Probing Baryogenesis with Displaced Vertices at the LHC

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- Phys.Rev.D, 87,11603, YC and Raman Sundrum
- JHEP 1312 (2013) 067, YC
- JHEP 1502 (2015) 049, YC and Brian Shuve
- Ongoing corporation with ATLAS displaced jets working group

GGI LHC13 Workshop
Oct 1 2015

Outline

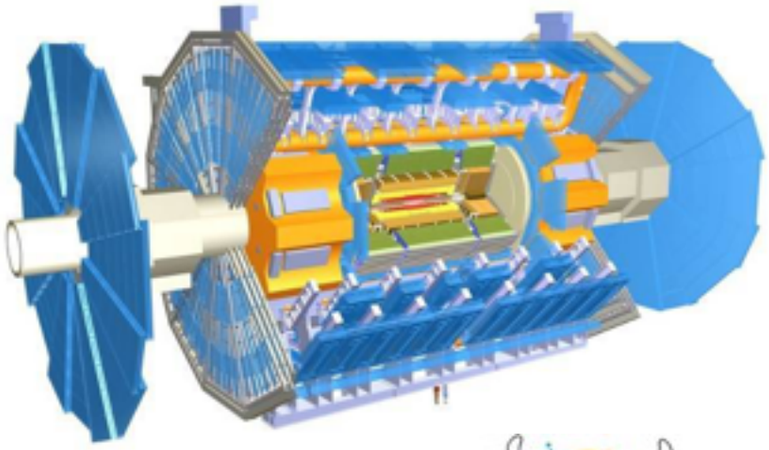
- **A mini-review of long-lived particle (displaced vertex) searches at the LHC:** motivation, status
- **A general cosmological motivation: baryogenesis triggered by weak scale new particle decay**
- **A motivated example: WIMP baryogenesis**

  embed in natural/split SUSY
- **Recast existing LHC analyses with theorists' tools:**

  Baryogenesis as an example, easy to generalize!
- **Conclusion/Outlook**

Long-lived Particle Searches at the LHC

- Nearly all SM particles decay **promptly** or have **small masses** relative to the LHC partonic CM energy
- Energetic objects reconstructing a high mass can emerge from all parts of the detector, giving **displaced vertices (DV)**



☞ Displaced vertex signal is spectacular! 

- low SM background, sensitive to **rare signal events** (new long-lived particles…)

Long-lived Particle Searches at the LHC

Displaced vertex signal is spectacular!

- But, we could easily miss it entirely!…

- Most LHC searches require that objects pass through the **primary vertex (PV)** to reject cosmics, mis-reconstructed objects, etc.
- In most searches, the transverse impact parameter (distance of closest approach to the beam) has to be

  ≲ 100 μm - 1 mm (= *prompt*) (track quality cut)

☞ Without dedicated efforts, DV signal events may fail to be even **triggered** on!

Long-lived Particle Searches at the LHC

Rising interests+ endeavours from **both** experimentalists and theorists in the recent years!

- A (incomplete) list of related ATLAS/CMS publications based on 8 TeV data:
  - ATLAS displaced dijets (arxiv:1504.03634)
  - ATLAS displaced lepton pairs/multitrack (arxiv:1504.05162)
  - ATLAS displaced muon+tracks (ATLAS-CONF-2013-092)
  - CMS displaced dijets (arxiv:1411.6530)
  - CMS displaced dilepton (CMS-PAS-B2G-12-024) …
- Rising # of related papers by theorists…
- Displaced higgs decay: A focus of the exotic Higgs decay working group of the LHC collaboration
- Dedicated workshop: e.g. at UMass-Amherst, Nov 2015…

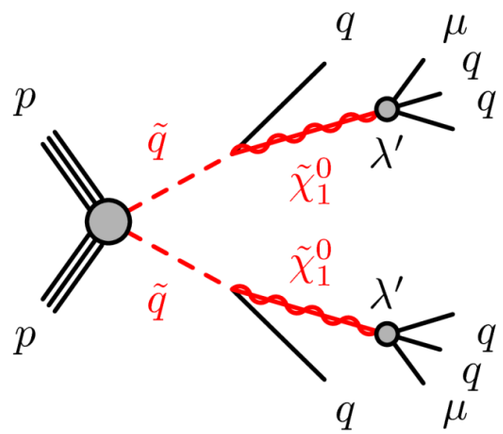
Theoretical Motivations

- **Naturalness:** long lifetime from approximate Z_2 symmetry

SUPERSYMMETRY

- Can evade MET searches with (small) *R*-parity violation
- 'Displaced SUSY'

(Graham, Kaplan, Rajendran, Saraswat 2012…)

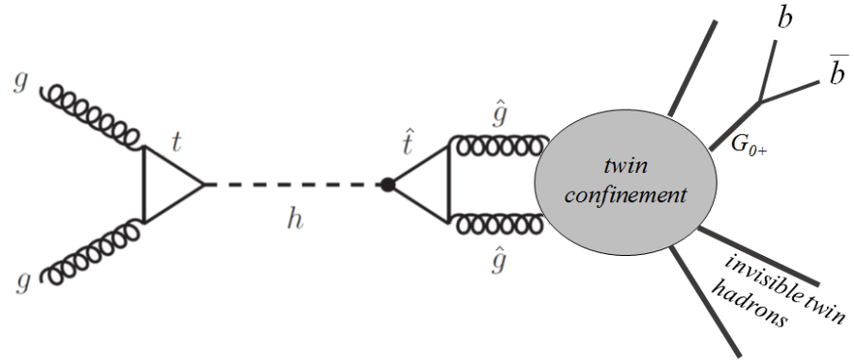


- Long-lived LSPs can also arise with split spectra

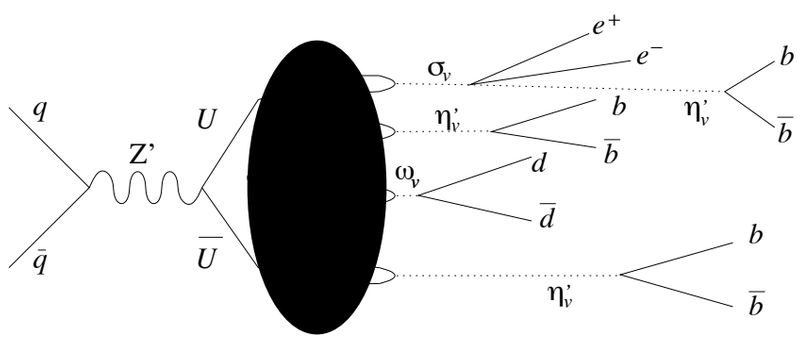
- **General hidden valley type of new physics** *(Strassler, Zurek 2006…)*

TWIN HIGGS

- Approximate Z_2 symmetry relates SM fields to `twin' fields, cancelling the top divergence
- Breaking must be non-zero to obtain observed EWSB, but small to obtain a natural theory



(Craig, Katz, Strassler, Sundrum 2015…)

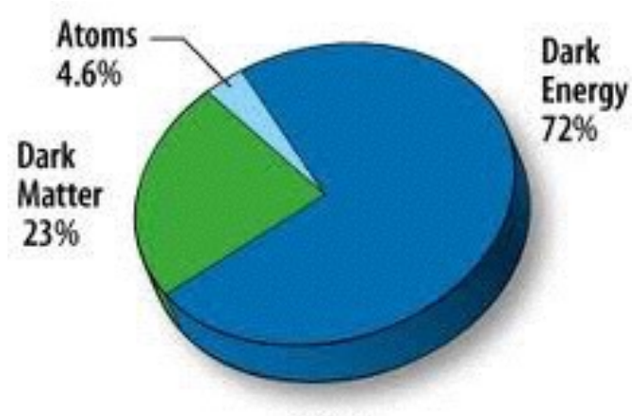


Theoretical Motivations *(new)*

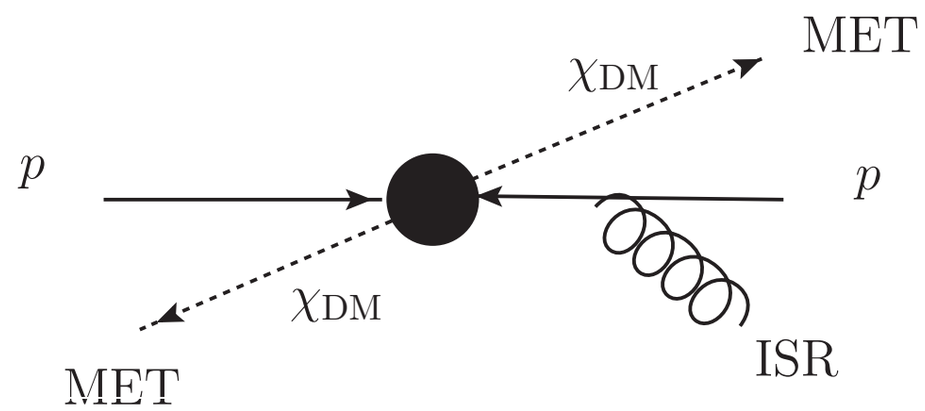
Baryogenesis from Metastable Weak-scale New Particle

Could LHC shed light on prominent puzzles in modern cosmology?

$\Omega_{DM} \approx 23\%$, $\Omega_B \approx 5\%$, $\Omega_B \sim \Omega_{DM}$



- Familiar/well-studied case: WIMP dark matter (Ω_{DM})
  - Mass ~O(10-100) GeV, can be produced within E_{LHC} =14 TeV
  - Pair produced (Z_2), invisible, MET + X



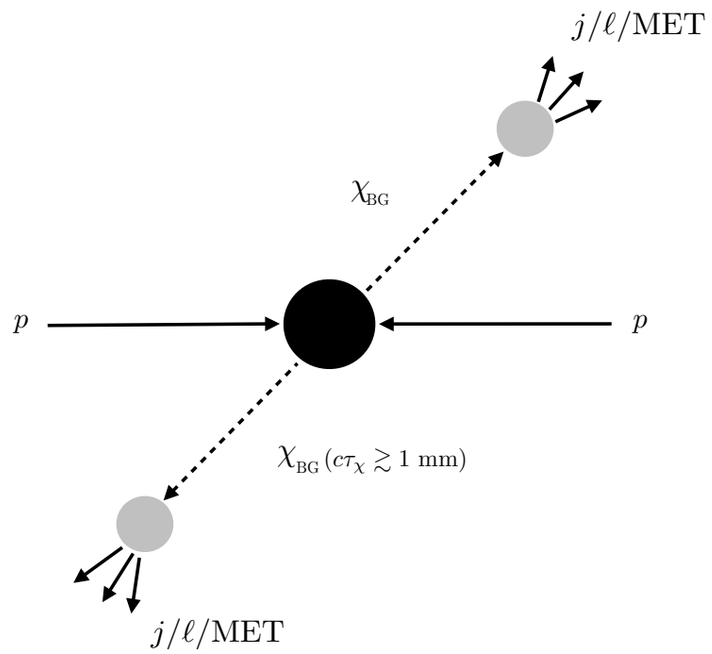
Theoretical Motivations *(new)*

Baryogenesis from Metastable Weak-scale New Particle

- **New opportunity**: baryogenesis (address Ω_B , possibly + $\Omega_B \sim \Omega_{DM}$)
  - New <u>metastable</u> particle (baryon parent), w/mass ~O(10-100) GeV
  - Pair produced (approx. Z_2), via Z/Z', or Higgs portal
  - Cosmological condition

