SUSY, BSM and Future Colliders at Snowmass 2021

Mikael Berggren[1]

[1] DESY, Hamburg

ILD general meeting, April, 2023

Outline

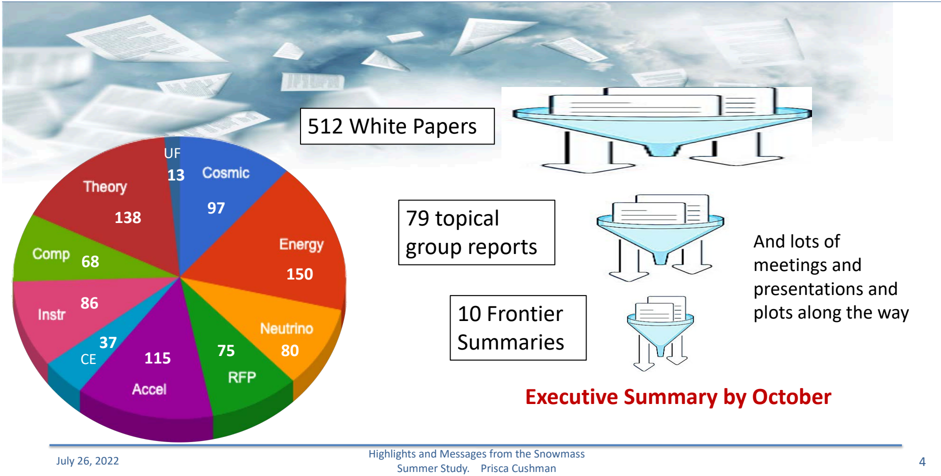
1. Outline
2. Introduction
3. The Energy Frontier at Snowmass
4. Direct BSM at the Energy Frontier at Snowmass
5. Snapshot of the contents of the BSM report
   - SUSY at high energy lepton colliders
     - SUSY with no loop-holes
     - SUSY@lepton colliders: non-Exclusion = Discovery
   - SUSY In The Briefing-book/Snowmass report
   - Z', ALPs, HNL, ...
6. Conclusions

The frontiers at Snowmass

10 Frontiers	80 Topical Groups
Energy	Higgs Boson properties and couplings, Higgs Boson as a portal to new physics, Heavy flavor and top quark physics, EW Precision Phys. & constraining new phys., Precision QCD, Hadronic structure and forward QCD, Heavy Ions, Model specific explorations, More general explorations, Dark Matter at colliders
Neutrino Physics	Neutrino Oscillations, Sterile Neutrinos, Beyond the SM, Neutrinos from Natural Sources, Neutrino Properties, Neutrino Cross Sections, Nuclear Safeguards and Other Applications, Theory of Neutrino Physics, Artificial Neutrino Sources, Neutrino Detectors
Rare Processes	Weak Decays of b and c, Strange and Light Quarks, Fundamental Physics and Small Experiments. Baryon and Lepton Number Violation, Charged Lepton Flavor Violation, Dark Sector at Low Energies, Hadron spectroscopy
Cosmic	Dark Matter: Particle-like, Dark Matter: Wave-like, Dark Matter: Cosmic Probes, Dark Energy & Cosmic Acceleration: The Modern Universe, Dark Energy & Cosmic Acceleration: Cosmic Dawn & Before, Dark Energy & Cosmic Acceleration: Complementarity of Probes and New Facilities
Theory	String theory, quantum gravity, black holes, Effective field theory techniques, CFT and formal QFT, Scattering amplitudes, Lattice gauge theory, Theory techniques for precision physics, Collider phenomenology, BSM model building, Astro-particle physics and cosmology, Quantum information science, Theory of Neutrino Physics
Accelerator	Beam Physics and Accelerator Education, Accelerators for Neutrinos, Accelerators for Electroweak and Higgs Physics, Multi-TeV Colliders, Accelerators for Physics Beyond Colliders & Rare Processes, Advanced Accelerator Concepts, Accelerator Technology R&D: RF, Magnets, Targets/Sources
Instrumentation	Quantum Sensors, Photon Detectors, Solid State Detectors & Tracking, Trigger and DAQ, Micro Pattern Gas Detectors, Calorimetry, Electronics/ASICS, Noble Elements, Cross Cutting and System Integration, Radio Detection
Computational	Experimental Algorithm Parallelization, Theoretical Calculations and Simulation, Machine Learning, Storage and processing resource access (Facility and Infrastructure R&D), End user analysis
Underground Facilities	Underground Facilities for Neutrinos, Underground Facilities for Cosmic Frontier, Underground Detectors
Community Engagement	Applications & Industry, Career Pipeline & Development, Diversity & Inclusion, Physics Education, Public Education & Outreach, Public Policy & Government Engagement
Snowmass Early Career	Snowmass Early Career to represent early career members and promote

7/17/22 Snowmass Greeting, July 17, JB 21

The Snowmass process: Getting there



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- Will touch on the uptake on BSM from ‘our” Frontier
  - The Energy Frontier
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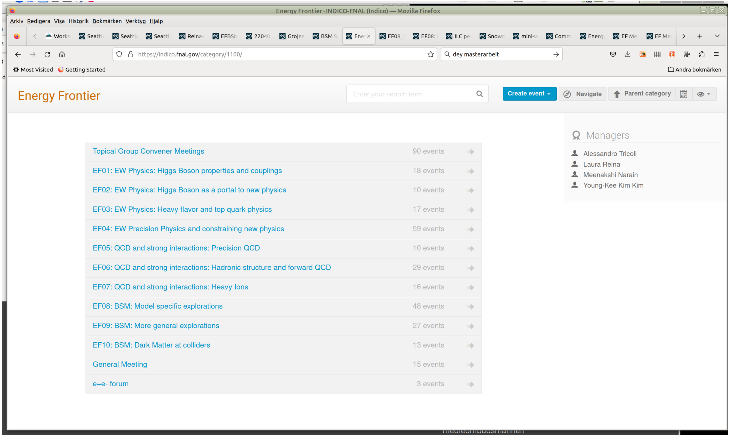
The Energy Frontier at Snowmass

Lots of meetings for $\sim$ two years *before* the final Seattle work-shop



269 open meetings !

Direct BSM at the Energy Frontier at Snowmass

July 2021

- Jul 22 EF08: BSM: Model specific explorations Biweekly Meeting
- Jul 08 EF08: BSM: Model specific explorations Biweekly Meeting

May 2021

- May 14 EF08: BSM: Model specific explorations: Anomalies (g-2, etc) chat

December 2020

- Dec 10 EF08: BSM: Model specific explorations Biweekly Meeting

November 2020

- Nov 12 EF08: BSM: Model specific explorations Biweekly Meeting
- Nov 11 EF08 : Snowmass pMSSM scans
- Nov 04 EF08 : Snowmass pMSSM scans

October 2020

- Oct 29 EF08: BSM: Model specific explorations Biweekly Meeting
- Oct 15 EF08: BSM: Model specific explorations Biweekly Meeting

September 2020

- Sep 17 EF08: BSM: Model specific explorations Biweekly Meeting
- Sep 03 EF08: BSM: Model specific explorations Biweekly Meeting

August 2020

- Aug 06 EF08: BSM: Model specific explorations Biweekly Meeting

June 2020

- Jun 25 EF08: BSM: Model specific explorations Biweekly Meeting
- Jun 11 EF08: BSM: Model specific explorations Biweekly Meeting

May 2020

- May 28 EF08: BSM: Model specific explorations - Kick off meeting with community

15 meetings in EF08 (Direct BSM in specific models - my focus).

Direct BSM at the Energy Frontier at Snowmass

The final report (arXiv:2209.13128)

Cornell University

the Sim

arXiv > hep-ph > arXiv:2209.13128

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High Energy Physics - Phenomenology

[Submitted on 27 Sep 2022 (v1), last revised 18 Oct 2022 (this version, v2)]

Report of the Topical Group on Physics Beyond the Standard Model at Energy Frontier for Snowmass 2021

Tulika Bose, Antonio Boveia, Caterina Doglioni, Simone Pagan Griso, James Hirschauer, Elliot Lipeles, Zhen Liu, Nausheen R. Shah, Lian-Tao Wang, Kaustubh Agashe, Juliette Alimena, Sebastian Baum, Mohamed Berkat, Kevin Black, Gwen Gardner, Tony Gherghetta, Josh Greaves, Maxx Haehn, Phil C. Harris, Robert Harris, Julie Hogan, Suneth Jayawardana, Abraham Kahn, Jan Kalinowski, Simon Knapen, Ian M. Lewis, Meenakshi Narain, Katherine Pachal, Matthew Reece, Laura Reina, Tania Robens, Alessandro Tricoli, Carlos E.M. Wagner, Riley Xu, Felix Yu, Filip Zarnecki, Amin Aboubrahim, Andreas Albert, Michael Albrow, Wolfgang Altmannshofer, Gerard Andonian, Artur Apresyan, Kétévi Adikle Assamagan, Patrizia Azzi, Howard Baer, Michael J. Baker, Avik Banerjee, Vernon Barger, Brian Batell, Martin Bauer, Hugues Beauchesne, Samuel Bein, Alexander Belyaev, Ankit Beniwal, Mikael Berggren, Prudhvi N. Bhattiprolu, Nikita Blinov, Alain Blondel, Oleg Brandt, Giacomo Cacciapaglia, Rodolfo Capdevilla, Marcela Carena, Cesare Cazzaniga, Francesco Giovanni Celiberto, Cari Cesarotti, Sergei V. Chekanov, Hsin-Chia Cheng, Thomas Y. Chen, Yuze Chen, R. Sekhar Chivukula, Matthew Citron, James Cline, Tim Cohen, Jack H. Collins, Eric Corrigan, Nathaniel Craig, Daniel Craik, Andreas Crivellin, David Curtin, Smita Darmora, Arindam Das, Sridhara Dasu, Annapaola de Cosa, Aldo Deandrea, Antonio Delgado, Zeynep Demiragli, David d'Enterria, Frank F. Deppisch, Radovan Dermisek, Nishita Desai, Abhay Deshpande, Jordy de Vries, Jennet Dickinson, Keith R. Dienes, Karri Folan Di Petrillo, Matthew J. Dolan, Peter Dong, Patrick Draper, Marco Drewes, Etienne Dreyer et al. (222 additional authors not shown)

This is the Snowmass2021 Energy Frontier (EF) Beyond the Standard Model (BSM) report. It combines the EF topical group reports of EF08 (Model-specific explorations), EF09 (More general explorations), and EF10 (Dark Matter at Colliders). The report includes a general introduction to BSM motivations and the comparative prospects for proposed future experiments for a broad range of potential BSM models and signatures, including compositeness, SUSY, leptoquarks, more general new bosons and fermions, long-lived particles, dark matter, charged-lepton flavor violation, and anomaly detection.

