Dark matter at colliders

Lian-Tao Wang
University of Chicago

PPC 2011, CERN
June 15, 2011
We have solid evidence that dark matter:
We have solid evidence that dark matter:

- gravitates.
We have solid evidence that dark matter:

- gravitates.
- is dark.
We have solid evidence that dark matter:

- gravitates.
- is dark.
- Only NP beyond SM discovered so far.
TeV dark matter: WIMP miracle.

- If dark matter is
  - Weakly interacting: $g_D \sim 0.1$
  - Weakscale: $M_D \sim 10s$ GeV - TeV
  - We get the right relic abundance of dark matter.

- A major hint of TeV scale new physics.
  - We can produce and study them at the LHC!

Rate in thermal eq. $\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$

Freeze out: dropping out of thermal eq.

Stronger coupling, lower abundance.
Candidates, models, scenarios...

Different spin

Different $Z_2$

LSNPs:

SUSY LSP

Extra Dim. LKP

T-parity LTP

LZP

L...P

$Z_3$
Candidates, models, scenarios...

Model independent

Effective operator

Different spin
different $Z_2$

LSNPs:
SUSY LSP
Extra Dim. LKP
T-parity LTP
LZP
L...P
$Z_3$
Candidates, models, scenarios...

Model independent

Different spin different $Z_2$

Effective operator

Extended Models

LSNPs:
- SUSY LSP
- Extra Dim. LKP
- T-parity LTP
- LZP
- L...P
- $Z_3$

dark sectors

Wednesday, June 15, 2011
Searching for WIMP dark matter

Indirect detection:
AMS2, PAMELA, Fermi-LAT

Direct detection:
CDMS
CoGeNT
COUPP
CRESST
DAMA
XENON

Collider searches:
LEP
LHC
Tevatron
Searching for WIMP dark matter

Indirect detection:
AMS2, PAMELA, Fermi-LAT

DM

Direct detection:
CDMS
CoGeNT
COUPP
CRESST
DAMA
XENON

Collider searches:
LEP
LHC
Tevatron

This talk.
This talk, a brief overview of

- Search for SUSY dark matter, and measure its properties.
  ▶ Highlight challenges.

- Connection between collider searches and direct detection.

- Dark sector.
Search for SUSY dark matter
Discovering dark matter:

- DM candidate embedded in an extended TeV new physics scenario

- Could be early discovery.

Lightest superpartner (LSP)
Neutral and stable.

partners: $\tilde{g}$, $\tilde{q}$, $\tilde{W}$, $\tilde{Z}$, $\tilde{\ell}$, ...

DM candidate
Could be harder to make sure.

- For example: the “well tempered” scenario. Nearly degenerate NLSP and LSP.

\[ m_{\text{NLSP}} - m_{\text{LSP}} \sim 10 - 20 \text{ GeV} \]

See also, S. Gori, P. Sechwaller, C. Wagner, 1103.4138
LHC prospect for well tempered DM

G. Giudice, T. Han, K. Wang and LTW, 1004.4902

LHC at 14 TeV.
Soft muon:
3 GeV < $p_{T}$ < 10 GeV

- Light-ish gluino or squark.
  - Discovery from jets+MET.
  - soft leptons ↔ well tempered, long term.

- No light gluino or squark, very hard.
  - VBF, Drell-Yan.
After discovery, hard to interpret

- After the discovery, we can derive some basic properties, such as whether the new particles are colored or not, whether they decay to leptons, and so on.

- Many possible interpretations.

  Degeneracies! Quantum number, mass, spin...
  For example: in supersymmetry, bino vs wino, squark vs gluino...
Possible degeneracies in:

- The identity of new physics particles. For example:

\[ \tilde{q}, \tilde{g}, ... \quad \tilde{q}, \tilde{g}, ... \]

Two different SUSY spectra.

Identity swap, hard to distinguish

Arkani-Hamed, Kane, Thaler, and Wang, JHEP 0608:070,2006

- \( M_{\text{LSP}} \).

- Spin.

