SUSY @ CLIC

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Physics at CLIC
— CERN —

17-18 July 2017

Is low energy SUSY still alive?

..still addresses many BSM open issues…

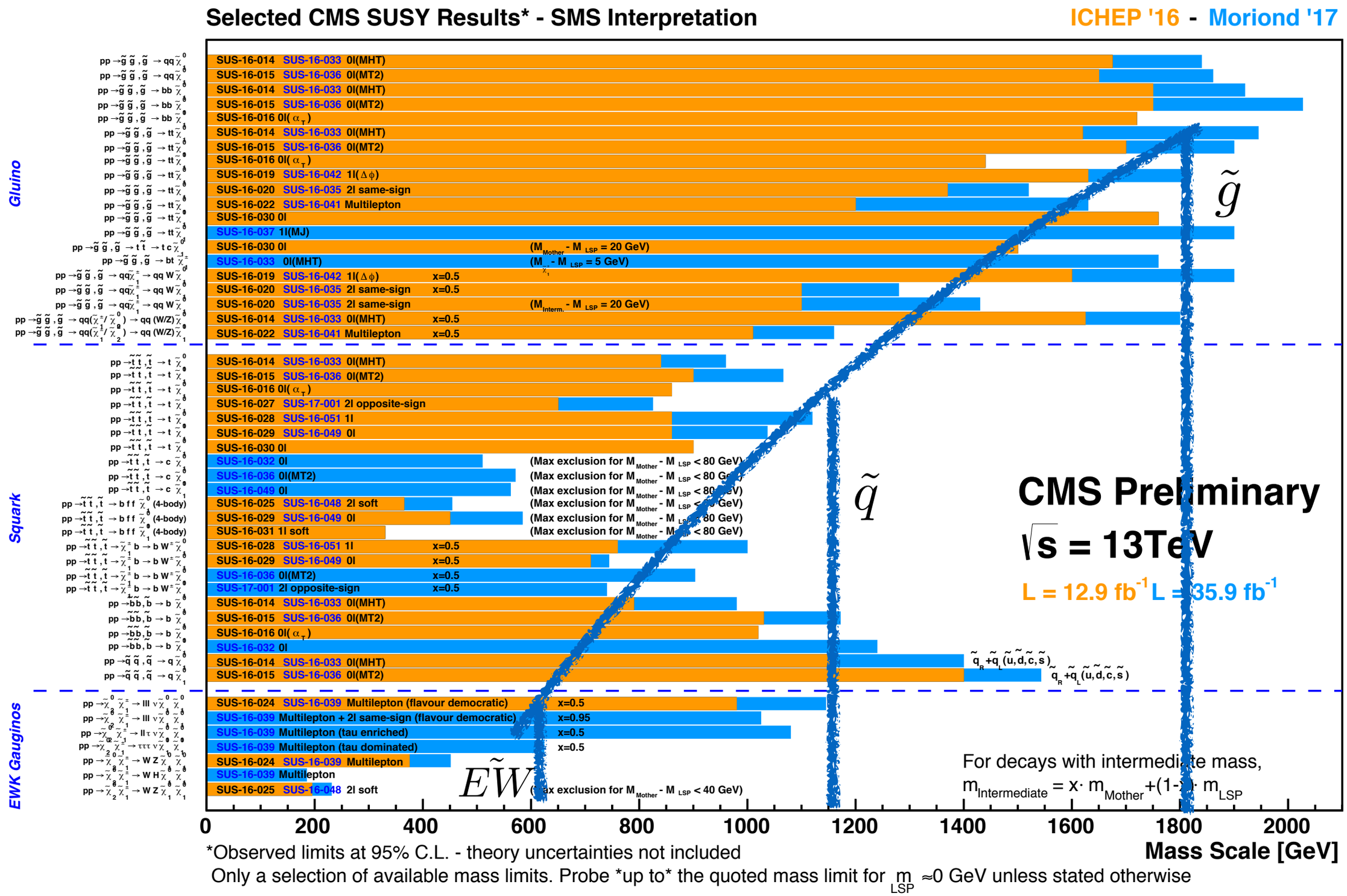
SUSY

★*What is left for SUSY at the LHC?*

★*What can be done for SUSY@CLIC?*

★*Is SUSY there? Is SUSY non minimal?*

SUSY at LHC 13



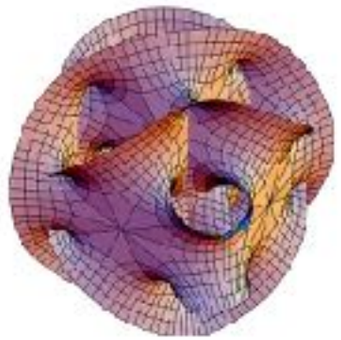
*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise

Why SUSY?

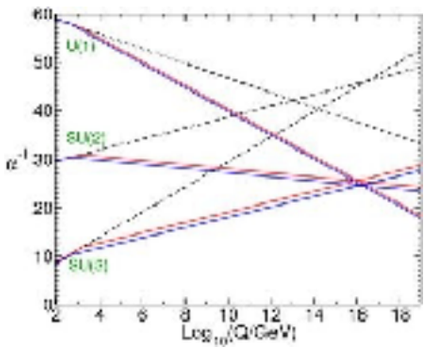
Pre LHC

- Solve hierarchy problem and naturalness

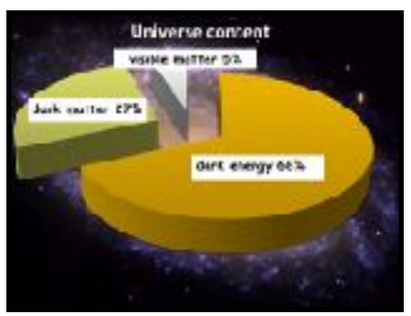


- Necessary in unified description with gravity

- Gauge coupling unification



- Dark matter candidate (LSP)



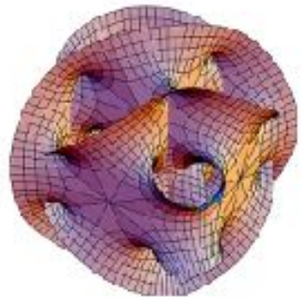
- Admit a low energy SM limit (including EWPT and flavour)

Why still SUSY?

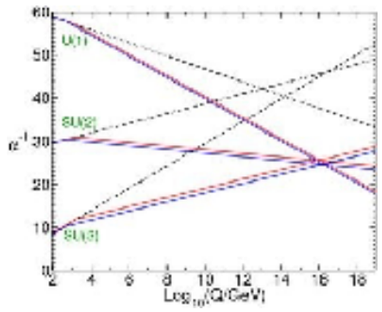
After/During LHC era

✳ ***Address*** hierarchy problem and naturalness (little fine-tuning)

✳ Necessary in unified description with gravity



✳ Gauge coupling unification



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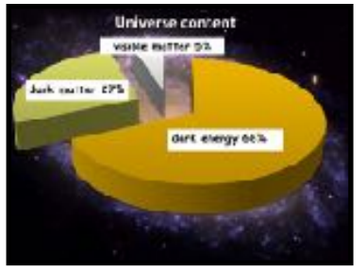


✳ Admit a low energy SM limit (including also ***SM-like H boson***)

Naturalness status

Little hierarchy problem

Negative LHC results brings in a minimal amount of fine tuning

Similar argument applies to standard SUSY and other BSM models

What next options?

1. *Give up some further assumption (e.g. RPV...)*
2. *Accept Little Fine Tuning and aim at next collider*
3. *Investigate alternative natural models and their signatures*

Maybe just a bridge over the little fine-tuning

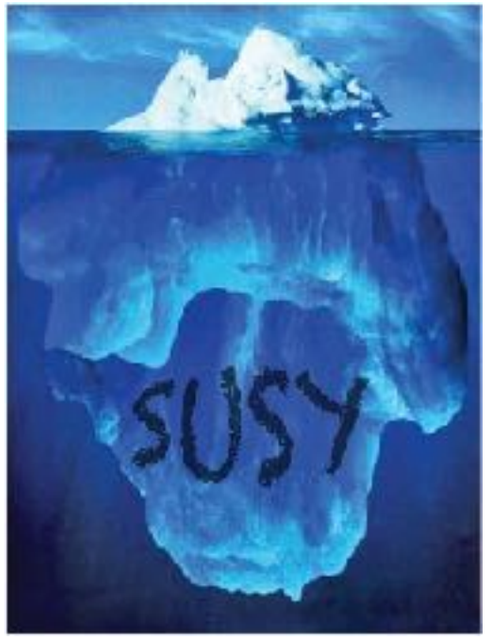
SUSY as BSM paradigm

- ***Probably several BSM talks of this workshop are eventually embedded in SUSY UV Completions …***
- ALP …
- Extra scalars …
- Twin Higgs …

SUSY as a proxy for a variety of BSM scenarios

CLIC vs SUSY

CLIC opportunities for SUSY?



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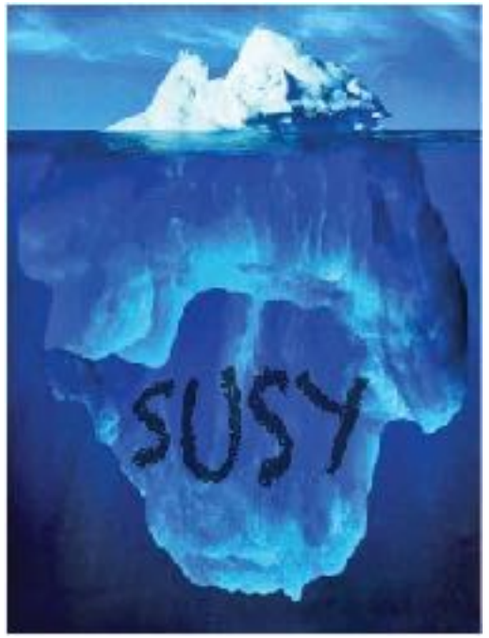


Options at the end of LHC

SUSY discovered!

New Physics

Hints of new Physics

No BSM physics

SUSY discovered at LHC

If SUSY discovered at the LHC then CLIC will provide crucial information on the sparticle spectrum

- Precision mass measurement
- Couplings and mixing angles measurement
- CP and Spin property of sparticles
- Possibility to probe sparticle mass unification and origin

Documented in initial physics program for CLIC

"… If nature is indeed supersymmetric, it is likely that the LHC will have observed part of the spectrum by the time CLIC comes into operation …" *hep-ph/0412251*

… optimistic perspective …

SUSY leftover at LHC

? What is left if LHC does not find any SUSY ?

Several scenarios are not effectively probed by LHC

- **EW sector weakly constrained:**
  - Higgsino, Sleptons, heavy Higgses
- **Compressed spectra**
  - Relevant for Dark Matter co-annihilation
- **Neutral SUSY**
  - Folded SUSY, Twin SUSY
- **RPV**
- **Displaced vertices**
- **.....**
- **Heavy SUSY** …

They all reduce current bounds for different reasons

What is CLIC prospect in these cases?

