Overview of LC Physics and Detector Requirements

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Nov. 9, 2004, ACFA LCWS@Taipei
Many materials from

- ACFA LC report (2001)
- TESLA TDR (2001)
- LC physics resource book for Snowmass (2001)
- GLC Project (2003)
- Linear collider report from WWS (2003)
- LHC-LC note (G.Weiglein et al. 2004)
- Response to ITRP questions (2004)
- Many from LHC, LC related workshops
- … … …

Many thanks to all
A part of Examples of Physics research covered by ILC

1st stage: $E_{cm} = 210 - 500$ GeV,
Luminosity $= \sim 200 - 500 / fb / year \times$ several years.

2nd stage: $E_{cm} = 1$ TeV

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**Goals of ILC**

1. “Unexpected” new signals
2. Electroweak symmetry breaking and mass-generation
3. Direct signals for **new physics** (SUSY, extra-dimensions, Z’….) and determine **The Physics**
4. **GUT and Planck scale** physics
Powerful Tools at ILC

- Electron/positron collision (elementary process)
- High Energy and High Luminosity
- Energy scan (controllable)
- Controllable beam polarization
- Very sensitive detectors & Trigger free
- Precise theoretical calculation (<1%)

Precise physics information & long energy reach

LHC gives us a new global (mixed) picture.

ILC gives us new dynamic multi-dimensional total views.
Signal and background Cross-section

LHC
proton - (anti)proton cross sections

ILC

Number of events / 500 fb⁻¹

$\sigma (fb)$

$\sqrt{s}$ (TeV)

events / sec for $\ell$ = 10⁻³ cm⁻²

$\sqrt{s}$ (GeV)

$\sigma (fb)$

500 x 10³

5 x 10⁴

50

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Detector Requirements

The best summarized in World-wide “Linear Collider Detector R&D”


Complete document is available from

http://blueox.uoregon.edu/~lc/randd.ps (.pdf)
Performance Goal of ILC Detectors

- **VXT**
  - Impact Parameter resolution: $< 5\mu m + 10\mu m / p(\text{GeV}) \sin^{-3/2} \theta$

- **Tracker**
  - Momentum resolution: $dp/p < 5 \times 10^{-5} \times p(\text{GeV})$ (central region)
    $3 \times 10^{-4} \times p(\text{GeV})$ for forward region
  - Angular resolution: $d\theta < 2 \times 10^{-5} \text{ rad}$ (for $|\cos \theta| < 0.99$)

- **Jet energy resolution**: $dE/E < 0.3 / \sqrt{E(\text{GeV})}$

- **Excellent Hermeticity**: down to $\theta < 5-10 \text{ mrad}$ (active mask)
In order to accomplish our physics goal at ILC

With respect to detectors at LHC:

- Inner VTX layer: 3--6 times closer to IP
- VTX pixel size: 1 / 30
- VTX materials: 1 / 30
- Materials in Tracker: 1 / 6
- Track mom. resolution: 1 / 10
- EM cal granularity: 1 / 200 !!
Most of physics needs information from all sub-detectors.

In most cases, physics sensitivity is determined by how well the sub-detectors are combined and optimized as a single detector, rather than how well each sub-detector works.

How to combine and optimize the total performance of detector

"Detector concept" is essential

Next 3 talks
To accomplish the detector optimization and comparison in the most effective way:

Need

- **Common (for ALL “concepts”) Physics Benchmarks**
  - Physics models
  - Particle properties (mass..) and decay Br
  - Energy and luminosity points
- Choose different type of event topologies

- **Common sets of Event generators**
- **Common Simulation platform(s) -- simulators/data format**
- **Common archive for Analyses Tools**
- **Common data archive**

Very good starting points: Snowmas points, Le Houche accord, etc..

It’s time for “Taipei points / scheme” for ILC
Back to ILC physics

Introduction

Higgs, SUSY, etc..
Sensitivity, Physics reach and precision

**Single production**
- Higgs
- Extra-Dimension

**Pair production**
- SUSY
- Heavy Higgs

**Intermediate state**
- Extra-Dimension
- Strong EWSB
- Z', contact Int.

**Loop effect**

<table>
<thead>
<tr>
<th><strong>LHC</strong></th>
<th><strong>ILC</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>~a few TeV</td>
<td>~1 TeV</td>
</tr>
<tr>
<td>ds/s &gt; 10 %</td>
<td>δσ/σ ~ 1%</td>
</tr>
<tr>
<td></td>
<td>δ(dσ/dΩ) ~ 1%</td>
</tr>
</tbody>
</table>