Many recent progresses. For example, Dutta’s talk in this workshop
Spin measurements. Supersymmetry?
Spin measurements. Supersymmetry?

Example: spin of $\tilde{N}$
Spin measurements. Supersymmetry?

Example: spin of $\tilde{N}$

Clean exclusive sample
Spin measurements. Supersymmetry?

Example: spin of $\tilde{N}$

Clean exclusive sample

Boost (kinematics) vs matrix element (spin)

$\rightarrow$ Consider $m_{q\ell}$
Spin measurements. Supersymmetry?

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Boost (kinematics) vs matrix element (spin)

→ Consider $m_{q\ell}$

Combinatorics
Spin measurements. Supersymmetry?

Example: spin of $\tilde{N}$

Clean exclusive sample

Boost (kinematics) vs matrix element (spin)

→ Consider $m_{q\ell}$

Combinatorics

No universally applicable method. Different strategies will be used in different scenarios.

A review: LTW and Yavin, arXiv:0802.2726

More information of the signal, masses and underlying processes, is crucial.
Possible path to measure mass and spin.

- With early data, $O(fb^{-1})$
  - Rough estimate of mass scale.
  - A guess of the spin.

- With high statistics, $O(100 \ fb^{-1})$
  - Precise mass measurement.
  - Spin measurement.

- Early estimates can help designing best strategies for precise study.

Model dependent
Connection with direct detection
Probe NP with direct detection

XENON 100, 1104.2549

[Diagram showing WIMP-Nucleon Cross Section vs. WIMP Mass with various detection limits and exclusions.]

This result excludes a large fraction of previously unexcluded spin-independent elastic WIMP-nucleon cross-sections. The acceptance-corrected exposure, weighted with the standard analysis, is consistent with the absence of a signal above background and is also shown as the thick blue line together with the backgrounds. This limit is weaker than expected, taking into account all relevant systematic uncertainties.}

Uncertainties in the energy scale are indicated in the analysis. Due to the presence of Poisson fluctuations, the resulting confidence intervals are profiled out and have a minimum at lower masses. The energy resolution is negligible at higher masses. The new result challenges results as being due to light mass WIMPs. We are grateful to LNGS for hosting and supporting XENON. We acknowledge funding from SNF, STCS, DFG, and the Weizmann Institute of Science. We thank the LHC for making supersymmetric WIMP dark matter accessible by the LHC.
Probe NP with direct detection

$M_{\text{WIMP}} = O(10^2)$ GeV.

DM of “Typical” scenarios: SUSY LSP, ...
Probe NP with direct detection

This result excludes a large fraction of previously unexplored spin-independent elastic WIMP-nucleon cross-sections. The acceptance-corrected exposure, weighted with the sensitivity of the experiment, is calculated and is consistent with the absence of a signal above background. This limit is shown as the thick blue line together with the background expectations. The impact of uncertainties in the energy scale is taken into account. The resulting confidence interval is shown as the shaded regions from vMSSM are indicated at gP and kP. The sensitivity is the expected limit in the absence of a signal above background and is also shown as the thick blue line.}

The plot shows the WIMP-Nucleon Cross Section [cm$^2$] as a function of WIMP mass [GeV/c$^2$]. The acceptance-corrected exposure, weighted with the sensitivity of the experiment, is calculated and is consistent with the absence of a signal above background. This limit is shown as the thick blue line together with the background expectations. The impact of uncertainties in the energy scale is taken into account. The resulting confidence interval is shown as the shaded regions from vMSSM are indicated at gP and kP. The sensitivity is the expected limit in the absence of a signal above background and is also shown as the thick blue line.
Probe NP with direct detection

$m_{\text{WIMP}}$: O(1-10) GeV
Much larger $\sigma_{\text{dir}}$
Much larger $O(1\text{-}10)\ \text{GeV}$

$\sigma_{\text{dir}}$

This result excludes a large fraction of previously undetected $\sigma_{\text{dir}}$

