Dark Matter and Baryon Asymmetry
- Probing the Cosmic Origin of Matter at the LHC

Yanou Cui
UC Riverside

DM@LHC workshop,
UCI, Apr 3 2017
Probing the Origin of Matter with the LHC?

- Baryon (atomic matter): $\Omega_B \approx 4\%$
- Dark Matter: $\Omega_{DM} \approx 23\%$
- Coincidence/Similarity: $\Omega_{DM} \sim \Omega_B$
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- Familiar/well-studied case: WIMP dark matter ($\Omega_{DM}$)
  - Stable, mass $\sim O(10-100)$ GeV, can be produced within $E_{LHC}=14$ TeV
  - Pair produced ($Z_2$),
  - Invisible, MET + X
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- **Direct** test for $\Omega_B$, $\Omega_B \sim \Omega_{DM}$ @LHC?
\[ \Omega_{DM} \sim \Omega_B \ (\Omega_{DM}/\Omega_B \approx 5) \]

- A mere cosmic coincidence or deep connection?

- DM and atomic matter almost decoupled today!
- \( \Omega_B, \Omega_{DM} \) often explained by separate physics mechanisms

Naive expectation: evolve independently, drastically different today!
\[ \Omega_{\text{DM}} \sim \Omega_{\text{B}} \quad (\Omega_{\text{DM}}/\Omega_{\text{B}} \approx 5) \]

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Candidate theories addressing the “coincidence”:

- Asymmetric Dark Matter (Kaplan 1982; Nussinov 1985; Kaplan, Luty, Zurek 2009…): no WIMP miracle, asymmetry to be explained
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• Alternatives: compatible with WIMP DM! + new BG mechanism
  
  • WIMPy baryogenesis: BG from WIMP DM freezeout (YC, Randall, Shuve 2011)
  
  • Baryogenesis from metastable WIMPs (YC, Sundrum 2012)
\[ \Omega_{\text{DM}} \sim \Omega_B \quad (\Omega_{\text{DM}}/\Omega_B \approx 5) \]

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✓ Spectacular signals at the LHC!
Probing the Cosmic Origin of Baryons with Displaced Vertices at the LHC

- **New opportunity**: baryogenesis (address $\Omega_B$, possibly $+\Omega_B \sim \Omega_{DM}$)
- New weak scale metastable particle (e.g. long-lived WIMP) as baryon parent
- Pair produced (approx. $Z_2$)
- Displaced decay to $j/\ell/MET$ by cosmological conditions!

**Generic event topology**
(analogy to WIMP DM search!)

\[ L_{dec} \geq 1 \text{ mm} \]
Baryogenesis 101
Baryon $\Omega_B \approx 5\%$
— The Unknown Aspects of the Known

- **Baryon**: proton, neutron $\rightarrow$ atoms, stars, ourselves!
- Where does $\Omega_B$ come from?
  = Where do we ourselves come from?
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**Initial $B - \bar{B}$ asymmetry**

$$\eta_B = (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$$

Baryon  Anti-baryon
Baryon $\Omega_B \approx 5\%$

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Today

symmetric annihilation
Baryogenesis
- the Origin of the Baryon Asymmetry

The Universe starts with $B = 0$, $\rightarrow$ $B \neq 0$

$B - \bar{B}$ asymmetry
Baryogenesis
- the Origin of the Baryon Asymmetry

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$B - \bar{B}$ asymmetry
Baryogenesis

Sakharov Conditions (1967):
Baryogenesis

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• Require baryon number violation

![](image)
Baryogenesis

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- Require C-, CP-symmetry violation
Baryogenesis

Sakharov Conditions (1967):

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• Require C-, CP-symmetry violation

• Require departure from equilibrium!

