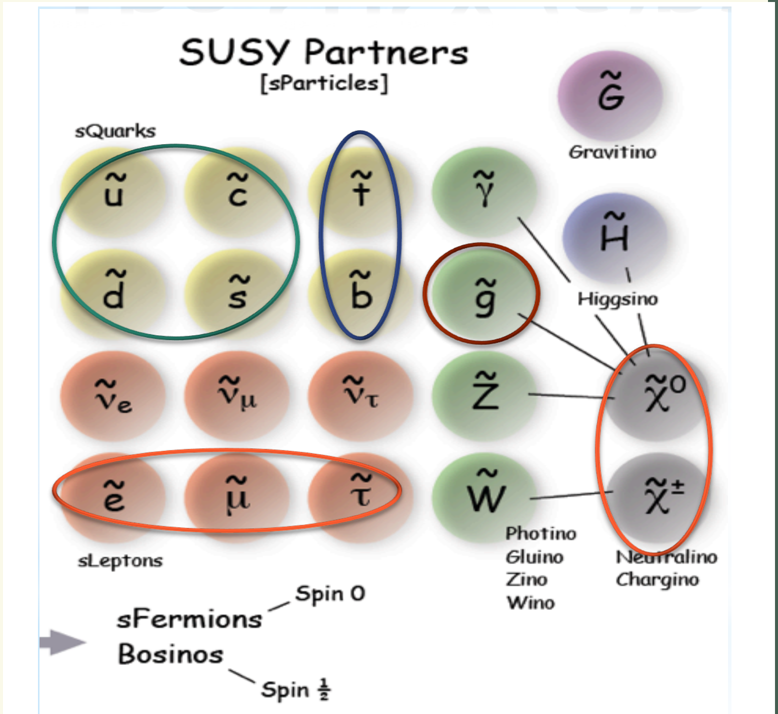

UNIVERSITY OF LIVERPOOL

SUSY studies from European Strategy process

Monica D'Onofrio
University of Liverpool

EF08-Snowmass meeting
28/5/2020

The context

- The European Strategy process culminated in the publication of the Briefing Book. Prior to that:
  - Facilities and experiments made HUGE efforts with detailed and extended submissions
  - Yellow Reports for HL- and HE-LHC were made in this spirit, as well as detailed reports from other facilities
- Preparatory groups (PPG) were put in charge to rationalise these efforts

> - The **PPG / BSM** focused on BSM at colliders, collaborating with other groups where relevant (e.g. DM)
> - One of the goals of PPG/BSM was to **compare** the exploratory power of different types of searches and/or different projects.

A joint effort by the PPG/BSM group !


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Andrea Wulzer
EWSB dynamics and resonances


Andreas Weiler
Supersymmetry


Veronica Sanz
Extended Higgs sectors & HE flavour dynamics


Gilad Perez
Feebly-interacting particles


Matthew McCullough
Dark matter at colliders


Gian Giudice
Coordination

The context (2)

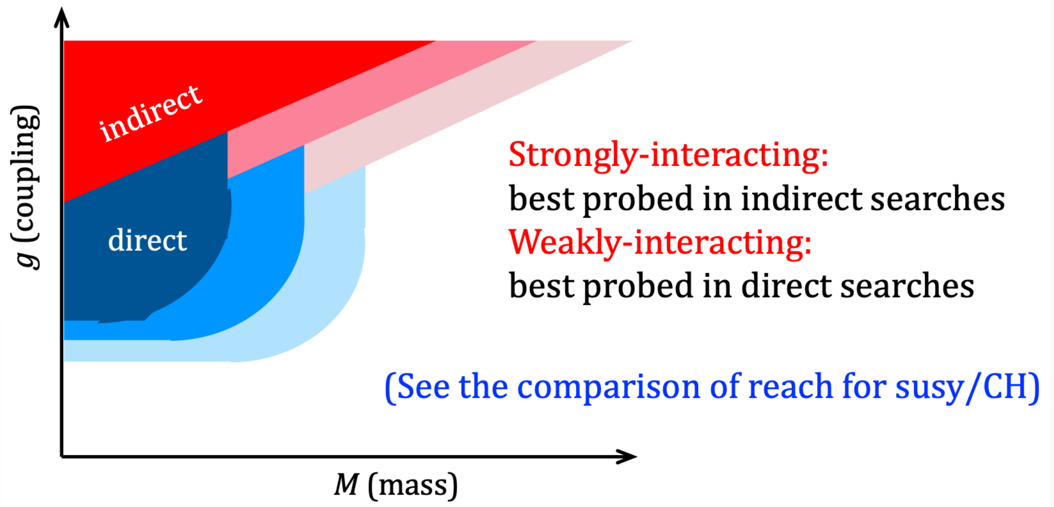
- To compare different types of searches and/or different projects is very hard to do, e.g. going beyond a model-by-model comparison.
- Three approaches have been pursued by the PPG/BSM, which allow for comparisons direct/indirect and *e+e-/pp* (under specific hypotheses):

• mapping **"classes"** of new physics into a single mass (*M*) and coupling (*g*). E.g. SUSY simplified models, feebly interacting particles benchmarks..

• Follow principles, e.g. **naturalness** as it provides a robust guidance (under specific hypotheses) for comparing quantitatively the exploratory power of different experimental programs: Higgs couplings / EW precision data / direct searches.

• Focus on **Dark Matter WIMP**, that provides a framework (under specific hypotheses) for quantitative comparison.

From G. Giudice discussion slides, Granada 2019



Very difficult to find other ways of presenting global quantitative comparisons

Outline

- Many variants to be considered (MSSM, NMSSM, gauge mediation, stealth …)
  - **Phenomenology depends on the model and on the sparticle mass hierarchy**
- As indication of the potential for various experiments/facilities, consider **benchmarks**
  - Strong production (**gluinos**, 1st and 2nd generation squarks, **top squarks**): dominated by hadron colliders, interplay with experiments devoted to feebly interacting particles and with lepton colliders in case of 'compressed' scenarios.
  - Weak production (**charginos, neutralinos, sleptons**): complementarities among colliders especially in 'compressed' scenarios.
- Targeted signatures depend on assumptions. In the following, we consider:
  - R-parity conserving SUSY: characterised by the presence of missing transverse momentum (E_T^{Miss}); lightest neutralino is the LSP in most cases. Role of EWK-sector mixing highlighted (bino/wino/higgsino) where relevant.
  - R-parity violating SUSY OR highly compressed SUSY spectra: leading to feebly interacting or non-prompt signatures; specialised techniques are used → Examples in back up

sources and discussions

- In this talk, **I will mostly focus on the experimental aspects**
  - SUSY experiments: https://indico.cern.ch/event/808335/contributions/3366289/
- More on the theory implications and on the overall theory discussions in
  - SUSY theory: https://indico.cern.ch/event/808335/contributions/3365251/
  - Discussion sessions - joined with EWSB dynamics and resonances and extended higgs sector: https://indico.cern.ch/event/808335/contributions/3372668/attachments/1844551/3025820/BSM_Discussion-Triplet.pdf

EWSB dynamics and resonances

1. Which is the best way to find new interactions/particles around or above the electroweak scale using high-energy probes?
2. How can we tell whether the Higgs is composite (or not)?

Supersymmetry

1. If nature is supersymmetric, which masses of strongly- or weakly-interacting super-partners can we reach?
2. Can we see signs of gauge coupling unification?
3. Is nature fundamentally fine-tuned?

Extended Higgs sectors & HE flavour dynamics

1. Is the Higgs sector minimal?
2. Could the EW phase transition be strong 1^{st} order?
3. Could we understand the UV origin of flavor with colliders?

Given the large amount of material, impossible to cover in 20 min, I will go fast on details and focus on lessons learned

Facilities and assumptions

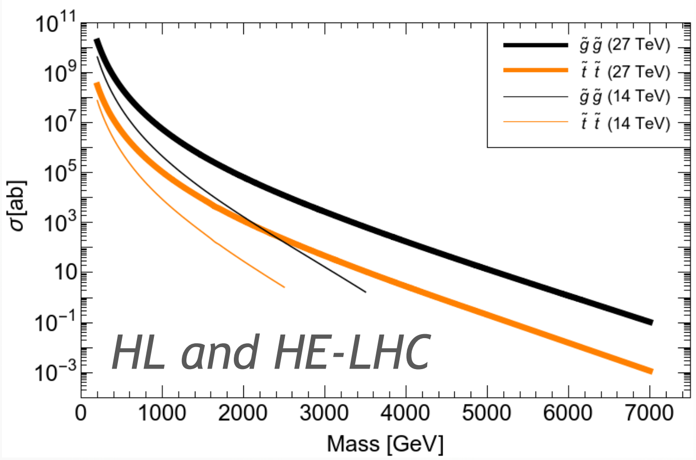
(arXiV:1905.03764)

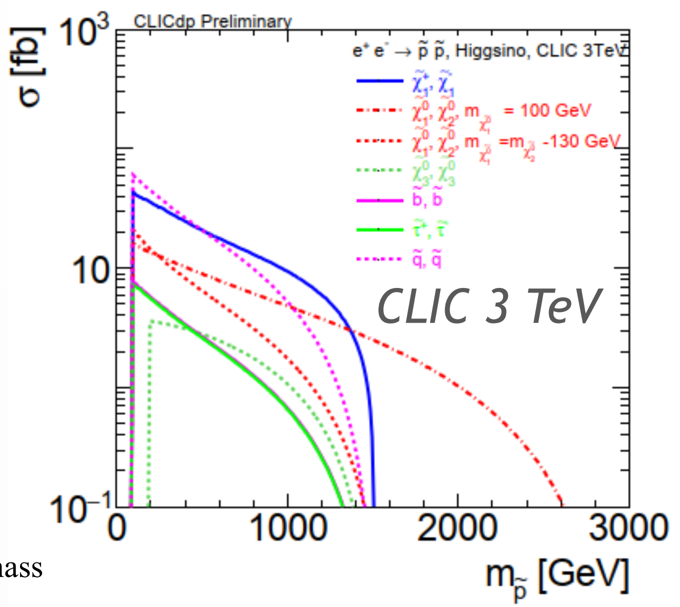
- Studies from: HL-LHC, HE-LHC, FCC (ee/eh/hh), LHeC, ILC500, CLIC (1.5 and 3 TeV), MATHUSLA
  - Potential of muon / very high-energy lepton colliders outlined separately as more speculative
- e+e- facilities with c.o.m. below ~350 GeV not directly considered
  - Limited potential for discovery of low-mass SUSY given current LHC results

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\rm inst}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]
HL-LHC	pp	14 TeV	-	2	5	6.0	12
HE-LHC	pp	27 TeV	-	2	16	15.0	20
FCC-hh	pp	100 TeV	-	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5
							(+1)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5
							(+1)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8
							(+4)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25

+MATHUSLA: to be matched with HL-LHC

Examples of production x-sections





uncertainties on PDF as high as 60% for gluinos at high mass

NOTE(1): In some cases, results with a reduced datasets wrt benchmarks are used

NOTE(2): HL/HE/FCC-hh results refer to a **single experiment** unless differently stated

Foreword: methodologies

The results considered in the ES process used different approaches

- Care must be taken when comparing simple projections with full analyses e.g. from experiments and/or in published papers
- In addition to the available material in submitted documents, collaborations and experiments have provided follow-up results in response to our questions
  - Several results were unpublished and/or resulting from discussions with experiments/facilities
- Examples of studies:
  - Full analysis with parameterized detector performance
  - Parton-level studies with (sometimes) simplistic rescaling by response-functions
  - Projections based on other facilities: e.g. current LHC searches or HL-LHC studies used for some of the HE and FCC-hh results where not available
- Assumptions on systematic uncertainties, detector performances, contributions from rare background might be very relevant
- Summary plots are presented considering 95% CL exclusions
- **A number of comments were made about discovery vs characterization at pp and ee → a route which can be perhaps followed up within Snowmass !**

RPC Gluinos: HL and HE-LHC

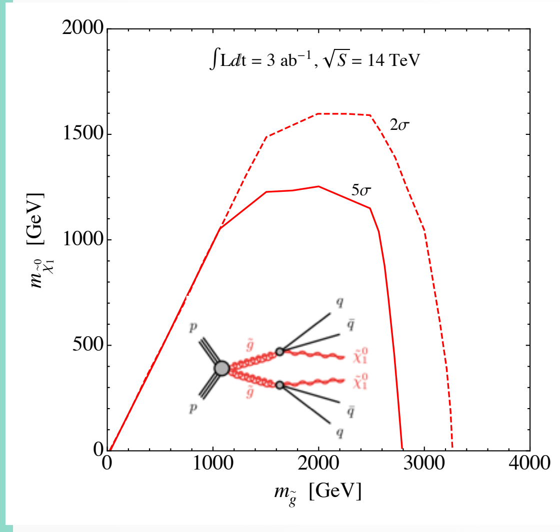
https://arxiv.org/pdf/1812.07831.pdf

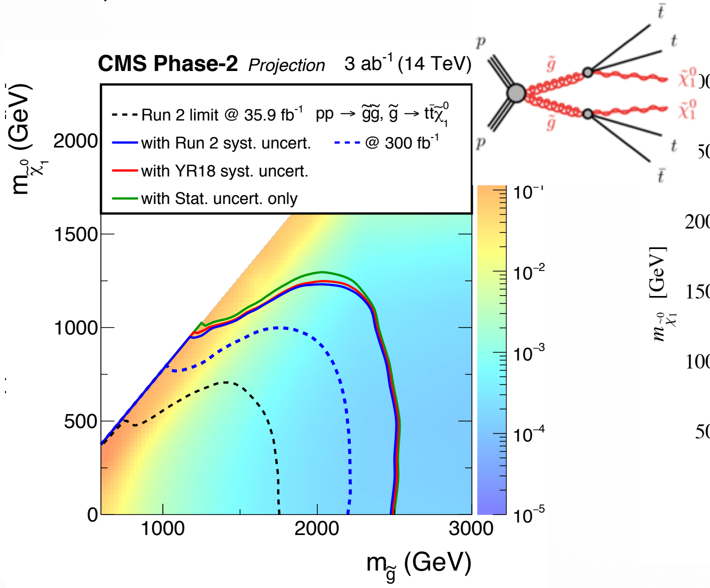
	Model	e, μ, τ, γ	Jets	Mass limit		
Gluino	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	4 jets	$\tilde{g}$	2.9 (3.2) TeV	m($\tilde{\chi}_1^0$)=0
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	4 jets	$\tilde{g}$	5.2 (5.7) TeV	m($\tilde{\chi}_1^0$)=0
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	Multiple	$\tilde{g}$	2.3 (2.5) TeV	m($\tilde{\chi}_1^0$)=0
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{c}\tilde{\chi}_1^0$	0	Multiple	$\tilde{g}$	2.4 (2.6) TeV	m($\tilde{\chi}_1^0$)=500 GeV
	NUHM2, $\tilde{g}\to t\tilde{t}$	0	Multiple/2b	$\tilde{g}$	5.5 (5.9) TeV	

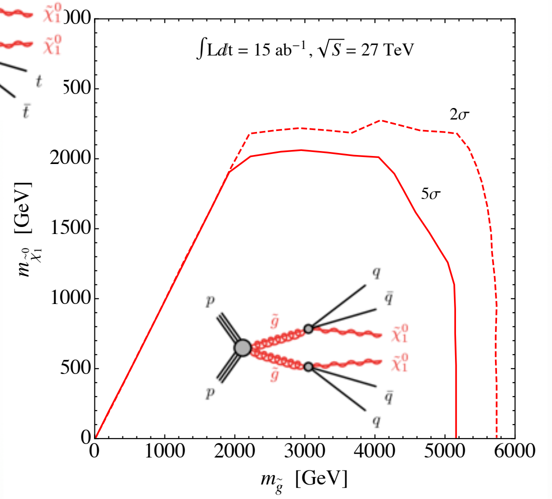
HL-LHC, $\int\mathcal{L}\,dt$ = 3ab^{-1}: 5σ discovery (95% CL exclusion)
HE-LHC, $\int\mathcal{L}\,dt$ = 15ab^{-1}: 5σ discovery (95% CL exclusion)

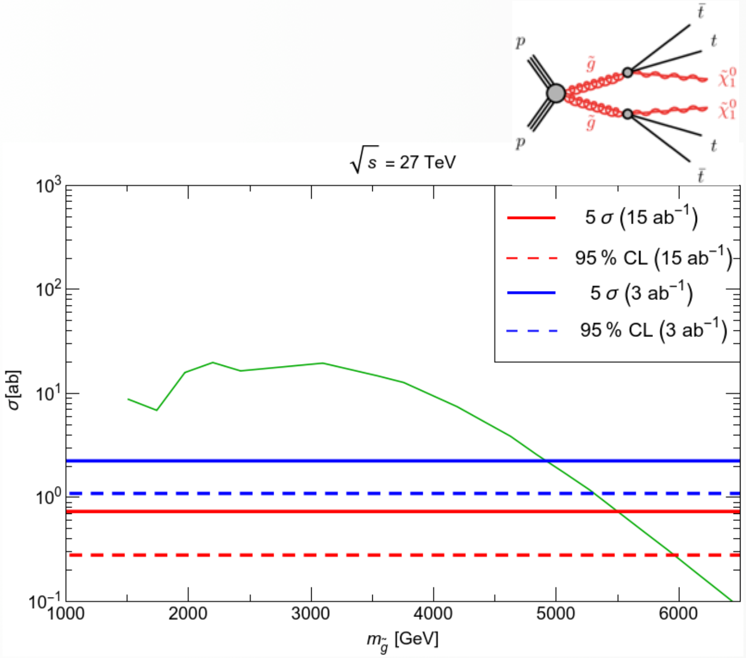
- At the **HL-LHC,** exclusion 3.2 TeV (qqχ^0), 2.5 TeV (ttχ^0), 2.6 TeV (tcχ^0)
- At the **HE-LHC:** exclusion 5.7 TeV (qqχ^0), 5.5 TeV in natural scenarios
  - Valid for low χ^0 mass; reach deteriorates when increasing m(N1)

Searches: **Jets(+b/lepton)+E$_T^{Miss}$**
Discovery potential: **~500 GeV _lower_ than exclusion**



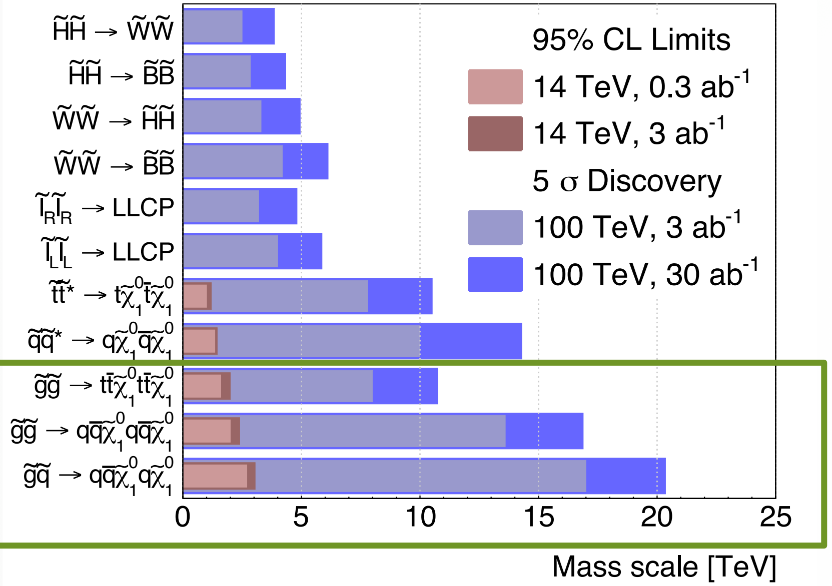






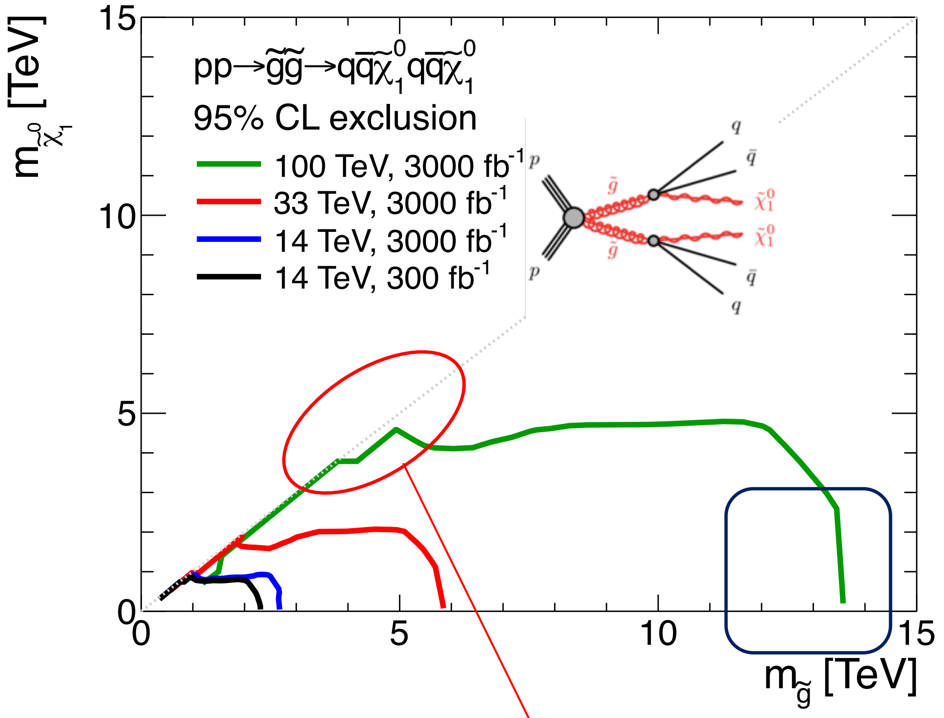
RPC Gluinos: FCC-hh

- max reach 15-20 TeV with 30/ab



- Compressed SUSY: **monojet studies**
  - $\Delta M = m_{gl} - m_{LSP} = 10$ GeV
  - Conservative as based on 8 TeV results
  - Improvements on SM background estimates and uncertainties achieved in Run 2 analysis not taken into account

Searches: Jets(+b/lepton)+E_T^{Miss}
Discovery potential: ~ 1 TeV lower than exclusion



Reach from **13 TeV → 17 TeV** with factor of 10 luminosity

Projections using CollidérReachTool :
HL → 1.5 TeV; HE → 2.6 TeV; **FCC-hh: 7.5 TeV**

RPC gluinos: summary

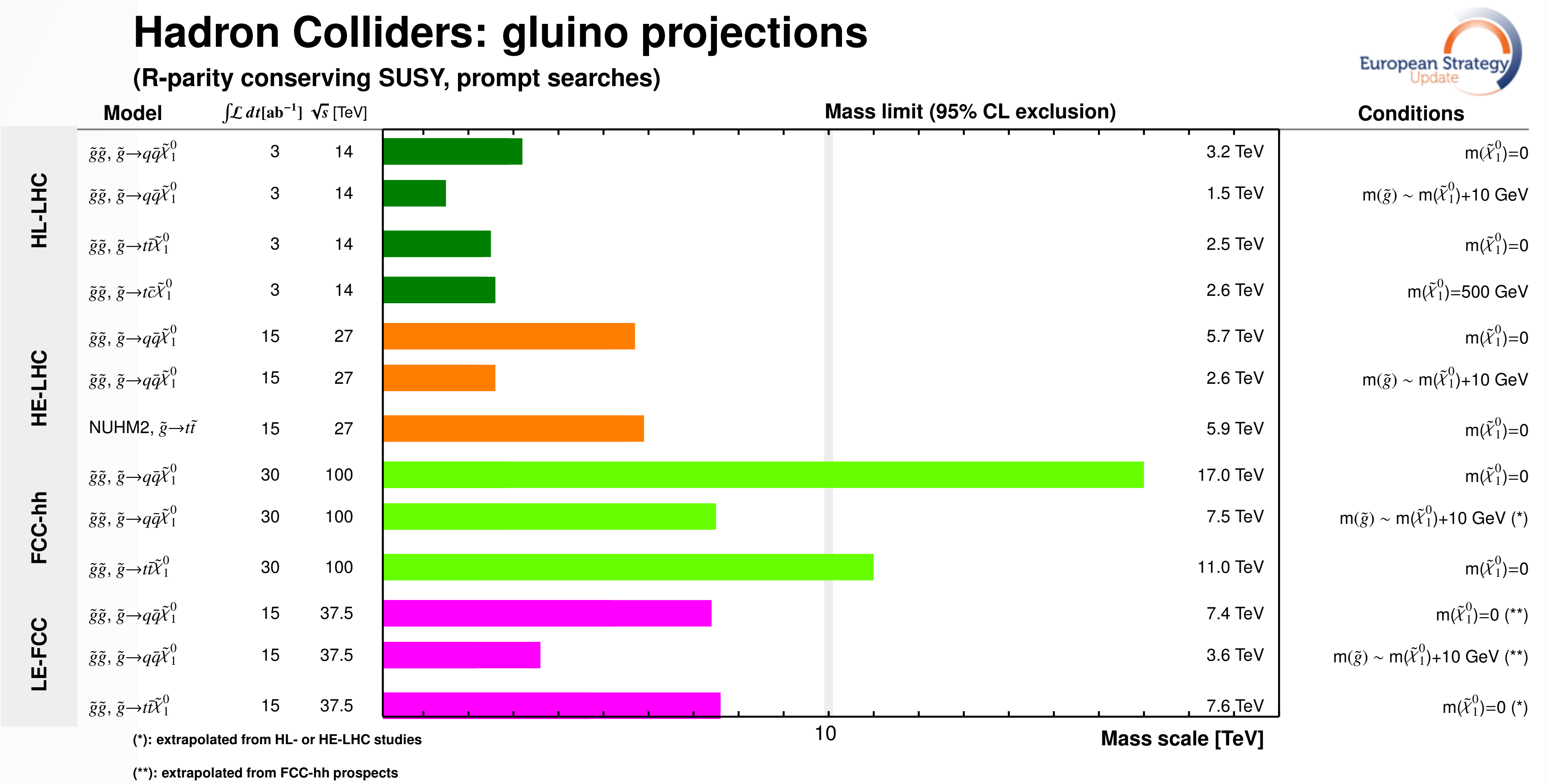


Fig. 8.6: Gluino exclusion reach of different hadron colliders: HL- and HE-LHC [443], and FCC-hh [139, 448]. Results for low-energy FCC-hh are obtained with a simple extrapolation.

