Material for BSM Discussion Session
QUESTIONS
Questions from participants

1. Is the example of a universal $Z'$ really representative? Does it miss important information about flavour?
2. What is the impact of the decay into $h$ on the $pp$ EWKino reach from $\chi_2\chi^+$ production?
3. Comments on discovery vs characterization at $pp$ vs $e^+e^-$. 
4. Comments and discussion about gaps and uncovered scenarios due to oversimplification of benchmarks.
5. Have the indirect EWKino effects in $e^+e^-$ been overlooked?
6. If the $g$-$2$ anomaly is confirmed, how do we look foe a susy explanation?
Questions from participants

7. Comments and discussion on HE flavour opportunities at $pp$ vs $\, e^+e^-$. 
8. Is it reasonable to have HE flavour effects in view of low-energy constraints? 
9. Should CERN take any role in being a hub for technology/experiment/theory/computing towards DM searches?
Dark matter at colliders
1. How do we search for DM at colliders, depending on its properties?
2. What cases of thermal relic WIMPs are still unprobed and can be covered by collider searches?
3. How will direct and indirect DM detection experiments inform/guide accelerator searches and vice-versa?

Feebly-interacting particles
1. To what extent can we test FIPs at accelerators?
EWSB dynamics and resonances
1. Which is the best way to find new interactions/particles around or above the electroweak scale using high-energy probes?
2. How can we tell whether the Higgs is composite (or not)?

Supersymmetry
1. If nature is supersymmetric, which masses of strongly- or weakly-interacting super-partners can we reach?
2. Can we see signs of gauge coupling unification?
3. Is nature fundamentally fine-tuned?

Extended Higgs sectors & HE flavour dynamics
1. Is the Higgs sector minimal?
2. Could the EW phase transition be strong 1\textsuperscript{st} order?
3. Could we understand the UV origin of flavor with colliders?
Dark matter at colliders

Feebly-interacting particles
Projected Wino Limits

Indirect
FCC–hh
FCC–eh
HE–LHC
HL–LHC
CLIC
ILC
CLIC
FCC–ee
CEPC

Kinematic Limit: $\sqrt{s}/2$

$2\sigma$, Disappearing Tracks

$2\sigma$, Indirect Reach

Sources detailed in backup slides.
Projected Higgsino Limits

Sources detailed in backup slides.
Projected Axial-Vector Limits

Light dark matter, $M_\chi = 1$ GeV.

$$g_{DM} = 1, \quad g_{SM} = 0.25$$
Axial-Vector Relic Density

$g_{DM} = 1, \ g_{SM} = 0.25$

For the quark couplings only, the relic density in this simplified model* takes the following form. Upper limit comes from non-perturbative couplings.

FCC-hh can cover the entire mass range.

*Relic density in simplified models always to be taken with a pinch of salt.
Summary, DM@colliders

(continuing from M. McCullough’s talk)

CATERINA DOGLIONI - LUND UNIVERSITY

Code, inputs and discussion for summary plots:
PPG BSM, PPG DM, PPG Higgs, ATLAS Collaboration,
Jean-Jacques Blaising, Antonio Boveia, Oleg Brandt, Ulrich Haisch,
Phil C. Harris, Isabelle John, Matt McCullough, Jocelyn Monroe,
Hideki Okawa, Marco Rimoldi, Ulrike Schnoor, Emma Tolley,
Francesca Ungaro, Andrea Wulzer
Big question # 1 (DM PPG): motivation for DM@colliders

How do we search for DM at colliders, depending on its properties?

- Generally assume some properties for the DM particle
  - interacts with SM particles → we can produce it at colliders

Caveat: very simplified diagram

- [a matter of preference] is a thermal relic → WIMP
- dark, stable → invisible to detectors

SM    DM

known particle collision production of DM particles
Big question #2 (BSM PPG): coverage in benchmark space

What cases of thermal relic WIMPs are still unprobed and can be covered by collider searches?

Problem: unable to cover all cases!

• Large number of model possibilities for WIMPs, even limiting to the simplest models (see e.g. LHC Dark Matter Forum/WG documents)

• Higgs portal and scalar mediator are only examples
• Why choosing them as benchmarks?
  • newly discovered Higgs
  • Higgs portal: simple interaction, only DM as new particle
  • Scalar cross-sections are small → can probe with future colliders

Big question #2 (BSM PPG): coverage in benchmark space

What cases of thermal relic WIMPs are still unprobed and can be covered by collider searches?

- Very simple models, so careful with taking relic density at face value
- If Higgs portal is to make up 100% of DM, can exclude using DD and colliders

Caveat: EFT validity in Higgs-DM interaction not guaranteed beyond HL-LHC
Big question #2 (BSM PPG): coverage in benchmark space

What cases of thermal relic WIMPs are still unprobed and can be covered by collider searches?

- Very simple models, so careful with taking relic density at face value
- If scalar mediator model is to make up 100% of DM, still much unprobed territory

Keep in mind: these plots are only valid for the couplings specified, even in the limited space of a benchmark model!
Big question #3 (DM PPG): complementarity

**How will Direct and Indirect DM Detection experiments inform/guide accelerator searches and vice-versa?**

- Why we need complementarity:
  - DD/ID can discover DM with cosmological origin
  - Colliders can probe the dark interaction (even when DM is inaccessible)

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arXiv:1606.00947

Caterina Doglioni - 2019/05/13 - European Strategy Update
A collider discovery will need confirmation from DD/ID for cosmological origin
A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction
A future collider program that increases sensitivity to invisible particles coherently with DD/ID serves this purpose
Introduction

To confirm a discovery, need to maximise ”common sensitivity”!

