Direct BSM at ILC at E_{cms}= 250 GeV ?

Mikael Berggren[1]

[1]DESY, Hamburg

ALCW, Fukuoka, May, 2018

Outline

1. Direct BSM @ 250
2. Dark matter
3. SUSY
   - SUSY with no loop-holes
   - Compressed spectra

A few random points from me

While it is true that 250 is not much more than the maximum energy of 208 that LEP reached, there are other features that are ameliorated by orders of magnitude:

- The luminosity is 1000 times higher
- both beams are polarised
- the beam-spot is sub-microscopic in size.
- Many aspects of the detectors are better than the LEP ones by a factor 10 or more.
- Computing power has been increased by orders of magnitude, meaning that no trigger is needed: if it happens, it is recorded!

All this means that much more subtle effects can be probed for at energies that in principle was reachable at LEP.

A few random points from me

Many of these features also are relevant in exploiting LHC:s blind-spots:

- anything out-side the coloured sector
- effects with soft final states,
- things where full kinematic reconstruction is needed (not just in the transverse direction)
- and so on.

A few random points from me

What other direct BSM signals than the typical SUSY signatures, that are already much-studied by the experimentalists, should one try to attack?
Typical SUSY signatures means "some SM stuff + missing stuff", and also catches other models.
However, what about new couplings, rather than new particles, eg. flavour signatures? Can the ILC@250 do something there?

- Visible signs of a dark sector?
- R-parity violating SUSY, and the like (ie. nothing missing, but new states)?
- Neutral long-lived states, seeable in calorimeters, but not by trackers (eg. neutral R-hadrons)?
- And so on ...

Direct BSM @ 250

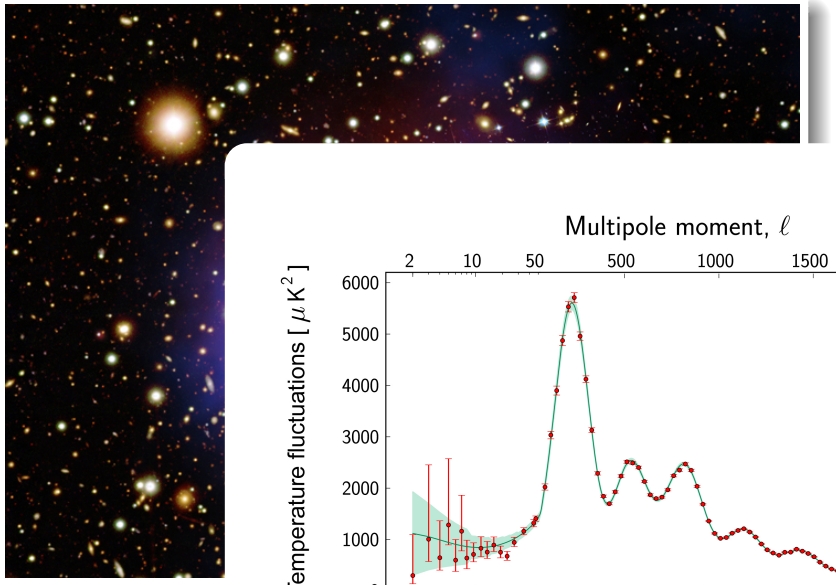
In this talk:

1. DM: Because it's there.
2. 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 $\rightarrow$ good experimental testing-ground.

