

Probing Baryogenesis with Displaced Vertices at the LHC

Yanou Cui

Perimeter Institute

- 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
- Work in prep, YC and Takemichi Okui, Arash Yunesi

*LHC LLP Mini-Workshop
@CERN, May 12, 2016*

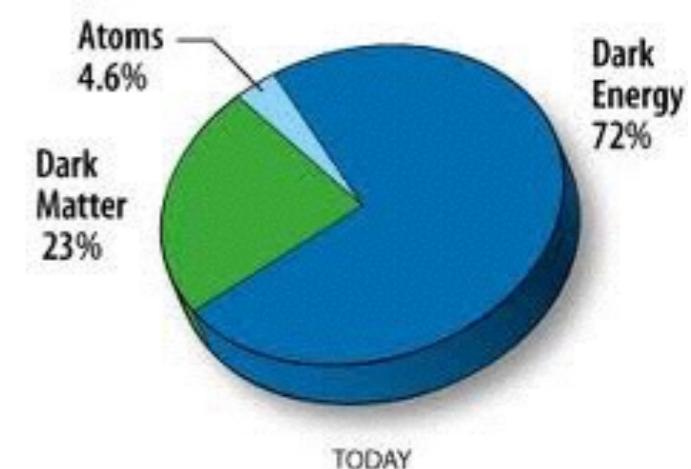
Cosmological Motivation for LLP Searches

- Baryogenesis from Metastable Weak-scale New Particle

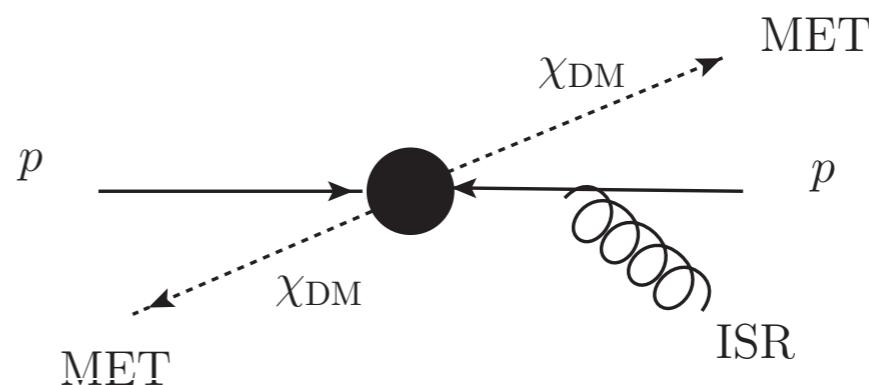


Could LHC shed light on prominent puzzles in modern cosmology?

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



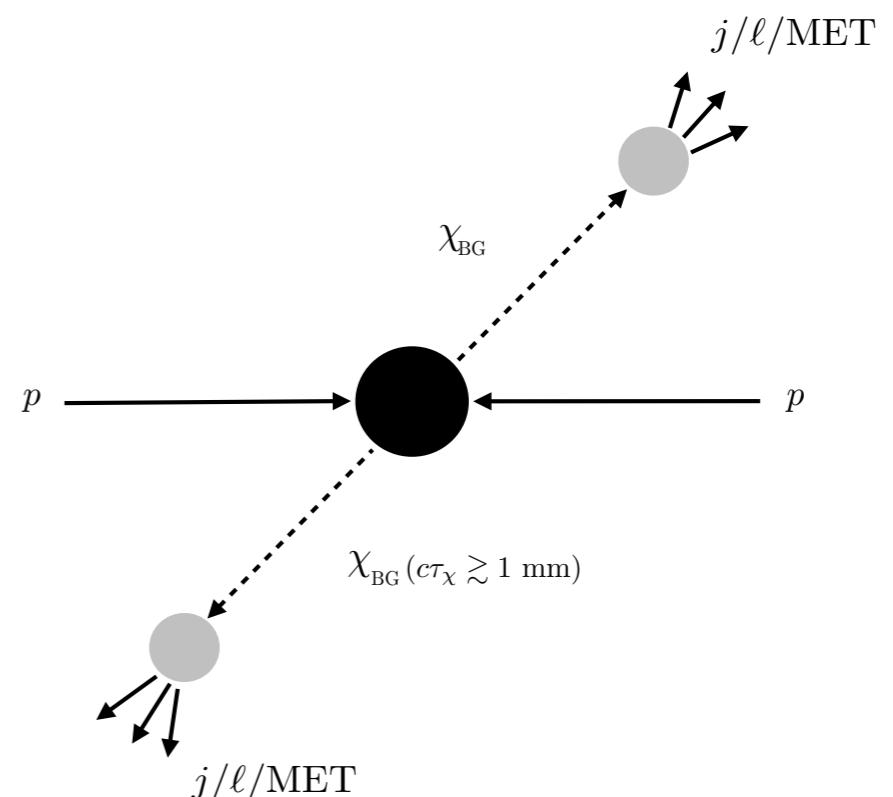
- Familiar/well-studied case: WIMP dark matter (Ω_{DM})
 - Stable, mass $\sim O(10-100)$ GeV, can be produced within $E_{\text{LHC}} = 14$ TeV
 - Pair produced (Z_2),
 - Invisible, MET + X



