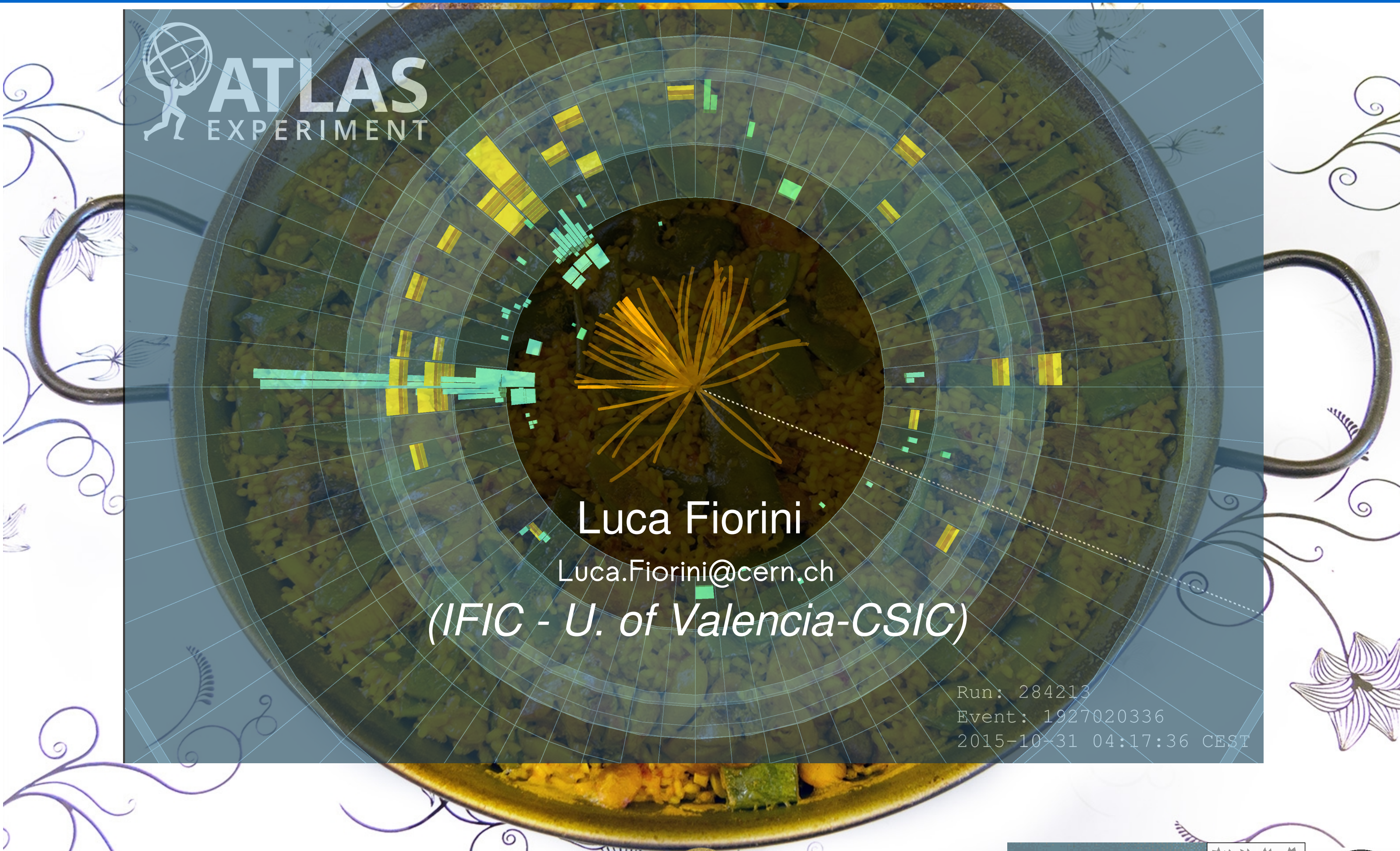
Experimental Higgs Physics (2)



Luca Fiorini
Luca.Fiorini@cern.ch
(IFIC - U. of Valencia-CSIC)

IDPASC 2018
22nd May 2018

EXCELENCIA SEVERO OCHOA

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC

VNIVERSITAT DE VALÈNCIA

Outline

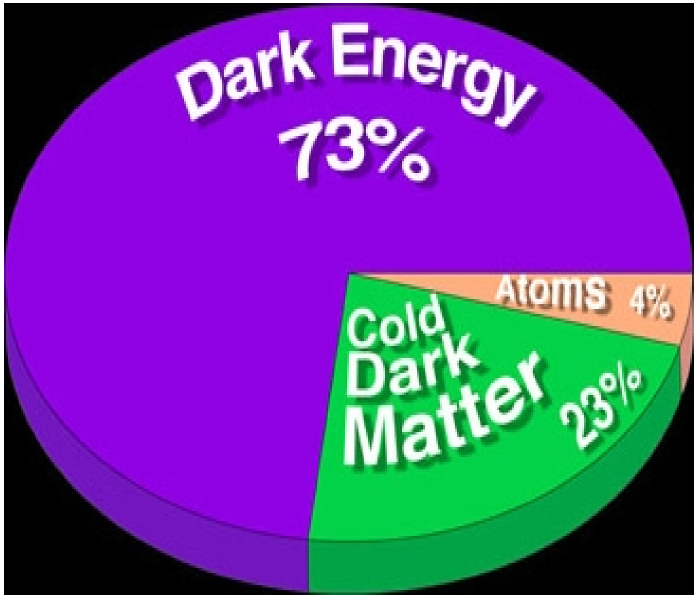
New Physics in the HIggs sector:

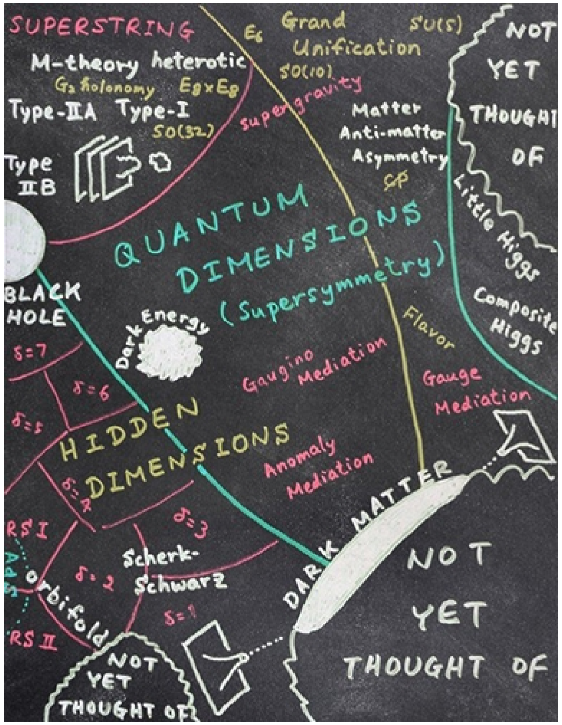
• Limited time to discussed all the New Physics Models $\rightarrow$ focus on few concrete examples.

• Standard Model:
 some remaining puzzles, despite its amazing success

• Open Questions in Particle physics

• BSM Higgs sector

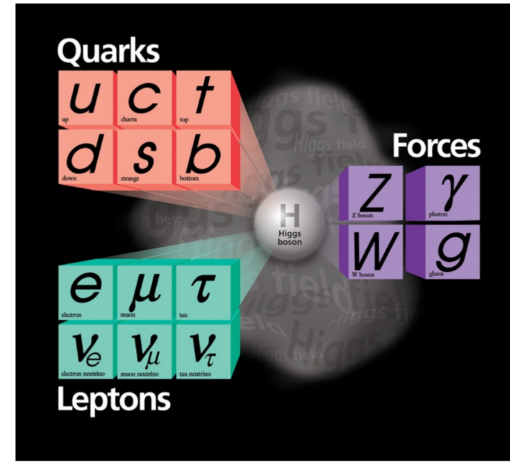




Standard Model Status

Theory describing subatomic particles and their interactions:

- Matter made of spin ½ particles, Fermions: Leptons and quarks.
- Forces carried by spin 1 particles, Bosons: *W,Z,γ* and gluons.
- Higgs Boson, spin 0, responsible of the EW symmetry breaking.

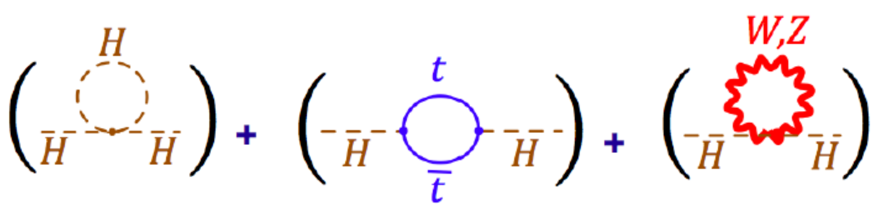


Very successful description of known phenomena, **but:**

- **What is the nature of the discovered Higgs boson?**
- Fine tuning issues of the SM, in particular the Higgs mass hierarchy problem;
- The SM accounts for only ~4% of the the energy density of the universe;
- The SM fails to quantitatively explain matter/anti-matter asymmetry (CPV)

… and other open questions.

$m_H^2 - m_{\text{bare}}^2 =$



$$\lambda \int^{\Lambda} d^4k \, (k^2 - m_H{}^2)^{-1}$$

$\Delta m_H{}^2 \sim \lambda\Lambda^2$

but $m_H \ll \Lambda$

Open questions in particle physics

Fabiola Gianotti talk – LHCP 2014

Higgs boson and EWSB
- m_H natural or fine-tuned ?
  -> if natural: what new physics/symmetry?
- does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- elementary or composite Higgs ?
- is it alone or are there other Higgs bosons ?
- origin of couplings to fermions
- coupling to dark matter ?
- does it violate CP ?
- cosmological EW phase transition (is it responsible for baryogenesis ?)

Neutrinos:
- ν masses and and their origin
- what is the role of H(125) ?
- Majorana or Dirac ?
- CP violation
- additional species or sterile ν ?

Dark matter:
- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- one type or more ?
- only gravitational or other interactions ?

The two epochs of Universe's accelerated expansion:
- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

Quarks and leptons:
- why 3 families ?
- masses and mixing
- CP violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

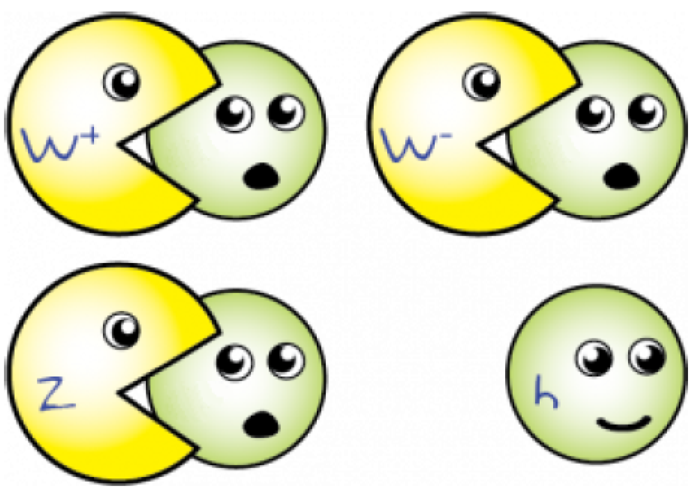
Physics at the highest E-scales:
- how is gravity connected with the other forces ?
- do forces unify at high energy ?

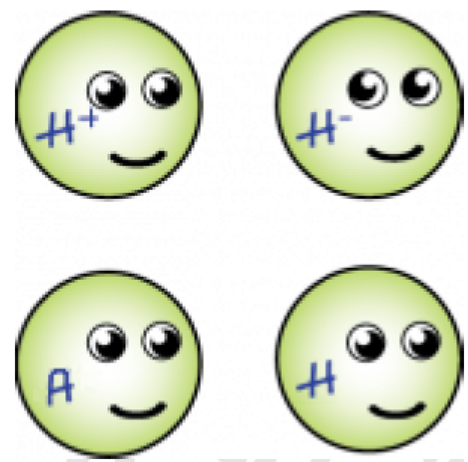
At what E scale(s) are the answers ?

BSM Higgs Sector

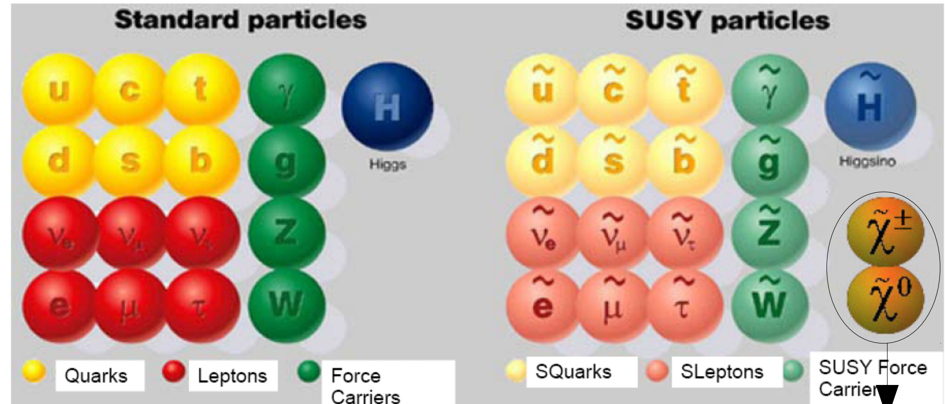
• After the discovery of a Higgs boson at 125 GeV, a major question is whether this is the scalar particle predicted by the Standard Model to break the electroweak symmetry... or is it the first state of an extended Higgs sector?

•Several BSM models predict an extended scalar sector, e.g. with two Higgs doublets (2HDM) or Higgs triplets, all containing neutral and charged Higgs bosons.





SuperSymmetry (SUSY)



gaugino/higgsino mixing

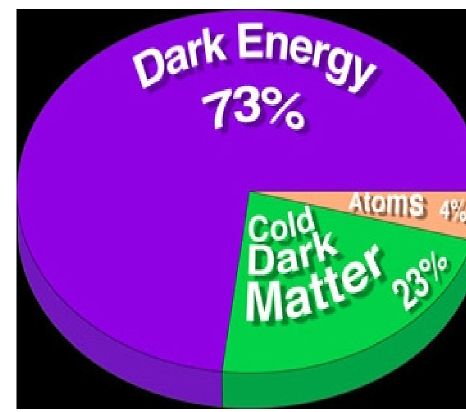
- SM extension with spin-based symmetry relating Fermions and Bosons:

  Q|Boson> = |Fermion>

  Q|Fermion> = |Boson>

Minimal Supersymmetric SM (MSSM):

- Mirror spectrum of particles
- Enlarged Higgs sector:
  h, H, A, $H^{\pm}$
- tan(β) = ratio of the v.e.v. of the 2 Higgs doublets.
- R-parity, $R = (-1)^{3(B-L)+2s}$
  spin *s*, baryon number *B*, and lepton number *L*
- R = 1 for SM particles,
- R = -1 for MSSM partners



Natural solution to the Higgs mass hierarchy problem:
→ *Discovery of the Higgs makes SUSY even more appealing*

- ***No SUSY particle found yet:***
  - SUSY symmetry is broken → partners of SM particles are heavier.

2HDM and MSSM

- 2 Higgs Doublet Models (2HDM) predict 5 physical bosons: *h*, *H* (CP=+1), *A* (CP=-1), H^+ and H^-

Family	Type-I	Type-II	Lepton-specific	Flipped	Type-III
u	Φ_2	Φ_2	Φ_2	Φ_1	Φ_1, Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1	Φ_1, Φ_2
e	Φ_2	Φ_2	Φ_1	Φ_2	Φ_1, Φ_2

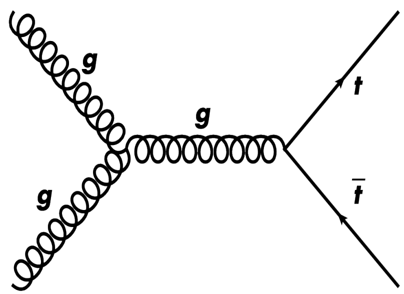
- MSSM is a special case of type-II 2HDM, often used as benchmark. It can be described by two parameters at tree-level:
  - **$\tan\beta$**$=\langle\Phi_1\rangle/\langle\Phi_2\rangle$
  - **m_A** : mass of the CP-odd Higgs boson
- MSSM scenarios commonly used:
  - **m_h^{max}** (stop mixing yielding maximum m_h)
  - **$m_h^{mod\pm}$** (modified stop mixing)
  - **hMSSM**: m_h=125 GeV used as input to generate the rest of the phenomenology.

