SUSY with Compressed Spectrum

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Outline

The MEXT questions

The MEXT ILC advisory panel requested a clear vision for new particle discovery potential. They required prospects for new particle discoveries in each of the following three cases:

1. LHC finds no new particle. ($\Rightarrow$ Tomohiko's talk)
2. LHC finds new particle(s) within ILC reach, or that at least hints to new particles within reach. Eg. a 1.6 TeV gluino.
3. LHC finds new particle(s), but none in ILC reach, nor hinting that there would be any in reach. Eg. a gluino at 3 TeV.

(This is not exactly what is said in the "Summary of the International Linear Collider (ILC) Advisory Panelâs Discussions to Date", which is more vague, but is what Keisuke has extracted from further discussions.)

Where do the “hints” come from ?

Why would the mass of the gluino gives a hint for the ILC?

- Based on bosino mass unification on the GUT scale.
- This is different from coupling unification at the GUT scale.
- The latter is an indication for new physics at the weak-scale; If there is no new physics between weak and GUT scales, the RGE running makes strong, EM and weak couplings equal at different points for any pair of couplings. If there is, they can all unify at a single point.
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- Mass-unification was useful at LEP, to be able to combine different searches into a single picture.
- However: already with current LHC limits, this assumption is becoming an increasingly bad idea:
  - The p-value of CMSSM fit to the data is close to exclusion.
  - The high masses of the electro-weak sector that LHC+mass-unification implies $\Rightarrow$ SUSY less and less a possible explanation to the problems of the SM.
- In addition: While the assumption couples all gaugino-masses, it does not constrain the higgsino-masses.

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What *do* we know ?

The three scenarios are quite similar as far as SUSY a ILC is concerned: Naturalness, hierarchy, DM, g-2 all prefers light elector-weak sector. Whether LHC finds nothing, light coloured, or heavy coloured particles does not change the state of the matter, because

- Except for 3d gen. squarks, the coloured sector doesn't enter the game.
- Even if LHC finds NP, it will be very hard to identify as SUSY.
- In natural SUSY the LSP *is* a higgsino, and the electro-weak sector is "compressed", ie. there is at least some of the EW's that are close to the LSP.
- $\Rightarrow$ most sparticle-decays are via cascades including bosinos/sleptons, and at the end of these cascades, the mass difference is small $\Rightarrow$ invisible to the LHC !
- Hence, that "LHC finds new particle(s), but none in ILC reach" does *not* mean that there *aren't* any SUSY particles with in ILC

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Why compressed spectra ? Natural SUSY: Light, degenerate higgsinos

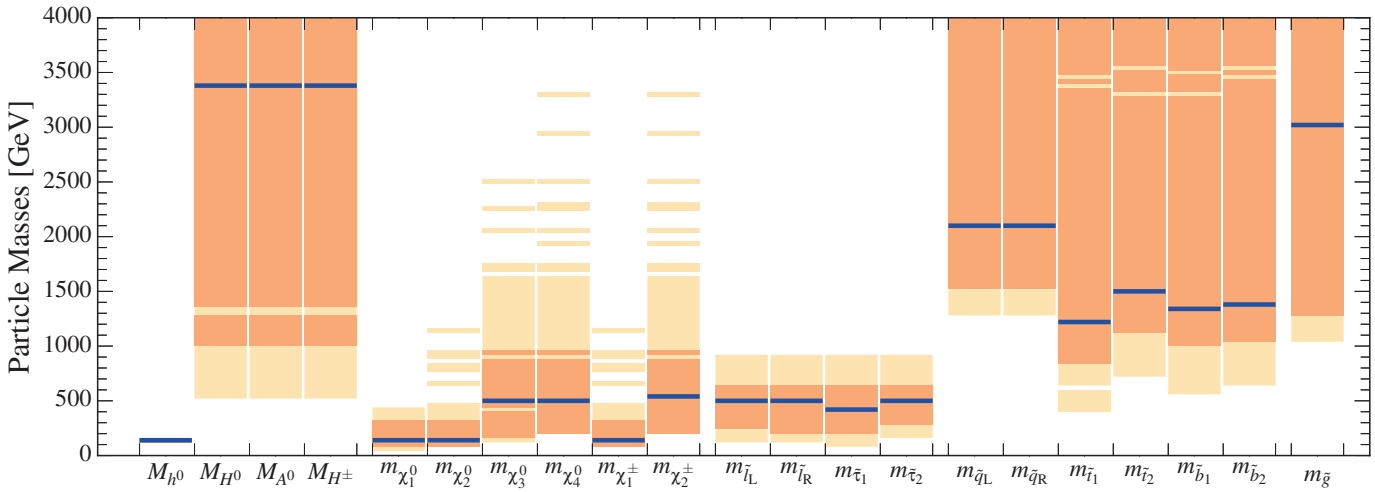
Why would one expect the spectrum to be compressed ?

- Natural SUSY:
  - $m_Z^2 = 2\frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{1-\tan^2\beta} - 2\,|\mu|^2$
  - $\Rightarrow$ Low fine-tuning $\Rightarrow$ $\mu = \mathcal{O}$(weak scale).
  - If multi-TeV gaugino masses:
    - $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ pure higgsino. Rest of SUSY at multi-TeV.
    - $M_{\tilde{\chi}_{1,2}^0}, M_{\tilde{\chi}_1^\pm} \approx \mu$
    - Degenerate (ΔM is 1 GeV or less)

Why compressed spectra ? Global fits

pMSSM10 prediction: best-fit masses

[2015]



⇒ high colored masses

⇒ relatively low electroweak masses

partially with not too large ranges

⇒ clear prediction for ILC and CLIC

The ILC is not LHC

OK, if the new particles are invisible for LHC, why can ILC see them ?

- Lepton-collider: Initial state is known.
- Production is EW $\Rightarrow$
  - Small theoretical uncertainties.
  - No "underlaying event".
  - Low cross-sections wrt. LHC, also for background.
  - $\Rightarrow$ Trigger-less operation.

$\Rightarrow$ for detectors:

- Low background $\Rightarrow$ detectors can be:
  - Low cost, low p_T cut, low resolution.
  - Low cost, low p_T cut, high resolution.
  - Low cost, high p_T cut, high resolution.
  - Low cost, high p_T cut, low resolution.
  - Low cost, high p_T cut, low resolution, low granularity.
- Importance of hermeticity for the searches: $\gamma\gamma$ rejection !

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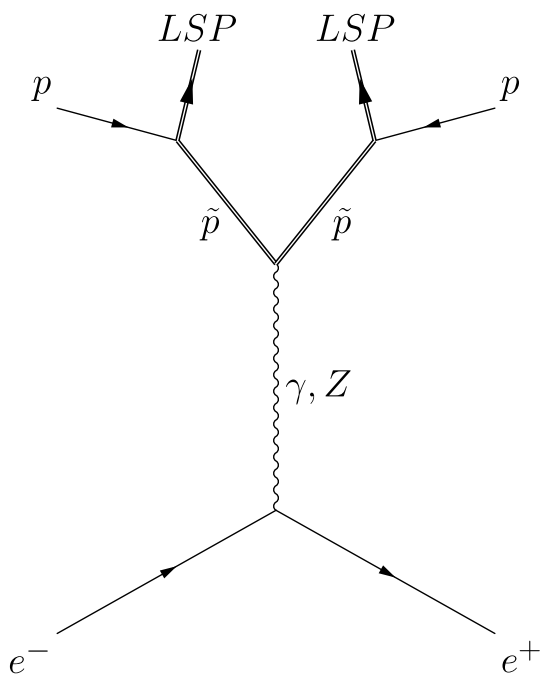
$\Rightarrow$ for detectors:

- Low background $\Rightarrow$ detectors can be:
  - Thin : few % X_0 in front of calorimeters
  - Very close to IP: first layer of VXD at 1.5 cm.
  - Close to 4π: holes for beam-pipe only few cm = 0.2 msr un-covered = Area of Suisse Romande (or Schleswig-Holstein, or Conneticut - sorry, there's nothing that small in Canada) relative to earth.
- Importance of hermeticity for the searches: $\gamma\gamma$ rejection !

Loop-hole free SUSY searches

- All is known for given masses, due to SUSY-principle: “sparticles couples as particles”.
- This doesn’t depend on the SUSY breaking mechanism !
- Obviously: There is one NLSP.



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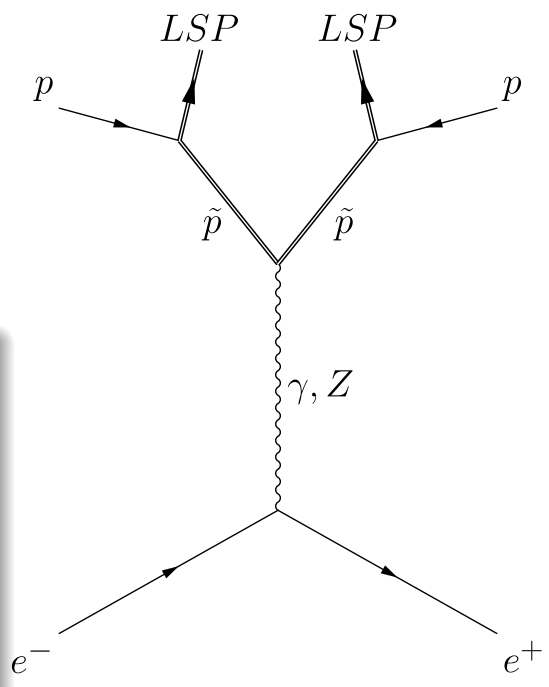
So, at ILC :

- Model red independent exclusion/ discovery reach in $M_{NLSP} - M_{LSP}$ plane.
- Repeat for all NLSP:s.
- Cover entire parameter-space in a hand-full of plots
- NLSP search $\leftrightarrow$ “simplified models” @ LHC!



Simplified models

- Simplified methods at hadron and lepton machines are different beasts.
- At lepton machines they are quite model independent, at LHC model dependent.
- A few examples (M.B. arXiv:1308.1461)
  - $\tilde{\mu}_R$ NLSP
  - $\tilde{\tau}_1$ NLSP (minimal σ).

