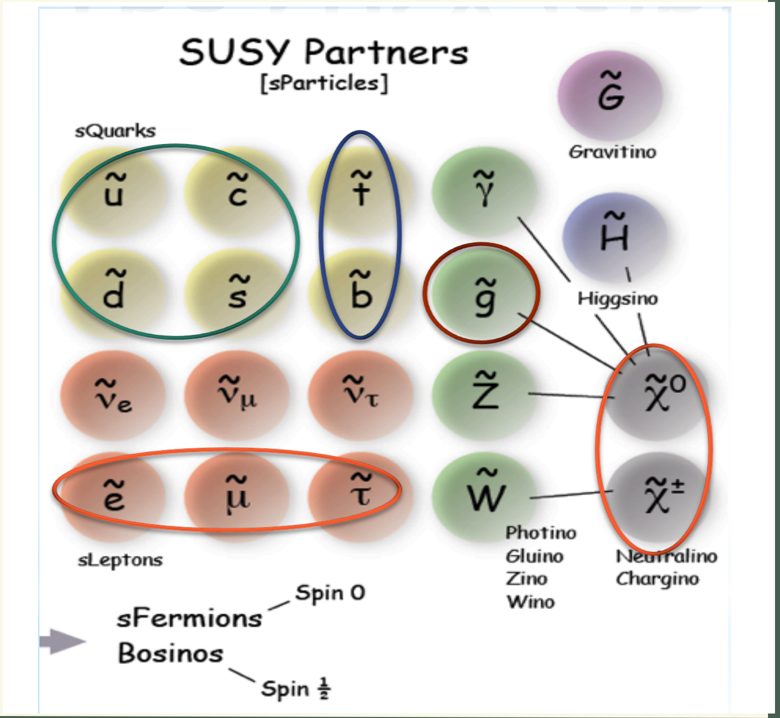



UNIVERSITY OF LIVERPOOL

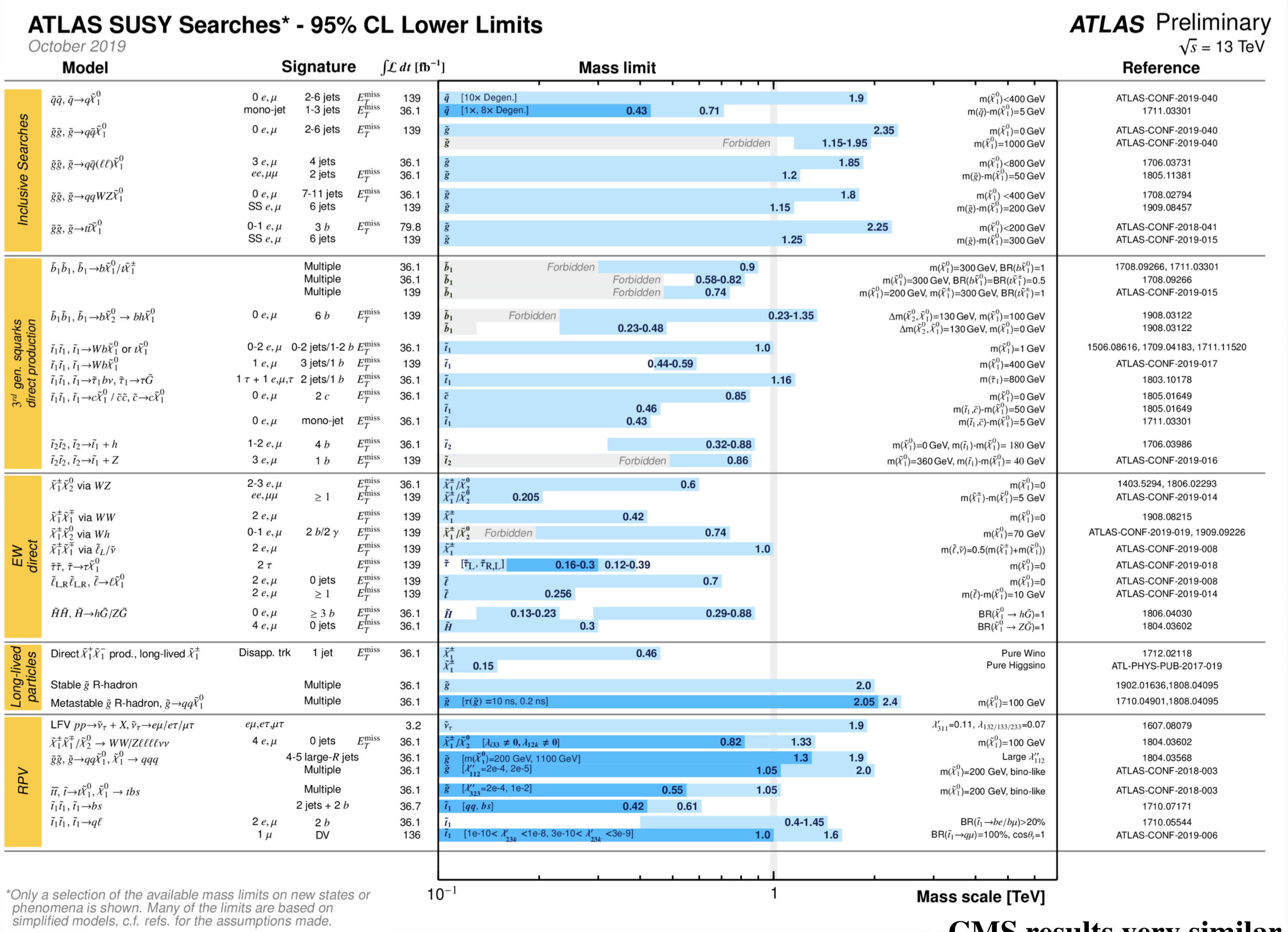
# BSM at the FCC-hh: Supersymmetry

Monica D'Onofrio
University of Liverpool

FCC-France workshop
15/5/2020

# Supersymmetry: status of the art

- SUSY is one of the main focus of the ATLAS and CMS programmes since Run 1.
- Searches cover strong and electroweak particles production in R-parity conserving (RPC) and violating (RPV) SUSY models, considering prompt and non-prompt decays
- Inclusive and dedicated searches with thousands of signal regions are performed → results can be generalized




CMS results very similar

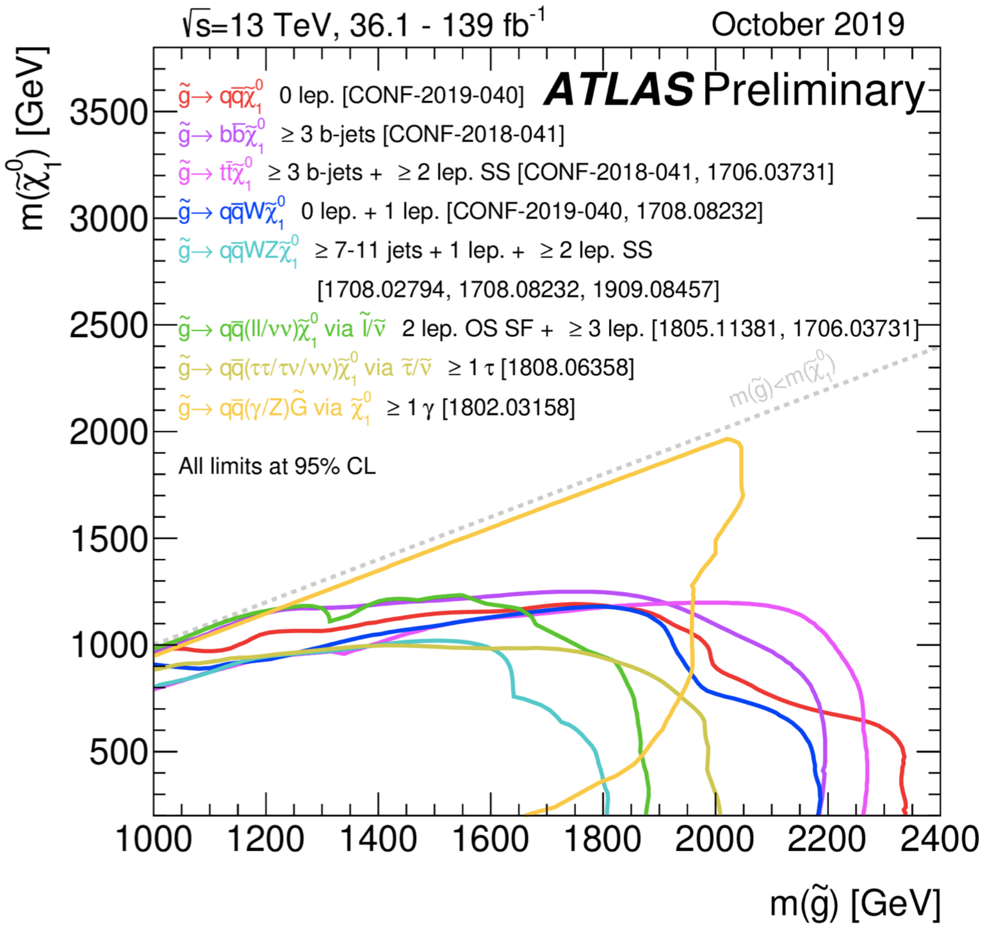
**Searches for SUSY are relevant well beyond SUSY itself!**

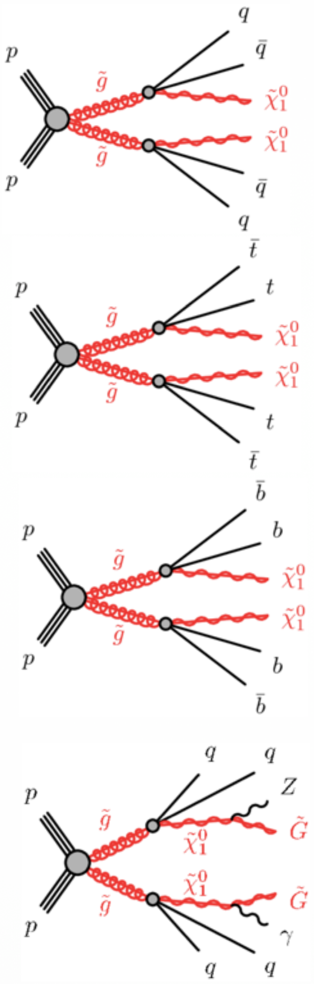
# FCC-hh prospects on SUSY: outline

- 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, consider **benchmarks - often simplified models**
  - Strong production (**gluinos**, 1st and 2nd generation squarks, **top squarks**): where the energy reach counts the most
  - Weak production (**charginos, neutralinos, sleptons**): rarer processes, depending on model parameters difficult but not impossible, also in 'compressed' scenarios.
- Targeted signatures depend on assumptions. In the following, we consider **direct** searches for:
  - RPC 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.
  - (an example of) RPV SUSY OR highly compressed RPC SUSY spectra: leading to feebly interacting or non-prompt signatures; specialised techniques are used → very difficult to assess feasibility at these early stages
- Various sources:
  - FCC Volume 1 book and references therein: CERN-ACC-2018-0056.pdf, https://arxiv.org/pdf/1606.00947.pdf
  - European Strategy Briefing book: https://arxiv.org/abs/1910.11775
    - **current LHC searches/HL-LHC studies used for some of the FCC-hh results where not yet available**

# 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

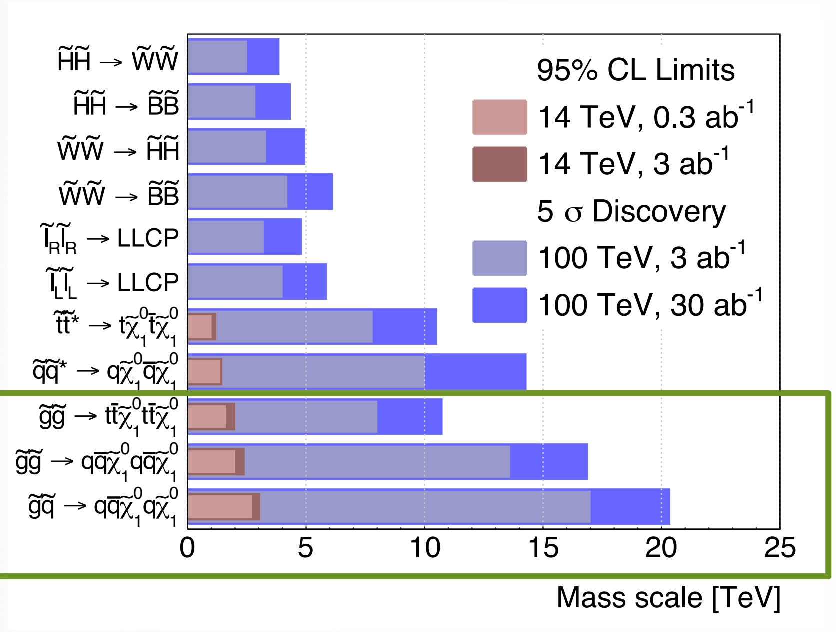
Stringent constraints for gluino into 3rd generation quarks ($tt\chi^0$ and $bb\chi^0$)

