Stop and Decay of Long-lived Charged Massive Particles at the LHC detectors

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Collaborated with
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Main Claim of This Talk

Long-lived charged massive particle produced at LHC

Some of them stop in the LHC detector

Detect the decay in beam-off period

• Beam damping signal by Event Filter
• Winter shutdown

Lifetime Measurement
Plan

1. Long-lived charged massive particle
2. Stop of charged particle
3. Measurement of stopped particle decay
4. Summary
1. Long-lived charged massive particle
Long-lived charged massive particle (CHAMP)

CHAMP appears in various beyond-standard model

e.g., in SUSY framework:

Scalar tau lepton $\tilde{\tau}$ in Gauge Mediation

$$\tilde{\tau} \rightarrow \tilde{G}_{3/2} + \tau$$

$$\tau_{\tilde{\tau}} \sim 10^5 \text{ sec} \left( \frac{m_{\tilde{\tau}}}{100 \text{ GeV}} \right)^{-5} \left( \frac{m_{3/2}}{1 \text{ GeV}} \right)^2$$
Other Examples

Charged Wino $\tilde{W}^\pm$ in Anomaly Mediation

Scalar tau lepton $\tilde{\tau}$ in Gravity Mediation

R-parity breaking model
CHAMP’s Impacts

CHAMP is important in particle physics and cosmology

e.g., Solution to Li7 problem in BBN
CHAMP’s Impacts

CHAMP is important in particle physics and cosmology

e.g., Solution to Li7 problem in BBN

However,
Most important point:

Greatest Evidence of the BSM
CHAMP at the LHC

Long-lived CHAMPs are produced

Charged track $\sim$ heavy muon

Kinematical information:

Mass, Spin, Flavor of CHAMPs

What is the Next Target?
CHAMP at the LHC

Long-lived CHAMPs are produced

\[ \text{Charged track} \sim \text{heavy muon} \]

Kinematical information:

Master CHAMPs

Decay of the CHAMP

What is the Next Target?
Decay of CHAMP

CHAMP must decay
(otherwise, charged dark matter)

Decay of CHAMP may provide fundamental physics
Decay of CHAMP

Example: Gauge Mediation model

\[ \tilde{\tau} \rightarrow \tilde{G}_{3/2} + \tau \]
Decay of CHAMP

Example: Gauge Mediation model

\[ \tilde{\tau} \rightarrow \tilde{G}_{3/2} + \tau \]

\[ \mathcal{L}_{\text{SUGRA}} \sim \frac{m_{\tilde{\tau}}^2}{M_P m_{3/2}} (\tilde{\tau} \tilde{G}_{3/2} \tau) \]

\( M_P \): Planck mass
Decay of CHAMP

Example: Gauge Mediation model

\[ \tilde{\tau} \rightarrow \tilde{G}_{3/2} + \tau \]

\[ \mathcal{L}_{\text{SUGRA}} \sim \frac{m_{\tilde{\tau}}^2}{M_P m_{3/2}} (\tilde{\tau}\tilde{G}_{3/2}\tau) \]

\[ M_P: \text{Planck mass} \]

\[ \tau_{\tilde{\tau}} \sim \frac{M_P^2 m_{3/2}^2}{m_{\tilde{\tau}}^5} \]

\[ M_P^2 \sim \frac{m_{\tilde{\tau}}^5}{m_{3/2}^2 \tau_{\tilde{\tau}}} \]
Decay of CHAMP

\[ \tilde{\tau} \rightarrow \tilde{\mathcal{G}}_{3/2} + \tau \]

\[ M_P^2 \sim \frac{m_{\tilde{\tau}}^5}{m_{3/2}^2 \tau \tilde{\tau}} \]

\[ M_P: \text{ Planck mass} \]
Decay of CHAMP

\[ \tilde{\tau} \rightarrow \tilde{G}_{3/2} + \tau \]

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Kinematic information

\[ M_P: \text{ Planck mass} \]

Lifetime measurement
Decay of CHAMP

\[ \tilde{\tau} \rightarrow \tilde{G}_{3/2} + \tau \]