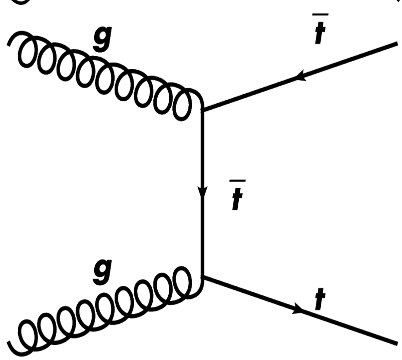
H/A → Fermions Search

ggH/A → ttbar:

- Branching ratio is larger for low tanβ
- Interference between the signal and ttbar background production modes taken into account.

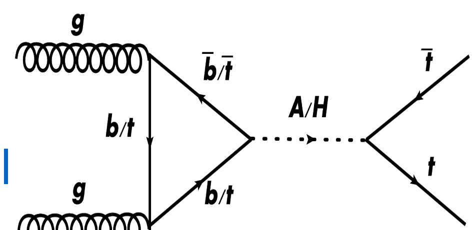
- Signal+Interference obtained from "**diagram subtraction**" and from "**diagram removal**" schemes (Madgraph modified to remove ttbar background diagrams).





- Difference between the approaches taken as systematics: 0.4%

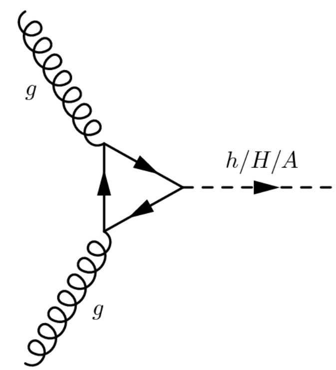
- bbH-> ttbar has no interference, but it is a more complicated final state.

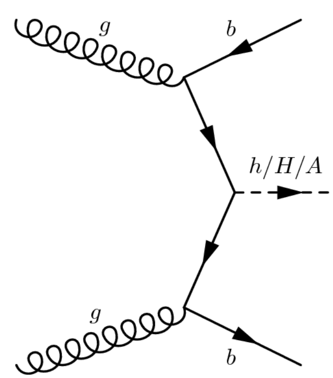


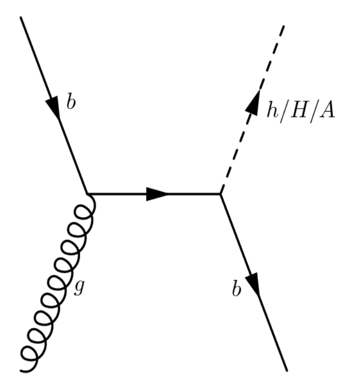
H/A → ττ:

- For $m_A >> m_Z$ (decoupling limit) the lightest scalar h has SM-like couplings;
- The heavier H/A bosons are almost degenerate in mass and coupling to *b* and τ is enhanced for high tanβ

→ exploit *b*-tag and *b*-veto categories







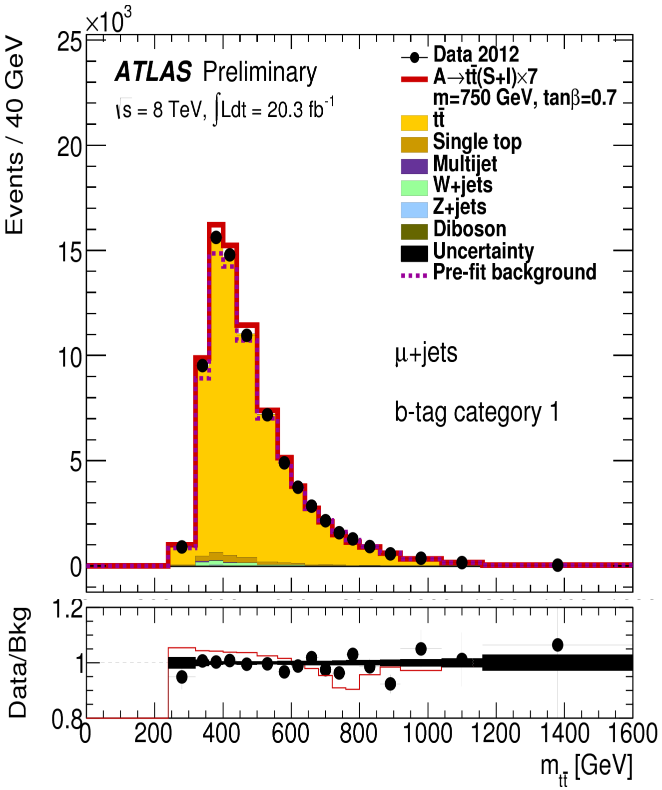
$H,A \rightarrow$ ttbar Search

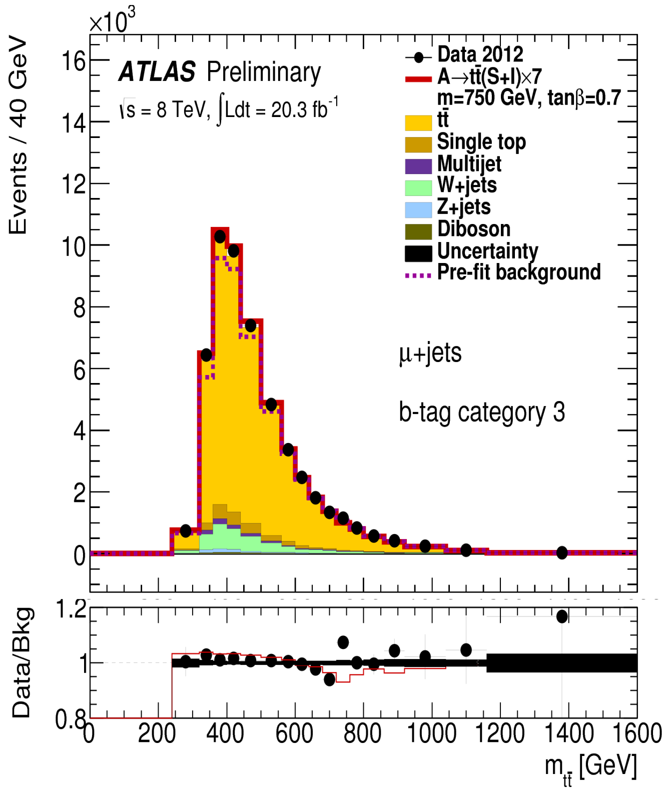
- **ATLAS-CONF-2016-073, 20.3 fb^{-1} of 8 TeV data**
- Revisit ATLAS Run-1 ttbar resonance search: JHEP 08 (2015) 148
- e,μ +jets final states, 3 *b*-tag categories for each final state.
- 4 jets, >= 1 b-tag jet, E_T^{miss} > 20 GeV, $E_T^{miss}+m_T$ > 60 GeV

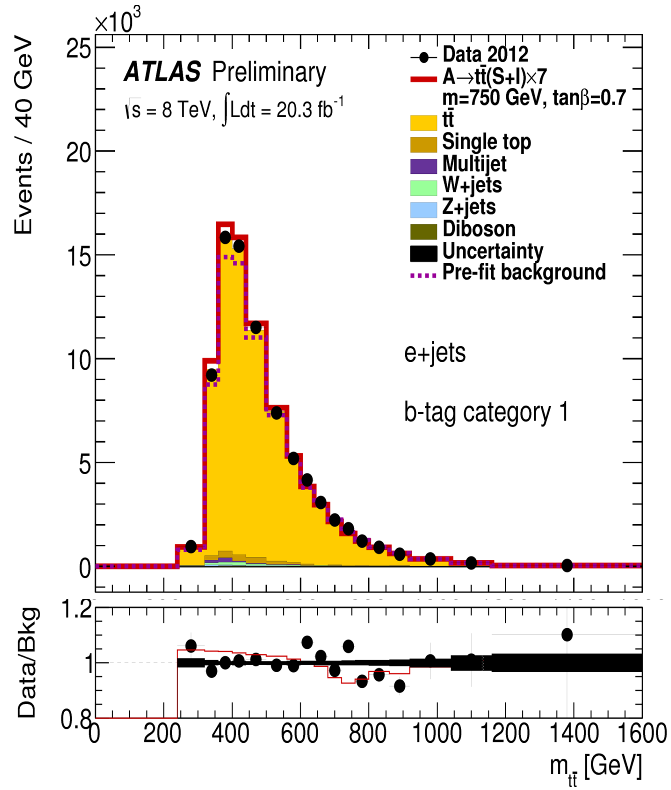
$$m_T^W = \sqrt{2 \cdot p_T^\ell \cdot E_T^{miss} \cdot (1 - \cos\phi_{\ell\nu})},$$

- Kinematic fit (χ^2) of the event (constraints on top and W masses)

- **Main backgrounds**: ttbar and W+jets (the latter estimated from data).

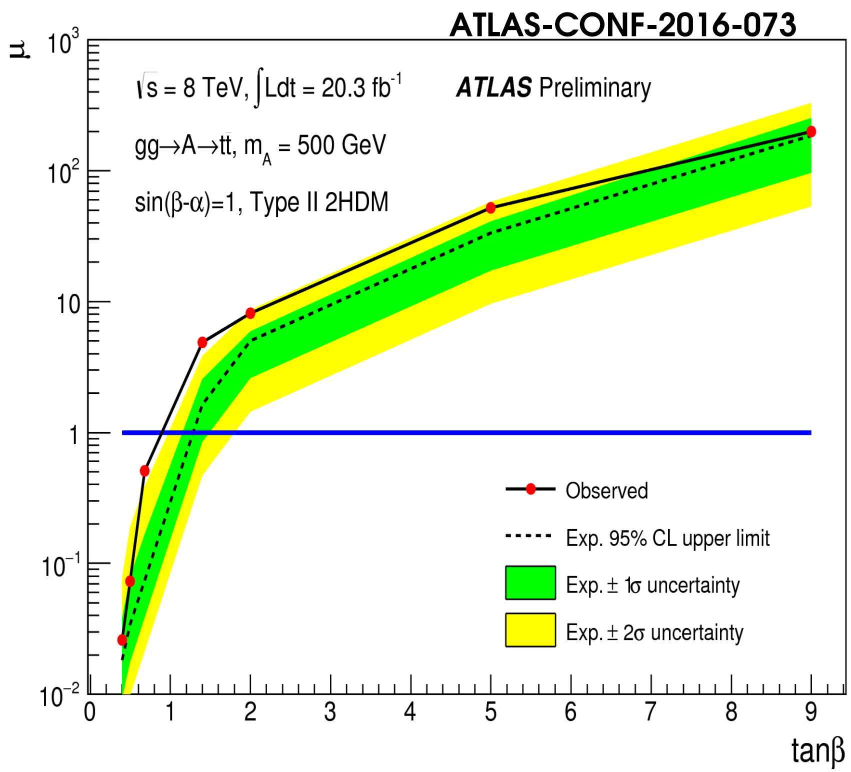


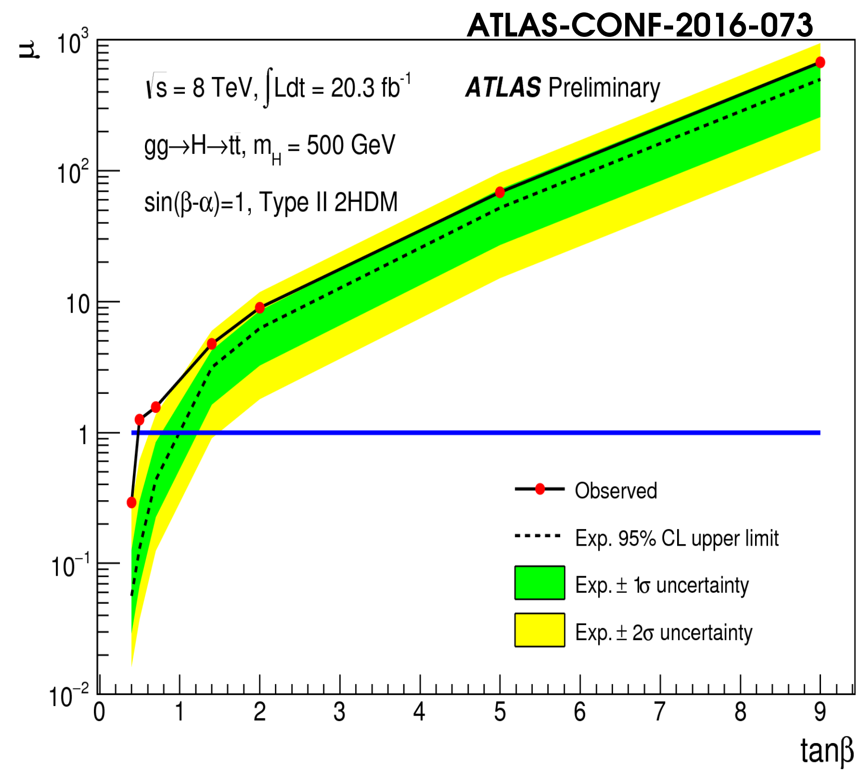




H,A→ ttbar Results

- Upper limits as a function of the parameter tanβ are set for a neutral scalar H and pseudoscalar A with benchmark masses of 500 GeV and 750 GeV.
- μ=1 corresponds to the signal strength in a Type-II 2HDM with sin(β-α)=1 and m_h= 125 GeV.



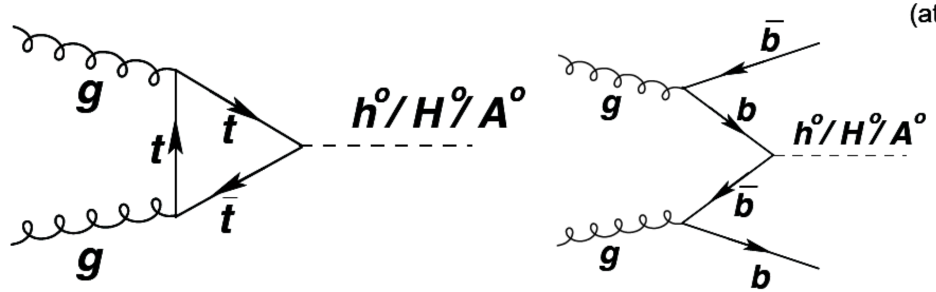


- tanβ < 0.85 and < 0.45 are excluded for m_A=500 GeV and m_H=500 GeV at 95% CL
- No tanβ values can be excluded for the higher mass point of 750 GeV.