⇒ typical decay final states:

Displaced decay , to $j/\ell/\mathrm{MET}$



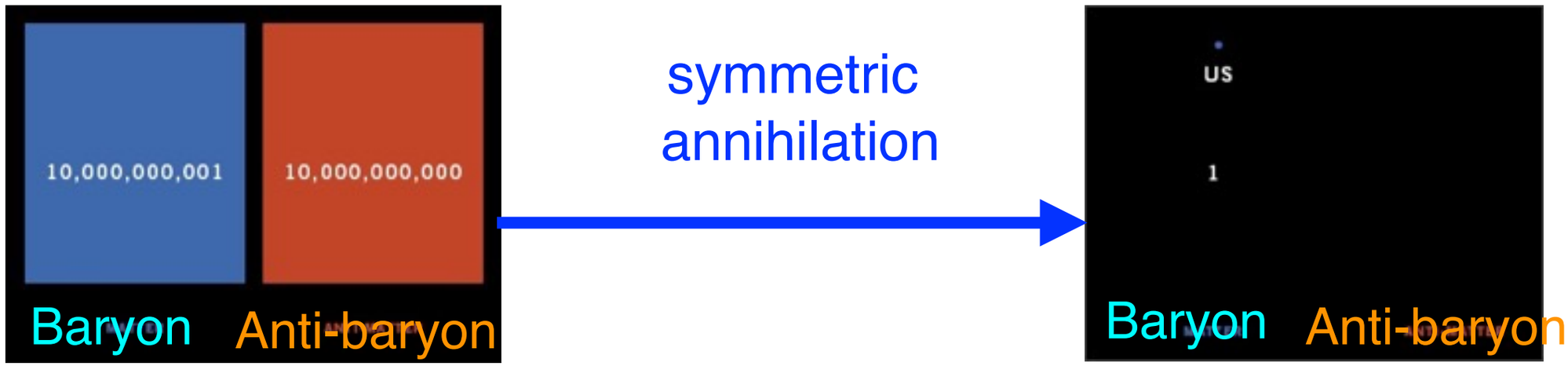
Mini-Review of Baryogenesis

- **Origin of Ω_B ? = Where do we ourselves come from?**

We do not know!

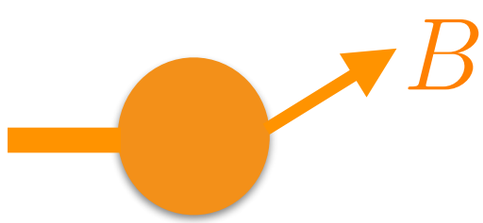
Initial $B - \bar{B}$ asymmetry

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

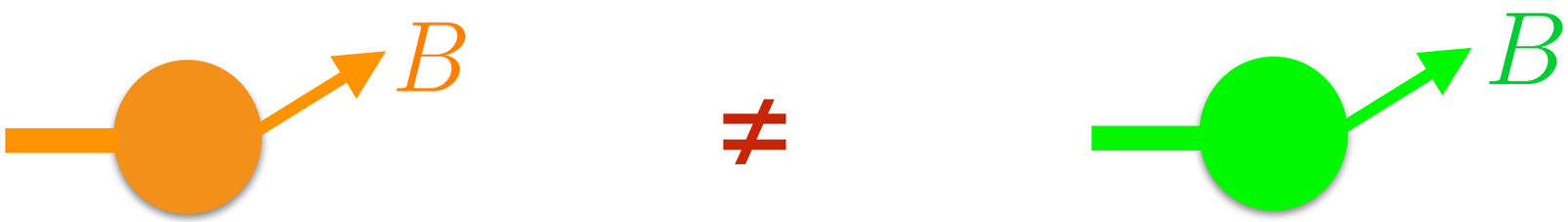


Sakharov Conditions (1967):

- **Require baryon number violation**



- **Require C-, CP-symmetry violation**

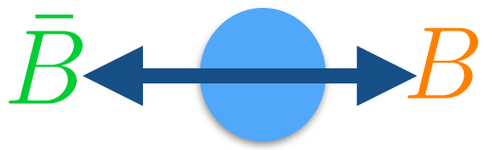


Mini-Review of Baryogenesis

Sakharov Conditions (cont.):

In thermal equilibrium:

$$n_B(p)^{\rm eq} \sim \exp\left[\left(-\sqrt{p^2+m_B^2}+\mu\right)/T\right],\ \ n_{\bar{B}}(p)^{\rm eq} \sim \exp\left[\left(-\sqrt{p^2+m_{\bar{B}}^2}-\mu\right)/T\right]$$



☞ $\mu = 0$

CPT symmetry ☞ $m_B = m_{\bar{B}}$

⇒ $n_B^{\rm eq} = n_{\bar{B}}^{\rm eq}$, $\langle B \rangle_{\rm eq} = 0$

$\Omega_B \approx 5\%$: Need beyond the Standard Model Physics!

- **Require departure from equilibrium!**

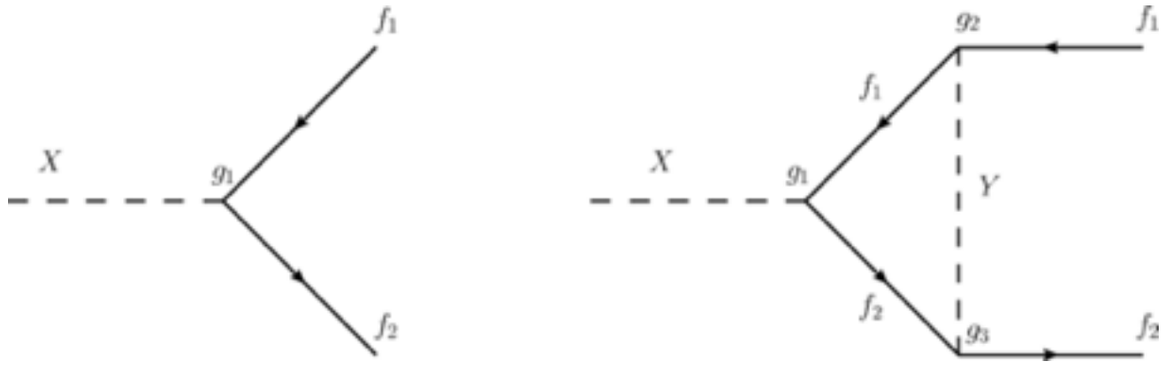
❖ Existing baryogenesis mechanisms: (leptogenesis, EWBG…)

Most involve high M or/and T, *direct* experimental test impossible (c.f. WIMP DM for $\Omega_{\rm DM}$)

Baryogenesis from Out-of-Equilibrium Decay

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

- Assume a massive neutral particle χ
- Baryon asymmetry can be produced in its decay (B-, CP-violating)



$$\Gamma(\chi \to f) \neq \Gamma(\chi \to \bar{f})$$

$$n_f - n_{\bar{f}} \neq 0$$

- Typically, the inverse processes efficiently erase the asymmetry
- But, if χ is long-lived, and <u>decays only after $T_f < M_\chi$</u> :

Inverse decay:
Boltzmann suppressed

$$e^{-M_\chi / T_{\rm decay}}$$

☞ **Out-of-equilibrium decay** ⇨ Sakharov conditions ✓

Baryogenesis from Out-of-Equilibrium Decay

- Asymmetry is robustly preserved if (*H*: Hubble expansion rate)

$$\Gamma_\chi < H(T = M_\chi)$$ ☞ Weak washout scenario

An intriguing observation (**YC**, Sundrum 2012; **YC**, Shuve, 2014)

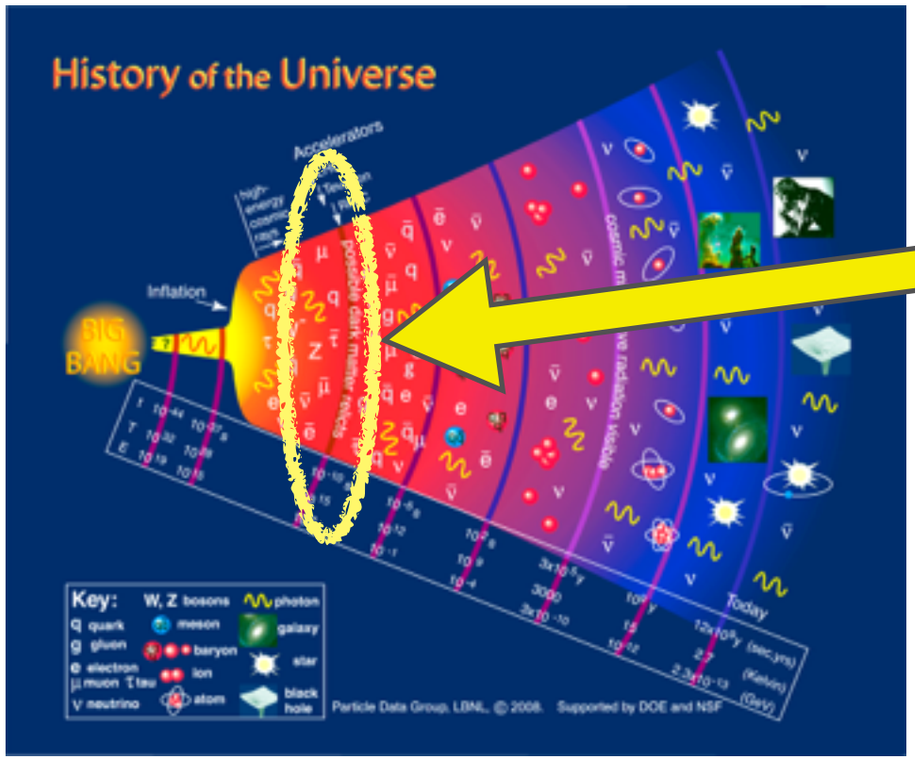
- If χ has mass at weak scale (the new energy frontier LHC is exploring!), numerology gives $c\tau_\chi^{-1} < H(T_{\rm EW}) \sim 10^{-13}\ {\rm GeV}$
- Converting to decay length:

$$c\tau_\chi \gtrsim {\rm mm}$$ ☞ Displaced vertex regime @LHC!

