Leptons for New Physics
Open Questions on the “big picture” on fundamental physics circa 2020

- why QCD does not violate CP?
- how have baryons originated in the early Universe?
- what is the dark matter in the Universe?
- what originates flavor mixing and fermions masses?
- what gives mass to neutrinos?
- why gravity and weak interactions are so different?
- what fixes the cosmological constant?

end of “The Boltzmann Way”
Open Questions on the “big picture” on fundamental physics circa 2020

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Open Questions on the “big picture” on fundamental physics circa 2020

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- What is the dark matter in the Universe?
- What gives mass to neutrinos?
- Why gravity and weak interactions are so different?
- What fixes the cosmological constant?
(Standard) Exploration needed

- $\rightarrow h+X$ (explore couplings of first ever fundamental(?) scalar)
- $\rightarrow hh+X$ (explore the shape of the Higgs boson potential)
- $\rightarrow t\bar{t}h+X$ (explore the shape of the Higgs-top interface, CPV?)
- $\rightarrow W_LW_L$ (Dynamics of Goldstone Bosons of SM)
(Beyond Standard) Exploration needed

• $\chi \chi + X$ (explore couplings of SM and Dark Matter)

• $\{H^0, A, a, \phi, \phi_{\text{twin}}, h, Z, W\}^2$ (explore the sub-TeV Higgs “sector”)

• $F \bar{F} + X$ (explore partner fermions)

What to collide?
(Beyond Standard) Exploration needed

- \( \eta \rightarrow \chi \chi + X \) (explore couplings of SM and Dark Matter)

- \( \eta \rightarrow \{H^0,\pm,A,a,\varphi,\phi_{\text{twin}},h,Z,W\}^2 \) (explore the sub-TeV Higgs “sector”)

- \( \eta \rightarrow F \bar{F} + X \) (explore partner fermions)

How much to collide?
Challenges we can see already from here

LUMINOSITY TAKES TIME WE DON'T HAVE

LHC / HL-LHC Plan

LHC: New Physics is either heavy or shows up in subtle ways

ICHEP14

ICHEP16

ICHEP18

LHC: New Physics is either even heavier or shows up in even subtler ways

Roberto Franceschini
Challenges we can see already from here

A BALANCING PROBLEM
Challenges we can see already from here

A BALANCING PROBLEM

Roberto Franceschini

Vladimir Shiltsev

\[ L \propto s \]

\[ L \propto s \]

Luminosity [cm\(^{-2}\)s\(^{-1}\)]

Center of Mass Energy [TeV]

Fig. 3: "Luminosity vs Energy" paradigm shift (see text)

Finally, one can try to assess options for "far future" post-FCC energy frontier collider facility with c.o.m. energies (20-100 times the LHC (300-1000 TeV)). We surely know that for the same reason the circular e+e- collider energies do not extend beyond the Higgs factory range (~0.25 TeV), there will be no circular proton-proton colliders beyond 100 TeV because of unacceptable synchrotron radiation power – they will have to be linear. It is also appreciated that even in the linear accelerators electrons and positrons become impractical above about 3 TeV due to beam-strahlung (radiation due to interaction at the IPs) and about 10 TeV due to radiation in the focusing channel (<10 TeV). That leaves only μ+μ- or pp for the "far future" colliders. If we further limit ourselves to affordable options and request such a flagship machine not...
Set targets to

- attain sufficient reach for new physics production

\[ \sigma_{\text{hard}} \sim \frac{1}{s} \]  
Drell-Yan, Vector Boson Fusion, Compton-like … 10^β events of

\[
\begin{align*}
\circ \circ \rightarrow \chi \chi \\
\circ \circ \rightarrow \phi + X \\
\circ \circ \rightarrow N_R + X
\end{align*}
\]

- attain sufficient precision to test the SM

★ … but how much precision is enough?
Set targets to

• attain sufficient reach for new physics production

\[ \int d\Phi \mathcal{L}_\Phi \sigma_{\text{hard}} \sim \frac{1}{\alpha} \]  
Drell-Yan, Vector Boson Fusion, Compton-like … \[ 10^\beta \] events of \[ \{ \begin{align*} \circ \circ \rightarrow \chi \chi \\ \circ \circ \rightarrow \varphi + X \\ \circ \circ \rightarrow N_R + X \end{align*} \]

• attain sufficient precision to test the SM

★ … but how much precision is enough?
“Precision” physics
What is precision?

$\frac{\delta O}{O} \approx 1$

not precise, we can agree on that

$\frac{\delta O}{O} \approx 0.01$

precise? not precise?

depends on what you compare it to!

NEED SOME "BIAS" ON THE SOUGHT NEW PHYSICS EFFECT

SM works wonderfully!

New Physics may fit well in a EFT (new contact interactions)

- effects grow at larger energies like $\nu e^-\rightarrow\nu e^-$ in Fermi Theory

$m_W, m_Z, \sin \theta_W, A_{FB}^{\text{whatever}}, h \rightarrow Z\gamma, h \rightarrow ZZ, t \rightarrow b\tau\nu$

- dominant energy scale is low
- measurement is simple to grasp
- progress is easy to measure (in)significant digits

measurements dominated by a single mass scale

measurements sensitive to a range of mass scales

$\frac{d\sigma}{dp_T}$

- sensitive to a range of energy scales
- measurement of a spectrum (not so?!?) simple to grasp
- progress is easy to measure: bounds on new Fermi constants

NEED SOME "BIAS" ON THE SOUGHT NEW PHYSICS EFFECT
What is precision?

**BIAS**

Sometimes is good

\[
\frac{\delta O}{O} \approx 1
\]

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  \]

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  \]

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measurements sensitive to a range of mass scales

as NP effects may grow quadratically with energy

\[ \Delta O = O_{NP} - O_{SM} \sim \left( \frac{E}{v} \right)^2 \]

1% at $m_Z$ is worse than 10% at 1 TeV

$\frac{d\sigma}{dp_T}$

- sensitive to a range of energy scales
- measurement of a spectrum (not so?!?) simple to grasp
- progress is easy to measure: bounds on new Fermi constants

SM works wonderfully!
Phase transition during which the electroweak symmetry is broken. We find that CLIC can exhaustively
Higgs and top compositeness if the compositeness scale is below

\[ \mathcal{L}_{\text{universal}}^{d=6} = c_H g_s^2 \frac{g^2}{m_s^2} \mathcal{O}_H + c_T \mathcal{N}_T \frac{g_s^2}{(4\pi)^2 m_s^2} \mathcal{O}_T + c_6 \frac{g^2}{m_s^2} \mathcal{O}_6 + \frac{1}{m_s^2} [c_W \mathcal{O}_W + c_B \mathcal{O}_B] + \frac{g_s^2}{(4\pi)^2 m_s^2} [c_HW \mathcal{O}_{HW} + c_{HB} \mathcal{O}_{HB}] + \frac{g_s^2}{(4\pi)^2 m_s^2} [c_BB \mathcal{O}_{BB} + c_{GG} \mathcal{O}_{GG}] \\
+ \frac{1}{g_s^2 m_s^2} [c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g^2 \mathcal{O}_{2B}] + c_{3W} \frac{3g^2}{(4\pi)^2 m_s^2} \mathcal{O}_{3W} + c_w \frac{g^2}{m_s^2} \mathcal{O}_{W} + \frac{g_s^2}{m_s^2} \mathcal{O}_{B} + c_{bB} \frac{g^2}{m_s^2} \mathcal{O}_{bB} \]

will consider a 3 TeV e+e- collider with \( L = \text{few} 1/ab \) as an ambitious but feasible option

complementary bounds from:
- Drell-Yan (high-pT probe) \( \frac{d\sigma}{d\cos\theta} \) of \( e^+e^- \rightarrow ff \) and
- Higgs boson (high-luminosity probe) \( e^+e^- \rightarrow h + \ldots \rightarrow XX + \ldots \)

High energy lepton colliders can probe the large set of dim-6 operators

for universal theories (least flavor puzzling) bounds are improving one order or better w.r.t. HL-LHC
CLIC is ready to be built