Search for MSSM Heavy Higgs

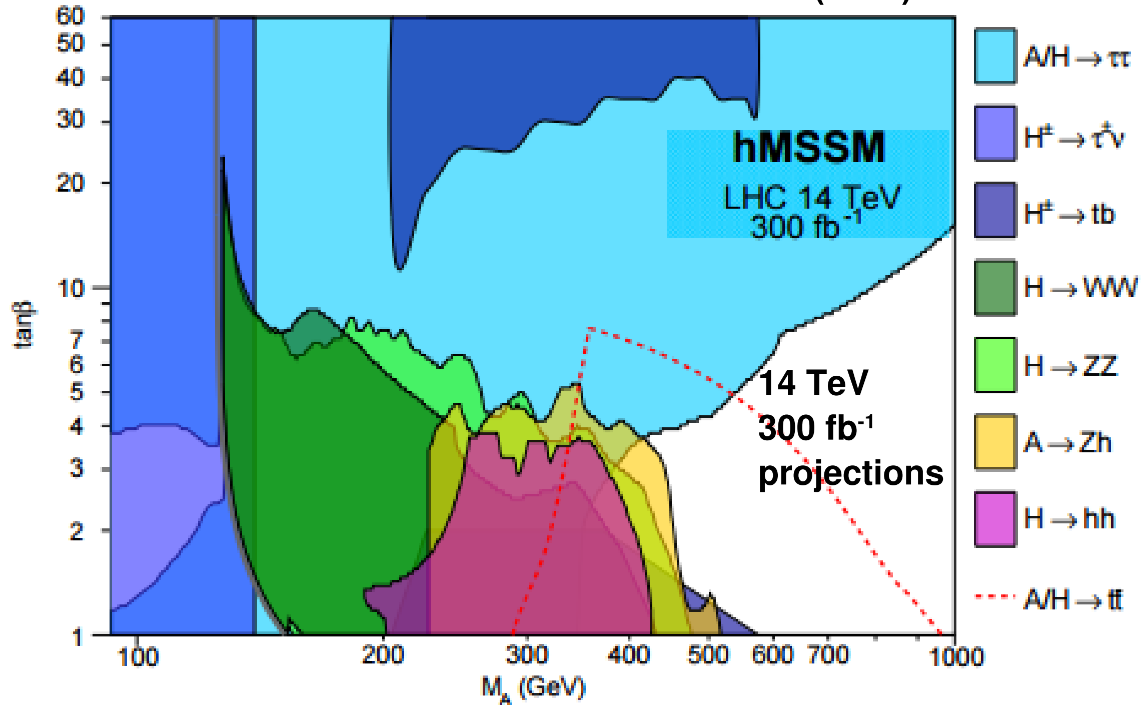
• In the MSSM, the Higgs coupling to τ-leptons is enhanced in a large part of the parameters space.

(at tree level)



enhanced by $\tan^2(\beta)$

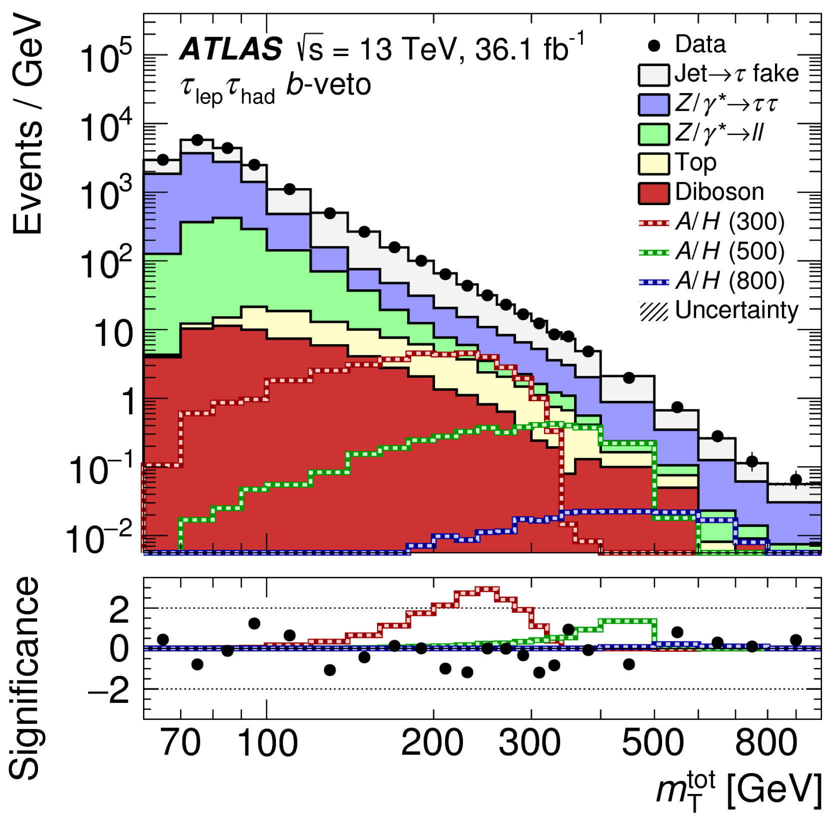
JHEP06 (2015) 168

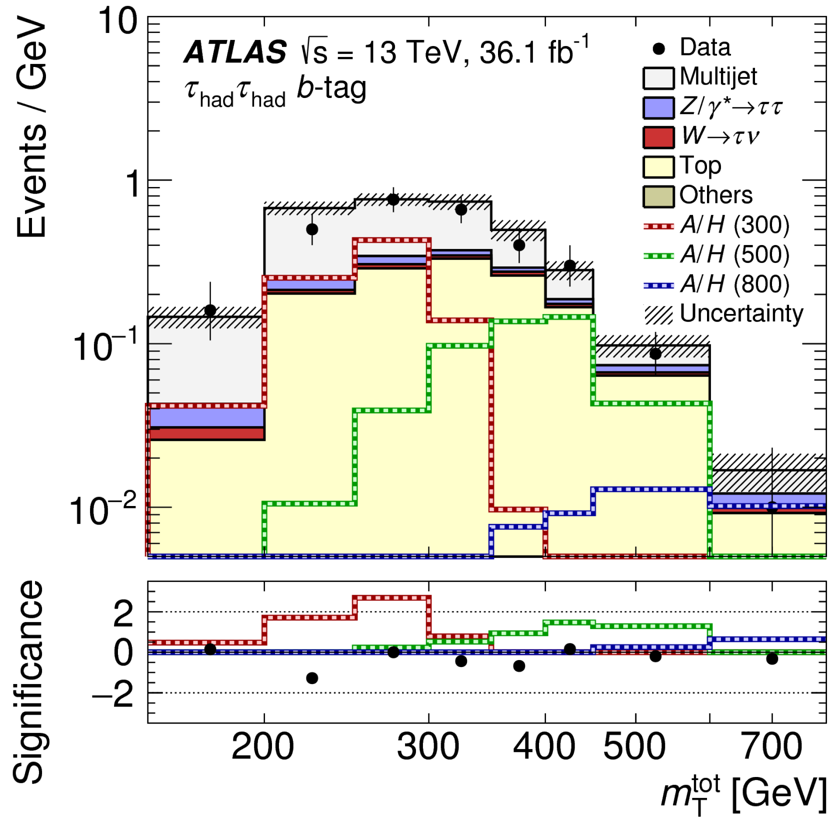


$H/A \rightarrow \tau\tau$ Search

- **JHEP 01 (2018) 055 <=36.1 fb^{-1} of 13 TeV data**
- $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels (they dominate the sensitivity at high mass)
- *b*-tag and *b*-veto categories.
- m_T^{tot} variable used in both channels
- **Backgrounds:**
  - $\tau_{lep}\tau_{had}$: multi-jet and W-jets/top estimated with data-driven methods.
  - $\tau_{had}\tau_{had}$: multi-jet and fake taus in other backgrounds: data-driven methods

$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)},$$



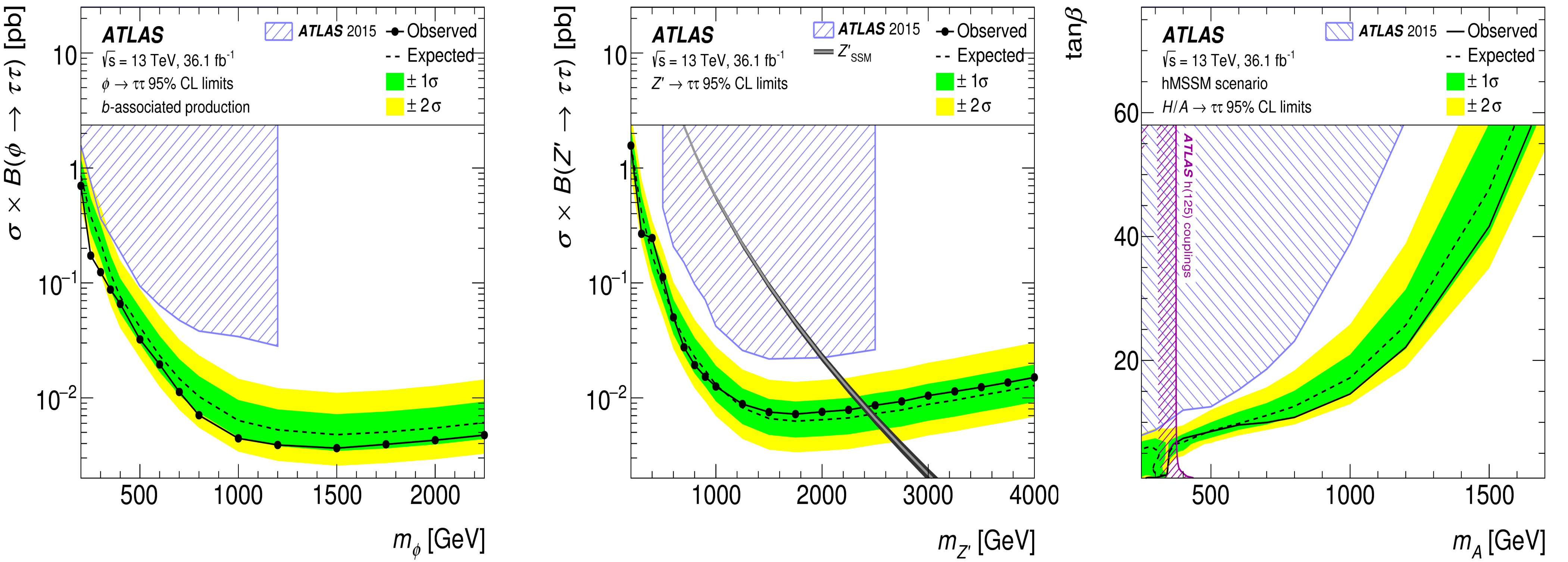


H/A→ττ Results

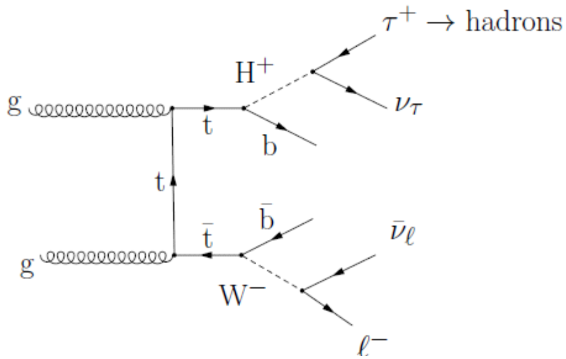
JHEP 01 (2018) 055 results: both model independent and MSSM scenarios:

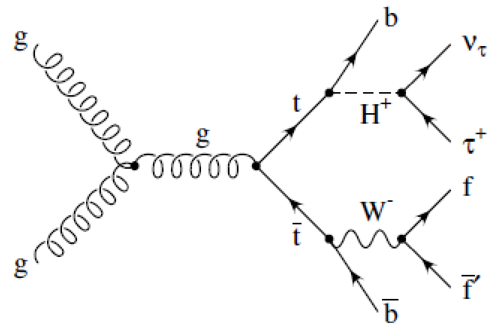
- hMSSM scenario: tanβ>1.0 for mA = 0.25 TeV and tanβ>42 for mA = 1.5 TeV excluded at the 95% confidence level.
- Sequential Standard Model, Z′SSM with mZ′<2.42 TeV

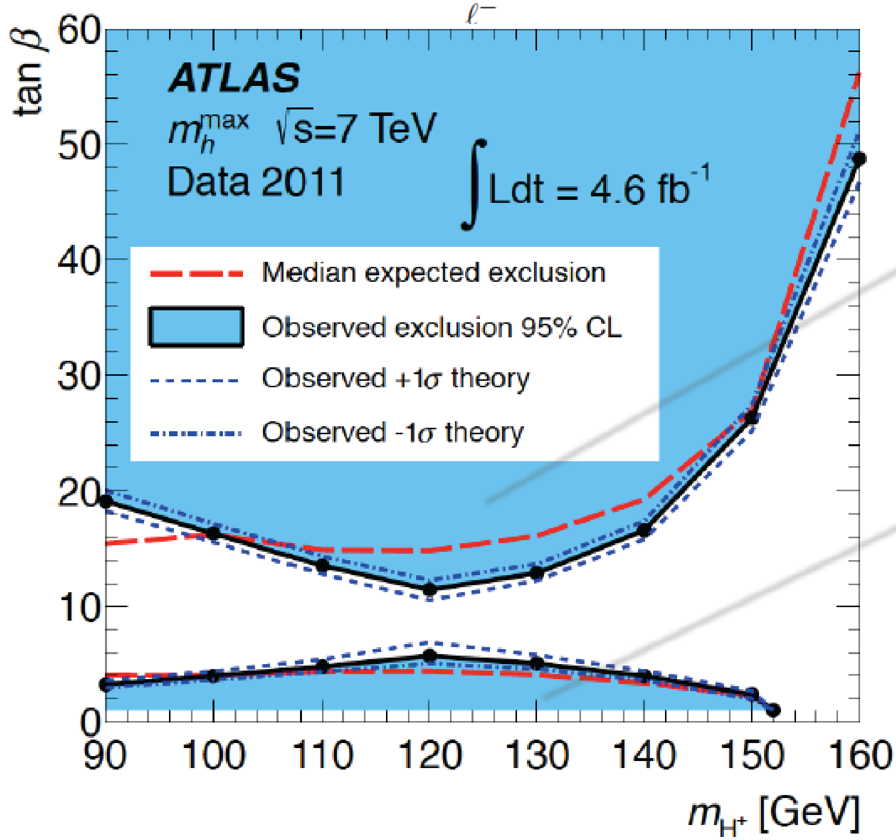
- ggH limits: 0.78-0.0058 pb for m_A=200-2250 GeV
- bbH limits: 0.70-0.0037 pb for m_A=200-2250 GeV



Search for MSSM Charged Higgs





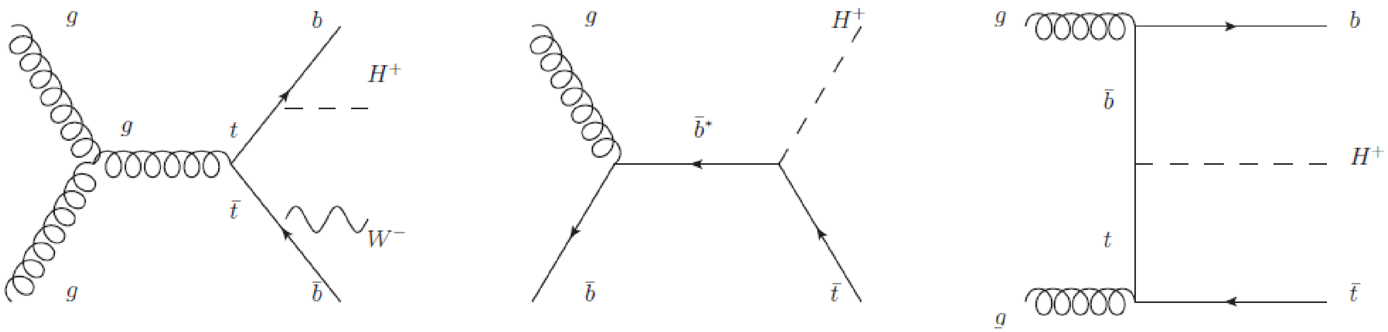


$m_b \tan\beta$

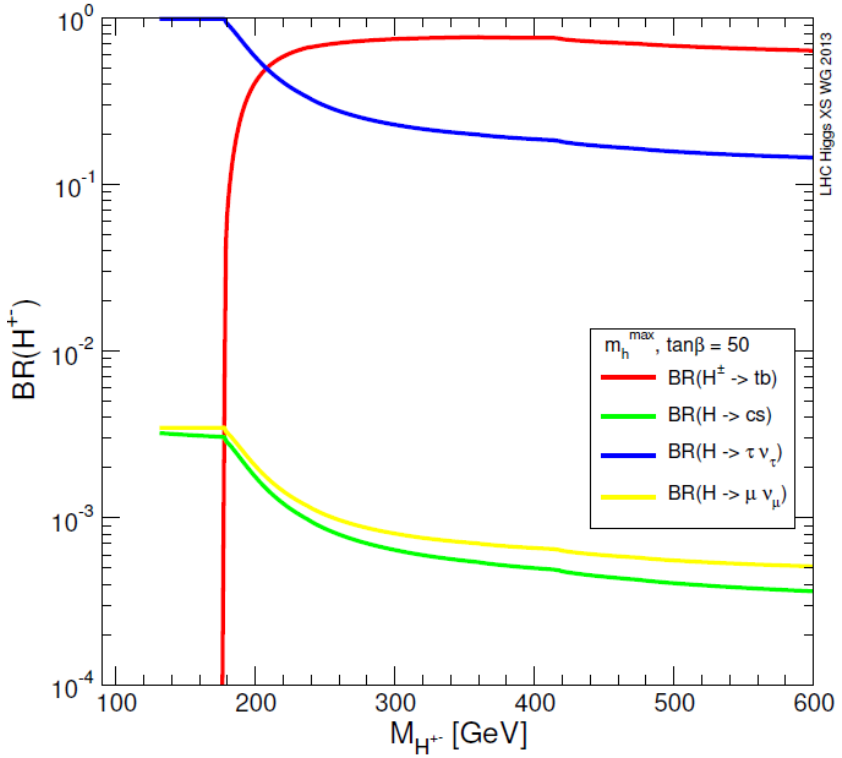
$\frac{m_t}{\tan\beta}$

Charged Higgs decaying to tau and neutrino: $H \rightarrow \tau\ \nu$

Search for MSSM Charged Higgs



Look at top decays if charged higgs lighter than top, look at associated production otherwise.