Comments: 108 pages + 38 pages references and appendix, 37 figures, Report of the Topical Group on Beyond the Standard Model Physics at Energy Frontier for Snowmass 2021. The first nine authors are the Conveners, with Contributions from the other authors

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)

Cite as: arXiv:2209.13128 **[hep-ph]**

(or arXiv:2209.13128v2 **[hep-ph]** for this version)

https://doi.org/10.48550/arXiv.2209.13128

300+ authors, most of whom really did contribute (talks, White papers, discussions): No tourists!

Direct BSM: SUSY

In this talk: Concentrating on

- SUSY:
    - *The* most complete theory of BSM.
    - Most studied model with serious simulation: In most cases, full simulation of ILD, with all SM backgrounds, all beam-induced backgrounds included.
    - Serves as a boiler-plate for BSM: almost any new topology can be obtained in SUSY...
    - Under some stress(?) by LHC. However, in particular ILC offers
        - Complete coverage of Compressed spectra - the most interesting case.
        - Loop-hole free searches.
- + A few slides on non-SUSY BSMs...

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Studied projects (For all of EF, not only BSM)

Higgs-boson factories (up to 1 TeV c.o.m. energy)

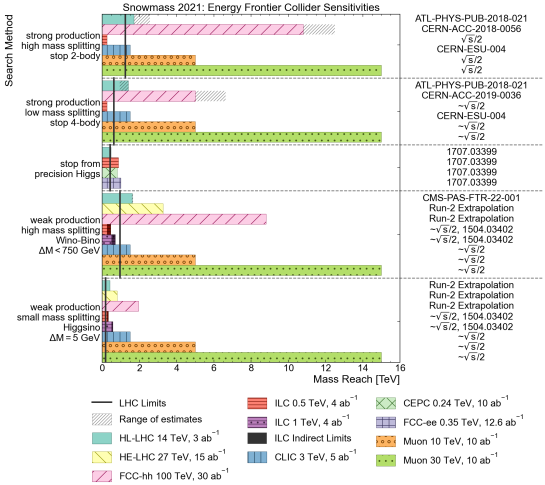
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2	2028	2038
		350 GeV	$\pm80/\pm30$	0.2		
		500 GeV	$\pm80/\pm30$	4		
		1 TeV	$\pm80/\pm20$	8		
CLIC	ee	380 GeV	$\pm80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2\ M_{top}$		0.8		
μ-collider	$\mu\mu$	125 GeV		0.02		

Multi-TeV colliders (> 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm80/0$	2.5	2052	2058
		3.0 TeV	$\pm80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

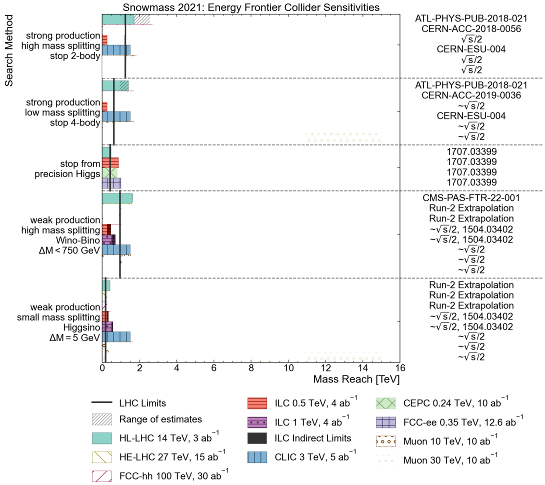
SUSY in the Energy Frontier report

SUSY summary plot in the EF report



SUSY in the Energy Frontier report

SUSY summary plot in the EF report ... before 2050



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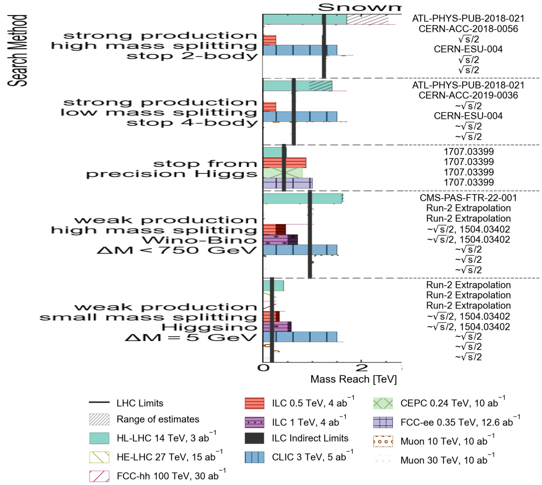
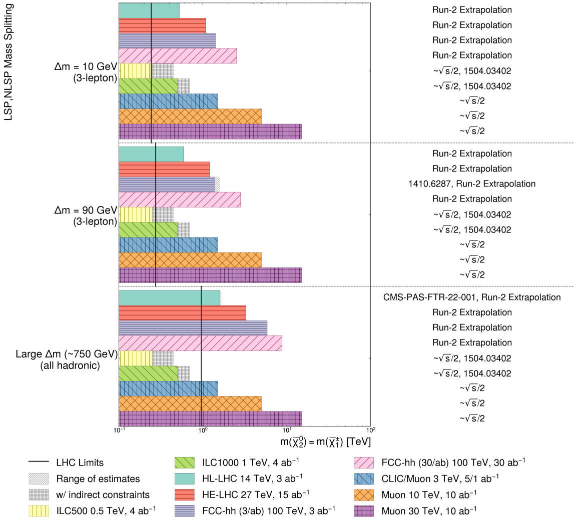


Details from the BSM topical group report: Winos



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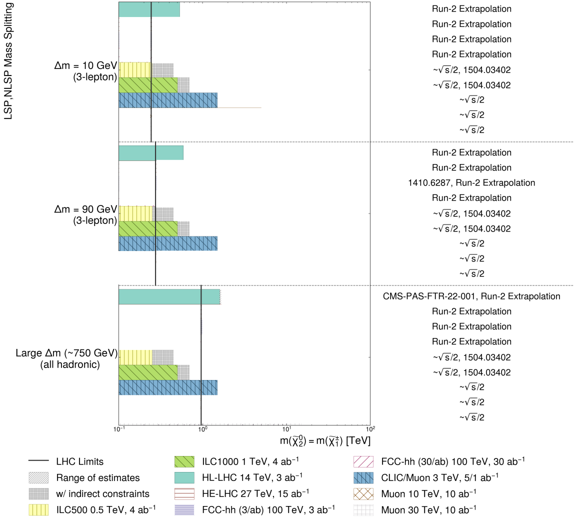

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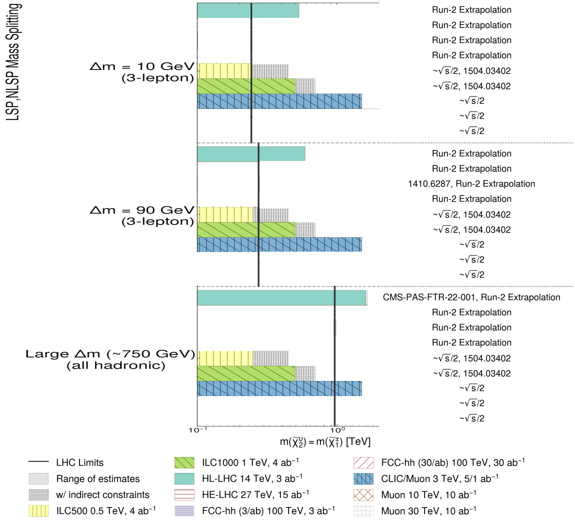
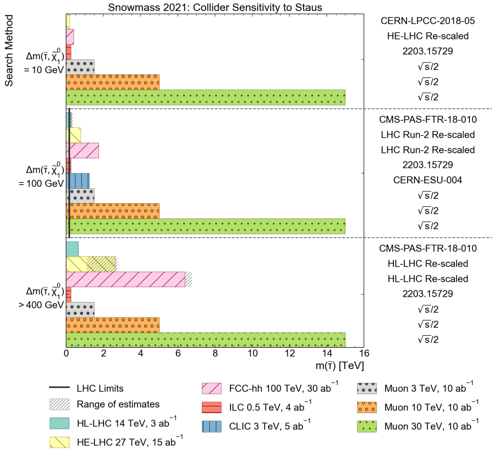


Details from the BSM topical group report: $\tilde{\tau}$:s



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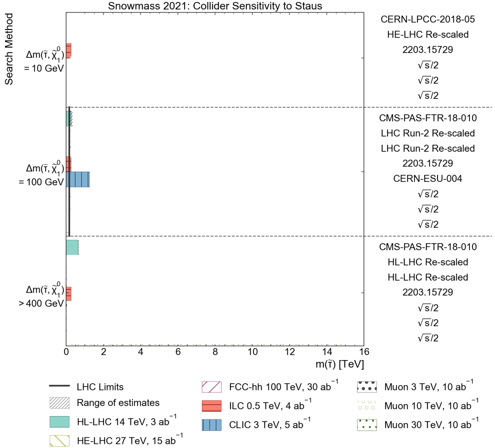

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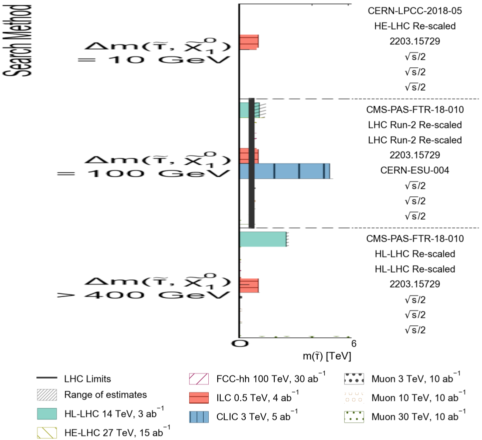
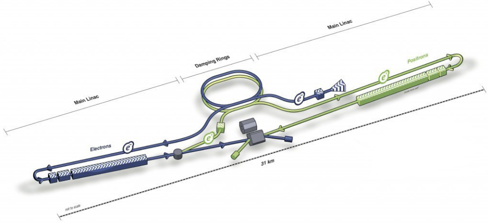


SUSY at high energy lepton colliders - ILC as an example (but relevant for C^3, HELEN, CLIC, ...)

