



*Low
scale*

*R.I.P. or
Resurrection?*

Sezen Sekmen, Kyungpook National Univ.
LHC Ski 2016, 10-15 April 2016, Obergurgl



Is SUSY in trouble?
Which observations challenge SUSY?
and what is the outcome?

750 GeV
diphoton
"excess"



Direct LHC
searches



Higgs



Dark matter



EW/Flavor



Is SUSY in trouble?
Which observations challenge SUSY?
and what is the outcome?



Why do we keep searching for SUSY?

SM is an effective theory. We would like to understand physics in a more generic framework which completes the missing pieces.

SM does not incorporate gravity. SUSY could.

Fine tuning in the corrections to the Higgs mass can be resolved by adding new particles with different spin. SUSY contributions to Higgs mass cancel SM contributions and stabilize the EW scale.

W
H
Y



?

SUSY unifies gauge couplings at the GUT scale because contributions from new particles modify running of the gauge couplings.

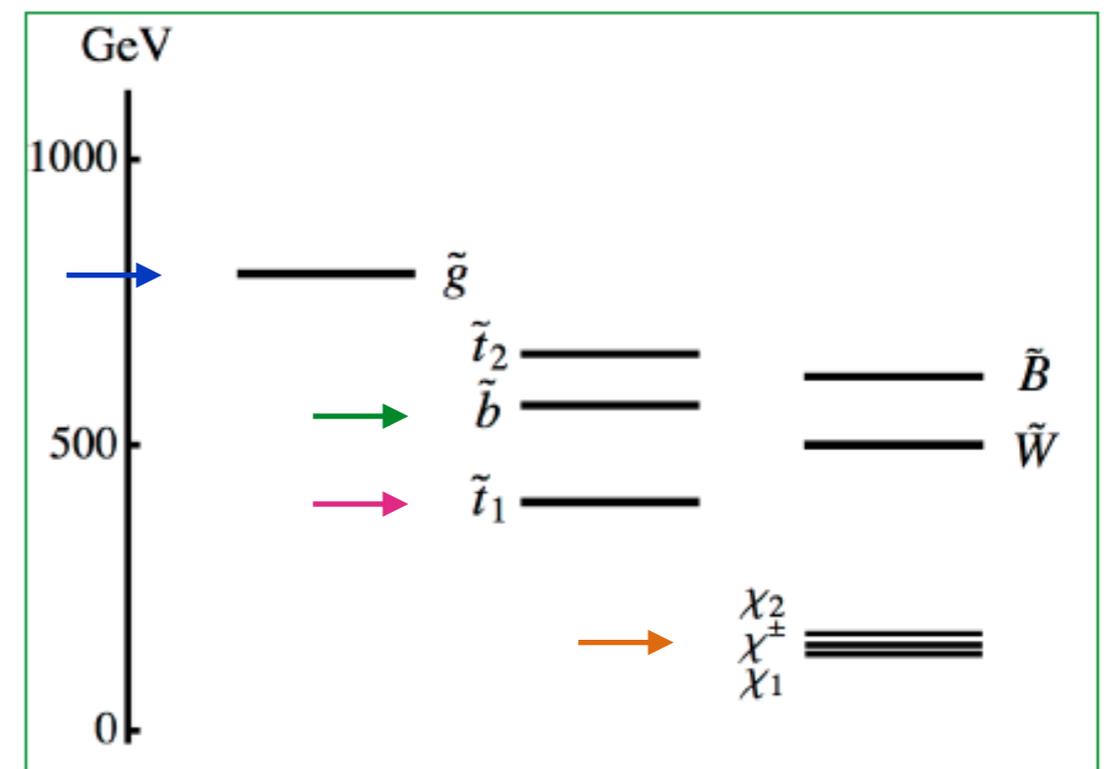
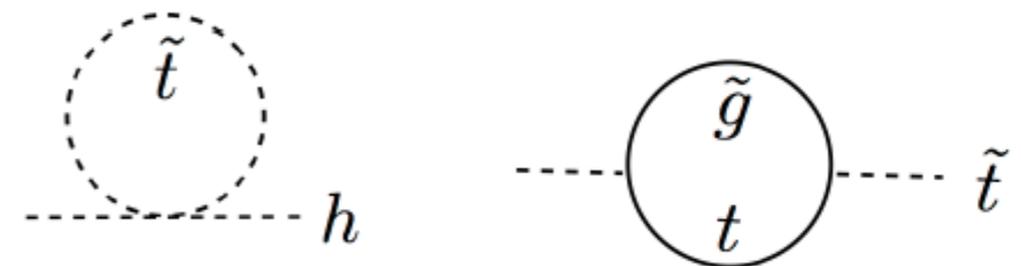
A symmetry called R-parity forces the lightest supersymmetric particle (LSP) to be stable. When LSP is heavy, neutral and stable, it is a good dark matter candidate.



Naturalness drives most LHC searches

Hierarchy problem: Measured Higgs mass is 125 GeV despite the divergent corrections from the top loop. The divergencies can be cancelled and EW scale can be stabilized by contributions from SUSY particles – but this imposes requirements on the SUSY mass spectrum:

- Leading contribution to the Higgs mass comes from **Higgsinos** $\rightarrow \leq$ few hundred GeV
- **Stops** contribute to Higgs mass via 1-loop corrections $\rightarrow \leq$ few hundred GeV
- **Sbottom left** is tied to stop left $\rightarrow \leq$ few hundred GeV.
- **Gluginos** contribute to Higgs mass via 2-loop corrections $\rightarrow \leq$ few TeV
- Rest of the spectrum can be **decoupled / heavy**.





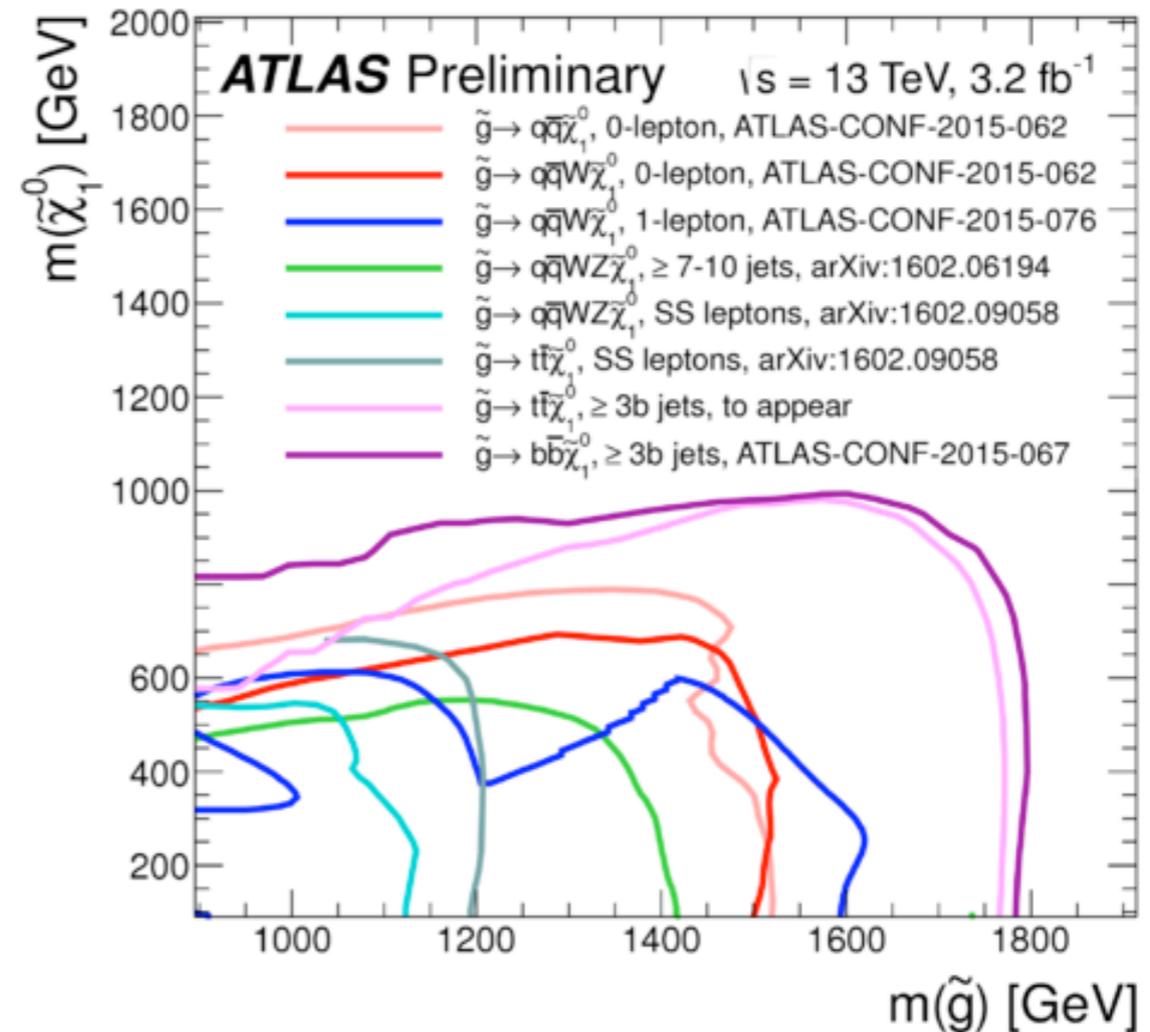
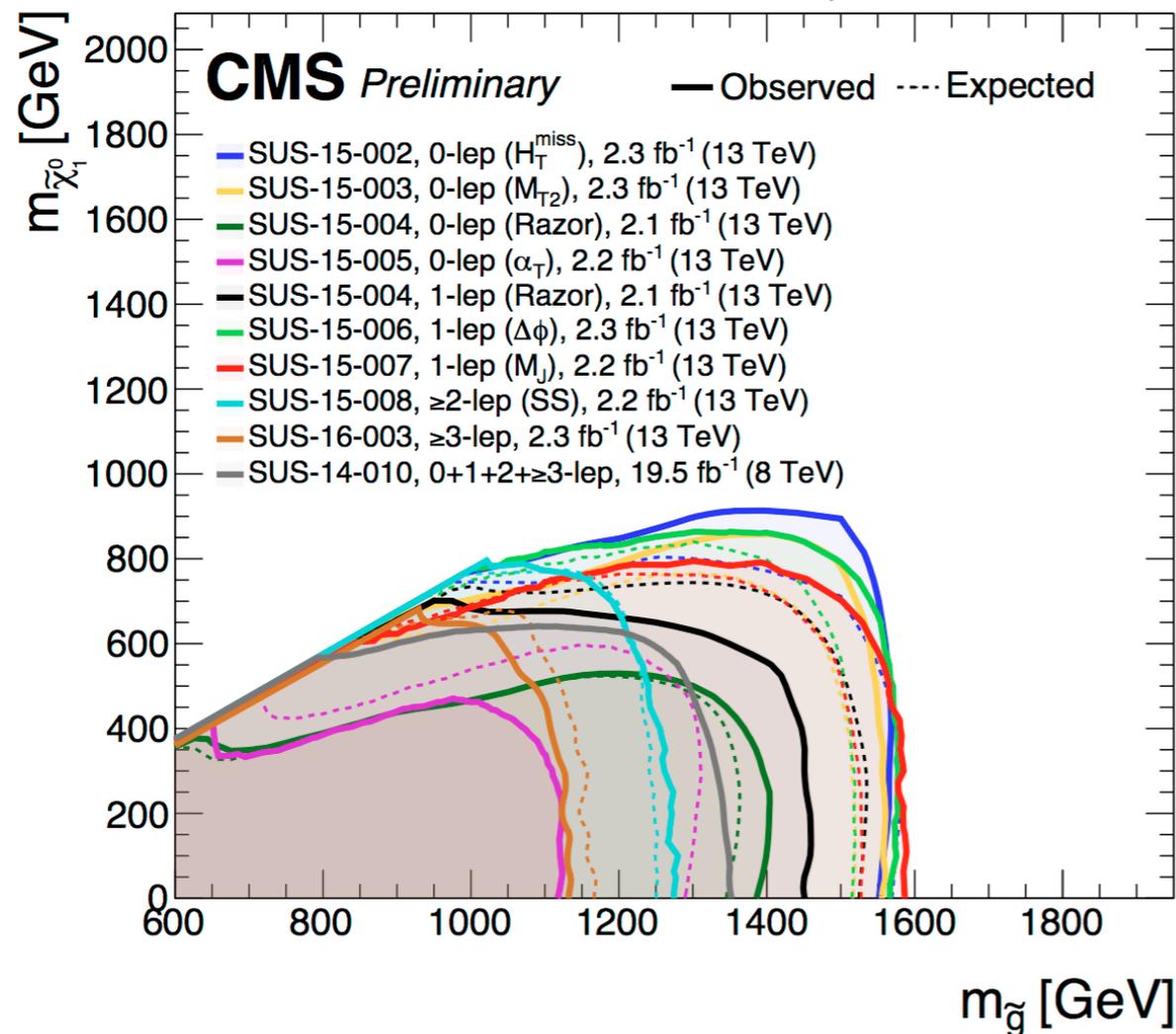
Inclusive searches (gluinos / squarks) - I

- Inclusive searches are sensitive to:
 - mainly gluinos due to their **high production cross sections** and **diverse decay modes**.
 - also **squarks** and **EW gauginos**.
- Used **multiple objects** (jets, b jets, leptons, photons, E_T^{miss}).
- **Final states**: fully hadronic, single or dileptons, single or diphotons.
- Used **kinematic variables** designed to discriminate final states with heavy particles and/or E_T^{miss} :
 - ATLAS: E_T^{miss} , $m_{\text{effective}}$, transverse mass M_{T2} , razor variables M_R & R^2 , ...
 - CMS: E_T^{miss} , H_T , H_T^{miss} , α_T , transverse mass M_{T2} , razor variables M_R & R^2 , ...
- Used **multiple search regions** defined by **different object multiplicities** and **kinematic variables**.
- Current integrated luminosity allows us to work with **disjoint search regions**.



Inclusive searches (gluinos / squarks) - II

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ Moriond 2016

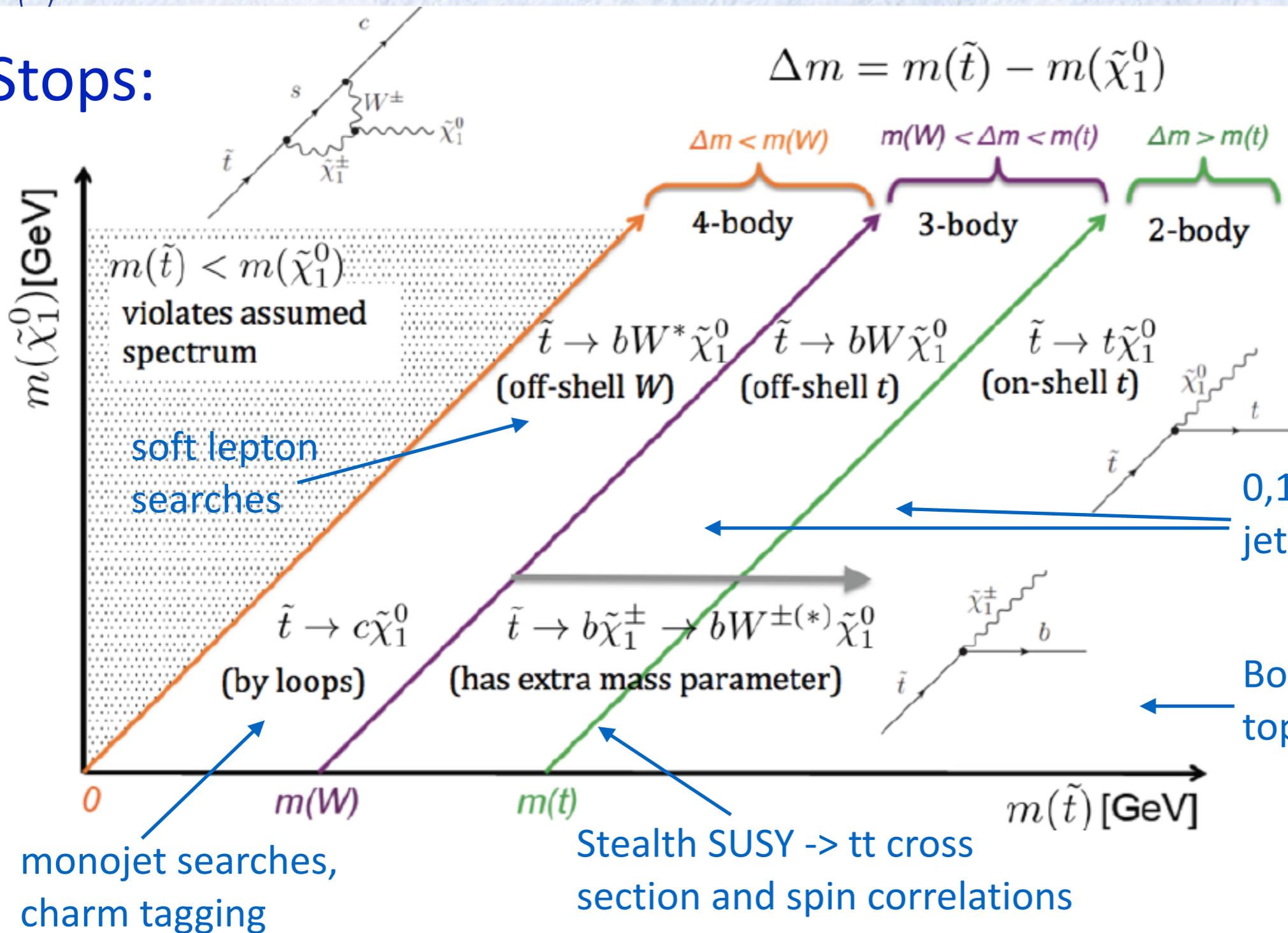


- Probed gluinos up to mass $\sim 1.8\text{TeV}$ and 1st/2nd generation squarks up to $\sim 1.2\text{TeV}$ in different decay channels. ATLAS and CMS have similar results.
- Having different searches provides sensitivity to different final states and kinematical regions.
- Probed gluino masses are still consistent with Naturalness.