(*) indicates projection using parton lumi rescaling (ColliderReachTool)

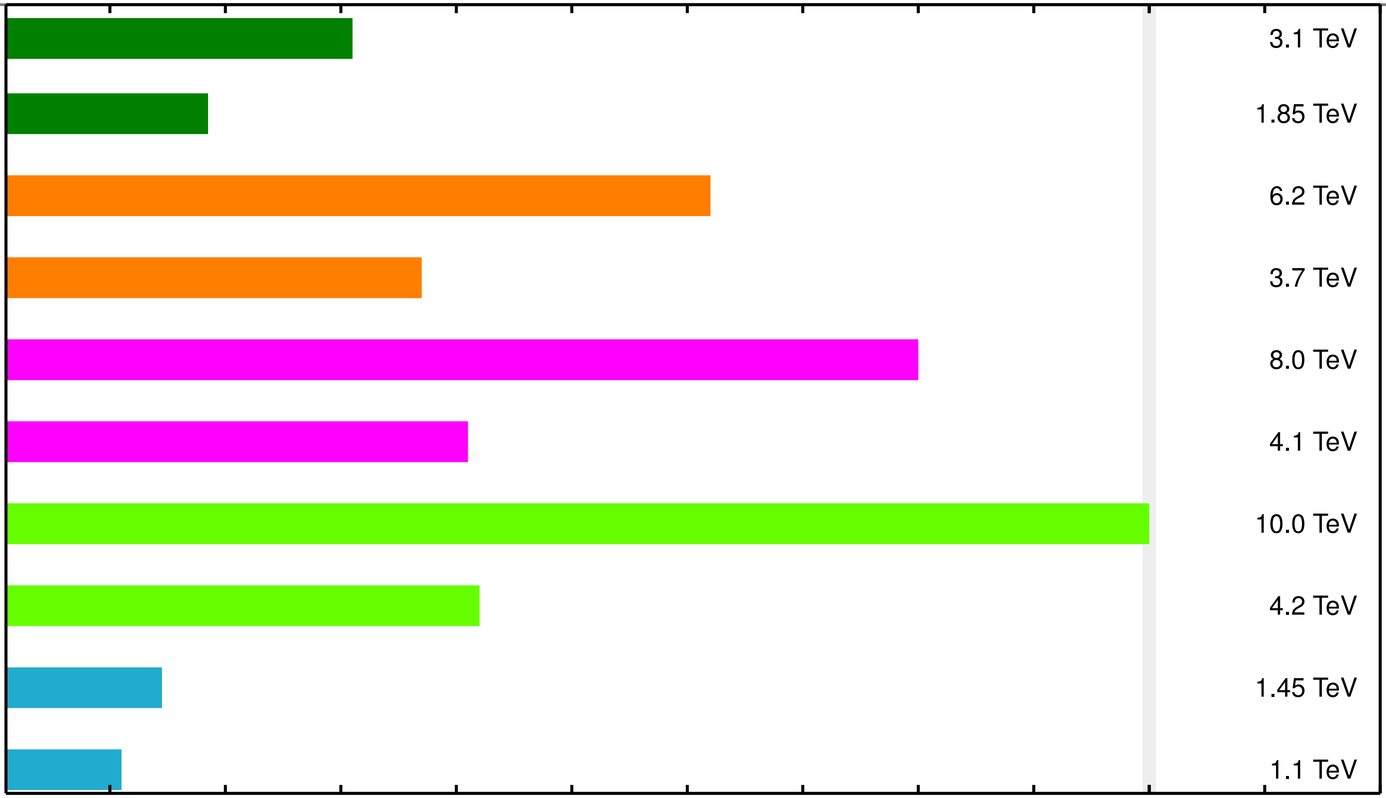
Summary of 1st and 2nd generation squarks

All Colliders: squark projections

(R-parity conserving SUSY, prompt searches)

European Strategy Update

Collider	Model	$\int \mathcal{L}\, dt [\mathrm{ab}^{-1}]$	$\sqrt{s}$ [TeV]	Mass limit (95% CL exclusion)	Conditions
HL-LHC	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	3	14	3.1 TeV	m($\tilde{\chi}_1^0$)=0 (*)
HL-LHC	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	3	14	1.85 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+5 GeV (*)
HE-LHC	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	15	27	6.2 TeV	m($\tilde{\chi}_1^0$)=0 (*)
HE-LHC	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	15	27	3.7 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+5 GeV (*)
LE-FCC	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	15	37.5	8.0 TeV	m($\tilde{\chi}_1^0$)=0 (*)
LE-FCC	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	15	37.5	4.1 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+5 GeV (*)
FCC-hh	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	30	100	10.0 TeV	m($\tilde{\chi}_1^0$)=0
FCC-hh	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	30	100	4.2 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+10 GeV (**)
CLIC_{3000}	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	5	3.0	1.45 TeV	m($\tilde{\chi}_1^0$)=0
CLIC_{3000}	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	5	3.0	1.1 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+50 GeV



(*): extrapolated from Run 2, 36/fb studies

(**): monojet results not included

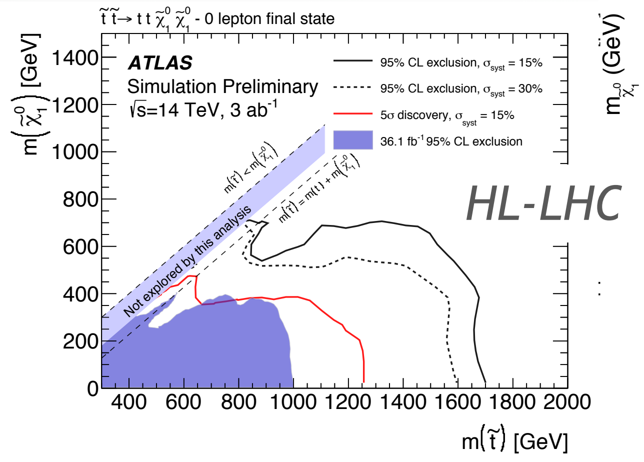
Lessons learned: gluinos and 1st / 2nd generation squarks

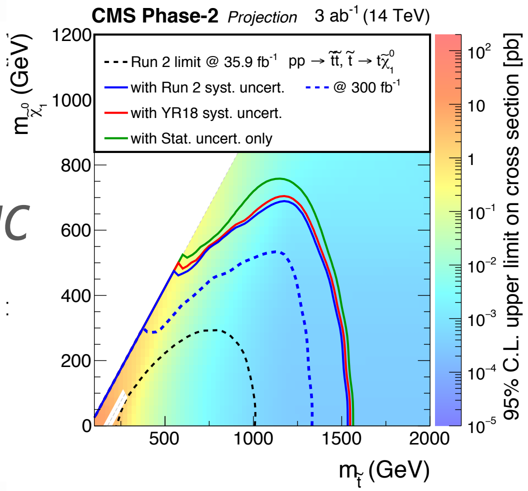
- Not much to be done on prospects for gluinos and 1st / 2nd generation squarks
  - although more dedicated analyses might push the boundaries further, it is clear that hadron colliders are the only players - unless new models are suggested which might evade constraints?
- Characterisations of possible hints for strongly produced particles at HL-LHC might be performed at FCC-hh (or HE-LHC, if that is considered a still valuable option)
  - In this respect, impact of PDF uncertainties on predictions might be relevant for gluinos
- Additional studies for long-lived scenarios involving gluinos are a separate matter
  - see later in these slides

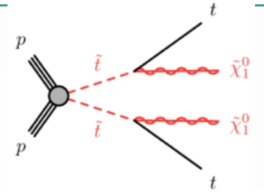
Top squarks: Hadron collider prospects

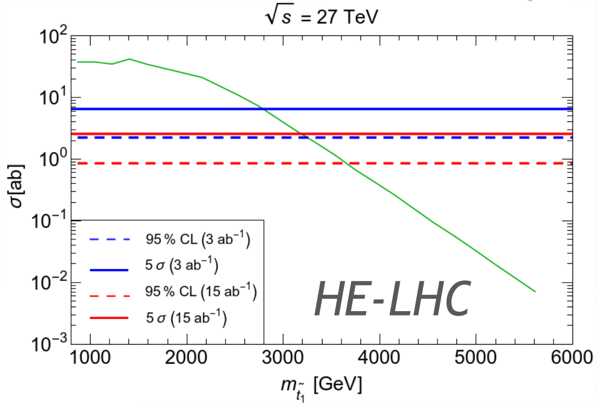
- Analyses for large and medium ΔM (stop, N1)

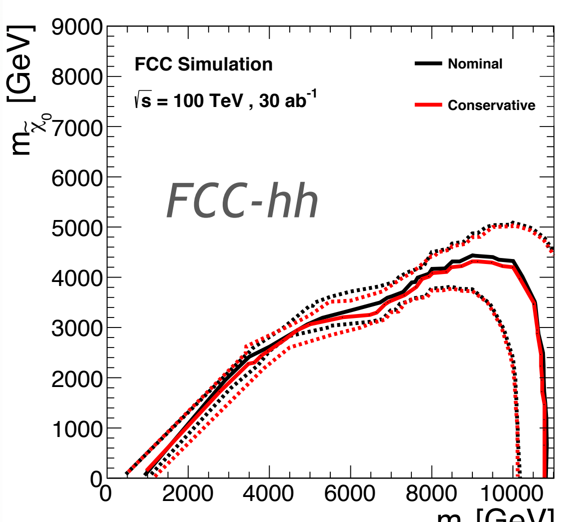
https://arxiv.org/pdf/1812.07831.pdf







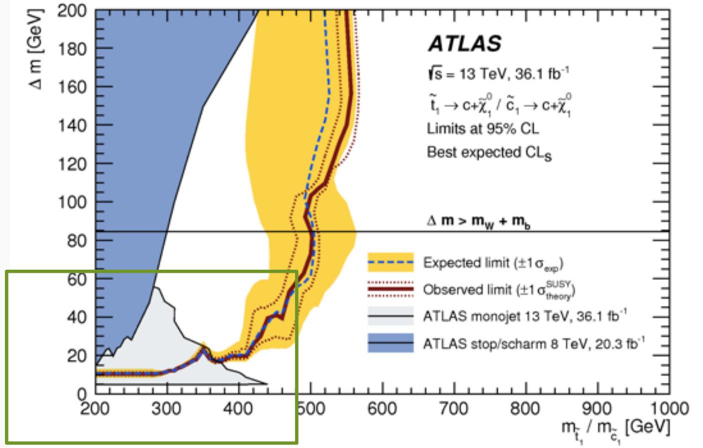




CERN-ACC-2018-0056.pdf

- Compressed scenarios, small ΔM = m_{stop} – m_{LSP} :

JHEP 09 (2018) 050



Good potential from analyses:
(1) **monojet** (ΔM ~ 2 – 10 GeV) →
(2) soft leptons

Projections with ColliderReachTool:
HL-LHC → 0.95 TeV;
[confirmed by theorists' studies]
HE-LHC → 2 TeV;
FCC-hh → 5 TeV

→ Might be conservative: e.g. recoil-jet pt thresholds can be adjusted

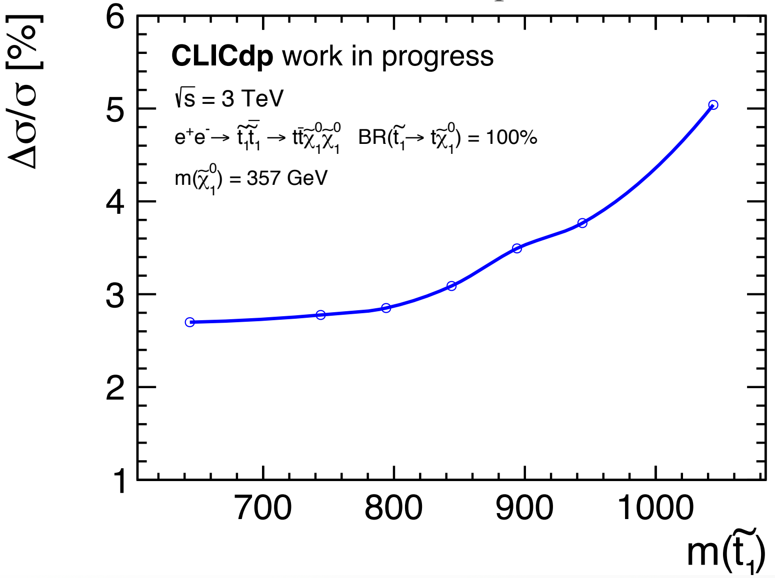
Top squarks: e+e- colliders prospects

Discoverability of stops with masses up to sqrt(s)/2 for e+e- colliders

- **Precision of O(%) measurements achievable**

CLIC studies on MSSM-benchmark models show potential for precise mass measurements for stops up to 1.1-1.2 TeV for m(χ^0) up to 1 TeV

ES-follow up communication



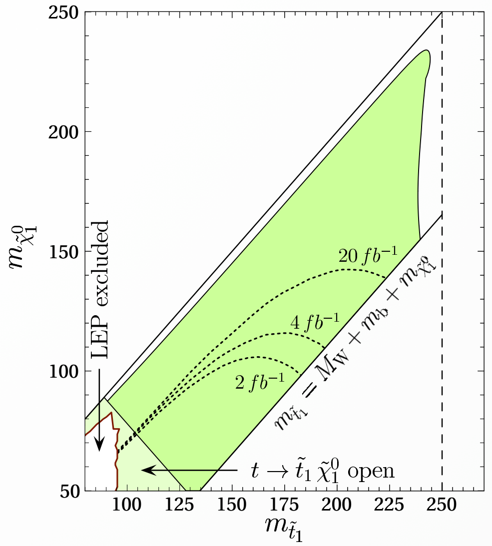
channel	$P(e^-) = -0.8$	$N(\epsilon_s = 10\%)$	$N(\epsilon_s = 75\%)$	$P(e^-) = +0.8$	$N(\epsilon_s = 10\%)$	$N(\epsilon_s = 75\%)$
$\tilde{b}_1^*\tilde{b}_1$	0.070 fb	13.9	105	0.010 fb	1.0	7.8
$\tilde{b}_1^*\tilde{b}_2$ + c.c.	0.023 fb	4.6	34.4	0.018 fb	1.7	13.3
$\tilde{b}_2^*\tilde{b}_2$	0.037 fb	7.3	54.9	0.005 fb	0.5	3.7
$\tilde{t}_1^*\tilde{t}_1$	0.503 fb	100.6	754.5	0.264 fb	26.4	197.9
$\tilde{t}_1^*\tilde{t}_2$ + c.c.	0.022 fb	4.4	33.7	0.017 fb	1.7	13.1
$\tilde{t}_2^*\tilde{t}_2$	0 fb	0	0	0 fb	0	0

CLIC: https://arxiv.org/pdf/1812.02093.pdf

From ILC, early studies on low-mass stop

- Performed for charm final states but possibly applicable to 4-body decays and stop → b+chargino
- However, scenarios considered are mostly covered by LHC

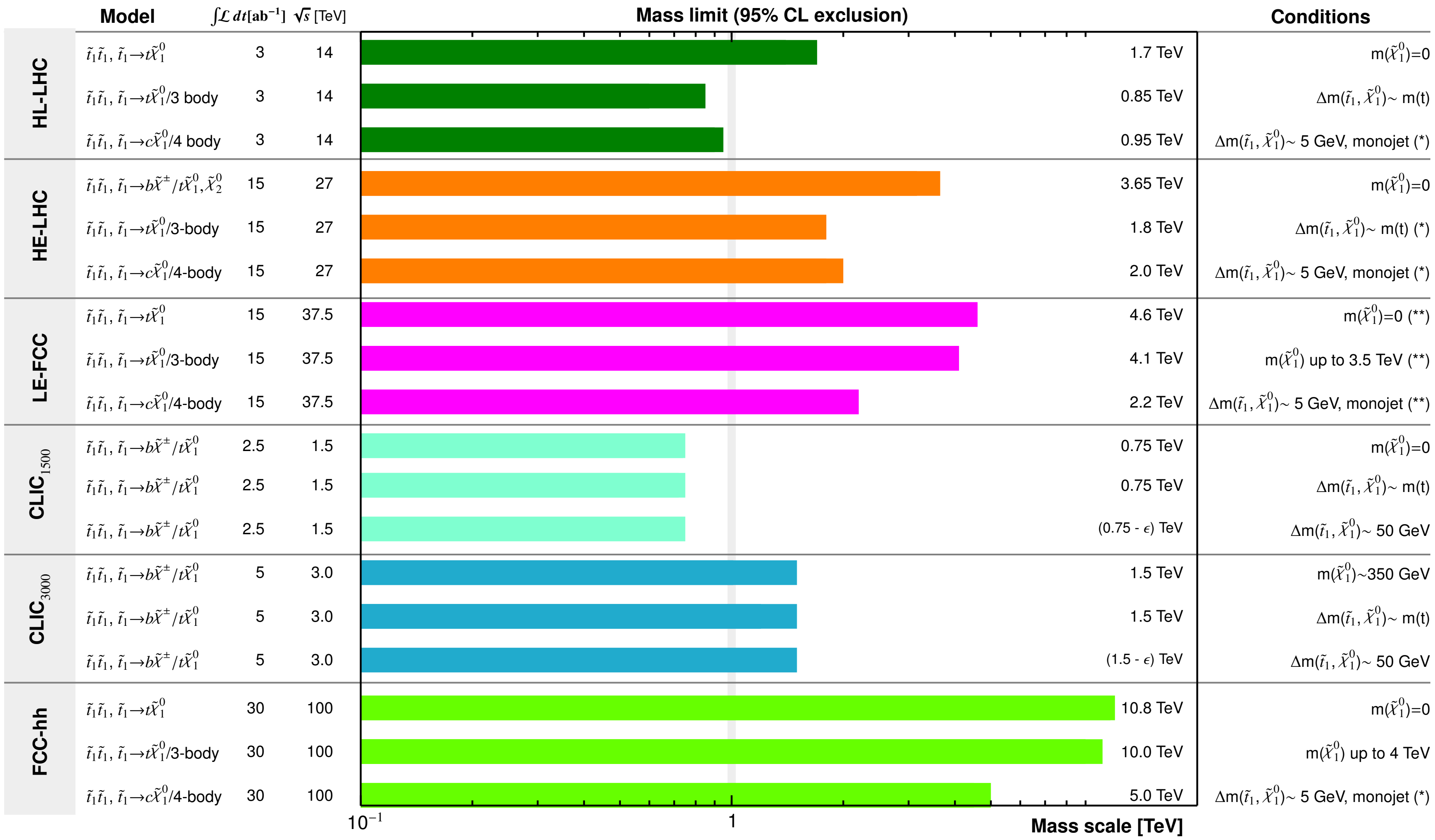
References in: https://arxiv.org/abs/1903.01629



Top squarks: summary

All Colliders: Top squark projections

(R-parity conserving SUSY, prompt searches)



(*) indicates projection of existing experimental searches

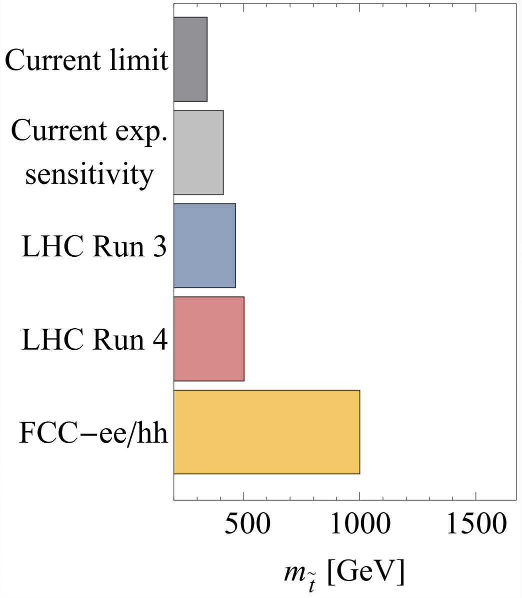
(**) extrapolated from FCC-hh prospects

ϵ indicates a possible non-evaluated loss in sensitivity

ILC 500: discovery in all scenarios up to kinematic limit $\sqrt{s}/2$

Indirect limits and implications for naturalness

- Leading **indirect effect of top squarks** → they modify some of the properties of the Higgs boson, i.e. interactions between the Higgs boson and gluons and also between the Higgs boson and the photon.
  - None of these interactions exist at the classical level → particularly sensitive to new strongly coupled degrees of freedom like top squarks.
- Combined projected indirect constraints on stops from LHC Higgs measurements are dominated by e-e colliders
- **Level of tuning for MSSM Higgs**



