Indirect and Direct BSM Searches at $\sqrt{s} \leq 500$ GeV

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Motivation

• The short-comings of the Standard Model convince us that there must be new physics:
  • Hierarchy problem
  • Dark Matter
  • Matter-Antimatter Asymmetry
  • Origin of neutrino masses
  • ....

• MEXT review ask us to make more clear the prospects for “discoveries”

• **Create a joint picture of direct and indirect searches for BSM**
Solving the Hierarchy Problem
The basic solutions to the Hierarchy problem

Reminder: If SM valid up to the Planck scale, immense fine-tuning is required to prevent the Higgs mass from being driven to the Planck scale by loop corrections as expected for an elementary scalar.

- protect Higgs mass by new symmetry which provides cancellation of divergent loop diagrams

=> SUSY:
  - SM-like top couplings, but deviations in ew precision
  - deviations in Higgs couplings
  - new light states (Higgsinos, stops, …)

“deny the problem”:
- Higgs not elementary and/or Planck scale much lower than it seems

=> compositeness / extra dim.:
  - deviations in top electroweak couplings & ew precision
  - deviations in Higgs couplings
  - new states often assumed heavy

=> not necessarily, cf F.Richard’s talk in physics session
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C.f. Marcel’s talk
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c.f. Jim’s talk

c.f. Marcel’s talk
Probing BSM with precision Higgs couplings

….by the power of precision measurements of $h\gamma\gamma$, $h\tau\tau$, $h_{bb}$ couplings:

- HL-LHC 3000 fb$^{-1}$
- ILC (1150 fb$^{-1}$@250 GeV & 1600 fb$^{-1}$@500 GeV)

[Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1407.7021 [hep-ph]]

- colour scale: fraction of scan points excluded via coupling precisions
- white lines: LHC / HL-LHC direct search reach for heavy Higgses

Precisions achievable with $e^+e^-$ machine provide powerful probe for heavy Higgs bosons up to ~2 TeV - for any $\tan(\beta)$
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We should have more such examples illustrating the BSM capabilities of precision measurements!

Precisions achievable with e$^+e^-$ machine provide powerful probe for heavy Higgs bosons up to ~2 TeV - for any tan($\beta$)
Direct Searches for Supersymmetry

Nothing left? Give up on TeV-scale SUSY?
Plenty of room left for SUSY - naturally!

simplified models don’t give the full story
(e.g. 100% BR assumption rarely fulfilled)
-> c.f. pMSSM scan by ATLAS [arXiv:1508:06608]
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natural SUSY: small $\mu$ => light Higgsinos

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only ~30% excluded below limit
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- Natural SUSY: small $\mu$ => light Higgsinos
  - LEP chargino limit!
  - Only ~30% excluded below limit

- => No change in level of fine-tuning due to ATLAS exclusions (Barbieri-Giudice measure)
Natural SUSY

[H.Sert, K.Rolbiecki, H.Baer]

- key prediction: small $\mu \Rightarrow 3$ light Higgsinos with small mass differences
- “invisible” at LHC
- loop-hole free detection at ILC up to $\sqrt{s}/2$
  (clean environment & beam polarisation required!)
- determination of gaugino masses - even if in multi-TeV regime

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![Graph: Events vs. $\sqrt{s}/GeV$](image)

- Fast sim - ILD full sim in progress
- $dM770$
- $M_{\chi_1^0}^{fit} = 168.6 \pm 1.0 \text{ GeV}$
- $dM770 \Delta M(\chi_2^0 \chi_1^0) \leq 2 \text{ ab}^{-1}$

![Graph: Mass vs. $M_1/TeV$](image)

- “Wino” mass
- “Bino” mass
- Mass unification
- $\tan \beta \leq 50$
**Natural SUSY** [H.Sert, K.Rolbiecki, H.Baer]

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- **Fast sim - ILD full sim in progress**

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**ILD + Theory**

- **M_2 / TeV**
  - $\Delta M(\chi_2^0, \chi_1^0)$, $2 \text{ ab}^{-1}$
  - $\tan\beta \leq 50$

- **“Wino” mass**
  - $\tan\beta = 50$

- **“Bino” mass**
  - $M_1 / \text{TeV}$

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**dM770**
- $M_{\chi_1^0} = 168.6 \pm 1.0 \text{ GeV}$
- Events/10 GeV
Natural SUSY

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A real challenge for the detectors due to very soft visible final state
- has not yet been fully demonstrated in full detector simulation!