Thermal equilibrium + CPT symmetry

\[
\langle B \rangle_{eq} = 0
\]
Baryogenesis

Sakharov Conditions (1967):

- Require baryon number violation
  \[ B \xrightarrow{} \bar{B} \]

- Require C-, CP-symmetry violation
  \[ B \xrightarrow{} \bar{B} \neq \bar{B} \xrightarrow{} B \]

- Require departure from equilibrium!

Thermal equilibrium + CPT symmetry

\[ n^\text{eq}_B = n^\text{eq}_{\bar{B}}, \quad \langle B \rangle_{\text{eq}} = 0 \]

\[ B \xrightarrow{} B = \bar{B} \xrightarrow{} \bar{B} \]

\( \Omega_B \approx 5\%: \) Need beyond the Standard Model Particle Physics!
Baryogenesis from Out-of-Equilibrium Decay

A general class of baryogenesis models (e.g. leptogenesis)

- Consider an unstable massive neutral particle $\chi$
- Baryon asymmetry produced in its decay (B-, C-, CP-violating)

Typically, the inverse processes efficiently erase the asymmetry

But, if $\chi$ is long-lived, and decays only after $T_f < M_\chi$:

Inverse decay: Boltzmann suppressed

$e^{-M_\chi/T_{\text{decay}}}$
Baryogenesis from Out-of-Equilibrium Decay

Out-of-equilibrium decay $\rightarrow$ Sakharov conditions ✓

An intriguing observation (YC, Sundrum; YC, Shuve):
If $\chi$ has weak scale mass,

$$\Gamma_\chi < H(T = M_\chi) \quad \text{and} \quad cT_\chi \gtrsim \text{mm}$$
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- A generic connection between cosmological slow rates at $T \sim 100 \text{ GeV}$ and displaced vertices at colliders!
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- A **generic connection** between cosmological slow rates at \( T \sim 100 \text{ GeV} \) and **displaced** vertices at colliders!

Our universe around EW phase transition was just slightly bigger than LHC tracking resolution!
Displaced Vertices at the LHC

• Nearly all SM particles decay **promptly**
  \[ \lesssim 100 \mu m \text{ - } 1 \text{ mm} (= \text{prompt}) \]

• Ubiquitous predictions from motivated new physics:
  long-lived particles, **displaced decay vertices** from all part of the detector \( (L_{\text{dec}} \gtrsim 1 \text{ mm}) \) (SUSY,twin-Higgs,hidden valley, sterile \( \nu \)...)

✦ **Spectacular signal!** **low SM background**, sensitive to rare signal events 😊
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Conventional LHC searches impose “prompt” cuts (reject cosmic ray/mis-reconstruction), may not be triggered on!
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**Impressive developments, dedicated studies in the**
**past a few years (experimentalists + theorists)!**
Baryogenesis from WIMPs

— A New Proposal to Address $\Omega_B, \Omega_B \sim \Omega_{DM}$

- YC, JHEP 1312 (2013) 067
Cosmic Evolution of a stable WIMP

- Equilibrium
- Annihilation
- Thermal freezeout

Departure from equilibrium: key to $\Omega_{\text{WIMP}}$!

(recall $\Omega_B$?)
• Cosmic Evolution of a stable WIMP $\chi$

- Universe expands, cools, $T \downarrow$
- thermal freezeout
- Departure from equilibrium: key to $\Omega_{WIMP}$!

• Relic abundance:

$$\Omega_\chi \propto \langle \sigma_{\text{ann}} v \rangle^{-1}$$

$$\sim 0.1 \left( \frac{G_{\text{Fermi}}}{G_\chi} \right)^2 \left( \frac{M_{\text{weak}}}{m_\chi} \right)^2$$

WIMP Miracle!