- CLIC baseline – a drive-beam based machine with an initial stage at 380 GeV
- The CTF3 (CLIC Test Facility at CERN) programme addressed all drive-beam production issues
- Accelerating gradient at ~100 MV/m demonstrated in numerous prototypes
- Other critical technical systems (alignment, damping rings, beam delivery, etc.) addressed via design and/or test-facility demonstrations
- A klystron-based CLIC machine is also an option for 380 GeV – hardware demonstrated in accelerating-structure test stands
- Two C-band XFELs (SACLA and SwissFEL) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs
Lots of material from

Yellow Report
The CLIC Potential for New Physics

CLIC detector&physics + Theory community


http://clicdp.web.cern.ch/content/wg-physics-potential
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New physics effects can be all encapsulated in gauge and Higgs bosons couplings

- High energy lepton colliders can probe a large set of dim-6 operators.
- Bounds are improving one order or better w.r.t. HL-LHC
- Tighter constraints in all directions, including Z-pole “classics” e.g. S parameter
EFT

NEW SCALAR  SM+HEAVY SINGLET

\[ h_{125} = h_0 \cdot \kappa + S \cdot \sqrt{1 - \kappa^2} \]
\[ h_{125} = h_0 \cdot \kappa + S \cdot \sqrt{1 - \kappa^2} \]
Higgs sector
Higgs + Singlet

- Broad coverage of BSM scenarios: (N)MSSM, Twin Higgs, Higgs portal, modified Higgs potential (Baryogenesis)

- Phenomenology is also useful as “simplified model”
Higgs + Heavy Singlet

The mass of the singlet-like state, while double production is in principle sensitive also to other parameters of the Higgs sector via a cubic and quartic term. Given the structure of the model it is very convenient to define the Lagrangian which describes the most general renormalisable interactions of a real scalar singlet with the SM, that couples to 1.2.1 Production of the singlet-like state

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} (\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - a_S S |H|^2 - \frac{1}{2} \lambda_H S^2 H^2 - V_S(S) \]

h = h_0 \cos \gamma + S \sin \gamma,
\phi = S \cos \gamma - h_0 \sin \gamma,

\[ \Gamma(h \to XX) = \Gamma^{(\text{SM})}(h \to XX) \cdot (1 - \sin^2 \gamma) \]
\[ \sigma(e^+e^- \to \nu \nu S) \sim \sin^2 \gamma \log(\sqrt{s}/M_S) \]

S decays as a “would-be” SM heavy Higgs boson (ZZ=hh=0.5 WW)

ZZ and WW final states look less promising due to larger backgrounds

Clean e+e- environment allows to use most abundant hadronic hh final state
Higgs + Heavy Singlet

\[
\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - a_S S |H|^2 - \frac{1}{2} \lambda_{HS} S^2 |H|^2 - V_S (S)
\]

\[
h = h_0 \cos \gamma + S \sin \gamma,
\]

\[
\phi = S \cos \gamma - h_0 \sin \gamma,
\]

\[
\Gamma (h \to X X) = \Gamma^{(SM)} (h \to X X) \cdot (1 - \sin^2 \gamma)
\]

\[
\sigma (e^+ e^- \to \nu \nu S) \sim \sin^2 \gamma \log (s/M_S)
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Higgs + Heavy Singlet

**MIXING VS. MASS** $e^+e^- \rightarrow \nu\nu S \quad S \rightarrow hh \rightarrow 4b$

CLICdet Delphes module  [https://github.com/delphes/delphes](https://github.com/delphes/delphes)

VLC-jets exclusive $N=4 \ R=0.7 \ p_T > 20 \ GeV$

Double resonance ($S \ & \ 2h$)

Backgrounds:

$\sigma \sim 1 \ fb: \ e^+e^- \rightarrow \nu\nu \ 4b \ (incl. \ \nu\nu ZZ, \ \nu\nu hh)$
Higgs + Heavy Singlet

MIXING VS. MASS $e^+e^- \rightarrow \nu\nu S \quad S \rightarrow h h \rightarrow 4b$

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CLICdet Delphes module [GitHub Link]

VLC-jets exclusive N=4 R=0.7 $p_T > 20$ GeV

Double resonance (S & 2h)

Backgrounds:
$\sigma \sim 1$ fb: $e^+e^- \rightarrow \nu\nu 4b$ (incl. $\nu\nu ZZ$, $\nu\nu hh$)

$\sin^2\gamma < 0.9\%$ 95% CL (stage 1)
$\sin^2\gamma < 0.24\%$ 95% CL (stage 1, 2, 3)

Test motivated values of the mixing beyond TeV singlet mass

Interplay between direct S search and H coupling indirect sensitivity
Higgs + Heavy Singlet

**SPECIFIC MODELS**

$e^+e^− \rightarrow vv\, S \quad S \rightarrow hh \rightarrow 4b$

- Assume $h(125)$ and $S$ are the lightest NMSSM Higgs bosons
- $h$-$S$ mixing is determined from masses and $\tan\beta$
- Test of the model well above TeV Singlet mass

Complementarity between Direct searches (blue lines) and Indirect probes (h couplings, pink lines)
**Higgs + Heavy Singlet**

**SPECIFIC MODELS**

\[ e^+e^- \rightarrow \nu\nu S \quad S \rightarrow hh \rightarrow 4b \]

- \( S \) is a SM singlet state from the Twin Sector
- \( h-S \) mixing is order \( v/f \)
- Direct test of the model well above TeV Singlet mass
- Indirect test of the model well above \( f \sim \) TeV

**Indirect probes (h couplings, pink lines) probe f \sim few\ TeV**

![Figure 4: Left: NMSSM with couplings](image-url)

![TWIN HIGGS](image-url)

- Strong first order phase transition (a necessary condition for electro-weak baryogenesis), that should match to the one-step scenario of [4].
- Moreover we consider the case where the \( Z_2 \) is slightly broken, assuming it does not interfere with the dynamics of the finite temperature evolution, given the fact that the bounds attainable on \( \sin^2 \theta \) are so strong that the above condition can be easily satisfied with a decay of the singlet-like state within the detector. Therefore we plot in figure 5 isolines of 3 number of events for \( e^+e^-\rightarrow(4h+\nu\nu)[\nu\nu] \) at CLIC in the plane of \((M, HS)\), highlighting the region where EWPT is likely to happen:

\[ v_c/T_c \sim O(1) \quad \text{and} \quad M_2 \sim v_2^2/2 \]

(possibly with a cancellation between the bare and temperature-dependent mass term).
SM + light singlet

\[ \theta \approx m_1/m_2 \quad g_{\phi h} \approx m_\phi^2/\nu \]

\[ \Gamma_i = k^2 \Gamma_{i,SM} \]

Higgs couplings global fit
\[ \text{BR}(h \rightarrow \text{untagged}) < 4.3\% \quad @95\% \text{ CL} \]
\[ \sin^2 \theta < 2.3\% \quad @95\% \text{ CL} \]

\[ \Gamma(h \rightarrow \phi \phi) \propto m_\phi^4/(m_h v^2) \]

\[ \Gamma(i \rightarrow \phi \phi) = k^2 \Gamma_{i,SM} \]

Z-recoil: \( e^+e^- \rightarrow Z \phi \rightarrow Z + \text{blind} \)

3 TeV may improve a factor few thanks to
\[ e^+e^- \rightarrow 4f \]

rescaling 1801.09662

rescaling 1612.09284
Higgs + Scalars

- Even broader coverage of BSM scenarios: complex scalars, 2HDM (CP and CPV), 2HDM+Singlet
- Phenomenology is also useful as “simplified model”
Testing Naturalness
\( m_h = 125 \text{ GeV} \)

\[
\begin{align*}
\Delta &\equiv \frac{p}{O} \cdot \frac{\partial O}{\partial p} \\
m_h^2 &\approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[ \ln \frac{m_Z^2}{m_t^2} + \frac{X_t^2}{m_t^2} \left( 1 - \frac{X_t^2}{12m_t^2} \right) \right] \\
\Delta &\equiv \Delta_{\text{exp}} - \Delta_{\text{theory}}.
\end{align*}
\]