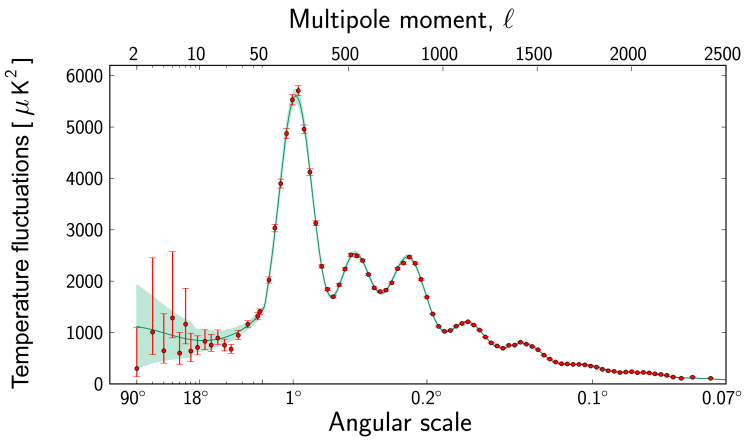
Dark Matter

Bullet cluster

Dark Matter

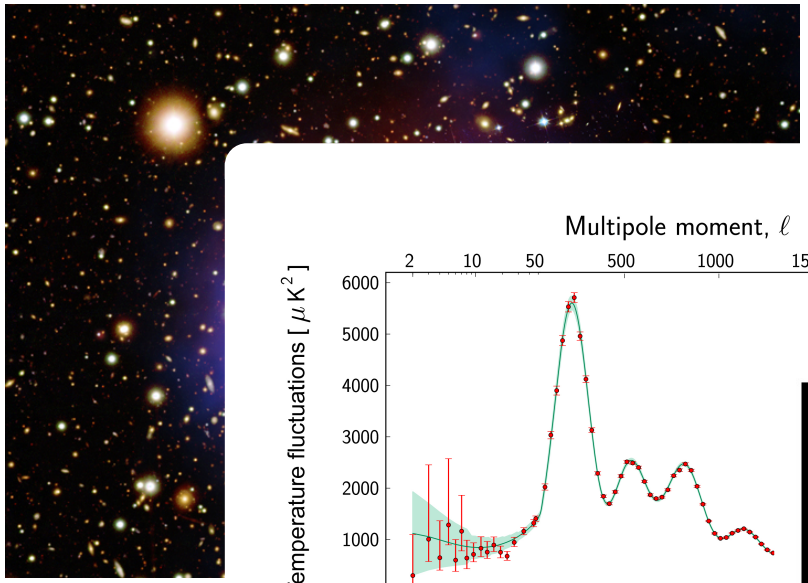


Bullet

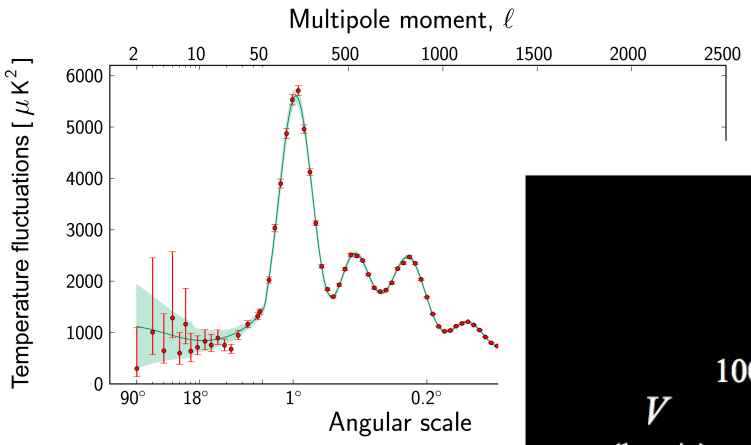


Plank CMB

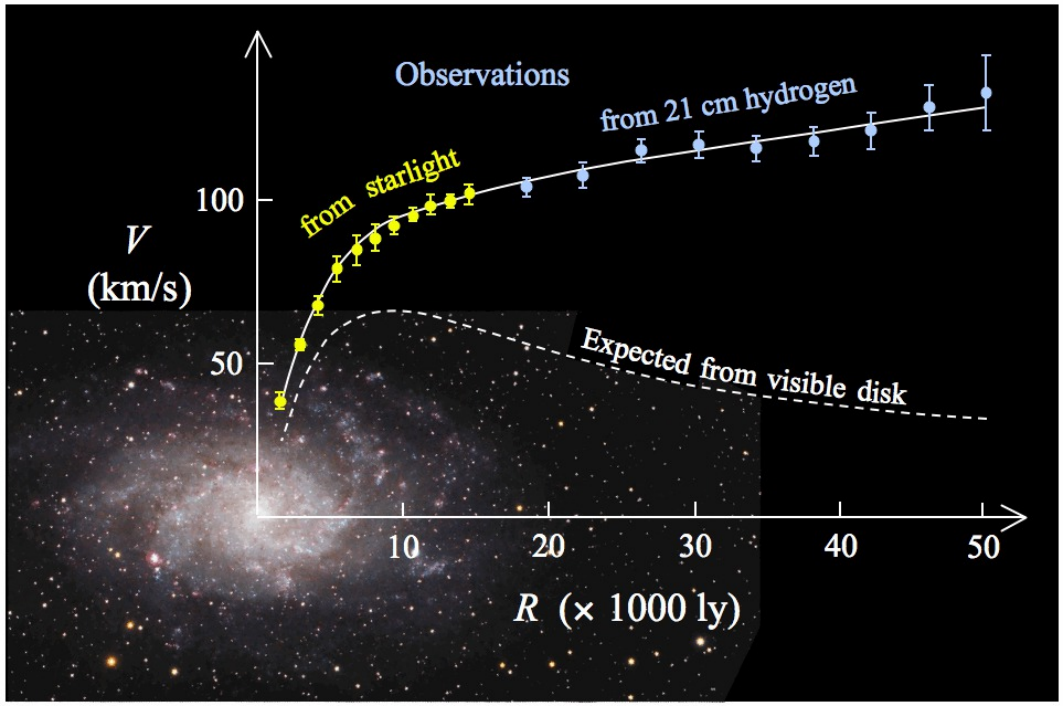
Dark Matter



Bullet



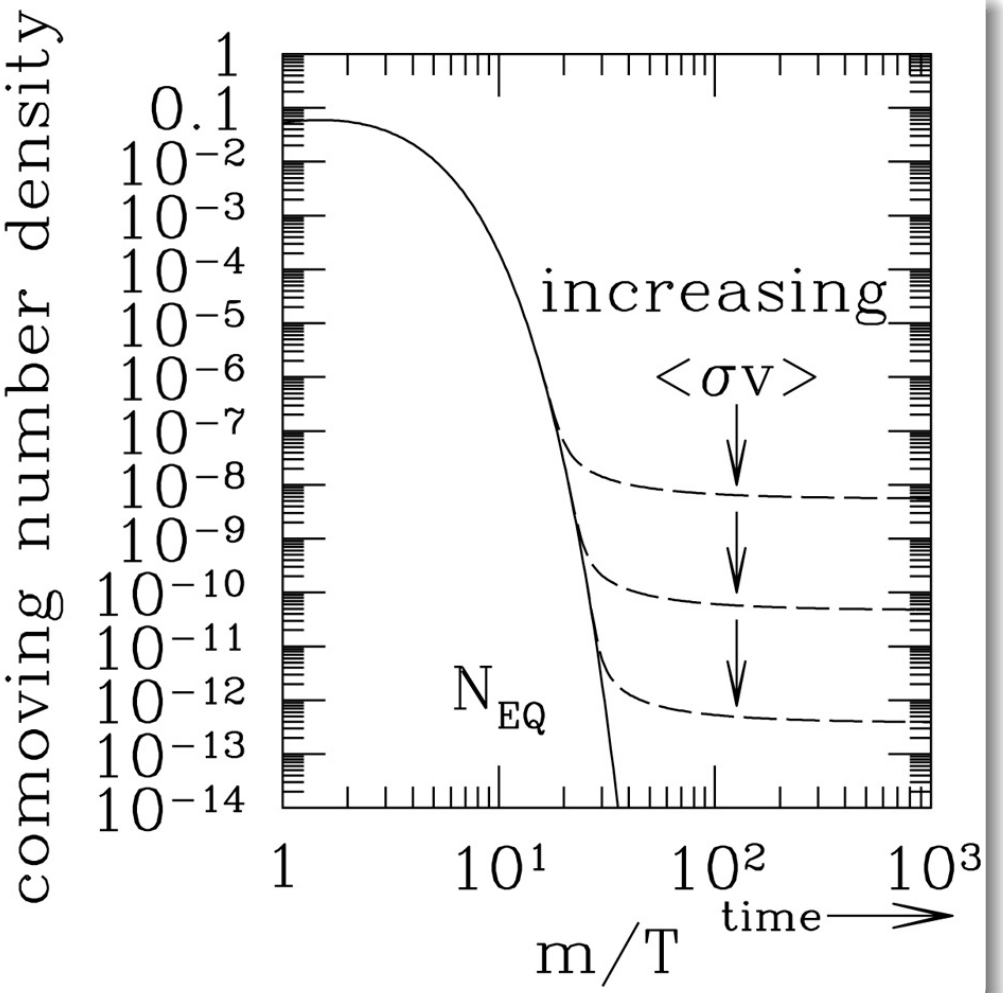
Plank CMB



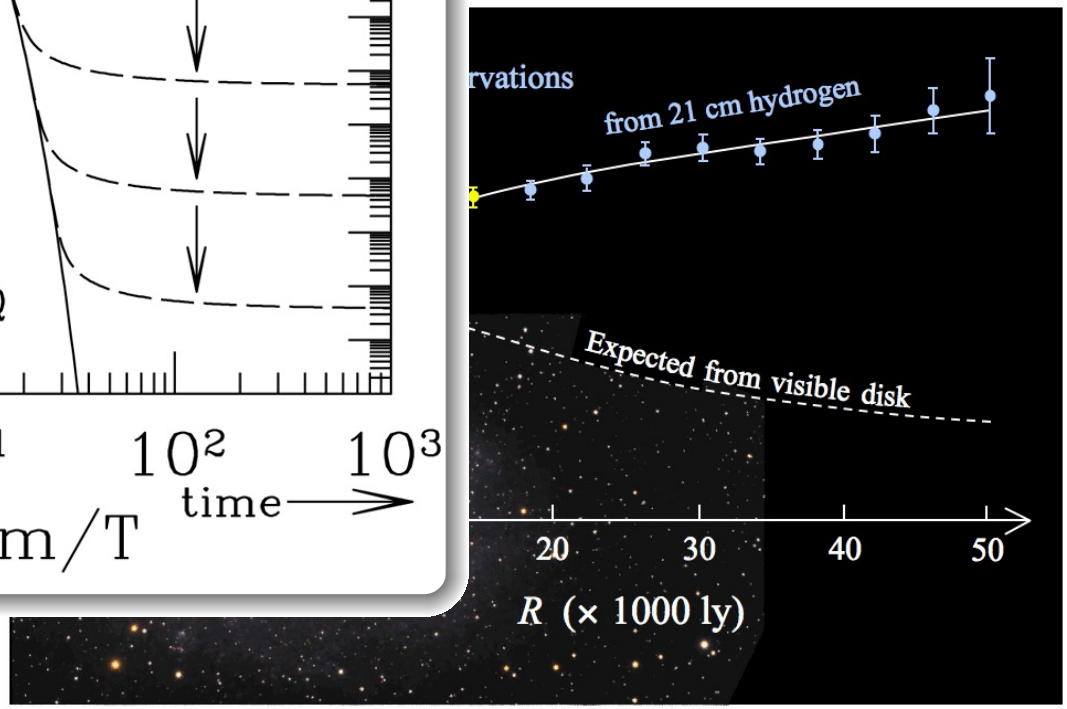
M33 rotation curve

Dark Matter

Bullet



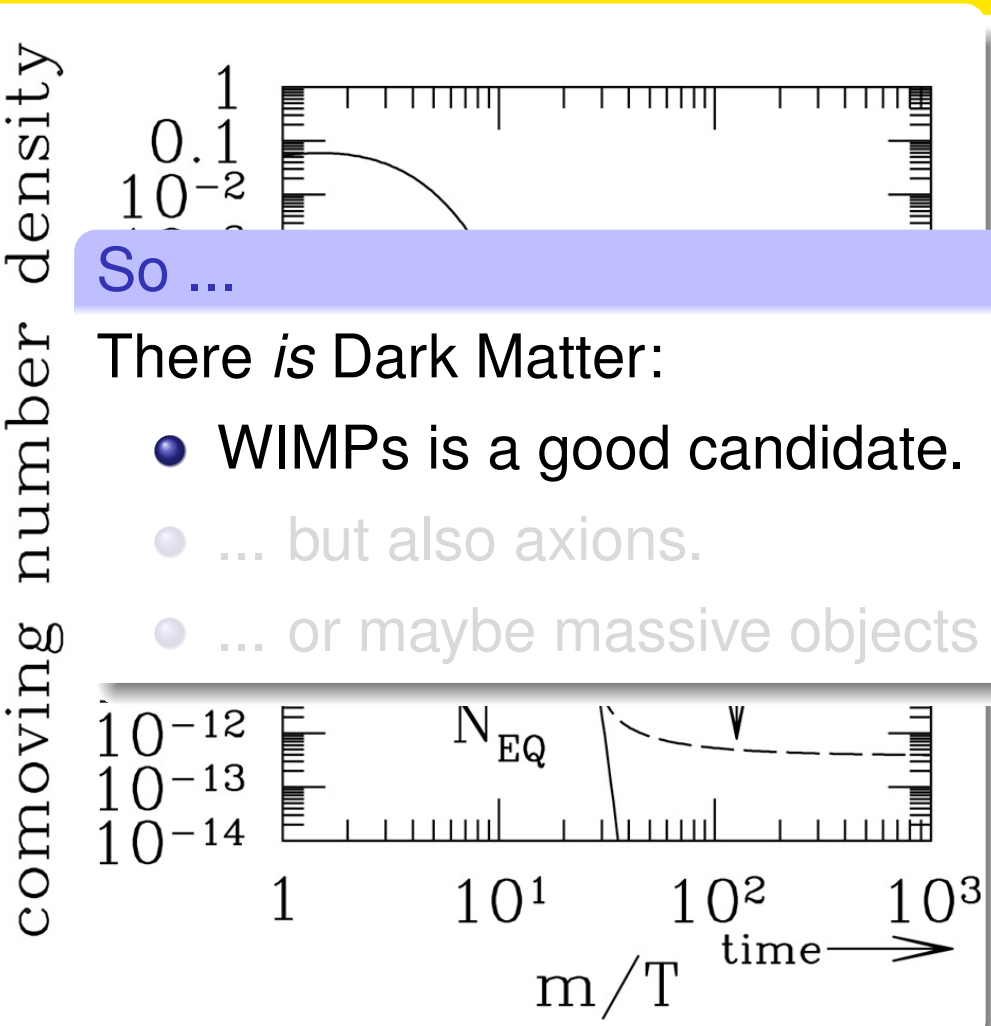
The WIMP miracle !



M33 rotation curve

Dark Matter

Bullet

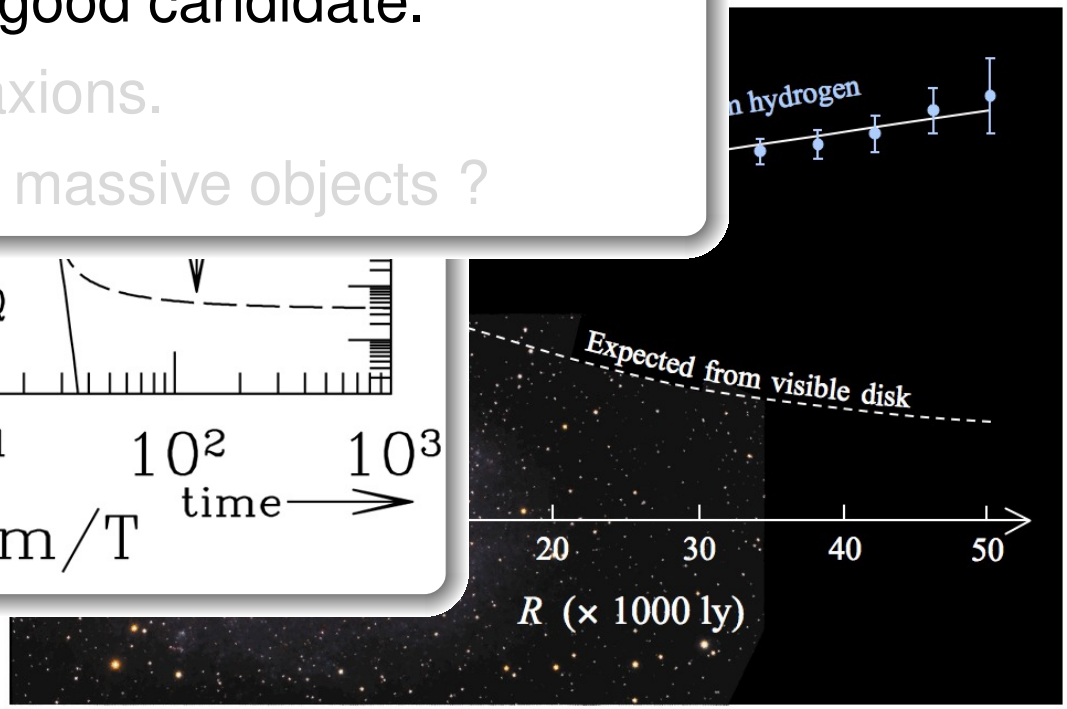


The WIMP miracle !

So ...