Direct 3rd gen searches (stops / sbottoms) - I

Stops:

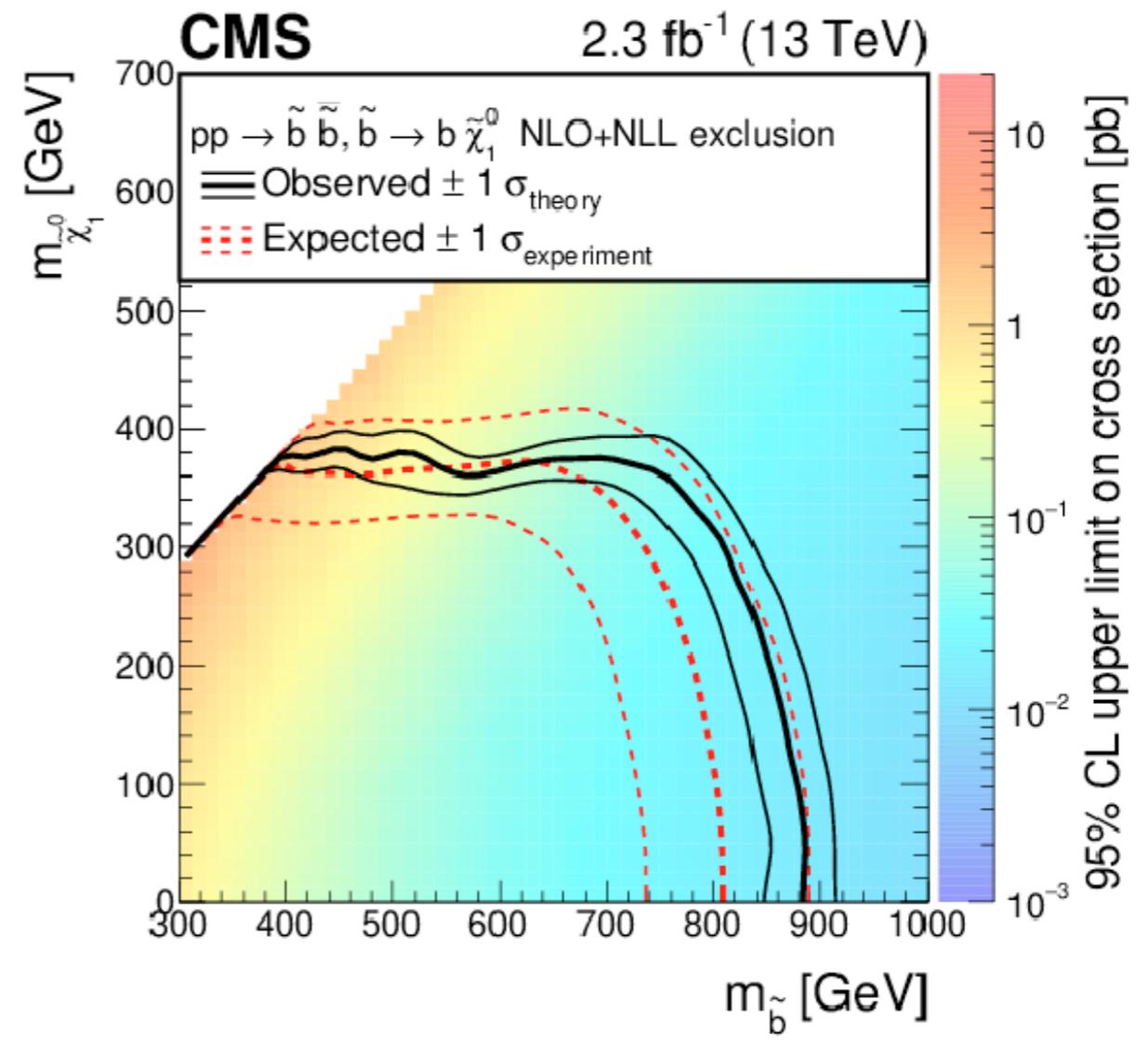
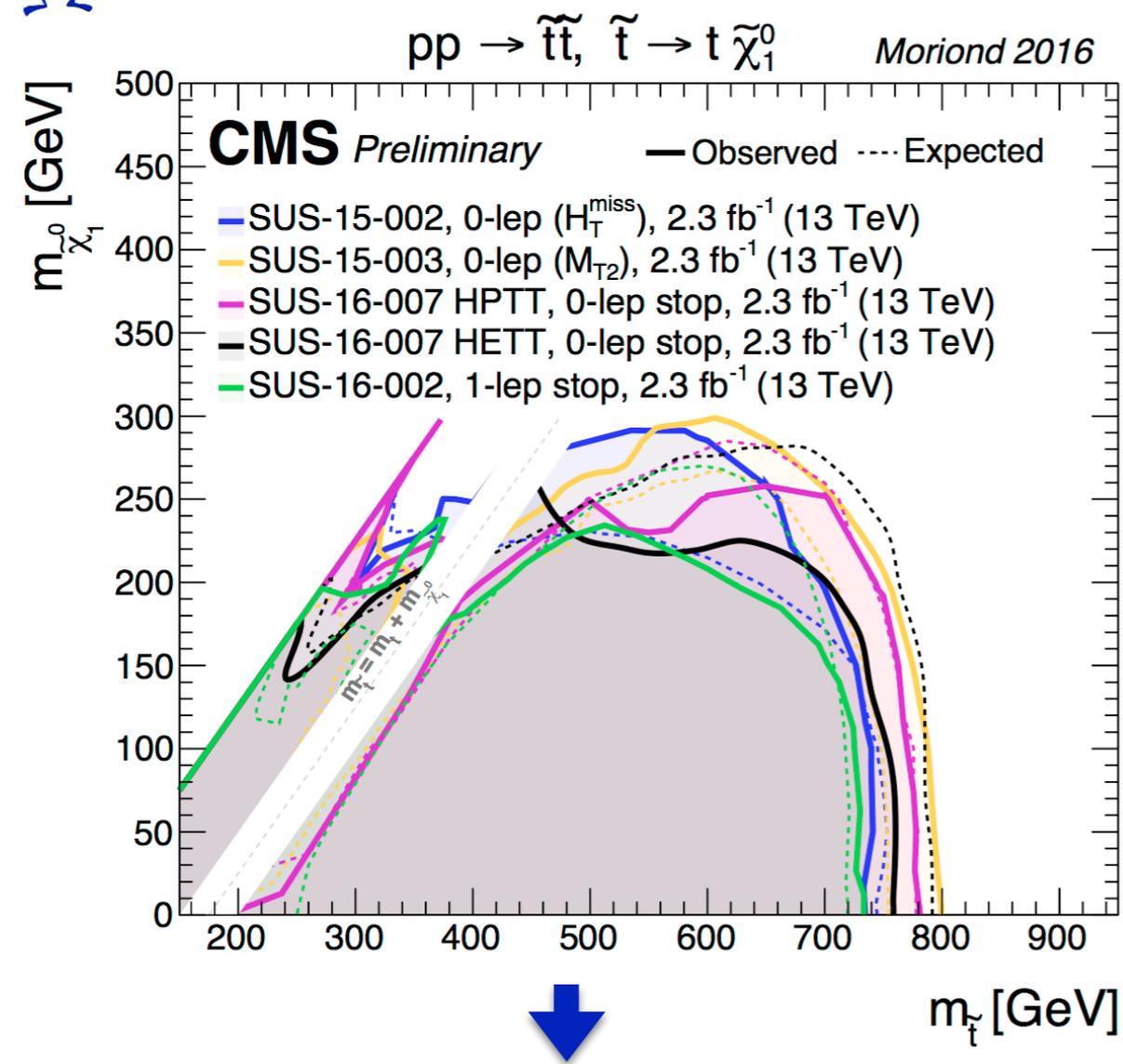


Differences from inclusive searches: top reconstruction, b-tagging, softer cuts on jets and MET...

- ## Sbottoms:
- Dijet + E_T^{miss} + $>1b$ searches for direct sbottom pair production with $\tilde{b} \rightarrow b \tilde{\chi}_1^0$.
 - M_{CT} , the boost corrected contranverse mass variable discriminates signal.



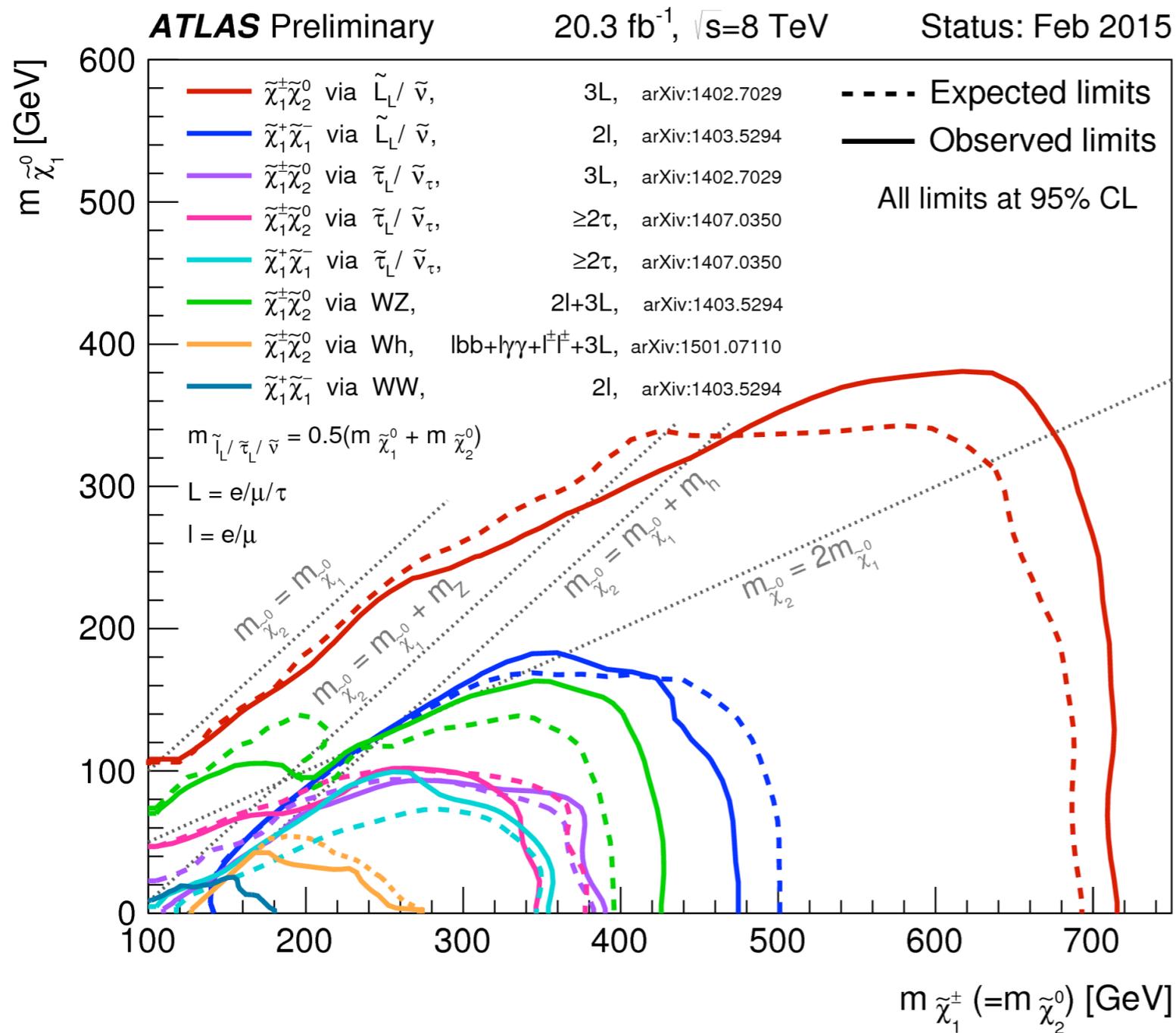
Direct 3rd gen searches (stops / sbottoms) - II ⁸



- Limits getting close to a TeV. Creates **tension with Naturalness** - however remember that the **stop branching ratios are 100%**!
- The most difficult region is around $m_{\text{stop}} - m_{\text{neutralino}} = m_{\text{top}}$. Hard to discriminate from SM $t\bar{t}$.
- Exploring **top quark properties, which would discriminate stop pair production from top pair production** could further help to close the gaps.



EW gaugino searches



- 13 TeV searches in progress.
- Highest sensitivity achieved in **decays via sleptons**, in the **trilepton** final states.
- Remember that **BRs are 100%**.
- However **we need the other channels** for complementarity, since in full models, EW gauginos decay to many channels, and BRs will be less than 100%.
- Does not necessarily conflict with Naturalness.



R parity violating SUSY searches

R parity violating terms are allowed in the SUSY Lagrangian.

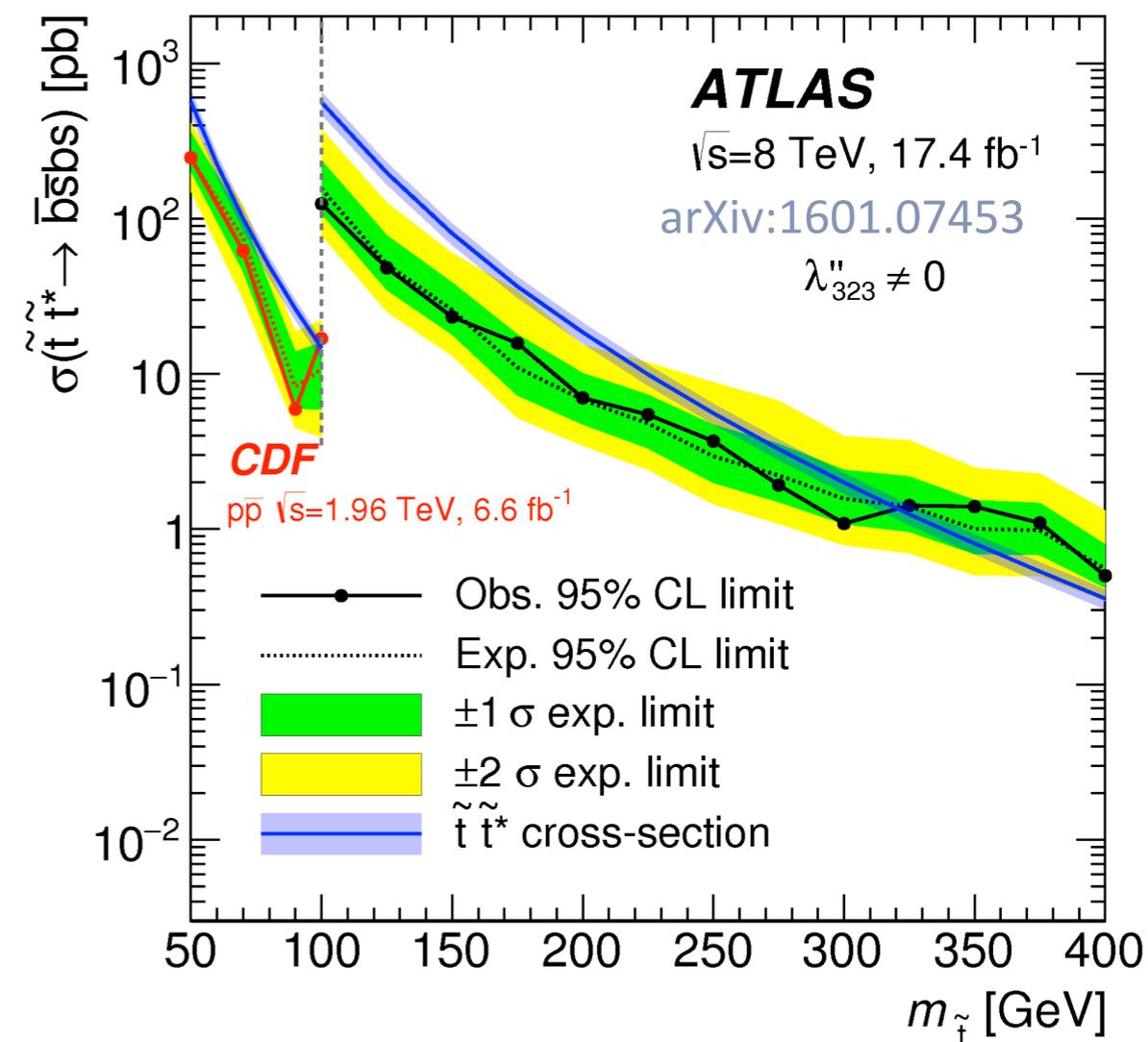
Lightest SUSY particle is not stable, and decays to SM particles \rightarrow Need different candidates for DM (e.g. axions). But other good features of SUSY remain.

- Search for **stop \rightarrow RPV neutralino + top** in final states with ≥ 3 leptons + **b jets + low E_T^{miss}** (E_T^{miss} arises from top decays; 1 lepton from top decay, 2 from neutralino decay). CMS SUS-13-003
- Searches for decays of **RPV gluinos** ($\tilde{g} \rightarrow qqq$) and **RPV stops** ($\tilde{t} \rightarrow bs$). \rightarrow Reconstruct gluinos or stops from the **decay products**.

ATLAS arXiv:1502.05686, ATLAS arXiv:1601.07453

Searches have probed:

- **Gluinos/squarks:** up to ~ 1.35 TeV
- **Charginos:** up to ~ 750 GeV
- **Stops:** up to ~ 300 GeV

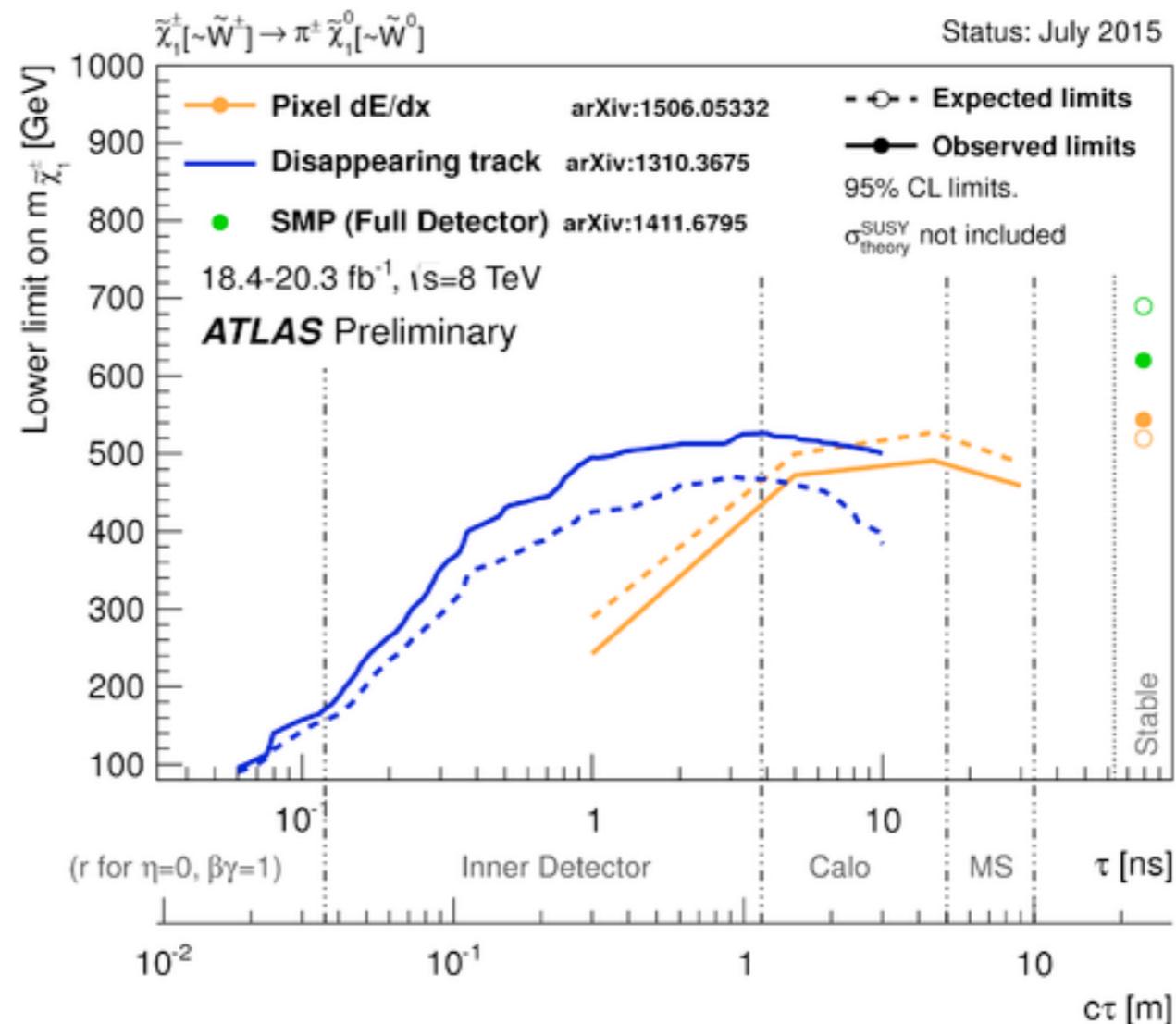
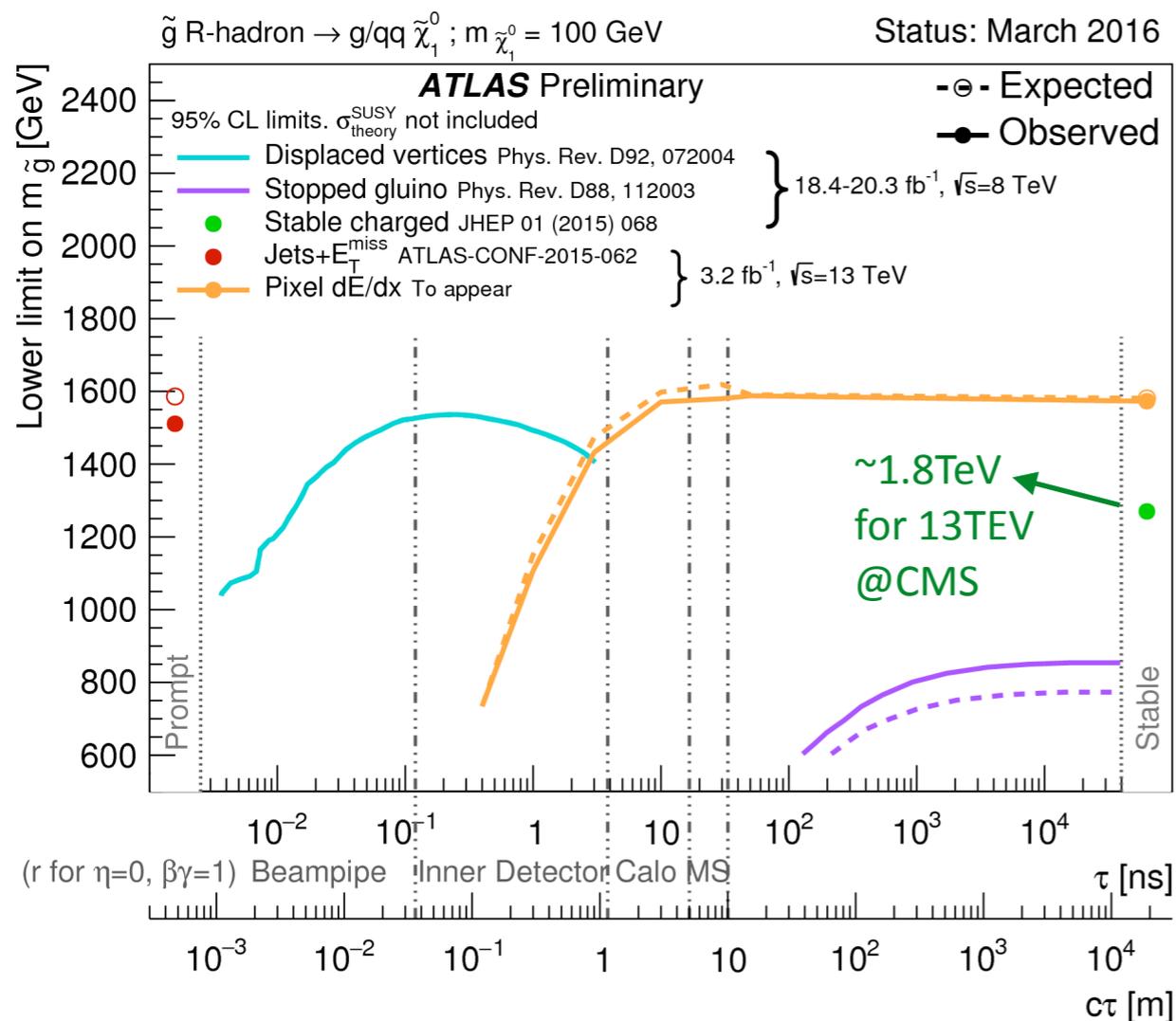




Non-prompt searches

In many cases, particles may decay non-promptly, outside the beamspot.