Lepton collider and SUSY

In a nutshell: $e^+e^- \to \widetilde{X}\widetilde{X}^*$

- All EW sparticles probed at kinematical threshold $m_{\widetilde{X}} \leq \frac{\sqrt{s}}{2}$
- SUSY parameters measured with accurate precision
- SUSY can be background
- $\gamma\gamma \to \text{hadrons}$ relevant bkg

No gluino

Rest of SUSY spectrum matters

- Often existing results displayed in terms of benchmarks
- Not always straightforward the comparison with LHC

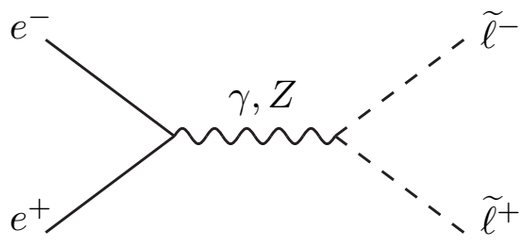
Purpose precise parameter reconstruction

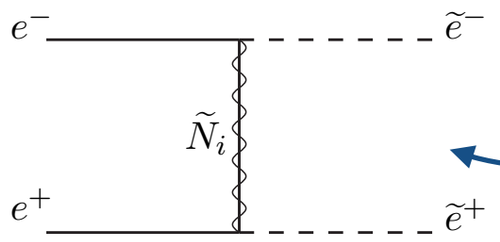
- *I will review results from ILC and FCC-ee and CLIC studies* *1702.05333 1202.5940 1504.01726*
- *I will try to identify interesting open questions in relation to LHC era*
- *Personal naive selection, please add comments/remarks/suggestions*

SUSY Production (sfermions)

SUSY particles are produced in pairs through weak interaction

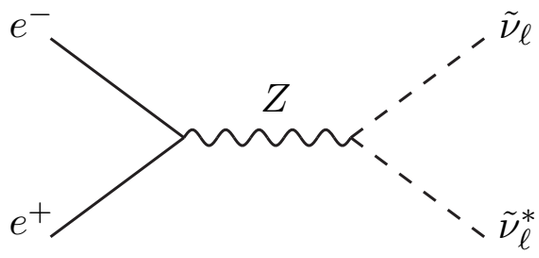
✳ Selectron produced via both s-channel and t-channel

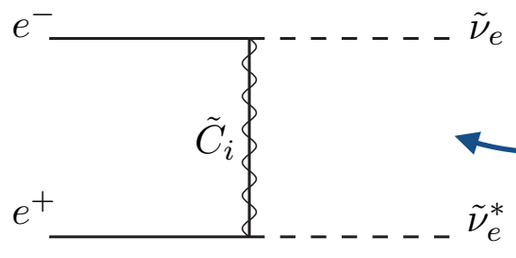




Dependence on neutralino spectrum

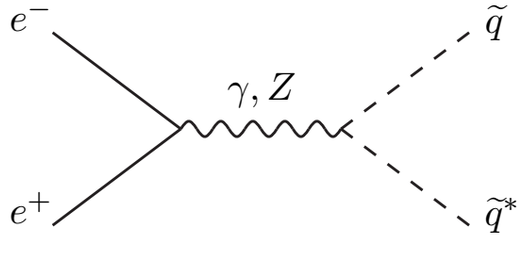
✳ Sneutrino produced via both s-channel and t-channel





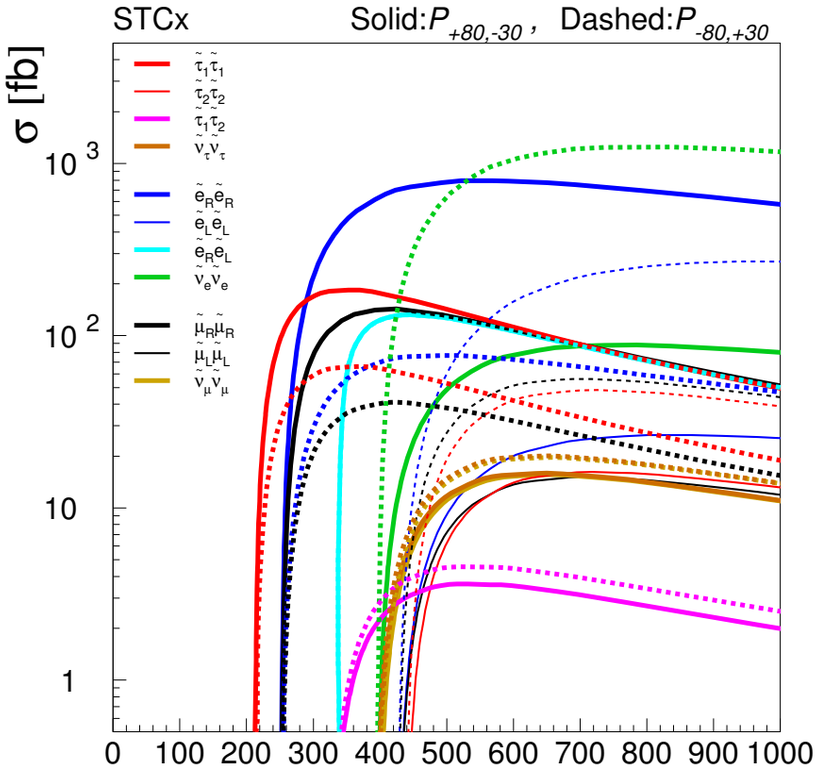
Dependence on chargino spectrum

✳ Squarks and other sleptons only via s-channel



Model independent

SUSY Production (sfermions)



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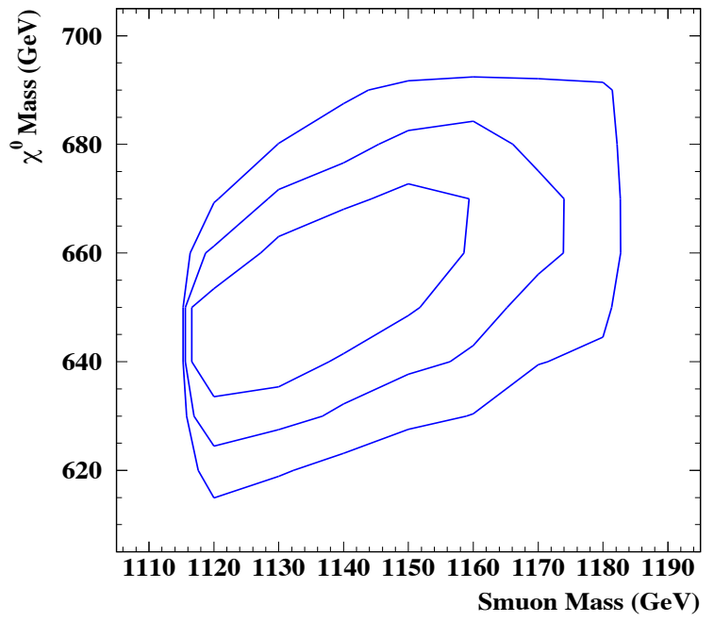
- Cross sections decreases for $\sqrt{s} \gg m_{\tilde{X}}$
- $\tilde{e}$ and $\tilde{\nu}_e$ extra t-channel contributions

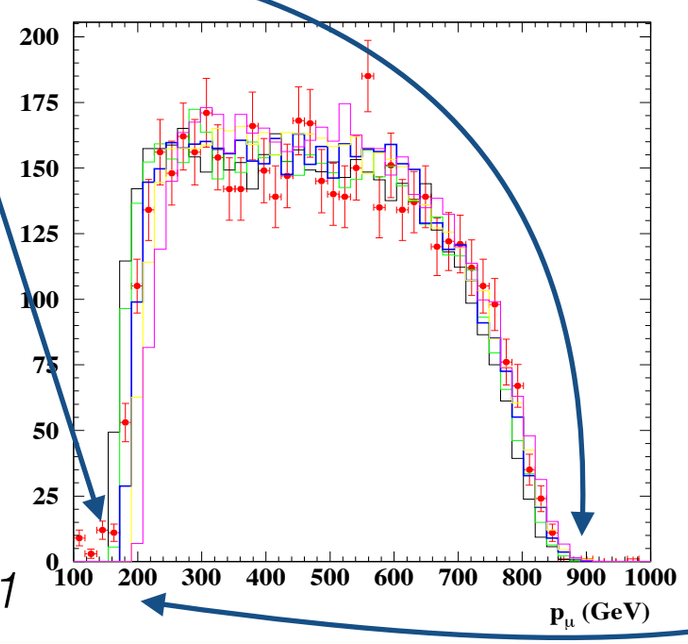
Sparticle masses can be reconstructed from distribution

Eg: $e^+e^- \to \tilde{\mu}_L\tilde{\mu}_L^* \to \chi_0\chi_0\mu^+\mu^-$

$$E_{\max/\min} = \frac{M_{\tilde{\mu}}}{2}\left(1 - \frac{M^2_{\tilde{\chi}^0_1}}{M^2_{\tilde{\mu}}}\right) \times \left(1 \pm \sqrt{1 - \frac{M^2_{\tilde{\mu}}}{E^2_{\text{beam}}}}\right)$$



hep-ph/0412251



Good knowledge of energy beam needed!

Not obvious for squarks

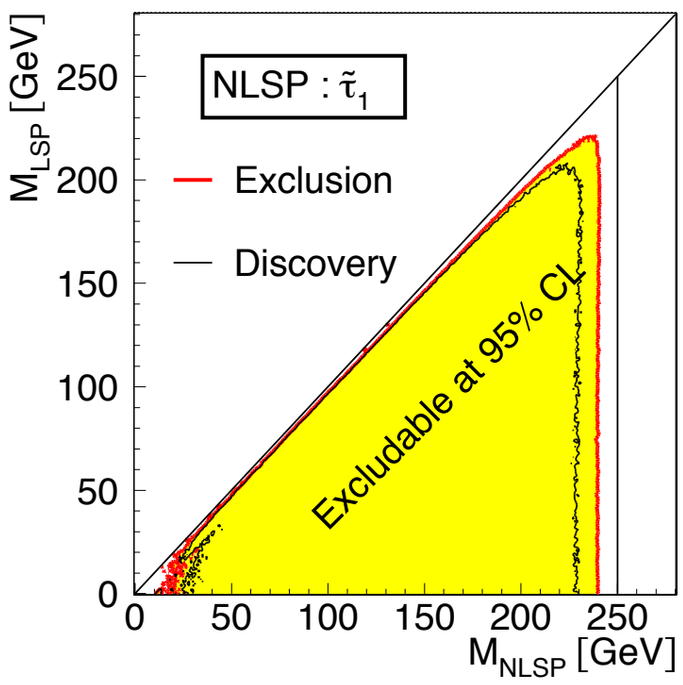
Reach for sfermions

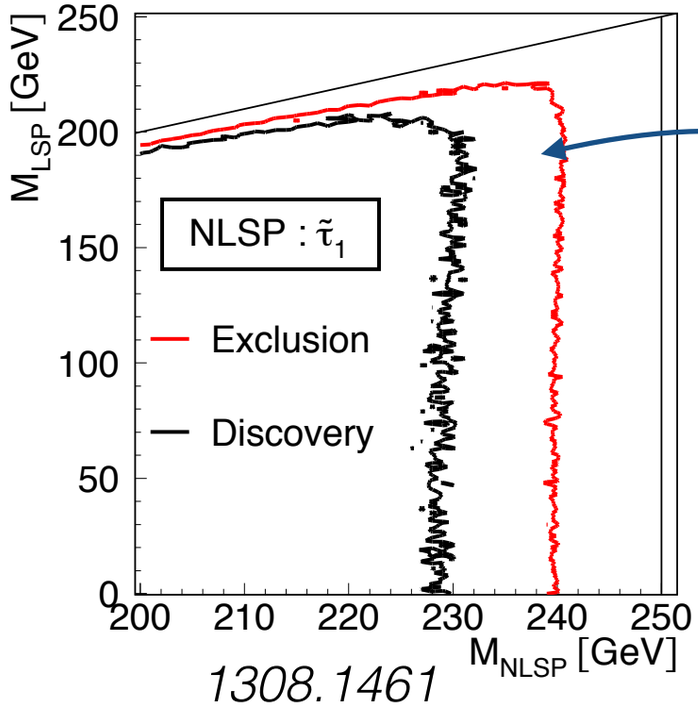
CLIC will probe kinematical threshold also in compressed region

