Beyond-collider physics opportunities at a Linear Facility

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The Physics Beyond Colliders (PBC) program aims to leverage the infrastructure of accelerator facilities to create new value.

Examples are the Fixed Target and Far Detector experiments, which have a strong sensitivity to light new particles (MeV~10 GeV) that feebly couple to SM particles.

The PBC programs can complement the collider experiment in the absence of heavy new particles (~TeV) at the LHC.

Many studies on PBC in the last decade (e.g., [1], [2]) have a significant impact on the design of future facilities.

This talk will focus on the PBC opportunity at the ILC.

Beam dumps at a linear collider

Circular

Beams are not often dumped during collider experiment.

Linear

Beams are always dumped

Collider Expt. and Beam dump Expt. coexist naturally
15 Beam dumps at ILC

 Photon beam dump

Tune-up dump for $e^+$

Main beam dumps

Tune-up dump for $e^-$

Focus on the potential of main beam dumps
Main beam dumps

e+/e- Beams
125 GeV, 2.6 MW
(@ Initial stage)

From collision point

11 m (~30 X₀)
1.8 m

Water

(Base design) P. Satyamurthy, et al., NIM A 679 (2012)
Being developed by N. Terunuma and Y. Morikawa
Secondary particles

Shower particles can create a large number of secondary particles and rare events.

\[ \frac{d\mathcal{L}}{d\ln x} \text{ [ab}^{-1}/\text{year]} \]

Luminosity between shower particles and proton/neutron

125 GeV, e\(^{-}\)
(1 injection)

125 GeV, 2.6 MW
Application examples of the main beam dump:

(1) Large-area irradiation field

(2) New physics search
ILC beam dumps may provide atmospheric-like radiation fields

- Material of the same weight as the ILC beam dump is piled up on the ground.

Primary cosmic rays

Primary proton spectrum (E > 1 GeV) = \(1/E^P\) (\(P = 1\) to 2.7)

Shower photon spectrum = \(1/E^2\)

1,013 hPa (= 10.3 m water pressure)

Primary beams

~10 m
Atmospheric-like radiation field is needed for soft error studies

- Soft error is a temporary malfunction of transistor, mainly caused by atmospheric neutrons and muons.

See talk of M. Hashimoto @ ILCX2021

Atmospheric Neutrons & Muons

Transistor size smaller
Error rate increase!

Hit & Error

Our life depends on integrated systems
e.g., self-driving car

- Irradiation fields that provide high-intensity, large-area, and atmospheric-like spectra are favored.

Neutrons and muons at ILC beam dump have atmospheric-like spectra?
Atmospheric-like neutrons are obtained. (consistent up to a few GeV!)

- High-energy tail behavior slightly depends on z-range
- Especially consistent at z=6-7m (~30 degrees)
- Both neutrons and muons have atmospheric-like spectra.
- Muon dominant beam is available with thick shielding.

**ILC can also be used for industrial studies.**
Application examples of the main beam dump:

(1) Large-area irradiation field

(2) New physics search
Main beam dump experiment

11 m
Beam dump

~80 m
Muon shield

50~100 m
Decay volume / Multi-layer trackers

~5 m
Calorimeter

Passive muon shield

Active muon shield

LCLS-II BSY @SLAC

Iron blocks for muon
(for radiation safety)

• Simply placed heavy objects
• Better for radiation issues
• Lower costs?

Magnetic shielding
• Effective even at High-Energy ILC
New particles from shower particles

- ILC is sensitive to small coupling and high mass region due to its large luminosity and energy.

Axion-like particles

Leptophilic Scalar

1st study: S.Kanemura, T.Moroi, T.Tanabe, 1507.02809
Heavy mesons & Tau leptons

Meson $X$

Non-diffractive

Hard QCD

$D_s^-$

$\tau^-$

$\nu_\tau$

$Br = 5.48\%$

$E_{\text{beam}} = 125\,\text{GeV}$

$D: 7 \times 10^{16}/\text{year}$

$\tau: 3 \times 10^{14}/\text{year}$

$B: 4 \times 10^{12}/\text{year}$

$E_{\text{beam}} = 500\,\text{GeV}$

$D: 5 \times 10^{17}/\text{year}$

$\tau: 2 \times 10^{15}/\text{year}$

$B: 3 \times 10^{14}/\text{year}$

M.M. Nojiri, YS, K. Tobioka, D. Ueda, 2206.13523
Heavy Neutral Leptons (HNLs)

\[
\mathcal{L} = -\lambda_{iI}(\bar{L}_i \tilde{H}) N_I - \frac{1}{2} M_I \bar{N}_I^c N_I + \text{h.c.,}
\]

\[
U_{II}^2 = \frac{v^2 |\lambda_{iI}|^2}{M_I^2}
\]

For simplicity, consider single HNL and omit index of HNL \( I \).

