How to exploit the available LHC data

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Why BSM at LHC?

TODO list of particle physics:

- Dark Matter
- Dark Energy
- Origin of Baryon
- Origin of Neutrino Mass
- Naturalness
- Quantum Gravity
- ....
Why BSM at LHC?

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DM Candidates

• Axion

• (Primordial) Black hole

• WIMP

• Others…
WIMP Dark Matter

Weakly Interacting Massive Particle

DM abundance

DM

Standard Model (SM) particle

SM

500 GeV DM

500 GeV DM

Dark Matter Yield n_{DM}/s

Temperature T [GeV]

Time
WIMP Miracle

\[ \Omega_{\text{DM}} \simeq 0.2 \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{ cm}^3/\text{s}} \right)^{-1} \]

\[ 10^{-26} \text{ cm}^3/\text{s} \simeq 10^{-9} \text{ GeV}^{-2} \sim \frac{\pi \alpha^2}{m_{\text{DM}}^2} \]

Heavier DM → More DM abundance.

To avoid too much DM abundance,

\[ m_{\text{DM}} < O(1) \text{ TeV} \]
Plan

1. WIMP Dark Matter
2. Wino Dark Matter
   - Direct Signal of Wino
   - Indirect Signal of Wino
3. Synergy with other DM Searches
4. Summary
So Many WIMP Candidates...

- Bino
- Wino
- Higgsino
- KK photon
- T-odd Photon
- Technibaryon
- Minimal 5plet fermion
- Minimal singlet scalar
- Minimal 7plet scalar
- ...
Why Wino.

- Natural prediction of anomaly mediation model.
  - SUSY models consistent with flavor/CP, Higgs mass and GUT.
- Most minimal dark matter.
  - Only one free parameter.
- Rich signature at direct/indirect dark matter search.
  - Within a few decades, both searches can cover all the region.
- Rich signature at LHC.
  - LHC search technology is also applicable to broad BSM
Wino Property

- Majorana fermion
- Hypercharge $Y=0$
- $SU(2)_L$ triplet
- Mass $< 3$ TeV

[Hisano, Matsumoto, Nagai, Saito & Senami, 06]
Wino Spectrum

\[ \Delta m \simeq 165 \text{ MeV} \]

\[ c\tau(\tilde{W}^\pm \to \tilde{W}^0 \pi^\pm) \simeq 7 \text{ cm} \left( \frac{\Delta m}{165 \text{ MeV}} \right)^{-3} \]

[Ibe, Matsumoto, Sato 12]
Direct LHC Signals

Jet + Missing energy
+ Charged track
+ (Displaced) Soft pion

$O(1-10)\text{cm}$
Indirect Signatures

Indirect probe of quantum effect of DM

Precision measurement of SM processes
LHC Signatures of Wino

- Mono-jet + missing energy
- (Disappearing) charged tracks
- (Displaced) soft tracks
- Quantum effects to the SM processes

More detailed studies are important for not only Wino but more generic BSM.
Direct Signals
Mono-jet Signatures

- Most generic signals of BSMs including DM.
- Huge Background.
- Large systematic uncertainties.
- Current Wino constraints is around 150 GeV.
Mono-jet Signatures

350 GeV Wino
Beyond Mono-Jet?

- Combination of jet + photon + MET.
  - S/N can be improved by around 50%
    [Ismail, Izaguirre & Shuve, 1605.00658]

- Mono W or Z.
  - Most sensitive in some DM model.
    [Bai & Tait, 1208.4361]
Disappearing track

- So far, most powerful probe for Wino.