Escape LHC

Co-annihilating DM

✳ Example from ILC500 study: stau-neutralino





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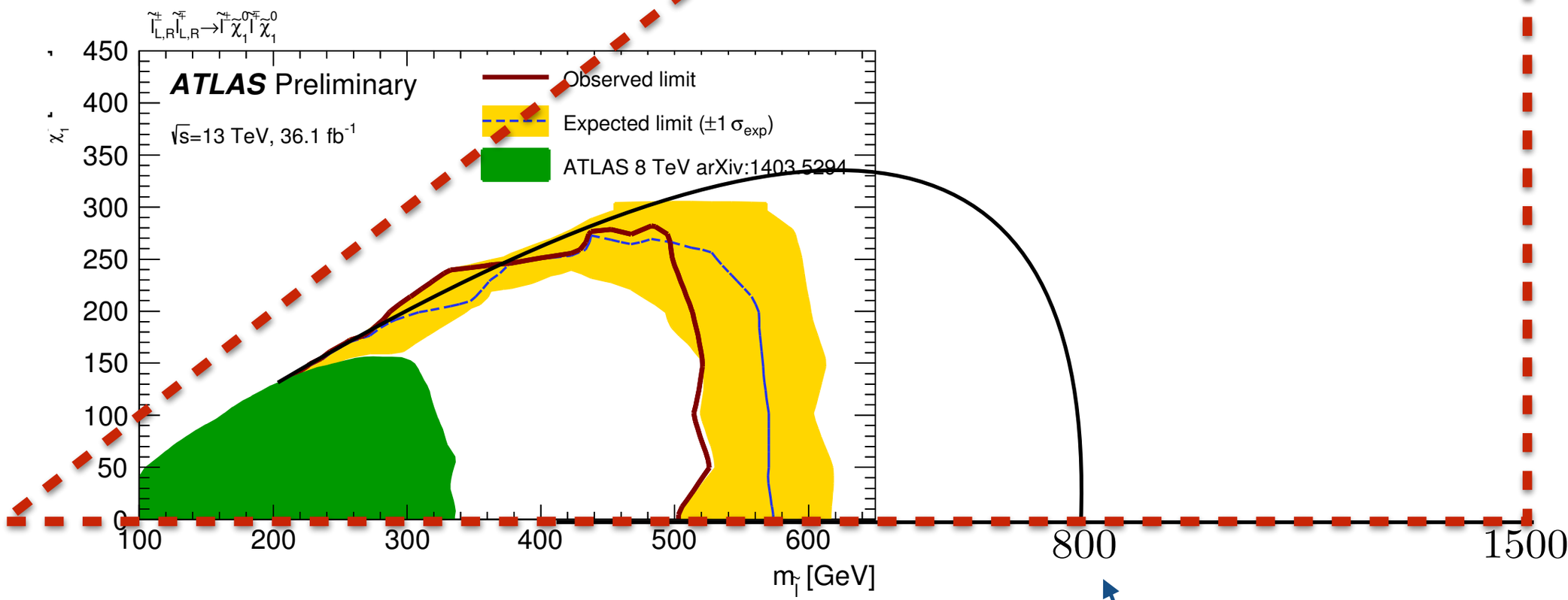
ISR photon can be used to better probe this region

Stau-neutralino co-annihilation covered

Slepton reach

Comparing CLIC reach with LHC prospects

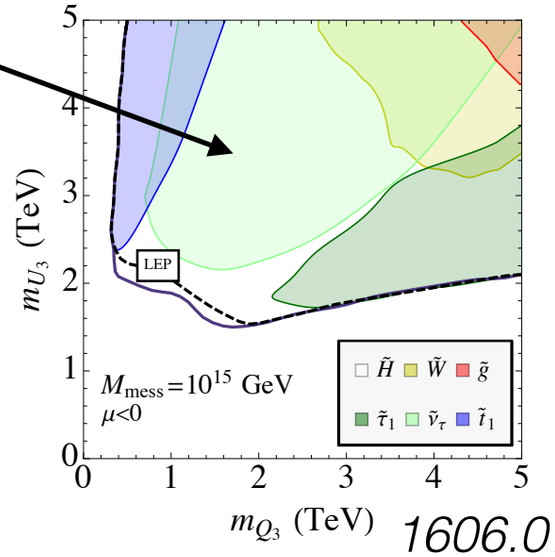
EW sfermion



- At HL-LHC we expect to probe $m_{\tilde{l}} \sim 800\ \mathrm{GeV}$
- ***CLIC over performant on EW states!***

Sneutrino NLSP

- Motivated in portion of GGM parameter space to get Higgs mass
- Colored sparticles very heavy



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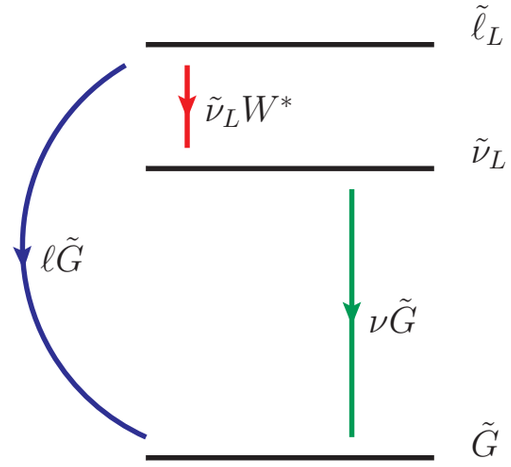
Simplified model



- Small mass splitting

$$\Delta_{\tilde{m}} \equiv m_{\tilde{l}_L} - m_{\tilde{\nu}} = \frac{m_W^2 \sin^2 \beta}{m_{\tilde{l}_L} + m_{\tilde{\nu}}}$$

- *Final state too soft to be probed at LHC!!!*

What about CLIC?

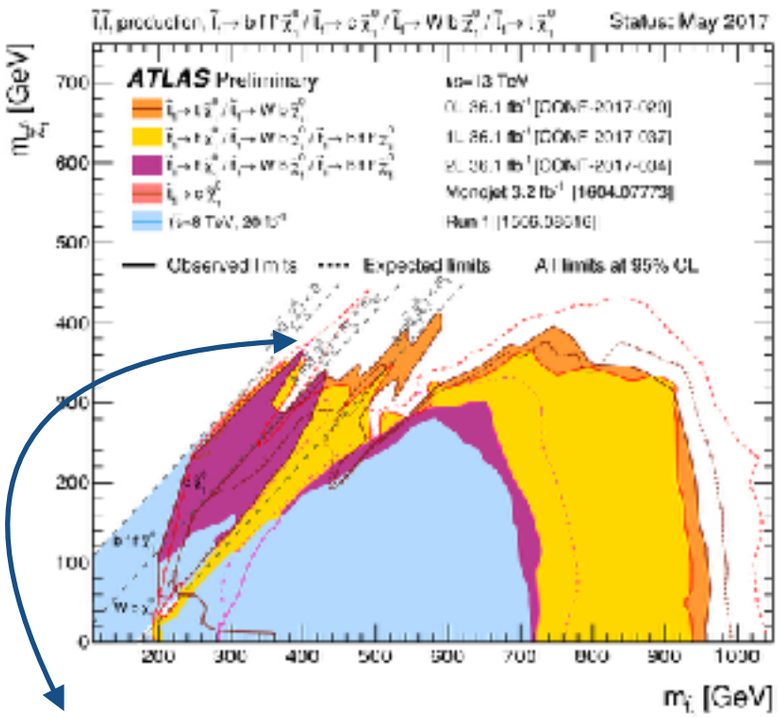
- Look for leptonic decay of off-shell W (OS different flavour)
- SM background from WW and tau-tau production
- Impose E(lep) and DPhi cuts to remove SM background
- ***Left handed slepton probed up to kinematical limit !!!***

