BARYOGENESIS FROM WIMPS
Y. Cui, L. Randall, and BS, arXiv:1112.2704 (JHEP)
Y. Cui and BS, arXiv:1409.6729 (PRD)

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Probing the Electroweak Phase Transition with a Next-Generation pp Collider

19 September 2015
Cosmology at the Weak Scale

We have a new scale in particle physics.

Electroweak baryogenesis links the baryon asymmetry to this new scale (but need new dynamics!)
Cosmology at the Weak Scale

Coincidentally, we also see this scale imprinted in cosmology

\[ \Omega_{DM} \sim \frac{1}{\langle \sigma v_{DM} \rangle} \sim 0.27 \left( \frac{\alpha_W}{\alpha_{DM}} \right)^2 \left( \frac{M_{DM}}{\text{TeV}} \right)^2 \]

perturbative unitarity: \( M_{DM} \lesssim 100 \text{ TeV} \)

Griest, Kamionkowski 1990

What does this have to do with baryogenesis? Some hints....

1) Comparable energy densities of baryons and DM \( \Omega_{DM} \approx 5 \Omega_{\Delta B} \)

see also Asymmetric Dark Matter models (recent renewal of interest: ex. Kaplan, Luty, Zurek 2009)

2) Common features in DM/baryogenesis dynamics
   • Out-of-equilibrium dynamics, CPV, self-conjugate particles
Baryogenesis-WIMP connections

I will briefly review two possible WIMP baryogenesis mechanisms, focusing on connections between cosmology and weak-scale probes.

Baryogenesis from WIMP Annihilation ("WIMPy Baryogenesis"):

- Typically predict new gauge-charged states
- Collider and DM probes

Baryogenesis from Meta-Stable WIMP Decay:

- Colliders (long-lived decays)

Cui, Randall, BS 2011
Cui, Sundrum 2012
Cui 2013
Cui, BS 2014
WIMPy Baryogenesis

\[ B - L = 0 \]

\[ B - L > 0 \]
WIMPy Baryogenesis

Sakharov conditions:

1. Violation of $B-L$

- If DM is a colour singlet, no $B-L$ violation allowed for pair of SM final states
- Need to couple to an exotic $B/L$ charged state

- Equal and opposite asymmetries in regular baryons & exotic baryons
- Need asymmetries to be sequestered or for the exotic baryon to have additional couplings to quarks that change its effective baryon number
WIMPy Baryogenesis

2. Violation of CP

- Generally have phases in new couplings
- Might provide phenomenological handle!

- Physical CP violation comes from interference with on-shell states in loop:

\[
\epsilon \equiv \frac{\Gamma(XX \rightarrow \psi \bar{u}) - \Gamma(X^\dagger X^\dagger \rightarrow \psi^\dagger \bar{u}^\dagger)}{\Gamma(XX \rightarrow \psi \bar{u}) + \Gamma(X^\dagger X^\dagger \rightarrow \psi^\dagger \bar{u}^\dagger)}
\]

EFT diagrams from Bernal et al., 2012
WIMPy Baryogenesis

3. Departure from Thermal Equilibrium

- Opening the loop gives rise to washout processes
- We want these to be inactive at some point during DM annihilation

$$\Gamma_{\text{washout}} \sim \langle \sigma v_{\psi \bar{u} \rightarrow \psi^\dagger \bar{u}^\dagger} \rangle Y_\psi Y_u + \ldots$$

$$\Gamma_{\text{DM ann.}} \sim \langle \sigma v_{XX \rightarrow \psi \bar{u}} \rangle Y_X$$

- Annihilation, asymmetry production and washout depend on same couplings
- Generally, washout only freezes out before DM annihilation for $M_X \lesssim M_\psi \lesssim 2M_X$ and $\psi$ in equilibrium

Can be somewhat relaxed in EFT (Bernal et al., 2012)
WIMPy Baryogenesis: Asymmetry

Example simplified model:

\[ \mathcal{L} \supset \lambda_i S_i X^2 + y_i S_i \psi \bar{u} + \frac{1}{\Lambda^2} (\psi n)(\bar{u} \bar{d}) + \text{h.c.} \]

- \( S \) is a real scalar mediator
- \( n \) is a Majorana singlet (can be dark radiation), keeps \( \psi \) in equilibrium
- Avoid \( \psi \)-quark mixing due to some discrete (or global) symmetry
- Can have \textit{leptogenesis} if \( \psi \) instead couples to leptons

\[ M_S = 5 \text{ TeV}, \quad M_X = 3 \text{ TeV} \]
WIMPy Baryogenesis: Pheno

Colliders are the best way of probing WIMPy baryogenesis!