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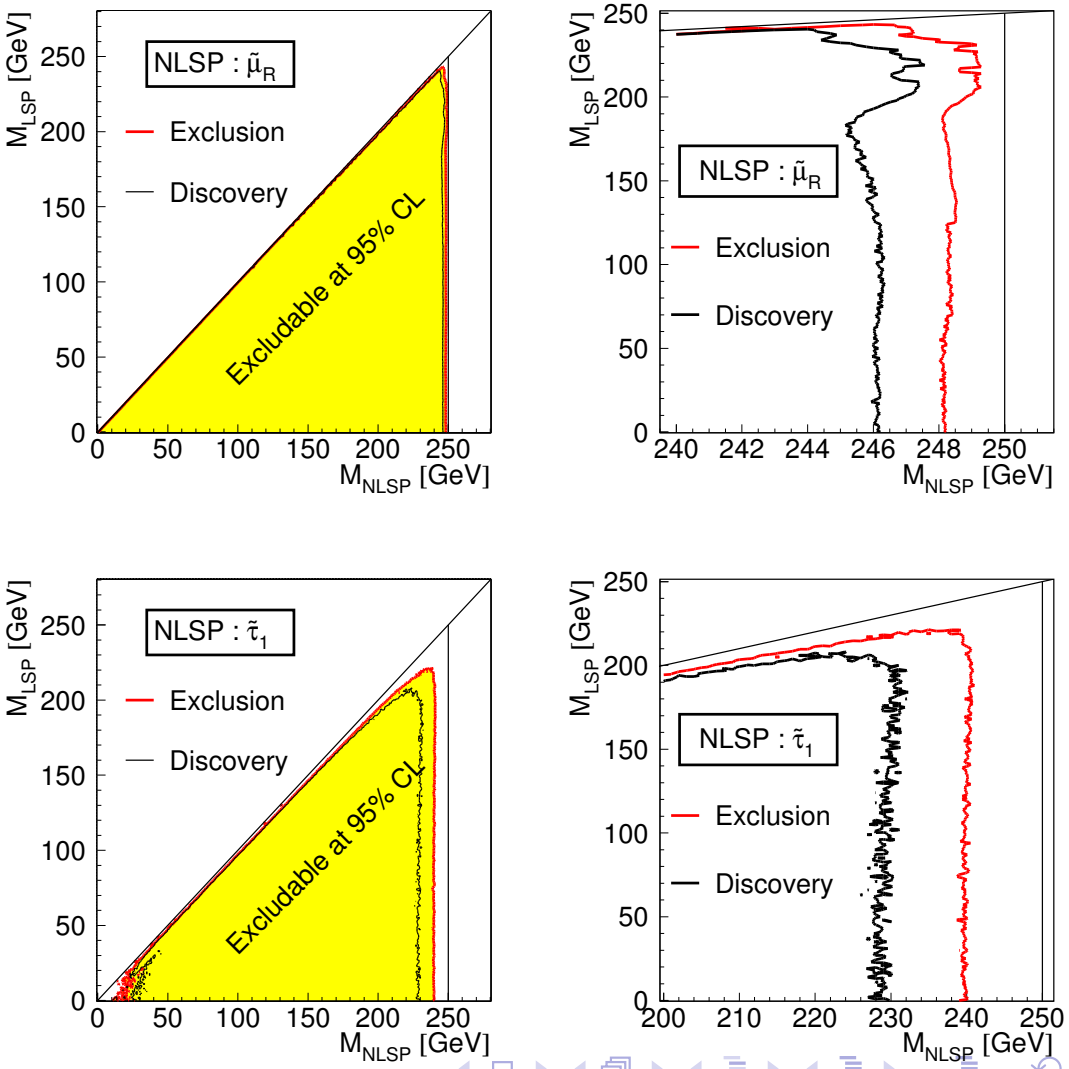

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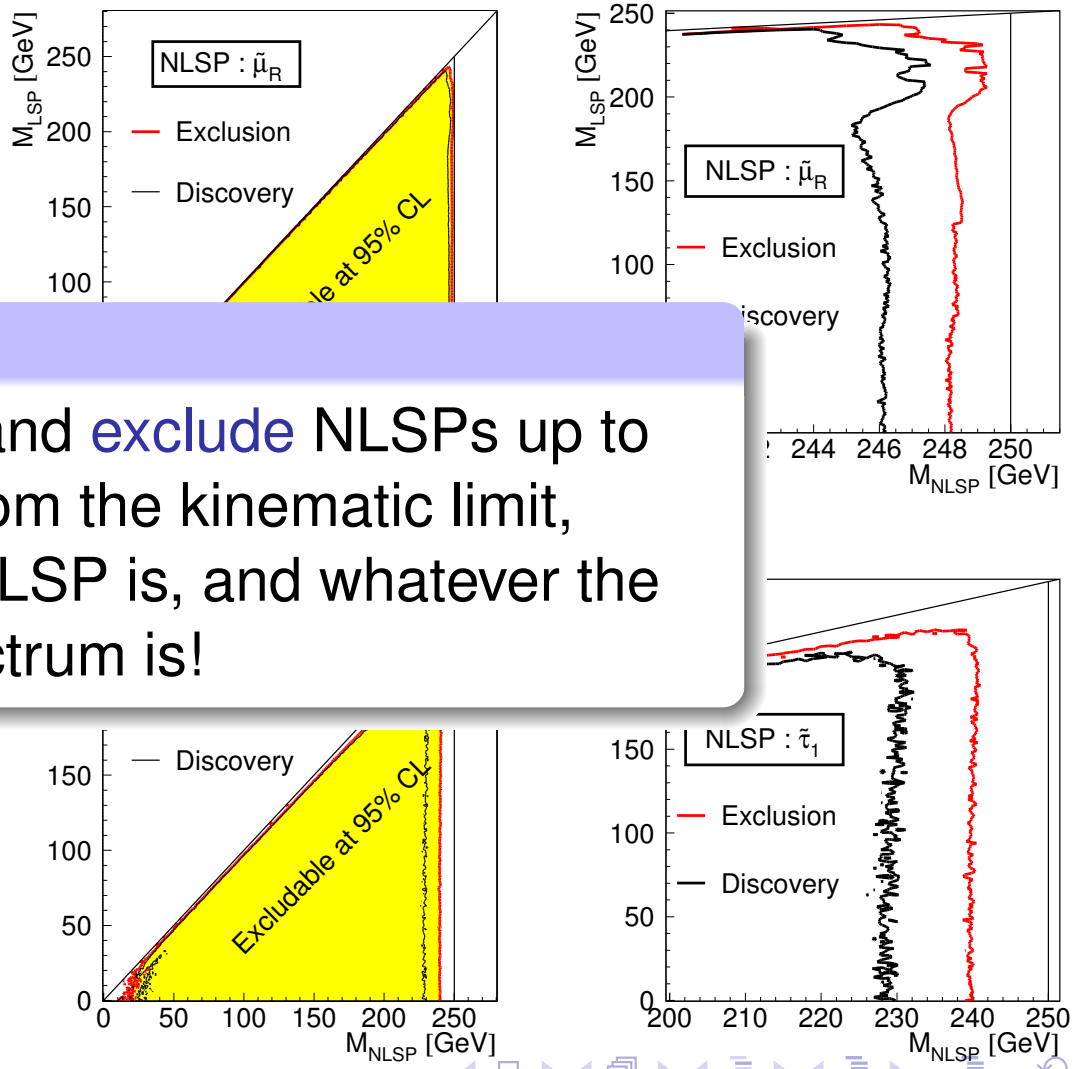
At ILC

Both discover and exclude NLSPs up to some GeV:s from the kinematic limit, whatever the NLSP is, and whatever the rest of the spectrum is!



No loop-holes

- Compare with LHC, here Atlas (arXiv:1403.5294v1):
  - Di- and tri-lepton searches, $M_{\tilde{\chi}_2^0} = M_{\tilde{\chi}_1^\pm}$, Br($\chi \to W^{(*)}/Z^{(*)}\tilde{\chi}_1^0$)=1.
- Note cut x-axis! Here is LEP, $\tilde{\chi}_1^\pm$ only, any decay-mode!
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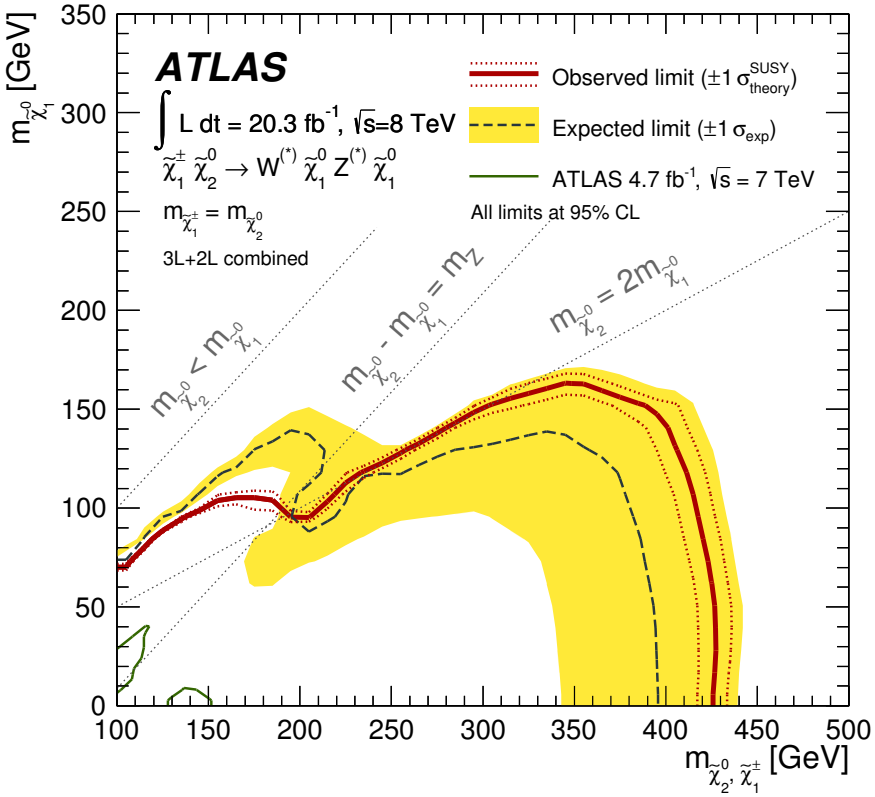

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at 500 GeV...and 1 TeV⇒ Lots of plain vanilla SUSY to explore at ILC!

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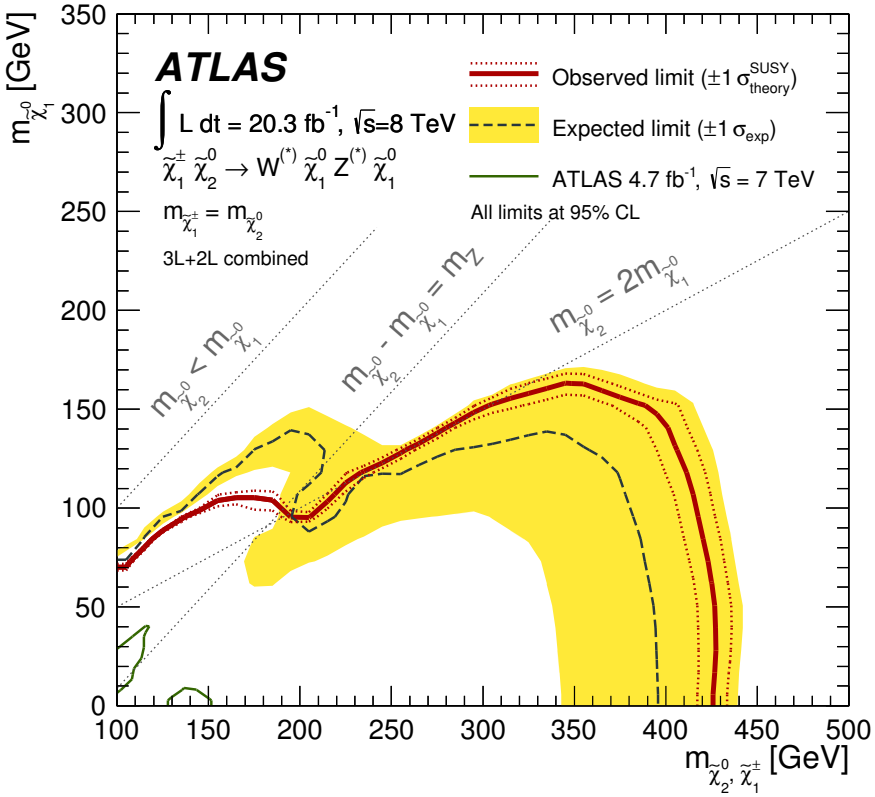