Preliminary result

Stop reach

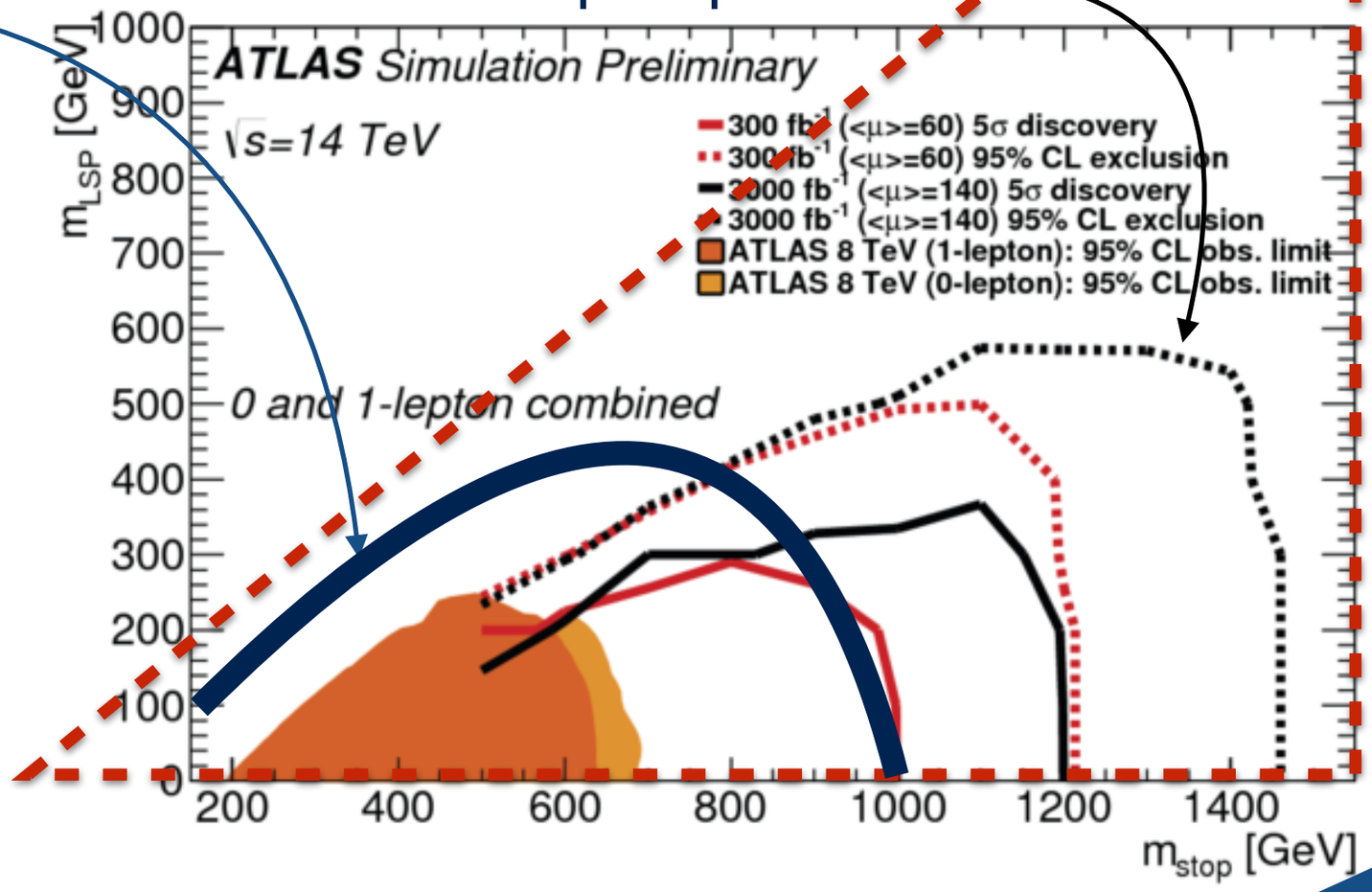
Comparing CLIC reach with LHC prospects

Current coverage



Rich pheno

HL-LHC prospects



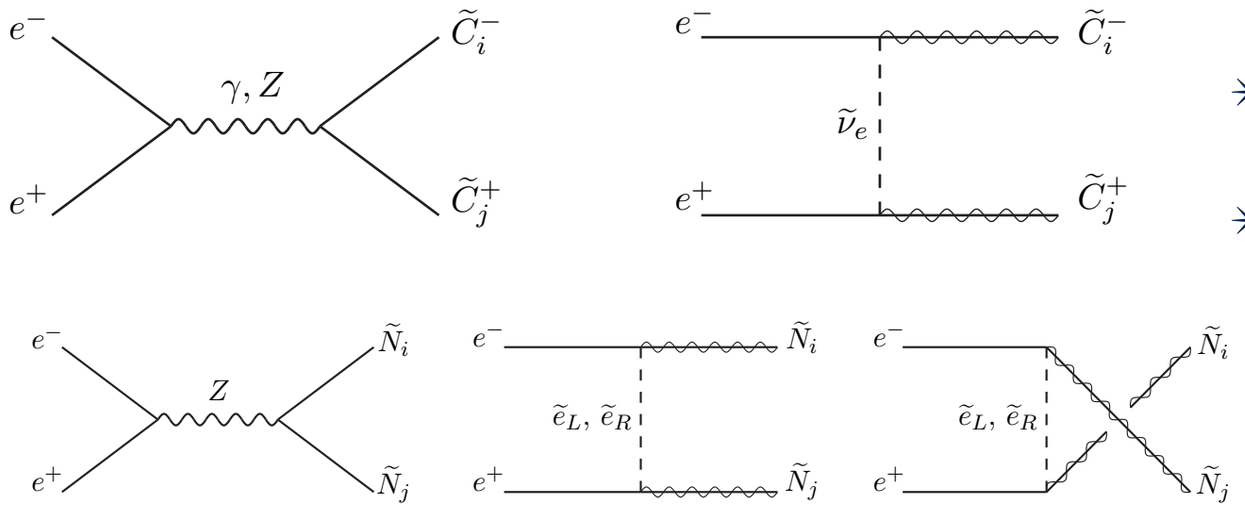
CLIC can potentially cover the compressed region!

Explore Stop-Bino co-annihilation

$10\text{GeV} < \Delta M < 100\ \text{GeV}$

SUSY Production (gauginos)

CLIC has enormous potential in unraveling the EW-ino sector



- s-channel
- t-channel contributions

Model independent

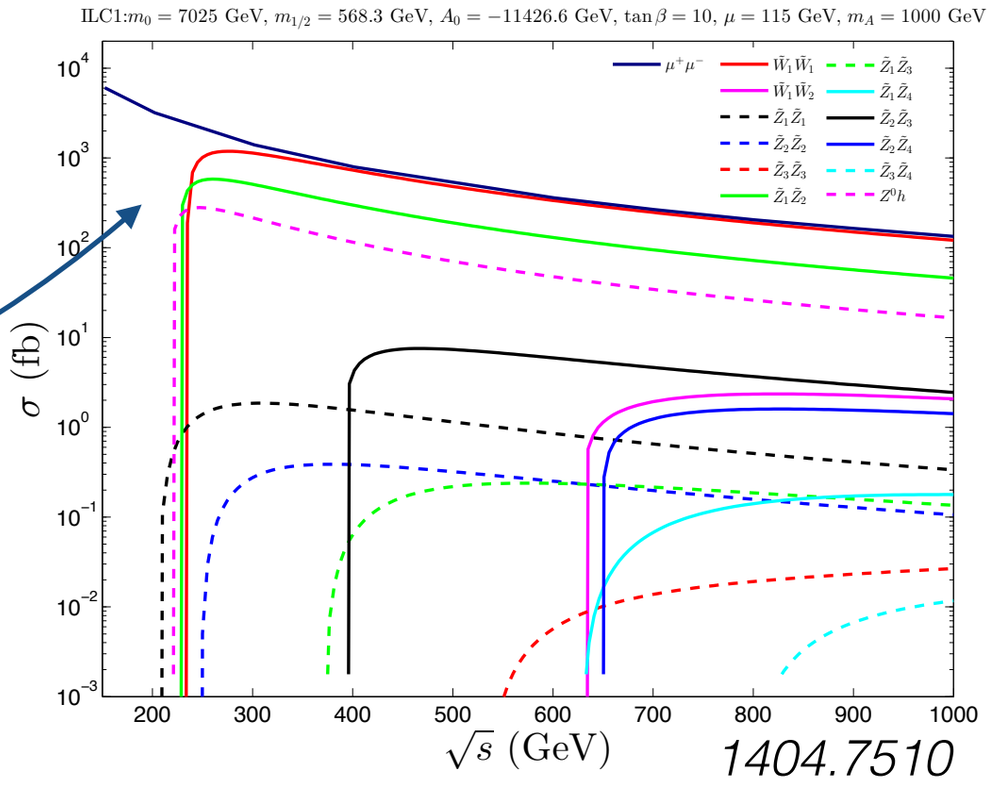
Dependence on slepton spectrum

- *All parameters in mass matrix can be reconstructed* (M1,M2,\mu,tanb)

See e.g.1104.0523, 1202.5489

Challenging LHC channel motivated by naturalness

- Higgsino LSP
- Higgsino Factory



1404.7510

Higgsino LSP

Challenging LHC channels motivated by naturalness

$\mu \ll M_1, M_2 \longrightarrow \chi_1^\pm \ \chi_1^0 \ \chi_2^0$ ***Mass degenerate*** $\Delta M \sim \mathrm{GeV}$

$$\Delta M \lesssim \mathrm{GeV}$$

- Employ ISR photon to reduce $\gamma\gamma$ background
- Masses reconstructed from fit to kinematic variables (at few %)

Ex: chargino pair production

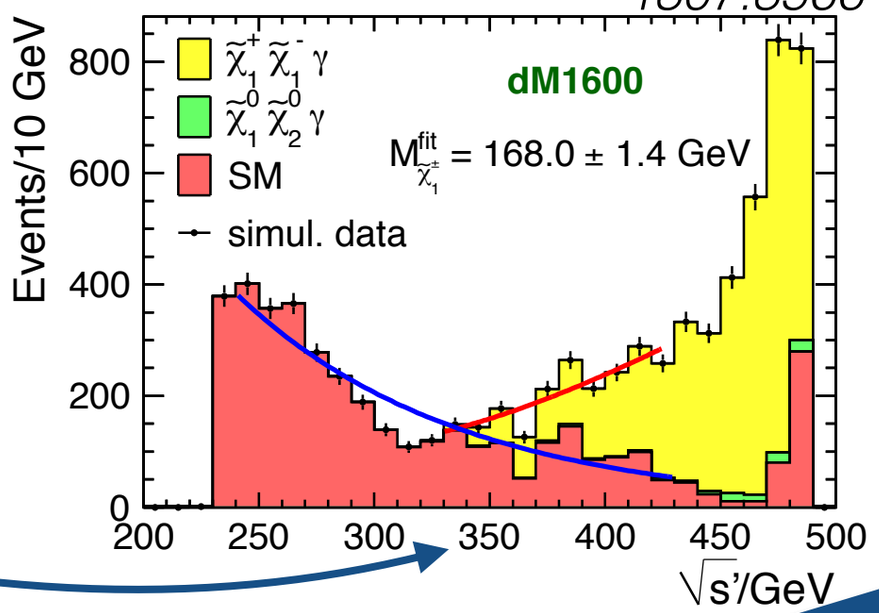
- Focus on semi-leptonic decay
- Reduced c.o.m. of chargino system

