BSM at future linear e^+e^- colliders - an experimentalists view

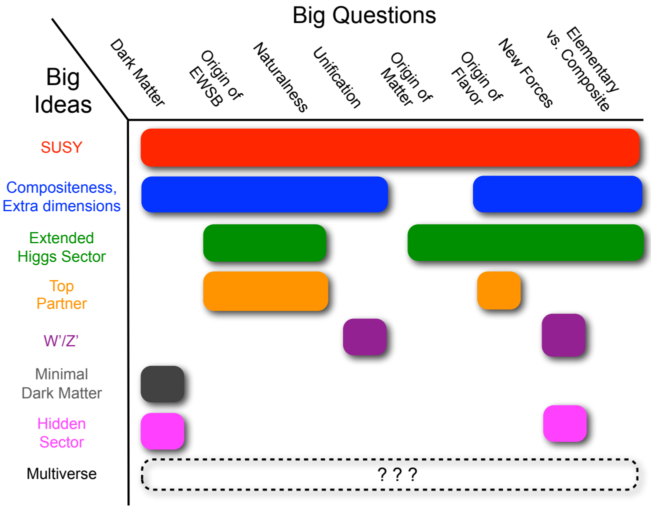
Mikael Berggren[1]

[1]DESY, Hamburg

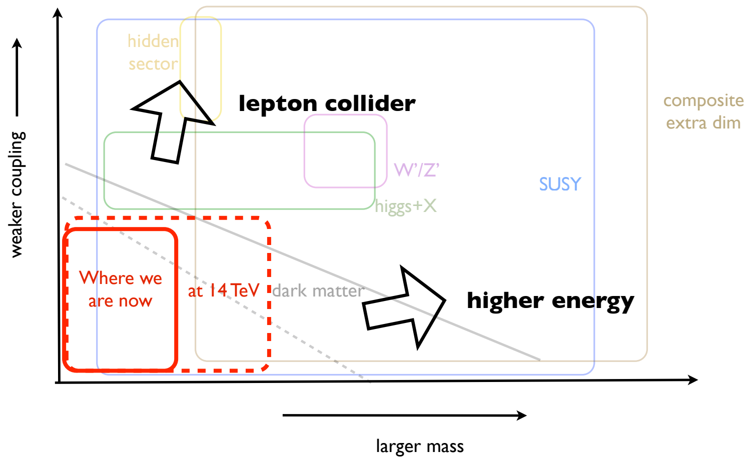
CLIC workshop, CERN, Jan., 2016

Outline

Big questions - Big ideas (from L-T Wang)



Exploring the space (also from Lian-Tau)



BSM

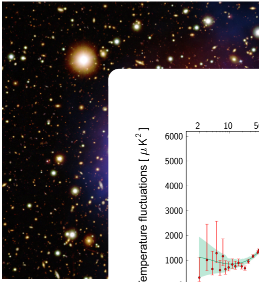
In this talk:

1. DM: Because it's there.
2. Z': Because it could be direct observation of BSM
3. (A little about) Precision measurements - mostly covered by Philipp and Nacho in the previous talks.
4. SUSY - always considering LHC prospects
   - Because it's *the* theory that can address all the "Big Questions"
   - Also because different version of it predicts a vast variety of BSM signals good experimental testing-ground.
   - High-lights LC - LHC interplay.

Dark Matter

Bullet cluster

Dark Matter



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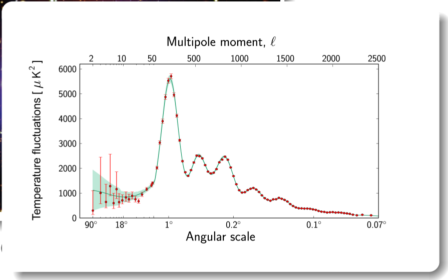

Plank CMB

Dark Matter

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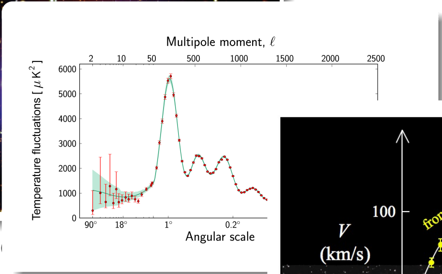

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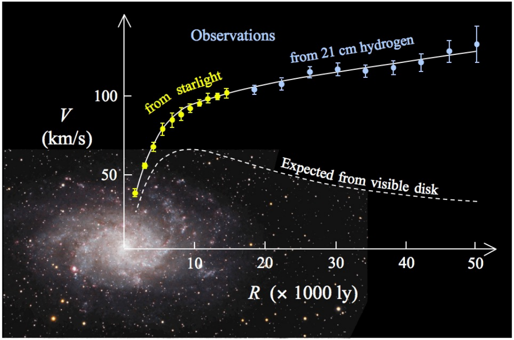
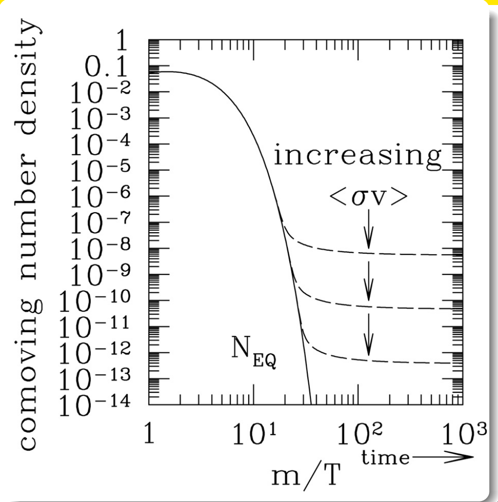


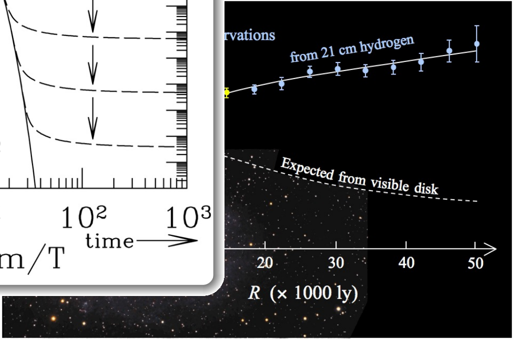
M33 rotation curve

Dark Matter

Bullet



The WIMP miracle !