There *is* Dark Matter:

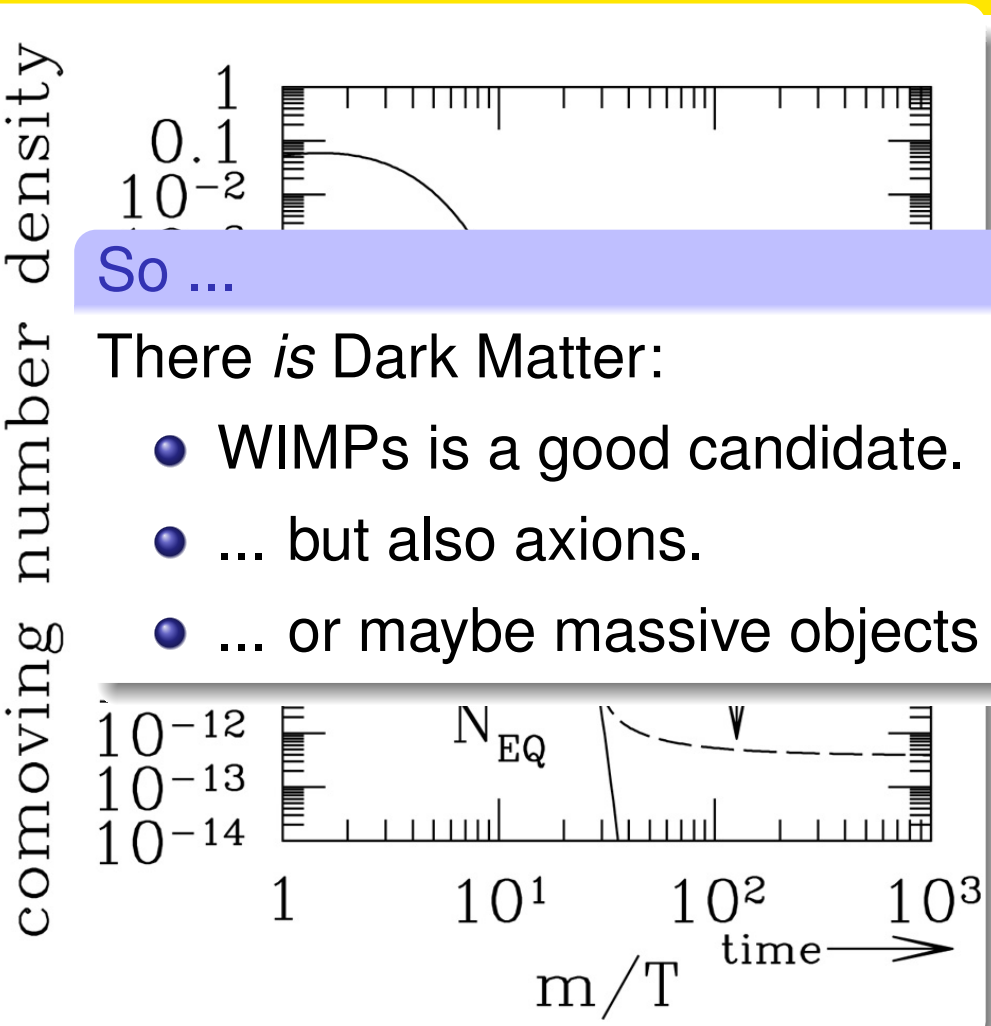
- WIMPs is a good candidate.
- ... but also axions.
- ... or maybe massive objects ?



M33 rotation curve

Dark Matter

Bullet

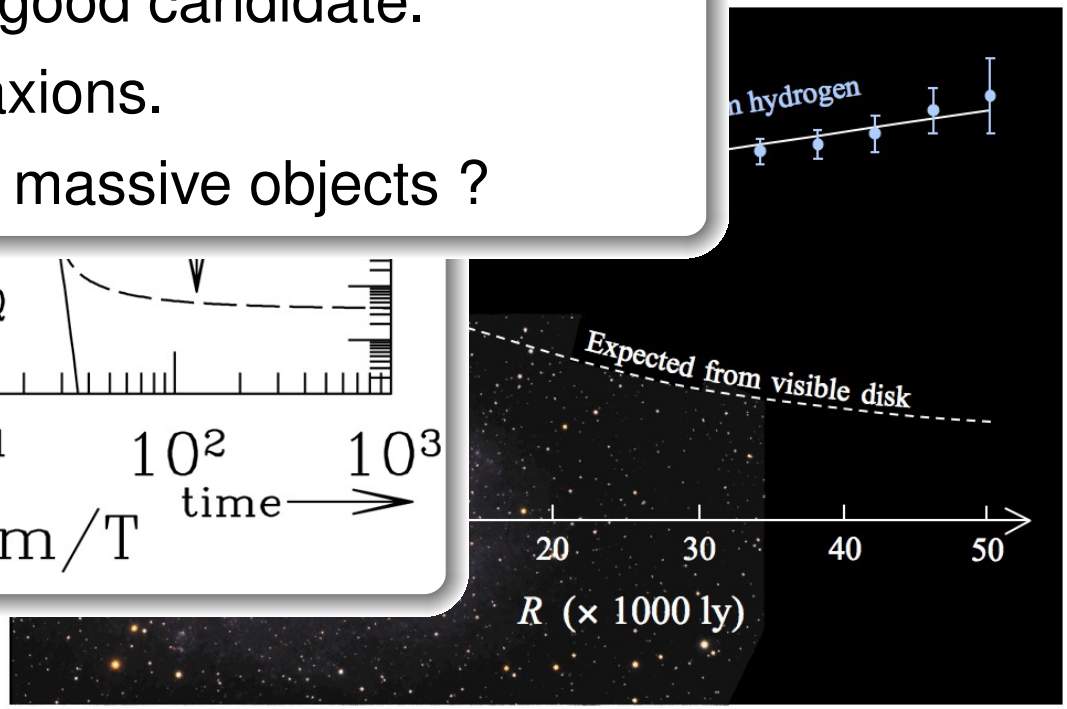


The WIMP miracle !

So ...

There *is* Dark Matter:

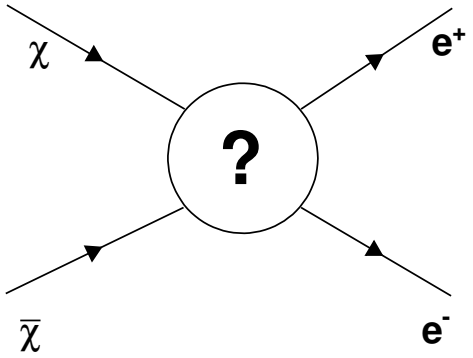
- WIMPs is a good candidate.
- ... but also axions.
- ... or maybe massive objects ?



M33 rotation curve

Only WIMPs

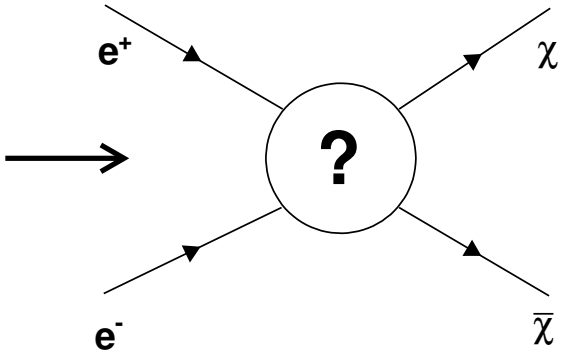
- Cosmology $\Rightarrow$ 25% of universe = Dark Matter
- One possibility: WIMPs (χ). What if this is the only accessible NP ?



- Search for direct WIMP pair-production at collider : Need to make the invisible visible:
  - Require initial state radiation which will recoil against "nothing"
  - LHC: $pp \to \chi\chi g$ or $\chi\chi\gamma$
  - LC: $e^+e^- \to \chi\chi\gamma$ (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.

Only WIMPs

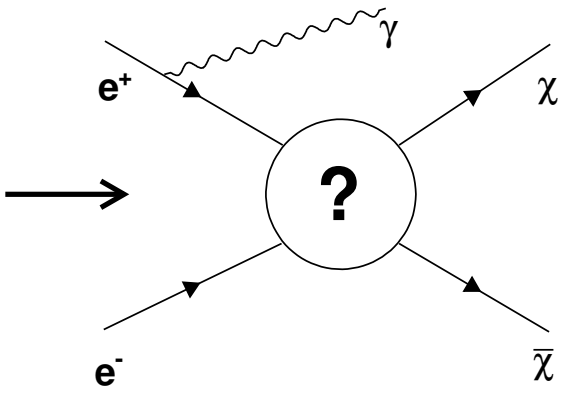
- Cosmology $\Rightarrow$ 25% of universe = Dark Matter
- One possibility: WIMPs (χ). What if this is the only accessible NP ?



- Search for direct WIMP pair-production at collider : Need to make the invisible visible:
  - Require initial state radiation which will recoil against "nothing"
  - LHC: $pp \to \chi\chi g$ or $\chi\chi\gamma$
  - LC: $e^+e^- \to \chi\chi\gamma$ (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.

Only WIMPs

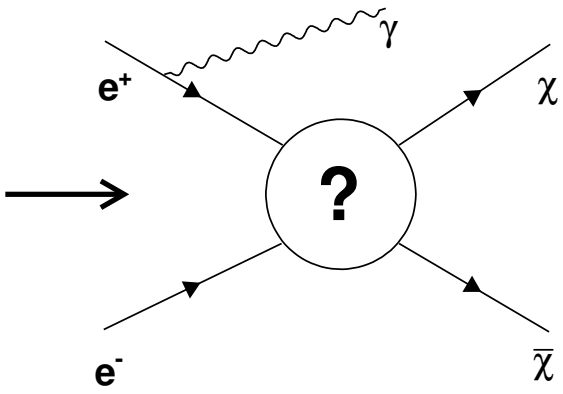
- Cosmology $\Rightarrow$ 25% of universe = Dark Matter
- One possibility: WIMPs (χ). What if this is the only accessible NP ?



- Search for direct WIMP pair-production at collider : Need to make the invisible visible:
  - Require initial state radiation which will recoil against "nothing"
  - LHC: $pp \to \chi\chi g$ or $\chi\chi\gamma$
  - LC: $e^+e^- \to \chi\chi\gamma$ (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.

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: $pp \to \chi\chi g$ or $\chi\chi\gamma$
  - LC: $e^+e^- \to \chi\chi\gamma$ (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.

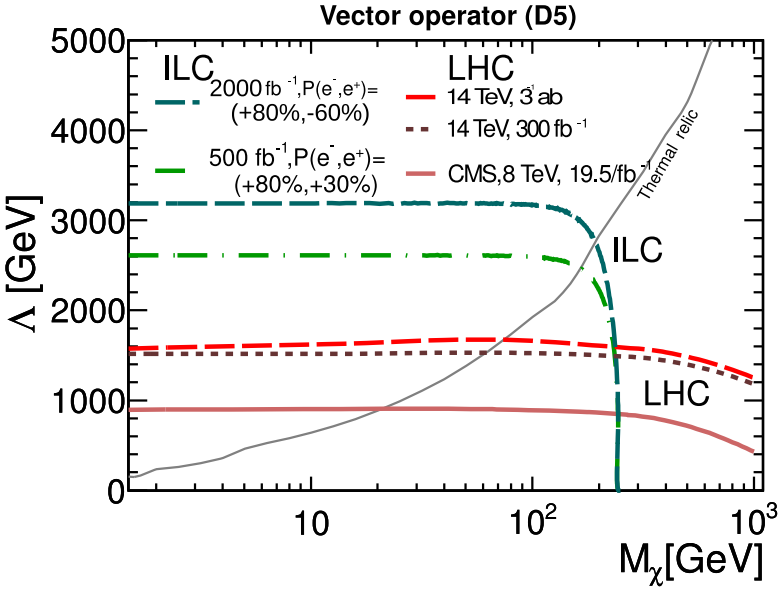
LC and LHC exclusion

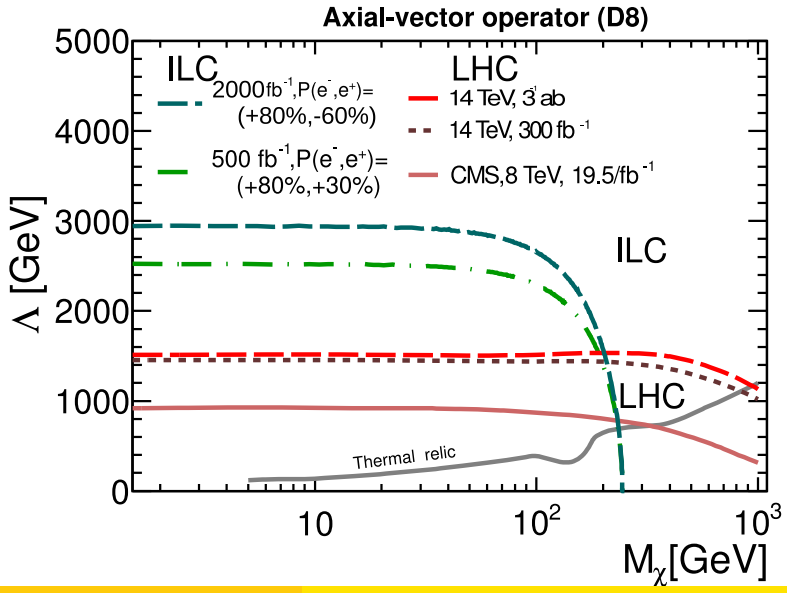
- Examples:
  - Vector operator ("spin independent"), $S_\chi = 1/2$
  - Axial-vector operator ("spin dependent"), $S_\chi = 1/2$