- A multitude of non-prompt particle searches complement prompt searches.
- Not much SM background outside the beamspot. Mostly detector noise, cosmic rays, reconstruction failure, etc. estimated from data.
- Dedicated long lived particle searches increase sensitivity as lifetimes increase.





Impact on full models: pMSSM

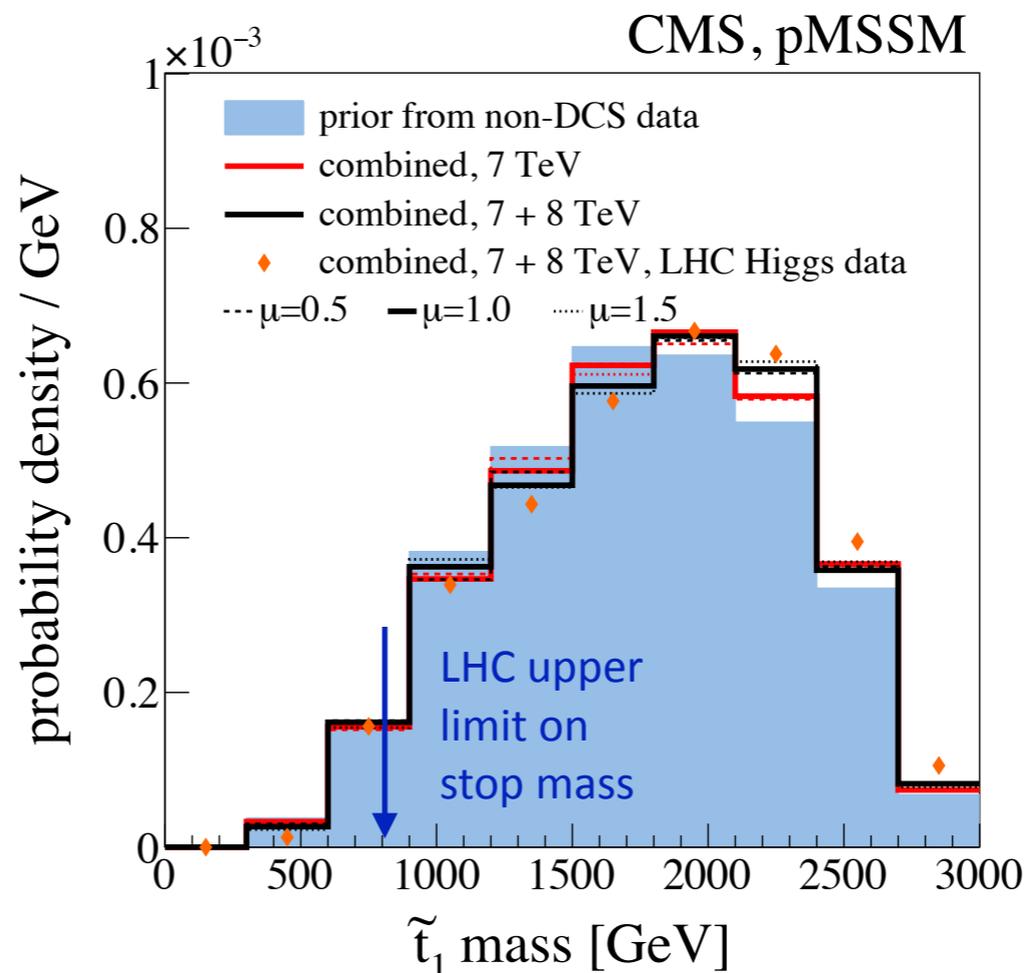
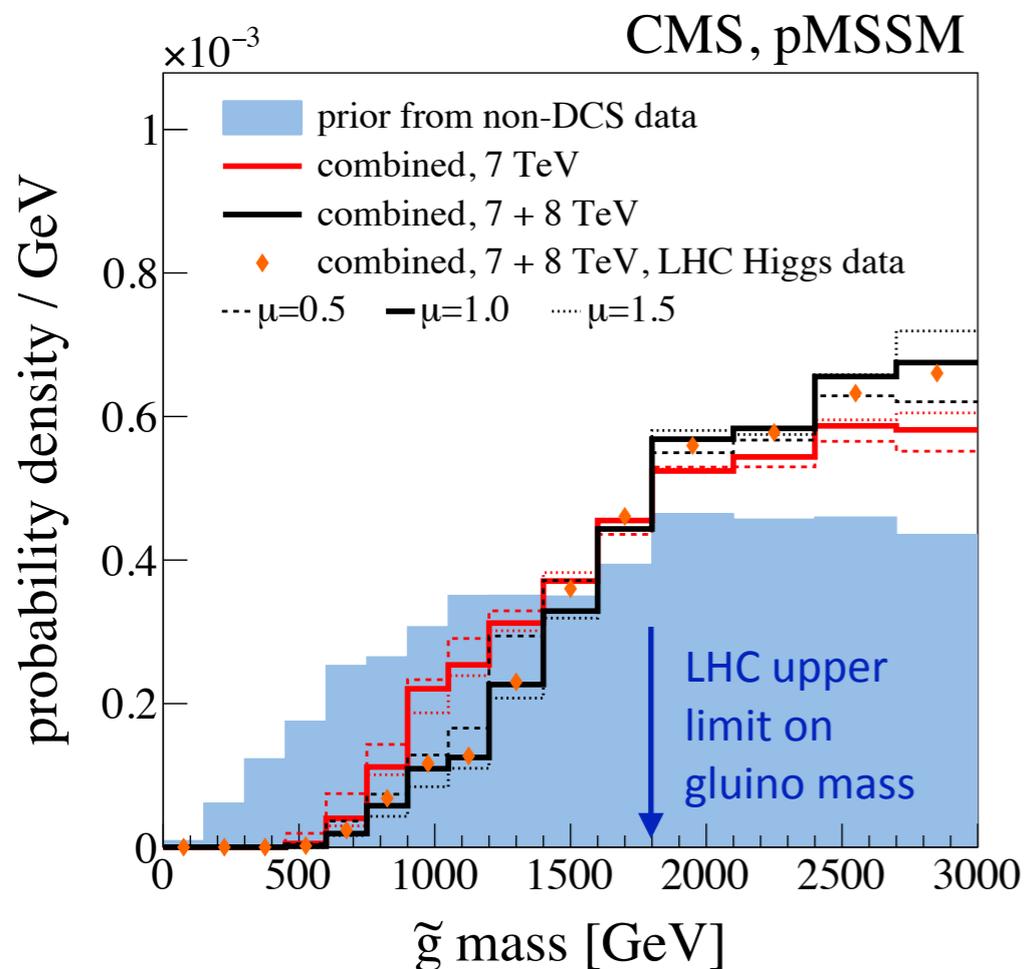
LHC SUSY limits set with simplified models: good for characterizing signatures.

But making **actual statements on SUSY requires full models.**

Example: **p(phenomenological)MSSM: 19 parameter realization of SUSY at the \sim weak scale.** Captures most phenomenological features of the MSSM with neutrino LSP.

- CMS: Global Bayesian analysis done to obtain posterior probability distributions of **model parameters, masses and predicted observables.** CMS SUS-15-010
- ATLAS: Selection/elimination of model points, **survival rates.** arXiv:1508.06608

Both experiments use indirect constraints and direct SUSY search results.



Looser constraints compared to SMSs.
Greatest use:
Find **unexplored model regions**
—> explore their signatures
—> **design dedicated searches.**



Higgs impact on MSSM: mass

Higgs mass in the MSSM is defined as:

$$m_h^2 = m_Z^2 \cos^2 2\beta + \Delta m_h^2$$

Need a **~100% mass correction** of the order of the Z mass ($\Delta m_h^2 > 85 \text{ GeV}^2$) to obtain the measured 125 GeV:



$$\Delta m_h^2 = \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left(\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12 M_S^2} \right) \right)$$

$$X_t = A_t - \mu \cot \beta$$

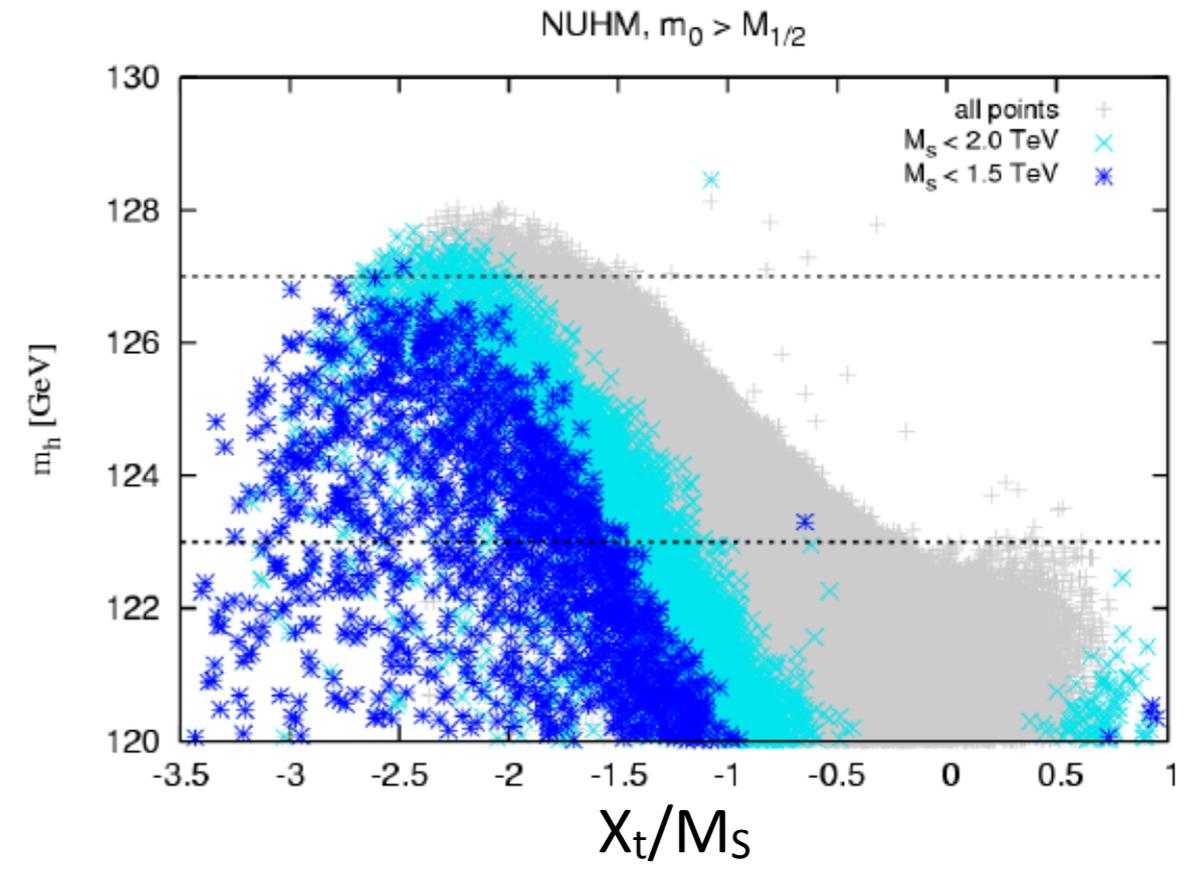
$$M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$$

$m_h = 125 \text{ GeV}$
implies

heavy
stops

maximal
mixing
(large A_t)

This creates tension with Naturalness.

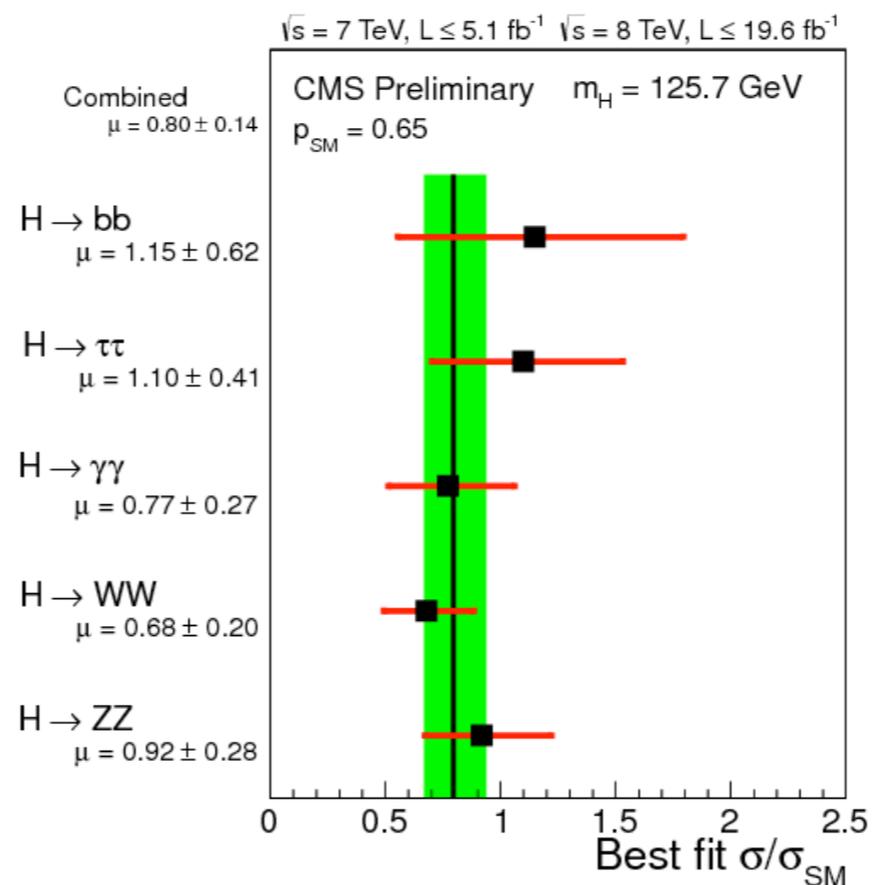
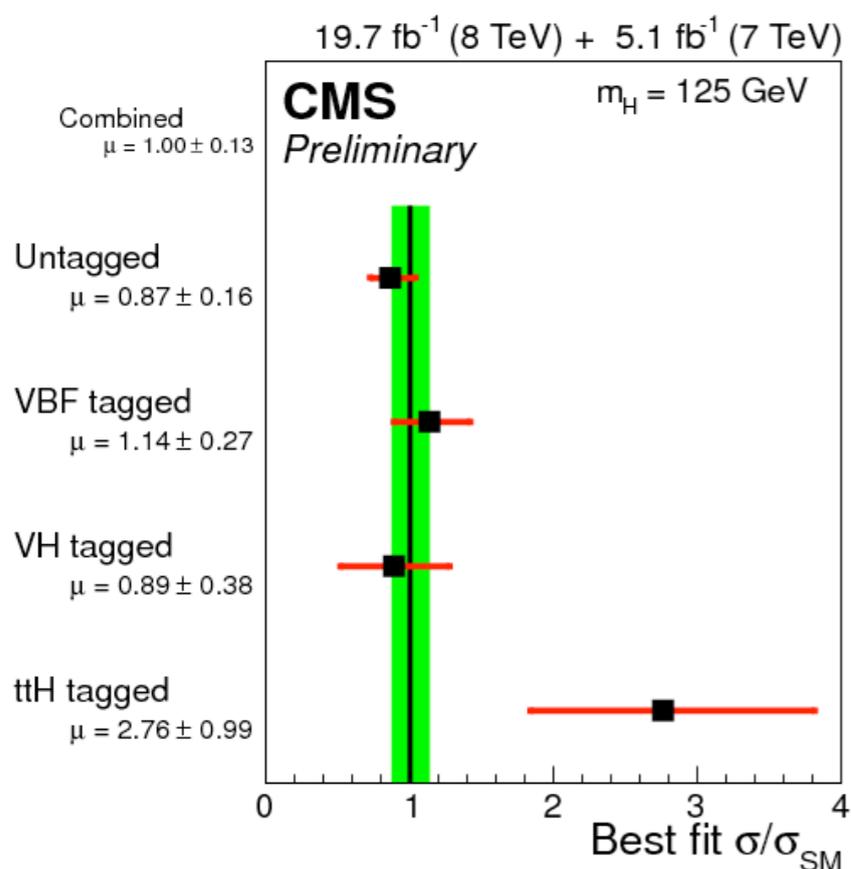


Brummer, Kraml, Kulkarni
arXiv:1204.5977



Higgs impact on MSSM: couplings

Higgs couplings seem to be **SM-like**:



Large stop mixing
(favored by $m_h = 125$ GeV)

- suppresses $\sigma(gg \rightarrow h)$
 - enhances $BR(h \rightarrow \gamma\gamma)$ - light staus and charginos also add to the effect.
- reproducing observation.

SM-like Higgs width is **dominated by $h \rightarrow bb$** (BR $\sim 57\%$), which is not well-constrained yet.

SUSY **corrections to b Yukawa coupling** (thus to $h \rightarrow bb$) would be **large for heavy SUSY spectrum**.

But, a significant deviation in $h \rightarrow bb$ would imply significant deviations in the other channels, which do not exist.