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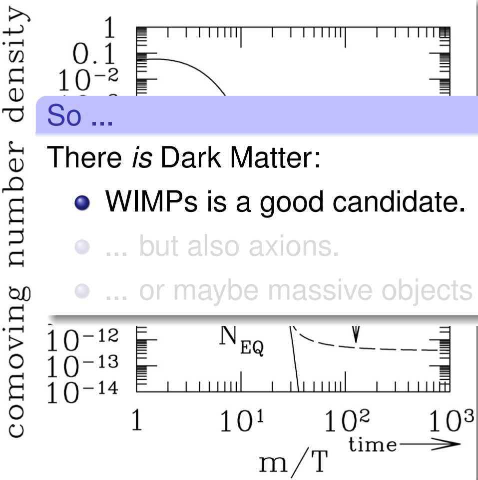
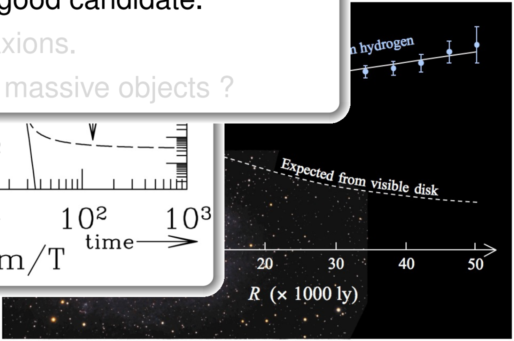


The WIMP miracle !

So ...

There *is* Dark Matter:

- WIMPs is a good candidate.
- ... but also axions.
- ... or maybe massive objects ?



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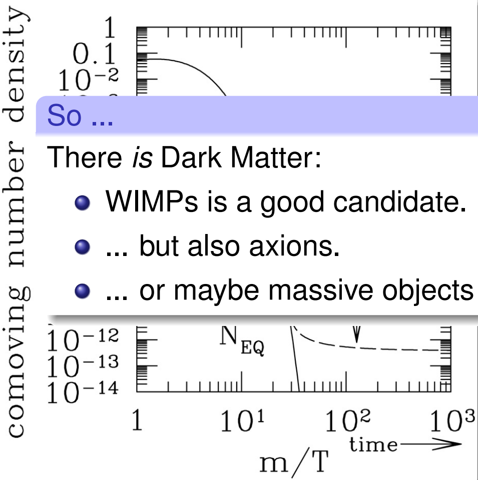

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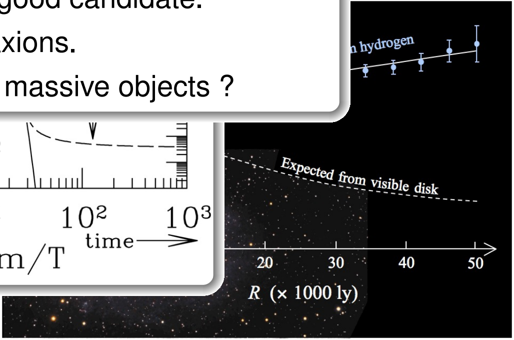

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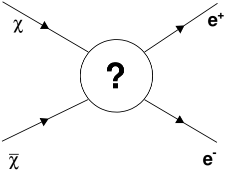
Only WIMPs

- Cosmology $\Rightarrow$ 25% of universe = Dark Matter
- One possibility: WIMPs (χ). What if this is the only accessible NP ?



- Search for direct WIMP pair-production at collider : Need to make the invisible visible:
  - Require initial state radiation which will recoil against "nothing"
  - LHC: $pp \rightarrow \chi\chi g$ or $\chi\chi\gamma$
  - LC: $e^+e^- \rightarrow \chi\chi\gamma$ (Full simulation study. C. Bartels, J. List, M.B. arXiv:1206.6639v1, and A. Chaus, Thesis,in preparation.)
- Model-independent Effective operator approach to "?"
  - Exclusion regions in M_χ/Λ plane, for each operator.

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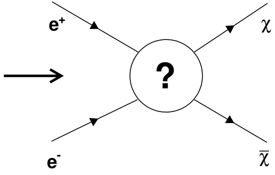

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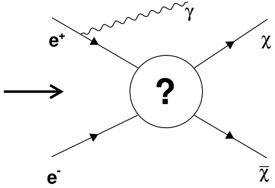

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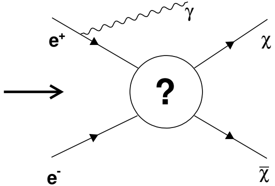

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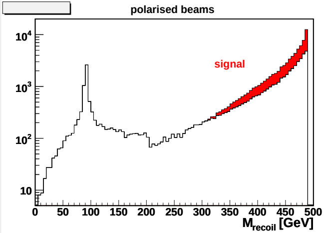
Backgrounds and Signal extraction

Irreducible Backgrounds

- $ee \to \nu\nu\gamma$
  - Recoil-mass peaks at M_Z
  - "switched off" by $P(e^-)$=1.
- $e^+e^- \to e^+e^-\gamma$
  - mimics signal if e^+e^- undetected
  - crucial to apply veto from low angle calorimeter



$P(e^-, e^+)$	$\nu\bar{\nu}\gamma$	$e^+e^-\gamma$
$(0\%, 0\%)$	67%	23%
$(+80\%, -60\%)$	25%	75%

Mass & σ from spectrum shape

- fractional event counting: Weight events by $S_{bin}/\sqrt{B_{bin}}$
- Include systematic errors.

Comparison with current LHC Results

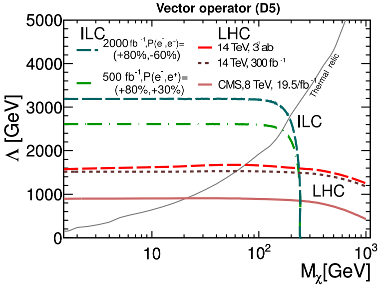
- Examples:
  - Vector operator ("spin independent"), $S_\chi = 1/2$
  - Axial-vector operator ("spin dependent"), $S_\chi = 1/2$

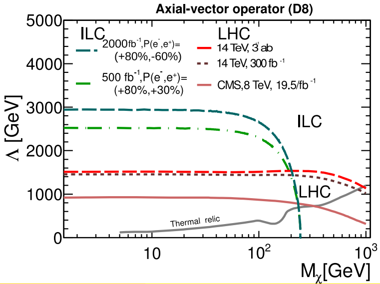
LHC data: CMS PAS EXO-12-048,projections: arXiv:1307.5327

- LHC reaches higher masses, ILC smaller cross-section.

Note:

- LHC curves assume pure coupling to hadrons, while
- ILC curves assume pure coupling to leptons.
- Not a priori comparable, rather complementary!