Planck Scale Measurement at collider

Kinematic information

Lifetime measurement
Decay of CHAMP

\[ \tilde{\tau} \rightarrow \tilde{G}_{3/2} + \tau \]

Planck Scale Measurement at collider

Kinematic information

Lifetime measurement

Test of Supergravity at collider
Lifetime Classification

Case I: short lifetime \( \mathcal{O}(1) \text{ cm} < c\tau < \mathcal{O}(10) \text{ m} \)

Case II: semi-long lifetime \( \mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km} \)

Case III: long lifetime \( \tau > \mathcal{O}(0.01) \text{ sec} \)
For Short Lifetime

Case I: short lifetime $\mathcal{O}(1) \text{ cm} < c\tau < \mathcal{O}(10) \text{ m}$
How can we measure the Lifetime

Case II: semi-long lifetime $\mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km}$
How can we measure the Lifetime

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Almost all CHAMPs escape

Beam
How can we measure the Lifetime

Case II: semi-long lifetime $\mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km}$

Almost all CHAMPs escape

Fraction of decays occur in detector
How can we measure the Lifetime

Case II: semi-long lifetime $\mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km}$

Almost all CHAMPs escape

$$c\tau \sim \frac{\text{# of CHAMPs}}{\text{# of decays inside of detector}} \times \text{detector size}$$

Fraction of decays occur in detector
Summary of shorter lifetime measurement

**Case I**: short lifetime \( \mathcal{O}(1) \text{ cm} < c\tau < \mathcal{O}(10) \text{ m} \)

Direct measurement of decay length

**Case II**: semi-long lifetime \( \mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km} \)

Number counting of in-flight decays

\[ \mathcal{O}(10^{-3}) \text{ sec} \]

How about \( >\mathcal{O}(0.01) \text{ sec} \) case?
2. Stop of charged massive particle
Main claim of this section

Some fraction of CHAMPs have low velocity

Low velocity CHAMP stops in matter
Model Point

For concreteness, we assume SUSY benchmark point SPS7

- $\tilde{g}$
- $\tilde{q}$
- $\tilde{\chi}_1^0$
- $\tilde{\tau}$ 124 GeV

Gauge mediation
Event Topology at the LHC

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

Charged track
Stopping CHAMPS

$\beta\gamma$ distribution of $\tilde{\tau}$
Stopping CHAMPs

$\beta\gamma$ distribution of $\tilde{\tau}$

Stopping range

$R/M (g \text{ cm}^{-2} \text{ GeV}^{-1})$ vs $\beta\gamma = p/Mc$
Stopping CHAMPs

$\beta\gamma$ distribution of $\tilde{\tau}$

For 1 m Fe and 124 GeV CHAMP
Stopping CHAMPs

$\beta\gamma$ distribution of $\tilde{\tau}$

For 1 m Fe and 124 GeV CHAMP
Stopping CHAMPs

$\beta\gamma$ distribution of $\tilde{\tau}$

For 1 m Fe and 124 GeV CHAMP
Summary of this section

Some fraction of CHAMP have low velocity

Low velocity CHAMP stops in Matter
3. Measurement of Stopped CHAMP decay
Previous Attempt

Stopper and detector

[K.Hamaguchi, M.M.Nojiri, A.Roeck 06]
Previous Attempt

Stopper and detector

Needs additional detector!

[K. Hamaguchi, M. M. Nojiri, A. Roeck 06]
Our Present Study

LHC detector is very massive

CHAMP stops in LHC detector

For ATLAS HCAL

Barrel 1440 mm Fe
Endcap 1400 mm Cu
Our Present Study

For ATLAS HCAL

Existing detector as Stopper

Barrel 1440 mm Fe

Range corresponding to HCAL

about 800 stopping CHAMPs for 10 fb\(^{-1}\)

(All CHAMPs: 70000)
Detection of Late-time Decay

Stopped CHAMPs (stau) decay in some time

Detection of the decay?
Detection of Late-time Decay

Stopped CHAMPs (stau) decay in some time

However...