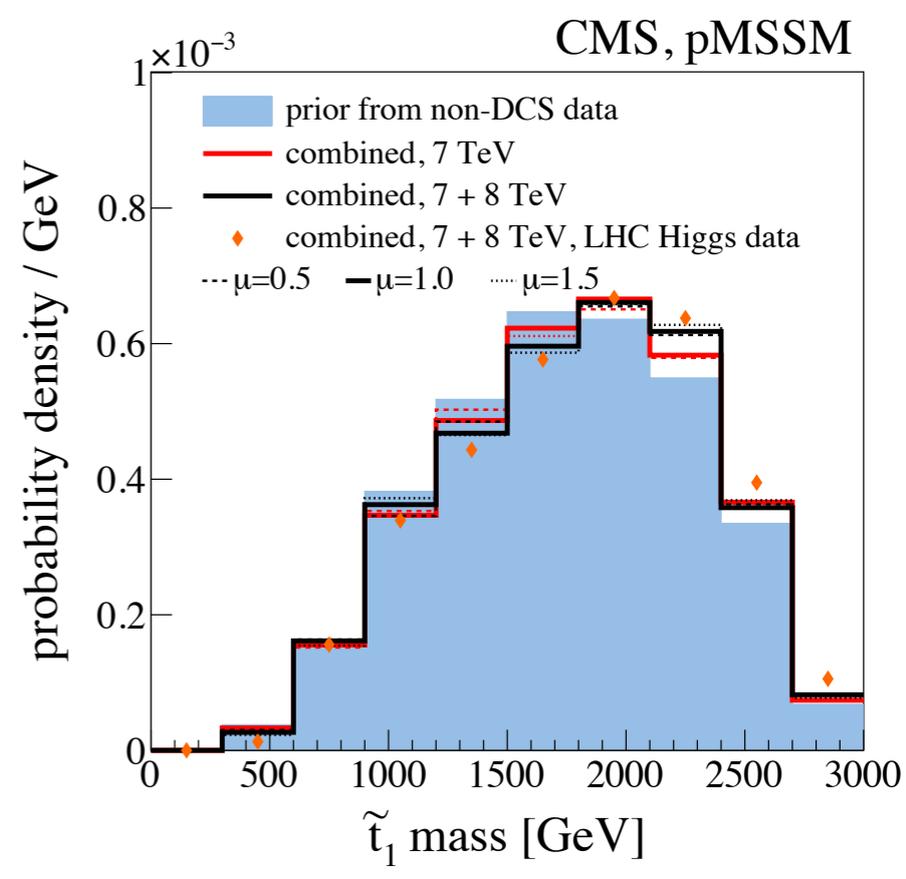
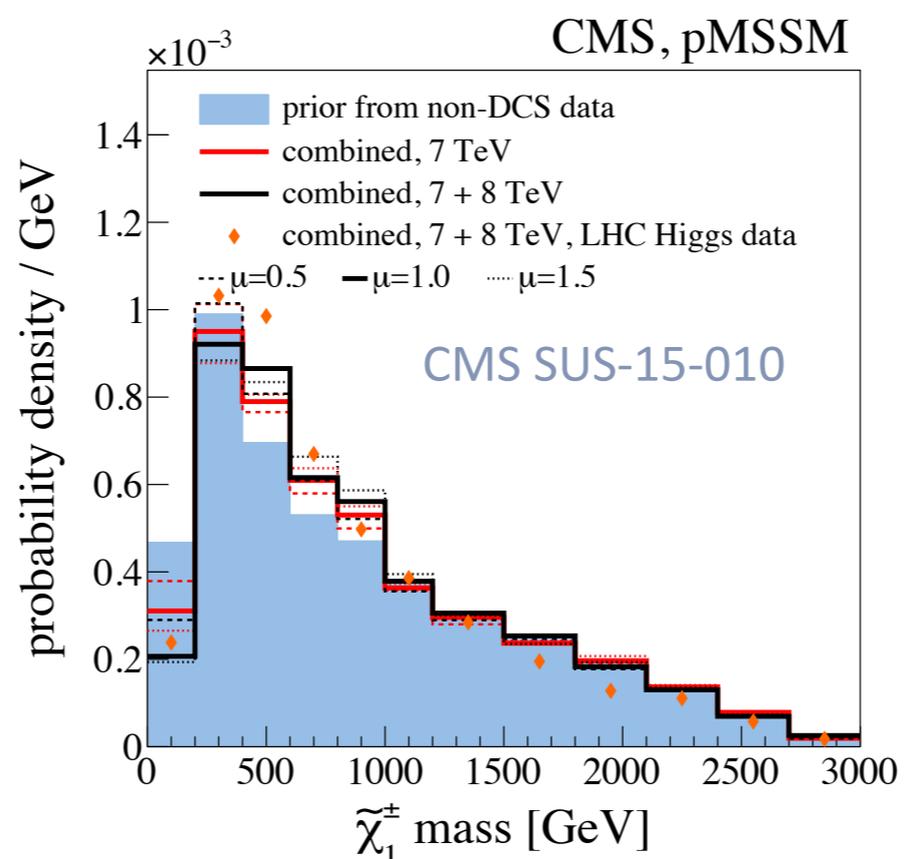
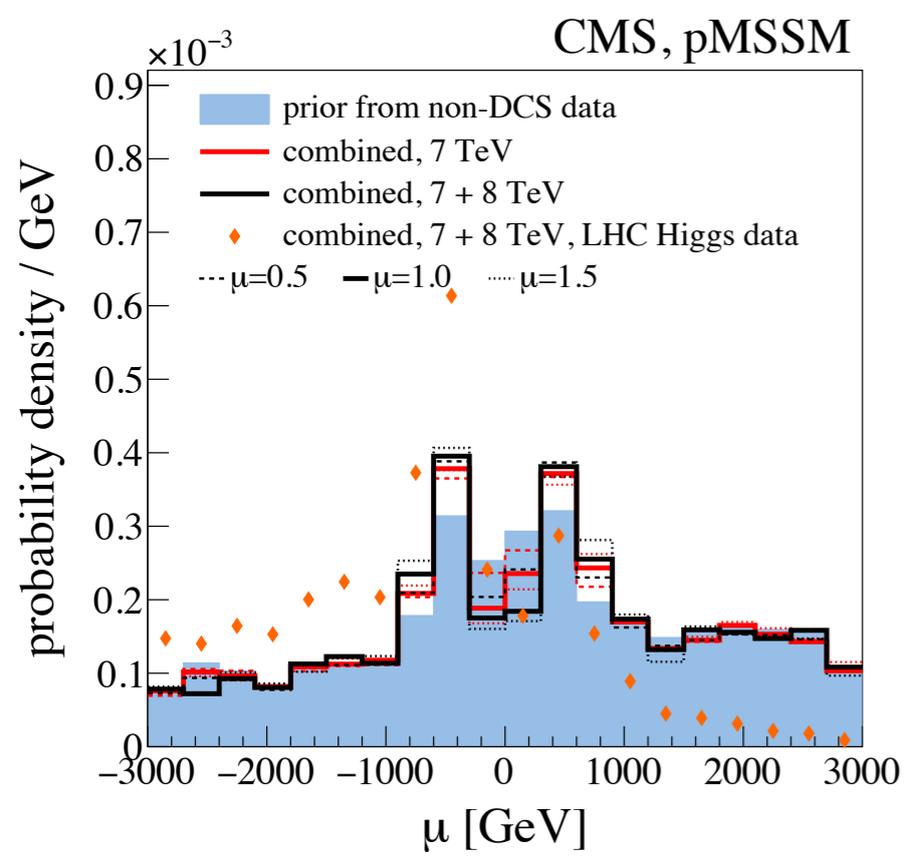
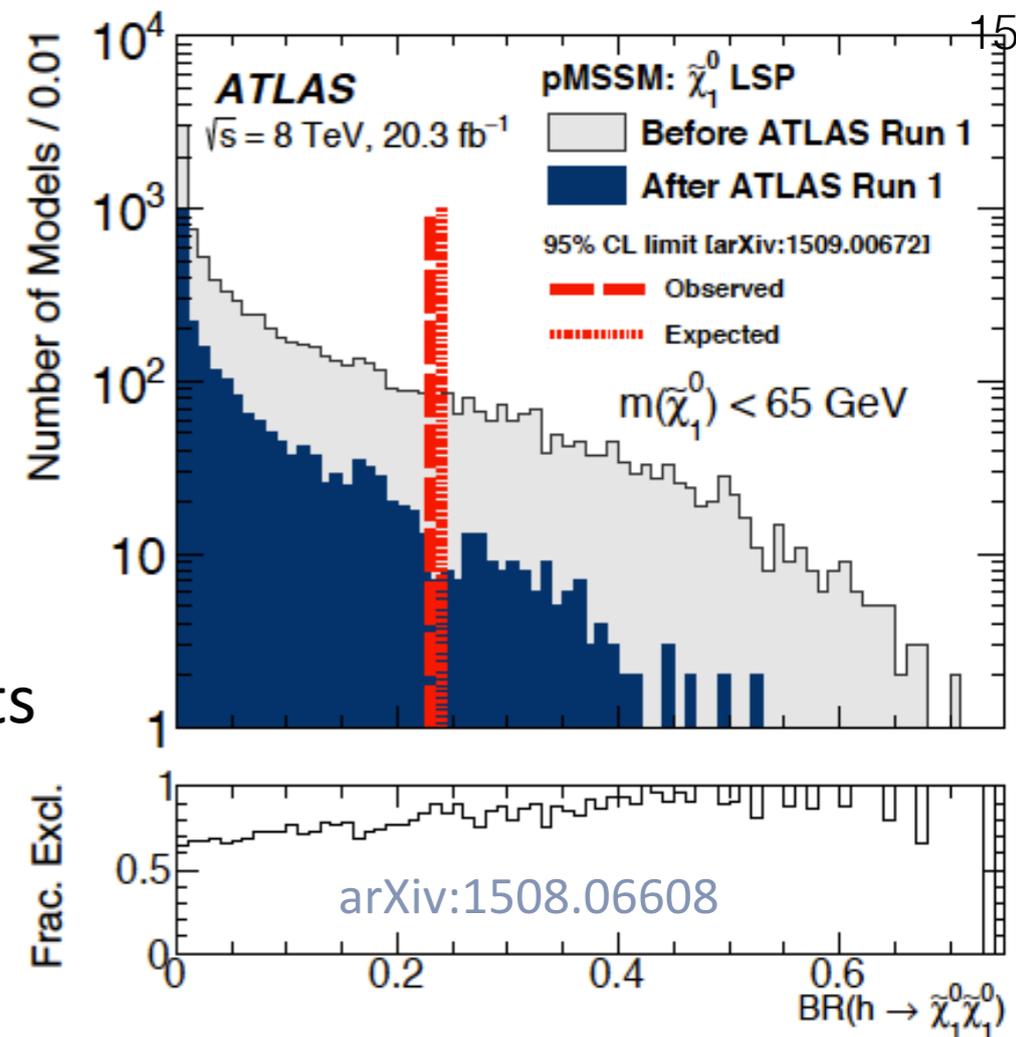
Light Higgs and pMSSM

ATLAS and CMS used pMSSM to quantify the impact of LHC Higgs measurements on MSSM.

Colored sparticle masses are generally not effected except for stops (and stop trilinear coupling).

More visible effect on the μ parameter, which reflects to the EW sector sparticles.

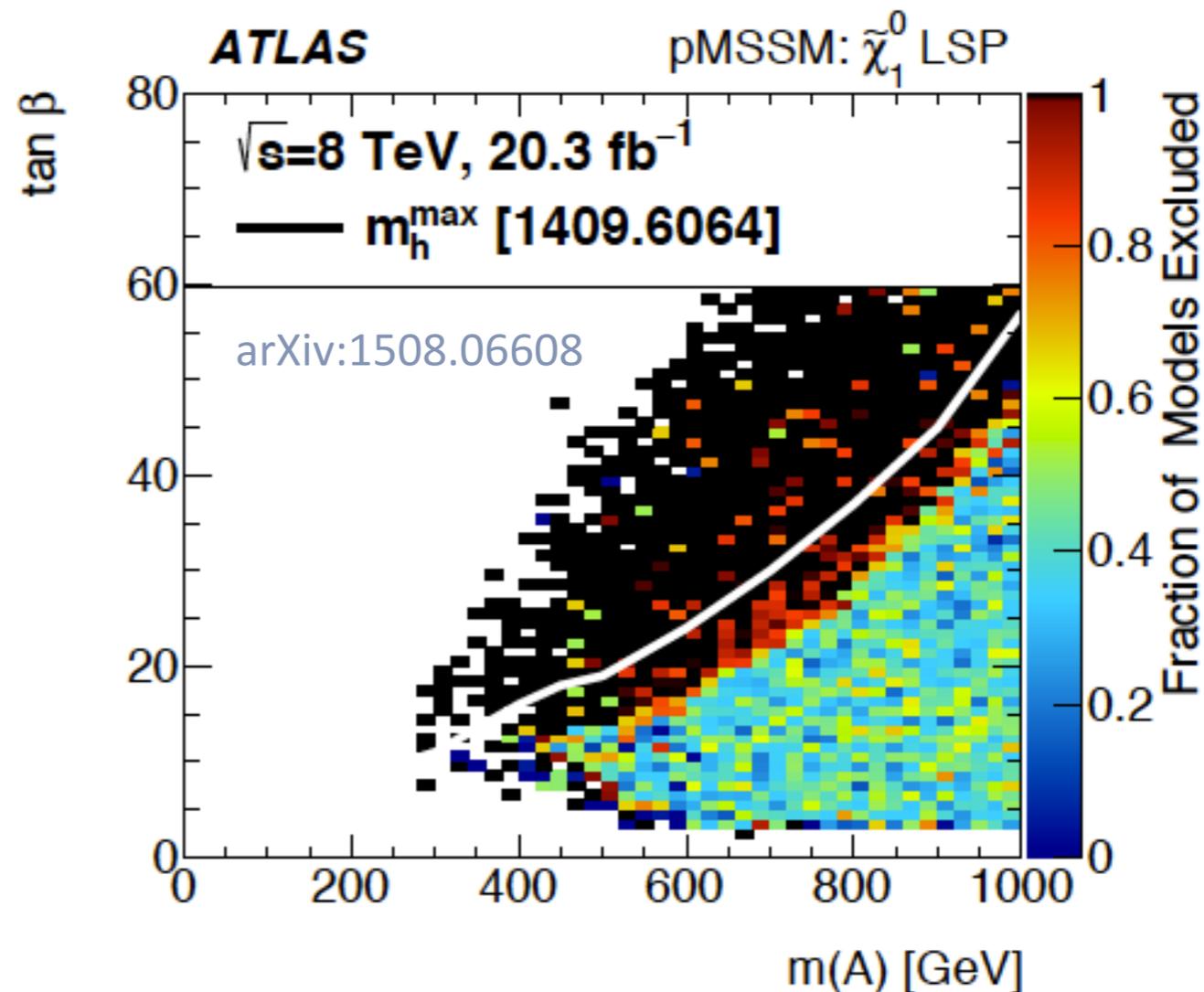
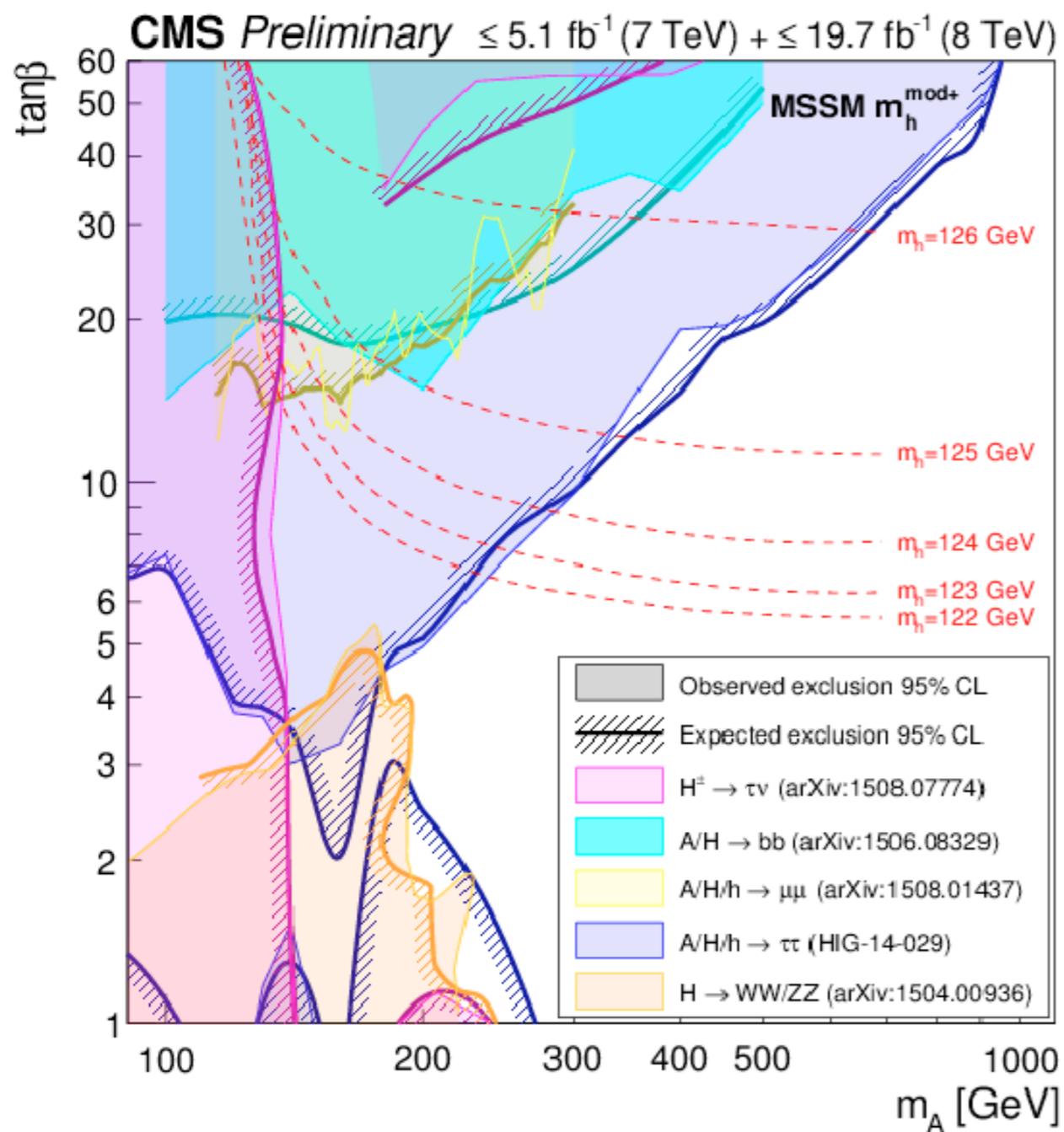
ATLAS has studied the pMSSM phase space excluded by $H \rightarrow$ invisible decays.





Heavy Higgs, MSSM, pMSSM

ATLAS and CMS used both **direct searches for heavy Higgs** and **indirect light Higgs coupling measurements** to constrain the parameters effecting heavy MSSM Higgses.



Fraction of pMSSM models excluded by ATLAS searches, including direct heavy Higgs searches.



Higgs@125 vs Naturalness: Remedies

125GeV Higgs + no sign of light stops implies increasing fine-tuning at the EW scale.

However fine tuning measures are rather subjective, and fine tuning measures can be redefined such that, we could e.g.:

- permit only independent quantities in the evaluation of a fine tuning measure. E.g., in supergravity, all soft terms depend on gravitino mass $m_{3/2}$ → Use only $m_{3/2}$ and μ when calculating the fine tuning measure → Lower fine tuning.

Baer et.al., arXiv:1212.2655

- also include constraints other than those of radiative EWSB, e.g. FCNC suppression, proton decay suppression, and combine

Nath, arXiv:1501.01679

Next-to-MSSM: MSSM + gauge singlet superfield S

Higgs mass term: $\mu \hat{H}_u \hat{H}_d \rightarrow W_{\text{NMSSM}} = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + \dots$

The real scalar component of S develops a vev $\langle S \rangle \rightarrow$ the first term generates an effective μ -term, $\mu_{\text{eff}} = \lambda(S)$.

This μ_{eff} constitutes an extra tree level contribution to the Higgs mass

→ much easier to obtain $m_h = 125$ GeV, while keeping μ small and “Natural”.



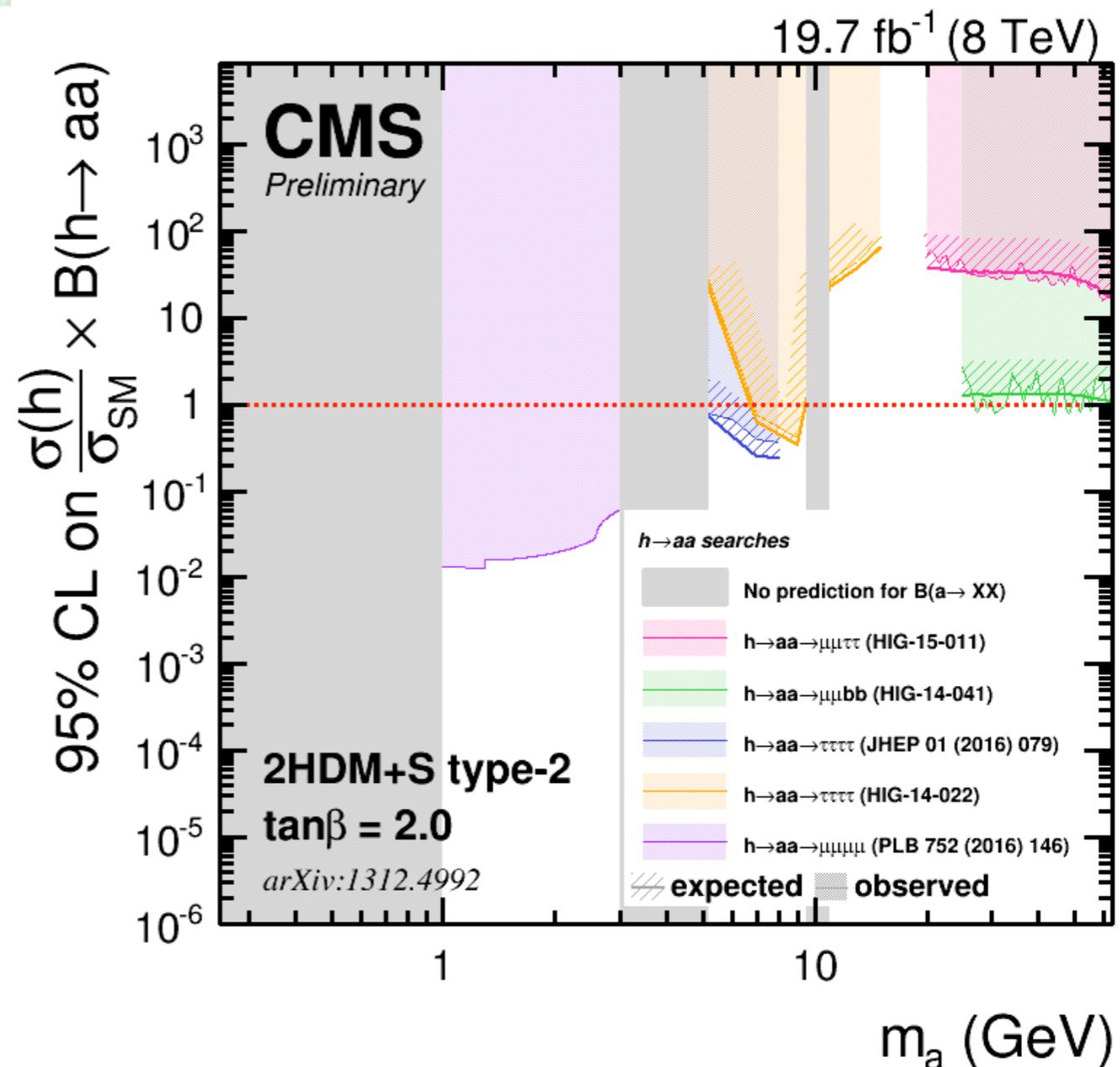
NMSSM Higgs searches

NMSSM Higgs sector hosts

- 3 neutral CP-even (h_1, h_2, h_3)
- 2 neutral CP-odd (a_1, a_2)
- 2 charged states.

Lightest or 2nd lightest states h_1, h_2 can be the observed 125GeV Higgs.

One way to probe NMSSM is to look for $h \rightarrow a_1 a_1 \rightarrow X$.



Another suggestion is to search for a singlet-like h_1 , consistent with a $h_2 = h_{LHC}$.

- Directly, via $gg \rightarrow h_1 \rightarrow \gamma\gamma$ (most promising at Run2)
- Indirectly, via modified reduced couplings of h_2 , or production of h_2 in heavier Higgs states.



