SUSY and Dark Matter

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on behalf of ATLAS, CMS and theoretical community

HL/HE-LHC Physics Workshop: final jamboree
1 March, 2019 CERN

arXiv.1812.07831

It is a great pleasure to present this impressive set of studies:

~ 30 contributions, 20 minutes
Apologies if some of your plots or details are skipped…

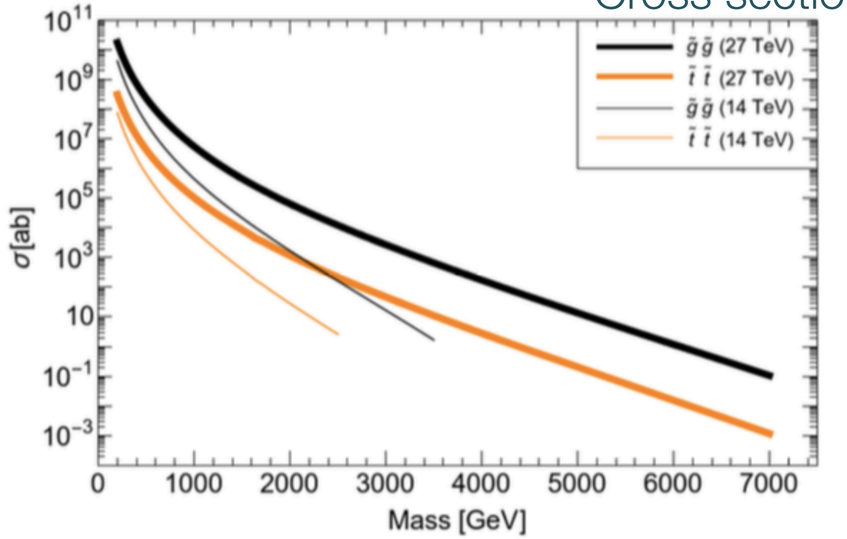
SUSY: General remarks

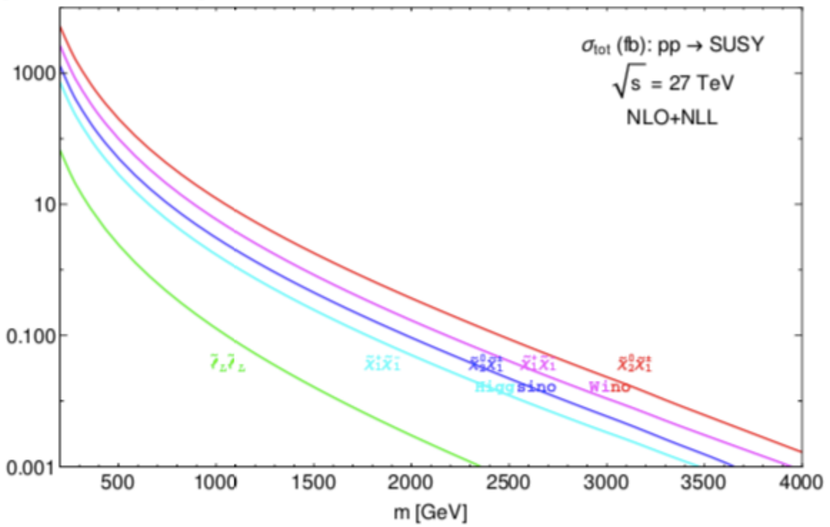
Searches for SUSY particles are presented under various theoretical hypotheses:
— the Minimal Supersymmetric Standard Model (MSSM)
— phenomenological MSSM
— models with light higgsinos
— simplified models
R-parity conservation and prompt particle decays are generally assumed.

— RPV signatures leading to long-lived particles in Xabier's talk.
(disappearing track is actually a RPC signature. RPV can also give us displaced decays, but that can happen in RPC as well)

Cross sections with NLO+NLL

arXiv:1407.5066

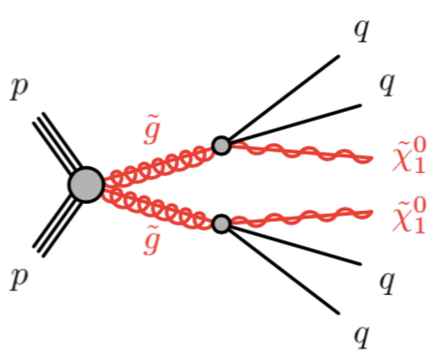


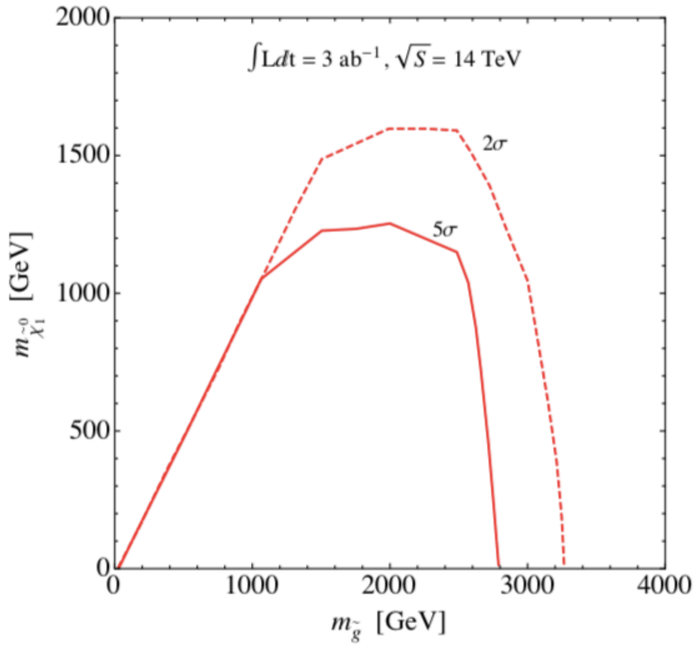


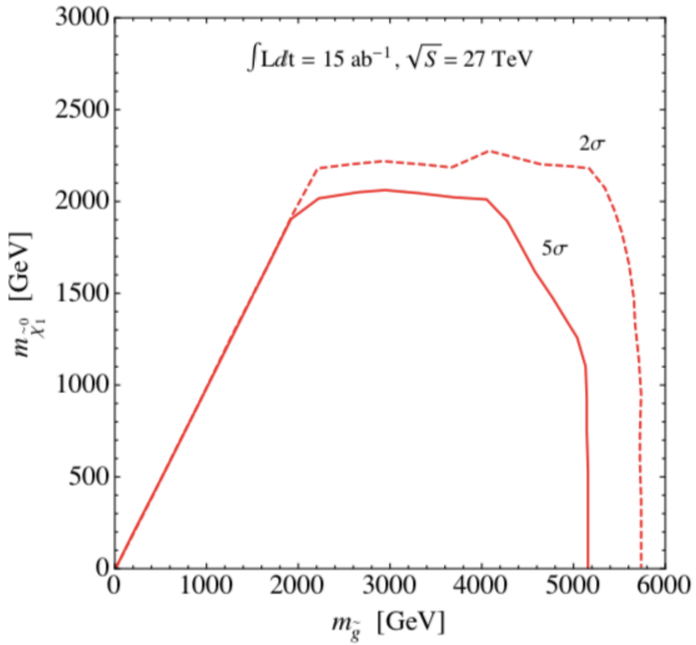
PDF uncertainties dominant for strongly produced particles.

Searches for strongly produced **SUSY** particles: *Gluino-pair production*

— Gluinos in MSSM scenario, decaying directly $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ (bino-like LSP)
— Selection based on re-optimised ATLAS 0L, 2-6j+EtMiss search





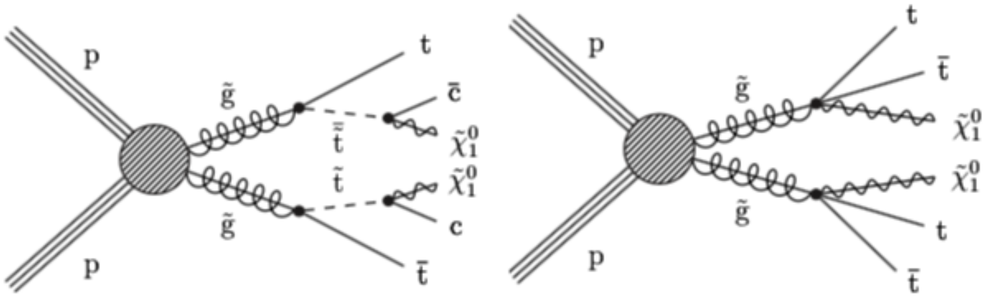


Sec 2.1.1

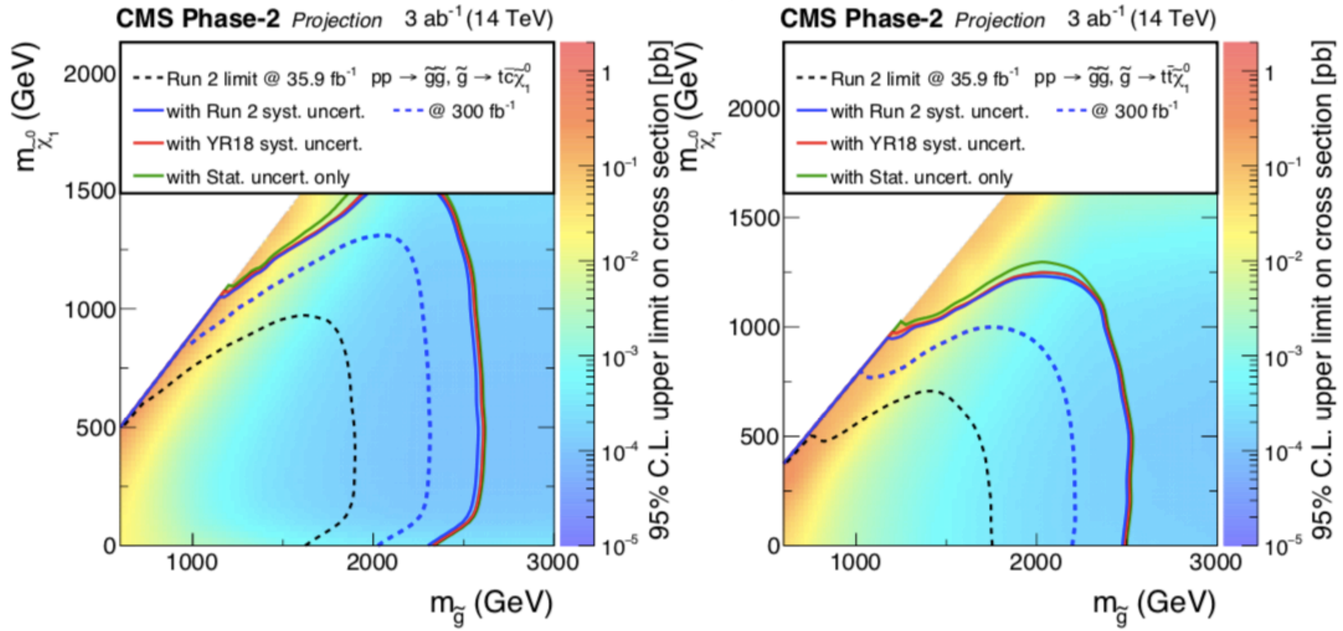
- HL-LHC: gluino of approximately **3.2 TeV** can be probed for a massless LSP, with a discovery potential up to **2.9 TeV**.
- HE-LHC: the **discovery (exclusion)** reach is roughly **5.2** (**5.7**) **TeV** for massless LSP.
- With the signal varied within a 50% band (mimicking current PDF uncertainties for high mass gluinos) the HL-LHC (HE-LHC) exclusion reach will decrease by about 200 (400) GeV

Searches for strongly produced **SUSY** particles:
Gluinos in hadronic boosted signatures (gluino-mediated stops)

— Hadronic final states with at least one boosted W-jet and one b-jet, or at least one boosted top-jet, using razor kinematic variables (binned in M_R and R^2)



projection, CMS-PAS-FTR-18-037



- $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$: the **discovery (exclusion)** reach is **2.3 (2.5) TeV** for massless LSP.
- $\tilde{g} \to t\bar{c}\tilde{\chi}_1^0$: the **discovery (exclusion)** reach is **2.3 (2.6) TeV** for m(LSP)=500 GeV.