\( \Delta^{\text{exp}} \approx 0.04 - 0.08 \Rightarrow X_t @ 10\% - 20\% \\
\Delta^{\text{theory}} \approx 0.6 \Rightarrow m_t @ 1\% - 2\% \\
\Delta^{\text{exp}} \approx 0.006 \Rightarrow \tan \beta @ 30\% \\
\Delta^{\text{theory}} \approx 0.006 \Rightarrow m_t @ 30\% 

\[ X_t = A_t - \mu \cot \beta. \]
$m_h = 125$ GeV

- EFT and diagrammatic calculations still in some disagreement
- 1-2 GeV uncertainty within each calculation ⇒ Future Improvements

multi-TeV lepton colliders can probe cornerstone Higgs mass prediction of SUSY
$m_h = 125$ GeV

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multi-TeV lepton colliders can probe cornerstone Higgs mass prediction of SUSY
\[ m_h = 125 \text{ GeV} \]

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**Fig. 15:** Higgs mass dependence determined with \( \tilde{\mu} \) in both \( M_Q \) and \( \tilde{\mu} \). Corresponding mass formulae can be derived, see e.g. Ref. [113], [510].

Dercks, Moortgat-Pick, Rolbiecki

**Future Improvements**

- multi-TeV lepton colliders can probe cornerstone Higgs mass prediction of SUSY.
Testing the MSSM Higgs mass prediction

3rd Gen. Squarks at CLIC

\( \theta \)

\( \sigma(e_L e_L) \) and \( \sigma(e_R e_R) \) in principle both accessible

Pol1: \( \sigma(\tilde{t}_1), \sigma(\tilde{b}_{1,2}) \)

Pol2: \( \sigma(\tilde{t}_1), \sigma(\tilde{b}_{1,2}) \)

Pol1&2: \( \sigma(\tilde{t}_1 \tilde{t}_2) \) mixed production \( \propto \theta \)

\( \tilde{t}_1 \& \tilde{t}_2 \Rightarrow \Delta m_h = 0.2 - 1.0 \text{ GeV} \)

\( \tilde{t}_1 \& \tilde{b}_{1,2} \Rightarrow \Delta m_h = 0.1 - 0.5 \text{ GeV} \)

\( \tilde{t}_{1,2} \& \tilde{b}_{1,2} \Rightarrow \Delta m_h = 0.1 - 0.4 \text{ GeV} \)

\( \mu = 1 \text{ TeV} \)

\( \tan \beta = 20 \)

\[ \hat{h} \]

\( \begin{align*}
\hat{t}_2 & \quad 1.6 \text{ TeV} \\
\hat{b}_2 & \quad 1.4+ \text{ TeV} \\
\hat{b}_1 & \quad 1.3+ \text{ TeV} \\
\hat{t}_1 & \quad 1.2 \text{ TeV} \\
\hat{b}_1 & \quad 1.0 \text{ TeV} \\
\hat{b}_2 & \quad 0.3 \text{ TeV} \\
\end{align*} \]

6 OBSERVABLES

\( \text{MU3, MD3, MQ3, AU3, AD3} \)

improved Higgs mass prediction in MSSM required
Testing the MSSM Higgs mass prediction

3rd Gen. Squarks at CLIC  Polarization to extract $\theta_t$

Poll1: $\sigma(\tilde{t}_1), \sigma(\tilde{b}_{1,2})$
Poll2: $\sigma(\tilde{t}_1), \sigma(\tilde{b}_{1,2})$
Poll1&2: $\sigma(\tilde{t}_1\tilde{t}_2)$ mixed production $\propto \theta_t$

Test of MSSM or prediction of a gluino mass range

Predict $m_h$ with known $m_{\tilde{g}}$

Constrain $m_{\tilde{g}}$ with known $m_h$
Dark Matter
Electroweak Dark Matter: LSP (+NLSP)

- Wide open spectra
- Co-annihilation
- WIMP-like multiplet
- Accidental Dark Matter
- DM SM singlet
- $\Delta m$ (GeV)
- 0
- Generic leptons + missing momentum
- Soft-objects + missing momentum
- Short (disappearing) tracks
- Mono-photon

Electroweak Precision Tests
Electroweak Dark Matter: LSP (+NLSP)

Δm

Wide open spectra
Co-annihilation
WIMP-like multiplet
Accidental Dark Matter
DM SM singlet
\(e^+e^- \rightarrow Z' \rightarrow \chi \chi\)

0

Generic leptons + missing momentum
Soft-objects + missing momentum
Short (disappearing) tracks
Mono-photon

Electroweak Precision Tests
\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{g^2 C_{WW}^{\text{eff}}}{8} W_{\mu\nu}^{a} \Pi \left( - D^{2} / m_{\chi}^{2} \right) W^{a\mu\nu} + \frac{g^2 C_{BB}^{\text{eff}}}{8} B_{\mu\nu} \Pi \left( - \partial^{2} / m_{\chi}^{2} \right) B^{\mu\nu} \]
\[ e^+ e^- \to \bar{f}f \]

**Angular Distribution**

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{g^2 C_{WW}^{\text{eff}}}{8} W^\alpha_{\mu \nu} \Pi \left(-D^2/m^2\right) W^{\alpha \mu \nu} + \frac{g^2 C_{BB}^{\text{eff}}}{8} B_{\mu \nu} \Pi \left(-\partial^2/m^2\right) B^{\mu \nu} \]

**Heavy New Physics (EFT Limit)**

\[ \Pi \left(\frac{s}{m^2}\right) \approx \frac{1}{480 \pi^2} \cdot \frac{s}{m^2} \]

\[ C_{WW}^{\text{eff}} = \kappa (n^3 - n)/6, \quad C_{BB}^{\text{eff}} = \kappa 2 n Y^2 \]

\[ \kappa = \begin{cases} \frac{1}{2}, & \text{for RS,CS,MF,DF} \\ 1.4, & \text{else} \end{cases} \]

\[ W = \frac{g^2 C_{WW}^{\text{eff}}}{960 \pi^2} \frac{m^2_W}{m^2_\chi} \quad Y = \frac{g^2 C_{BB}^{\text{eff}}}{960 \pi^2} \frac{m^2_W}{m^2_\chi} \]

**Effects Grow with Energy**

\[ \chi \] is heavy/light new physics
\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{g^2 C_{\text{eff}}}{8} W_{\mu \nu} \Pi(-D^2/m_\chi^2) W^{\mu \nu} + \frac{g^2 C_{\text{eff}}}{8} B_{\mu \nu} \Pi(-\partial^2/m_\chi^2) B^{\mu \nu} \]

**Light New Physics**

\[ \Pi(x) = \begin{cases} 
\frac{8(x-3)+3x\left(\frac{x+4}{x}\right)^{3/2}}{12+5x+3\sqrt{\frac{x+4}{x}}(x+2)\log\left(\frac{1}{2}\left(\sqrt{\frac{x+4}{x}}-1\right)x+2\right)} & \text{(scalars)} \\
\frac{144\pi^2 x}{288\pi^2 x} & \text{(fermions)} 
\end{cases} \]

**Heavy New Physics (EFT Limit)**

\[ \Pi \left( \frac{s}{m^2} \right) \sim \frac{1}{480\pi^2} \cdot \frac{s}{m^2} \]

\[ C_{\text{WW}} = \kappa (n^3 - n)/6, \quad C_{\text{BB}} = \kappa 2nY^2 \]

\[ \kappa = \frac{1}{2}, 1, 4, 8 \text{ for RS, CS, MF, DF} \]

\[ W = \frac{g^2 C_{\text{eff}}}{960\pi^2} \frac{m_W^2}{m_\chi^2}, \quad Y = \frac{g^2 C_{\text{eff}}}{960\pi^2} \frac{m_W^2}{m_\chi^2} \]

