CMS Experiment at the LHC, CERN
Data recorded: 2015-Oct-27 11:51:17.472320 GMT
Run / Event / LS: 260043 / 994191540 / 754

Searches for an extended Higgs sector, investigations of Higgs couplings and heavy resonances at LHC (summary of the Mini-workshop on BSM Higgs and more)

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IPN Lyon (IN2P3-CNRS)/Université Claude Bernard Lyon 1

5th International Conference on New Frontiers in Physics (ICNFP2016)

Orthodox Academy of Crete
Kolymbari, July 14 2016

CMS Experiment at the LHC, CERN
Data recorded: 2015-Oct-31 09:16:09.743936 GMT
Run / Event / LS: 260431 / 715537073 / 425

This talk is an attempt to summarize presented results on: Higgs boson Couplings, Heavy Higgs bosons and other resonances, and Higgs pair production:

- Mini-workshop July 11 (A. Carvalho,T. Dorigo, M. Gouzevitch):
  - STAMOU Emmanuel (Weizmann Institute) "Higgs couplings to fermions: opportunities at the LHC"
  - CARMONA Adrian (CERN) "Shedding some light on the diphoton excess"
  - HALLADJIAN Garabed (Michigan State University, US) "Search for new resonances with mass between 500 GeV and 1 TeV with final states other than two photons (ATLAS+CMS)"
  - GROEBER Ramona (INFN Sezione di Roma Tre) "Pair production of beyond the Standard Model Higgs bosons"
  - SUN Xiaohu (SFU Simon Fraser University, CA) "Searches for HH production by the ATLAS collaboration"
  - POZDNYAKOV Andrey (National Central University, TW) "Searches for HH production by the CMS collaboration"
  - SNYDER Scott (Brookhaven National Laboratory,US) "Searches for Heavy A, H, H++ by the ATLAS and CMS collaborations and interpretation

- Parallel Sessions July 8, 9, 11,13:
  - DORDEVIC, Milos (Vinca Institute, University of Belgrade) "ttH production at 13 TeV (CMS)"
  - SAXENA, Pooja (Deutsches Elektronen-Synchrotron) "Higgs decay to fermions (CMS)"
  - MAZINI, Rachid (Academia Sinica) "Search for non-standard and rare decays of the Higgs boson with the ATLAS detector"
  - CATA, Oscar (LMU Munich) "Higgs couplings: upgrading the kappa formalism with EFT"
  - CHENG, Tongguang (Chinese Academy of Sciences) "Higgs couplings (CMS)"
  - DI LUZIO, Luca (University of Genoa) "Perturbative unitarity and the LHC di-photon excess"

- MALEK Fairouz (LPSC-Grenoble)"Search for a high mass diphoton resonance using the ATLAS detector"
- CHECCHIA Paolo (Universita e INFN) "BEH Boson (CMS)"

- Plenary talks July 7, 9, 13:
  - CARVALHO Alexandra (CERN)"Searches for production of Higgs boson pairs and a heavy extended Higgs sector"
  - BIINO Cristina (INFN Torino)"Selected Recent Results from CMS"
  - QUITTNAT Milena (Eidgenoessische Tech. Hochschule Zuerich) "Diphoton searches (CMS)"

Higgs boson (125 GeV) Couplings: Knowing 'the known' better

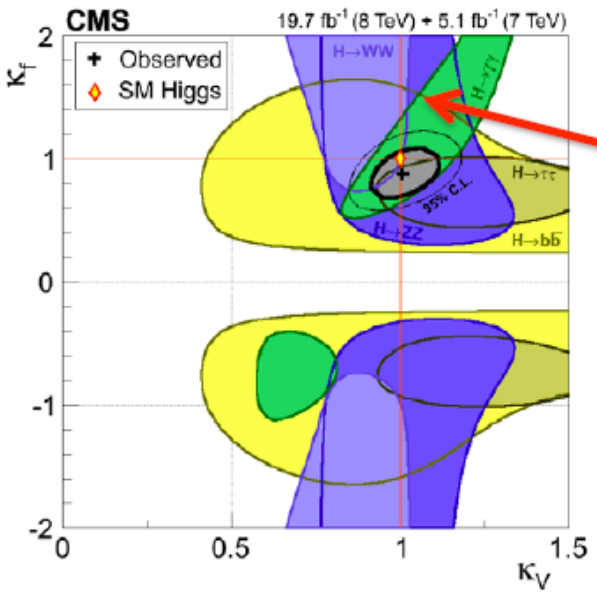
- **Five main decay channels all published**
- **All results consistent with SM Higgs**

CMS only

$$m_H = 125.02\ ^{+0.26}_{-0.27}\ (stat.)\ ^{+0.14}_{-0.15}\ (syst.)\,GeV$$

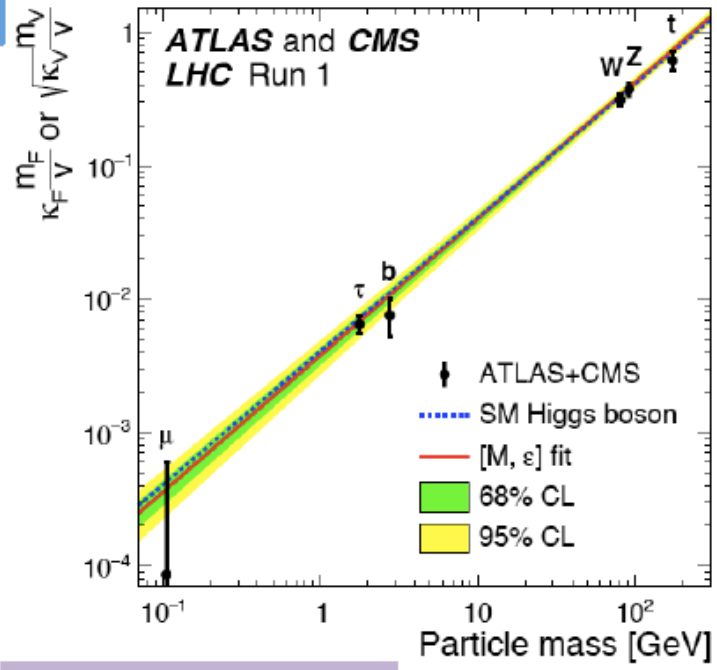
$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV}$$

ATLAS & CMS



SM

Channel	Obs (σ)	Exp(σ)
H → ZZ	6.5	6.3
H → γγ	5.6	5.3
H → WW	4.7	5.4
H → ττ	3.8	3.9
H → bb	2.0	2.6
H → μμ	<0.1	0.4

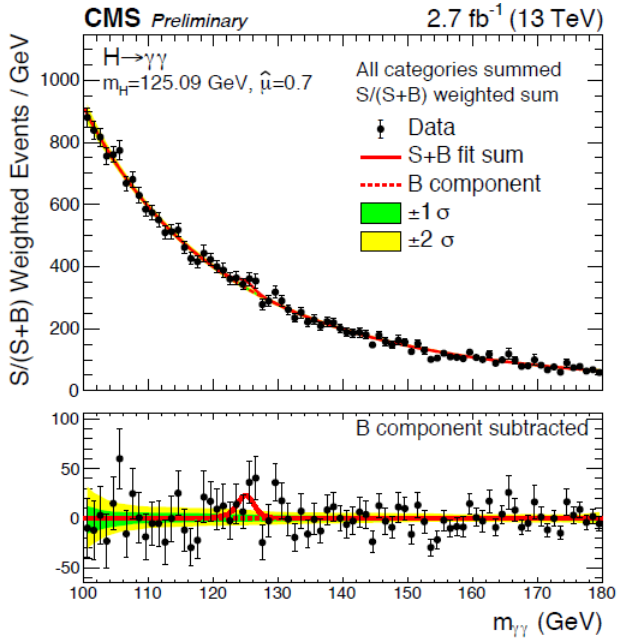


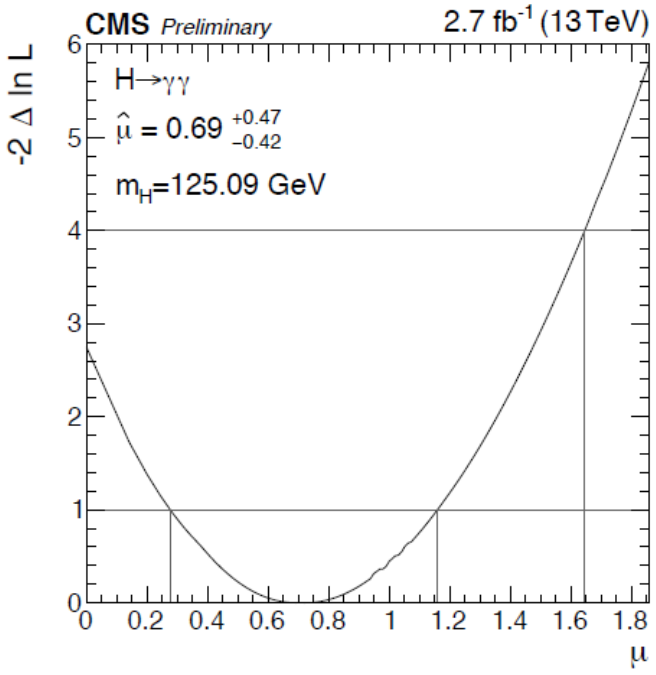
arXiv: 1606.02266

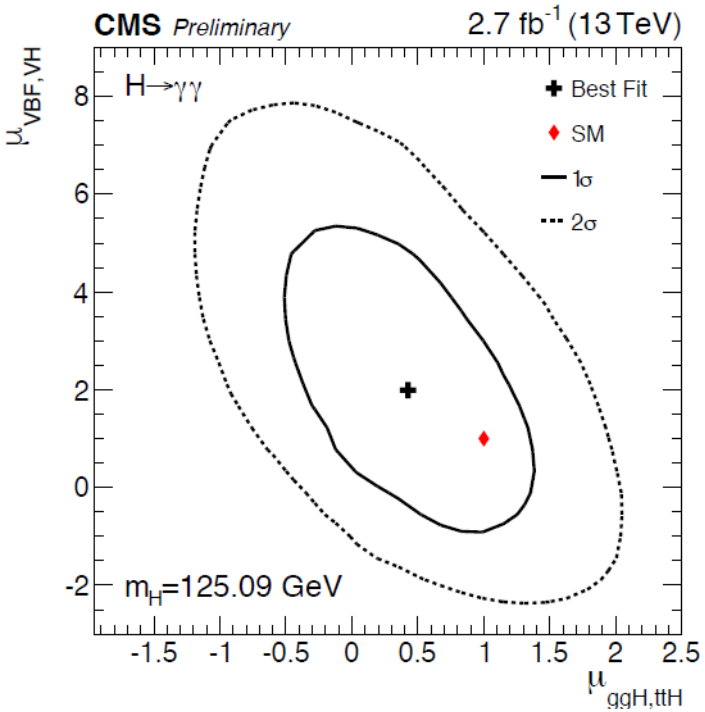
A. Carvalho, C. Biino, M. Gouzevitch , P. Saxena, R. Mazini

- "Space" left for BSM: BR to new particles <34%, uncert. on μ leave ~10%.

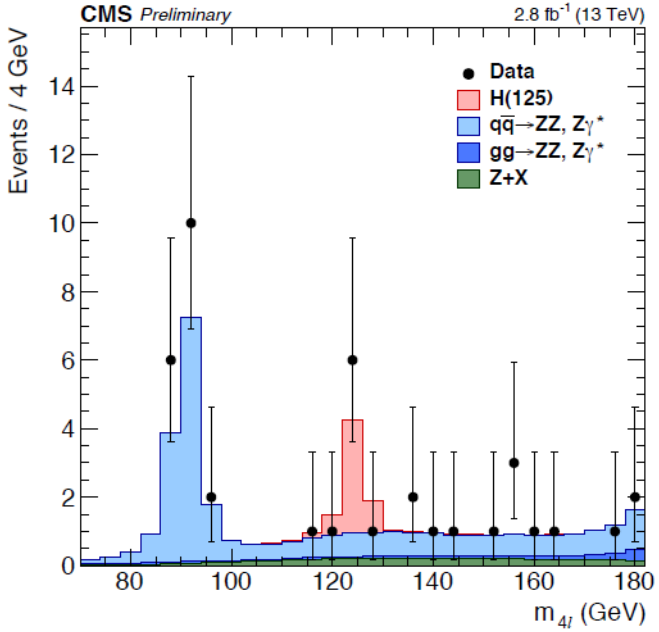
Higgs boson (125 GeV) Couplings: H→γγ, H→ZZ*→4l (CMS)

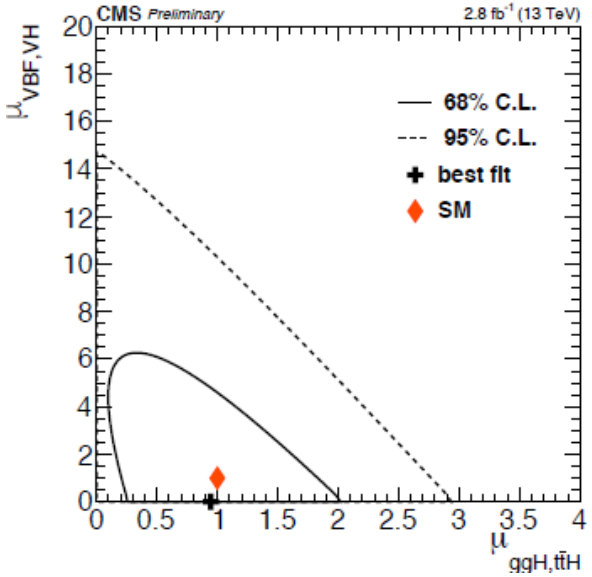


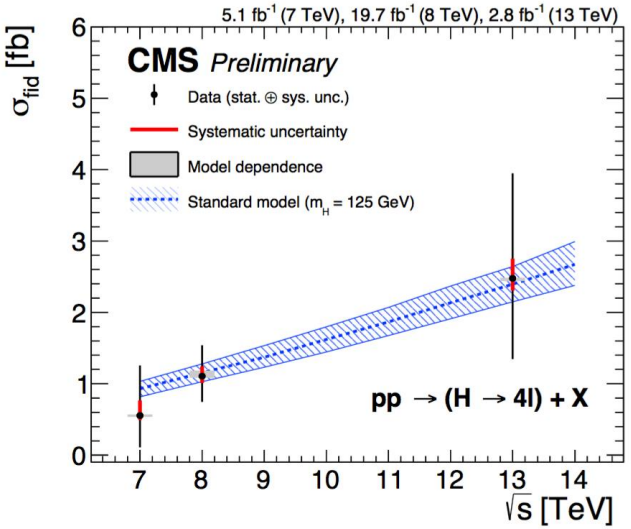




T. Cheng,
P. Checchia ,
C. Biino



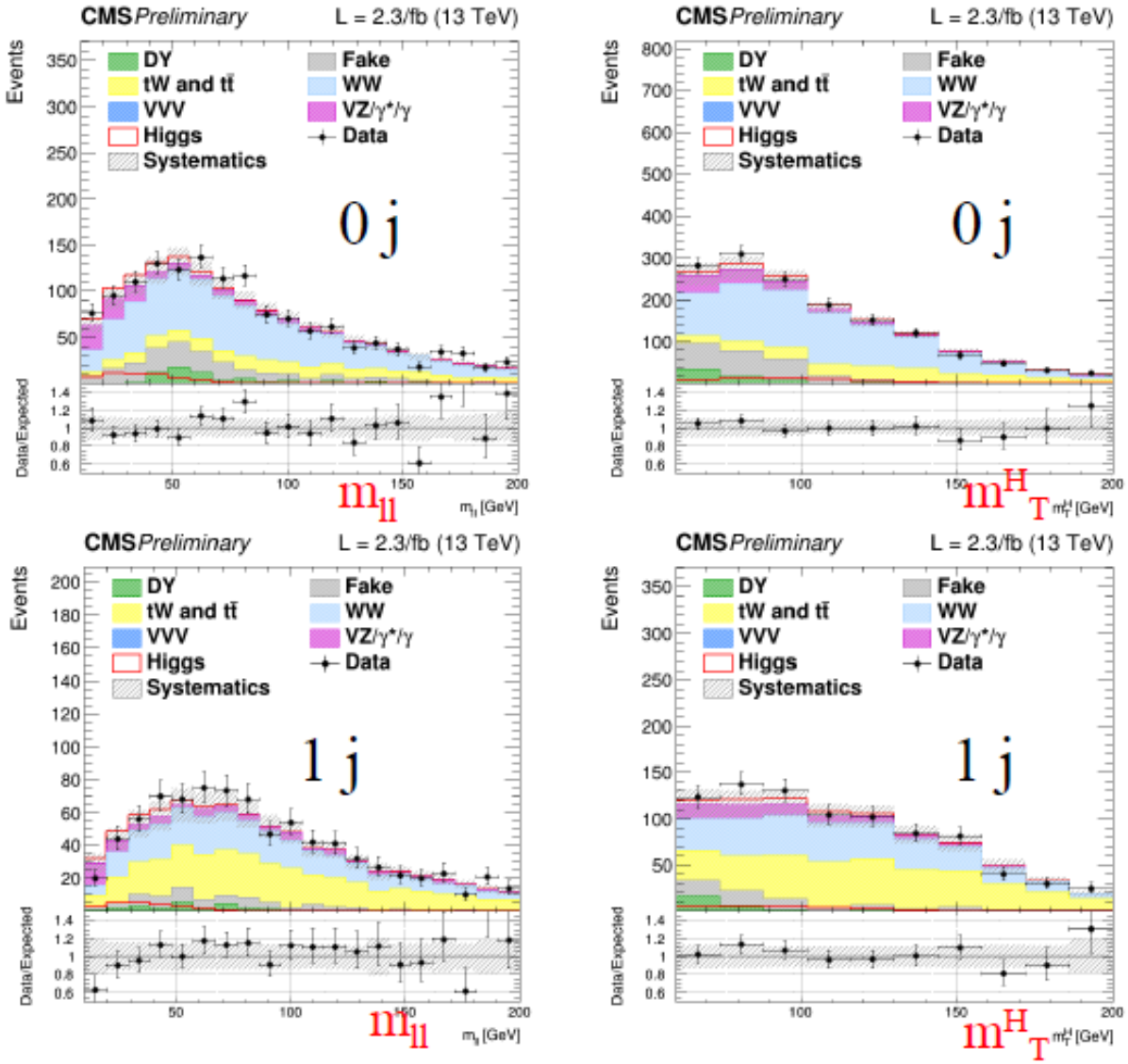




Higgs boson (125 GeV) Couplings: H→WW (CMS)