=> requires:
- reconstruction and PID for < 2 GeV particles
- hermeticity in the forward region
- more differential techniques to deal with $\gamma\gamma$ -> hadron overlay

ILD selected this channel as one of the benchmarks for detector optimisation
ILD Study on Radiative Natural SUSY

- special version of natural SUSY which can be implemented as GUT-scale model (e.g. NUHM2)
- mass differences 10-20 GeV, no ISR tag needed

**NEW!**

Chargino pair production with semileptonic decay
\[ e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 qq' \ell \nu \]

Neutralino mixed production with leptonic decay
\[ e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^- \]
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- target: masses and polarised cross sections
- determination of SUSY parameters
- test GUT- scale unification!
NMSSM Higgs Bosons

- Light Higgs bosons and neutralinos in NMSSM, e.g.:
  \[ M(a_1) = 10 \text{ GeV}, \]
  \[ M(h_1) = 60 \text{ GeV}, \]
  \[ M(h_2) = 125 \text{ GeV} \]

- \( h_1 / a_1 \) have reduced couplings to \( Z \)
  \( \Rightarrow \) produce in \( \chi^0 \) cascades

- Work in progress using SiD card for Delphes

- Very good mass resolution and strong polarisation dependence

\[ a_1 \rightarrow \mu^+\mu^- \]

\[ h_1 \rightarrow bb \]
Identifying Dark Matter
Generic Dark Matter: Mono-photons

- **full complementarity to LHC / direct detection:**
  - lepton vs hadron couplings
  - large mediator scale vs large DM mass:
    - ILC500: up to $\Lambda = 3$ TeV for $M_\chi < 250$ GeV
- **beam polarisation is essential:**
  - suppress background by factor ~10 => gains 1 TeV in reach!
  - *and:* analysis of potential signal

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**Diagram:**

- 90% CL, Vector operator (D5)
- ILC
- LHC
- Snowmass 14 TeV, 3/ab, Ref. arXiv:1307.5327
- CMS 8 TeV, 3.5 ab
- CMS 14 TeV, 300 fb
- ATLAS, 14 TeV, 3ab
- ATL-PHYS-PUB-2014-007

**Graph:**

- 3$\sigma$ observation reach, ILC 500 GeV, L=500fb$^{-1}$

**Legend:**

- Bkg: x 0.1
- Background unpolarized beam
- Background (Pe,Pp)=(80%,0%)
- Background (Pe,Pp)=(80%,60%)

**Table:**

| $M_\chi$ [GeV] | ILC | LHC |
|---------------|-----|-----|
| 50            |     |     |
| 100           |     |     |
| 150           |     |     |
| 200           |     |     |
| 250           |     |     |

**Analysis:**

- 90% CL and 5% syst on background
- CMS, 8 TeV, 19.5 fb
- 3.5 fb
- 3.5 ab

**Note:**

- Ref. arXiv:1307.5327
- Ref. CMS PAS EXO-12-048
- CMS, 8 TeV, 19.5 fb
- ATLAS, 14 TeV, 3/ab

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[Generic Dark Matter: Mono-photons [A.Chaus, M.Habermehl]]
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**remaining background:**
- radiative Bhabhas \( e^+e^- \rightarrow e^+e^-\gamma \)

\[ \Rightarrow \text{crucially depends on highly efficient veto in forward region} \]