- A collider discovery will need confirmation from DD/ID for cosmological origin
- A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction
- A future collider program that increases sensitivity to invisible particles coherently with DD/ID serves this purpose

Summary plot for direct detection/colliders

The best region to find DM in!
A collider discovery will need confirmation from DD/ID for cosmological origin.

A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction.

A future collider program that increases sensitivity to invisible particles coherently with DD/ID serves this purpose.
**Take-home messages**

Huge progress planned on DD and ID front (see earlier talks in this session)

Future colliders can follow: essential complementarity between

These slides covered simple models used for comparison and contextualization:
- SM-DM interactions mediated by Higgs boson
- SM-DM interactions mediated by new scalar particle

Strengths in WIMP searches both in future lepton and hadron options:
- combined FCC program shows best sensitivity to benchmarks
  - still, needs complementary experiments (DM != WIMP only)
- lepton colliders alone can probe large (& yet unknown) parts of phase space thanks to precision environment / lower backgrounds

Next 10 years: hope for concerted effort between DD/ID/colliders/other experiments to discover and understand a possible particle nature of DM
## Inputs from DM discussion session

The DD/astrophysics community would like to work in synergy with the future collider program of DM searches

How can CERN respond to the DD community submission wishlist, as e.g. a:

- technology / science / theory hub
  - [J. Monroe's talk, computing session]

- place to exchange software expertise
  - [C. Tunnell, HEP Software Foundation/OSG/WLCG workshop]
Naturalness @ 21st century => FIPS & new crisis

Not common for naturalness-based models; the anchor for energy frontier which conventionally satisfies the equation:

\[
\text{Naturalness} \iff \text{TeV new physics (NP)}
\]

New ideas cast doubt on this “equation”.

eg: “Cosmic attractors”, “dynamical relaxation”, “N-naturalness”, “relating the weak-scale to the CC” & “inflating the Weak scale”.

New scalar-FIPs common to all of above: consider for ex. the relaxion.

Relaxion models can be described via a scalar that mixes with the Higgs:
What makes accelerator FIP-searches special?

(i) Case for (thermal) dark matter (DM) & its portal

(ii) Case for ALP & its quality problem

(iii) Case for relaxion/scalar-portal & its natural parameter space
Accelerators & log crisis: among 3 probes of physical models

The 3 fronts where natural models of mixing can be probed

- Precision frontier
- Astro frontier
- Accelerator frontier

natural region

Equivalence principle

Eötvös-Wash Be-Ti

Casimir

Stanford

LEP

FCCee

FCCee

max

mix

Halo

courtesy: Elina Fuchs

Log$[m_{\phi}/eV]$

Log$[\sin \theta]$
Interplay, colliders vs beam dumps (small-scalar-Higgs-mixing)
Conclusions

- Feebly interacting particles (FIPs) are generically motivated.

- FIPs bring with them log crisis/opportunity calls for experimental diversity.

- Accelerator provided a unique opportunity to look for well motivated FIPs.

- Practical compromise - FIPs benchmarks.

- Results & sensitivity plots shown in following talk by Gaia Lanfranchi.
Questions to guide the discussion session

1. To what extent can we test FIPs at accelerators?
   i) log-crisis: we need a multi-scale & multi-experiment approach: call for a diversity program.
   ii) a concrete example: the four portals.
   iii) within the four portals we can investigate parameters regions that could address
       some fundamental theoretical and experimental problems eg: thermal DM,
       maximal mixing in relaxion models, RHN below the EW scale, etc.

2. Interplay:
   2a. what is the interplay between colliders and fixed-target/beam dump experiments
   2b. what is the interplay (beyond mere complementarity) between accelerators
       and low energy probes (neutrino physics, CPV-EDM, helioscopes, table top experiments etc ...).

3. Inverse problem:
   - if we get a FIP-like signal, how can we probe its nature?
Vector portal: coverage and complementarity

Improvements by several orders of magnitude both in low-mass low-coupling regime (beam-dump) and in high-mass large-coupling regime (colliders).

Nice complementarity between beam-dump and colliders’ experiments
Vector Portal: interplay with Light Dark Matter DD experiments

Model where minimally coupled viable WIMP dark matter model can be constructed. The parameter space for this model is:

$$\sigma v \sim \alpha_D e^2 \frac{m_A^4}{m_A^2} \times \frac{1}{m^2}$$

$A' \rightarrow \chi \chi$

$A' \rightarrow e^+e^-, \mu^+\mu^-$

Nice complementarity between accelerator-based proposals, colliders and Light DM direct detection experiments.
High-mass range can be excluded by the knowledge of the Higgs couplings; Improvements by several orders of magnitude possible in low-mass low-coupling regime using direct searches.