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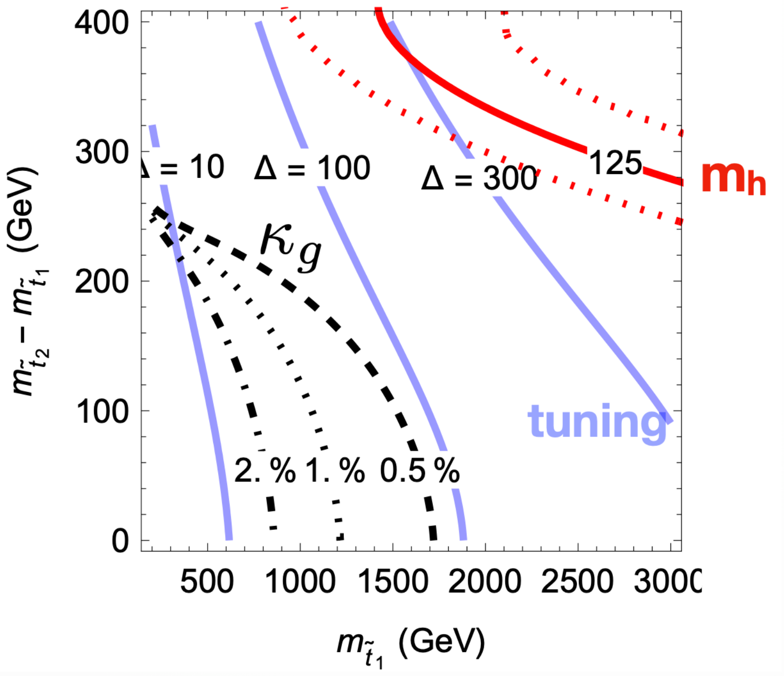
$$X_t = X_t^{\max}$$

w/ low-scale mediation:
tuning of ≲ 1%



ε	High-scale mediation	Low-scale mediation
stop	$5\times10^{-5}\left(\frac{10\text{ TeV}}{m_{\tilde{t}}}\right)^2$	$2\times10^{-3}\left(\frac{10\text{ TeV}}{m_{\tilde{t}}}\right)^2$
gluino	$7\times10^{-6}\left(\frac{17\text{ TeV}}{m_{\tilde{g}}}\right)^2$	$6\times10^{-3}\left(\frac{17\text{ TeV}}{m_{\tilde{g}}}\right)^2$

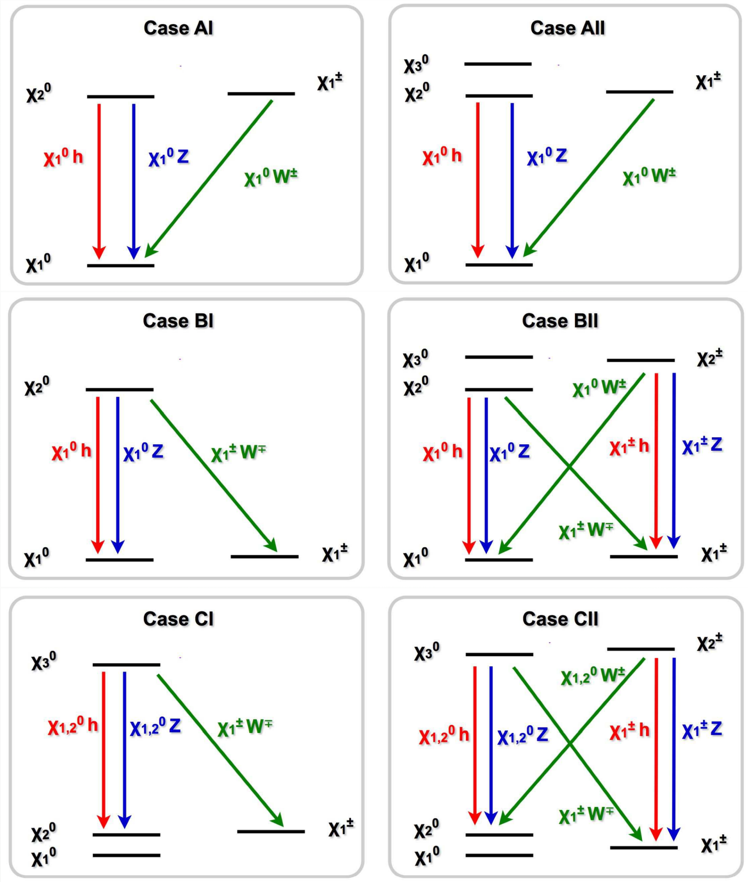
In the minimal SUSY model, the prediction of the Higgs mass agrees with the experimental value only for stops in the multi-TeV range or larger.
→ The most relevant range of stop masses can therefore be probed only at future hadron colliders.

Lessons learned: top squarks

- In Granada, there were a number of discussions, especially triggered by e+e- communities, about gaps and uncovered scenarios due to the possible over-simplification of benchmarks:
  - Clearly, now that we are closer to end of Run 2 we are in a better position to say whether there are still 'gaps' in low-mass top squarks regions or not → personally I think not ☹
- Might be good to study more in depth possible indirect constraints from e+e-
- For high mass top squarks, it would be great to see:
  - Direct studies for compressed scenarios (3-body and 4-body decays are only extrapolated even for HL-LHC). This includes monojet and soft-leptons analyses, or dedicated charm tagging analyses for stop into charm+MET.
  - Characterization of possible hints for top squarks at the end of HL-LHC, e.g. performed by FCC-hh (or HE-LHC) or even by CLIC for compressed scenarios would be interesting (not much info on that)

EWK SUSY: Phenomenology

- Mass and hierarchy of the four neutralinos and the two charginos, as well as their production cross sections and decay modes, depend on the M_1, M_2, μ (bino, wino, higgsino) values and hierarchy
  - EWK phenomenology broadly driven by the LSP and Next-LSP nature
  - Examples of classifications (cf: arXiV: 1309.5966)



- **Scenario A:** $M_1 < M_2, |\mu|$

  Bino LSP

- **Scenario B:** $M_2 < M_1, |\mu|$

  Wino LSP

- **Scenario C:** $|\mu| < M_1, M_2$

  Higgsino LSP

Used as benchmarks:

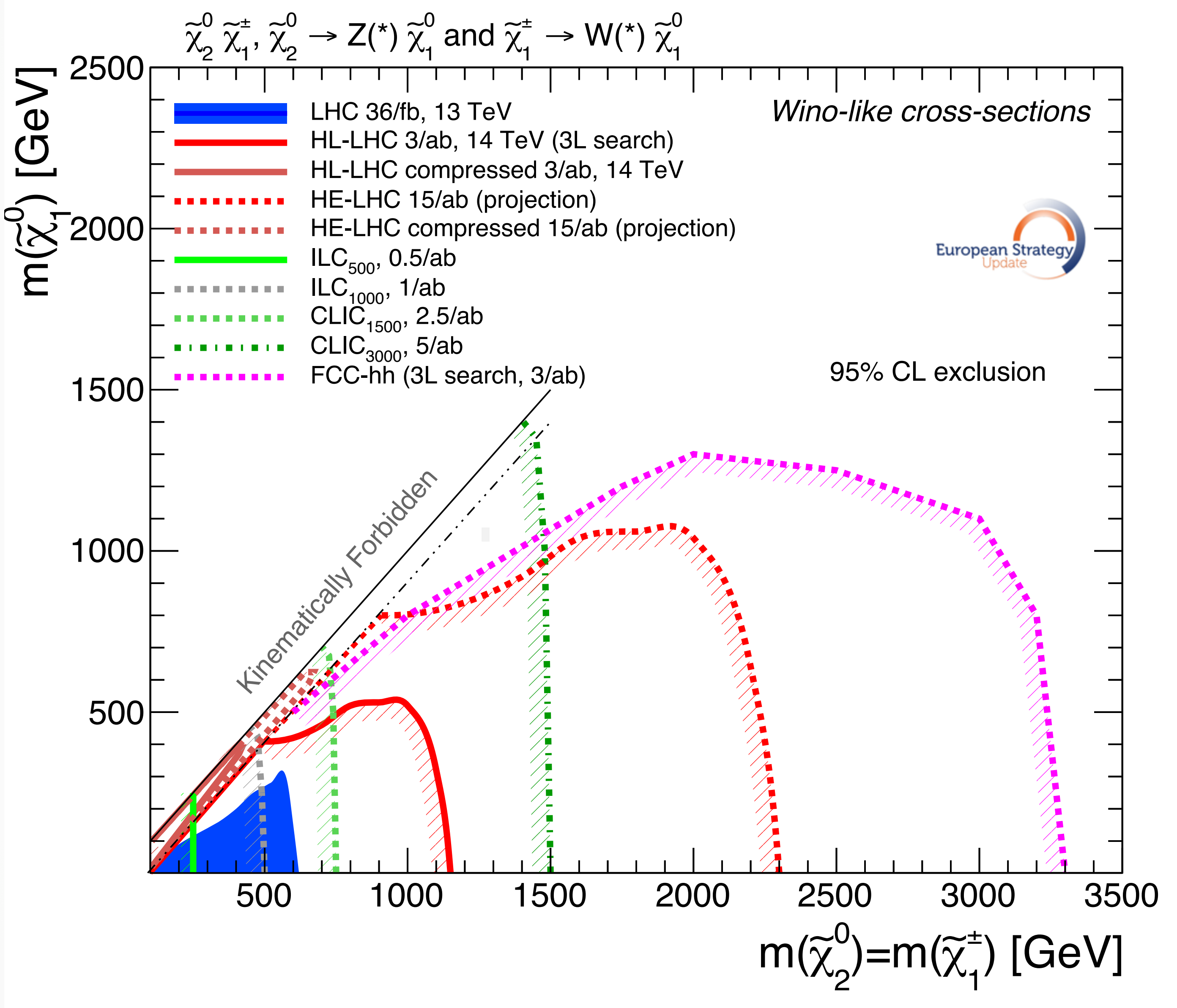
- Bino LSP, wino-bino cross sections
  (1) Mass($\chi^{\pm}_1$) = Mass (χ^0_2)
  (2) $\chi^+_1\chi^-_1$ and $\chi^{\pm}_1\chi^0_2$ processes

$$\sigma_W(\chi^{\pm}_1\chi^0_2) \sim 2\, \sigma_W(\chi^+_1\chi^-_1)$$

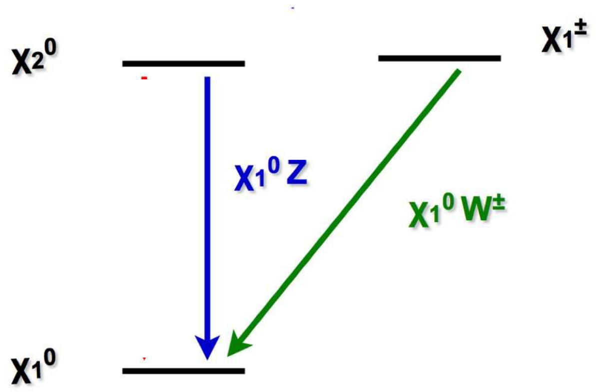
- Higgsino-LSP, higgsino-like cross sections
  (1) Small mass splitting χ^0_1, $\chi^{\pm}_1$, χ^0_2
  (2) Consider triplets for cross sections
  (3) Role of high-multiplicity neutralinos and charginos also relevant

$$\sigma_H(\chi^{\pm}_1\chi^0_2 + \chi^+_1\chi^-_1 + \chi^{\pm}_1\chi^0_1) < 0.7\text{-}0.5\ \sigma_W(\chi^{\pm}_1\chi^0_2)$$

Wino-like cross section: $\chi^{\pm}{}_1\chi^0{}_2$

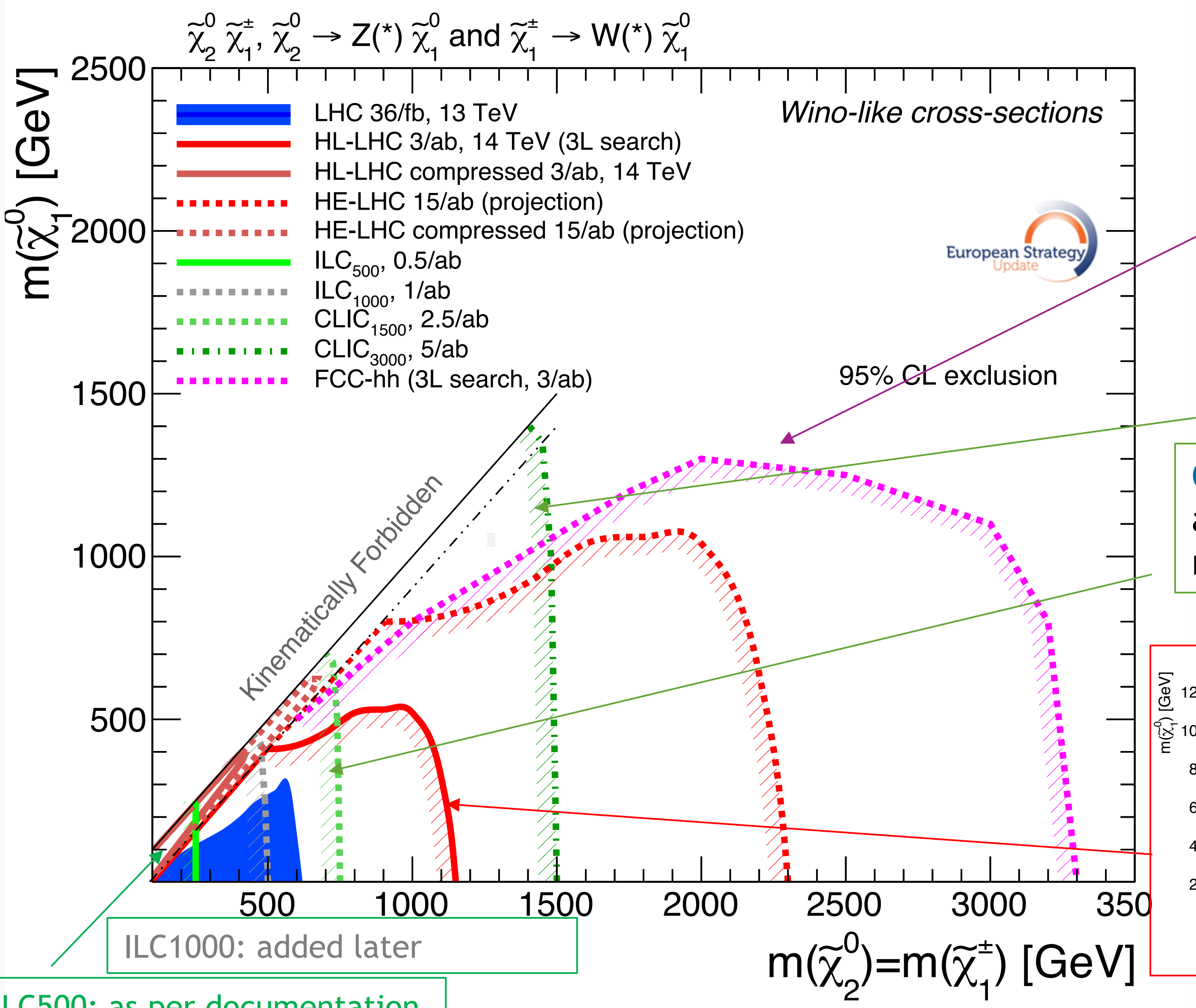


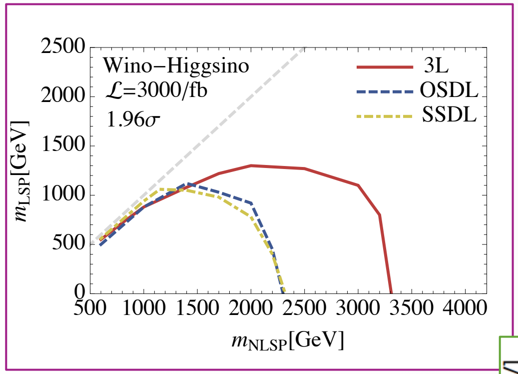
$\chi^{\pm}{}_1\chi^0{}_2$ = NSLP, $m(\chi^{\pm}{}_1) = m(\chi^0{}_2)$



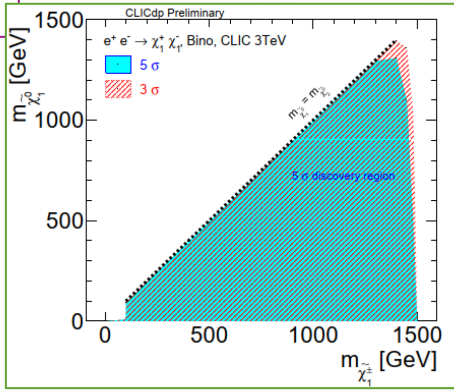
[$\chi^0{}_2 \to h\,\chi^0{}_1$ not in this plot]

Wino-like cross section: $\chi^{\pm}{}_1\chi^0{}_2$

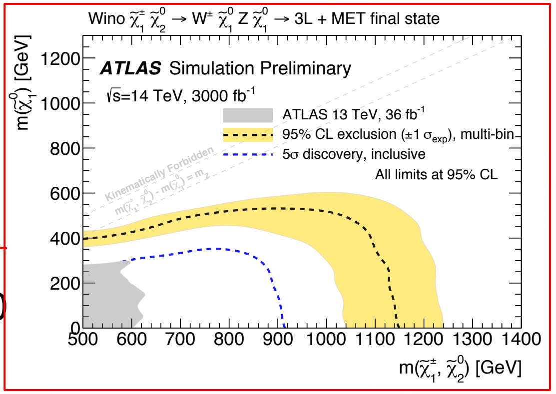




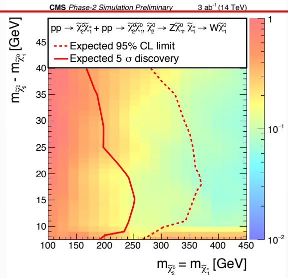
FCC-hh Contour of the 3-lepton search



CLIC: Assume reach for $\chi^+{}_1\chi^-{}_1$ and $\chi^{\pm}{}_1\chi^0{}_2$. CLIC 1.5 TeV reach / 2 up to ΔM~5 GeV



HL-LHC compressed: reinterpretation of higgsino $\chi^{\pm}{}_1\chi^0{}_2$ results



ILC1000: added later

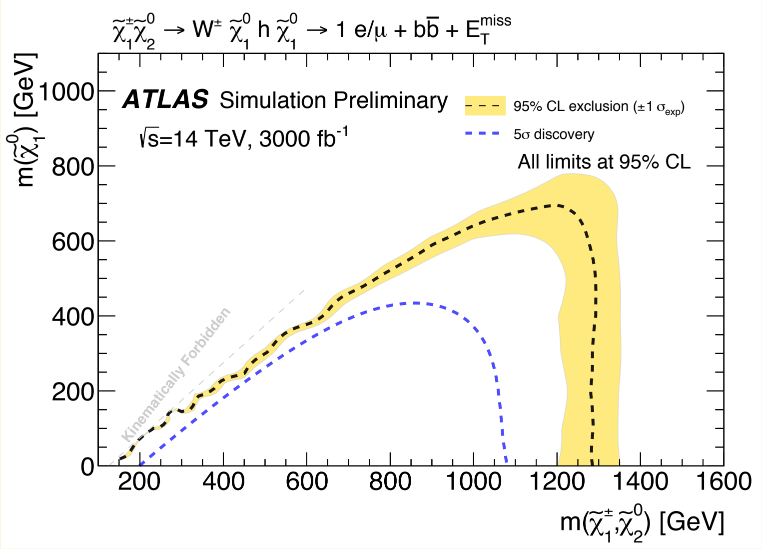
ILC500: as per documentation

HE-LHC → projections with ColliderTool Reach

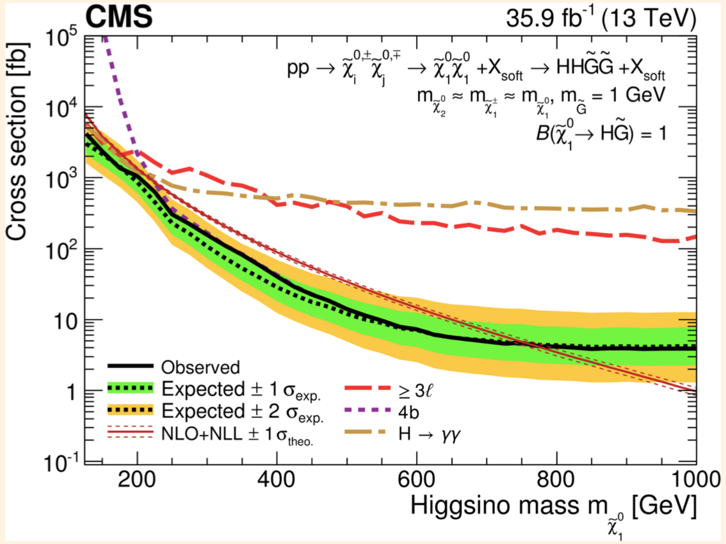
Lessons learned: chargino-neutralinos

- We also had studies on chargino pair production (see back-up)
  - Dedicated studies for compressed scenarios seem to cover a wide range of models – to be refined?
- In Granada, there were a number of discussions about neutralino2 decays into higgs + neutralino1. Prospect studies show that HL-LHC can be quite powerful, perhaps this might be exploited further, i.e. sensitivities for higgsino scenarios in GGM models. E.g. we had (1) but not (2)

(1)



(2)

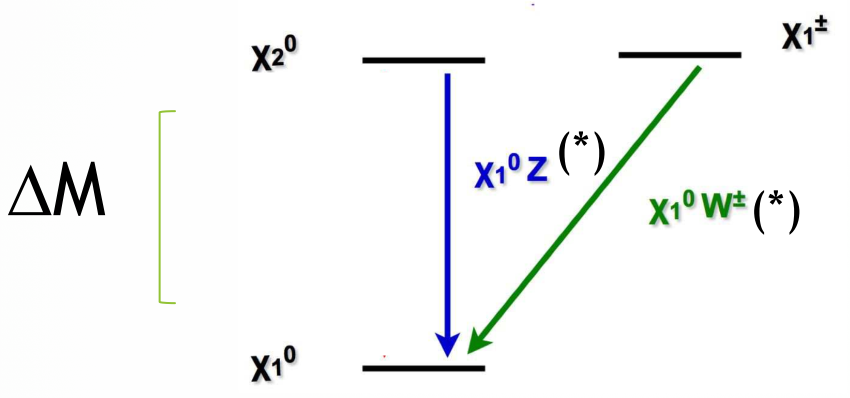


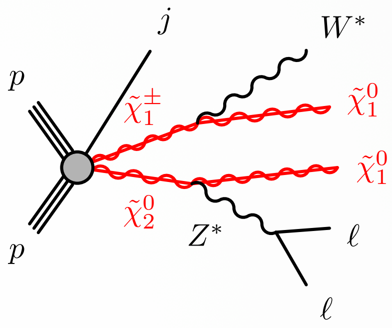
- As usual, characterization of possible hints in HL-LHC data could be studied further

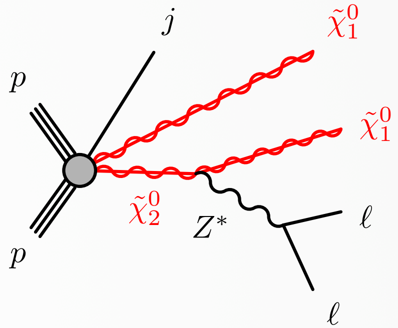
Higgsino-like EWK processes

Processes: $\chi^{+}_{1}\chi^{-}_{1}$, $\chi^{\pm}_{1}\chi^{0}_{2}$, $\chi^{0}_{1}\chi^{0}_{2}$