**ILD currently studies this in context of reduced L***

\[ \text{bkg: } x 0.1 \]

\[ \text{Entries} \]

| Entries | Background unpolarized beam | Background \((P_e,P_p)=(80\%,0\%)\) | Background \((P_e,P_p)=(80\%,-60\%)\) |
|---------|-----------------------------|----------------------------------|---------------------------------|
| 50      | 10^4                        | 10^3                             | 10                             |
| 100     | 10^3                        | 10^2                             | 1                              |
| 150     | 10^2                        | 10                               | 1                              |
| 200     | 10                           |                                  |                                |
| 250     | 1                         |                                   |                                |

\[ E_\gamma [\text{GeV}] \]

90% CL, Vector operator (D5)

\[ \text{reach: } +1 \text{ TeV} \]

\[ M_\chi [\text{GeV}] \]

\[ \text{Vector operator} (\text{D5}) \]
SUSY Dark Matter: Co-annihilation

- additional motivation for small mass differences
  => very challenging at LHC, gold-plated ILC case
- example study of a full SUSY model with stau-LSP co-annihilation, incl. interplay with LHC

NEW:
- which observables required with which precisions to determine relic density?
- simulation study of neutralinos, e.g.:

\[ \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tilde{\chi}_1^0 \]

⇒ 1% variation of \( M_{\tilde{\tau}} \) or \( M_{\tilde{\chi}_1^0} \) changes abundance by 5%.
⇒ 1% variation of \( \theta_{\tilde{\tau}} \) or \( N_{11} \) changes abundance by 1% and 3.5%, respectively.

Resolution on endpoint ~700 MeV
Explaining the Matter-Antimatter-Asymmetry
Baryogenesis

requires:

- CP violation
- baryon number violation
- first order phase transition

Can this be the electroweak phase transition?  “electroweak baryogenesis”

- not in the SM with $M_H = 125$ GeV (2\textsuperscript{nd} order PT)
- need $\lambda > 1.2 \lambda_{SM}$
BSM effects in Higgs pair production

- always multiple diagrams contributing - with and without Higgs self-coupling $\lambda$
- interference induces non-trivial relations between cross sections and $\lambda$
- VHH has opposite behaviour to VBF /ggF=> important independent information!
- largest sensitivity to $\lambda$ near threshold => restriction to high energy / high mass does not help
- unique for $e^+e^-$ @ 500 GeV: access to VHH

[arxiv:1401.7340]
Measurement prospects at $\text{e}^+\text{e}^-$ colliders

- gives access to two complementary production processes:
  - **ZHH @ \sim 500 \text{ GeV}**
    - unique feature: increases if $\lambda > \lambda_{\text{SM}}$
    - additional dependency on $g_{\text{ZZHH}}$
  - **vvH (VBF) @ ECM > 1 \text{ TeV}:** large cross section, in particular with polarised beam
    - additional dependency on $g_{\text{WWHH}}$
  - **ZHH $\rightarrow$ Zbbbb / ZbbWW / Zbb$\tau\tau$ / ...:**
    - very complex final states
    - small statistics
    - need to exploit *all* the information provided by our detectors

$\Rightarrow$ requires further developments of the reconstruction!

**ILD FullSim**

**ILD preliminary**

\begin{align*}
\sqrt{s} & = 500 \text{ GeV}, \quad 2000 \text{ fb}^{-1} \\
P(e^+e^-) & = (+0.3,-0.8) \\
\end{align*}
Measurement prospects at $e^+e^-$ colliders

- gives access to two complementary production processes:
  - **ZHH @ ~500 GeV**
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    - additional dependency on $g_{ZZHH}$
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**update of ZHH @ 500 GeV in full simulation of ILD to come soon…**

**ILD FullSim**

[C.Dürig, J.Tian, M.Kurata]
From cross section to self-coupling in $e^+e^-$ in BSM