Searches for strongly produced **SUSY** particles: *Stop-pair production*

- Optimised selections for <u>large Δm</u> (Δm(stop, LSP)>>m_t) and <u>small Δm</u> (Δm(stop, LSP)~m_t) regions
- Exploit the potential presence of boosted top quarks and W bosons
- Recursive jigsaw reconstruction variables

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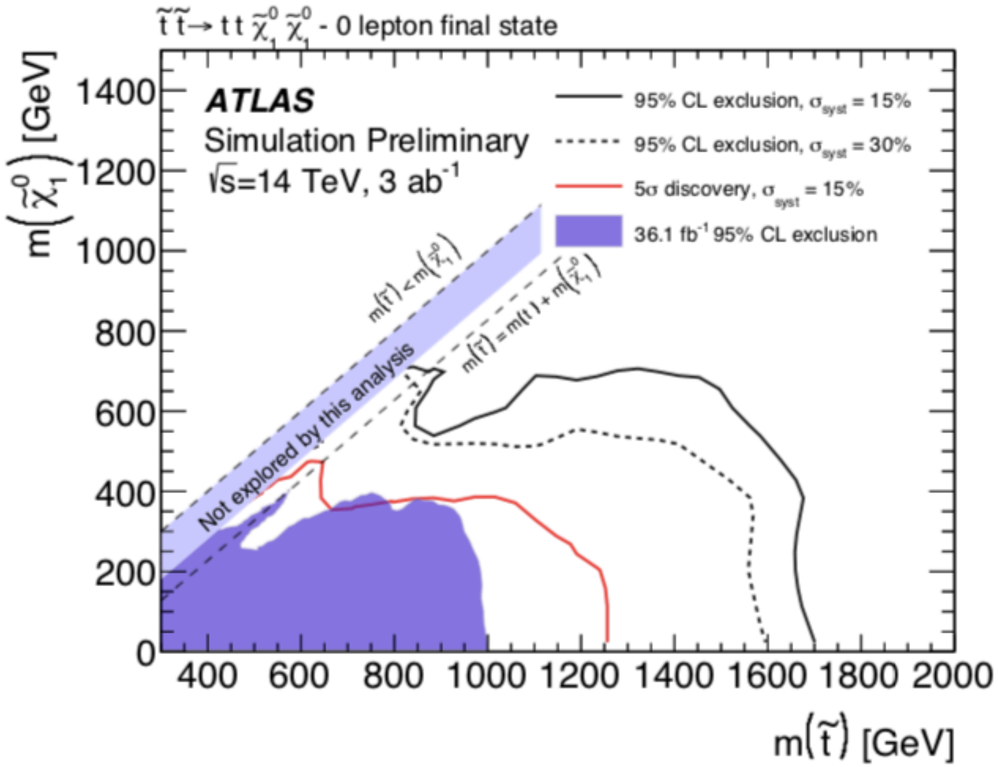
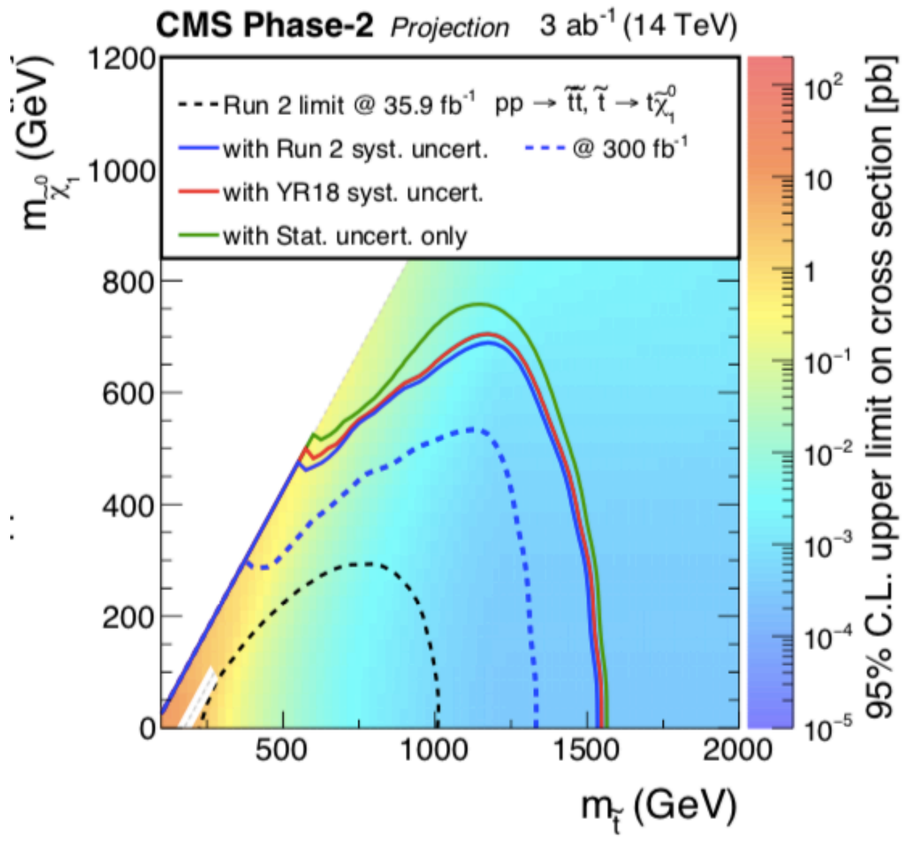




projection, <u>CMS-PAS-FTR-18-037</u>

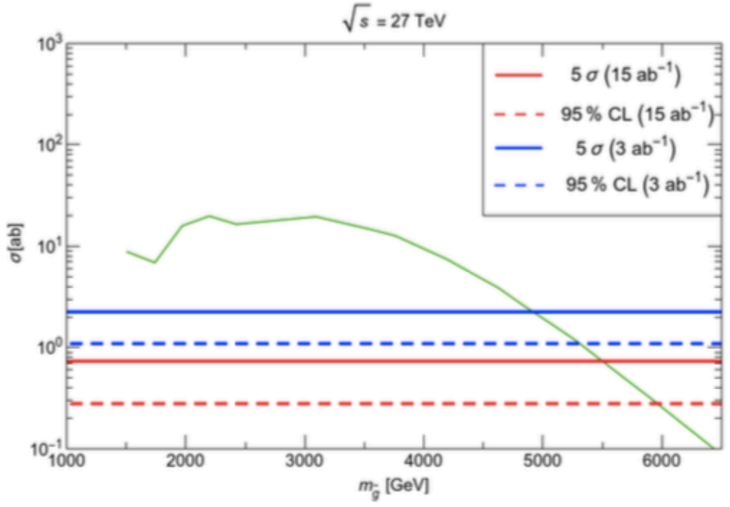
- Top squarks can be **discovered (excluded)** up to masses of **1.4 (1.7) TeV** @ HL-LHC
- In small Δm region, **discovery (exclusion)** reach is **650 (850) GeV**

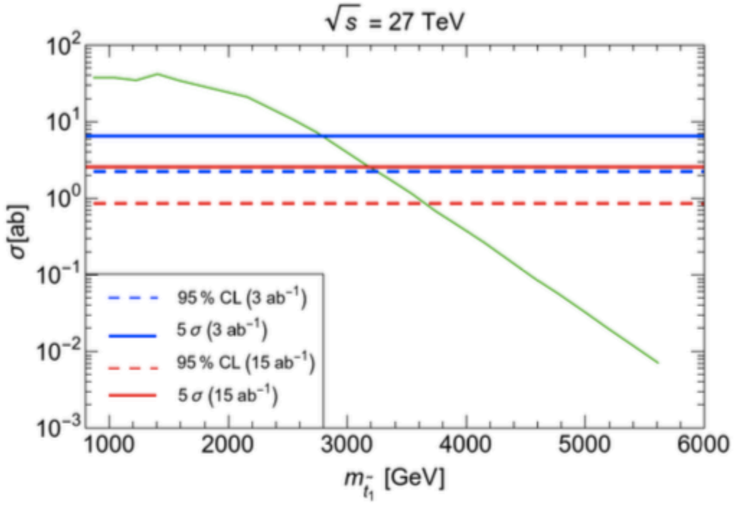
Searches for strongly produced **SUSY** particles: *gluino- and stop-pairs in natural SUSY models*

— Models with light higgsinos (natural SUSY)

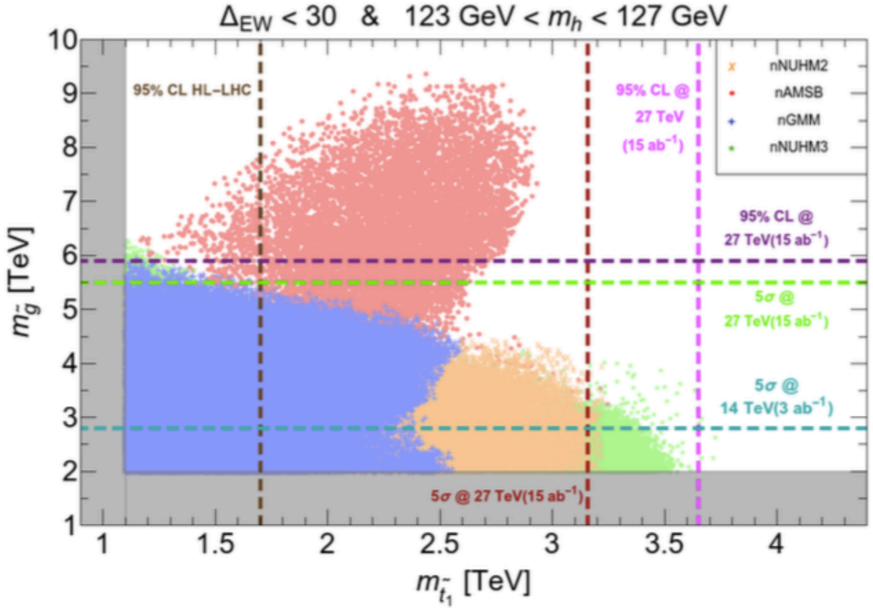
$\tilde{g} \to t\tilde{t}_1, \tilde{t}_1 \to b\tilde{\chi}_1^+, \tilde{t}_1 \to t\tilde{\chi}_{1,2}^0$, invisible decay products of higgsinos