Monojet searches cover also low $\Delta M$(gluino, $\chi^0$) - down to 5-10 GeV

**@ HL-LHC, gluino masses up to 3.2 TeV will be excluded depending on model, with chance for discovery up to ~ 3 TeV**

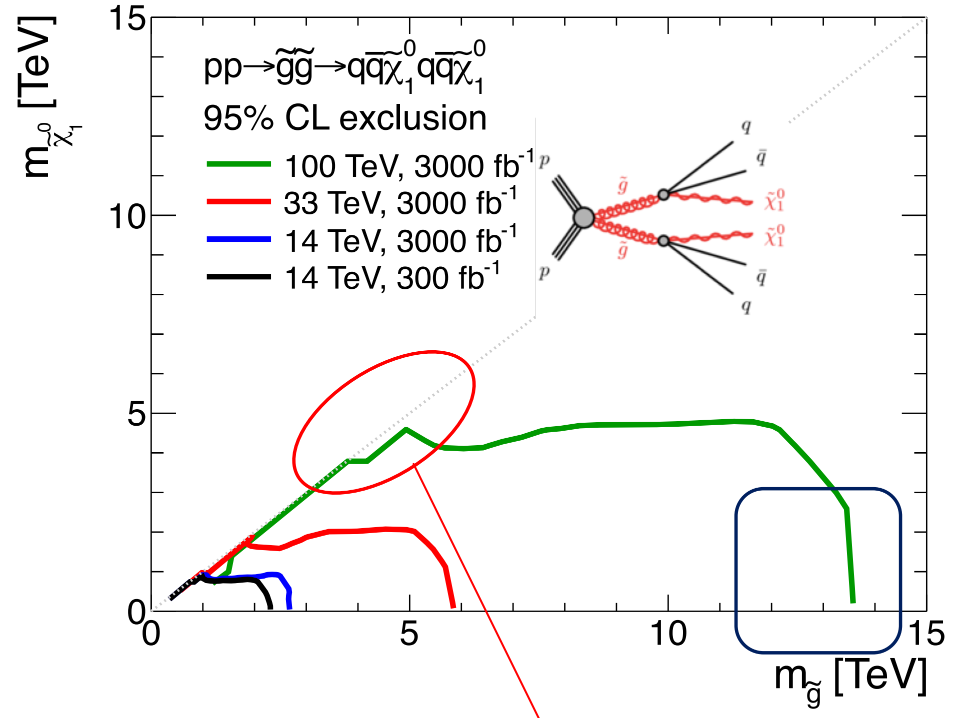
# RPC Gluinos: FCC-hh

- 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: **~ 500 GeV - 1 TeV lower than exclusion**




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

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

# RPC gluinos: summary

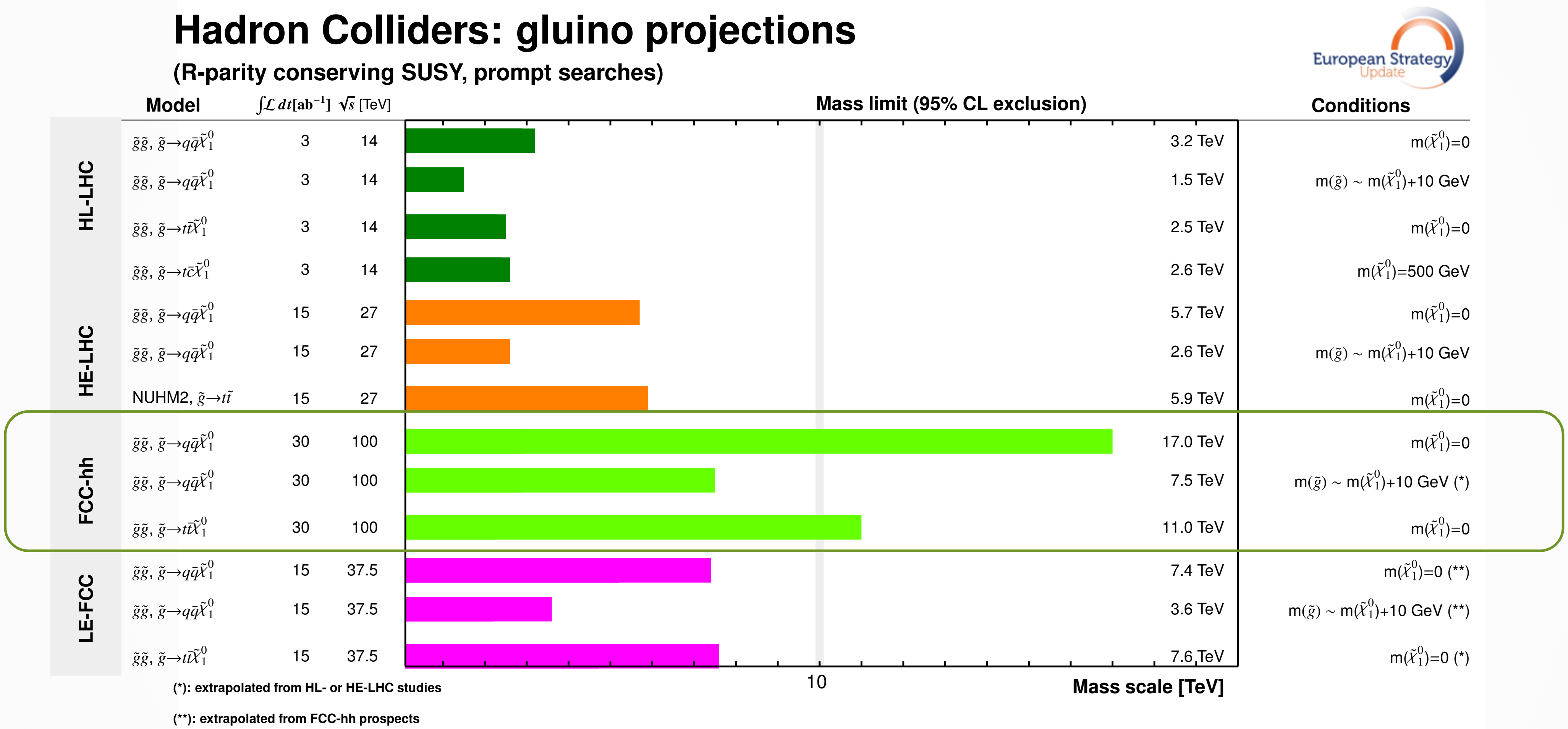



Fig. 8.6: Gluino exclusion reach of different hadron colliders: HL- and HE-LHC [443], and FCC-hh [139, 448]. Results for low-energy FCC-hh are obtained with a simple extrapolation.

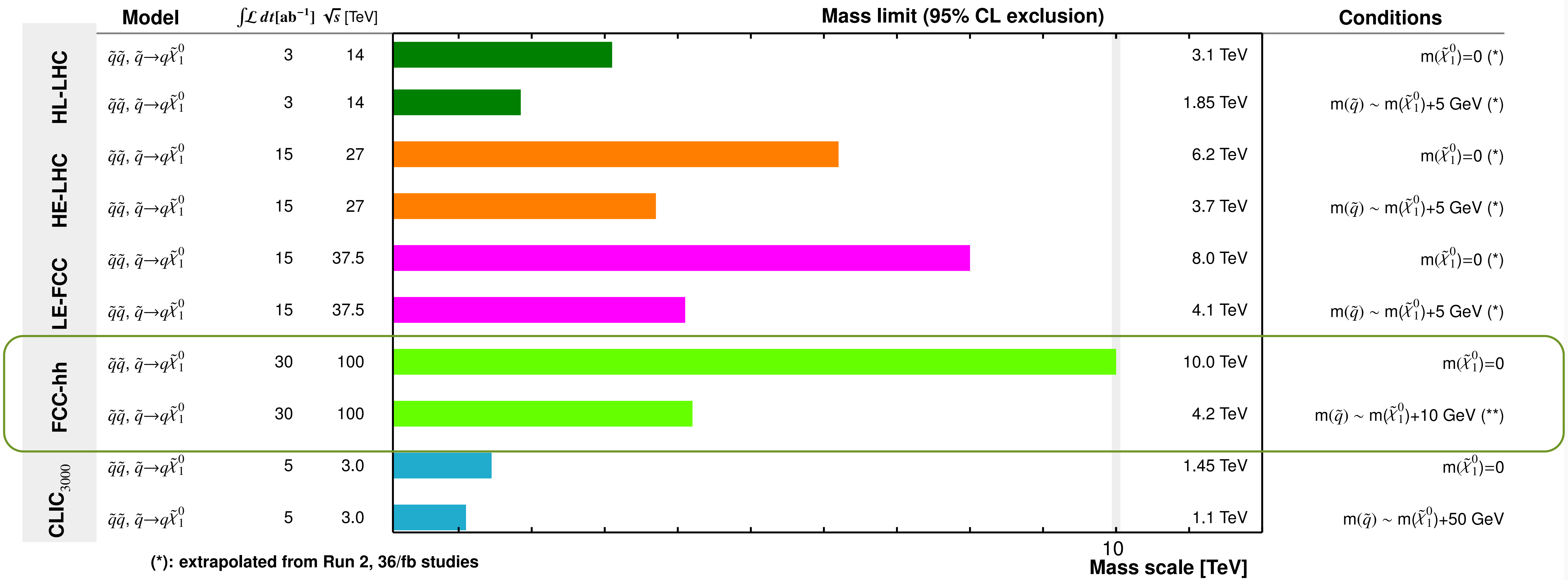
(*) indicates projection using parton lumi rescaling (ColliderReachTool)