- $\delta \lambda / \lambda = k \delta \sigma / \sigma$ ; n.b.: $k = \left(\frac{\partial \sigma}{\partial \lambda}\right)^{-1} |_{\lambda=\lambda_{\text{obs}}}$

|                   | 500 GeV ZHH | 1 TeV vvHH | 1.4 TeV vvHH | 3 TeV vvHH | 1.4 TeV vvHH, pol | 3 TeV vvHH, pol |
|-------------------|-------------|------------|--------------|------------|------------------|----------------|
| $\int L dt$       | 4 ab$^{-1}$ | 2.5 ab$^{-1}$ | 1.5 ab$^{-1}$ | 2 ab$^{-1}$ | 1.5 ab$^{-1}$ | 2 ab$^{-1}$ |
| $\delta \sigma / \sigma$ | 16 %       | 13 %       | 26 %         | 11 %       | 20 %            | 8 %            |
| $k_{\text{SM}}$   | 1.64        | 0.76       | 1.22         | 1.47       | 1.22            | 1.47           |
| $\delta \lambda / \lambda |_{\text{SM}}$ | 27 %       | 10 %        | 32 %        | 16 %        | 24 %            | 12 %           |

- $\delta \sigma / \sigma \leq 20\% \Rightarrow \geq 5\sigma$ discovery of Higgs pair production

- for SM case, 1 TeV is a “sweet spot” with $k < 1$ (sensitivity to $\lambda$ largest close to threshold!)

- **BSM can change the picture**: consider e.g. $\lambda = 1.5 \lambda_{\text{SM}}$

  - $500\text{GeV}$: $\delta \sigma / \sigma \sim= 12\%$; $\delta \lambda / \lambda \sim= 20\%$
  - $1\text{TeV}$: $\delta \sigma / \sigma \sim= 16\%$; $\delta \lambda / \lambda \rightarrow "\infty"$

- with combination of 500 GeV and 1 TeV we’re always on the safe side!
Higgs self-coupling from loop corrections?

- sub-% precision on $\sigma_{ZH}$ possible at all proposed e+e- colliders
- indirect and model-dependent method
- interesting consistency check, not an independent measurement
- n.b.: what about other loop contributions?
  - top $\rightarrow y_t$? W $\rightarrow g_{WWH}$?
  - or even BSM?
- better look at plot the other way round: will we need at some point O(10%) direct measurement of $\lambda$ in order to achieve permille-level extraction of $g_{ZZH}$ from $\sigma_{ZH}$!?
- n.b.: at 500 GeV, NLO effects from $\lambda$ on $\sigma_{ZH}$ are $\sim$7 times smaller than at 250 GeV.....
Neutrino Masses & Leptogenesis

- search for heavy neutrinos at ILC
- study various ECM based on SiD card for Delphes

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**SiD Delphes**

[O. Fischer]

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**SiD Delphes**

[O. Fischer]
Conclusions
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• “indirect” searches:
  • we’re in good shape with estimating (statistical) precisions on observables (but watch out for systematics, theory & Co!)
  • need more efforts to interpret precisions in various BSM scenarios
    => crucial for selling the physics case!

• “direct” searches
  • offer significant complementarity with LHC
  • have special detector requirements, e.g.
    • hermeticity in forward region
    • reconstruction and ID of low momentum particles

$e^+e^-$ collisions will tell us a lot about physics beyond the Standard Model
- even at $\sqrt{s} \leq 500$ GeV: BSM is an integral part of the physics case!
Backup
Top Couplings and BSM

ILC precision allows model discrimination
- sensitivity in $g_{Z_L}$, $g_{Z_R}$ plane complementary to LHC

Sensitivity to huge variety of models with compositeness and/or extra-dimensions complementary to resonance searches

- RS with Z-Z' Mixing
- Light top partners Alternative 1
- Light top partners Alternative 2
- SUSY
- SM
- 4D Composite Higgs Models
- Little Higgs
- RS with Custodial SU(2)
- Composite Top