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

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

Note:





LC and LHC exclusion

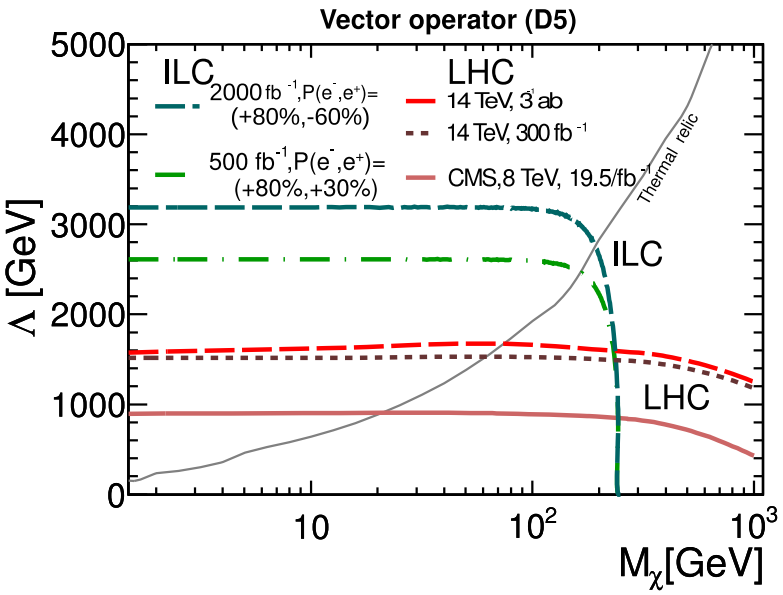
- Examples:
  - Vector operator ("spin independent"), $S_\chi = 1/2$
  - Axial-vector operator ("spin dependent"), $S_\chi = 1/2$

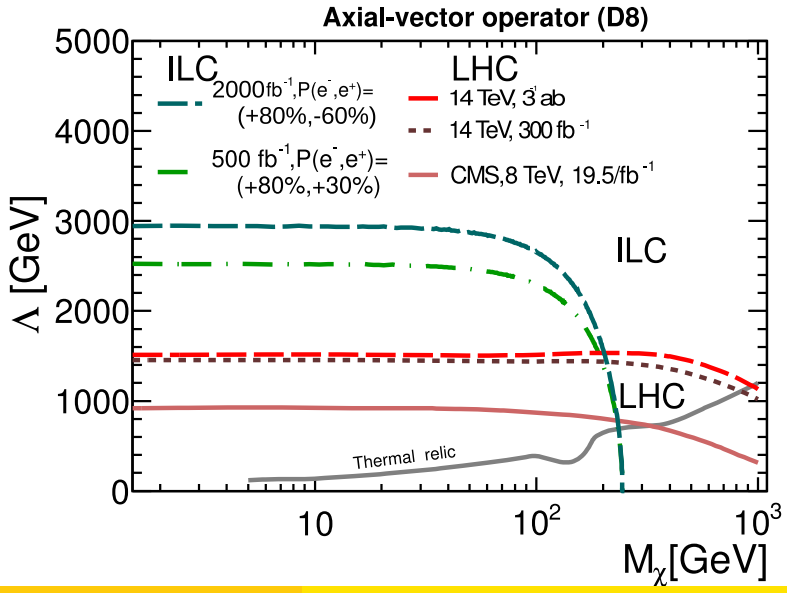
LHC data: CMS PAS EXO-12-048,projections: arXiv:1307.5327

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

Note:

- LHC: coupl. to hadrons, LC: coupl. to leptons.
- LC beats LHC on Λ = lumi, not $E_{cms} \Rightarrow 250$ *is* useful





LC and LHC exclusion

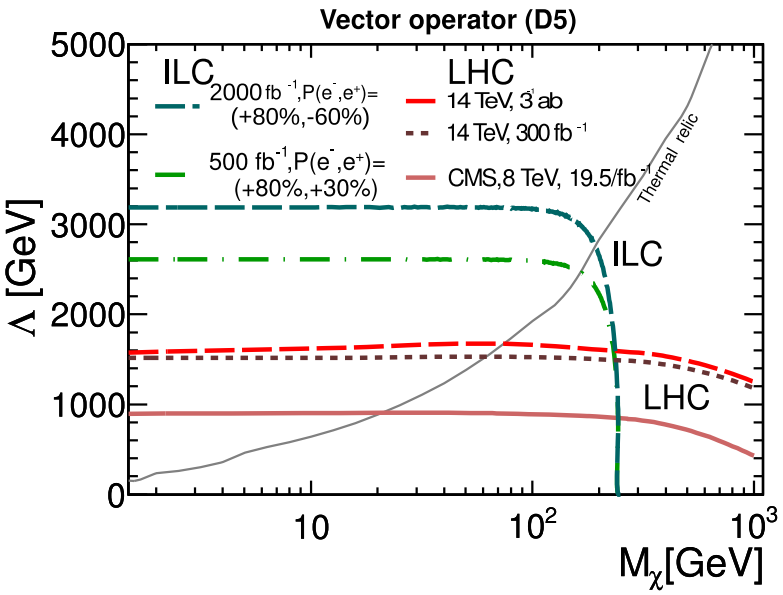
- Examples:
  - Vector operator ("spin independent"), $S_\chi = 1/2$
  - Axial-vector operator ("spin dependent"), $S_\chi = 1/2$

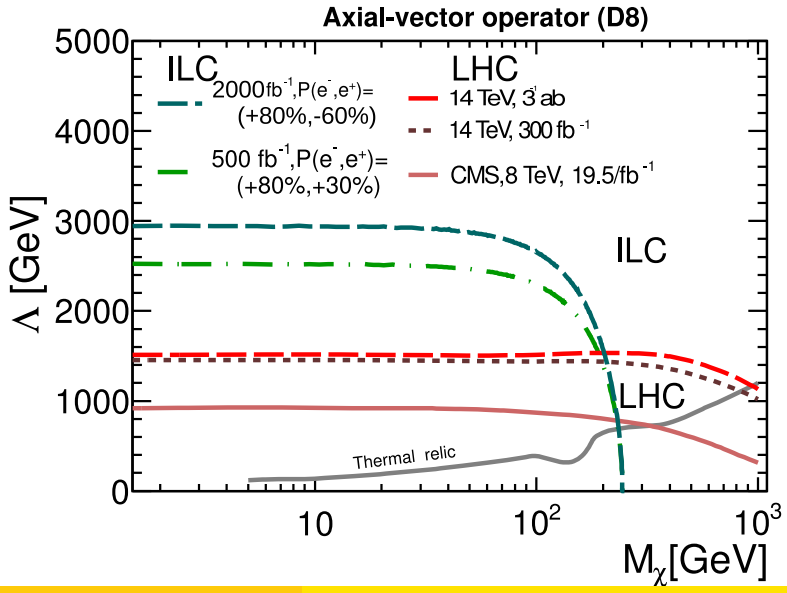
LHC data: CMS PAS EXO-12-048,projections: arXiv:1307.5327

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

Note:

- LHC: coupl. to hadrons, LC: coupl. to leptons.
- LC beats LHC on Λ = lumi, not $E_{cms} \Rightarrow 250$ *is* useful





LC and LHC exclusion

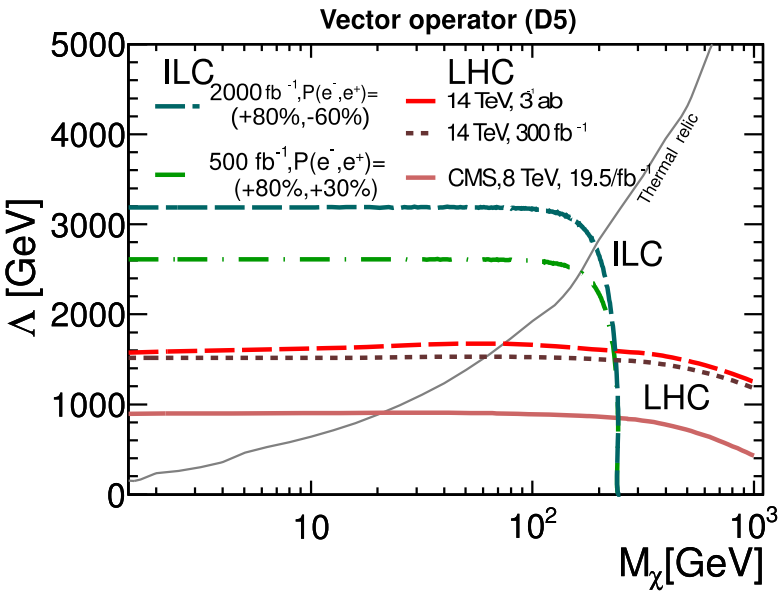
- Examples:
  - Vector operator ("spin independent"), $S_\chi = 1/2$
  - Axial-vector operator ("spin dependent"), $S_\chi = 1/2$

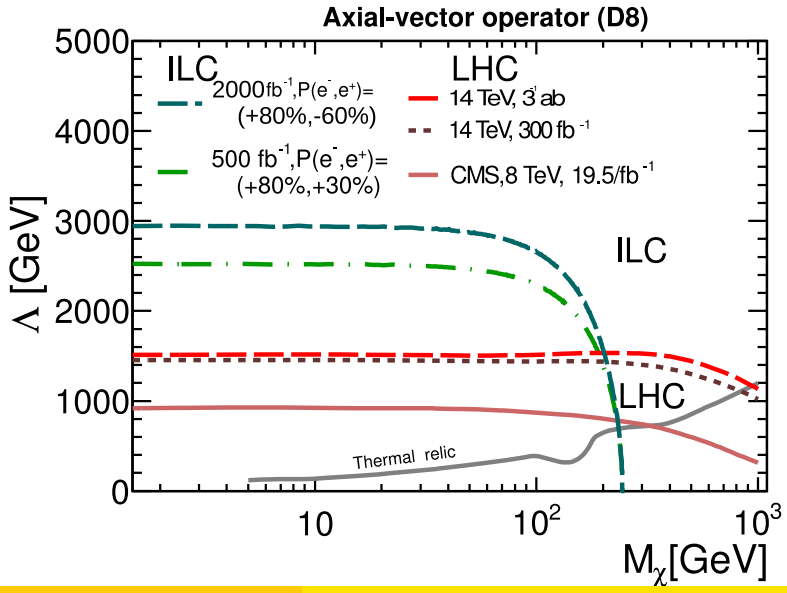
LHC data: CMS PAS EXO-12-048,projections: arXiv:1307.5327

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

Note:

- LHC: coupl. to hadrons, LC: coupl. to leptons.
- LC beats LHC on Λ = lumi, not $E_{cms} \Rightarrow 250$ *is* useful





SUSY: 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 !