| **Energy scan, Beam pol** |
| ~0.5 TeV (any type) |
| δσ/σ ~ 1 % |
| Energy scan, Beam pol |

| **~2-3 TeV (colored)** |
| ~several TeV |
| resonance |

| >10 TeV |
| δσ/σ ~ 1 % |
| Energy scan, Beam pol |
| Coupling, spin |

| A few % level effect | A few % level effect | A few % level effect |

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Examples: Reach and beyond

Large Extra Dimension Reach

- ILC w/ transverse polarization
- ILC
- LHC

Energy Scale

- 15 TeV
- 10 TeV
- 5 TeV

Graviton emission

δn=2  δn=4  δn=6

Graviton exchange (virtual production)

Numbers are taken from J. Hewett et al

Not only the reach!

The size and number of the extra-space to be determined at ILC.

K. Odagiri

ILC w/ transverse polarization

ILC

LHC

M_D

Λ

MD (GeV)

√s = 500 GeV
= 1000 GeV
= 1500 GeV

# of extra-dimensional space

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Everyone knows power of Precision

**LEP/SLC/Tevatron**

SU(3)$_c$ X SU(2)$_L$ X U(1) Gauge interaction

3 generations

Higgs is light (114-260 GeV for SM Higgs)

SUSY GUT indication
Precision gives us a lot!
Very High precision at ILC

<table>
<thead>
<tr>
<th></th>
<th>$\delta m_W$ (MeV)</th>
<th>$\delta m_{\text{top}}$ (GeV)</th>
<th>$\delta \sin^2\theta_{\text{eff}} \times 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>now</td>
<td>34</td>
<td>3.9</td>
<td>17</td>
</tr>
<tr>
<td>TeV Run 2</td>
<td>16</td>
<td>1.4</td>
<td>29</td>
</tr>
<tr>
<td>LHC</td>
<td>15</td>
<td>1-2</td>
<td>14-20</td>
</tr>
<tr>
<td>$\text{ILC(+GigaZ)}$</td>
<td>7</td>
<td><strong>0.1</strong></td>
<td>1.3</td>
</tr>
</tbody>
</table>

$\delta m_W$ and $\delta m_{\text{top}}$ are precision parameters at various colliders. $\sin^2\theta_{\text{eff}}$ is a key parameter in EW precision at ILC+GigaZ.
First Step = Higgs

- Higgs is
  - Spin 0 (elementary?) particle
  - very sensitive to Physics between O(100GeV) to GUT/Planck scale

- Structure and coupling of Higgs sector are keys to
  - Origin of mass and spectrum of particle masses
  - Vacuum structure of Universe
  - Physics between O(100GeV) to GUT scale
  - SUSY structure and spectrum
  - Electroweak Baryogenesis
Higgs Mechanism

**Coupling-mass relation**

The Higgs vacuum-expectation-value

\[ m_i = \mathbf{v} \times \kappa_i \]

Particle mass \( \uparrow \) \( \downarrow \) Higgs coupling constant

**Higgs boson branching ratios**

**Top Yukawa coupling**

**Higgs Self-coupling**

**Mass-generation mechanism**

If one Higgs generate all masses

Different pattern If SUSY, Multi-Higgs etc..

Higgs Self-coupling

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Higgs Sector is unknown

Almost NOTHING is known

- NOTHING is known for **Yukawa-coupling**
- NOTHING is known for **self-coupling**

- Single Higgs? Two Higgs field doublets?
- Additional singlet? Triplet?

- SUSY? Extra-dimension?
- Composite?
- Type-I? Type-II?

- Why top is so heavy? Special for 3rd generation?
- **CP-violation** in Higgs sector?

- More exotics?

Electroweak fit at LEP/SLC/Tevatron tells At least one should exist below 300 GeV which couples to Z and W
LHC Higgs signal

$H \rightarrow \gamma \gamma$

CMS, SM

Bkg.

$ttH \rightarrow WbWb \rightarrow l\nu jj bbbb$

ATLAS

30 fb$^{-1}$

Bkg.