$\tilde{t}_1 \to b\tilde{\chi}_1^\pm(50\%), \tilde{t}_1 \to t\tilde{\chi}_{1,2}^0(2 \times 25\%)$





Combined reach for stops and gluinos

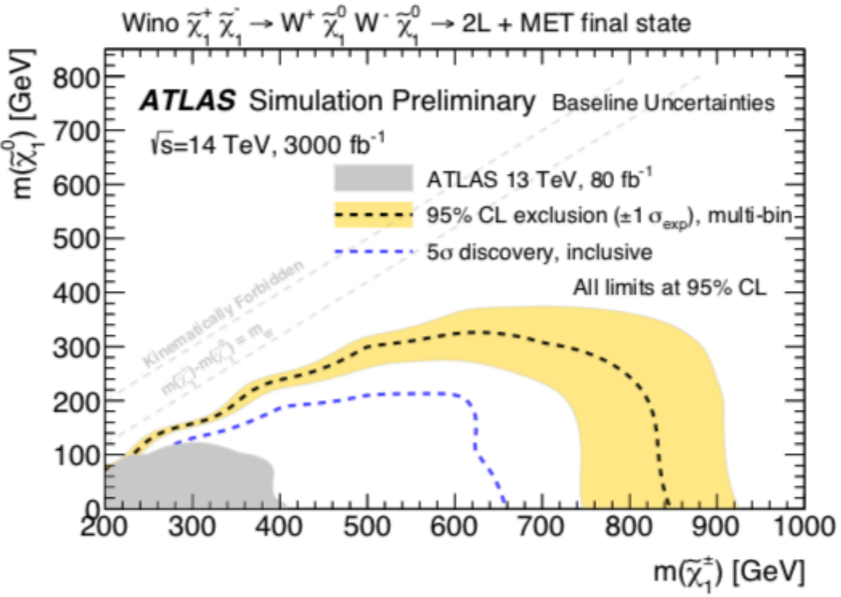


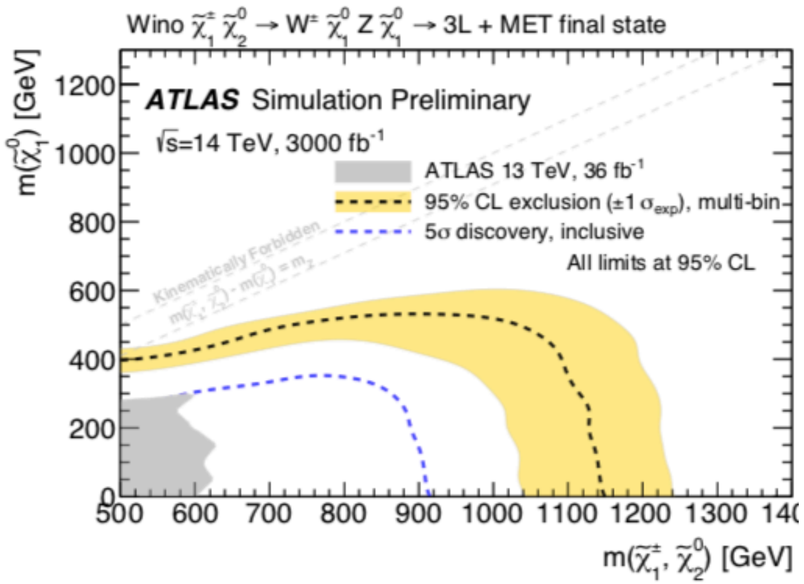
arXiv:1612.00795 arXiv:1708.09054

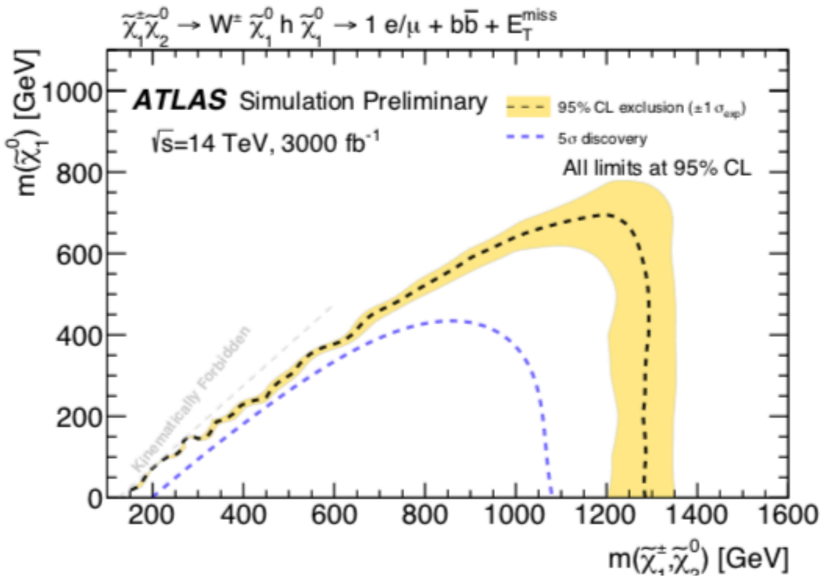
- Gluino-pair @ HE-LHC: the **discovery (exclusion)** reach is **5.5 (5.9) TeV** (5σ discovery at LHC14 at 3ab-1: 2.8 TeV)
- Stop-pair @ HE-LHC: the **discovery (exclusion)** reach is **3.15 (3.65) TeV**

=> HE-LHC will allow for exclusion of almost all SUSY natural scenarios in case of null observation.

Searches for electroweak **SUSY** processes:
Chargino-pair, chargino-neutralino production

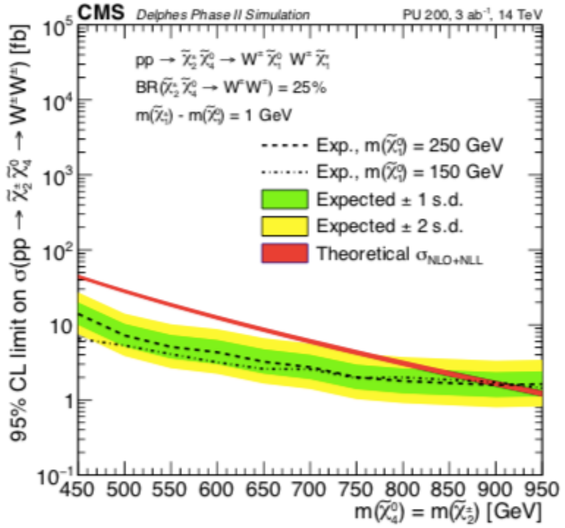






ATL-PHYS-PUB-2018-048

C1C1: C1 can be **discovered (excluded)** up to masses of **660 (840) GeV**
C1N2 to 3L+Etmiss (via WZ): C1,N2 can be **discovered (excluded)** up to **920 (1150) GeV**
C1N2 to 1L+bb+EtMiss (via Wh): C1,N2 can be **discovered (excluded)** up to **1080 (1280) GeV**
C2N4 to 2 same charge W bosons: wino-line C2,N4 can be excluded up to **900 GeV**
for both N1=150, 250 GeV

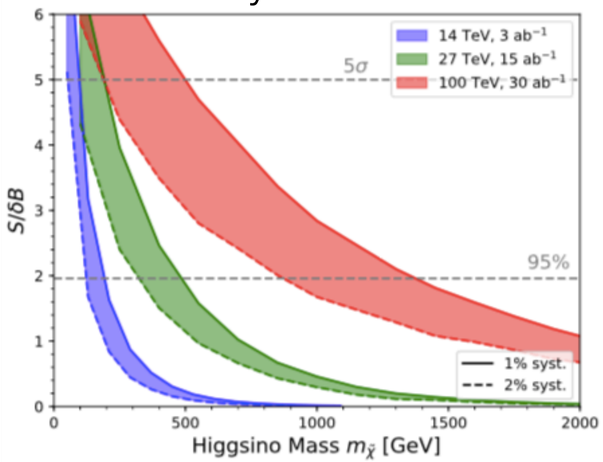


CERN-LHCC-2017-023

Searches for electroweak **SUSY** processes:
Compressed electroweakino mass spectra - Higgsino search

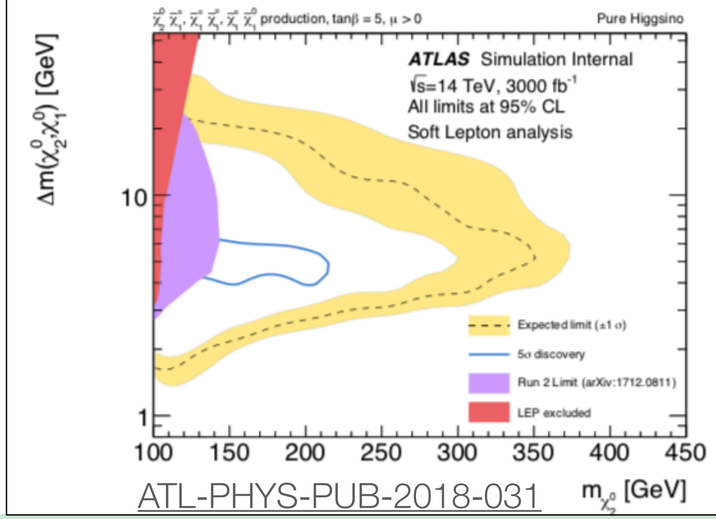
According to the level of compressness:
very low Δm - monojet search; low Δm - disappearing track (Xabier's talk); medium low Δm - soft leptons

very low Δm



arXiv:1805.00015

medium low Δm



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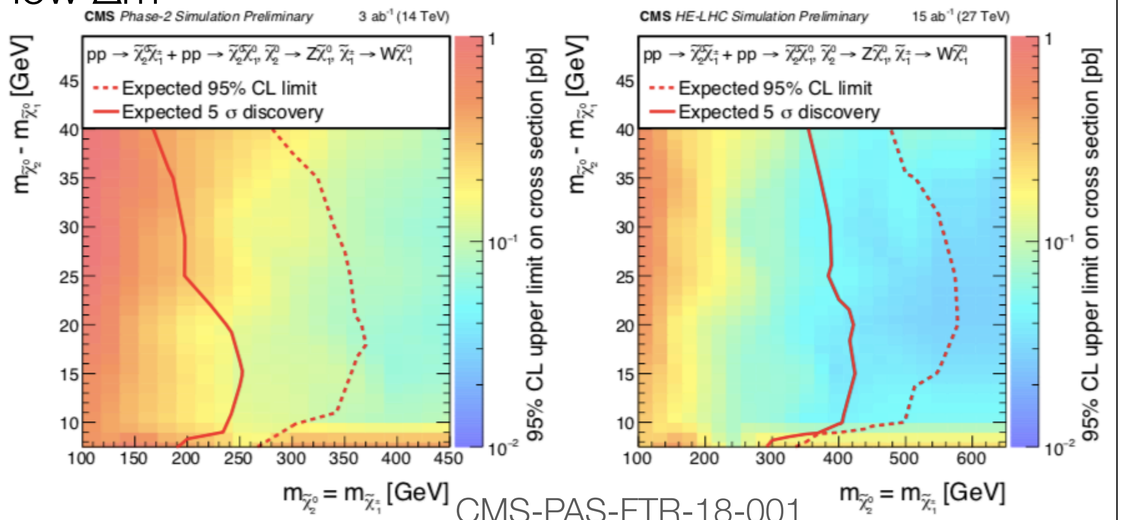


