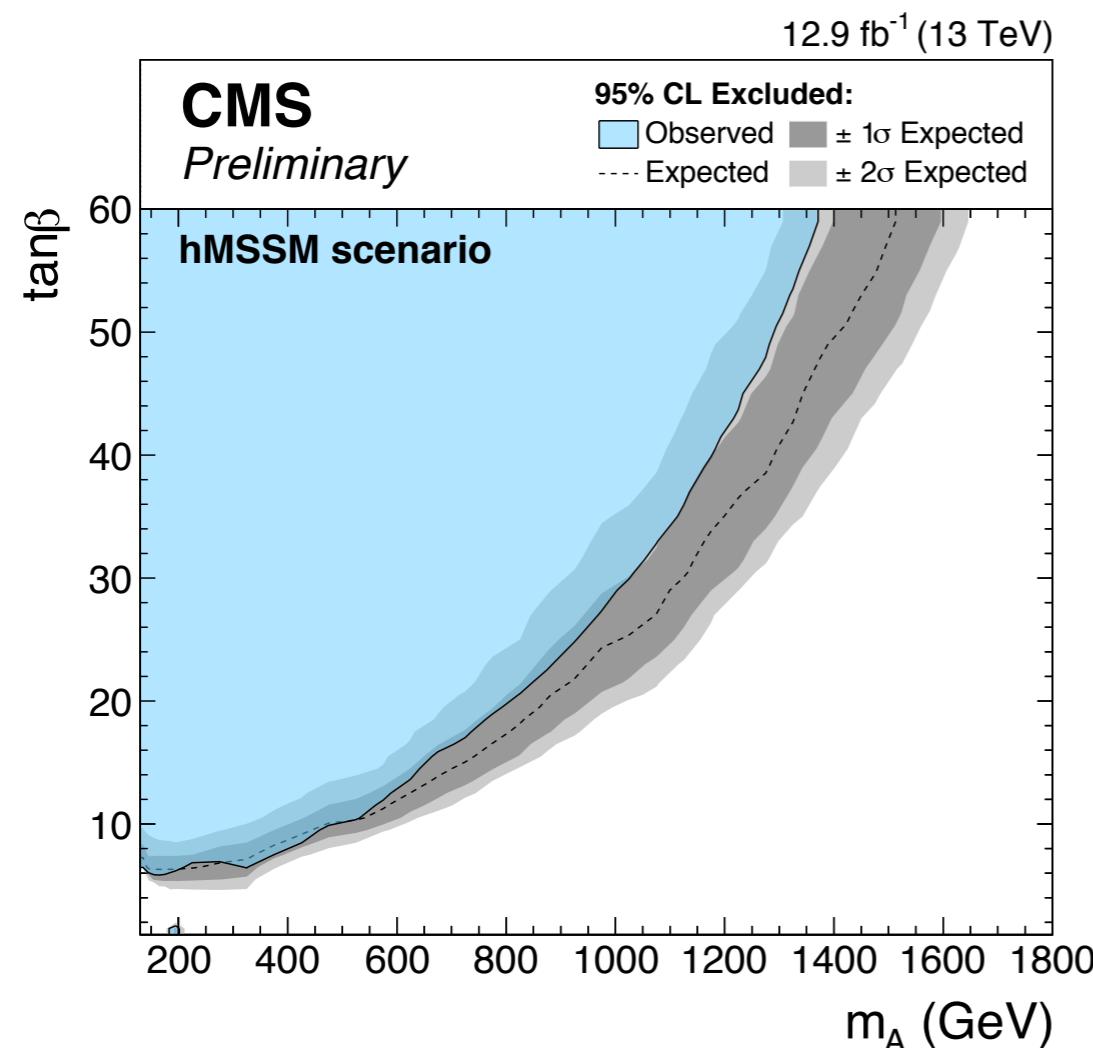
(a)