H+ → τν and H → tb decays dominate.

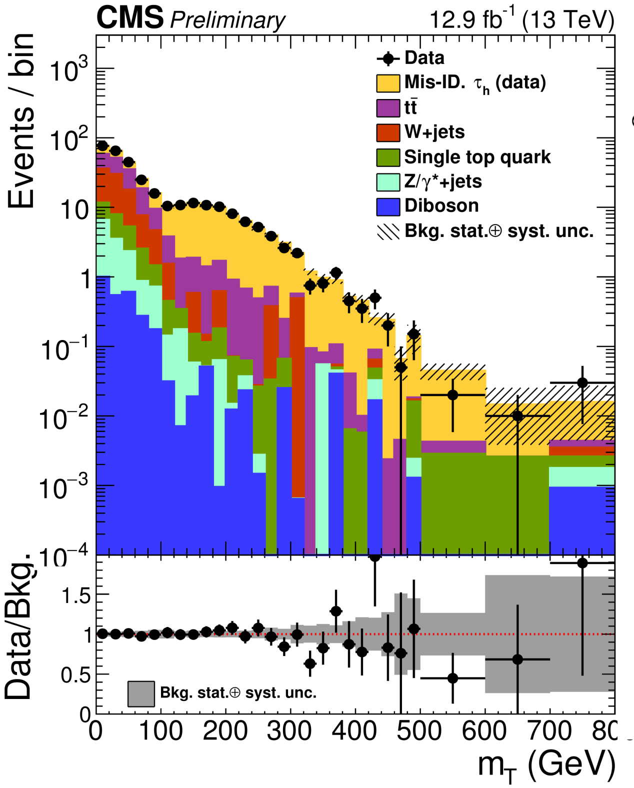
Charged Higgs $H^{\pm} \to \tau\nu$ Search

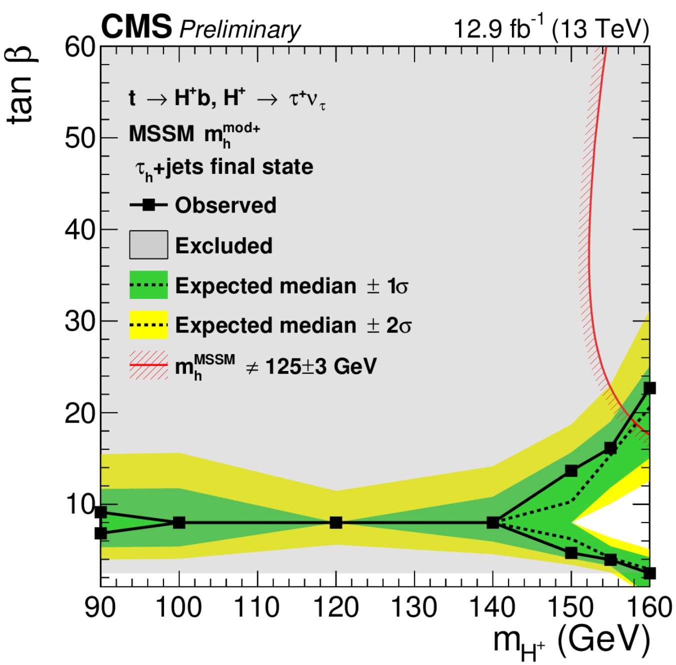
- For $m_{H^{\pm}} > m_t$, production in association with top-quark is dominant
- **$H^{\pm} \to \tau\nu$ search: ATLAS-CONF-2016-088**
- Discriminant variable is m_T:

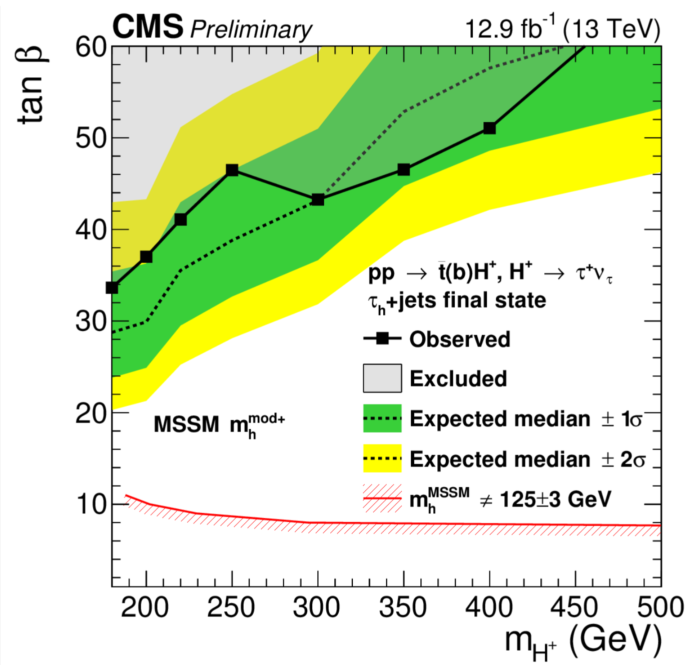
$$m_T = \sqrt{2 p_T^{\tau} E_T^{miss} (1 - \cos \Delta\phi_{\tau, E_T^{miss}})},$$

- **Backgrounds:**
  - True τ_{had}: MC estimation
  - Jet $\to \tau_{had}$ fakes: Data-driven estimation

- **Signal Regions:**
  - High mass: higher thresholds on E_T^{miss} and tau p_T and Njets>2
  - Low mass: lower thresholds on E_T^{miss} and tau p_T
  - Observed hMSSM exclusion: tanβ>42-60 @ $m_{H^{\pm}}$ = 200-540 GeV



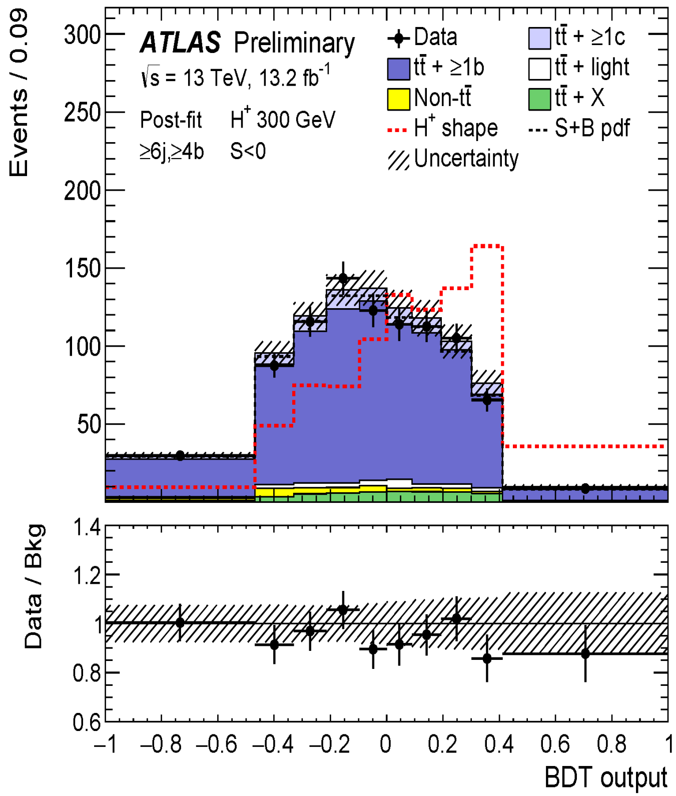




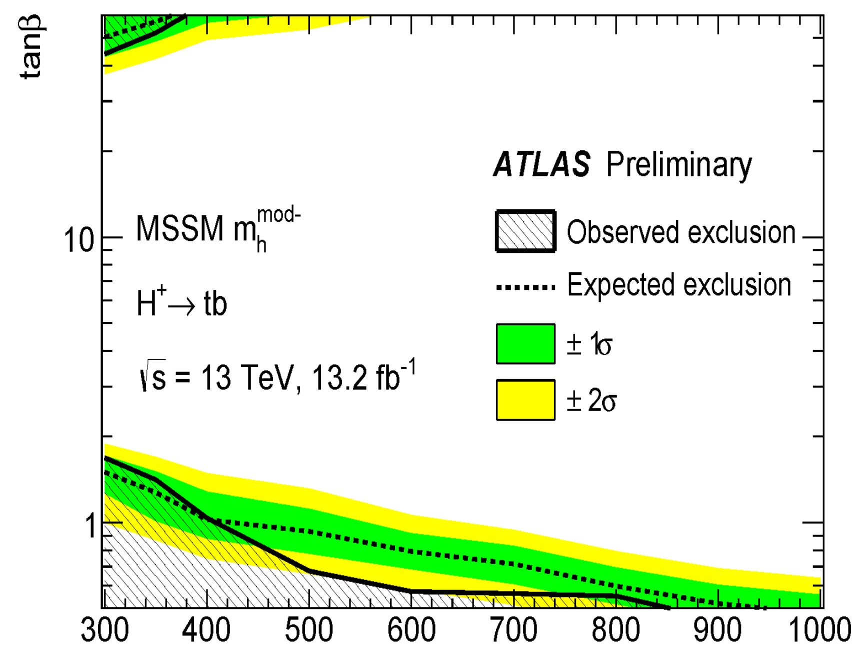
Charged Higgs $H^{\pm} \rightarrow tb$ search

- For $m_{H^{\pm}} > m_t$, production in association with top-quark (b)t$H^{\pm}$ is dominant

- **$H^{\pm} \rightarrow tb$ search:** **ATLAS-CONF-2016-089**
- **lepton+jets final state (lep=e,μ)**
- Discriminant variable is a BDT-score calculated from 12 input variables
- Signal Regions:
  - 1 lepton with p_T > 25 GeV
  - 5j3b, 5j≥4b, ≥6j3b and ≥6j≥4b



- **Backgrounds:**
- ttbar+jets production dominates, modelled using Powheg + Pythia6: reweight ttbar+light and ttbar+≥1c to NNLO and ttbar+≥1b to NLO
- Control Regions: 4j2b, 4j≥3b, 5j2b and ≥6j2b
- H_T^{had} (Sum of p_T of selected jets) used for CR



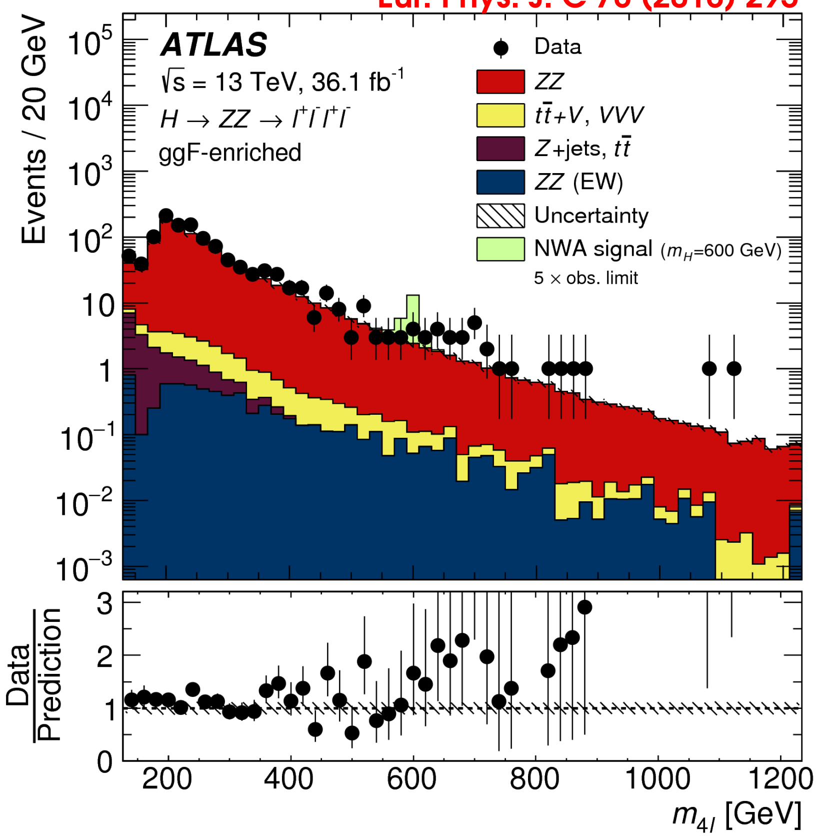
Observed m_h^{mod-} exclusion:

tanβ<1.7-0.5 @ $m_{H^{\pm}}$ = 300-855 GeV

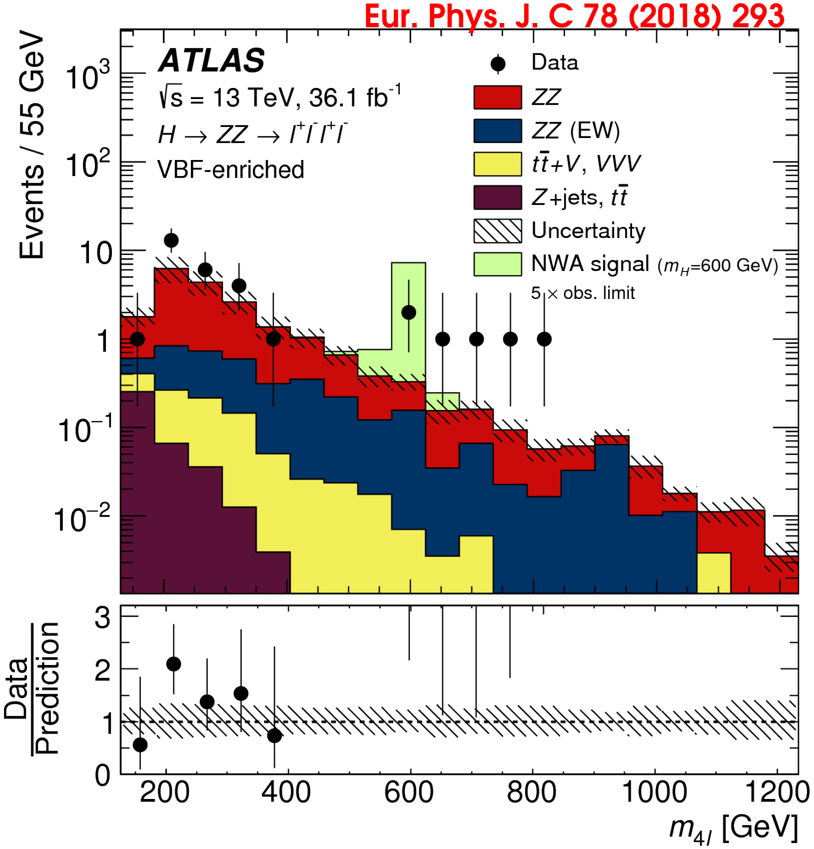
$H \rightarrow ZZ \rightarrow 4l$ searches

- **$H \rightarrow ZZ \rightarrow 4l$ (4e, 2eμ, 24μ):** 36.1 fb^{-1}@13 TeV
- Same selection as SM, but requires both Z on-shell
- **VBF-enriched category**: mjj > 400 GeV and Δηjj > 3.3 (all flavours together)
- **ggH-enriched category**: the rest, pslit by flavour
- For large-width H, interference effects with h and the gg → ZZ continuum are taken into account.
- Limits set for VBF and ggH production and 4.07 MeV, 1%, 5% and 10% widths