Nice complementarity between beam-dump, astrophysics boundaries and colliders. Together they can explore a large fraction of the “natural” relaxion region.
Scalar Portal: Interplay
ALPs with photon coupling: coverage, complementarity, interplay

Sub-eV range accessible at helioscopes and haloscopes

MeV-10 GeV range accessible at accelerators’ based experiments

Nice complementarity of accelerator-based experiments, experiments in the sub-eV range, and cosmological bounds
Fermion Portal: coverage, complementarity, interplay

Back to the initial plot:

SU(2)xU(1)\textsubscript{L} singlet Right Handed Neutrinos responsible of the neutrinos’ mass generation can have any coupling/mass in the white area, assuming an approximate U(1)\textsubscript{L} global symmetry.

With beam dump and future colliders’ experiments we can explore (light) RHN in the mass range 0.1-90 GeV almost down to the see-saw limit.
Prospects for CEPC: 10 ab\(^{-1}\) at the Z-pole and 5 ab\(^{-1}\) at 240 GeV.

**Production mechanisms at e\(^{+}\) e\(^{-}\) colliders:**

- **Displaced vertex searches:** Several decay modes accessible
- **Higgs BR:** Presence of HNL modifies the Higgs width and BRs. The more sensitive is the H→WW which constrains H→ν N (and Θ\(^{2}\))

**EWPO:**

The PMNS matrix in presence of HNLs is not unitary. Modification of the theory prediction of precision observables. Present constraints include: EWPO, lepton universality, charged LFV, CKM unitarity

**Mono-Higgs:**

If m\(_{N}\) is above the Higgs mass, N → ν H, H → hadronically (dijet).

Source:

CEPC report, arXiv: 1811.10545

Based on arXiv:1612.02728
Fermion Portal: a possible connection to $0\nu\beta\beta$ decay

Correlation of $|m_{\beta\beta}|$ and RHN mass and mass degeneracy for $N=2$ scenario for 68% and 90% CL contours probability for successful baryogenesis

P. Hernandez et al, arXiv:1606.06719
See also: Drewes, Eijima arXiv:1606.06221

Red contours: log M prior, Blue contours: log DM prior
Fermion Portal: possible connection to active-neutrinos oscillation data

Antusch, Drewes et al.
arXiv:1710.03744

Figure 9: The region within the black lines is allowed by light neutrino oscillation data. The colour indicates the largest mixing angle $U^2$ consistent with the observed BAU and seesaw constraints for the cases of normal ordering (left) and inverted ordering (right) for right-handed neutrino with an average mass $\bar{M} = 30 \text{GeV}$. Note that the largest viable mixing angles are found in the case of a highly flavour asymmetric flavour pattern, where $U_\alpha^2 \ll U^2$ for any of the flavours.
EWSB dynamics and resonances

Supersymmetry

Extended Higgs sectors & HE flavour dynamics
Seeing the “peak”. Mass reach:
- mass < $\sqrt{s}$ for lepton colliders
- mass $\leq 0.3-0.5 \sqrt{s}$ in hadron colliders for couplings ~ weak couplings

Deviations in high-mass tails:
- Better suited for lepton colliders; sensitive to $[\text{mass/coupling}] \gg \sqrt{s}$
- Hadron colliders relevant for $g_{Z'} > g_{SM}$ couplings: $[\text{mass/coupling}] \gg 0.5 \sqrt{s}$
Characterization

- Well studied at ILC/CLIC for resonance masses below the center-of-mass energy, and also above $\sqrt{s}$ for the characterization of spin/couplings/deviations:

  - Also possible at hadron colliders. Example: $Z'$ resonance of 6 TeV seen at HL-LHC and “characterized” at HE-LHC via cross sections, $A_{FB}$ and central/forward ratios:

    - **Dilepton 3-dim analysis**
    - **qq,bb,tt rates**

[References]

4-fermion contact interactions

- Interpretation of dilepton mass spectra ($l\nu$, $ll$) for hadron colliders and $\sigma^*\text{Br}$ limits in terms of constraints on $W$ and $Y$:

$$\frac{g^2 W}{m_W^2}, \frac{g'^2 Y}{m_W^2} \rightarrow \Delta\left(\left[\frac{\text{coupling}}{\text{Scale}}\right]^2\right)$$

**HL-LHC**

**HE-LHC**

**FCC-hh**
Contact interactions in ep: eeqq

Inputs not included in EWK/HIG fits, competitive reach
(Note: limits to be divided by \( \sqrt{4\pi} \) to compare with numbers in previous tables)
Other inputs for 2f-2boson contact interactions

- Other measurements contributing sizably to constrain $O_W$ and $O_B$ operators (and thus to 2f-2boson contact interactions):
  - $S$ parameter constraints (dominant constraint at $Z$ pole)

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S parameter at the Z pole
(CEPC example)

ZH at CLIC (global analysis of angular observables)

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J. Alcaraz, Resonances and EWSB, ESU19 Symposium
Top partners: Vector-Like Quark (VLQ) $X_{5/3}$