P. Checchia

H→WW **WW→eμ 0/1 jet**



NEW

HIG-15-003

Signal/bckg as function of m_{ll} and m^H_T

events divided in 4 categories:
μe, eμ (leading p_t)
0j , 1j

Two dimensional plot (m_{ll},m_T)

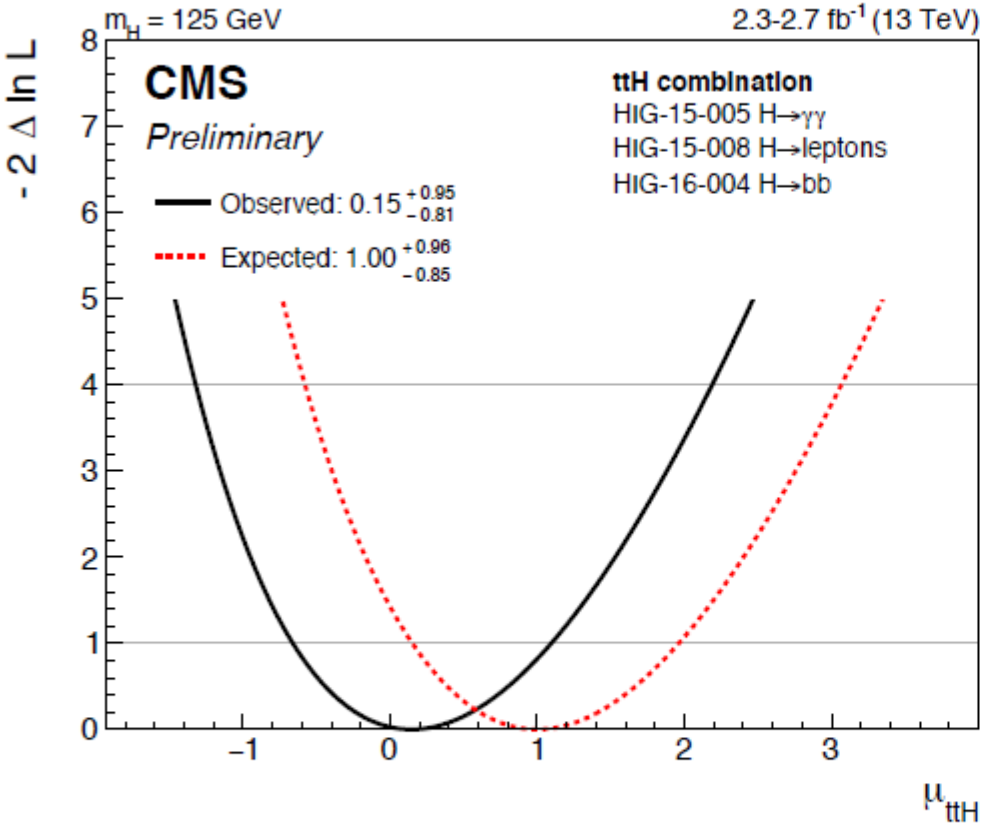
Significance w.r.t. bckg only:
0.7 σ (2.0)

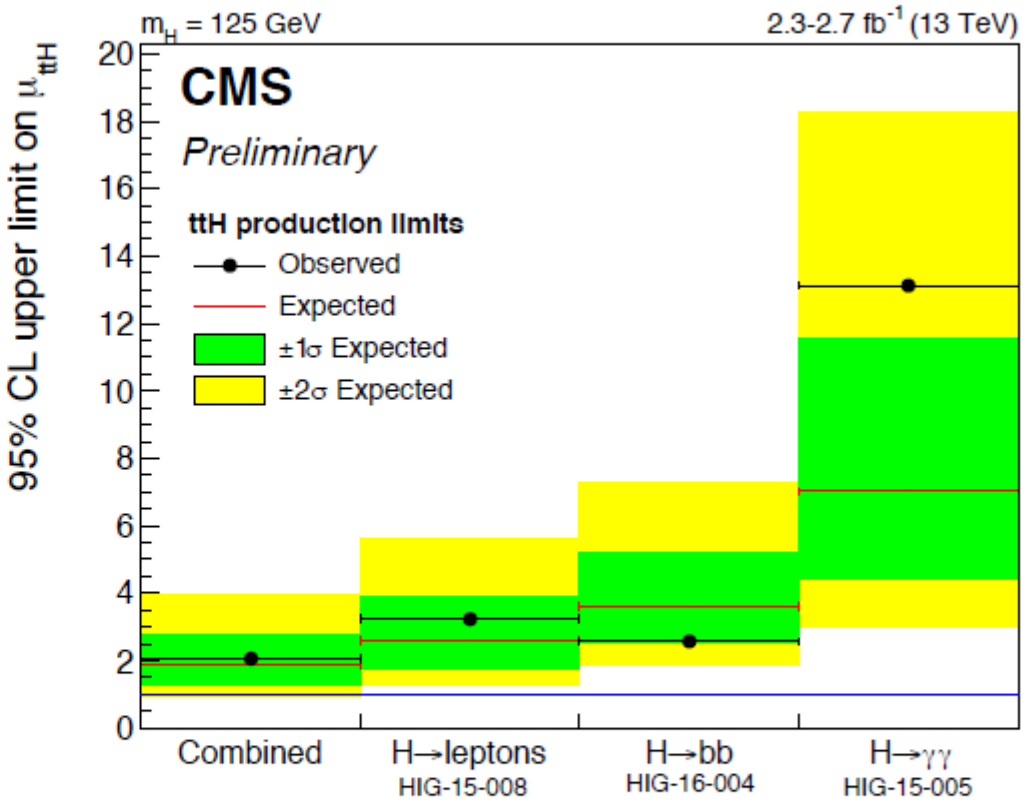
16

Higgs boson (125 GeV) Couplings: ttbarH (CMS)

M. Dordevic, T. Cheng, P. Checchia

https://twiki.cern.ch/twiki/bin/view/CMSPublic/TTHCombMoriond2016





Best fit value : $\mu_{ttH} = 0.15^{+0.95}_{-0.81}$

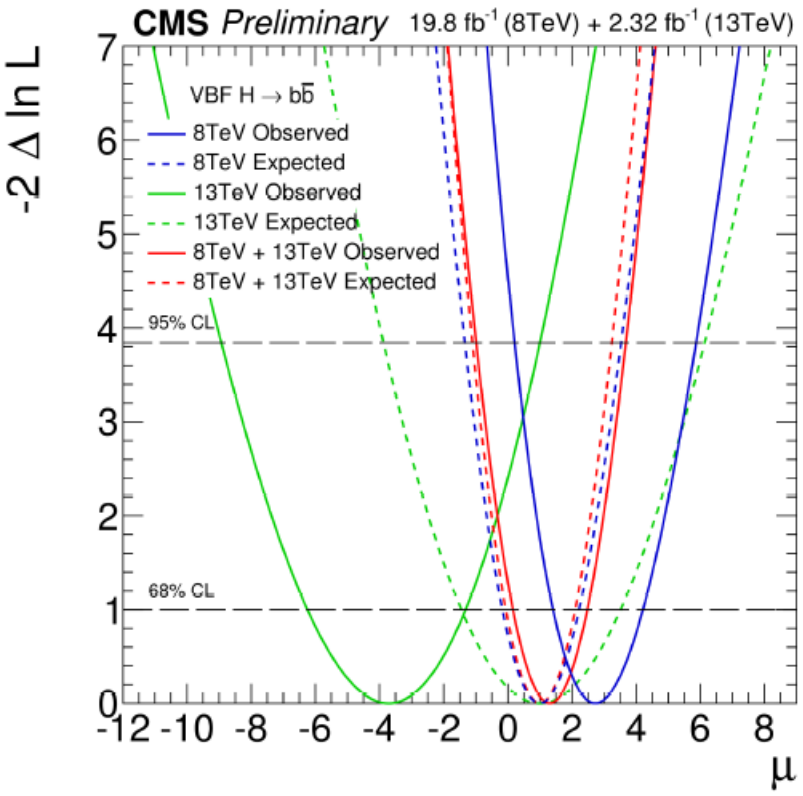
Run 1 : $\mu_{ttH} = 2.8 \pm 1.0$

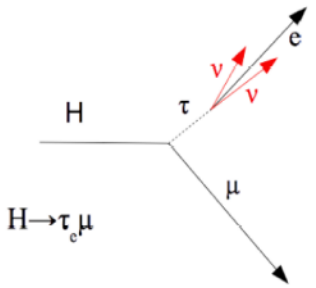
Observed (expected) limit : μ_{ttH} = 2.1 (1.9)

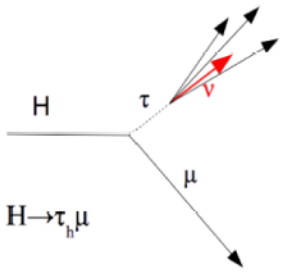
Run 1: μ_{ttH} = 4.5 (1.7)

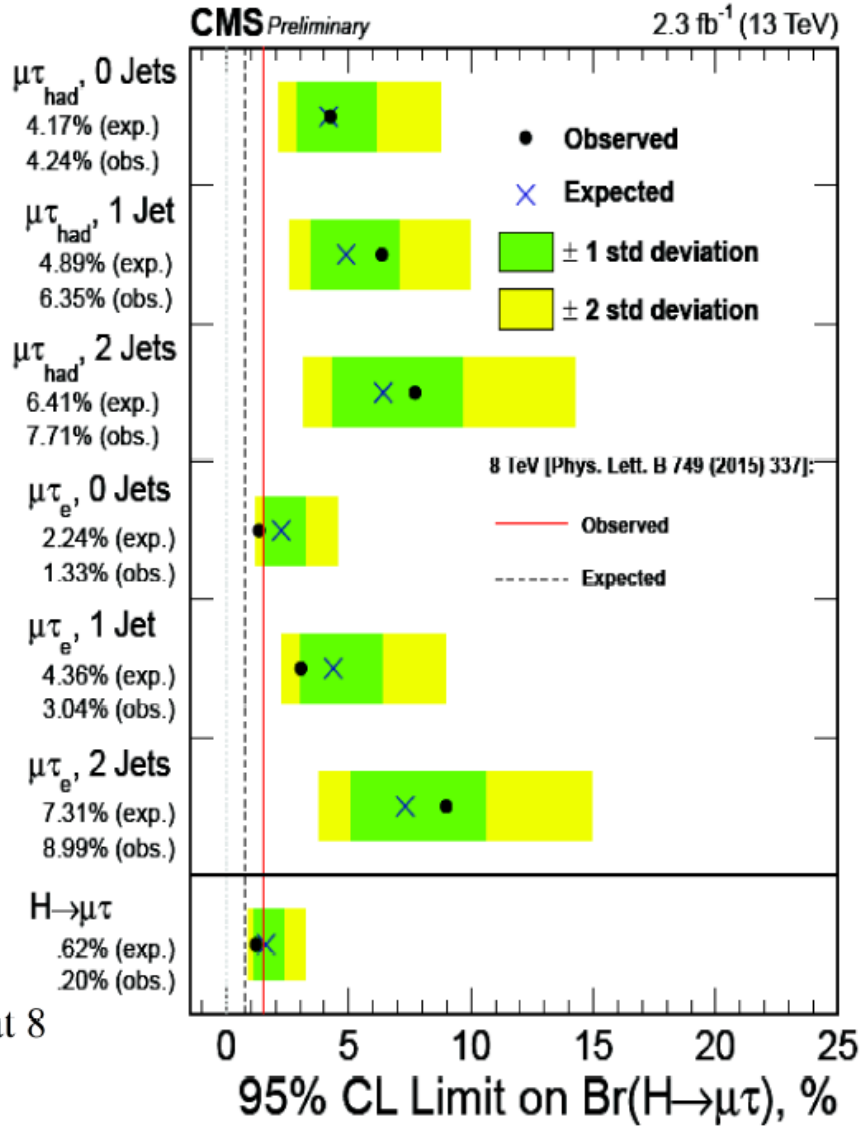
H125 Couplings: H→bb (VBF), H→μτ (LFV) (CMS)

T. Cheng, P. Saxena









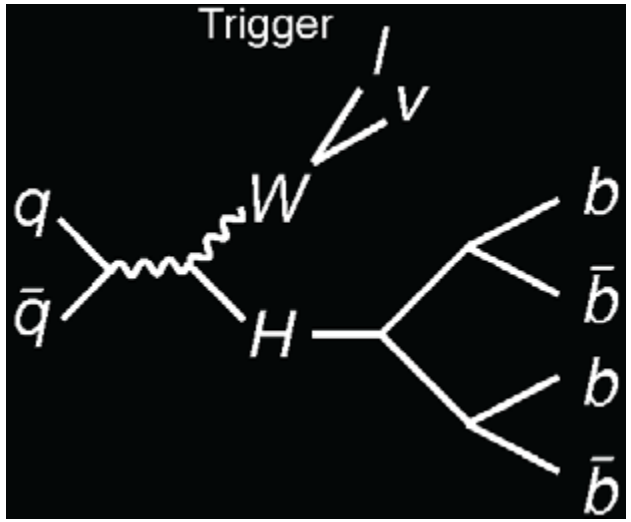
- Combination Runs 1+2:

$\mu = \sigma/\sigma_{SM} = -1.3^{+1.2}_{-1.1}$

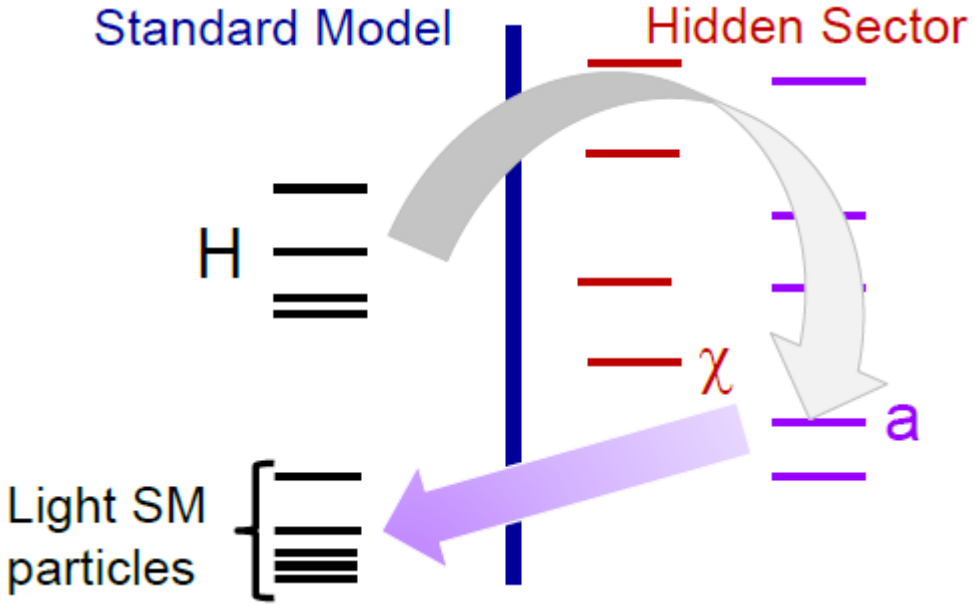
- Observed limit 1.20 % (exp. 1.62%)
  - Slightly tighter than the previous limits at 8 TeV [obs 1.5% (exp 0.8)]
  - Significantly less statistics than at 8 TeV

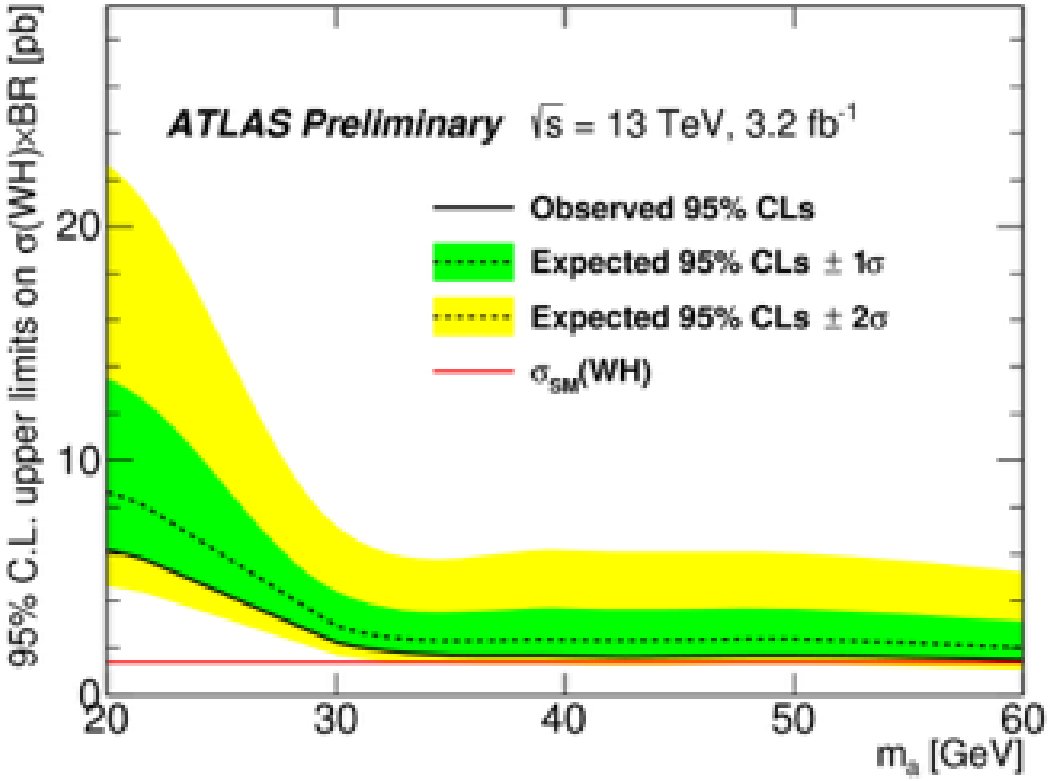
Higgs125 Couplings: WH→lνaa→lνbbbb (ATLAS)