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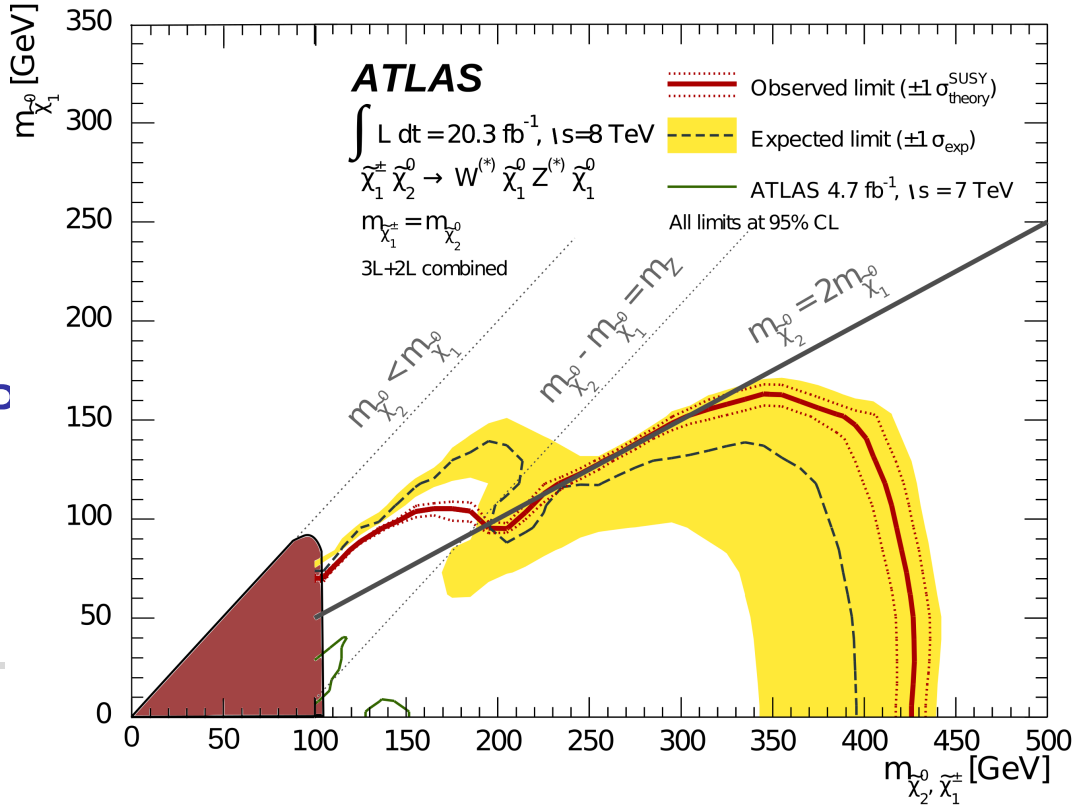

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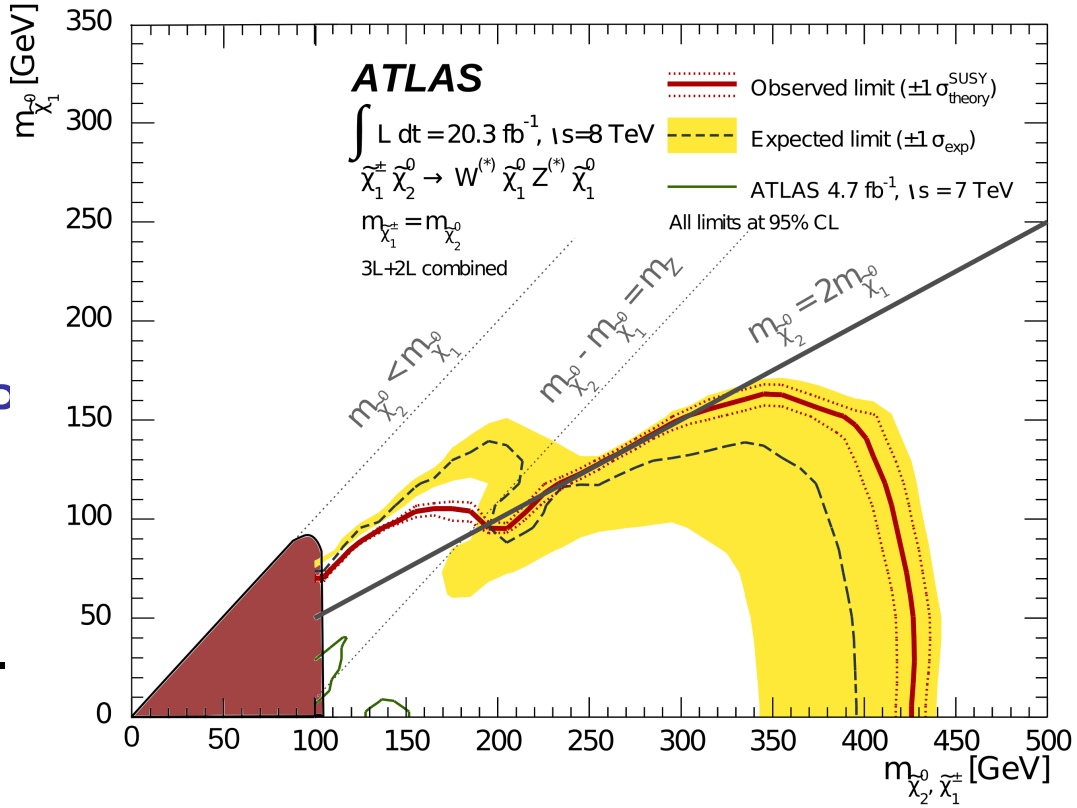

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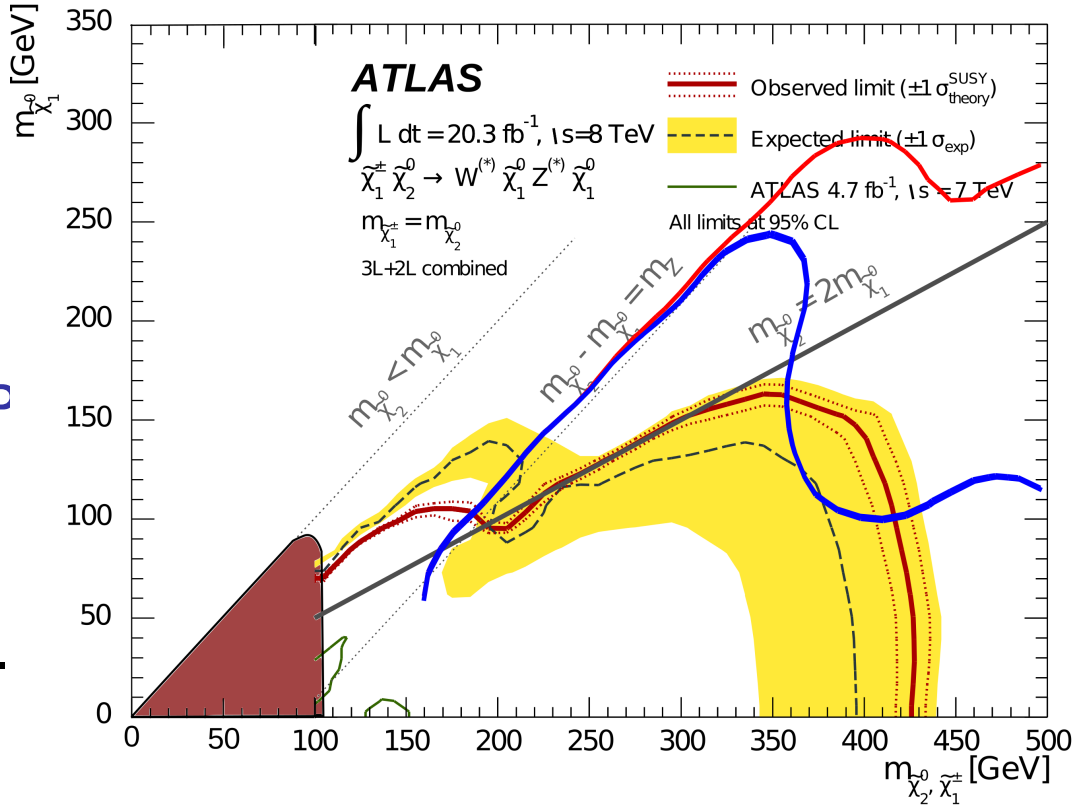

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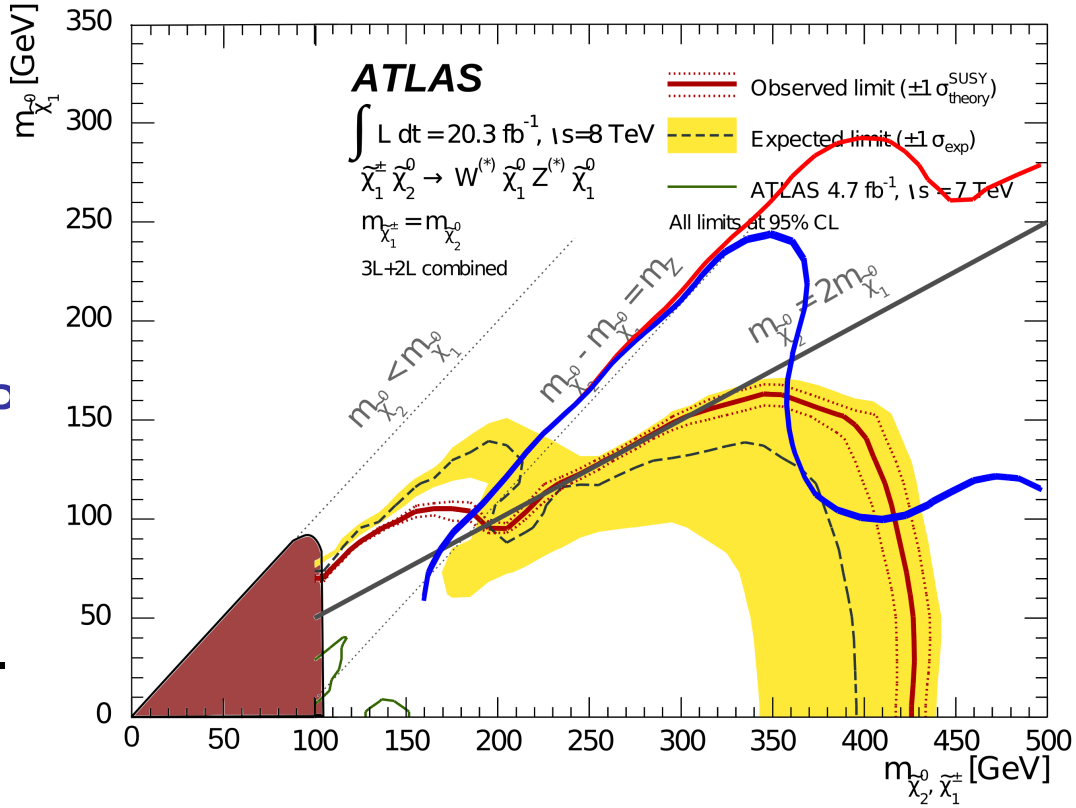