Direct Baryogenesis \((XX \to \bar{u}\psi)\)

\[
\Delta \mathcal{L} = \frac{1}{\Lambda^2} (\psi n)(\bar{u}^\dagger \bar{d}^\dagger)
\]

Leptogenesis \((XX \to L\psi)\)

\[
\Delta \mathcal{L} = LH^* n
\]

\(M_\psi\) bound

- 8 TeV, 20 / fb: 1.35 TeV
- 14 TeV, 3 / ab: 2.5 TeV
- 100 TeV, 3 / ab: 11.5 TeV

\(M_\psi\) bound

- 8 TeV, 20 / fb: 720 GeV
- 14 TeV, 3 / ab: 1 TeV
- 100 TeV, 3 / ab: 3.3 TeV

Recast from Cohen et al., 2013 (Snowmass)

Gori, Jung, Wang, Wells 2014
WIMPy Baryogenesis: Pheno

- Perturbative direct baryogenesis parameter space largely covered @ 100 TeV, 3/ab
- Leptogenesis more challenging near perturbativity limit
- In extended models, other signatures are possible (ex: RPV-like decays of charged states)

Other possible constraints:

1. **EDMs**
   - Naïve two-loop result cancels, giving suppressed EDMs in minimal model (may be larger in extended models)

2. **Direct detection**
   - Naïve one-loop result cancels, giving velocity-suppressed spin-independent rates

3. **Indirect detection**
   - Subdominant to collider constraints (but more model-independent)
Baryogenesis from WIMP Decay
Baryogenesis from WIMP Decay

- In WIMPy baryogenesis, baryogenesis comes from WIMP dynamics but the asymmetry is not directly related to the WIMP abundance.

- Alternatively, if DM is produced through the decay of a meta-stable WIMP, the asymmetry is automatically proportional to a DM-like abundance.

\[ \epsilon = \frac{\Gamma(\chi \rightarrow B) - \Gamma(\chi \rightarrow \bar{B})}{\Gamma(\chi \rightarrow B) + \Gamma(\chi \rightarrow \bar{B})} \]

\[ \Omega_{\Delta B} \approx \epsilon \frac{M_{\text{nucleon}}}{M_\chi} \Omega_\chi^{\tau_\chi \rightarrow \infty} \]

- WIMP dynamics can give an overabundance of \( \chi \), compensating for the suppression factors.

- To inherit the freeze-out abundance, \( \Gamma_\chi \lesssim H(T_{f.o.}) \)
  * Earlier decay can generate some asymmetry, but it is diluted due to rapid \( \chi \) scattering.

Cui, Sundrum 2012
Baryogenesis from WIMP Decay

• How big was the universe around the weak scale?

\[ H(100 \text{ GeV}) \sim 10^{-14} \text{ GeV} \sim (1.3 \text{ cm})^{-1} \]

\[ 10 \text{ GeV} \rightarrow (1.3 \text{ m})^{-1} \]

\[ 1 \text{ TeV} \rightarrow (0.13 \text{ mm})^{-1} \]

• Recall \( z_{f.o.} \sim 20 \)

• For WIMP masses \(~100 \text{ GeV-TeV}\), the particle is long-lived if we can make it at a collider!

