Displaced RPV SUSY & Baryogenesis

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Perimeter Institute

Long-lived BSM particles @ LHC workshop
UMass-Amherst, Nov 12, 2015

Displaced SUSY

- Gauge mediation: NLSP→gravitino + SM
  decay suppressed by $1/F^2$, displaced with $F \gtrsim 10^4$TeV
- Anomaly mediation: co-LSP winos
  decay suppressed by mass degeneracy $\Delta m \sim m_\pi$
  ⇒long disappearing track
- Mini-split spectrum: NLSP→SM + LSP (RPC)
  decay suppressed by $1/(m_0)^4$ + 3-body
- R-parity violation: decay suppressed by tiny RPV couplings (UDD, LLE, QDL…) (or w/mini-split spectrum)

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(see Brock's talk for more!)

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  ☞ pre-existing baryon abundance efficiently erased by $\not{B}$ scatterings, e.g. $\tilde{H}_u t \to \bar{d}_i \bar{d}_j$,, if $\lambda^{ij} \gtrsim 10^{-7}$!

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★ Estimate of washout: exponential reduction if $\Gamma_W \gtrsim H\,(T_{EW})$

$$Y_B(0) = Y_B^{\rm ini} e^{-\int_0^{T_{\rm ini}} \frac{\Gamma_{\rm W}(T)}{H(T)} \frac{dT}{T}} \sim Y_B^{\rm init} e^{-\frac{\lambda_{ij}^2 y_t^2}{g_*^{1/2}} \frac{M_{\rm pl}}{m_{\rm EW}}}$$

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What are possible solutions to this problem?

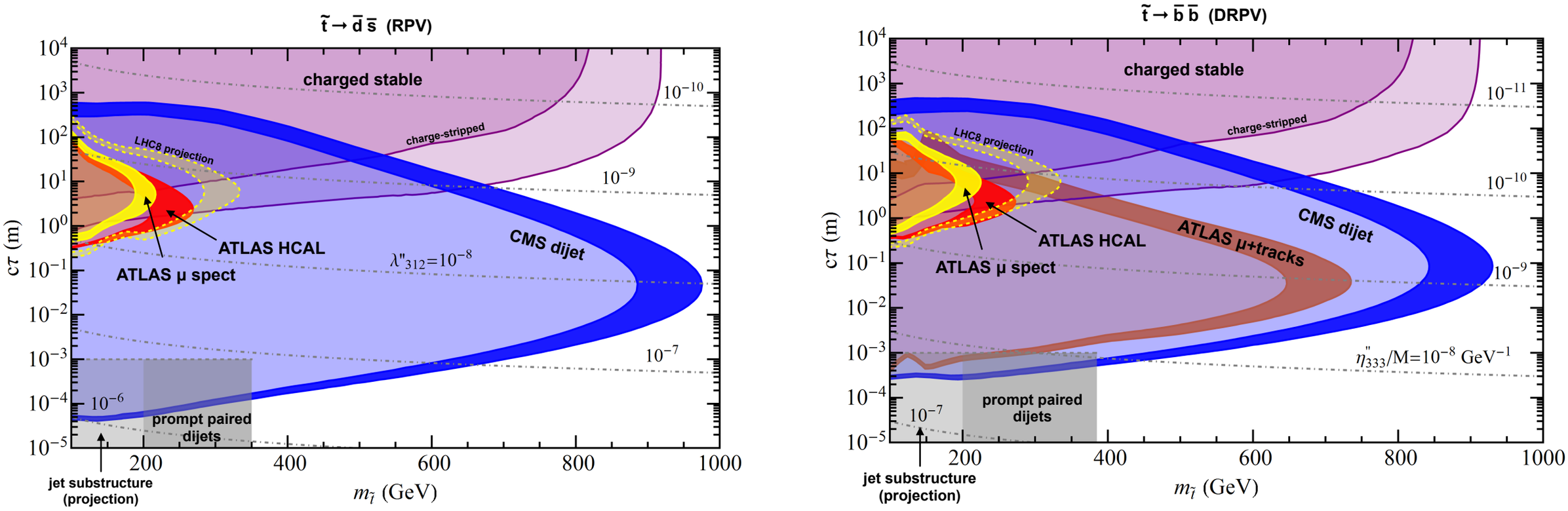
Avoid the Problem:
Suppress RPV Washout

- To ensure successful baryogenesis at $T \gtrsim T_{EW}$ … (?)

Natural SUSY with $\lambda^{ij} \lesssim 10^{-7}$ ⇒ Displaced Stop at LHC!

(Barry, Graham and Rajendran 2013)

★ Good coverage up to m~1TeV w/recent development at ATLAS/CMS! (colored, low bkg)



Liu and Tweedie, 2015

Solve the Problem:
Baryogenesis from RPV

- Baryogenesis at $T \lesssim T_{EW}$, after all washout processes decouple ($\Gamma_w \lesssim H$) ?
  - RPV reset/regenerate Ω_B **!?** (new ideas…)

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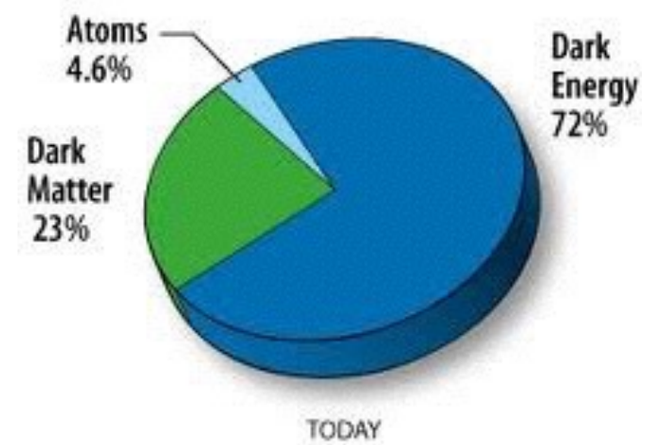
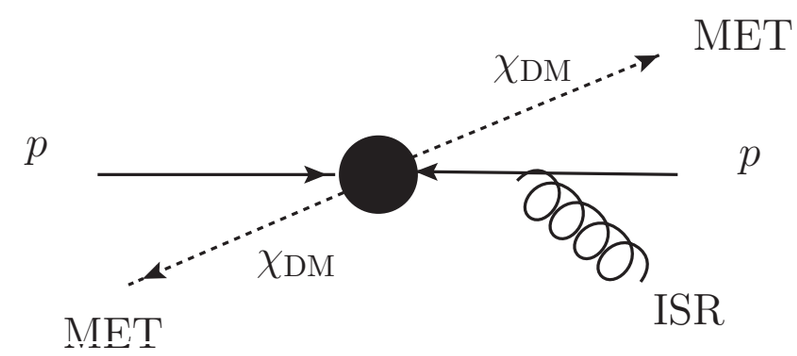


- **Could SUSY shed light on prominent puzzles in modern cosmology?**

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

- Familiar/well-studied case: (RPC) LSP WIMP dark matter, MET+X search @LHC



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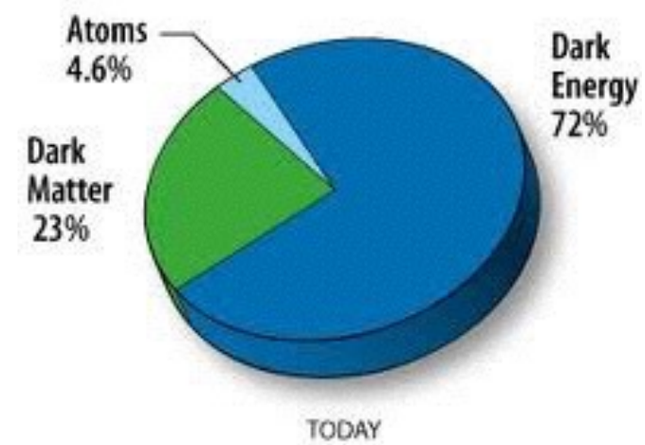

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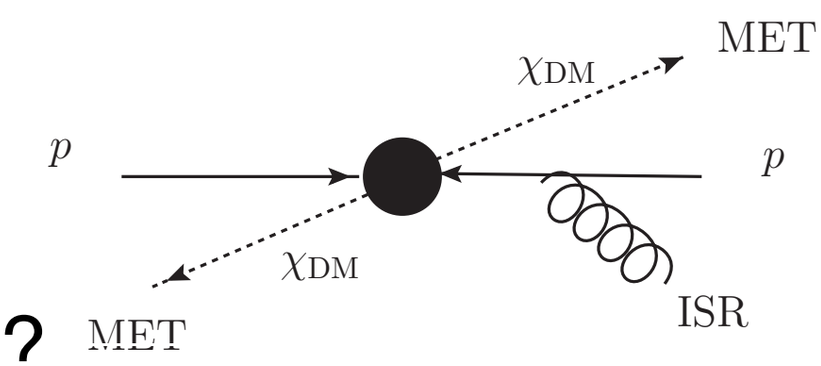

- Potential addressing Ω_B, $\Omega_B \sim \Omega_{DM}$ w/RPV?

$\Longrightarrow$ (again) Displaced vertices @LHC!

Let's start a journey beyond SUSY, then come back…

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Mini-Review of Baryogenesis

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

Initial $B - \bar{B}$ asymmetry

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

symmetric component annihilated away →

Asymmetric Ω_B today

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<u>Sakharov Conditions</u> (1967):

- Baryon number violation
- C-, CP-violation

  (- provided by RPV SUSY ?…)
- Out-of equilibrium (CPT) $n_B^{\rm eq} = n_{\bar{B}}^{\rm eq}, \quad \langle B \rangle_{\rm eq} = 0$

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$\Omega_B \approx 5\%$: Need BSM Physics!

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$\Omega_B \approx 5\%$: Need <u>BSM</u> Physics!

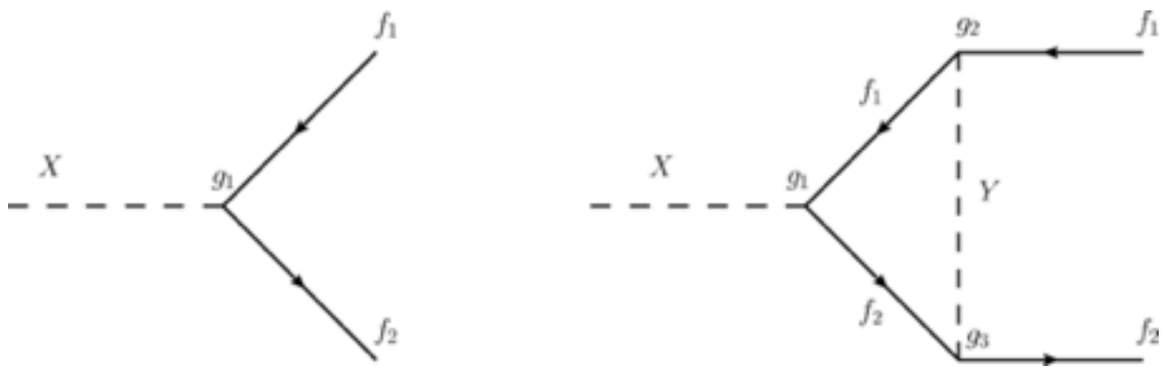
❖ Existing baryogenesis mechanisms: (leptogenesis, EWBG…)

Most involve high M or/and T, *<u>direct</u>* experimental test impossible (c.f. WIMP DM for Ω_{DM})