R. Mazini

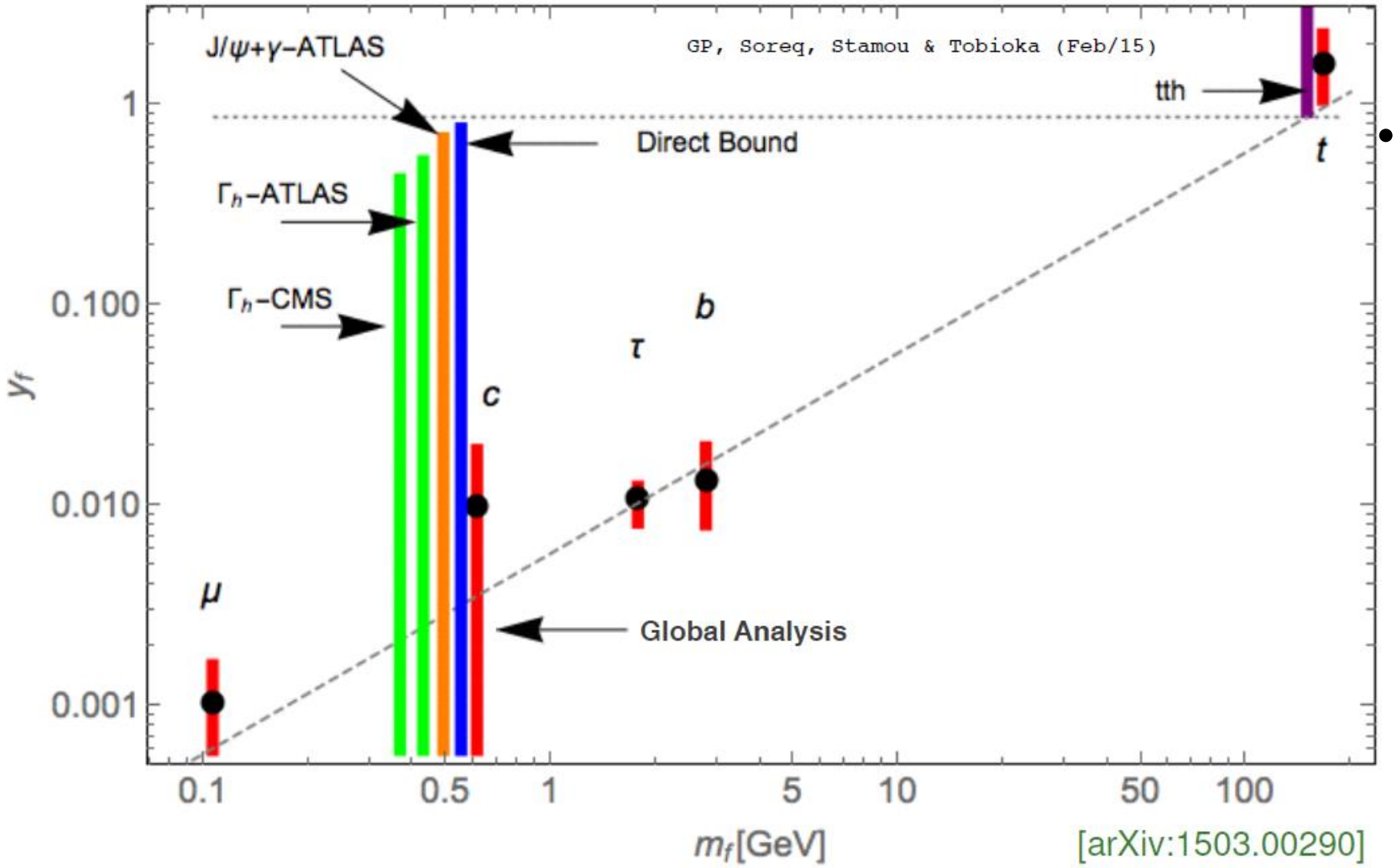


- Search range: $20 < m_a < 60$ GeV
- Upper limits on σXBR: 6.2pb, m_a=20GeV
  1.5pb, m_a=60GeV





Higgs125 Couplings: Light Quarks



E. Stamou

- Try to measure light quark Yukawa couplings via light flavor tagging (especially c)

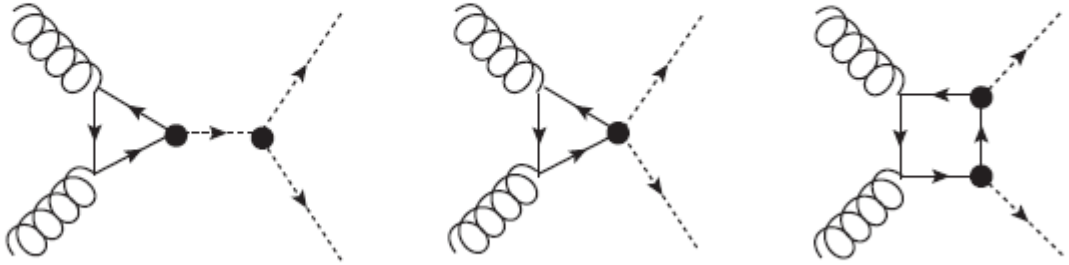
Higgs125 Couplings: How to update the "κ" formalism

O. Catà

- The κ formalism can be embedded in a consistent QFT framework if interpreted as the leading Lagrangian of a (nonlinear) EFT. Well-defined way to improve it to include kinematical distributions (though very suppressed...)

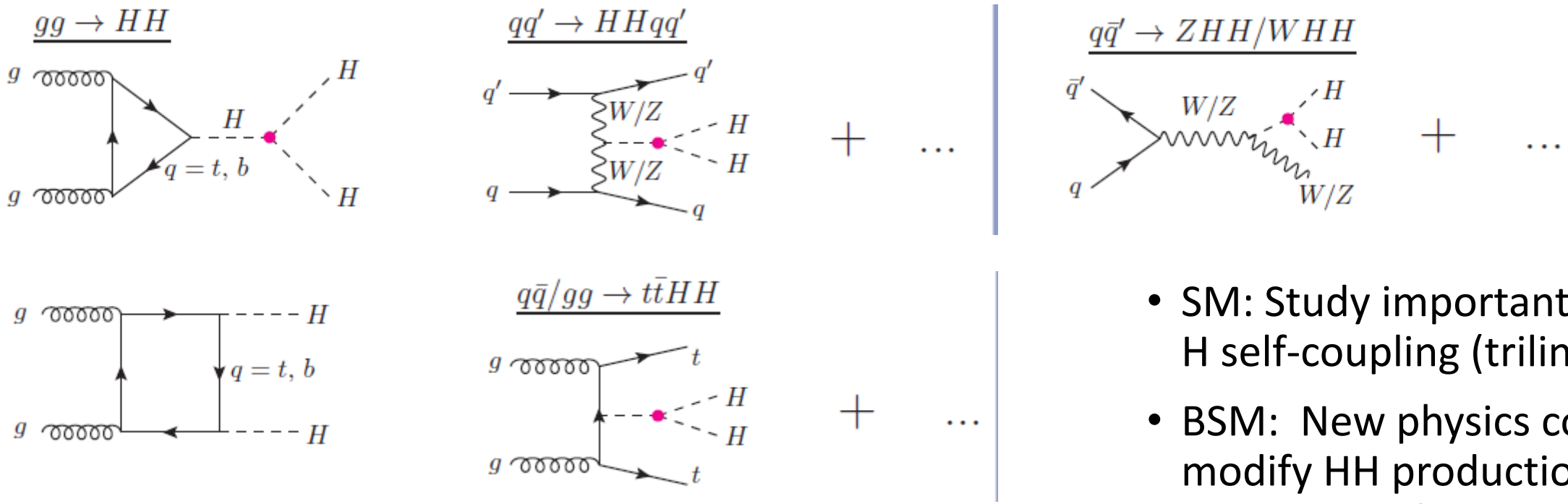
- NONLINEAR EFT. Modifications at LO:

Name	Meaning	Symbol
Signal strength	$\frac{\sigma(\mathrm{BR})}{\sigma^{\mathrm{SM}}(\mathrm{BR}^{\mathrm{SM}})}$	μ
Coupling modifiers	$\frac{g_{HXX}}{g_{HXX}^{\mathrm{SM}}}$	κ_X
Total width modifier	$\frac{\Gamma_{\mathrm{tot}}}{\Gamma_{\mathrm{tot}}^{\mathrm{SM}}}$	κ_H^2
Ratio of coupling modifiers	$\frac{\kappa_X}{\kappa_Y}$	λ_{XY}



Higgs boson pair production

R. Grober



- Example (Modified/new couplings): Composite Higgs models (CHM)
- Non-linear: $\mathcal{L} = \frac{f^2}{2}(D_\mu \Sigma)^T (D^\mu \Sigma)$,

gauge: $\Sigma = (0, 0, 0, \sin H/f, \cos H/f)$

Parameter $\xi = \frac{v^2}{f^2} = \sin \frac{\langle H \rangle}{f}$

light, since pseudo-Goldstone boson

spin 0: H, ...

spin 1/2: T, B, $X^{5/3}$,...

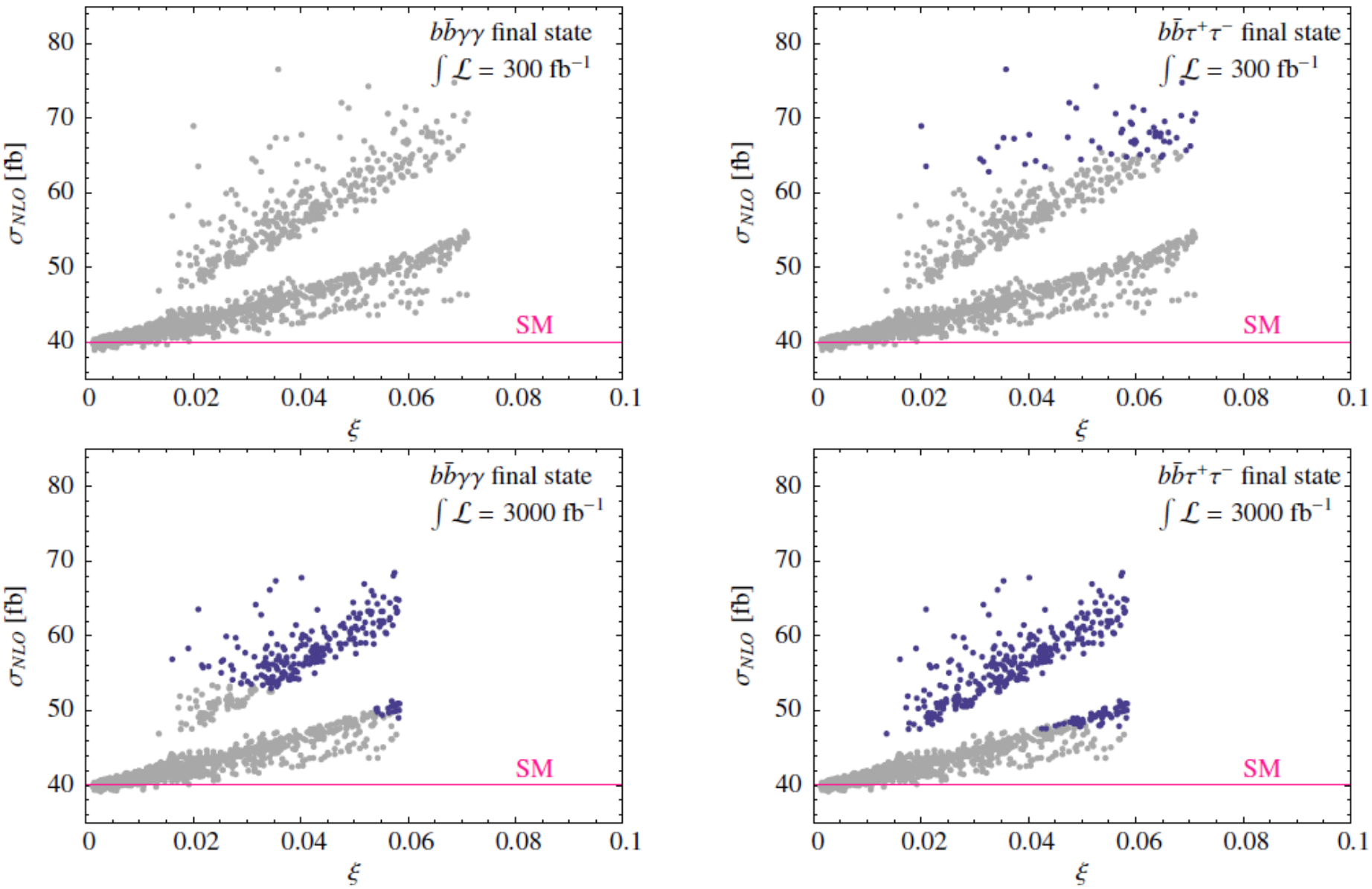
spin 1: ρ, a,...

strongly interacting sector

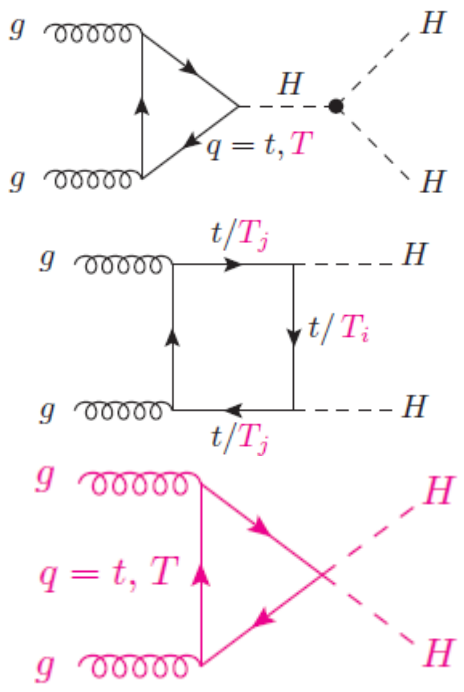
- SM: Study important to probe H self-coupling (trilinear)
- BSM: New physics could modify HH production through: **Shift** in the trilinear Higgs coupling or in other Higgs boson couplings, **Additional Higgs bosons or particles** in loops, **Novel couplings**.

HH production: Source of possible first NP observation?

[RG, Mühlleitner, Spira '16]



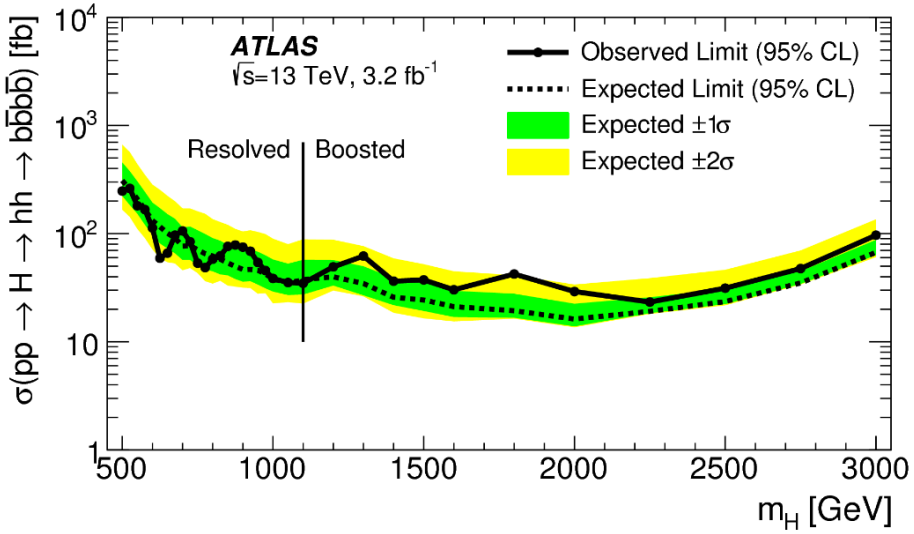
R. Grober

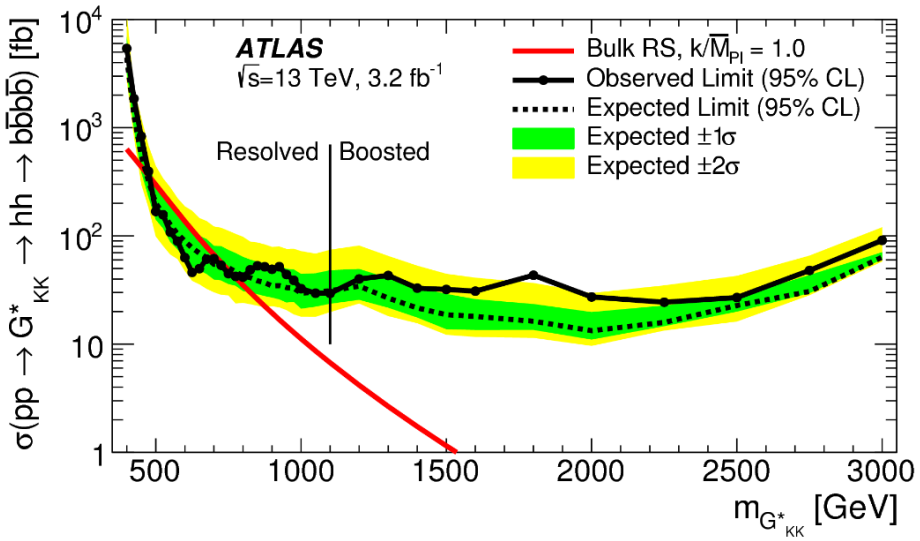


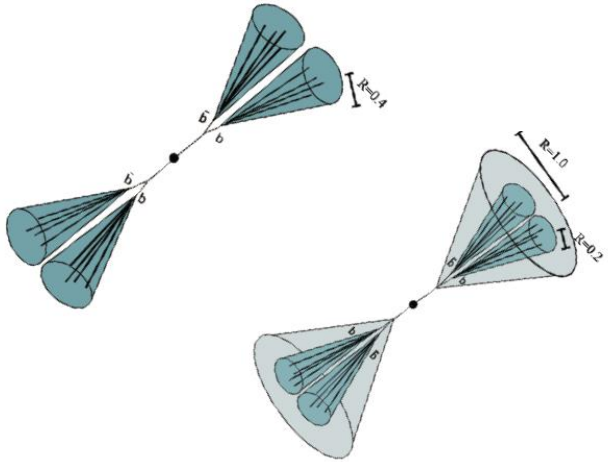
- MCHM10 model: Both bottom and top partners
- All points theoretically allowed, blue points →cross section distinguishable from SM at >3σ