Displaced Vertices Motivated by Baryogenesis

$$\Gamma_\chi < H(T = M_\chi) \quad \Longleftrightarrow \quad c\tau_\chi \gtrsim \text{mm}$$

- A **generic connection** between cosmological slow rates at *T ~100 GeV* and displaced vertices at colliders
- **The universe around EW phase transition was just slightly bigger than LHC tracking resolution!**



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

$$10\ \text{GeV} \to (1.3\ \text{m})^{-1}$$

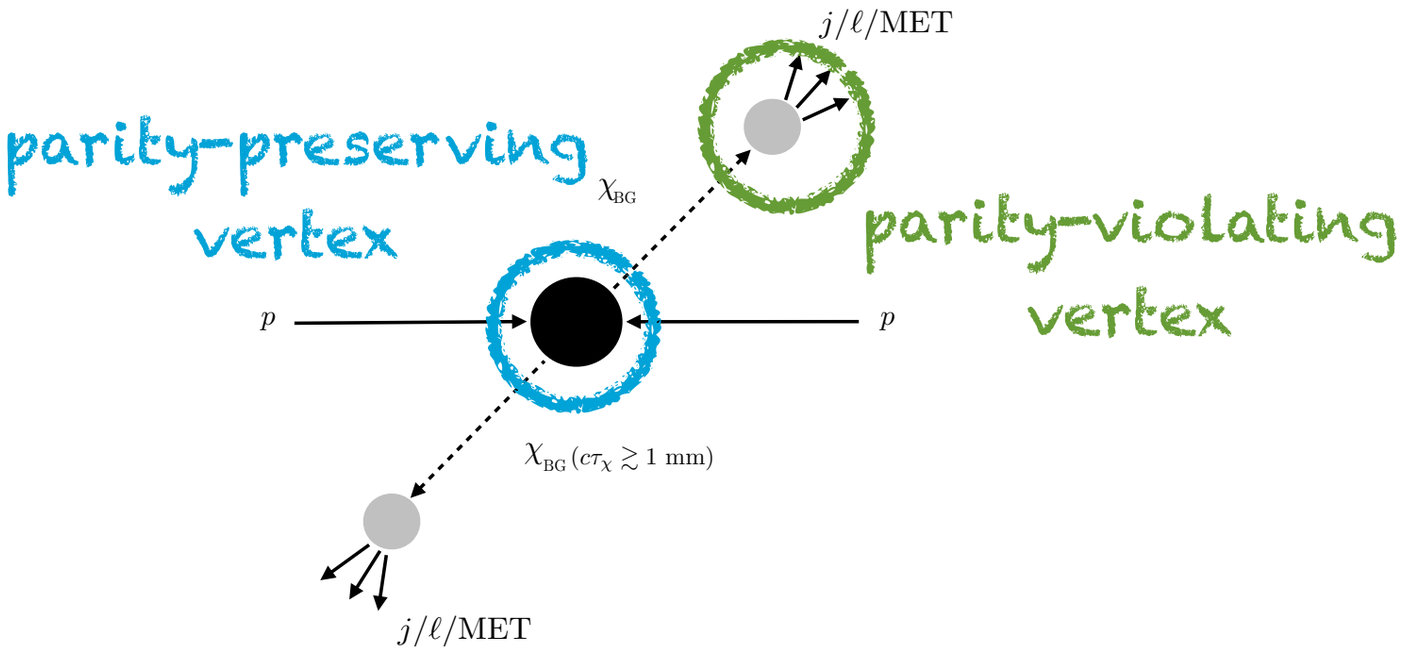
$$1\ \text{TeV} \to (0.13\ \text{mm})^{-1}$$

also see: Chang, Luty, 2009

Displaced Vertices Motivated by Baryogenesis

- **Production at the LHC?**

  No conflict between a **small** decay rate and a **large** production rate



- Long lifetime due to approximate symmetry (e.g. Z_2 parity)
- Recover MET signal for DM in the limit of exact symmetry!

Concrete, motivated baryogenesis models as example?

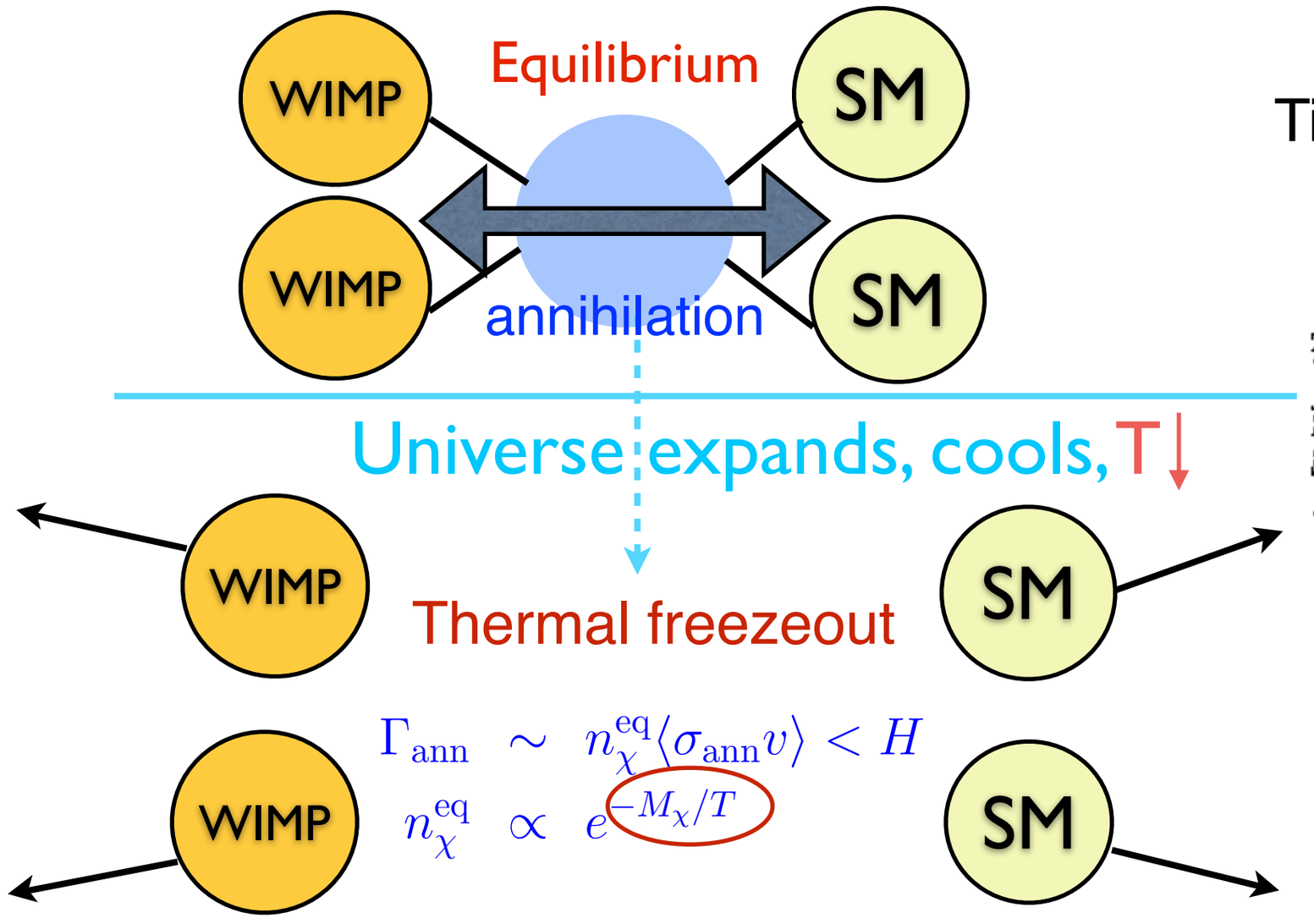
Baryogenesis from WIMPs

- YC and Raman Sundrum, Phys.Rev.D,11603 (2012)
- YC, JHEP 1312 (2013) 067

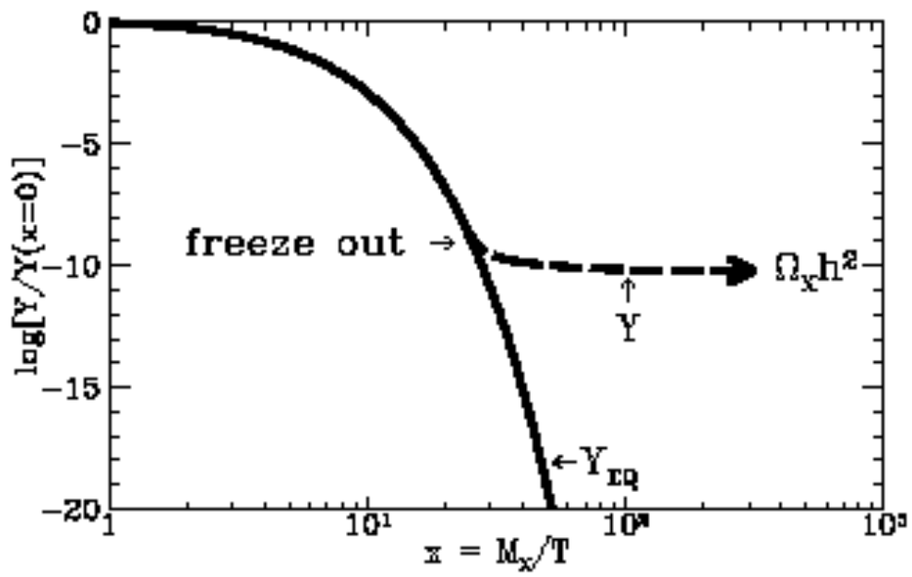
WIMP Miracle for DM

— Ω_{DM} by weak scale new physics

- Cosmic Evolution of a <u>stable</u> WIMP χ :



Time evolution of χ abundance:



→ time

Departure from equilibrium: key to Ω_{WIMP} !

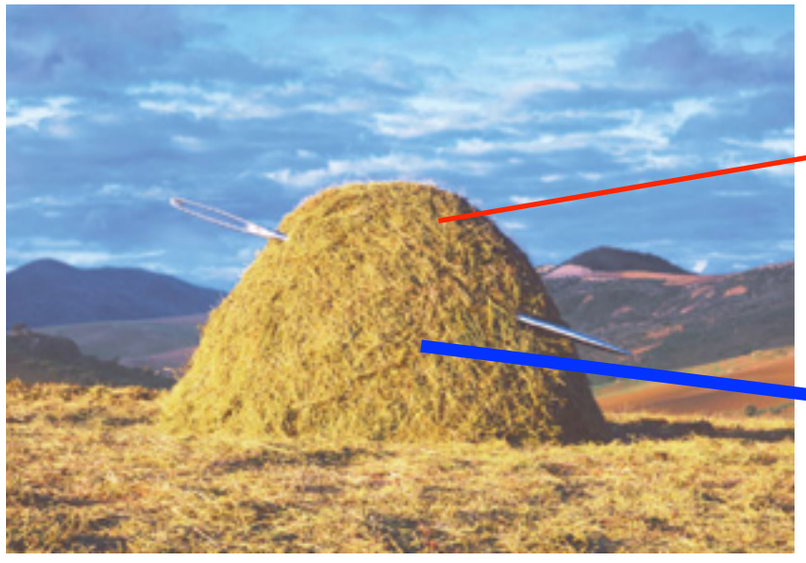
WIMP DM Miracle

- Neat prediction for the <u>absolute</u> amount of $\Omega_{\rm DM}$:

$$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1} \sim 0.1 \left(\frac{G_{\rm Fermi}}{G_\chi}\right)^2 \left(\frac{M_{\rm weak}}{m_\chi}\right)^2$$

With $m_\chi \sim M_{\rm weak}$, $G_\chi \sim G_{\rm Fermi}$, readily gives $\Omega_{\rm DM} \approx 23\%$!