SUSY: 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 !

SUSY: 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 !

SUSY: 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 !

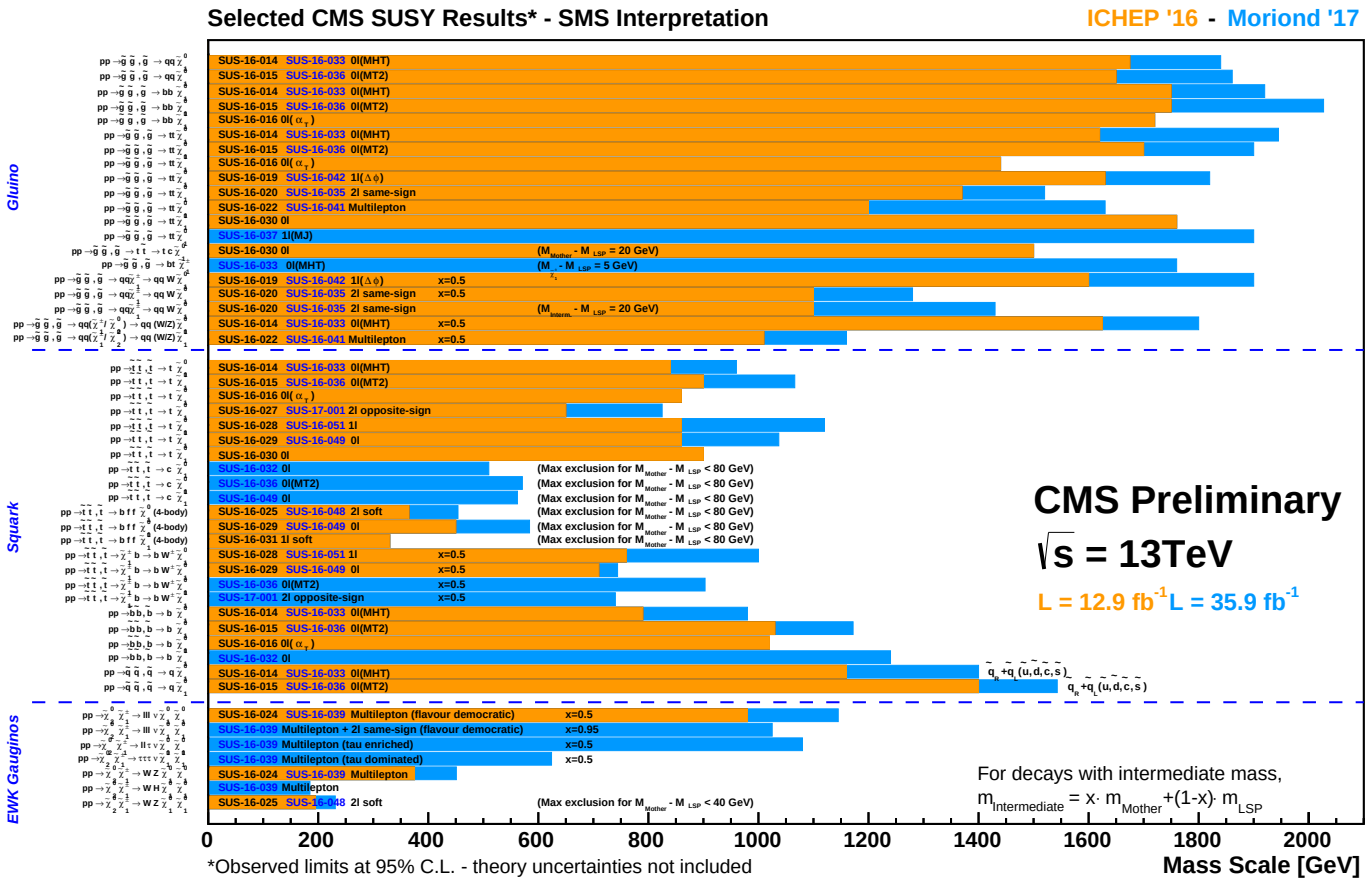
SUSY: What *do* we know ?

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 [illegible] as SUSY.
- In "natural" S[illegible] lectro-weak sector is "co[illegible] of the EW's that are close to [illegible]
- ⇒ most sparticle-decays are via cascades including bosinos/sleptons, and at the end of these cascades, the mass difference is small ⇒ invisible to the LHC !

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.

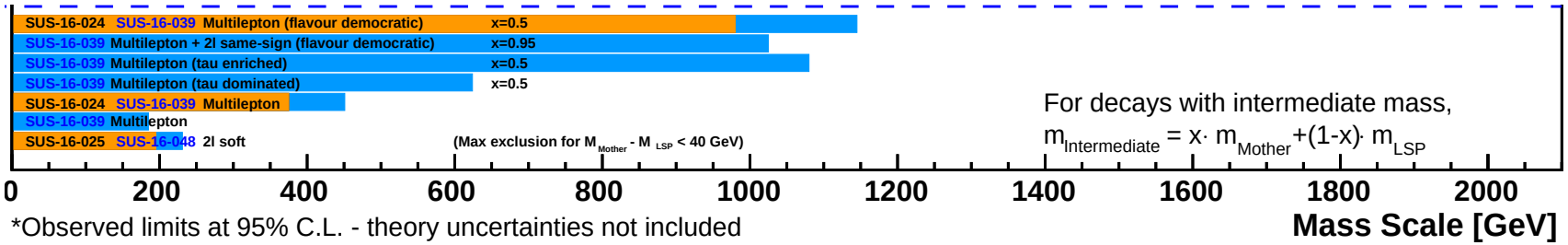
SUSY@LHC: Read the fine-print



*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

SUSY@LHC: Read the fine-print

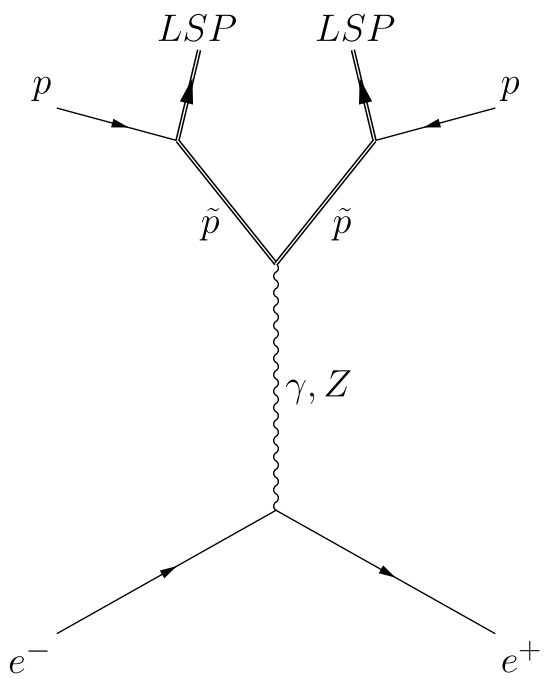


*Observed limits at 95% C.L. - theory uncertainties not included

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

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.

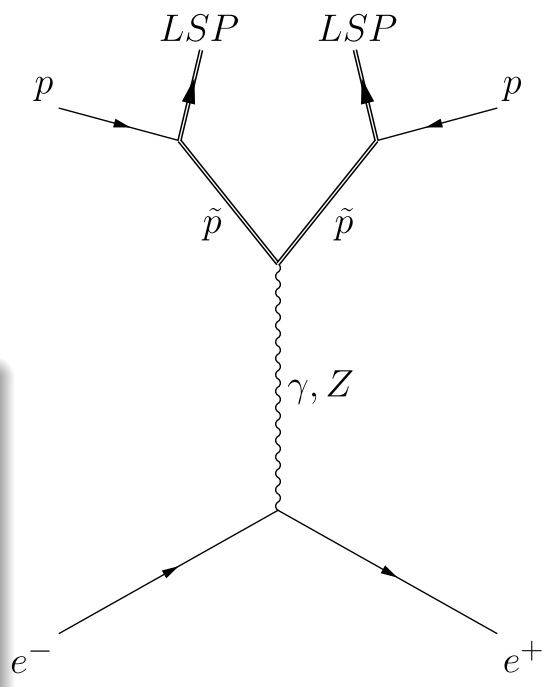


Loop-hole free SUSY searches

- 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.

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 $\leftrightarrow$ “simplified models” @ LHC!