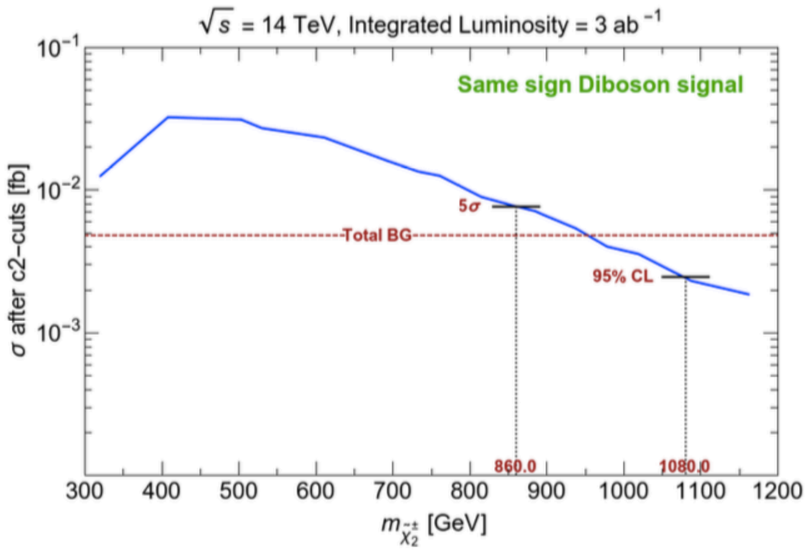
CMS-PAS-FTR-18-001

very low Δm:
Higgsino-like DM mass could be excluded up to **200 (490) GeV** at HL(HE)-LHC
medium low Δm:
C1,N2 masses **250 (360) GeV** could be **discovered (excluded)** for Δm(N2,N1)=15GeV @ HL-LHC
C1,N2 masses **420 (550) GeV** could be **discovered (excluded)** for Δm(N2,N1)=15GeV @ HE-LHC
N2 masses up to **210 (350) GeV** could be **discovered (excluded)** for Δm(N2,N1)=5GeV,
and **Δm(N2,N1) between 2 and 20** GeV for m(N2) =150 GeV @ HL-LHC

Searches for Higgsinos and Winos: *Natural* ***SUSY***

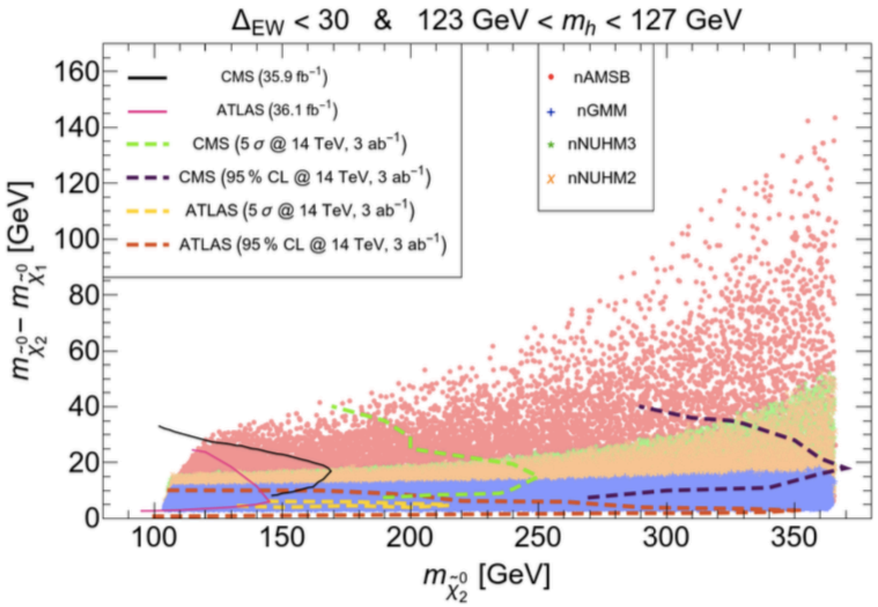
— Wino-pair production (C2N4) in models with light Higgsinos in jet-free same-sign diboson final states.

Sec 2.4.2



— N2N1j production in final states with 2 soft OS leptons.

— Scan over various natural SUSY model parameter space.

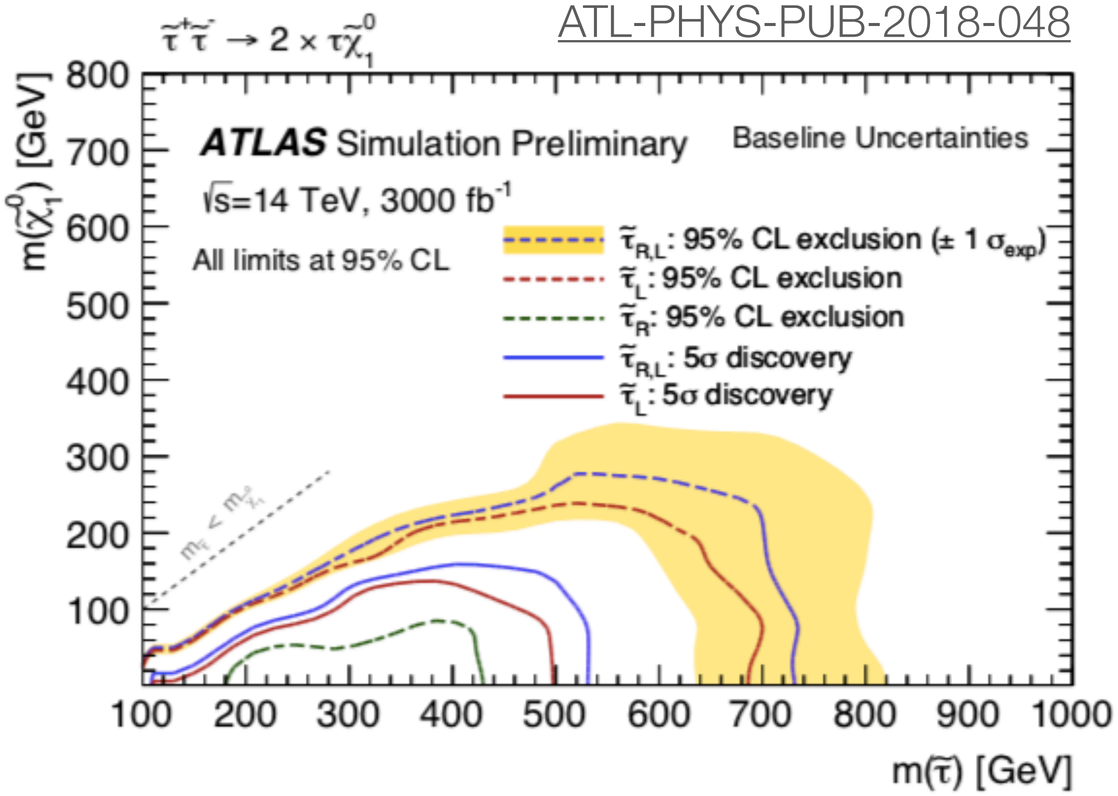


Sec 2.4.2

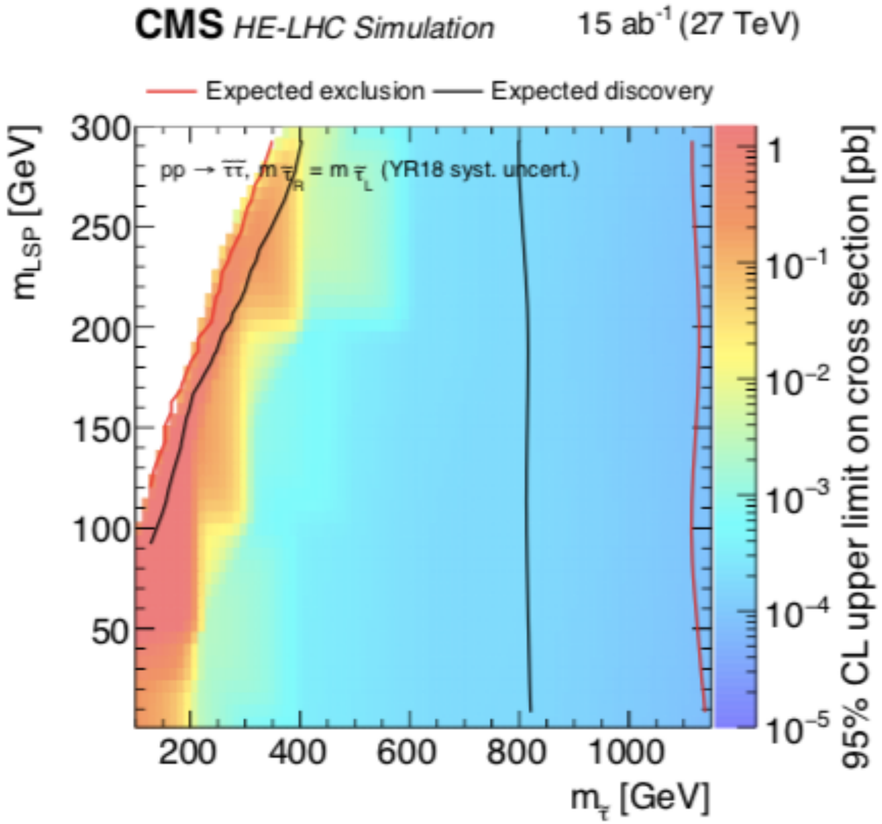
- Wino masses up to **860 (1080) GeV** could be **discovered (excluded)** @ HL-LHC
- Higgsino models: important for future searches to focus at Δm(N2,N1) region between 3-5 GeV