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ILC Higgs signal

Typical numbers

Tagging efficiency
~ 30-50 %

S/N > 1
3 main production modes

\[ \begin{align*}
e^+ & \rightarrow H e^- & \rightarrow W^+ e^- \\
Z^* & \rightarrow e^+ e^- & Z & \rightarrow W^+ W^- \\
e^+ & \rightarrow Z^* e^- & \rightarrow W^+ Z^- \\
e^- & \rightarrow Z^- e^+ & \rightarrow W^- Z^+ \\
e^+ & \rightarrow Z e^- & \rightarrow W^+ Z^- \\
e^- & \rightarrow \overline{Z} e^+ & \rightarrow W^- \overline{Z}^+ \\
e^+ & \rightarrow \overline{Z} e^- & \rightarrow W^+ \overline{Z}^- \\
e^- & \rightarrow Z e^+ & \rightarrow W^- Z^+ \\
e^+ & \rightarrow e^- \overline{Z} & \rightarrow e^- W^+ \\
e^- & \rightarrow e^+ Z & \rightarrow e^+ W^- \\
\end{align*} \]

$>10^5$ Higgs for 500fb$^{-1}$
Higgs coupling measurements at LHC

**Ratio** can be obtained using events with “similar” topology


\[ \Gamma_{\text{tot}} \text{ is unknown..} \]

\[ \text{Absolute strength is difficult to measure} \]

\[ \int L \, dt = 300 \, \text{fb}^{-1} \]

**Model Assumed**

- Using moderate model assumption
  - Limit on \( g_W^2 \) and \( g_Z^2 \):
    \[ \frac{g_W^2}{g_W^2(\text{SM})} , \frac{g_Z^2}{g_Z^2(\text{SM})} < 1 + 5\% \]
  - For \( M_h \) 115-150 GeV
    \[ \delta \Lambda_t / \Lambda_t \sim 15\% \]
    \[ \delta \Lambda_b / \Lambda_b > 20\% \]
  - Mainly from \( tth \) process
    \[ \delta \Lambda_{\text{top}} / \Lambda_{\text{top}} \sim 15-20\% \]
Examples of Higgs Model Independent Analyses

**Mass & Cross-section measurement**

\[ \Gamma_W = f(M_h) \times \sigma \]

\[ \delta g/g \approx 1\% \quad \delta M_h \approx 40\text{MeV} \]

**Energy scan**

- **Spin, Parity**
- **Beam polarization**
  - ZZ\(h\), WWH production (selectable)
  - CP, SU(2)\(_L\) x U(1)

**Branching ratio measurements**

**Total width measurement**

\[ \Gamma_{\text{tot}} = \Gamma_W / \text{Br}(H \rightarrow WW) \]

\[ \delta \Gamma_{\text{tot}} / \Gamma_{\text{tot}} \approx 5\% \]

**Invisible width**

Use Recoil mass (no bias)

**Absolute strength of Yukawa-Coupling determination**

\[ \Lambda_f^2 = C(M_h) \times \text{Br}(H \rightarrow ff) \times \Gamma_{\text{tot}} \]

\[ \delta \Lambda_b / \Lambda_b \approx 3\%, \quad \delta \Lambda_t / \Lambda_t \approx 4\%, \quad \delta \Lambda_c / \Lambda_c \approx 8\%, \quad \delta \Lambda_U / \Lambda_U \approx 4\% \]

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Higgs potential = Origin of EW symmetry breaking

The first access to the Higgs potential through double Higgs-boson production.

\[ \delta \Lambda / \Lambda \sim 10 - 15\% \]
Coupling Precision

LHC 300 fb^{-1} x 2

Model assumption

\[ \frac{g_W^2}{g_W^2(\text{SM})}, \frac{g_Z^2}{g_Z^2(\text{SM})} < 1 + 5\% \]
Coupling Precision

Deviation from SM value

+30%  Γ_h  c  τ  b  t  W  Z  H

0%(SM)

-30%

Model Independent Analyses
SUSY or 2HDM

ILC

Model Independent Analyses

Deviation from SM value

\[ \Gamma_h \]

\[ \cos \alpha / \sin \beta \]

\[ \sin (\alpha - \beta) \]

\[ \sin \alpha / \cos \beta \]
Extra-dimension (radion-Higgs mixing)

Model Independent Analyses
Electroweak Baryogenesis

(S.Kanemura, Y.Okada, E.Senaha '04)

Model Independent Analyses

Deviation from SM value

\[ \begin{align*}
\text{Γ}_h & \quad c \quad \tau \quad b \quad t \quad W \quad Z \quad H \\
+30\% & \quad +20\% & \quad +10\% & \quad 0\%(\text{SM}) & \quad -10\% & \quad -20\% & \quad -30\% \\
-30\% & \quad -20\% & \quad -10\% & \quad 0\%(\text{SM}) & \quad +10\% & \quad +20\% & \quad +30\% \\
\end{align*} \]

\[ m_h = 120 \text{GeV}, \sin(\alpha - \beta) = 1, \tan \beta = 1 \]

\[ m_w = M_1, m_w - m_\nu, m_\nu - m_b \]