- e^+e^- collider with E_{CMS} = 250 - 500 (- 1000++) GeV, and polarised beams
- e^+e^- means EW-production ⇒ Low background.
  - Detectors w/ $\sim 4\pi$ coverage.
  - Rad. hardness not needed: only few % X_0 in front of calorimeters.
  - No trigger
- e^+e^- means colliding point-like objects ⇒ initial state known
- 22 year running → 2 ab^{-1} @ 250 GeV + 4 ab^{-1} @ 500 GeV.
- Construction under political consideration in Japan.



SUSY: What *do* we know ? And why does that give lepton colliders an edge ?

Naturalness, hierarchy, DM, g-2 all prefer light electroweak sector.

- Except for 3rd gen. squarks, the coloured sector doesn't enter the game.
- Many models and the global set of constraints from observation points to a compressed spectrum.
- So, most sparticle-decays are via cascades, with small $\Delta(M)$ at the end.
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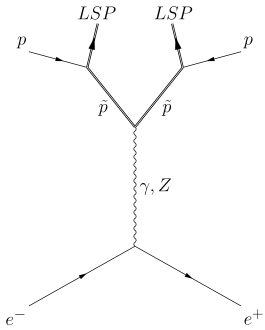
SUSY@lepton colliders: Loop-hole free searches

- 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, and it must have 100 % BR to it’s SM-partner and the LSP.



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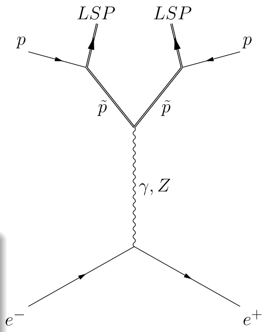

So, at ILC :

- Model independent exclusion/ discovery reach in $M_{NLSP} - M_{LSP}$ plane.
- Repeat for all NLSP:s.
- Cover entire parameter-space in a few plots
- No fine-print!

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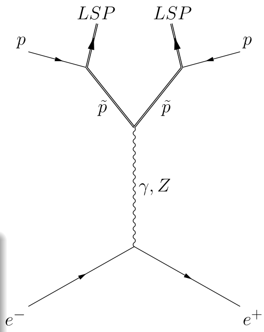

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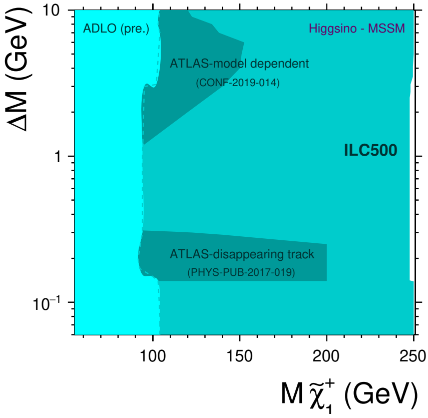
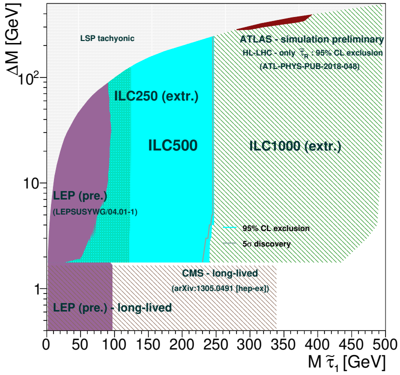
ILC projection for Higgsino or $\tilde{\tau}$ NLSP

From arXiv:2002.01239





From arXiv:2105.08616

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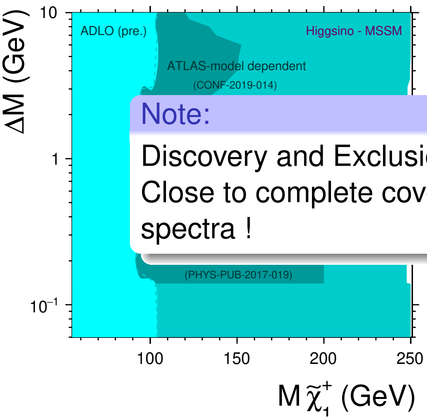
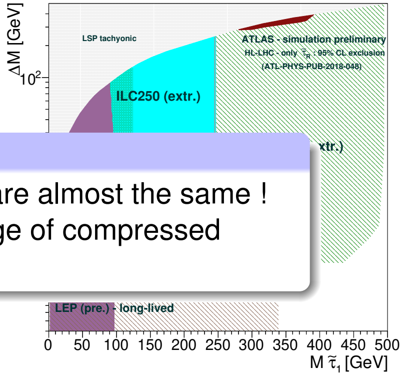


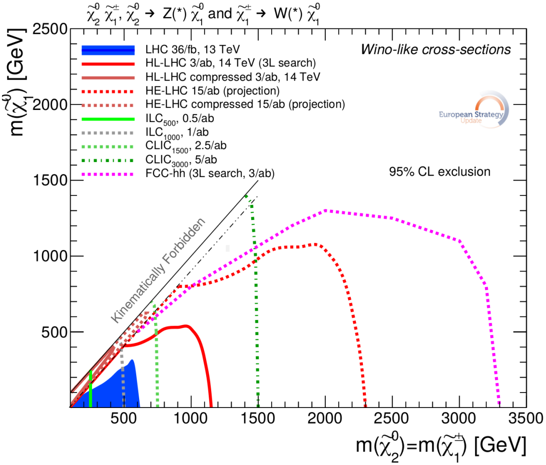


Note:

Discovery and Exclusion are almost the same !
Close to complete coverage of compressed spectra !

From arXiv:2105.08616

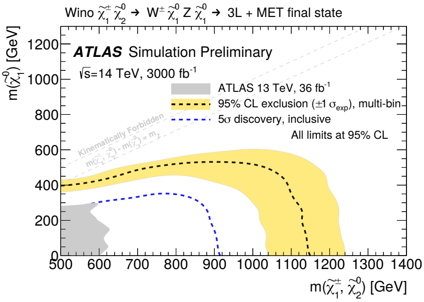
SUSY In The Briefing-book (≈ Snowmass) : Bino LSP (ie. large Δ_M)



(This is refered to, and not updated @ Snowmass)

SUSY In The Briefing-book: Bino LSP - Sources

- From PHYS-PUB-2018-04 (ATLAS HL-LHC projection). Then extrapolated (up *and* *down*)
- Note that the BB curve is exclusion, not discovery!
- This is for the best decay mode!
- The other decay mode
- Better at M_{LSP}=0, weaker at lower Δ_M.



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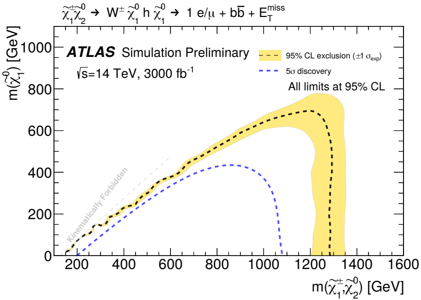
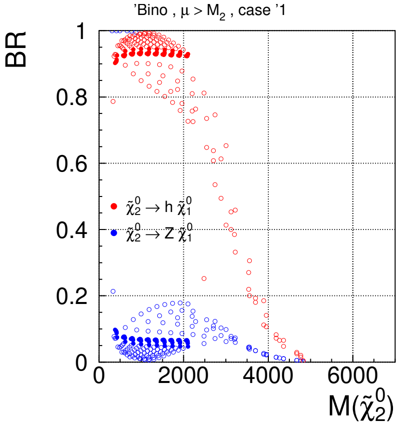


Bino LSP: BRs

Why is the decay-mode an issue? Here's why :

- Vary relative signs of μ, M_1, and M_2, for $\mu > M_2$
- Conclusion: Whether the Z or the H decay-mode of $\tilde{\chi}^0_2$ dominates is pure speculation and
- The exclusion-region is the *intersection* of the two plots, not the *union*!



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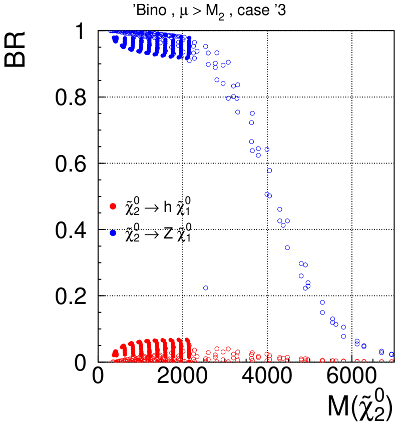

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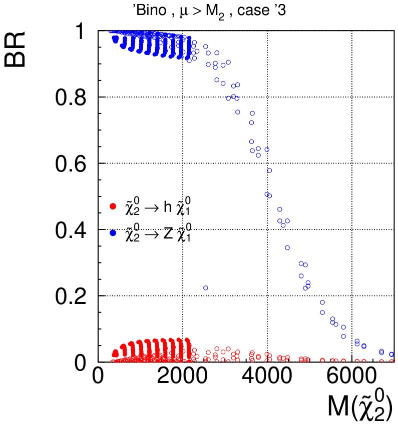

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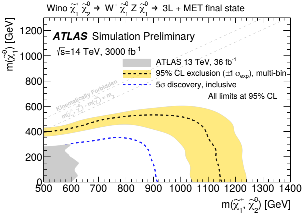
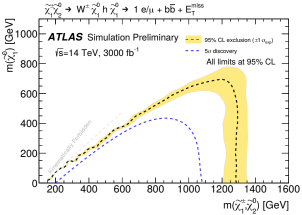
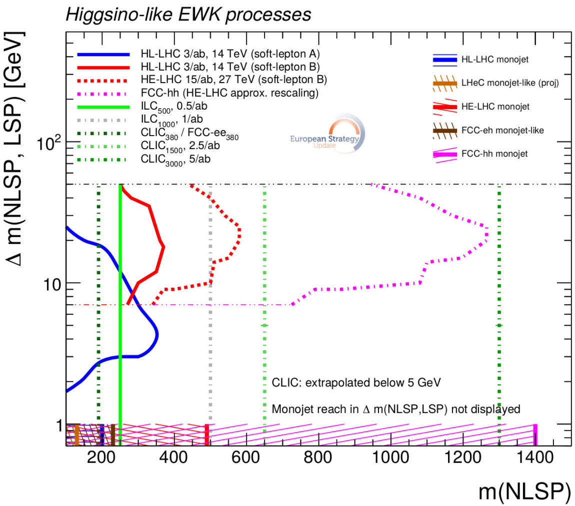