Searches for sleptons (**SUSY**): *Stau-pair production*

ATL-PHYS-PUB-2018-048

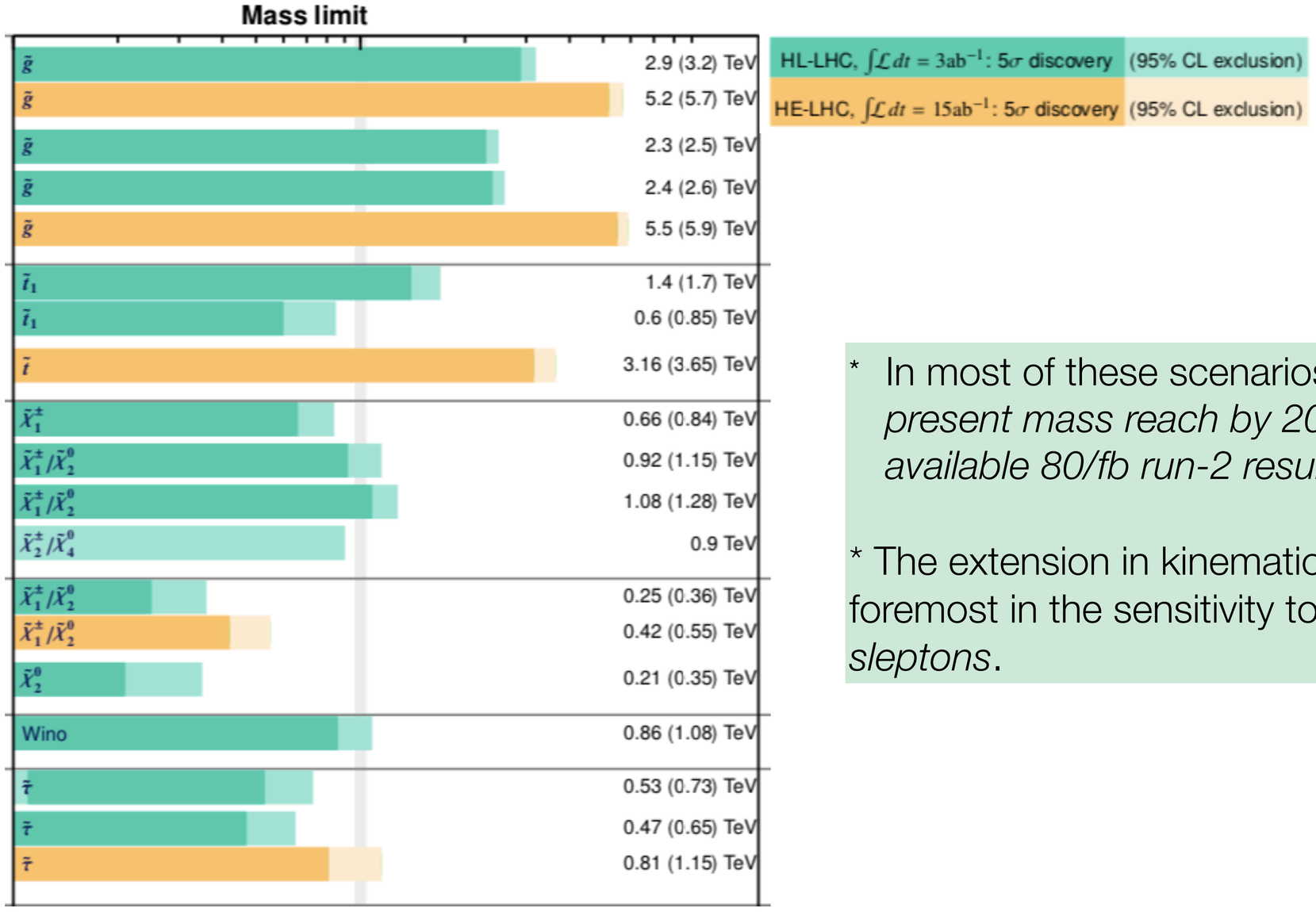


CMS-PAS-FTR-18-010



HL-LHC: Staus could be **discovered (excluded)** up to **530 (730) GeV** for combined $\tilde{\tau}_L^+ \tilde{\tau}_L^-$ and $\tilde{\tau}_R^+ \tilde{\tau}_R^-$ production
HE-LHC: Staus could be **discovered (excluded)** up to **810 (1150) GeV** for mass-degenerate scenario @ HE-LHC

Summary of the HL/HE LHC **SUSY** prospect studies:



* In most of these scenarios HL-LHC will *increase present mass reach by 20-50% (compared to available 80/fb run-2 results).*

* The extension in kinematic reach is reflected foremost in the sensitivity to *EW states, including sleptons*.

Dark Matter

— Most of the SUSY models I've shown to this point have a dark matter candidate particle.

— Dedicated DM searches: Categorise the search strategies for DM according to the visible activity:

<u>DM production in association with:</u>

- high pT jet
- heavy flavour quarks
- or through interactions with EW gauge bosons

Will report on DM + X production (X = jets, heavy flavours, photons, Z) considering simplified models as benchmark.

Other Dark matter candidates (dark photons, axions) will be in the following talks.

Dark Matter and jets: *monojet signatures*

Monojet channel (jet+EtMiss signature)

- 3 syst. uncert. scenarios: run-2, run-2/2, run-2/4.

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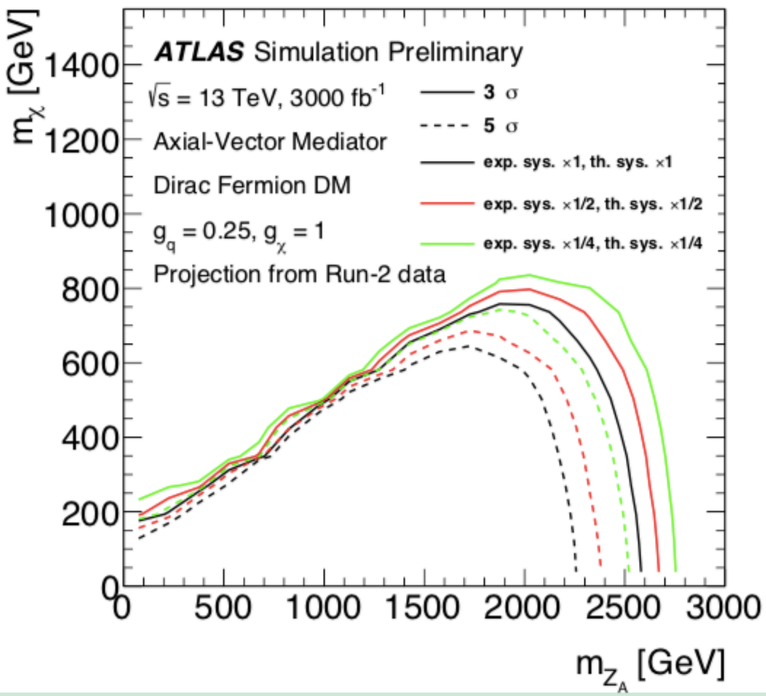
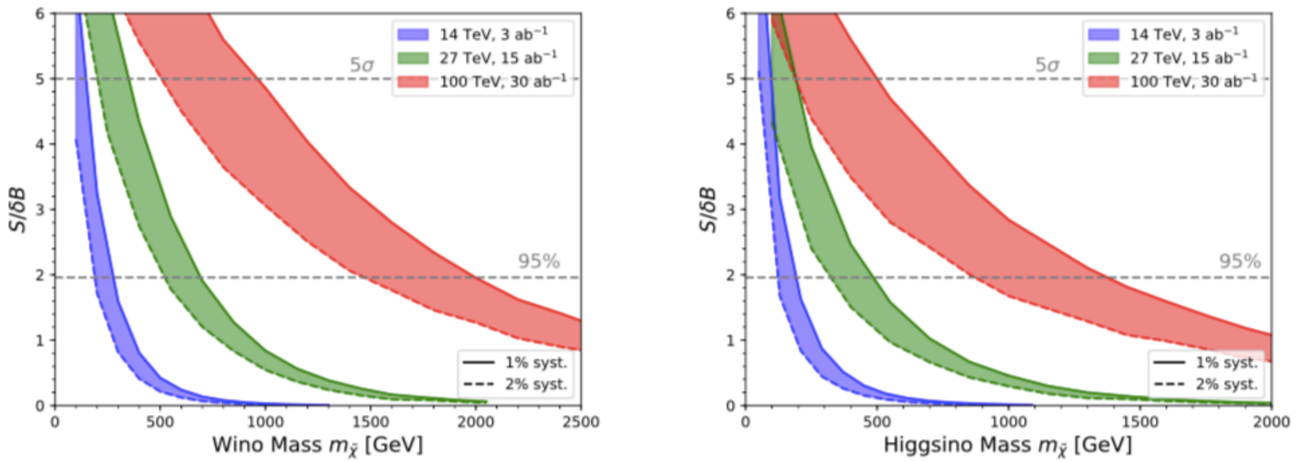


- m(Z_A) masses up to **2.25 (2.65) TeV** could be **discovered (excluded)**, for m(DM)=1 GeV.

Electroweakinos in monojet final state

- two DM scenarios: wino-like $SU(2)_L$ triplet or higgsino-like $SU(2)_L$ doublet.



95% C.L.	Wino	Higgsino
14 TeV	280 GeV	200 GeV
27 TeV	700 GeV	490 GeV
100 TeV	2 TeV	1.4 TeV

arXiv:1805.00015

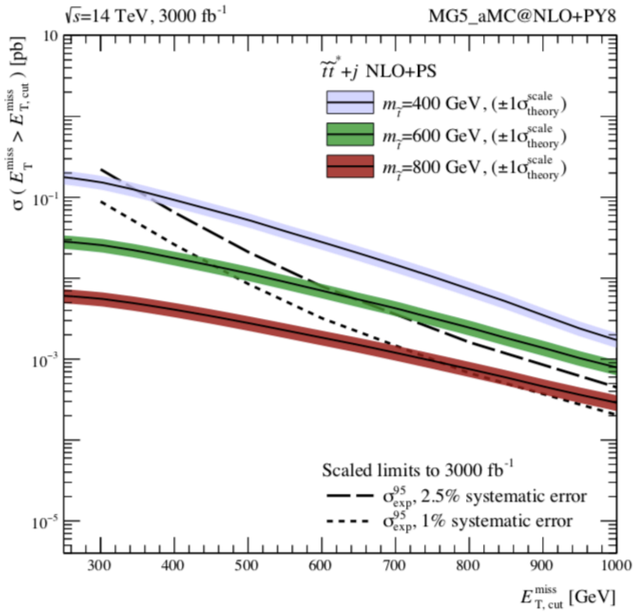
Results mainly affected by modelling uncertainties of signal and SM background processes, and jet/EtMiss scale and resolution uncertainties (experimental).

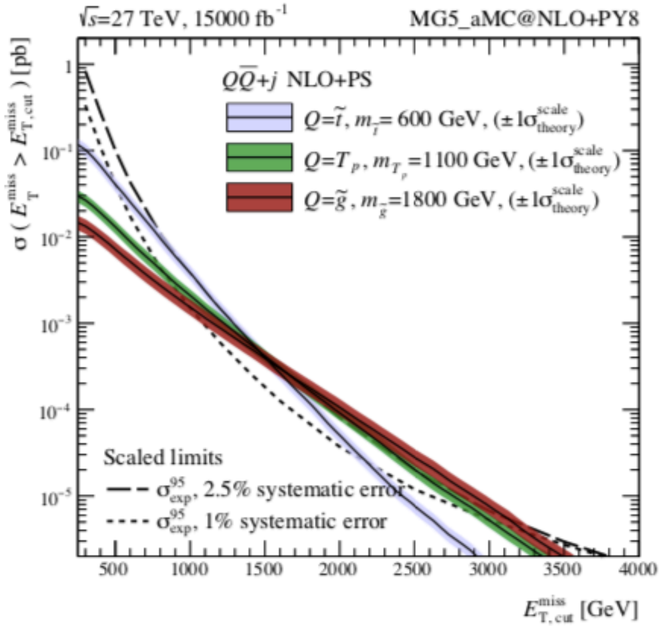
Dark Matter and jets:
monojet signatures (cont.)