$\chi^{\pm}_{1}, \chi^{0}_{2}$ = NSLP, $m(\chi^{\pm}_{1}) \sim m(\chi^{0}_{2})$







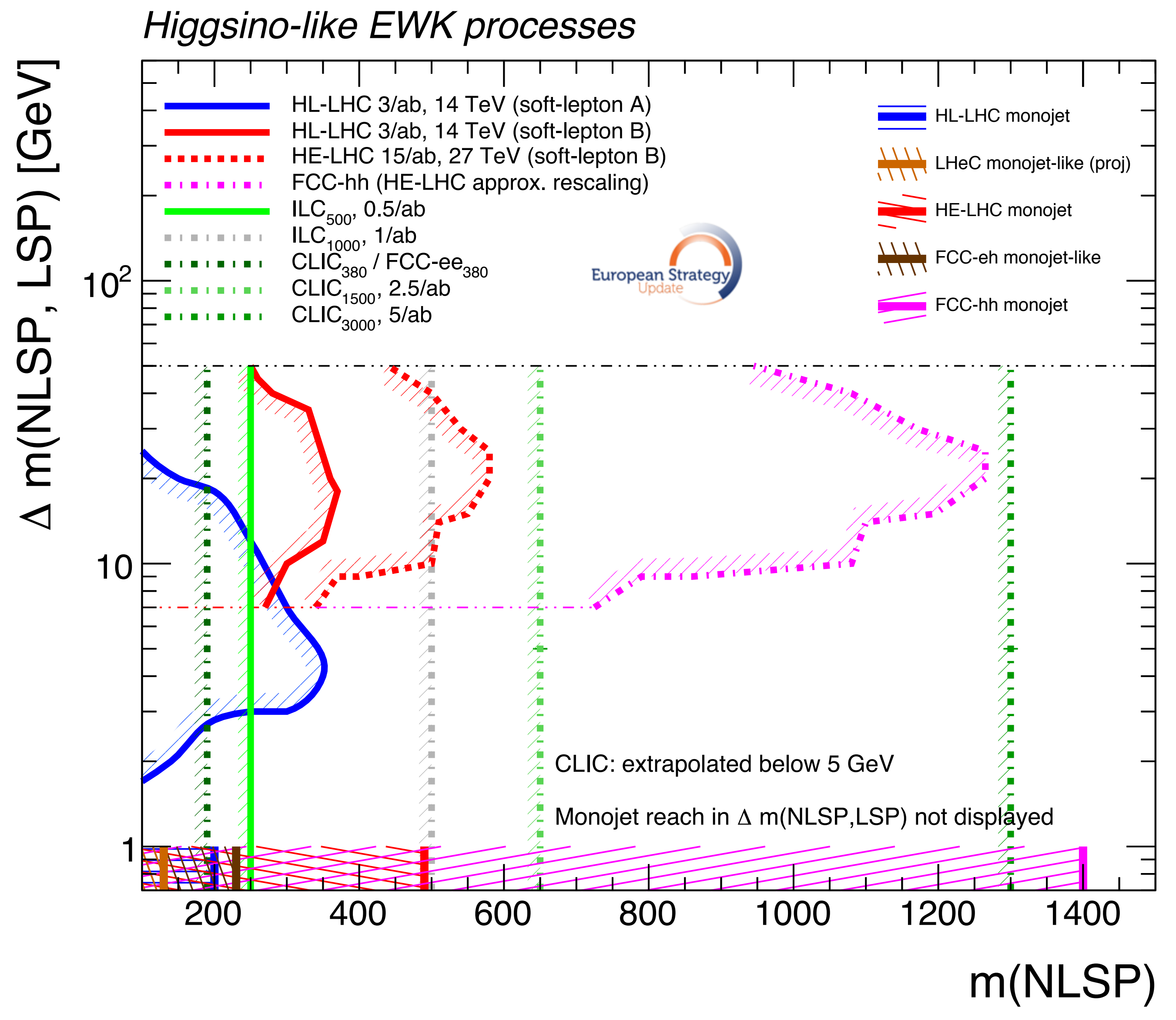
Higgsino-like (i.e. large higgsino component but not pure):

→ **ΔM(NLSP, LSP) ~ O(GeV)**

Pure-higgsino:

→ **ΔM ~ 160 MeV** – targeted by disappearing track analyses

Higgsino-like EWK processes



Processes: $\chi^+_1\chi^-_1,\ \chi^\pm_1\chi^0_2,\ \chi^0_1\chi^0_2$

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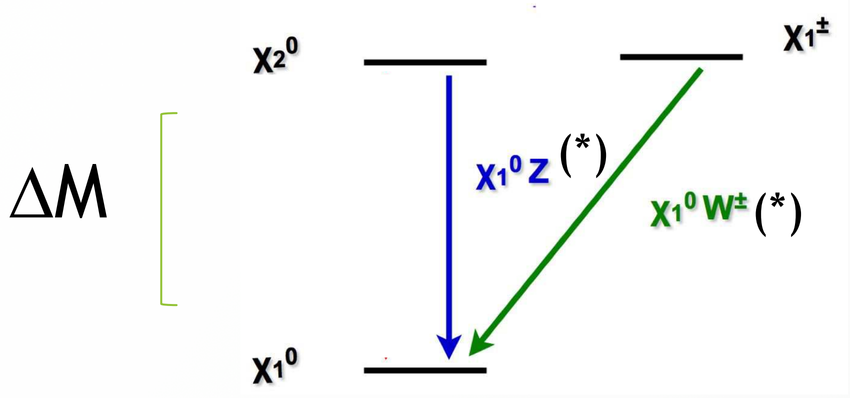
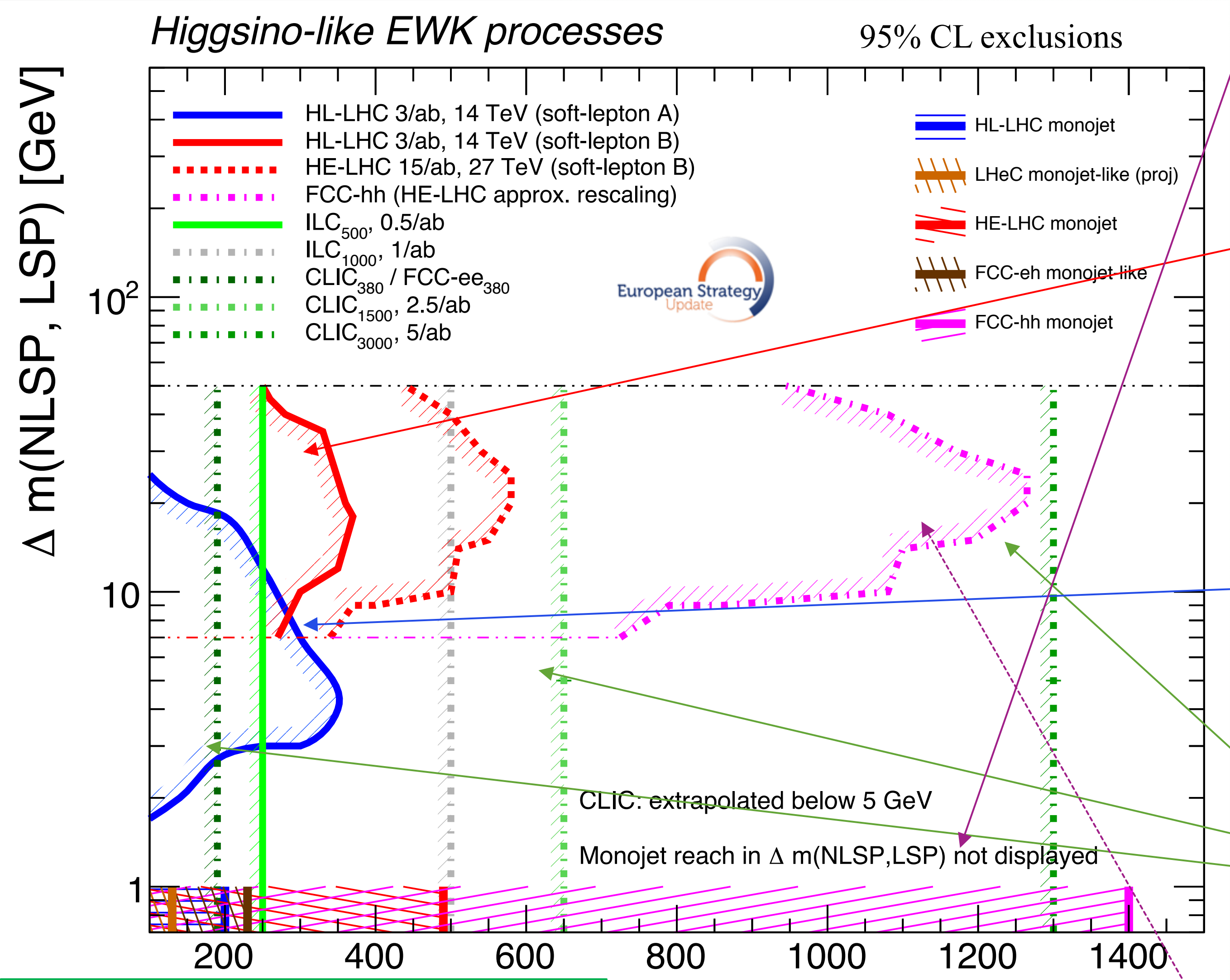
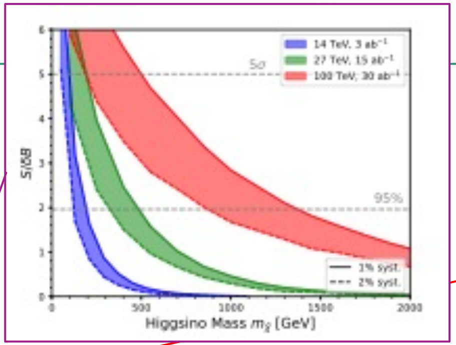


Higgsino-like EWK processes

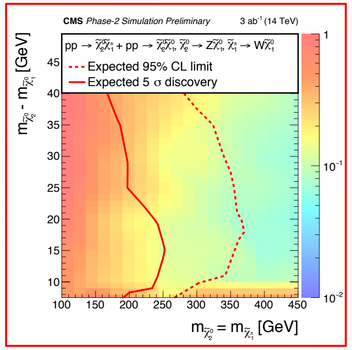


ILC sensitive up to sqrt(s)/2 and down to O(100 MeV)

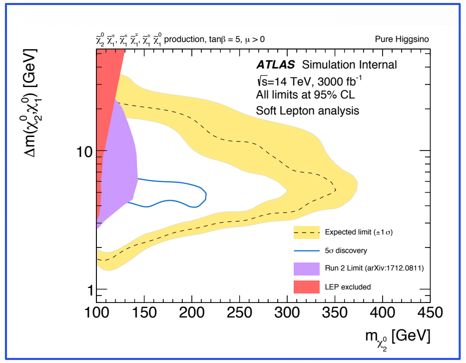
Monojets (HL/HE/FCC-hh/LHeC/FCC-eh)



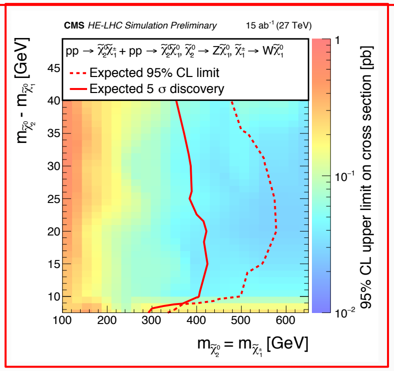
HL-LHC soft lepton analysis CMS

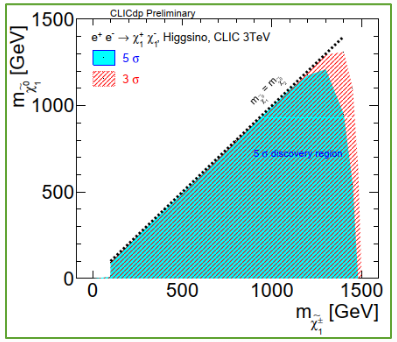


HL-LHC soft lepton analysis ATLAS



HE-LHC soft lepton analysis





CLIC 3 TeV, results rescaled also for CLIC1.5, CLIC380, FCC-ee **(tbc)**
Analysis done for DM(NLSP,LSP)=5 GeV – below: extrapolated

Indicative partonic rescaling of HE for FCC-hh soft-lepton

Discovery reach in EWK sector

- HL-LHC analyses now target also compressed scenarios with soft-lepton + ISR analyses and/or monojet
  - Good prospects, but discovery potential is limited **(~ 200 GeV for higgsino-like models)**
- ILC500 (→ CLIC 1.5 TeV, 3 TeV) might allow discovery in case deviations are observed at HL-LHC
  - Characterization of the EWK sector possible at e^+e^- for sparticles with masses below ~ sqrt(s)/2
- FCC-hh has certainly a high potential for EWK particles (with mass up to 3-4 TeV)
  - Together with CLIC 3 TeV, FCC-hh could go beyond ~ 1 TeV for higgsino scenarios
- Potential of monojet searches at pp colliders might be further exploited to evaluate exclusion reach. However:
  - What if a deviation in monojet final states is observed at the HL-LHC? → multiple interpretations are possible → additional EWK processes (i.e. from heavier charginos/neutralinos) must be searched for (see some examples in back-up for e+e- and pp).

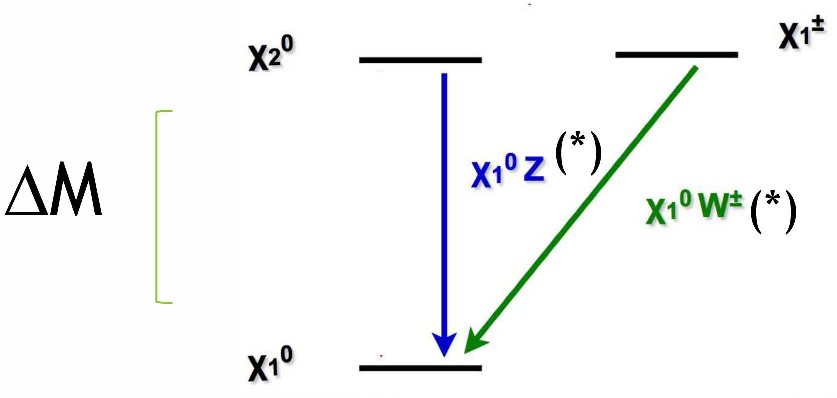
Lessons learned: higgsino-like scenarios

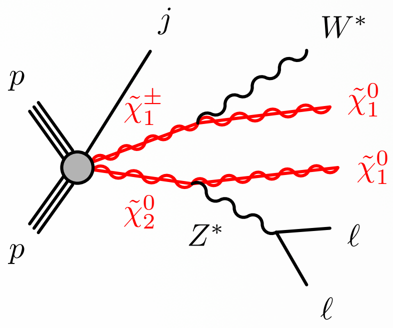
- At the time of the Yellow Report and ES document ATLAS and CMS managed to reach an excellent set of results in compressed scenarios → one could envisage a **better coherence on the model assumptions** used for the soft lepton analyses
- As compressed scenarios are the most interesting for complementarities with e+e- colliders, **reinterpretation of monojet analyses** in the higgsino-like scenario as a function of ΔM would be fundamental, i.e. in the 1-20 GeV range
  - we can expect some sensitivity there!
  - It is very important to understand (1) complementarities with e+e- and e-p colliders (2) impact on systematics and discovery potential
- There are **no dedicated studies for FCC-hh**, only extrapolations → would be very important to perform a more realistic and dedicated set of analyses!
- Follow up on possible deviations observed at HL-LHC should be made

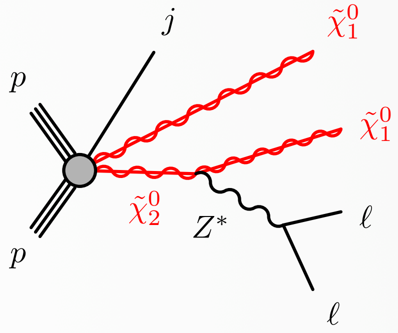
Higgsino-like EWK processes

Processes: $\chi^{+}{}_{1}\chi^{-}{}_{1},\ \chi^{\pm}{}_{1}\chi^{0}{}_{2}\, ,\chi^{0}{}_{1}\chi^{0}{}_{2}$

$\chi^{\pm}{}_{1}, \chi^{0}{}_{2}$ = NSLP, $m(\chi^{\pm}{}_{1}) \sim m(\chi^{0}{}_{2})$



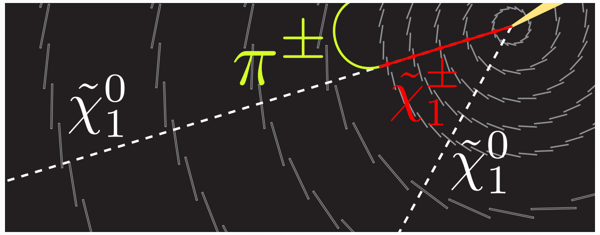


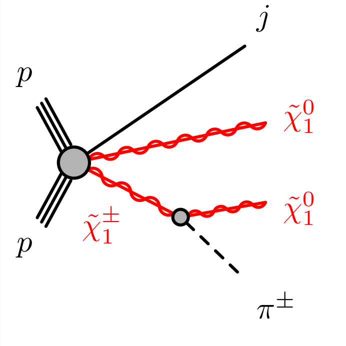


Higgsino-like (i.e. large higgsino component but not pure):
→ ΔM(NLSP, LSP) ~ O(GeV)

Pure-higgsino:
→ **ΔM ~ 160 MeV** – targeted by disappearing track analyses

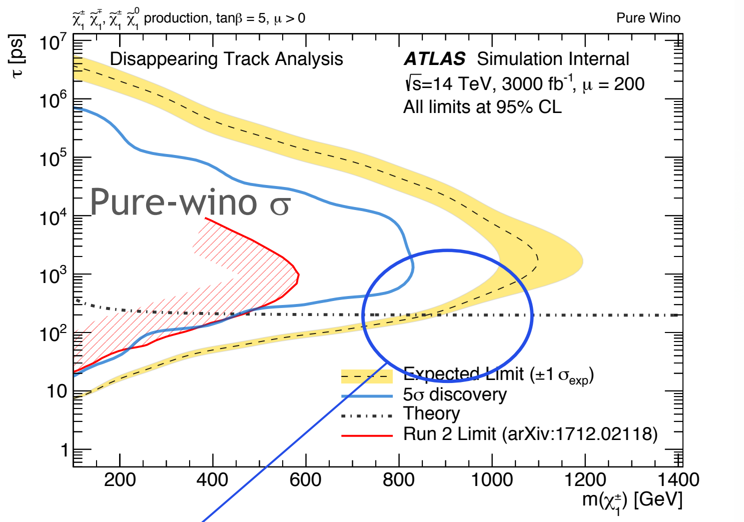
Disappearing track signatures

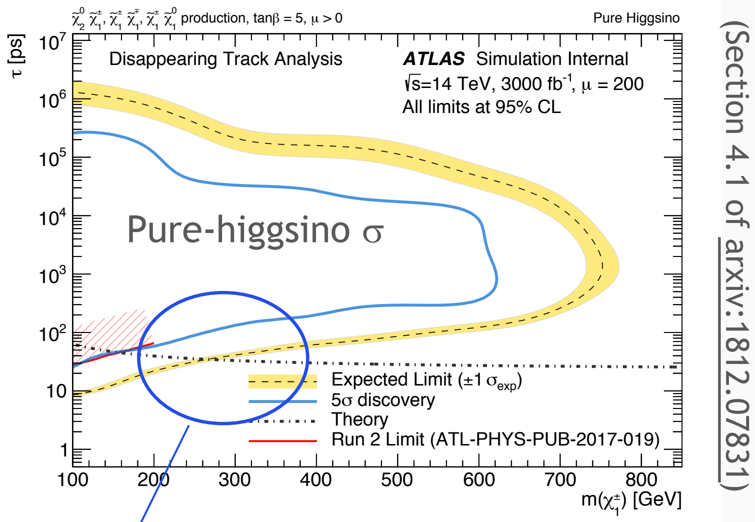




Very challenging with high pile-up and high rate of fake tracks!

HL-LHC

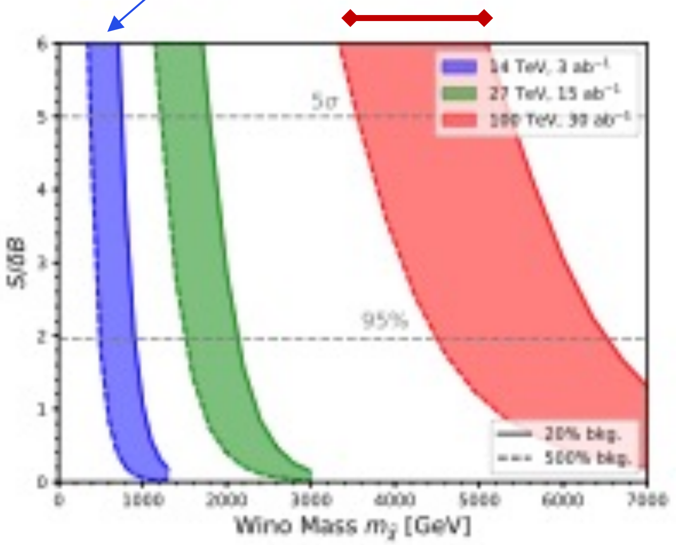


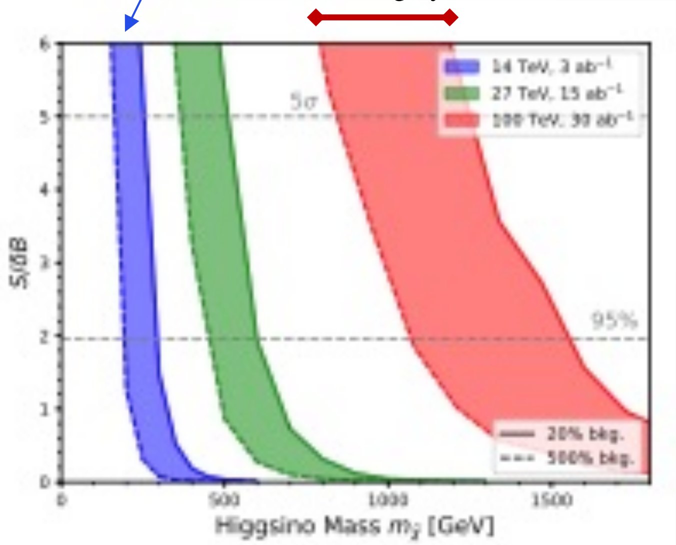


(Section 4.1 of arxiv:1812.07831)

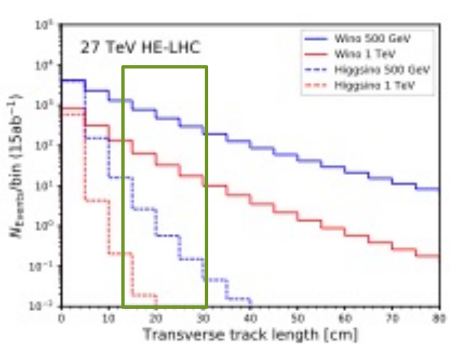
HL-LHC/HE-LHC/FCC-hh

Variation of bkg by factor 5





transverse charged track length must be in specific ranges to retain sensitivity



(Not available for FCC-hh)