\( \chi \) is heavy/light new physics

- **Precision**
- **Angular Distribution**

**Effects Grow with Energy**
$e^+e^- \rightarrow f\bar{f}$

**Precision**

**Angular Distribution**

\[ \cos \theta < 0.95 \text{ for all final states} \]

- $e^+e^- \rightarrow \mu^+\mu^- \sqrt{s} = 3\text{ TeV}$
  - $BSM$ effects $\sim 1\%$

- $e^+e^- \rightarrow \mu^+\mu^- \sqrt{s} = 3\text{ TeV}$
  - Beams polarization is beneficial to increase NP effects

$\chi$ is heavy/light new physics
The cross-section and 
\[ e^+e^- \rightarrow \bar{f}f \]

\[ \chi \text{ is heavy/light new physics} \]

\[ |\cos \theta| < 0.95 \text{ for all final states} \]

\[ \chi^2 = \sum_{i=1}^{10} \left( \frac{N_i^{SM+BSM} - N_i^{SM}}{N_i^{SM} + (\epsilon_i N_i^{SM})^2} \right)^2 \]

\[ \text{Systematic Unc.} \]

beams polarization is beneficial to increase NP effects
$e^+e^- \rightarrow \bar{f}f$

$|\cos \theta| < 0.95$ for all final states

\[
\chi^2 = \sum_{i=1}^{10} \frac{(N_i^{\text{SM+BSM}} - N_i^{\text{SM}})^2}{N_i^{\text{SM}} + (\epsilon_i N_i^{\text{SM}})^2}
\]

\( \chi^2 \) over 10 bins

Systematic Unc.

$\chi$ is heavy/light new physics

The relatively simple kinematic properties of the incoming beams polarization is beneficial to increase NP effects

Roberto Franceschini
WIMP: EW-ino as Dark Matter

MSSM WITH R-PARITY

large parts of parameters space have almost degenerate multiplets
WIMP is under a fair amount of pressure, still an interesting candidate to test the capabilities of a future collider.
Direct Searches

WIMP is under a fair amount of pressure, still an interesting candidate to test the capabilities of a future collider
Electroweak Dark Matter: LSP (+NLSP)

Wide open spectra
Co-annihilation
WIMP-like multiplet
Accidental Dark Matter
DM SM singlet
\( e^+e^- \rightarrow Z' \rightarrow \chi\chi \)

\[ \Delta m \]
\( \text{GeV} \)

Generic leptons + missing momentum
Soft-objects + missing momentum
Short (disappearing) tracks
Mono-photon

Electroweak Precision Tests
Electroweak Dark Matter: LSP (+NLSP)

- Wide open spectra
- Co-annihilation
- WIMP-like multiplet
- Accidental Dark Matter
- DM SM singlet
  \[ e^+e^- \rightarrow Z' \rightarrow \chi \chi \]

\[ \Delta m \]

- Generic leptons + missing momentum
- Soft-objects + missing momentum
- Short (disappearing) tracks
- Mono-photon

Electroweak Precision Tests
Short (disappearing) tracks

Higgsinos with disappearing tracks

- Higgsino LSP $\rightarrow$ nearly degenerate $\chi^0$ and $\chi^\pm$
- Results in track stub in detector
- Relies on accurate, multi-layer tracking to identify tracks that “disappear”
- Good reconstruction efficiency down to $\sim 20$ cm
- Main challenge measuring detector-induced fake track stubs
  - Further study will improve limits

**Short (disappearing) tracks**

**Higgsino DM**

- Neutral
- Charged
- Any charge

**O(CM) Disappearing Tracks**

- Displaced dilepton
- BSM lepton
- Quark
- Photon
- Anything

Clean experimental environment:
- No trigger
- No QCD background
- Tracker is closer to the beam

Challenges:
- Boost cannot make $\tilde{h}$ tracks longer

**CLIC Efficient at $d \approx 4$ cm**

**LHC Efficient at $d \approx 10$ cm**

Assume track is seen when
- $c\tau > 4.4$ cm/sin$\theta$ ($19^\circ < \theta < 90^\circ$)
- $c\tau > 22$ cm/cos$\theta$ ($13^\circ < \theta < 19^\circ$)
- $c\tau > 29$ cm/cos$\theta$ ($0^\circ < \theta < 13^\circ$)

HL-LHC can put bounds on Higgsino up to $\sim 400$ GeV

Exponential rate gain when $c\tau < 10$ cm

**Simplified Reconstruction**
Short (disappearing) tracks

HIGGSINO DM  O(CM) DISAPPEARING TRACKS

ASSUME PURE HIGGSINO LIFETIME

$c\tau = 1.2 \text{ cm} @ 200 \text{ GeV} \rightarrow 0.7 \text{ cm} @ 1 \text{ TeV}$

95% C.L. (Assuming Zero Background)

- $\geq 1$ stub
- 2 stub
- $\geq 1$ stub + $\gamma(50)$
- $\geq 1$ stub + $\gamma(100)$
- $\geq 1$ stub + $\gamma(200)$
- 2 stub + $\gamma(50)$
- 2 stub + $\gamma(100)$
- 2 stub + $\gamma(200)$

$380 \text{ GeV}$  $1.5 \text{ TeV}$  $3.0 \text{ TeV}$

$0 200 400 600 800 1000 1200$

$95\% \text{ Exclusion Reach}$

$380 \text{ GeV}$  $1.5 \text{ TeV}$  $3.0 \text{ TeV}$

$\geq 1$ stub + $\gamma(200)$  $\geq 1$ stub + $\gamma(100)$  $\geq 1$ stub + $\gamma(50)$

$\geq 1$ stub  2 stub

$m_h [\text{GeV}]$

thermal relic DM

Discussion & Conclusions

Assuming a given set of selection requirements is sufficient to attain zero expected background in the signal region, the 95% exclusion limit can be obtained for each analysis by requiring $N_{\text{evts}} = 3$. The corresponding 95% exclusion reach is illustrated in Figure 3 for each of the eight analysis strategies discussed above, at each of the three CLIC operating configurations.

All analysis strategies are capable of covering a significant range of higgsino masses, well in excess of current collider limits. The most optimistic analysis strategies – namely, those requiring at least one charged stub, or at least one charged stub in conjunction with an ISR photon of energy $\geq 50 \text{ GeV}$ or $\geq 100 \text{ GeV}$ – are capable of covering higgsino masses up to the thermal dark matter target of $m_{\tilde{h}} \approx 1 \text{ TeV}$. This demonstrates the potential for CLIC to cover a highly motivated range of supersymmetric parameter space using a search for charged stubs, though detailed study of backgrounds is required in order to determine whether the zero-background assumption is justified in each analysis strategy.
Short (disappearing) tracks

**Higgsino DM**

**O(CM) Disappearing Tracks**

**Assume Pure Higgsino Lifetime**

\[ c \tau = 1.2 \text{ cm} @ 200 \text{ GeV} \rightarrow 0.7 \text{ cm} @ 1 \text{ TeV} \]

**Discussion & Conclusions**

Assuming a given set of selection requirements is sufficient to attain zero expected background in the signal region, the 95% exclusion limit can be obtained for each analysis by requiring \( N_{\text{evts}} = 3 \). The corresponding 95% exclusion reach is illustrated in Figure 3 for each of the eight analysis strategies discussed above, at each of the three CLIC operating configurations.

All analysis strategies are capable of covering a significant range of higgsino masses, well in excess of current collider limits. The most optimistic analysis strategies – namely, those requiring at least one charged stub, or at least one charged stub in conjunction with an ISR photon of energy \( > 50 \text{ GeV} \) or \( > 100 \text{ GeV} \) – are capable of covering higgsino masses up to the thermal dark matter target of \( m_{\tilde{\chi}} \leq 1 \text{ TeV} \). This demonstrates the potential for CLIC to cover a highly motivated range of supersymmetric parameter space using a search for charged stubs, though detailed study of backgrounds is required in order to determine whether the zero-background assumption is justified in each analysis strategy.