Monojet signatures from heavy coloured particles:

- compressed mass spectrum scenarios where hypothetical coloured particle decays to DM+SM
- jets + (very soft leptons) + EtMiss: monojet-like topology

Particle name		Colour Rep.	Lorentz Rep.	Decay
Fermionic Top partner	(T_p)	**3**	Dirac fermion	$q + X$
Top squark	$(\tilde{t})$	**3**	Complex scalar	$t^* X \to bq\bar{q}' + X$
Gluino	$(\tilde{g})$	**8**	Majorana fermion	$q\bar{q} + X$





arXiv:1805.05346

- HL-LHC: Fermionic top partners with masses up to **800 GeV**, gluinos up to **1000 GeV**, and stops with masses up to **600 GeV** can be excluded.
- HE-LHC: with L = 3 – 15 /ab, one can probe the compressed spectra featuring fermionic top partners with masses up to **1100 GeV**, gluinos up to **1800 GeV**, and stops with masses up to **600 GeV**.

Dark Matter and Heavy Flavour:
DM + top/bottom quarks

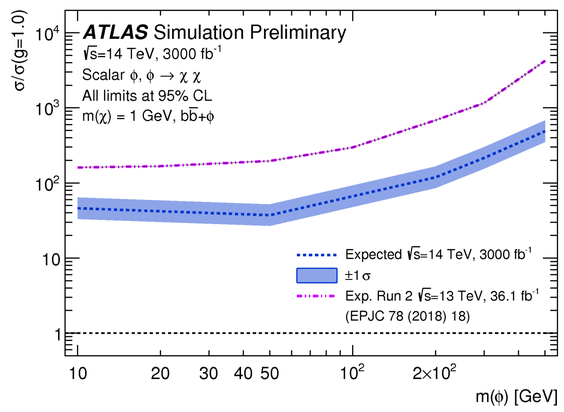
DM+tt, DM+Wt, DM+bb

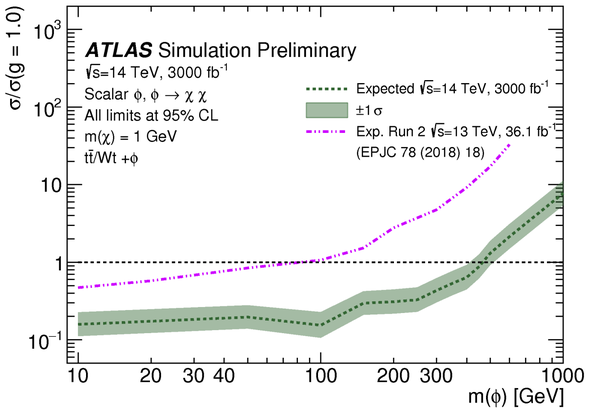
— Results converted into a limit on the spin-independent DM–nucleon scattering xsec

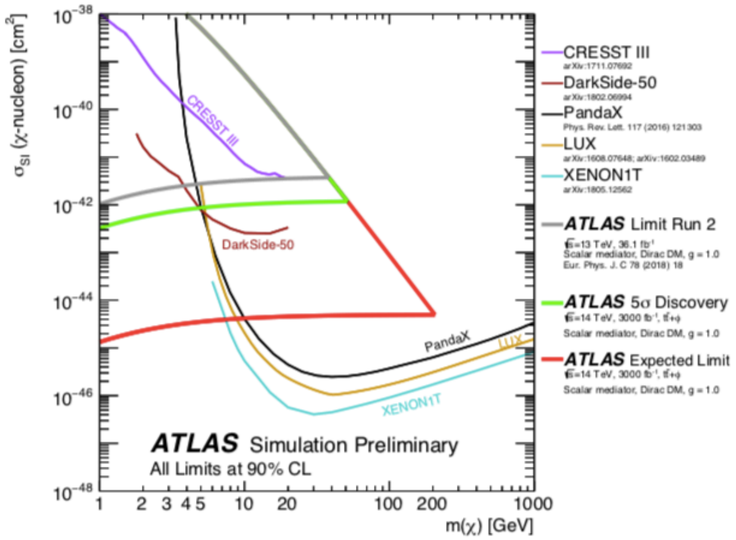
ATL-PHYS-PUB-2018-036

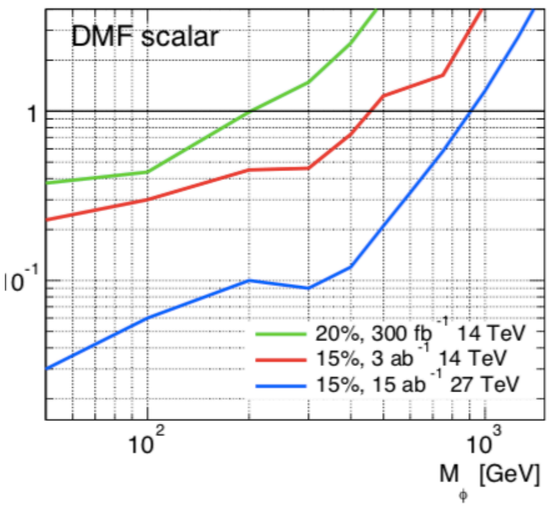
tt+EtMiss, tX+Etmiss

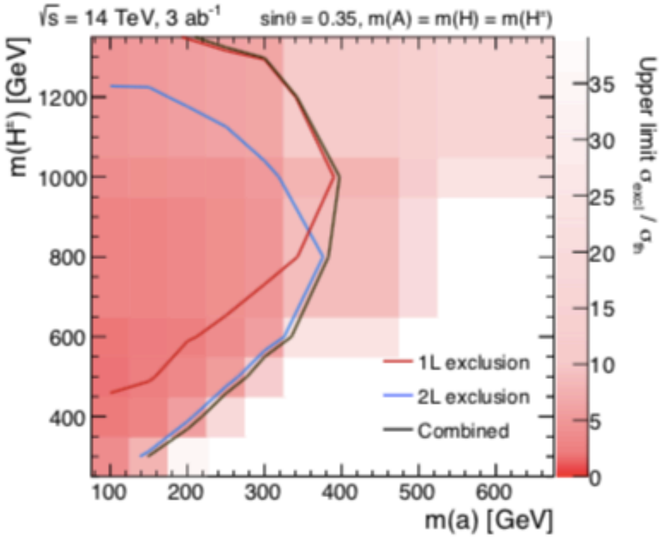
arXiv:1611.09841
arXiv:1712.03874
arXiv:1803.10379











- Exclusion limits on DMF scalar (pseudoscalar) mediators are expected to be around **450 GeV (500 GeV)** and **900 GeV (950 GeV)** at the HL-LHC and the HE-LHC
- For 2HDM+a model (tt+EtMiss), excluded masses of the 2HDM+a pseudoscalar mediator a are **m(a)<=150 GeV** (HL-LHC) and **m(a)<=350 GeV** (HE-LHC) [**400 (500) GeV** for tX+EtMiss]
- Limit on m($H^{+/-}$) and tanB also provided for 2HDM+a model

Dark Matter and Heavy Flavour:
DM + single top; Four-top signatures

DM+single top

- non-resonant production of exotic state decaying into a pair of invisible DM particle candidates in association with a right-handed top quark:
-monotop events, lep+b+EtMiss

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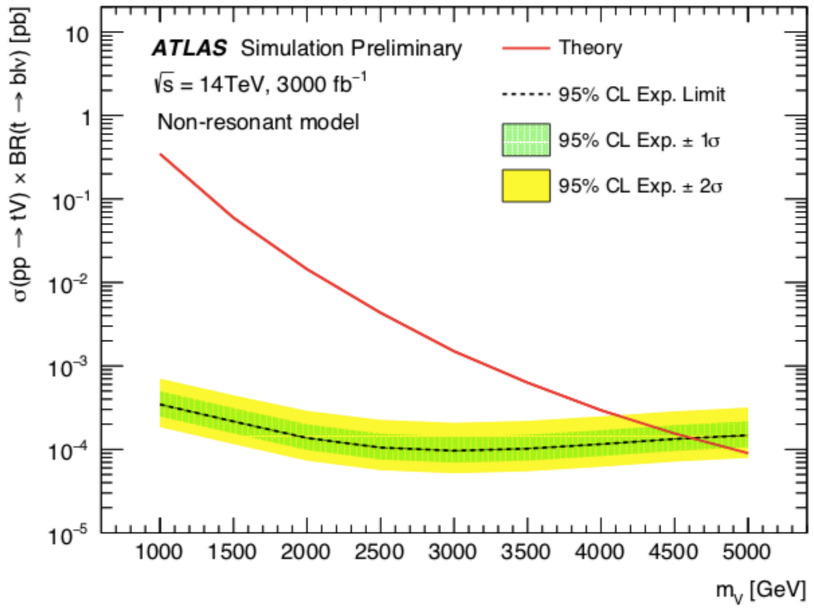

HL-LHC:The expected mass limit **4.6 TeV**; the discovery reach is **4.0 TeV**

Four-top signatures

- 2HDM+a model
- four neutral bosons can contribute to 4-top final state if masses above ttbar threashold
- m_a and sinθ sensitivity scans performed

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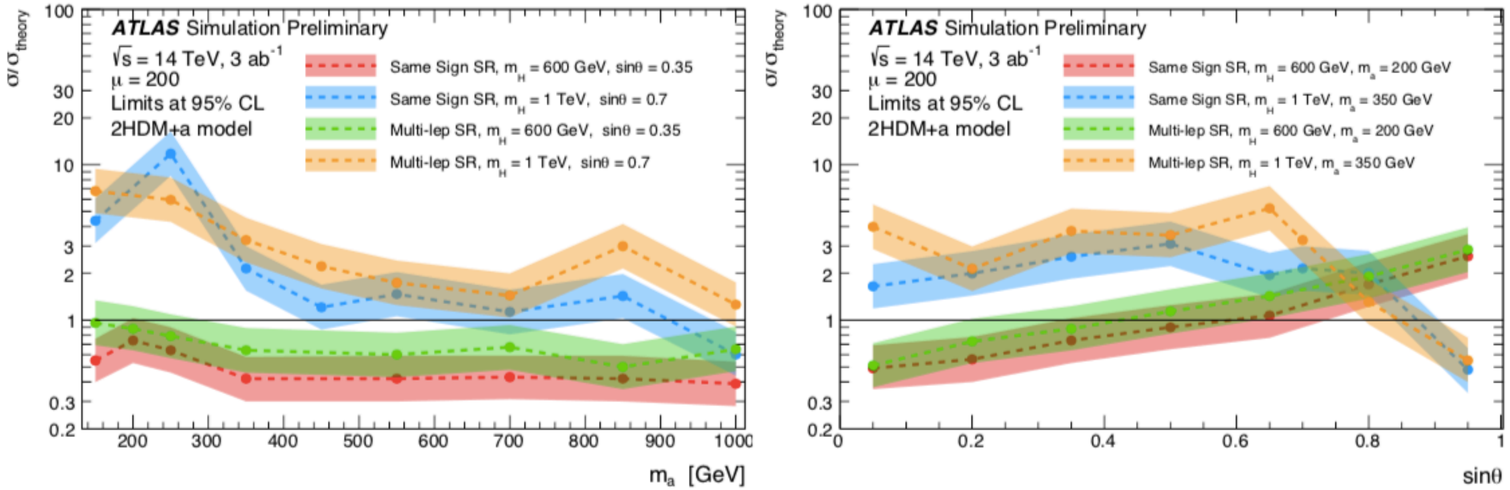