• Heavier particles are closer to \( B \) lifetime, but mass discrimination is better

see also Barry, Graham, Rajendran 2013
Baryogenesis from WIMP Decay

- The method of collider production is similar to DM: cross the diagram

- Large production + late decay consistent with approximate stability symmetry

- Direct link between cosmological condition and collider signature

- Look at representative models to see possible production modes, and then use simplified models approach for collider study
SUSY Model

• An RPV-SUSY model illustrates the possible long-lived particles
  • Many $CP$ phases (ex. gaugino masses)
  • $B-L$ violation can come from udd, QdL, LLE-type superpotential terms or RPV terms in Kähler potential
  • Mini-split spectrum alleviates EDM constraints, makes LSP long-lived

• Bino typically gives overabundance, so it is a natural candidate for $\chi$
  • Asymmetry is largest when there is some other on-shell Majorana state that can run in loop

Tree-level Decay

\[ \tilde{B} \rightarrow d_i \nonumber \]
\[ \tilde{d} \nonumber \]
\[ u_k \nonumber \]

Loop-level Decay

\[ \tilde{B} \rightarrow d_i \nonumber \]
\[ \tilde{d} \nonumber \]
\[ \tilde{g} \nonumber \]
\[ u_k \nonumber \]

Freeze-out

\[ \tilde{B} \rightarrow H \nonumber \]
\[ \tilde{H} \nonumber \]
\[ H^* \nonumber \]

• Can also have light \textbf{gauge-charged} states with same parametric lifetime

\textit{Cui 2013}
**WIMP decay baryogenesis: Pheno**

- Similar to EWBG, factorize CPV from equilibrium criterion
- By analogy with DM, classify pair production modes, such as...

**SM gauge interactions:**
Majorana = gaugino-like (wino)

**Higgs portal:**
singlet-like

fix $\chi$ mass @ 150 GeV, study coupling reach

Model-independent constraints on Higgs mixing relatively weak

*Profumo, Ramsey-Musolf, Wainwright, Winslow 2014*
WIMP decay baryogenesis: Pheno

- Unlike DM, we also have to specify decay modes (also two examples):

  **Baryon number violating:**
  
  \[ \chi \rightarrow u_i d_j d_k \]
  
  displaced jets (all-hadronic)
  
  CMS, arXiv:1411.6530

  **Lepton number violating:**
  
  \[ \chi \rightarrow Q_i Q_j (d_k^c)^\dagger \]
  
  displaced muon + hadrons
  
  ATLAS-CONF-2013-092

- We specifically looked at inner-detector decays (consistent with saturating cosmological criteria), but decays in other components important too

- Very low SM backgrounds give good sensitivity even for small cross sections

Later comprehensive analyses in RPV SUSY: Liu, Tweedie 2015; Csaki et al., 2015; Zwane 2015

In context of naturalness: Craig et al., 2015; Csaki et al., 2015;
Fully hadronic displaced vertices

**8 TeV:**

- **wino**
  - \( \text{wino } \rightarrow 3j, \sqrt{s} = 8 \text{ TeV} \)
  - \( \sigma_{\chi\chi} \) 95\% CL (fb)

- **singlet (Higgs portal)**
  - (singlet-like, \( M_\chi = 150 \text{ GeV} \))
  - no bound

**13 TeV:**

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

- **singlet (Higgs portal)**
  - \( L_{xy} = 3 \text{ cm} \)
  - \( \text{Higgs portal } \chi \rightarrow 3j, 1\text{DV vs. 2DV comparison } \sqrt{s} = 13 \text{ TeV} \)

- \( m_\chi = 150 \text{ GeV} \)
Displaced muon + hadrons

**wino**

wino → μ + tracks, $\sqrt{s} = 8$ TeV

- $<L_{xy}> = 0.3$ cm
- $<L_{xy}> = 3$ cm
- $<L_{xy}> = 30$ cm
- $\sigma_{\chi\chi}$ (NLO)

$\sigma_{\chi\chi}^{95\% \text{ CL}}$ (fb)

100.0
10.0
1.0
0.5
0.1

$M_{\chi}$ (GeV)

200
400
600
800

**singlet (Higgs portal)**

(singlet-like, $M_{\chi} = 150$ GeV)

8 TeV

no bound

13 TeV

**wino**

wino → μ + tracks, $\sqrt{s} = 8$ TeV

$<L_{xy}> = 0.3$ cm
$<L_{xy}> = 3$ cm
$<L_{xy}> = 30$ cm
$\sigma_{\chi\chi}$ (NLO)

$\sigma_{\chi\chi}^{95\% \text{ CL}}$ (fb)

1000
100
10
1

$M_{\chi}$ (GeV)