$\chi_{\text{Spin}Z_{\text{independent elastic WIMP}}nucleon\text{crosssection}}$

acceptance$_{\text{corrected exposure}}$

weighted with the specie$_{\text{based only on events in the WIMP search region with an}}$

one from the standard analysis$_{\text{which calculates the limit}}$

weaker than expected$_{\text{This limit is consistent with the}}$

in Figure$_{\text{The impact of}}$

taking into account all relevant systematic uncertainties$_{\text{is}}$

two events around $kg\ \text{keV}$

and a density of $\text{grayV}$

$v_{\text{greenV}}$

$\text{orangeV}$

$\text{and vwMS}$

$\text{Sensitivity of this run Tshaded blue band}$

The limits from

$\chi_{\text{incorporated into the limite}}$

The resulting $\text{confidence interval}_{\text{Fige}}$

$\text{accounte}$

Uncertainties in the energy scale as indicated in

resolution$_{\text{governed by Poisson fluctuations}}$

is taken into

account$_{\text{Due to the presence of}}$

$\text{DAMA/Na}$

CoGeNT$_{\text{as well as the kaP vL areas favored by vozeNT}}$

$\text{XENON100 (2011)}$

$\text{EDELWEISS}$

$\text{XENON100 (2010)}$

$\text{WIMP Mass [GeV/c^2]}$

$\text{WIMP-Nucleon Cross Section [cm^2]}$

$\text{WIMP-Nucleon Cross Section [cm^2]}$

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$\text{WIMP-Nucleon Cross Section [cm^2]}$
Basic channel

- Pair production + additional radiation.

- Large Standard Model background, about 10 times the signal.

- Very challenging.
Effective operator approach
Effective operator approach

momentum exchange

$q \sim 100 \text{ MeV} \ll m_\phi$

effectively,

\[ \frac{1}{\Lambda_d} \chi \phi J_{SM} \]
Effective operator approach

Use colliders to constrain and probe the same operator

\[ \frac{1}{\Lambda d} \chi \chi J_{SM} \]

Momentum exchange \( q \sim 100 \text{ MeV} \ll m_\phi \) effectively,
Recent studies.

1. Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
2. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286
3. Bai, Fox, Harnik, 1005.3797
4. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783
5. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1009.0008
6. Fox, Harnik, Kopp, Tsai, 1103.0240
7. Fortin, Tait, 1103.3289
8. Cheung, Tseng, Yuan, 1104.5329
For example, 1008.1783

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783

FIG. 1: Current experimental limits on spin-independent WI

\( \sigma \) (cm\(^2\)) vs. \( m_\chi \) (GeV)

D1 LHC reach
D11 LHC reach
D5 LHC reach
D11 Tevatron exclusion
CoGeNT favored
CoGeNT
CDMS
Xenon 10
Xenon 10 reach
Xenon 100
Xenon 100 reach
SCDMS reach

D1 \( \bar{\chi} \chi \bar{q} q \)
D5 \( \bar{\chi} \gamma^\mu \chi \bar{\gamma} \gamma_\mu q \)
D11 \( \bar{\chi} \chi G_{\mu\nu} G^{\mu\nu} \)

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783

Wednesday, June 15, 2011
For example, 1008.1783
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783

For small $m_\chi$, collider rates controlled by larger mass scales, i.e., $p_T$ cut; does not depend on $m_\chi$. Collider bounds flat and stronger.
Effective operator effective?

\[ \frac{1}{\Lambda^d} \chi \chi J_{SM} \]

Independent of the details?
Effective operator effective?

Use colliders to constrain and probe the same operator

\[ \frac{1}{\Lambda} \chi \chi J_{\text{SM}} \]

However, \( E_{\text{cm}} = 100 \text{s GeV} \sim m_\Phi \), probing more structure of the s-matrix.

Depending on more details of the mediator.

The dependence on the mass of the mediator has been explored in: 1105.3797, 1103.0240
Mediator, two typical examples.

N = Ar, Ge, Xe, ...

\( g_D \)

mediator, \( \phi \)

\( g_{SM} \)
Mediator, two typical examples.