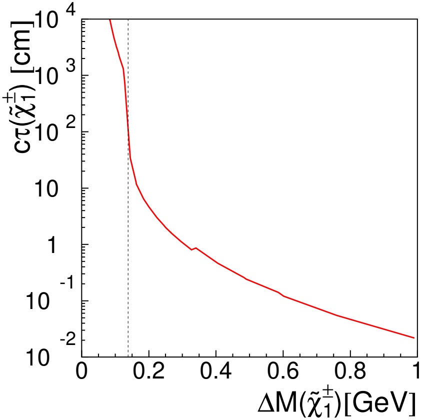
SUSY In The Briefing-book: Wino/Higgsino LSP



(This, too, is refered to, but also gets an update @ Snowmass)

Key element for “Disappearing tracks”: $\Delta(M)$

- $c\tau$ vs. $\Delta(M)$ for charginos. Note where 1 cm is...
- Higgsino LSP. The line is the absolute limit mentioned in the BB.
- Let other parameters vary, any signs, M_1 and M_2 close to μ .... Note that the LSP often would be the $\tilde{\chi}_1^{\pm}$!
- Reason: 1703.09675 considers *only SM* effects on the mass-splitting, ie. that M_1 and $M_2 >> \mu$
- Same for Wino LSP.



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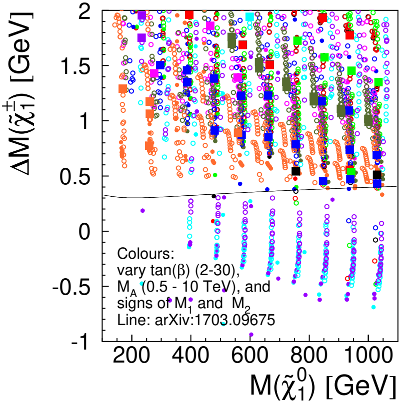

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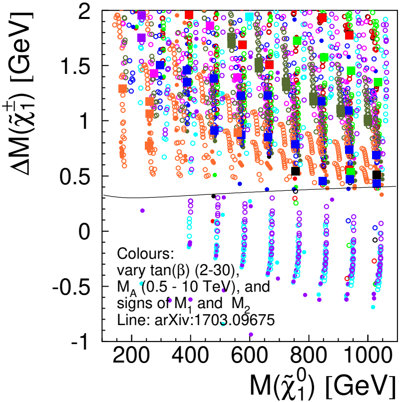

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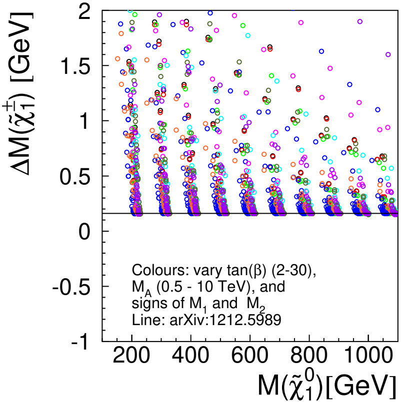
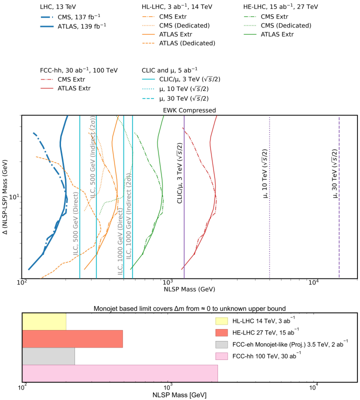
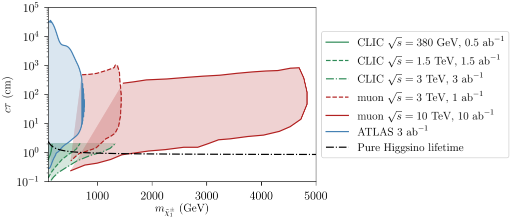


Wino/Higgsino LSP: Snowmass update

Leptons and Mono-X

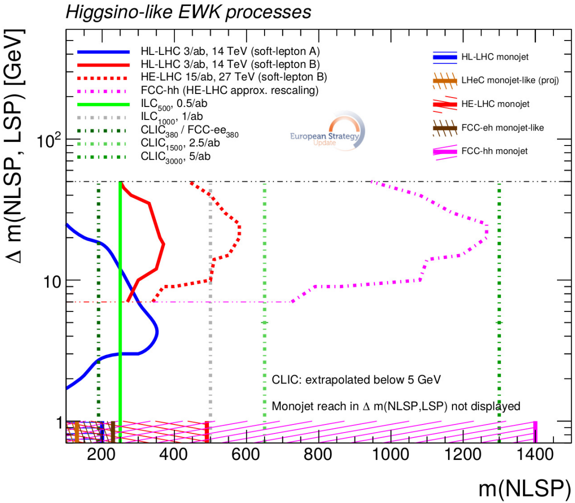


Disapearing tracks



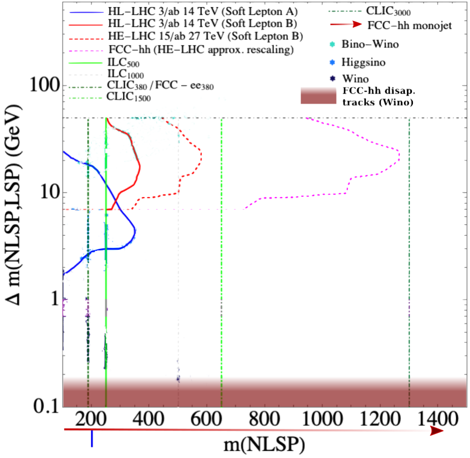
NB. Irrelevant for lepton colliders - The standard search gives stronger limits.

SUSY In The Briefing-book: Wino/Higgsino LSP



So: Disappearing tracks exclusion is actually off the scale !

SUSY In The Briefing-book: Re-boot



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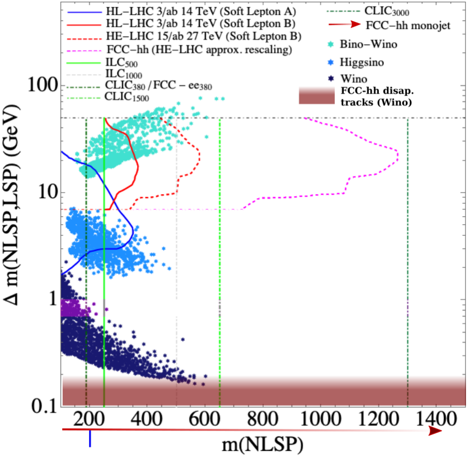
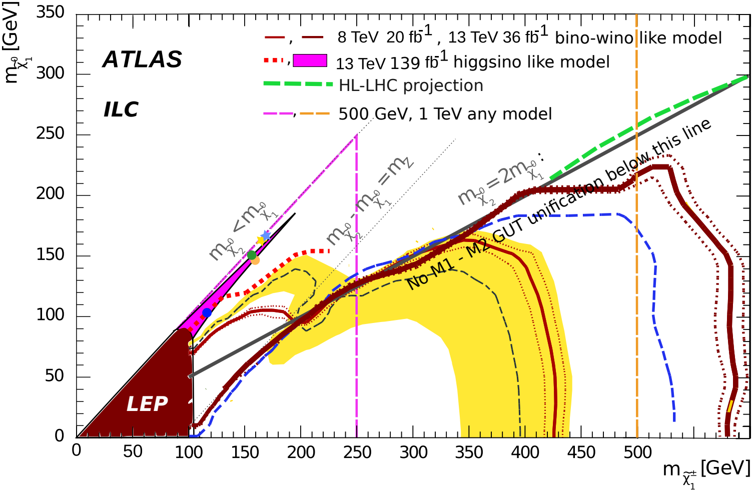


With models that are consitent with g-2 and no over-production of DM
From `arXiv:2103.13403`.

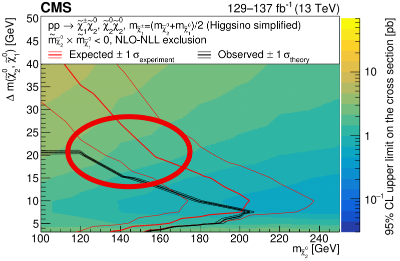
SUSY bosinos - All-in-one

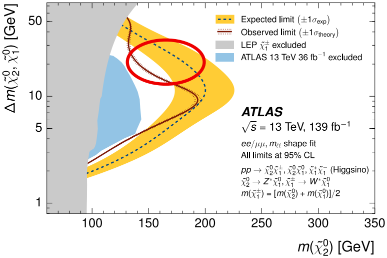


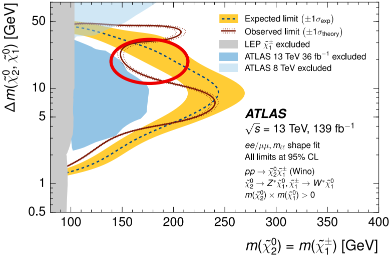
ATLAS Eur Phys J C 78,995 (2018), Phys Rev D 101,052002 (2020), arXix:2106.01676;

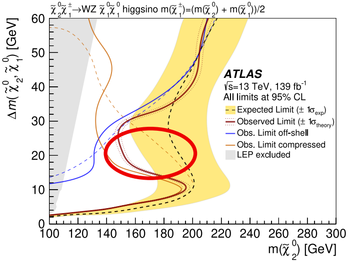
ATLAS HL-LHC ATL-PHYS-PUB-2018-048; ILC arXiv:2002.01239; LEP LEP LEPSUSYWG/02-04.1

LHC Run 3 teaser: Maybe...