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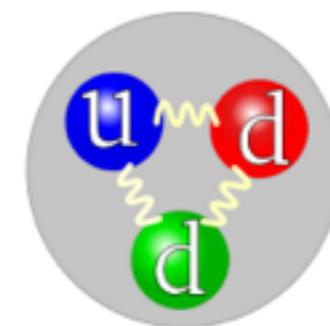
- **New opportunity:** baryogenesis
(address Ω_B , possibly + $\Omega_B \sim \Omega_{DM}$)
 - New metastable particle (baryon parent), w/mass $\sim O(10-100)$ GeV
 - Pair produced (approx. Z_2)
 - Displaced decay to $j/\ell/MET$ by cosmological condition!



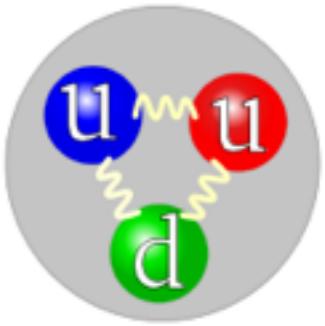
Baryon $\Omega_B \approx 5\%$

– The Unknown Aspects of the Known

- **Baryon**: proton, neutron \rightarrow atoms, stars, ourselves!
- Where does Ω_B come from?
= Where do we ourselves come from?



NEUTRON
Quark structure



PROTON
Quark structure

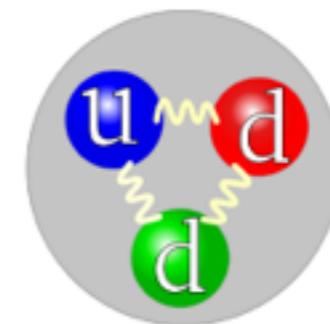
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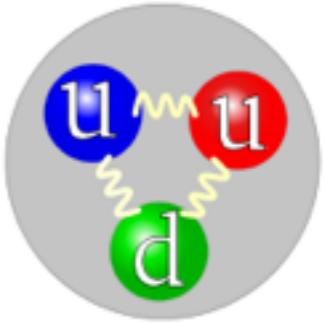
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We do not know!



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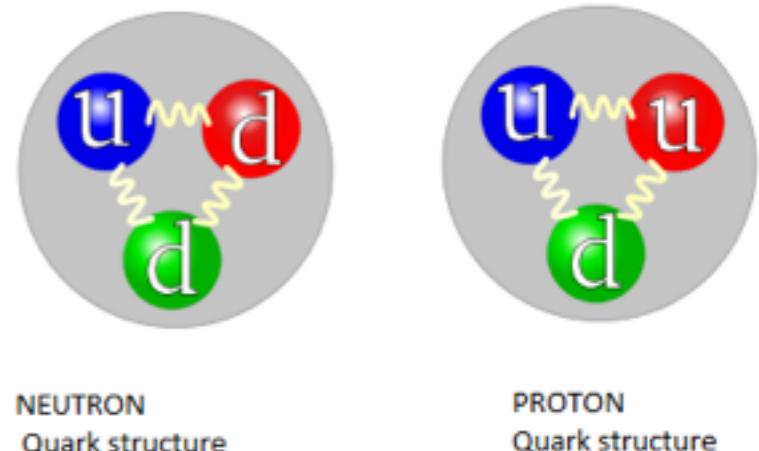
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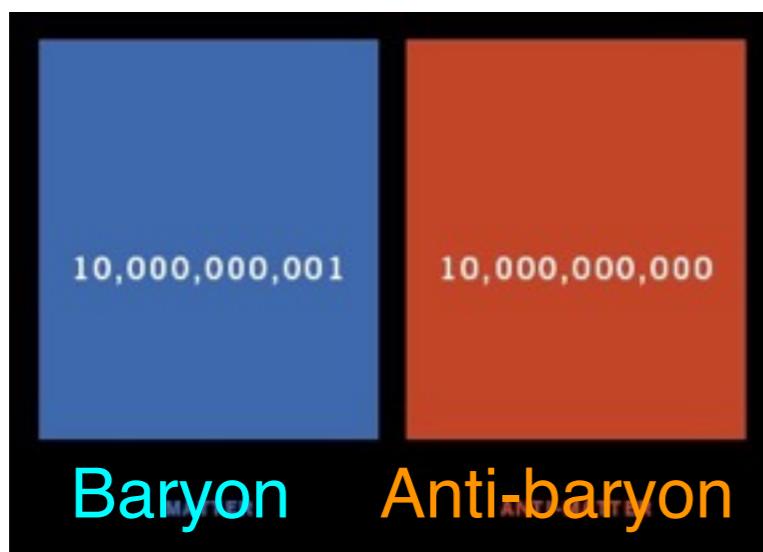