- $\phi = $ Higgs
  - $g_{SM} \approx (100 \text{ MeV}) / (100 \text{ GeV})$
  - $m_x \approx 100 \text{ GeV}$
  - $\sigma_n \approx 10^{-43} - 10^{-45} \text{ cm}^{-2}$

$N = \text{Ar, Ge, Xe, ...}$
Mediator, two typical examples.

- $\phi$=Higgs
  - $g_{SM} \approx (100 \text{ MeV})/(100 \text{ GeV})$
  - $m_x \approx 100 \text{ GeV}$
  - $\sigma_n \approx 10^{-43} - 10^{-45} \text{ cm}^{-2}$

- $\Phi$=100 GeV spin-1, $D$=dirac fermion
  - $\sigma_n \approx 10^{-36} - 10^{-38} \text{ cm}^{-2}$

N= Ar, Ge, Xe, ...
Probe NP with direct detection

SUSY, typically Higgs mediated.
Probe NP with direct detection

Light DM spin-1 mediator.

SUSY, typically Higgs mediated.
Case study: a spin-1 $Z'$

Xiang-Dong. Ji, Haipeng An, LTW in progress

\[
\mathcal{L} = Z'_\mu \left[ \bar{q} \left( g_{Z'} \gamma^\mu + g_{Z'5} \gamma^\mu \gamma_5 \right) q + \bar{X} \left( g_D \gamma^\mu + g_{D5} \gamma^\mu \gamma_5 \right) X \right]
\]

Only couples to SM quarks and DM.

$N = \text{Ar, Ge, Xe, ...}$
Effectiveness of effective operator

Tevatron rate for Monojet + (MET> 80 GeV)

\[ g_D = g_{Z'}, \quad \text{fix } g_{Z'}/M_{Z'} \]
Effectiveness of effective operator

Figure 2: When \( Q \ll M_{\text{pole}} \), the above equation can be further simplified to be
\[
\sigma(A_{\text{eff}}(Q)) \sim g^2(\Lambda^2) - M_{\text{pole}}^2 - \frac{g^2(\Lambda^2)}{8\pi}[L(\Lambda/Q) - M_{\text{pole}}^2].
\]

Then, we can set \( \Lambda = M_{\text{pole}} \) so that the loop factor is small. Then we can get
\[
\sigma(A_{\text{eff}}(Q)) \sim -\frac{g^2}{M_{\text{pole}}}.
\]
Effectiveness of effective operator

$g_D = g_{Z'}$, fix $g_{Z'}/M_{Z'}$

Figure 2: Therefore, we can get

$$A(Q) \sim g^2(\Lambda) Q^2 - M^2_{pole} - g^2(\Lambda) 8\pi \left[ -M^2_{pole} \right].$$

When $Q \ll M_{pole}$, the above equation can be further simplified to be

$$A(Q) \sim g^2(\Lambda) M^2_{pole}.$$

Then, we can set $\Lambda = M_{pole}$ so that the loop factor is small. Then we can get

$$g_D = g_{Z'}, \text{ fix } g_{Z'}/M_{Z'}$$
Therefore, we can get

$$A(Q) \sim g^2(\Lambda) Q^2 - M^2_{\text{pole}} - g^2(\Lambda) \frac{8\pi}{\Lambda Q_{\text{pole}}} \left[ -M^2_{\text{pole}} L \left( \frac{\Lambda}{M_{\text{pole}}} \right) \right].$$

When $Q \ll M_{\text{pole}}$, the above equation can be further simplified to be

$$A(Q) \sim -g^2(\Lambda) M^2_{\text{pole}}.$$

Then, we can set $\Lambda = M_{\text{pole}}$ so that the loop factor is small. Then we can get

$$g_D = g_{Z'}, \quad \text{fix } g_{Z'}/M_{Z'}$$
Effectiveness of effective operator