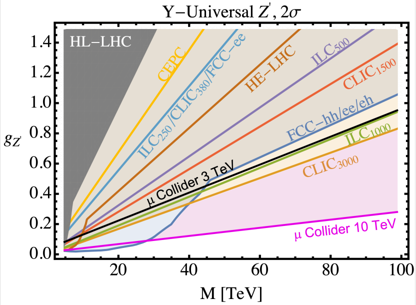








Z′, ALPs, HNL, ...

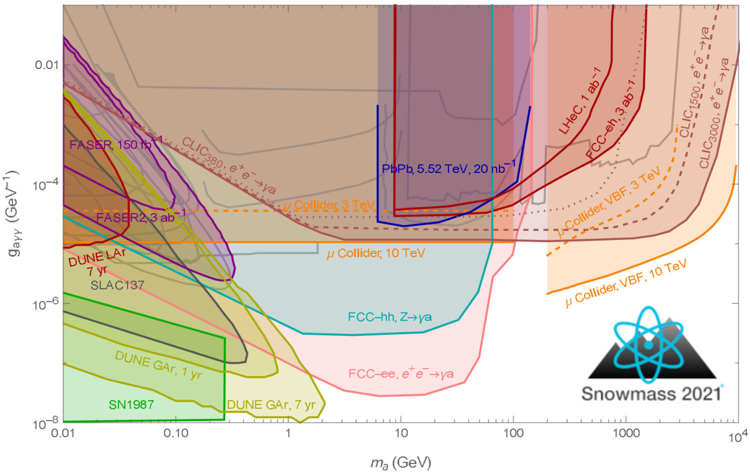


Machine	Type	√s (TeV)	∫L dt (ab⁻¹)	Source	Z′ Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \to$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \to l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \to l^+ l^-$	6.3	6.8
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	6
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \to f^+ f^-$	4.9	7.7
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	7
HE-LHC/ FNAL-SF	p p	27	15	EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	11
				ATLAS	$Z'_{SSM} \to e^+ e^-$	12.8	12.8
ILC	$e^+ e^-$	0.5	4	ILC	$Z'_{SSM} \to f^+ f^-$	8.3	13
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	13
CLIC	$e^+ e^-$	1.5	2.5	EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	19
Muon Collider	$\mu^+ \mu^-$	3	1	IMCC	$Z'_{Univ}(g_{Z'}=0.2)$	10	20
ILC	$e^+ e^-$	1	8	ILC	$Z'_{SSM} \to f^+ f^-$	14	22
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	21
CLIC	$e^+ e^-$	3	5	EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	24
FCC-hh	p p	100	30	R.H.	$Z'_{SSM} \to$ dijet	25	32
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	35
				EPPSU	$Z'_{SSM} \to l^+ l^-$	43	43
Muon Collider	$\mu^+ \mu^-$	10	10	IMCC	$Z'_{Univ}(g_{Z'}=0.2)$	42	70
VLHC	p p	300	100	R.H.	$Z'_{SSM} \to$ dijet	67	87
Coll. In the Sea	p p	500	100	R.H.	$Z'_{SSM} \to$ dijet	96	130

Increasing Z′ Sensitivity

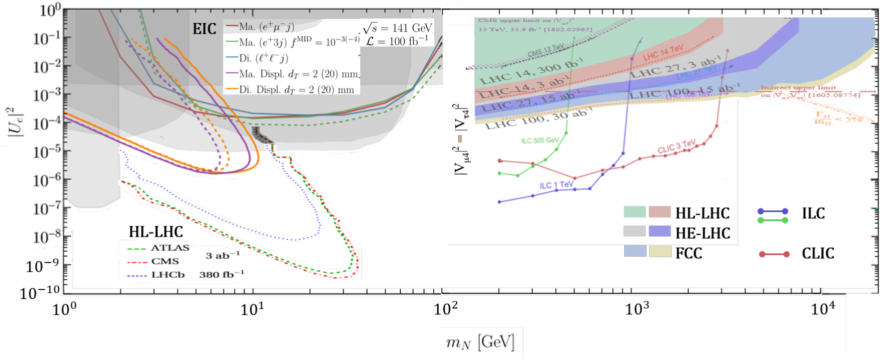
Already the Higgs factories are expected to go beyond the HL-LHC reach....

Z′, ALPs, HNL, ...



0.01
10^{-4}
10^{-6}
10^{-8}
$g_{a\gamma\gamma}$ (GeV^{-1})
0.01
0.10
1
10
100
1000
10^4
m_a (GeV)
FASER, 150 fb^{-1}
CLIC$_{380}$, $e^+e^- \to \gamma a$
FASER2, 3 ab^{-1}
DUNE LAr 7 yr
SLAC137
DUNE GAr, 1 yr
SN1987
DUNE GAr, 7 yr
μ Collider, 3 TeV
μ Collider, 10 TeV
PbPb, 5.52 TeV, 20 nb^{-1}
FCC–hh, $Z \to \gamma a$
FCC–ee, $e^+e^- \to \gamma a$
LHeC, 1 ab^{-1}
FCC–eh, 3 ab^{-1}
CLIC$_{1500}$, $e^+e^- \to \gamma a$
CLIC$_{3000}$, $e^+e^- \to \gamma a$
μ Collider, VBF, 3 TeV
μ Collider, VBF, 10 TeV
Snowmass 2021

Z', ALPs, HNL, ...


EIC
Ma. ($e^+\mu^-j$)
Ma. (e^+3j) $f^{\rm MID} = 10^{-3(-4)}$
Di. ($\ell^+\ell^-j$)
Ma. Displ. $d_T = 2$ (20) mm
Di. Displ. $d_T = 2$ (20) mm
$\sqrt{s} = 141$ GeV
$\mathcal{L} = 100$ fb^{-1}
HL-LHC
ATLAS
CMS
LHCb
3 ab^{-1}
380 fb^{-1}
$|U_e|^2$
$|V_{\mu 4}|^2 = |V_{\tau 4}|^2$
LHC 14, 300 fb^{-1}
LHC 14, 3 ab^{-1}
LHC 27, 15 ab^{-1}
LHC 100, 30 ab^{-1}
LHC 27, 3 ab^{-1}
LHC 100, 15 ab^{-1}
LHC 14 TeV
ILC 500 GeV
ILC 1 TeV
CLIC 3 TeV
HL-LHC
HE-LHC
FCC
ILC
CLIC
m_N [GeV]

The Energy Frontier: in 5-10-15 years

EF Resources and Timelines

➢ Five year period starting in 2025

- Prioritize *HL-LHC physics program,* including auxiliary experiments
- Establish a targeted *e+e- Higgs Factory detector R&D* for US participation in a global collider
- Develop an *initial design for a first stage TeV-scale Muon Coll.* in the US (pre-CDR)
- Support critical *detector R&D towards EF multi-TeV colliders*

➢ Five year period starting in 2030

- Continue strong support for *HL-LHC program*
- Support and advance *construction of an e+e- Higgs Factory*
- Demonstrate principal risk mitigation and deliver *CDR for a first-stage TeV-scale Muon Coll.*

➢ After 2035

- Support continuing *HL-LHC physics program* to the conclusion of archival measurements
- Begin and support the *physics program of the Higgs Factories*
- Demonstrate readiness to construct and deliver *TDR for a first-stage TeV-scale Muon Coll.*
- Ramp up funding support for *detector R&D for EF multi-TeV colliders*

18

Impressions from Seattle

- Very intense 10 days - with no day off.
- Great organisation:
  - Mornings with Frontier/topical group parallels (Meaning that I was almost only following EF-BSM parallels)
  - Afternoons with plenaries - each frontier got its, non-shared, plenary.
  - Also specific cross-frontier parallels eg. Energy/Accelerator
- 735 on-site participants (+654 remote). All having a 2 hour lunch on University Street, just off-campus ⇒ lots of opportunities for off-the-record cross-frontier discussions.
- About 35 Europeans, 10 Japanese on-site.
- Lab directors (US of course, but also CERN, KEK, IHEP, Triumf) , APS, ICFA, STFC and IDT chairs present ....

Impressions from Seattle

- The Americans didn't "make the Wave" about FCC - more noted with interest the activities in Europe.
- Fabiola's sobering presentation on the FCC time-line probably contributed to that.
- Surprises :
  - US wants to get back with a domestic Energy Frontier facility.
  - ILC in US on the table !
  - Great revival of the interest in the muon collider.
  - Little mention of Plasma Wakefields, at least outside the AF ...
  - And: The closest to a mention of the war in Ukraine in any talk was a mention of current "supply-chain difficulties" in the DoE talk - quite a stark contrast to ICHEP the week before !

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What now?

- The P5 is working. Inform yourself on
  - The (beutifully old-school) P5 Web page
- Note: Beate Heinemann (DESY-FH director) and Shoji Asai (ILC-Japan spokesperson) among the four non-US members of P5. And Hitoshi Murayama is P5 Chair.
- Join the P5 town-hall meeting next week. It is the one devoted to the Energy Frontier.
  - P5 Town Hall Meeting at BNL
- P5 is asked to deliver its report to HEPAP (High Energy Physics Advisory Panel (a goverment panel)) by end of summer.
- P5 has a broad mandate but tends to focus on large projects and facilities, and presents the priorities given several funding scenaria.
- The P5 report is written under interactions with the Department Of Energy (DoE), and is finally delivered to them by HEPAP.
- The actual decision is made by congress...

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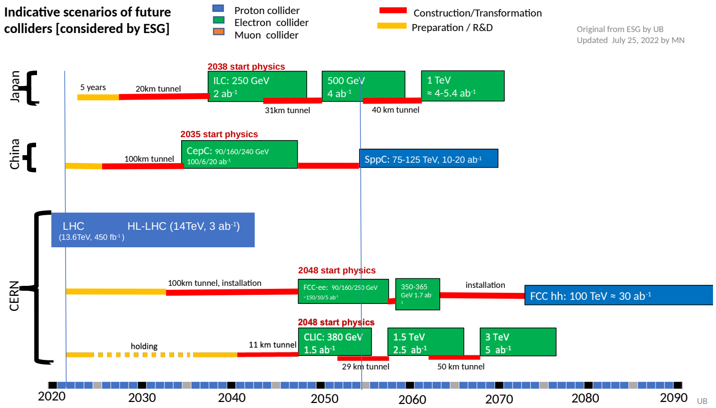
That's all Folks!