# Summary of 1st and 2nd generation squarks

## All Colliders: squark projections

**(R-parity conserving SUSY, prompt searches)**

European Strategy Update



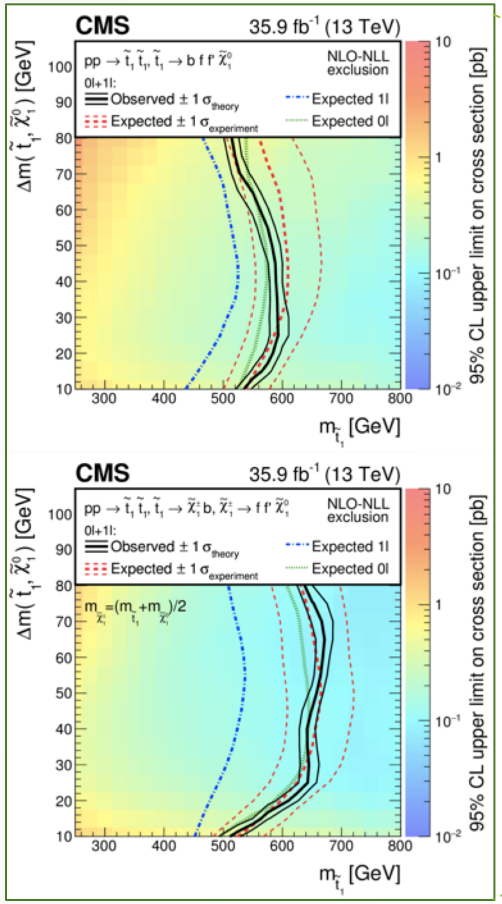

**(*): extrapolated from Run 2, 36/fb studies**

**(**): monojet results not included**

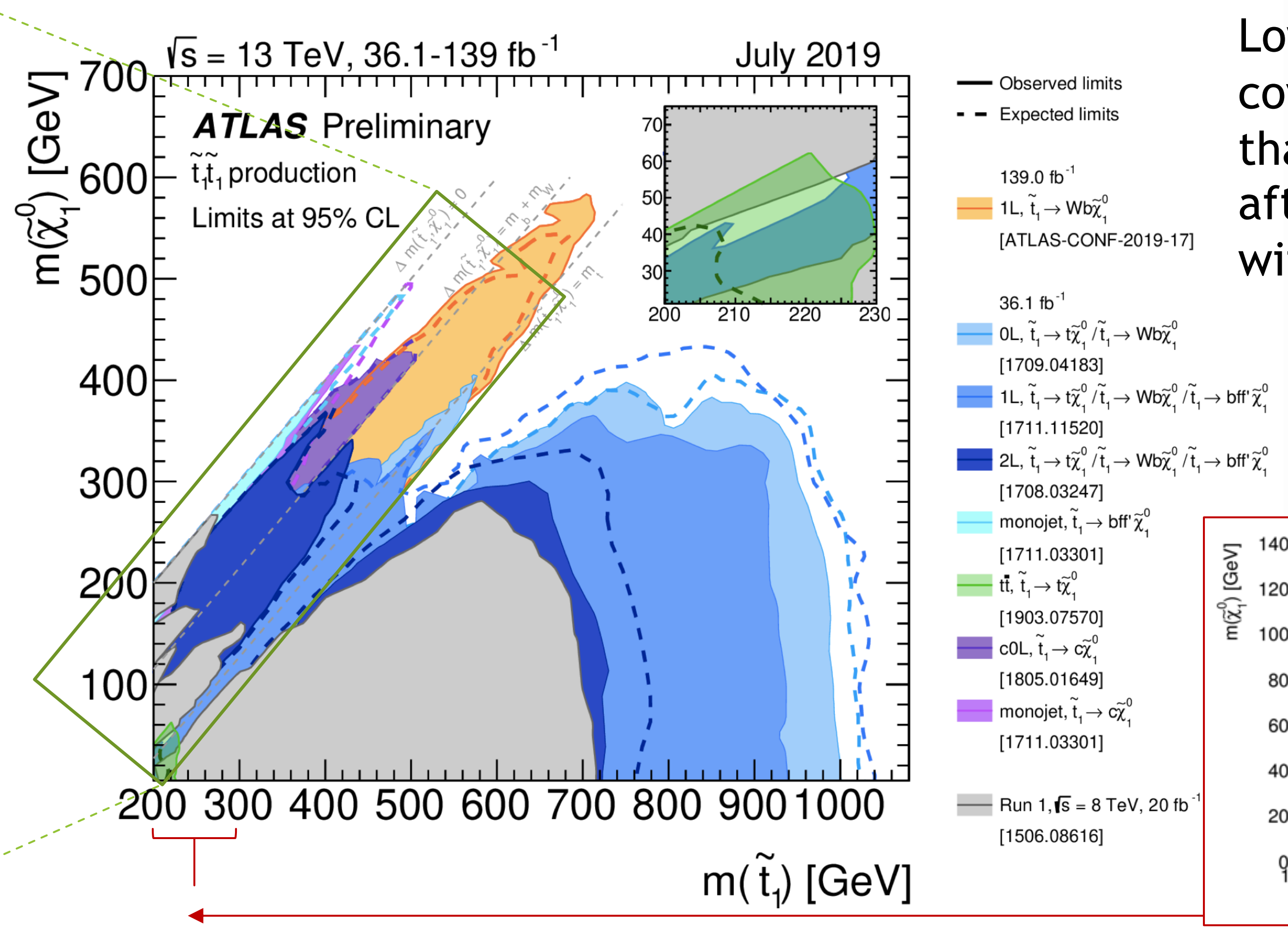
# Top squarks: current status

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

4 body decays

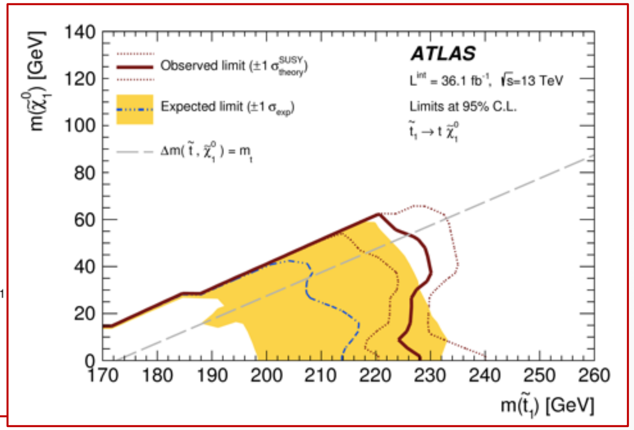



Stop → b + chargino



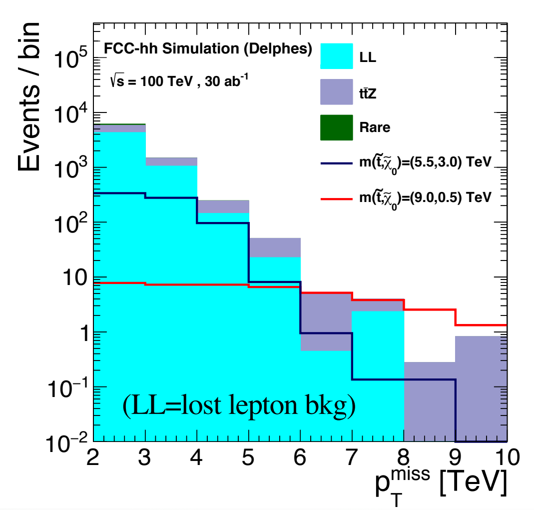

Low-mass region almost all covered; hard to imagine that loop-holes will still exist after HL-LHC [to be explored with full Run 2 data]

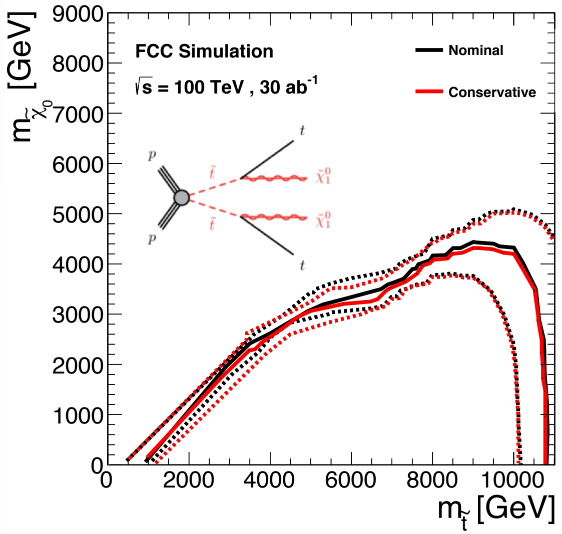
M(stop)~m(top) → spin correlation measurements

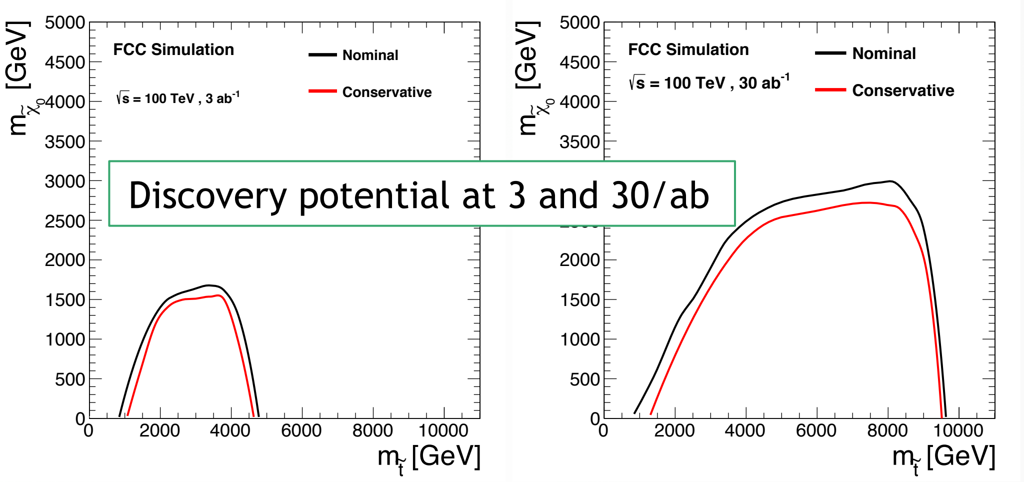


# Examples of prospects for top squarks

- Analyses for large and medium ΔM (stop, N1): here, using reconstructed top and b-jets

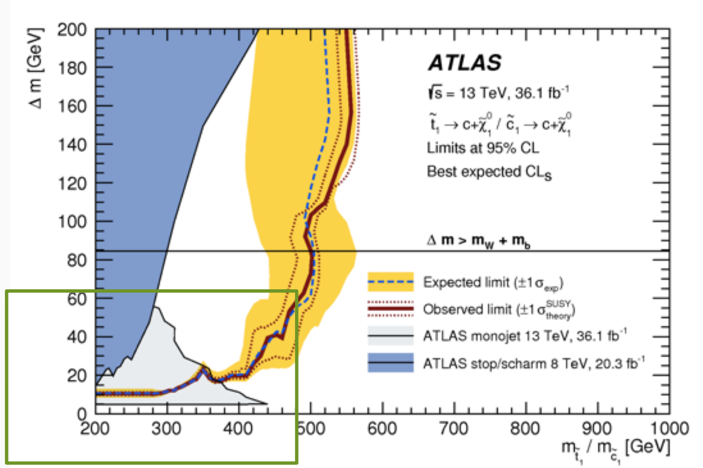



Discovery potential at 3 and 30/ab

- Compressed scenarios, small $\Delta M = m_{stop} - m_{LSP}$ :




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**

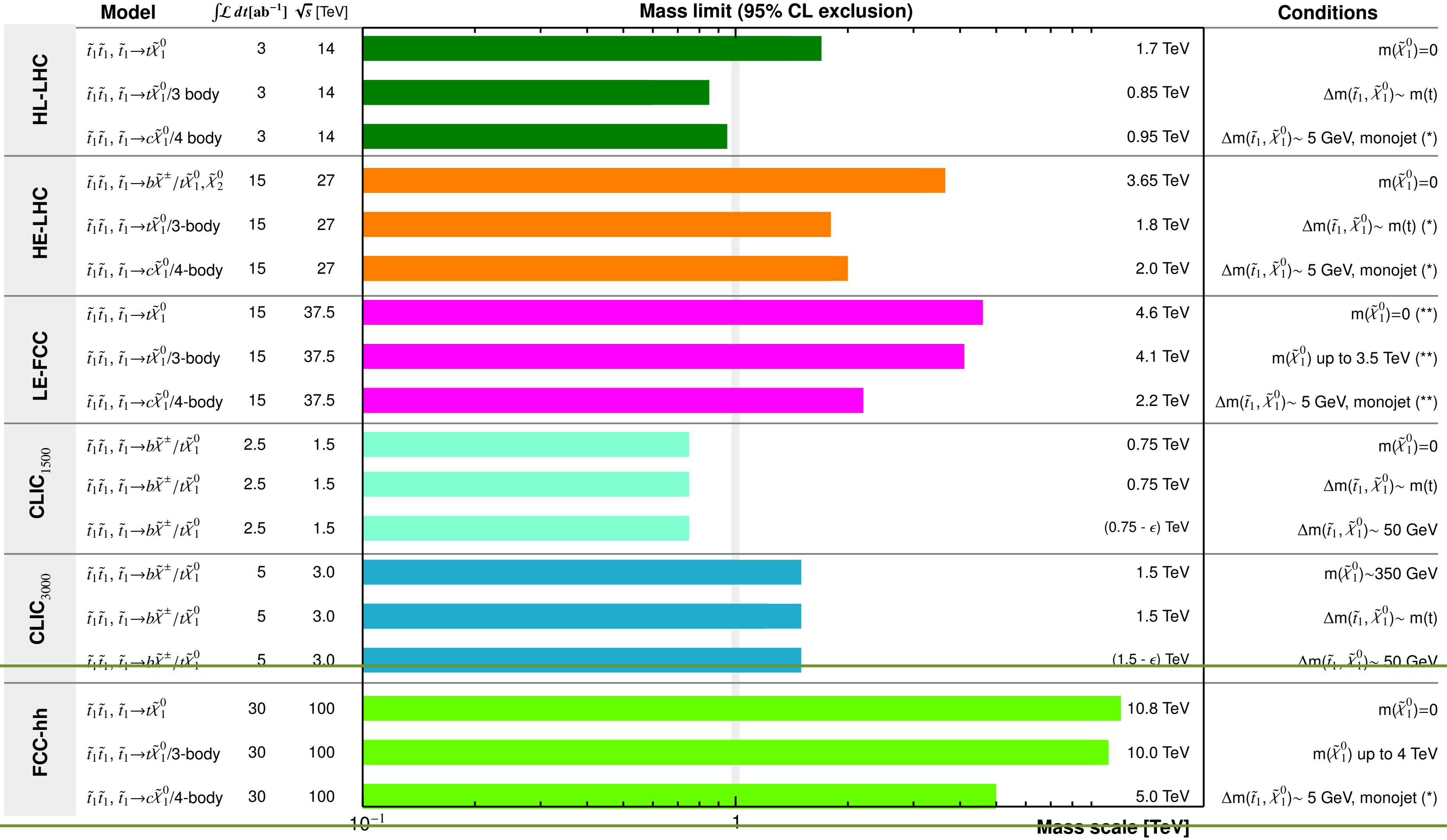
→ Might be conservative: e.g. recoil-jet pt thresholds can be adjusted