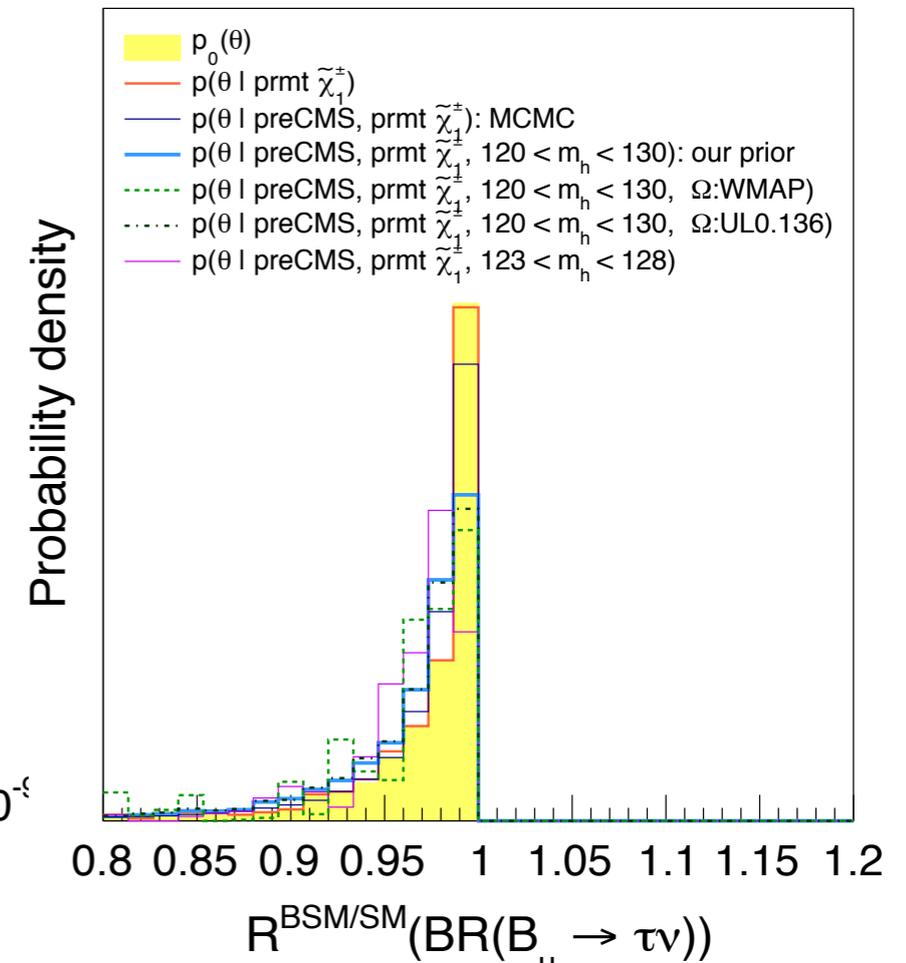
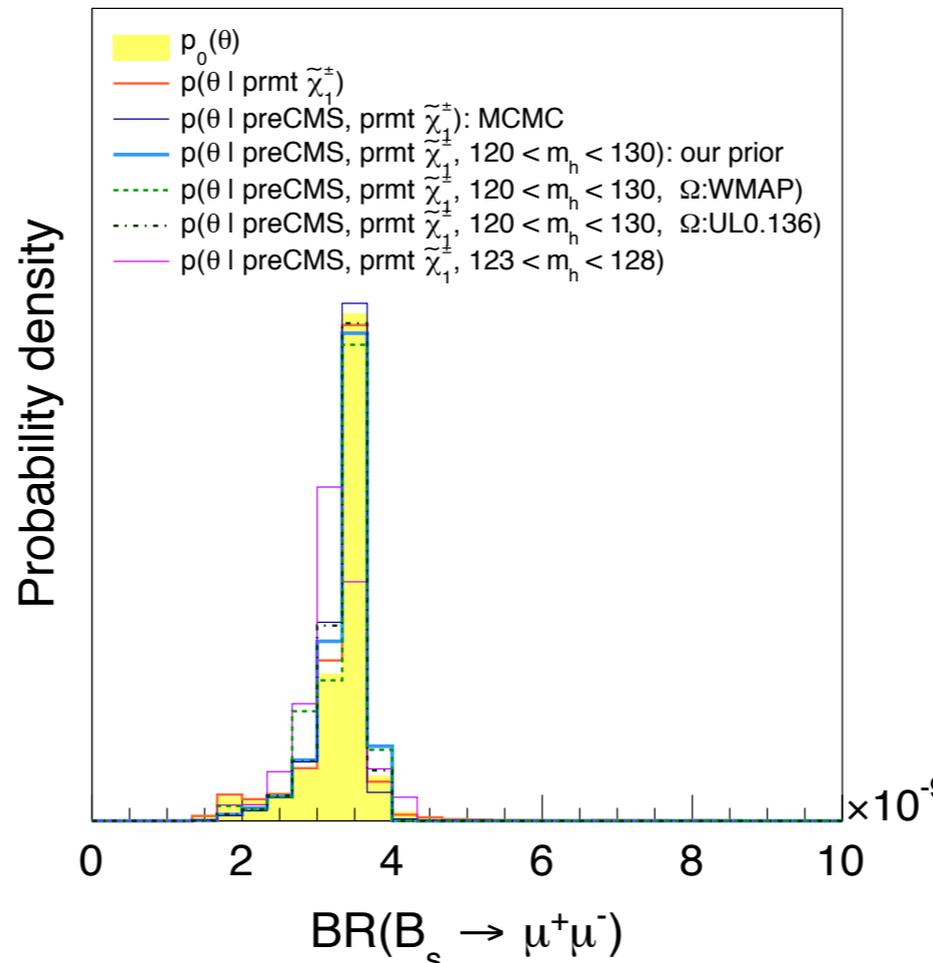
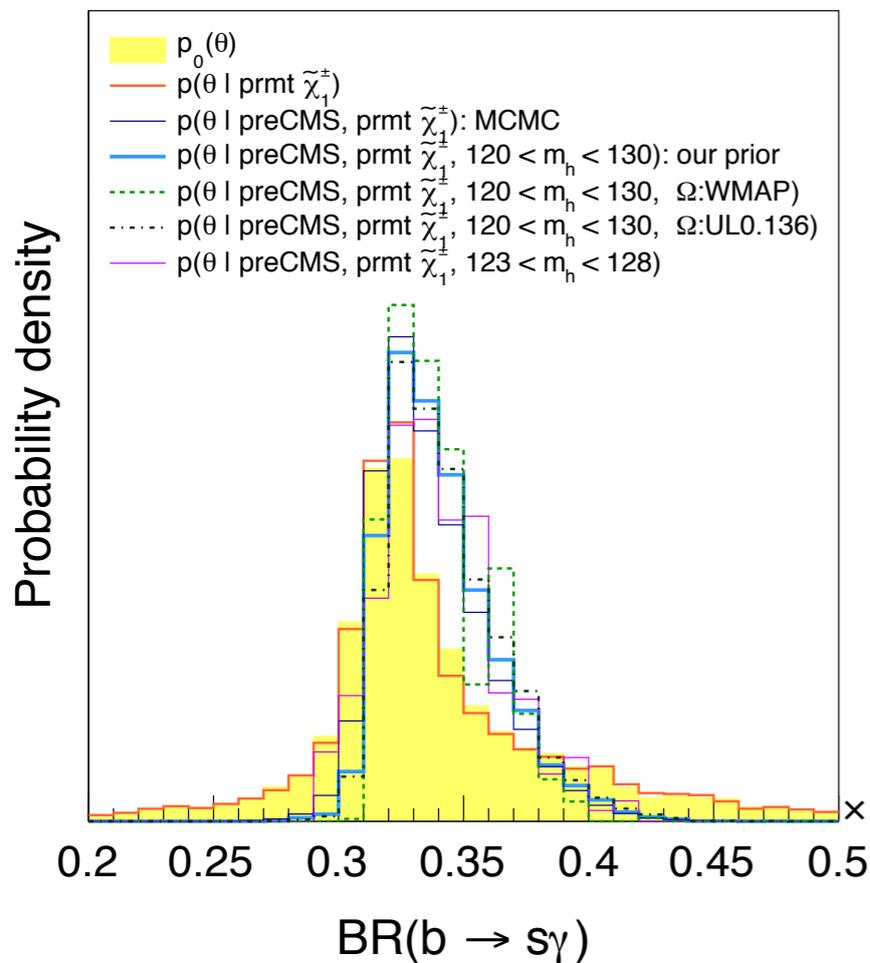
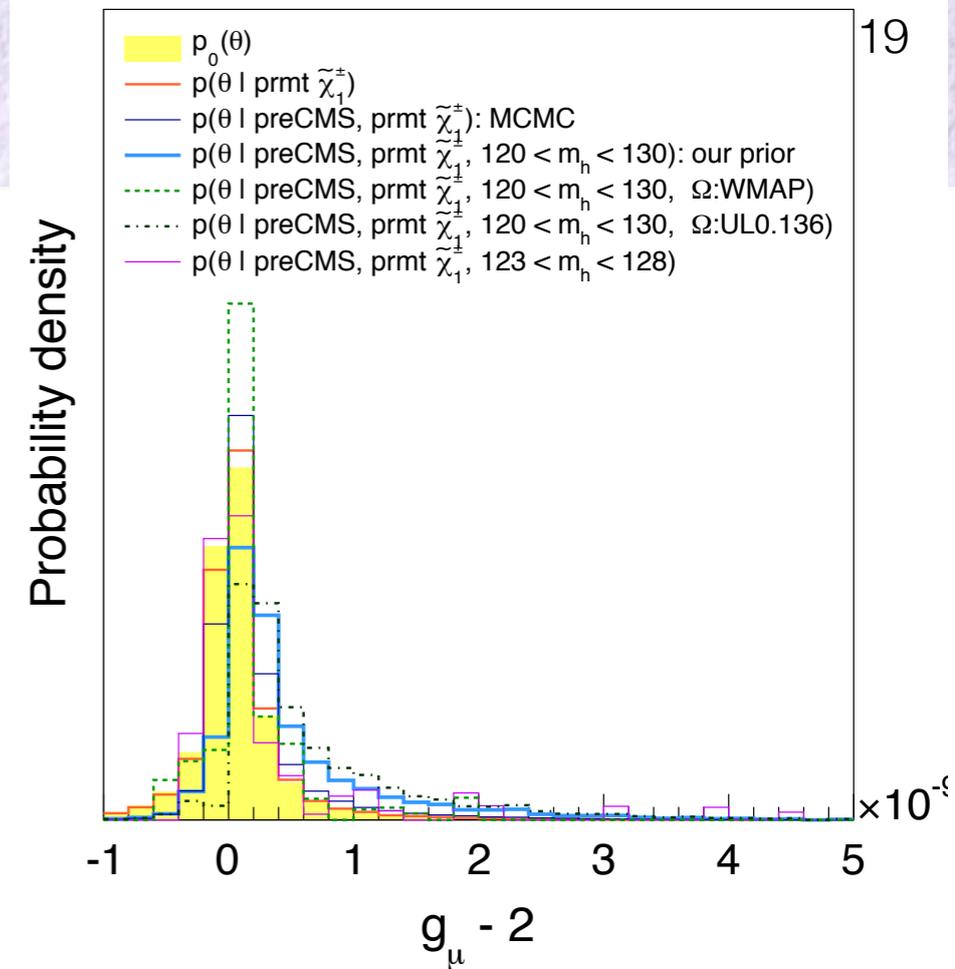
EW precision observables

EW precision observables, especially $g - 2$ and rare decays / FCNCs can constrain SUSY.

Figures show the combined impact of the EW observables on pMSSM (not the latest results, but recent results would not significantly change the overall effect). CMS SUS-12-030

Global analysis of recent $b \rightarrow sll$ measurements in agreement with MSSM. Mahmoudi et.al. arXiv:1401.2145

SUSY easily endures - though $b \rightarrow s\gamma$ brings tension on standard Naturalness.





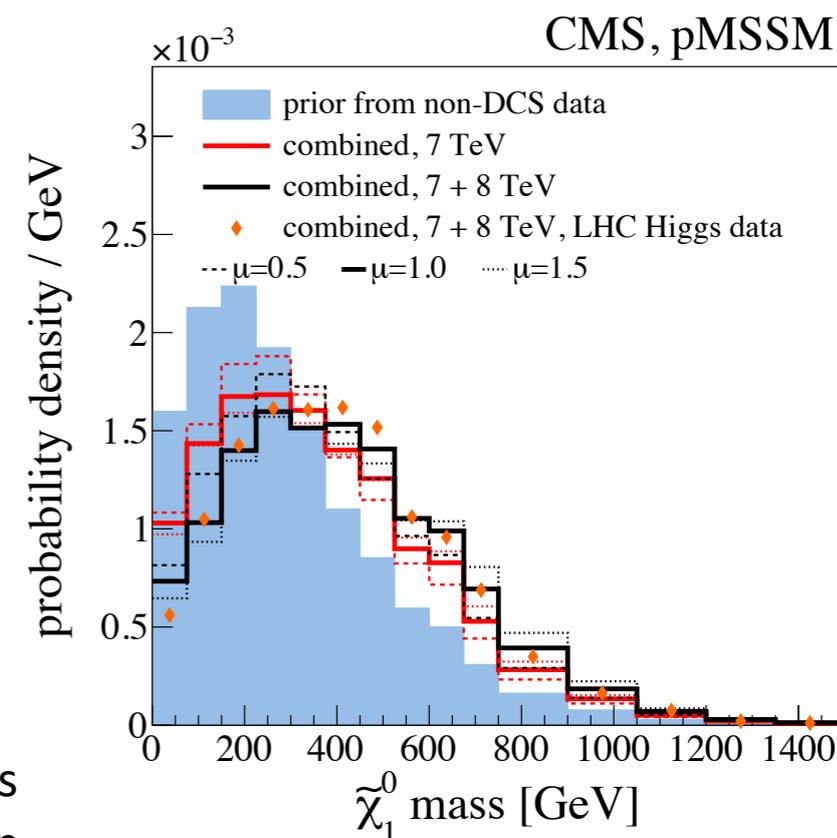
SUSY neutralino DM: LHC constraints

SUSY is constrained by direct or indirect measurements effecting dark matter related observables.

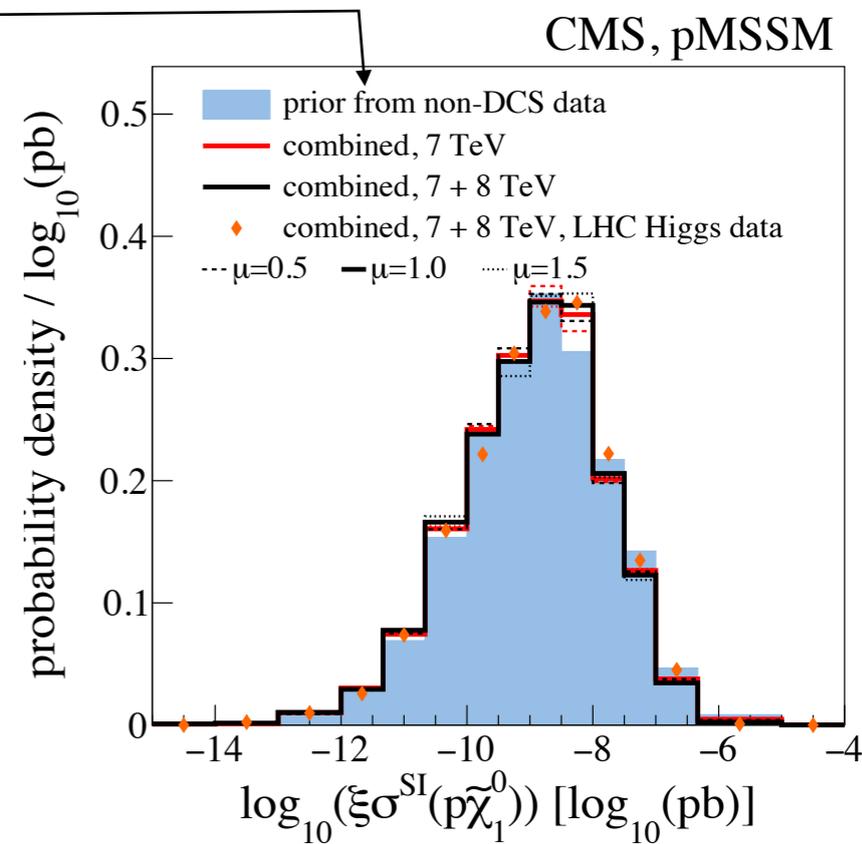
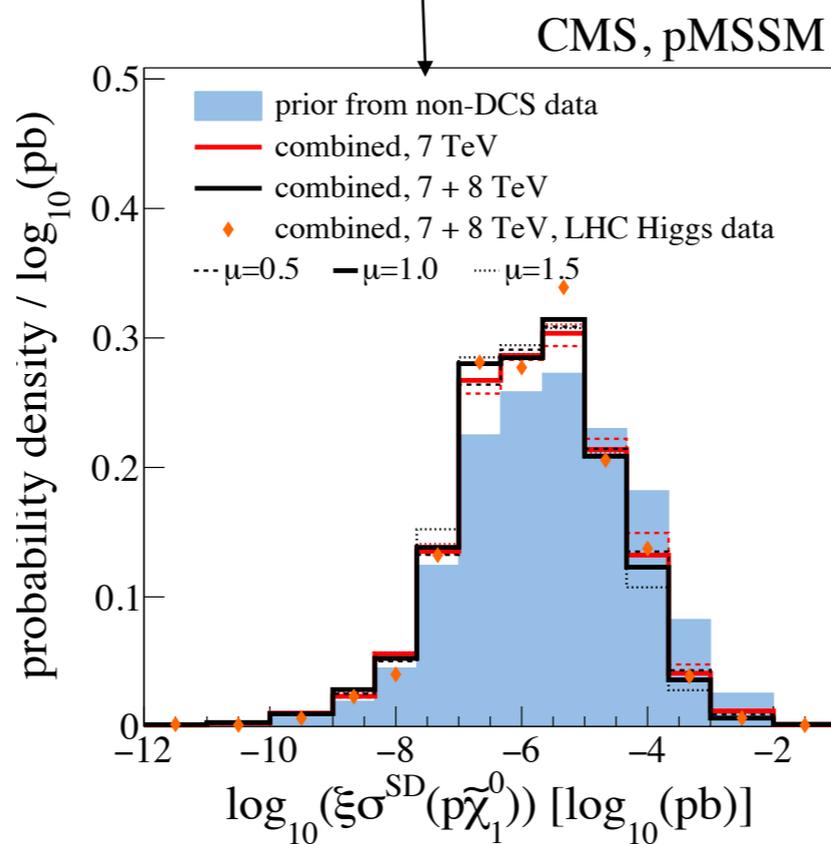
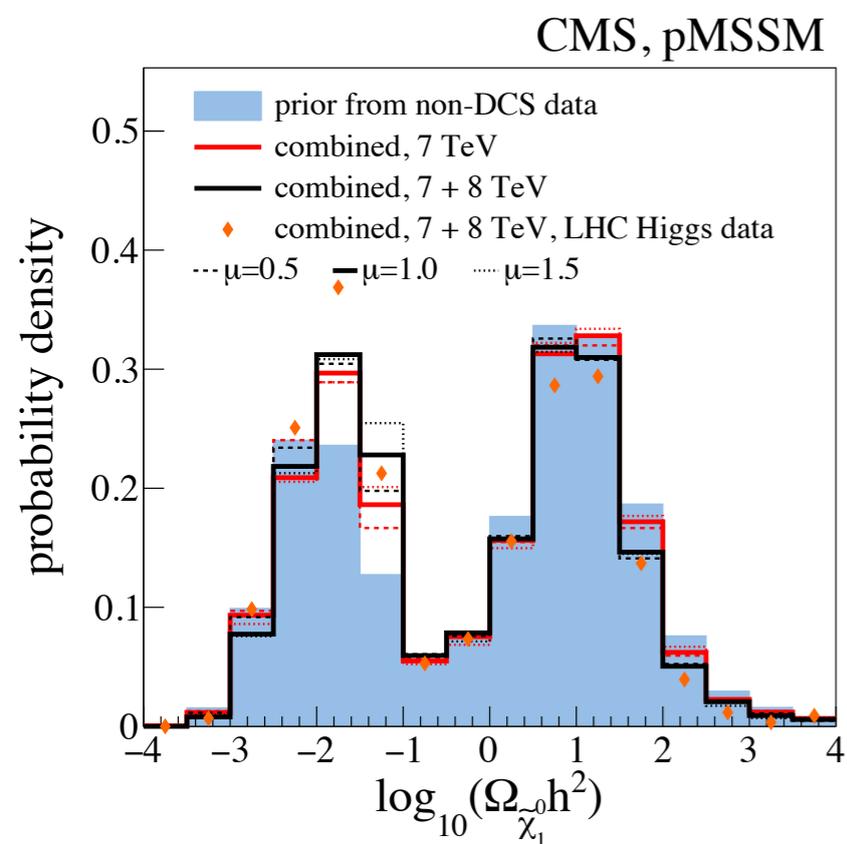
LHC SUSY searches have indirect impact on DM observables.

The impact, shown for pMSSM here, comes mainly from inclusive hadronic searches, and though it is visible, it is small.