Eur. Phys. J. C 78 (2018) 293



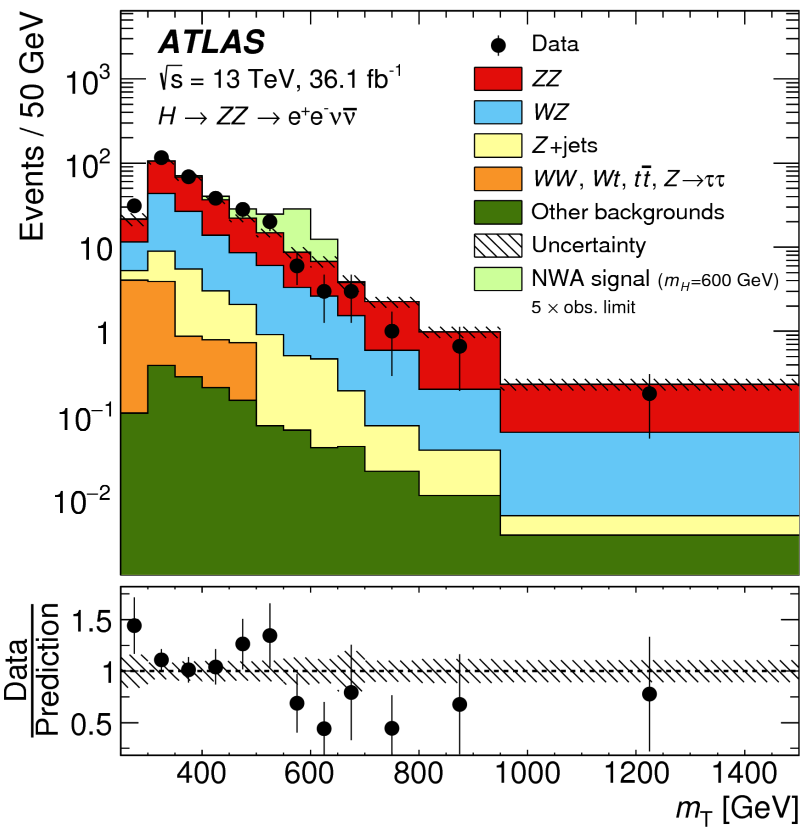
Eur. Phys. J. C 78 (2018) 293

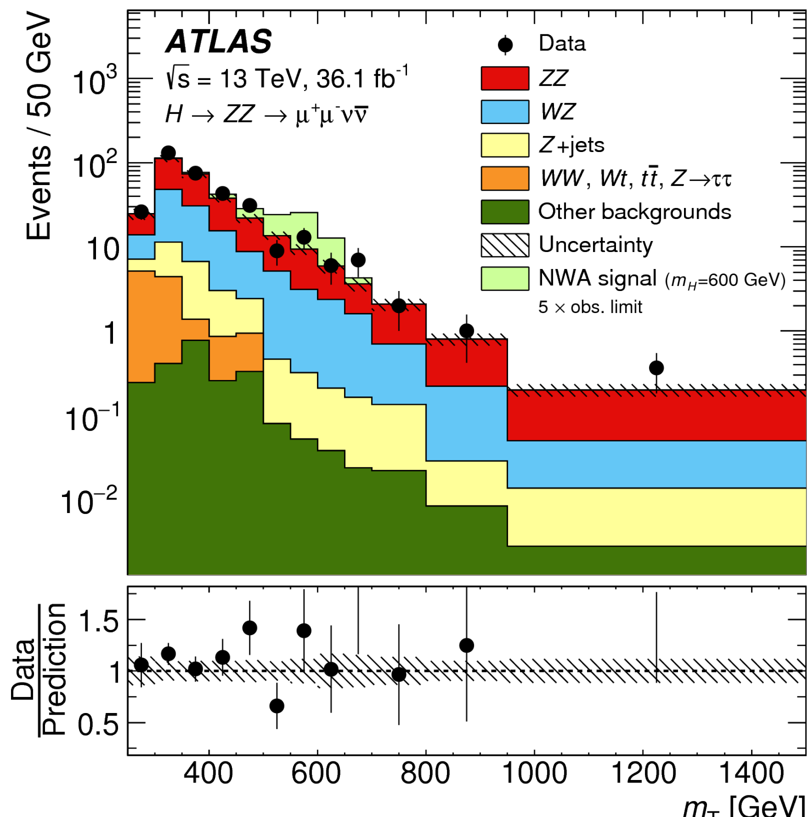


$H \to ZZ \to ll\nu\nu$ search

H→ZZ→llνν :

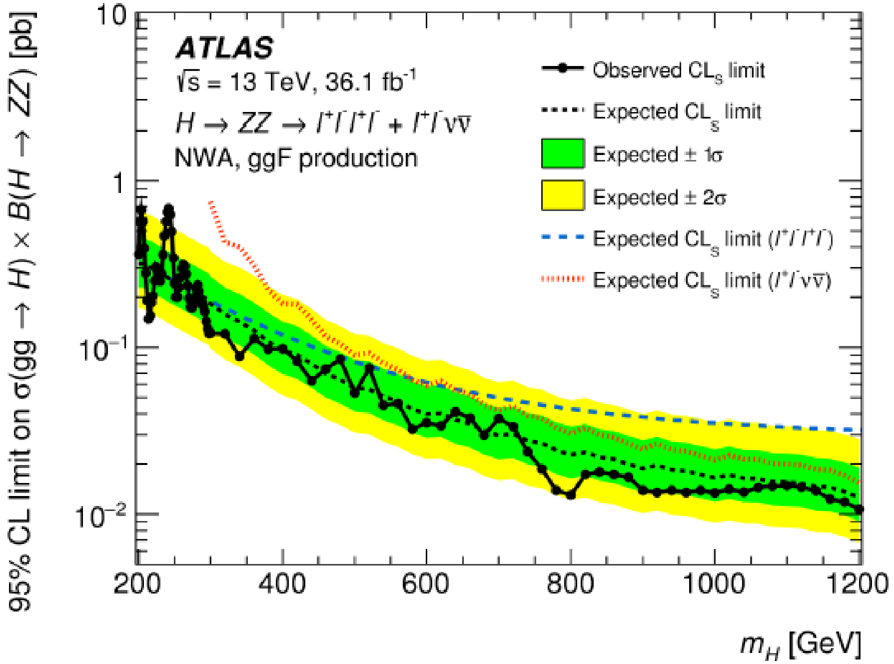
- OS ee, mm pair
- E_T^{miss} >120 GeV
- Discard events with a b-jet.
- VBF category (2 jets, $|\Delta\eta_{jj}|$ > 4:4, m_{jj} > 550 GeV);
- Transverse invariant mass mT of the dilepton system and E_T^{miss} as discriminant.

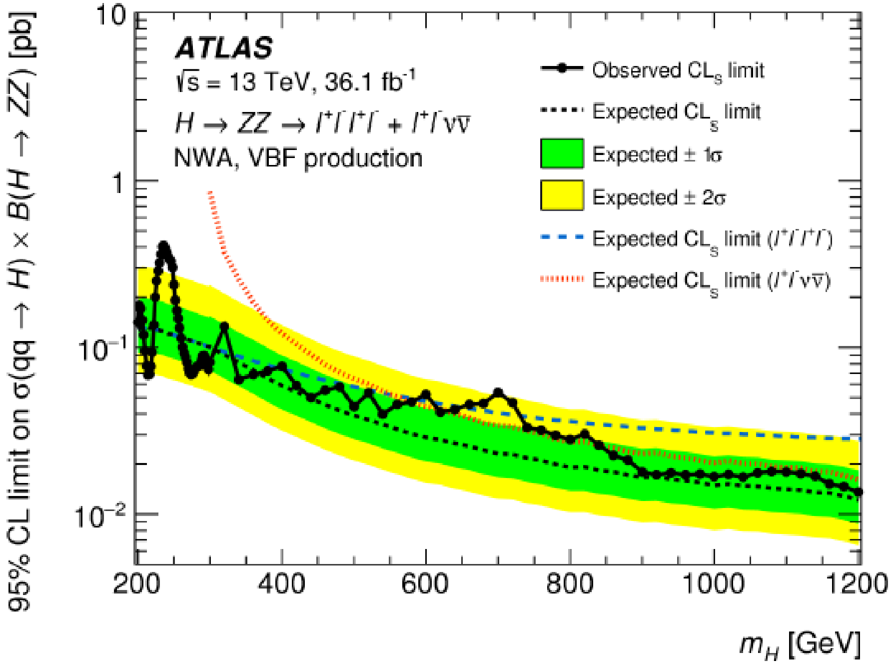




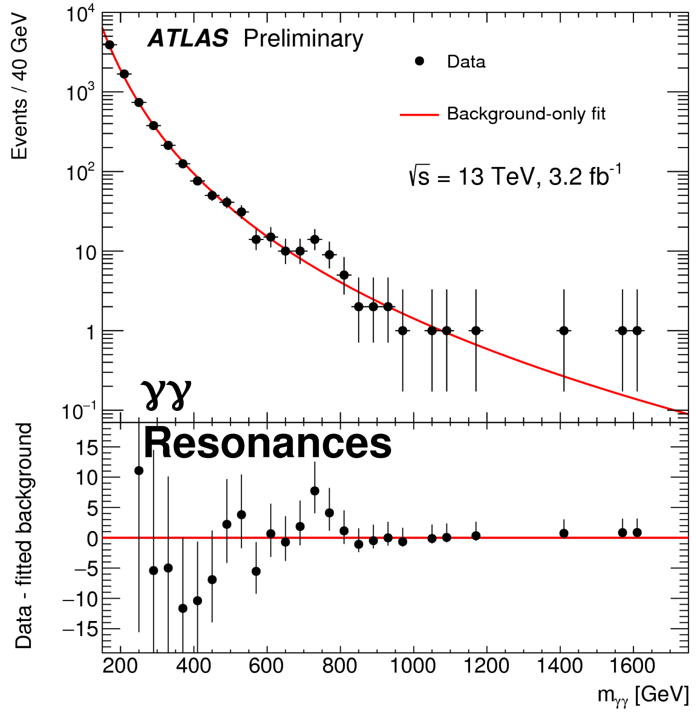
H→ZZ→4l/llνν results

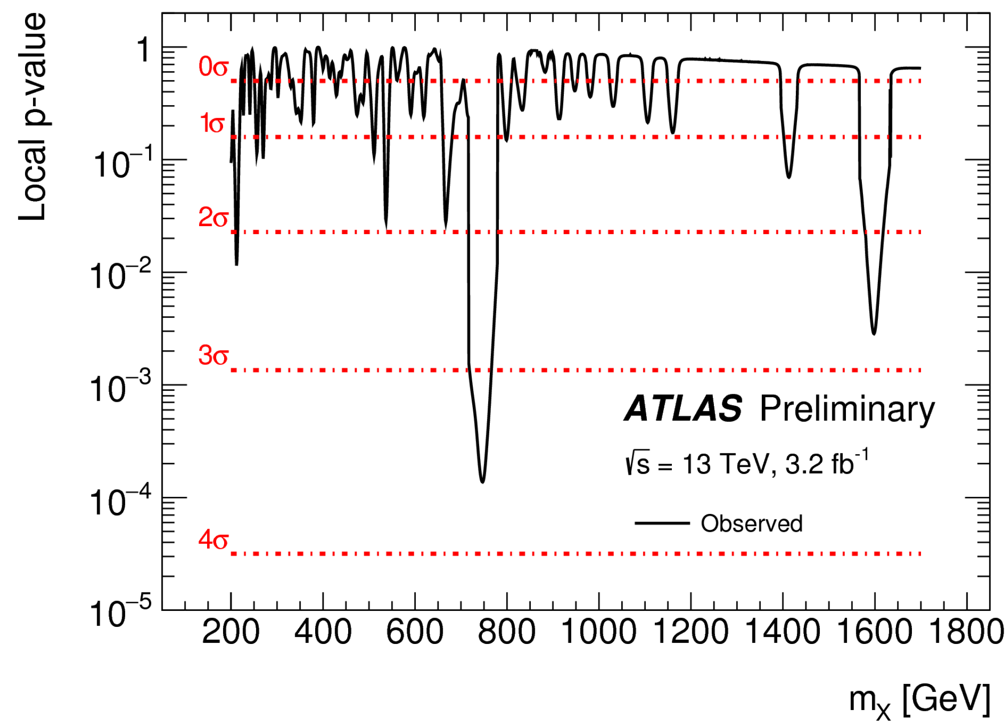
- Two 3.6 σ excesses at 240 GeV in the 4e channel mostly (not covered by llνν) and at 700 GeV in all 4l channels but excluded at 95% CL by the llνν search) → only 1.3 global excess in data.

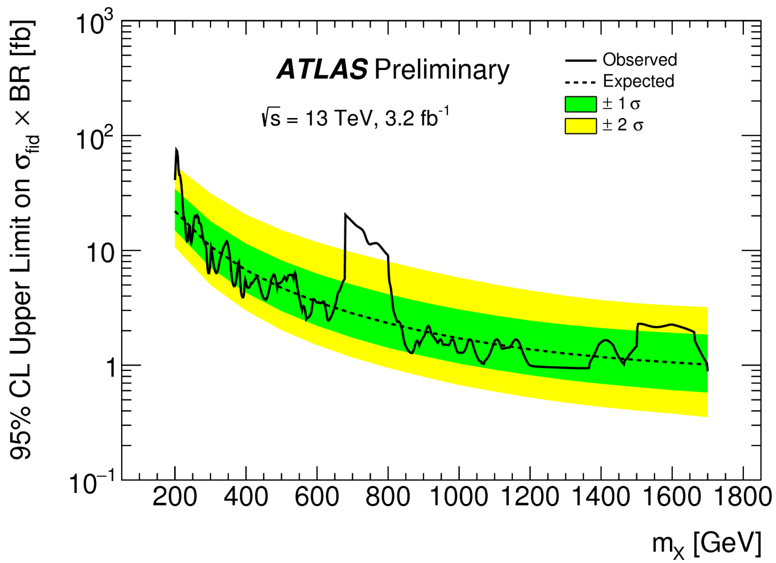




Highlight of 2015 data



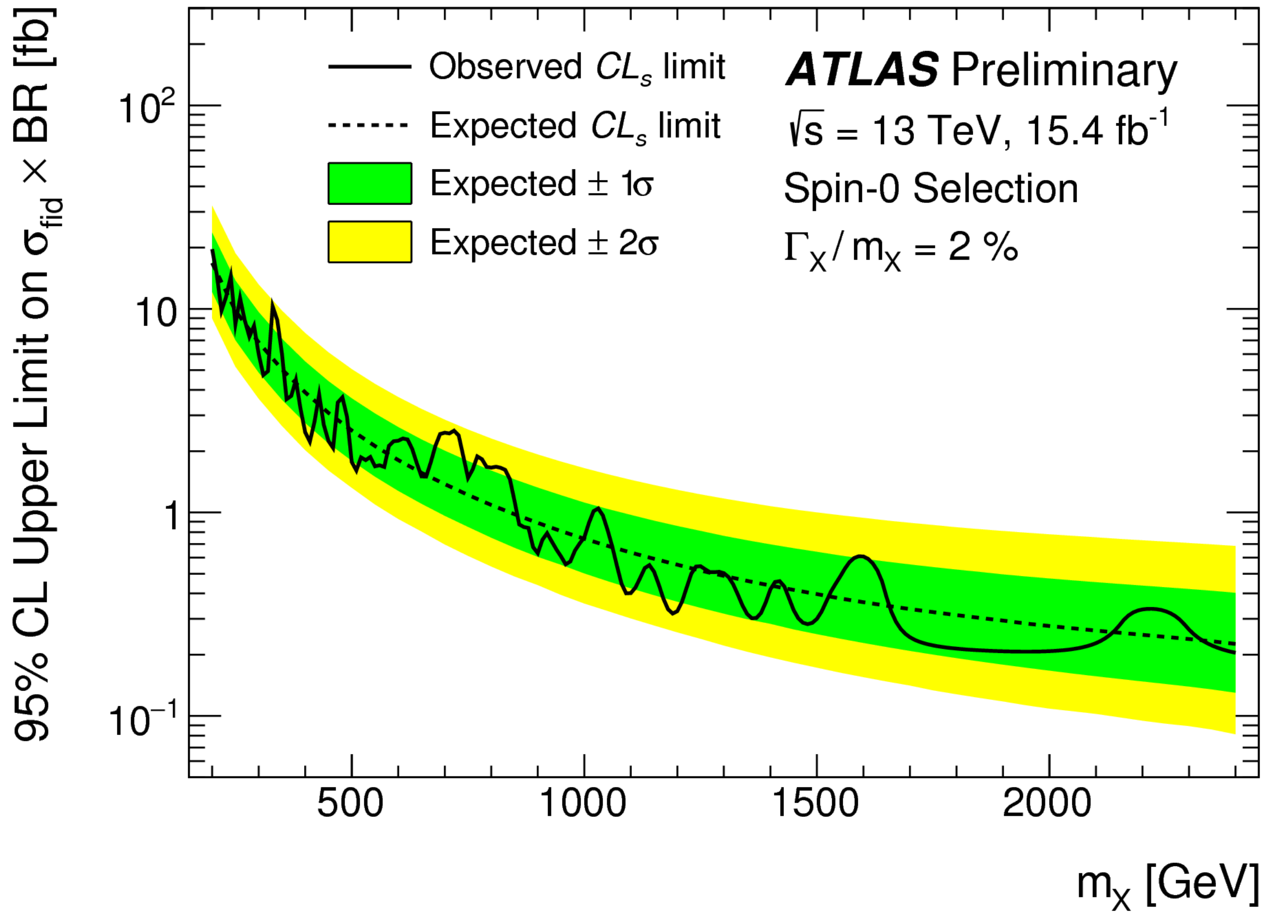




Excess of 3.6 σ (local) at 750 GeV, corresponding to 1.9 σ global significance, taking into account LEE.