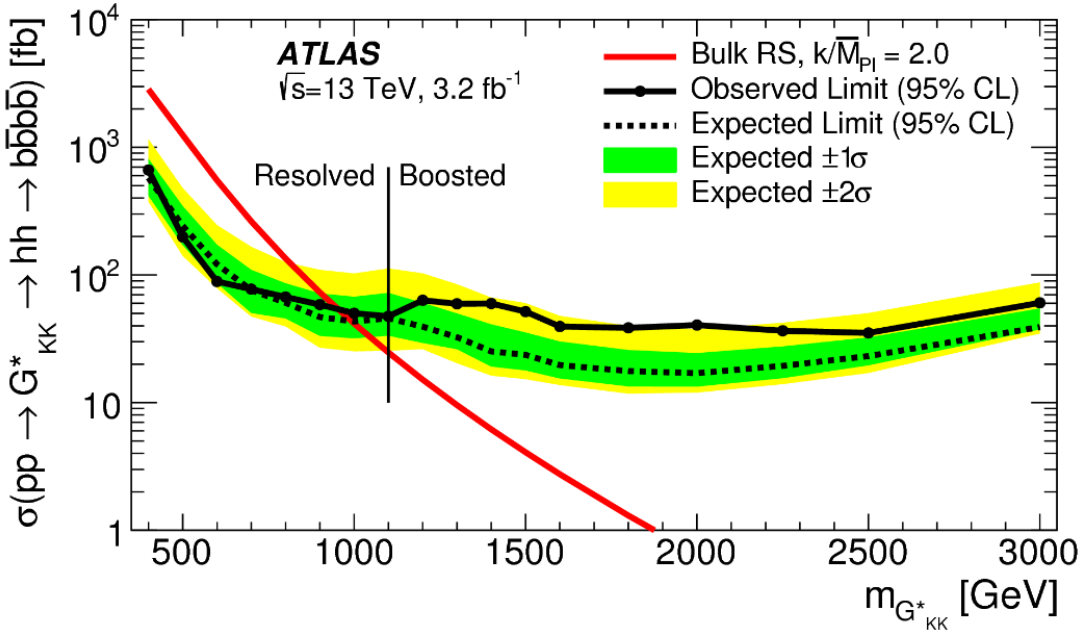
HH→bbbb: ATLAS/CMS 13 TeV Results

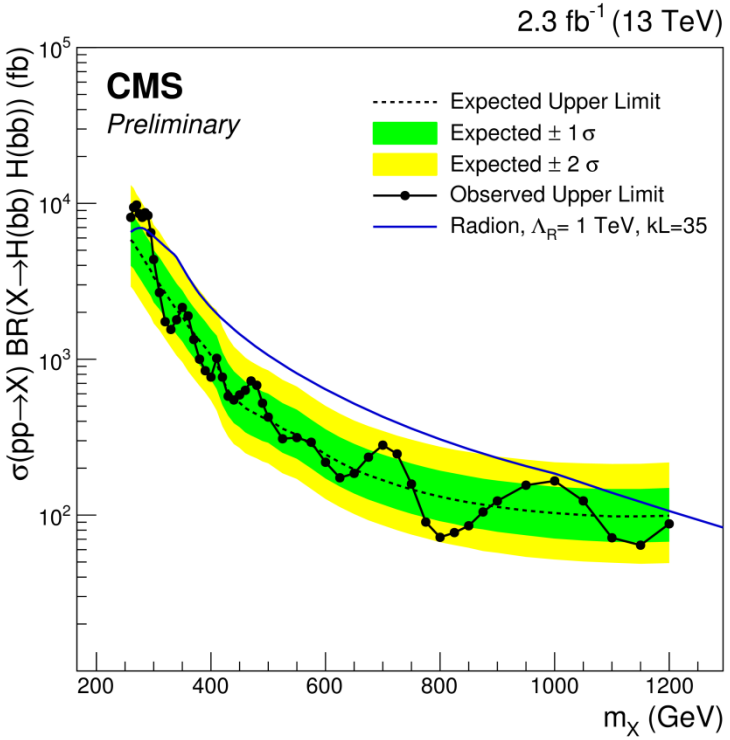
X. Sun, A. Pozdnyakov





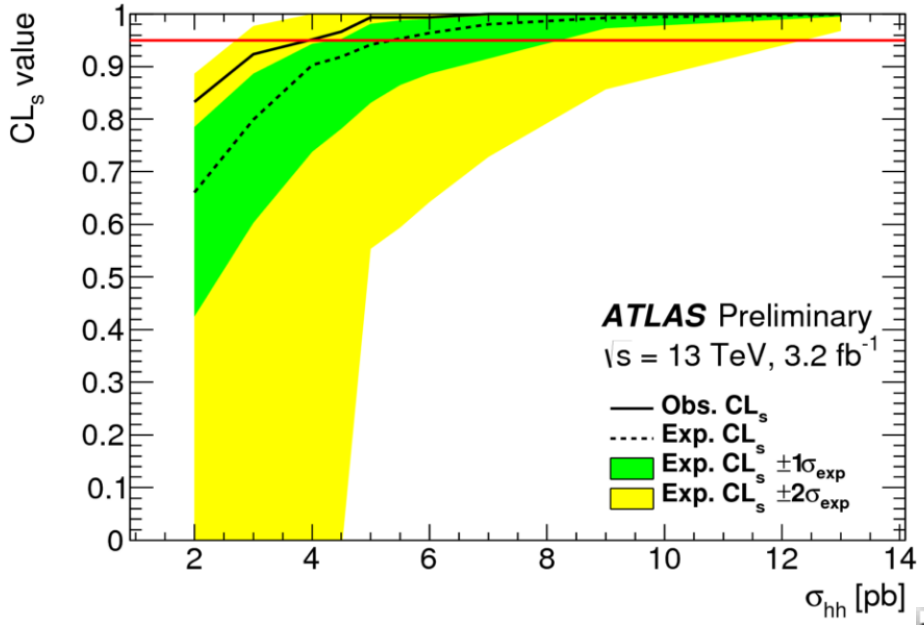


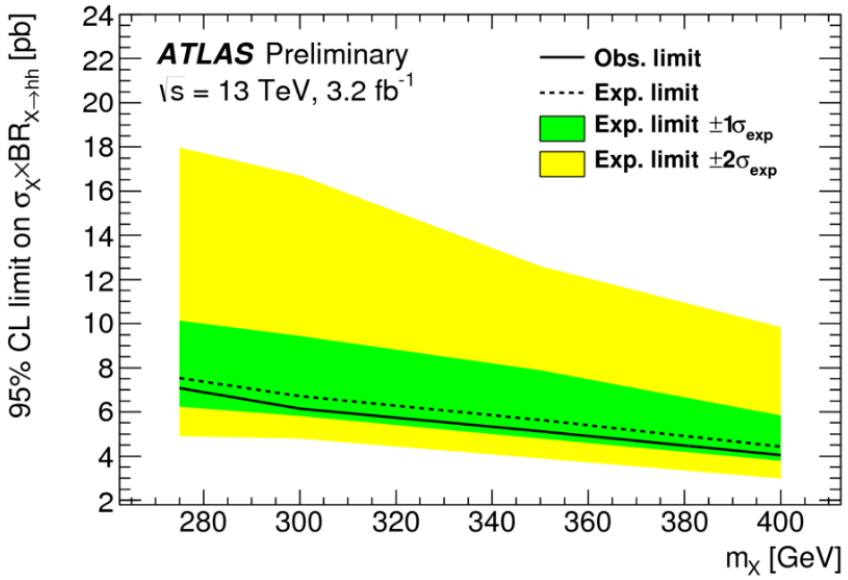




- ATLAS: Resolved and boosted (large-R jet) analyses
- ATLAS Resonant limits in both H and 2 KK Graviton interpretations
- ATLAS non-resonant limit: σXBr<1.22 pb (not shown)
- CMS non-resonant limit

HH→γγbb: ATLAS 13 TeV Results

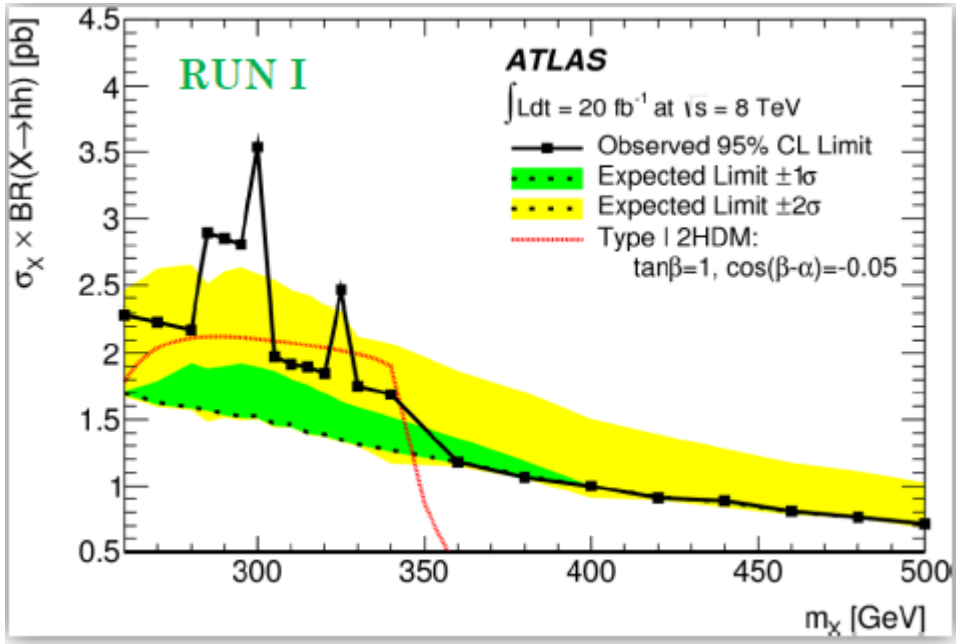




X. Sun

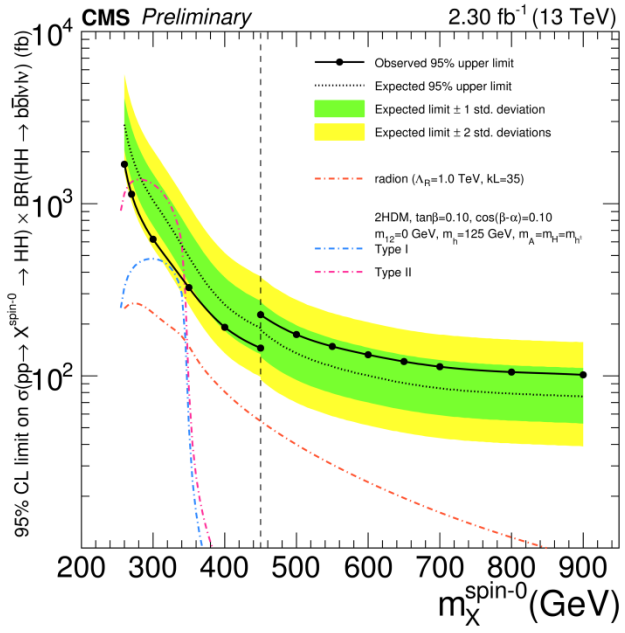
- Resonant search limits in range 275-400 GeV
- Expected: [7.5, 4.4] pb
  Observed: [7.0, 4.0] pb
- The RUN II upper limits do not exclude RUN I results

- Non-resonant 95% CL upper limit on σ: Observed (Expected)= 3.9 (5.4)pb

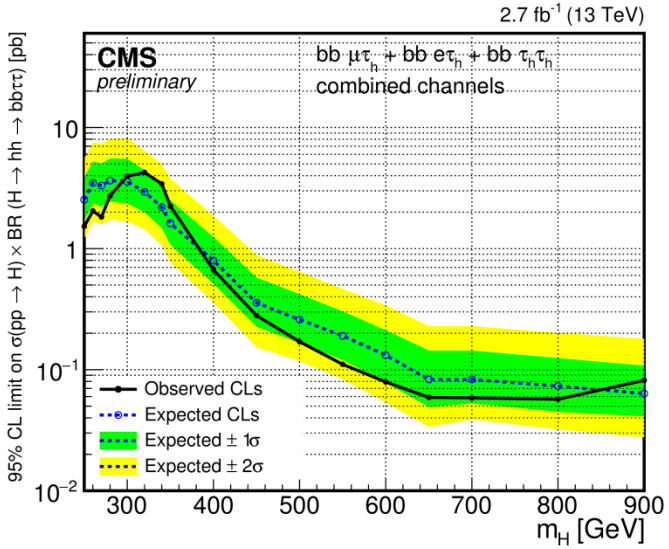


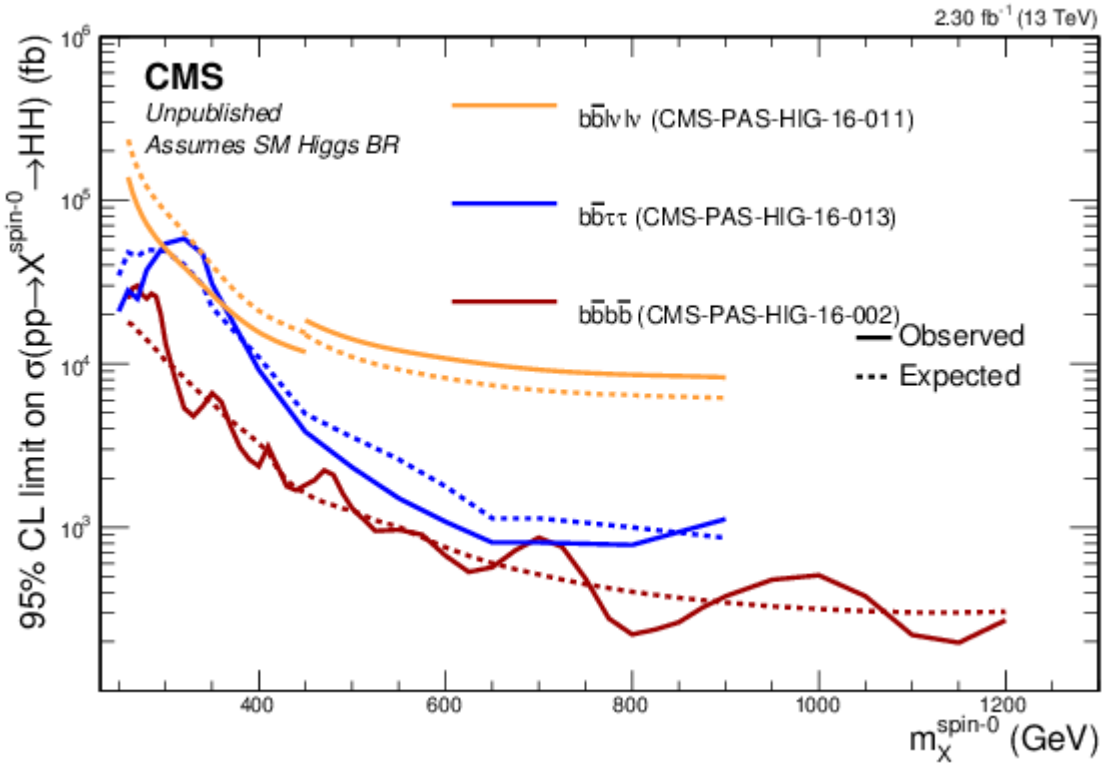
HH→bbWW, bbττ, : CMS 13 TeV Results

A. Pozdnyakov



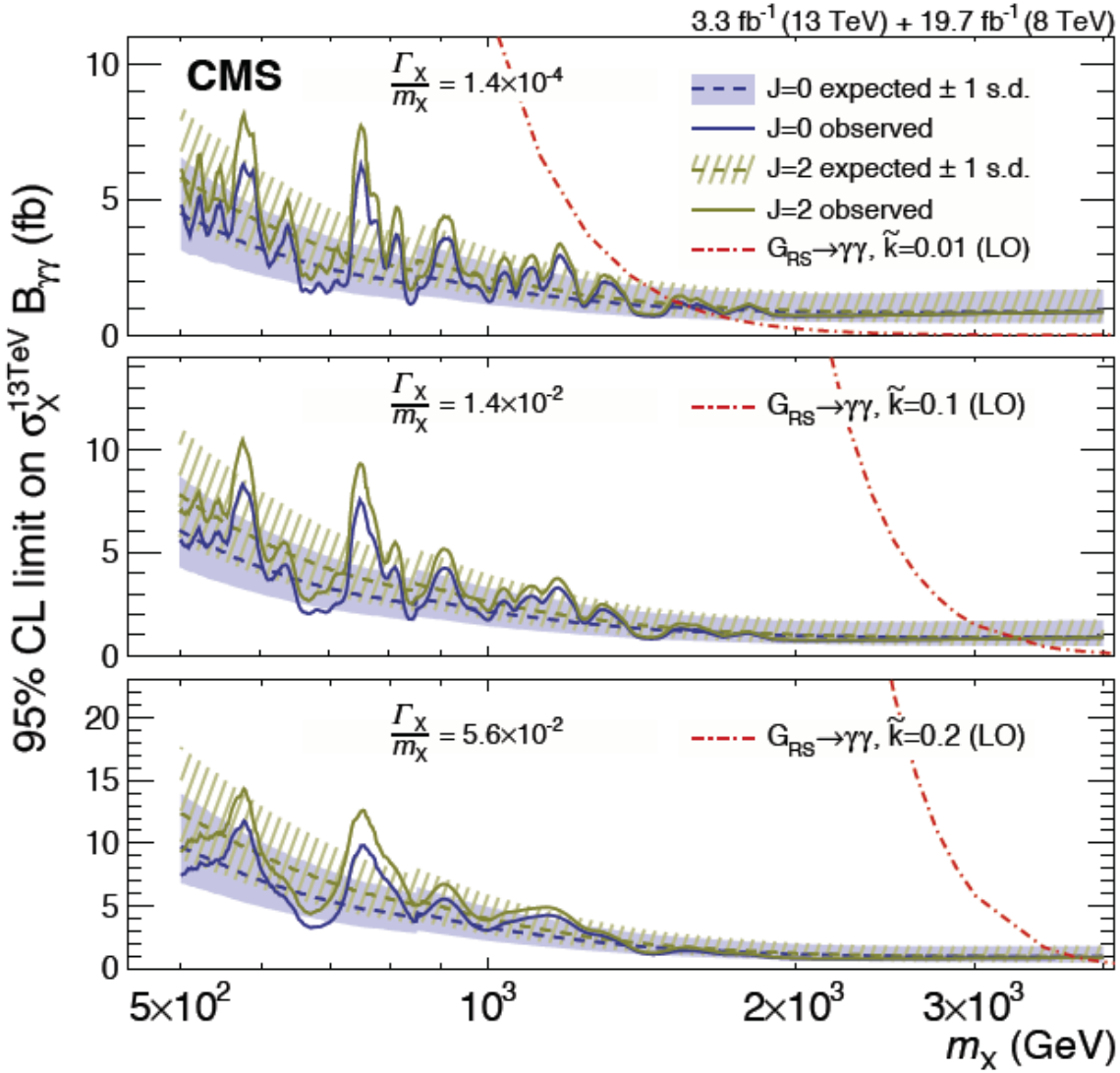
- X(spin-0)→HH→bbww: Radion and 2HDM interpretations (Types I,II)
- H→hh→ bbττ
- Summary of all 3 channels assuming SM Higgs BR