- Robust, insensitive to cosmic initial condition
- **Miracle:** Predicts the right location of <u>a needle in a haystack</u>!

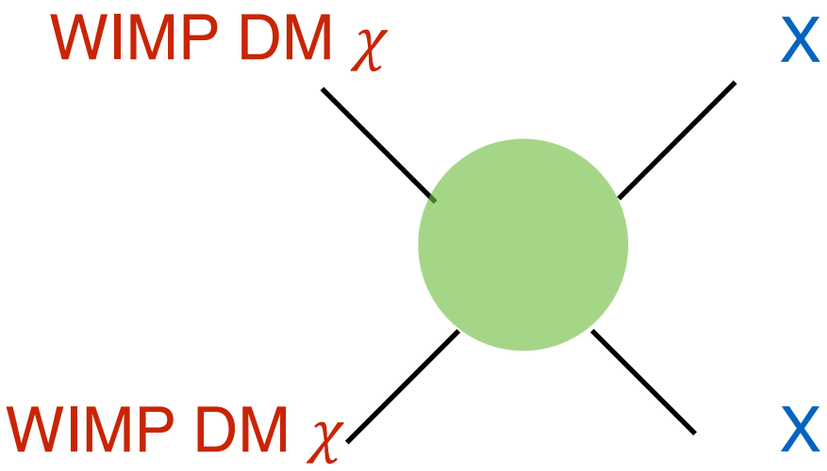


Observed $\Omega_{\rm DM} \approx 23\%$

yet *not precise*

Vast possible range of a cosmological quantity: e.g. $\Omega_{\rm DM}^{\rm theory} \sim (10^{-7} - 10^{35})$

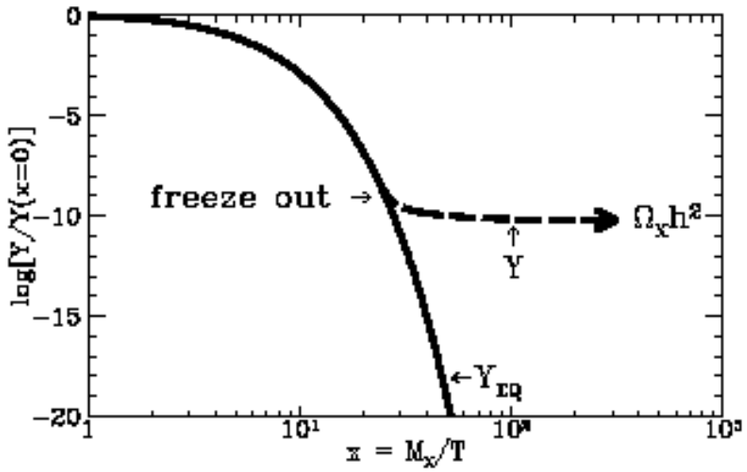
- **The familiar story of a stable WIMP**



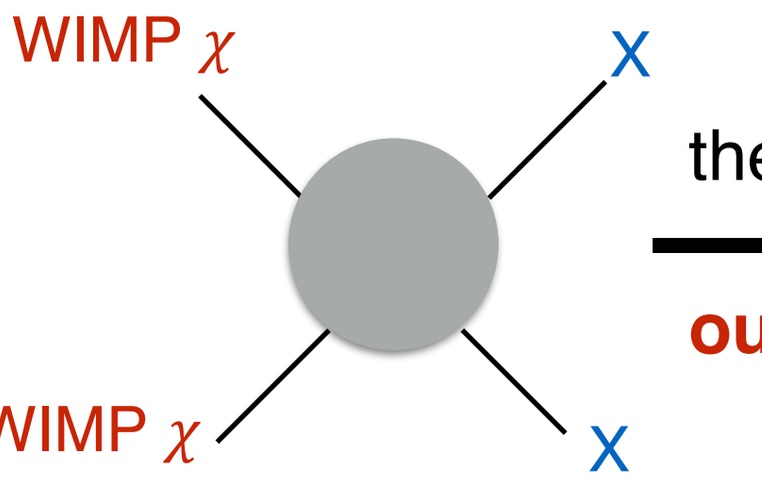
thermal freeze out

out-of-equilibrium

Ω_{DM}



- **A different story of a (general) WIMP?**



thermal freeze out

out-of-equilibrium

?

Stable χ_{DM}, Ω_{DM}

Metastable χ_B?
(later decay)

✴ **Diverse lifetimes**: generic in nature

(symmetry, mass/coupling hierarchy)

e.g. long lifetime of b-quark, muon

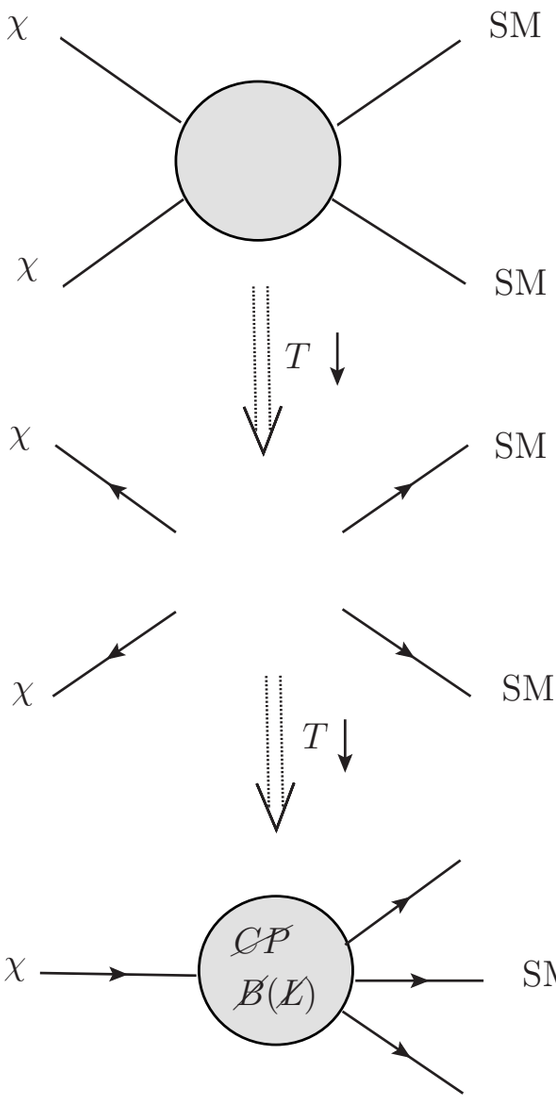
($m_W \gg m_b, m_\mu$), SUSY WIMP w/RPV

+ B-, C-, CP-violating decay

YC and Sundrum 2012;

YC 2013

Baryogenesis from Metastable WIMP Decay



★ Thermal freezeout

$$\Omega_{\rm WIMP}^{\tau\to\infty}$$

$$\Gamma_\chi \lesssim H(T_{\rm freezeout})$$

★ Baryogenesis from decay

$$\Omega_B = \epsilon_{\rm CP}\frac{M_p}{M_{\rm WIMP}}\Omega_{\rm WIMP}^{\tau\to\infty}$$

- A new baryogenesis mechanism w/weak scale new physics:

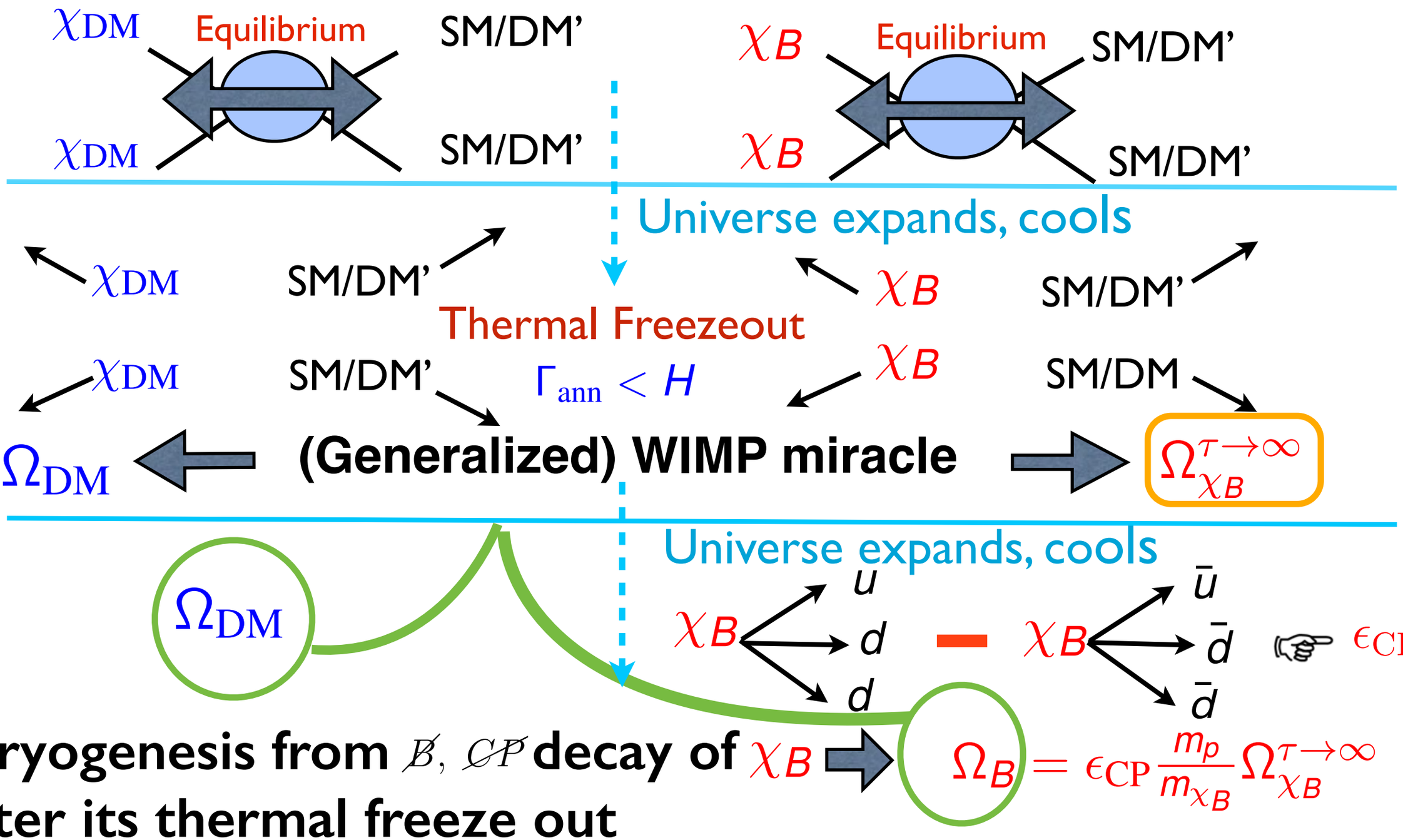
  A WIMP miracle for baryons, can occur well below T_{EW}