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FCC-hh</th>
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</thead>
<tbody>
<tr>
<td>$X_{5/3} \rightarrow Wt$, discovery reach in $pp \rightarrow XX$ pair production</td>
<td>1.5 TeV (Snowmass study, arxiv:1309.2234, 3 ab$^{-1}$, &gt;140 pileup),</td>
<td>2 TeV (BSM HL/HE-HLC report, arxiv:1812.07831, analysis described in arxiv:1710.02325) (Snowmass study arxiv:1309.2234 also used as proxy for $\sqrt{s}$=27 TeV, 15 ab$^{-1}$)</td>
<td>4.7 TeV (from arxiv:1710.02325, extrapolated to 30 ab$^{-1}$ integrated luminosity; this is the reference used for the HE-LHC estimate in the BSM report)</td>
</tr>
</tbody>
</table>

- **Pair production, same-sign di-lepton signature**
  - Non-negligible backgrounds, margin for improvements in studies
  - Capability to disentangle left and right $XWt$ coupling scenarios

- **Single production should be dominant at very high energies, but production model dependent**

J. Alcaraz, Resonances and EWSB, ESU19 Symposium
A New Gauge Force?

Results: HE-LHC vs circular lepton colliders

$Y$–Universal $Z'$, $2\sigma$

- HE-LHC
- FCC-ee
- CEPC

Preliminary, Granada 2019
A New Gauge Force?

Results: FCC-hh vs linear colliders

Y–Universal $Z'$, $2\sigma$

M [TeV]

$g_{Z'}$

FCC–hh
CLIC
ILC$_{500}$

HL–LHC

Preliminary, Granada 2019
A Composite Higgs?

Scale-Coupling estimate of indirect effects:  

\( \mathcal{L}_{\text{SILH}} = \frac{c_\phi}{\Lambda^2} \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi) + \frac{c_T}{\Lambda^2} \frac{1}{2} (\phi^\dagger D_\mu \phi)(\phi^\dagger D^\mu \phi) - \frac{c_6}{\Lambda^2} \lambda (\phi^\dagger \phi)^3 + \left( \frac{c_y}{\Lambda^2} y_i^f \phi^\dagger \phi \psi_{Li} \phi \psi_{Rj} + \text{h.c.} \right) \)

+ \frac{c_W}{\Lambda^2} \frac{ig}{2} \left( \phi^\dagger \delta_{\mu}^{\nu} \phi \right) D_\nu W^{a \mu \nu} - \frac{c_B}{\Lambda^2} \frac{ig'}{2} \left( \phi^\dagger D_\mu \phi \right) \partial_\nu B^{\mu \nu} + \frac{c_{\phi W}}{\Lambda^2} i g D_\mu \phi^\dagger \sigma_a D_\nu \phi W^{a \mu \nu} + \frac{c_{\phi B}}{\Lambda^2} i g' D_\mu \phi^\dagger \sigma_a D_\nu \phi B^{\mu \nu}

+ \frac{c_Y}{\Lambda^2} g^2 \phi^\dagger \phi B^{\mu \nu} B_{\mu \nu} + \frac{c_g}{\Lambda^2} g^2 \phi^\dagger \phi G^A \mu \nu G^A_{\mu \nu}

- \frac{c_{2W}}{\Lambda^2} g^2 \left( D^\mu W^a_{\mu \nu} \right) \left( D_\rho W^a_{\nu \rho} \right) - \frac{c_{2B}}{\Lambda^2} \frac{g^2}{2} \left( \partial^\mu B_{\mu \nu} \right) \left( \partial_\rho B^{\rho \nu} \right) - \frac{c_{2G}}{\Lambda^2} \frac{g^2}{2} \left( D^\mu G^A_{\mu \nu} \right) \left( D_\rho G^A_{\rho \nu} \right)

+ \frac{c_3_{\text{W}}}{\Lambda^2} g^3 \varepsilon_{abc} W^a_\mu \varepsilon_{\nu} W^b_\rho \varepsilon_{\mu} W^c_\rho + \frac{c_{3G}}{\Lambda^2} g^3 f_{ABC} G^A_{\mu \nu} G^B_\rho G^C_{\mu}

\text{Expected } O_H = O_\phi: \quad \frac{c_\phi}{\Lambda^2} = \frac{g^2_*}{m^2_*} \\
\text{Expected } O_W: \quad \frac{c_W}{\Lambda^2} = \frac{1}{m^2_*} \\
\text{Expected } O_{2W}: \quad \frac{c_{2W}}{\Lambda^2} = \frac{1}{g^2_* m^2_*}

Up to order one numerical coefficients
### A Composite Higgs?

#### Indirect Searches Input: [see more in Juan’s talk]

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<th></th>
<th>HL-LHC</th>
<th>LHeC</th>
<th>HE-LHC</th>
<th>ILC$_{250}$</th>
<th>ILC$_{500}$</th>
<th>CLIC$_{380}$</th>
<th>HL-LHC + CLIC$_{1500}$</th>
<th>CLIC$_{3000}$</th>
<th>CEPC</th>
<th>FCCcr240</th>
<th>FCCcr</th>
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<td>$c_\phi/\Lambda^2$</td>
<td>0.51</td>
<td>(0.28)$^\dagger$</td>
<td>0.15</td>
<td>0.29</td>
<td>0.14</td>
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<td>0.14</td>
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<td>0.033</td>
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<td>(0.002)</td>
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<td>$c_W/\Lambda^2$</td>
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<td>(0.022)</td>
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<td>$c_{2W}/\Lambda^2$</td>
<td>0.32</td>
<td>(0.028)</td>
<td>0.27</td>
<td>0.21</td>
<td>0.059</td>
<td>0.04</td>
<td>0.066</td>
<td>0.046</td>
<td>0.039</td>
<td>0.14</td>
<td>0.15</td>
<td>0.1</td>
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</table>

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From Higgs group

**Plus the formulas:**

\[
\frac{c_\phi}{\Lambda^2} = \frac{g^2}{m^2_*}
\]

\[
\frac{c_W}{\Lambda^2} = \frac{1}{m^2_*}
\]

\[
\frac{c_{2W}}{\Lambda^2} = \frac{1}{g^2 m^2_3}
\]
A Composite Higgs?