Backup

BACKUP SLIDES

The Energy Frontier: Timelines



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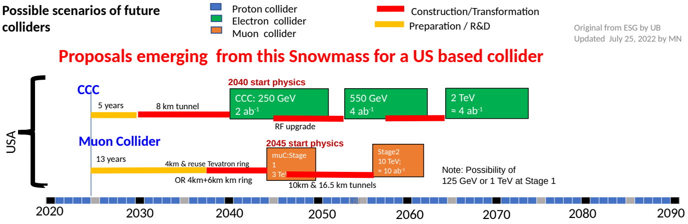
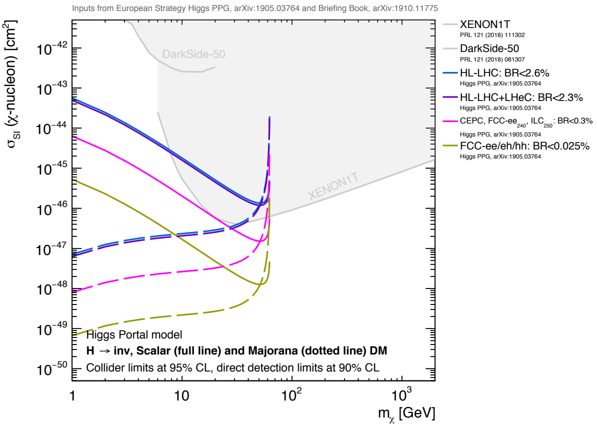


- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

- Consider proposing hosting ILC in the US.

DM



Inputs from European Strategy Higgs PPG, arXiv:1905.03764 and Briefing Book, arXiv:1910.11775
σ_SI (χ-nucleon) [cm²]
10^-42
10^-43
10^-44
10^-45
10^-46
10^-47
10^-48
10^-49
10^-50
DarkSide-50
XENON1T
Higgs Portal model
H → inv, Scalar (full line) and Majorana (dotted line) DM
Collider limits at 95% CL, direct detection limits at 90% CL
1
10
10^2
10^3
m_χ [GeV]
XENON1T
PRL 121 (2018) 111302
DarkSide-50
PRL 121 (2018) 081307
HL-LHC: BR<2.6%
Higgs PPG, arXiv:1905.03764
HL-LHC+LHeC: BR<2.3%
Higgs PPG, arXiv:1905.03764
CEPC, FCC-ee_240, ILC_250: BR<0.3%
Higgs PPG, arXiv:1905.03764
FCC-ee/eh/hh: BR<0.025%
Higgs PPG, arXiv:1905.03764

At ILC: discovery in a week...

ILD fast detector simulation studies: Selectrons in a co-annihilation model (EPJC 76,183 (2016)), after:

- 5 $fb^{-1} \approx$ 1 week

and

- 500 $fb^{-1} \approx$ 2 years.

Will never be in “3 σ limbo” !

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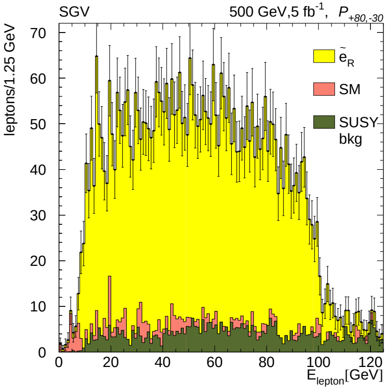

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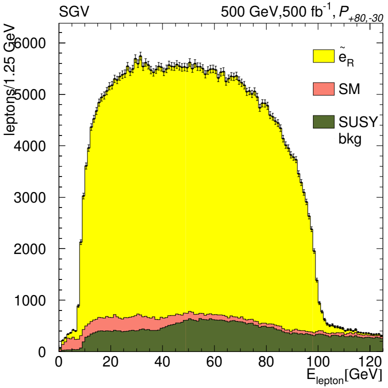

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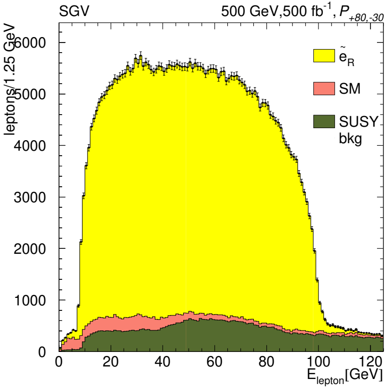

ILC = the LEP of SUSY

ILD detector simulation studies:

- Typical slepton signal ($\tilde{\tau}$ and $\tilde{\mu}$), in a co-annihilation model (FastSim). (EPJC 76,183 (2016))
- Typical chargino signal...
- ... and typical neutralino signal, higgsino-LSP model, with moderate ΔM (FullSim) (Phys Rev D 101,095026 (2020))
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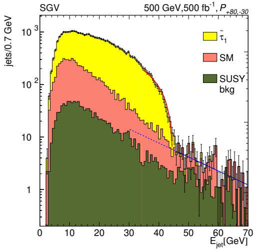

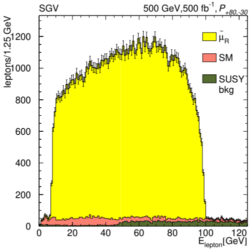

ILC = the LEP of SUSY

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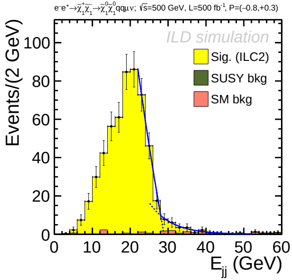

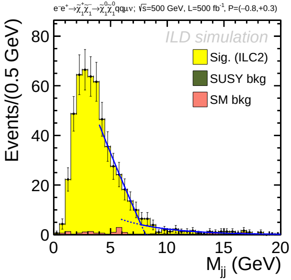

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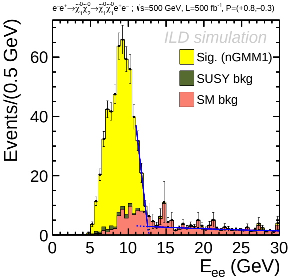

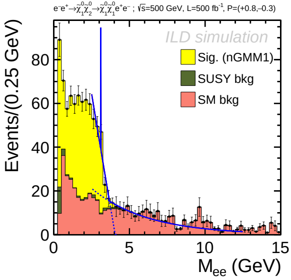

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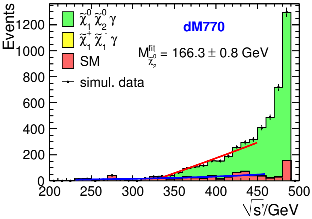

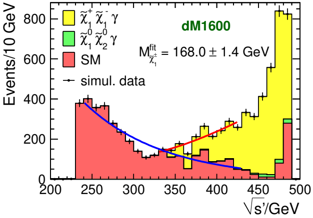

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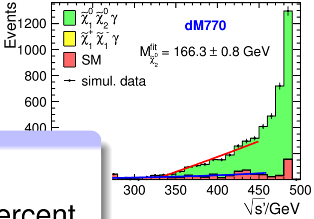

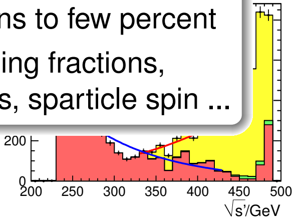

In all cases:

- SUSY masses to sub-percent
- Cross-sections to few percent
- Also: Branching fractions, mixing angles, sparticle spin ...

Why compressed spectra ?

- Higgsino or Wino LSP:
  - If the LSP is Higgsino or a Wino, several other bosinos *must* be close to the LSP.
  - $\Rightarrow$ Compressed spectrum.
    - In addition: if the LSP is higgsino: *Natural SUSY*:
    - $m_Z^2 = 2\frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{1-\tan^2\beta} - 2|\mu|^2$
    - Low fine-tuning $\Rightarrow \mu = \mathcal{O}(m_Z)$
- Bino LSP: Overabundance of DM.
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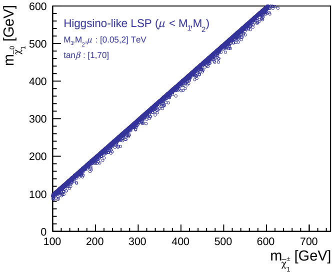

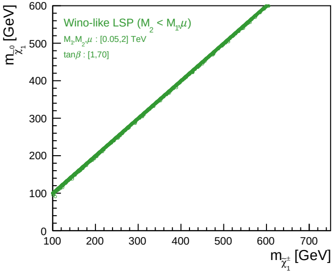

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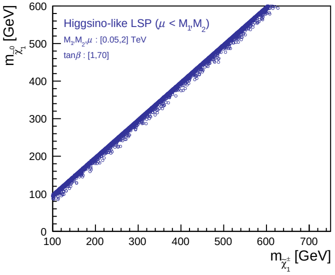

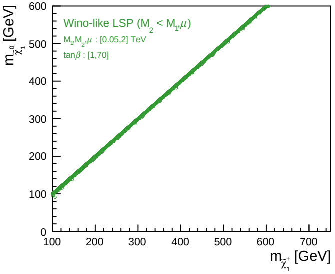

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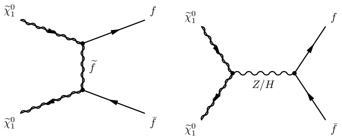

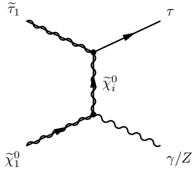

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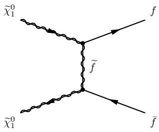
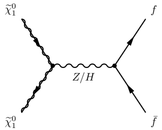
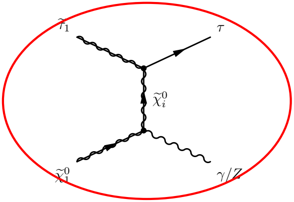
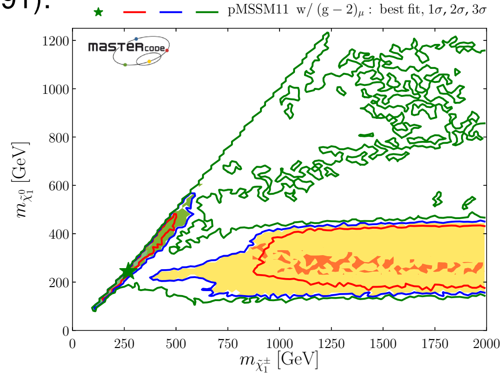






Why compressed spectra ? Global fits

pMSSM11 fit by Mastercode to LHC13/LEP/g-2/DM(=100% LSP)/precision observables (arXiv:1710.11091):



$M_{\tilde{\chi}_1^\pm}$ - $M_{\tilde{\chi}_1^0}$ plane

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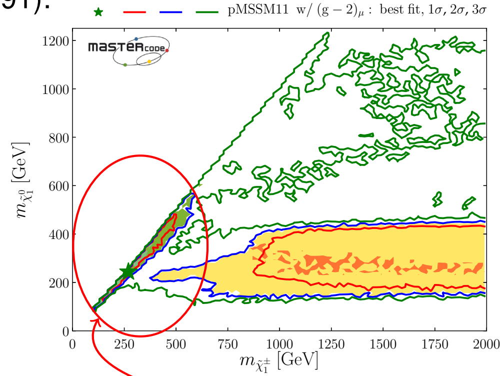


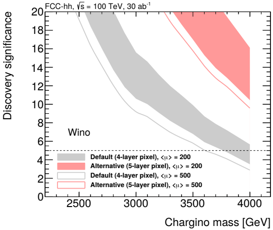
Low $\Delta(M)$!