$$s' = s - 2\sqrt{s}E_\gamma$$

- Signal kicks in for $\frac{1}{2}\sqrt{s'} \geq M_{\chi_1^\pm}$

See alsoe.g.: 0103167; 0104086

1307.3566



- For $\Delta M \sim O(10\ \mathrm{GeV})$ no need of ISR photon

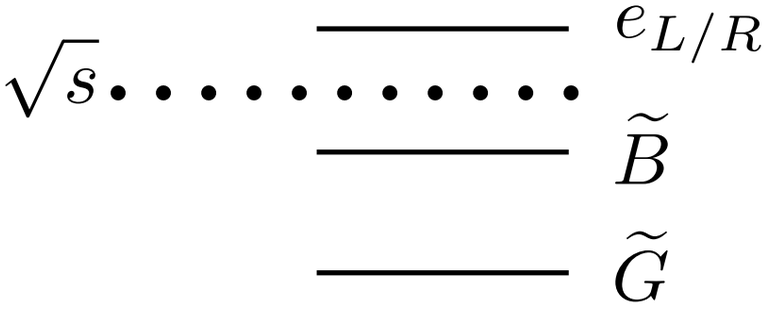
1404.7510

These studies performed for ILC …

Probing the scale of SUSY br

✳ Investigate processes with goldstino production

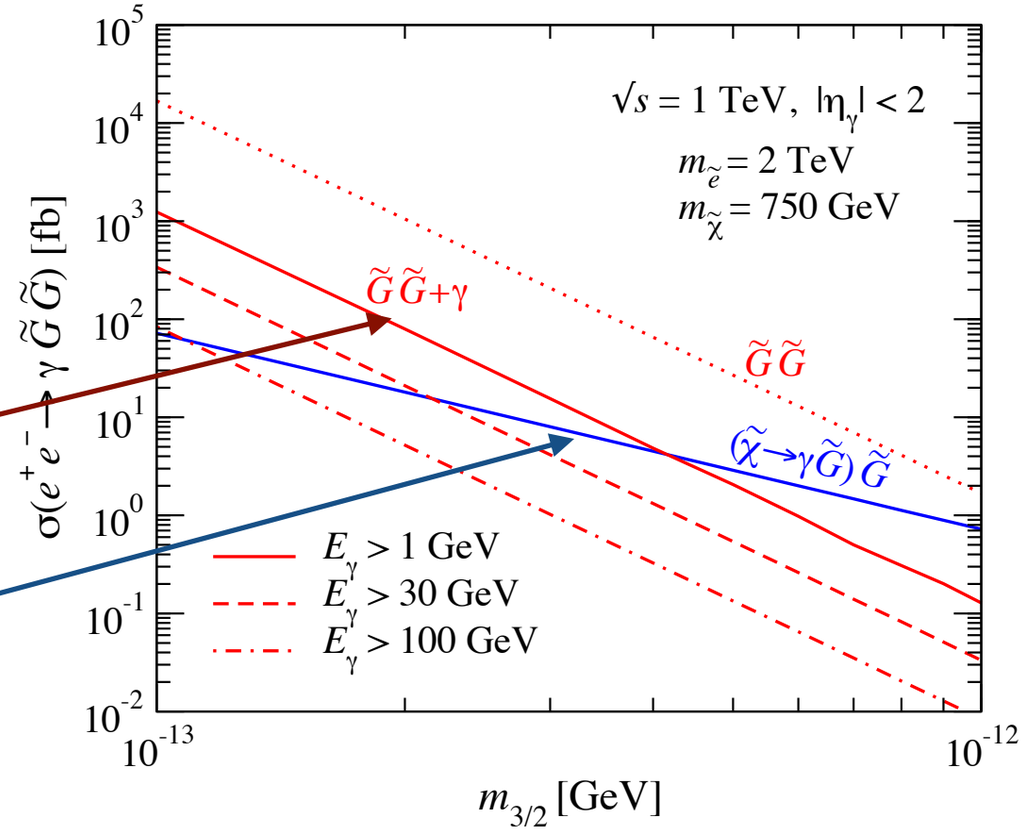
Simplified model



Mono-photon + MET

$$\begin{cases} e^+e^- \to \widetilde{G}\widetilde{G}\gamma & \sim \dfrac{1}{m_{3/2}^4} \\ e^+e^- \to \widetilde{G}\widetilde{B} \to \widetilde{G}\widetilde{G}\gamma & \sim \dfrac{1}{m_{3/2}^2} \end{cases}$$

1402.3223



✳ We can provide bound on gravitino mass (SUSY br scale)

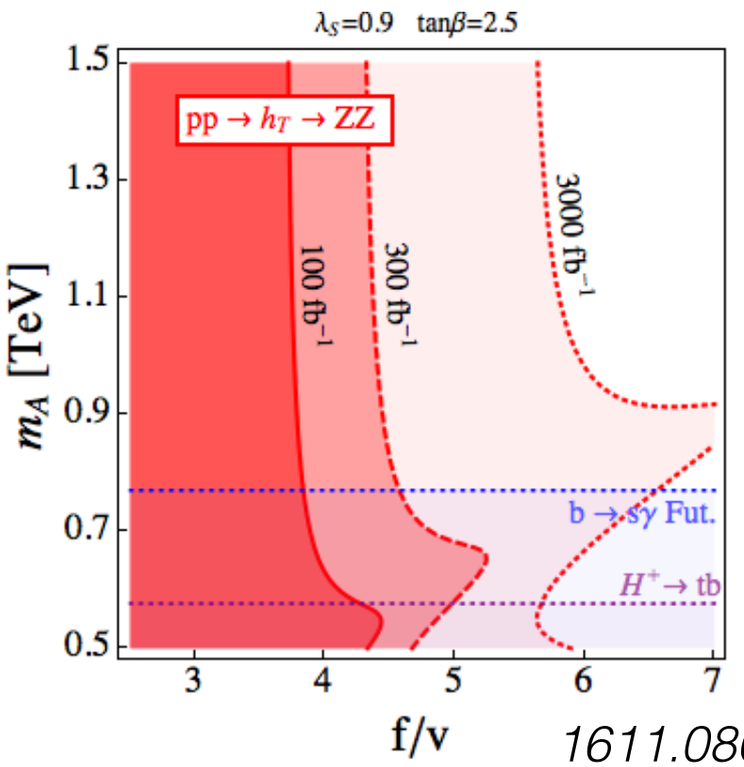
✳ LEP: $m_{3/2} \gtrsim 10^{-14}$ GeV , what can do CLIC?

LHC similar
1502.01637

Neutral SUSY

SUSY can manifest in QCD neutral states

- Folded SUSY
  - Still traces in EW charged folded stops…
- Twin SUSY
  - Higgs portal to hidden sector
  - Handle on the (Twin) Higgs and its possible exotic decays
- Extended MSSM-like scalars augmented with MET



1611.08615

Double copy of MSSM scalar sector

Spectrum controlled by two parameters

- m_A ***MSSM-like scalars***
- f ***Twin-Higgs***

At LHC constraints from resonance searches and MSSM scalar searches

Neutral SUSY

SUSY can manifest in QCD neutral states

- Folded SUSY
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  - Handle on the Twin Higgs possible exotic decays
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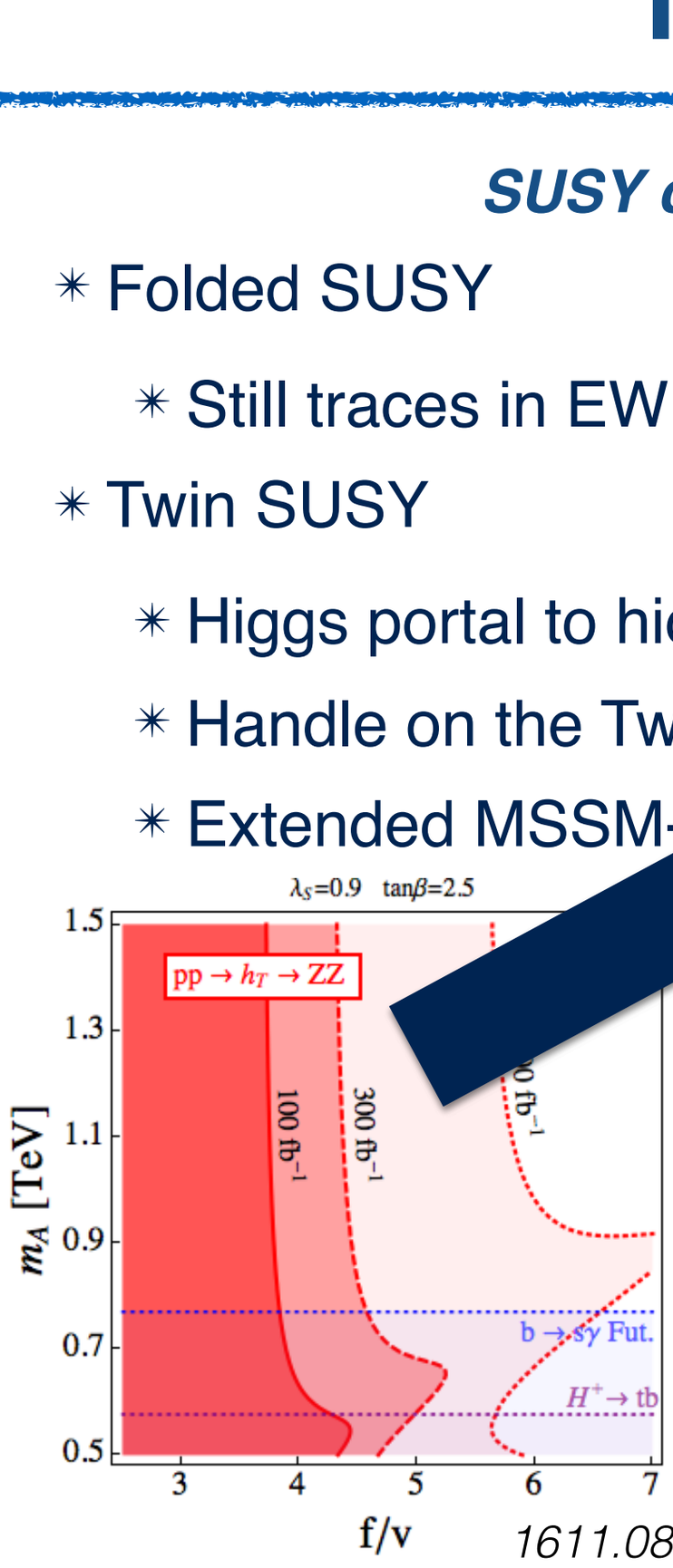
Prospects for CLIC???



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Double copy of MSSM scalar sector