Baryogenesis from Out-of-Equilibrium Decay

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

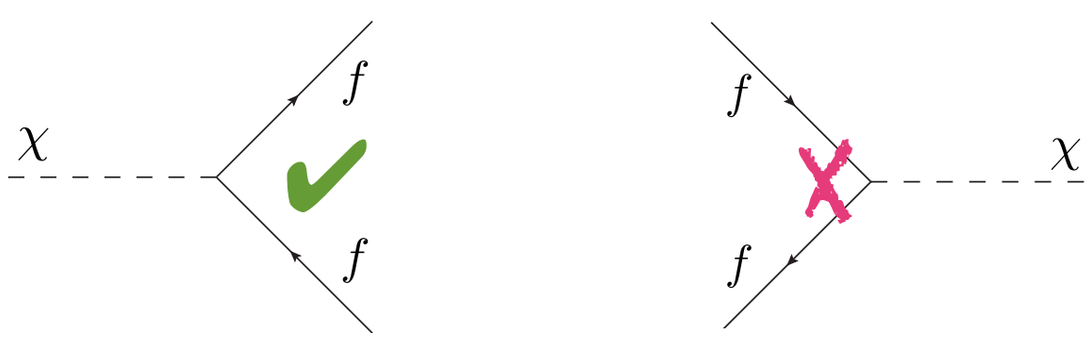
- Assume a massive neutral particle χ
- Baryon asymmetry can be produced in its decay (B-, CP-violating)



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

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

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



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)

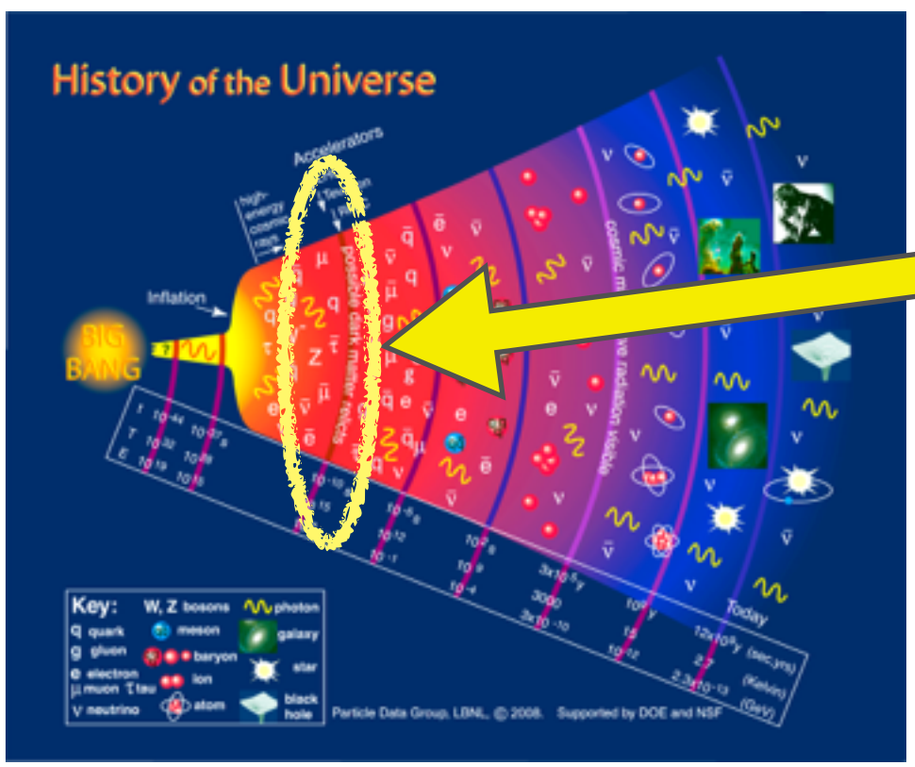
- If χ has mass at weak scale (the new energy frontier LHC is exploring!), numerology gives $c\tau_\chi^{-1} < H(T_{\rm EW}) \sim 10^{-13}\ {\rm GeV}$
- Converting to decay length:

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

Displaced Vertices Motivated by Baryogenesis

$\Gamma_\chi < H(T = M_\chi)$ ⟷ $c\tau_\chi \gtrsim \mathrm{mm}$

- 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!**



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

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

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

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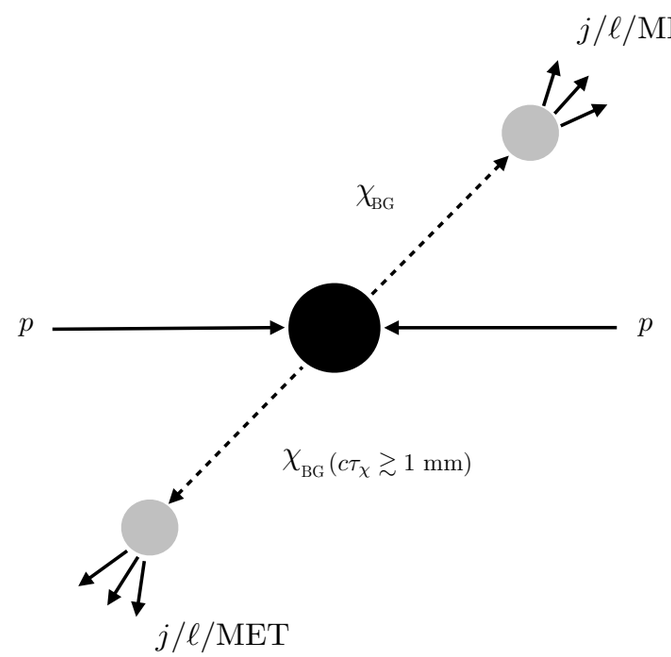
- **Production at the LHC?**

  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!

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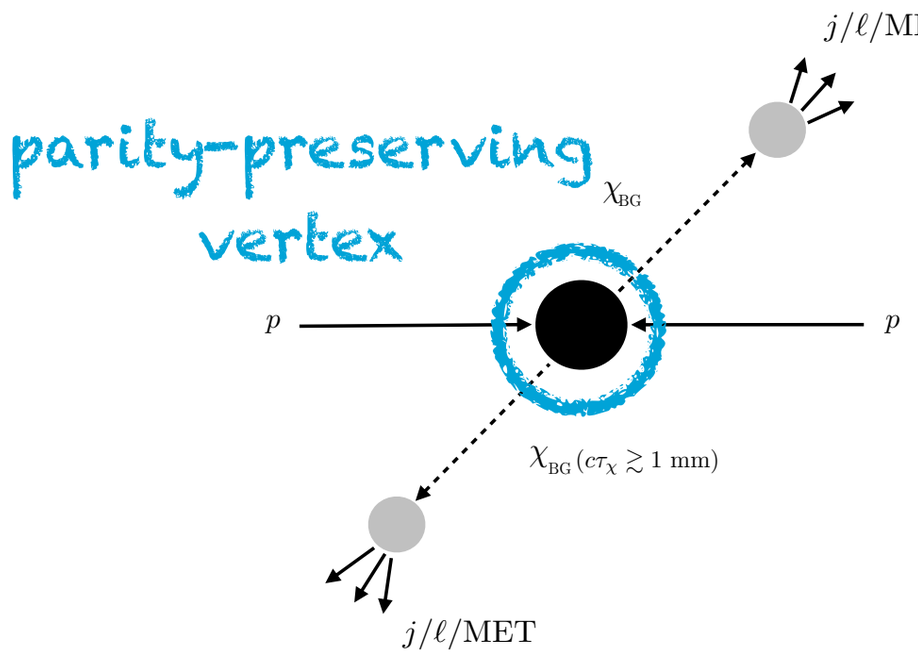

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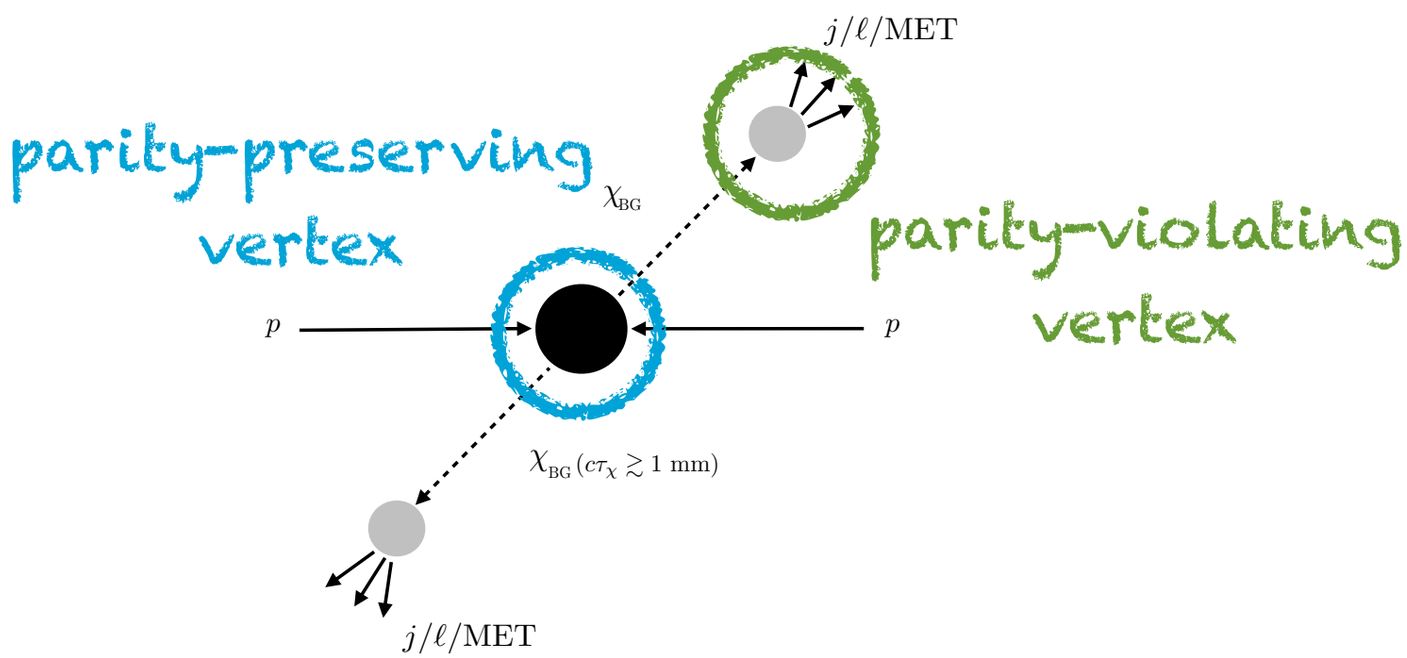