Results: HE-LHC vs FCC-ee

Composite Higgs, $2\sigma$, FCC$_{ee}$ vs HE–LHC

$g^*_*$ vs $m^*_*$ [TeV]

- HE–LHC
- $C_\phi$
- $C_W$
- $C_{2W}$

Preliminary, Granada 2019
A Composite Higgs?

Results: FCC-hh vs ILC

Composite Higgs, $2\sigma$, ILC$_{500}$ vs FCC$_{all}$

$g^*_*$ vs $m^*_*$ [TeV]

- ILC$_{500}$
- FCC$_{all}$
- HL-LHC

Preliminary, Granada 2019
A Composite Higgs?

Results: FCC-hh vs CLIC

Composite Higgs, $2\sigma$, CLIC vs FCC$_{\text{all}}$
Conclusions

New Gauge Force:
CLIC is the only lepton collider that competes with hadron ones

Higgs Compositeness:

Natural Higgs Compositeness:
Very High Energy Lepton Collider

Tuning Reach:
(very) tentative  [Buttazzo, Franceschini, AW. in prog.]

Compositeness Reach:

Higgs compositeness scale, 2σ reach
Hadron Colliders: gluino projections

(R-parity conserving SUSY, prompt searches)

<table>
<thead>
<tr>
<th>Model</th>
<th>$\int L , dt$ [ab$^{-1}$]</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>Mass limit (95% CL exclusion)</th>
<th>Conditions</th>
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<tr>
<td>HL-LHC</td>
<td>$\tilde{g} \tilde{g} \to q\bar{q}\tilde{\chi}^0_1$</td>
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<td>FCC-hh</td>
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<td>7.5 TeV</td>
<td>$m(\tilde{\chi}^0_1) \sim m(\tilde{\chi}^0_1)+10$ GeV (*)</td>
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<td>30 100</td>
<td>11.0 TeV</td>
<td>$m(\tilde{\chi}^0_1) = 0$</td>
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(*) indicates projection using parton lumi rescaling (ColliderReachTool)

14/5/19
SUSY Experimental prospects, Monica D’Onofrio
### All Colliders: Top squark projections

**(R-parity conserving SUSY, prompt searches)**

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<tr>
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<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i)</td>
<td>3</td>
<td>14</td>
<td>1.7 TeV, (m(t^{'})=0)</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/3) body</td>
<td>3</td>
<td>14</td>
<td>0.85 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=m(t))</td>
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<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/4) body</td>
<td>3</td>
<td>14</td>
<td>0.95 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=5) GeV, monojet (\ast)</td>
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<tr>
<td><strong>HE-LHC</strong></td>
<td></td>
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<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>15</td>
<td>27</td>
<td>3.65 TeV, (m(t^{'})=0)</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/3) body</td>
<td>15</td>
<td>27</td>
<td>1.8 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=m(t)) (\ast)</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/4) body</td>
<td>15</td>
<td>27</td>
<td>2.0 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=5) GeV, monojet (\ast)</td>
</tr>
<tr>
<td><strong>ILC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>4</td>
<td>0.5</td>
<td>0.25 TeV, (m(t^{'})=0) (lbc)</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>4</td>
<td>0.5</td>
<td>0.25 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=m(t))</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>4</td>
<td>0.5</td>
<td>0.25 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=10) GeV</td>
</tr>
<tr>
<td><strong>CLIC Sk.2</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>2.5</td>
<td>1.5</td>
<td>0.75 TeV, (m(t^{'})=0)</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>2.5</td>
<td>1.5</td>
<td>0.75 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=m(t))</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>2.5</td>
<td>1.5</td>
<td>0.75 - 1 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=50) GeV</td>
</tr>
<tr>
<td><strong>CLIC Sk.3</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>5</td>
<td>3.0</td>
<td>1.5 TeV, (m(t^{'})=350) GeV</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>5</td>
<td>3.0</td>
<td>1.5 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=m(t))</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/\tilde{f}^0_i, \tilde{f}^0_i)</td>
<td>5</td>
<td>3.0</td>
<td>1.5 - 1 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=50) GeV</td>
</tr>
<tr>
<td><strong>FCC-hh</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i)</td>
<td>30</td>
<td>100</td>
<td>10.8 TeV, (m(t^{'})=0)</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/3) body</td>
<td>30</td>
<td>100</td>
<td>10.0 TeV, (m(t^{'})=4) TeV</td>
</tr>
<tr>
<td>(\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{f}^0_i/4) body</td>
<td>30</td>
<td>100</td>
<td>5.0 TeV, (\Delta m(t^{'}, \tilde{f}^0_i)=5) GeV, monojet (\ast)</td>
</tr>
</tbody>
</table>