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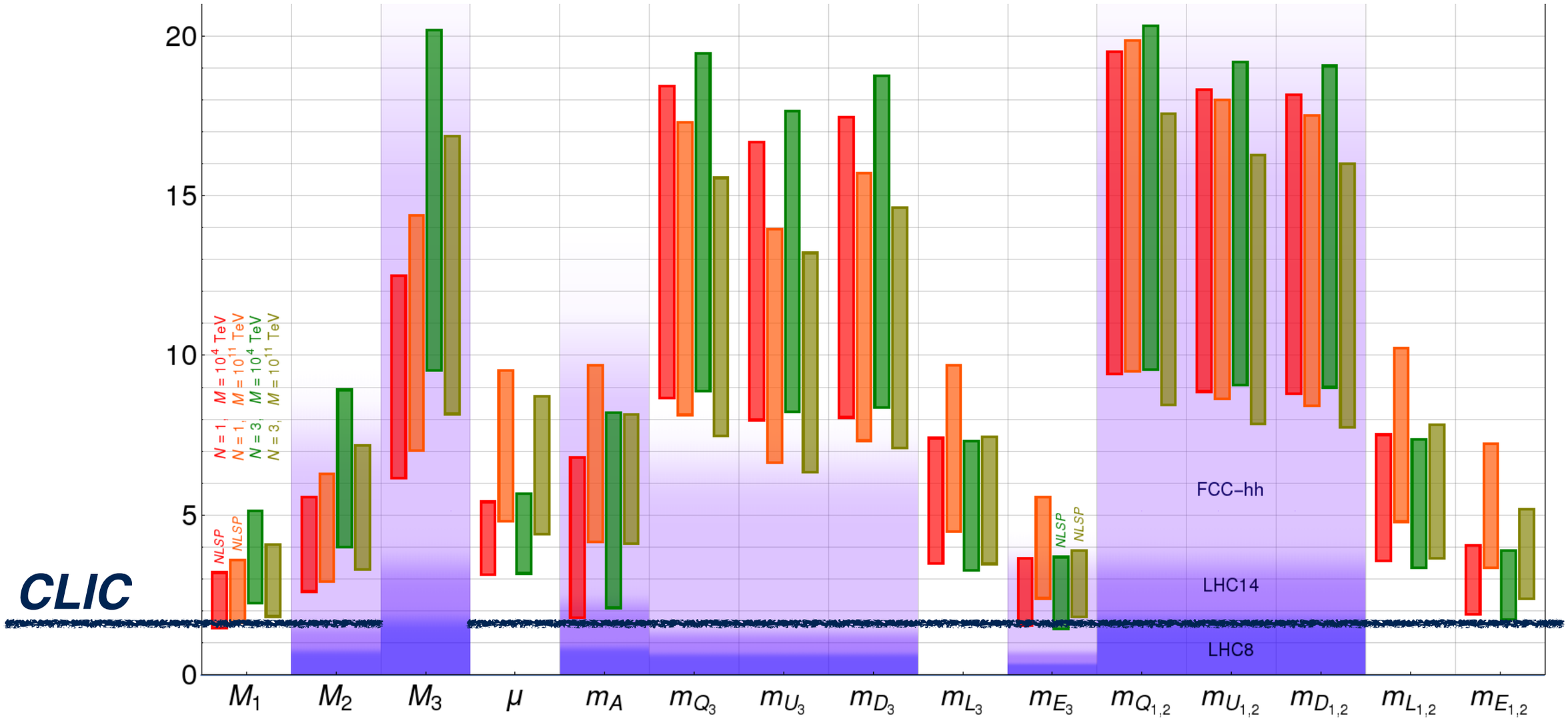
At LHC constraints from resonance searches and MSSM scalar searches

CLIC vs Heavy SUSY

Minimal GMSB models consistent with Higgs mass

1504.05200



CLIC

CLIC vs Heavy SUSY

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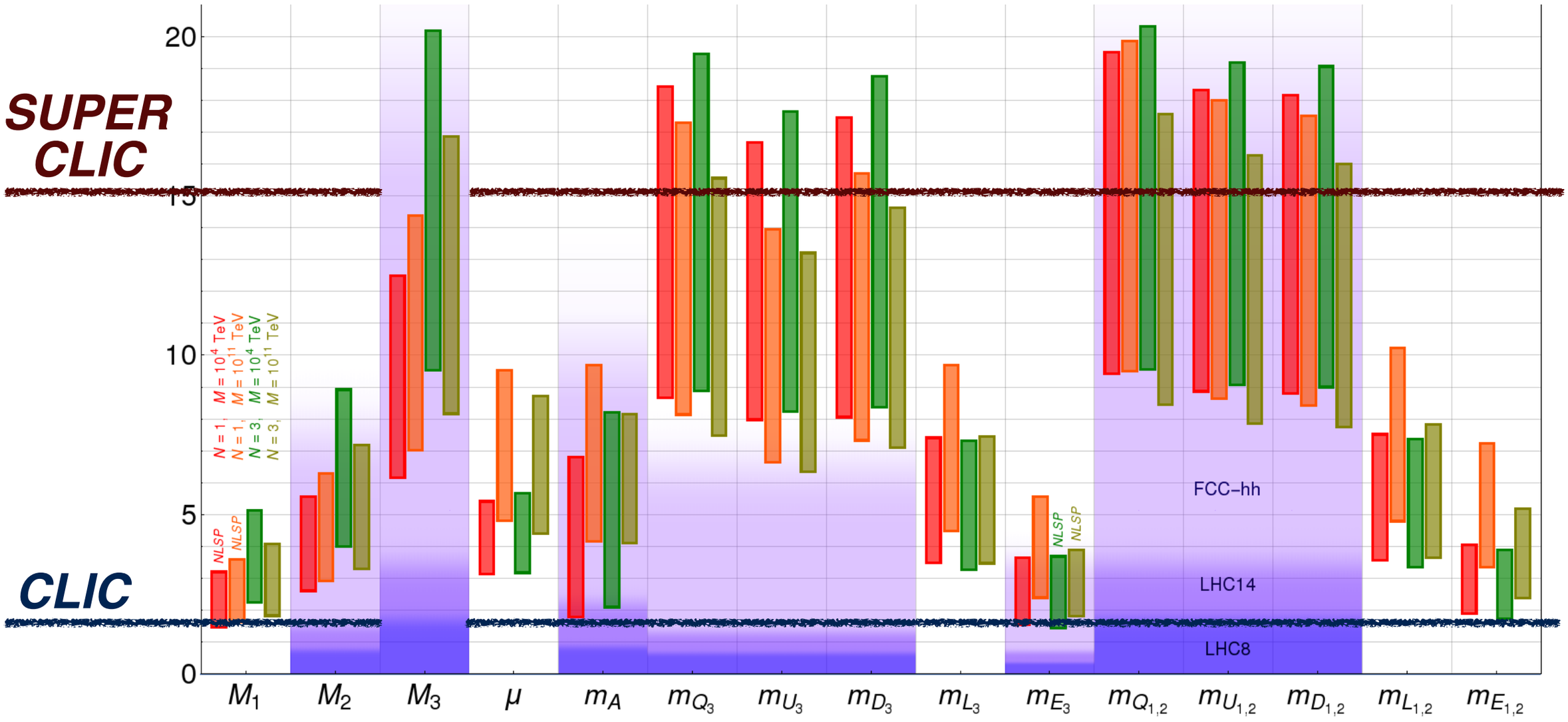


For competing with FCC-HH in heavy SUSY we need "SUPER"-CLIC

CLIC for SUSY

What CLIC can bring to SUSY?

SUSY discovered @ LHC

★ CLIC will measure sparticle spectrum/couplings precisely

SUSY not discovered @ LHC

★ CLIC will pursue complementary SUSY exploration

- **★ Cover holes left by LHC**
- **★ EW sector**
  - ✳ *Higgsino LSP*
  - ✳ *Sleptons*
  - ✳ *Sneutrino*
- **★ Compressed scenarios (co-annihilating DM)**
- **★ Goldstino production and SUSY br scale**

CLIC for SUSY

What CLIC can bring to SUSY?

... and more ...

★ CLIC will pursue complementary SUSY exploration

- **★ MSSM Higgses**
- **★ Indirect probes from precise measurements**
- **★ Non Standard SUSY**
  - ✳ *Neutral SUSY*
  - ✳ *RPV*
  - ✳ *....*
- **★ Heavy SUSY ... high energy CLIC ?**

...

Thanks for the attention

EW gauginos

CLIC has enormous potential in unraveling the EW-ino sector

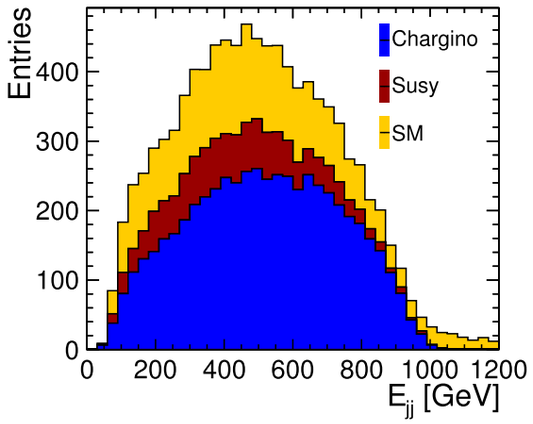
- Masses can be reconstructed (at % level)

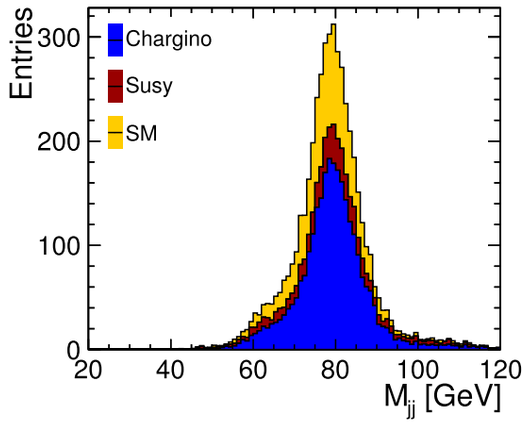
Ex: chargino into bosons

S: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-\tilde{\chi}_0\tilde{\chi}_0$

B: ***SM:*** $e^+e^- \to W^+W^-\nu_e\bar{\nu}_e$

SUSY: $e^+e^- \to \tilde{\chi}_2^+\tilde{\chi}_2^- \to W^+W^-\chi_2\chi_0$





Particle	Mass (GeV)
χ_1^0	340.3
χ_2^0	643.2
χ_3^0	905.5
χ_4^0	916.7
$\chi_1^\pm$	643.2
$\chi_2^\pm$	916.7

1104.0523
1202.5489

- If all neutralino/chargino are accessible challenge is disentangle the topologies
- Model dependence introduced by slepton t-channel
- All parameters in mass matrix can be reconstructed (M1,M2,\mu,tanb)
- Only accessing few neutralino/chargino one can still reconstruct parameters