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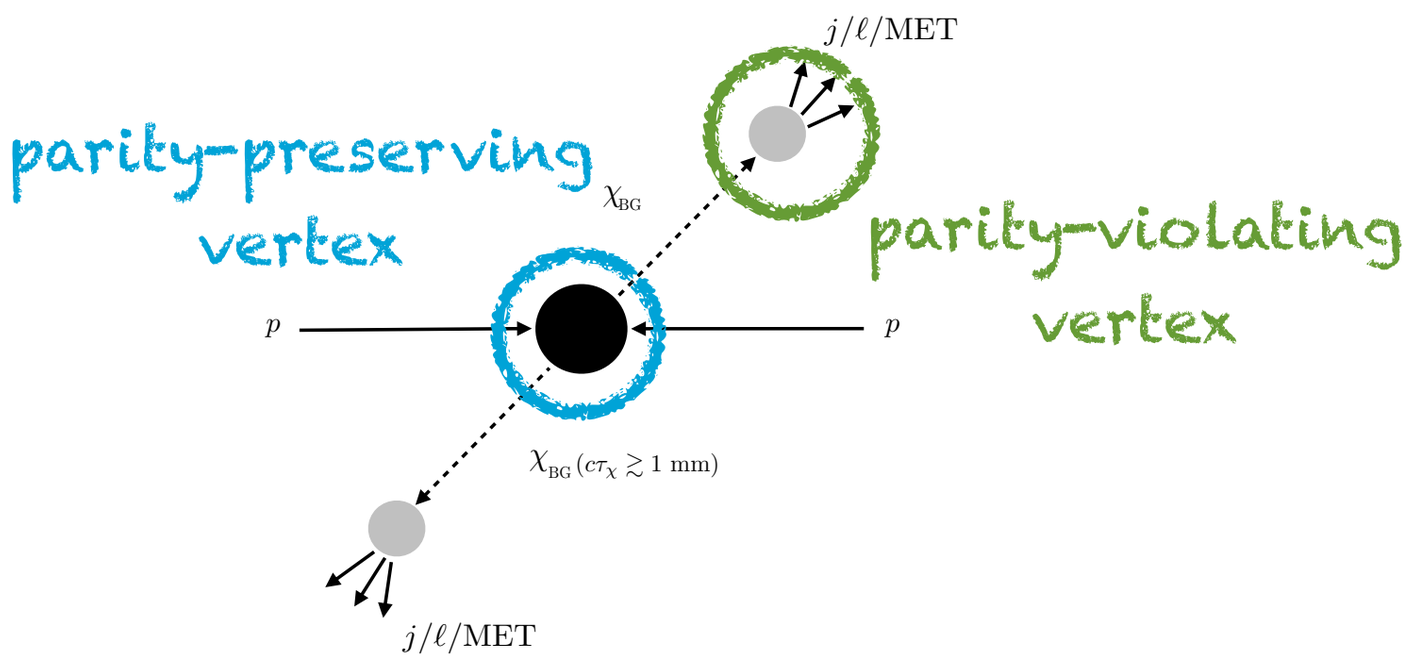

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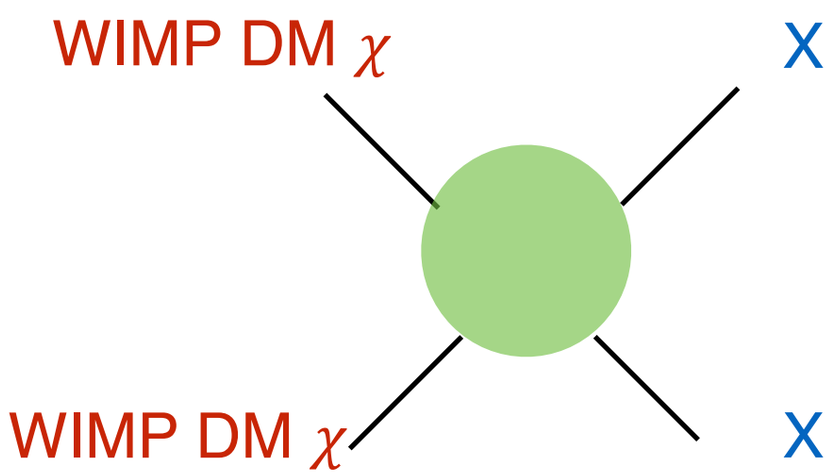
Concrete, motivated baryogenesis models as example?

Baryogenesis from WIMPs

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

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



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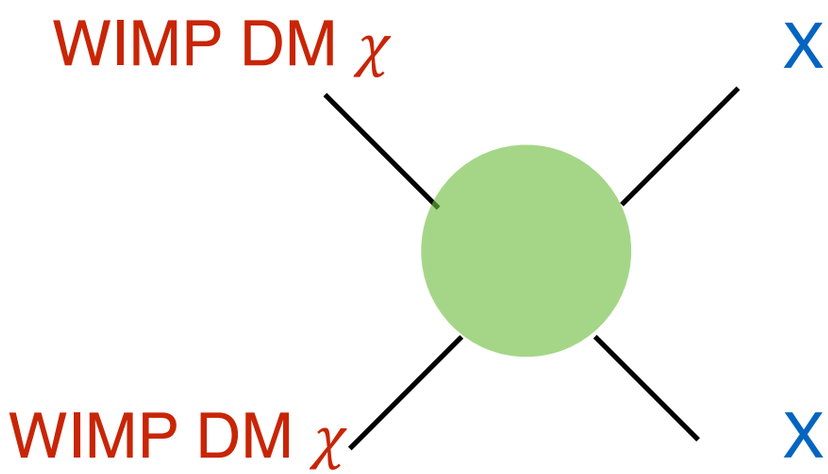
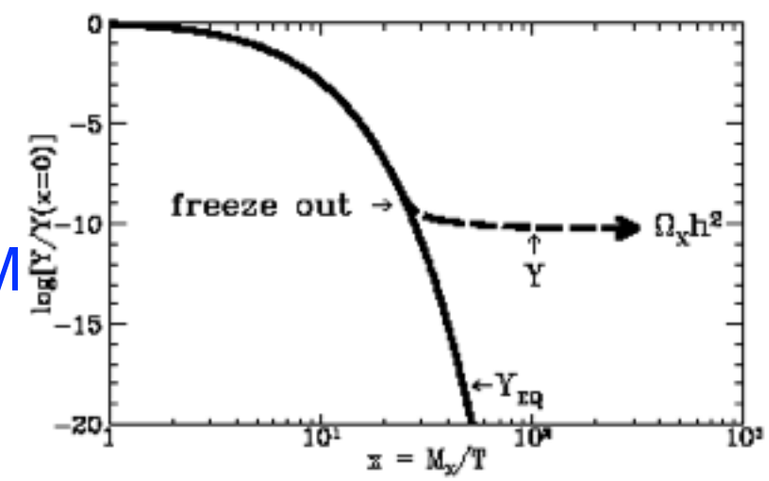


thermal freeze out

out-of-equilibrium

Ω_{DM}



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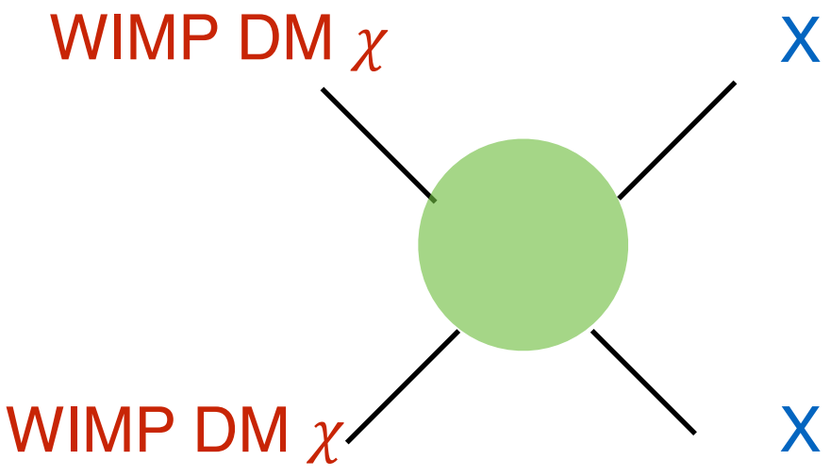

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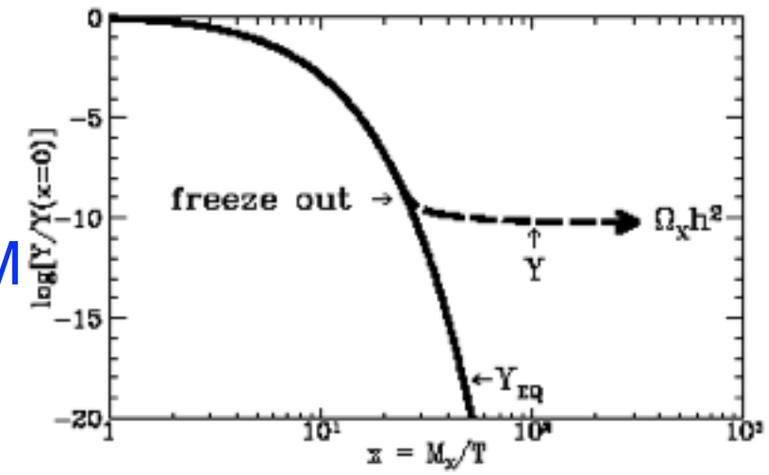

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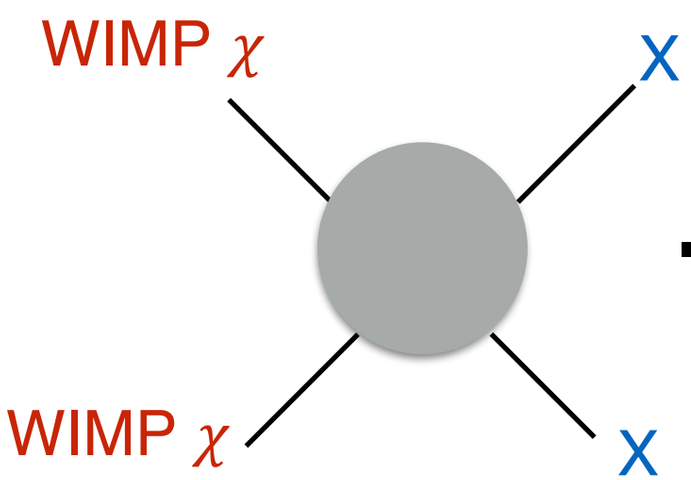

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Stable χ_{DM}, Ω_{DM}

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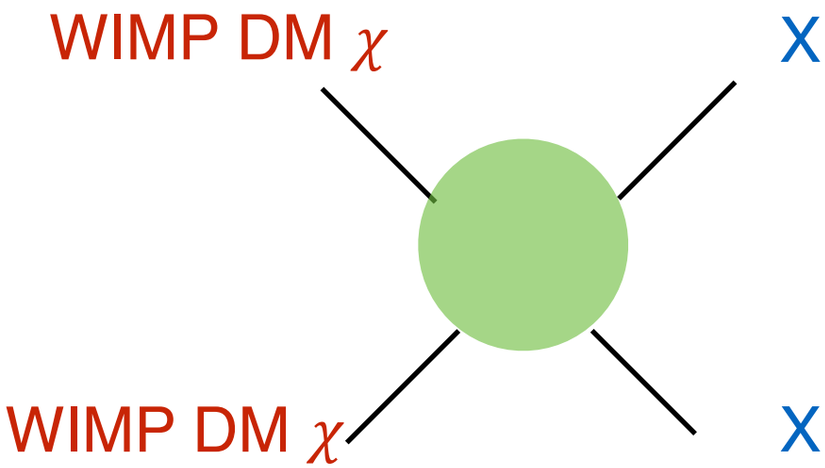

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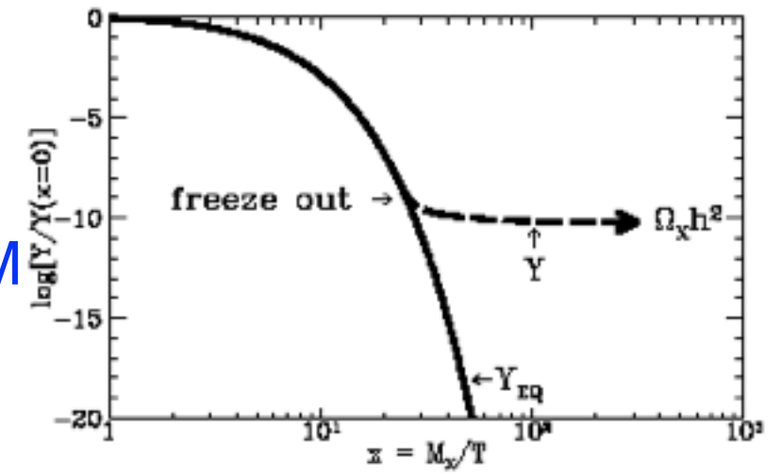