# Summary: RPC Top squark

## All Colliders: Top squark projections

**(R-parity conserving SUSY, prompt searches)**

European Strategy Update




(*) indicates projection of existing experimental searches

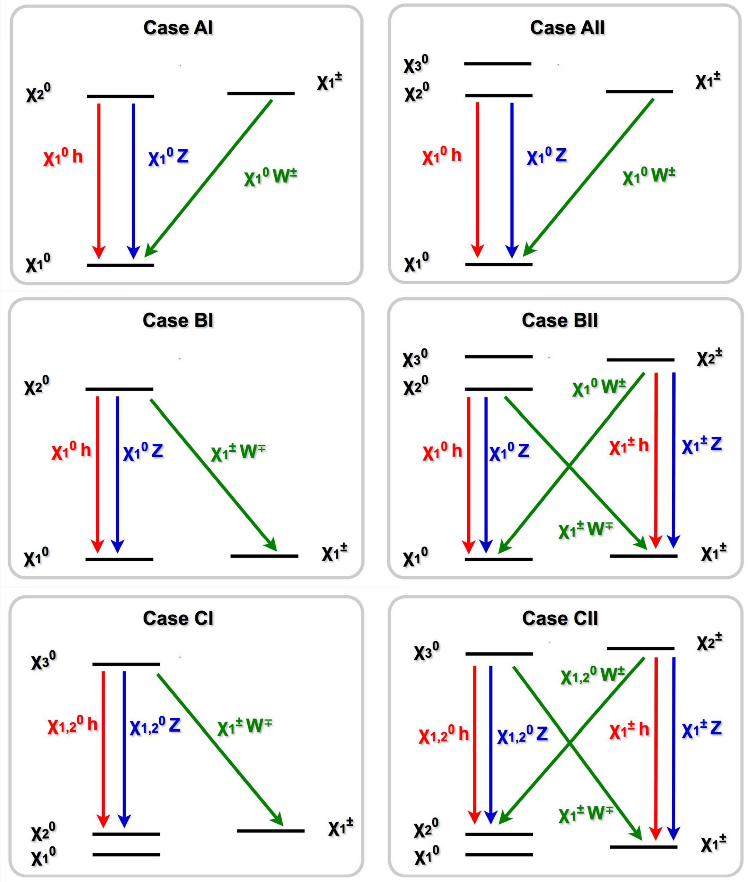
(**) extrapolated from FCC-hh prospects

$\epsilon$ indicates a possible non-evaluated loss in sensitivity

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

# 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 $M_1$, $M_2$, $\mu$ (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:**

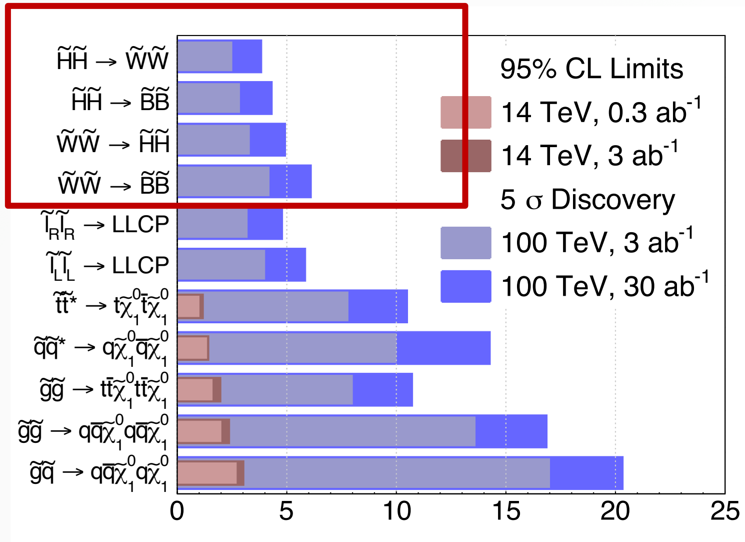
- Bino LSP, wino-bino cross sections
  (1) Mass($\chi^\pm_1$) = Mass ($\chi^0_2$)
  (2) $\chi^+_1\chi^-_1$ and $\chi^\pm_1\chi^0_2$ processes

$$\sigma_W(\chi^\pm_1\chi^0_2) \sim 2\ \sigma_W(\chi^+_1\chi^-_1)$$

- Higgsino-LSP, higgsino-like cross sections
  (1) Small mass splitting $\chi^0_1, \chi^\pm_1, \chi^0_2$
  (2) Consider triplets for cross sections
  (3) Role of high-multiplicity neutralinos and charginos also relevant

$$\sigma_H(\chi^\pm_1\chi^0_2 + \chi^+_1\chi^-_1 + \chi^\pm_1\chi^0_1) < 0.7\text{-}0.5\ \sigma_W(\chi^\pm_1\chi^0_2)$$

# 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)

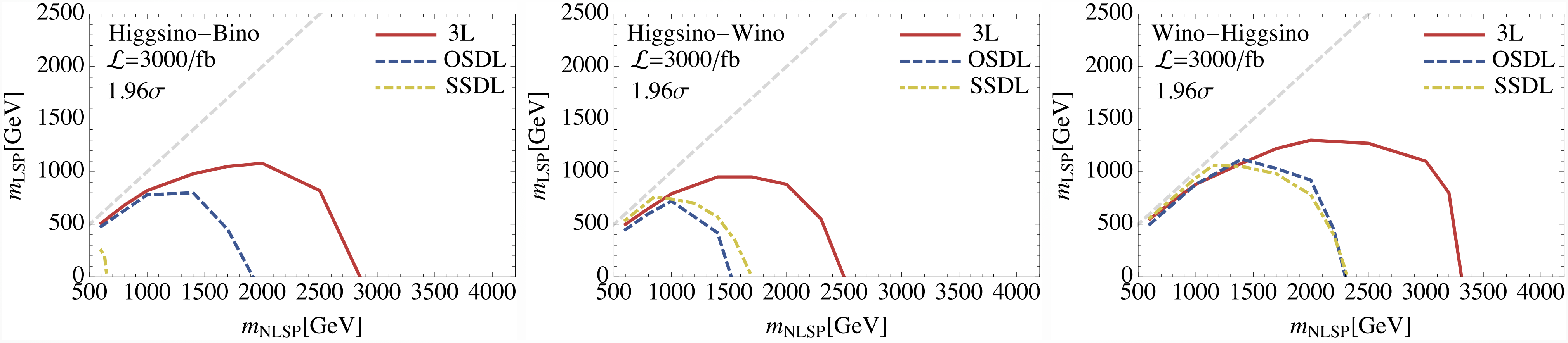
$$\chi_2^{0,\pm} \to \chi_1^{0,\pm} Z/h, \quad \chi_2^{0,\pm} \to \chi_1^{\pm,0} W,$$

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

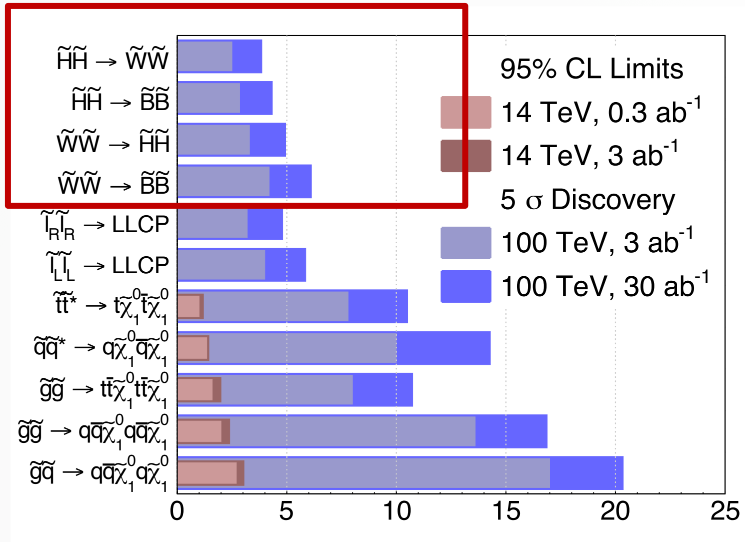
Results presented depending on the nature of the next-LSP and LSP

- 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




CERN-ACC-2018-0056.pdf

- Searches in multilepton final state events + missing $E_T$
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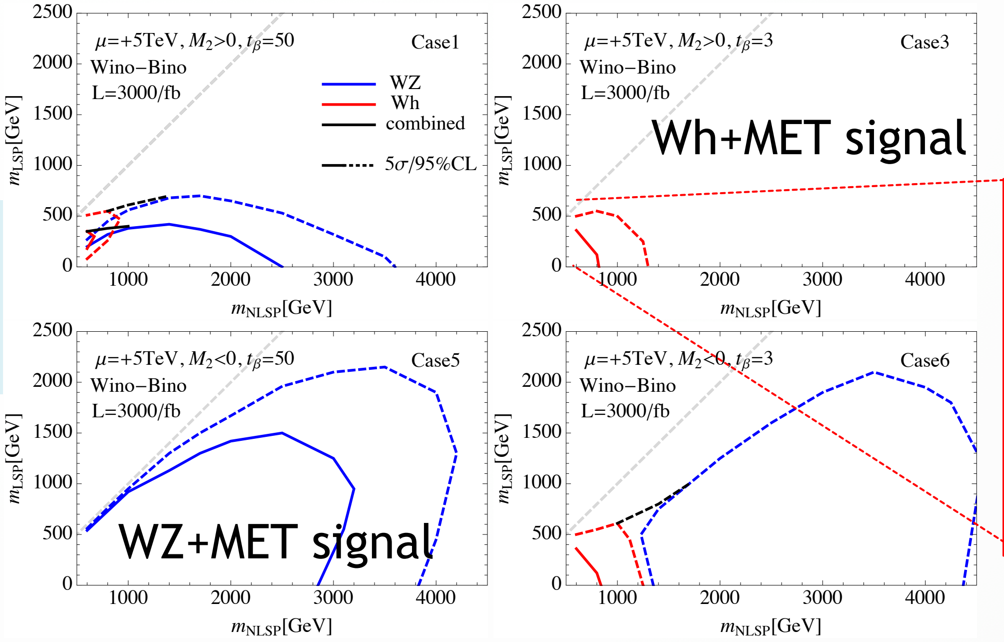
$$W \to \ell\nu, \quad Z \to \ell^+\ell^-, \quad h \to ZZ^*, WW^* \to 4\ell, 2\ell 2\nu$$

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

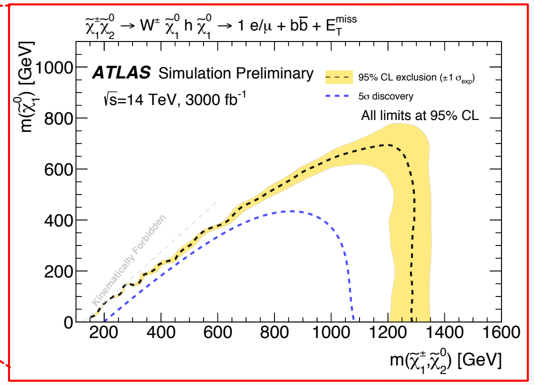
- Wino NLSP and Bino LSP (Wino-Bino) : $\mu \gg M_2 > M_1$.

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

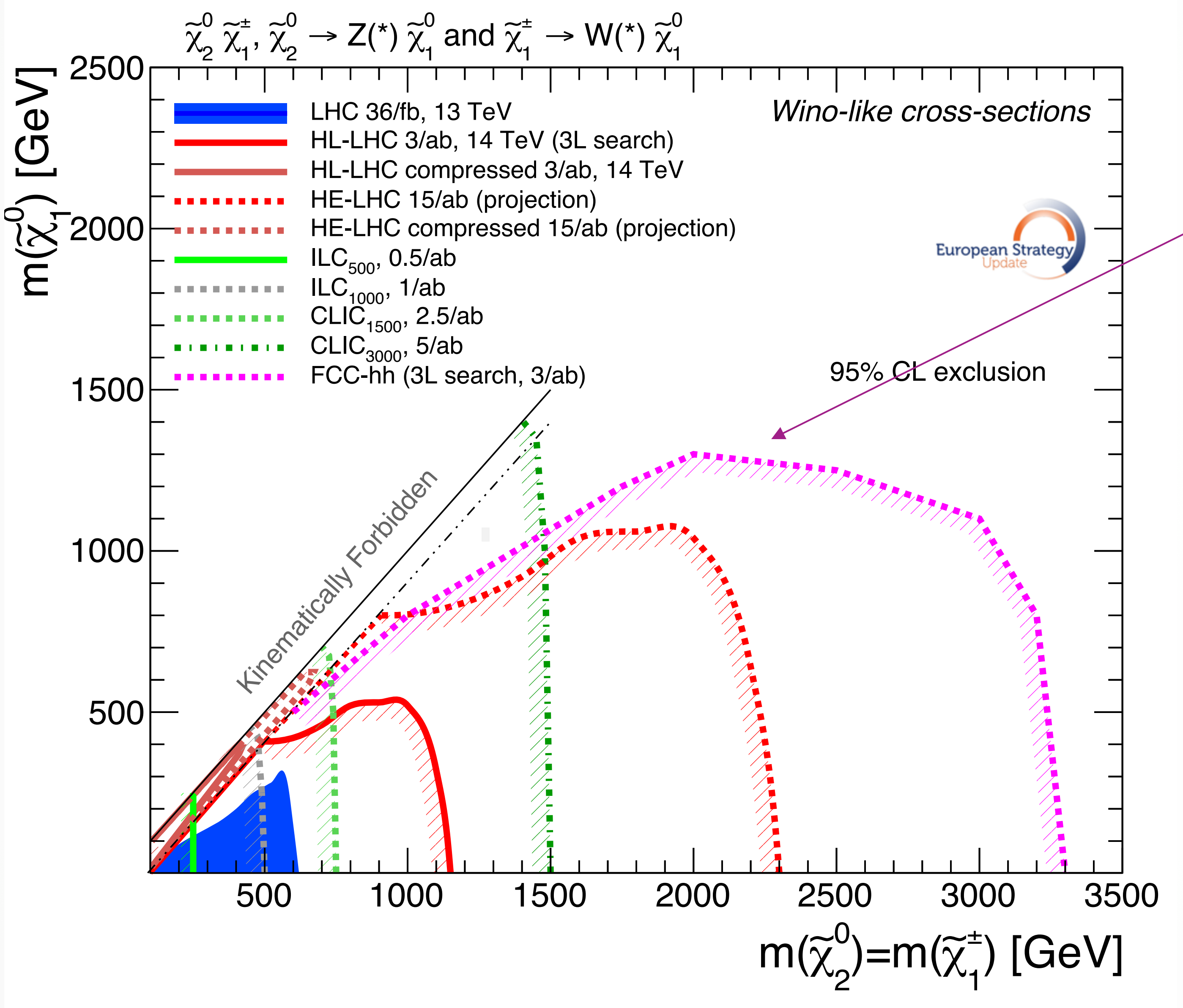
Note: this and other results are for a single experiment