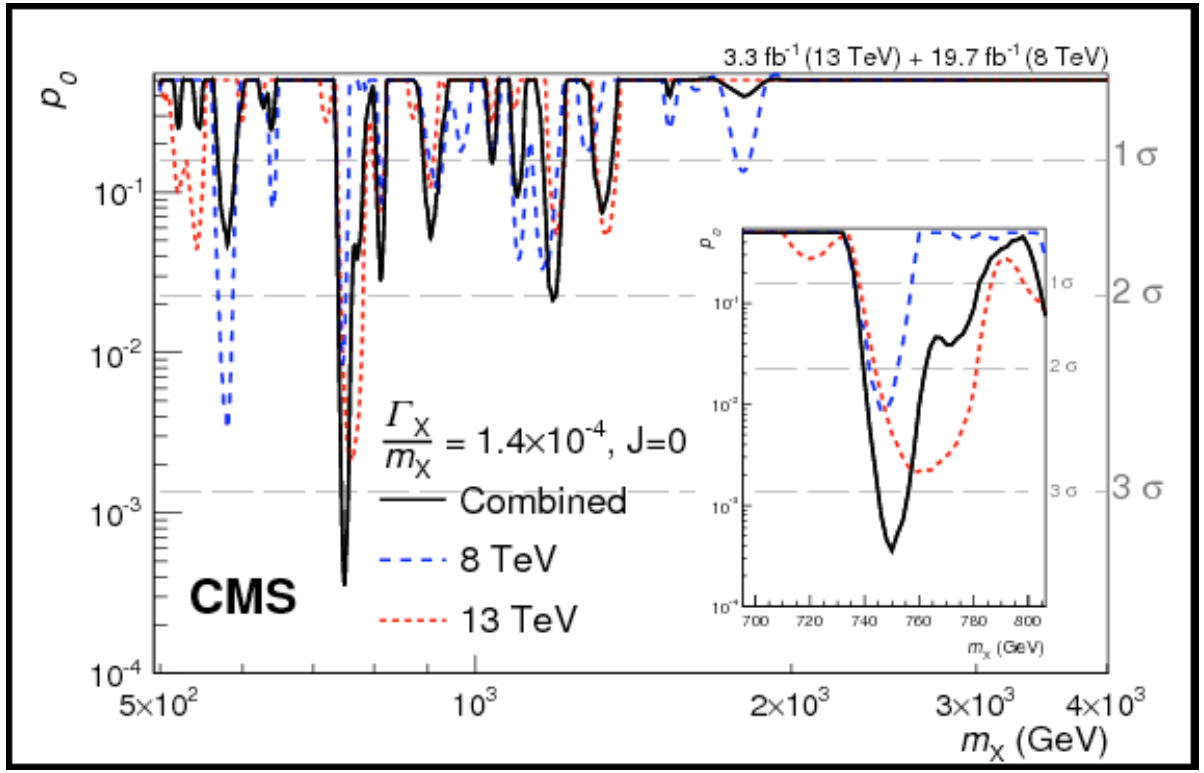


Heavy resonances: Diphotons —Who ordered that? (CMS)

M. Quittnat



local significance: 3.4σ, "global" significance ~ 1.6σ



- Largest excess observed at mX = 750 GeV and for narrow width

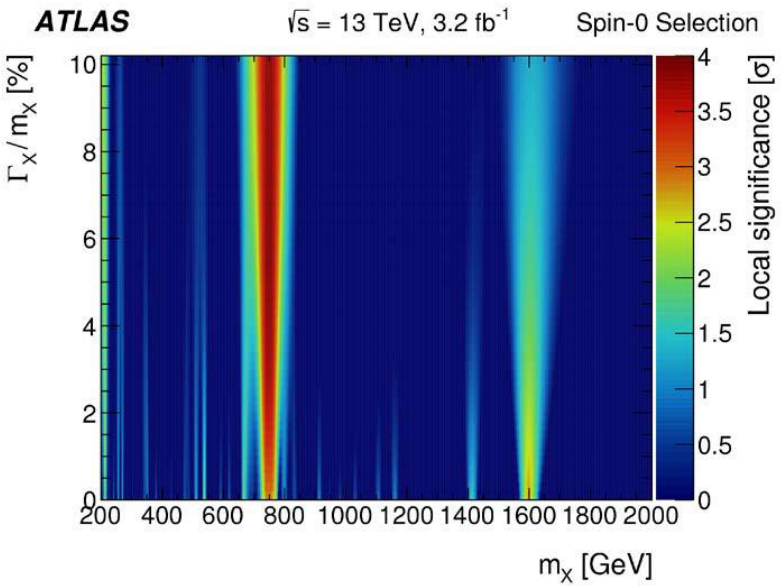
Heavy resonances: Diphotons —Who ordered that? (ATLAS)

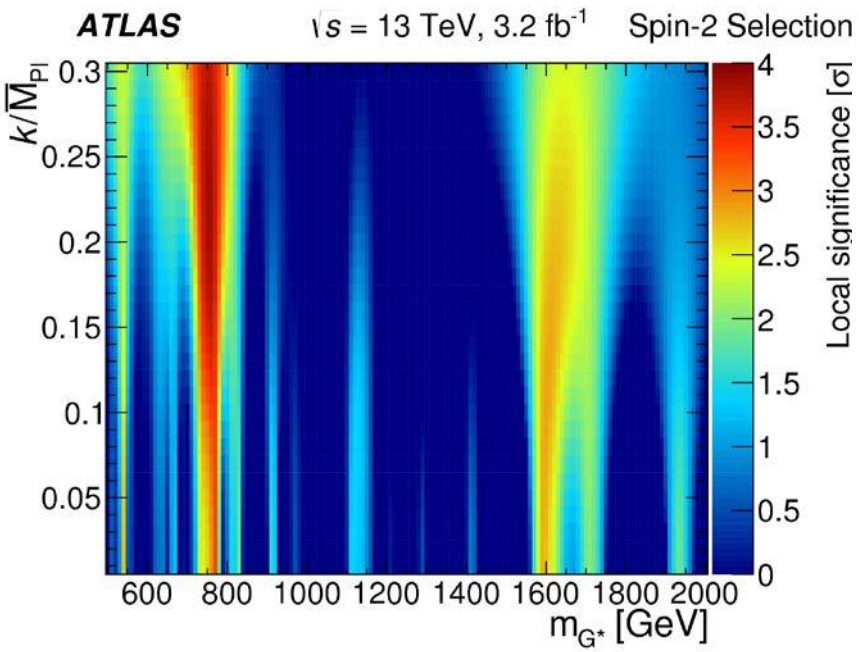
F. Malek

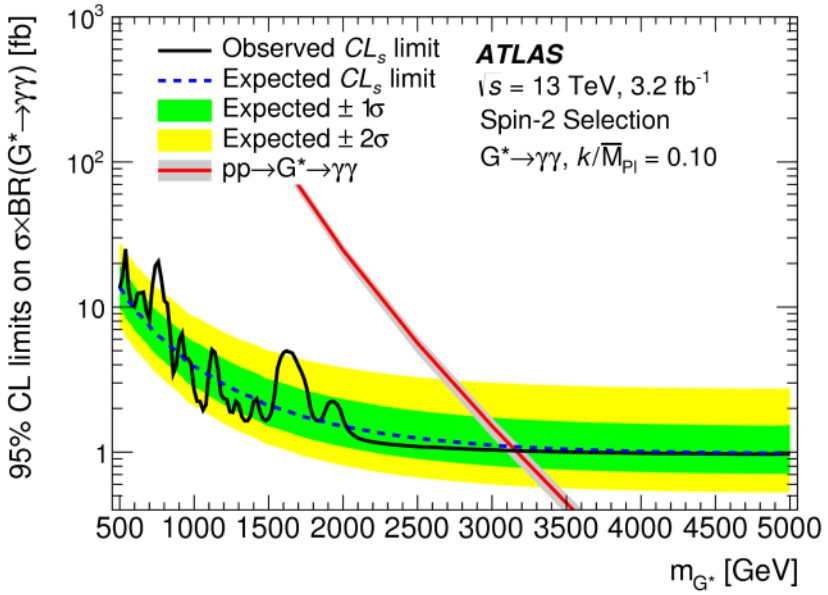
Largest deviation at 750 GeV and coupling k/M_{Pl}=0.23 (57 GeV) Local σ=3.8; Global σ=2.1

Largest deviation at 750 GeV and ΓX/mX=6% (45 GeV) Local σ=3.9; Global σ=2.1

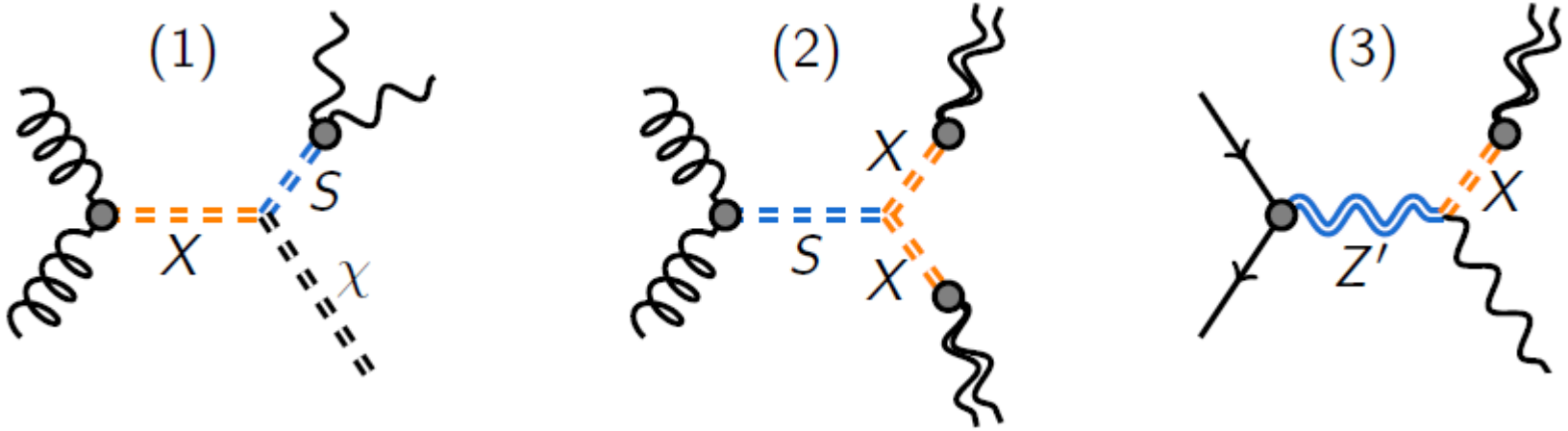
m_{G^*} excluded to 3.4 TeV for k/M_{Pl} =0.1 (2.66 TeV@8TeV)





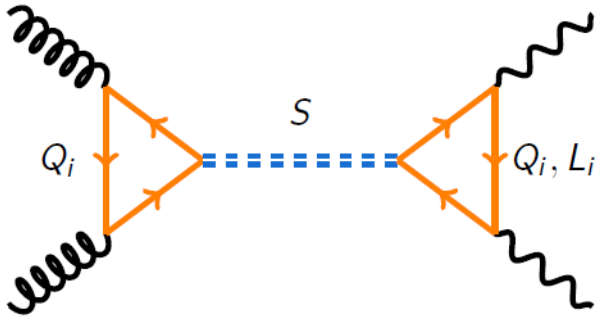


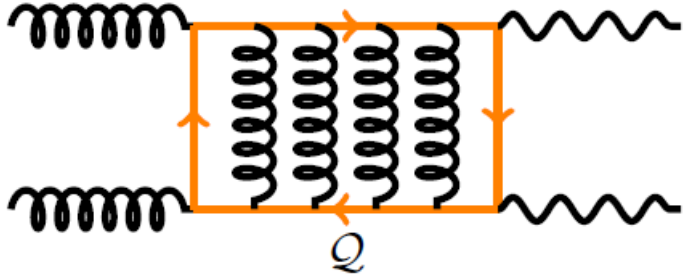
$m_{\gamma\gamma}$~750 GeV: Theory: Who/what could have ordered that?

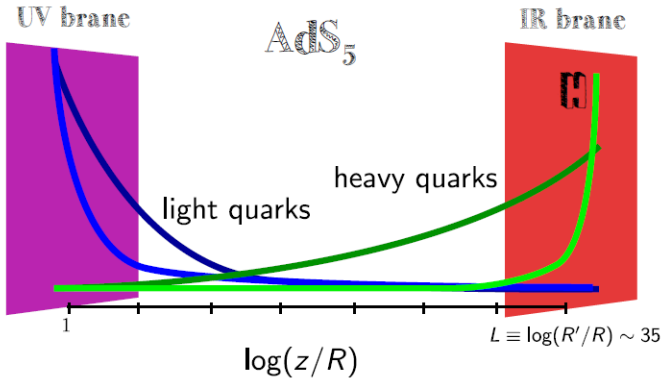


A. Carmona

- Kinematics more that what meets the eye/detector: 3-body decay of something even heavier(1), not 2 photons but 4 (2), 3-body decay of Z'→X + γ with X to collimated γ





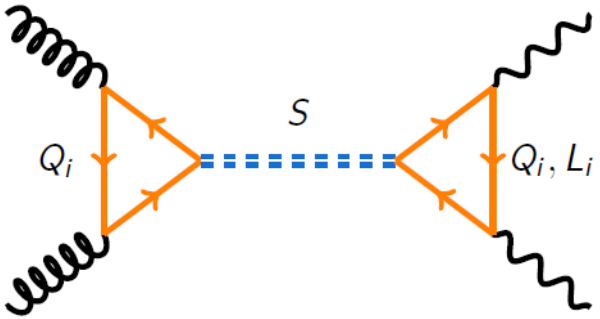


- Additional scalar singlet ('Vanilla' shown), 'Known' or 'new' strong dynamics (bound state of heavy q or scalars), Extra dimensions (radion/dilaton, graviton, RS + singlet), goldstino…

$m_{\gamma\gamma}$~750 GeV: Range of validity of EFT for an additional 'vanilla' singlet

L. Di Luzio

- Use perturbative (partial wave) unitarity
- EFT of a di-photon resonance breaks down at scales of few tens of TeV



$$\sqrt{s} \lesssim 11 \div 59 \text{ TeV} \left(\frac{\Gamma_{\gamma\gamma}/M_S}{10^{-4}}\right)^{-1/2}$$ → independently of production mechanism

$$\sqrt{s} \lesssim 24 \text{ TeV} \left(\frac{\Gamma_{gg}/M_S}{10^{-3}}\right)^{-1/2}$$ → gg initiated production

$$\sqrt{s} \lesssim 6.2 \text{ TeV} \left(\frac{\Gamma_{q\bar{q}}/M_S}{0.06}\right)^{-1/2}$$ → q-qbar initiated production

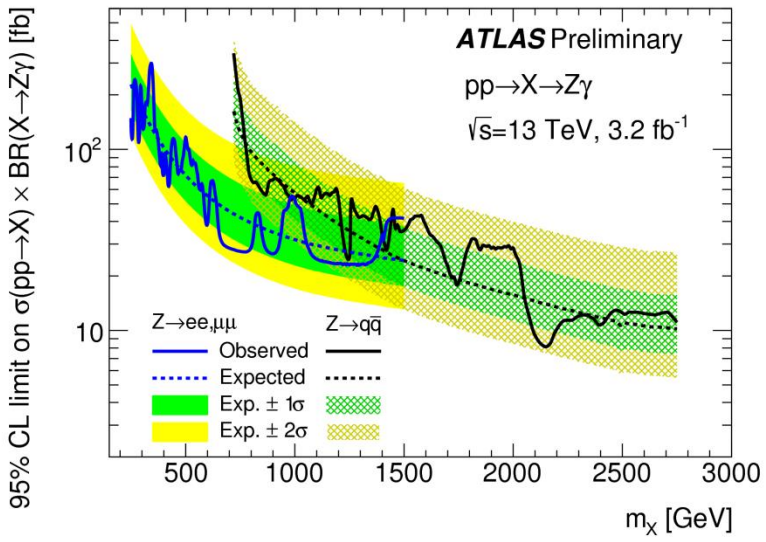
- new d.o.f. unitarizing the amplitudes' growth are expected below this scale