\(\ast\) indicates projection of existing experimental searches

\(\ast\) indicates a possible non-evaluated loss in sensitivity

---

**Discovery potential HL/HE-LHC**

\(~ up to 1.4/3.2\ TeV\)

**Discovery potential e+e-**

\(~ up to \sqrt{s}/2\)

(with possible exception for compressed scenarios)

**Discovery potential FCC-hh**

\(~ up to 8\ TeV\)
Current status on top squark searches

Reach up to 1 TeV for low LSP mass, covering LSP mass hypothesis up to ~ 400 GeV

4 body decays

Stop $\rightarrow b +$ chargino

Low-mass region almost all covered; loop-holes might still exist [to be explored with full Run 2 data]

$M(\text{stop}) \sim m(\text{top}) \rightarrow$ spin correlation measurements
Wino-like cross section: $\chi_{1}^{\pm} \chi_{2}^{0}$

**Preliminary Granada 2019**

- **LHC 36/ fb, 13 TeV**
- **HL-LHC 3/ ab, 14 TeV (3L search)**
- **HL-LHC compressed 3/ ab, 14 TeV**
- **HE-LHC 15/ ab (projection)**
- **HE-LHC compressed 15/ ab (projection)**
- **ILC500 0.5/ ab**
- **CLIC 1.5 TeV**
- **CLIC 3 TeV**
- **FCC-hh (3L search, 3/ ab)**

**95% CL exclusion**

**CLIC: Assume reach for $\chi_{1}^{\pm} \chi_{2}^{0}$ and $\chi_{1}^{\pm} \chi_{2}^{0}$. CLIC 1.5 TeV reach / 2 up to $\Delta M \sim 5$ GeV**

**ILC500: as per documentation**

**FCC-hh Contour of the 3-lepton search**

**HE-LHC compressed: reinterpretation of higgsino $\chi_{1}^{\pm} \chi_{2}^{0}$ results**

**HL-LHC → projections with ColliderTool Reach**
Wino-like cross section: $\chi^+_1 \chi^-_1$

- **FCC-hh Contour of the 2-lepton search used for $\chi^+_1 \chi^-_1$**
  - CLIC 1.5 TeV
  - HL-LHC 3/ab, 14 TeV

- **95% CL exclusions**
  - CLIC 1.5 TeV: reach / 2
  - CLIC 1.5 and 3: Reach down to $\Delta M(\chi^+_1, \chi^-_1) = 5$ GeV

- **HL-LHC compressed: reinterpretation of higgsino**
  - $\chi^+_1 \chi^-_1$ results in $\chi^+_1 \chi^-_1$ - wino

- **HE-LHC → projections with ColliderTool Reach**

- **ILC@500: as per documentation**

- **Wino–Higgsino: reach curve, and in the relative importance of representative choices of additional parameters –**

- **such cancellation does not occur, making the decay to the Higgs boson always dominate, and the result small in the NLSP branching ratios as the additional parameters change.**

- **Here, the Wino–Higgsino case depends sensitively on**

- **dotdashed) searches at a 100 TeV**

- **m(\tilde{\chi}^0_1) [GeV], \tilde{\chi}^+_1 = NLSP**

- **Expected 5 Discovery contours and expected 95% CL limit**

- **All limits at 95% CL**

- **Expected**

- **Figure S. Amoroso, J. K. Anders, F. Meloni, C. Merlassino, B. Petersen, J. A. Sabater Iglesias, M. Saito, R.**

- **Figure 2.2.13: S. Amoroso, J. K. Anders, F. Meloni, C. Merlassino, B. Petersen, J. A. Sabater Iglesias, M. Saito, R.**

- **HE-LHC 15/ab (projection)**

- **HE-LHC compressed 15/ab (projection)**

- **HE-LHC 3/ab, 14 TeV**

- **CLIC 3 TeV**

- **CLIC 1.5 TeV**

- **ILC500 0.5/ab**

- **LHC 36/fb, 13 TeV**
Mixture of Chi2 with higgs decays?

• Dedicated analysis for higgs decays as well

Some if:
• if neut2 → h chi10 and neut2 = charg, results in (1) would be valid and constraints pushed from (4) for realistic models under these assumptions, + (3) for compressed cases
• If only neut2 are accessible, and decay into higgs, like in GGM models, higgsino analyses as performed by ATLAS and CMS can be performed
• Mixed cases, high LSP mass etc to be understood
Higgsino-like EWK processes

**Higgsino-like EWK processes**

- HL-LHC 3/ab, 14 TeV (soft-lepton A)
- HL-LHC 3/ab, 14 TeV (soft-lepton B)
- HE-LHC 15/ab, 27 TeV (soft-lepton B)
- FCC-hh (HE-LHC approx. rescaling)
- ILC500 0.5/ab
- CLIC 1.5 TeV
- CLIC 3 TeV
- CLIC / FCC-ee 380 GeV

**95% CL exclusions**

- HL-LHC monojet
- HE-LHC monojet
- FCC-hh monojet
- FCC-ee monojet-like
- LHC monojet-like (proj)