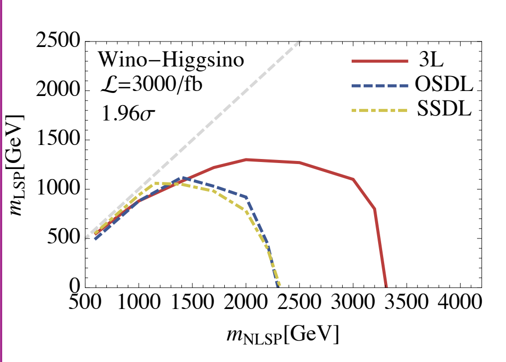



Conservative ! good sensitivity **at HL-LHC using H→bb signatures**



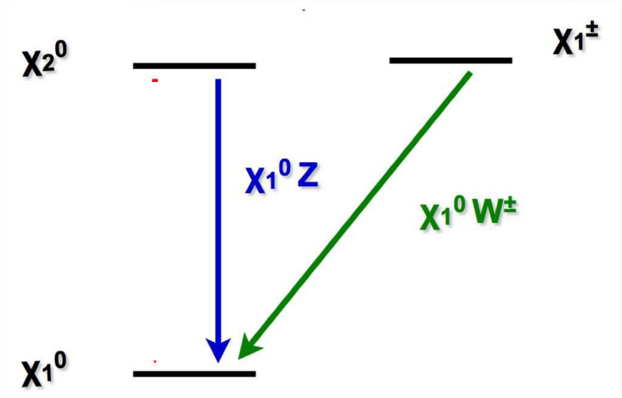
# Wino-like cross section: $\chi^{\pm}_1\chi^0_2$



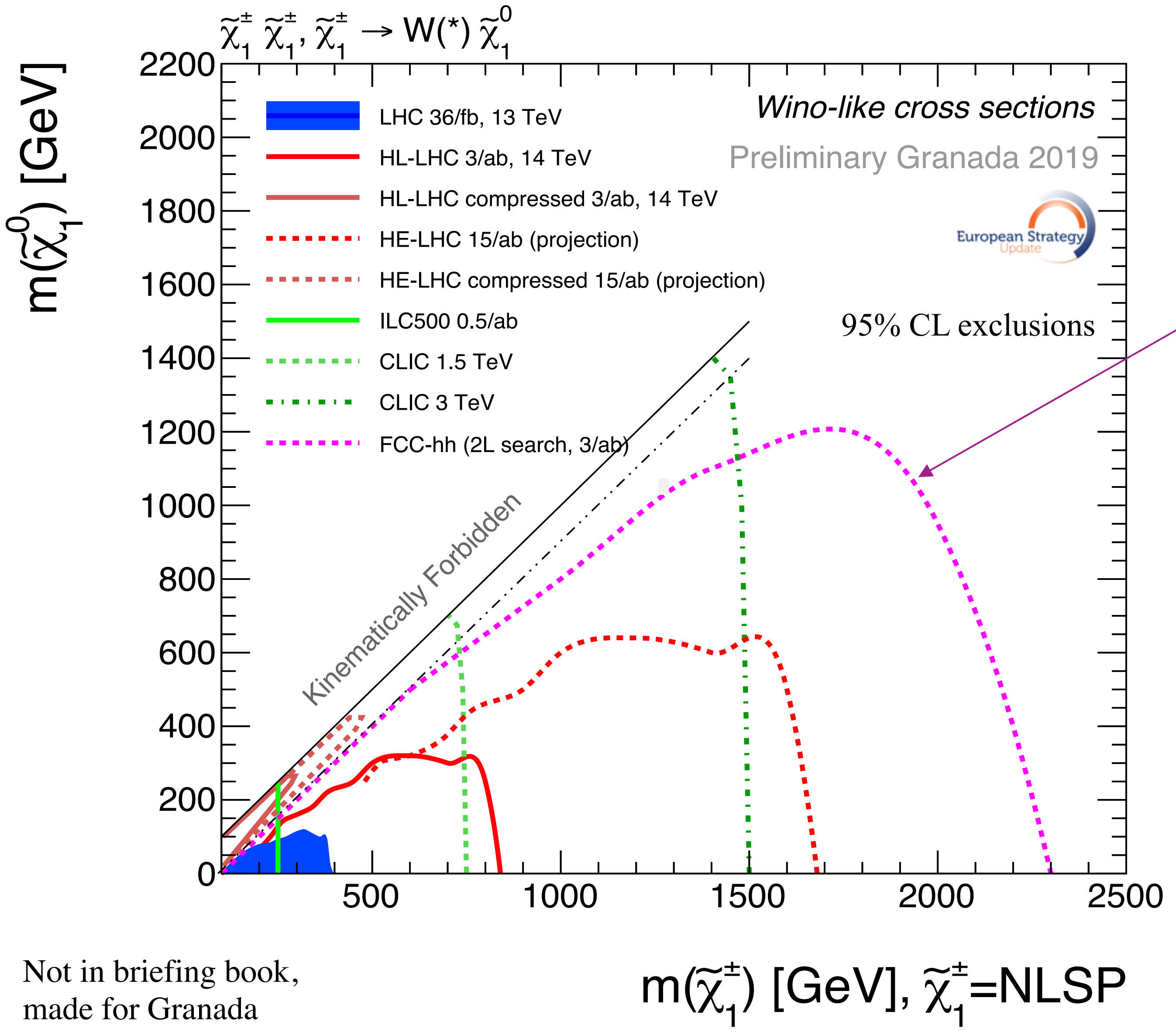

FCC-hh Contour of the 3-lepton search

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



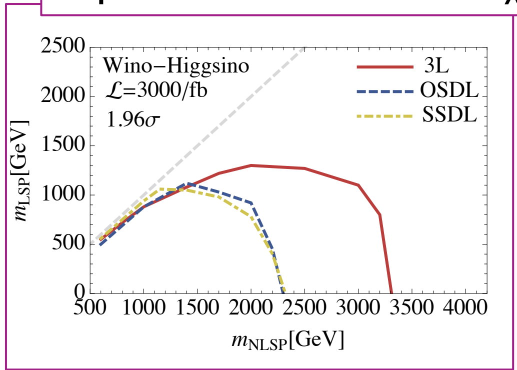

[$\chi^0_2 \rightarrow h\,\chi^0_1$ not in this plot]

# Wino-like cross section: $\chi^+{}_1\chi^-{}_1$

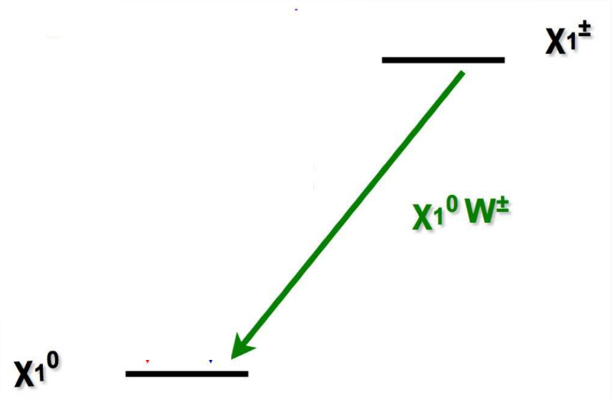



Not in briefing book,
made for Granada

FCC-hh Contour of the 2-lepton search used for $\chi^+{}_1\chi^-{}_1$



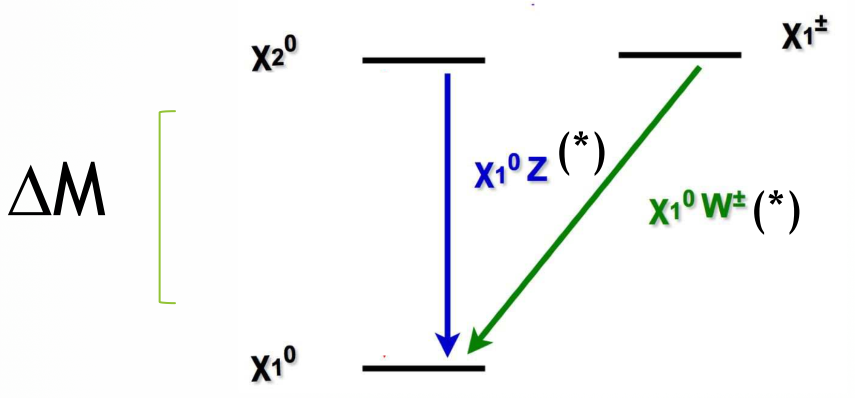

$\chi^{\pm}{}_1$ = NSLP, $\chi^0{}_2$ decoupled

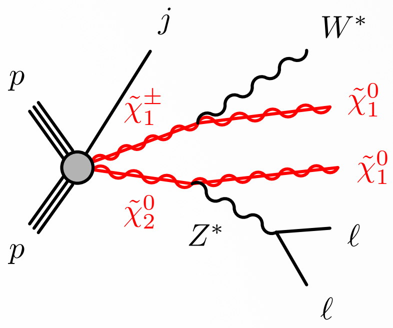


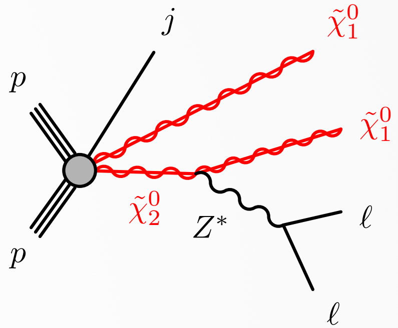
# Higgsino-like EWK processes

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($\chi^{\pm}{}_{1}$) ~ m($\chi^{0}{}_{2}$)