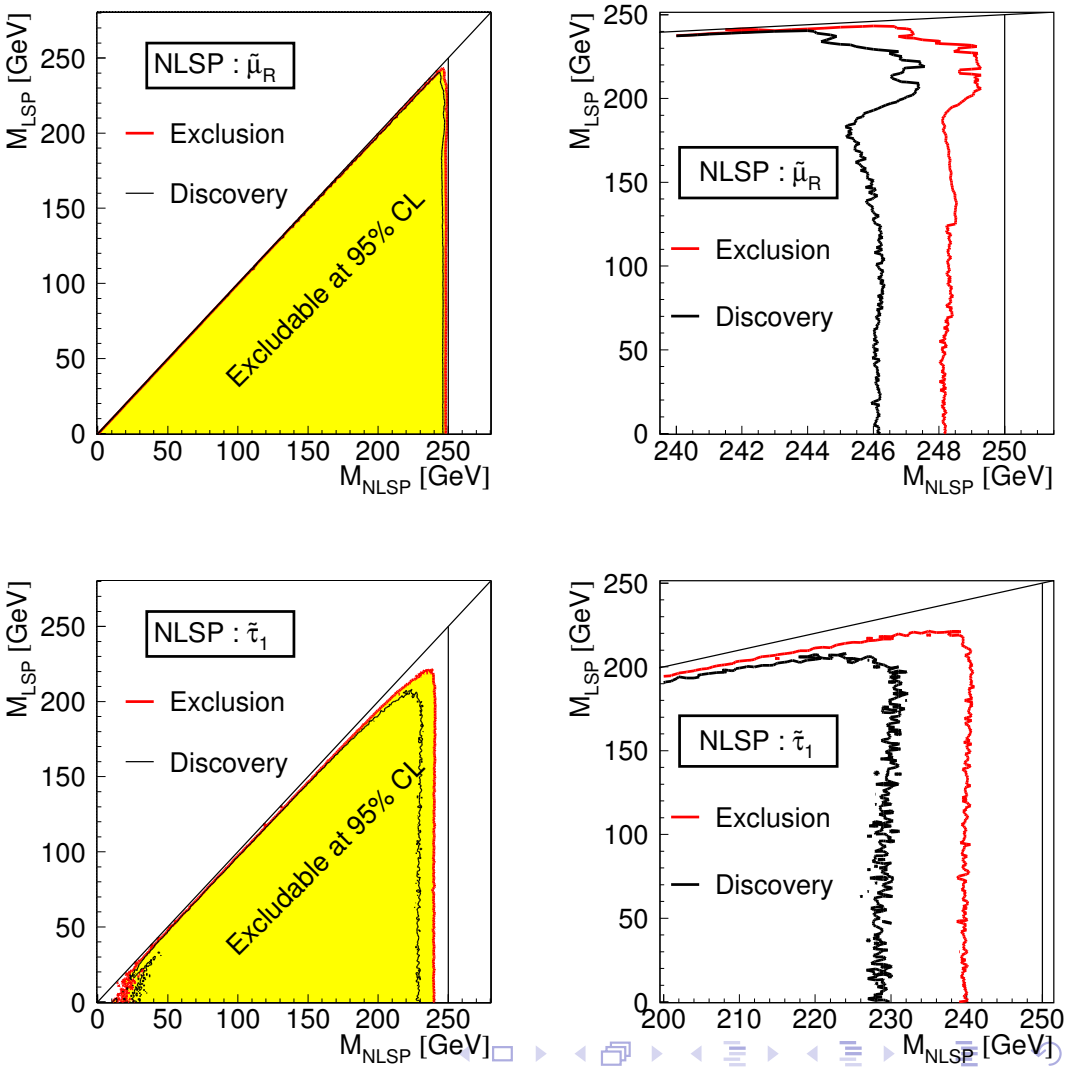


Simplified models

- 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).

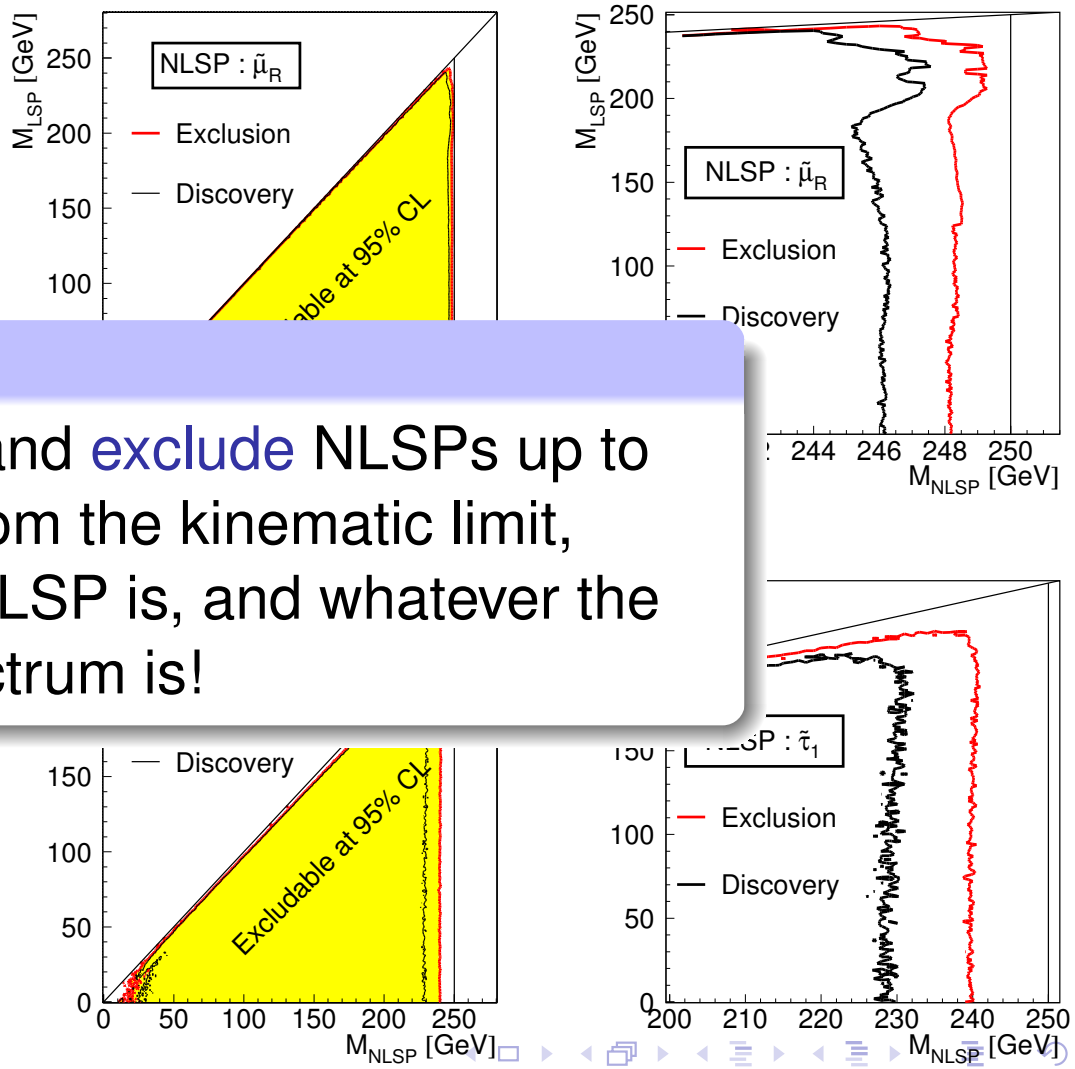
Simplified models

- 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).



Simplified models

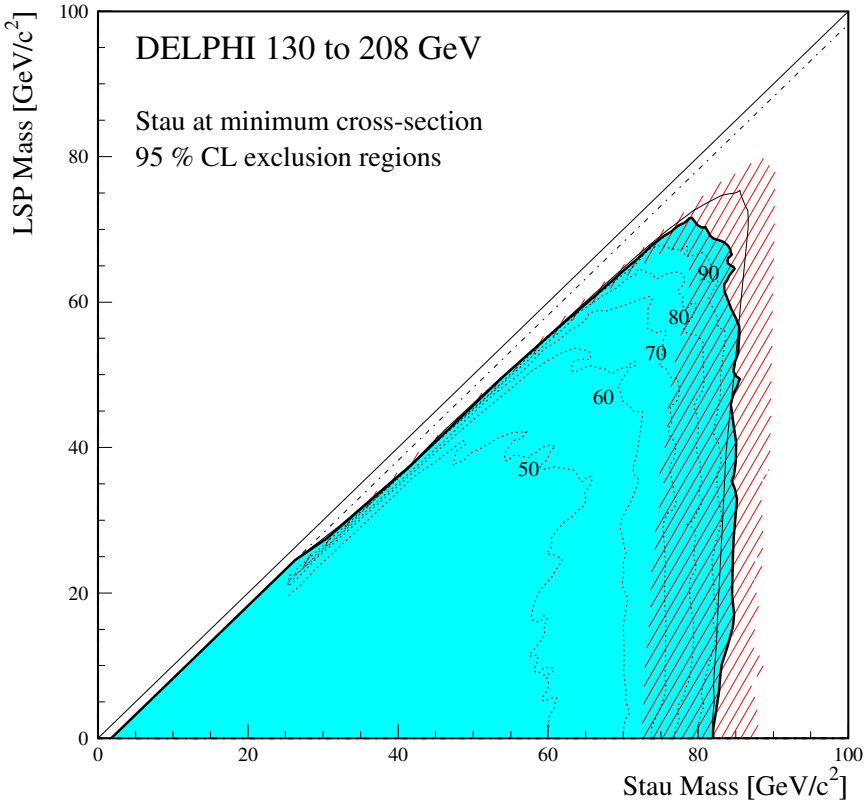
- Simplified methods at hadron and lepton machines are different beasts.
- At lepton machines they are c independ model de
- A few exa arXiv:1308.1461)
  - $\tilde{\mu}_R$ NLS
  - $\tilde{\tau}_1$ NLSP (minimal σ).

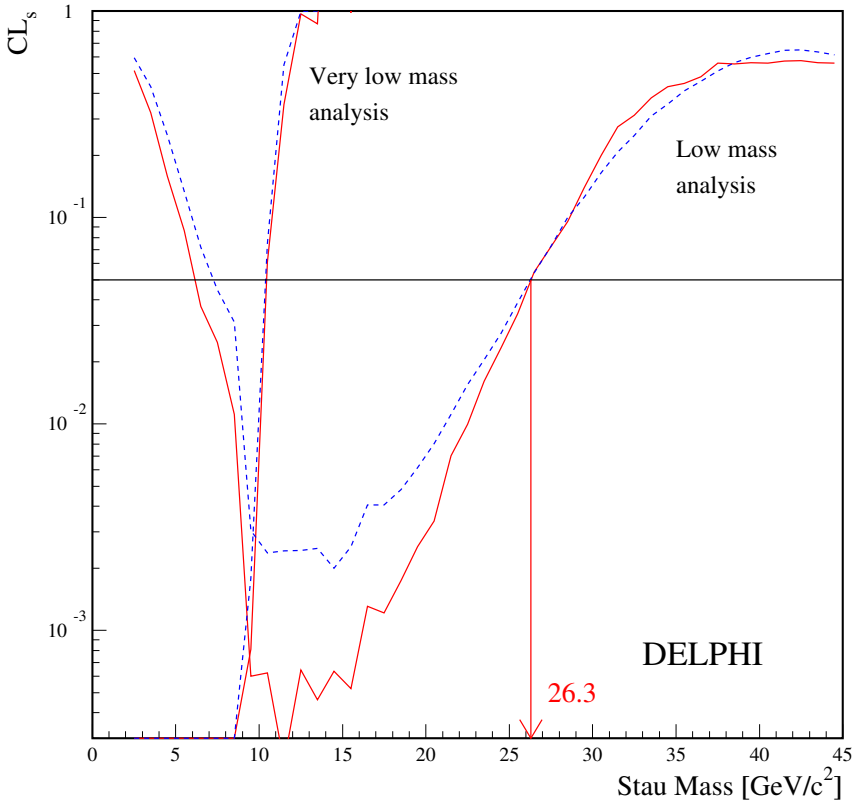


At ILC

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!