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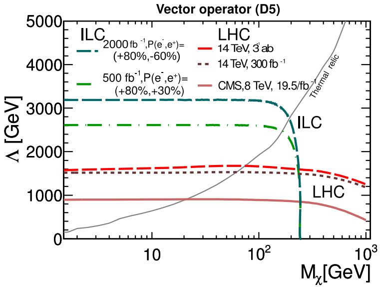

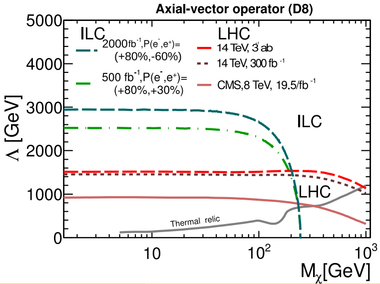

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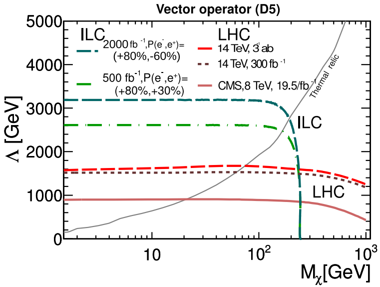

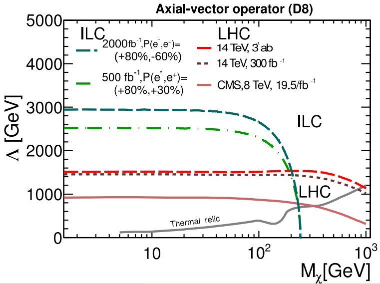

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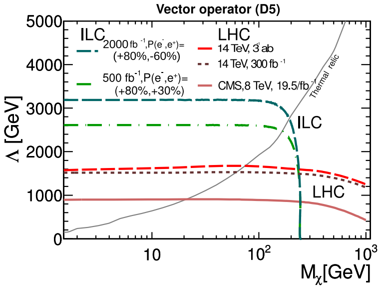

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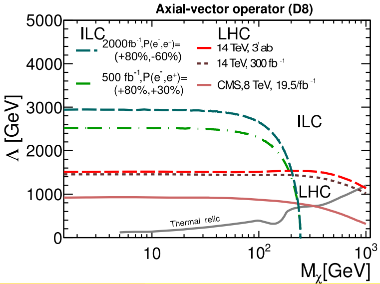

Z' and friends

- Z' is "everywhere" : Strings, extra-dimesions, composite models, ...
- If a resonance seen: Obviously BSM.
- Direct observation of resonace peak vs. Indirect evidence from modified behavior (couplings, asymetries, angular distributions).
- First case: E_{CMS} is king; Second case: precision is the one.
- Ie. Direct detection favours hadron colliders, indirect lepton colliders

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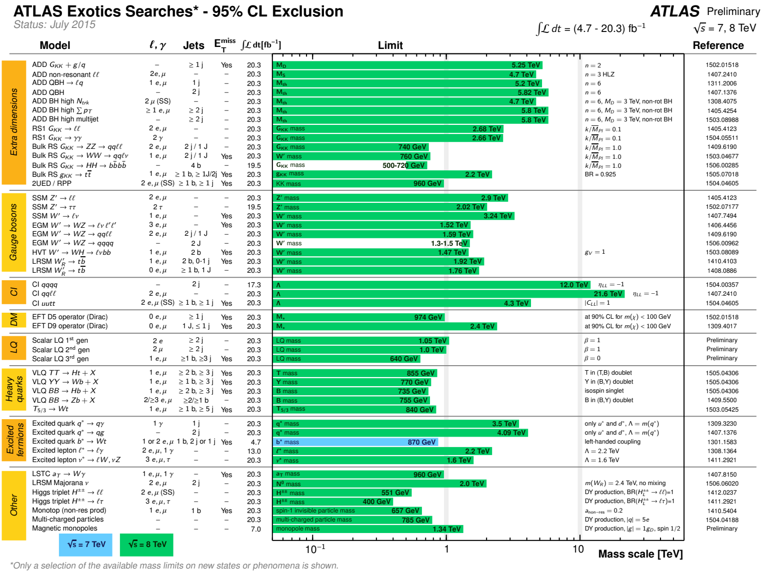
Z' and friends: Direct observation at LHC



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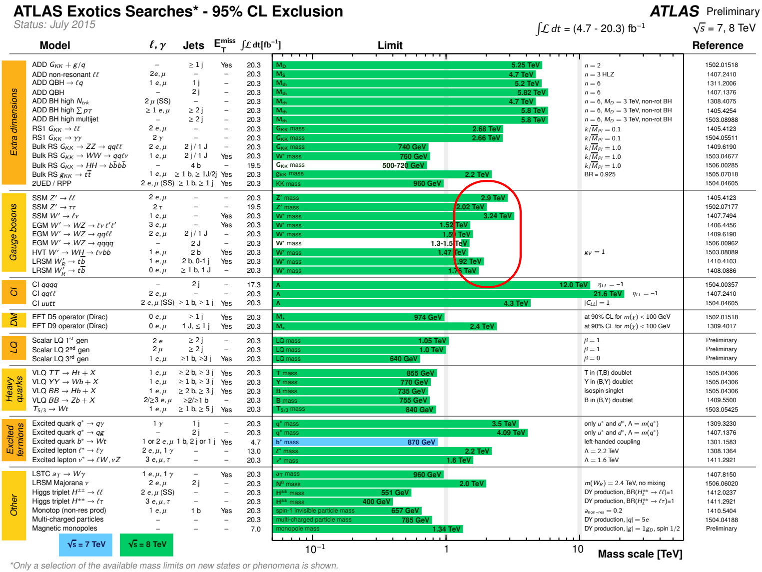

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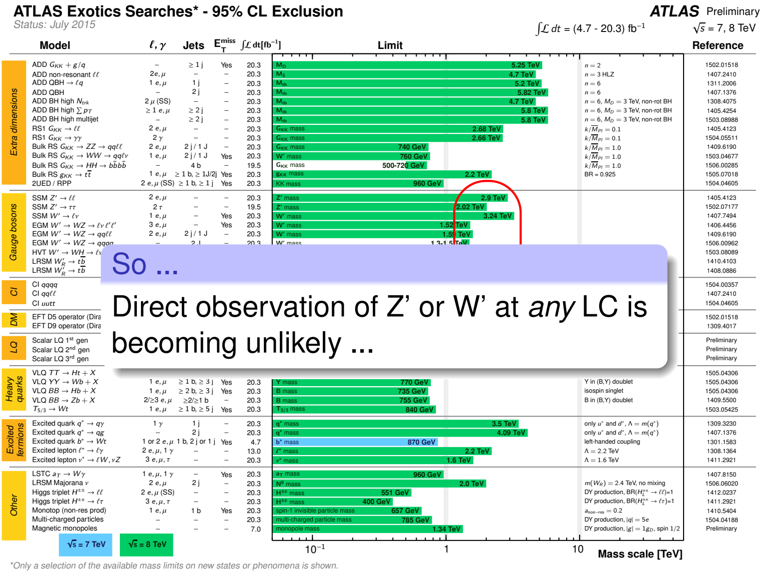
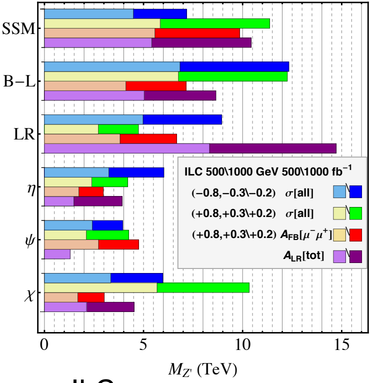


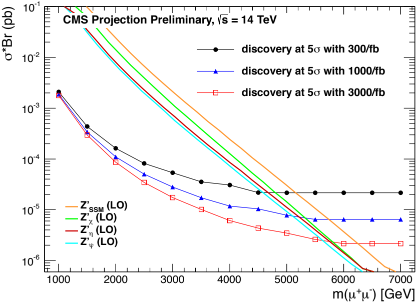
So ...