CMS SUS-15-010

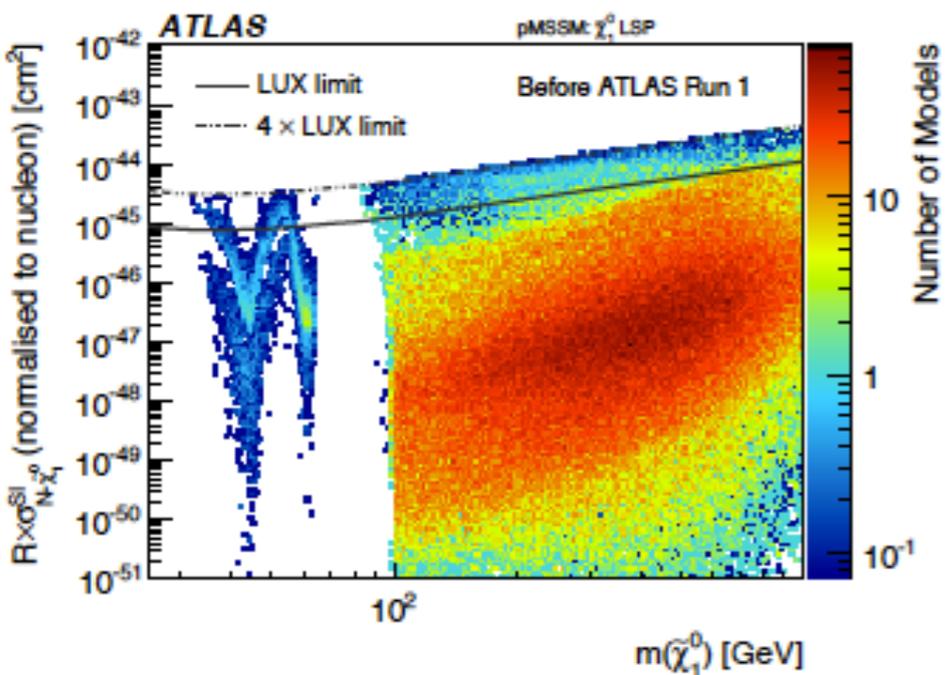
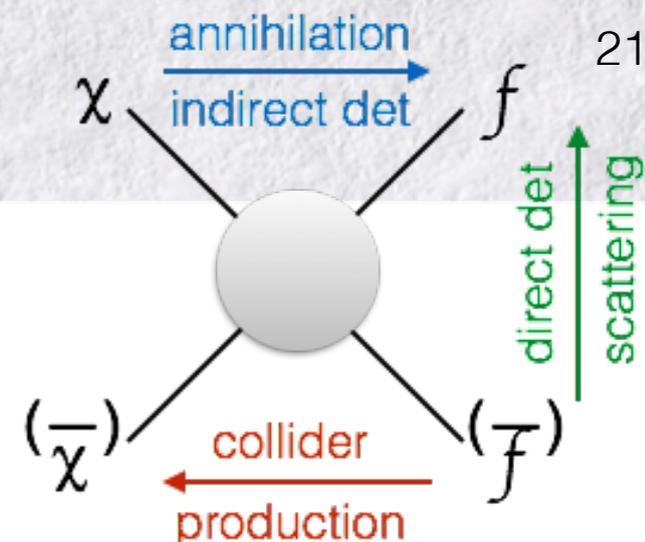


neutralino-nucleon cross
sects for direct detection

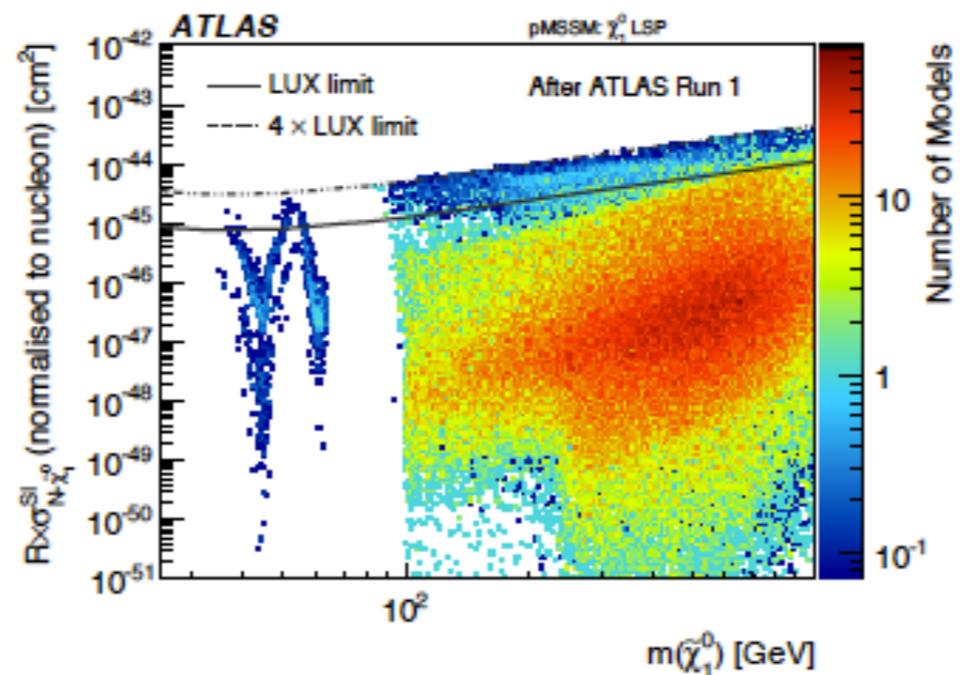




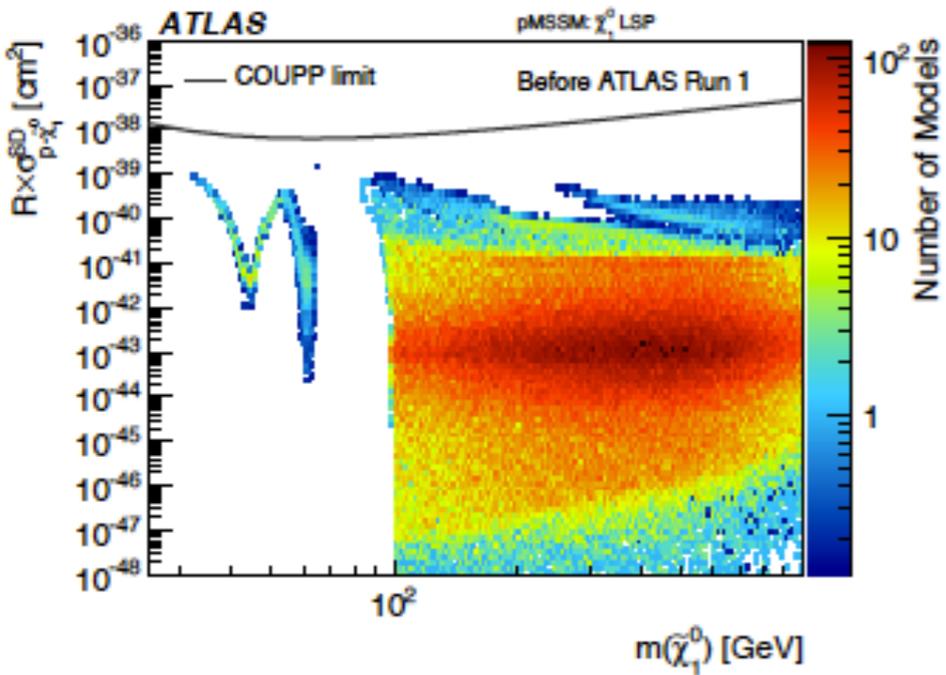
SUSY neutralino DM: LHC + DD



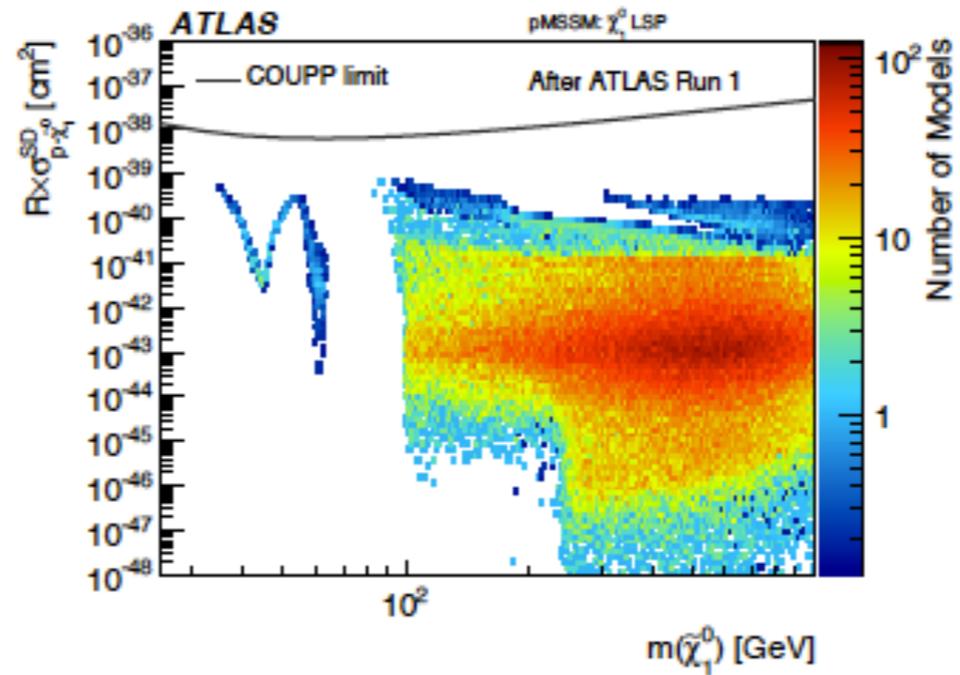
(a) Spin independent, before ATLAS Run 1



(b) Spin independent, after ATLAS Run 1



(c) Spin dependent, before ATLAS Run 1



(d) Spin dependent, after ATLAS Run 1

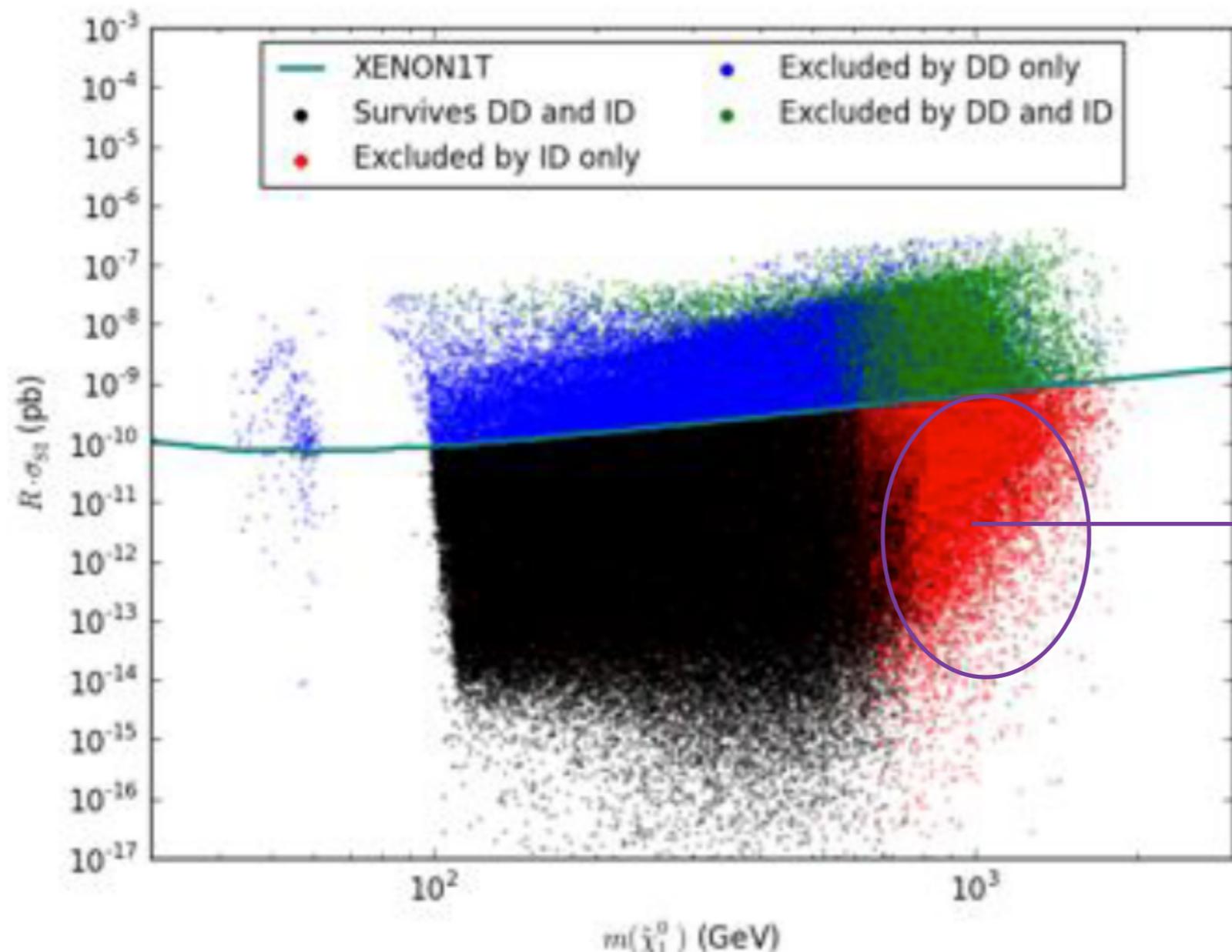
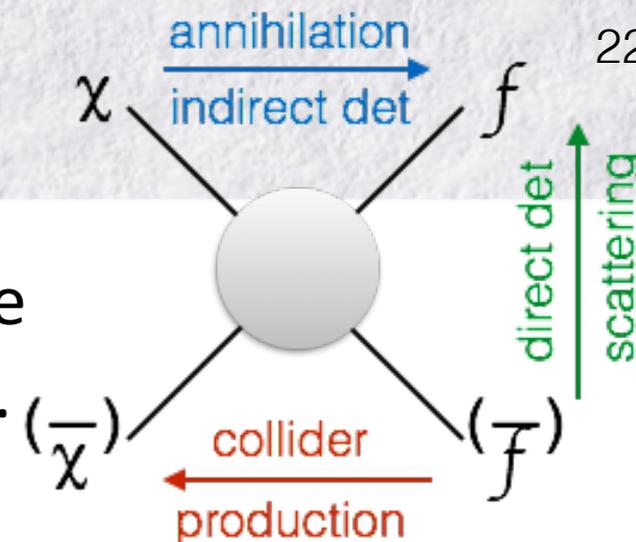
Currently, LHC provides stronger constraints on SUSY wrt DM direct detection experiments. However, next generation DM direct detection experiments like Xenon-1ton, LZ(10) and DARWIN will push the probed x-sections down by 10^{-2} - 10^{-4} , and test the bulk of the pMSSM phase space.



Indirect DM detection

DM annihilation could produce high energy neutrinos from the center of the Sun, or excess gamma-rays from galactic centers. DM decays would also lead to excess SM radiation.

Multitude of experiments are working / being built to chase such signals. Their measurements complement DD and collider searches.



Snowmass 2013

Indirect DM detection report

Indirect detection experiments will be probing a part of the SUSY space

- which cannot be accessed by DD
- which cannot be easily accessed by the LHC due to very heavy neutralinos.



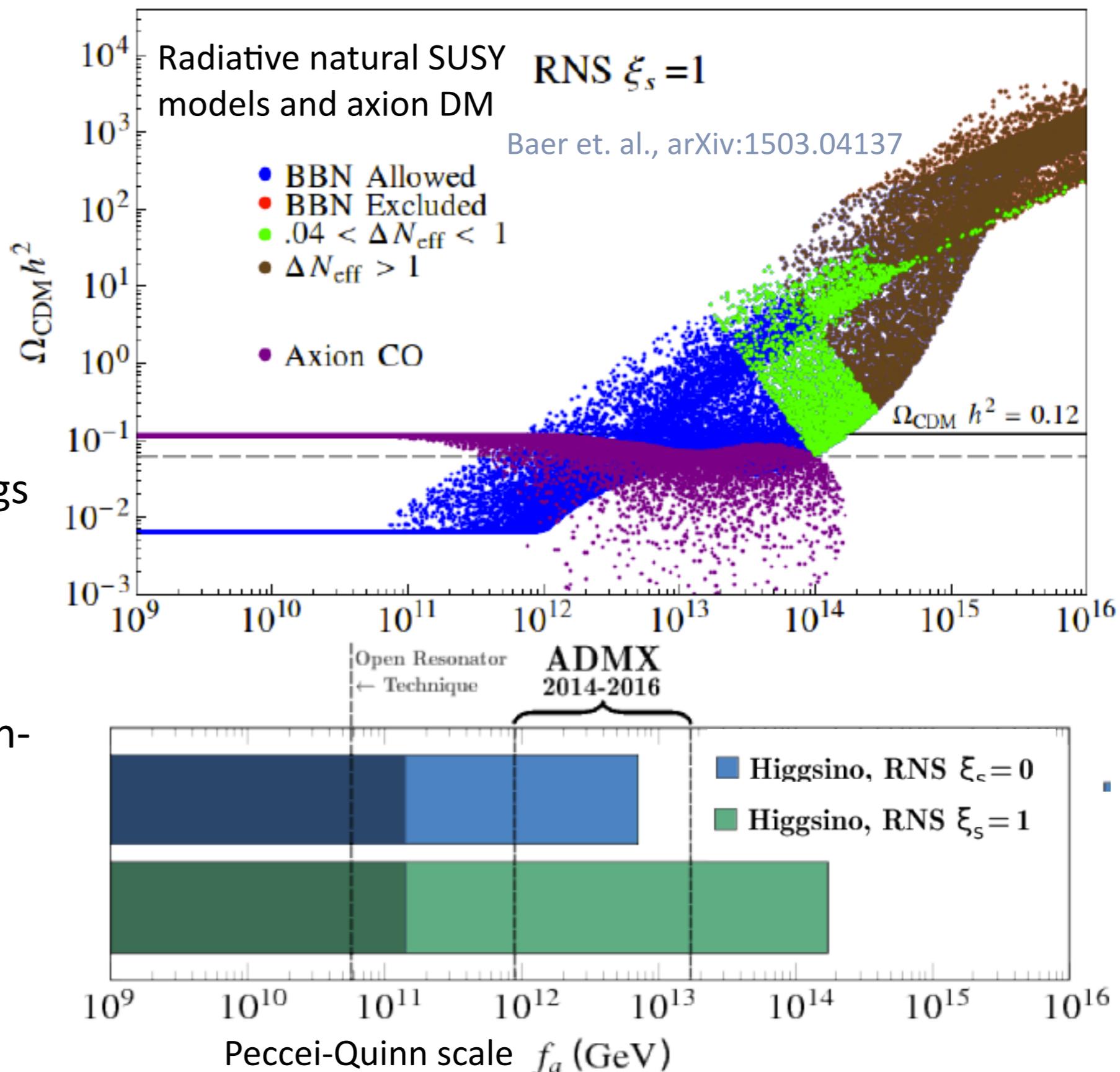
Axions & co. as DM

Axions arise from the elegant Peccei-Quinn solution to the strong CP problem. They can also constitute DM: alone or mixed with WIMPs.

Axions are unified into SUSY by a new axion superfield, which also brings along scalar saxions and fermionic axinos.