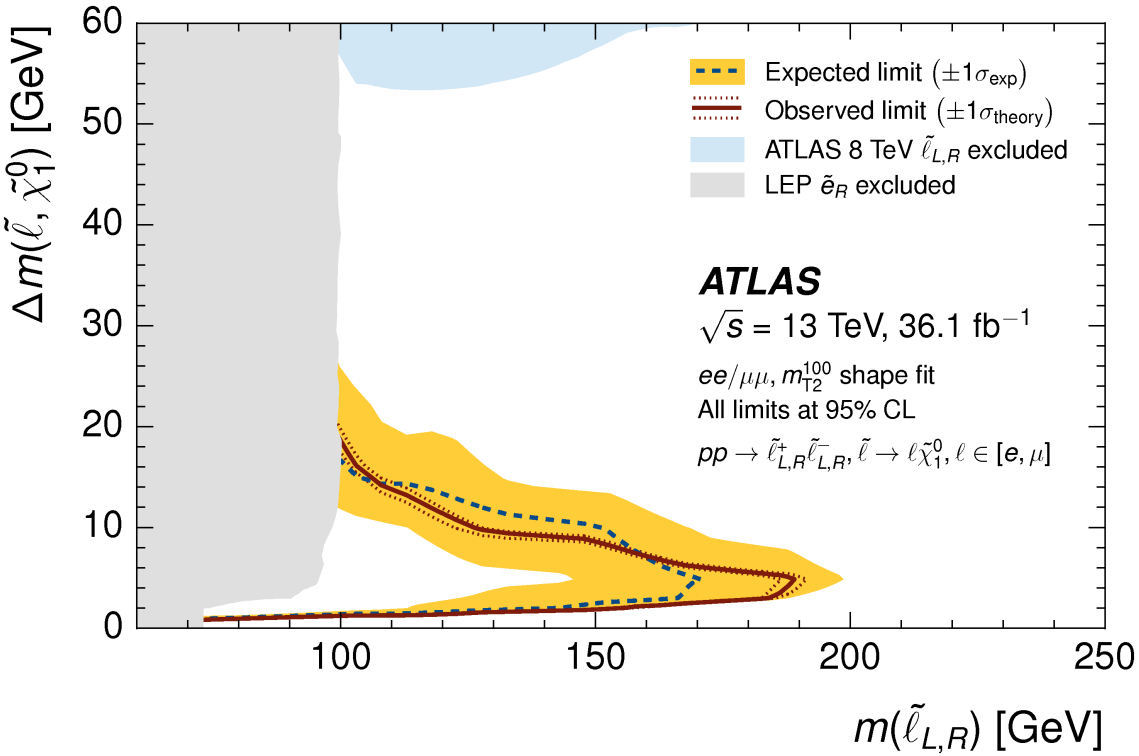
In real life: LEP $\tilde{\tau}$ limits

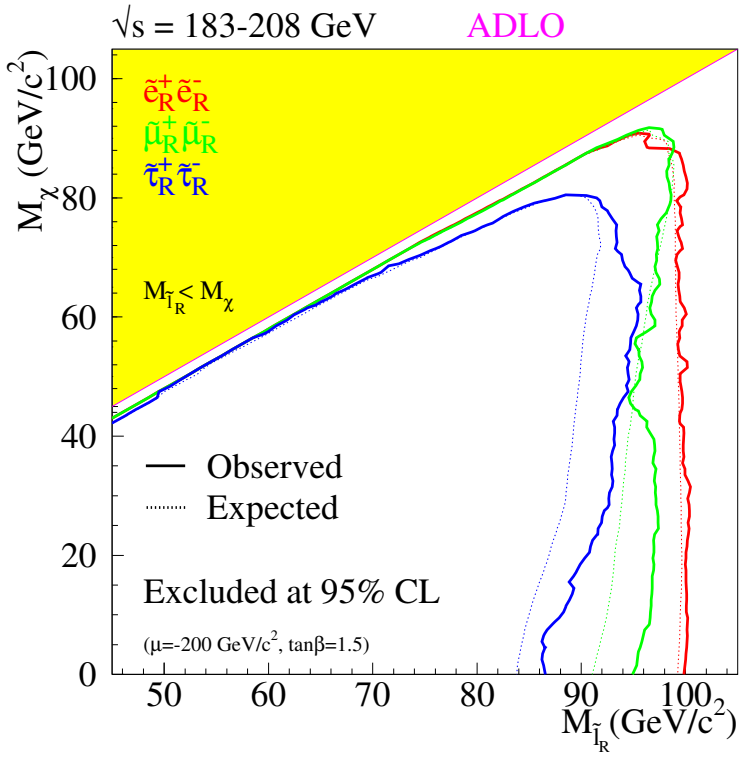




Latest Atlas (13 TeV, 36 fb^{-1}) and LEP on sleptons

arXiv:1803.02762





This is assuming $\tilde{\mu}_L, \tilde{\mu}_R, \tilde{e}_L$ and $\tilde{e}_L$ all have the same mass !!!

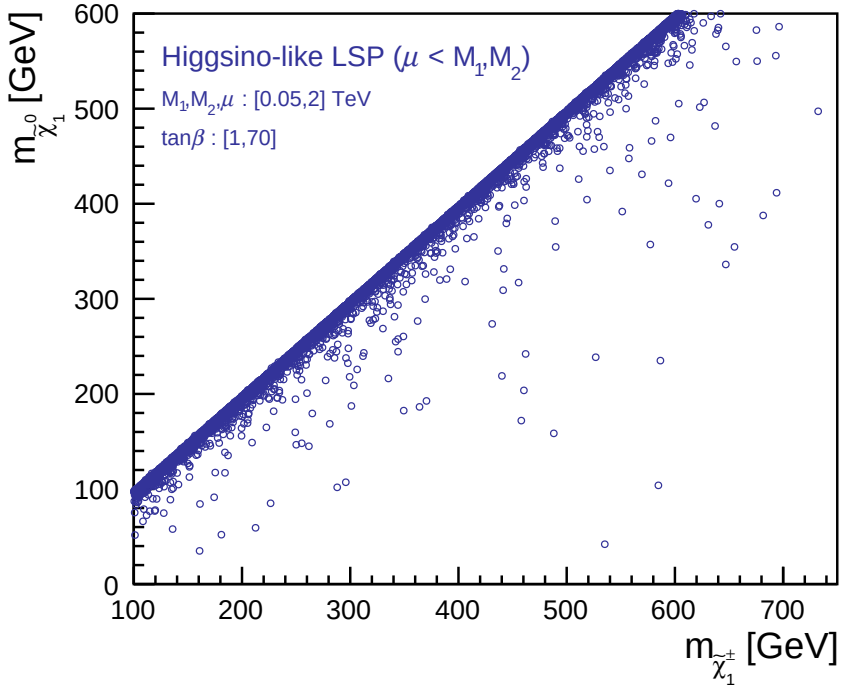
This is $\tilde{e}_R, \tilde{\mu}_R$ and $\tilde{\tau}_R$ *only*, separately!

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 ...

quite generic:
Parameter-scan by T. Tanabe:

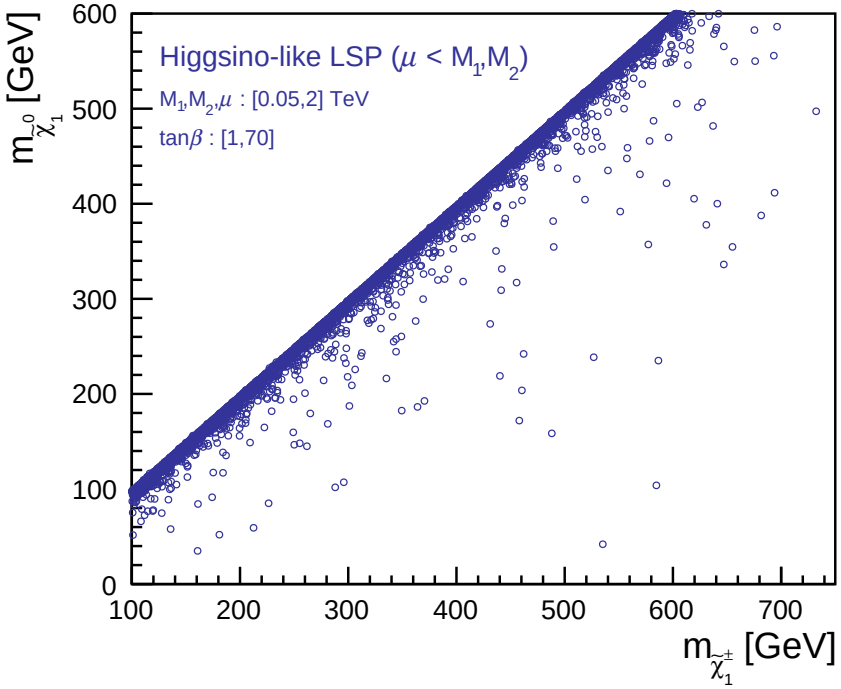


Why compressed spectra ? Natural SUSY: Light, degenerate higgsinos

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 ...

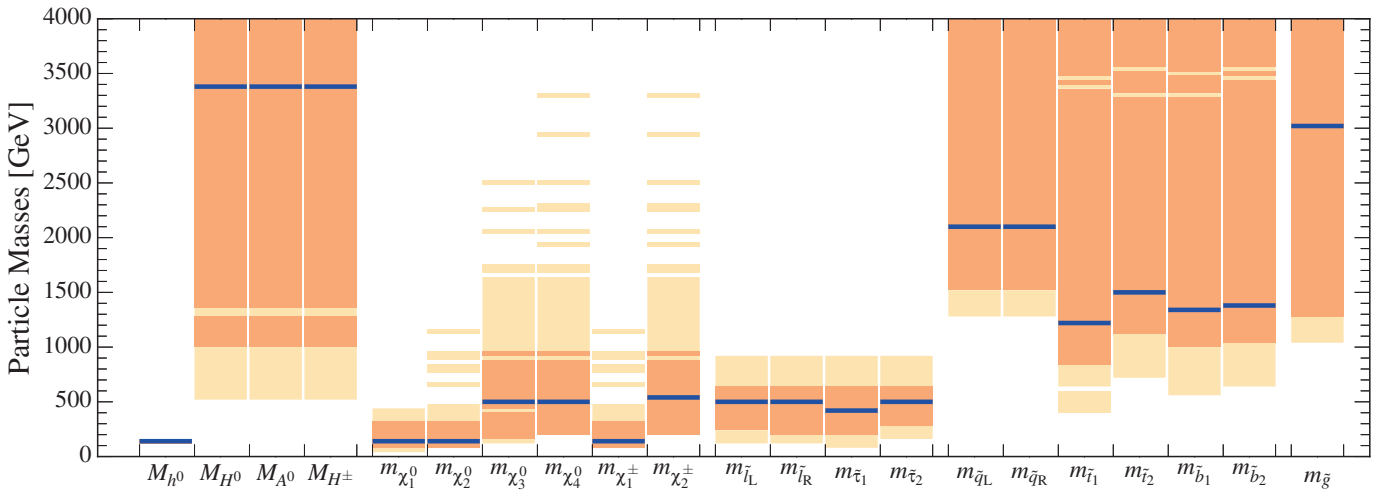
quite generic:
Parameter-scan by T. Tanabe:



Why compressed spectra ? Global fits

pMSSM10 prediction: best-fit masses

[2015]