- If + A stable WIMP DM

  ☞ new path addressing $\Omega_B \sim \Omega_{DM}$

Consider a stable WIMP $\chi_{\rm DM}$ as DM;
In addition, a metastable WIMP χ_B as baryon parent

- **Cosmic evolution of the two WIMPs:**



Baryogenesis from $\not{B}$, $\not{CP}$ decay of χ_B after its thermal freeze out

Central Result:

Generalized WIMP Miracle

$$\Omega_{\rm DM} \sim \Omega_B = \epsilon_{\rm CP} \frac{m_p}{m_{\chi_B}} \Omega_{\chi_B}^{\tau\to\infty}$$

- Robust: insensitive to model details (weak washout typical)
- Novel low scale baryogenesis (independent of WIMP DM)
- Extra factor $\epsilon_{\rm CP} \frac{m_p}{m_{\chi_B}}$ ($\epsilon_{\rm CP} \sim 1\%, m_{\chi_B} \sim 100\ {\rm GeV}$), compensated by

$\Omega_{\chi_B}^{\tau\to\infty} > \Omega_{\chi_{\rm DM}}$ — accommodated by O(1) different masses/couplings associated w/ $\chi_{\rm DM}$ and χ_B (χ_B: a "weaker" WIMP)

☞ **Recall: WIMP miracle is not precise!**

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

A Minimal Model Example

- We add to the Standard Model Lagrangian ($\not{B}$, $\not{CP}$):

$$\begin{aligned}\Delta\mathcal{L} &= \lambda_{ij}\phi d_i d_j + \varepsilon_i \chi \bar{u}_i \phi + M_\chi^2 \chi^2 + y_i \psi \bar{u}_i \phi + M_\psi^2 \psi^2 \\ &+ \alpha \chi^2 S + \beta |H|^2 S + M_S^2 S^2 + \text{h.c.}\end{aligned}$$

ϕ: di-quark scalar w/same charges as SM u-quark;

χ, ψ: SM singlet Majorana fermions;

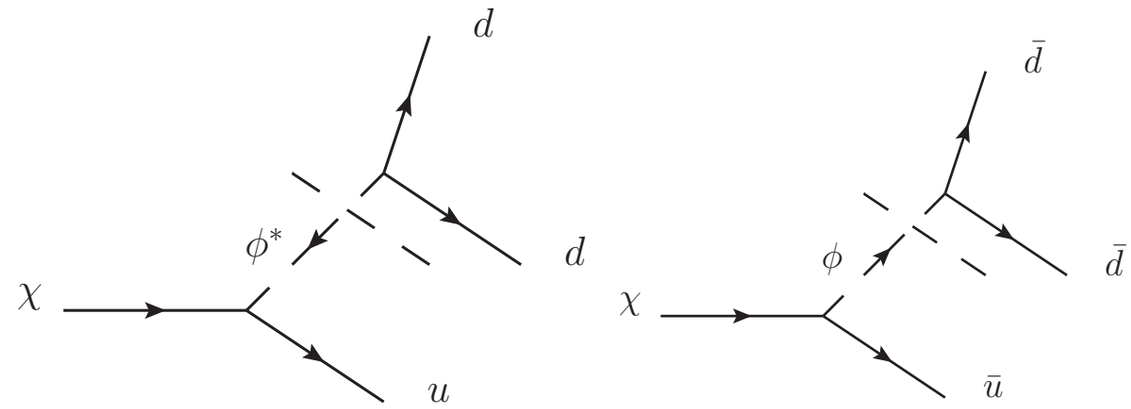
$\varepsilon_i \ll 1$: small breaking of a χ-parity ⇨ long-lived χ

$\chi \equiv \chi_B$, the WIMP parent for baryogenesis

S: singlet scalar, mediate WIMP annihilation $\chi\chi \to \text{SM}$ via h-portal

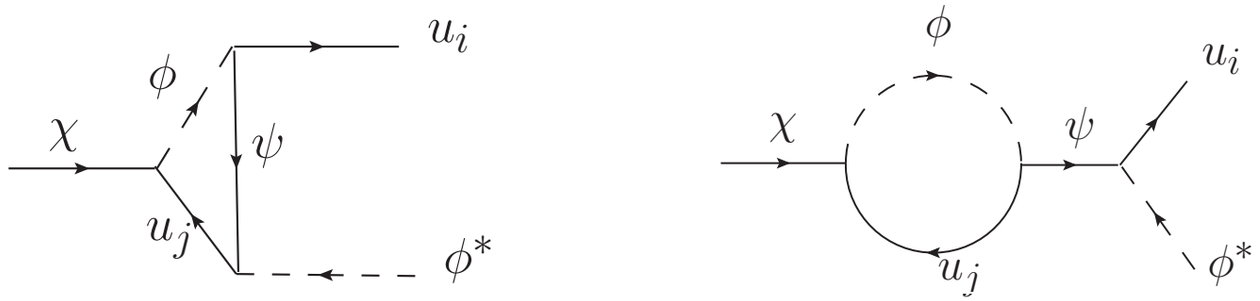
A Minimal Model Example

- Out-of-equilibrium decay of χ ➡ Ω_B



- Interference of tree- & loop-level decay

➡ CP asymmetry $\epsilon_{\rm CP} \equiv \dfrac{\Gamma(\chi \to \phi^* u) - \Gamma(\chi \to \phi \bar{u})}{\Gamma(\chi \to \phi^* u) + \Gamma(\chi \to \phi \bar{u})}$



- Check other constraints ($n \to \bar{n}$ oscillation, neutron EDM…)

➡ With weak scale masses, new particles couple mostly to heaviest quarks (b, t) (just like the Higgs boson!)

Meeting Particle Physics Frontier
—Embedding in Supersymmetry (SUSY)

- **Our mechanism: generic** low scale baryogenesis

Embed in motivated theory framework, e.g. SUSY?

Favored viable SUSY models after LHC runs:

- "Natural" SUSY: light stop $m_{\tilde{t}} \ll m_{\tilde{q}_{1,2}}$ and/or B-(L-) violation
- (Mini-)Split SUSY ($m_{\text{gauginos}} \ll m_{\text{sfermions}}$)

Embedding in Natural SUSY: Model

Our minimal model: direct "blueprint"

- Promote singlets χ, S to chiral superfields, add to the MSSM.

$\not{B}$ superpotential:

$$W \supset \lambda_{ij} T D_i D_j + \varepsilon' \chi H_u H_d + y_t Q H_u T + + \mu_\chi \chi^2$$
$$+ \mu H_u H_d + \mu_S S^2 + \alpha \chi^2 S + \beta S H_u H_d .$$

- Assume ~~*SUSY*~~ pattern: scalar χ and $\tilde{q}_{1,2}$ heavy, decoupled, as in "natural SUSY"

- Mapping: (minimal model $\longrightarrow$ SUSY model)
  - Diquark $\phi \longrightarrow$ light $\tilde{t}_R$ in superfield T
  - Baryon parent singlet $\chi \longrightarrow$ fermion singlet χ
  - Majorana $\psi \longrightarrow$ MSSM gaugino
  - Singlet scalar $S \longrightarrow$ singlet S, mixes with H_u , enables χ annihilation
  - Small parameter $\varepsilon \longrightarrow \varepsilon'$, enables late decay $\chi \to \bar{\tilde{t}} t$ via $\chi - \tilde{H}_u$ mixing

Embedding in Natural SUSY
- Also a remedy!

Potential cosmological crisis of $\not{B}$ natural SUSY:

- An important channel of natural SUSY search at the LHC: light stop with B-violating prompt decay
  ⇒ TD_iD_j coupling ($\lambda_{ij} \gtrsim 10^{-7}$)
- **Cosmological problem:**
  Assume conventional baryogenesis at $T \gtrsim m_{EW}$ ⇒ pre-existing $Y_B^{\rm init}$ can be efficiently washed out by $\not{B}$ scattering
  e.g. $\tilde{H}_u t \to \bar{d}_i \bar{d}_j$ with ($\lambda_{ij} \gtrsim 10^{-7}$) !
- **Our model in Natural SUSY:** Baryon asymmetry regenerated below weak scale when all washout decouple

⇒ **A robust cure to this problem!** 

Embedding in Mini-Split SUSY

(Cui, JHEP 1312 (2013) 067)

Interesting (surprising) finding: successful baryogenesis from **minimal** SUSY standard model (WIMP $\tilde{B}$ decay)!

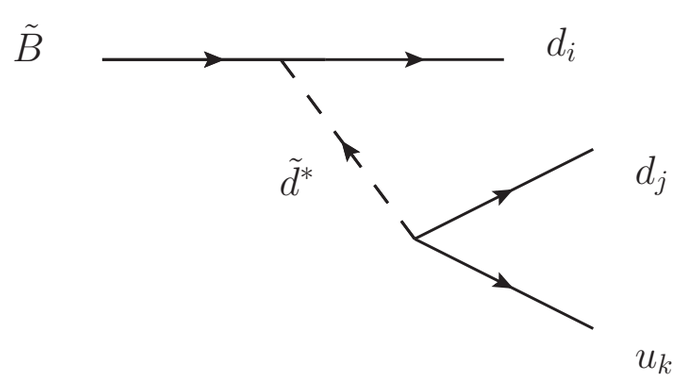
$\tilde{B} \to \Delta B$!

Sakharov#1: out-of equilibrium ✓

Split SUSY+ O(1) RPV: Natural long life-time of gauginos

Split spectrum $O(100-1000)\mathrm{TeV} \sim \mathrm{m_{scalar}} \gg \mathrm{m_{gaugino}} \sim \mathrm{TeV}$ + RPV

➡ Late decay automatic! e.g. $\chi \to udd$ (heavy mediator, 3-body...)



Embedding in Mini-Split SUSY

★ Sakharov #2, #3 (CP-, B/L-violation) ✓

rich CPV sources in SUSY (e.g. Majorana gaugino masses), $\not{B}$ ($\not{L}$) from RPV couplings (safer w/heavy scalars)

★ WIMP parent χ for baryons with "would-be" over-abundance ✓ : Bino $\tilde{B}$! (not desirable if it is DM in RPC SUSY...)