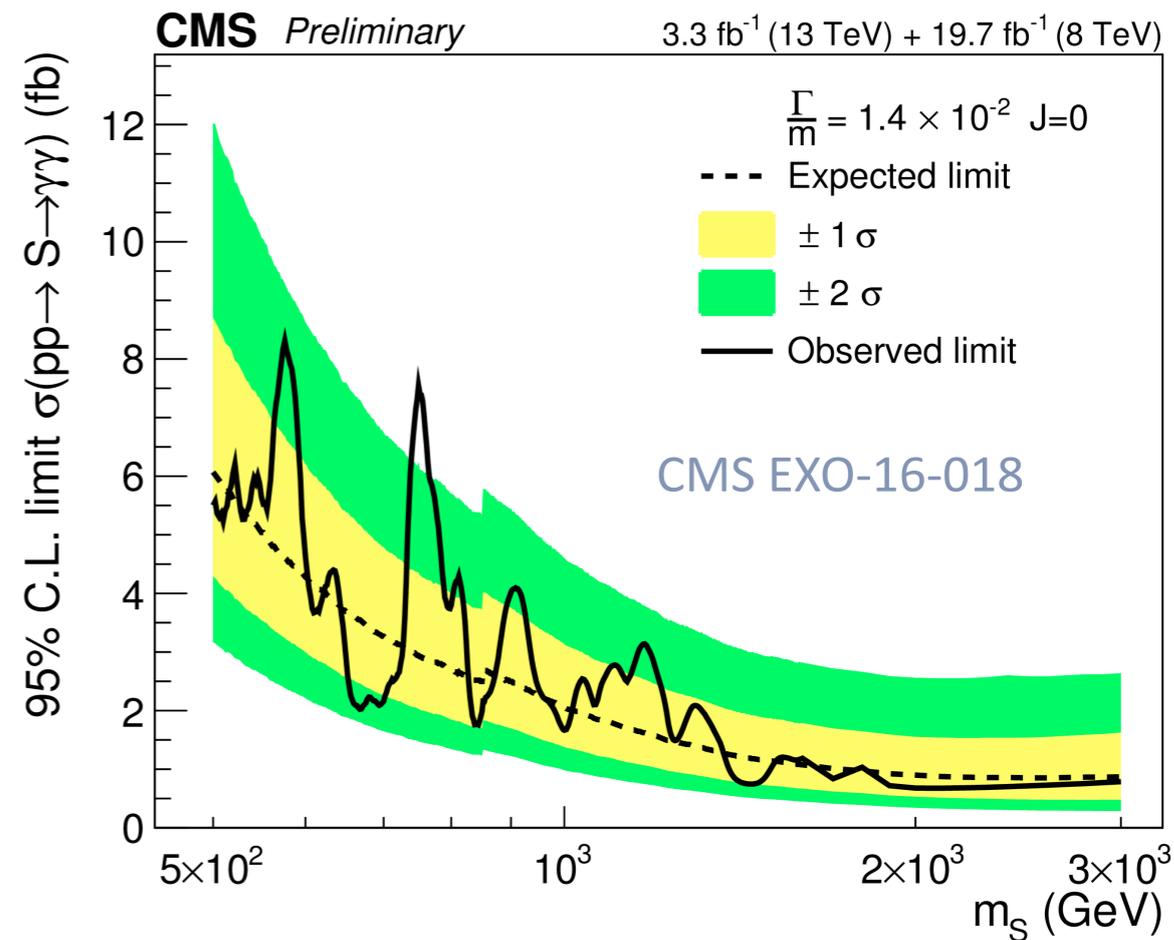
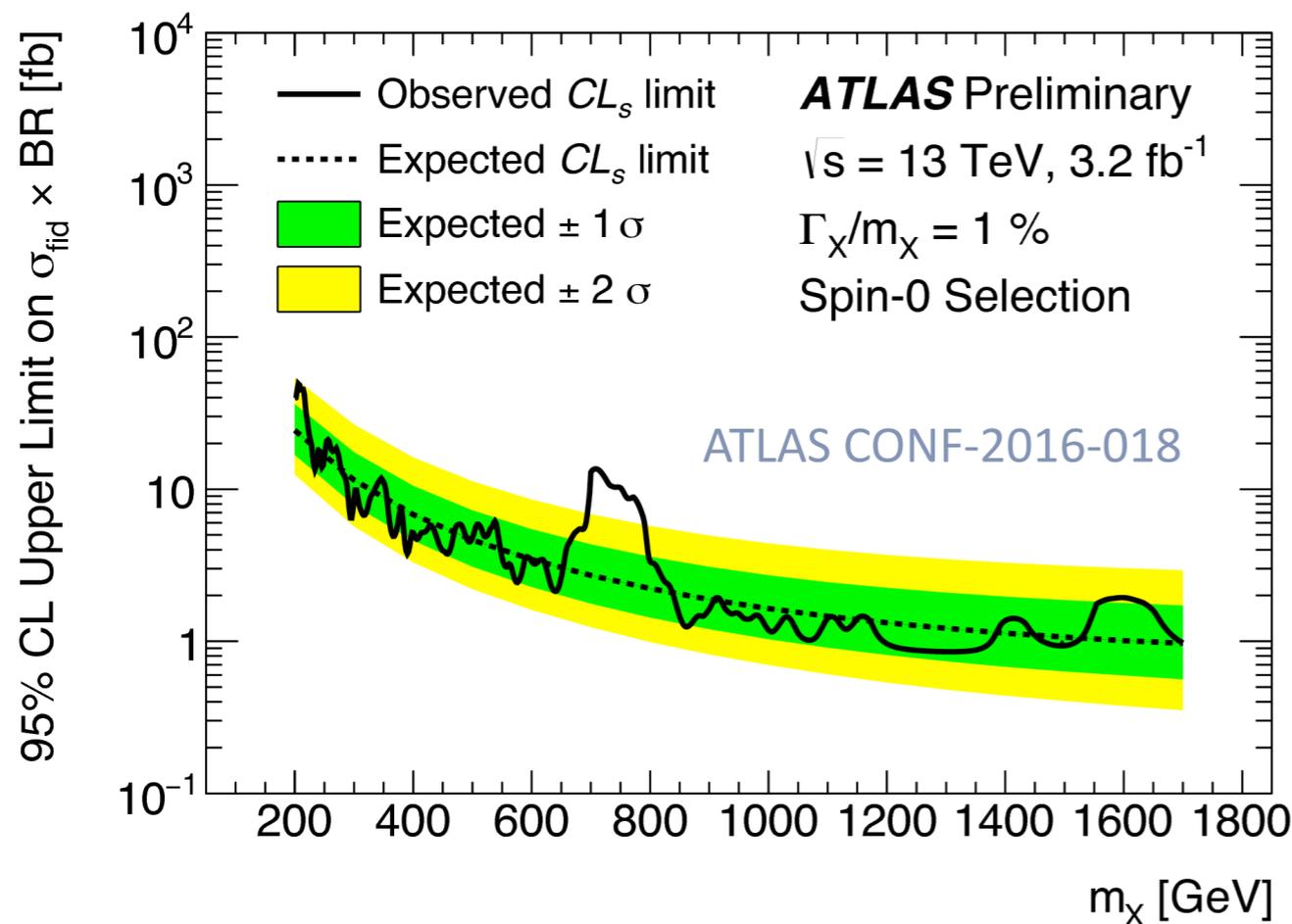
While axions directly contribute to DM, the axion-saxino duo regulates the abundance of neutralinos.

Axions are good DM candidates for natural models.





The diphoton excess - March 2016



ATLAS: Improved analysis separately for spin 0 and spin 2; new calibration; and combination with Run1.

CMS: New calibration (10% sensitivity increase; spin 0 and spin 2 tested; added 25% statistics with no B field.)

	spin 0 Local	spin 0 global	spin2 Local	spin 2 Global
Atlas (13 TeV only) - width 6%	3.9σ	2.0σ	3.6σ	1.8σ
CMS (13 TeV+8TeV) narrow width	3.4σ	1.6σ	~3.4σ	~1.5σ

Corresponds to a rate of a few fb.

No compelling evidence yet, but what if it is there?

Situation after diphotons



The **diphoton excess** cannot be accommodated in the standard MSSM.

Heavy MSSM Higgs states fail to reproduce the observed $\gamma\gamma$ rate. MSSM rates are lower.



Situation after diphotons (BUT...)



It just so happens that your friend here is only mostly dead. There is a big difference between mostly dead and all dead.



Threshold enhancement

The resonance is a **pseudoscalar boson A** with a $\gamma\gamma$ decay mediated by a **charged and uncolored fermion** which has

- **mass at the $1/2M_A$ threshold**
- very small **decay width < 1 MeV**
—> regulates a Coulomb singularity that enhances the $A\gamma\gamma$ amplitude.

MSSM implication:

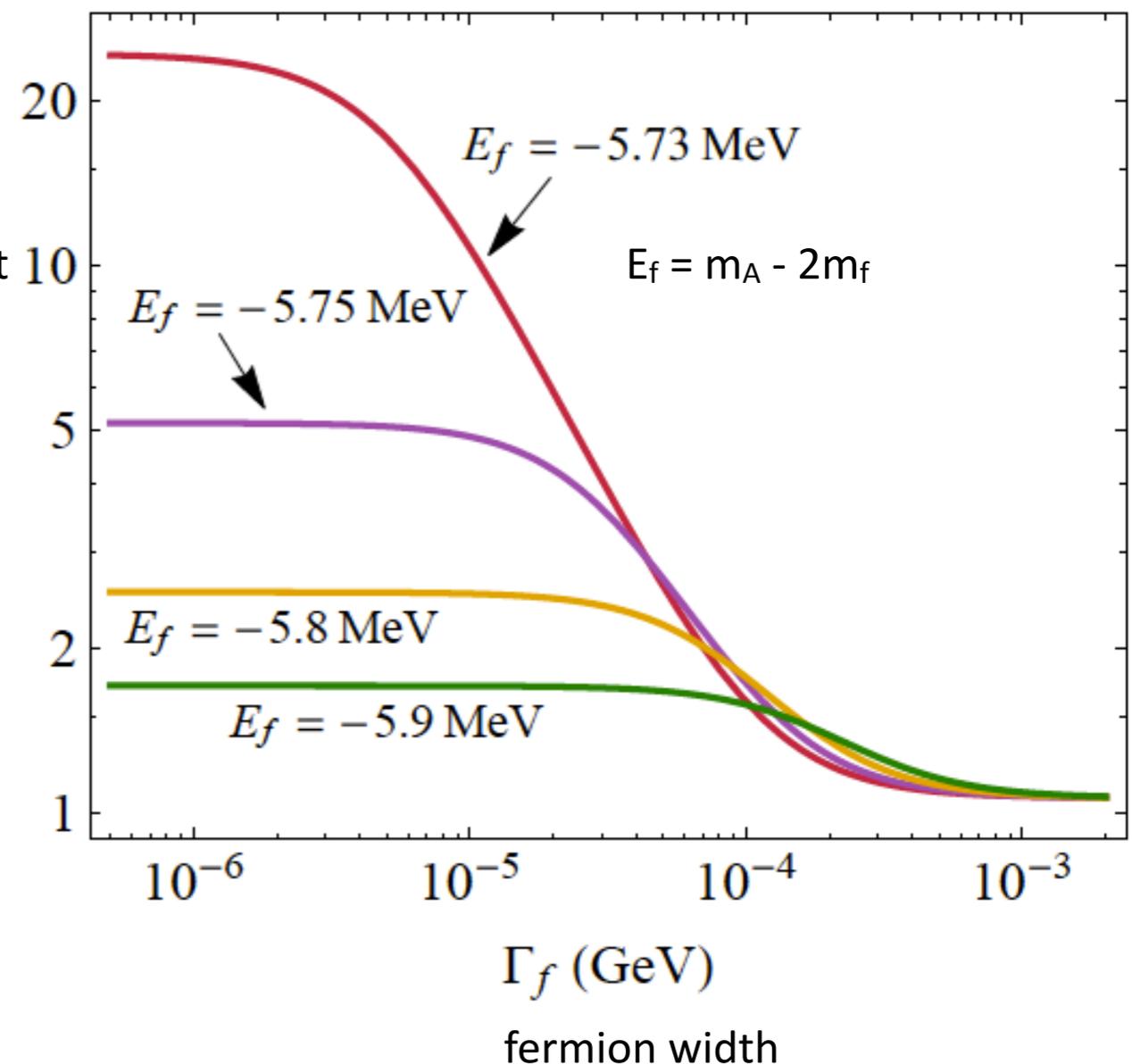
- A state is produced via the **top quark mediated gluon fusion** process
- A decays into $\gamma\gamma$ predominantly through **loops of charginos** with masses close to $1/2M_A$.

Bharucha, Djouadi, Goudelis,
arXiv:1603.04464



Enhancement
on the form
factor $\Lambda_A^{1/2}$

F





RPV MSSM

MSSM with leptonic R parity violation:
Sneutrino serves as the 750 GeV
resonance.

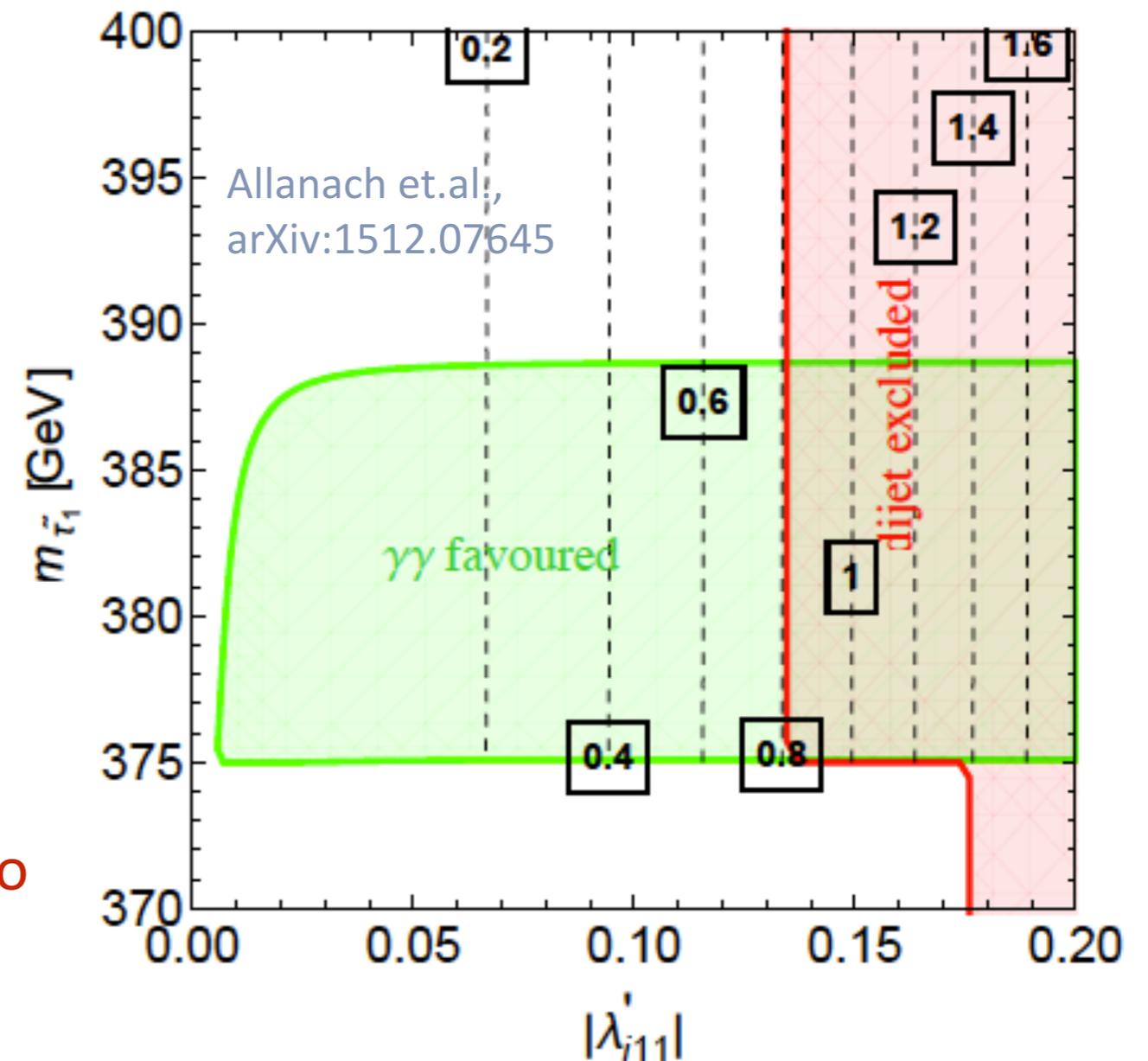
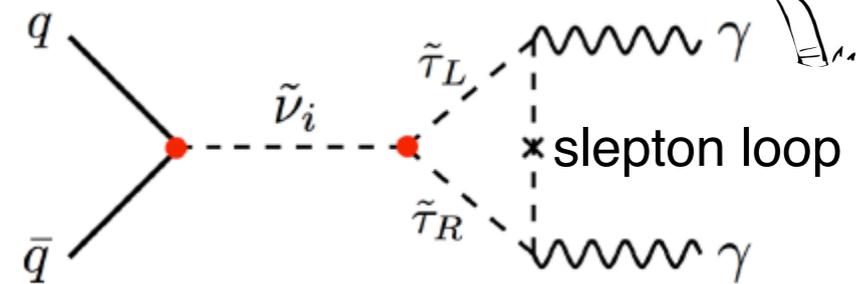
Sleptons in the loops enhance the
diphoton rate when the trilinear
couplings are sufficiently large.

Two independent calculations
considering different couplings - some
overlap.

Ding et.al., arXiv:1508.06608

Allanach et.al., arXiv:1512.07645

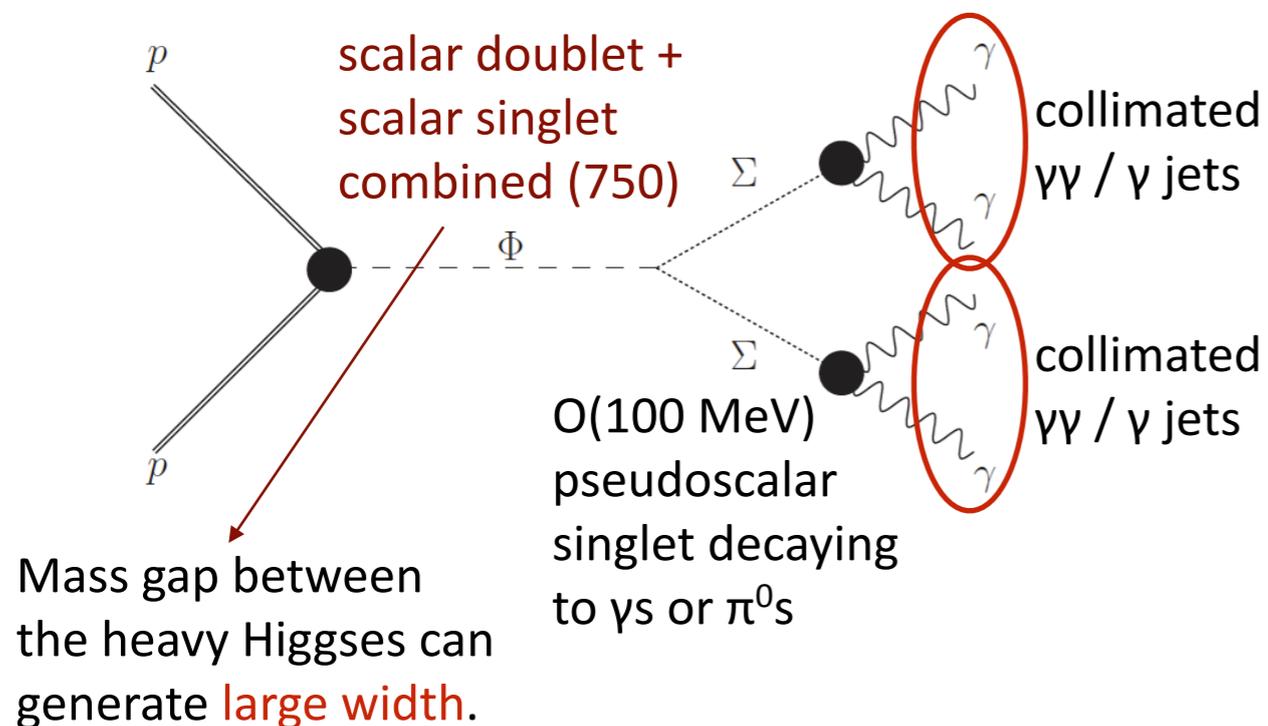
- Predicts light staus and smuons
around 300-400 GeV → to be easily
tested soon.
- Predicts significant sneutrino decays to
dijets.





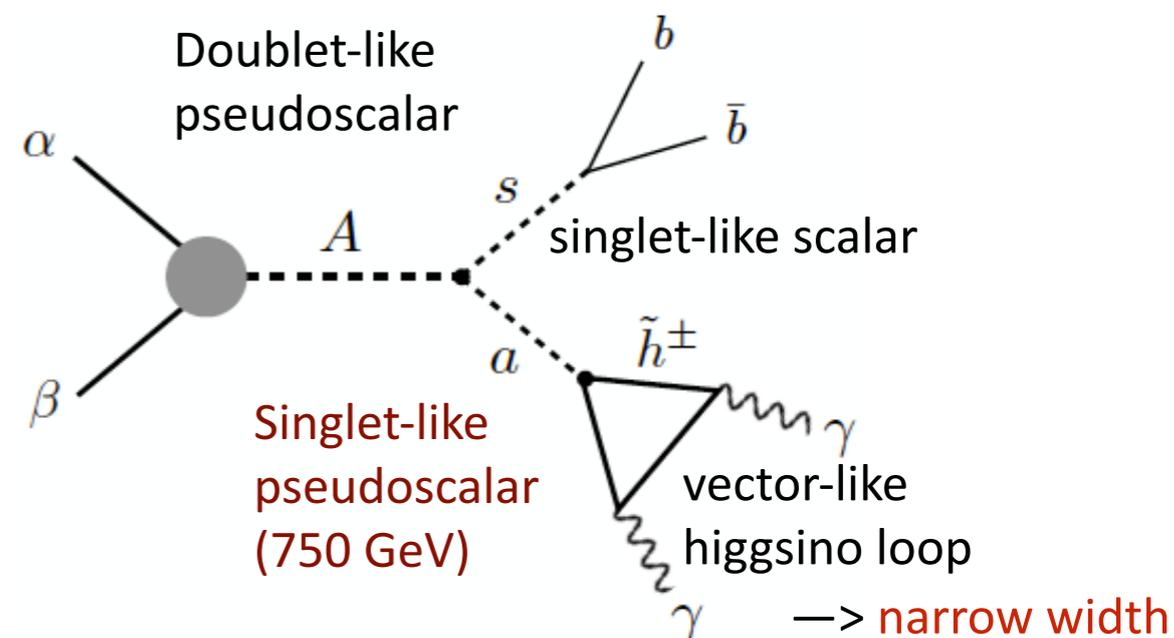
With very light
pseudoscalars:

Ellwanger et.al., arXiv:1602.03344
Domingo et.al., arXiv:1602.07691



750 GeV pseudoscalar Higgs:

Badziak et.al., arXiv:1603.02203



NMSSM with vector-like particles:

Wang et.al., arXiv:1512.08434
Tang et.al., arXiv:1512.08323, ...