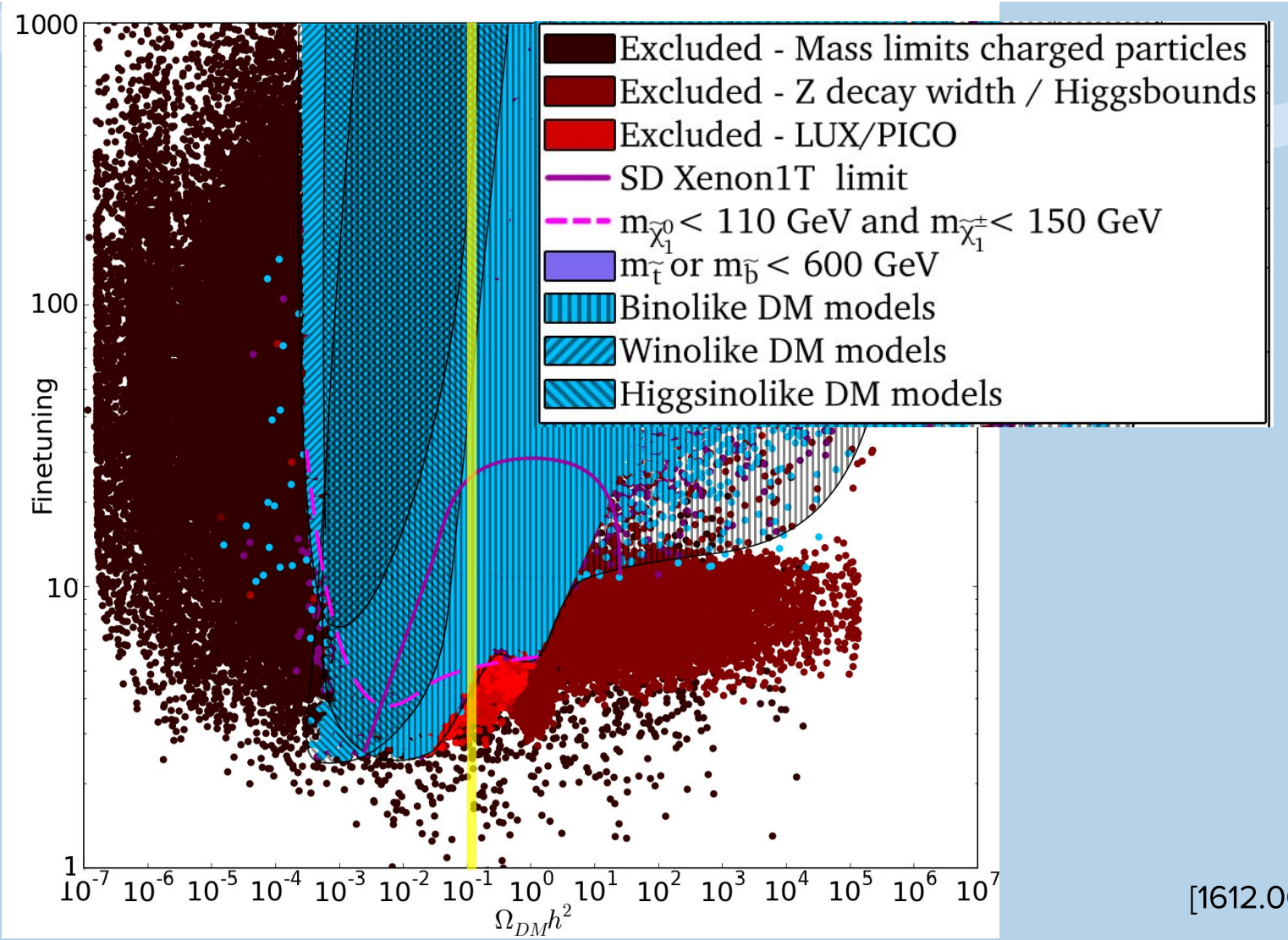
⇒ high colored masses

⇒ relatively low electroweak masses

partially with not too large ranges

⇒ clear prediction for ILC and CLIC

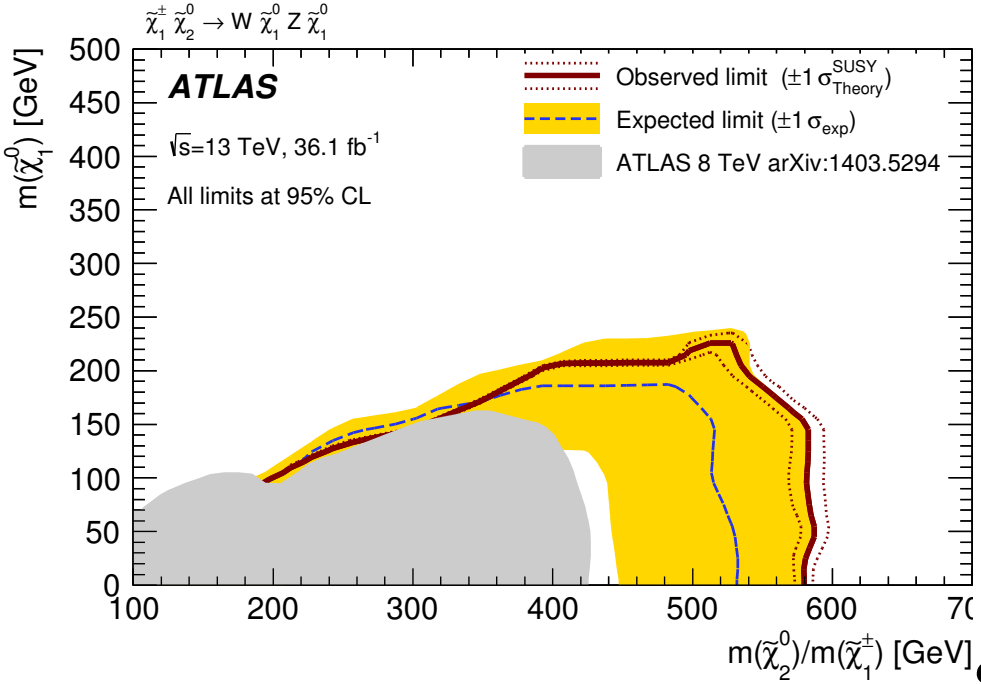
Why compressed spectra ? pMSSM scans



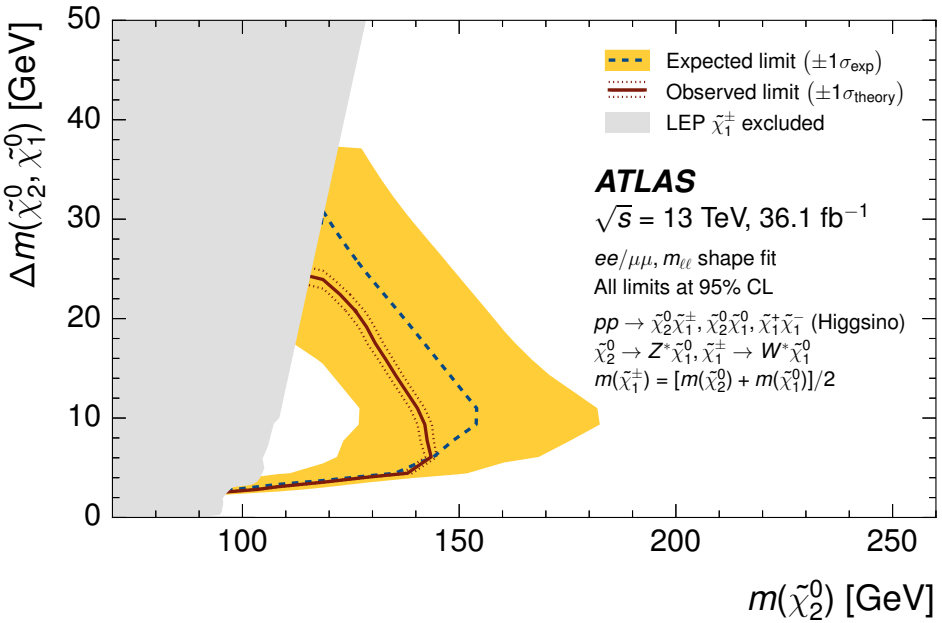
[1612.06333]

Latest Atlas (13 TeV, 36 fb^{-1}) on EWkinos

arXiv:1712.08119



arXiv:1803.02762

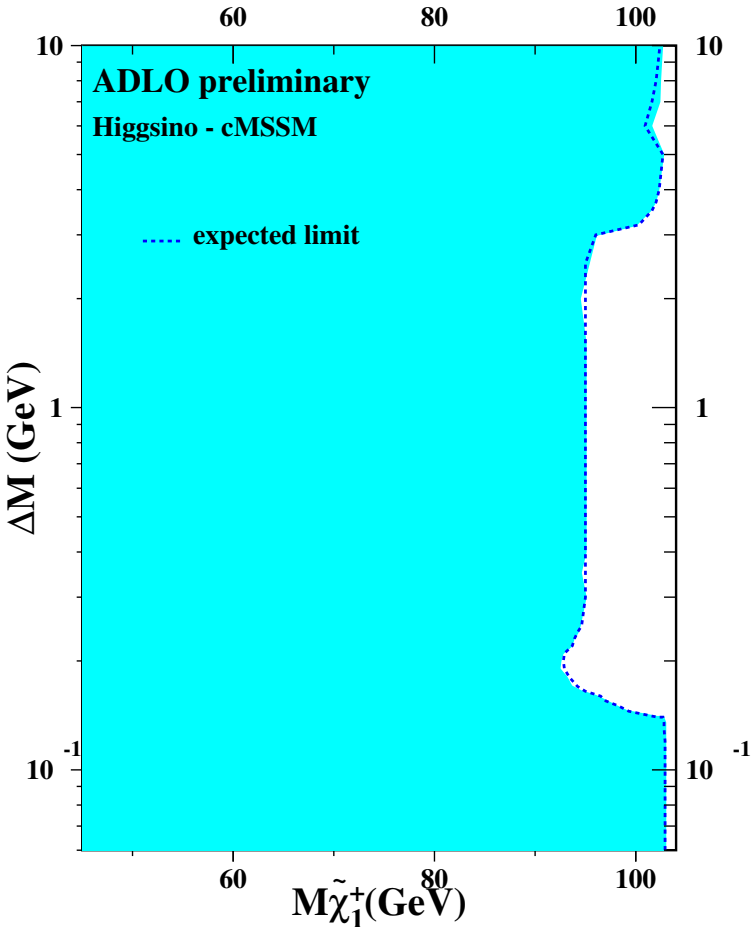


$\sim$ same analysis as shown in talk. Only extends below the $M_{\tilde{\chi}_2^0}$ (or $M_{\tilde{\chi}_1^{\pm}}$) $> 2M_{\tilde{\chi}_2^0}$ line. *No progress in Higgsino region !*

Same channel as in talk. Look at $\Delta(M) \sim 1$ GeV and $M_{\tilde{\chi}_2^0} \sim 160$ GeV. The actual limit is the LEP one. *Wrongly represented !*

Latest Atlas (13 TeV, 36 fb^{-1}) and LEP on EWkinos

This in $\tilde{\chi}_1^{\pm}$!



... and this is $\tilde{\chi}_2^0$. In the higgsino region:

$\Delta(M)(\tilde{\chi}_1^{\pm}) \sim \frac{1}{2}\Delta(M)(\tilde{\chi}_2^0)$