Direct observation of Z' or W' at *any* LC is becoming unlikely ...

Z' and friends: Indirect observations at LCs



ILC



LHC

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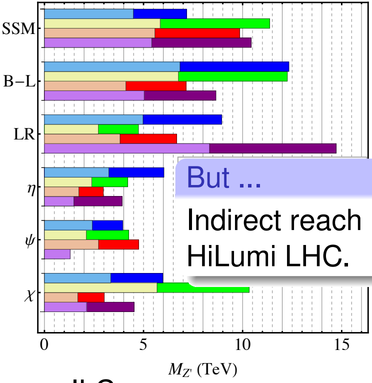

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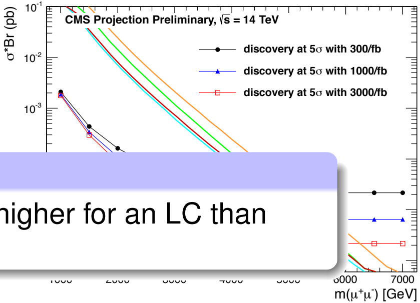


LHC

But ...

Indirect reach is higher for an LC than HiLumi LHC.

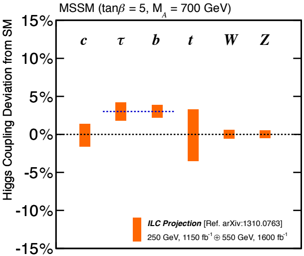
Precision measurements: Higgs, top, ...

Just one example:

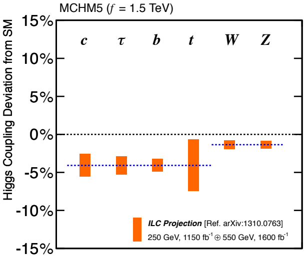
Fingerprinting

Elementary v.s. Composite

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



ILC 250+550 LumiUP

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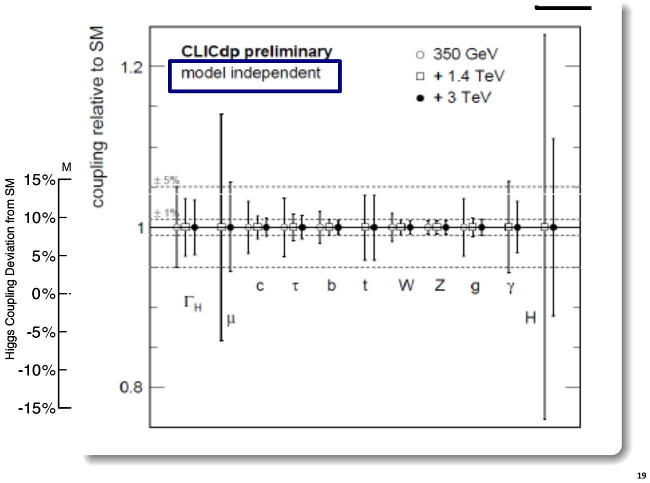

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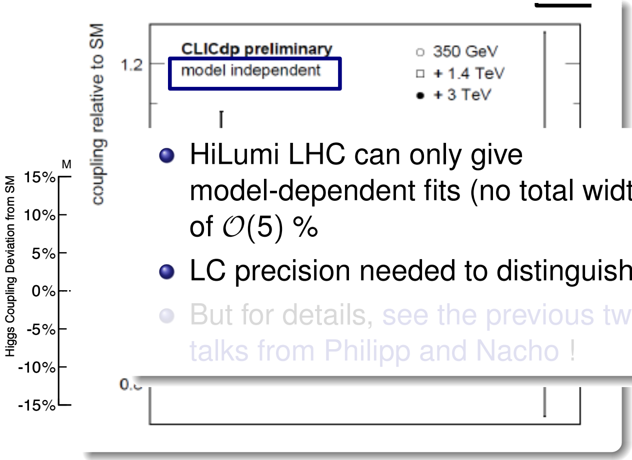

- HiLumi LHC can only give model-dependent fits (no total width!), of $\mathcal{O}(5)$ %
- LC precision needed to distinguish !
- But for details, see the previous two talks from Philipp and Nacho !

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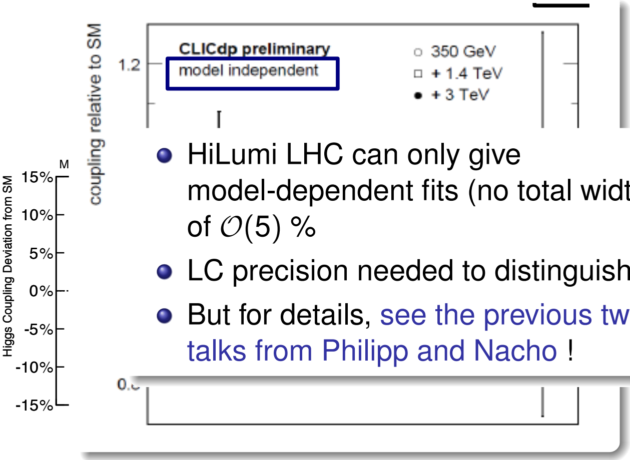

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SUSY: the LHC-LC connection

What if ...

1. LHC finds nothing new.
2. LHC finds new particle(s) within LC reach, or that at least hints to new particles within reach.
3. LHC finds new particle(s), but none in LC reach, nor hinting that there would be any in reach.

Where do the “hints” come from ?

Why would the mass of the gluino (the sparticle-of-excellence for LHC) give a hint for the LC?

- 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.
- The former is just an assumption, used to reduce the number of free parameters (CMSSM/mSUGRA). It has no profound reason to be, but was useful at LEP-times.
  - *This* assumption is now challenged by the data.

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What *do* we know ?

The three LHC scenarios are quite similar as far as SUSY an LC 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 !

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- 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 !

What *do* we know ?

The three LHC scenarios are quite similar as far as SUSY an LC 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 … as SUSY.
- In "natural" S… lectro-weak sector is "co… of the EW's that are close to …
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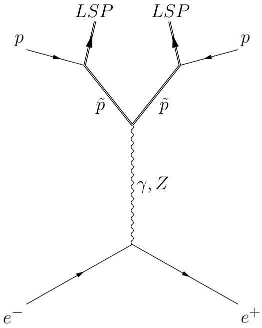
Hence, that "LHC finds new particle(s), but none in LC reach" does *not* mean that there *aren't* any SUSY particles with in LC reach.