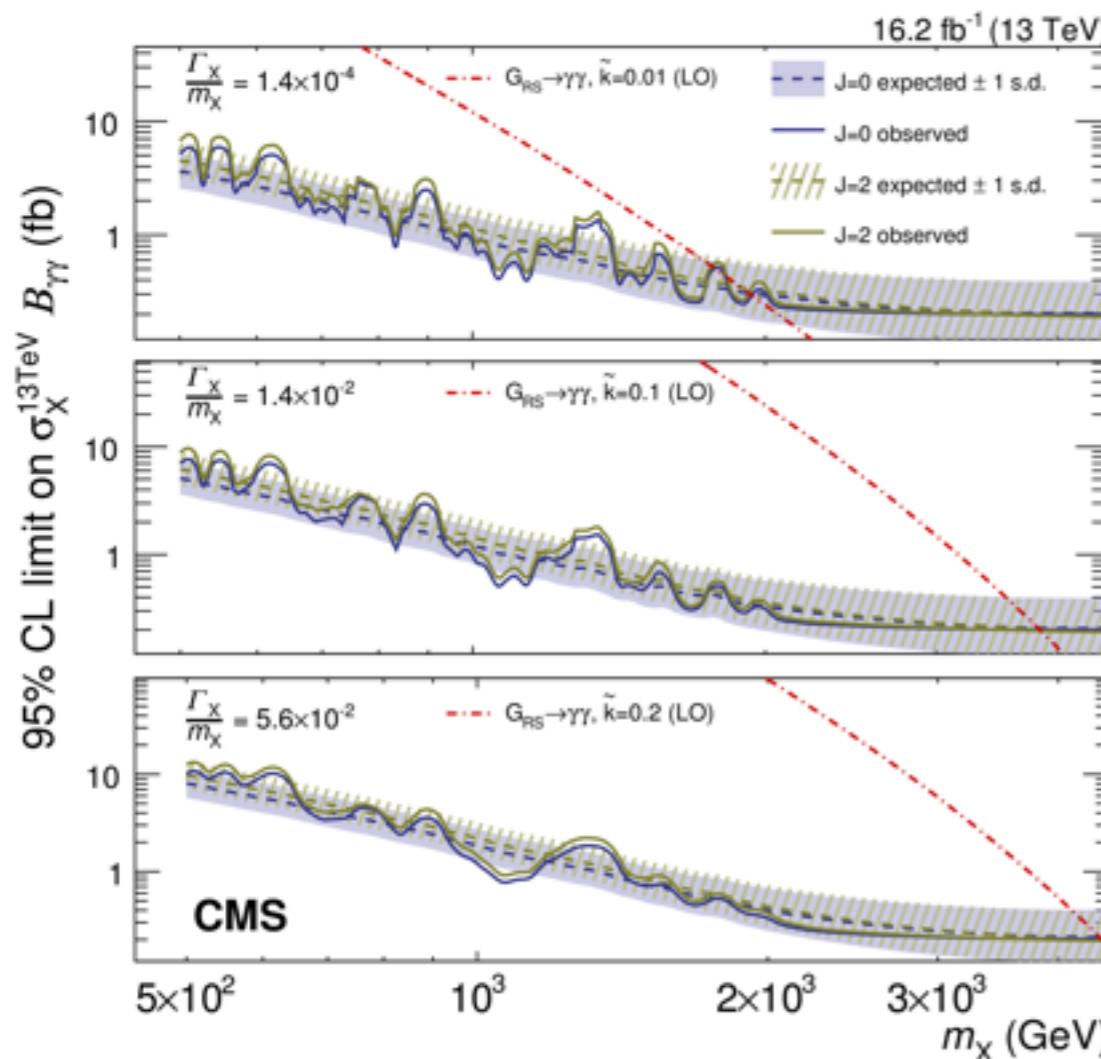
(b)



(c)