Mixing of the **nearly degenerate scalar and pseudoscalar singlet like Higgs bosons** give the 750 GeV resonance. Mass difference accounts for a large width.

Diphoton decays are dominated with **vector-like squarks with large mixing**.

Vector like squarks also enhance the $gg \rightarrow h$ production cross section.



Low SUSY breaking and (s)goldstinos

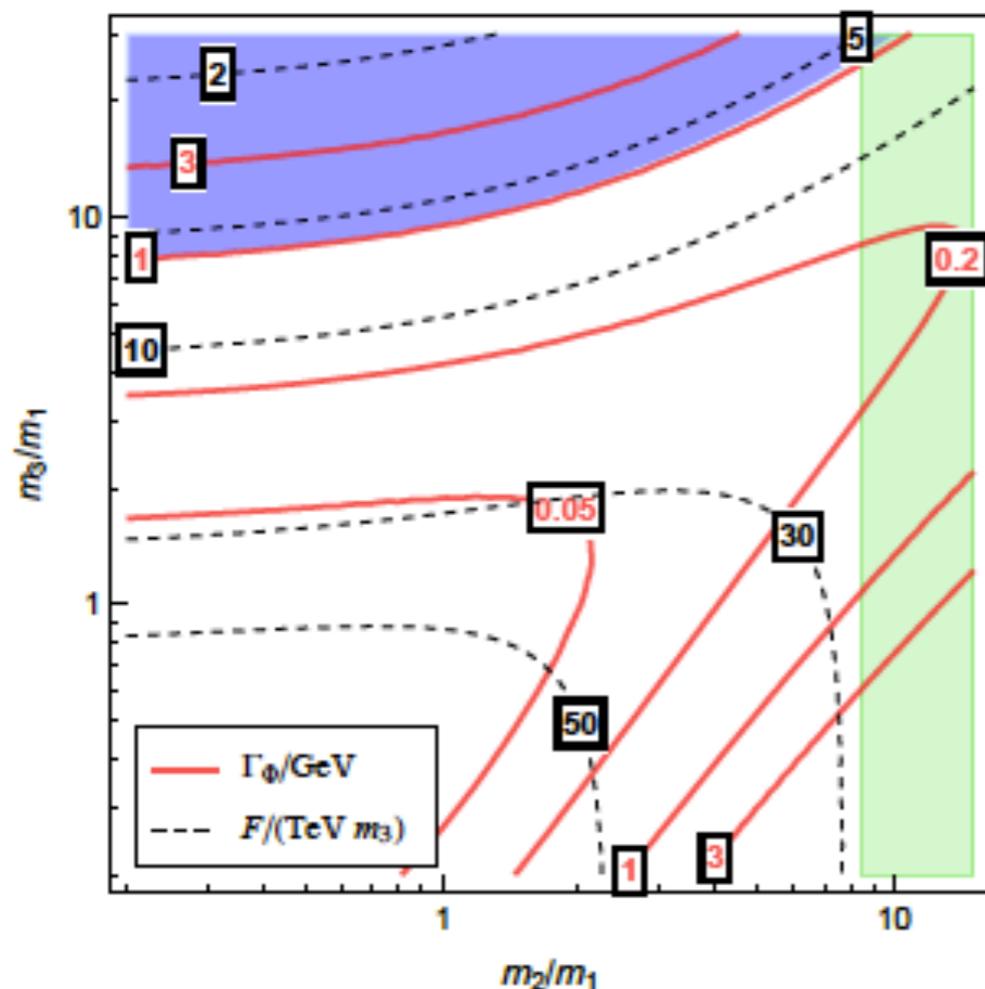
Low scale SUSY breaking scenarios have soft SUSY breaking and mediation at $\sim \text{TeV}$.

Low energy effective theory includes the **chiral superfield ϕ** responsible for SUSY breaking: ϕ has fermionic (**goldstino**) and scalar (**sgoldstino**) degrees of freedom.

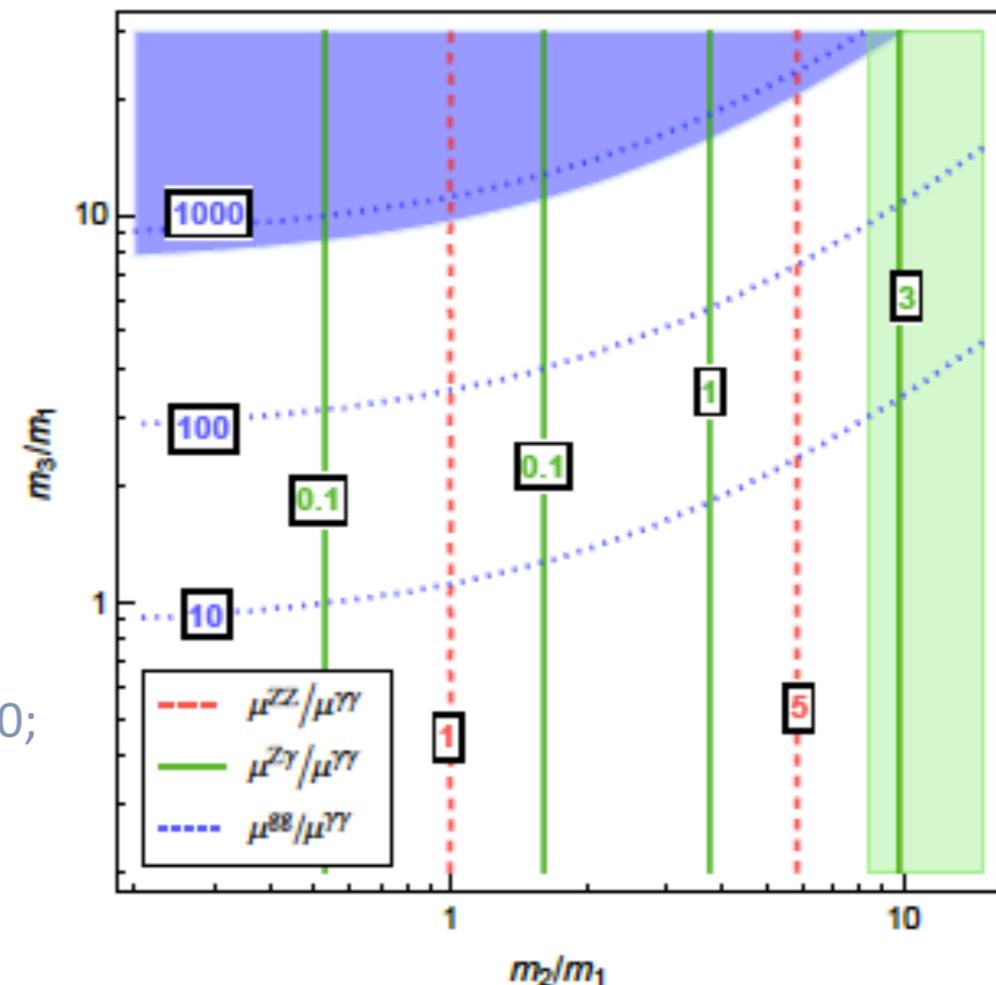
(s)goldstino coupled directly with gluons and photons is the **750 GeV resonance** \leftarrow effective production via gluons and decay into diphotons.

Partial widths into gluons (photons) depends on gluino (photino) mass / SSB scale F . **Sgoldstino-SM interactions suppressed with high SSB** \rightarrow we need low SSB.

Bellazzini et.al., arXiv:1512.05330; Petersson et.al., arXiv:1512.05333; Cases et.al., arXiv:1512.07895



Bellazzini et.al.,
arXiv:1512.05330;





Deflected AMSB; Dirac gauginos

Deflected anomaly mediation SUSY breaking.

Has a **singlet field S** and **vector-like messengers** (which solve the tachyonic slepton problem in minimal AMSB).

Scalar component of S is the resonance.

$\gamma\gamma$ decay mediated by loops involving messengers \rightarrow need **light messengers**

\leftarrow implies large messenger species N_F and deflection parameter d .

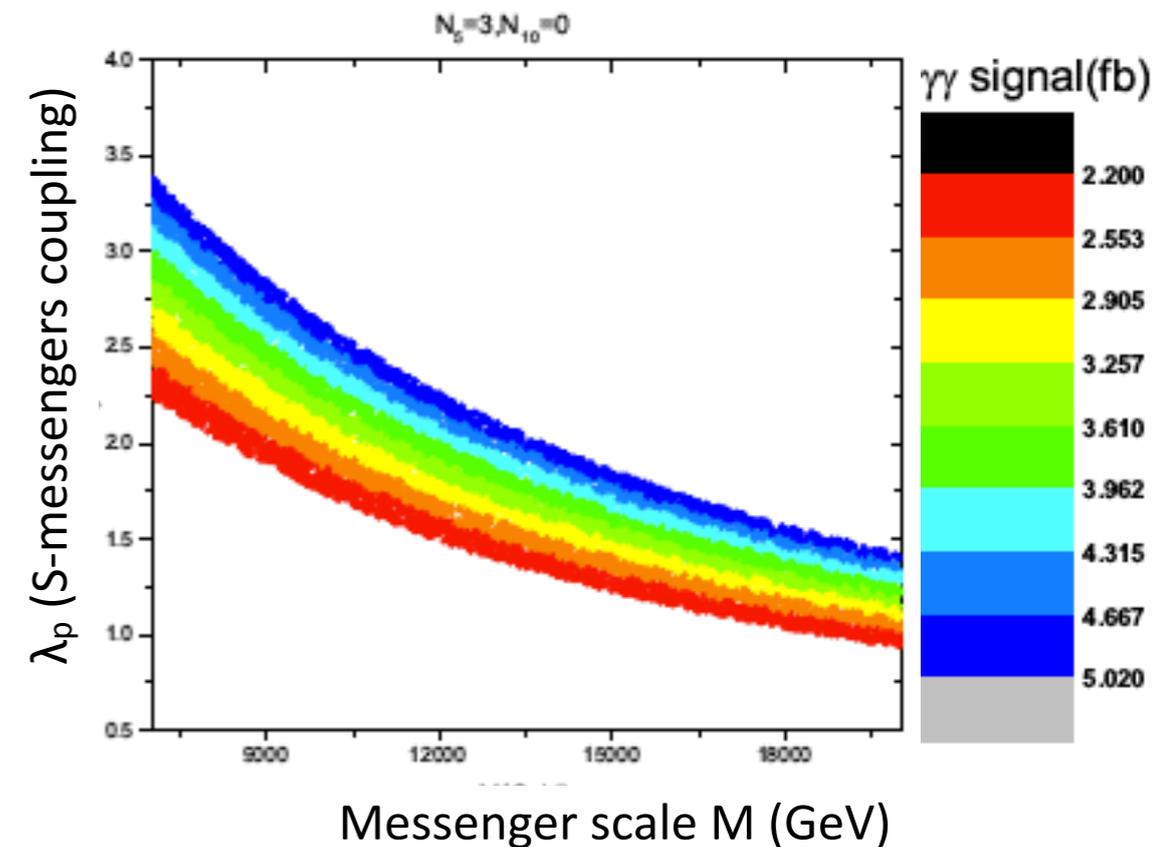
Consistent with **125 GeV Higgs** and also **$g-2$** .

SUSY with Dirac gauginos:

Resonance is **sbino**: Real component of the scalar partner of the field giving Dirac mass to bino \rightarrow scalar SM singlet, has large width due to tree level decays to h and higgsinos - **couples to pairs of dibosons through loops of squarks and sleptons.**

ZZ , $Z\gamma$, WW and hh decays expected (which generate constraints).

Wang et.al., arXiv:1512.06715



Carpenter et.al., arXiv:1512.06107



MSSM with lepton and baryon symmetries

MSSM extended with $U(1)_B$ and $U(1)_L$ corresponding to baryon and lepton number symmetries.

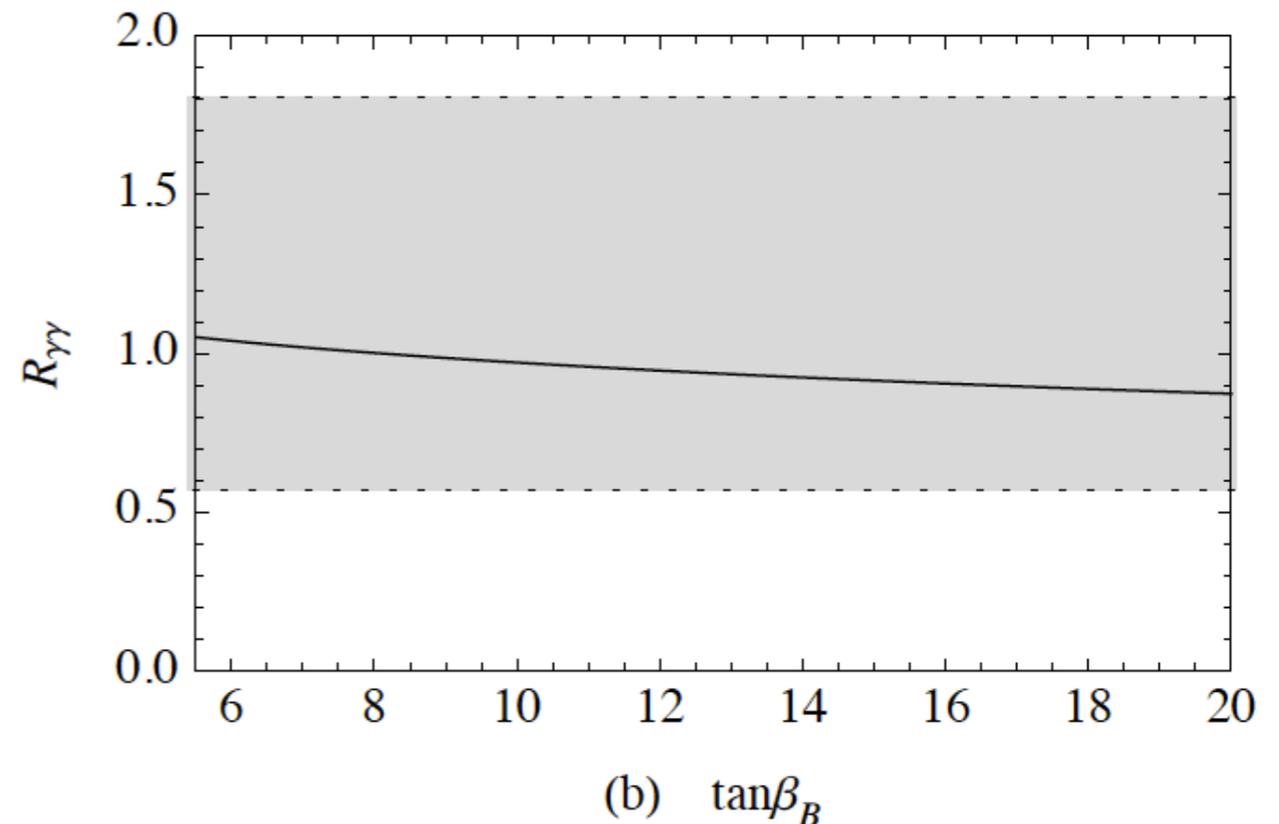
750 GeV resonance can be the CP-odd A^0_B which results from breaking the $U(1)_B$.

SM decays of A^0_B only at loop level. $Z\gamma$, ZZ , WW signals not expected.

Decays to DM particles are likely.



Feng et.al., arXiv:1512.06696



MSSM extended with $U(1)_{B-L}$ (similar to the above).

Additional $U(1)_{B-L}$ symmetry broken by a superpotential constructed from a pair of Higgs superfields ϕ and a gauge singlet scalar superfield S .

Scalar components of the S - ϕ - ϕ system give a resonance system consisting of 4 spin-0 states, which can constitute the 750 GeV resonance.

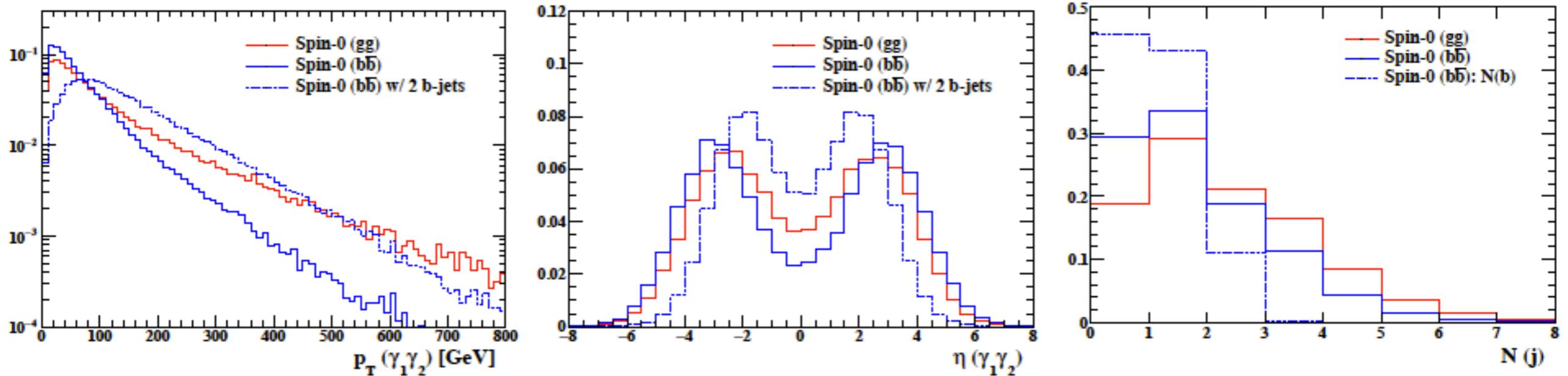
Lazarides et.al., arXiv:1602.07866



Characterizing the diphoton signal

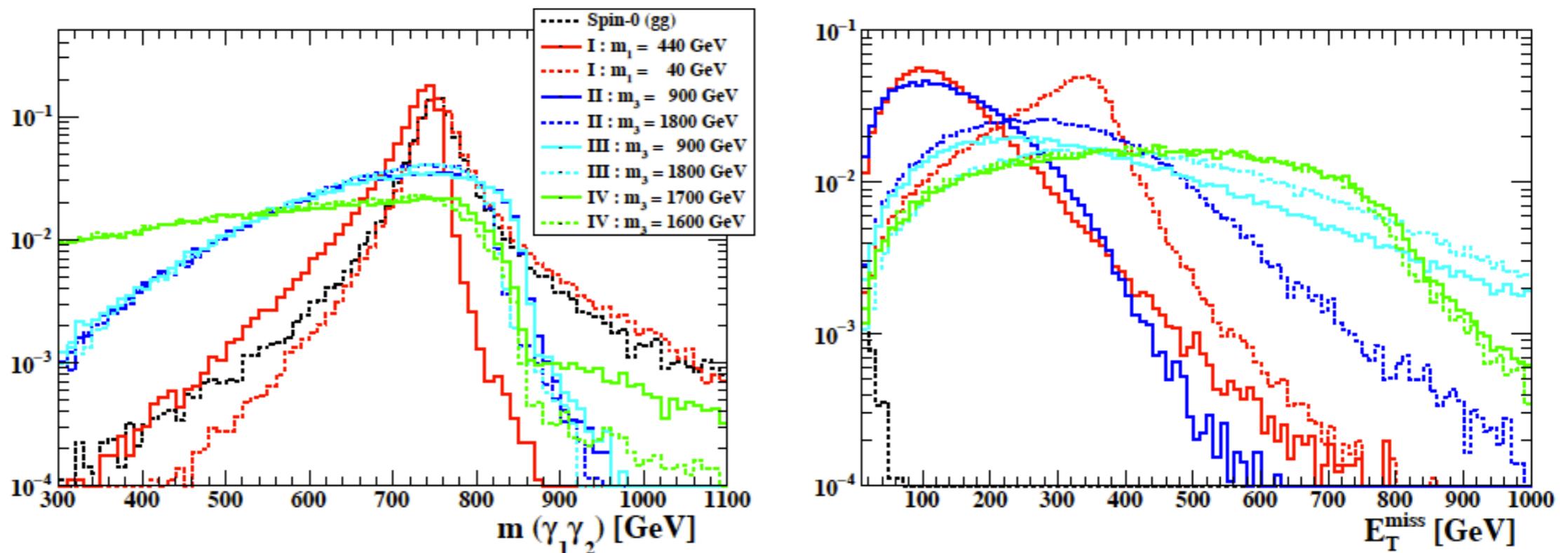
Studied **kinematic distributions** that could characterize the excess in Run2.

- $\gamma\gamma$ system and leading γ distributions discriminate **topology and mass spectra**.
- **QCD radiation patterns** discriminate the **production mechanism**.
- Studied **heavy parent resonance** $\rightarrow X(750) + Y$. E_T^{miss} can discriminate.



Bernon et.al.,
arXiv:1603.03421

$m(\gamma\gamma)$ and
 E_T^{miss} from
heavier
resonance
decays.





Situation after diphotons



Life is less simple for SUSY.
Resurrection / reconciliation needs thought and effort.

But perhaps with more data and inspiration, SUSY might some day return like this:





*SUSY endures.
Let's continue searching...*