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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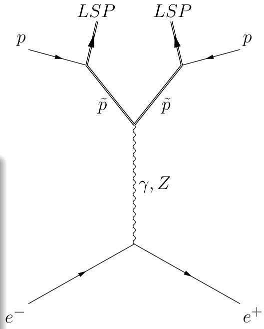

So, at an LC :

- Model 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 ↔ “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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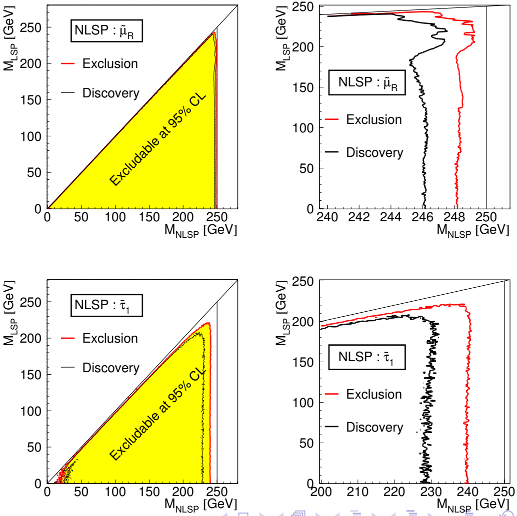

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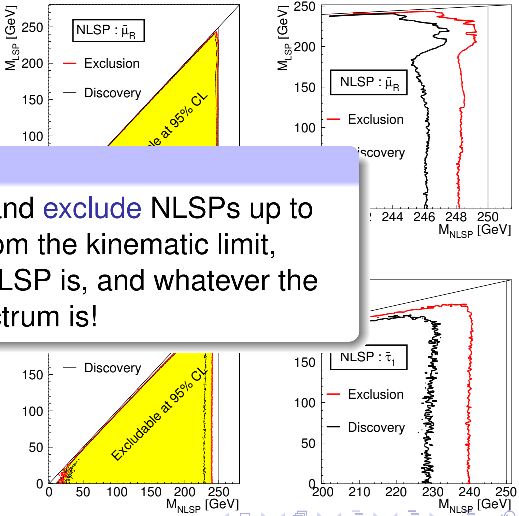

At ILC

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($\chi \rightarrow W^{(*)}/Z^{(*)}\tilde{\chi}_1^0$)=1.
- Note cut x-axis! Here is LEP, $\tilde{\chi}_1^\pm$ only, any decay-mode!
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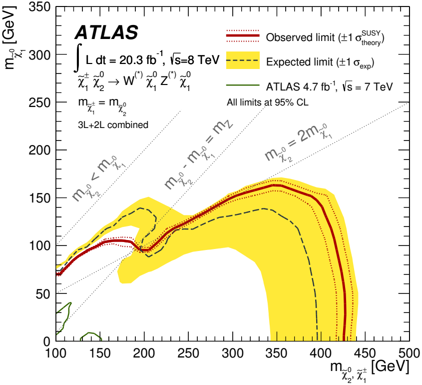

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ILC at 500 GeV...at 1 TeV...and CLIC at 3 TeV ⇒ Lots of plain vanilla SUSY to explore at LC:s!

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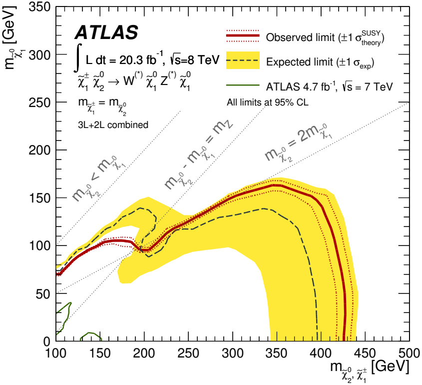

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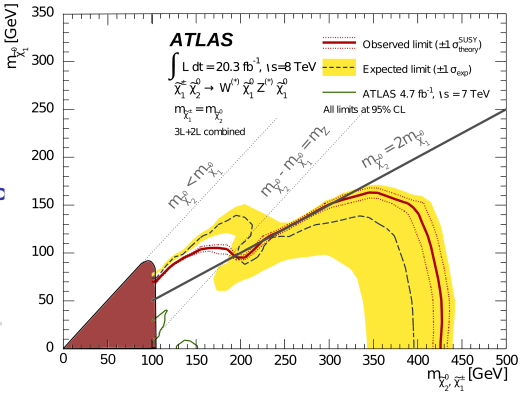

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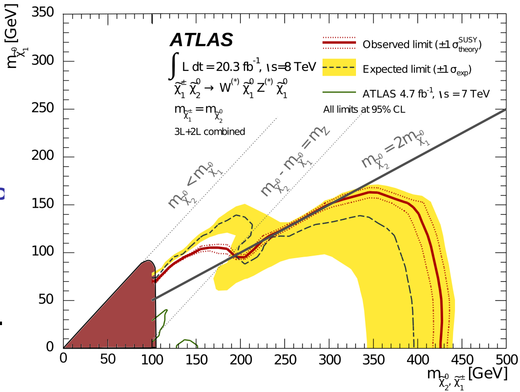

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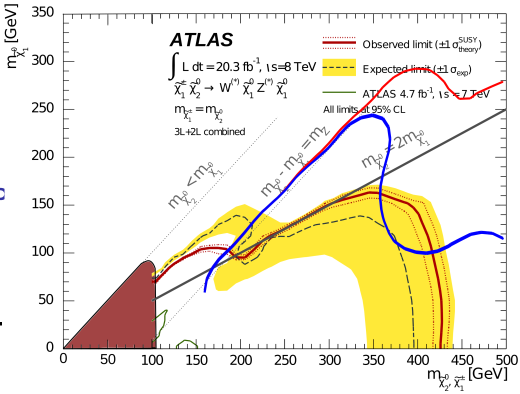

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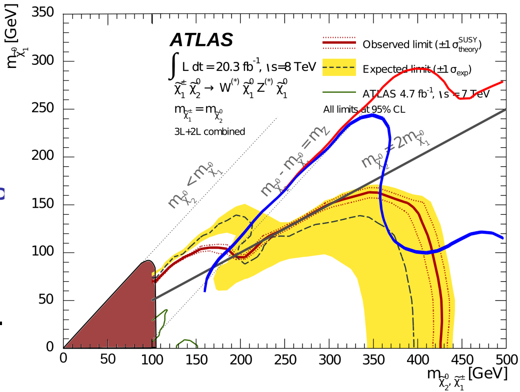

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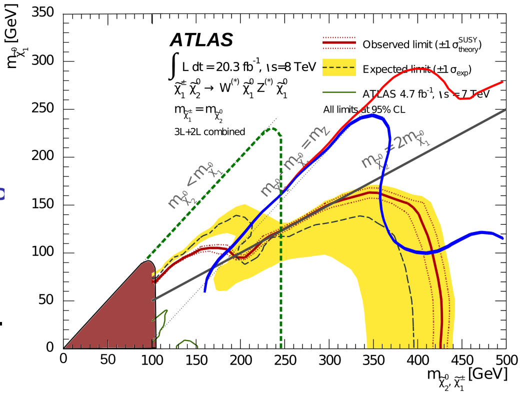