- With combination with MET, Wino constraint is 460 GeV.
Disappearing track

When I worked on [Asai, Azuma, Jinnouchi, Moroi, SS, Yanagida, 0807.4987 ]

I was told:

“TRT (Transition Radiation Tracker) is a must, and so CMS cannot.”
But CMS did
Disappearing track

![Diagram showing the expected track and measurements for TRT, SCT, Pixel, and IBL layers.](image)
Much shorter track

- How short tracks can be used at Run 2 or future?
  - Reconstruction of smaller number of hits is possible?
  - Useful for Higgsino or 5plet DM search.
  - Measurement of lifetime of charged particle.
- Two disappearing tracks events are detectable?
  - Background reduction.
  - Measurement of production channel.
- Events without MET can be detectable?
  - Now, MET is a must as trigger.
Minimal fermionic DM

<table>
<thead>
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<th>$U_Y(1)$ Charge</th>
<th>$\mathbf{SU_L}(2)$ Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y$</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>C</td>
</tr>
<tr>
<td>1/2</td>
<td>C</td>
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<td>C</td>
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<tr>
<td>3/2</td>
<td>C</td>
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<tr>
<td>2</td>
<td>C</td>
</tr>
<tr>
<td>...</td>
<td>C</td>
</tr>
</tbody>
</table>
Interplay with DM direct detection

In SUSY,

Lifetime of charged Higgsino

Direct detection rate

Gaugino masses

Spin independent

Cross section [cm$^2$]
Interplay with DM direct detection

In SUSY,

Lifetime of charged Higgsino

Direct detection rate

Gaugino masses

Direct detection

Collider

0.5 TeV Higgsino
Soft Tracks

I was also told:

“Soft tracks from Wino decay are invisible”

\[ \Delta m \approx 165 \text{ MeV} \]

Soft objects were important for the wino search at LEP.

So how about (displaced) tracks from

- 350 MeV, 500 MeV, O(1) GeV?
- Higgsino
- 5plet DM
- Natural SUSY
Soft Tracks

Soft pions are crucial for measurement of mass spectrum

Determination of quantum number of DM and heavier physics

Soft objects are generic feature of DM coannihilation scenario.
Indirect Signals
Indirect Probe at LHC

Interference between SM and BSM gives correction
Observed Data
Correction from DM

Relative correction from 300 GeV Wino
Correction from DM

Relative correction from 300 GeV Wino

gauge running. $\sim \log(s)$

$\Delta \sim - \left( \frac{n}{3} \right)^3 \%$

$\frac{(\hat{\sigma}_{BSM} - \hat{\sigma}_{SM})}{\hat{\sigma}_{SM}}$
Indirect Probe at LHC
Indirect Probe at LHC

# of SU(2)\textsubscript{L} representation
Mono-lepton Case

Mono-lepton signal may be better.
Indirect Probe at LHC

# of SU(2) representation

dilepton

mono-lepton
Indirect Search

- Precision measurements can probe DM, and be as powerful as mono-jet + MET search.
  - Future 100 TeV collider covers even Higgsino DM.
    [Chigusa, Ema & Moroi, 1810.07349, and Luzio, Grober & Panico, 1810.10993]

- Applicable to any kinds of BSM particle which has gauge charge.

- Independent on how particle decays.
Precision measurement

• R-parity violation, Z prime and lepto-quark has tree-level correction.

• Resonance with very huge width.

• Generic higher-dimensional operator search.

• …
Precision with Run 2 Data

• Reduction of uncertainty in low-mass region.

• More detailed public data:
  • Useful for theorists to test own models.
  • E.g., correlation of error of each data bin.
Synergy with other DM searches
DM Search and synergy

At collider, we can discover DM-like particles.

But we cannot conclude this is really DM particle.

The most important feature of DM is its lifetime

\[ > 10^{27} \text{ sec} \]

Lifetime measurement is difficult at collider.
DM Search and synergy

Large Wino annihilation rate
[Hisano, Matsumoto, Nojiri, Osamu & Saito, 04]

Wino-Nucleon XS $\sim 10^{-47}$ cm$^2$
[Hisano, Ishiwata & Nagata, 12]
DM Search and synergy

Biggest advantage of collider for DM physics is measurement of DM particle property.

- Cross section
- Mass spectrum
- Lifetime of DM partner
- ...

Cross check of direct/indirect DM signatures is essential.
Summary and Discussion

- LHC result is wonderful.
- Still it is important to investigate harder experimental signatures.
  - Shorter tracks, softer tracks.
  - Further reduction of systematic uncertainty of SM process.
  - Possible with higher luminosity/energy?
- ATLAS and CMS combined analysis is possible?
- Knowing limit of ability of Run2 is essential for future collider strategy.

- Not only discovery but future measurement should be considered.
Fit