**Figure 3:** The 95% CLIC exclusion reach for pure higgsinos in each of the eight analysis strategies, assuming zero background in each analysis.
Short (disappearing) tracks

Assume pure higgsino lifetime

$c\tau = 1.2 \text{ cm} @ 200 \text{ GeV} \rightarrow 0.7 \text{ cm} @ 1 \text{ TeV}$

95% C.L. (Assuming Zero Background)

- ≥1 stub
- 2 stub
- ≥1 stub + γ(50)
- ≥1 stub + γ(100)
- ≥1 stub + γ(200)
- 2 stub + γ(50)
- 2 stub + γ(100)
- 2 stub + γ(200)

Preliminary

$380 \text{ GeV}$
$1.5 \text{ TeV}$
$3.0 \text{ TeV}$

$m_{\tilde{h}} [\text{GeV}]$

thermal relic DM

background evaluation needed

CLIC 3 TeV yields 10 events per ab$^{-1}$ for 1.1 TeV Higgsino thermal DM candidate

Figure 3: The 95% CLIC exclusion reach for pure higgsinos in each of the eight analysis strategies, assuming zero background in each analysis.
HIGGSINO DM | O(CM) DISAPPEARING TRACKS

ASSUME PURE HIGGSINO LIFETIME

\( cT = 1.2 \text{ cm} @ 200 \text{ GeV} \rightarrow 0.7 \text{ cm} @ 1 \text{ TeV} \)

95% C.L. (Assuming Zero Background)

- \( \geq 1 \text{ stub} \)
- 2 stub
- \( \geq 1 \text{ stub} + \gamma (50) \)
- \( \geq 1 \text{ stub} + \gamma (100) \)
- \( \geq 1 \text{ stub} + \gamma (200) \)
- 2 stub + \( \gamma (50) \)
- 2 stub + \( \gamma (100) \)
- 2 stub + \( \gamma (200) \)

Preliminary

\[ N_{ev} \]

CLIC 3 TeV yields 10 events per ab\(^{-1}\) for 1.1 TeV Higgsino thermal DM candidate

\( cT_{\tilde{h}} = 0.7 \text{ cm} \)

LIFETIME AS PARAMETER (NON-PURE HIGGSINO)

- thermal relic DM
- background evaluation needed

fixed number of events with \( \geq 1 \) stubs

- \( m_{\tilde{h}} \) [GeV]

fixed number of events with 2 stubs

- \( m_{\tilde{h}} \) [GeV]
Invisible system mass lower bounded by $2m_X$

Photon energy limited by $E_{\text{beam}} - m_X$
\[ e^+ e^- \rightarrow \gamma + X \]

Invisible system mass lower bounded by \(2m_X\)

Photon energy limited by \(E_{\text{beam}} - m_X\)

bounds on new effectively invisible electroweak states (e.g. EW-inos) up to kinematic reach
Electroweak Dark Matter: LSP (+NLSP)

Wide open spectra
Co-annihilation
WIMP-like multiplet
Accidental Dark Matter
DM SM singlet
$e^+e^- \rightarrow Z' \rightarrow \chi\chi$

$\Delta m$ GeV

Generic leptons + missing momentum
Soft-objects + missing momentum
Short (disappearing) tracks
Mono-photon

Electroweak Precision Tests
Electroweak Dark Matter: LSP (+NLSP)

Δm

- Wide open spectra
- Co-annihilation
- WIMP-like multiplet
- Accidental Dark Matter
- DM SM singlet
  \[ e^+e^- \rightarrow Z' \rightarrow \chi \chi \]

- Generic leptons + missing momentum
- Soft-objects + missing momentum
- Short (disappearing) tracks
- Mono-photon

Electroweak Precision Tests
Hidden Sector
via simplified models
Hidden Valley Displaced Vertex

**Process** | $\pi^0$ lifetime [ps] | $\pi^0$ mass [GeV/c$^2$] | cross section [pb]
--- | --- | --- | ---
$h^0 \rightarrow \pi^0 \pi^0$ | 1,10,100,300 | 25,35,50 | 0.42 $\cdot$ BR
$e^+ e^- \rightarrow q \bar{q}$ | - | - | 2.95
$e^+ e^- \rightarrow q \bar{q} v \bar{v}$ | - | - | 0.55
$e^+ e^- \rightarrow q \bar{q} q \bar{q}$ | - | - | 1.32
$e^+ e^- \rightarrow q \bar{q} q \bar{q} v \bar{v}$ | - | - | 0.07

Point Of Closest Approach + Distance Of Closest Approach

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Roberto Franceschini
Hidden Valley Displaced Vertex

**CLICdp Full Simulation**

$e^+ e^- \rightarrow h \nu \nu$  $h \rightarrow \pi_V \pi_V$  $\pi_V \rightarrow b\bar{b}$

- **N=4 exclusive $k_T$ jets**
  - $qq$  $qq\nu \nu$  $qqq$  $qqqq\nu \nu$
  - # of tracks
  - # of DV
  - Mass of DV

- **Mass of $jj$**
- **Mass of 4j**
- **Jets $y_{34}$ and $y_{23}$**

Boosted Decision Tree: $\varepsilon_S \approx 0.1$

- **CLICdp**
  - $m_H = 25 \text{ GeV/c}^2$
  - $m_H = 35 \text{ GeV/c}^2$
  - $m_H = 50 \text{ GeV/c}^2$

- **$\sigma(H) \times BR(H \rightarrow \pi_V^0 \pi_V^0)$ [pb]**

- **$\alpha(H) = 0.42 \text{ pb}$**

Lifetime [ps]
re-use of simplified models
Heavy Higgs Displaced Decay

"Neutral Naturalness" scenarios: Folded SUSY, fraternal Twin Higgs, ...

CLIC 3 TeV simplified analysis:
- Interaction point Significance > 16
- "Loose" 90% b-tag efficiency
- $\Delta R_{bb} > 0.5$ for isolation
- 0.5 efficiency for $N_{\text{track}}>5$

Validation of the simplified analysis

$m_H=125, 200, 400, 600, 800, 1000$ GeV

In general conservative good agreement
Heavy Higgs Displaced Decay

BASED ON CLICDP-NOTE-2018-001

$e^+e^- \rightarrow H \nu\nu \quad H \rightarrow LLP LLP \quad c\beta\gamma\tau_0 \quad LLP \rightarrow bb$

![Graphs showing the 95% CL limit from the 1DV and 2DV analysis for various values of $m_X$. From top to bottom, $m_H = 125$ GeV, $m_H = 600$ GeV, $m_H = 1000$ GeV.]
Heavy Higgs Displaced Decay

**Based on CLICDP-NOTE-2018-001**

$e^+ e^- \rightarrow H \nu \nu \quad H \rightarrow LLP \ LLP \quad \sigma \gamma \tau_0 \quad LLP \rightarrow bb$

### Probing Motivated Parameters Space

For various values of $m_X$ at $m_H = 125$ GeV, $m_H = 600$ GeV, and $m_H = 1000$ GeV, the $\sigma(H)_{SM} \cdot \left( \frac{m_h}{m_H} \right)^2$ values are shown as a function of $c\beta\gamma\tau_0$ for the 1DV and 2DV analyses.