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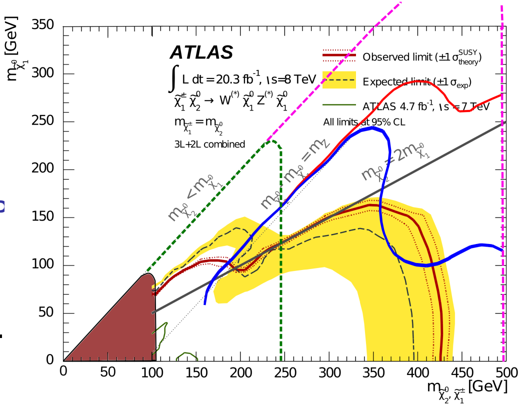

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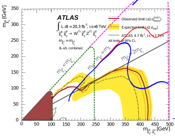

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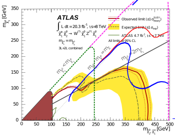

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SUSY at CLIC: Explore heavy spectra

- Eg. SUSY model III from CDR
- $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 W$
- $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$
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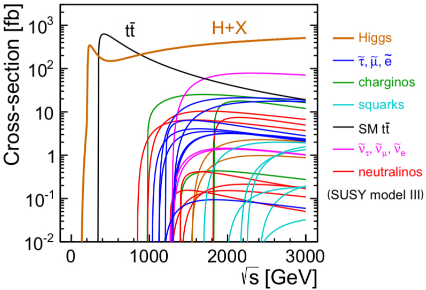

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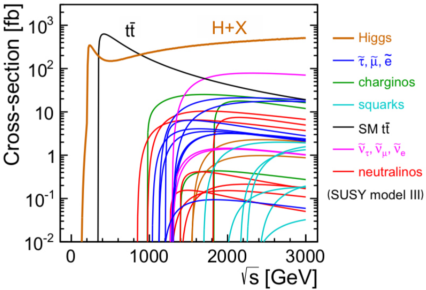

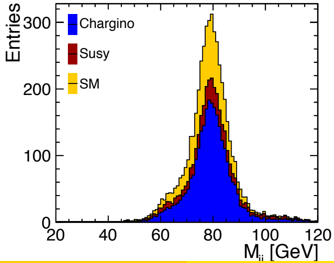

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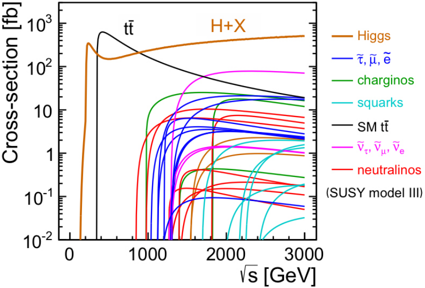

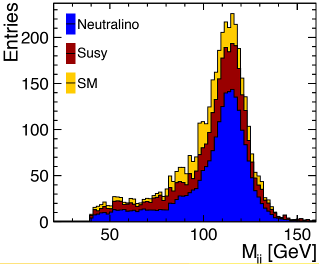

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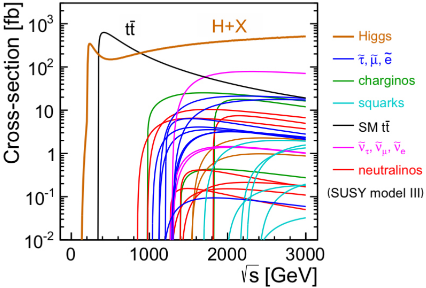

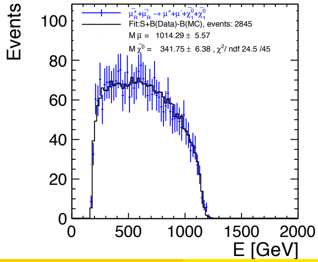

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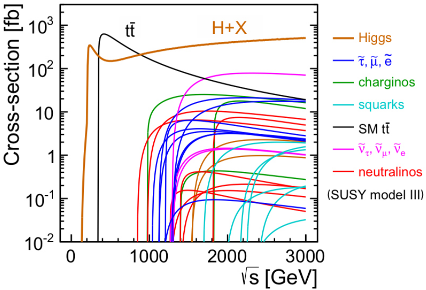

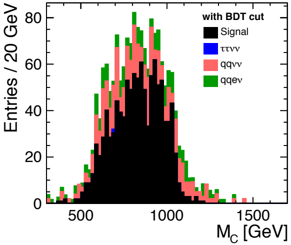

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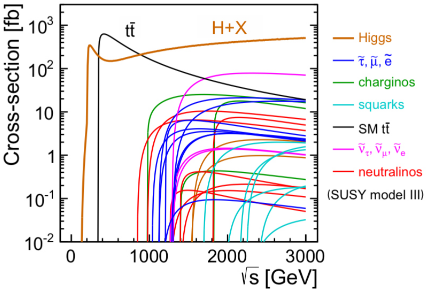
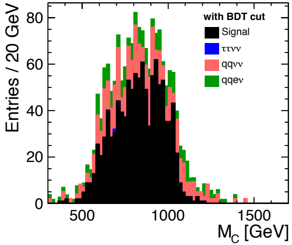


From these spectra, we can estimate $M_{\tilde{e}_R}$, $M_{\tilde{\mu}_R}$, $M_{\tilde{q}_R}$, $M_{\tilde{\chi}_1^0}$ and $M_{\tilde{\chi}_1^\pm}$ to < 3-6 GeV = few per mil for sfermions, few percent for bosinos.



Why compressed spectra ? Natural SUSY: Light, degenerate higgsinos

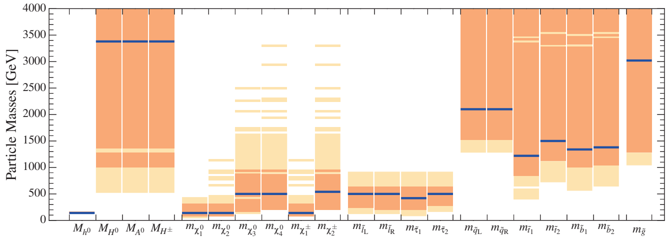
Why would one expect the spectrum to be compressed ?

- 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).
- But also: the data ...

Why compressed spectra ? Global fits

pMSSM10 prediction: best-fit masses

[2015]



$\Rightarrow$ high colored masses

$\Rightarrow$ relatively low electroweak masses

partially with not too large ranges

$\Rightarrow$ clear prediction for ILC and CLIC

Sven Heinemeyer, LCWS15, Whistler, 03.11.2015 14

Natural SUSY: Light, degenerate higgsinos

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  - $\Rightarrow$ 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)
- 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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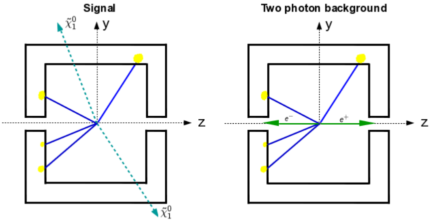

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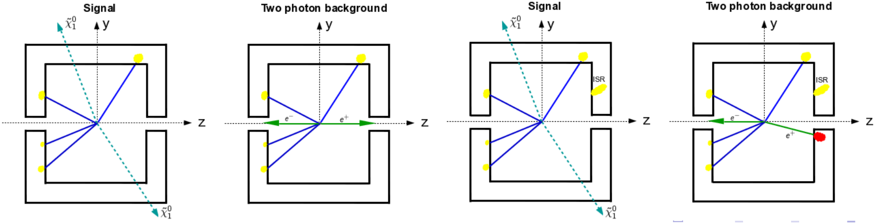