**Preliminary Granada 2019**

- ILC sensitive up to sqrt(s)/2 and down to O(100 MeV)
- Monojet reach in Δ m(NLSP, LSP) not displayed

**Monojets (HL/HE/FCC-hh/LHeC/FCC-eh)**

- HL-LHC soft lepton analysis CMS
- HE-LHC soft lepton analysis ATLAS
- CLIC 3 TeV, results rescaled also for CLIC1.5, CLIC380, FCC-ee (tbc)

**Indicative partonic rescaling of HE for FCC-hh soft-lepton**
Stau reach

(Section 2.3 of arxiv:1812.07831)

Details of searches in back-up

ES-follow up communication

SUSY Experimental prospects, Monica D’Onofrio

https://arxiv.org/abs/1903.01629
### EWK sector: disappearing track

- For very compressed EWK sector, **disappearing tracks-like analyses** are considered

---

**Low energy charged tracks analysis**

**Charged stub + photon analysis**

**HL-LHC/HE-LHC/FCC-hh comparisons**

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14/5/19  
SUSY Experimental prospects, Monica D’Onofrio

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SUSY physics questions

• If nature is supersymmetric, which masses of strongly- or weakly coupling super-partners can we reach?

• Can we see signs of gauge coupling unification?

• Is dark matter a thermal SUSY WIMP? (→ Caterina/Matthew)

• Is nature fundamentally fine-tuned? If the solution is supersymmetry, how well can we test this?
Indirect: Higgs precision

\[ X_t = X_t^{\text{max}} \]
New signature: exotic Higgs decays

Long-lived Glueballs; lightest have same quantum # as Higgs

\[ \mathcal{L} \supset -\frac{\alpha_3'}{6\pi} v h \frac{f}{f} G'_{\mu\nu} G'_a \]

\( \sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1}, \text{N} > 4 \)
New signature: exotic Higgs decays

Long-lived Glueballs; lightest have same quantum # as Higgs

\[ \mathcal{L} \supset -\frac{\alpha_3'}{6\pi} v \frac{h}{f f'} G_{\mu\nu} G'_{\mu\nu} \]
Standard Model + real scalar singlet

Potential for SM Higgs and a single real scalar

\[ V_0 = -\mu^2 |H|^2 + \lambda |H|^4 - \frac{1}{2} \mu_s S^2 + \frac{1}{4} \lambda_s S^4 + \lambda_{HS} |H|^2 S^2 \]

Higgs-singlet mixing:
\[ h = h_0 \cos \gamma + S \sin \gamma \]
\[ \phi = S \cos \gamma - h_0 \sin \gamma \]

Equivalence theorem:
\[ \text{BR}(\phi \to hh) = \text{BR}(\phi \to ZZ) = 25\% \]

Sensitivity from Higgs couplings:
\( c_H \) is overall scaling of the Higgs couplings (using sensitivity for this individual operator)

Sensitivity from EW precision observables:
S and T parameters derived from from \( c_{\phi WB} \) and \( c_T \) (simultaneous fit of both operators)

<table>
<thead>
<tr>
<th>Facility</th>
<th>95% C.L. limit on ( \sin^2 \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>0.034</td>
</tr>
<tr>
<td>LHeC</td>
<td>0.013</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>0.018</td>
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<tr>
<td>ILC 250 GeV</td>
<td>0.0073</td>
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<tr>
<td>ILC 500 GeV</td>
<td>0.0050</td>
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<tr>
<td>CLIC 380 GeV</td>
<td>0.0093</td>
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<tr>
<td>CLIC 1.5 TeV</td>
<td>0.0048</td>
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<tr>
<td>CLIC 3 TeV</td>
<td>0.0033</td>
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<tr>
<td>CEPC</td>
<td>0.0046</td>
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<tr>
<td>FCC-ee 240 GeV</td>
<td>0.0053</td>
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<tr>
<td>FCC-ee</td>
<td>0.0046</td>
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<tr>
<td>FCC-ee/-eh/-hh</td>
<td>0.0034</td>
</tr>
</tbody>
</table>
Lepton colliders:

- CLIC study of $e^+e^- \rightarrow \nu\bar{\nu}\phi$ (Delphes) at 1.5 and 3 TeV: $\phi \rightarrow hh \rightarrow b\bar{b}b\bar{b}$ most powerful channel

- $\mu^+\mu^- \rightarrow \nu\bar{\nu}\phi$; $\phi \rightarrow hh$ studied on generator level for 5 ab$^{-1}$ at $\sqrt{s} = 6$ and 20 ab$^{-1}$ at 14 TeV (also valid for an $e^+e^-$ collider based on novel accelerator techniques)

Hadron colliders:

- Current LHC sensitivity dominated by $\phi \rightarrow ZZ$ search (36 ab$^{-1}$ at 13 TeV)

- Extrapolation using quark parton luminosities to HL-LHC (3 ab$^{-1}$ at 14 TeV), HE-LHC (15 ab$^{-1}$ at 27 TeV), FCC-hh (30 ab$^{-1}$ at 100 TeV)

Sec. 4.2 of CERN-2018-009-M
JHEP 11,144 (2018)

Sec. 6.1.4 of CERN-LPCC-2018-005
JHEP 11,144 (2018)
SM + singlet: direct

At HL-LHC, HE-LHC and CLIC direct and indirect searches provide complementary information.