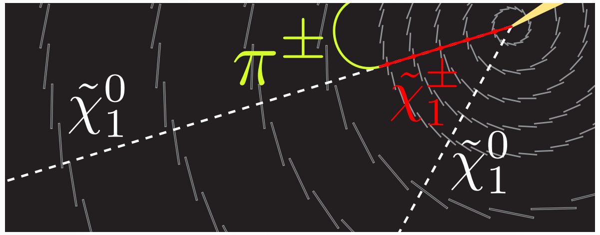
$12 < d < 30$ cm

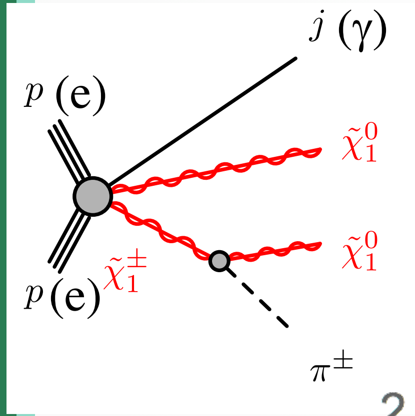
@ FCC: p_T track in 1-1.4 TeV range

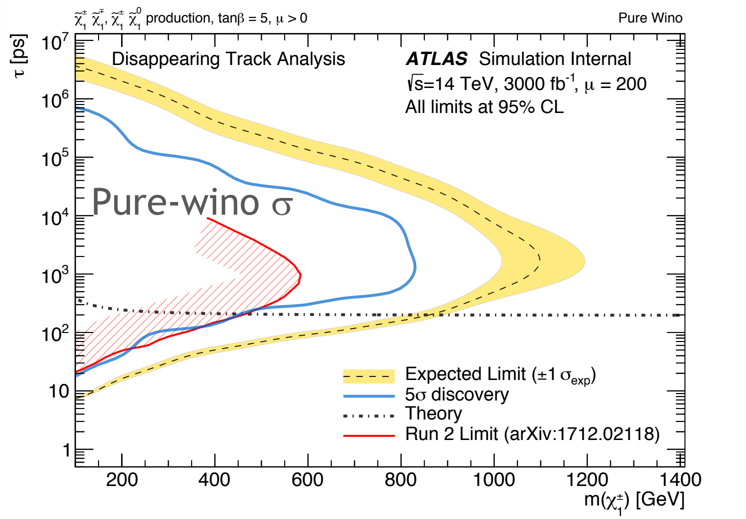
Disappearing track signatures

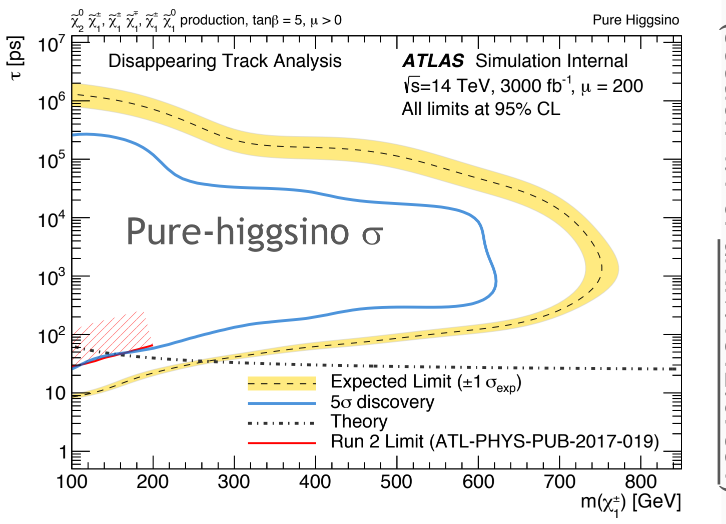
HL-LHC

(Section 4.1 of arxiv:1812.07831)

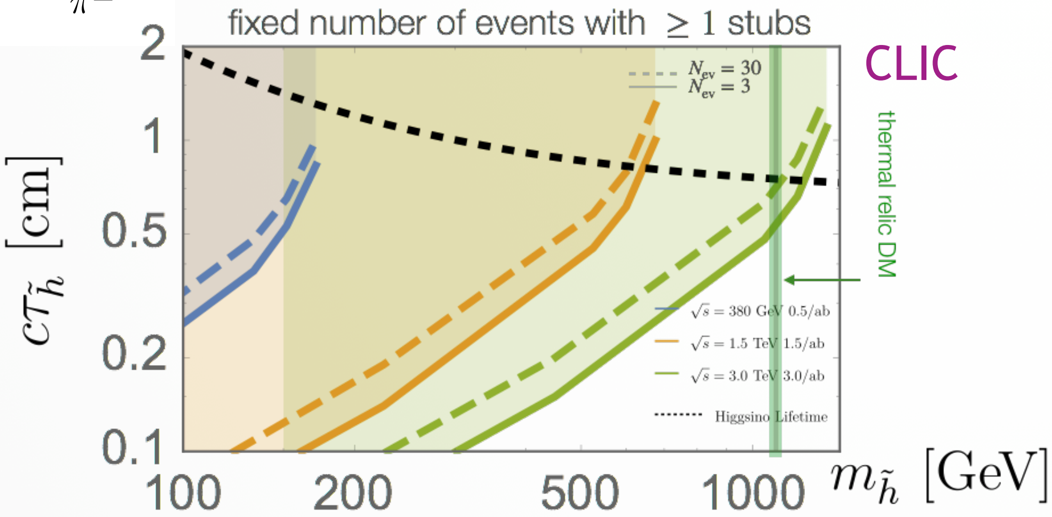






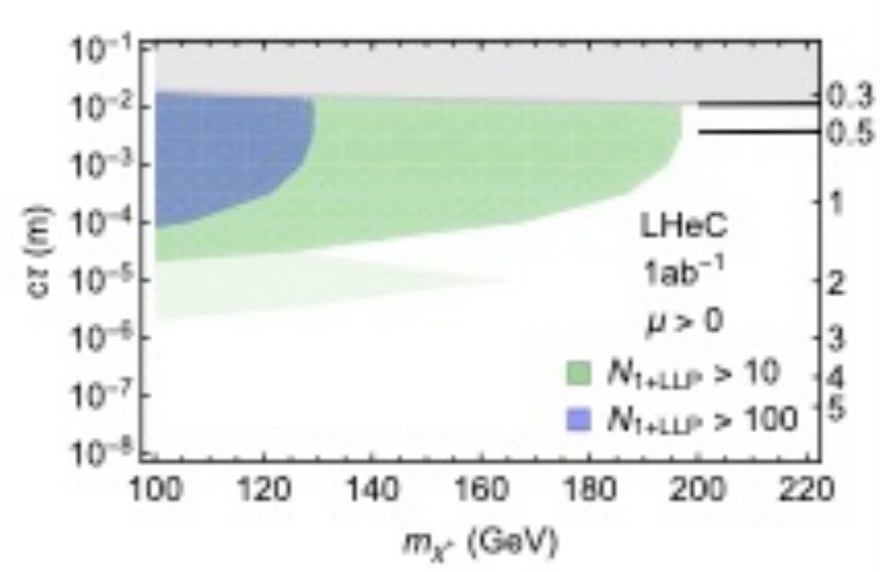


Charged stub + photon analysis



CLIC

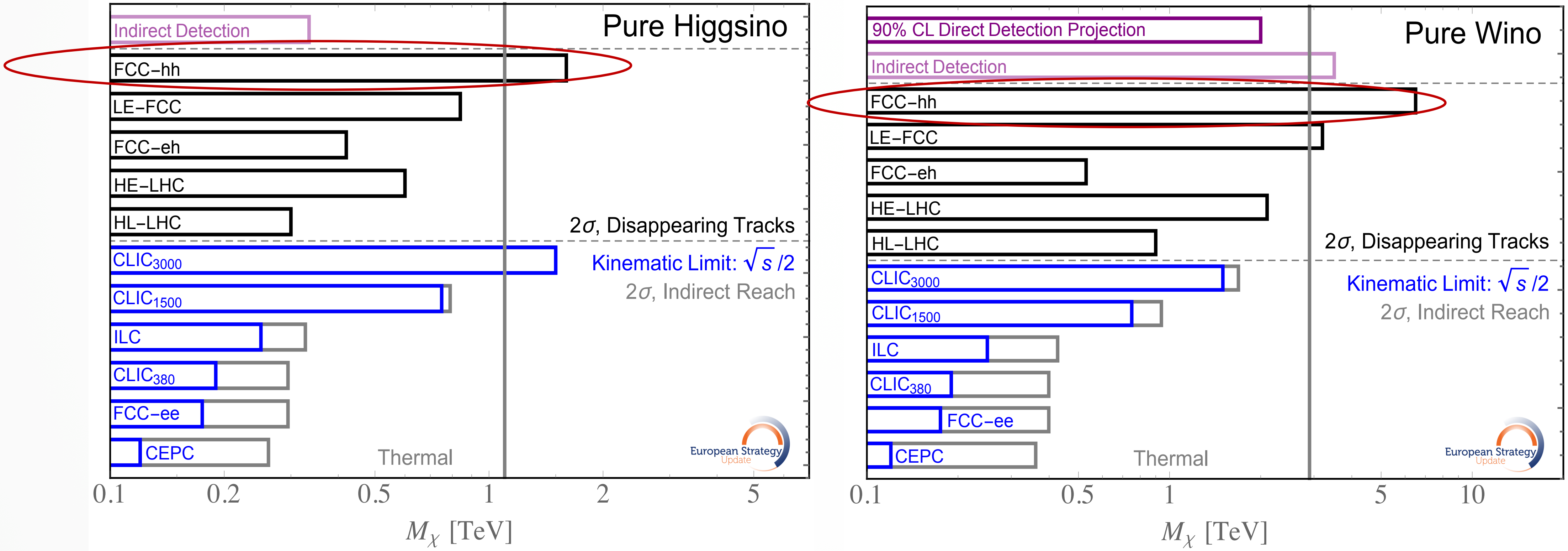
Low energy charged tracks analysis



E-p collider
LHeC

Thermal Higgsino/Wino dark matter

- Thermal freeze-out mechanism provides a cosmological clue for the observed DM density
- Most straightforward example of a DM thermal relic: massive particle with EW gauge interactions only
- Spin-1/2 particles transforming as doublets or triplets under SU(2) symmetry, usually referred to as Higgsino and Wino
  - Although they are not really "SUSY" related – phenomenology is equivalent



FCC-hh could conclusively test the hypothesis of thermal DM in both scenarios

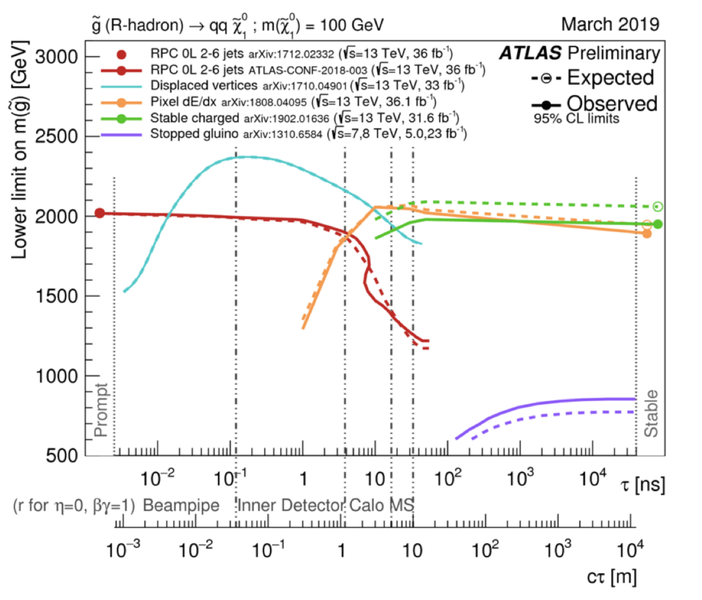
Lessons learned: pure-wino/higgsino and analyses

- Disappearing tracks analysis very challenging:
  - Review of the assumptions made for fake backgrounds by the ATLAS prospect studies might be good (e.g. extrapolation of bkg using 3 hits instead of 4 for tracklet reconstructions)
  - Prospect studies from CMS based on the recently published disappearing track analysis would be excellent
- Are prospects for FCC-hh realistic?
  - Dedicated analyses with specific assumptions on the detector layout and level of pile-up should be made to assess the reach

Lesson learned/follow up on other topics

- **Analyses for stau**
  - Stau are extremely challenging due to low cross section and difficult signatures (especially if **right-handed component dominates** – see back-up for summary plots)
  - There are **no dedicated studies at FCC-hh** and extrapolations are not straightforward
  - Good set of studies by ILC (published) and by CLIC (unpublished)
- **Analyses for long-lived SUSY particles**
  - A few examples were available at the time of the ES for HL-LHC
    - (see back up: Displaced vertex (DV) analysis, delayed photons)
  - Complementarities with other proposed facilities (e.g. MATHUSLA) attempted but difficult
  - Perhaps a coherent set of studies e.g. for gluinos, top squarks and EWK particles desirable also at e+e- colliders (not much existed at that time, aside for very specific cases like disappearing tracks)

Something like this? EF08/09 cross-over



Conclusions

- Searches for SUSY will remain a priority for HEP for some time
- **The discovery potential for strongly produced SUSY particles** such as **gluino, squarks** and in particular **top squarks** is dominated by hadron colliders, which allow higher mass reach
  - Gluinos decaying in jets + E_T^{Miss} will be excluded at least up to 1.5 TeV @ HL-LHC for $\Delta M = m_{gluino} - m_{LSP} > O(GeV)$
    - Long-lived gluinos (R-hadrons) up to 3 TeV for intermediate lifetime ranges
  - Compressed scenarios in case of top squarks might still have loop-holes after Run 2
    - Advanced analysis approaches at ATLAS/CMS are “filling the gaps” : will there be blind-spots for m(stop)<300 GeV?
- The **EWK SUSY sector** present several unexplored scenarios, especially in models characterized by a compressed mass spectrum
  - LHC (HL/HE) analyses now target also compressed scenarios with soft-lepton + ISR analyses
    - Still, cases such as stau pair production might be difficult under certain hypothesis (discovery challenging)
  - e+e- colliders might cover the gaps and allow a full characterization of the EWK sector in case of discovery of sparticles below sqrt(s)/2
  - The higgsino and wino cases are somewhat special:
    - Investigations in prompt / non-prompt scenarios show good complementarities of pp/ee/ep
  - FCC-hh has certainly a high potential for EWK particles with masses up to 3-4 TeV
    - For higgsinos, FCC-hh, together with CLIC 3 TeV (depending on assumptions), could reach ~ 1 TeV

Conclusions

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  - Gluinos decaying in jets + E_T^{Miss} will be excluded at least up to 1.5 TeV @ HL-LHC for $\Delta M = m_{gluino} - m_{LSP} > O(GeV)$
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Additional studies in key areas would be highly desirable, both at HL-LHC, FCC-hh and at e+e- colliders like CLIC

[perhaps obvious but..] Focusing on these (often challenging) studies would be more beneficial than redoing analyses already performed in the past

- T…
  c…

  - …?
  - …particles
  - The higgsino and wino cases are somewhat special:
    - Investigations in prompt / non-prompt scenarios show good complementarities of pp/ee/ep
  - FCC-hh has certainly a high potential for EWK particles with masses up to 3-4 TeV
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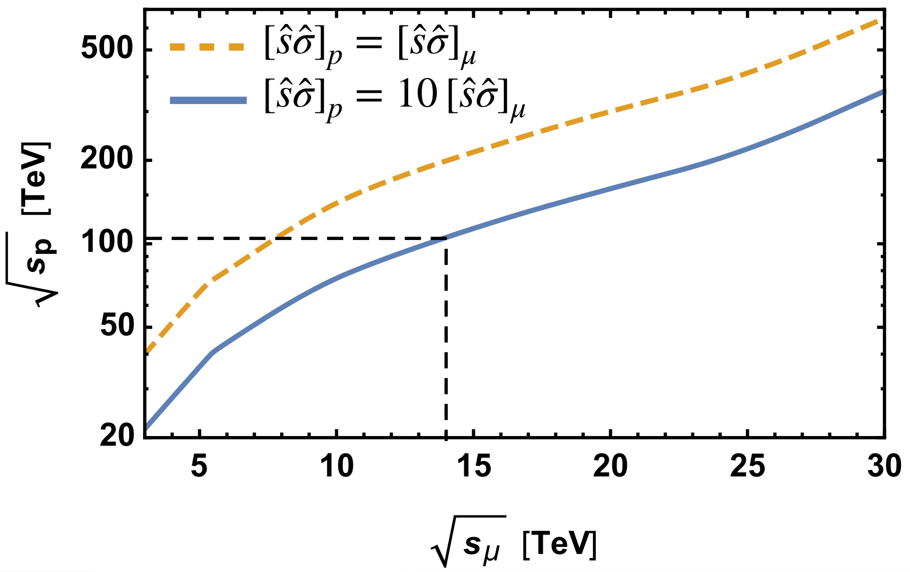
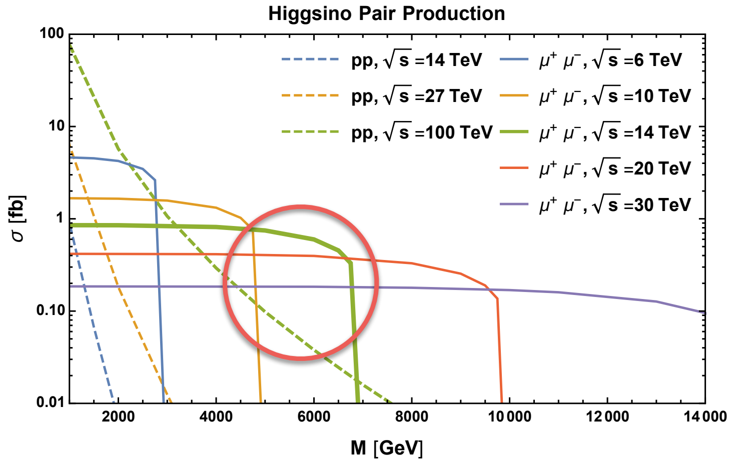
Back up

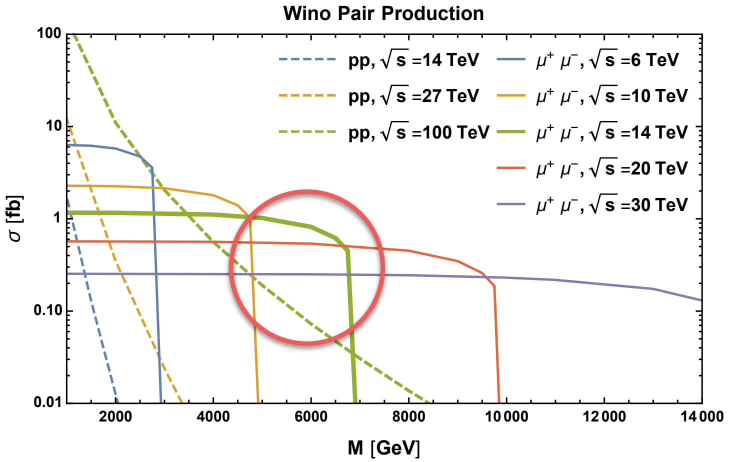
Muon collider / very-high energy lepton collider

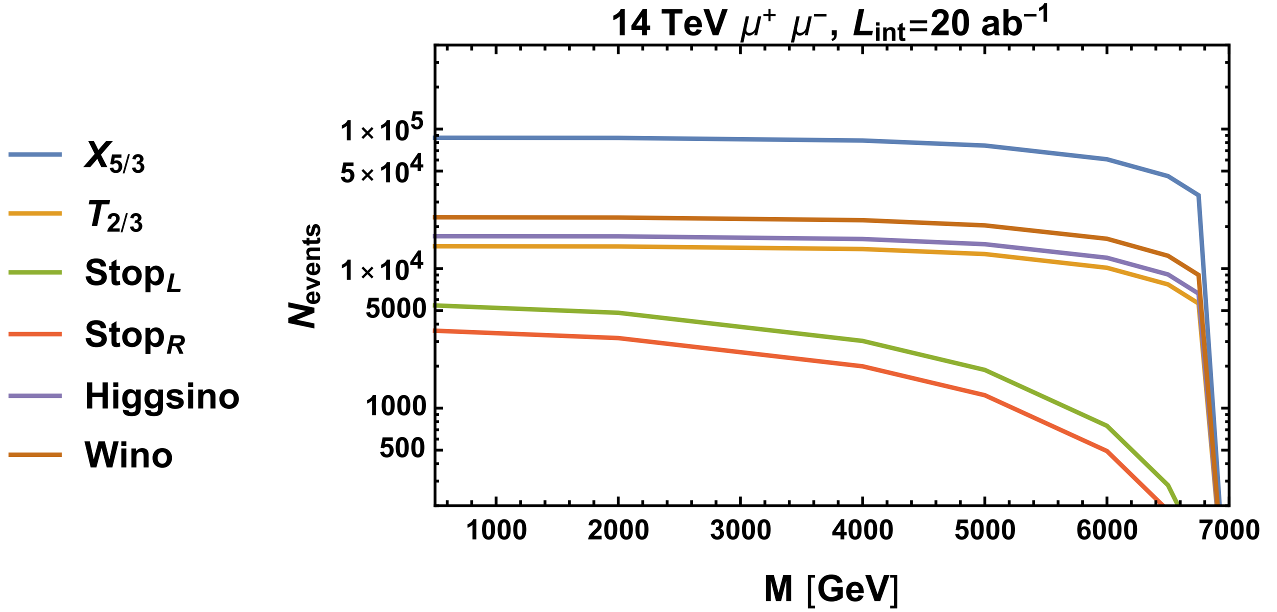
- More speculative but interesting for a forward look



14 TeV μ-collider nearly as good as the FCC at 100 TeV?



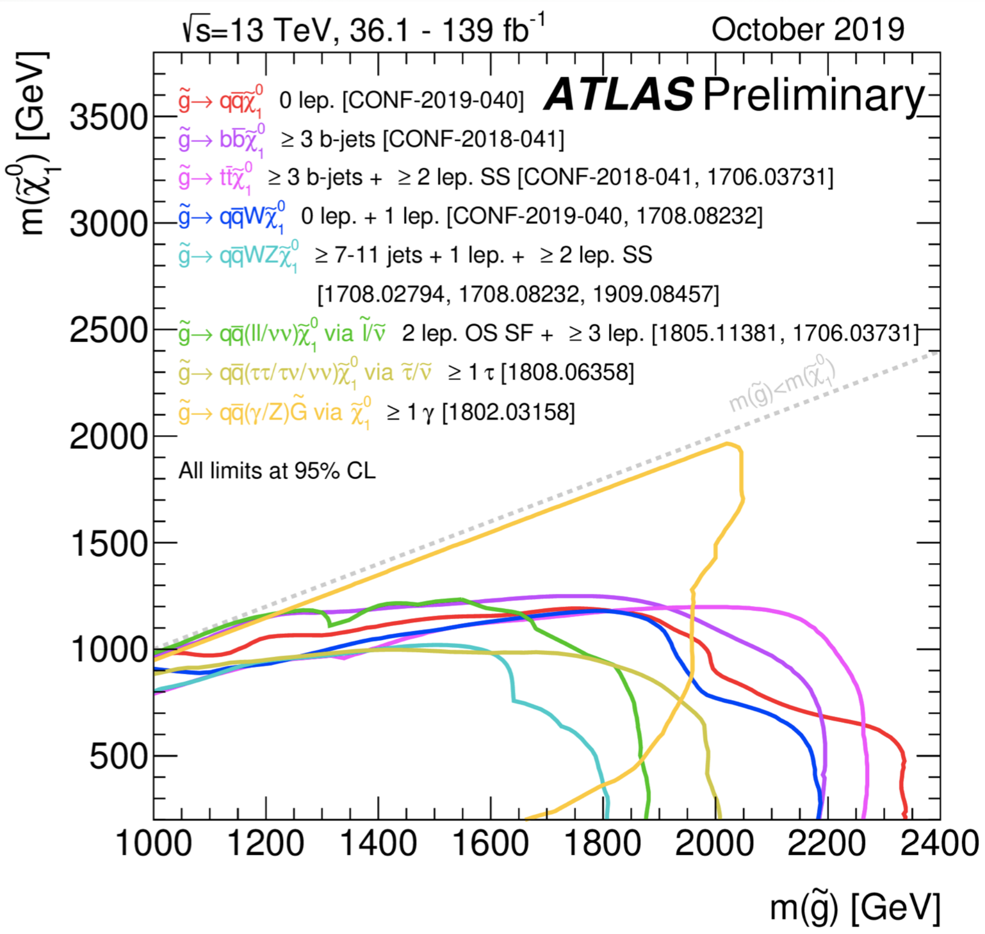


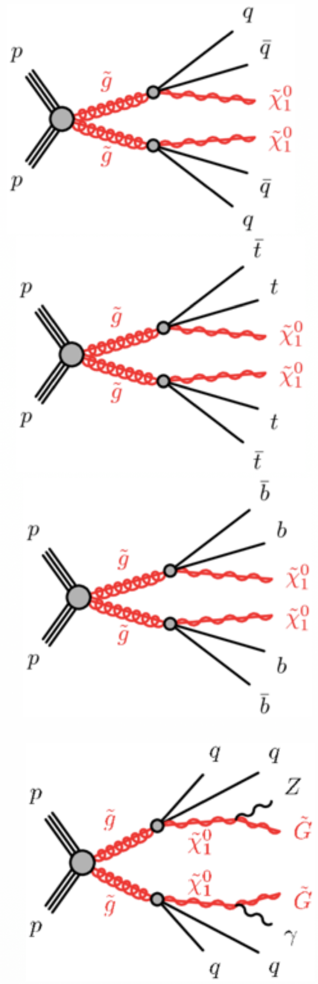


Excellent reach and potential for strong-production particles, as well as for higgsino and wino EWK