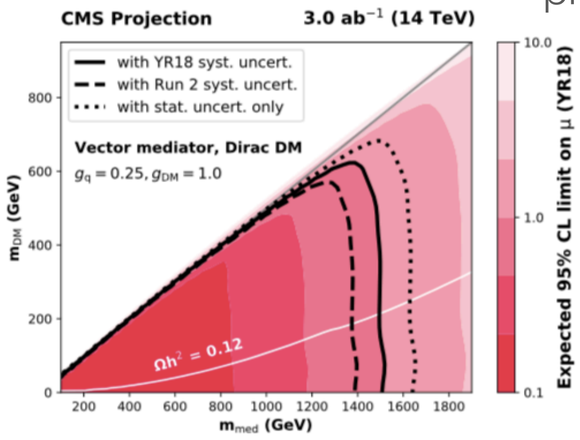
- 3σ significance is expected if **mH = 600 GeV** and **sin θ = 0.35**.
- **sin θ > 0.95** are also expected to be excluded for **ma = 350 GeV, mH = 1 TeV**
- **sin θ < 0.4** is excluded for **mH = 600 GeV, ma = 200 GeV**

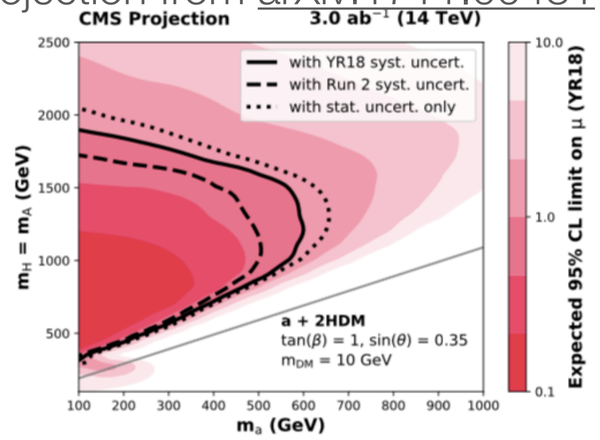
Dark Matter and EW bosons:
DM+Z boson, mono-photon and VBF+EtMiss

DM+Z boson

- minimal scenario with one new mediator boson and one new DM Dirac fermion
- 2HDM+a

projection from arXiv:1711.00431



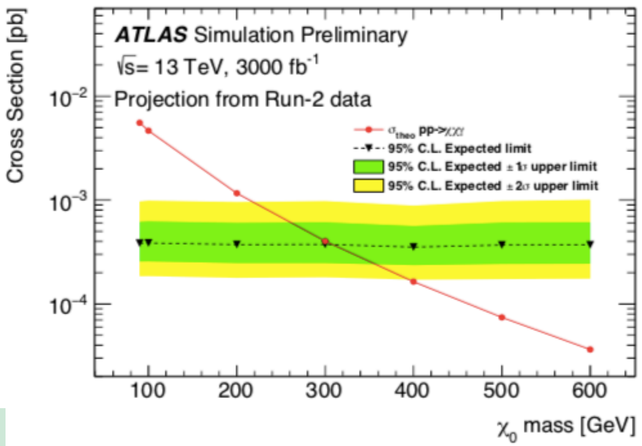


- A signal with a mediator of mass **750 GeV** could be discovered with 1 /ab, while a heavier mediator of **1 TeV** would require **3 /ab.**
- In the 2HDM+s model, light pseudoscalar masses up to **600 GeV** and heavy boson masses up to **1.9 TeV** will be probed.

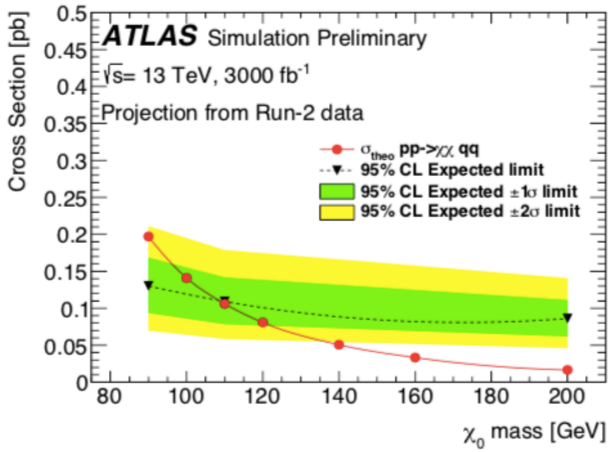
Mono-photon and VBF+EtMiss

- Model: SM extended by the addition of an EW fermionic triplet with null hypercharge

projection from arXiv:1704.03848



projection from arXiv:1809.06682

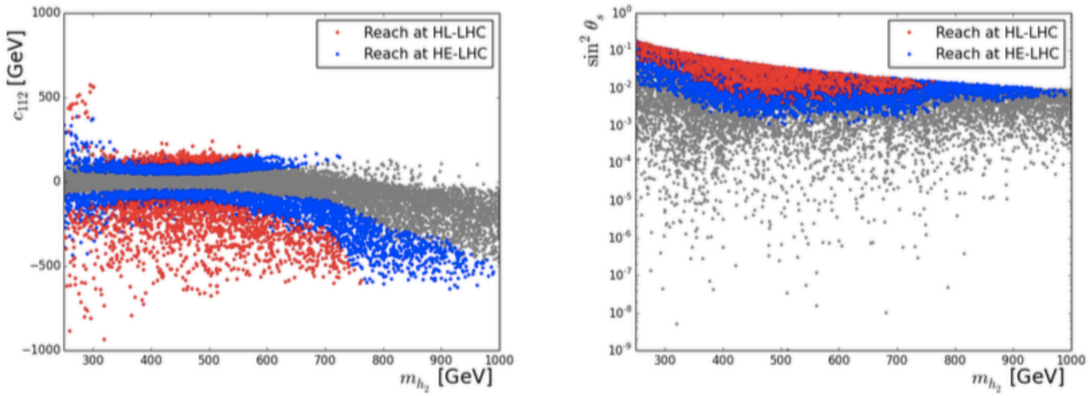


- Mono-photon: Masses of χ_0 below **310 GeV** can be excluded at 95% C.L. assuming the run-2 syst. uncert.
- VBF+EtMiss: M_χ ~ **110 GeV** can be excluded at 95% C.L.

Higgs portal **Dark Matter** models; Singlet **Dark Matter** with slepton-like partners

Higgs portal:
— Models can be categorised by the spin of DM as scalar, fermionic, or vector Higgs portal models.
— Benchmark model: Singlet Fermionic Dark Matter (SFDM)

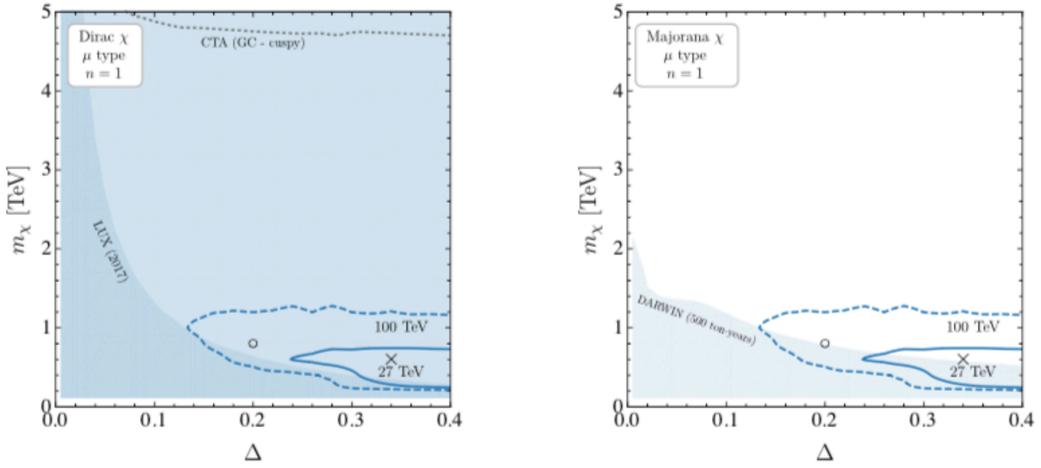
Expected parameter reach by searching for on-shell pp → h2 → h1h1 at HL-LHC (HE-LHC)



Sec 3.3.3

- HL-LHC (HE-LHC) can constrain the self-coupling parameter **|c112| up to 100 (50)**, which correspond to **sin2 θs ~ 0.004 (0.001)**.
HL-LHC can cover most of the parameter space unless |c122| is as small as ~ 5 GeV.

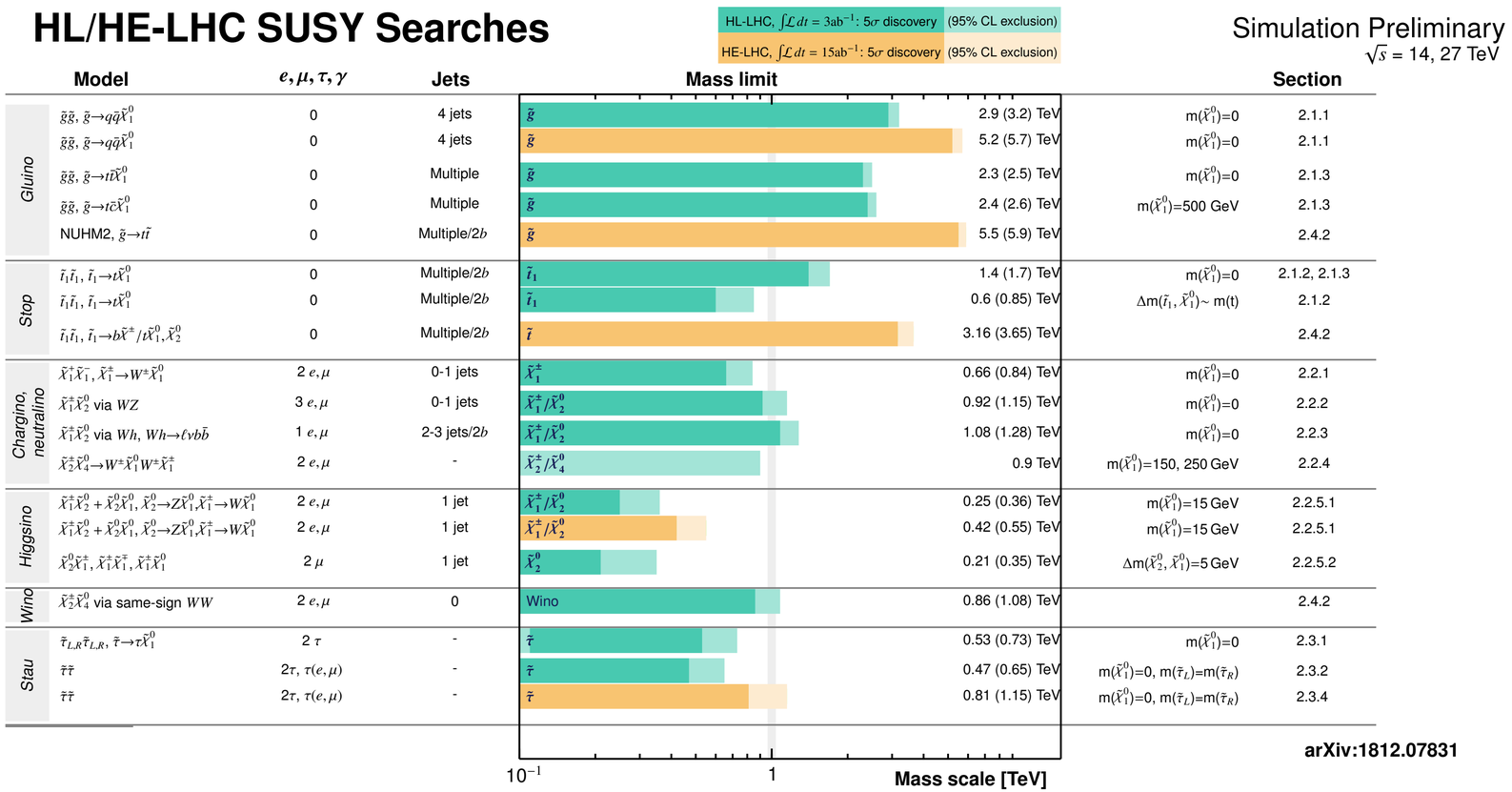
Singlet DM with lepton-like partners:
— Gauge-singlet Dirac or Majorana fermion DM which only couples to leptons