★ Nanopoulos-Weinberg Theorem for Baryogenesis:

additional $\not{B}$ source in the interference loop ✓

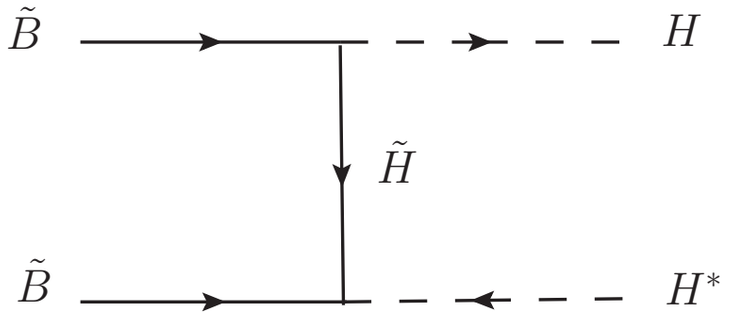
⇒ Another Majorana fermion in MSSM? $\tilde{w}$, $\tilde{g}$!

Minimal model (MSSM+RPV) gives everything needed for baryogenesis!

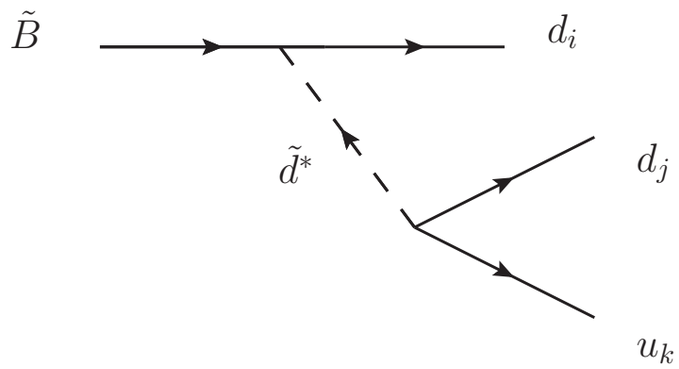
Embedding in Mini-split SUSY

- **Key processes:**

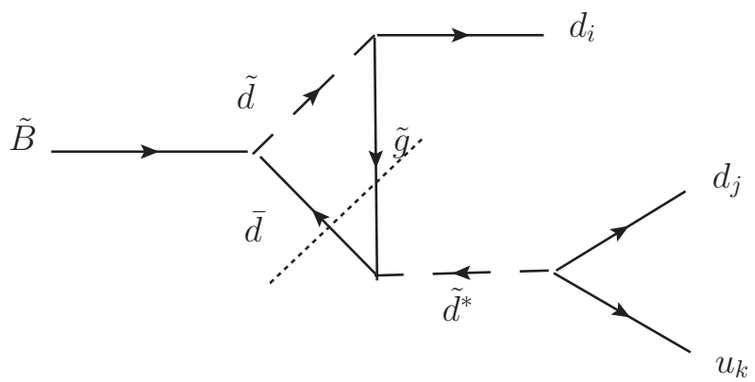
Thermal annihilation:

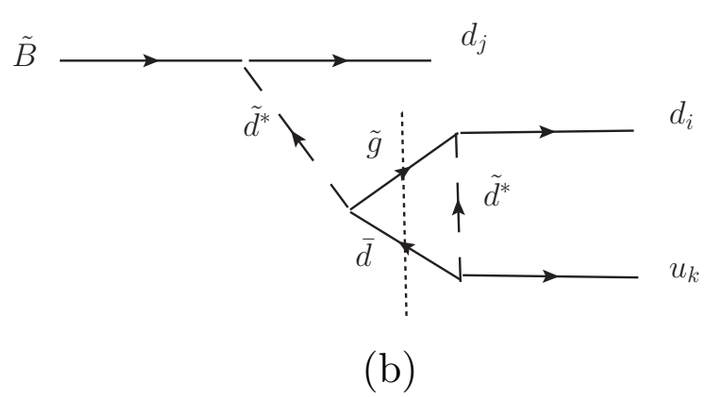


Tree-level RPV decay:



Interference loop:



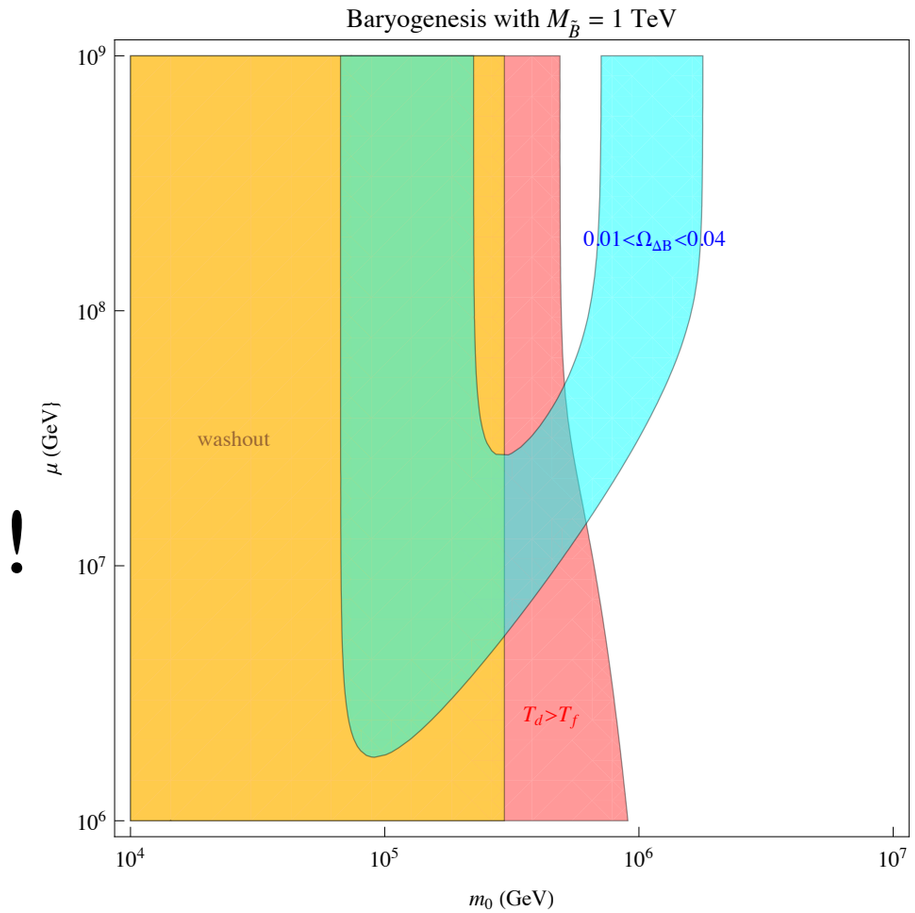


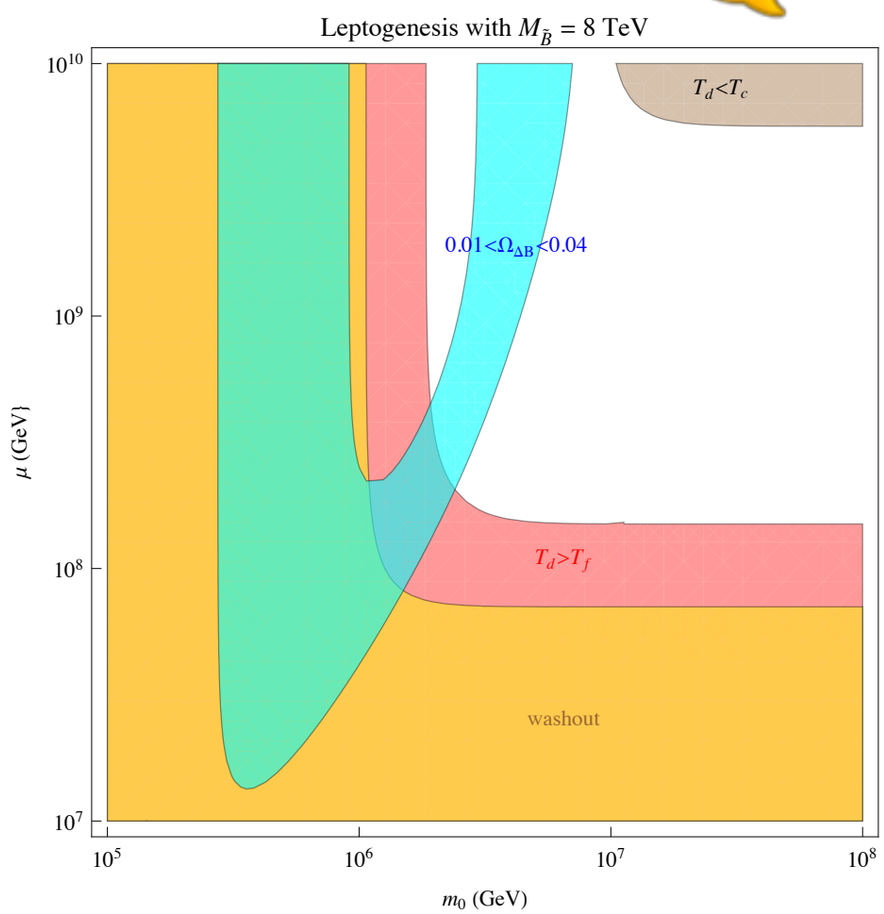
(RPC decays also included in analysis)

Numerical Results, examples

Include cosmological constraints: $\Omega_{\Delta B}$ …

⇨ mini-split: $m_{\text{scalar}} \sim O(100 - 1000)\text{TeV}$!





!

Loss of full naturalness: a compromise with anthropic/ environmental selection?

Figure 7: Cosmologically allowed regions of parameter space for (a) baryogenesis and (b) leptogenesis models. We set RPV couplings $\lambda^{''} = \lambda^{'} = 0.2$, $\phi = \frac{\pi}{2}$. Cyan region provides baryon abundance $10^{-2} < \Omega_{\Delta B} < 4 \cdot 10^{-2}$. In the case of leptogenesis the brown region is excluded by decay after EWPT at $T_c \approx 100$ GeV. The pink region is excluded by our simple basic assumption that bino decays after freezeout. Yellow region is excluded by requiring that washout processes are suppressed ($T_d < M_{\tilde{B}}$). Yellow region is in fact all included in the pink region (so appear to be orange in the overlapped region).

Baryogenesis from Out-of-equlibrium Decays

— Collider Phenomenology

YC and Shuve, arxiv:1409.6729, JHEP

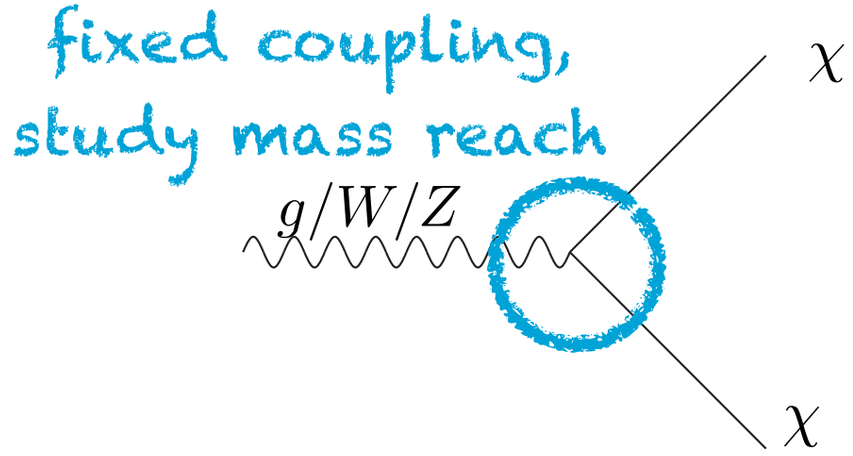
★ *Strategy/results generally applicable to other new physics search via displaced vertices*

Simplified Models

- Classify parity-invariant production modes (analogy to DM search @LHC!), e.g.