Natural SUSY: Light, degenerate higgsinos

- Studied model points:
  - dm1600: $\Delta(M)$=1.6 GeV, m_h=124 GeV, $M_{\tilde{\chi}^0_1}$=164.2 GeV.
  - dm770: $\Delta(M)$=0.77 GeV, m_h=127 GeV, $M_{\tilde{\chi}^0_1}$=166.6 GeV.
- Very hard for LHC.
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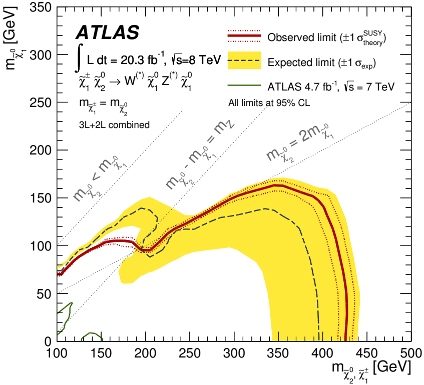

H. Sert, F. Brümmer, J. List, G. Moortgat-Pick, T. Robens, K. Rolbiecki, M.B., EPJC (2013) 73:2660 [arXiv:1307.3566v2]

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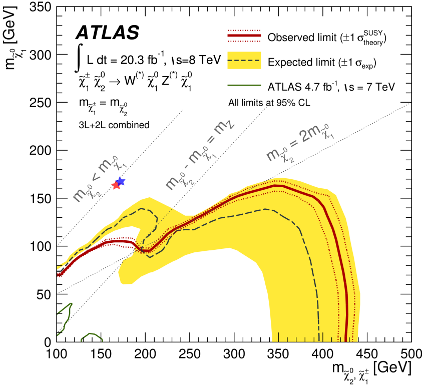

H. Sert, F. Brümmer, J. List, G. Moortgat-Pick, T. Robens, K. Rolbiecki, M.B., EPJC (2013) 73:2660 [arXiv:1307.3566v2]

Natural SUSY: Light, degenerate higgsinos

- Studied model points:
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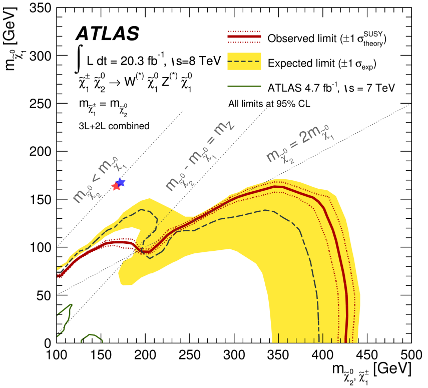

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SUSY with light bosinos, sleptons, heavy coloureds

Recall:

- The reason that mSUGRA/CMSSM is dead is the *irrelevant part*!
- Ie. : LHC excludes 1:st & 2:nd generation squarks and gluinos. These states have no influence on DM, g-2, naturalness, ...
- 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.
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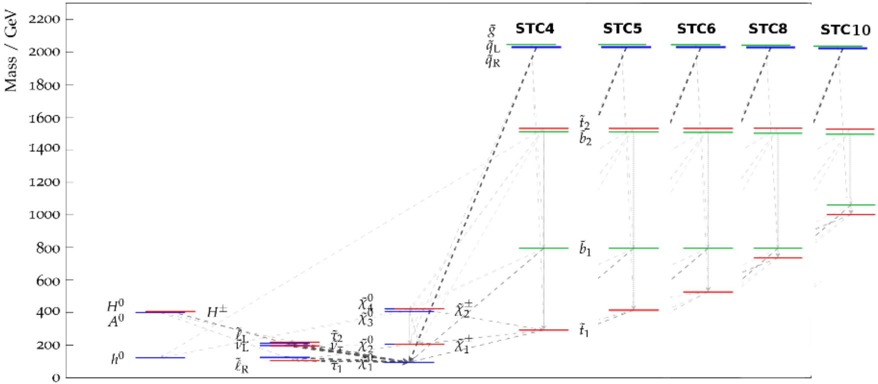
Full STCx mass-spectrum

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.
- Third generation squark production constitute a good compromise between cross-section and visibility, and will be the most powerful discovery channel. The lower cross-section in STC10 is compensated by higher visibility.

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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.

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

- Selections for $\tilde{\mu}$ and $\tilde{e}$:
  - Correct charge.
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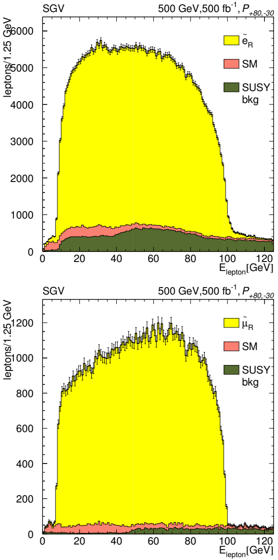

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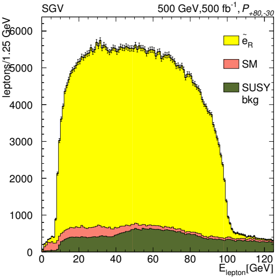
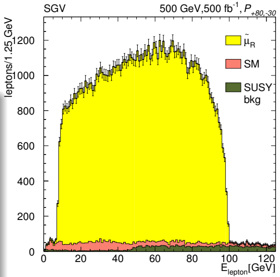
From these spectra, we can estimate $M_{\tilde{e}_R}$, and $M_{\tilde{\chi}^0_1}$ to < 0.2 GeV, and $M_{\tilde{\mu}_R}$ to < 0.5 GeV = few per mil.
From threshold scan: They *are* scalars.





BSM: Machine and Detectors

So, we found that experimentaly, LC-BSM is largely a question of SM-particles + missing stuff.
Ie. we need to See the unseen.

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- ... and determine the difference between the two.
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What is then the edge for LCs wrt. hadron colliders ?

- Lepton-collider: Initial state is known.
- Production is EW ⇒
  - Small theoretical uncertainties.
  - No “underlying event”.
  - Low cross-sections wrt. LHC, also for background.
  - ⇒ Trigger-less operation = hermetic in time.

⇒ for detectors:

- Low background ⇒ 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 relative to earth.

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Conclusions

BSM at any LC:

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  - Model-independent and LHC complementary reach.
- Z' etc.:
  - Indirect search reach much higher than LHC - excellent direct detection possibilities for CLIC, but LHC is closing the window.
- SUSY:
  - 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.
  - In models with a rich spectrum reachable by LCs, LHC discovery will be corroborate on.
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Thank You !