arXiv:1806.07896

- DARWIN will probe the full parameter space, while colliders will be sensitive for relatively low masses and large Δ.
- The small Δ region excluded by the existing bound from LUX.
- Future colliders are essential for probing the **large Δ region** of the parameter space

Summary



Sec 7

=> In most considered scenarios HL-LHC will increase present mass reach by 20-50%.

Dark Matter:

— HL-LHC will improve the sensitivity to mediator masses by a factor of 3 – 8 relative to the Run-2 searches with 36 /fb.

— At HE-LHC: Assuming the DM is lighter than half the mediator mass, a scalar or pseudoscalar mediator can be ruled out at 95% C.L. up to 900 GeV, a factor of 2 higher in mass compared to the HL-LHC bounds.

— HE will help excluding loads of natural scenarios.

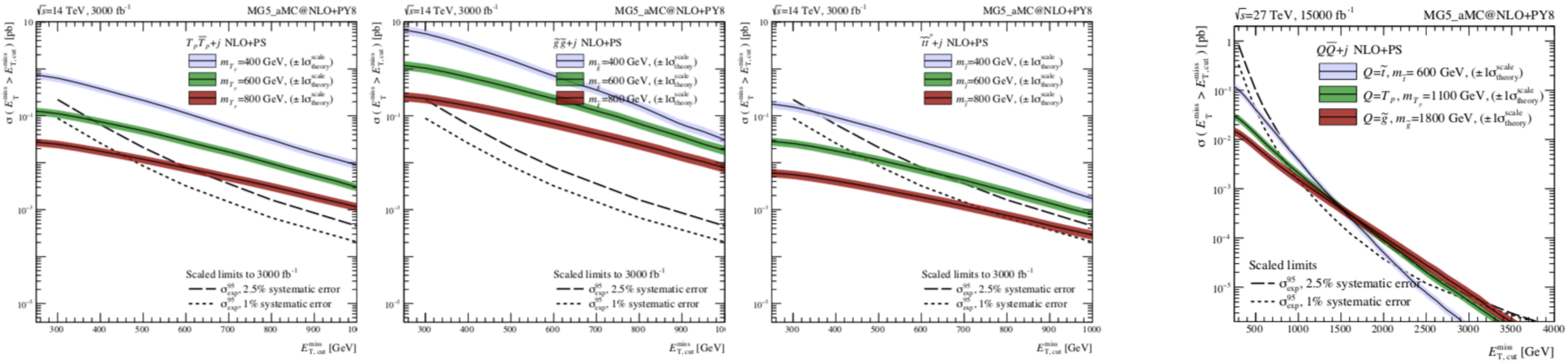
BACKUP

Dark Matter and jets:
monojet signatures (cont.)

Monojet signatures from heavy coloured particles:

- consider compressed mass spectrum scenarios where hypothetical coloured particle decays to DM+SM
- jets + (very soft leptons) + EtMiss: monojet-like topology

Particle name		Colour Rep.	Lorentz Rep.	Decay
Fermionic Top partner	(T_p)	**3**	Dirac fermion	$q + X$
Top squark	$(\tilde{t})$	**3**	Complex scalar	$t^* X \to bq\bar{q}' + X$
Gluino	$(\tilde{g})$	**8**	Majorana fermion	$q\bar{q} + X$

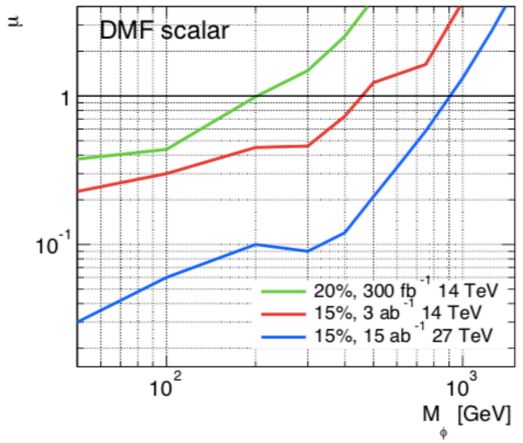


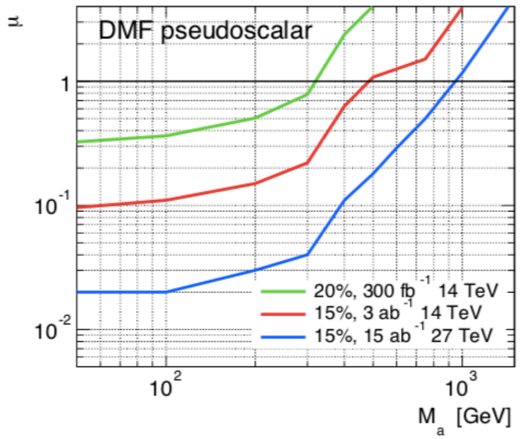
- HL-LHC: Fermionic top partners with masses up to **800 GeV**, gluinos up to **1000 GeV**, and stops with masses up to **600 GeV** can be excluded.
- HE-LHC: with L = 3 – 15 /ab, one can probe the compressed spectra featuring fermionic top partners with masses up to **1100 GeV**, gluinos up to **1800 GeV**, and stops with masses up to **600 GeV**.

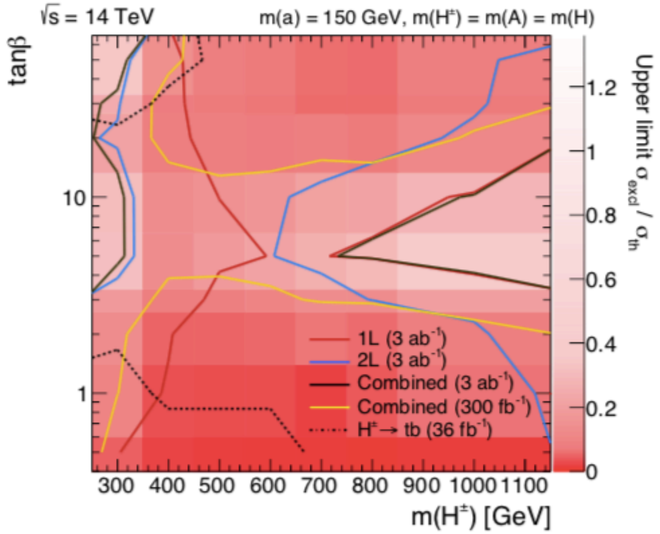
Dark Matter and Heavy Flavour:
DM + top quarks

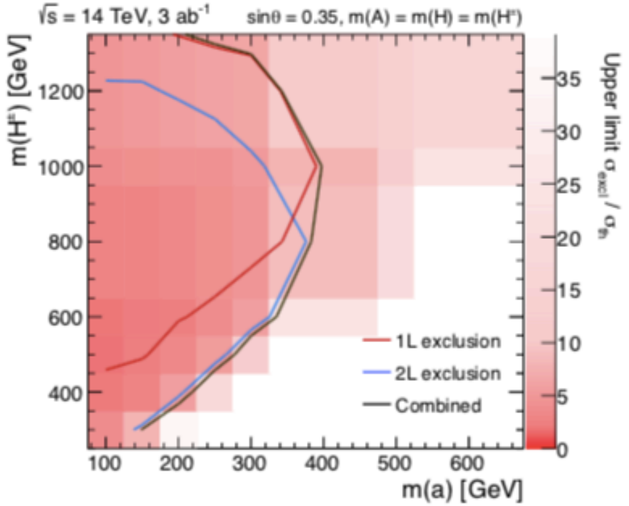
<u>tt+EtMiss, tX+Etmiss</u>

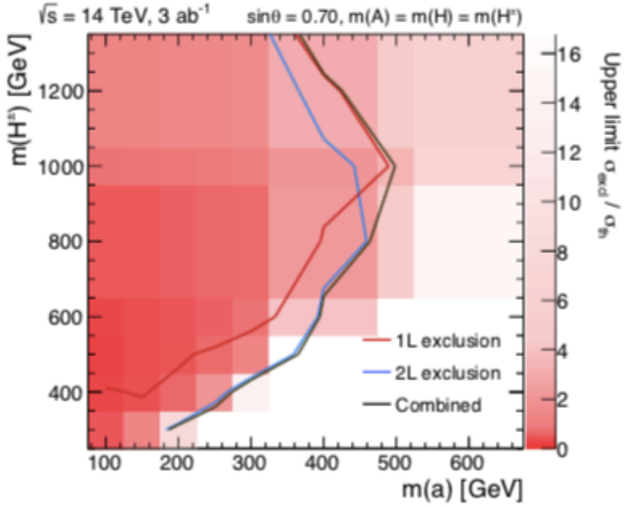
- final states with 2 leptons (tt+EtMiss) and 1 or 2 leptons (tX+EtMiss)











- Exclusion limits on DMF scalar (pseudoscalar) mediators are expected to be around **450 GeV (500 GeV)** and **900 GeV (950 GeV)** at the HL-LHC and the HE-LHC
- For 2HDM+a model, excluded masses of the 2HDM+a pseudoscalar mediator a are **m(a)<=150 GeV** (HL-LHC) and **m(a)<=350 GeV** (HE-LHC)
- Limit on m($H^{+/-}$) and tanB also provided for 2HDM+a model