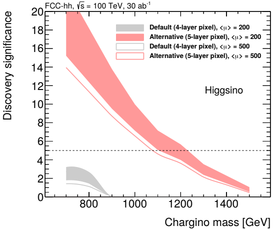
$M_{\tilde{\chi}^\pm_1}$ - $M_{\tilde{\chi}^0_1}$ plane

SUSY In The Briefing book: Wino/Higgsino LSP - Sources

(Don't look at the pink curves - they correspond to a detector that is never considered anywhere else i the CDR)

- The "Disappearing tracks" was done by FCChh (in the CDR)
  - FCChh-detector (better than ATLAS in this case: first layer of VD closer.)
  - FCChh-ish PU (but still to small: 500 vs. CDR number 955)
  - For higgsinos: Only *just* reaches 2 σ





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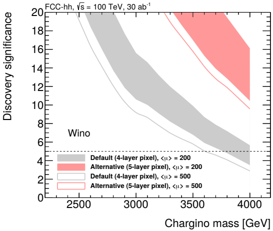
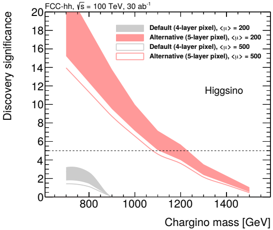
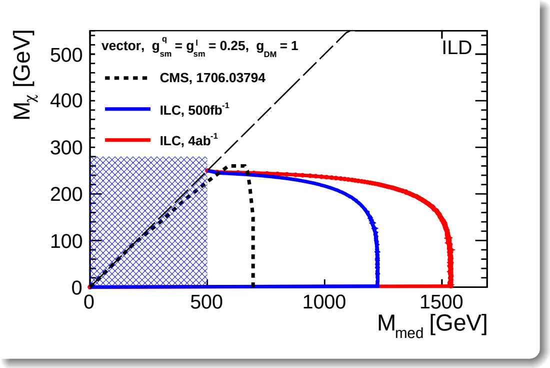




Other BSM: a gallery



DM from mono-γ (EFT)
(Phys. Rev. D 101, 075053 (2020))

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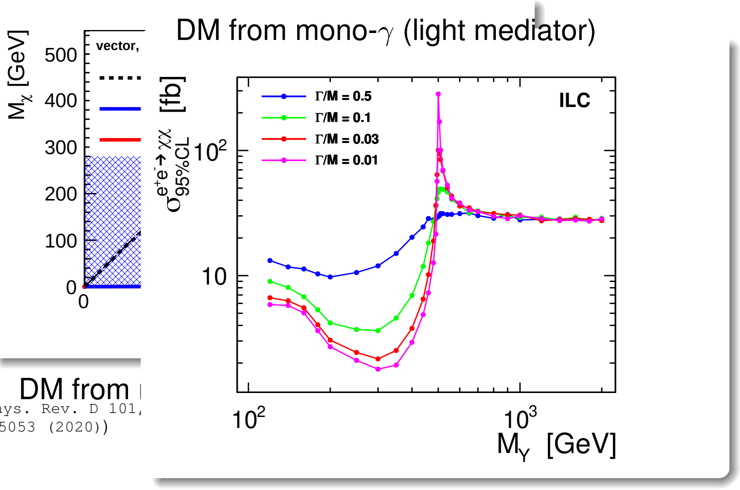

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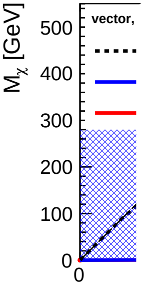

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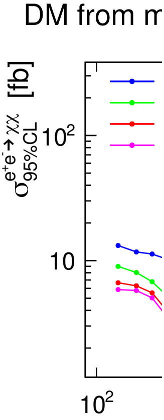
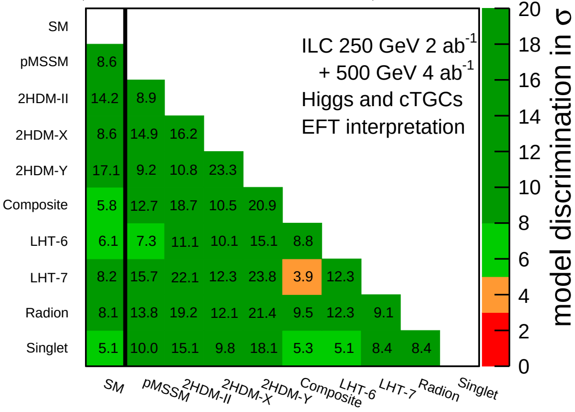


SMEFT model separation See talk by I. Bozovic - higgs session yesterday

(Phys. Rev. D 97,0535003 (2018))



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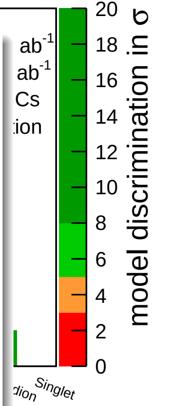
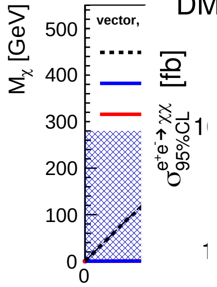


DM from m



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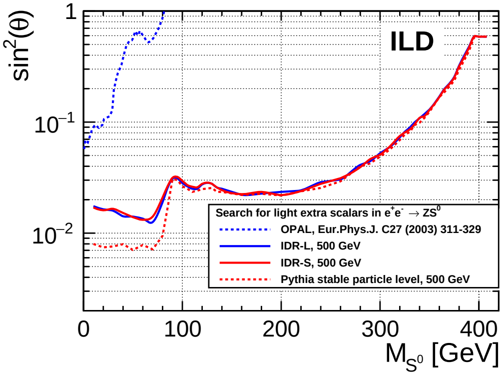
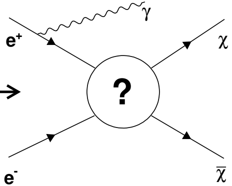


New scalar as peak in recoil-mass
(arXiv:2005.06265)

Only WIMPs

- 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” ⇒ Mono-X search.
  - At ILC: $\mathrm{e}^+\mathrm{e}^- \rightarrow \chi\chi\gamma$, ie. X is a γ

→ 

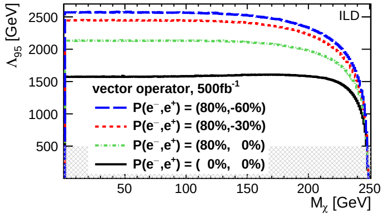
- ILC simulation studies: arXiv:1206.6639v1, A. Chaus, Thesis, M. Habermehl, Thesis,in preparation.
- Model-independent Effective operator approach to “?”
  - Analyse as an effective four-point interaction. Strength = Λ.
    - Allowable if direct observation the mediator is beyond reach. Mostly true at ILC, but not at LHC !
  - Write down all possible Lorentz-structures of the operators.
  - Exclusion regions in M_χ/Λ plane, for each operator.

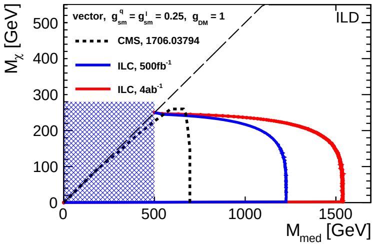
ILC and LHC exclusion

- Examples:
  - Vector operator ("spin independent"), Note how useful beam-polarisation is!
- At LHC, EffOp can't be used $\Rightarrow$ use "simplified models"
- Need to translate Λ to M_{med}: $M_{med} = \sqrt{g_{SM} g_{DM}} \Lambda$

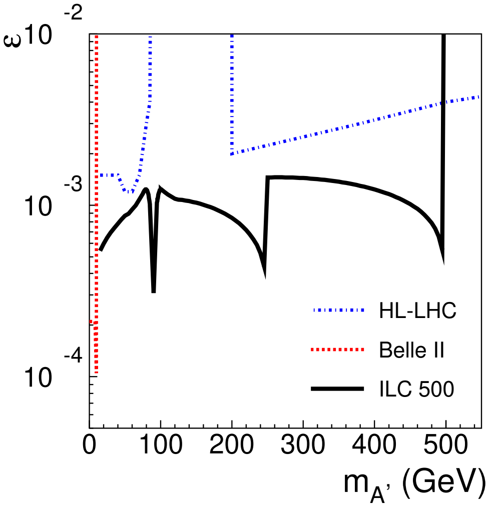
ILC/LHC complementarity

- LHC: coupling to hadrons, ILC: coupling to leptons.
- LHC has best M_χ reach, ILC best M_{med} reach





Dark photons



(Theory level estimate - FullSim in the works...)

What *would* be seen at colliders in the worst case?

- MSSM, R-parity conservation (R-parity violation always easier at e^+e^-)
  - Caveat: also CP-conservation. The experimental implication of CP violation needs study
- sfermions not NLSP (idem, except $\tilde{\tau}$ but even worse for pp...)
- Then: LSP is Bino, Wino, or Higgsino (more or less pure), same for the NLSP
- M_1, M_2 and μ are the main-players.
- Consider any values, and combinations of signs, up to values that makes the bosinos out-of-reach for any new facility $\sim$ a few TeV.
- Also vary other parameters (β, M_A, $M_{sfermion}$) with less impact.
- No other prejudice.