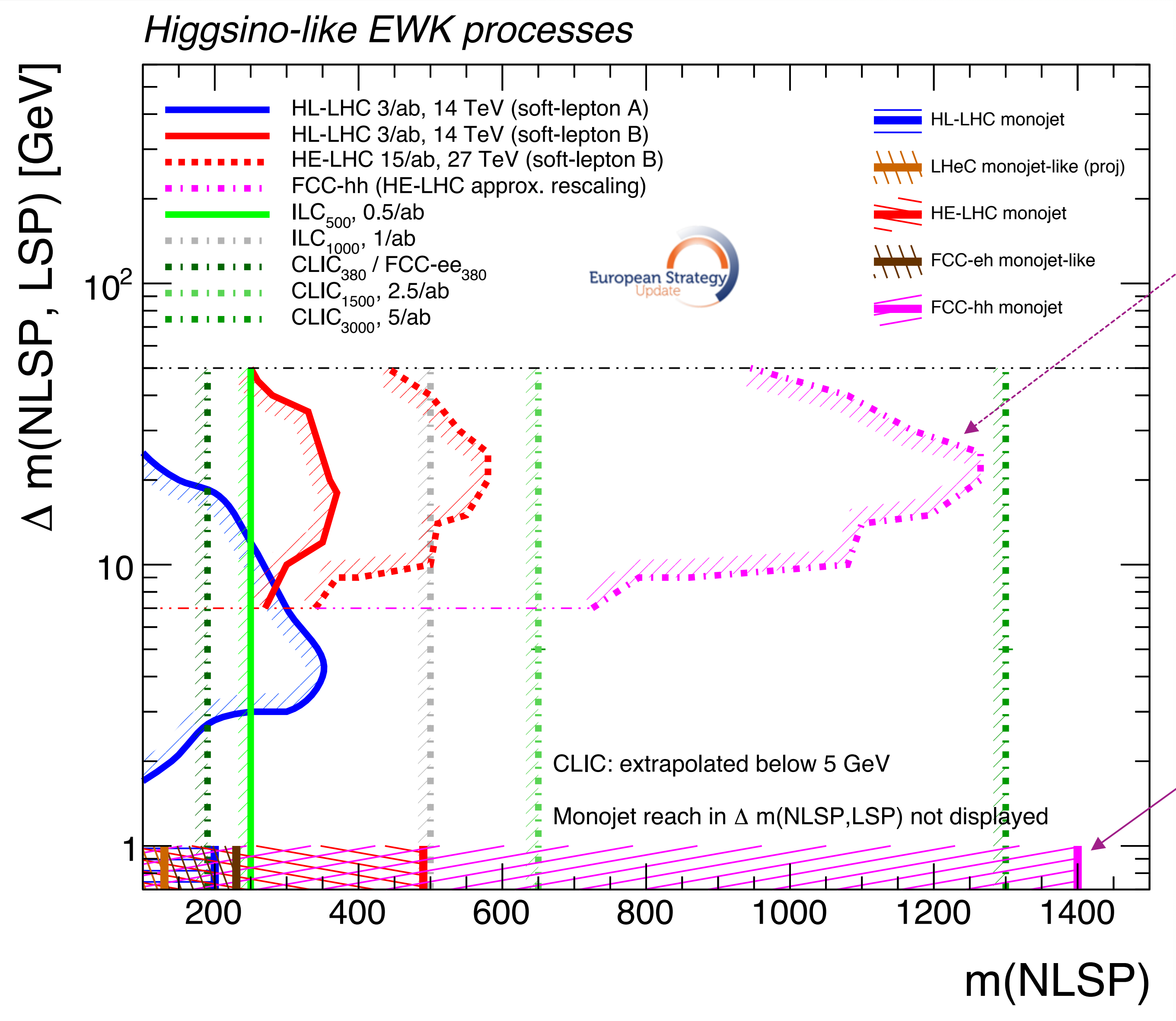

Higgsino-like (i.e. large higgsino component but not pure):

→ **ΔM(NLSP, LSP) ~ O(GeV)**

Pure-higgsino:

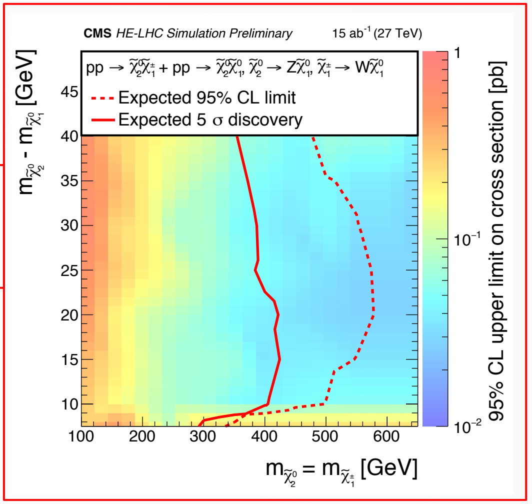
→ **ΔM ~ 160 MeV** – targeted by disappearing track analyses

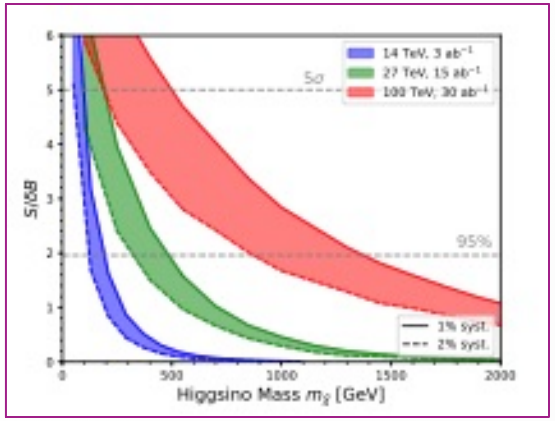
# Higgsino-like EWK processes




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

HE-LHC soft lepton analysis




Monojets (HL/HE/FCC-hh)

$$S/\sqrt{B + (\Delta_B B)^2 + (\Delta_S S)^2}$$

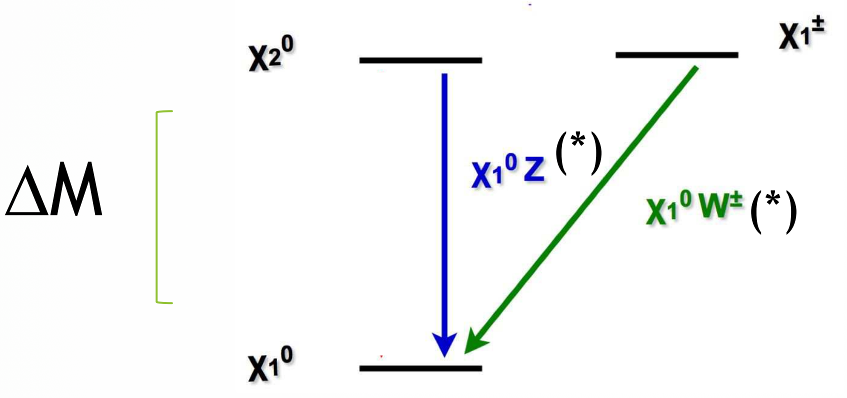
$$\Delta_B = 20\% \text{ and } \Delta_S = 10\%$$

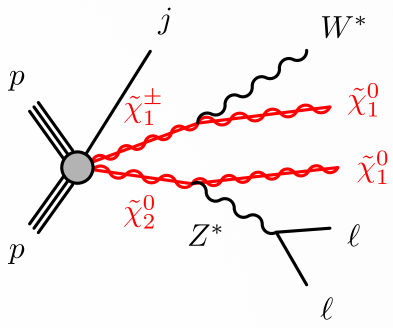
**FCC-hh could go beyond ~ 1 TeV for higgsino-like scenarios**

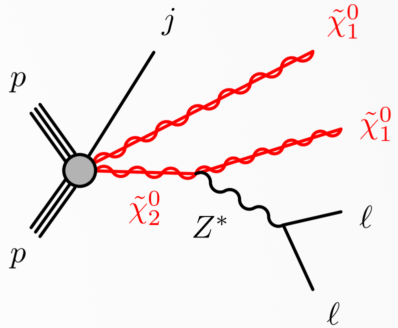
# Higgsino-like EWK processes

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):

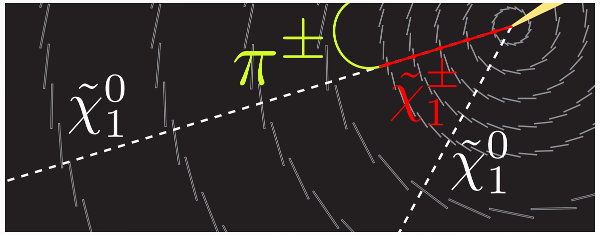
→ ΔM(NLSP, LSP) ~ O(GeV)

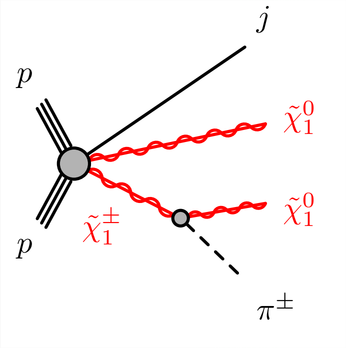
**Pure-higgsino:**

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

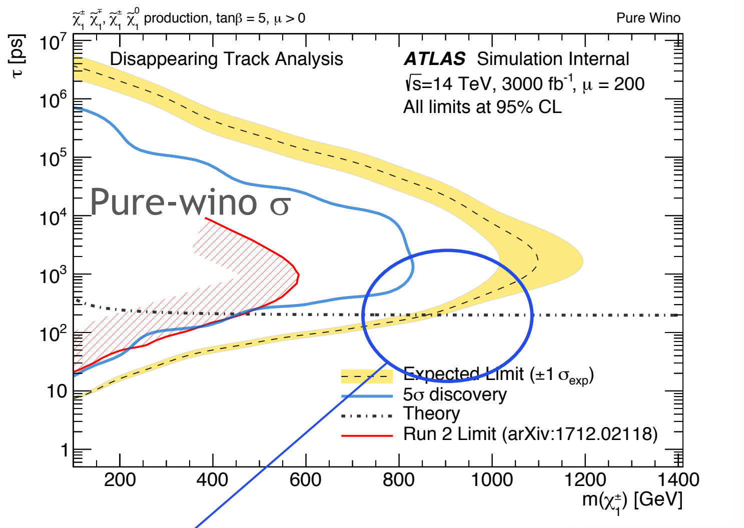
# Disappearing track signatures

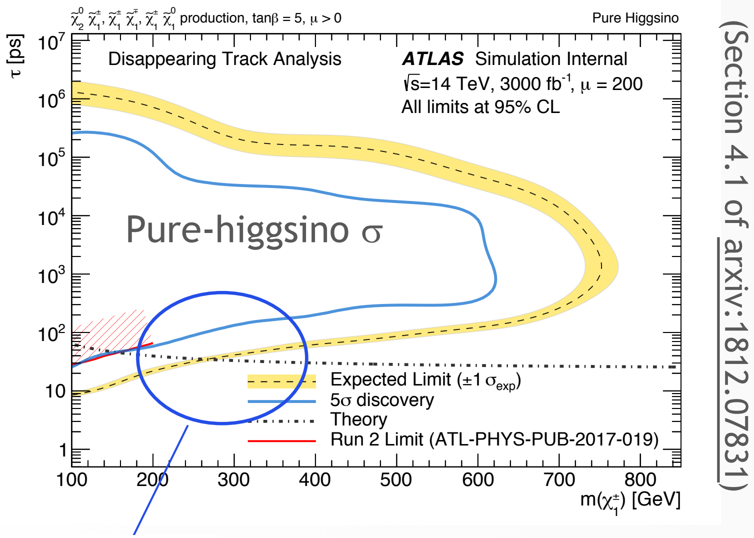
HL-LHC




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

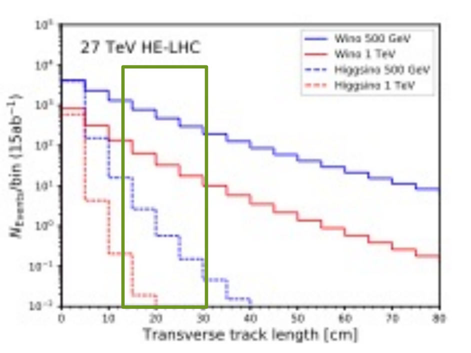



(Section 4.1 of arxiv:1812.07831)

HL-LHC/HE-LHC/FCC-hh

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

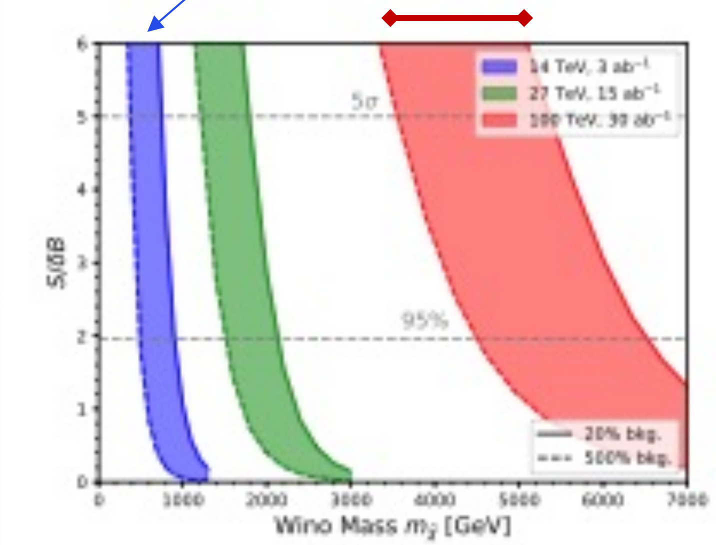


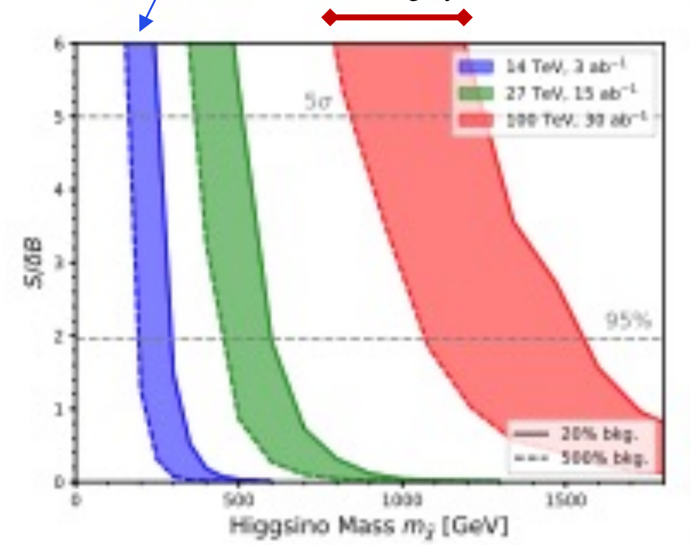

(Not available for FCC-hh)