500
1000
1500
2000
2500

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

$m_{\chi} = 150$ GeV

$\lambda_{S\chi\chi} \sin(2\alpha)$

0.0
0.5
1.0
1.5
2.0

luminosity (fb$^{-1}$)

0.001
0.01
0.1
1
10

$M_{\chi}$ (GeV)

500
1000
1500
2000
2500

$<L_{xy}> = 0.3$ cm
$<L_{xy}> = 3$ cm
$<L_{xy}> = 30$ cm
Prospects for HL/HE running

- Decays in other components: easy to trigger, harder to reconstruct
  - Best sensitivity ~3 orders of magnitude worse than inner detector

- High-mass physics: should have sensitivity up to kinematic limit!

- Main challenge is triggering on **all-hadronic, low-mass** new physics
  - Hidden valleys
  - Exotic Higgs decays
  - Neutral naturalness

- Other trigger options
  - Associated objects
  - “Volunteers”
  - Trackless jets or other use of tracking information
  - LHCb (better for high-multiplicity objects like emerging jets)

(Strassler, Zurek 2006)
(review: Curtin et al., 2013)
(Craig et al., 2015; Curtin, Verhaaren 2015)

Schwaller, Stolarski, Weiler 2015
Implications of Phase Transition

- In neither scenario are there direct links to the EWPT
  - **Leptogenesis** must occur prior to EWPT, so modifying the transition can change the allowed parameter space

- Phase transitions change masses of fields
  - If fields get their mass from symmetry breaking, this can change particle abundances and asymmetries, generate out-of-equilibrium abundances

- Finally, let’s not forget low-scale leptogenesis, which can be tested by:
  - SHiP
  - Exotic Higgs sectors
  - $B$-factories/LHCb
  - LHC + 100 TeV collider
  - ....

(BS, Yavin 2014)

(Izaguirre, BS 2015; Batell, Pospelov, BS in progress)

MANY, MANY REFERENCES!!
Conclusions

• WIMP-like dynamics can generate a baryon asymmetry in several ways, definitively linked to the weak scale

• Colliders serve as excellent probes of this new physics

• 100 TeV collider would allow the comprehensive study of the most favoured regions for WIMP-driven baryogenesis
Back-up slides
WIMPy Baryogenesis: Pheno

Other possible constraints:

1. EDMs
   - In the minimal model, new physics only couples to one chirality of fermion
   - Gives cancellation when summing over diagrams at two loops
   - In the quark-coupled model, may have EDM at $10^{-31}$ e cm level
   - CPV can be very large in extended models
WIMPy Baryogenesis: Pheno

Other possible constraints:

2. Direct detection

   - In the quark-coupled model, direct detection occurs naïvely at 1-loop
   - However, there is a cancellation among diagrams to give a $v$-suppressed rate
   - Again, this may be different beyond the minimal model

   ![Diagram of direct detection at one loop](image)

3. Indirect detection

   - Comparable to regular WIMPs annihilating to hadrons, gauge bosons, subdominant to collider constraints (but more model-independent)

   - Other bounds (flavour, n-nbar oscillation) could be large, are model-dependent
LHC Search Possibilities

**exotica & SUSY**

- prompt analyses
- heavy flavour decays
- disappearing tracks
- vertices from displaced tracks
- non-pointing photons
- stopped gluinos
- displaced lepton jets
- decays in HCAL
- decays in muon system
- stable charged particles
- missing energy searches
Displaced Jet Bounds

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

$m_\chi = 150$ GeV

(b) $\langle L_{xy} \rangle = 30$ cm
Decays in Other Components

Can also have decays in calorimeters and muon system

HCAL

muon system (MS)

(Atlas - arXiv:1501.0402)


trigger on jets with no ECAL deposition

trigger on large, isolated activity in MS

2 DV in tracker and/or MS

2 long-lived states each decaying in HCAL

• Common features
  • Limited acceptance due to requiring decays in specific places
  • Need stringent criteria + 2DV to suppress backgrounds
  • Worse limits than tracker decays for high-mass objects, comparable for low-mass
  • Thresholds won’t go up significantly for future running

With these tools…

Maybe this is what we can do!

25 June 2015

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