- Wrong timing and wrong direction
- Background

Difficult to trigger
Detection of Late-time Decay

Stopped CHAMPs (stau) decay in some time

However...

• Wrong timing and wrong direction
• Background

Difficult to trigger

... during PP collision
Main Idea

Stop the PP collision

Optimize the trigger menu for CHAMP decay
(only one isolated energetic cluster (> 10GeV) in HCAL)

Strategies

Short lifetime \( O(\text{sec}) - O(\text{hour}) \)
  • Beam damp signal

Long lifetime \( O(\text{day}) - O(\text{year}) \)
  • Winter shutdown of LHC operation
  • a couple of hours rest between each run
Beam Damp Strategy

Short lifetime $O(\text{sec}) - O(\text{hour})$

- Beam damp signal

Stopping event

Time
Beam Damp Strategy

- Stopping event
- Beam stop
- Online Event Filter

Short lifetime $O(\text{sec}) - O(\text{hour})$
- Beam damp signal
Beam Damp Strategy

Short lifetime $O(\text{sec}) - O(\text{hour})$

- **Beam damp** signal

Online
Event
Filter

Stopping event

Beam stop

Change trigger menu
$O(10) \text{ min} - O(1) \text{ hour}$
Beam Damp Strategy

Short lifetime $O(\text{sec}) - O(\text{hour})$

- Beam damp signal

Online Event Filter

Stopping event

Beam stop

Change trigger menu

$O(10) \text{ min} - O(1) \text{ hour}$

Restart PP collision

Time
Beam Damp Strategy

Online Event Filter

Stopping event

Beam stop

Decay

Change trigger menu
\( \mathcal{O}(10) \) min – \( \mathcal{O}(1) \) hour

Restart PP collision

Short lifetime \( \mathcal{O}(\text{sec}) – \mathcal{O}(\text{hour}) \)

• Beam damp signal
Beam Damp Strategy

**Short lifetime** $O$(sec) – $O$(hour)

- Beam damp signal

Online Event Filter

Beam stop

Decay

Restart PP collision

Dead time $O(1)$ sec

Change trigger menu

$O(10)$ min – $O(1)$ hour
Event Filter

$E_T > 100$ GeV

$p_{T_{jet1}} > 100$ GeV and $p_{T_{jet2,3}} > 50$ GeV
Event Filter

$E_T > 100 \text{ GeV}$

$p_{T\text{jet}_1} > 100 \text{ GeV}$ and $p_{T\text{jet}_{2,3}} > 50 \text{ GeV}$

\text{Standard SUSY cut}
Event Filter

$E_T > 100$ GeV
$\ p_{T_{\text{jet}1}} > 100$ GeV and $p_{T_{\text{jet}2,3}} > 50$ GeV

+ disappeared track
Event Filter

$E_T > 100 \text{ GeV}$

$p_{T_{\text{jet}1}} > 100 \text{ GeV}$ and $p_{T_{\text{jet}2,3}} > 50 \text{ GeV}$

Energy deposit $< 0.2 \times p$

No “muon” track

Muon chamber

Calorimeter

Inner tracker

Beam

Isolated track with $p_T > 0.1 \times m_{\text{CHAMP}}$
Event Filter

2.3 Events per day for $10^{33} \text{ cm}^{-2}\text{s}^{-1}$
0.6% of all SUSY events

Energy deposit < $0.2 \times p$

No “muon” track

Muon chamber

Calorimeter

Inner tracker

Beam

Isolated track with $p_T > 0.1 \times m_{\text{CHAMP}}$
## Result of Beam Damp Strategy

<table>
<thead>
<tr>
<th>lifetime</th>
<th>$\langle N_D \rangle$ (10 fb$^{-1}$)</th>
<th>$\sigma$ (10 fb$^{-1}$)</th>
<th>$\langle N_D \rangle$ (100 fb$^{-1}$)</th>
<th>$\sigma$ (100 fb$^{-1}$)</th>
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<tbody>
<tr>
<td>0.1 sec</td>
<td>0.008</td>
<td>±0.1 sec</td>
<td>0.08</td>
<td>±0.1 sec</td>
</tr>
<tr>
<td>0.2 sec</td>
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<td>±0.15 sec</td>
<td>12</td>
<td>±0.07 sec</td>
</tr>
<tr>
<td>0.5 sec</td>
<td>23</td>
<td>±0.1 sec</td>
<td>233</td>
<td>±0.04 sec</td>
</tr>
<tr>
<td>1 sec</td>
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For Long Lifetime