12 < d < 30 cm

@ FCC: $p_T$ track in 1-1.4 TeV range

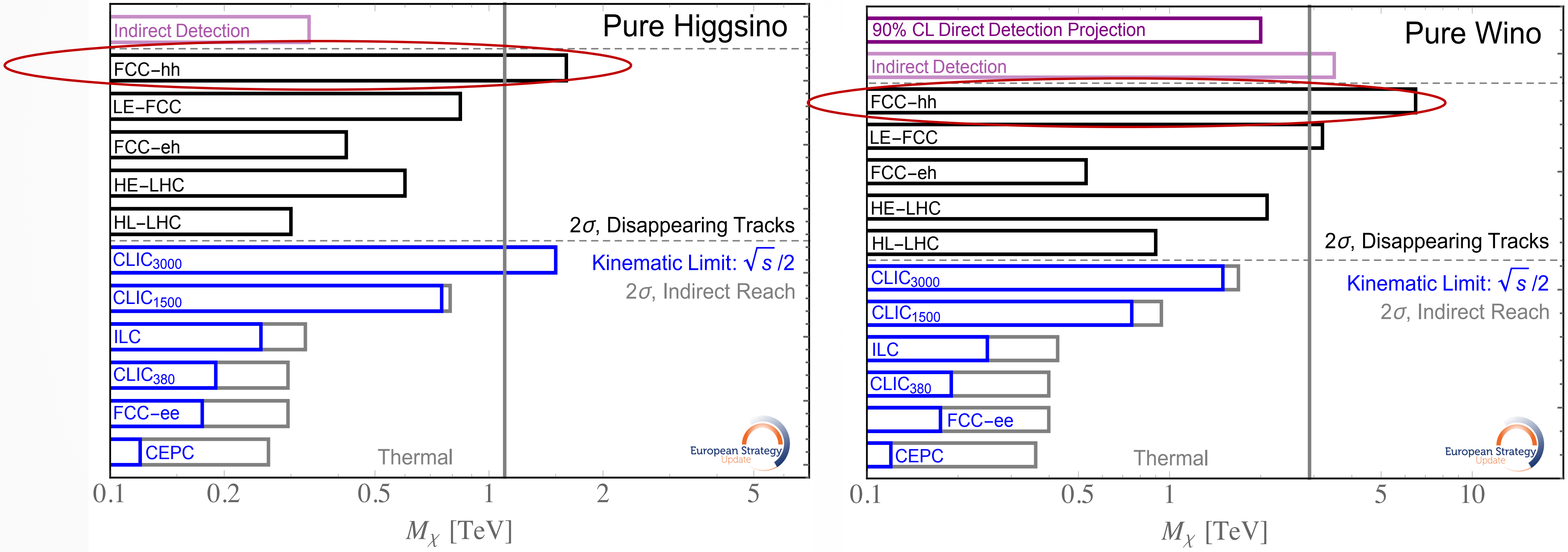
Variation of bkg by factor 5



# Thermal Higgsino/Wino dark matter

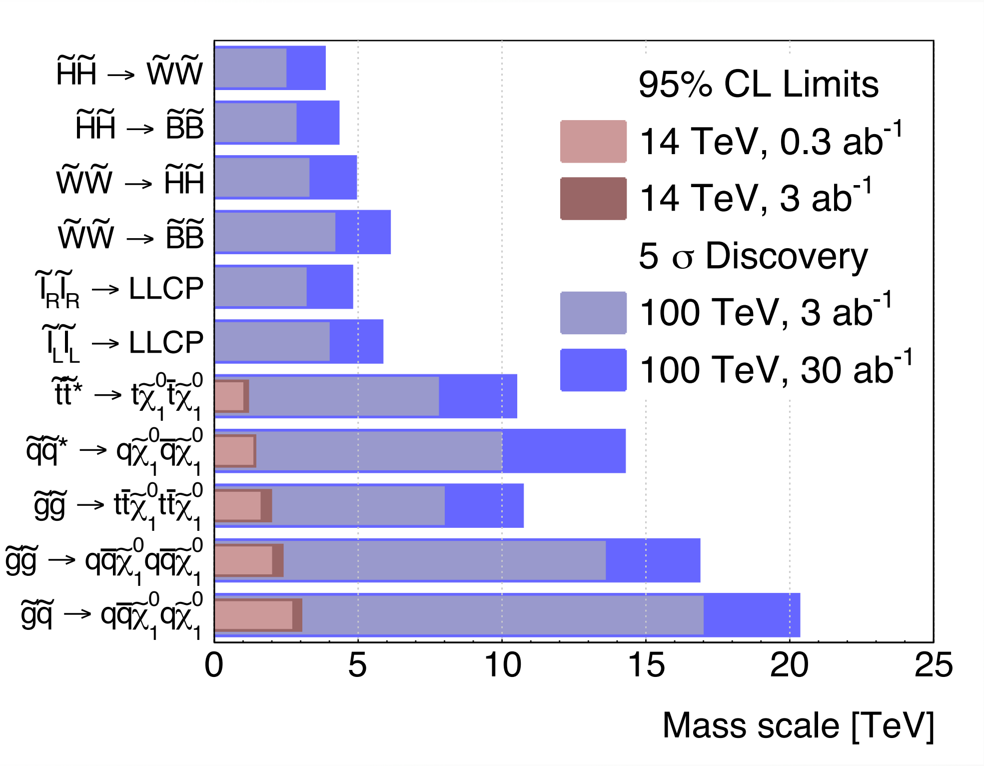
- Thermal freeze-out mechanism provides a cosmological clue for the observed DM density
- Most straightforward example of a DM thermal relic: massive particle with EW gauge interactions only
- Spin-1/2 particles transforming as doublets or triplets under SU(2) symmetry, usualy referred to as Higgsino 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!**

# Conclusions

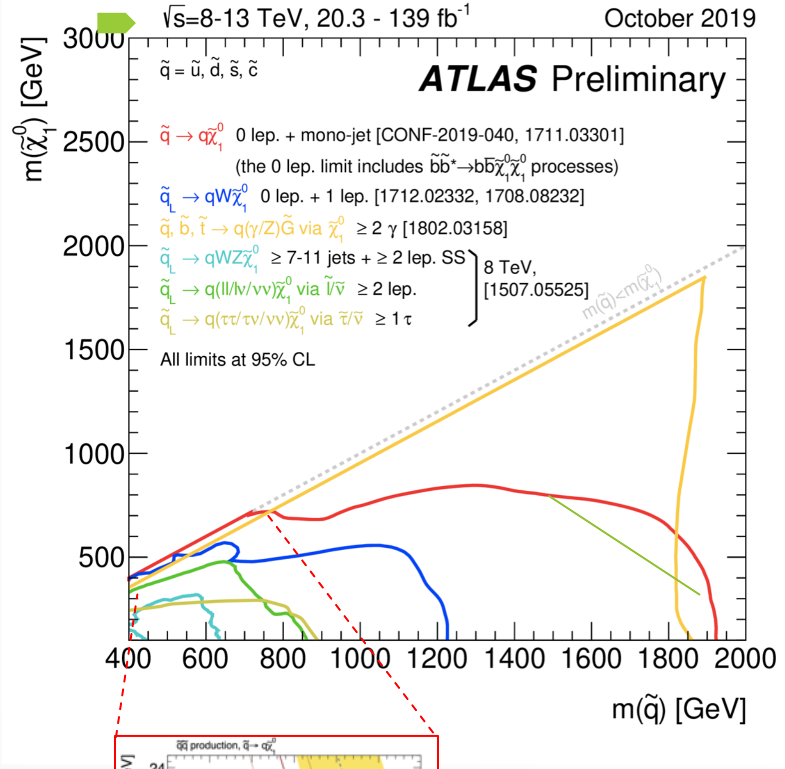
- Searches for SUSY will remain a priority for HEP for some time
- **The discovery potential for strongly produced SUSY particles** such as **gluino, squarks** and in particular **top squarks** is dominated by FCC-hh, which allow highest mass reach
- The **EWK SUSY sector** could be particularly challenging, but mixture of 'classic' signatures and exploitation of monojet-like and soft-lepton final states might allow very good reach
- Disappearing track analysis could be exploited for higgsino / wino Dark Matter models
- FCC-hh has certainly a high potential for EWK particles with masses up to 3-4 TeV
  - **can conclusively test the hypothesis of thermal DM in both scenarios!**