(recall $\Omega_B$?)
WIMP Miracle for Baryons?
- A generalization/variation of WIMP miracle
  \((YC, \text{ w/Sundrum})\)

\[ \text{WIMP } \chi \rightarrow \text{X/SM} \rightarrow \text{thermal freeze out} \rightarrow \text{out-of-equilibrium} \rightarrow ? \]
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\[ \text{WIMP } \chi \]
\[ \text{X/SM} \]

\text{thermal freeze out}
\[ \text{out-of-equilibrium} \]

\[ \text{Stable } \chi_{\text{DM}}, \Omega_{\text{DM}} \]
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WIMP $\chi$  X/SM  thermal freeze out

out-of-equilibrium

WIMP $\chi$  X/SM

Stable $\chi_{DM}$, $\Omega_{DM}$

Metastable $\chi_{B}$
(later decay)
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WIMP $\chi$

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Metastable $\chi_B$
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Recall:

$\Omega^{T\rightarrow\infty}_{\chi_B}$

freeze out $\rightarrow$

$\Omega_{x,h^2}$
WIMP Miracle for Baryons?
- A generalization/variation of WIMP miracle
  \( (Y_C, \text{w/Sundrum}) \)

\[
\Omega_B = \epsilon_{CP} \frac{m_p}{m_{\chi_B}} \Omega_{\chi_B}^{\tau \rightarrow \infty}
\]

\( \chi \) is insensitive to the precise lifetime \( \tau \) takes the form of WIMP miracle, with extra factor \( \epsilon_{CP} \).

\( \chi_{DM}, \Omega_{DM} \)

Stable \( \chi_{DM} \)

Metastable \( \chi_B \)
(later decay)

Introduction

Baryogenesis for WIMPs: General Formulation, Minimal Model

Meeting Particle Physics Frontier: Embed in SUSY

Conclusions

Central Result

For Keynote
WIMP Miracle for Baryons?
- A generalization/variation of WIMP miracle

\( \Omega_{\text{DM}} \) (w/Sundrum)

**Novel baryogenesis**
- \( \Omega_{B} \)

**Generalized WIMP miracle**
- (+ stable WIMP DM \( \Omega_{\text{DM}} \) )

\[ \Omega_{B} \sim \Omega_{\text{DM}} \]

\[ \Omega_{B} = \epsilon_{CP} \frac{m_p}{m_{\chi_{B}}} \Omega^{\tau \rightarrow \infty}_{\chi_{B}} \]
- **Minimal model example** *(Phys.Rev. D87 (2013) 11, YC w/Sundrum)*

CP asymmetry from: interferere w/

Easy embedding in RPV natural SUSY (+singlet)! \((\phi \to \tilde{t})\)

★ Late-time baryogenesis; a remedy for a potential cosmological crisis with RPV SUSY: RPV washout of existing \(\Omega_B\)
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• Baryogenesis with Minimal SUSY model!

(YC, JHEP 1312 (2013) 067)

Bino \(\tilde{B} \to \Delta B\) ! Cosmological motivation for mini-split SUSY!

interfere w/ 

\(\Omega\) from:

Late-time baryogenesis

\(\Delta B\) conserved decay.

\(\Delta B\) non-conserving decay.
• **Minimal model example**  
  (Phys.Rev. D87 (2013) 11, **YC** w/Sundrum)

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Bino $\tilde{B} \rightarrow \Delta B$! Cosmological motivation for mini-split SUSY!

Incorporate WIMP DM? Add a singlet $\chi_{DM}$ protected by an exact $Z_2$
Baryogenesis from Out-of-equilibrium Decays
— Collider Phenomenology

YC and Shuve, JHEP 1502 (2015) 049
(YC and Okui, Yunesi, Phys.Rev. D94 (2016))

★ Strategies/results generally applicable to other new physics searches via displaced vertices
Reproduce Baryogenesis at the LHC!
(YC w/Sundrum; w/Shuve)

- **WIMP** $m_\chi \sim O(100 \text{ GeV})$ can be produced within $E_{\text{LHC}}=14 \text{ TeV}$!