RPC Gluinos: current status

- Broad range of searches at current LHC experiments exploring a variety of final states and models





... and more

To remark:

Gluinos below 1-1.2 TeV excluded for any quark(+lepton)+E_T^{Miss} decay mode

Up to 2 TeV for GMSB-like SUSY models as well as for low LSP masses

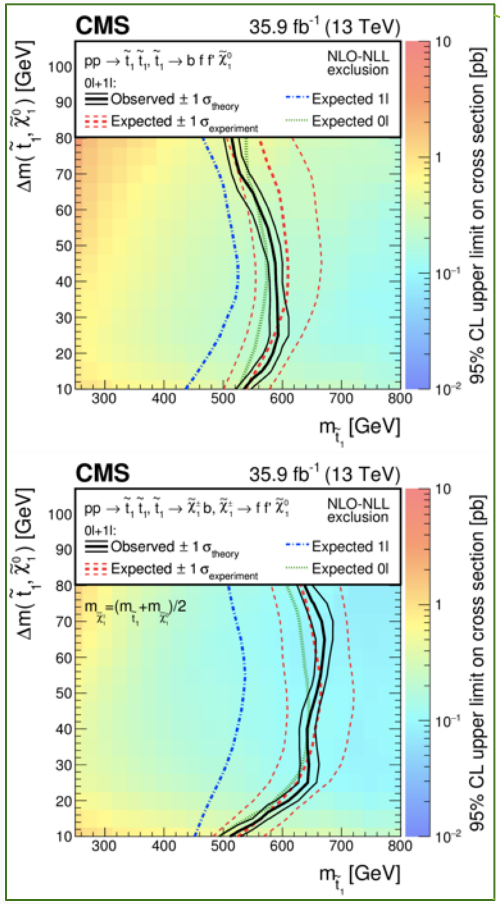
Stringent constraints for gluino into 3rd generation quarks ($tt\chi^0$ and $bb\chi^0$)

Monojet searches cover also low ΔM(gluino, χ^0) - down to 5-10 GeV

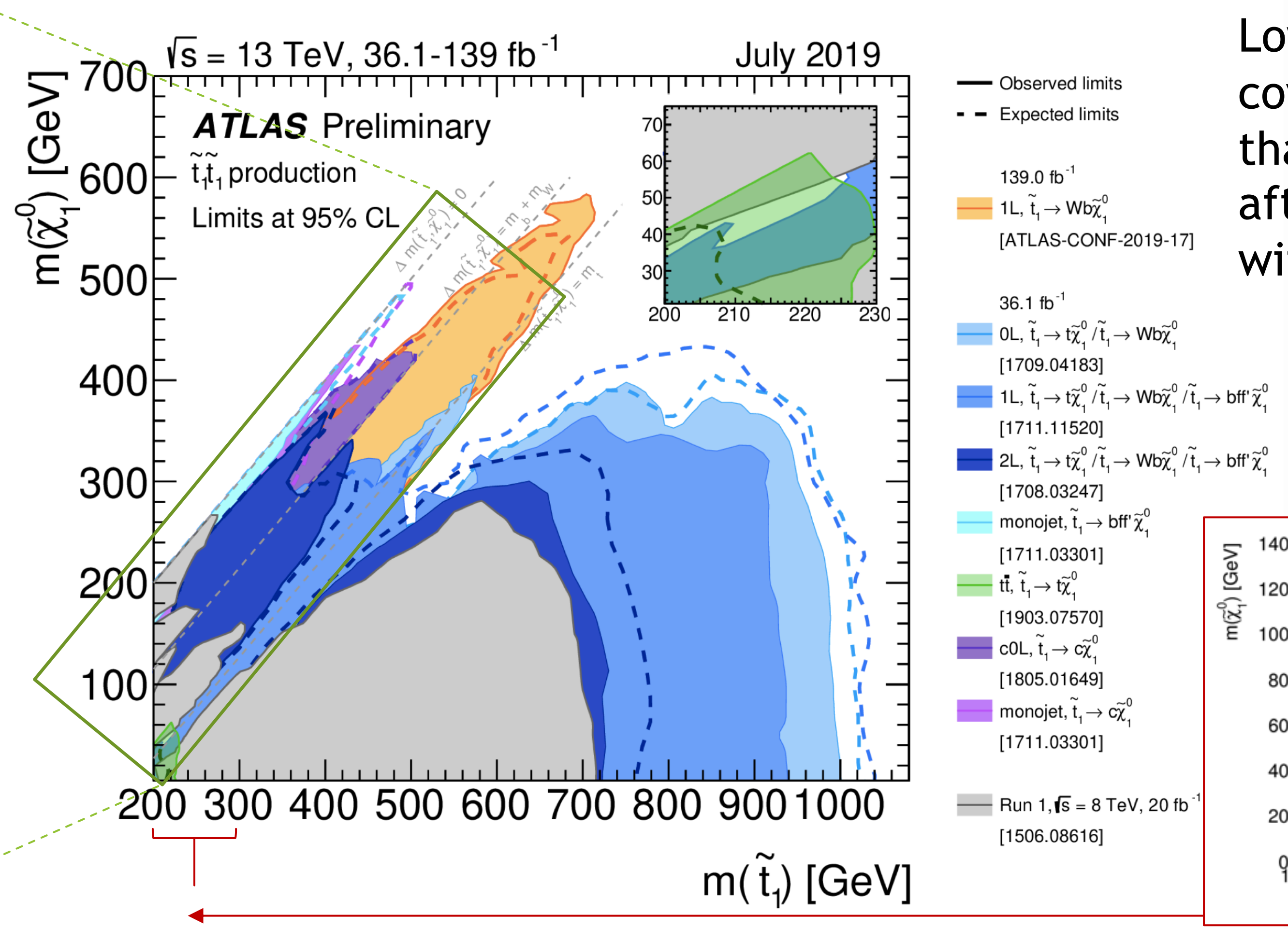
Top squarks: current status

Reach beyond 1 TeV for low LSP mass, covering LSP mass hypothesis up to ~ 400 GeV

4 body decays

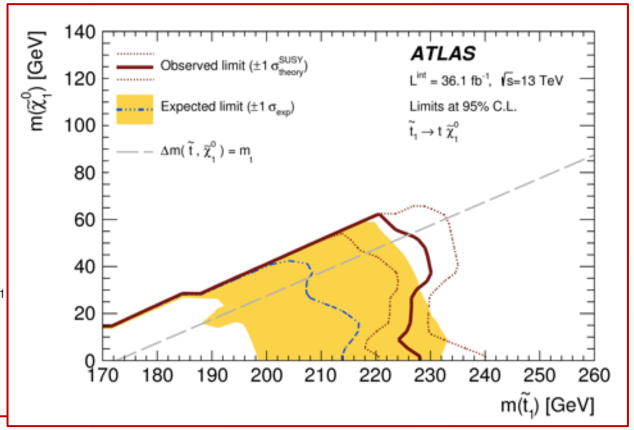


Stop → b + chargino



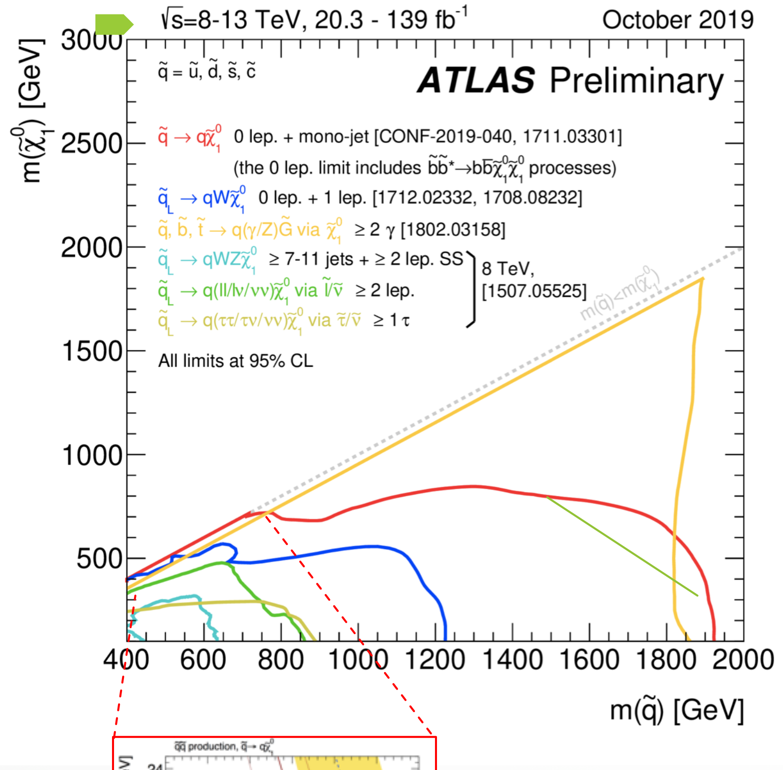
Low-mass region almost all covered; hard to imagine that loop-holes will still exist after HL-LHC [to be explored with full Run 2 data]

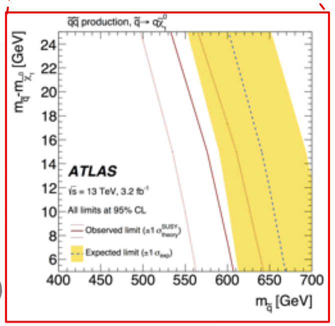
M(stop)~m(top) → spin correlation measurements



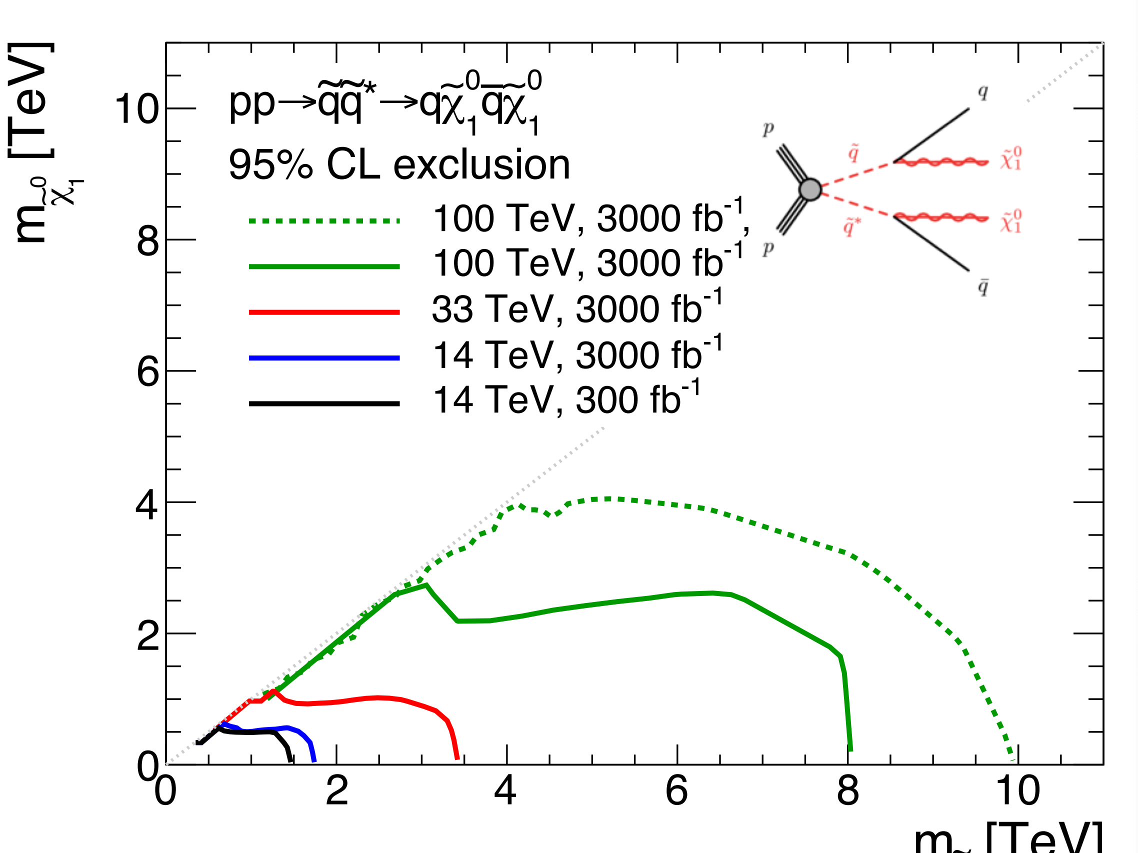
1st and 2nd generation squarks

- Projections available for HL-LHC, 33 TeV and 100 TeV
  - Current LHC reach depend on final state signature. Comparisons for jets+$\mathbf{E_T^{Miss}}$ final states:



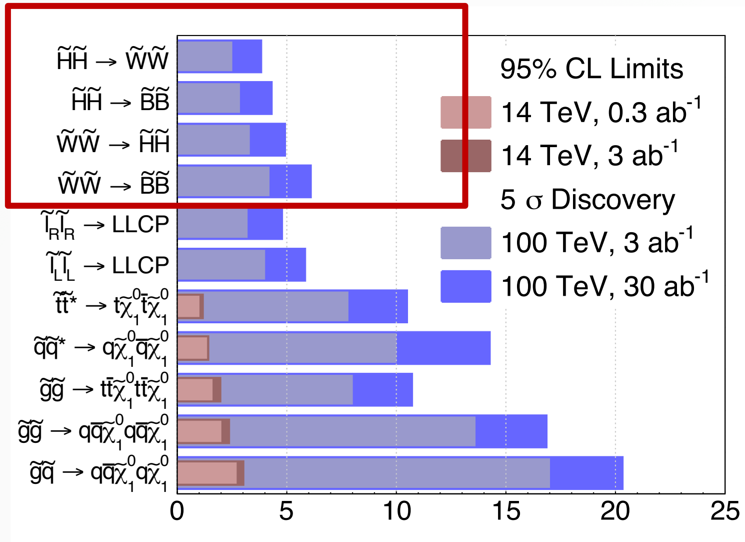


Coverage for compressed scenarios down to 5 GeV (prompt)



https://arxiv.org/pdf/1606.00947.pdf

charginos and neutralinos @ FCC-hh



CERN-ACC-2018-0056.pdf

- Searches in multilepton final state events + missing E_T
  - **3L** and **2L** (opposite-sign or same-sign different flavour)

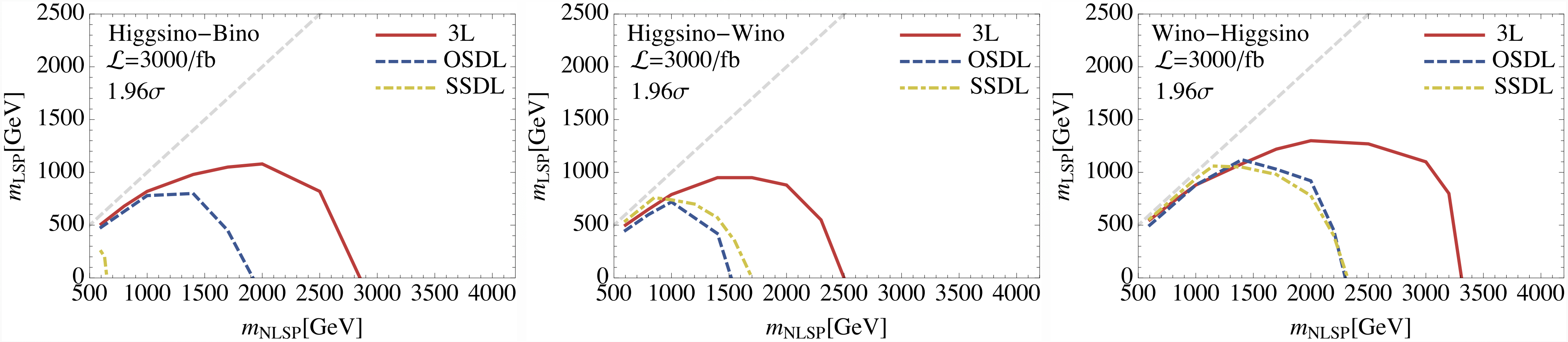
$$\chi_2^{0,\pm} \to \chi_1^{0,\pm} Z/h, \quad \chi_2^{0,\pm} \to \chi_1^{\pm,0} W,$$

$$W \to \ell\nu, \quad Z \to \ell^+\ell^-, \quad h \to ZZ^*, WW^* \to 4\ell, 2\ell 2\nu$$

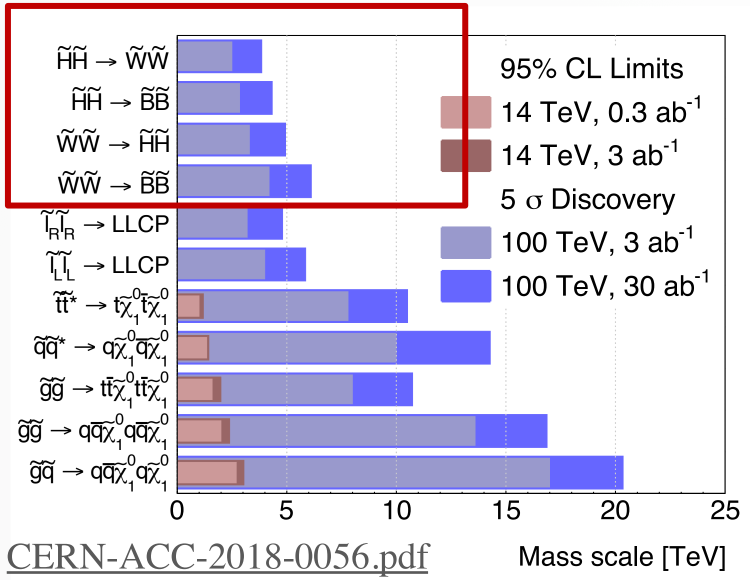
Results presented depending on the nature of the next-LSP and LSP

- Higgsino NLSP and Bino LSP (Higgsino-Bino) : $M_2 \gg \mu > M_1$.
- Higgsino NLSP and Wino LSP (Higgsino-Wino) : $M_1 \gg \mu > M_2$.
- Wino NLSP and Higgsino LSP (Wino-Higgsino) : $M_1 \gg M_2 > \mu$.