Many available results are on benchmarks

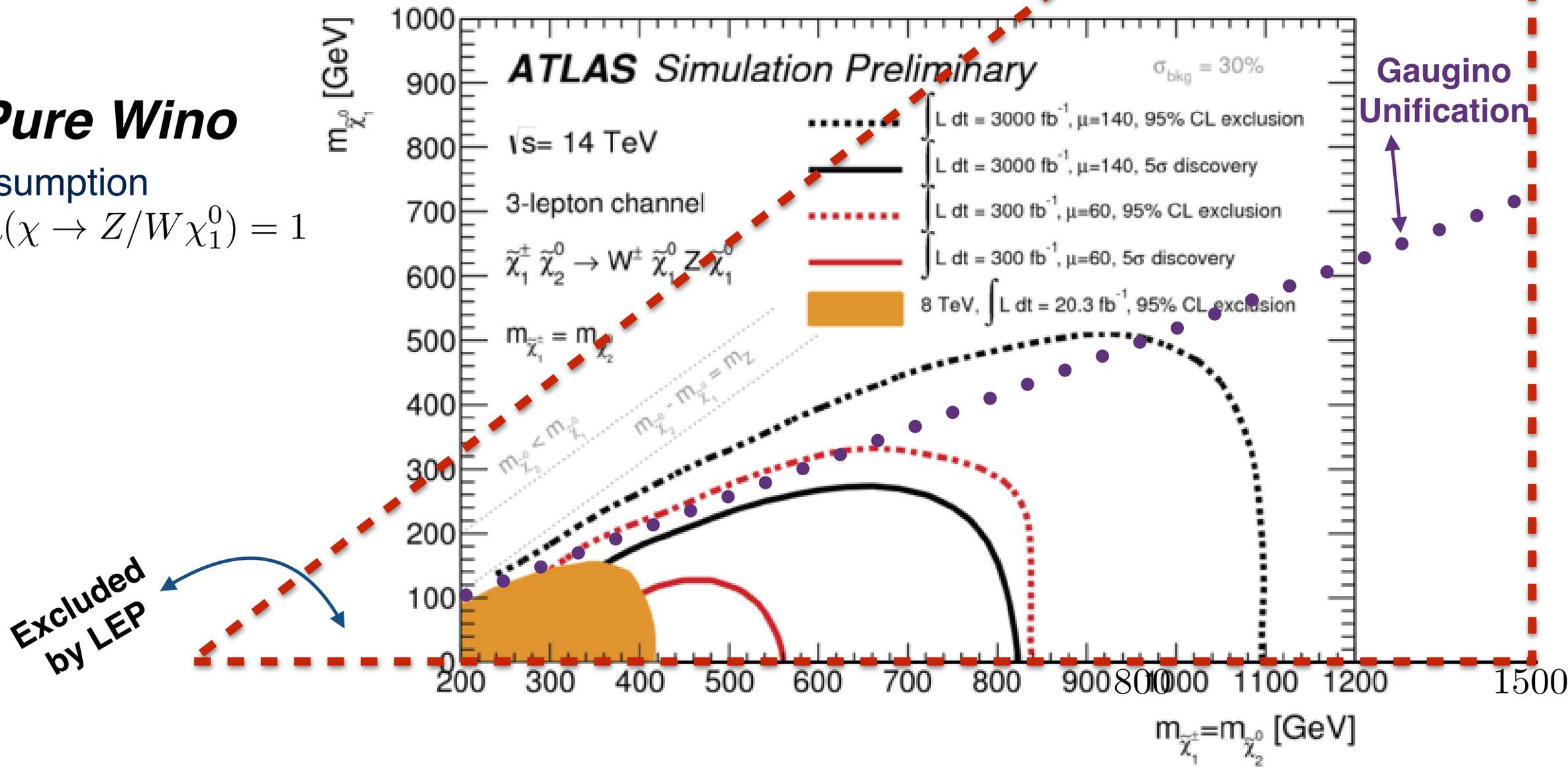
Polarization useful

Gaugino reach

Comparing CLIC reach with LHC prospects

Pure Wino

- Assumption
  $\mathrm{BR}(\chi \to Z/W\chi_1^0) = 1$



- ***CLIC over performant on EW states!***

MSSM Higgses

Heavy Higgses probed at the kinematic threshold

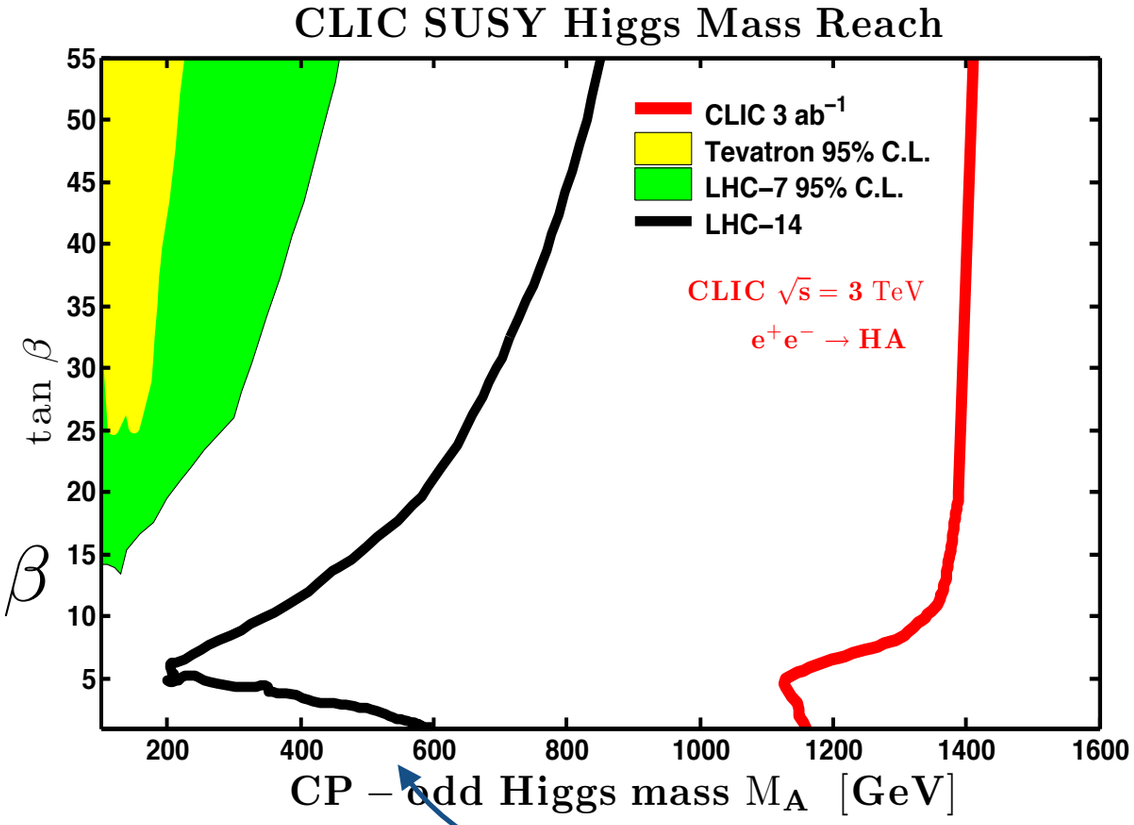
- Assume decoupling $m_A \gg m_h$

$$e^+e^- \to HA \to b\bar{b}b\bar{b} \text{ or } t\bar{t}t\bar{t}$$

- Also $\gamma\gamma$ production can be used
- Eg: tau fusion to measure large $\tan\beta$

0404119

1202.5940



- Also charged Higgs can be probed to kinematical threshold
- CP properties can be studied

More recent analysis based on ttH shows TeV reach at LHC

1605.08744

RPV susy at CLIC

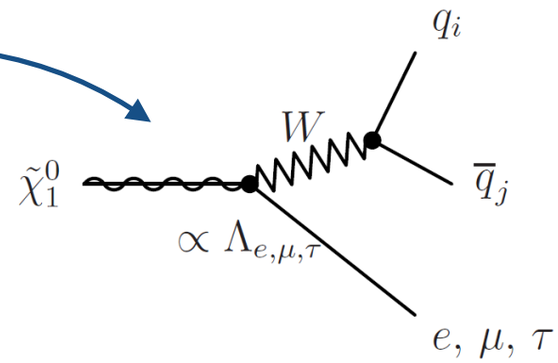
RPV couplings

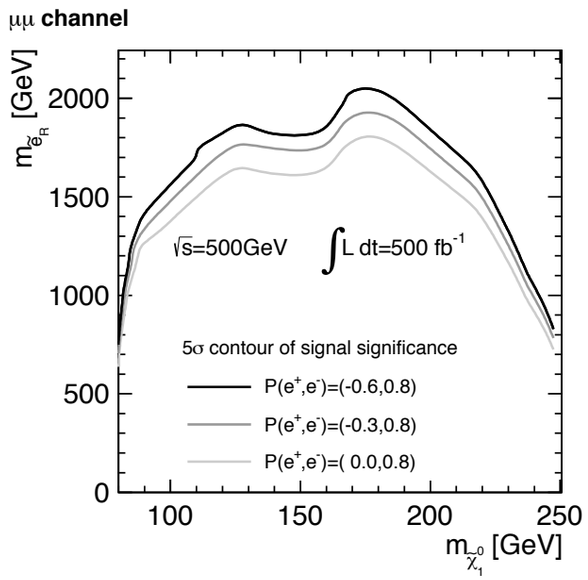
- *Displaced/long lived decays (also charged object)*
- *Prompt decay signal with multi-object final states*

Ex: bilinear RPV lepton violation

1307.4074

- Simplified spectrum with selectron and mostly bino neutralino
- Neutralino decay to W and leptons





- Mass reconstructed by energy distributions
- Model probed up to kinematical threshold

These studies performed for ILC …

What are prospects for RPV couplings with most impact in hiding LHC physics?

Vanilla Natural SUSY

1610.08059

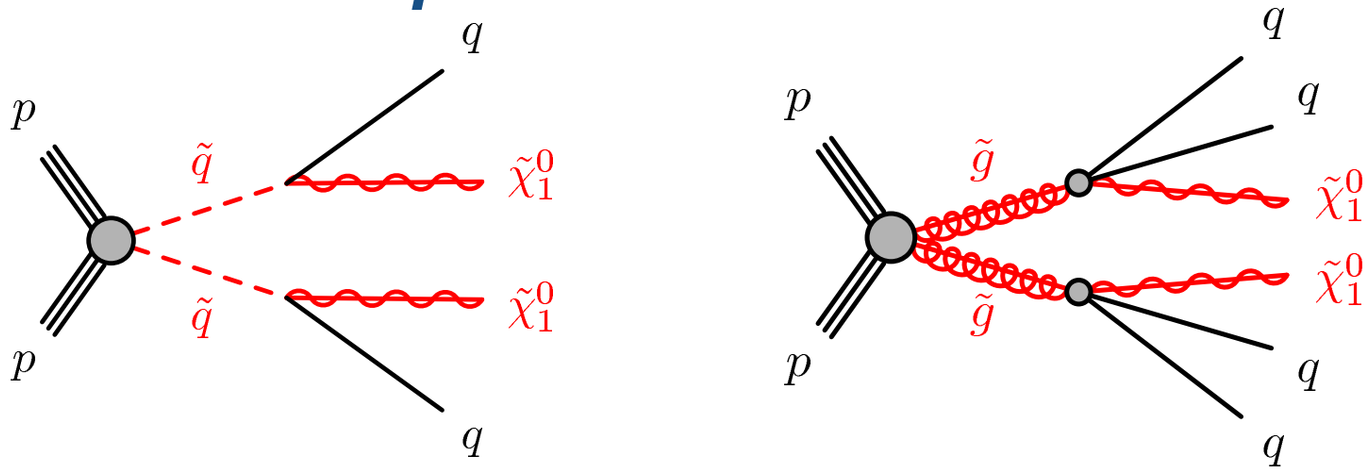
Simplified model with gluino, squarks, higgsino