High mass search for $\gamma\gamma$



\tilde{k}

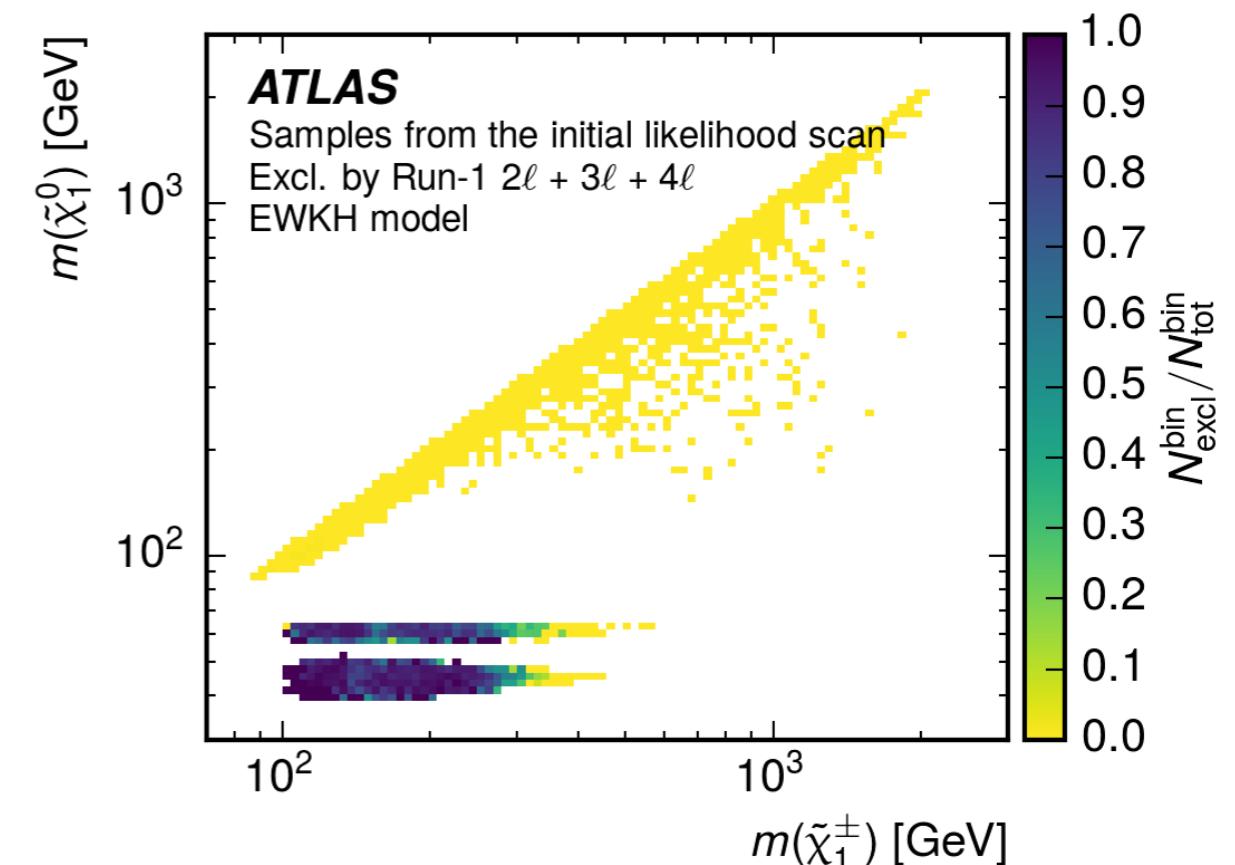
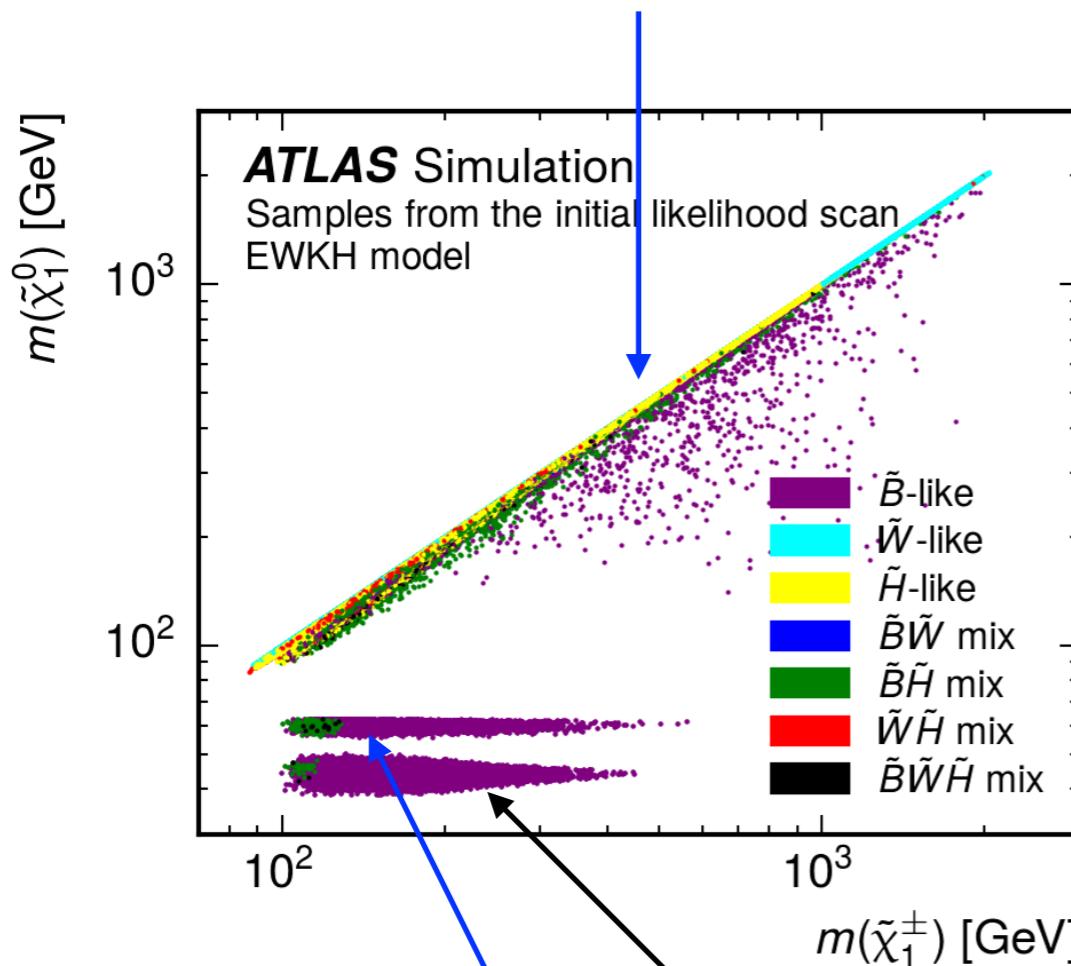
Exclusion

0.01 1.95 TeV, except 1.75-1.85 TeV

0.1 3.85 TeV

0.2 4.45 TeV

A-funnel : dark matter annihilates through the pseudo scalar Higgs boson pole



Z-funnel : annihilation rate is proportional to higgsino fraction of the neutralino

h-funnel : neutralino annihilates through a mechanism similar to Z-funnel but involving the lightest Higgs boson instead. Annihilation rate is proportional to the higgsino fraction as well as the combined bino and wino fraction