A factor of 3 in $\sigma_{\text{collider}}$ → a factor of 3 in $(g_{Z'})^2$

$\sigma_{\text{dir}} \propto (g_{Z'})^4$ → a factor of 9

$g_D = g_{Z'}$, fix $g_{Z'}/M_{Z'}$
Limits and reaches: monojet+MET

Tevatron 1 fb⁻¹, MET > 80 GeV, CDF, PRL 101, 2008

\[ M_{Z'} = 100 \text{ GeV}, 300 \text{ GeV}, 500 \text{ GeV}, 1 \text{ TeV} \]

\[ g_{Z'} = g_D, \quad g_{Z'^5} = g_{D^5} = 0 \]

Xiangdong Ji, Haipeng An, LTW, appearing soon.
Limits and reaches: monojet+MET

Tevatron 1 fb$^{-1}$, MET > 80 GeV, CDF, PRL 101, 2008

LHC, 7 TeV 5 fb$^{-1}$
MET > 200 GeV

$g_{Z'} = g_D$, $g_{Z'5} = g_{D5} = 0$

$M_{Z'} = 100$ GeV, 300 GeV, 500 GeV, 1 TeV

Xiangdong Ji, Haipeng An, LTW, appearing soon.
Limits and reaches: monojet+MET

Tevatron 1 fb⁻¹, MET > 80 GeV, CDF, PRL 101, 2008

LHC, 7 TeV 5 fb⁻¹
MET > 200 GeV

LHC 14 TeV, 100 fb⁻¹
MET > 500 GeV

M_{Z'} = 100 GeV, 300 GeV, 500 GeV, 1 TeV

Xiangdong Ji, Haipeng An, LTW, appearing soon.
Combining with early LHC data

More scenarios are under study.

Xiangdong Ji, Haipeng An, LTW, appearing soon.

$M_{WIMP} = 5 \text{ GeV}$

$g_D = 2.0, 1.0, 0.5$

$M_{Z'}$ (GeV)

$\sigma_{SI} (\text{cm}^2)$

CoGeNT 3.3 GeV

CoGeNT 5 GeV

Xenon 100 7 GeV

More scenarios are under study.

Xiangdong Ji, Haipeng An, LTW, appearing soon.
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LHC reach in monojet+MET.

More scenarios are under study.
Xiangdong Ji, Haipeng An, LTW, appearing soon.
LHC reach in monojet+MET.

LHC rate dominated by MET cut, insensitive to $M_{Z'}$.

$\rightarrow$ LHC bounds only on $g_{Z'}$.

Bounds on $\sigma_{SI} \propto (M_{Z'})^{-4}$

More scenarios are under study.

Xiangdong Ji, Haipeng An, LTW, appearing soon.
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→ LHC bounds only on $g_{Z'}$. 

Bounds on $\sigma_{SI} \propto (M_{Z'})^{-4}$

More scenarios are under study. 
Xiangdong Ji, Haipeng An, LTW, appearing soon.
Motivation of Light Dark Sector

- Dark Matter in the universe.
  - Cold, dark, and gravitationally coupled.

- Perhaps dark matter has self-interactions too.
  - Force carrier is an example of dark sector.

- Motivations from astrophysical observations.
  - Fermi, Pamela, ... \( M_{\text{dark}} \sim \text{GeV} \)
Motivation of Light Dark Sector

- Dark Matter in the universe.
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May or may not be the right motivation.

But this class of dark sector can be generic and interesting on its own.
A GeV dark sector.

- Dark matter self-interaction, mediated by $A_{\text{dark}}$
  - $m_A \sim 100s \text{ MeV} - \text{GeV}$
- Dark sector couples to SM with tiny couplings, parameterized by $\epsilon \sim 10^{-3}$
- Nice SUSY implementations.
New class of signal: dark Force

- Dark matter self-interaction, mediated by

\[ A^\text{dark}_\mu, \ m_{A^\text{dark}} \sim (100\text{s MeV} - \text{GeV}) \]

Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
Arkani-Hamed, Weiner 0810.0714
also see Pospelov, Ritz, Voloshin 0711.4866
Lepton Jets

- Decay of the dark photon arising from a heavier particle (Z boson, MSSM LSP) leads to a highly collimated lepton pair.