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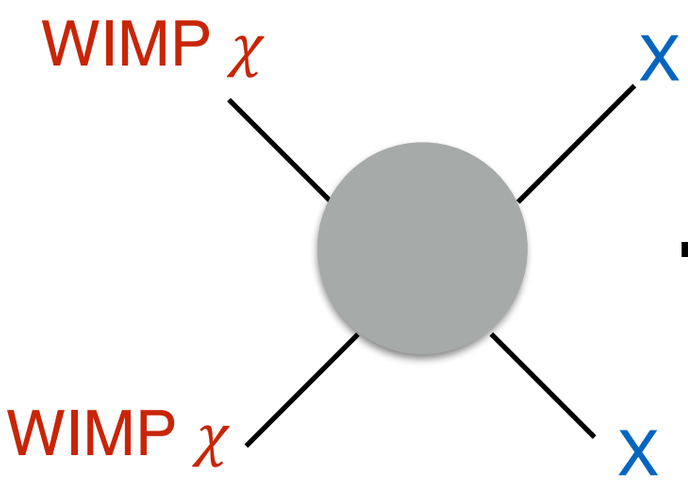

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Metastable χ_B?
(later decay)

✳ **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

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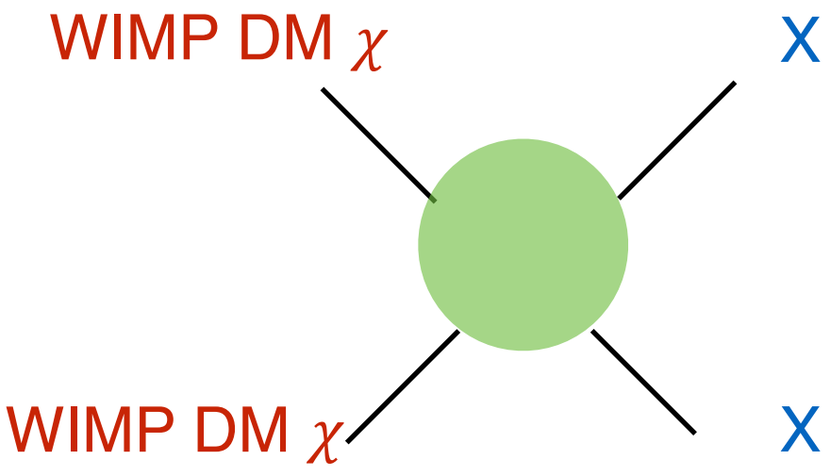

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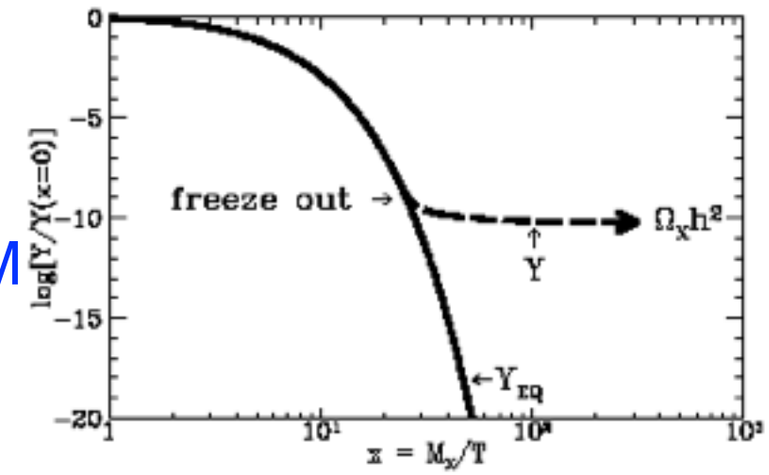

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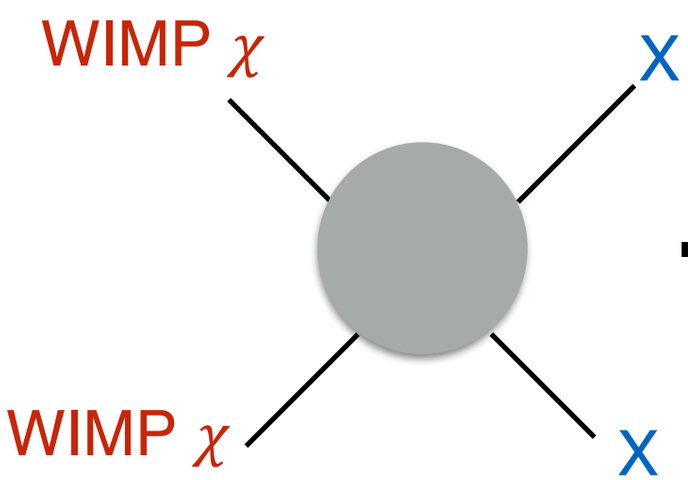

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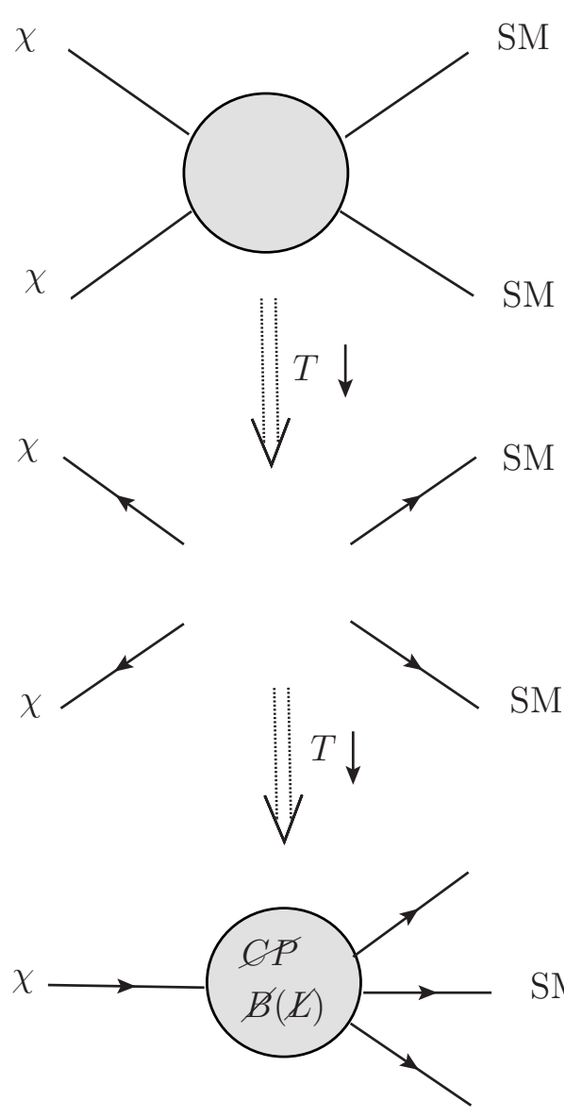
YC and Sundrum 2012;

YC 2013

Baryogenesis from Metastable WIMP Decay



★ Thermal freezeout

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

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

★ 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 $\Omega_B \sim \Omega_{DM}$

- A generalized WIMP miracle!

A Minimal Model Example

(easy embedding in RPV natural SUSY!)

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

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

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

χ, ψ: SM singlet Majorana fermions;

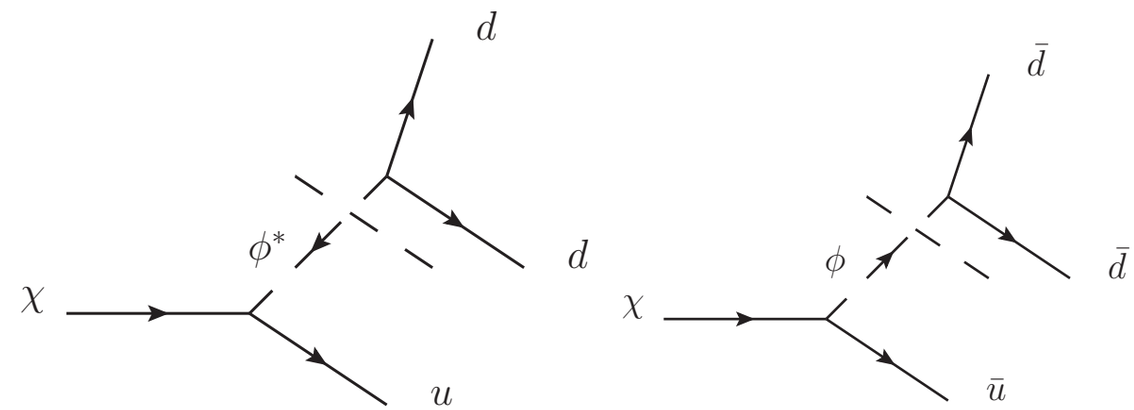
$\varepsilon_i \ll 1$: small breaking of a χ-parity ⇨ long-lived χ

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

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

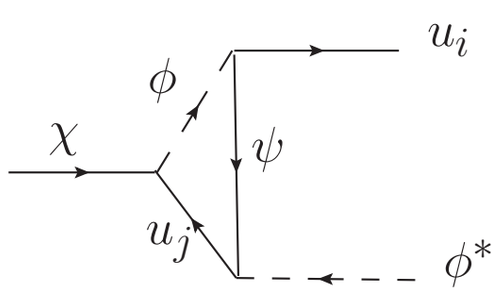
A Minimal Model Example

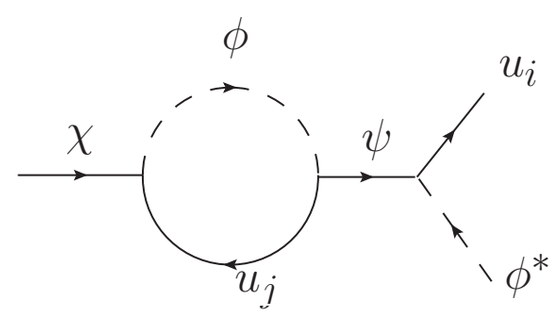
- Out-of-equilibrium decay of χ ➡ Ω_B



- 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!)

Coming back to RPV SUSY vs. baryogenesis…

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 $\chi \to \tilde{\bar{t}} t$ via $\chi - \tilde{H}_u$ mixing

Embedding in Mini-Split SUSY

(Cui, JHEP 1312 (2013) 067)

Interesting (surprising) finding: successful baryogenesis

from **minimal** SUSY standard model (WIMP decay)!

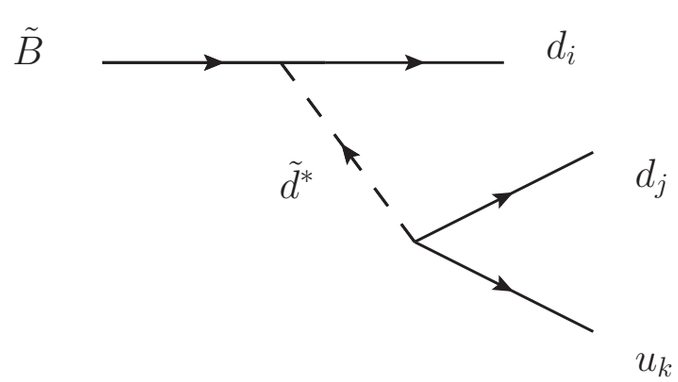
$\tilde{B} \to \Delta B$!