EW Baryogenesis possible

\[ \Delta m_{\text{tot}}/\Delta m_{\text{SM}} = 10\% \]

\[ \Delta m_{\text{tot}}/\Delta m_{\text{SM}} = 30\% \]

\[ \Delta m_{\text{tot}}/\Delta m_{\text{SM}} = 50\% \]

\[ \Delta m_{\text{tot}}/\Delta m_{\text{SM}} = 100\% \]
More than one Higgs boson?

$h, H, A, H^\pm$ in the Minimal Supersymmetric Standard Model.

\[
R_{WW/\tau\tau} \equiv \frac{B(h \rightarrow W^+W^-)}{B(h \rightarrow \tau^+\tau^-)}
\]

Accurate coupling measurements tell us $M_A$

Direct and indirect searches for heavy Higgs bosons at ILC.

Top mass is also essential
Heavy Higgs ($A^0, H^0, H^+$) Discovery Reach

**LHC**

Mhmax scenario

Only $h^0$ discovery

Discovery reach depends on $\tan\beta$ and model

Good at large $\tan\beta$ case

**ILC**

$\sqrt{s} = 1000$ (GeV)

Full discovery in many channels independent of $\tan\beta$

Reach up to ~ beam energy

If measured mass at ILC/LHC ≠ predicted mass by ILC

→ **Beyond MSSM, beyond 2HDM !**
Photon-photon collider option at ILC

- **Discovery Mode** for Heavier Higgs
- Discovery reach up to ~800 GeV
- CP mixing in Higgs sector
- Gamma decay width of light Higgs
Super Symmetry
# SUSY List

## SUSY particles

<table>
<thead>
<tr>
<th>spin</th>
<th>0</th>
<th>1/2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>squark</td>
<td>quark</td>
<td></td>
</tr>
<tr>
<td>Quark family</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\bar{u}_L, \bar{d}_L)</td>
<td>(\bar{c}_L, \bar{s}_L)</td>
<td>(\bar{t}_L, \bar{b}_L)</td>
<td></td>
</tr>
<tr>
<td>u_R</td>
<td>c_R</td>
<td>t_R</td>
<td></td>
</tr>
<tr>
<td>d_R</td>
<td>s_R</td>
<td>b_R</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Lepton family</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\bar{\nu}<em>{eL}, \bar{\nu}</em>{\mu L}, \bar{\nu}_{\tau L})</td>
<td>(\bar{\nu}_{\tau L})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\bar{\nu}<em>{eR}, \bar{\nu}</em>{\mu R}, \bar{\nu}_{\tau R})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higgs boson</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\phi_1, \phi_0^+)</td>
<td>(\phi_1, \phi_0^+)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\tilde{\phi}_1, \tilde{\phi}_0^+)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gagino</td>
<td>Gauge boson</td>
<td></td>
</tr>
<tr>
<td>(\tilde{\gamma}, \tilde{Z}^0, \tilde{\phi}_1, \tilde{\phi}_2)</td>
<td>(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\tilde{W}^\pm, \tilde{\phi}^\pm)</td>
<td>(\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LHC  
ILC  

$(\gamma, Z^0, \phi_1, \phi_2) \rightarrow (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$

$(\tilde{W}^\pm, \tilde{\phi}^\pm) \rightarrow (\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$
LHC would discover SUSY phenomena quickly by ~2009, however…

1. Complicated cascade chain
2. Large SM and other SUSY backgrounds
3. Model dependence of new physics analyses

conventional SUSY sneutrino LSP (Murayama et al)
‘bosonic supersymmetry’
(Cheng, Matchev, Schmaltz)

m (ℓℓ) end-point precision ~0.3%
m (ℓℓ)_{max} threshold precision ~2%

ATLAS 100 fb⁻¹
Huge research area at ILC

- measure sparticle properties (masses, cross sections, $J^{PC}$, coupling strength, chirality, mixing)