"Lepton jet."

$A_{\mu}^\text{dark} \rightarrow e^\pm, \mu^\pm \quad \delta\theta < 0.1 \rightarrow \text{Lepton Jet}$

Typical $E_{\gamma'} > 10$ GeV $\rightarrow \delta\theta \sim m_{\gamma'}/E_{\gamma'} < 0.1$

$m_{\gamma'} \sim \text{GeV}$

- Arkani-Hamed, Weiner 0810.0714;

- Baumgart, Cheung, Ruderman, LTW, Yavin 0901.0283; Cheung, Ruderman, LTW, Yavin 0909.0290
Supersymmetric dark force

- Most natural way of generating the GeV scale.
- Spectacular signal.
- Early discovery.
With LHC early data

CMS Preliminary 2010 \( \sqrt{s}=7 \) TeV \( L_{\text{int}}=35 \) pb\(^{-1} \)

\[
\begin{align*}
\{m(\tilde{g})\} &= \frac{m(\tilde{g})}{1.2} \\
\{m(h_d)\} &= 3 \text{ GeV/c}^2 \\
\{m(\gamma_d)\} &= 0.5 \text{ GeV/c}^2 \\
\text{Br}(\chi_d^{\pm} \rightarrow \tilde{\chi}_d \gamma_d / \tilde{\chi}_d h_d) &= 100\% \\
\text{Br}(h_d \rightarrow \gamma_d \gamma_d) &= 100\% \\
\text{95\% CL Upper Limit} \\
\text{Br}(\gamma_d \rightarrow \mu \mu) &= 100\% \\
\text{Br}(\gamma_d \rightarrow \mu \mu) &= 50\% \\
\text{Br}(\gamma_d \rightarrow \mu \mu) &= 33\% \\
\text{Theory} \\
\end{align*}
\]

\( \sigma(pp \rightarrow \tilde{g}g / \tilde{g}g) \text{, pb} \)

CMS, https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11013
Conclusion.

- One of the most exciting opportunities: Discovering the WIMP dark matter and measuring its properties.

- LHC will play a crucial role in this pursuit.

- Multiple aspects and approaches.
  - Search for “conventional” CDM.
  - More model independent searches.
  - Alternative models with distinct signatures.
extra
Dark photon decay.

\[ \gamma_d \text{ Branching Ratio} \]

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

Hadrons

\[ \gamma_d \text{ Mass [GeV]} \]

- Mixing can be removed:
  \[ A_\mu \rightarrow A_\mu + \epsilon \cos \theta W \gamma d_\mu \]
  \[ A_\mu J_\mu^{SM} \rightarrow A_\mu J_\mu^{SM} + \epsilon \cos \theta W \gamma d_\mu J_\mu^{SM} \]

- Therefore the SM fields are millicharges under the new photon.
- Consequently the hidden photon can decay to kinematically available SM fermions.
Basic dark sector model ingredients:

- Model choices:
  - Dark matter identity.
  - Self-interaction $G_d$ : gauge interaction...
  - GeV scale, dark higgs $h_d : v_d = \langle h_d \rangle \sim \text{GeV}$
  - Supersymmetric scenarios: natural generation of the GeV Scale.
Simplest choice: abelian dark sector

\[ G \supset U(1)_d \]

- Simplest self-interaction: \( G_d = U(1)_d \)

- Natural connection to the SM: kinetic mixing

\[ \mathcal{L}_{\text{kin.mix}} = -\frac{\epsilon}{2} b_{\mu\nu} F_{\gamma}^{\mu\nu} \]

- Supersymmetry can be an elegant way of generating the GeV scale.

For a very simple and predictive construction:
See also: D. E. Morrissey, D. Poland and K. M. Zurek, arXiv:0904.2567
Benefits of Collider searches

- More information of the S-matrix.
  - Precision measurement of the properties of the WIMP dark matter.

- Direct detection can have additional suppressions.
  - Spin dependent.
  - Velocity of WIMP.
  - Collider searches are not suppressed in these cases.