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...)



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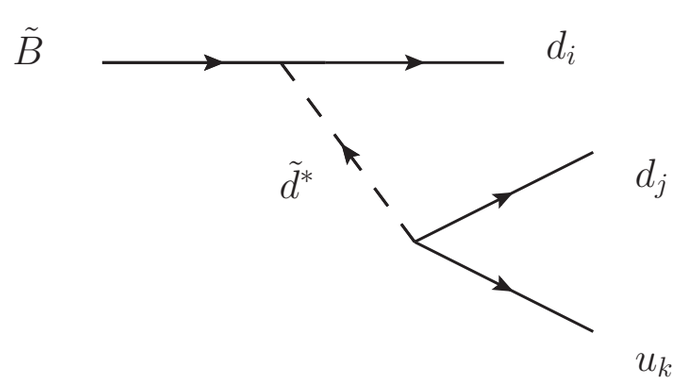


Embedding in Mini-Split SUSY

★ 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 ✓

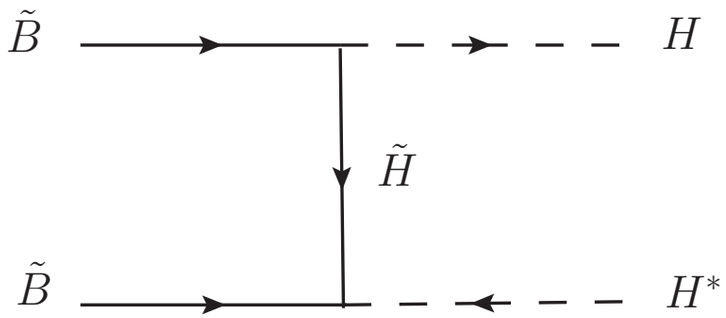
⇒ Another Majorana fermion in MSSM? $\tilde{w}$, $\tilde{g}$!

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

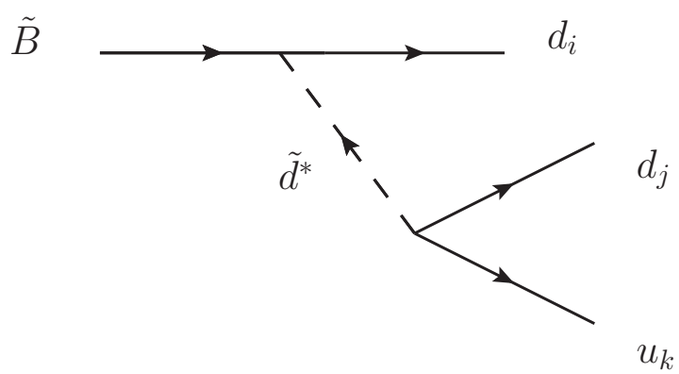
Embedding in Mini-split SUSY

- **Key processes:**

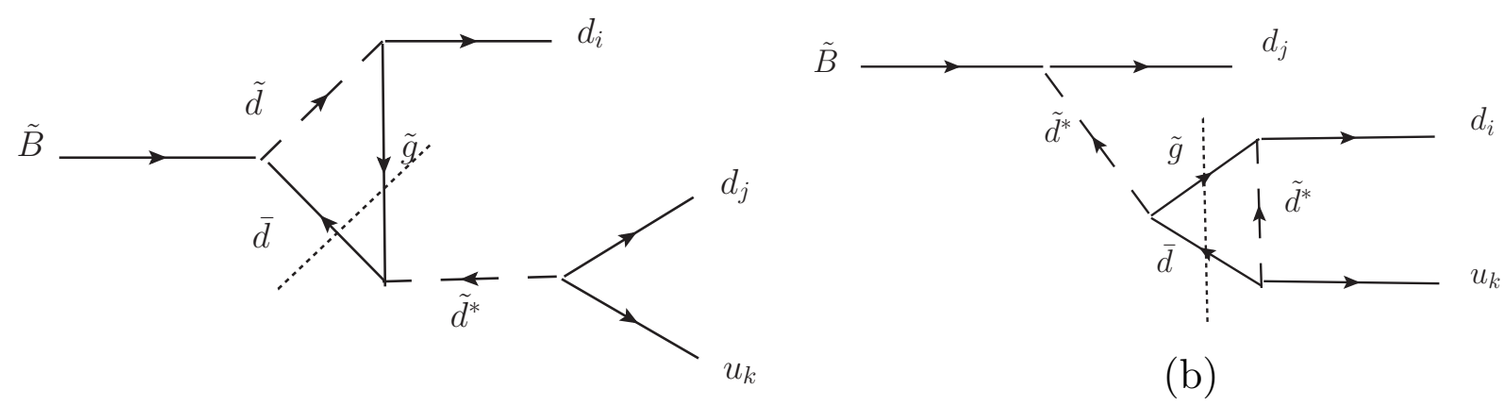
Thermal annihilation:



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?

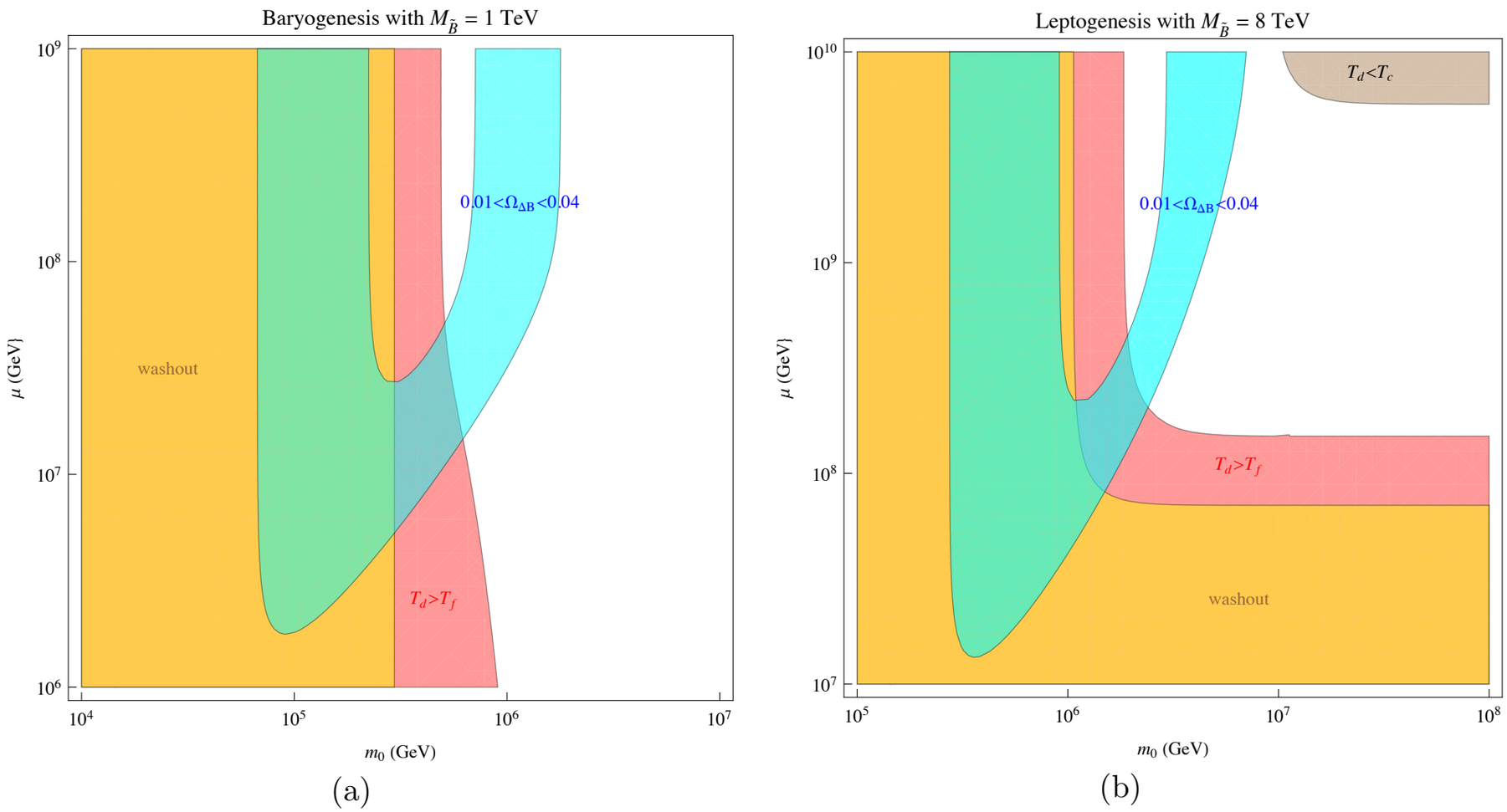


Figure 7: Cosmologically allowed regions of parameter space for (a) baryogenesis and (b) leptogenesis models. We set RPV couplings $\lambda'' = \lambda' = 0.2$, $\phi = \frac{\pi}{2}$. Cyan region provides baryon abundance $10^{-2} < \Omega_{\Delta B} < 4 \cdot 10^{-2}$. In the case of leptogenesis the 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.

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

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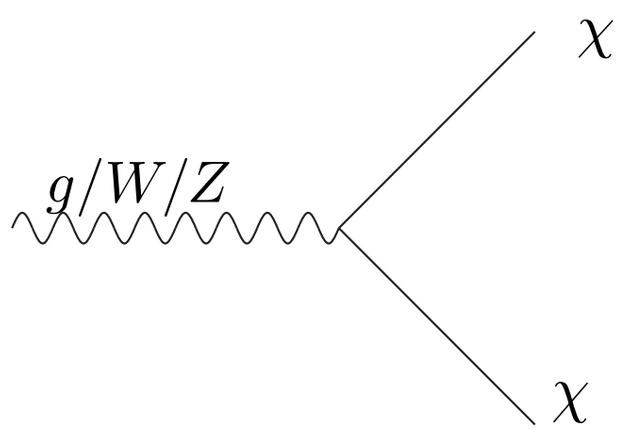
Charged under SM gauge interactions:

wino/gluino-like (state in interference loop)



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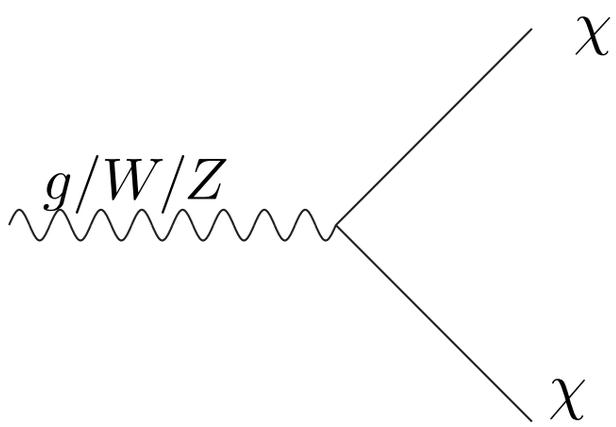
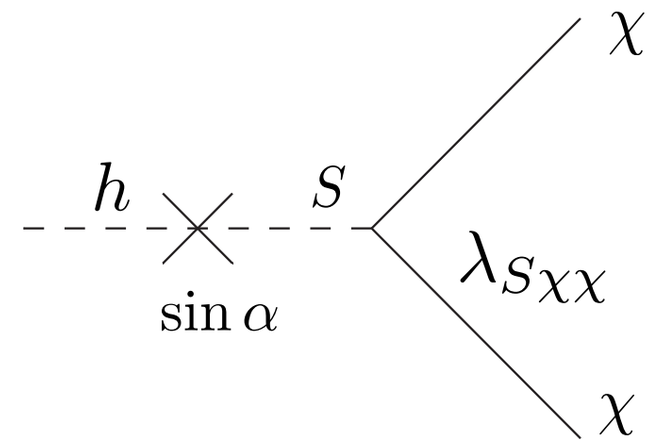