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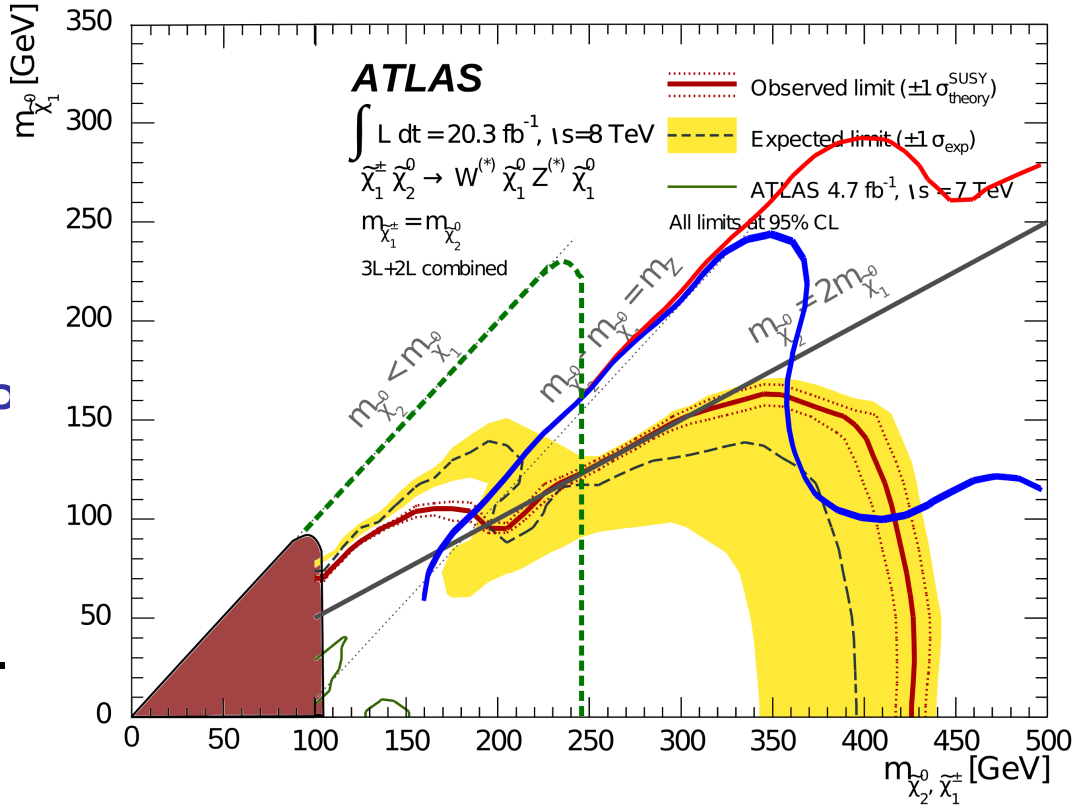

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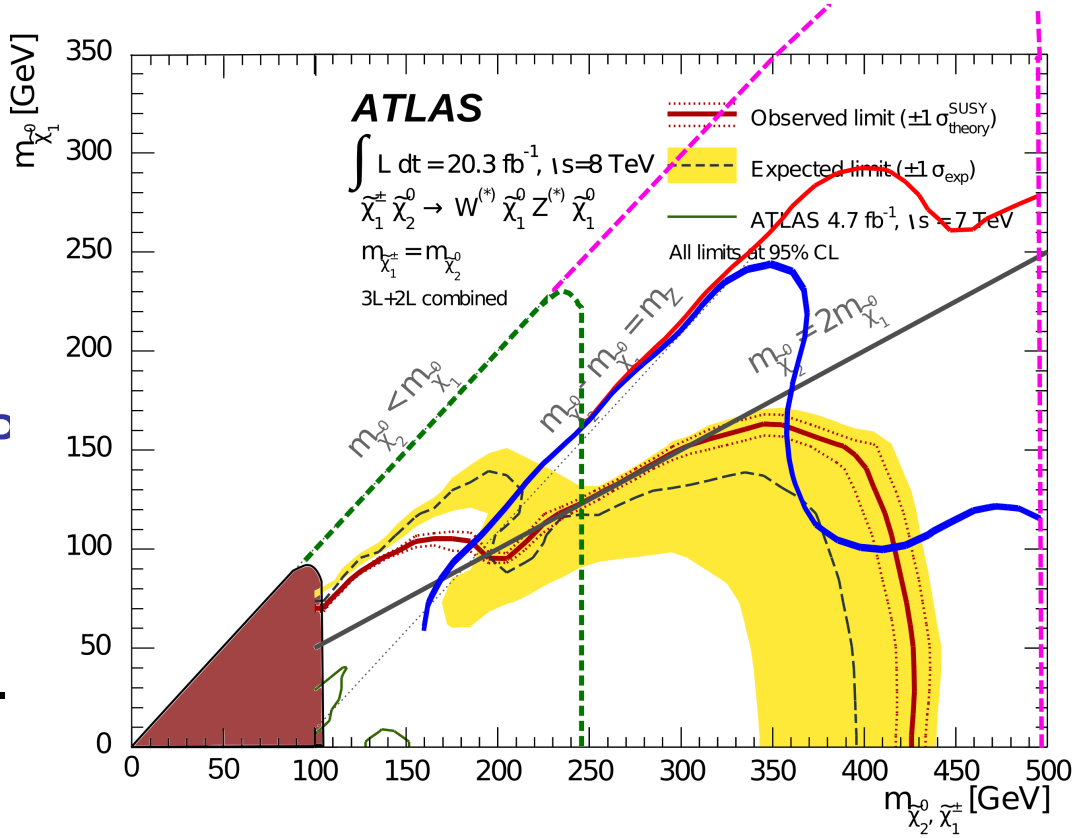

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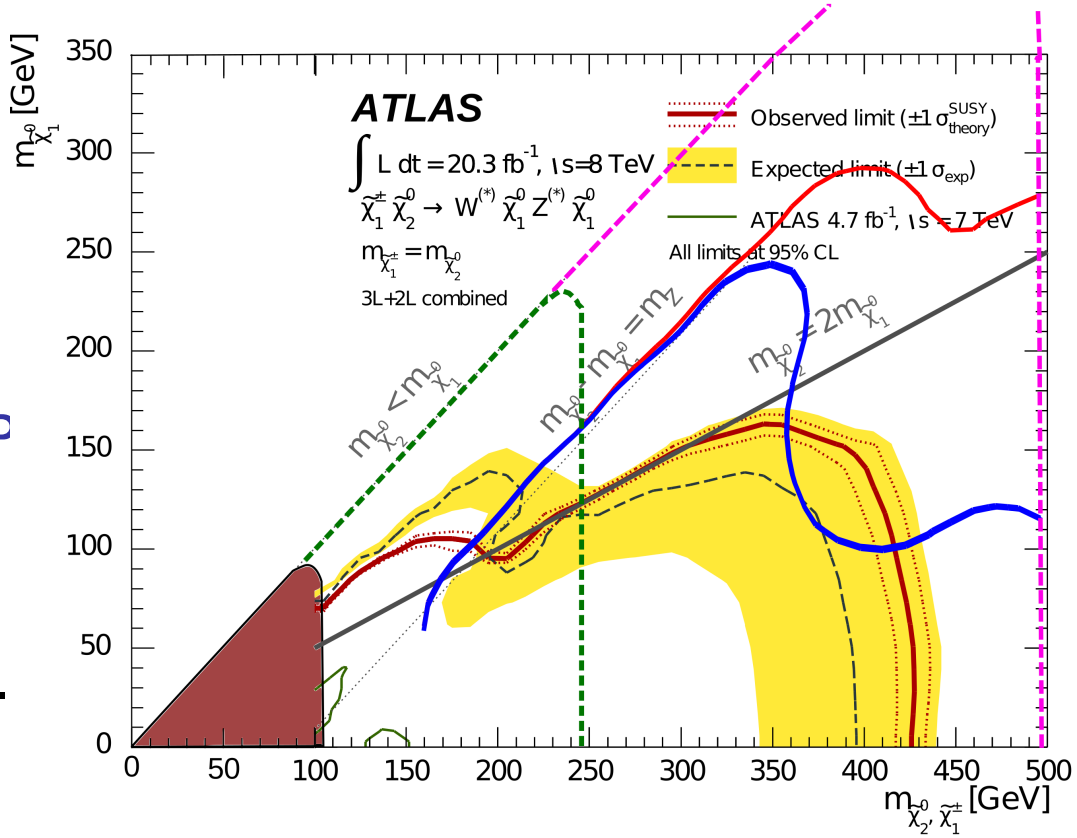

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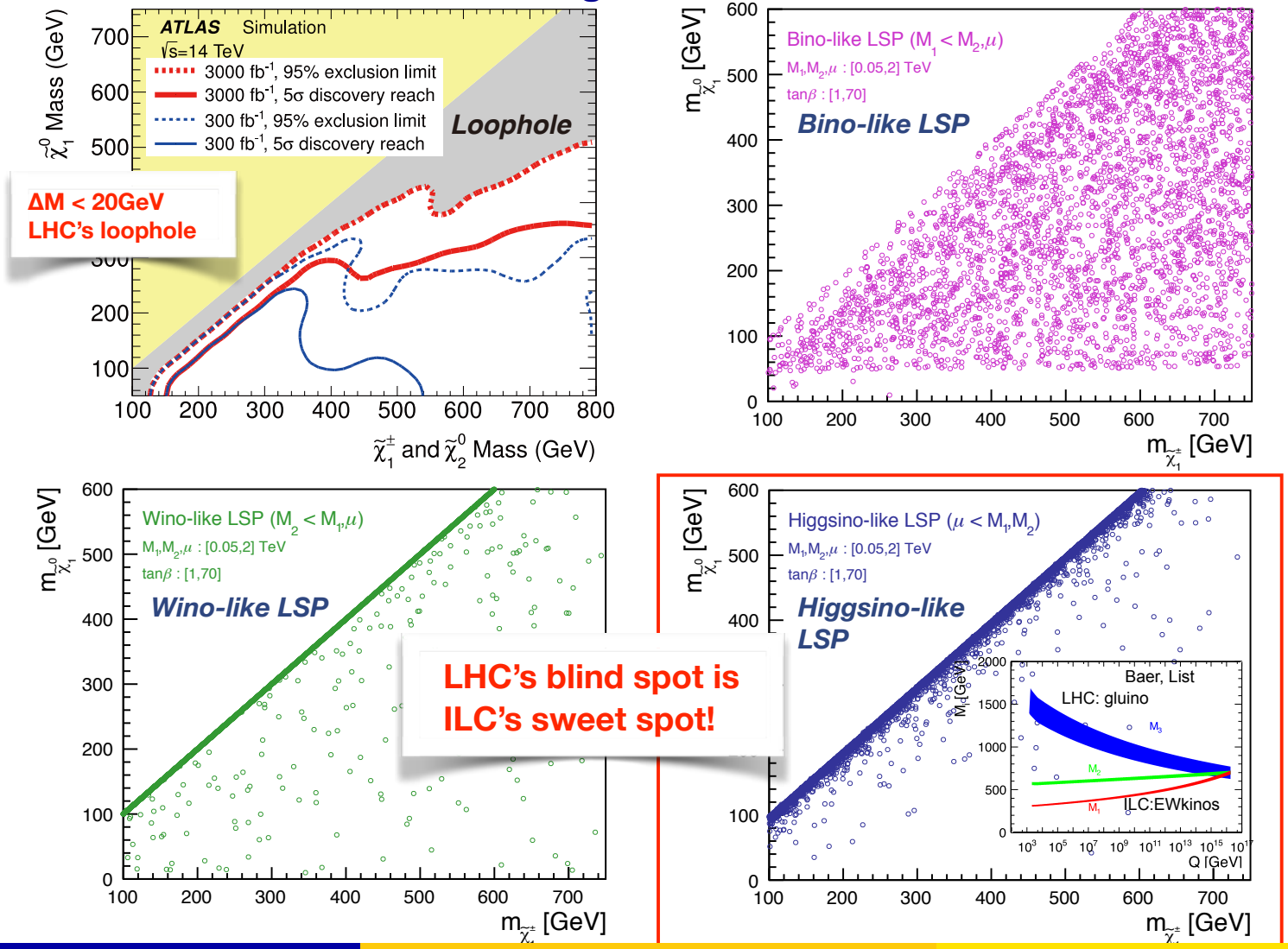
The LHC blind spot = the ILC sweet spot