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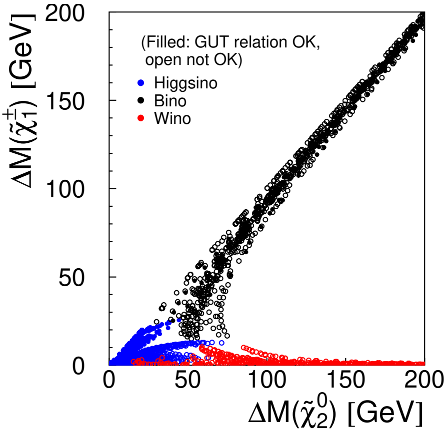
Aspects of the spectrum

Another angle: $\Delta(M)$ for $\tilde{\chi}_1^{\pm}$ vs. that of $\tilde{\chi}_2^0$: Important experimentally

- Three regions:
  - Bino: Both the same, but can be anything.
  - Wino: $\Delta_{\tilde{\chi}_1^{\pm}}$ small, while $\Delta_{\tilde{\chi}_2^0}$ can be anything.
  - Higgsino: Both often small
- But note, seldom on the "Higgsino line", ie. when the chargino is *exactly* in the middle of mass-gap between the first and second neutralino.



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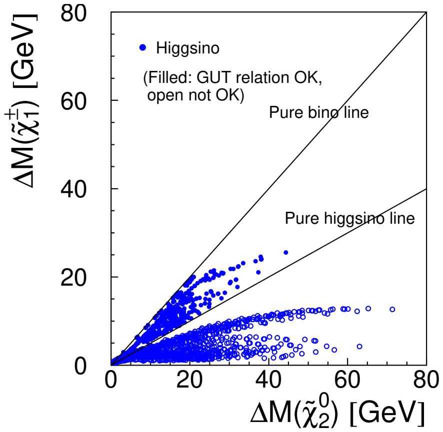

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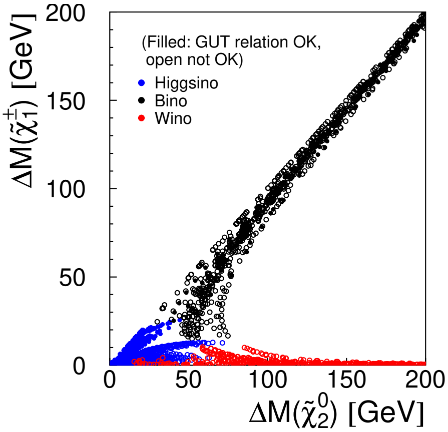
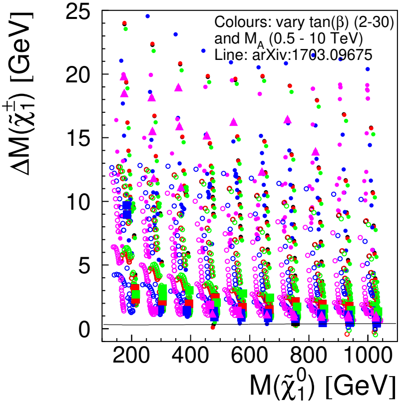


Key element for "Disappearing tracks": $\Delta(M)$

- Higgsino LSP.
- Zoom in. The line is the absolute limit mentioned in the BB.
- Reason: 1703.09675 considers *only SM* effects on the mass-splitting, ie. that M_1 and $M_2 >> \mu$
- Same for Wino LSP.



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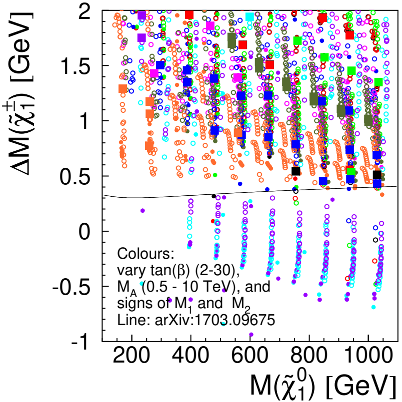

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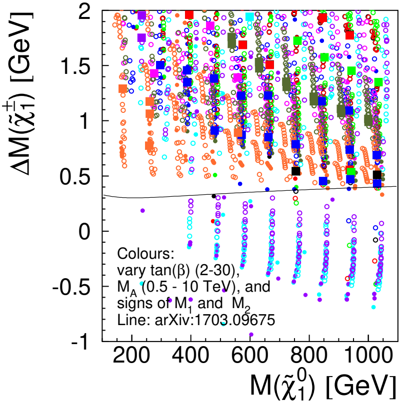

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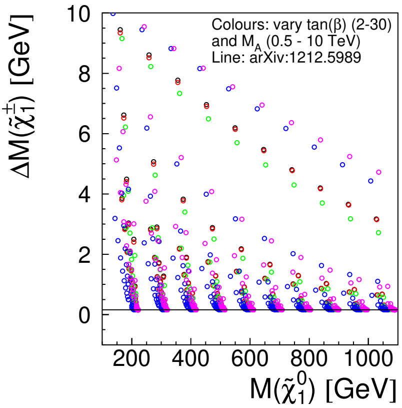

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Why is the decay-mode an issue? Here's why :

- Vary relative signs of μ, M_1, and M_2
- For $\mu > M_2$
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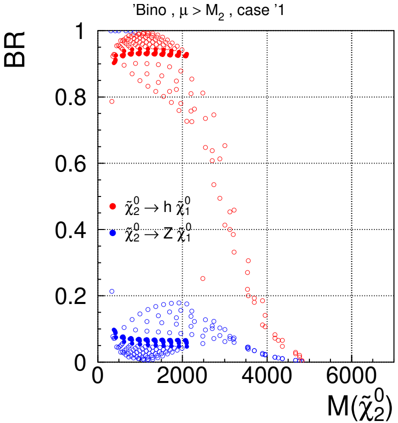
- Conclusion: Whether the Z or the H decay-mode of $\tilde{\chi}_2^0$ dominates is pure speculation and
- The exclusion-region is the *intersection* of the two plots, not the *union*!



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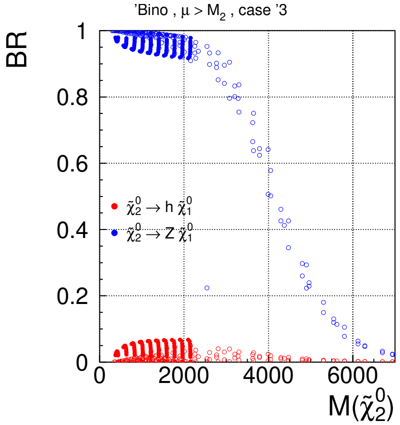

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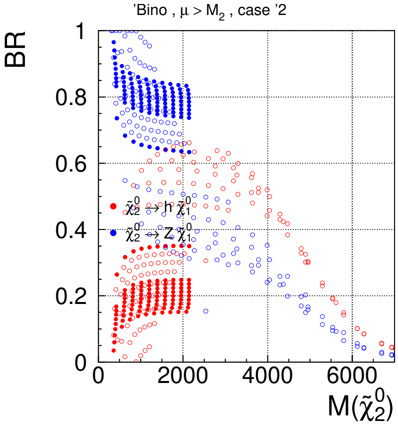

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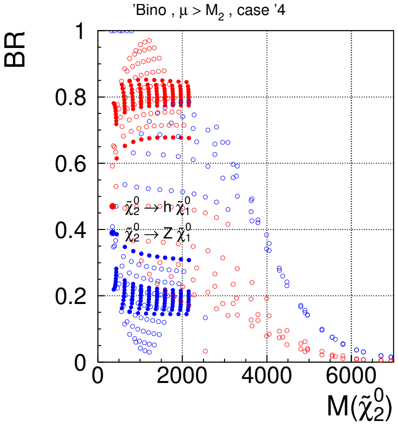

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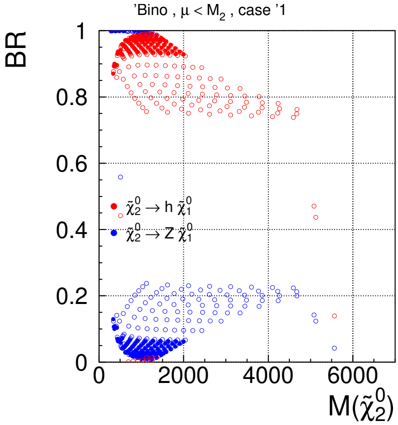

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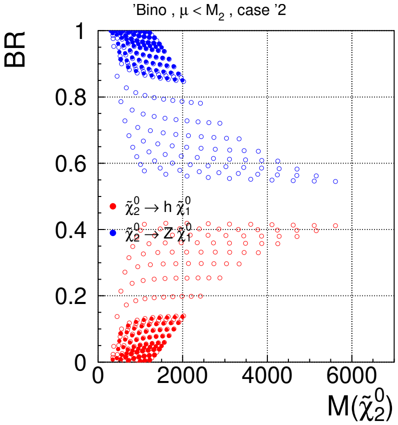

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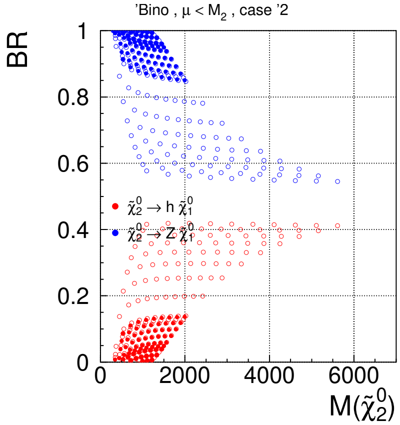

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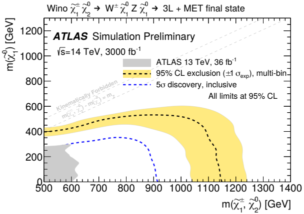

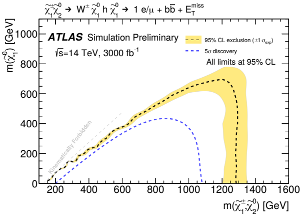

Conclusions

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  - SUSY: High mass vs. Low $\Delta(M)$. If SUSY is reachable at ILC, it means 5 σ discovery, and precision measurements.
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ILC input to the european strategy update

The Potential of the ILC for Discovering New Particles

and references therein ...

Thank You !