BACKUP

Natural SUSY: Light, degenerate higgsinos

- Few-body decays and radiative decays (for $\tilde{\chi}_2^0$) (calculated with Herwig).
- 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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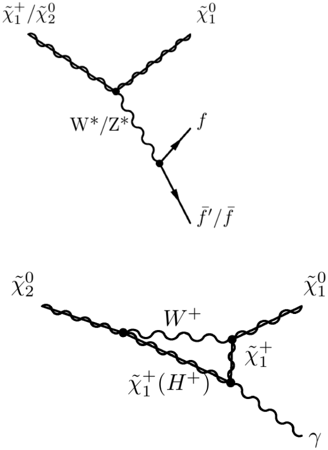

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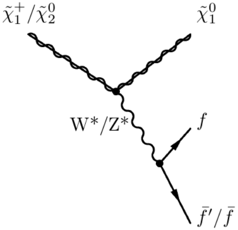

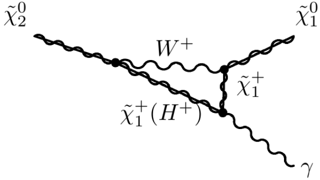

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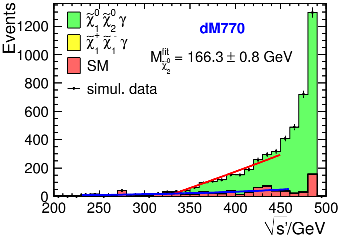

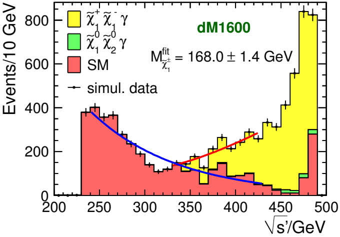

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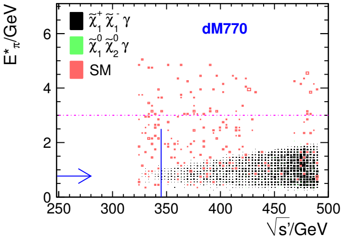

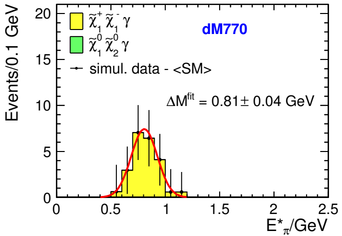

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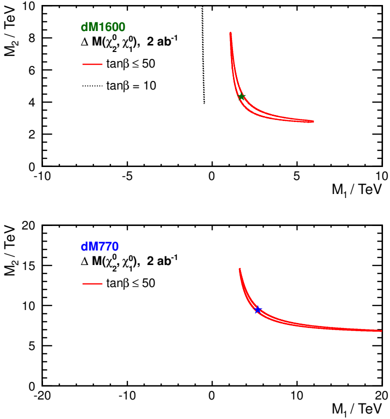

STCx @ LHC14

- STC8 and STC10 studied by I. Melee-Pullmans group at DEWY with fastsim (Delphes).
- Main features at LHC 14 TeV:
  - Cross-sections:
    - $\tilde{\chi}^0_k\tilde{\chi}^\pm_l > \tilde{\chi}^\pm_k\tilde{\chi}^\pm_l > \tilde{\tau}\tilde{\tau} > \tilde{\ell}\tilde{\ell} > \tilde{t}\tilde{t} > \tilde{b}\tilde{b} > \tilde{q}\tilde{q} > \tilde{\chi}^0_k\tilde{\chi}^0_l > \tilde{g}\tilde{g}$

    ranging from 1.5 pb to 1 fb. $M_{\tilde{t}}$ and $M_{\tilde{b}}$ is 200 GeV higher in STC10 $\rightarrow$ Cross-sections for $\tilde{t}\tilde{t}$ and $\tilde{b}\tilde{b}$ 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).
    - For $\tilde{\chi}^0$, the rest is either only bosons, or "nothing" (ie. neutrinos).
    - For $\tilde{\chi}^\pm$ the rest is other leptons.
  - The τ:s mostly come from $\tilde{\tau}_1 \rightarrow \tau\tilde{\chi}^0_0$, where the mass difference is only 10 $\mathrm{GeV} \Rightarrow$ little missing energy.
  - $\tilde{b}$ mostly decays to $b\tilde{\chi}^0$: $>$ 50 % to $b\tilde{\chi}^0_1$. But also to $t\tilde{\chi}^\pm$ (20%)
  - $\tilde{t}$ always goes to $t\tilde{\chi}^0$, but rarely to $t\tilde{\chi}^0_1$ ($\sim$ 10%).
  - The right-handed gen1 and 2 squarks almost always decay directly to quark+LSP.

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

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	

$\tilde{\mu}_R$ threshold scan

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

$\tilde{\mu}_R$ threshold scan

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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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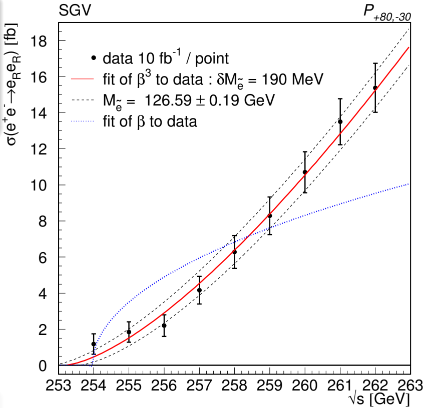

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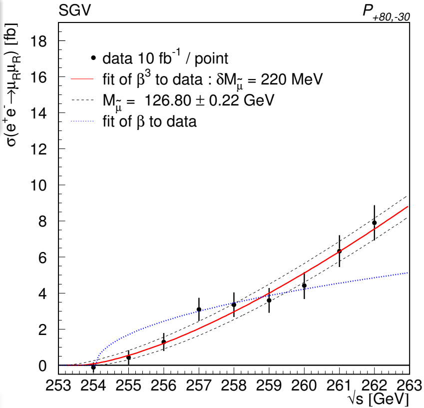

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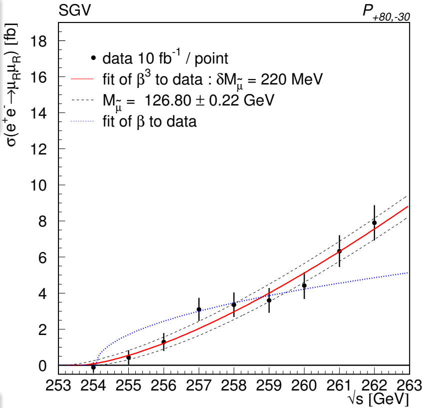

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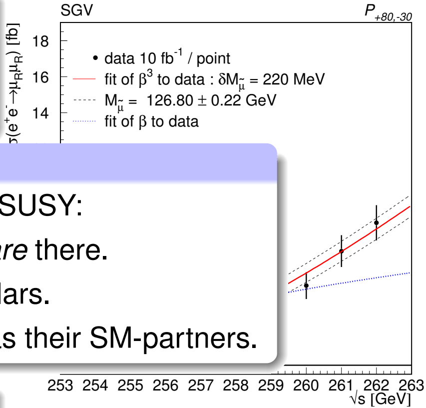
At ILC

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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