- Winter shutdown of LHC operation

Running period \quad \sim 100 \text{ days}
For Long Lifetime

Long lifetime $O(\text{day}) - O(\text{year})$

- Winter shutdown of LHC operation

Running period | Shutdown period \(\sim 100\) days

Stopping event
For Long Lifetime

- Long lifetime \( \mathcal{O}(\text{day}) - \mathcal{O}(\text{year}) \)

- Winter shutdown of LHC operation

Running period

Late-time decay

Stopping event

Shutdown period \( \sim 100 \) days

Time

Optimized trigger
Result of Shutdown Strategy

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<tr>
<td>300 year</td>
<td>0.5</td>
<td>—</td>
<td>5</td>
<td>$^{+224}_{-88}$ year</td>
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### Combined Result

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O(0.1) sec – O(100) year lifetime measurement

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Summary

• Measurement of CHAMP’s lifetime is important.

• CHAMP can stop in the LHC detector.

• By damping beam, CHAMP can be detected.

• Wide range of lifetime measurement is possible.
Discussion

• Other CHAMP study

• Other Strategies
  • Use of empty bunch
  • Changing the beam-orbit with Event Filter signal
Bunch Disposition in the LHC, SPS and PS

LHC (1-Ring) = 88.924 µs

SPS = 7/27 LHC

PS = 1/11 SPS

Filling Scheme

\[3564 = \{[(72b + 8e) \times 3 + 30e] \times 2 + [(72b + 8e) \times 4 + 31e]\} \times 3 + [(72b + 8e) \times 3 + 30e] \times 3 + 81e\]

Beam Gaps

\[\tau_1 = 12\ \text{missing bunches (72 bunches on h=84)}\]
\[\tau_2 = 8\ \text{missing bunches (SPS Injection Kicker rise time = 220 ns.)}\]
\[\tau_3 = 38\ \text{missing bunches (LHC Injection Kicker rise time = 0.94 µs.)}\]
\[\tau_4 = 39\ \text{missing bunches ( \" \")}\]
\[\tau_5 = 119\ \text{missing bunches (LHC Dump Kicker rise time = 3 µs.)}\]
Bunch

No collision timing is also available?

**Bunch Disposition in the LHC, SPS and PS**

LHC (1-Ring) = 88.924 μs

- 3-batch
- 4-batch

SPS = 7/27 LHC

3564 = \{(72h + 8e) x 3 + 30e\} x 2 + \{(72h + 8e) x 4 + 31e\} x 3

**Filling Scheme**

**Beam Gaps**

- \(τ_1 = 12\) missing bunches (72 bunches on h=84)
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P. Collier 12/6/2009
Missing Energy

Diagram showing particle interactions:
- Two protons (P) at the ends.
- Two charged tracks (charged track).
- Intermediate particles:
  - $\tilde{q}$
  - $q$
  - $\tilde{\chi}_1^0$
  - $\tilde{\tau}$
  - $\tau$
If stau is produced, tau fermion (including neutrino) is also produced. (flavor conservation)
If stau is produced, tau fermion (including neutrino) is also produced. (flavor conservation)

Neutrino emission (missing energy)
For Short Lifetime

Case I: short detector size

[S. Asai, T. Moroi, T. T. Yanagida 08]
For Long Lifetime

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**Running period**

**Late-time decay**

**Stopping event**

**Shutdown period $\sim 100 \text{ days}$**

\[ \Delta t_1 \]

\[ \Delta t_2 \]
For Long Lifetime

- Winter shutdown of LHC operation

Stopping event

Late-time decay

Running period

Time

\[ \Delta t_1 \]

\[ \Delta t_2 \]