Chargino Search



Natural SUSY: Light, degenerate higgsinos

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    - $M_{\tilde{\chi}_{1,2}^0}, M_{\tilde{\chi}_1^\pm} \approx \mu$
    - Degenerate (ΔM is 1 GeV or less)
- To detect: Tag using ISR photon, then look at rest of event:

SUSY signal and $\gamma\gamma$ background ... and with an ISR photon in addition

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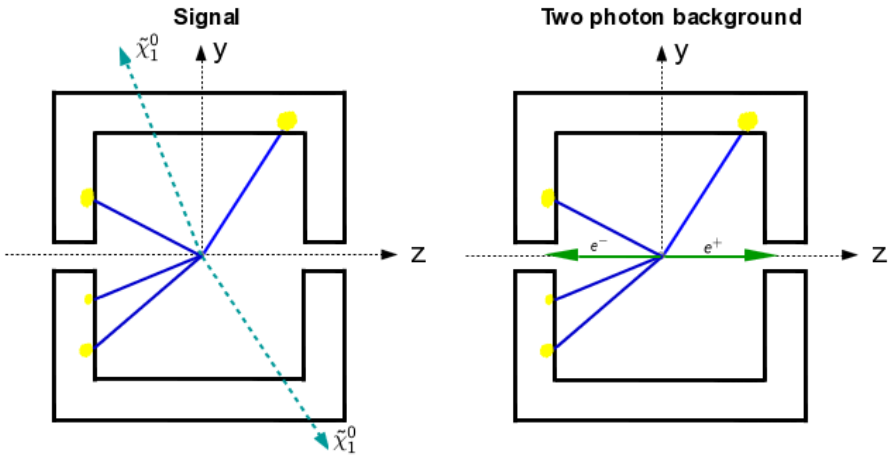

Natural SUSY: Light, degenerate higgsinos

- Natural SUSY:
  - $m_Z^2 = 2\frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{1-\tan^2\beta} - 2|\mu|^2$
  - $\Rightarrow$ Low fine-tuning $\Rightarrow$ $\mu = \mathcal{O}$(weak scale).
  - If multi-TeV gaugino masses:
    - $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ pure higgsino. Rest of SUSY at multi-TeV.
    - $M_{\tilde{\chi}_{1,2}^0}, M_{\tilde{\chi}_1^\pm} \approx \mu$
    - Degenerate (ΔM is 1 GeV or less)
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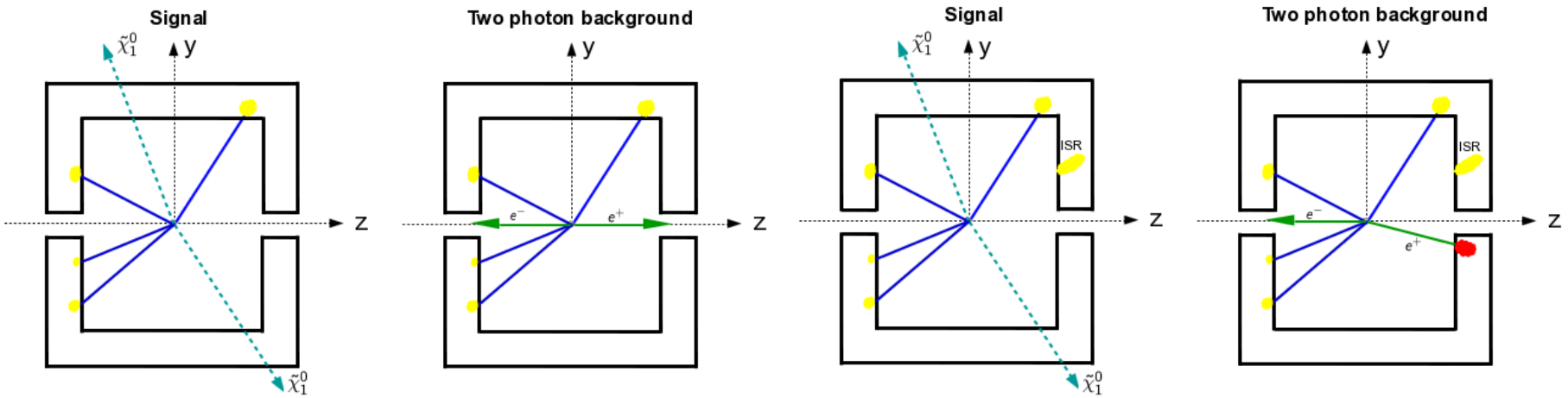

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- Studied model points:
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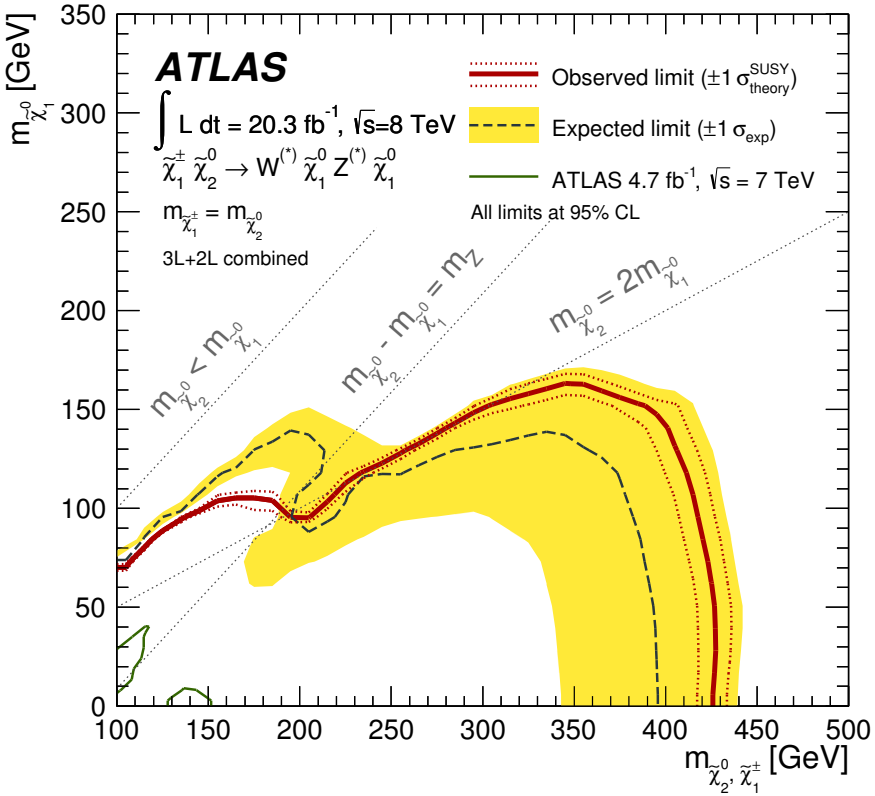
  - dm770: $\Delta(M)$=0.77 GeV, m_h=127 GeV, $M_{\tilde{\chi}_1^0}$=166.6 GeV.
- Very hard for LHC.
- Channels: Only $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ or $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ in s-channel (no $\tilde{\chi}_i^0\tilde{\chi}_i^0$ due to weak isospin, no t-channel due to higgsino nature)



H. Sert, F. Brümmer, J. List, G. Moortgat-Pick, T. Robens, K. Rolbiecki, M.B., EPJC (2013) 73:2660 [arXiv:1307.3566v2]

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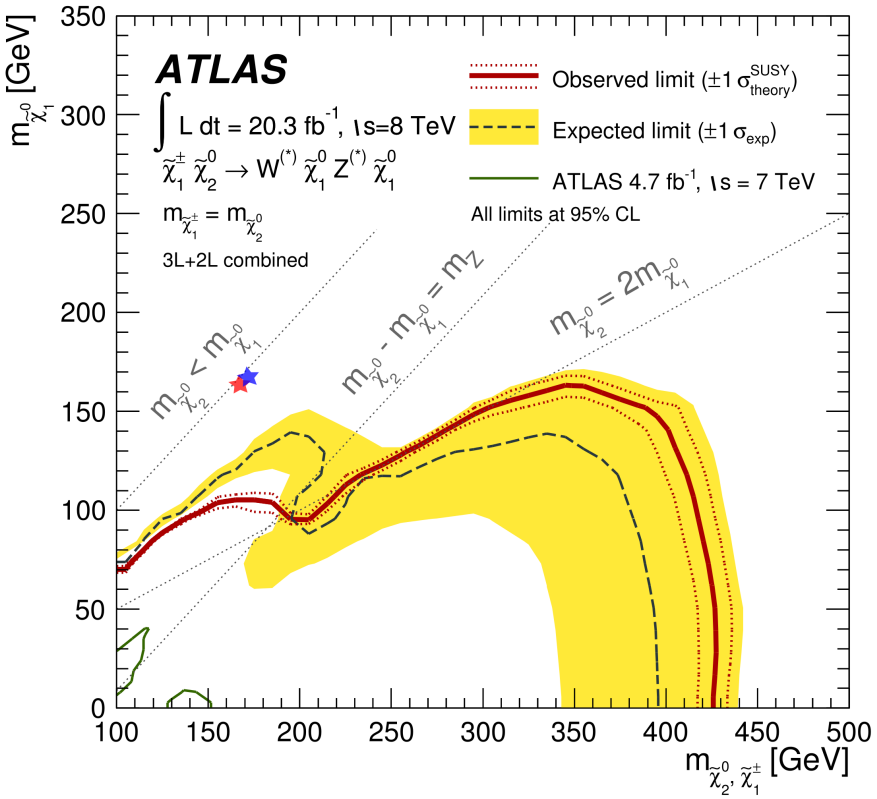

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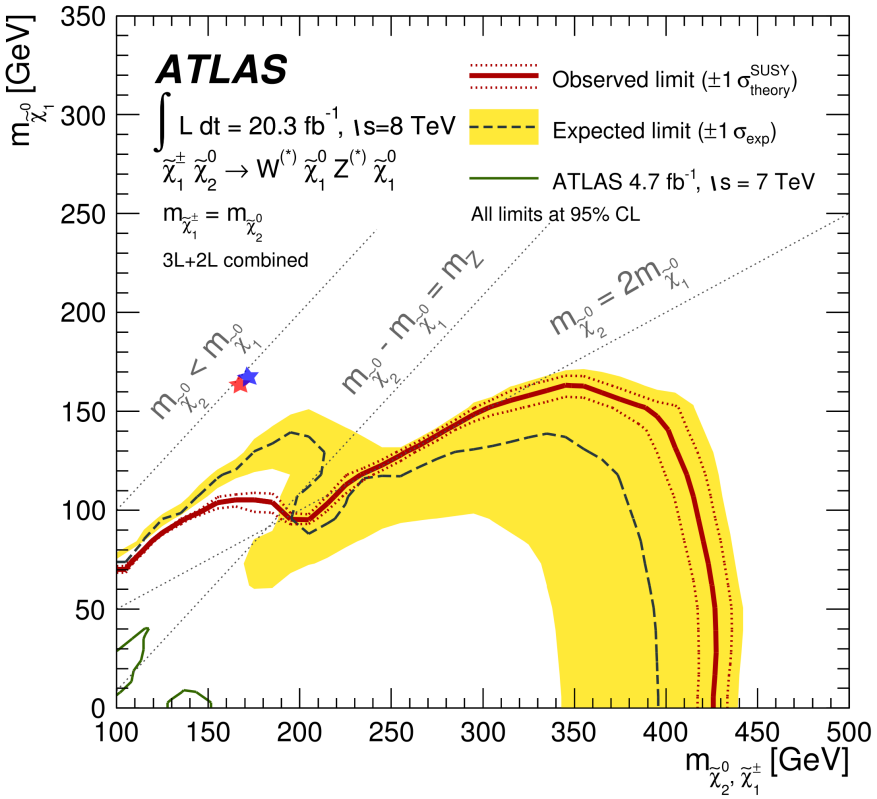

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SUSY with light bosinos, sleptons, heavy coloureds

Recall:

- The reason that mSUGRA/CMSSM is dead is the *irrelvant part*!
- Ie. : LHC excludes 1:st & 2:nd generation squarks and gluinos. These states have no influence on DM, g-2, natralness, ...
- Lifting the connection between 1:st & 2:nd generation squarks and gluinos on one side and the 3:d generation squarks and electro-weak sector on the other side avoids this, at the price of have a few more free parameters.
- Actually, the U(1) and SU(2) masses (M_1 and M_2) can still unify.