**Figure 4:** 95% CL limit from the 1DV analysis (left column) and the 2DV analysis (right column).
Baryogenesis
Would-be WIMP can be SM-singlet or SM-charged

$$\rho_{\text{singlet}}^\text{prod} \sim \frac{\mathcal{C}_H}{M^2} \frac{\chi^2}{2} \frac{\mathcal{C}_q^2}{M^2} (\chi \Sigma)(\Sigma \chi q) + \frac{\mathcal{C}_H}{M^2} \chi^2 (G_{\mu\nu})^2 + \ldots$$

Possible e+e- \rightarrow \nu\nu + 2 DV signal
WIMP Baryogenesis

\[ e^+e^- \rightarrow \chi\chi \nu\nu \rightarrow \nu\nu + 2 (DV \rightarrow jjj) \chi \]

assume 100% efficient vertex finder in \(3 \cdot 10^{-3} m < c\tau < 0.1 m\) (CLICdp-Note-2018-001)

\[ c\tau < 10^8 m \text{ for BBN} \]

Cosmology requires

- before nucleo-synthesis \(c\tau_\chi < 10^8 m\)
- out-of-equilibrium \(\tau_\chi > 1/H(T \sim m_\chi)\)
**EW phase transition**

- B violation
- C & CP-violation
- Modifications of the Higgs potential

With/Without S-H mixing:
- Yes/No H couplings modifications
- Yes/No single S production

No S-H mixing (exact $Z_2$ symmetry):
- HHH coupling modification
- H wave-function renormalization modification
- Pair S production

\[
\frac{\langle h \rangle}{T} \propto \frac{V_s}{T_c} > 1 \quad \text{for first order EW pt}
\]

Singlet loop makes $V(0,v)$ deeper

\[ V_{\text{therm}} \sim T^2 \]
Mixed Singlet for EW phase transition

\[ V(\Phi, S) = -\mu^2 (\Phi^\dagger \Phi) + \lambda (\Phi^\dagger \Phi)^2 + \frac{a_1}{2} (\Phi^\dagger \Phi) S + \frac{a_2}{2} (\Phi^\dagger \Phi) S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4. \]

- "healthy" potential (no runaway, minimum v=246 GeV, perturbative)
- 1st order phase transition
- HL-LHC sensitivity (from pp \( \rightarrow S \rightarrow ZZ \))
- CLIC380/3TeV Single Higgs couplings
- CLIC 1.4 TeV 3 TeV WBF S \( \rightarrow h h \rightarrow 4b \)
- CLIC hhh 20% @ 95% CL coupling measurement

Independent parameters:
\( \{v, m_1, m_2, \theta, a_2, b_3, b_4\} \).

Fixed, sampled, y-axis scanned, x-axis [0, 4\pi/3].

Parameters space of 1st order phase transition accessible by several probes.
Mixed Singlet for EW phase transition

**EW PHASE TRANSITION**

**IS IT FIRST ORDER?**

\[ V(\Phi, S) = -\mu^2 (\Phi^\dagger \Phi) + \lambda (\Phi^\dagger \Phi)^2 + \frac{a_1}{2} (\Phi^\dagger \Phi) S + \frac{a_2}{2} (\Phi^\dagger \Phi) S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4. \]

This potential is bounded from below. In the scalar potential, we have constraints which we discuss below:

- **Perturbative unitarity** and **perturbativity**
- **Absolute stability of EW vacuum**
- **Doublet mixing angle**
- **Singlet S state**
- **Mixed Singlet for EW phase transition**

In order to obtain a viable SM +Singlet +Higgs doublet, we require a vanishing vev for the singlet field in the EW broken minimum by requiring

\[ |a| < 0.05, \]

\[ \cos(p) \approx \sin(p) \approx \cos(p') \approx \sin(p') \approx \cos(p''), \]

\[ p, p', p'' \approx 0. \]

The bound on the value of \( V |a| \) is constrained by perturbative unitarity of the partial wave expansion of scattering amplitudes. The bound on the value of \( |a| \) is constrained by perturbative unitarity of the partial wave expansion of scattering amplitudes.

---

- “healthy” potential (no runaway, minimum v=246 GeV, perturbative)
- 1st order phase transition
- HL-LHC sensitivity (from pp \( \rightarrow \) S \( \rightarrow \) ZZ)
- CLIC380/3TeV Single Higgs couplings
- CLIC 1.4 TeV 3 TeV WBF S \( \rightarrow \) h h \( \rightarrow \) 4b
- CLIC hhh 20% @ 95% CL coupling measurement

The parameters space of 1st order phase transition accessible by several probes is shown in the diagram.
Mixed Singlet for EW phase transition

\[ V(\Phi, S) = -\mu^2 (\Phi^\dagger \Phi) + \lambda (\Phi^\dagger \Phi)^2 + \frac{a_1}{2} (\Phi^\dagger \Phi) S + \frac{a_2}{2} (\Phi^\dagger \Phi) S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4. \]

- \textbf{IS IT FIRST ORDER?}
- \textbf{EW PHASE TRANSITION}

○ “healthy” potential (no runaway, minimum \(v=246\) GeV, perturbative)
- 1st order phase transition
- HL-LHC sensitivity (from \(pp \rightarrow S \rightarrow ZZ\))
- CLIC380/3TeV Single Higgs couplings
- \textbf{CLIC 1.4 TeV 3 TeV WBF} \(S \rightarrow hh \rightarrow 4b\)
- CLIC \(hhh\) 20% @ 95% CL coupling measurement

Parameters space of 1st order phase transition accessible by several probes.

independent parameters \(\{v, m_1, m_2, \theta, a_2, b_3, b_4\}\).

fixed sampled \(y\)-axis scanned \(x\)-axis \([0, 4\pi/3]\).
Mixed Singlet for EW phase transition

\[ V(\Phi,S) = -\mu^2(\Phi^4) + \lambda(\Phi^4)^2 + \frac{a_1}{2} (\Phi^4)S \]

\[ + \frac{a_2}{2} (\Phi^4)S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4. \]

Independent parameters
\{v, m_1, m_2, \theta, a_2, b_3, b_4\}.

Fixed sampled y-axis scanned x-axis
[0, 4\pi/3]

“healthy” potential (no runaway, minimum v=246 GeV, perturbative)

1st order phase transition

HL-LHC sensitivity (from pp → S → ZZ)

CLIC380/3TeV Single Higgs couplings

CLIC 1.4 TeV 3 TeV WBF S → h h → 4b

CLIC hhh 20% @ 95% CL coupling measurement
Neutrinos, See-saw
**Neutrino mass mechanisms**

**LEPTON**

$L -$ violation

\((1,1,0)\) (at least 2)

\((1,1,0)\) (at least 2+1)

$L -$ not accidental

\(d = 5\) \((1,2,1/2)\) \(\frac{(LH)^2}{\Lambda}\)

\(d = 7\) \((1,1,2)\) \(\frac{(DH\sigma H)^2}{\Lambda^3} S^{--}\)

\(new\ physics\ before\ 2012\)

$L -$ gauged, SSB

\(SU(3) \otimes SU(2)_L \otimes SU(2)_L \otimes U(1)_{B-L}\)

\((1,2,1,1), (1,1,2,1), (1,2,2,1), (1,1,1,2),\)
Doubly Charged

Generically $S^{++} \to \ell^+ \ell^+$ (or $W^+ W^+$)

$$v_T = \frac{\kappa v^2}{\sqrt{2}M_T^2}$$

$$v_T < 100 \text{ KeV} \quad H^{++} \to \ell^+ \ell^+$$

$$v_T > 100 \text{ KeV} \quad H^{++} \to W^+ W^+$$

$$m_\nu \simeq \sqrt{2}v_T Y_\Delta$$

$$V(\Phi, \Delta) = - (\kappa \Phi^\dagger i\sigma^2 \Delta^\dagger \Phi + h.c.)$$

$$L_{Y_\Delta} = Y_\Delta \bar{\ell} c_i \sigma^2 \Delta \ell + H.c.$$
Mediator of Neutrino mass mechanism

**Doubly Charged**

Generically $S^{++} \to \ell^+ \ell^+$ (or $W^+W^+$)

\[
\nu_T = \frac{\kappa^2 v_T^2}{\sqrt{2} M_T^2}
\]

\[
\begin{align*}
\nu_T &< 100 \text{ KeV} \quad H^{++} \to \ell^+\ell^+ \\
\nu_T &> 100 \text{ KeV} \quad H^{++} \to W^+W^+
\end{align*}
\]

\[
m_\nu \simeq \sqrt{2} \nu_T Y_\Delta
\]

\[
V(\Phi, \Delta) = - (\kappa \Phi^\dagger i \sigma^2 \Delta^\dagger \Phi + h.c.)
\]

\[
\mathcal{L}_{Y_\Delta} = Y_\Delta \bar{\ell} c i \sigma^2 \Delta \ell + H.c.
\]