- use these + LHC to determine underlying SUSY model and SUSY breaking mechanism

- extrapolate to GUT scale using RGEs to determine SUSY GUT mechanism

Full investigation at ILC
1st step of SUSY at ILC

eg.) Smuon production and decay

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

Spin, CP, coupling strength, etc.
precisely measure

Discovery of SUSY principle

Selectron production

\[ e^- \rightarrow \tilde{e}^- \]

\[ \tilde{e}^- \rightarrow e^- + \chi^0 \]

\[ \sqrt{s} = 350\text{GeV} \]
\[ 100 \text{ fb}^{-1} \]
\[ \text{Pol.} e^- = +0.9 \]

\[ 100 \text{ fb}^{-1} \]
\[ \sqrt{s} = 500\text{GeV} \]

\[ (m_{\tilde{g}}, m_{\tilde{\ell}}) = (200, 100)\text{GeV} \]

\[ \Delta\chi^2 = 1.0 \]
Using the $M(\chi^0_1)$ from ILC

300 fb$^{-1}$@LHC
$\Delta M$ values in GeV

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>LHC+LC (0.2%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{\tilde{\chi}^0_1}$</td>
<td>4.8</td>
<td>0.19</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{\ell}}$</td>
<td>4.8</td>
<td>0.34</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{\chi}^0_2}$</td>
<td>4.7</td>
<td>0.24</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{q}_L}$</td>
<td>8.7</td>
<td>4.9</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{b}_1}$</td>
<td>13.2</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Significant improvements even if only $m(\chi^0_0)$ is measured at ILC

Strong correlation at LHC
An input from ILC resolve this correlation
Pin down physics models

Example 1)

**Discrimination between different SUSY-breaking scenarios**

Type-I string inspired models

EU: early unification at $10^{11}$ GeV

GUT: string scale at GUT scale $\sim 10^{16}$ GeV

Mirage: Intermediate string scale at $10^{11}$ GeV + Mirage unification

---

![Diagram showing discrimination between SUSY-breaking scenarios](image-url)
Discovery of a new principle: GUT

Discovery of M1-M2 gaugino Grand Unification

- Mass
- Coupling
- Chirality
- Mixing

From selectron and chargino productions

Δχ² = 1.00
= 2.28
= 4.61

Input: M₂ = 250 GeV

GUT: M₁ = \frac{5}{3} \tan^2 \theta_W M₂

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Evolution of scalar fermion mass parameters

(a) $M^2_j \ [10^3 \text{ GeV}^2]$  

(b) $M^2_j \ [10^3 \text{ GeV}^2]$

G.A.Blair, W.Porod, and P.M.Zerwas

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Determining SUSY breaking mechanism

LHC+ILC
Combined analysis

SUSY breaking scenario

Super Gravity (mSUGRA)
G.A.Blair, W.Porod, and P.M.Zerwas

Gauge Mediation

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Cosmology: Dark Matter = LSP?

WMAP \(0.094 < \Omega h^2 < 0.128\) (2 sigma)

\[\text{W}^{\text{WMAP}} \text{ Planck} \approx \text{LHC} \approx \text{ILC}\]

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- ‘WMAP’ \(7\%\)
- LHC \(\approx 15\%\)
- ‘Planck’ \(\approx 2\%\)
- ILC \(\approx 3\%\)
Flavor Violation in SUSY sector

e.g) SUSY-Seesaw model

ILC $E_{cm}=800$ GeV

$mSUGRA$ points

$\sigma(e^+e^-\rightarrow \tau^+\mu^-+2\chi^0)/$ fb

$Br(\tau \rightarrow \mu \gamma)$
Inspired by superstring theory, a scenario with large extra-dimension is proposed.

Quarks, leptons, and gauge bosons live in a 3-dimensional wall. Gravity can propagate in 3+n dimensional space.
Search for extra-space at ILC

Graviton emission to extra-space

Graviton exchange

The size and number of the extra-space may be determined at LC.
Number of dimension determination
By two energies at ILC

\[ e^+ e^- \rightarrow \gamma G_n \]

\( \sqrt{s} \) (GeV)

\[ \sigma \ (fb) \]

500 GeV

1 TeV

\( \delta = 2 \)

3

4

5

6

7

G. Wilson et al.
Final Goal of Physics at ILC together with LHC

Elucidate Mystery of VACUUM

Higgs

Vacuum structure

Origin of Mass

Dark Energy

Origin of UNIVERSE

Ultimate Theory

GUT
Quantum Gravity
Super String

New Principles

Space-time Structure

SUSY

Dark Matter
Super Gravity

5th-Dimension, Extra-Dimension

Brane world

Unexpected New World!

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