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The STCx models at LHC & ILC

- 11 parameters.
- All low-energy, cosmological, and LHC observations OK.
- Fine-tuning OK.
- Observable at LHC 14, so we will know within a few years.
- But we won't know what LHC saw - not even if it is SUSY, or some other BSM physics.
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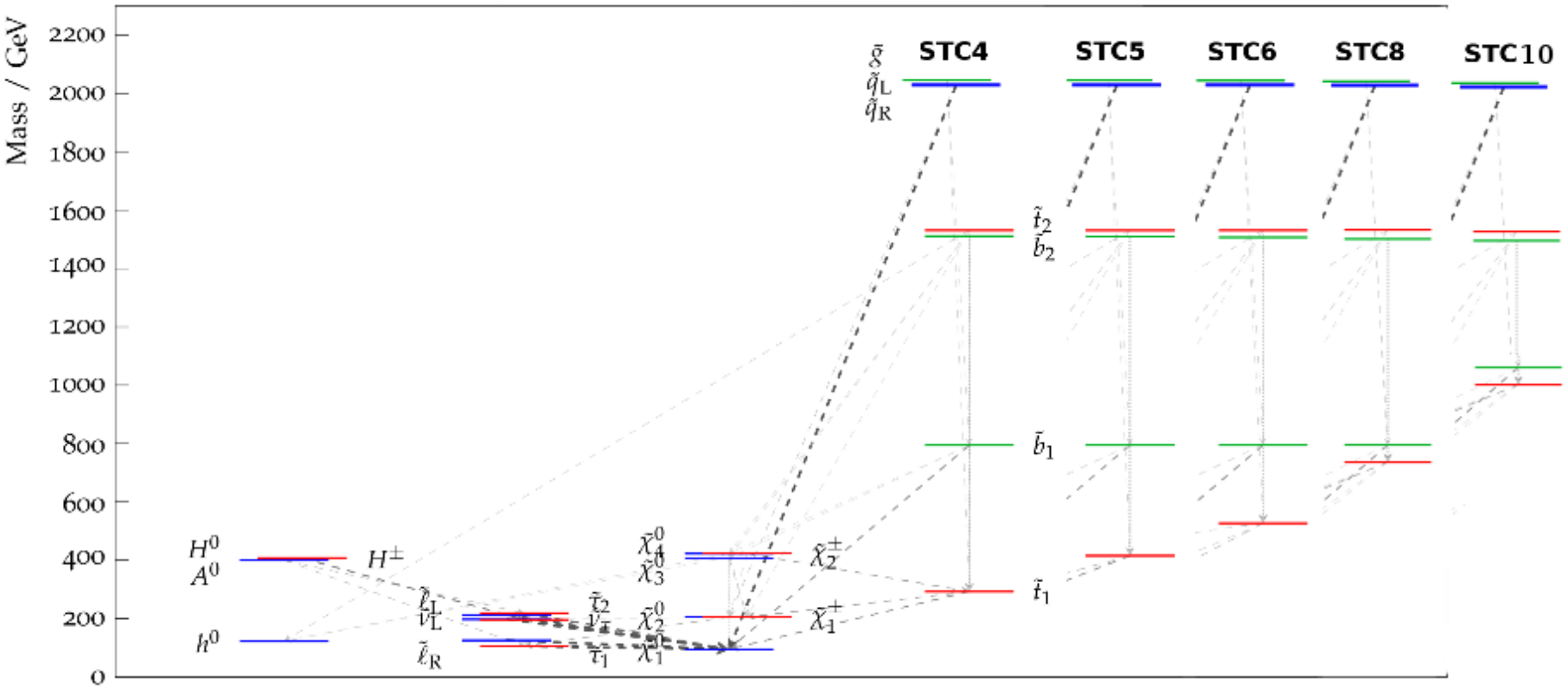
Full STCx mass-spectrum

High mass squarks+gluino



Well-tempered higgs, bosino and slepton sector

Varying 3-gen squarks

STCx @ LHC14

⇒ LHC expectations

- Despite the high cross-section, the low amount of missing E_T and the long decay chains will make direct bosino and slepton observations hard.
- The simple decay-chains and very high missing E_T will make first- and second-generation squark production easy to detect. However, the cross-section is so low that it is still challenging.
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- Discovery channel is $\tilde{t}$ pairs to single, isolated lepton.
- ... but low purity.
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- Although STCx will be discovered at LHC14 if it is realised in nature, it will be very hard to see that it is SUSY, not some other new physics.

STCx at ILC 250, 350 and 500 GeV

Channel	Threshold	Available at	Can give
$\tilde{\tau}_1\tilde{\tau}_1$	212	250	$M_{\tilde{\tau}_1}$, $\tilde{\tau}_1$ nature, τ polarisation
$\tilde{\mu}_R\tilde{\mu}_R$	252	250+	+ $M_{\tilde{\mu}_R}$, $M_{\tilde{\chi}^0_1}$, $\tilde{\mu}_R$ nature
$\tilde{e}_R\tilde{e}_R$	252	250+	+ $M_{\tilde{e}_R}$, $M_{\tilde{\chi}^0_1}$, $\tilde{e}_R$ nature
$\tilde{\chi}^0_1\tilde{\chi}^{0*)}_2$	302	350	+ $M_{\tilde{\chi}^0_2}$, $M_{\tilde{\chi}^0_1}$, nature of $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$
$\tilde{\tau}_1\tilde{\tau}_2{}^{*)}$	325	350	+ $M_{\tilde{\tau}_2}\theta_{mix\ \tilde{\tau}}$
$\tilde{e}_R\tilde{e}_L{}^{*)}$	339	350	+ $M_{\tilde{e}_L}$, $\tilde{\chi}^0_1$ mixing, $\tilde{e}_L$ nature
$\tilde{\nu}_{\tilde{\tau}}\tilde{\nu}_{\tilde{\tau}}$	392	500	7 % visible BR ($\rightarrow \tilde{\tau}_1 W$)
$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\pm *)}_1$	412	500	+ $M_{\tilde{\chi}^{\pm}_1}$, nature of $\tilde{\chi}^{\pm}_1$
$\tilde{e}_L\tilde{e}_L{}^{*)}$	416	500	+ $M_{\tilde{e}_L}$, $M_{\tilde{\chi}^0_1}$, $\tilde{e}_L$ nature
$\tilde{\mu}_L\tilde{\mu}_L{}^{*)}$	416	500	+ $M_{\tilde{\mu}_R}$, $M_{\tilde{\chi}^0_1}$, $\tilde{\mu}_R$ nature
$\tilde{\tau}_2\tilde{\tau}_2{}^{*)}$	438	500	+ $M_{\tilde{\tau}_2}$, $M_{\tilde{\chi}^0_1}$, $\tilde{\tau}_2$ nature, $\theta_{mix\ \tilde{\tau}}$
$\tilde{\chi}^0_1\tilde{\chi}^{0*)}_3$	503	500+	+ $M_{\tilde{\chi}^0_3}$, $M_{\tilde{\chi}^0_1}$, nature of $\tilde{\chi}^0_1$, $\tilde{\chi}^0_3$

*): Cascade decays.

+ invisible $\tilde{\chi}^0_1\tilde{\chi}^0_1$, $\tilde{\nu}_{\tilde{e},\tilde{\mu}}\tilde{\nu}_{\tilde{e},\tilde{\mu}}$.

STC4 sleptons @ 500 GeV:$\tilde{e}$, $\tilde{\mu}$

- Selections for $\tilde{\mu}$ and $\tilde{e}$:
  - Correct charge.
  - P_T wrt. beam and one ℓ wrt the other.
  - Tag and probe, ie. accept one jet if the other is “in the box”.
- Further selections for R:
  - Cuts on polar angle and angle between leptons.
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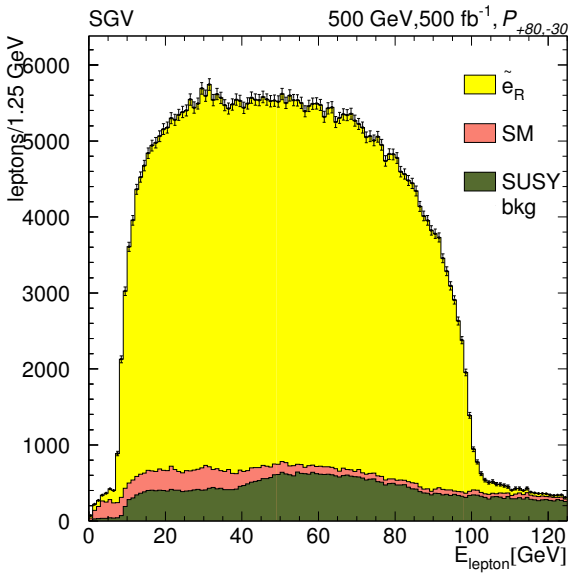

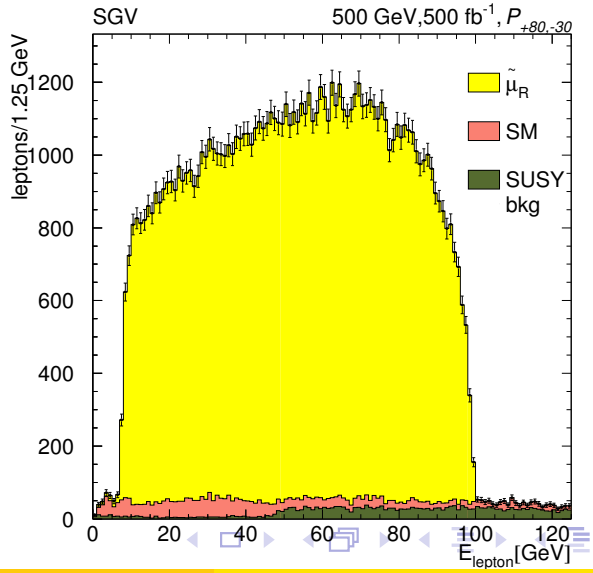

$\tilde{\mu}_{\mathrm{R}}$ threshold scan

From these spectra, we can estimate $M_{\tilde{e}_{\mathrm{R}}}$, and $M_{\tilde{\chi}_1^0}$ to < 0.2 GeV, and $M_{\tilde{\mu}_{\mathrm{R}}}$ to < 0.5 GeV.

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So: Next step is $M_{\tilde{\ell}}$ from threshold:

- 10 points, 10 fb^{-1}/point.
- Luminosity $\propto E_{CMS}$, so this is $\Leftrightarrow$ 170 fb^{-1} @ E_{CMS}=500 GeV.