- Beam dump Expt. and ILC Collider Expt. is complementary
- HNL direct production from \( e^\pm \) expand sensitivity at high mass region

\( \text{ILC-250} \)

\( \text{ILC-1000} \)

\( \text{ILC Giga-Z} \)

\( \text{SHiP} \)

\( \text{FASER2} \)

\( \text{DUNE} \)

\( \text{MATHUSLA} \)

\( \text{BBN} \)
Dark matter

Similar to BDX@JLab

Pseudo-Dirac DM

Scalar inelastic DM

K. Asai, S. Iwamoto, M. Perelstein, YS, D. Ueda. 2301.03816
Background

The neutrinos hit:
- the end of the muon shield
- the wall surrounding the decay volume
- the detector

Details of BG study by SHiP Collaboration
→ arXiv: 1310.1762, 1504.04956

The cosmic-ray BG is negrigible due to:
- the deep underground location
- timing coincidence with the bunched beams

\[ E_{\text{beam}} = 125 \text{ GeV} \]
Other places

Photon beam dump

Tune-up dump
for $e^+$

Tune-up dump
for $e^-$

Main beam dumps
Tune-up dumps

- Best place to perform dedicated experiments
  - Maximum beam energy available
  - Bunch charge can be adjusted
  - Beams in good condition before the collision is available

- The facility design in this area will be modified for various experimental possibilities.

See talks @ILC2021:
Strong QED with high-power laser, M.E. Peskin.
Exotic hadron photoproduction, N. Muramatsu.
Summary

- Two examples of PBC program at ILC:

- Atmospheric-like neutron and muon
- Soft error study for large integrated system

- Beamdump experiment for new physics search
- Sensitive to small coupling and high mass region

- The ILC can accommodate a variety of PBC programs, and the facility design is improving to maximize the potential of the programs.
Backup
Photon beam from Helical undulator

Photon beam dump

~$10^{24}$ photon/year. $E \sim 10$ MeV

Optical vortex
$m$: orbital angular momentum

Figure 1: Sketch of the undulator-based ILC positron source.

Figure From F. Dietrich et.al, 1902.07744

From Wikipedia
• Very forward muon beams are obtained by $e^\pm$ beams.

• Positron dump generates more high-energy muons.

• The flux are $\sim 10^8$ times greater than the cosmic-ray. (Neutron flux is $\sim 10^{11}$ times greater than the cosmic)
Study of non-linear QED phenomena by electron - laser bunch collisions

- This understanding can also affect other research such as astrophysics and future accelerator development.

- A large quantum parameter $\chi$ can be reached with ILC beams and high intensity lasers.

- This large number makes possible to study interesting non-linear QED processes.
Photoproduction of Exotic hadrons and Heavy hadrons

From Norihito Muramatsu’s talk @ ILCX2021

Setup for hadron photoproduction experiments

Exotic hadrons

- **uudcc** pentaquark
  - $P_{c}(4312)^{+}$ etc in $\Lambda_{b}^{0} \to J/\psi pK^{-}$
  - $P_{c}(4337)^{+}$ in $B_{s}^{0} \to J/\psi pp$

- 4-quark state including $c\bar{c}$
  - $X(3872)$ in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$
  - $Z'(4430)$ in $B^{0} \to K^{-}\pi^{+}\psi'$

Heavy hadron photoproduction

- Photoproduction cross sections & spin observables must be sensitive to hadron properties.
- Complementary to LHCb, Belle-II, J-PARC, ...

<table>
<thead>
<tr>
<th>reaction</th>
<th>$E_{y}$ threshold</th>
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<tbody>
<tr>
<td>$\gamma p \to J/\psi p$</td>
<td>$8.21$ GeV ($9.44$ GeV)</td>
</tr>
<tr>
<td>$\gamma p \to E_{c}(4312) \to J/\psi p$</td>
<td>$8.71$ GeV</td>
</tr>
<tr>
<td>$\gamma p \to D_{s}^{0}L_{s}^{0}$</td>
<td>$9.47$ GeV</td>
</tr>
<tr>
<td>$\gamma p \to X(3872) p$</td>
<td>$11.9$ GeV</td>
</tr>
<tr>
<td>$\gamma p \to Z^{+}(4430) n$</td>
<td>$14.9$ GeV</td>
</tr>
<tr>
<td>$\gamma p \to X(6900) p$</td>
<td>$32.3$ GeV</td>
</tr>
<tr>
<td>$\gamma p \to Y(1S) p$</td>
<td>$57.2$ GeV</td>
</tr>
<tr>
<td>$\gamma p \to B^{+}L_{b}$</td>
<td>$62.8$ GeV</td>
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Search on shorter lifetime region with shorter shielding setup

The use of short shielding increases sensitivity to short lifetime region