NB: FCC-hh and the muon collider will follow on the next slide.
SM + singlet: high-mass region

• Direct reach at FCC-hh better than precision Higgs couplings below 12 TeV
No mixing limit

Potential for SM Higgs and a single real scalar:

\[ V_0 = -\mu^2 |H|^2 + \lambda |H|^4 - \frac{1}{2} \mu_s^2 S^2 + \frac{1}{4} \lambda_S S^4 + \lambda_{HS} |H|^2 S^2 \]

Unbroken $Z_2$ symmetry:
no Higgs-singlet mixing \(\rightarrow\) new scalar escapes undetected

**Sensitivity from Higgs couplings:** limit on $\lambda_{HS}$ from $c_H$

**Direct sensitivity:**

**Hadron colliders:**
FCC-hh study of $pp \rightarrow \phi\phijj$ using VBF jets (Delphes)

**Lepton colliders:**
No projection for $e^+e^- \rightarrow \phi\phi e^+e^-$ or $\mu^+\mu^- \rightarrow \phi\phi \mu^+\mu^-$ available yet

JHEP 11, 127 (2014)
Sec. 11 of CERN-ACC-2018-0056
No mixing: direct vs. indirect

NB: The lines for FCC-ee and CEPC are identical

Preliminary, Granada May 2019
A/H → τ⁺τ⁻ at HL-LHC

- Combination of CMS and ATLAS Projections (6 ab⁻¹ in total)
- Direct access to heavy Higgs bosons of 2.5 TeV for tan β > 50
- Region of low tan β could be improved by A/H → tt

**Mₜ₊₂⁵ scenario:**
- tan β < 6 → light Higgs below 122 GeV
- Mₐ < 900 excluded by Higgs signal strengths
  (dependent on the benchmark scenario used)

Sec. 9.5 of CERN-LPCC-2018-04
MSSM Higgs bosons at FCC-hh

\[ pp \rightarrow bbH^0/A \rightarrow bb\tau \tau \text{ (large tan}\beta\text{)} \]
\[ pp \rightarrow bbH^0/A \rightarrow ttbb \text{ (int. tan}\beta\text{)} \]
\[ pp \rightarrow ttH^0/A \rightarrow tttt \text{ (low tan}\beta\text{)} \]

\[ pp \rightarrow btH^\pm \rightarrow bb\tau\nu \]
\[ pp \rightarrow btH^\pm \rightarrow tttb \]

- Studies using Delphes
- Exclusion limits better than 5 TeV for H^0/A
  (20 TeV at low tan β)
- Exclusion limits in the range 10 - 15 TeV for H^+

95% C.L. exclusion limits

<table>
<thead>
<tr>
<th>14 TeV</th>
<th>100 TeV</th>
<th>0.3</th>
<th>3</th>
<th>3</th>
<th>30 ab^{-1}</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>πτ</td>
<td>bb</td>
<td>tt</td>
<td></td>
</tr>
</tbody>
</table>

JHEP 01, 018 (2017)
JHEP 11, 124 (2015)
Sec. 6.7 of CERN-TH-2016-113
Top-quark FCNC: $t \rightarrow Hq$ and $t \rightarrow gq$

**HL-/HE-LHC**: Sec. 8.1 of CERN-LPCC-2018-06
**ILC**: Sec. 10.3 of arXiv:1903.01629
**CLIC**: Sec. 10 of arXiv:1807.02441
**LHeC**: EPPSU submission #159
**FCC-hh/-eh**: Sec. 6 of CERN-ACC-2018-0056
Top-quark FCNC: $t \rightarrow Zq$ and $t \rightarrow \gamma q$

HL-/HE-LHC: Sec. 8.1 of CERN-LPCC-2018-06
ILC: Sec. 10.3 of arXiv:1903.01629
CLIC: Sec. 10 of arXiv:1807.02441
LHeC: EPPSU submission #159
FCC-hh/-eh: Sec. 6 of CERN-ACC-2018-0056
$95\%$ C.L. limit on $\sin^2\gamma$ vs. $m_\phi$ [GeV]

Direct:
- HL-LHC
- HE-LHC
- CLIC 1.5 TeV
- CLIC 3 TeV
- FCC-hh
- $\mu\mu$, 6 TeV, 5 ab$^{-1}$
- $\mu\mu$, 14 TeV, 20 ab$^{-1}$

EWPO:
- HL-LHC
- HE-LHC
- LHeC
- ILC 500 GeV
- FCC-ee
- CEPC
- FCC-ee/eh/hh

Higgs couplings:
- HL-LHC
- HE-LHC
- LHeC
- ILC 500 GeV
- FCC-ee
- CEPC
- FCC-ee/eh/hh
- CLIC 3 TeV
A joint effort by the PPG/BSM group!

Juan Alcaraz Maestre
Monica D’Onofrio
Philipp Roloff
Gaia Lanfranchi
Caterina Doglioni
Paris Sphicas
Andrea Wulzer
Andreas Weiler
Veronica Sanz
Gilad Perez
Matthew McCullough
Gian Giudice

EWSB dynamics and resonances
Supersymmetry
Extended Higgs sectors & HE flavour dynamics
Feebly-interacting particles
Dark matter at colliders
Coordination