Error on $M_{\tilde{\mu}_R}$ = 197 MeV.

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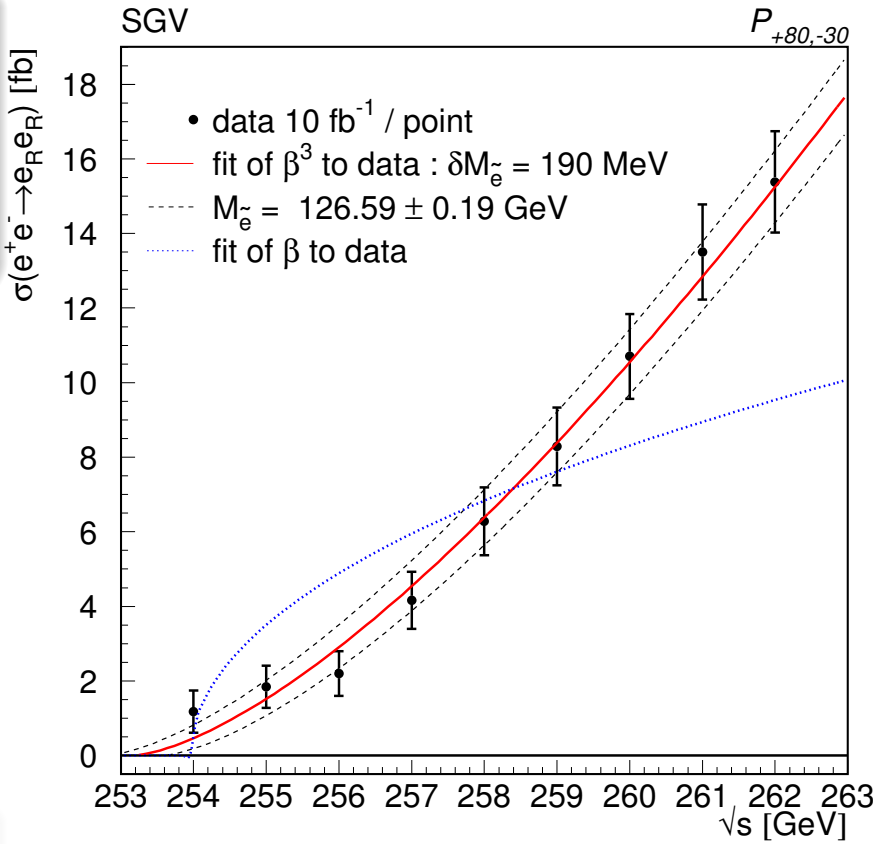

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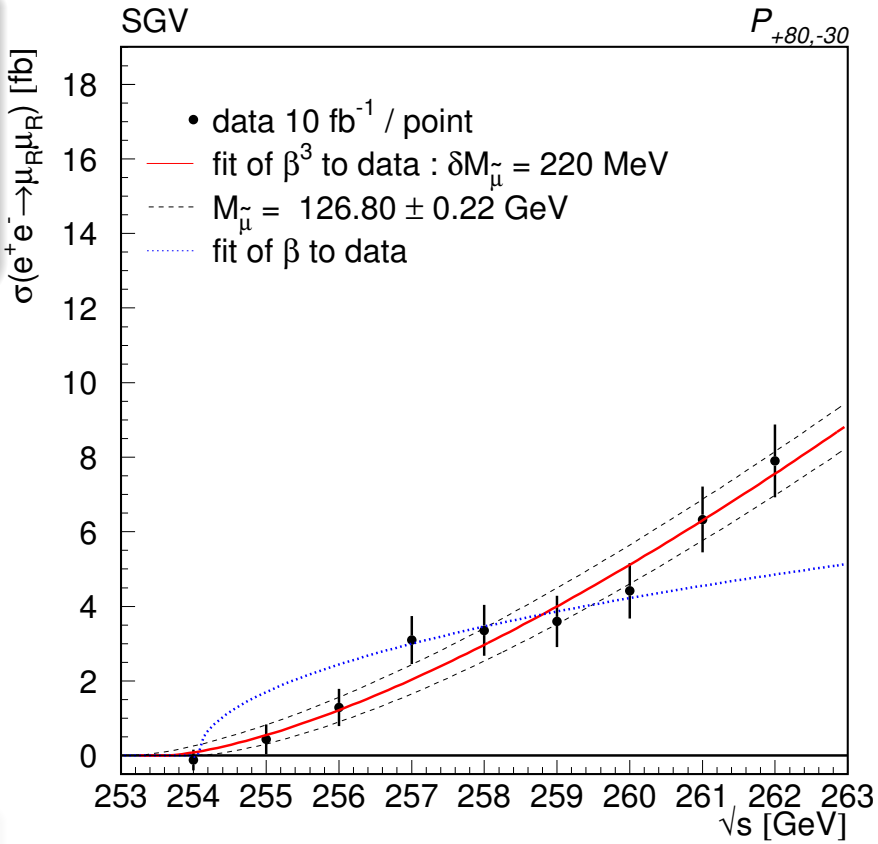

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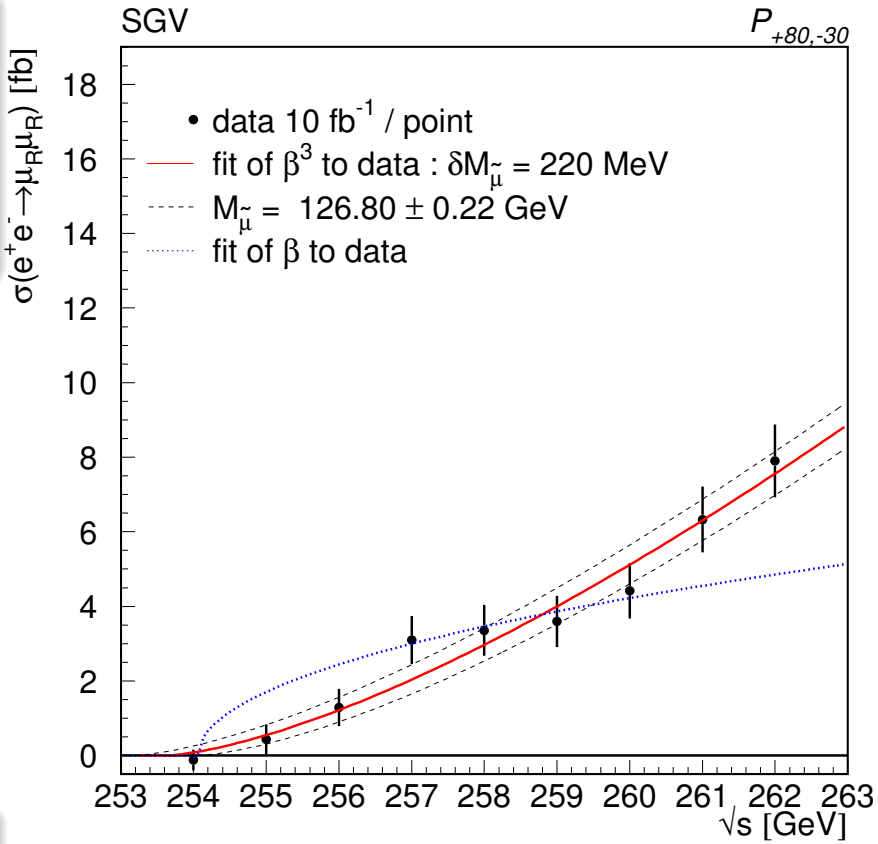

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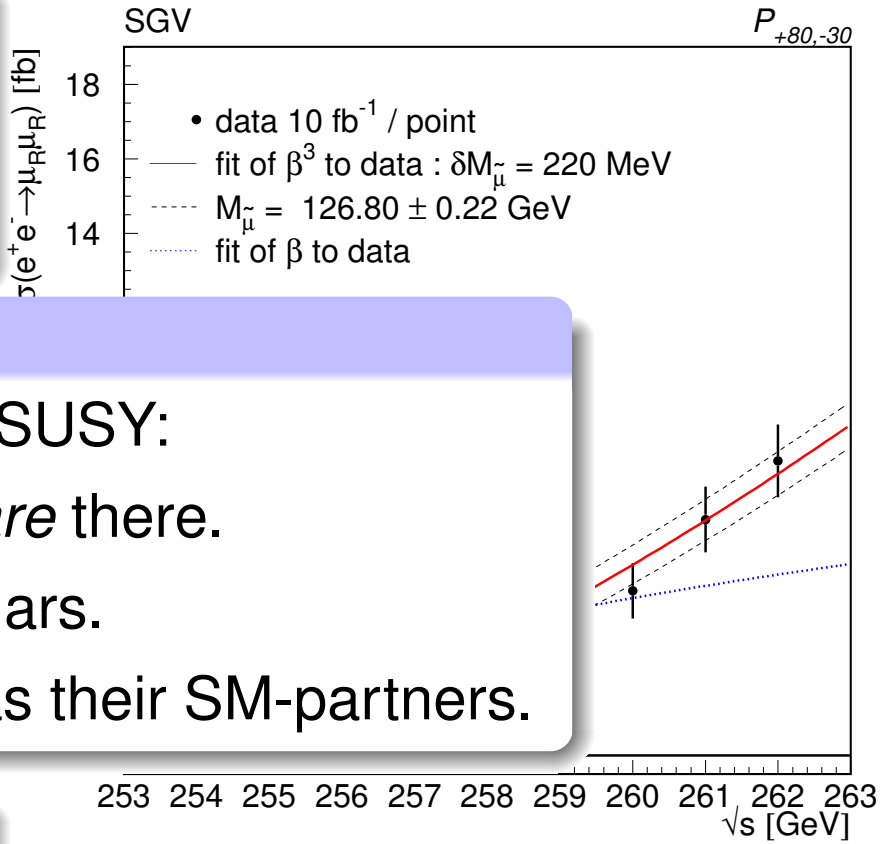

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At ILC

Can show that this *is* SUSY:

- All the sleptons *are* there.
- Sleptons *are* scalars.
- They *do* couple as their SM-partners.

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Conclusions

At ILC:

- Loop-hole free discovery potential for SUSY, up to the kinematic limit.
- Includes a vast and quite likely region of moderate-to-small LSP-NLSP mass-differences, not explorable by hi-lumi LHC.
- Even in natural SUSY scenarios where the only sparticles below the multi TeV range are almost mass-degenerate higgsinos: ILC can discover, and determine model-parameters, high-mass sector ones included.
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Thank You !