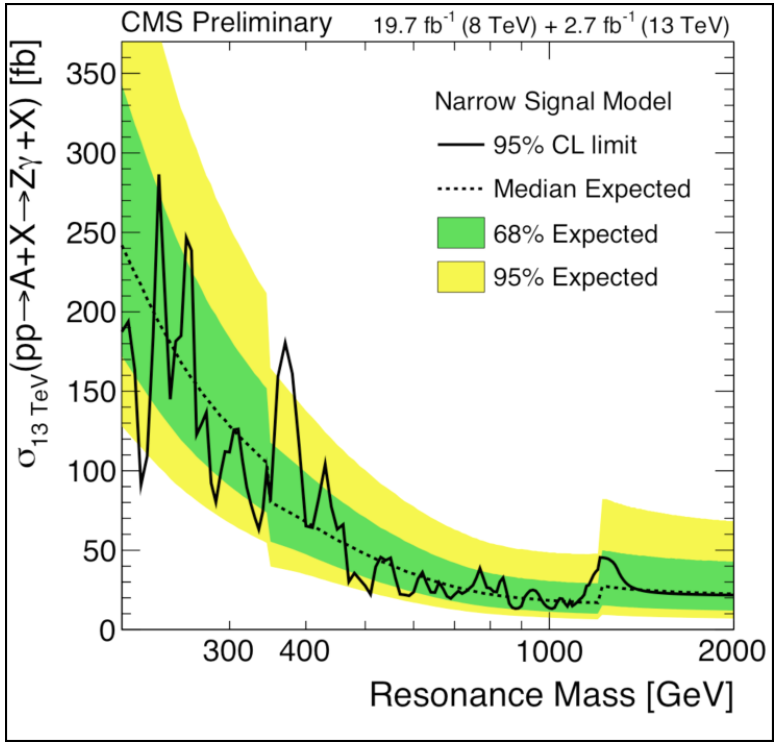
- a physics case for the 50 TeV collider

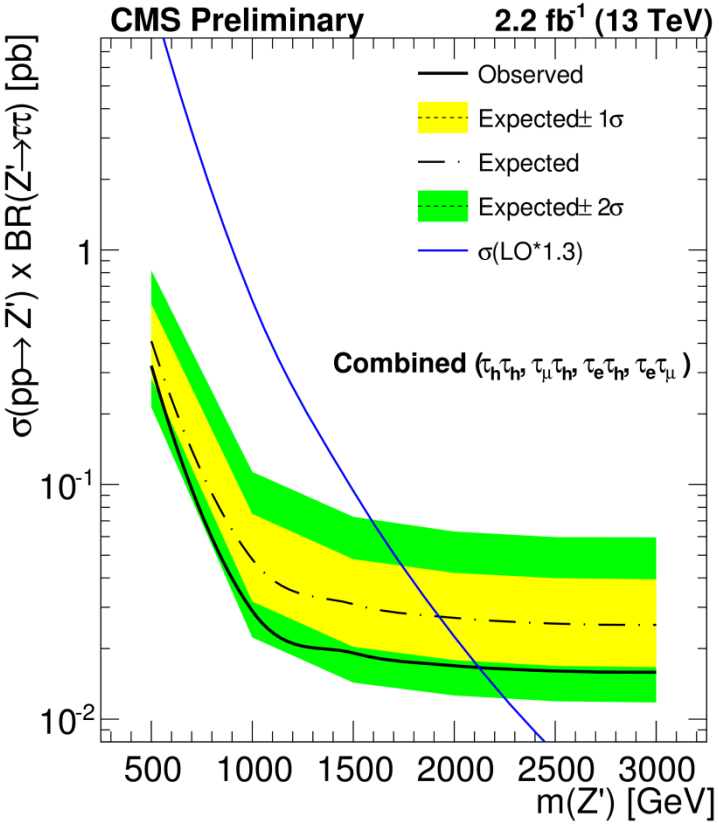
(a *worse case scenario*. In typical models new d.o.f. beyond S lie much below 10 TeV)

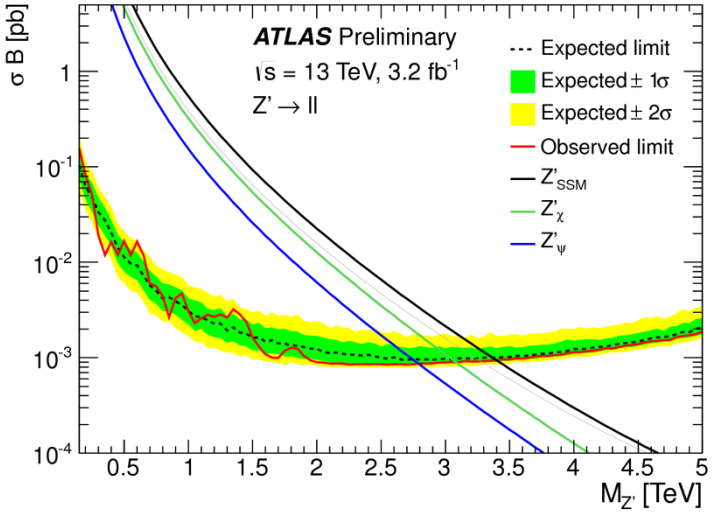
Heavy resonances other than diphotons: Zγ and Z’

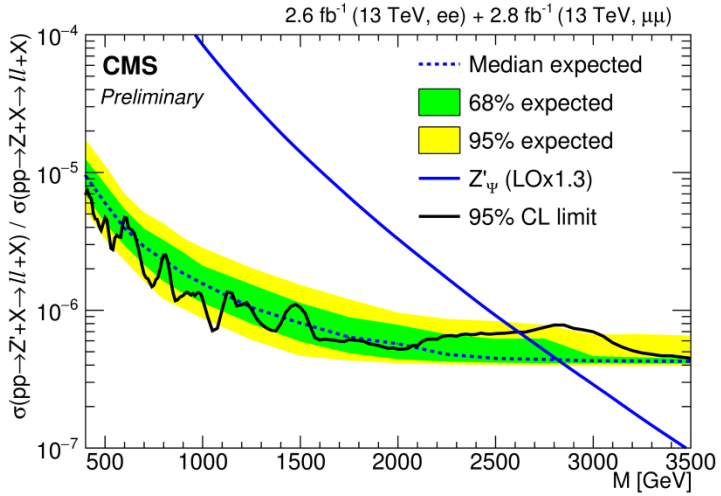
G. Halladjian





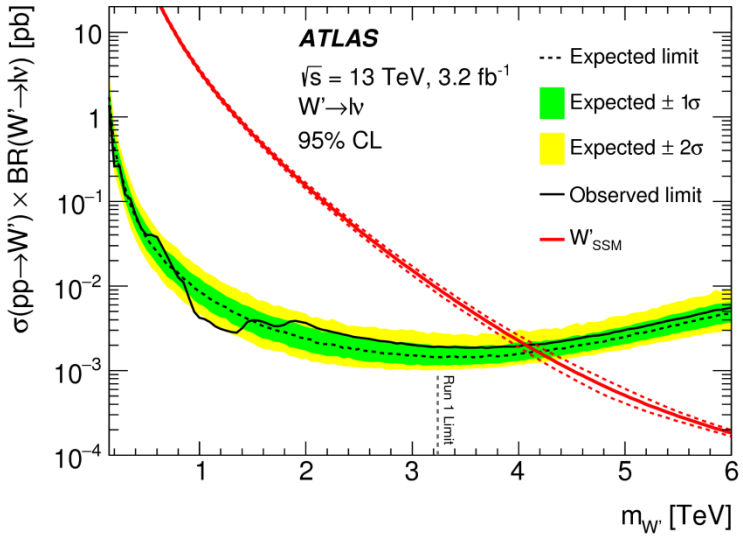


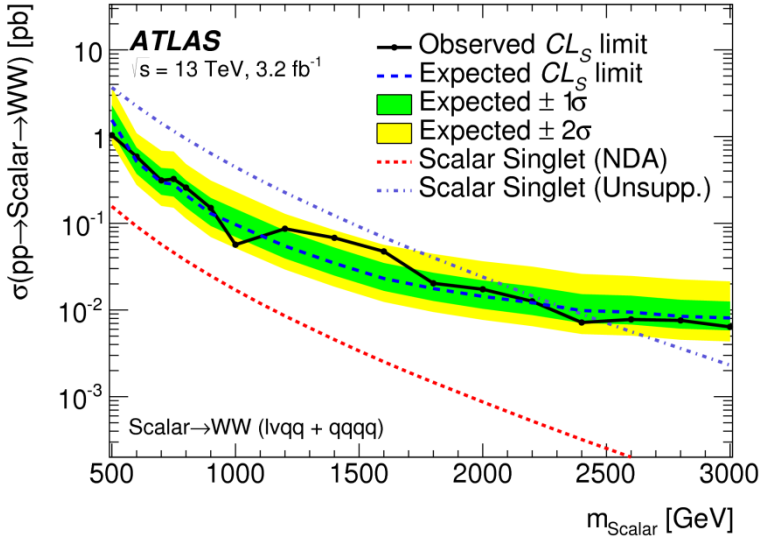


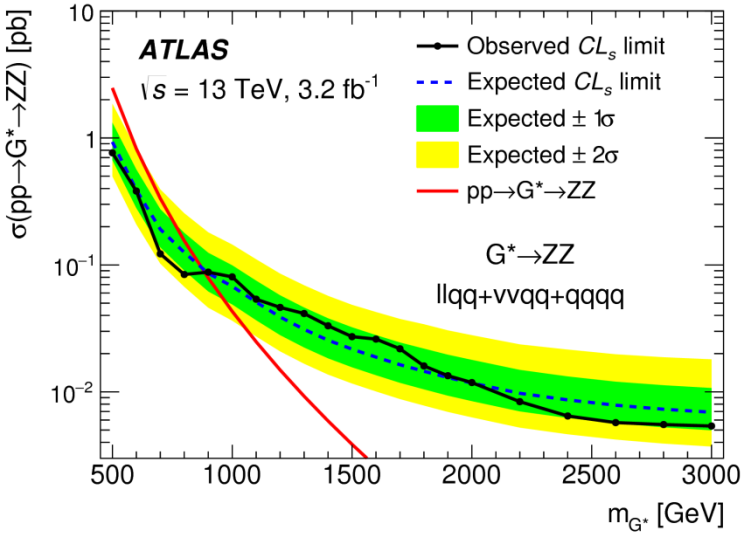


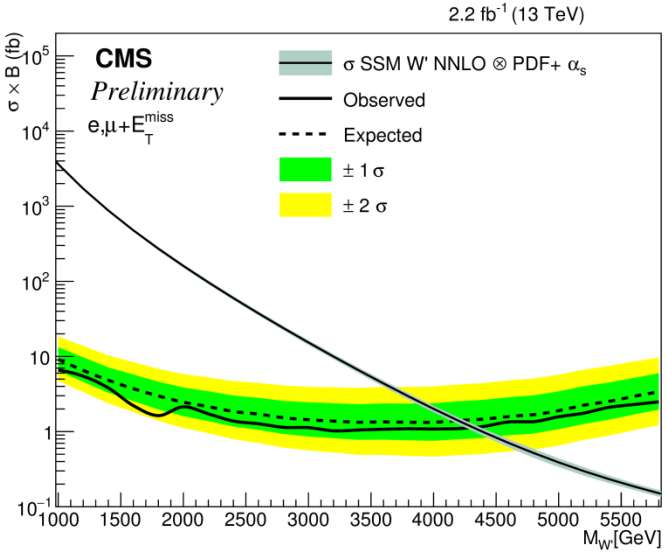
Heavy resonances other than diphotons: W' and VV

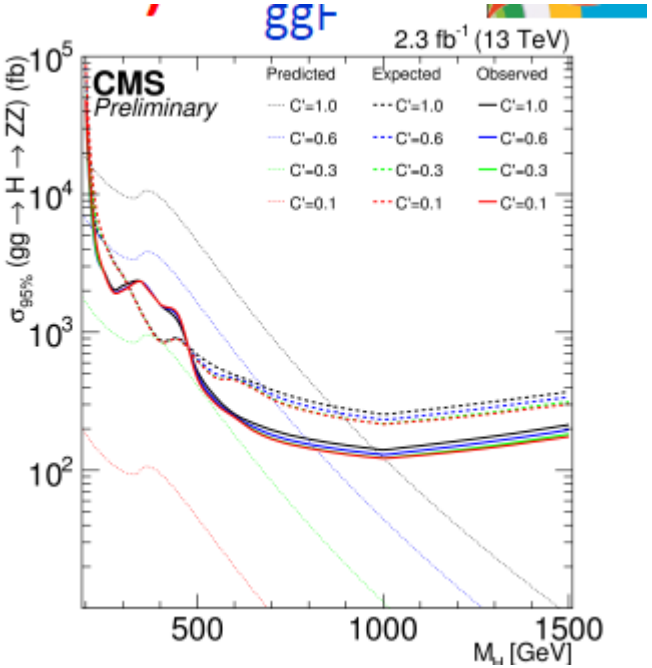
G. Halladjian

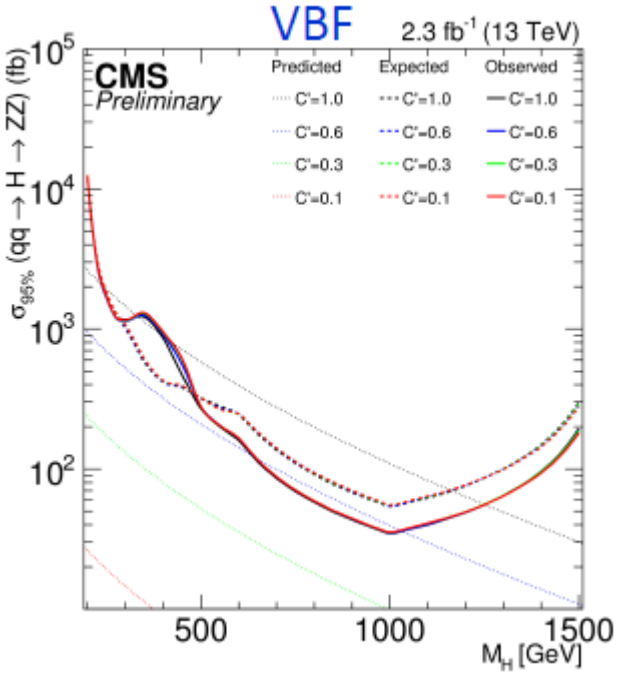






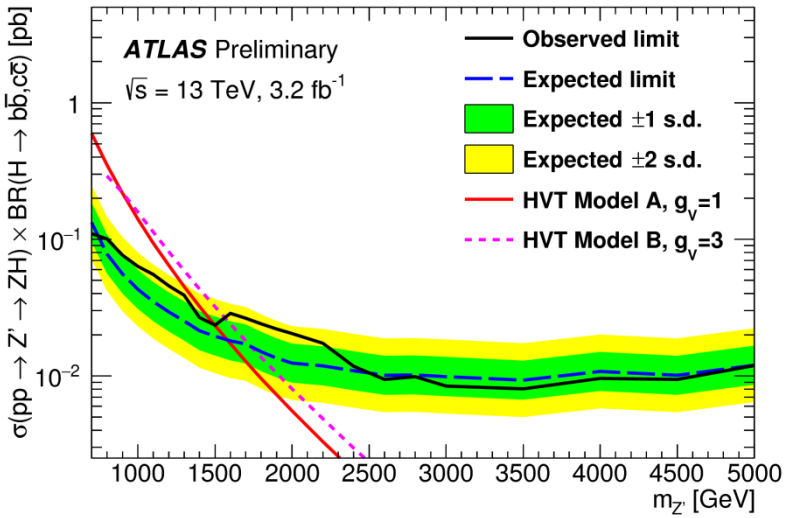


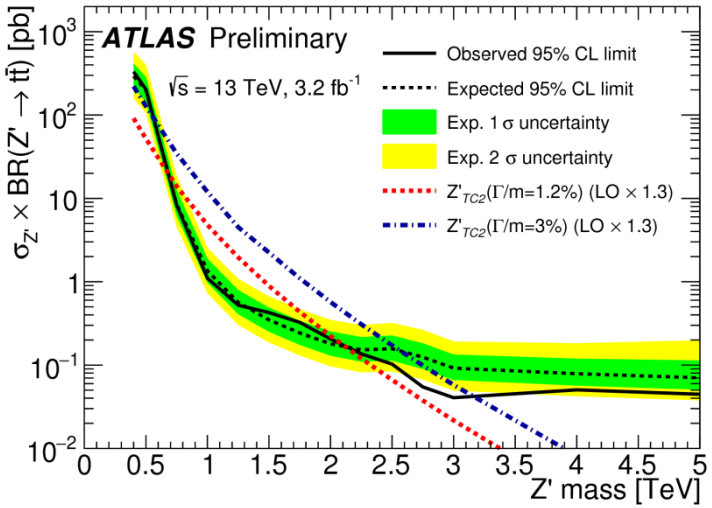


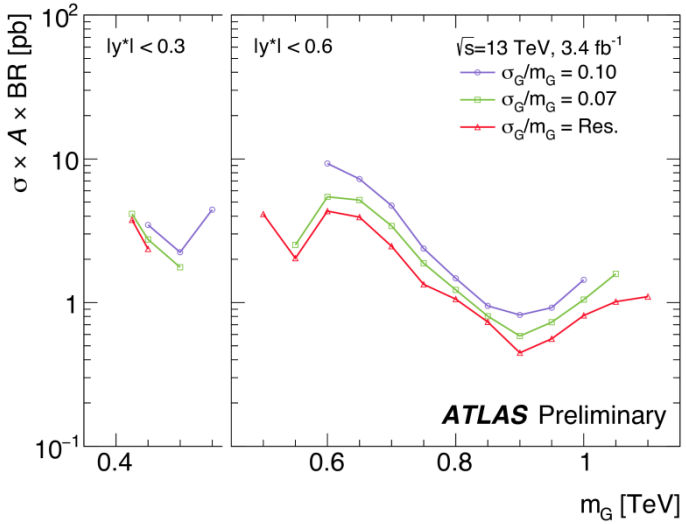


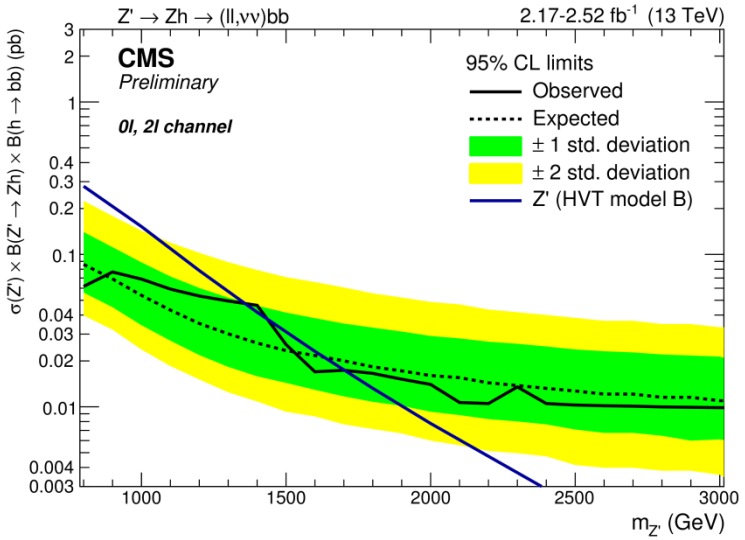
Heavy resonances other than diphotons: VH, ttbar, di-jets