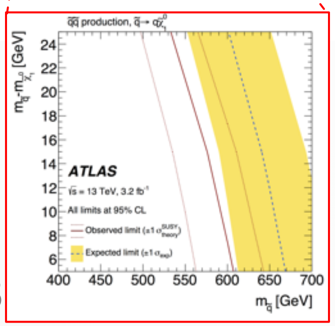


# Back up

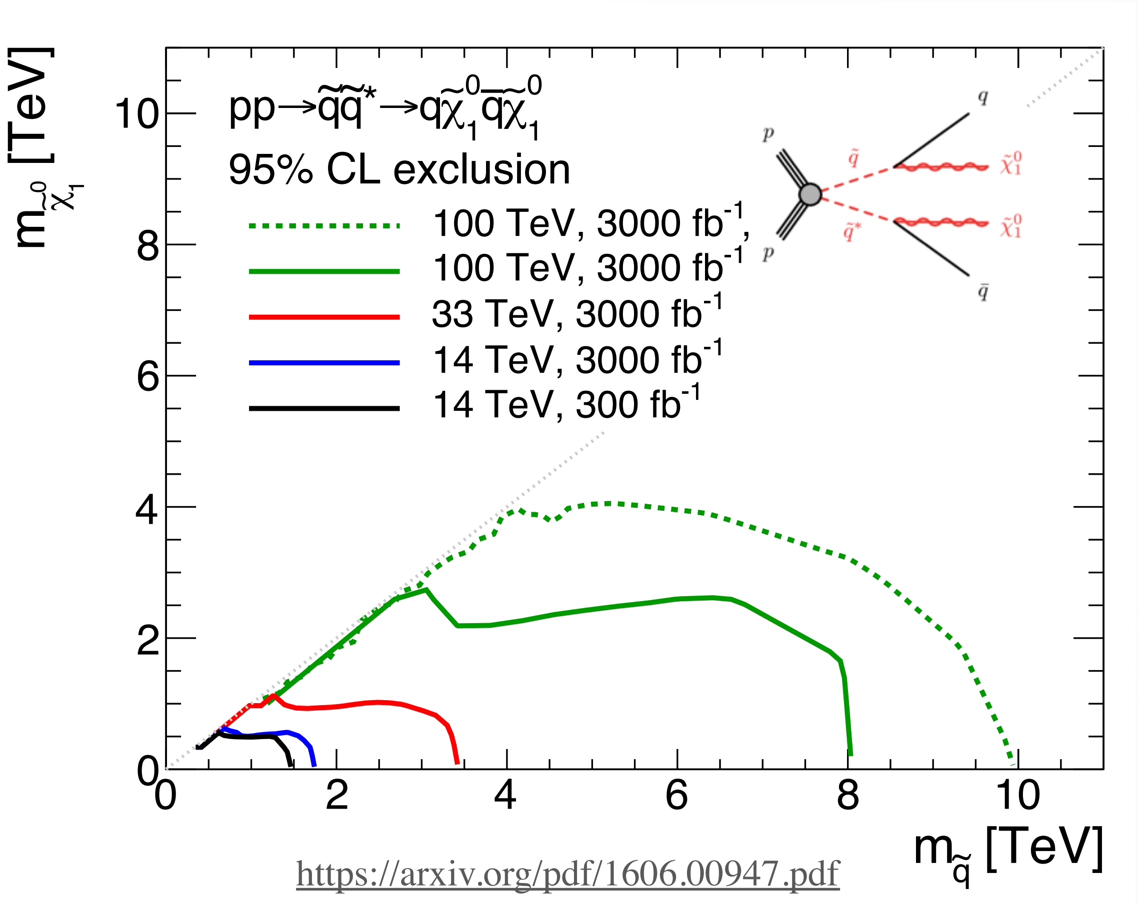
# 1st and 2nd generation squarks

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



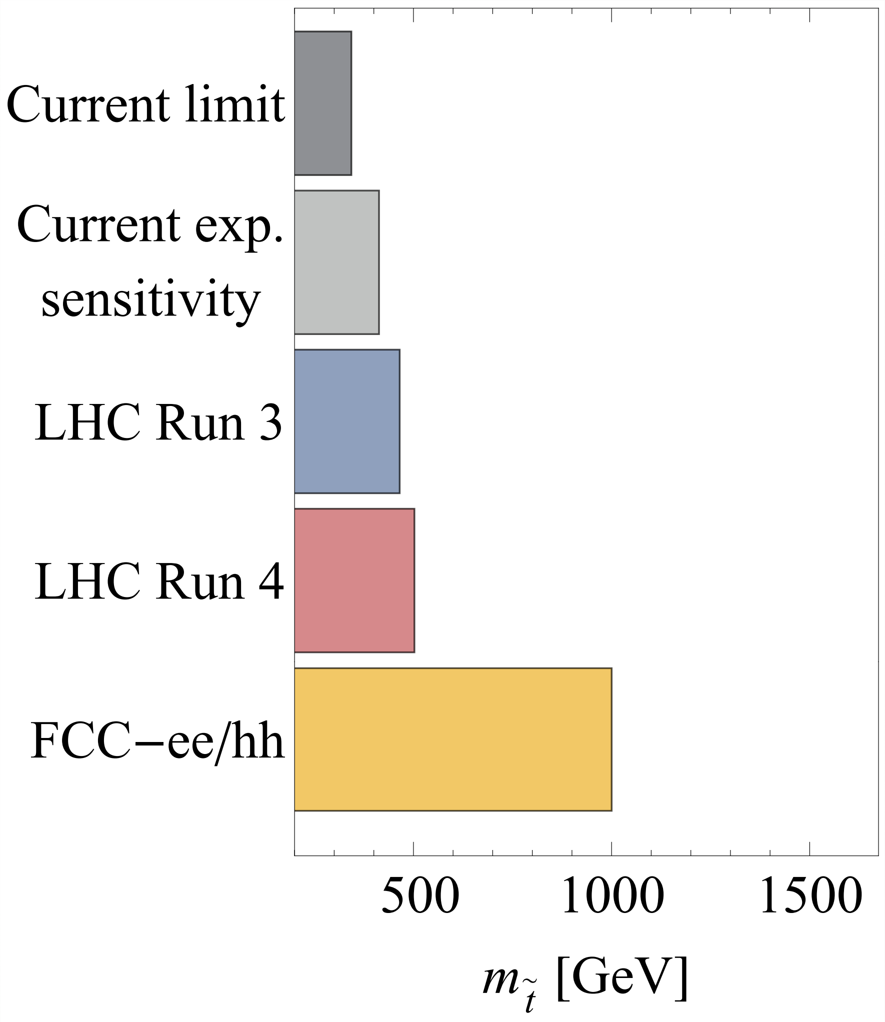

Coverage for compressed scenarios down to 5 GeV (prompt)




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

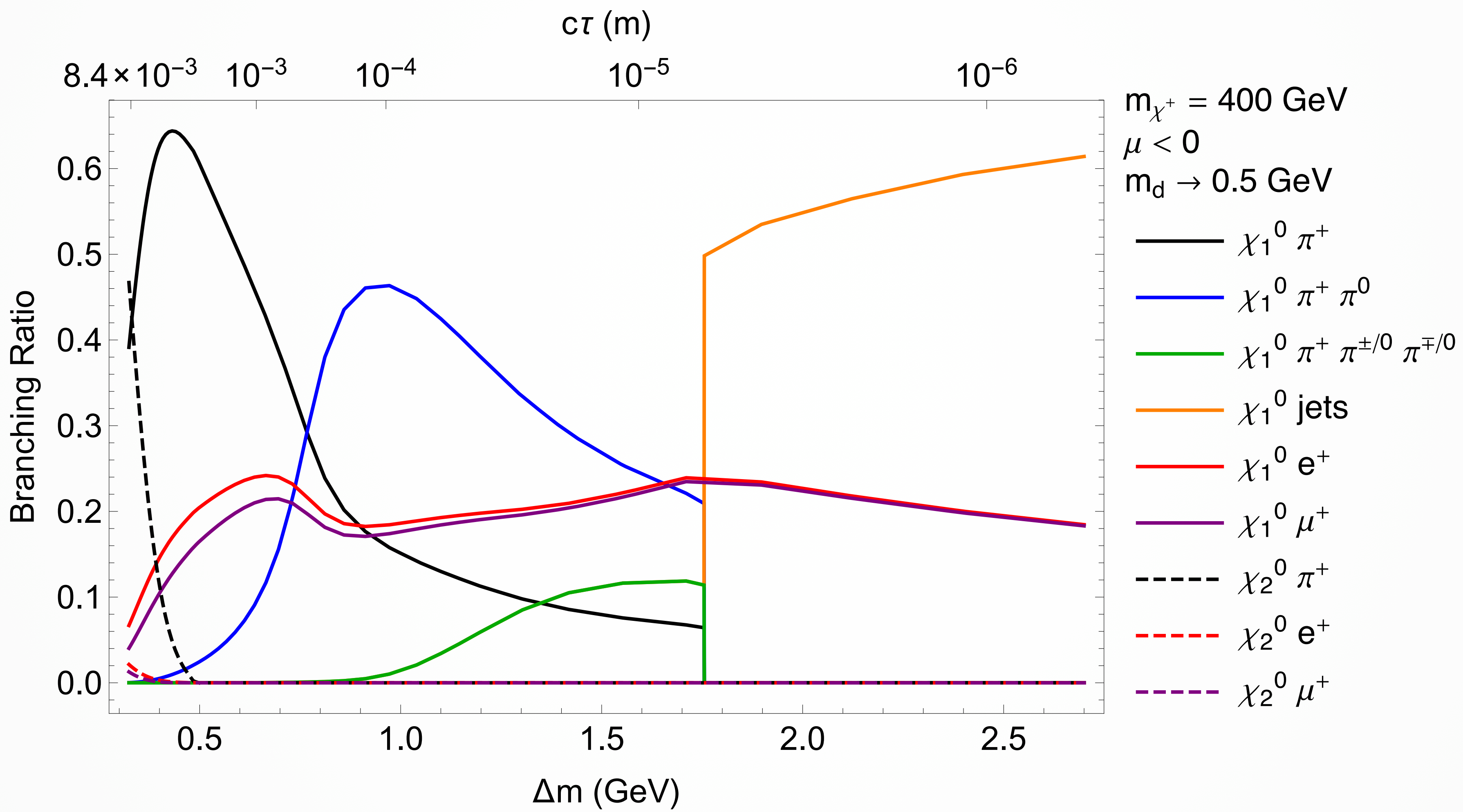
# Indirect stop limits

- leading indirect effect of top squarks is that 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 hence they are 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 the FCC-ee measurements.
- Dedicated studies at FCC-hh, using e.g. H+jet production at high invariant mass, could further reveal the structure of the indirect corrections to the Higgs interactions.



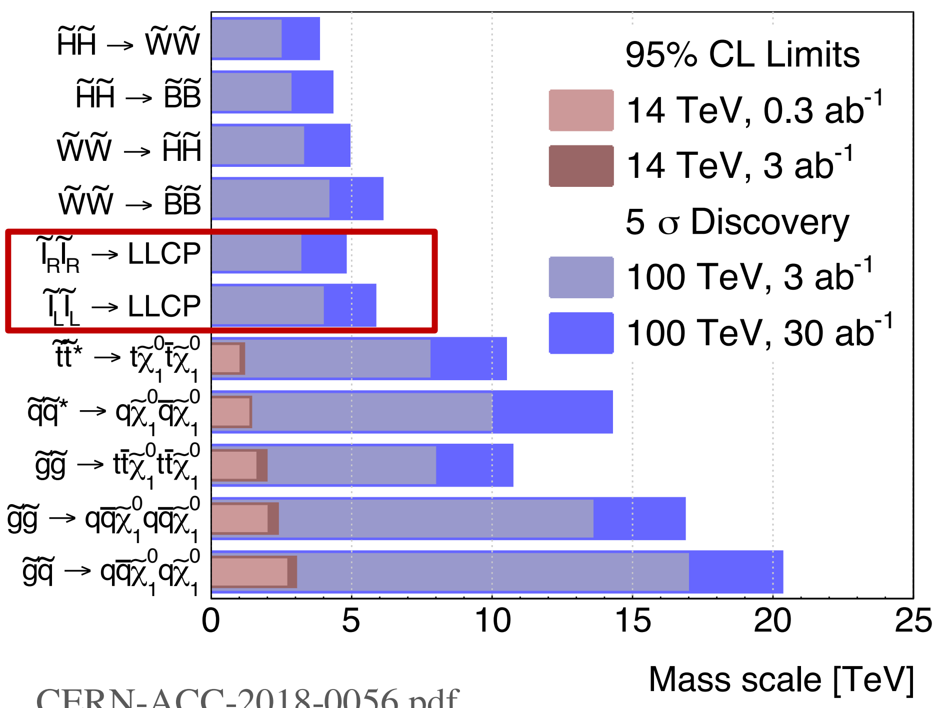
# Compressed scenarios EWK

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

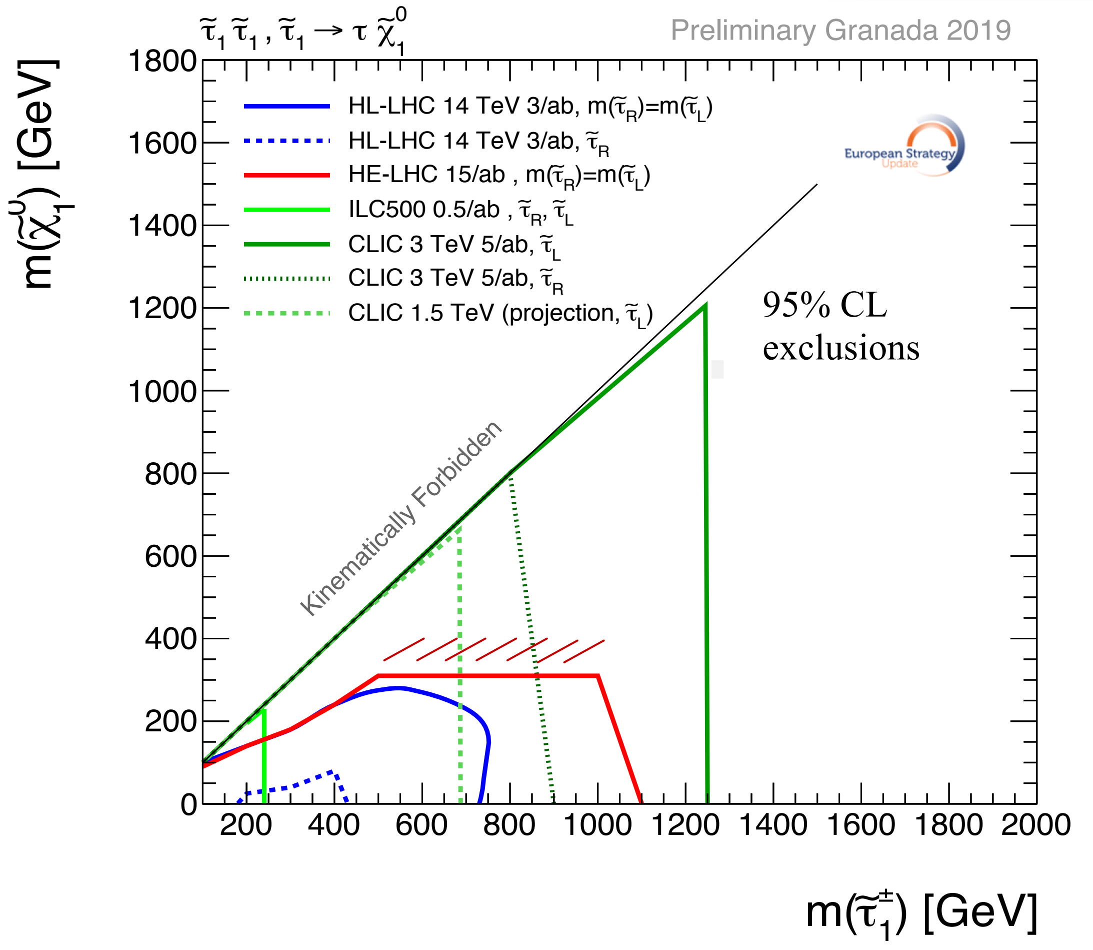


# Sleptons reach

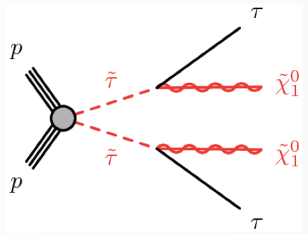
Constraints up to 4-5 TeV for selectrons and smuons depending on Left/Right component mixtures




CERN-ACC-2018-0056.pdf




Not in briefing book, made for Granada




$\tau_R$ very challenging!

FCC-hh could push boundaries up to 3-4 TeV (as for $\tilde{e}, \tilde{\mu}$)
(studies not yet performed. no 2D projections attempted)