Similar excess observed by CMS at 760 GeV with local significance of 2.6 σ, corresponding to 1.2 σ taking into account the LEE.

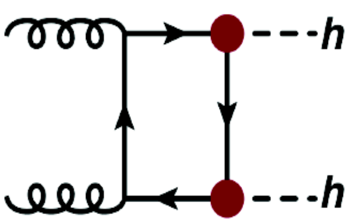
Answers from 2016 data



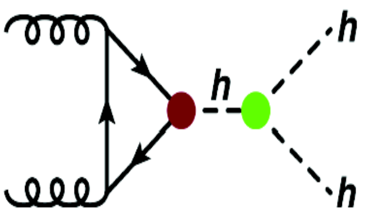
Unfortunately 2016 data didn't confirm the very intriguing excess of 2015!

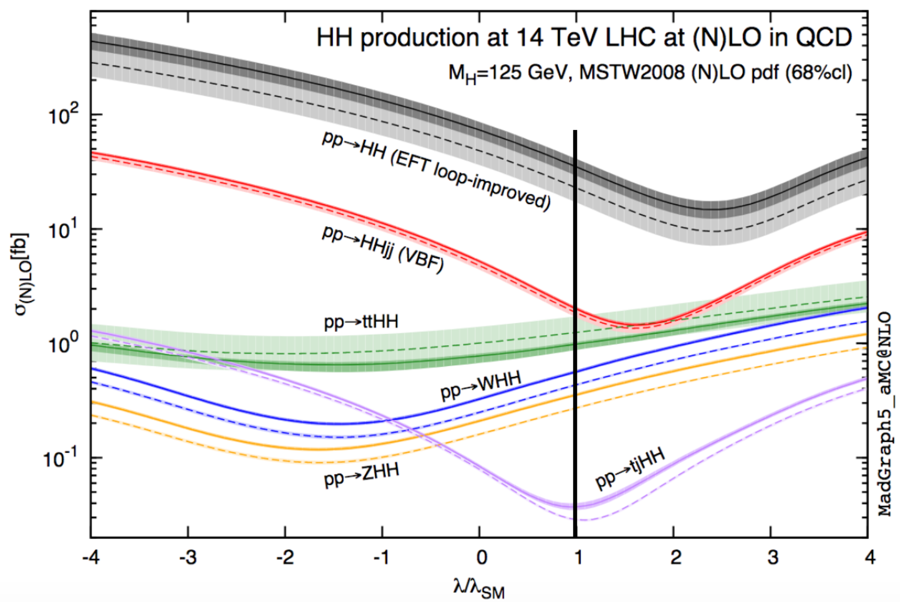
Di-higgs production

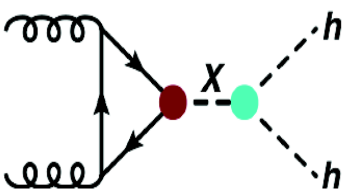
- **Di-higgs** production is very small in SM due to destructive interference:
  - 33.7 fb@pp,√s=13 TeV, non resonant

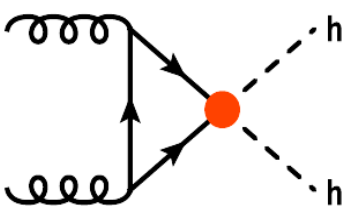


- In BSM, can be enhanced by:
  - Modified top Yukawa coupling or λ_{hhh} (**non-resonant production**).
  - **Resonant** production: 2HDM H→ hh (spin-0), KK gravitons (spin-2),....
  - modified kinematics (e.g. m_{hh}, p_T^h)







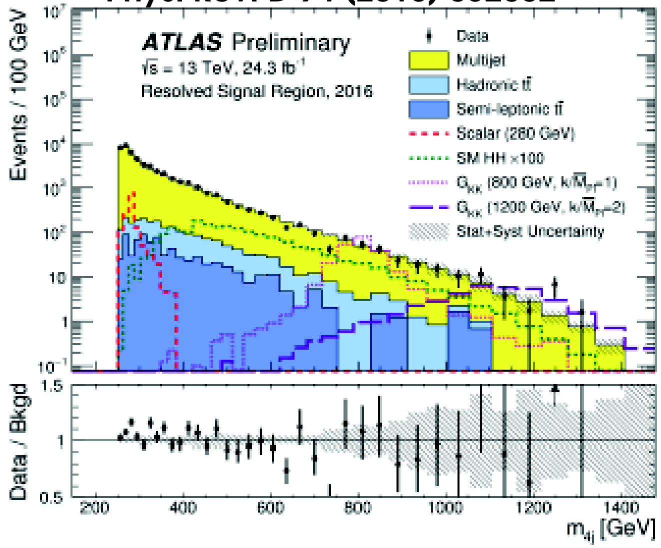


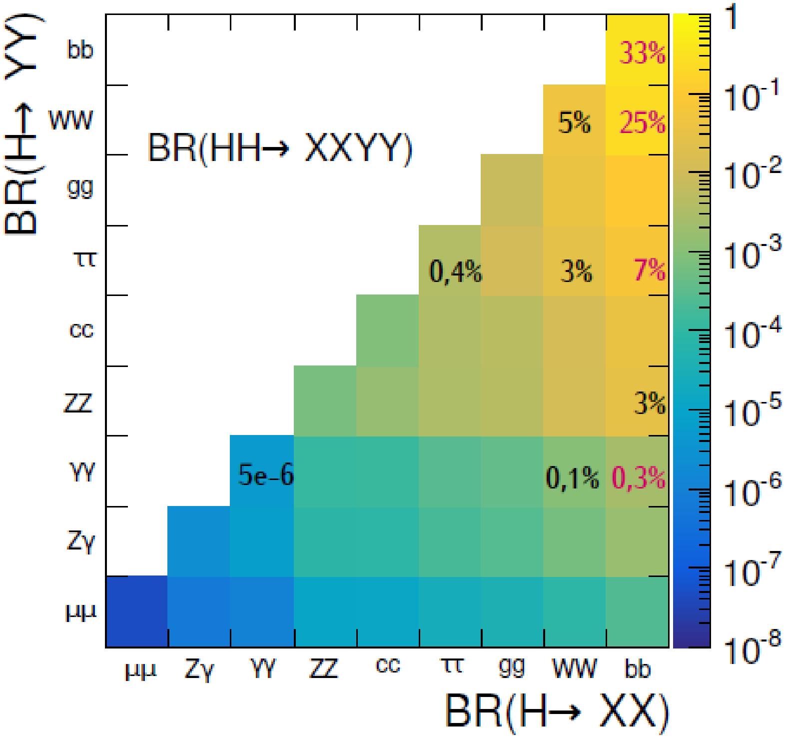
HH: di-Higgs production (2)

- Analyses exploit large $H \to bb$ branching ratio to improve sensitivity.

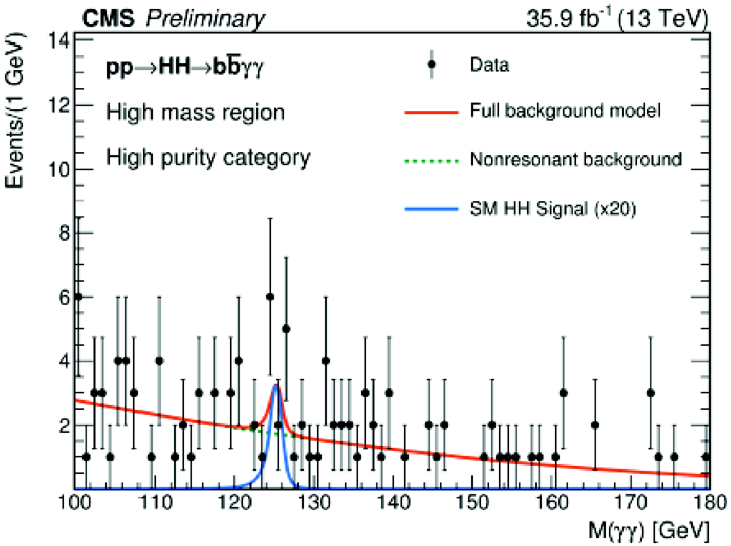
- The second Higgs decays to the main decay modes:
- $HH \to 4b$
- $HH \to bbWW$
- $HH \to bb\tau\tau$
- $HH \to bb\gamma\gamma$
- $HH \to bbZZ$
- $HH \to WW\gamma\gamma$

Phys. Rev. D 94 (2016) 052002



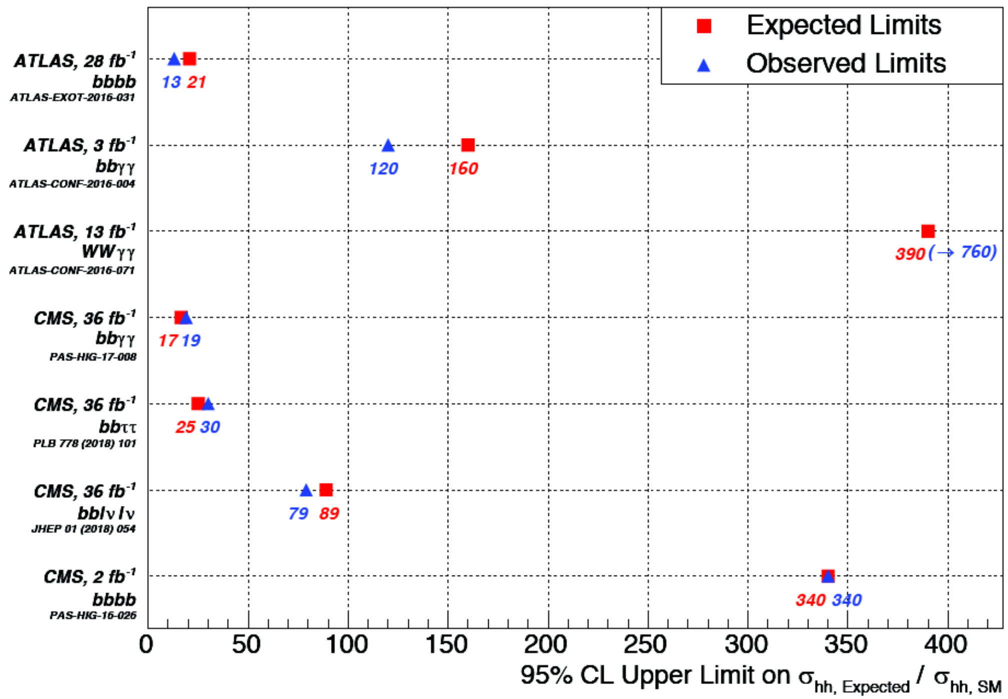


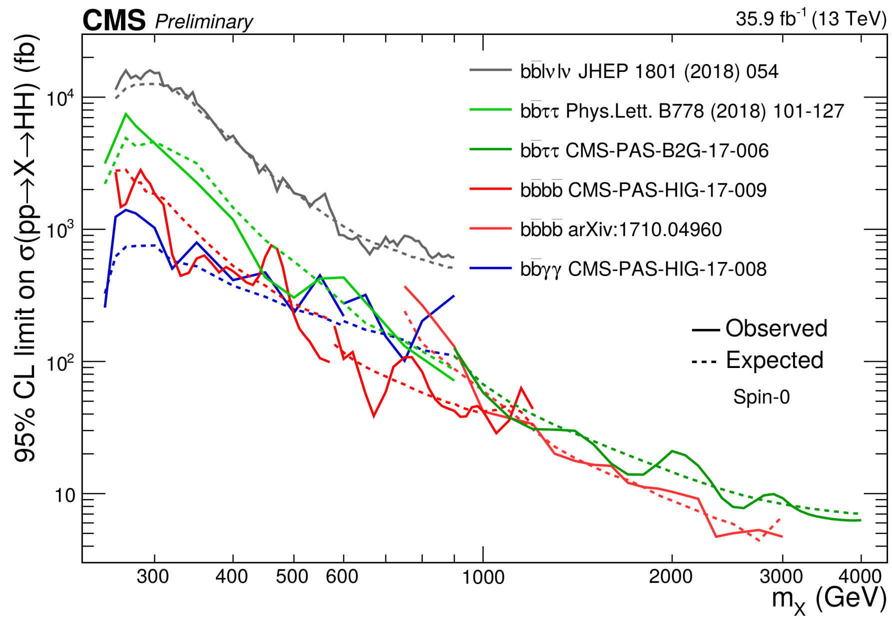
CMS-PAS-HIG-17-008



HH: double Higgs production (3)