2σ exclusion bounds



charginos and neutralinos @ FCC-hh



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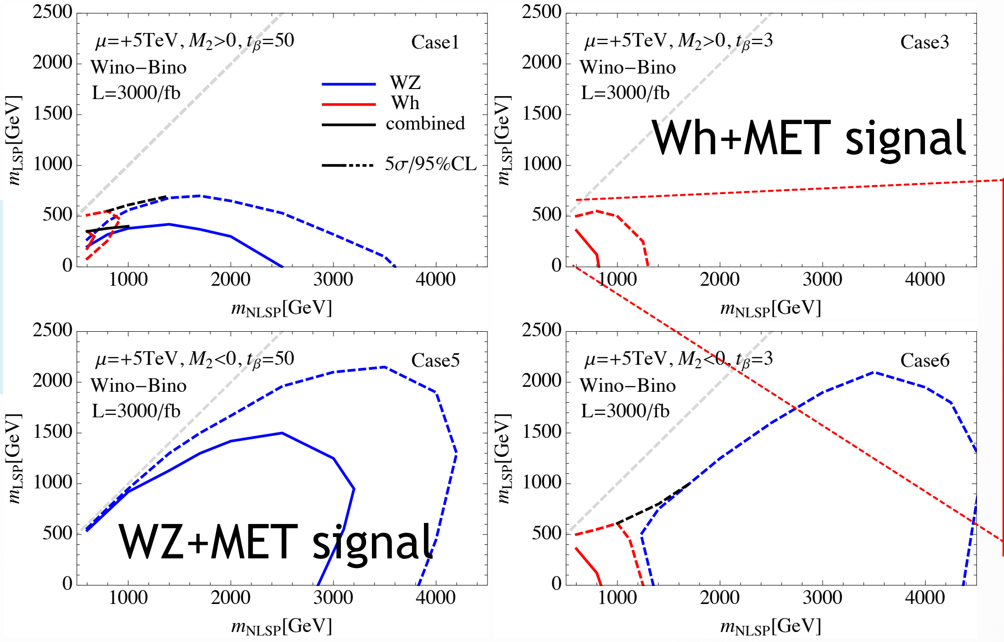
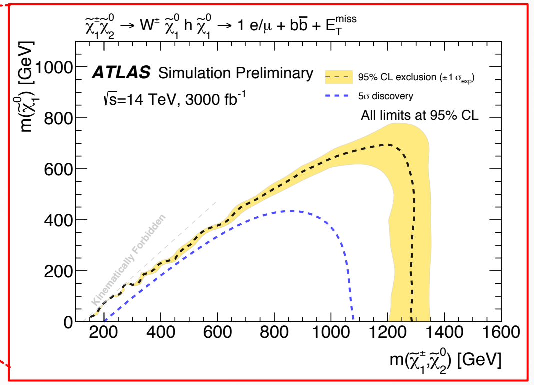


Conservative ! good sensitivity **at HL-LHC using H→bb signatures**



In summary: @ FCC-hh, results for wino-like to bino-like (higgsino-like) processes show sensitivity up to 4 (3) TeV with 3/ab

Note: this and other results are for a single experiment

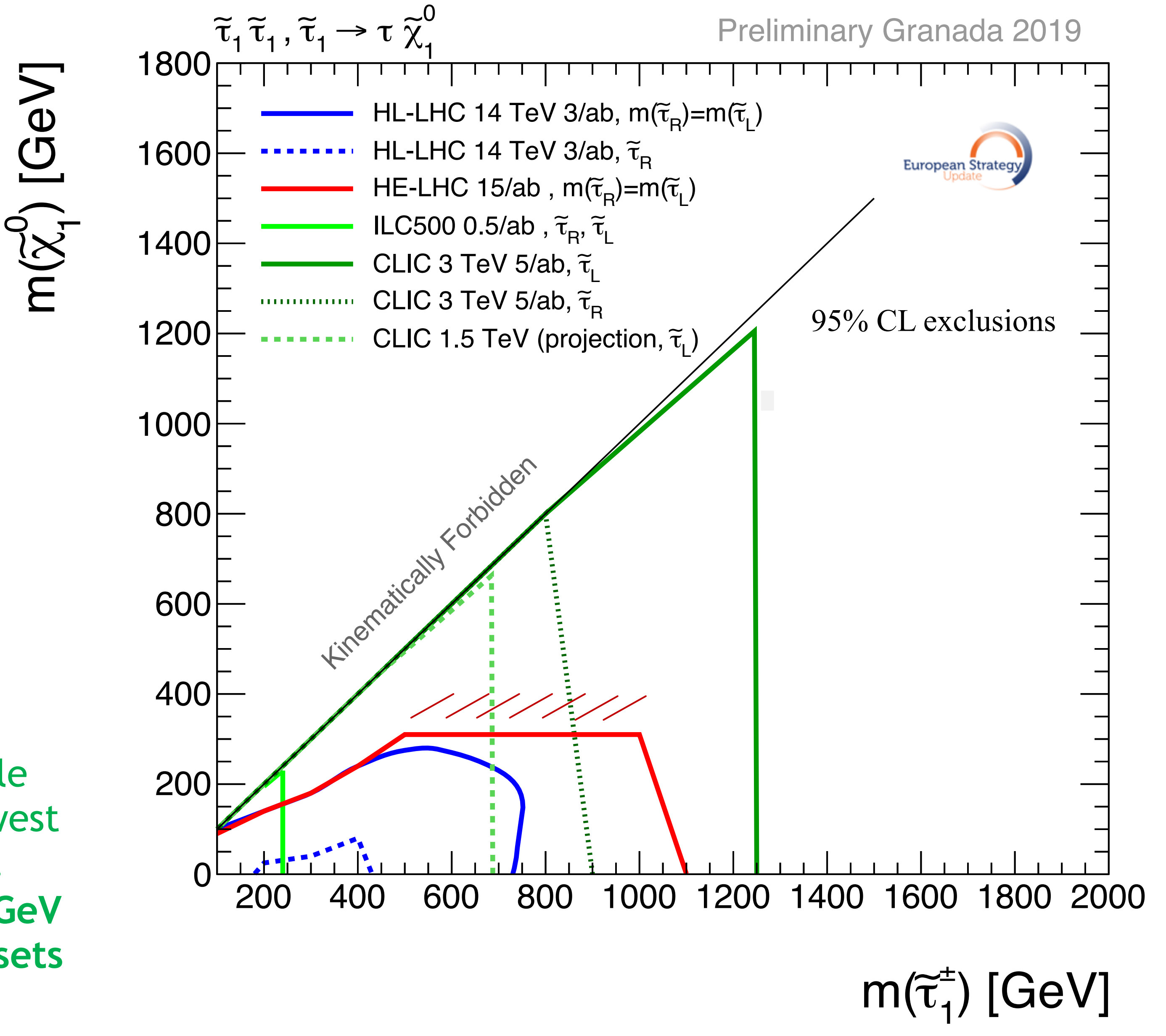
Stau reach

HL discovery up to 550 GeV ($\tilde{\tau}_R=\tilde{\tau}_L$)
For HE: ~ 800 GeV

Compressed regions can be addressed with ISR+$\tau\tau$

Reach for $\tilde{\tau}_R$ limited
(no discovery possible)

@ ILC500, mixing angle chosen to give the lowest possible production σ.
Discovery up to 230 GeV even with small datasets



For **CLIC 3 TeV**, studies performed with full simulation. Baseline case (4 ab^{-1} with P(e-) = -80% and 1 ab^{-1} with P(e-) = +80%) compared to non-polarized beams

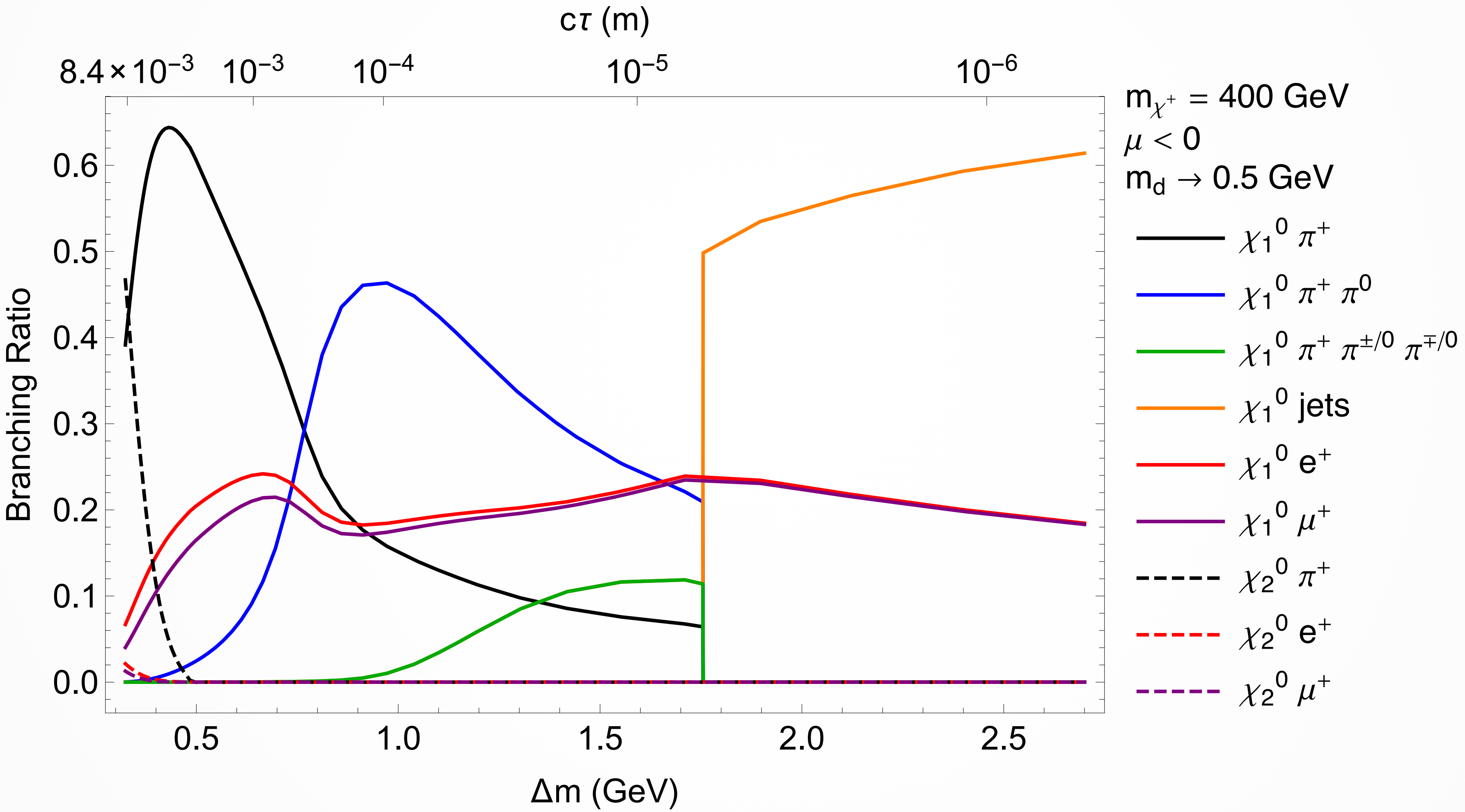
$\tilde{\tau}_L$: O(GeV) difference

$\tilde{\tau}_R$: ~ 150 GeV better for non-polarized beam

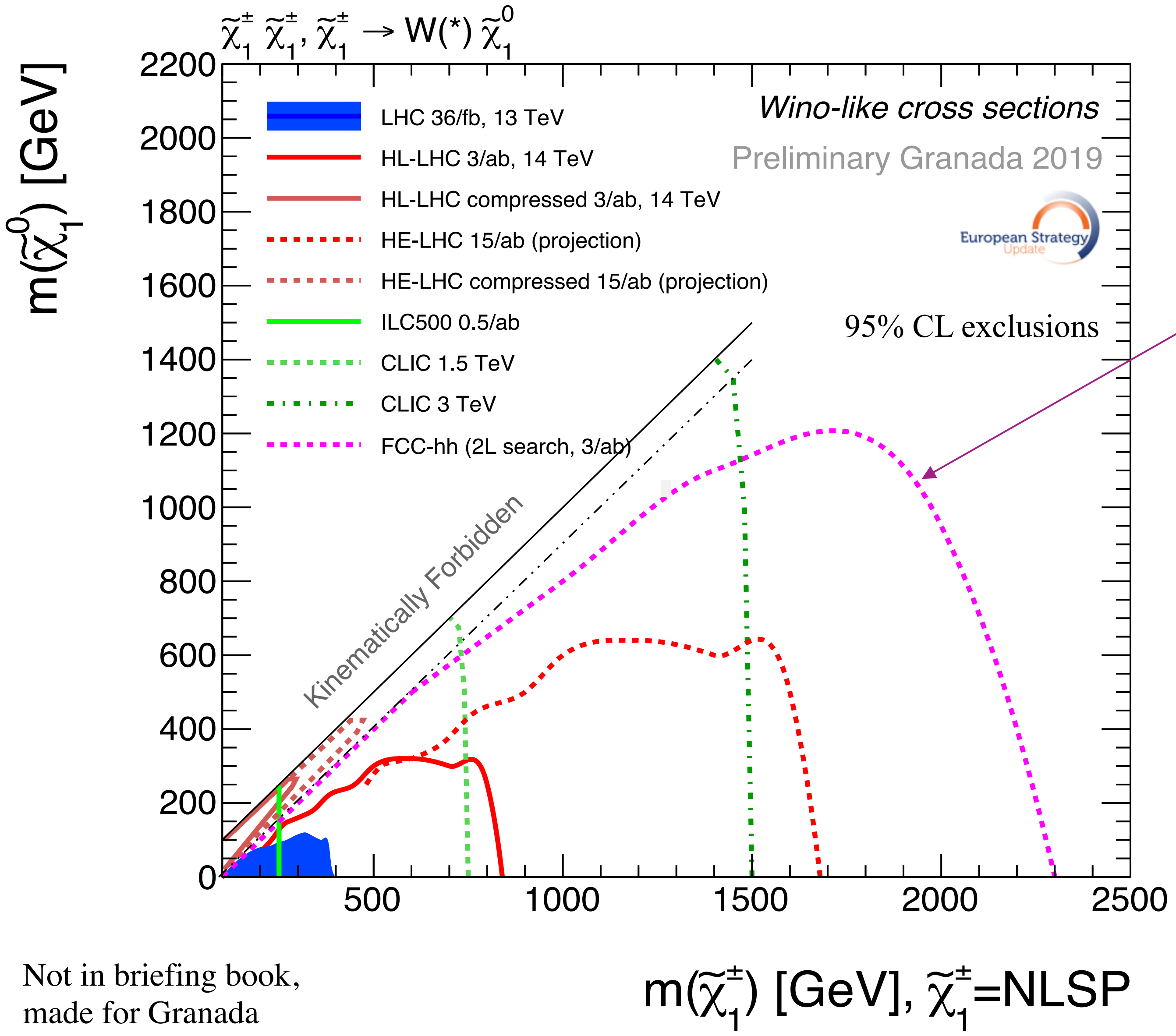
CLIC 3 discovery up to 1.1 TeV (700 GeV) for L(R) stau

Compressed scenarios EWK

- Decay branching ratios for a 400 GeV charged Higgsino as a function of Δm = and μ < 0

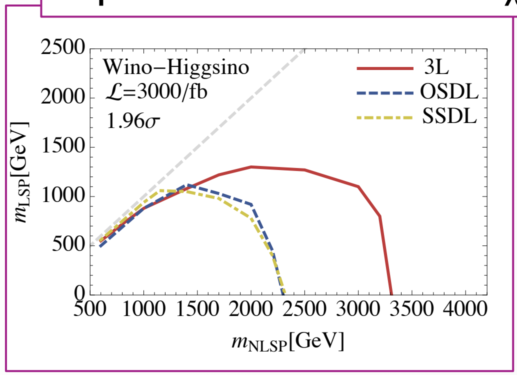


Wino-like cross section: $\chi^{+}{}_{1}\chi^{-}{}_{1}$

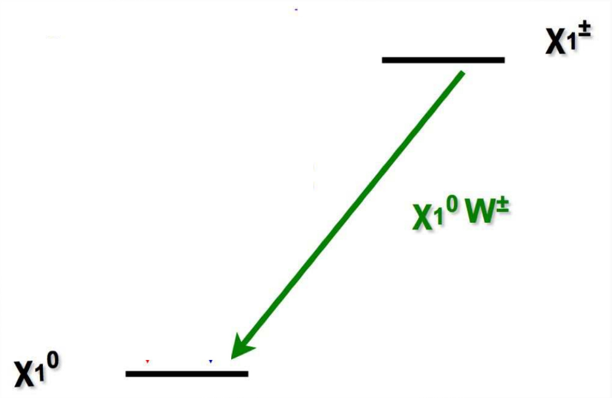


Not in briefing book,
made for Granada

FCC-hh Contour of the 2-lepton search used for $\chi^{+}{}_{1}\chi^{-}{}_{1}$

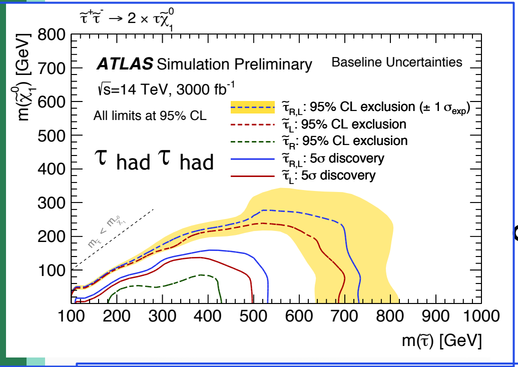


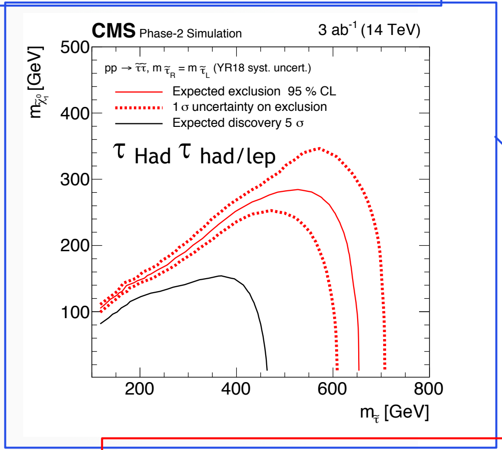
$\chi^{\pm}{}_{1}$ = NSLP, $\chi^{0}{}_{2}$ decoupled

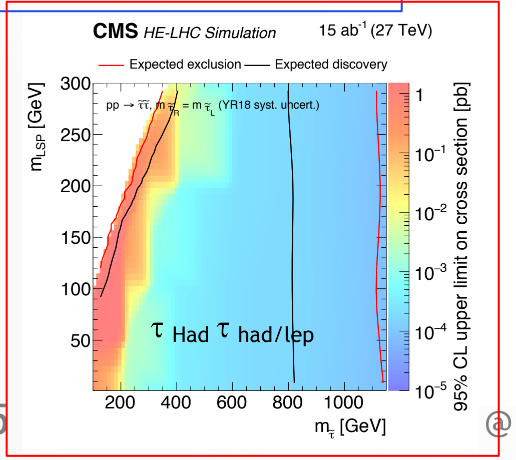


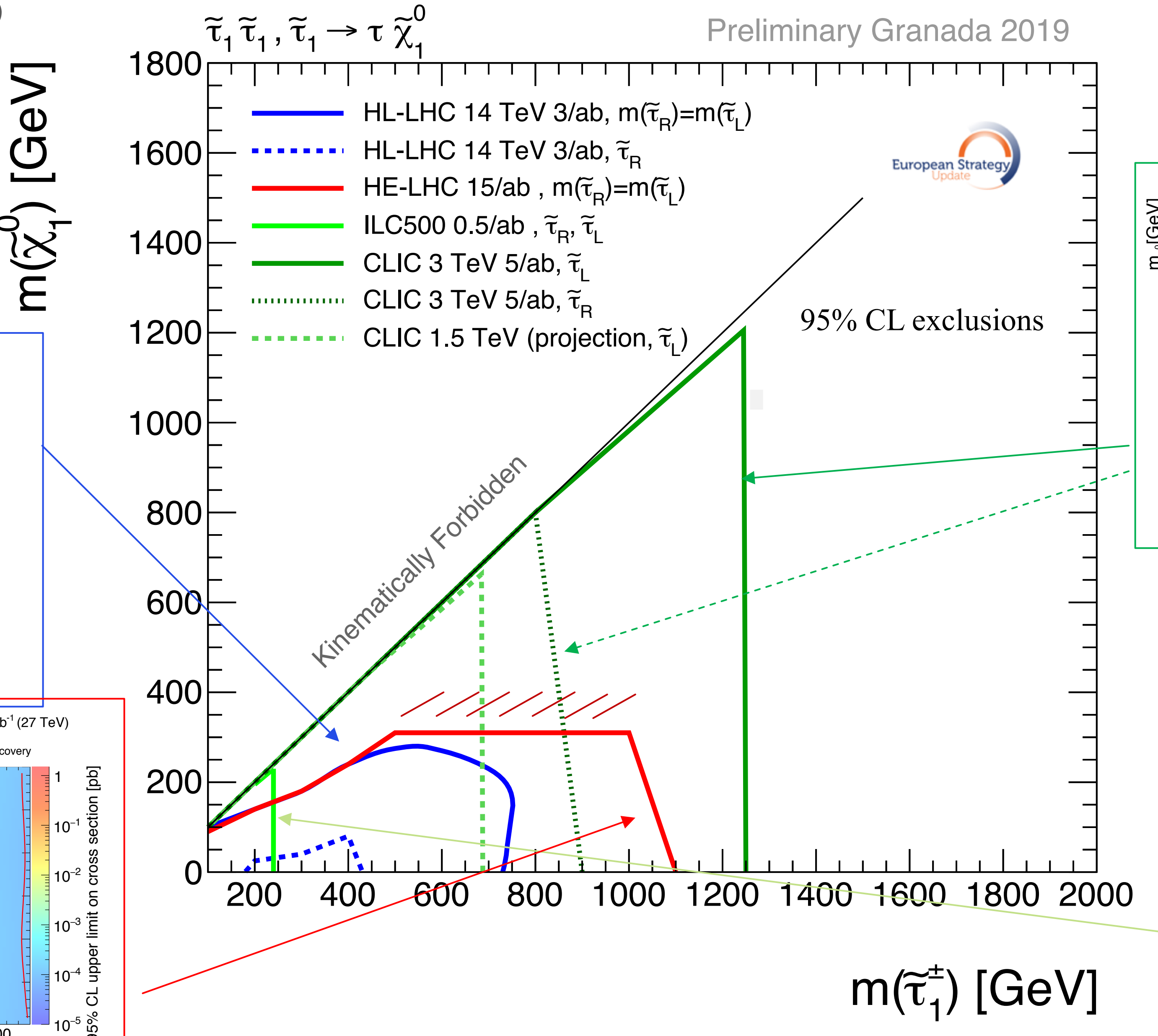
Stau reach

(Section 2.3 of arxiv:1812.07831)

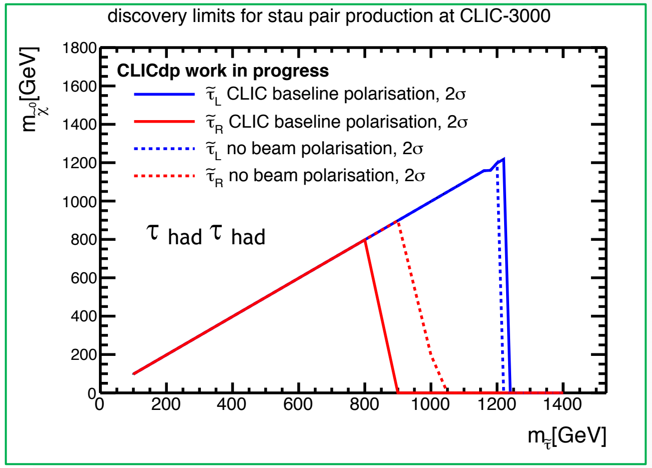


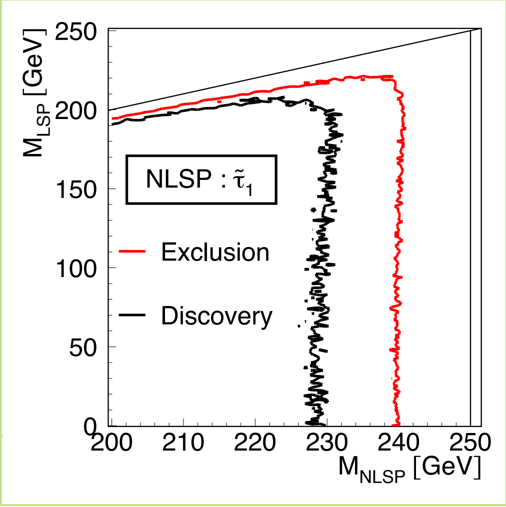






ES-follow up communication

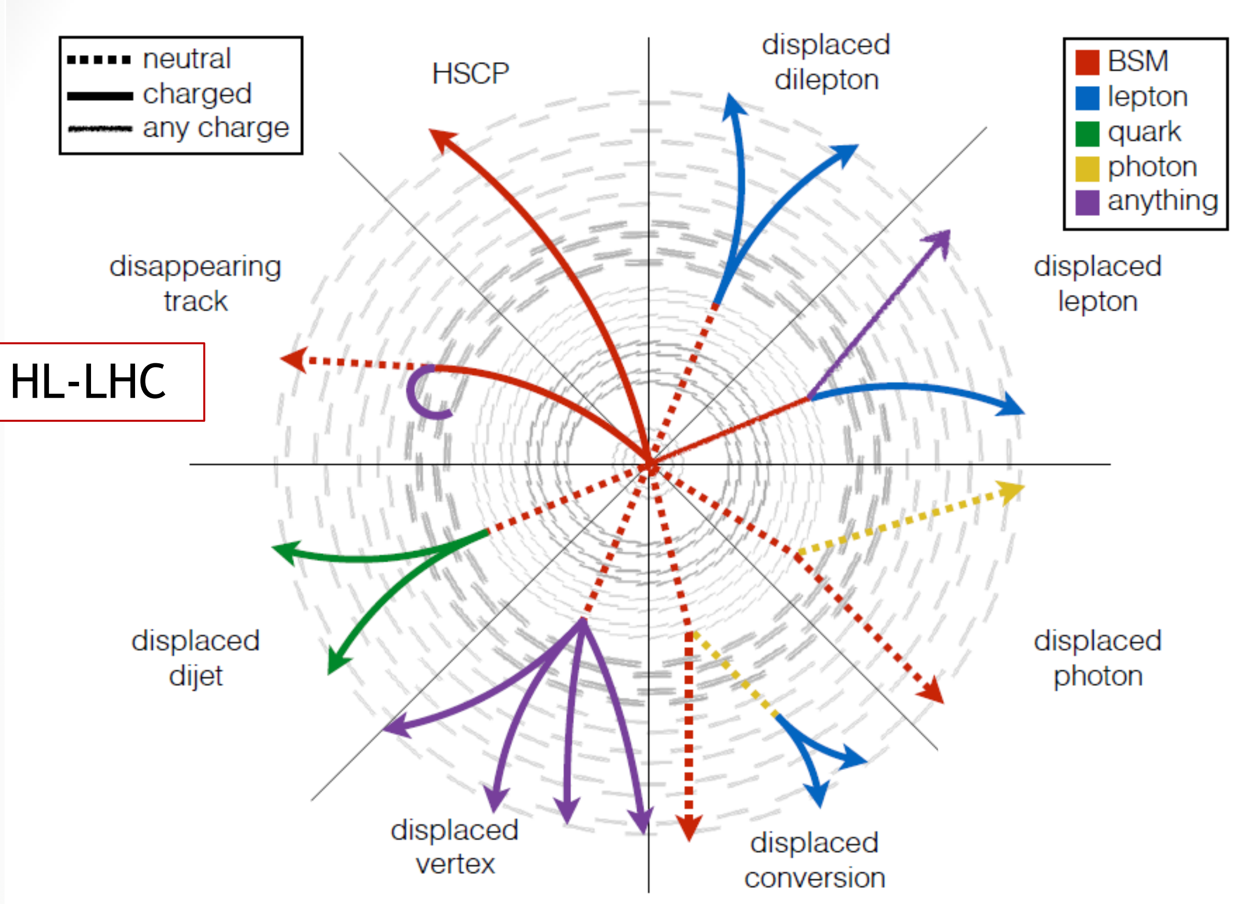




https://arxiv.org/abs/1903.01629

"Long-lived" SUSY particles

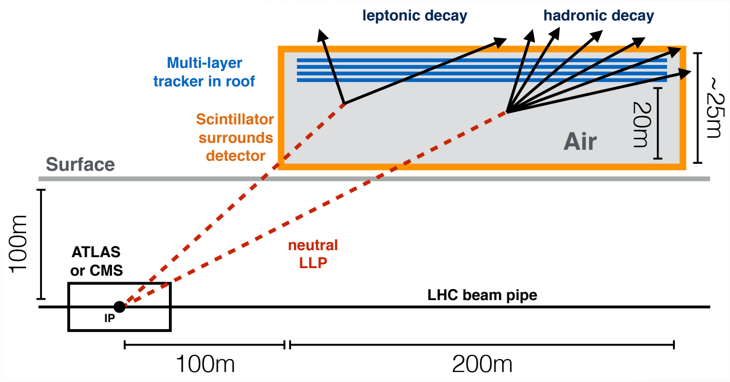
- Widely consider prompt production, non-prompt decays. In SUSY:
  - small couplings: RPV decays
  - small mass-splittings: almost degenerate next-LSP, decay through heavy squarks, Gauge-mediated models
- Phenomenology depends on lifetime and decays (hadrons, charged leptons, neutrals)