**Exclude Type-2 seesaw below 1.5 TeV**

for any Triplet VEV
**Mediator of Neutrino mass mechanism**

**Doubly Charged**

Generically $S^{++} \rightarrow \ell^+ \ell^+$ (or $W^+W^+$)

$$v_T = \frac{\kappa v^2}{\sqrt{2}M_T^2}$$

- $v_T < 100$ KeV  
  $H^{++} \rightarrow \ell^+\ell^+$

- $v_T > 100$ KeV  
  $H^{++} \rightarrow W^+W^+$

\[ V(\Phi, \Delta) = - (\kappa \Phi^\dagger i\sigma_2 \Delta \Phi + h.c.) \]

\[ \mathcal{L}_{Y_\Delta} = Y_\Delta \bar{c}i\sigma_2 \Delta \ell + H.c. \]

$m_\nu \simeq \sqrt{2}v_T Y_\Delta$

**CLIC**  
$e^+e^- \rightarrow \Delta^+\Delta^- \rightarrow WWW \rightarrow$ many jets

1.5 TeV

Exclude Type-2 seesaw below 1.5 TeV for any Triplet VEV
Mediator of Neutrino mass mechanism

\[ L_{UV} = L_{SM} + (D_{\mu}S^{++})^{\dagger}(D^{\mu}S^{++}) + \left(\lambda_{ab}(\ell_{R})_{a}(\ell_{R})_{b}S^{++} + \text{h.c.}\right) + \lambda_2(H^{\dagger}H)(S^{-}S^{++}) + \lambda_4(S^{-}S^{++})^2 + [...], \]

in total rate \( e^+e^- \rightarrow \ell^+\ell^- \)

Excluding Type-2 seesaw on the up to 10 TeV for triplet Yukawa ~0.1
Mediator of Neutrino mass mechanism

\[ \mathcal{L}_{\text{inverse}} = -Y_\nu \tilde{L} \phi R - M_R \overline{\nu}_R^c X - \frac{1}{2} \mu X \overline{X}^c X + \text{h.c.} \]

in total rate \( e^+e^- \rightarrow W^+W^-h \)

\[ M' = \begin{pmatrix} 0 & m_D & 0 \\ \lambda D & 0 & M_R \\ 0 & M_R^T & \mu X \end{pmatrix} \]

\[ m_\nu \approx \frac{m_D^2}{M_R} \mu X \]

\[ \Delta_{\text{BSM}} \text{ for } \sigma(e^+e^- \rightarrow W^+W^-H) \]

Excluded by the constraints

-25%, -40%, -28%, -25%, -35%, -30%, -25%, -30%, -40%
Time-scale

**How long**

**Does it take to get there?**

### 380 GeV Physics
- Construction
- Installation
- Commissioning

### 1.5 TeV Physics
- Construction
- Installation
- Commissioning
- Reconfiguration

### 3 TeV Physics
- Construction
- Installation
- Commissioning
- Reconfiguration

#### Construction and operation schedules

5.2.3 Schedules for the stages at higher energies and the complete project

5.2.2 380 GeV klystron-driven schedule

- Time needed for construction, installation and commissioning is eight years, compared to seven years for the 1.5 TeV and subsequent 3 TeV equipment.
- The overall upgrade schedule is very similar for the case in which the first stage is designed to be extended to higher energies.

#### 1.5 TeV Physics

- The decision about the next higher energy stage needs to be taken after 4.5 years of 380 GeV operation.
- The stop of two years in accelerator operation is needed between two energy stages.

#### 3 TeV Physics

- The stop of four years would be the minimum time needed to prepare for the next energy stage.
- A stop of two years is needed to adjust the modules for the next stage.

#### Cryogenics

- The cooling system for the klystrons and modulators is already installed underground.

#### Luminosity and integrated luminosity per year in the proposed staging scenario

- The figure shows the luminosity and integrated luminosity for 0.38 TeV, 1.5 TeV, and 3 TeV.
- The luminosity ramp-up is shown for three years.

#### Luminosity per year and integrated luminosity per year

- The total luminosity is shown in blue, and the luminosity above 99% of the peak is shown in red.
- Years are counted from the start of construction.
- About 7 years are scheduled for construction and commissioning.

#### Safety-related implementation issue

- Fire protection is the dominant safety-related implementation issue.
- Safety systems, access systems, and radiation protection systems have been studied and included in the schedules, cost and power estimates, covering all areas from injectors to beam-delivery system.

#### Experimental area

- The installation time in the main tunnel is longer, due to the RF units and the additional infrastructures required.
- The installation time is slightly different from the drive-beam option at the same CLIC energy of 380 GeV.

#### Experimental groups

- Prior to the three stages for data-taking, commissioning of the individual systems, and one full year of commissioning are needed.
- Data-taking at the first stage, commissioning of the individual systems, and one full year of commissioning are needed.
- The material presented is based on the CLIC CDR and the technology-driven CLIC schedule, showing the construction and commissioning period and decision making for the CLIC programme.

#### Annual and integrated luminosities

- Estimates of the integrated luminosity are based on an annual operational scenario.
- The above studies, carried out by the CERN civil engineering and infrastructure groups, follow the standards used for other accelerator implementations and studies at CERN (e.g. HL-LHC, FCC).

#### Technology-driven CLIC schedule

- The construction schedules presented in this section are based on the same methodologies as those used for the CLIC programme.
Time-scale (time \cdot 10^{\pm 1} ?)

- electroweak beam structure exposed
- WW scattering as a “ordinary” collision
- thoroughly explore weakly interacting physics one loop factor above weak scale
- WIMP in large SU(2) multiplets in reach
- directly access the scale of composite states or susy partners
• Standard “targets” such as vanilla SUSY, compositeness of Higgs and other states, sub-TeV WIMPs are all being probed and are under a fair amount of pressure

• Motivations for new physics to be out there are stronger than ever
- New physics can be accessible at future colliders, but no “no-loose theorem” as for LHC

★ next generation of new physics exploration has to be necessarily “broad-band”
• Searches for new physics at colliders are shifting towards increasingly *heavier* and *subtler* signals (both direct and indirect)

• multi-TeV leptonic colliders can cope well with the ever subtler heavy and light new physics signals

• multi-TeV leptonic colliders can deliver high-energy and high-luminosity ⇒ provide both *precision* and *mass reach* for BSM
• Robust potential to explore heavy new physics via EFT (universal theories dim-6, Higgs+Singlet, Higgs+scalars, …)

• Singlet Higgs boson directly probed beyond TeV for motivated values of the $h$-$S$ mixing (thorough test of NMSSM and Twin Higgs, direct+indirect)

• Precision 2→2 scattering sensitive to new electroweak states both below and above threshold (Thermal 3-plet “accidental” Dark Matter can be excluded, Sensitivity to compositeness of Higgs and rest of SM states)
• Models affecting Higgs boson potential can be probed and the nature of the EW phase-transition investigated (thorough HHH coupling, single H couplings and direct searches)

• Demonstrated sensitivity to Hidden Sectors through displaced vertexes signals in full detector simulation (ready for recast for “neutral naturalness”, baryogenesis models, …)

• Low-scale See-saw models can be probed thoroughly (Type-2&3 and gauge charged see-saw, inverse see-saw up to RH neutrinos in the 10s of TeVs)
Thank you!