BACKUP

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- Separate $\tilde{\chi}_1^\pm$ from $\tilde{\chi}_2^0$: Either semi-leptonic f.s.: Only $\tilde{\chi}_1^\pm$, or γ: only $\tilde{\chi}_2^0$.
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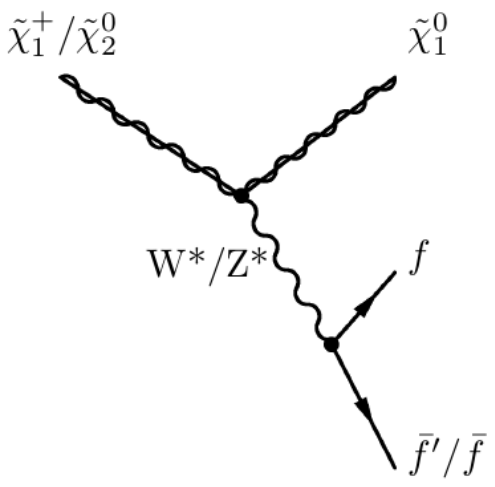

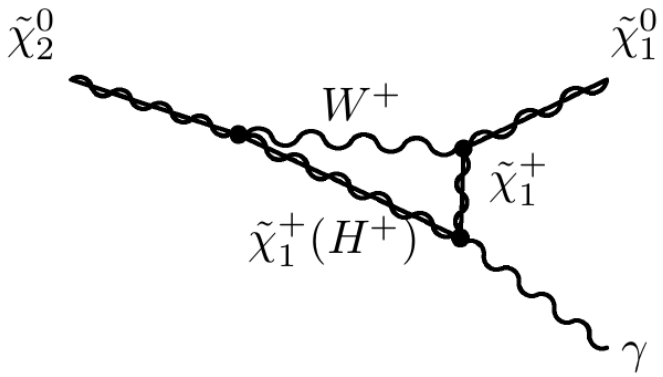

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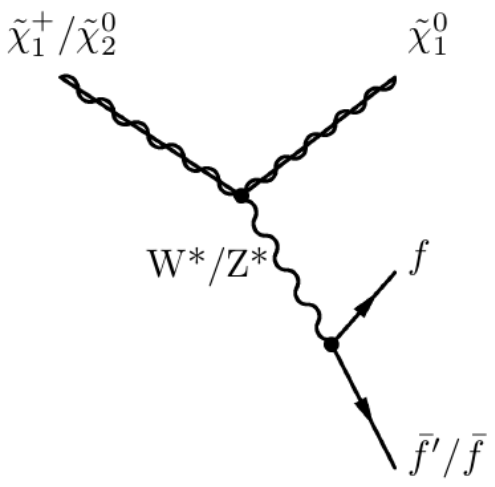

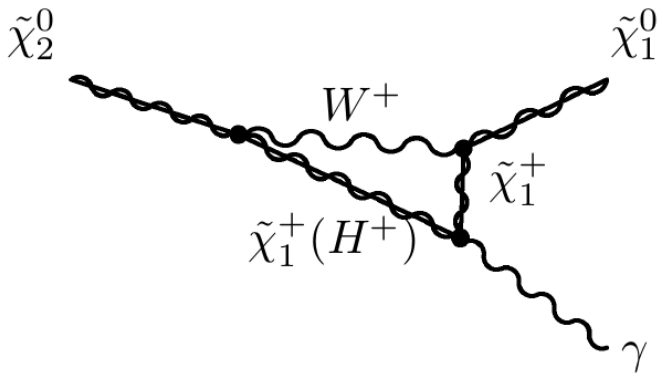

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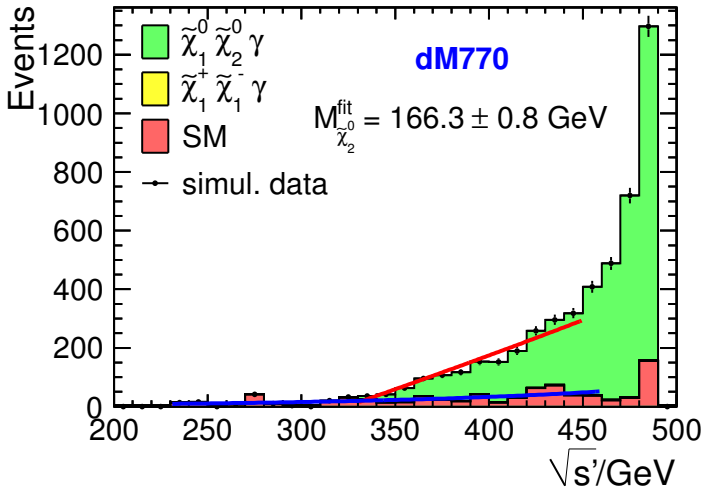

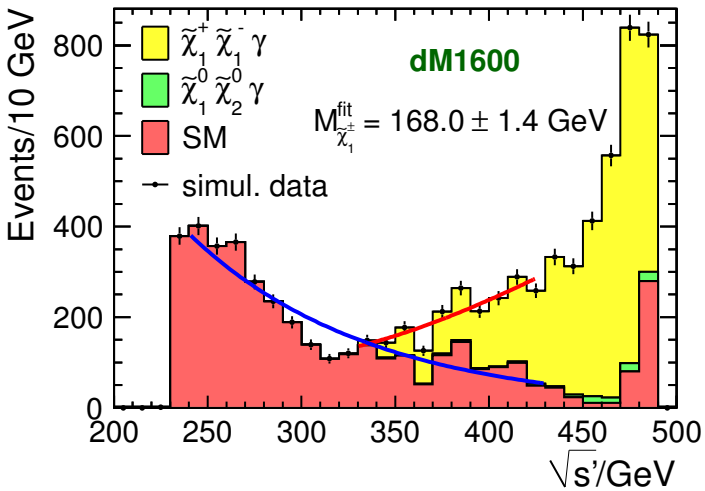

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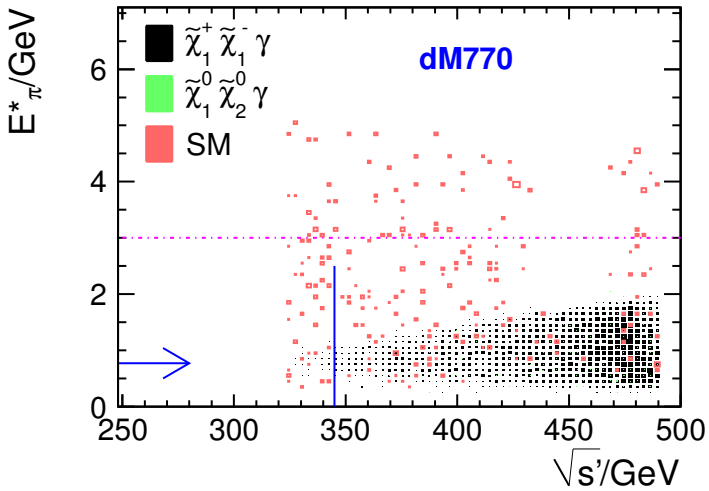
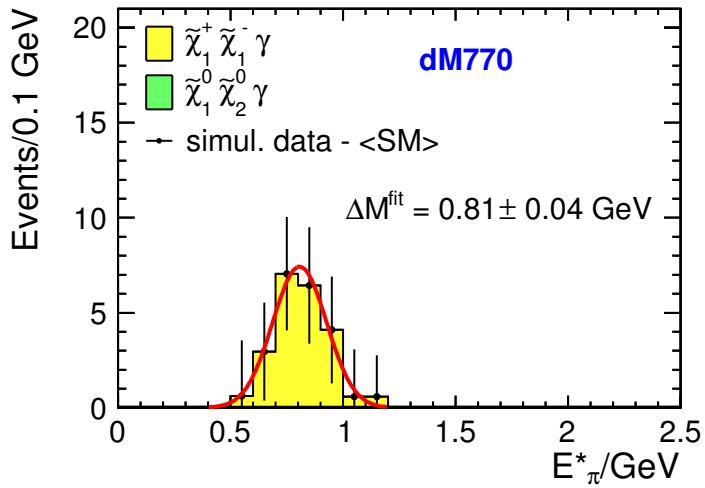
- Close to end-point, E_π gives $\Delta(M_{\tilde{\chi}_1^0}, M_{\tilde{\chi}_1^\pm})$ to $\sim$ 100 MeV.





Natural SUSY: Light, degenerate higgsinos

- Use to extract the model-parameters μ, M_1 and M_2 (little tan β dependence).
- μ can be determined to $\pm$ 4 %.
- Limits on M_1 and M_2 after $\int \mathcal{L} = 2\text{ab}^{-1}$.
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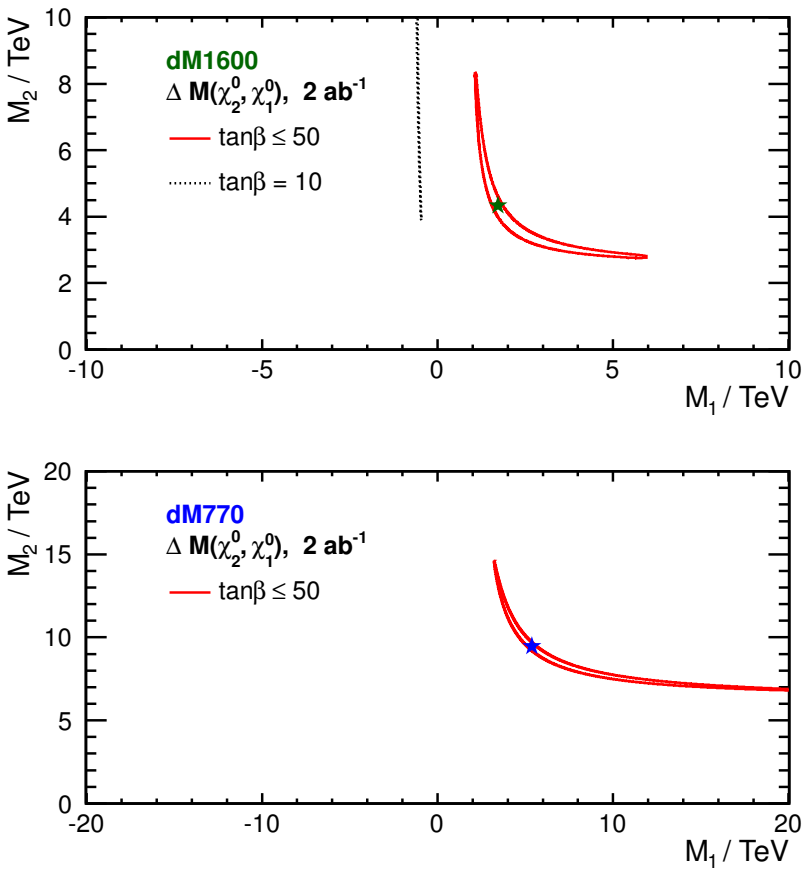

STCx @ LHC14

- STC8 and STC10 studied by I. Melee-Pullmans group at DEWY with fastsim (Delphes).
- Main features at LHC 14 TeV:
  - Cross-sections:
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    ranging from 1.5 pb to 1 fb. $M_{\tilde{\mathrm{t}}}$ and $M_{\tilde{\mathrm{b}}}$ is 200 GeV higher in STC10

    $\rightarrow$ Cross-sections for $\tilde{\mathrm{t}}\tilde{\mathrm{t}}$ and $\tilde{\mathrm{b}}\tilde{\mathrm{b}}$ 5 $\times$ smaller in STC10 wrt STC8.
  - $\tilde{\chi}$ cascade-decays to τ:s + the LSP in 75 % of the cases, often together with a boson (Z, W or h).
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⇒ LHC expectations

- Despite the high cross-section, the low amount of missing E_T and the long decay chains will make direct bosino and slepton observations hard.
- The simple decay-chains and very high missing E_T will make first- and second-generation squark production easy to detect. However, the cross-section is so low that it is still challenging.
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Observables:

Observable	Gives	If
Edges (or average and width)	Masses	... not too far from threshold
Shape of spectrum	Spin	
Angular distributions	Mass, Spin	
Invariant mass distributions from full reconstruction	Mass	... cascade decays
Angular distributions from full reconstruction	Spin, CP,	... masses known
Un-polarised Cross-section in continuum	Mass, coupling	
Polarised Cross-section in continuum	Mass, coupling, mixing	
Decay product polarisation	Mixing	... $\tilde{\tau}$ decays
Threshold-scan	Mass(es), Spin	