- **Cosmological condition for baryogenesis:**
  $\chi$ lives beyond its thermal freeze out time

  $\Gamma_\chi < H_{\text{fo}} \Leftrightarrow c\tau_\chi \gtrsim \text{mm}$

- **Distinctive signal:** displaced decay vertex inside detectors
  —not well-covered, low bkg search channel, rising interest!

**Metastable WIMP baryon parent@LHC:** displaced vertex

**Stable WIMP DM@LHC:** missing energy (analogy)
Simplified Model Approach for LHC Pheno

(YC and Shuve arxiv:1409.6729, JHEP)

• Classify production modes (analogy to DM search @LHC!)

• Classify decay modes (unlike DM search…)}
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**Charged under SM gauge interactions:**

wino/gluino-like (state in interference loop)

- Classify decay modes (unlike DM search…)

\[ \chi \]

\[ g/W/Z \]

\[ \chi \]
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**Higgs portal:**
singlet-like (e.g. $M_\chi = 150$ GeV)

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**Charged under SM gauge interactions:**
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  - fixed coupling,
  - study mass reach
  
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$g/W/Z$
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**Baryon number violating:**

\[
\chi \rightarrow u_i d_j d_k
\]
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**Baryon number violating:**

\[ \chi \rightarrow u_i d_j d_k \]

**Lepton number violating:**

\[ \chi \rightarrow L_i Q_j \bar{d}_k \]
\[ \chi \rightarrow L_i L_j \bar{E}_k \]
LHC DV Search Possibilities

- Prompt analyses
- Heavy flavour decays
- Disappearing tracks
- Vertices from displaced tracks
- Non-pointing photons
- Displaced lepton jets
- Decays in HCAL
- Decays in muon system
- Stable charged particles
- Missing energy searches

New detector: Mathusla? (Chou, Curtin, Lubatti + others)
Recast Existing LHC Searches

• **Focus on displaced decay in tracking volume**
  
  Near lower bound $c\tau_\chi \gtrsim \text{mm}$, better sensitivity to wide lifetime range, easier to model with theorists’ tools!

  (decay in other parts of detector important too!)
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- **Two concrete examples** (light-flavour only):
  
  **Baryon number violating:**
  
  $\chi \rightarrow 3q$
  
  displaced jets (all-hadronic)
  
  CMS, arXiv:1411.6530

  **Lepton number violating:**
  
  $\chi \rightarrow \ell + 2q$
  
  displaced muon + tracks
  
  ATLAS-CONF-2013-092
Recast Existing LHC Searches

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  Near lower bound $c\tau_\chi > mm$, better sensitivity to wide lifetime range, easier to model with theorists’ tools!
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  CMS, arXiv:1411.6530

  **Lepton number violating:**
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  displaced muon + tracks
  ATLAS-CONF-2013-092

• **Goal of our analysis:**
  • What is the coverage for our simplified models based on benchmarks chosen by the collaborations?
  • What advice can we provide for general experimental improvement?
Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:

\[ \text{wino} \rightarrow 3\text{j}, \sqrt{s} = 8 \text{ TeV} \]

\[ \langle L_{\chi \chi} \rangle = 3 \text{ cm} \]
\[ \langle L_{\chi \chi} \rangle = 30 \text{ cm} \]
\[ \langle L_{\chi \chi} \rangle = 300 \text{ cm} \]
\[ \sigma_{\chi \chi} \text{ (NLO)} \]

\[ \sigma_{\chi \chi} \, 95\% \text{ CL (fb)} \]

\[ M_{\chi} \, (\text{GeV}) \]

21
Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

**wino**

8 TeV:

![Graph showing the cross-section for wino production and decay](graph.png)

* singlet-like (Higgs portal) 

We studied a challenging case: 

\( M_\chi = 150 \text{ GeV}, \text{ moderately off-shell!} \)

No bound @ 8 TeV 20 fb\(^{-1}\)! 
Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

**wino**

8 TeV:

- $wino \rightarrow 3j$, $\sqrt{s} = 8$ TeV

- $\langle L_{xy} \rangle = 3$ cm
- $\langle L_{xy} \rangle = 30$ cm
- $\langle L_{xy} \rangle = 300$ cm
- $\sigma_{\chi \chi}$ (NLO)

No bound @ 8 TeV 20 fb$^{-1}$!