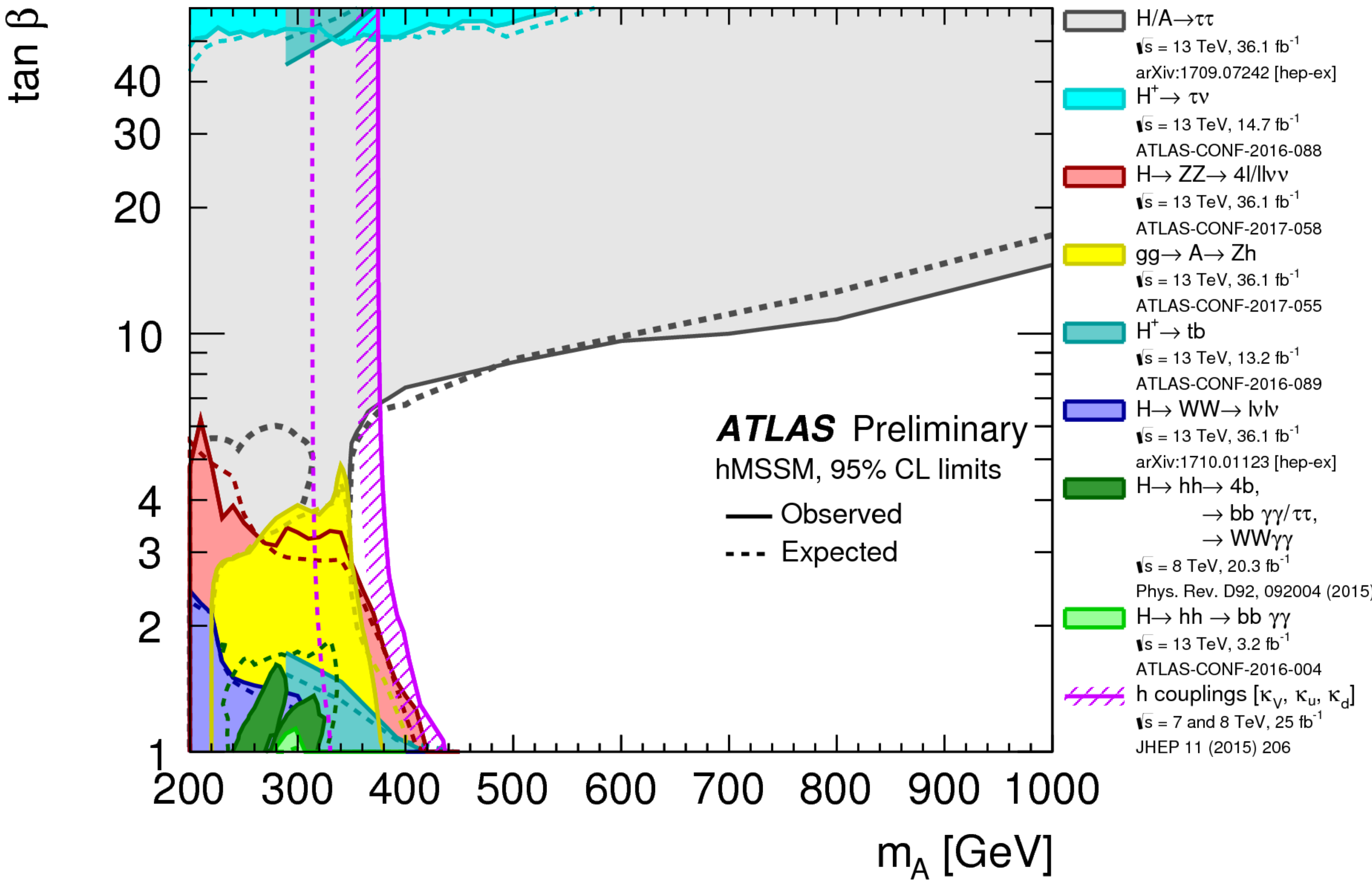
- Many channels making rapid progress on di-Higgs searches
- Assuming improvements scale with statistical uncertainty, by the end of Run 2 it will have single channel sensitivity on HH production cross-section at the level of $10 \bullet \sigma_{HH}^{SM}$ or better
- Limits on new resonances O(pb) – O(fb) depending on mass.





Run 2 Status Summary

Limits and reinterpretation of limits of the searches into the plane (m_A,tanβ) in the hMSSM framework.



Bonus Slides

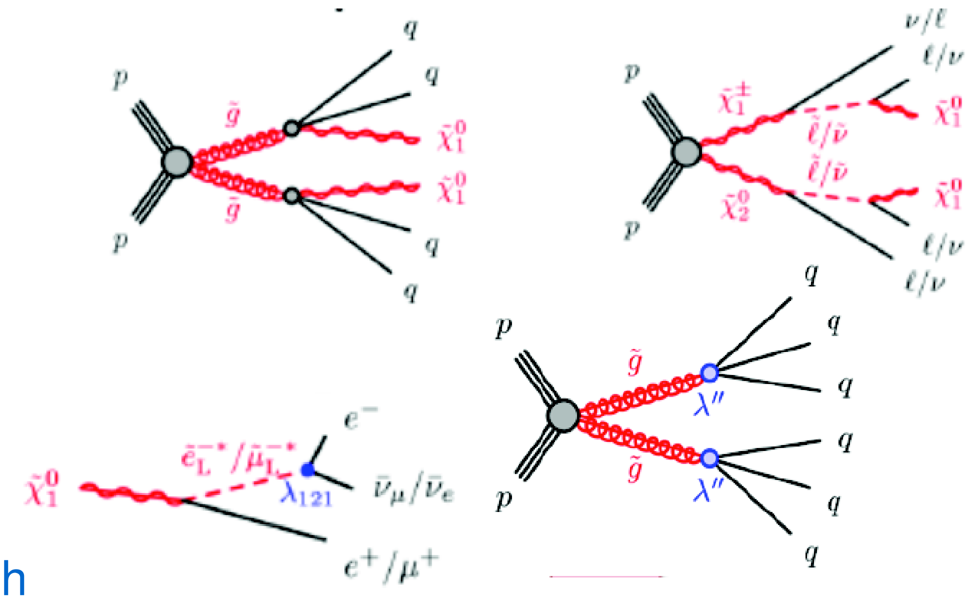
SuperSymmetry Phenomenology

SUSY as theoretical framework

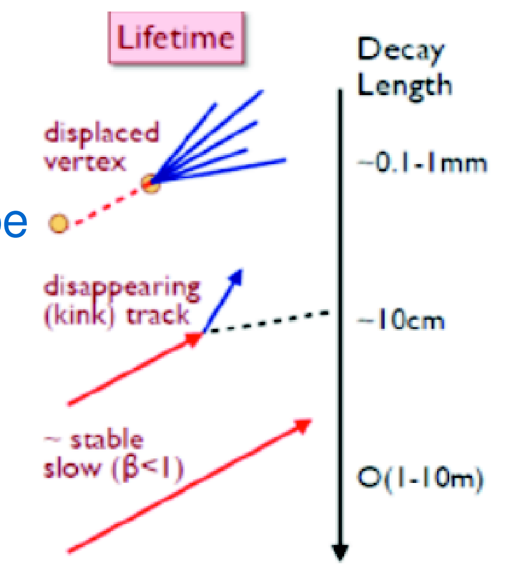
SUSY breaking mechanism and R-parity determines the phenomenology → sparticle decay modes, nature of the Lightest SUSY Particle, lifetime…

If R-parity is conserved (RPC)
→ sparticles produced in pairs at colliders
→ Lightest Supersymmetric Particle lead to high missing transverse momentum (ETMiss) final states.
Typical LSP: lightest neutralino (χ_1^0), gravitino (G)

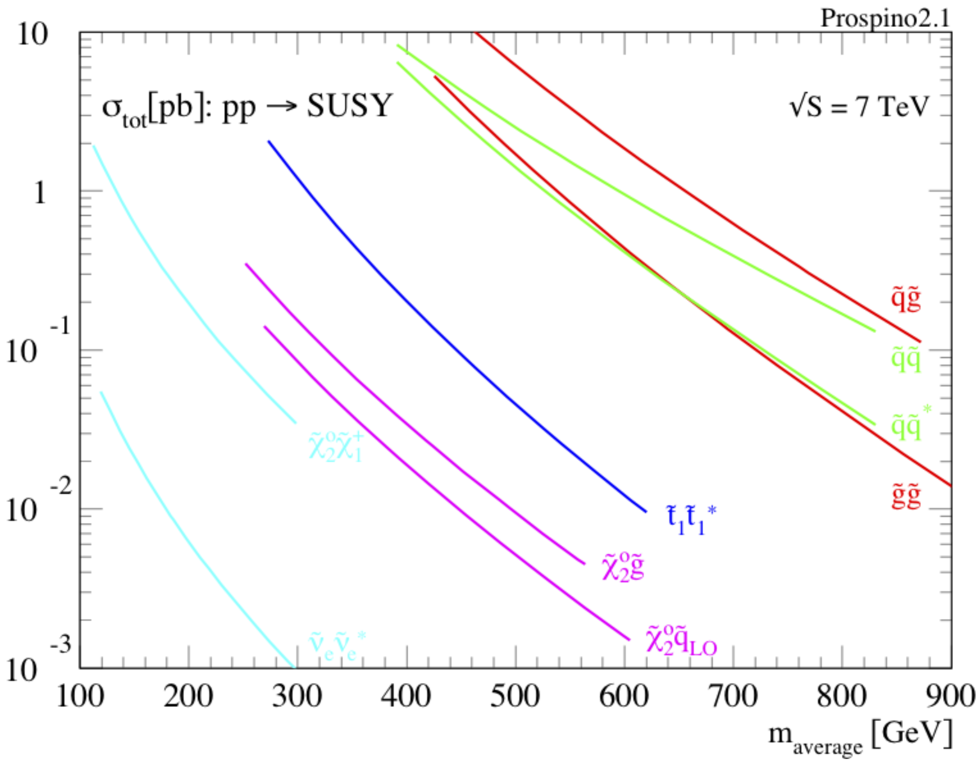
If R-parity is violated (RPV)
→ LSP no longer stable, rich and diverse phenomenology depending on the involved parameters (λ, λ’,λ’’)



Some SUSY particles can be long-lived



SUSY Production



Access to SUSY particles up to the TeV scale

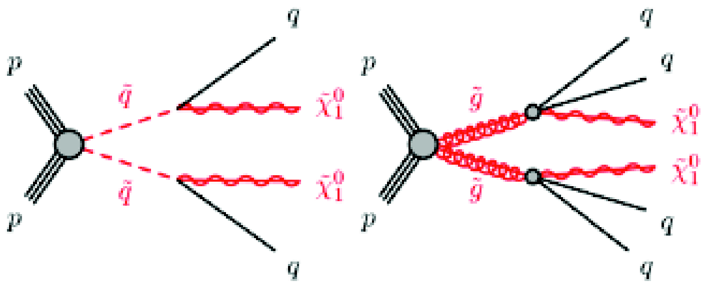
Main production modes involve squarks and gluinos in the final state

ATLAS&CMS search strategies designed to provide coverage for a broad class of SUSY models

- For each search, a number of signal regions is optimized based on a variety of final states
- Most of the final states involve chain decays of SUSY particles with several jets and leptons and large Etmiss.

Example of SUSY Searches

•1st / 2nd generation squarks and gluinos
Possibly complex final states, great variety of signatures ✉
main target of inclusive searches with several jets, possibly leptons and large ET Miss



Example: Inclusive jets+ETMiss analyses:

ATLAS Analysis:

• Minimum Jet multiplicity (2 to >=6j)
• Use Effective Mass (Meff= ET Miss +Sum pT jets)
• Thresholds from 800 GeV to 2.2 TeV
• But also: presence of boosted W → qq'
• Also merged products → jet mass (60-100 GeV)

CMS Analysis:

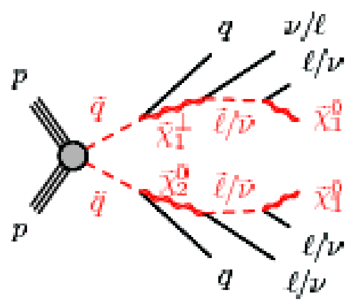
Three jet multiplicity categories (3–5, 6–7, and 8 jets)
• Selections in ETMiss and HT (Scalar Sum pT of the jets)

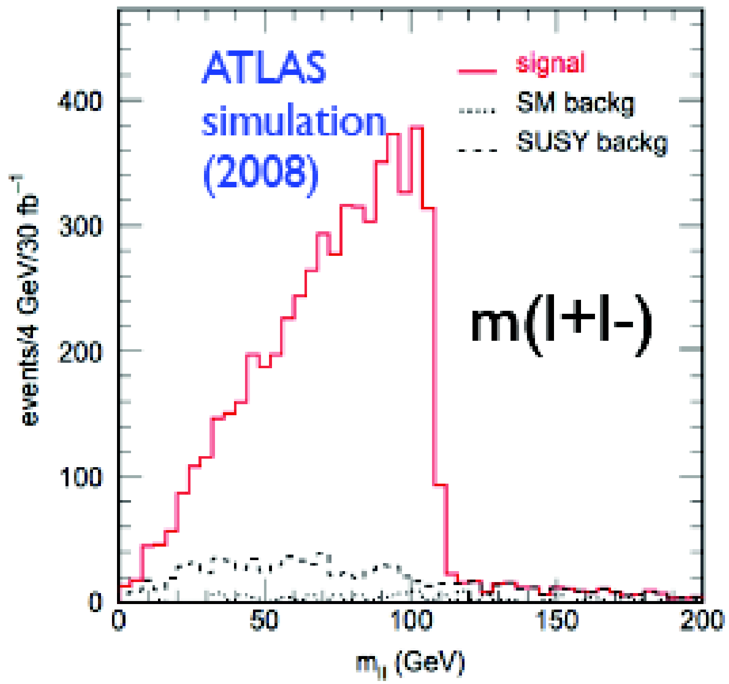
Example of di-lepton edges

Not only 'cut-and-count' searches

- Various interesting kinematic variables proposed before beginning of Run1 to characterize 'SUSY' signal (some used as discriminating quantities)
- Di-lepton mass:
  - end-point expected for some SUSY processes

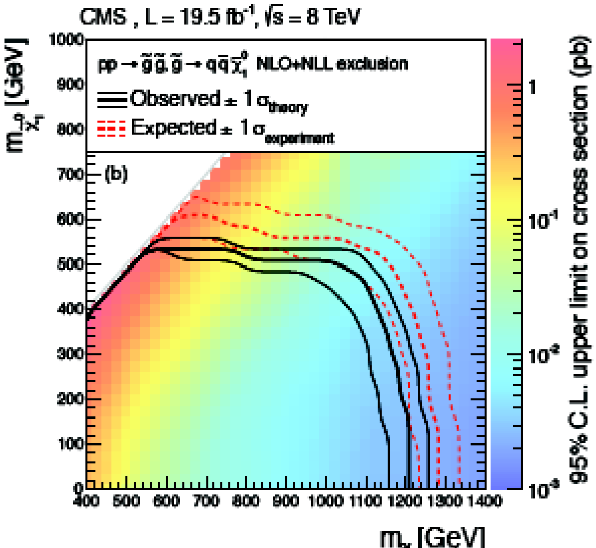
$$\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$$

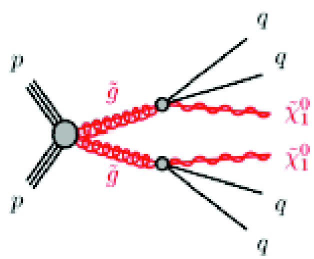


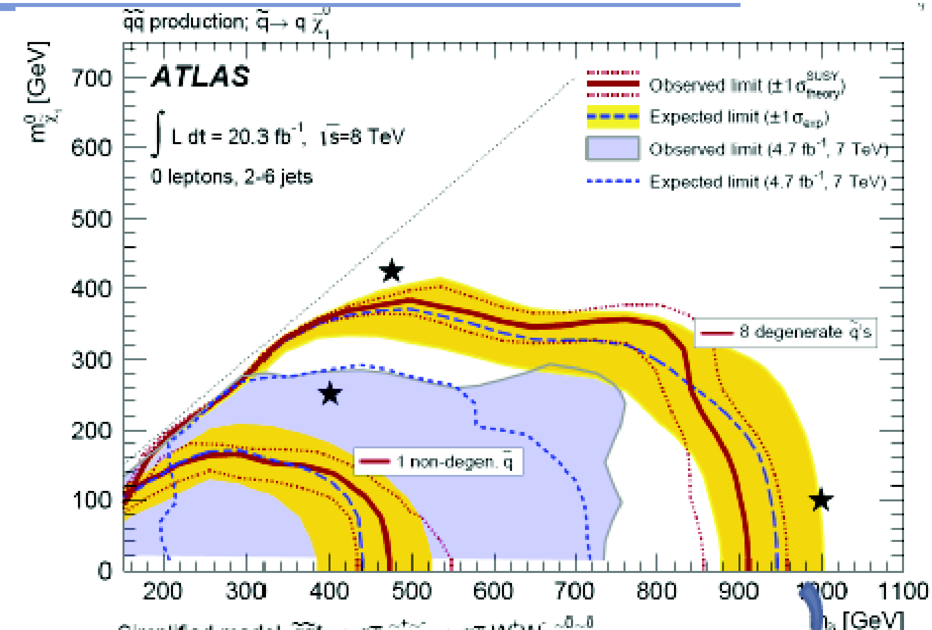


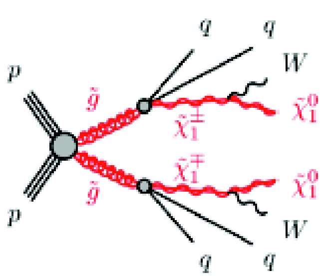
Some Results of SUSY Searches

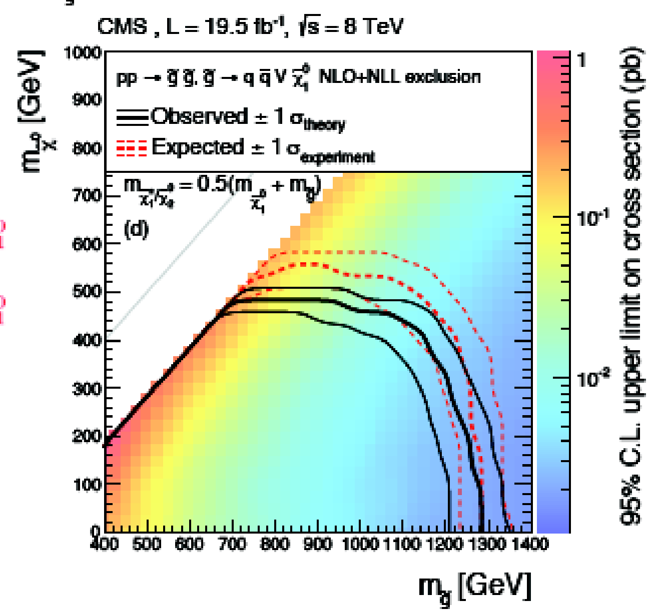
- Exclusions on gluino and squark masses