E.g. @ HL-LHC

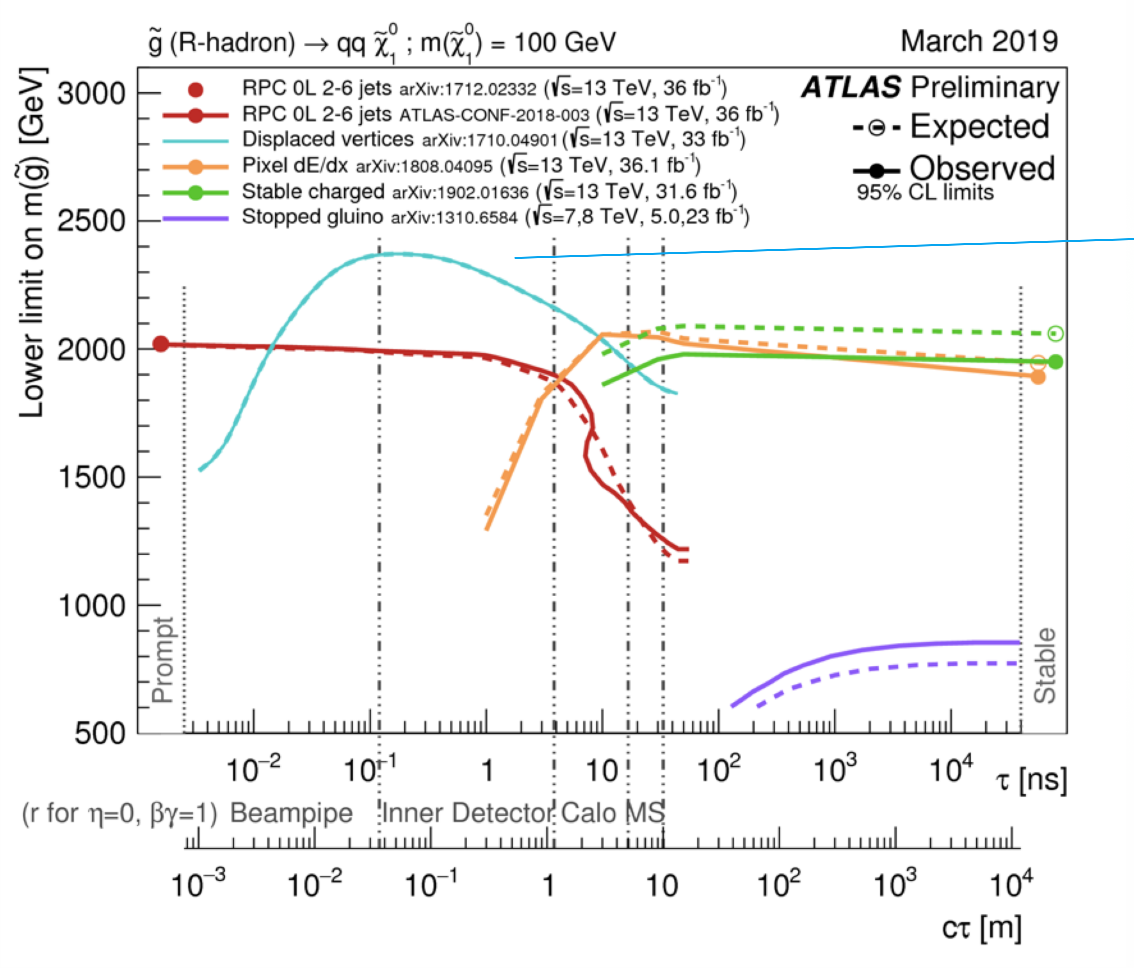
Response depends on the size/position of the detector!

For example:
@ HL-LHC: O(mm) → O(m)
@ Mathusla: O(100m) → O(km)

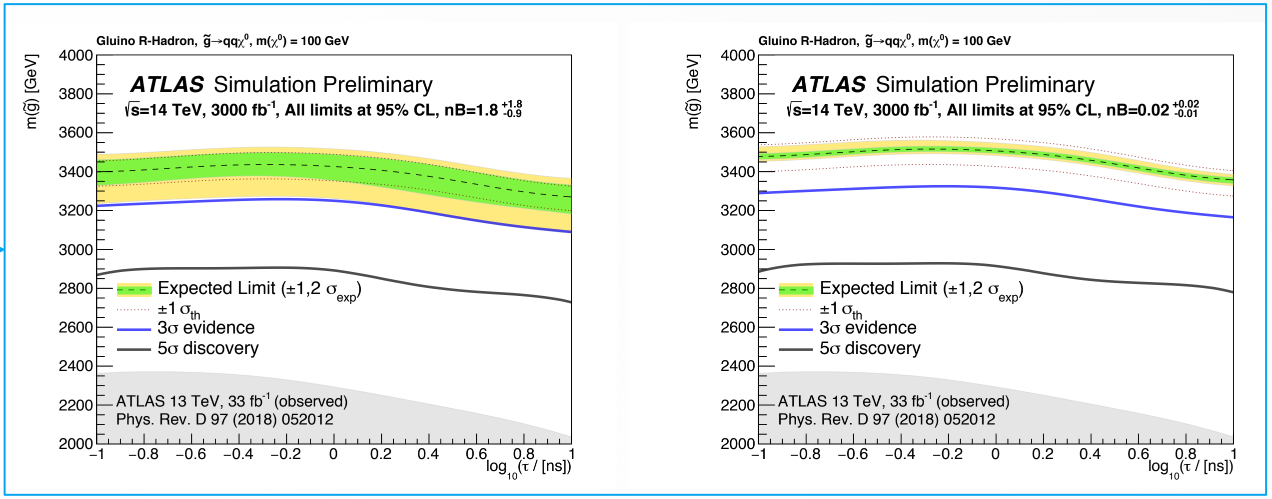


Gluino non-prompt signatures

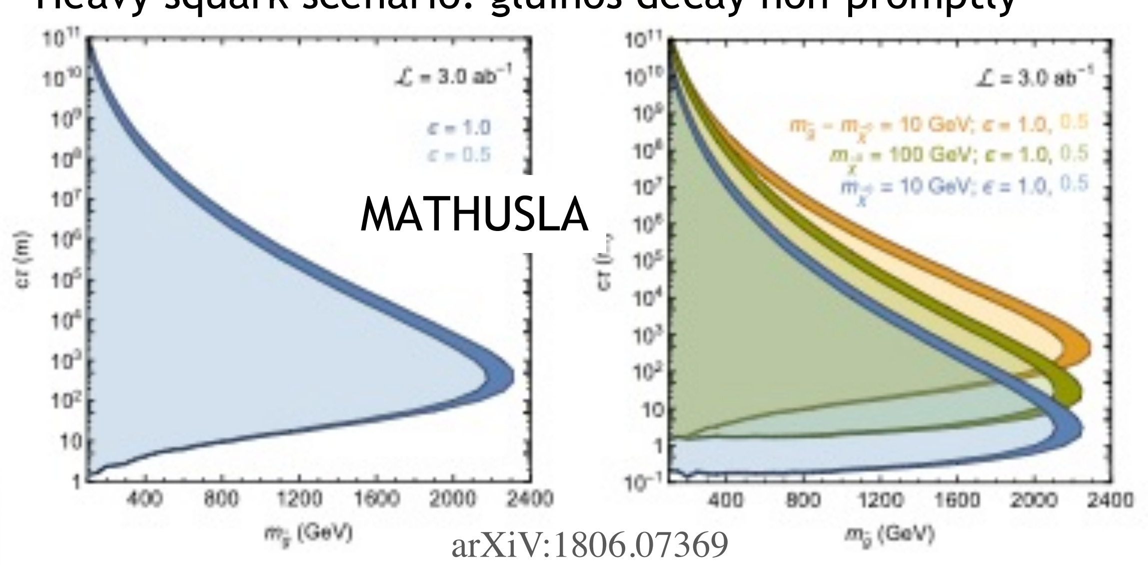
- From current LHC results to HL-LHC:



Displaced vertex (DV) analysis: very general for all sparticles decaying in hadrons within detector (Section 4.2.1 of arxiv:1812.07831)



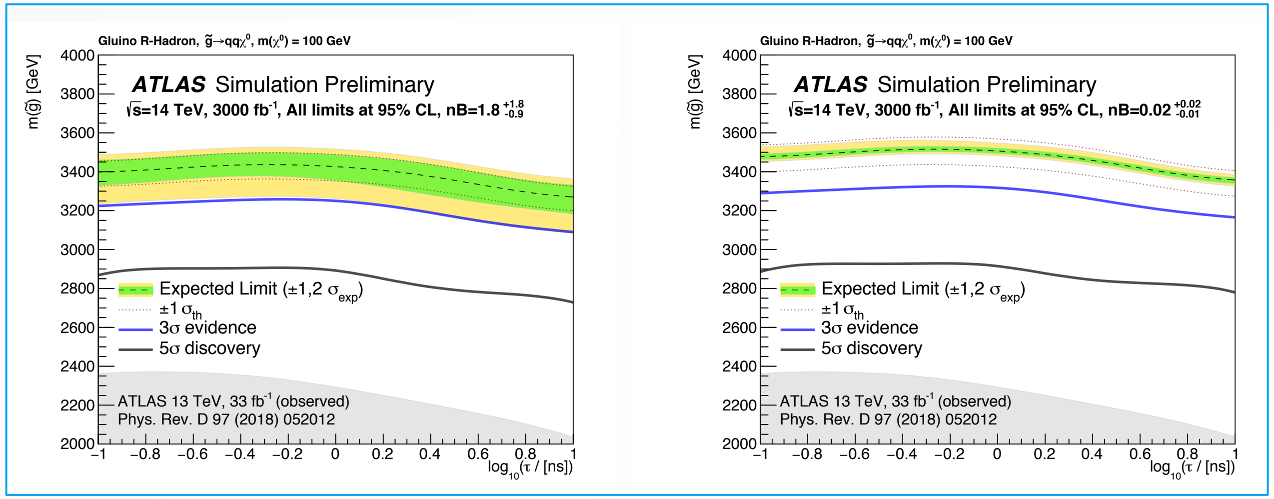
Heavy squark scenario: gluinos decay non-promptly



arXiV:1806.07369

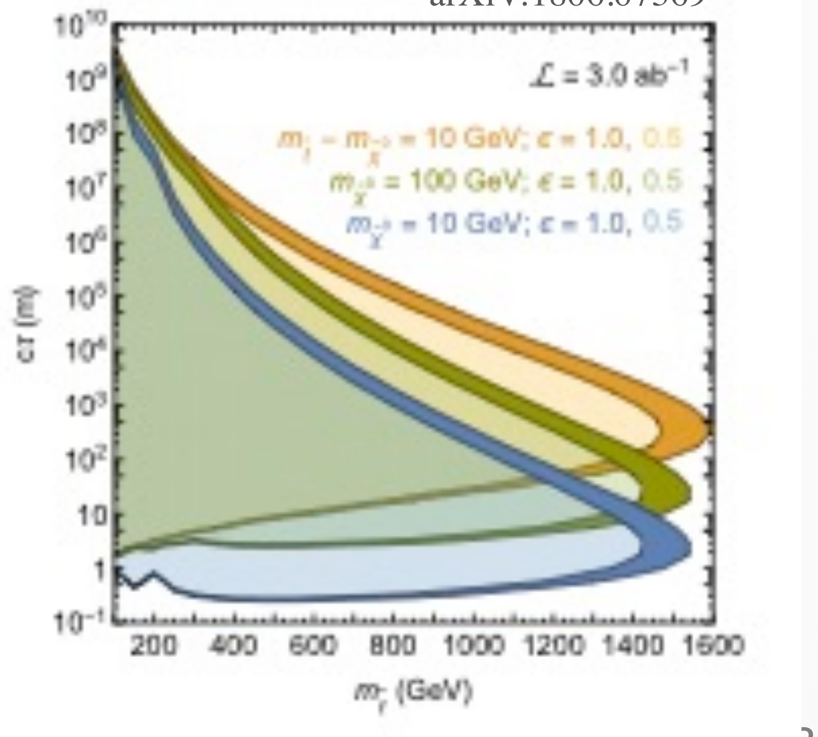
From gluino to stops

- Reinterpretation of DV analyses at HL-LHC could provide reach for stops:



HL-LHC reach for top squarks depends on cross section → Could be **as high as 2 TeV** considering the same kind of signatures for $c\tau$ O(m)

arXiV:1806.07369



MATHUSLA sensitive to various stop decays

Stop → particles via RPV λ'', λ' decays, e.g. same as shown for prompt RPV

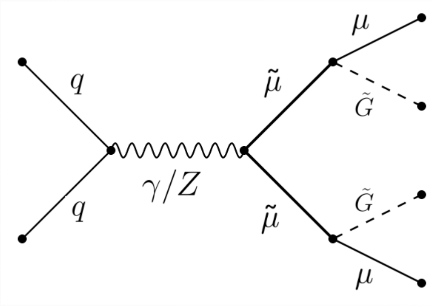
Complementarities for squarks in back-up

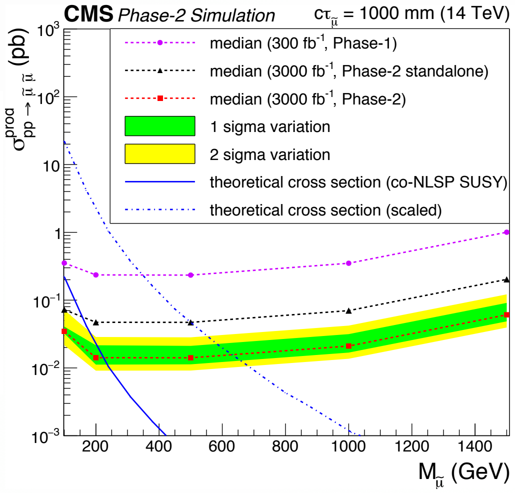
Other EWK SUSY and sleptons

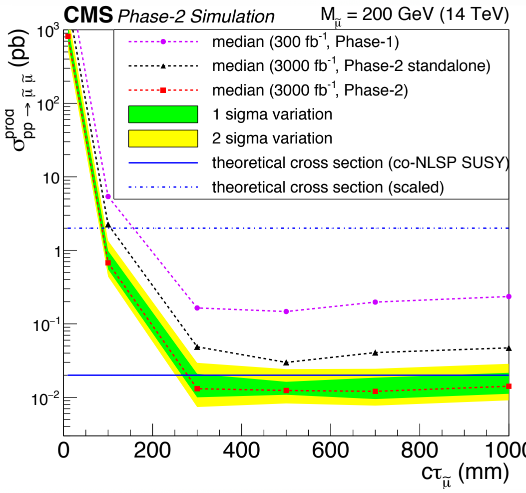
Various models might lead to displaced signatures.

(Section 4.2.2 of arxiv:1812.07831)

- GMSB @ HL-LHC





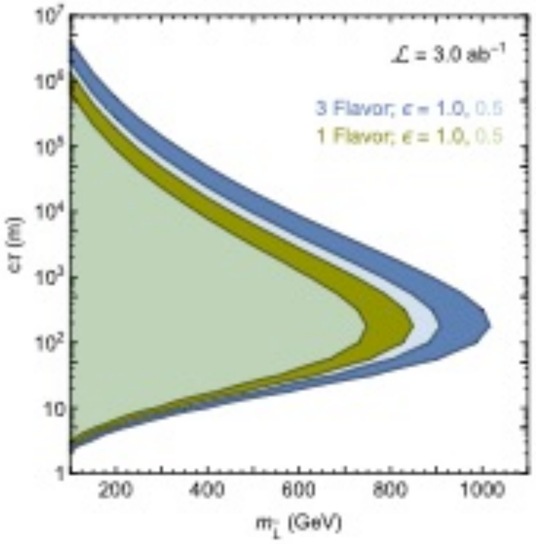


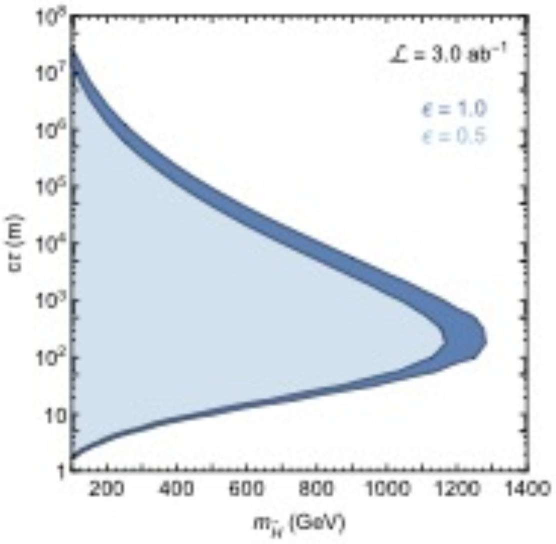
+ potential for stable non-zero charged particles (stau, gluino decays and more)

- RPV @ MATHUSLA

arXiV:1806.07369

sleptons





higgsinos

MATHUSLA sensitive to different cases wrt to disappearing tracks.

E.g. higgsino → particles via RPV λ'', λ' decays

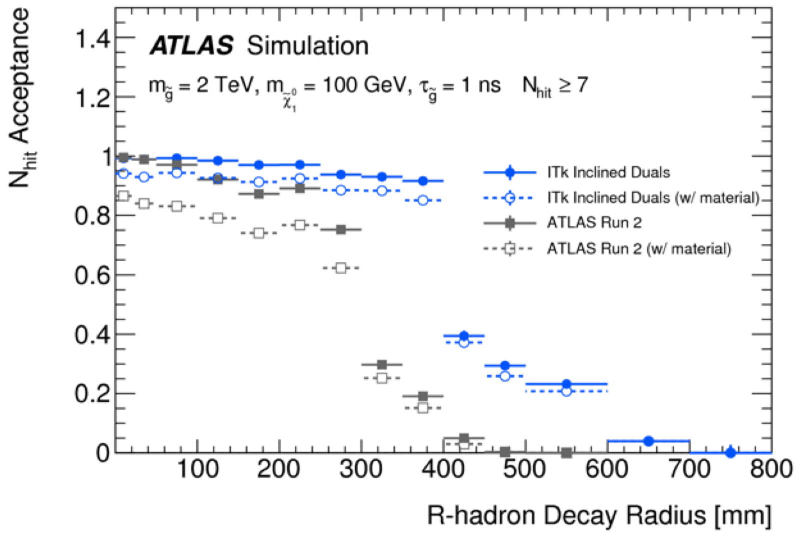
$\tilde H^0/\tilde H^\mp$	$(t/b)\,d\,d' + c.c$	λ'', η''
	$(t/b)\,\bar u\,\bar\nu + c.c$	η'
	$(t/b)\,\bar d\,\ell^- + c.c$	λ', η

Summary for long-lived particles

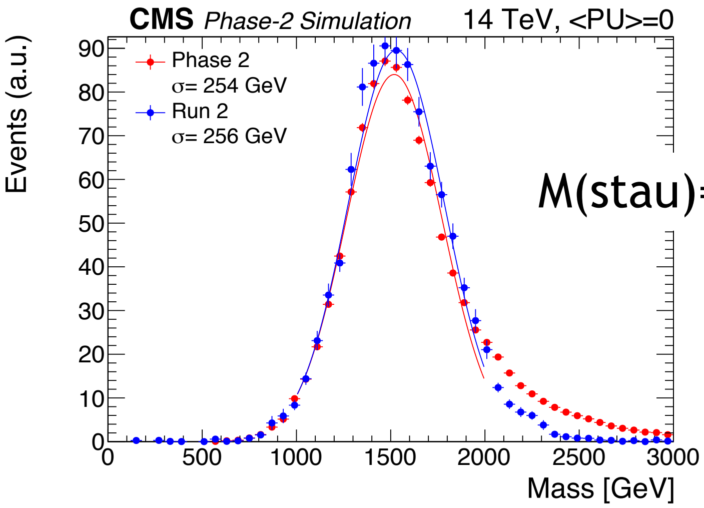
(Section 4 of arxiv:1812.07831)

- Non-prompt signatures studies require **specialized techniques** and good understanding of the detector performance
- Low or zero-background hypotheses as well as impact of high pile-up for pp machines must be verified
  - Several studies are presented considering two or more assumptions on N background and/or N signal events
- Overall, it is noticeable a good complementarities across facilities/experiments
  - HL-LHC and pp colliders allow the highest mass reach for R-hadrons and for stable massive particles in general
  - MATHUSLA can complement HL-LHC for 200 m < $c\tau$ < 5 km and extend sensitivity of the main detectors
  - In the short lifetime regime, $c\tau \sim O(10^{-4}\text{-}10^{-2}$ m), e+e- colliders have very good sensitivity as well as e-p colliders, with reaches depending on sqrt(s)

Displaced vertex @ ATLAS-HL-LHC



Mass resolution for stable stau with Time-Of-Flight info @ CMS-HL-LHC



M(stau)=1.6 TeV