**singlet-like (Higgs portal)**

We studied a challenging case:

- $M_\chi = 150$ GeV, moderately off-shell!

13 TeV:

- $L_{xy} = 3$ cm

- $wino \rightarrow 3j$, 2 DV, luminosity for 3 events, $\sqrt{s} = 13$ TeV

- $2$ DV
- $1$ DV, 10% syst.
- $1$ DV, 30% syst.

- $Higgs$ portal $\chi \rightarrow 3j$, 1DV vs. 2DV comparison $\sqrt{s} = 13$ TeV

- $m_\chi = 150$ GeV

- $\sigma_{\chi \chi}$ vs. $\lambda_{S\chi \chi} \sin(2\alpha)$
Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

**wino**

8 TeV:

- $wino \rightarrow 3j, \sqrt{s} = 8 \text{ TeV}$

<table>
<thead>
<tr>
<th>$\sigma_{\chi\chi} , 95% \text{ CL (fb)}$</th>
<th>$M_\chi (\text{GeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>400</td>
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<tr>
<td></td>
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<tr>
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- $<L_{xy}> = 3 \text{ cm}$
- $<L_{xy}> = 30 \text{ cm}$
- $<L_{xy}> = 300 \text{ cm}$
- $\sigma_{\chi\chi} \, \text{(NLO)}$

13 TeV:

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- $wino \rightarrow 3j, 2 \text{ DV}, \text{luminosity for 3 events}, \sqrt{s} = 13 \text{ TeV}$

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- 2 DV
- 1 DV, 10% syst.
- 1 DV, 30% syst.

- Tag 2 DVs: $M \sim 2.5 \text{ TeV}, \sigma \sim 1 \text{ ab}$
- $\text{Higgs portal } \chi \rightarrow 3j, 1\text{DV vs. 2DV comparison } \sqrt{s} = 13 \text{ TeV}$

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- Tag 2 DVs: $\sigma \sim 50 \text{ ab}$
- No bound @ 8 TeV 20 fb$^{-1}$!
**Displaced muon + Tracks**

*ATLAS-CONF-2013-092*

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**8 TeV**

**wino**

wino $\rightarrow \mu + \text{tracks}, \sqrt{s} = 8 \text{ TeV}

**13 TeV:**

Tag 1 DV

M~2.5 TeV

*(lower bkg than all-hadronic)*
Displaced muon + Tracks

**8 TeV**

- **wino**
  - wino $\rightarrow \mu +$ tracks, $\sqrt{s} = 8$ TeV
  - $\sigma_{\chi \chi}$ 95% CL (fb)
  - $\sigma_{\chi \chi}$ (NLO)
  - $<L_{xy}> = 0.3$ cm
  - $<L_{xy}> = 3$ cm
  - $<L_{xy}> = 30$ cm

- **singlet (Higgs portal)**
  - (singlet-like, $M_\chi = 150$ GeV)
  - No bound @ 8 TeV 20 fb\(^{-1}\)

- **13 TeV:** $\sigma_S \sim 50$ ab for $L_{xy} \sim 1$ cm
  - (Tag 1 DV)
  
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  - M~2.5 TeV
  - (lower bkg than all-hadronic)

- Higgs portal $\chi \rightarrow \mu +$ tracks, 1DV, luminosity for 3 events, $\sqrt{s} = 13$ TeV

- $m_\chi = 150$ GeV
  - $\lambda_{S_{xy}} \sin(2\alpha)$
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• More opportunities@LHC inspired by $\Omega_B \sim \Omega_{DM}, \Omega_B$? …