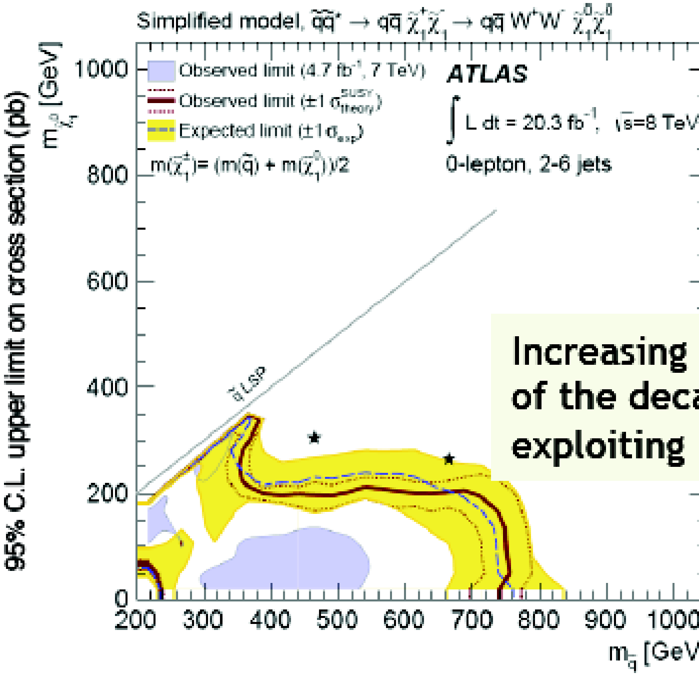


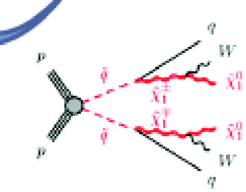






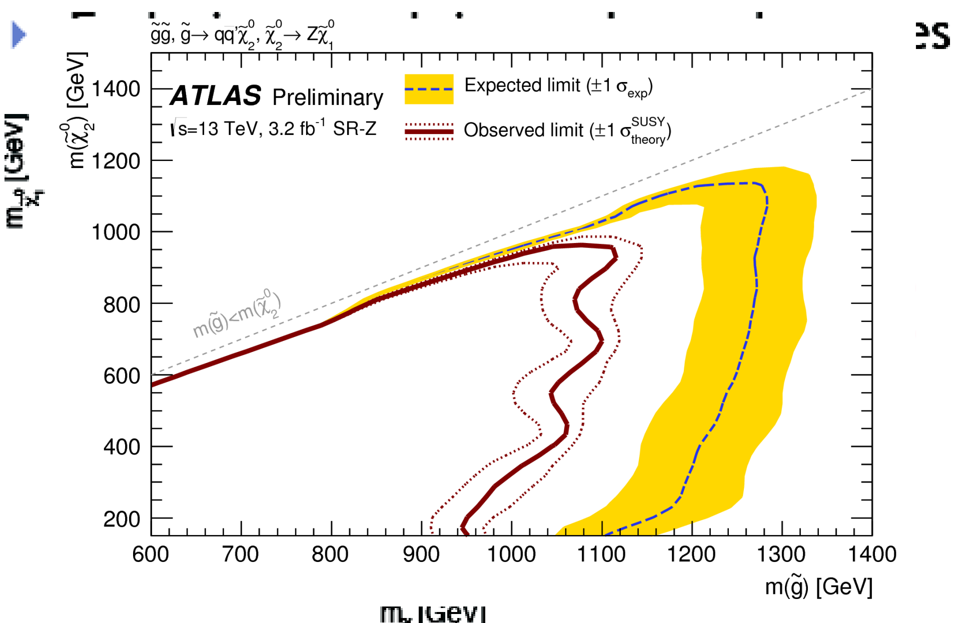


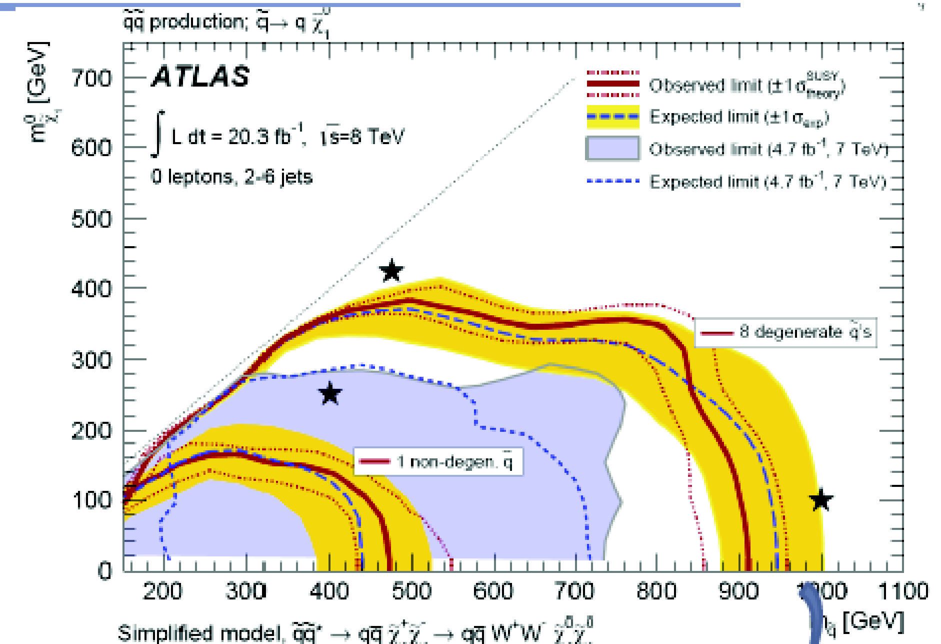


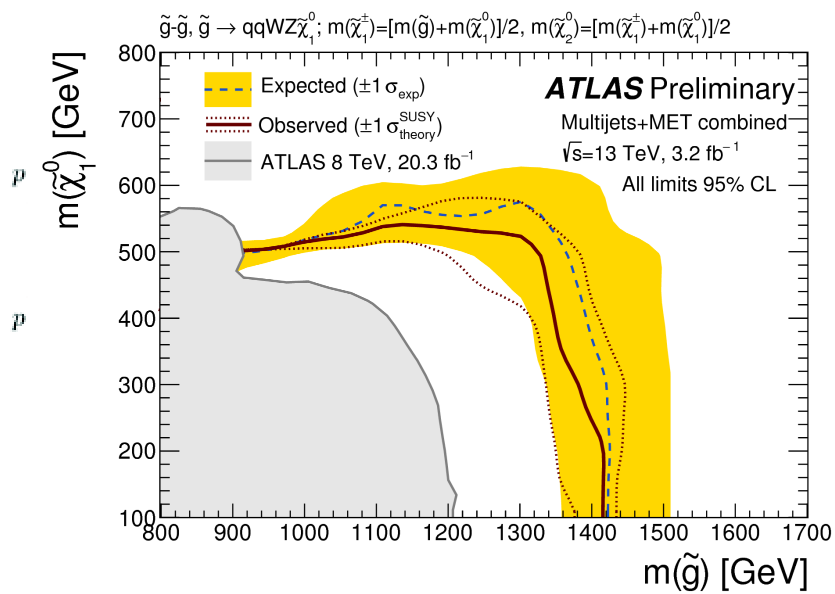


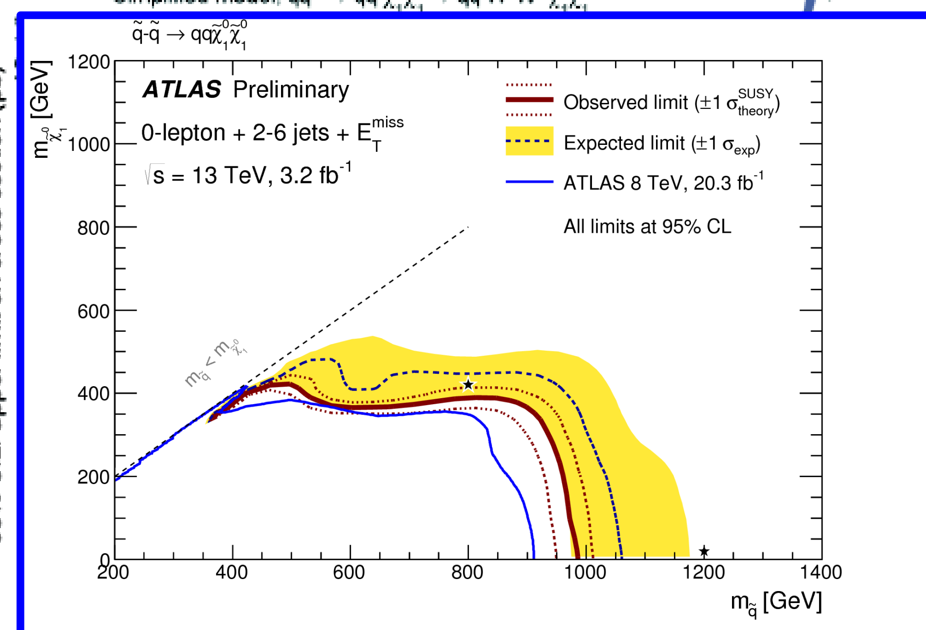
Increasing the complexity of the decay chain, exploiting boosted W

Some Results of SUSY Searches

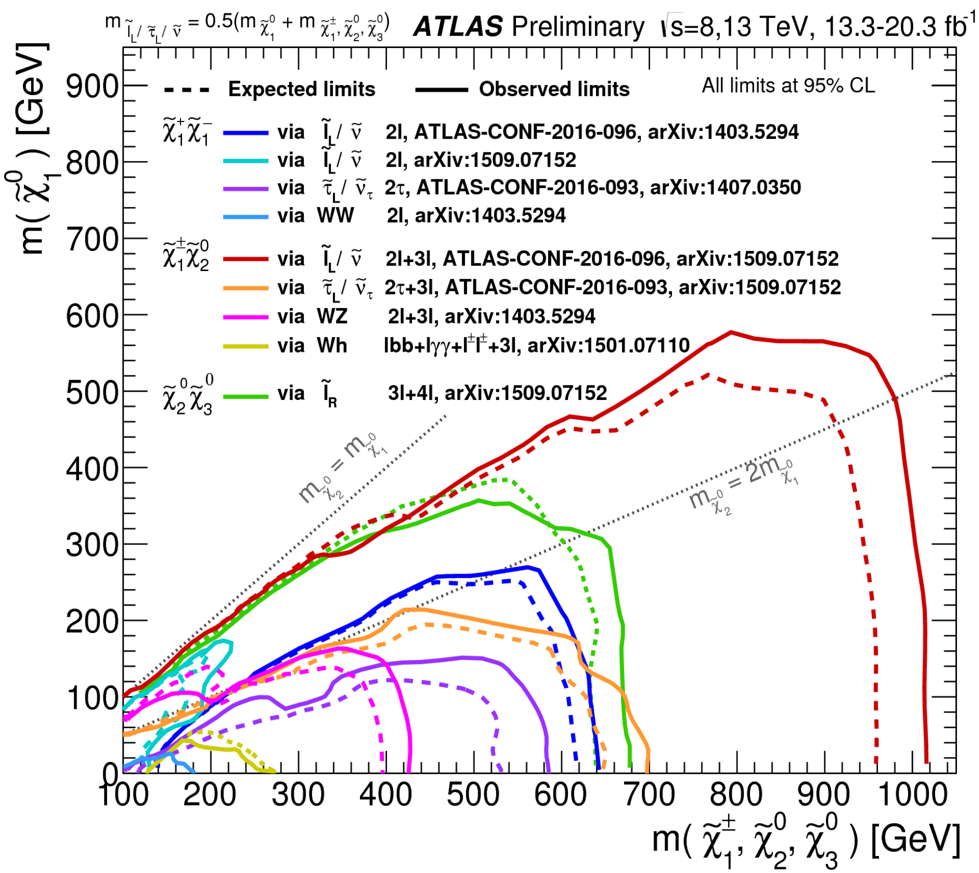


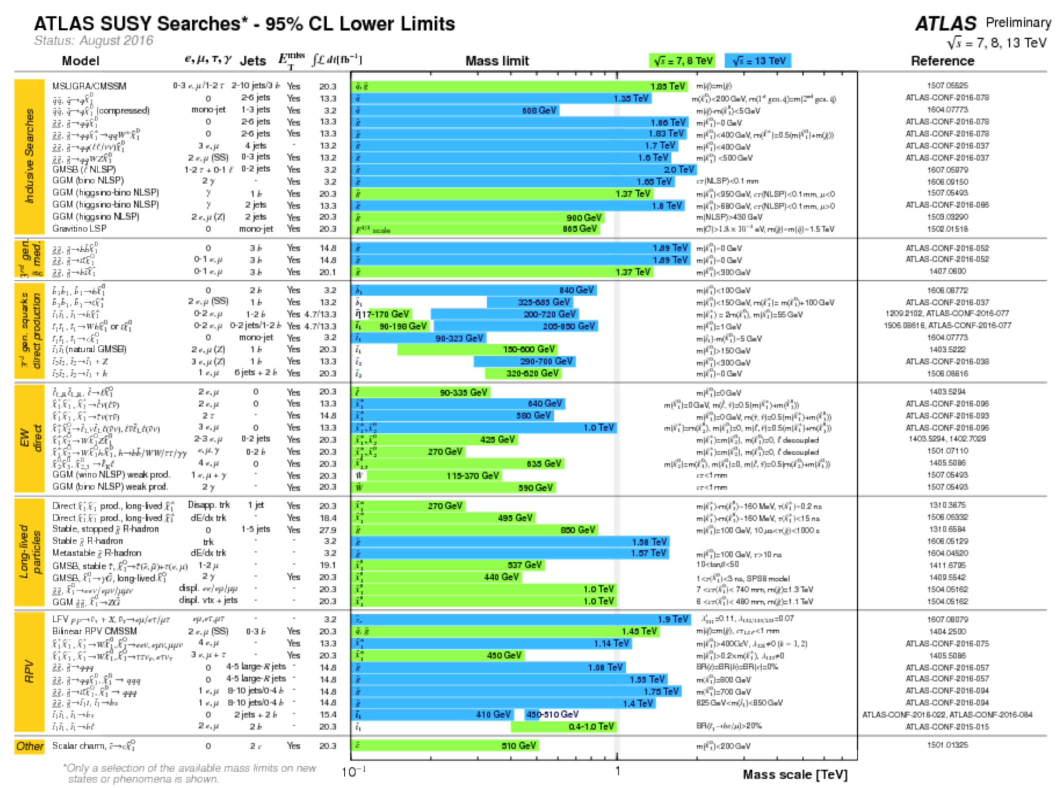






Searches Summary Plots





Summary of Neutralinos and Chargino searches and Summary of mass reach for the SUSY searches.
Many analysis results are summarized in these plots!