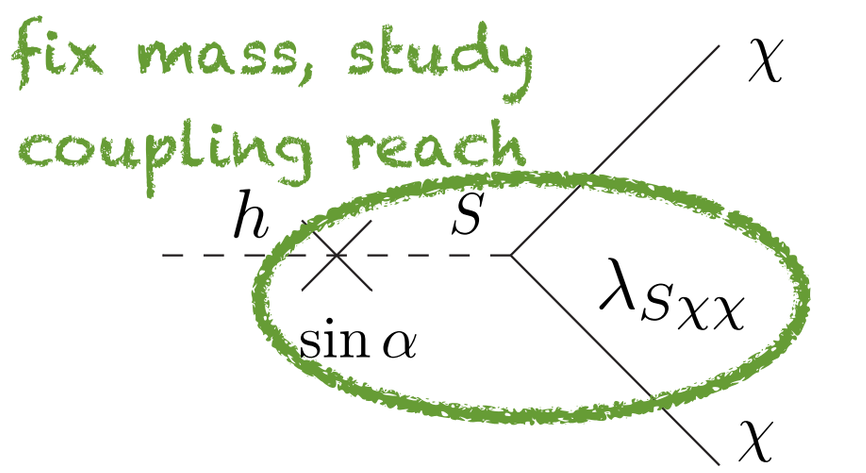
Charged under SM gauge interactions:

wino/gluino-like (state in interference loop)



Higgs portal:

singlet-like (e.g. $M_\chi = 150$ GeV)



- Classify decay modes (unlike DM search), e.g.

Baryon number violating:

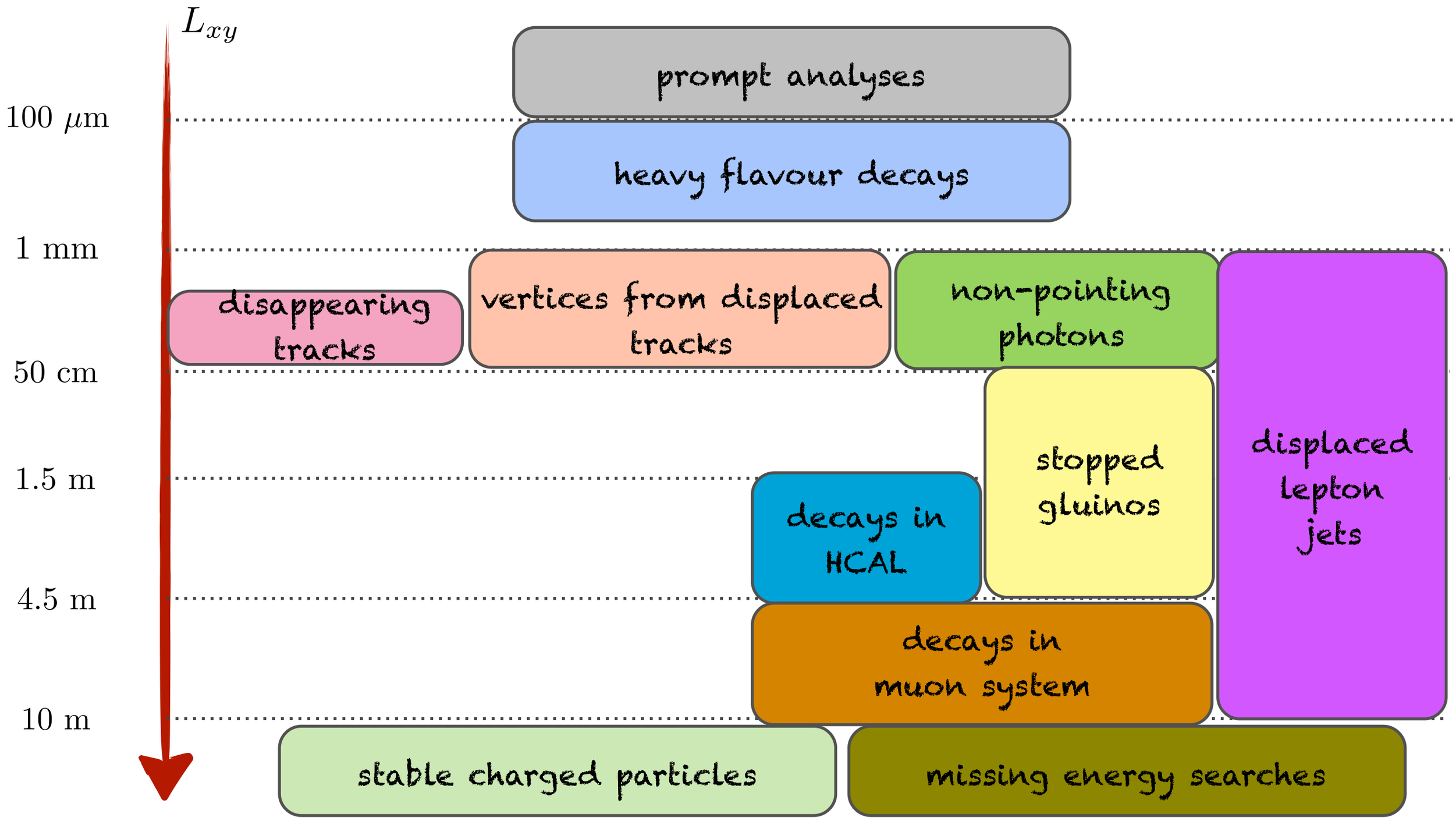
$$\chi \to u_i d_j d_k$$

Lepton number violating:

$$\chi \to L_i Q_j \bar{d}_k$$
$$\chi \to L_i L_j \bar{E}_k$$

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

LHC Search Possibilities



Experimental Searches

- Focus on displaced decay in tracking volume

- Near lower bound $c\tau_\chi \gtrsim \mathrm{mm}$ & better sensitivity, easier to model!

  (decay in other parts of detector important too…)

- Do recasts and reasonable variations of existing analyses due to modelling difficulties (for theorists!)

  - Two concrete examples (light-flavour only):

Baryon number violating:

$$\chi \to 3q$$

displaced jets (all-hadronic)

CMS, arXiv:1411.6530

Lepton number violating:

$$\chi \to \ell + 2q$$

displaced muon + hadrons

ATLAS-CONF-2013-092

- **Goal of our analysis:**

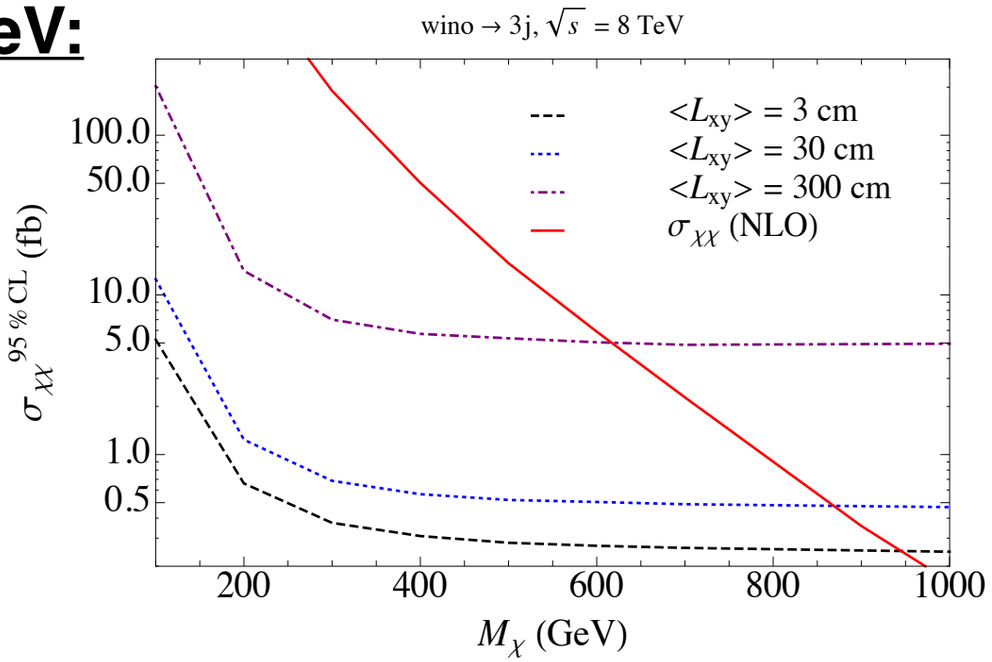
  - What is the coverage for our simplified models based on benchmarks chosen by the collaborations?
  - What advice can we provide for general experimental improvement?

Fully hadronic displaced vertices

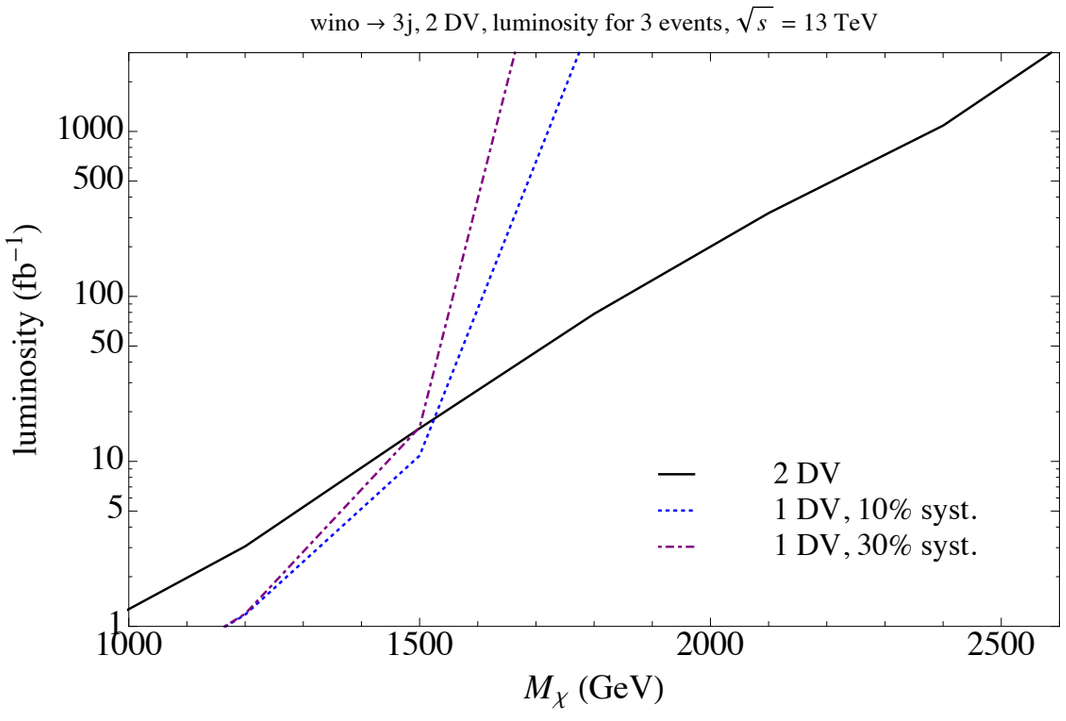
CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:



13 TeV:

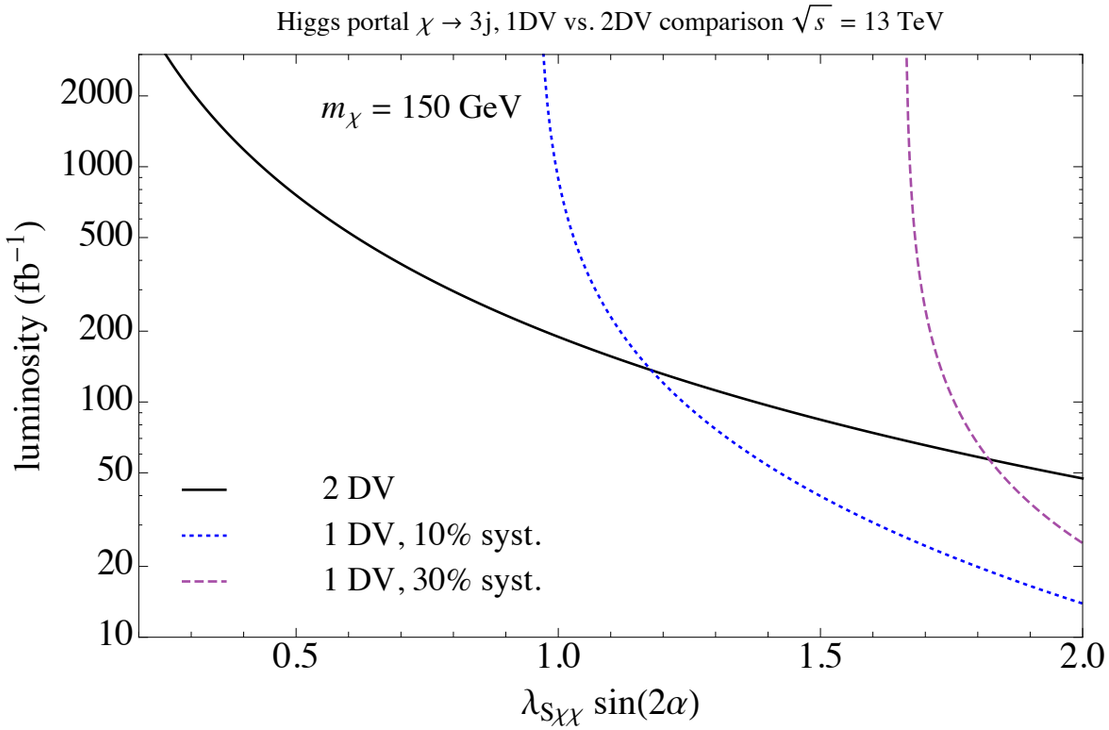


singlet-like (Higgs portal)

(we study a challenging case:
M_χ = 150 GeV, moderately off-shell!)

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

L_{xy} = 3 cm



Displaced muon + hadrons

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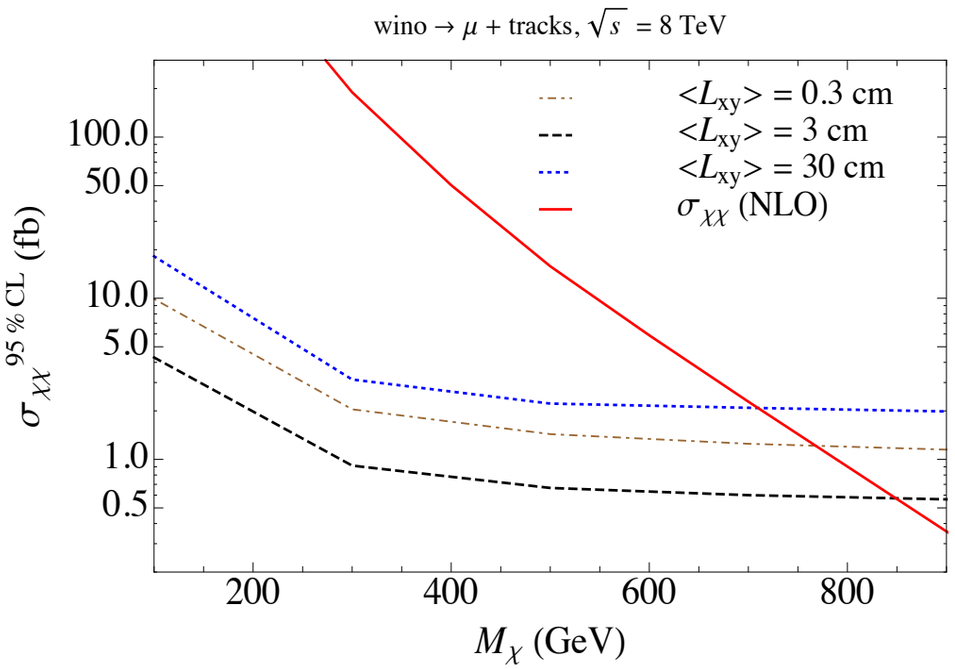
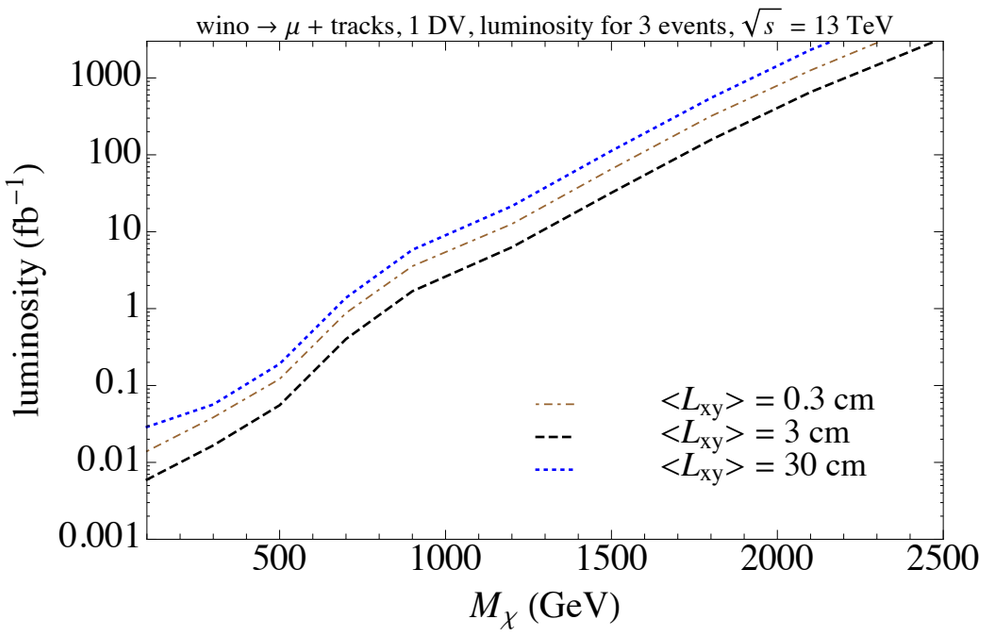
wino

8 TeV



13 TeV:
M~2.5 TeV

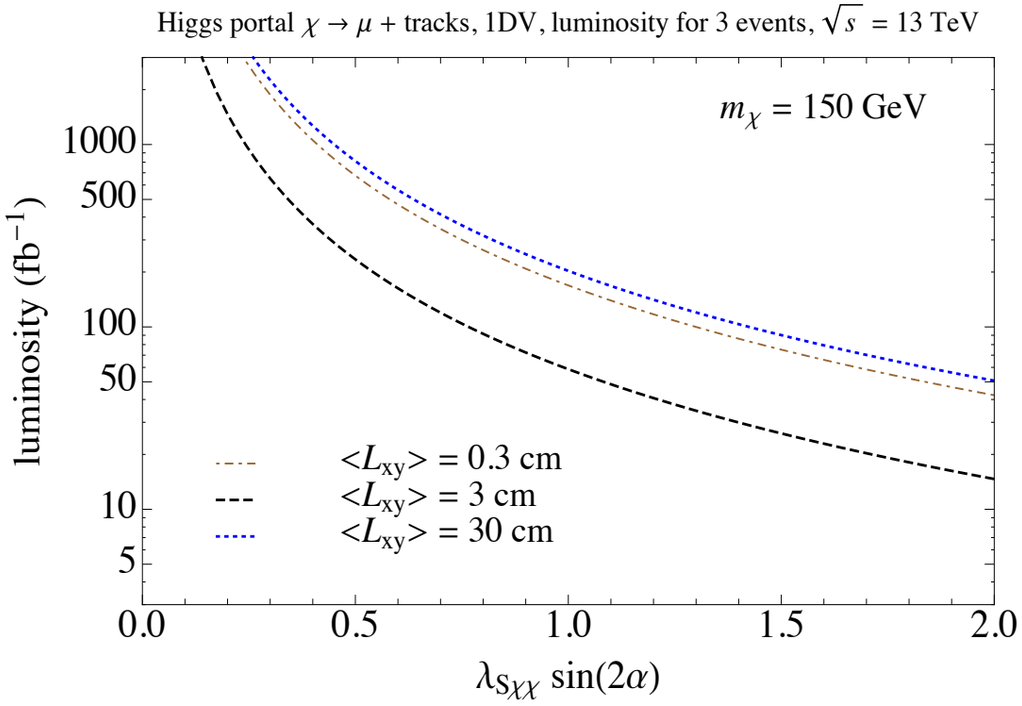


singlet (Higgs portal)

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

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

- 13 TeV: **σ_S~10 ab for L_{xy}~1 cm!**



Conclusion/Outlook

- Search for long-lived particles/DV at the LHC:
  - Spectacular channel, exciting developing field
  - Theoretically motivated, *not mere "exotic"!*
  - Challenges: e.g. trigger on low mass all hadronic states
- Baryogenesis from metastable weak scale particle decay:
  - A **robust cosmological motivation** for DV searches @ LHC
  - Exciting opportunity to reproduce the early universe BG @LHC!
- **WIMP baryogenesis:** a motivated example, new mechanism addressing Ω_B (+)$\Omega_B \sim \Omega_{DM}$, natural embedding in SUSY
- w/**ATLAS displaced jets working group:** working on implementing simplified models of WIMP BG as a benchmark example in official analysis w/LHC Run 2 data…

Thank you !