Contributors: S. Alipour-Fard\textsuperscript{1}, W. Altmannshofer\textsuperscript{2}, A. Azato\textsuperscript{3,4}, D. Azevedo\textsuperscript{5,6}, J. Baglio\textsuperscript{7}, M. Bauer\textsuperscript{8}, F. Bishara\textsuperscript{9,10}, J.-J. Blaising\textsuperscript{11}, S. Brass\textsuperscript{12}, D. Battaglia\textsuperscript{13}, Z. Chacko\textsuperscript{14,15}, N. Craig\textsuperscript{16}, Y. Cui\textsuperscript{17}, D. Dereks\textsuperscript{18}, L. Di Lazaro\textsuperscript{20,21}, S. Di Vita\textsuperscript{19}, G. Durieux\textsuperscript{22}, J. Fan\textsuperscript{23}, P. Ferreira\textsuperscript{5,24}, C. Frugiuele\textsuperscript{25}, E. Fuchs\textsuperscript{26}, I. Garcia\textsuperscript{27,28}, M. Ghezzi\textsuperscript{29,30}, A. Greljo\textsuperscript{31}, R. Gröber\textsuperscript{32}, C. Grojean\textsuperscript{33}, J. Gu\textsuperscript{34}, R. Hunter\textsuperscript{35}, A. Joglekar\textsuperscript{36}, J. Kalinowski\textsuperscript{37}, W. Kilian\textsuperscript{38}, C. Kific\textsuperscript{39}, W. Kotlarski\textsuperscript{40,41}, M. Kucharczyk\textsuperscript{42}, E. Leogrande\textsuperscript{43}, L. Linssen\textsuperscript{44}, D. Liu\textsuperscript{45,46}, Z. Liu\textsuperscript{47}, D. M. Lombardo\textsuperscript{48}, I. Low\textsuperscript{49,50}, O. Matsedonskij\textsuperscript{51}, D. Marzocca\textsuperscript{52}, K. Mimasu\textsuperscript{53}, A. Mitov\textsuperscript{54}, M. Mitra\textsuperscript{55}, G. Moortgat-Pick\textsuperscript{19,17}, M. Mühlleitner\textsuperscript{56}, S. Najafizadeh\textsuperscript{57}, N. van der Kolk\textsuperscript{58}, D. Dercks\textsuperscript{59}, 8, 57, 23, N. van der Kolk\textsuperscript{60}, D. Dercks\textsuperscript{59}, 8, 57, 23, N. van der Kolk\textsuperscript{60}, D. Dercks\textsuperscript{59}, 8, 57, 23, N. van der Kolk\textsuperscript{60}, D. Dercks\textsuperscript{59}, 8, 57, 23, N. van der Kolk\textsuperscript{60}, D. Dercks\textsuperscript{59}, 8, 57, 23, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1


http://clicdp.web.cern.ch/content/wg-physics-potential
$e^+e^- \rightarrow \bar{f}f$

**Precision**

Angular Distribution

$e^+e^- \rightarrow \mu^+\mu^- \; \sqrt{s} = 3 \text{TeV}$

$\frac{1}{\sigma} \cdot \frac{d\sigma}{d\cos\theta}$

$\frac{d\sigma_{\text{BSM}}}{d\cos\theta}$

BSM effects $\sim 1\%$

$e^+e^- \rightarrow \mu^+\mu^- \; \sqrt{s} = 3 \text{TeV}$

$W = 2g^2 \frac{M_W^2}{g^*_M^2}, \quad Y = 2g'^2 \frac{M_W^2}{g^*_M^2}.$

Global fit (Unpolarized ($\delta_{\text{sys}}=0.1\%, \; \delta_{\text{sys},\tau}$))

Global fit (Polarized ($\delta_{\text{sys}}=0.1\%$))

CLIC 380 GeV (1 ab$^{-1}$), CLIC 1400 GeV (2.5 ab$^{-1}$), CLIC 3000 GeV (5 ab$^{-1}$)

Status: First draft.
\[ e^+ e^- \rightarrow \bar{f}f \]

**Angular Distribution**

\[ |\cos \theta| < 0.95 \text{ for all final states} \]

\[ \chi^2 \text{ over 10 bins} \]

\[ \chi^2 = \sum_{i=1}^{10} \left( \frac{N_{i,\text{SM+BSM}} - N_{i,\text{SM}}}{N_{i,\text{SM}} + (\epsilon_i N_{i,\text{SM}})^2} \right)^2 \]

**Systematic Unc.**

\[ W = 2 \frac{g^2}{g_*^2} \frac{M_W^2}{M_*^2}, \quad Y = 2 \frac{g'^2}{g_*^2} \frac{M_W^2}{M_*^2} \]
\[ e^+e^- \rightarrow \bar{f}f \]

**ANGULAR DISTRIBUTION**

<table>
<thead>
<tr>
<th>( \chi )</th>
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- Higgsino of split-SUSY (heavy sfermions)
- Wino of split-SUSY (heavy sfermions)
- Accidental Dark Matter 3-plet Dirac Fermion

For all the other cases the thermal mass lie well above the CLIC-3 reach.
\[ e^+e^- \rightarrow \bar{f}f \]

**Table 1: MDM candidates, together with the corresponding masses saturating the DM relic density**

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**Diagrams:**

- **Angular Distribution:**
  - \( \sqrt{s} = 1.5 \text{ TeV} \)
  - \( \sqrt{s} = 3 \text{ TeV} \)

- **Precision:**
  - \( \delta \phi \) (Lorentz invariance)
  - \( \delta \phi \) (Lorentz invariance)

- **Systematic Error:**
  - 3% systematic error

---

**Text:**

For all the other cases the thermal mass lies well above the CLIC-3 reach. For \( \mu = 0 \) cases such as Sommerfeld enhancement and bound state formation. The MDM framework was extended in [1, 2, 3, 4, 5, 6, 7, 8, 9]. The exclusions refer only to the following the shape of the real part of the form factor above threshold (cf. Fig. 1).

### Figures:

- **Figure 1:** 95% CL exclusion limits for CLIC-2 (left panel) and CLIC-3 (right panel), indicating the detailed analysis of the analysis.
- **Figure 5:** Comparison EFT vs. full form factor. The milli-charge has hence no systematic errors, but does not matter much for e.g. 0

---

**References:**

- [1, 2, 3, 4, 5, 6, 7, 8, 9]
$e^+ e^- \rightarrow \tilde{f} \tilde{f}$

**Table 1: MDM candidates, together with the corresponding masses saturating the DM annihilation cross section to the state (100) which requires a stabilization mechanism beyond the SM gauge symmetry) are summarized in Table 1.**

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**Polarization is very advantageous.**

Higgsino of split-SUSY (heavy sfermions)

Wino of split-SUSY (heavy sfermions)

Accidental Dark Matter 3-plet Dirac Fermion

**From a more phenomenological point of view, one could ask the following question:**

**2.2 Accidental Matter**

**Figure 1: 95% CL exclusion limits for CLIC-2 (left panel) and CLIC-3 (right panel), obtained by combining the results of precision tests at lepton colliders.**

**Figure 2: Comparison EFT vs. full form factor (left panel) and dependence of the form factor on $m_t$ (right panel).**

**Figure 3: Impact of systematic error: this plot shows e.g. that the $0s/m$ channel has larger systematic errors, but does not matter much for e.g. $0e$, especially when $P_{e^-} = 1$.**

**Figure 4: Polarization $e^+ e^- \rightarrow \mu^+ \mu^-$ dependence on $m_t$ with the EFT dashed line obtained by expanding the form factor at LO.**

**Figure 5: Comparison EFT vs. full form factor ($P_{e^-} = +30\%$ for the EFT).**
$e^+ e^- \rightarrow \bar{f} f$

Polarization is very advantageous

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Short (disappearing) tracks

Sensitivities:
- $D > 4.4$ cm
- $D > 0(10)$ cm

Simplified Reconstruction:
- $c\tau > 4.4$ cm/sin$\theta$ ($19^\circ < \theta < 90^\circ$)
- $c\tau > 22$ cm/cos$\theta$ ($13^\circ < \theta < 19^\circ$)
- $c\tau > 29$ cm/cos$\theta$ ($0^\circ < \theta < 13^\circ$)
Short (disappearing) tracks

Charged-Neutral mass splitting can be different if Higgsino Mixed with other states (e.g. Wino)

TAKE LIFETIME AS FREE PARAMETER
ISOLINES FOR NUMBER OF EVENTS ASSUMED FOR DISCOVERY

$\sqrt{s} = 380$ GeV 0.5/ab
$\sqrt{s} = 1.5$ TeV 1.5/ab
$\sqrt{s} = 3.0$ TeV 3.0/ab

Higgsino Lifetime