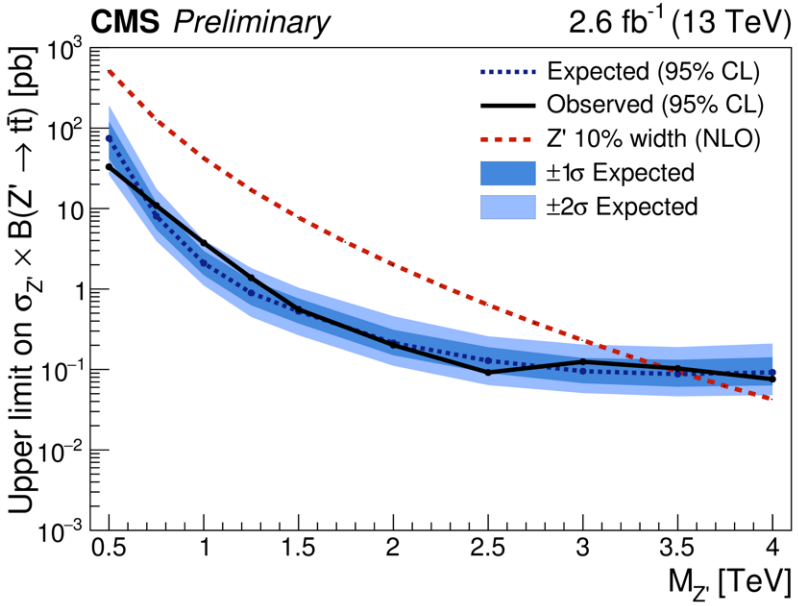
G. Halladjian

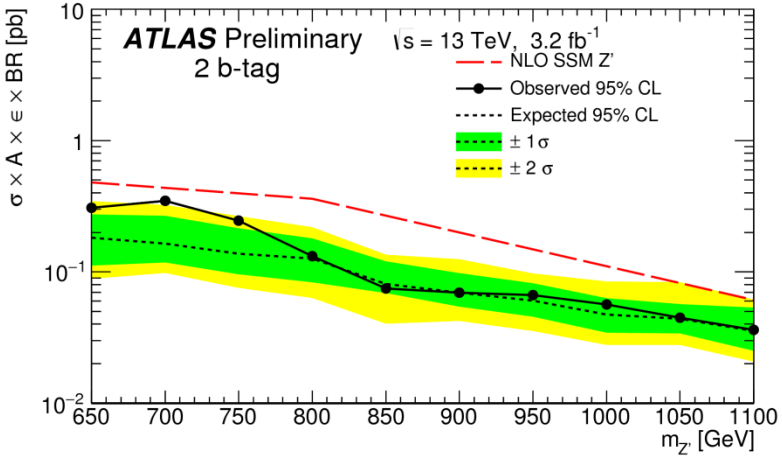






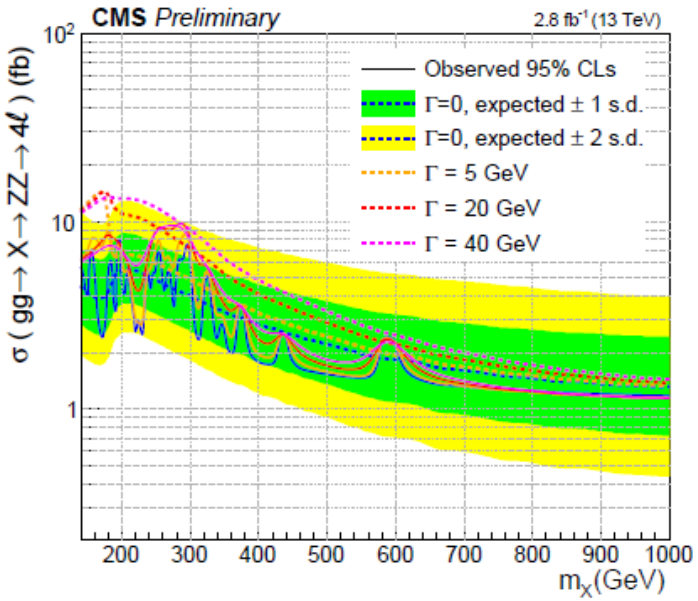


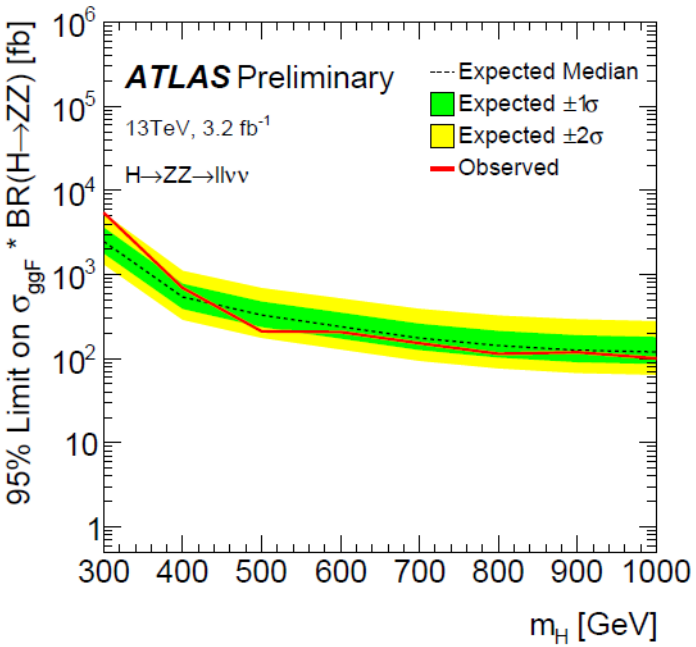


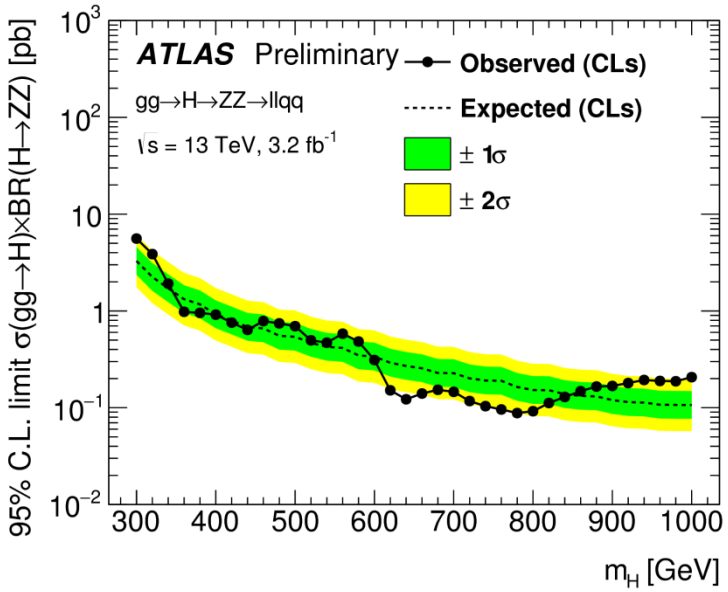


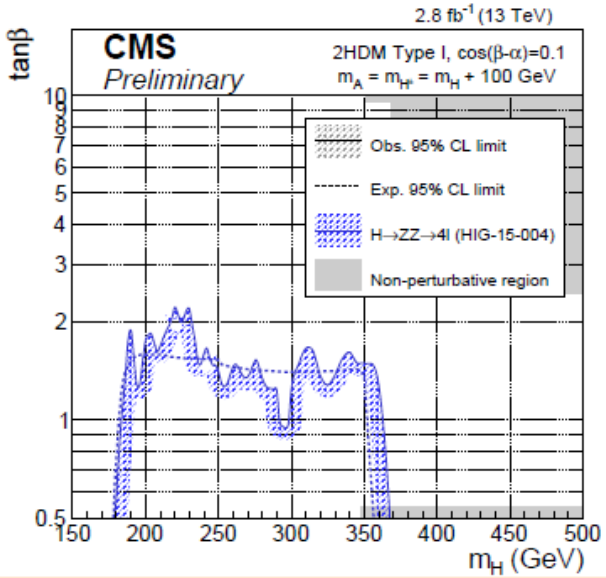
Heavy (BSM) Higgs bosons: H→ZZ*→4l,llνν,llqq

S. Snyder



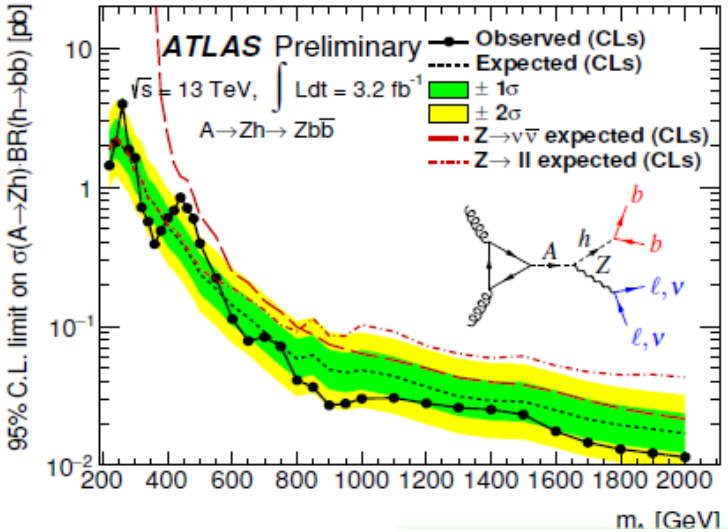


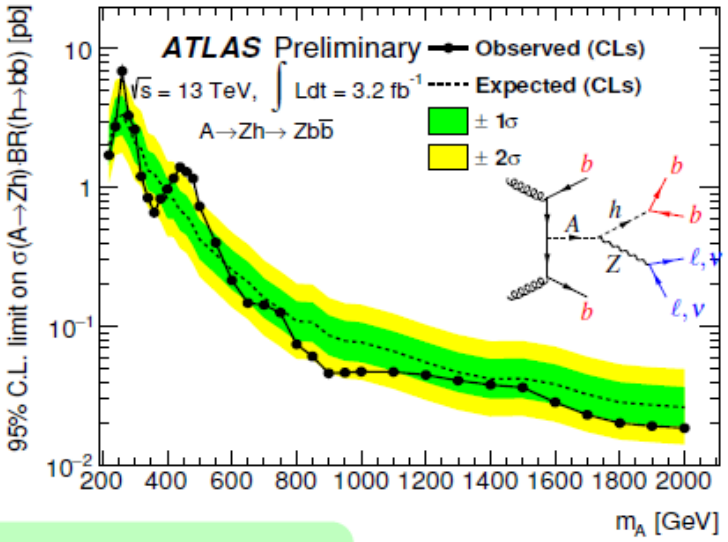


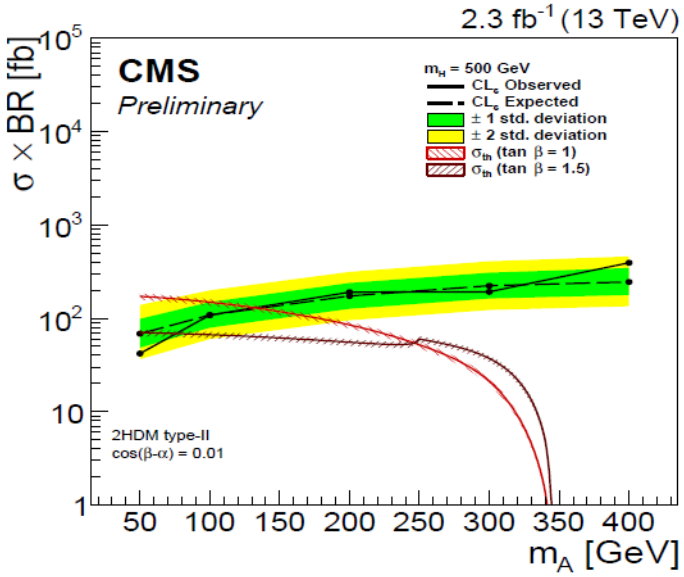


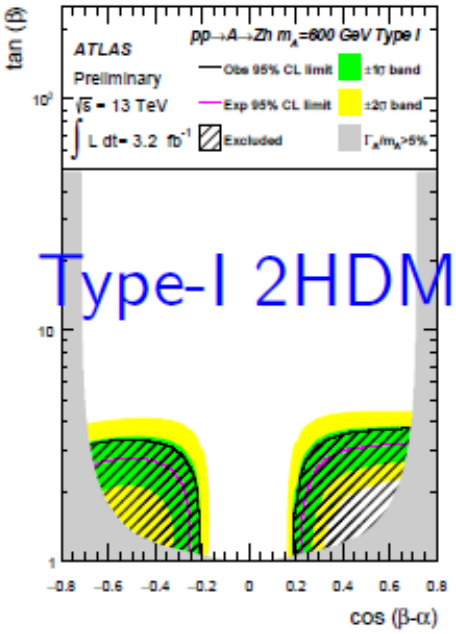
Heavy (BSM) Higgs bosons: H→ZA→llbb/ννbb

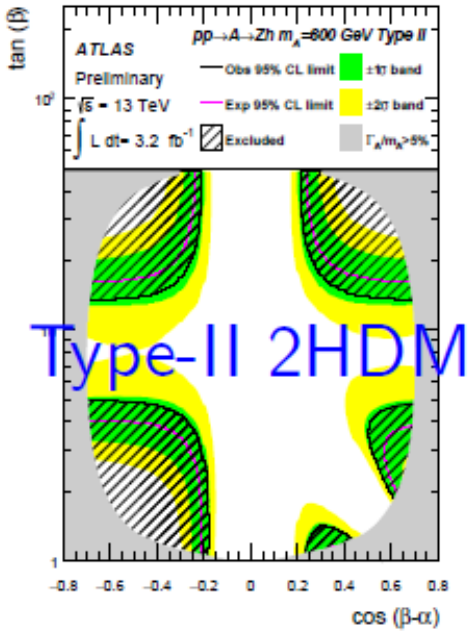
S. Snyder





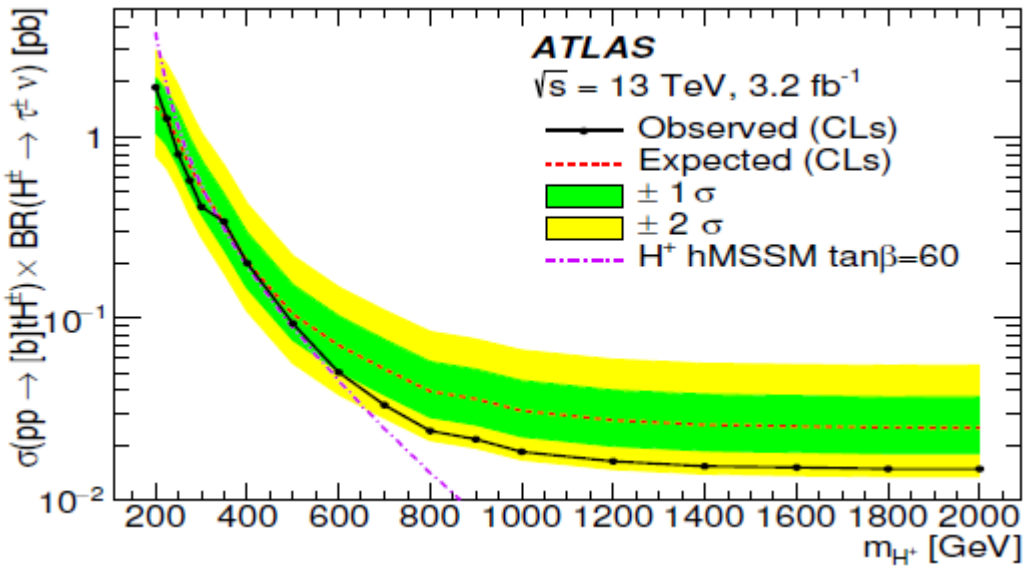


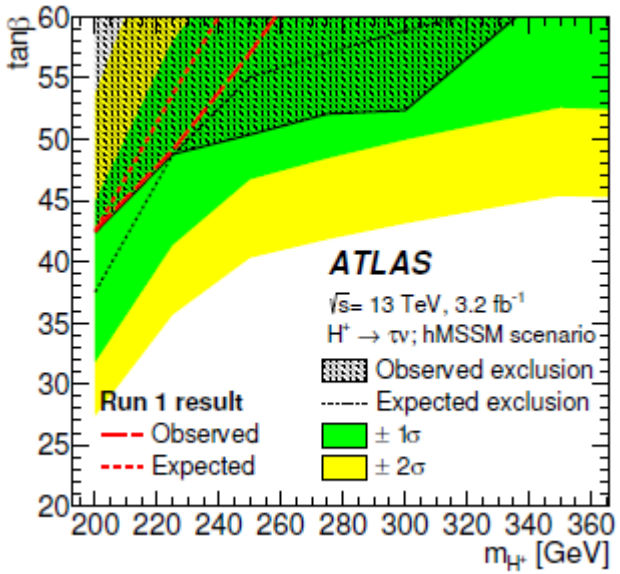




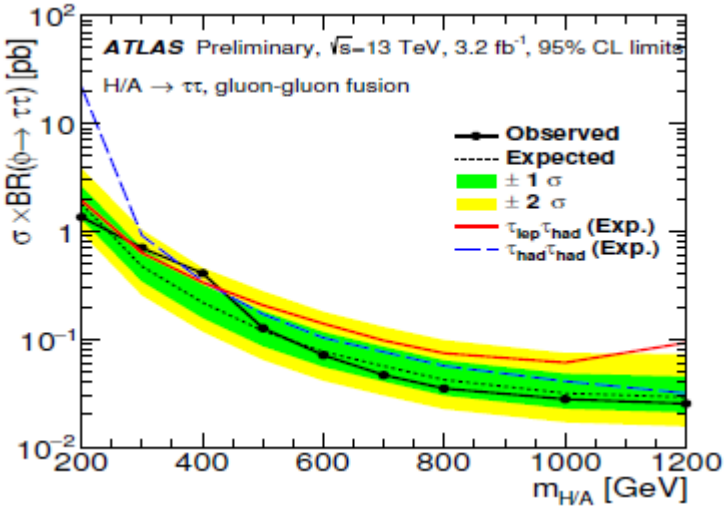
MSSM interpretations ($M_A = 600$ GeV)