LHC14, 3000 fb^{-1}
From Phys.Rev.D63 (2006) 034016

[Poeschl, Richard]
New Physics Reach of full ILC500 Program

….for typical BSM scenarios with **composite Higgs/Top and/or extra dimensions**

based on phenomenology described in Pomerol et al. arXiv:0806.3247

Can probe scales of ~20 TeV in typical scenarios

(… and up to 80 TeV for extreme scenarios)
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Measurement prospects at pp colliders

- HL-LHC:
  - significance for observation of Higgs pair production
    \( \sim 1.9 \sigma / \exp \) if \( \lambda = \lambda_{SM} \) (\( bb\gamma\gamma / bbWW / bb\tau\tau \))
  - \( \Rightarrow \) uncertainty on signal rate \( \sim 54\% / \exp \) => \( \sim 38\% \) combined
  - n.b.: this is not the uncertainty on \( \lambda \! \)
- 100 TeV: [TODO: check talk at FCC week on Wednesday]
  - cross section \( \sim 40\times \) larger
    => but still no sensitivity to VHH….
  - aim for 5-10%
- Common challenges:
  - “double solution” for \( \lambda \)
  - \( \lambda > \lambda_{SM} \Rightarrow \) rate drops!
  - correlation with top Yukawa coupling \( y_t \)
  - large NLO k-factors….
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  - deviations in top electroweak couplings & ew precision
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  => not necessarily, cf F.Richard’s talk in physics session
  - deviations in Higgs couplings
The basic solutions to the Hierarchy problem

Reminder: If SM valid up to the Planck scale, immense fine-tuning is required to prevent the Higgs mass from being driven to the Planck scale by loop corrections as expected for an elementary scalar.

- MSSM ($\tan\beta = 5$, $M_A = 700$ GeV)
- New symmetry protects Higgs mass which provides cancellation of divergent loop diagrams

=> SUSY:
- SM-like top couplings, but deviations in EW precision
- New light states (Higgsinos, stops, ...)
- Deviations in Higgs couplings "deny the problem": Higgs not elementary and/or Planck scale much lower than it seems

=> Compositeness / extra dim.:
- Deviations in top electroweak couplings & EW precision
- New states often assumed heavy => not necessarily, cf F. Richard's talk in physics session
- Deviations in Higgs couplings

Projected Higgs coupling precision (model-independent)

- ILC
- Model prediction

- 500 GeV, 4000 fb$^{-1}$ ⊕ 350 GeV, 200 fb$^{-1}$ ⊕ 250 GeV, 2000 fb$^{-1}$
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- SUSY:
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  - Deviations in Higgs couplings

"Deny the problem":
Higgs not elementary and/or Planck scale much lower than it seems

- Compositeness / extra dim.:
  - Deviations in top electroweak couplings & electroweak precision
  - New states often assumed heavy
  - In contrast, perhaps not necessarily, cf. F. Richard's talk in physics session

Projected Higgs coupling precision (model-independent)

- ILC
- Model prediction

Higgs' couplings covered in Jim's talk, - as essential as ever if direct hint for BSM become true!
Topics to address - indirect searches

- Higgs / top:
  - **fine-tune with other speakers**
  - focus mostly on BSM interpretations of achieved precisions
  - candidate examples:
    - Higgs couplings => pMSSM
    - Higgs self-coupling in BSM
    - top FCNC
    - top couplings in BSM
- Others:
  - TGCs / QGCs
  - EW precision / 2 fermions
Key messages I suggest to convey

• Indirect searches:
  • well covered with achievable precisions on experimental observables
  • need much more effort on **interpretation in BSM models**
    • => quantify discovery potential
    • => interplay with LHC

• Direct searches:
  • not only single benchmarks
  • need also discovery sensitivities in whole parameter planes
    (eg LEP chargino plot.....)
  • => demonstrate even more clearly complementarity to LHC