Higgs portal:

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



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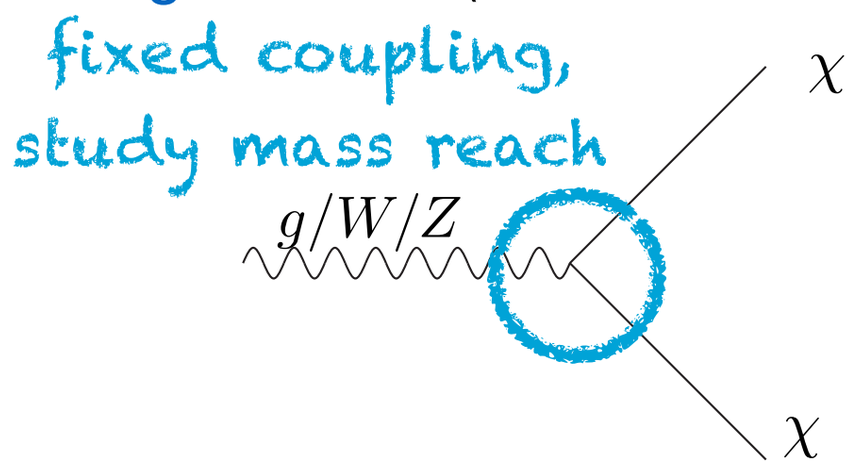

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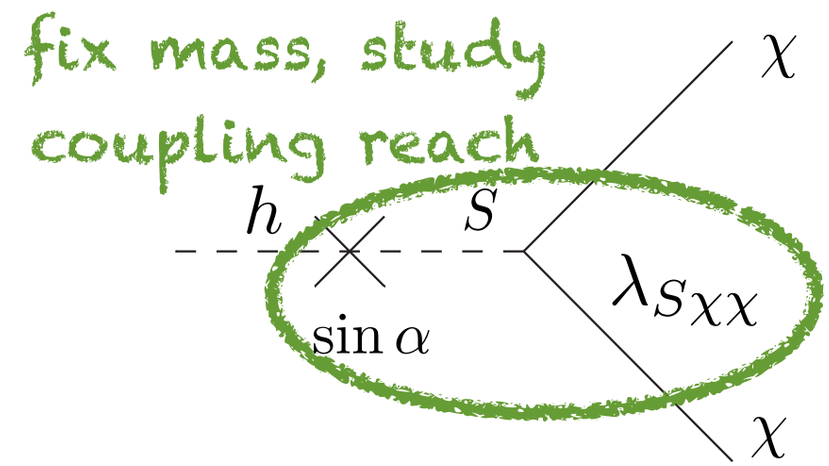

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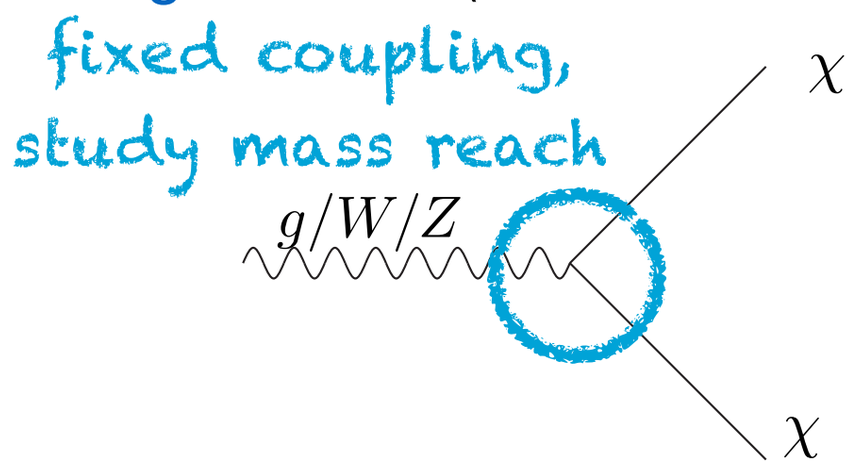

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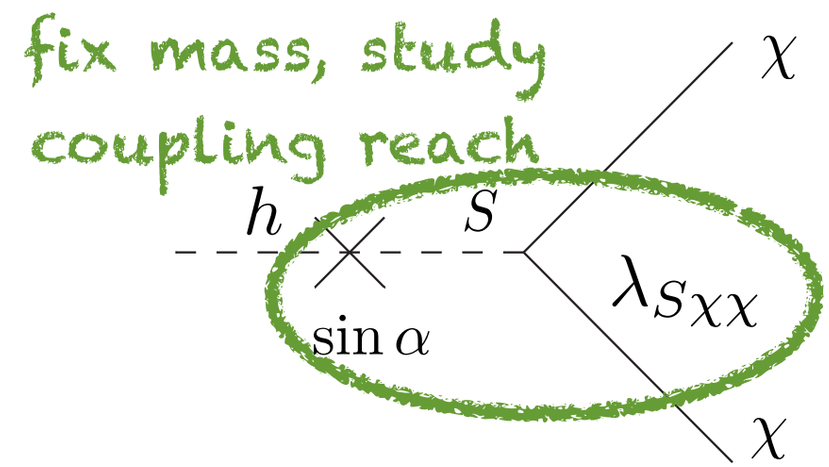

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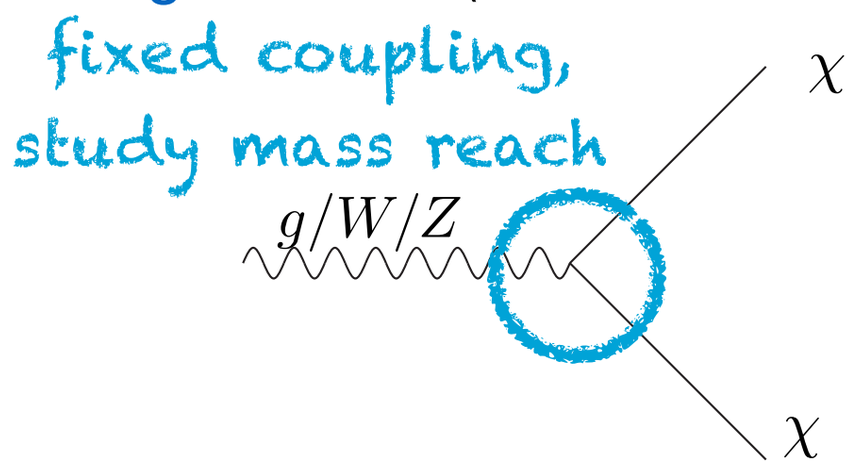

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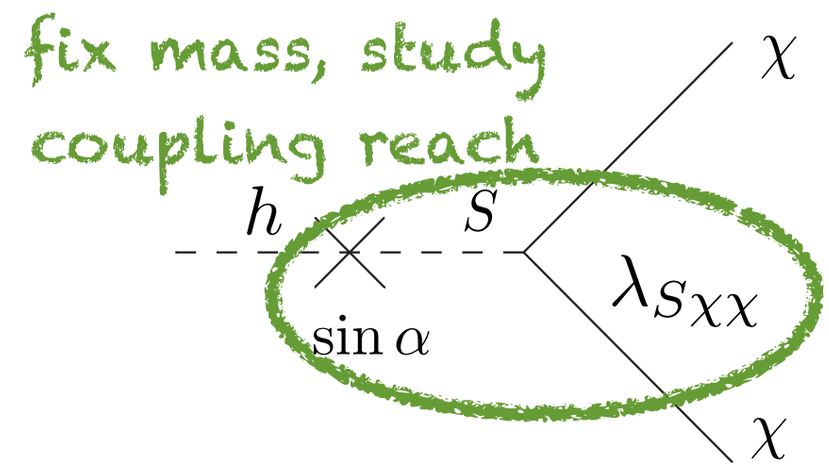

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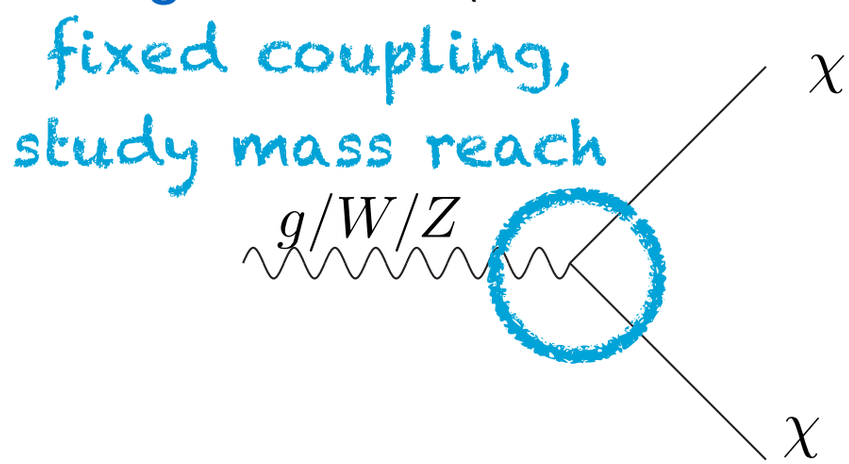

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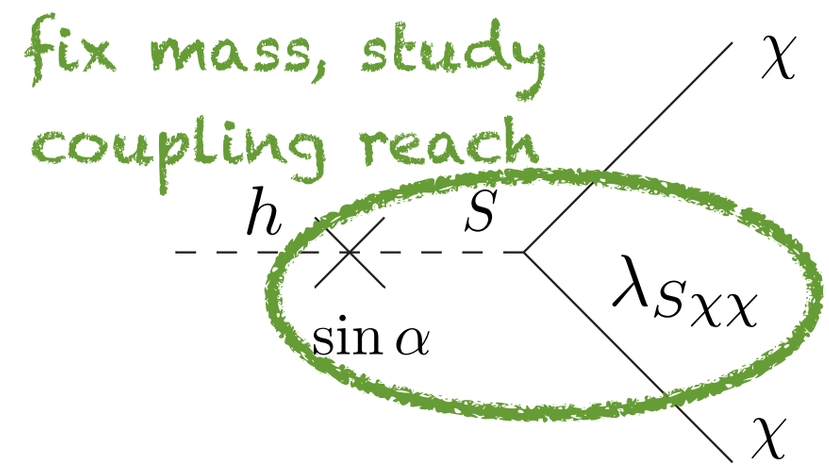

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Later comprehensive analyses in RPV SUSY: Liu, Tweedie 2015; Csaki et.al 2015; Zwanne 2015

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…)

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CMS, arXiv:1411.6530

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ATLAS-CONF-2013-092

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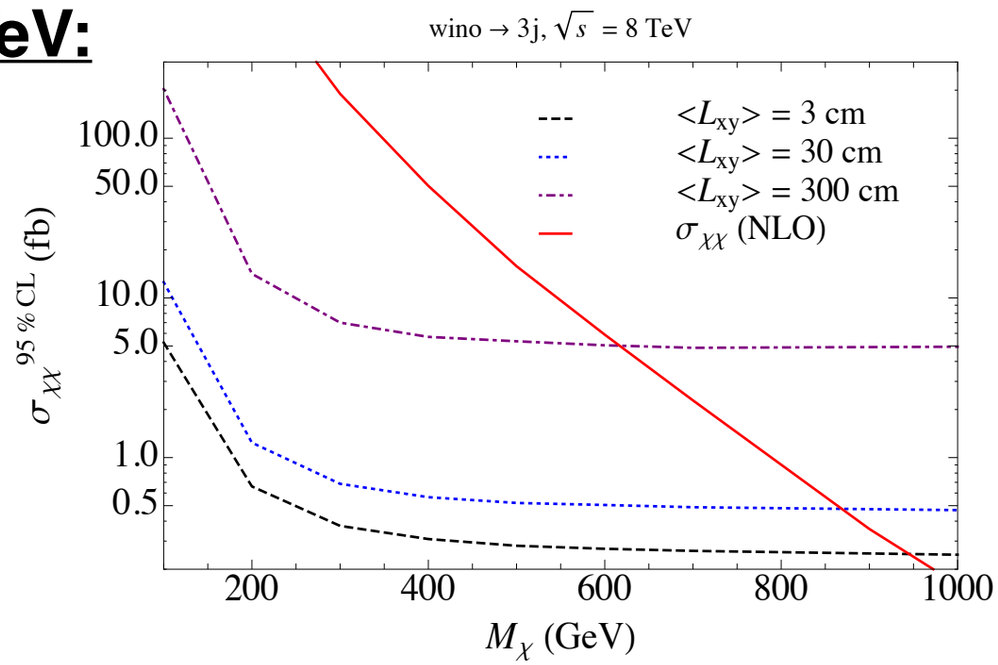
- **Goal of our analysis:**
  - What is the coverage for our simplified models based on benchmarks chosen by the collaborations?
  - What advice can we provide for general experimental improvement?

Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:



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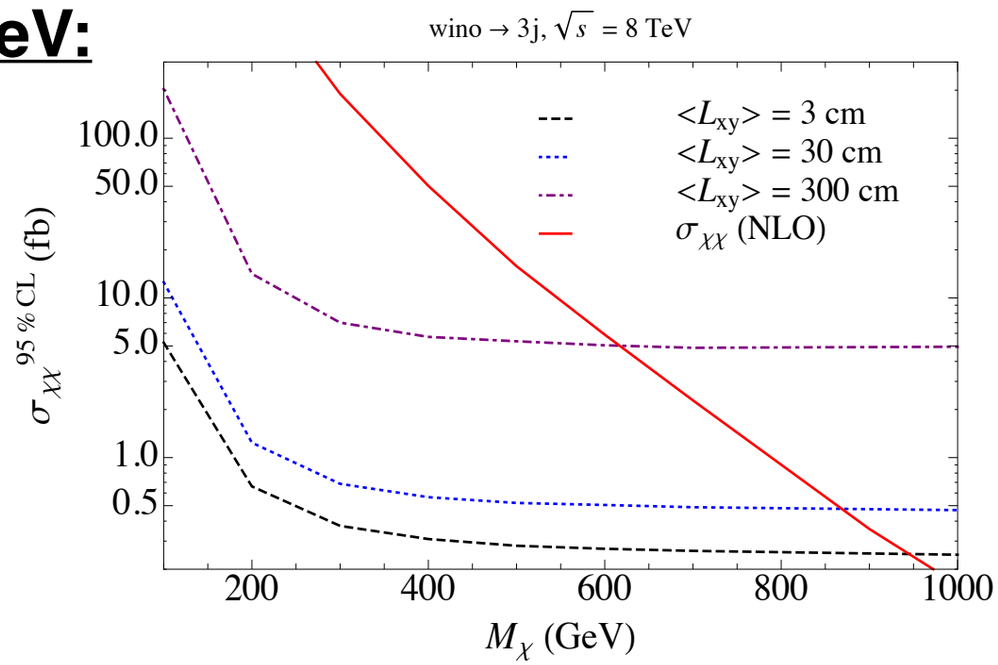

singlet-like (Higgs portal)

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

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

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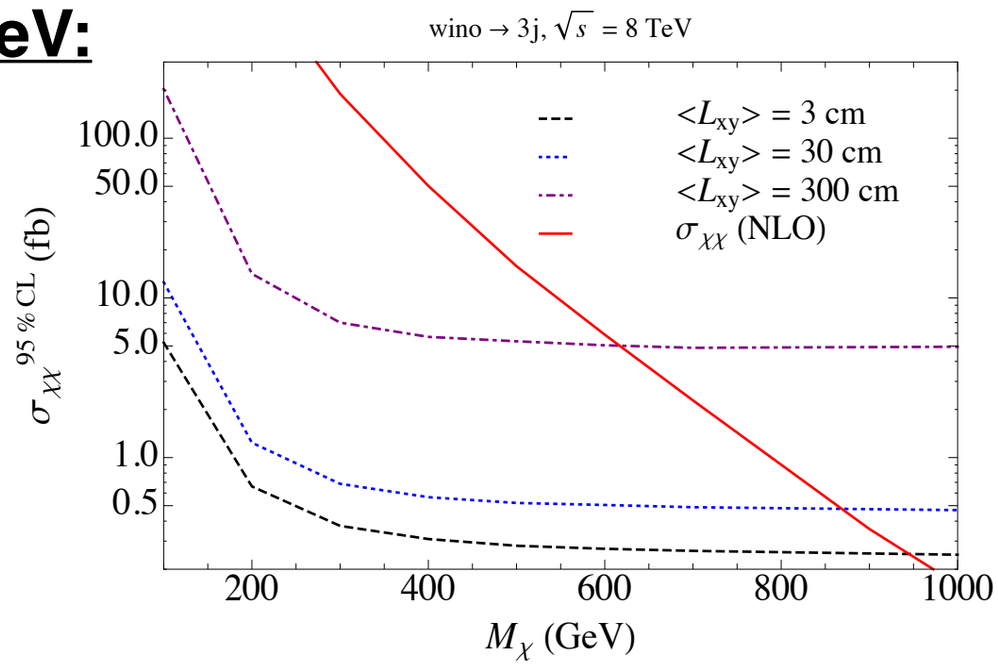

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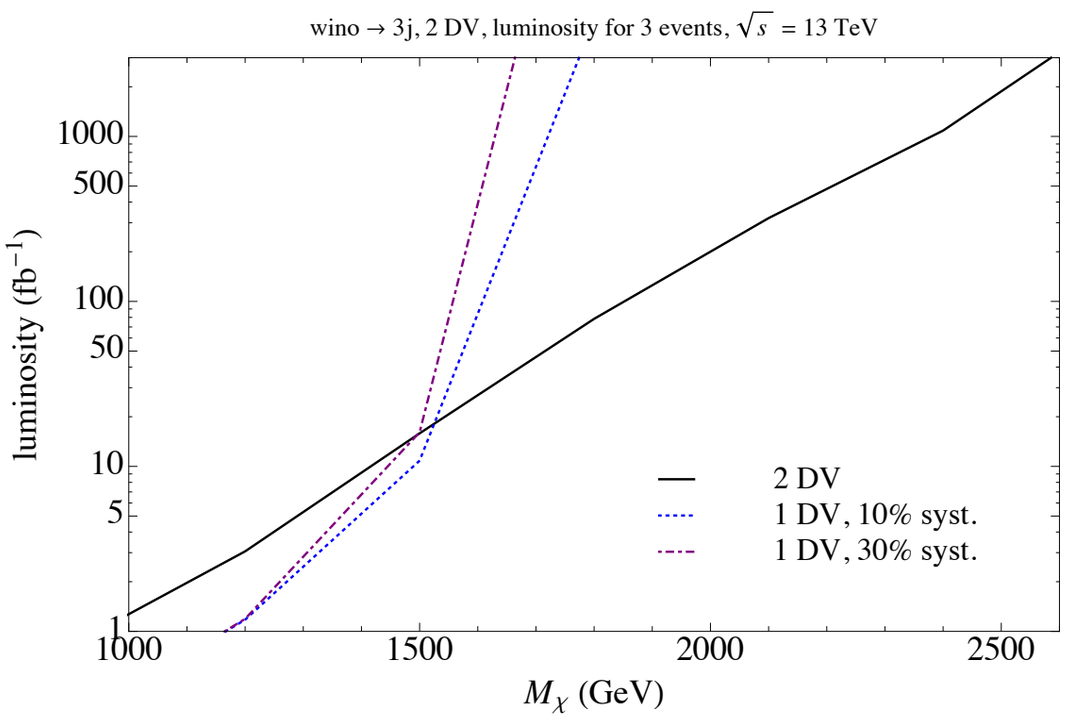
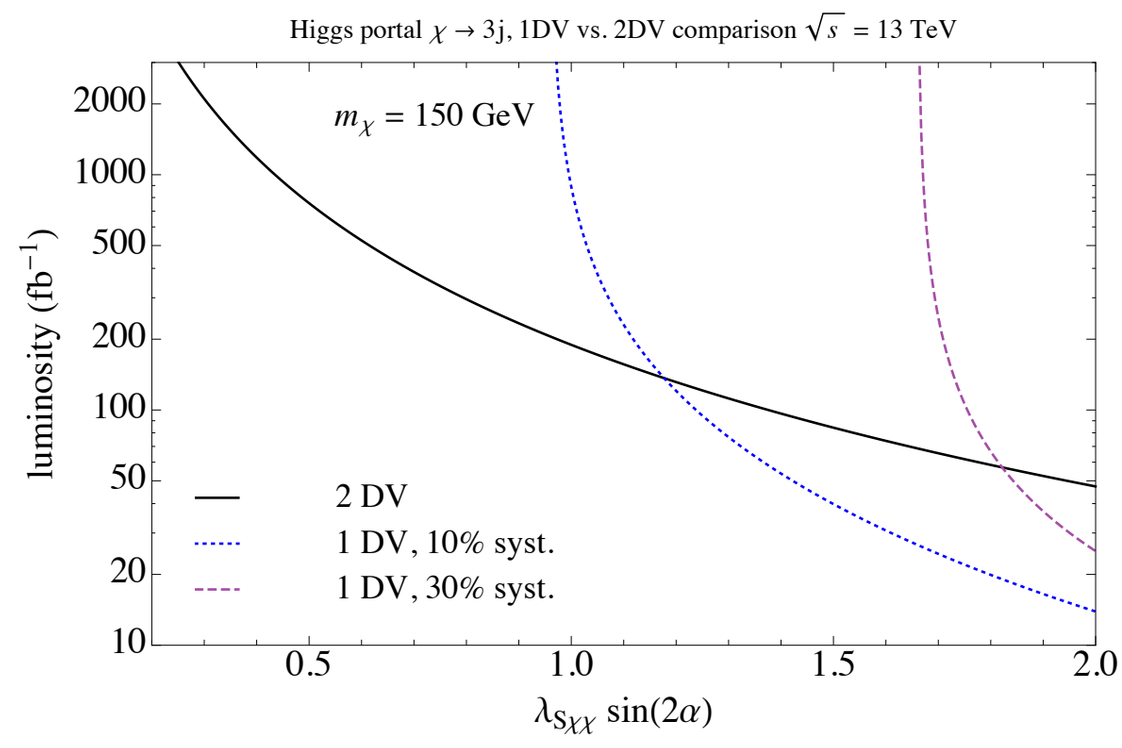
13 TeV:

L_{xy} = 3 cm



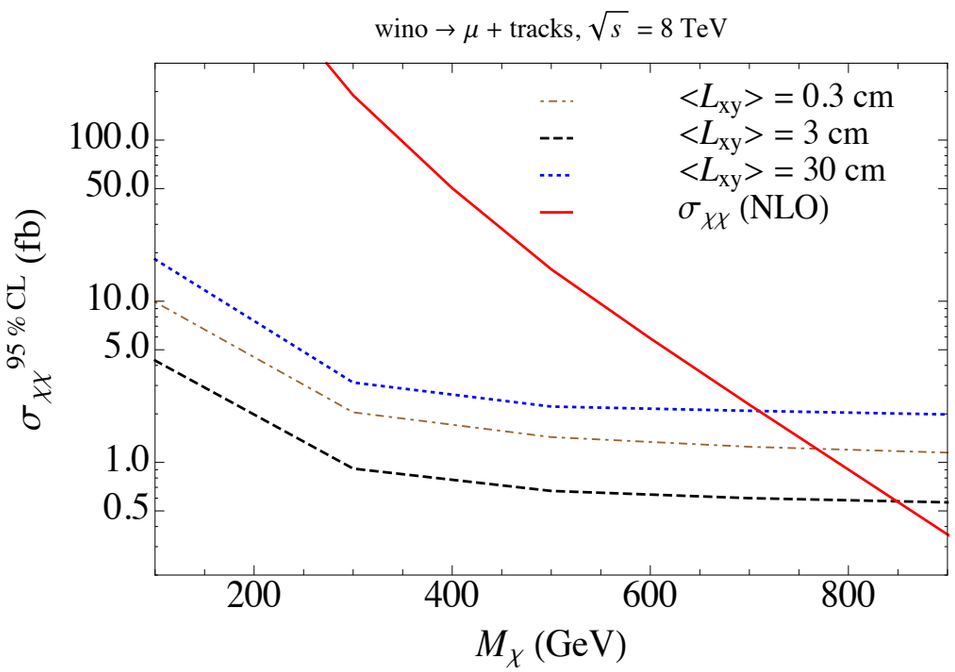


Displaced muon + hadrons

ATLAS-CONF-2013-092

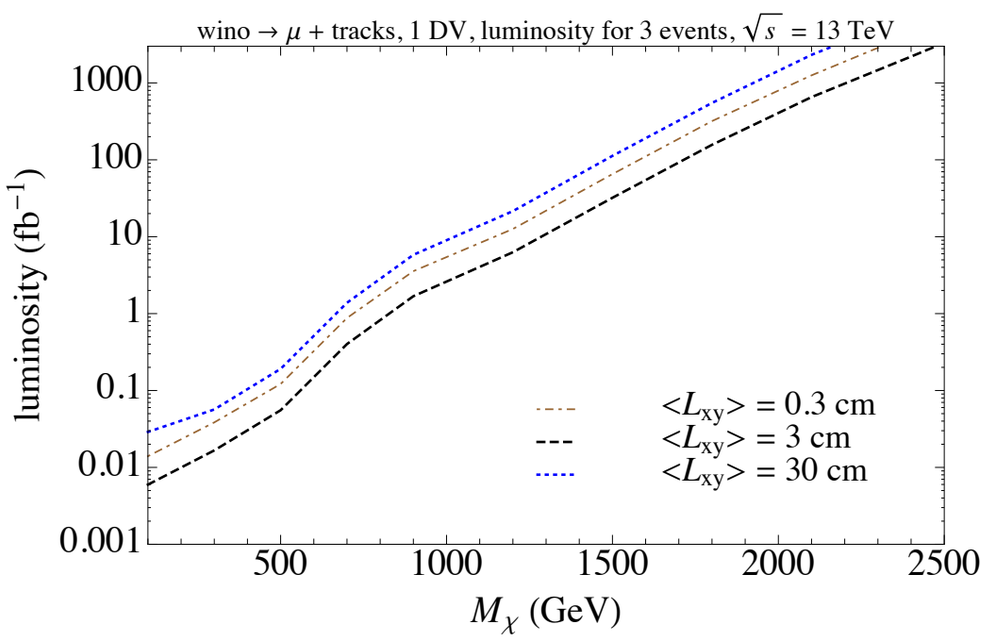
wino

8 TeV



13 TeV:

M~2.5 TeV



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ATLAS-CONF-2013-092

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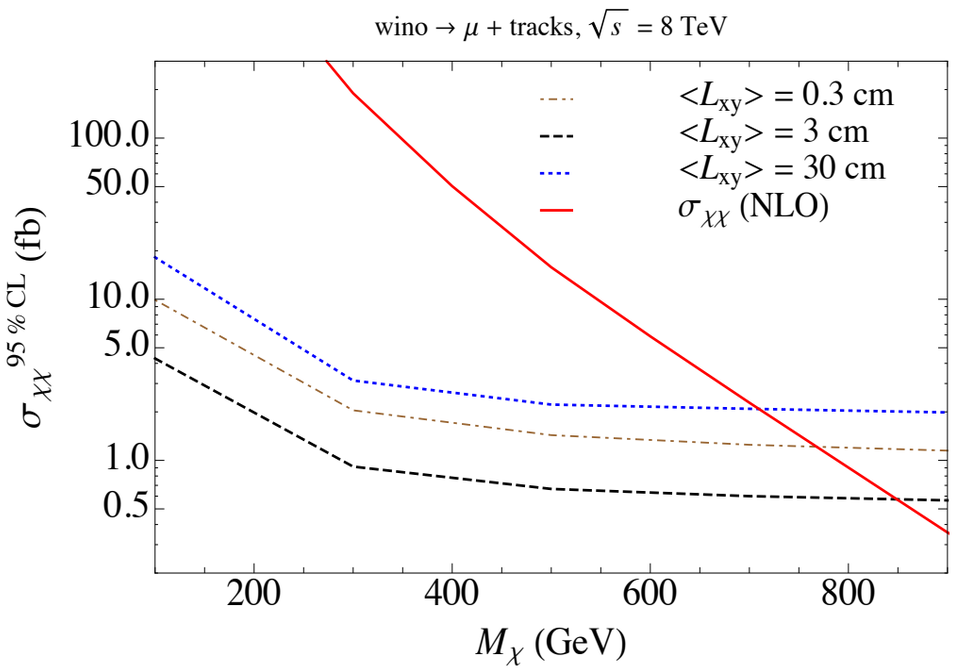

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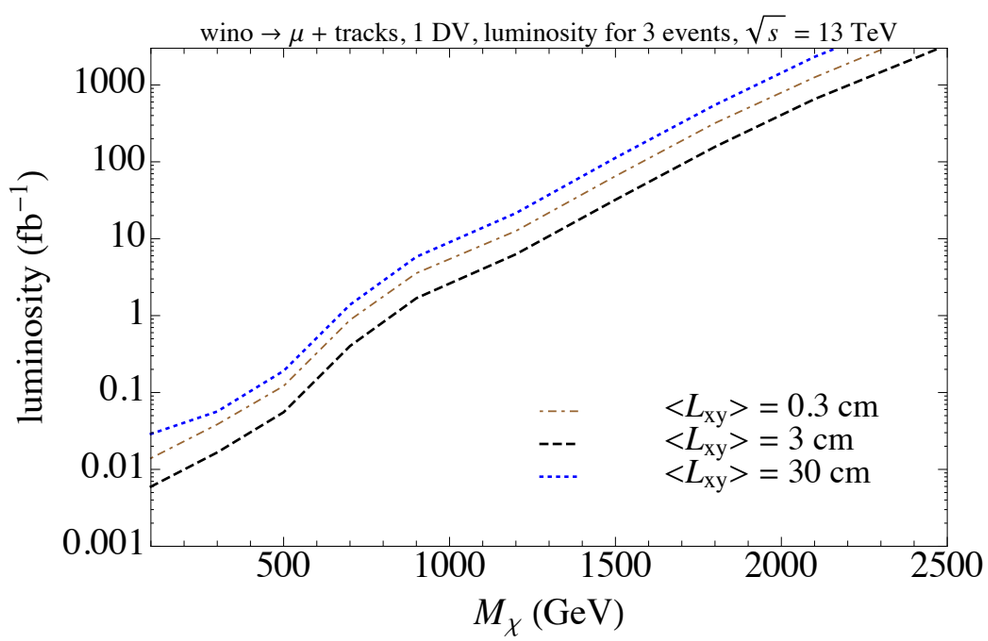

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(singlet-like, $M_\chi = 150$ GeV)

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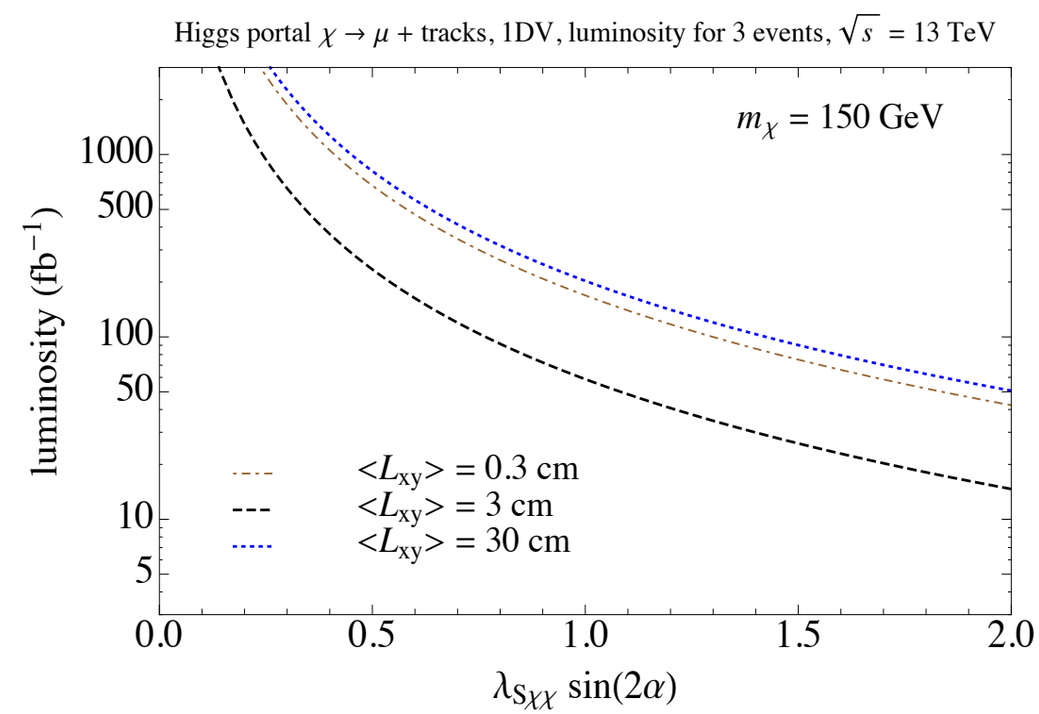
- 13 TeV: **σ_S~10 ab for L_{xy}~1 cm!**



Conclusion/Outlook-1

- A general conflict between RPV natural SUSY with *prompt* decay vs. conventional baryogenesis at $T \gtrsim T_{EW}$
- Passive solution: suppress RPV $\Longrightarrow$ displaced stop (good coverage)
- Natural alternative: (new) baryogenesis at $T \lesssim T_{EW}$
  - **WIMP baryogenesis** (Ω_B (+)$\Omega_B \sim \Omega_{DM}$) & RPV SUSY $\Longrightarrow$ displaced singlino/wino (sample high multiplicity DV, improve trigger/sensitivity for all-hadronic final states…)

Conclusion/Outlook-2

- Baryogenesis from metastable weak scale particle decay:
  - A **robust cosmological motivation** for DV searches at the LHC
  - Exciting opportunity to reproduce the early universe BG @LHC! (cf. WIMP DM search)
- w/**ATLAS displaced jets working group:** working on implementing our simplified models as a benchmark example in official analysis w/LHC Run 2 data…