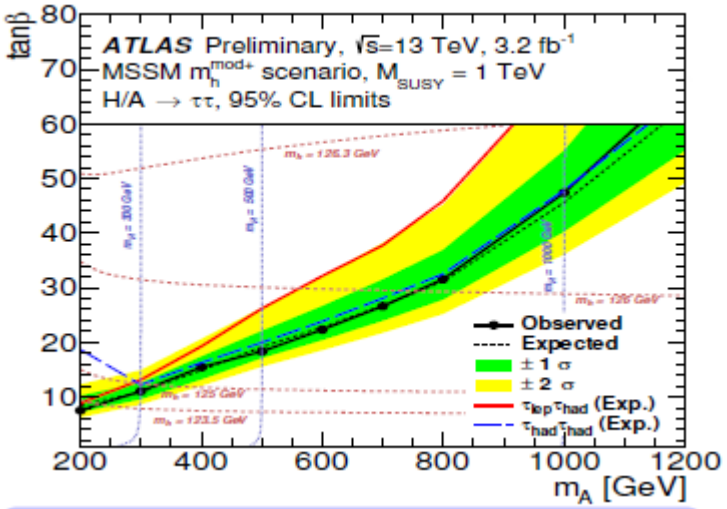
Heavy (BSM) Higgs bosons: $H^{+-} \rightarrow \tau\nu$ and $H/A \rightarrow \tau\tau$ (ATLAS)





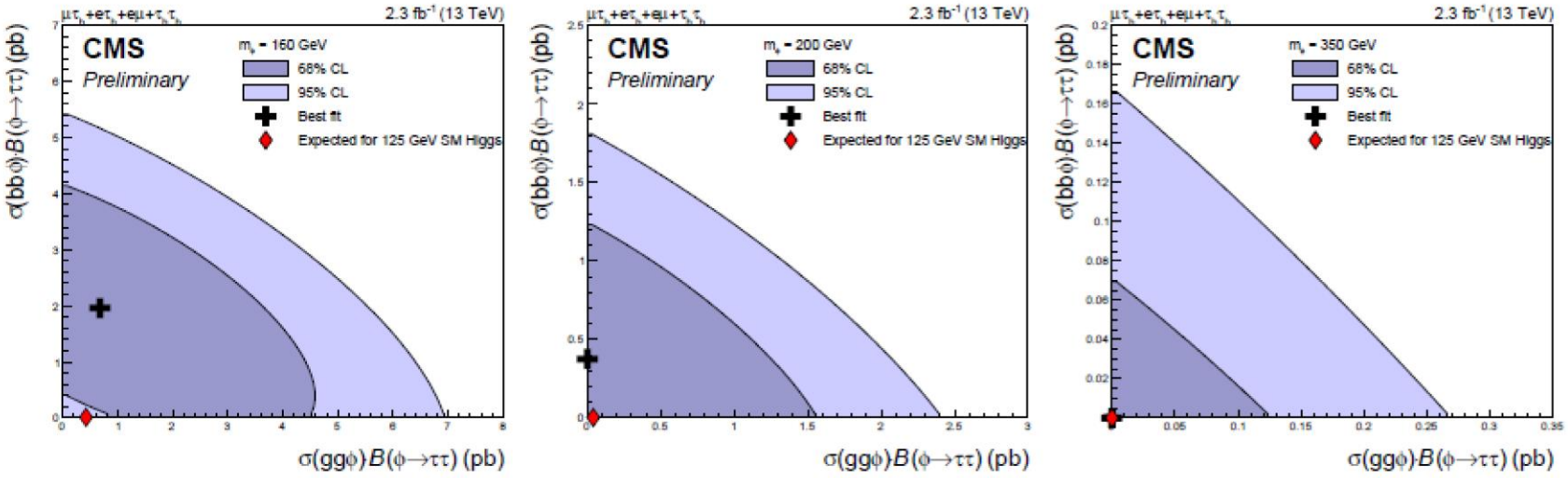
S. Snyder





Heavy (BSM) Higgs bosons: H ou bbH, H→ττ (CMS)

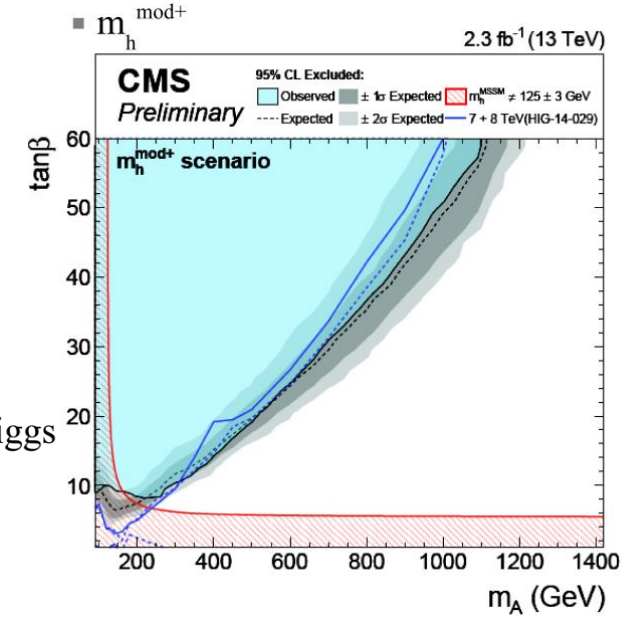
P. Saxena

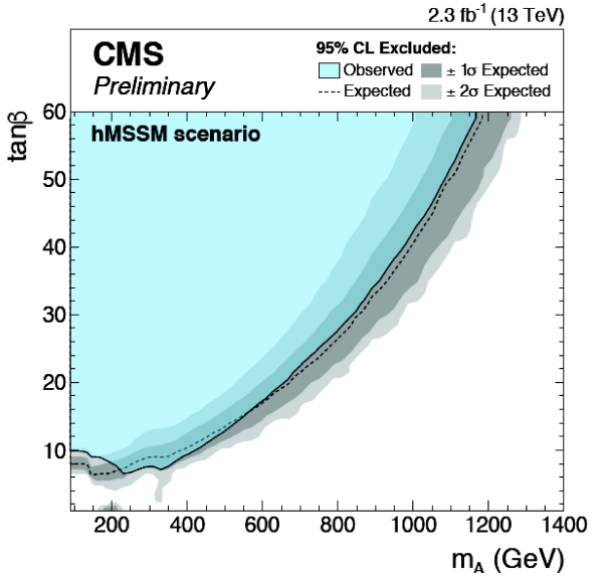


(d) $m_\phi = 160$ GeV (e) $m_\phi = 200$ GeV (f) $m_\phi = 350$ GeV

2D Limit on cross-section x BX (ggφ and bbφ)

- Fits are performed without taking SM(125) Higgs in background.
- ★ indicate the expected resulting fit with inclusion of a SM(125) Higgs

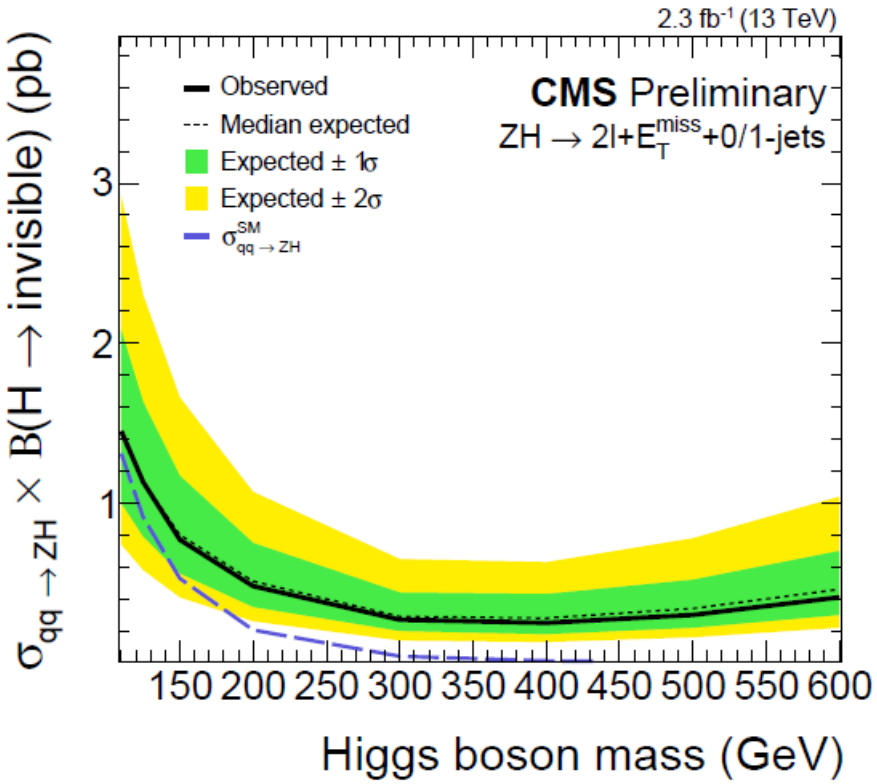


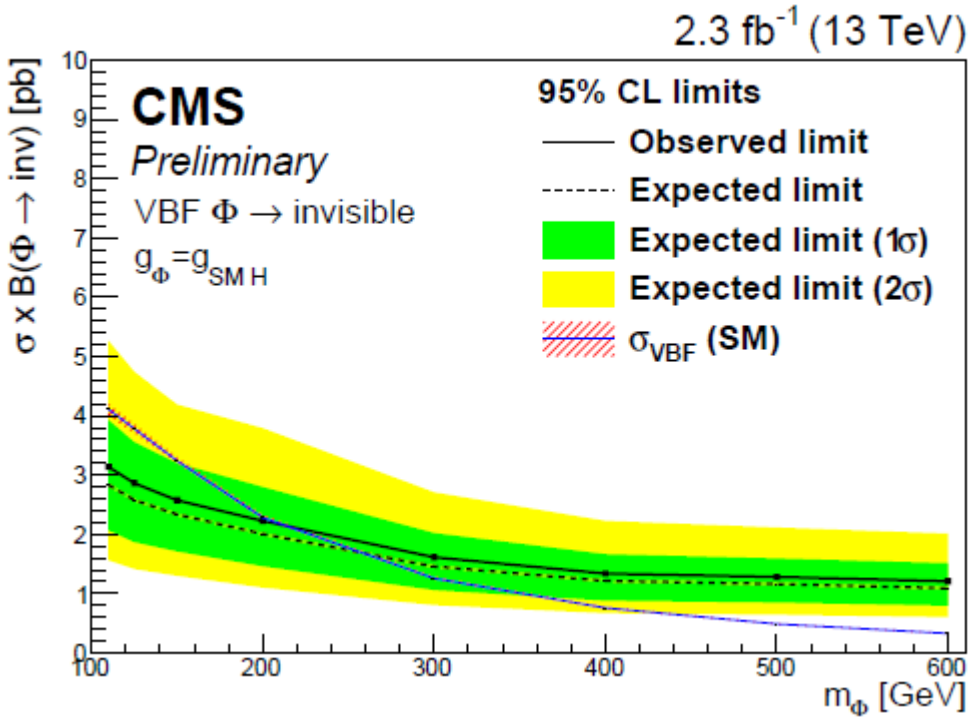


- Red exclusion at low tanβ, low mass attributed to existence of SM-125 Higgs
- Run-I results at 7 & 8 TeV are plotted as Blue lines
- Starting from m_A=300, the 13 TeV limits are stronger than 8 TeV limits

Heavy (BSM) Higgs bosons: ZH→ll+inv and H→inv

S. Snyder

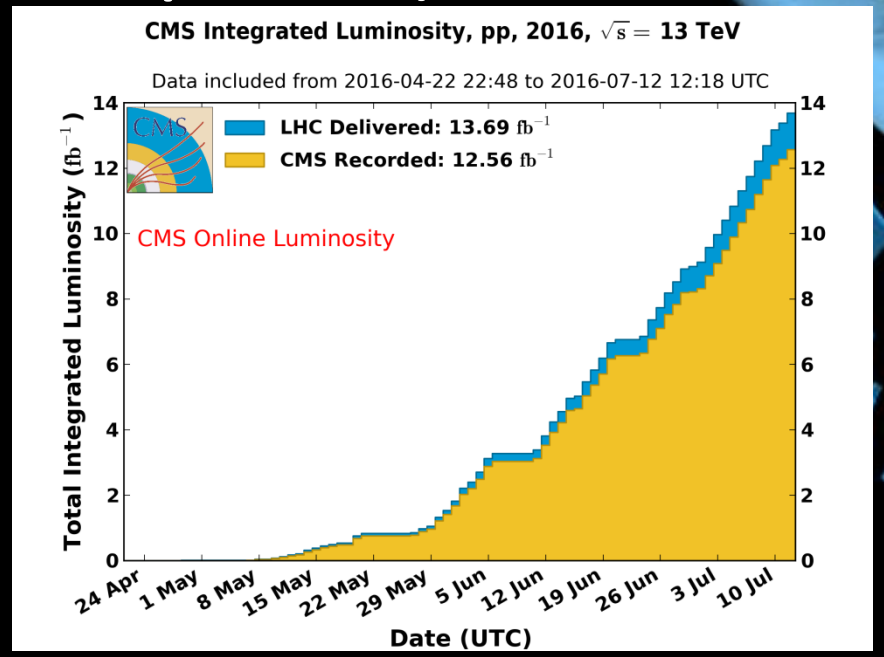


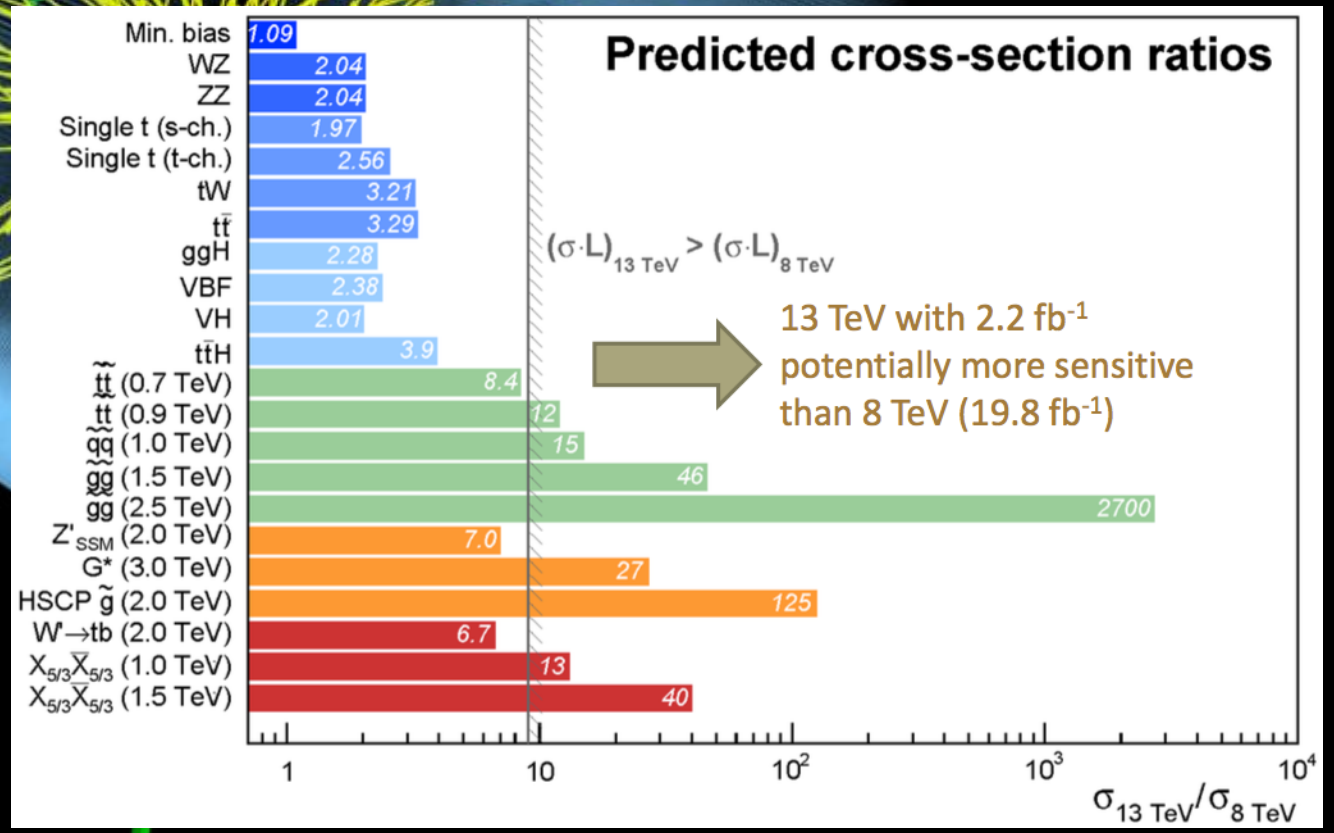


Summary and Conclusions

- The H125 is well on its way to being 'rediscovered', and continues to look SM-like
- Higgs pair production: 13 TeV results, not yet Run 1 sensitivity
- Both ATLAS and CMS have seen a modest excess of events at $m_{\gamma\gamma}$=750 GeV, but not in any other final state. No other significant excesses reported in any other BSM Higgs searches.
- LHC is running well: Stay tuned for ICHEP!

(~equivalent luminosities to Run 1 for Higgs production processes)





Final (no pun intended) note

What the little Portuguese boy really said to the despondent French football fan:

"Don't worry, there WILL be new physics at the LHC!"

Acknowledgements

- The conference organizers, BSM mini-workshhop convenors (A. Carvalho, T. Dorigo, M. Gouzevitch) and session convenors, all speakers and

Orthodox Academy of Crete

Backup