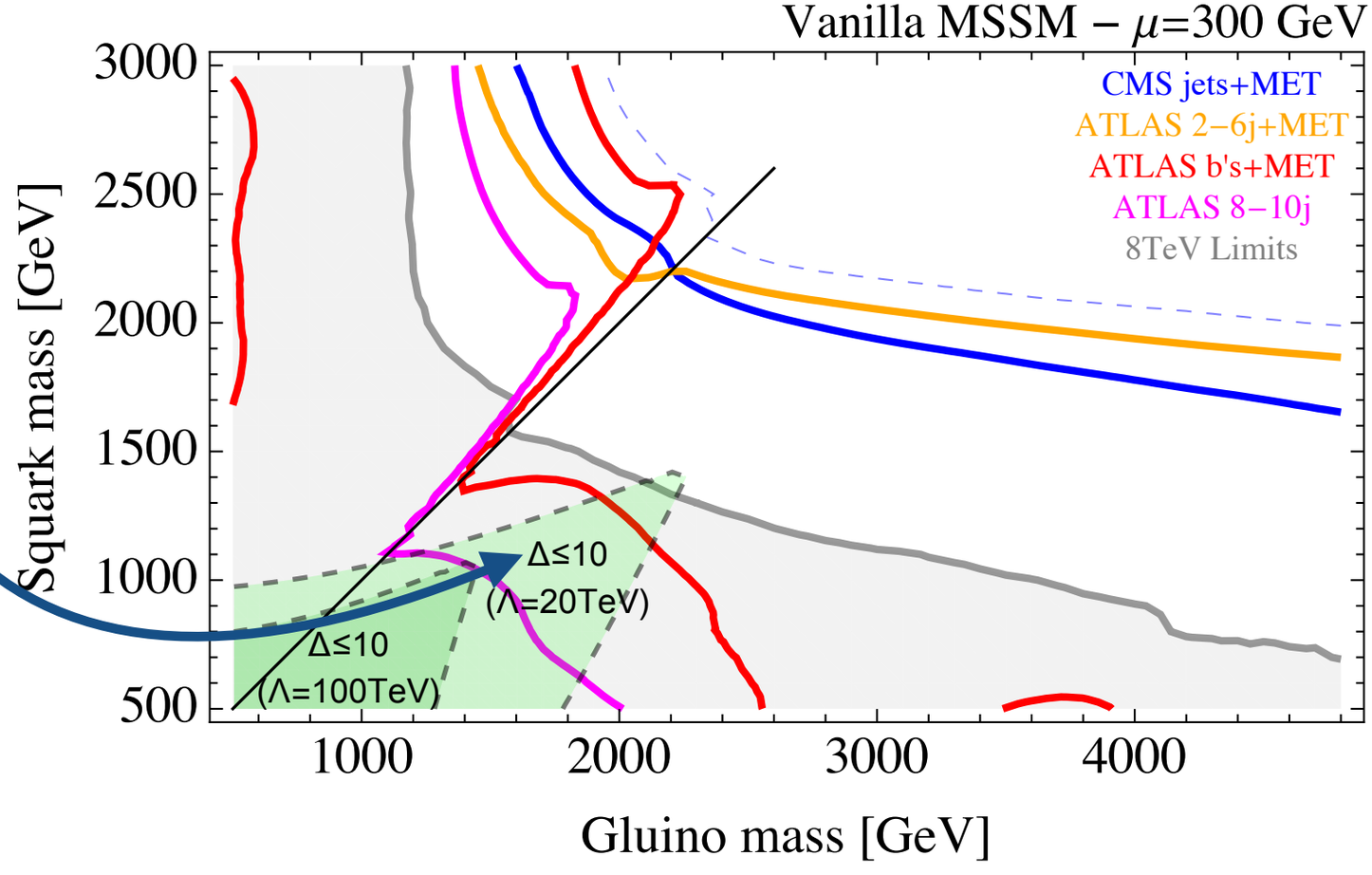
—— $\tilde{g}$

—— $\tilde{q}_R, \tilde{Q}_L$

—— $\tilde{H}$

Colored production channels





- Assumed UV scale at 20 TeV to minimize tuning
- Nevertheless 10% tuning excluded already at 8 teV

Non Vanilla Natural SUSY

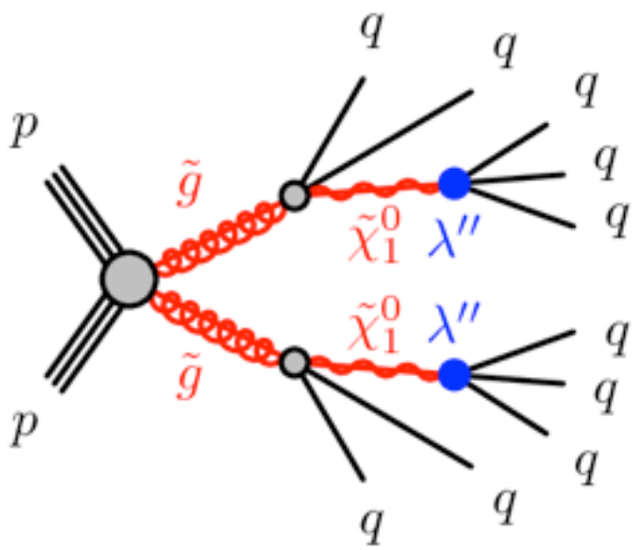
Simplified model with gluino, only stops, higgsino

— $\tilde{g}$

— $\tilde{t}_R, \tilde{t}_L, \tilde{b}_L$

— $\tilde{H}$

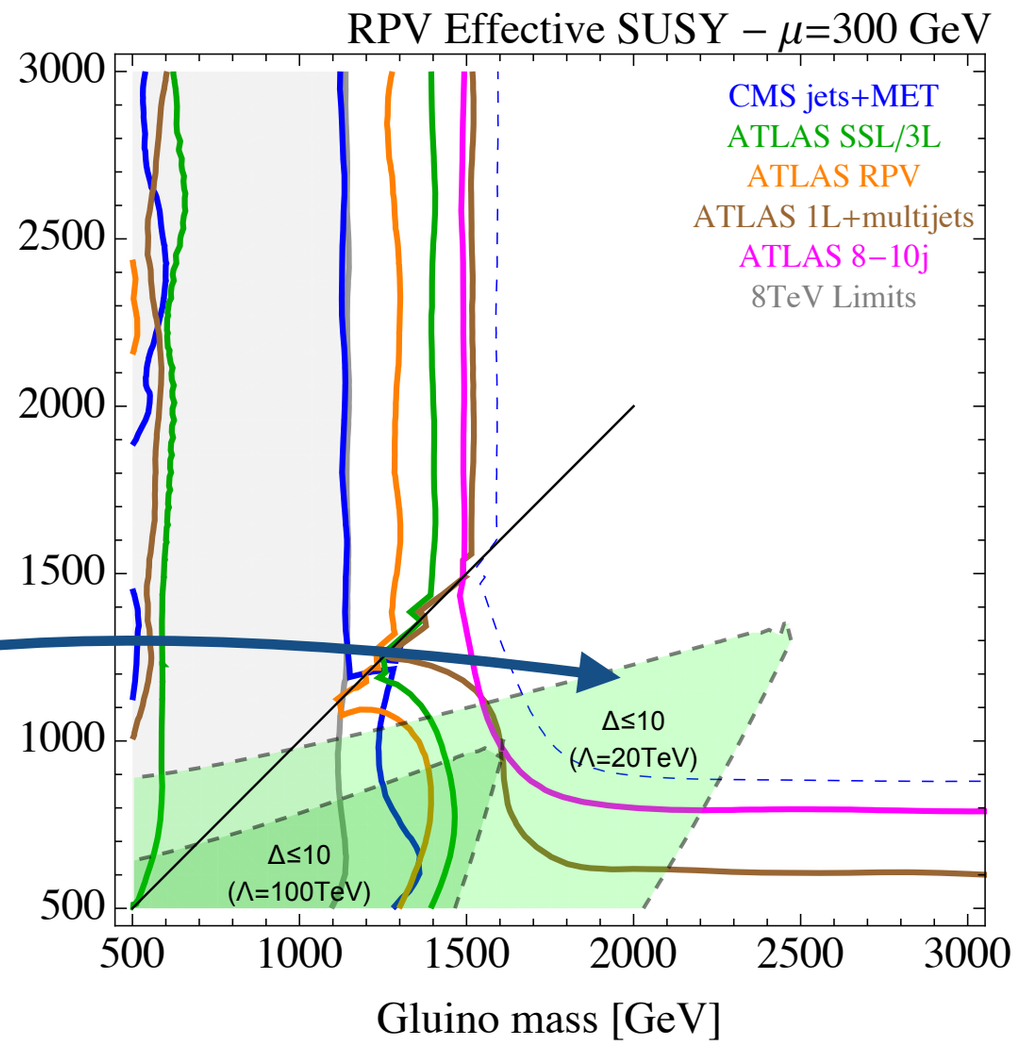
Add RPV decay of Higgsino



- Assumed UV scale at 20 TeV to minimize tuning
- 10% tuning allowed by 13 TeV data

1610.08059

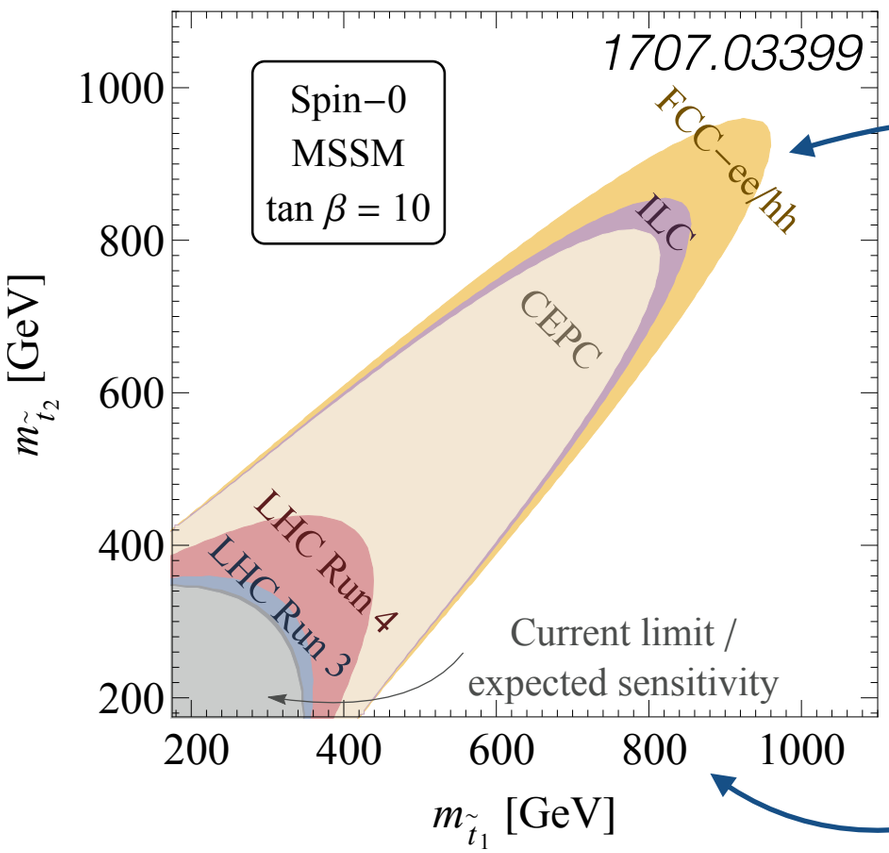
UDD RPV operator



Indirect Probe of SUSY

- Lepton collider offer opportunities for precise Higgs couplings
- Indirect probe of new physics!

- Measurement of Higgs coupling can shed light on naturalness
- Colored top partners will modify Higgs couplings to bosons



Contribution maximized when stops are degenerate

Stop probed up to TeV scales

- *Also Zh cross section measurement can provide sensitivity*