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Initial $B - \bar{B}$ asymmetry

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



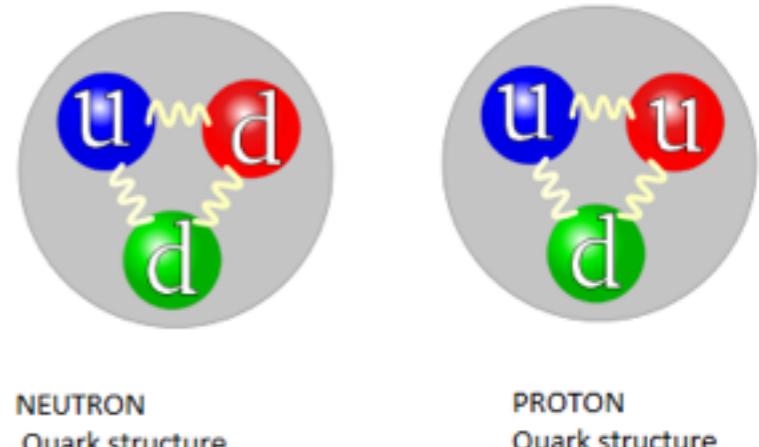
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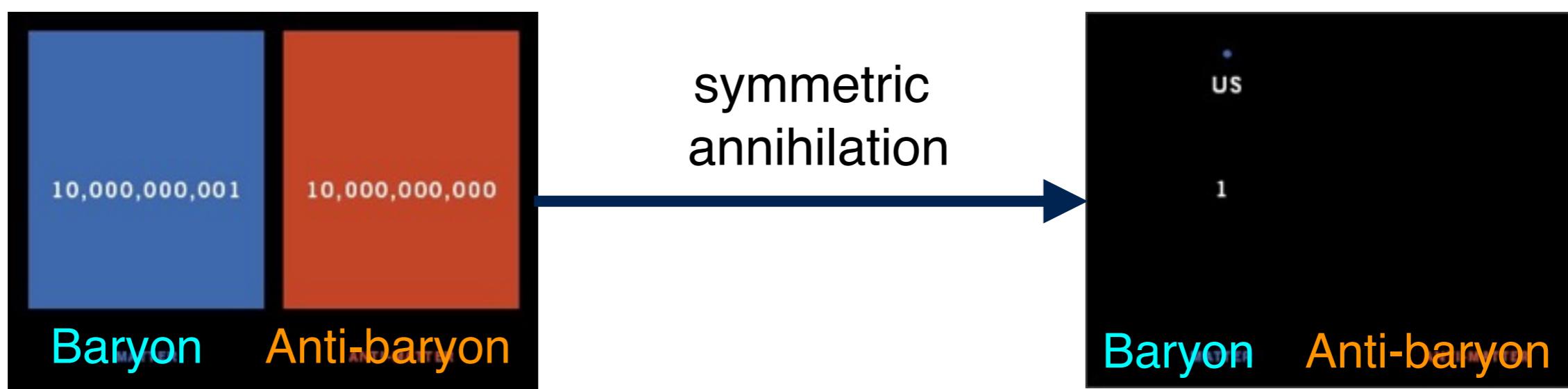
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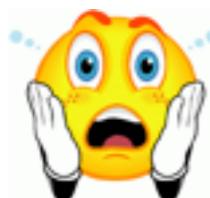
Today



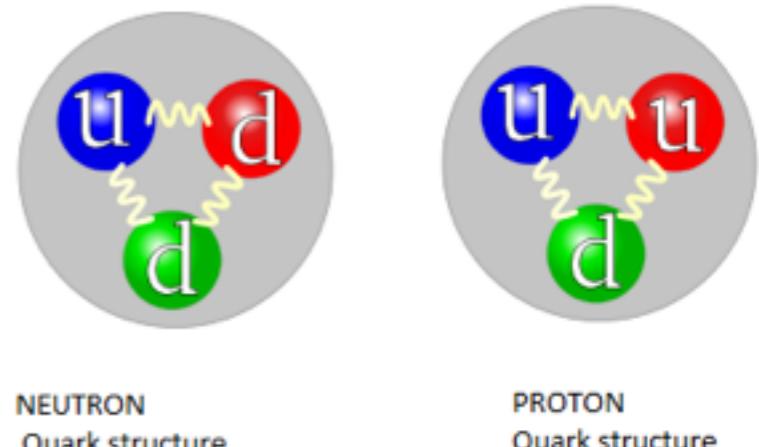
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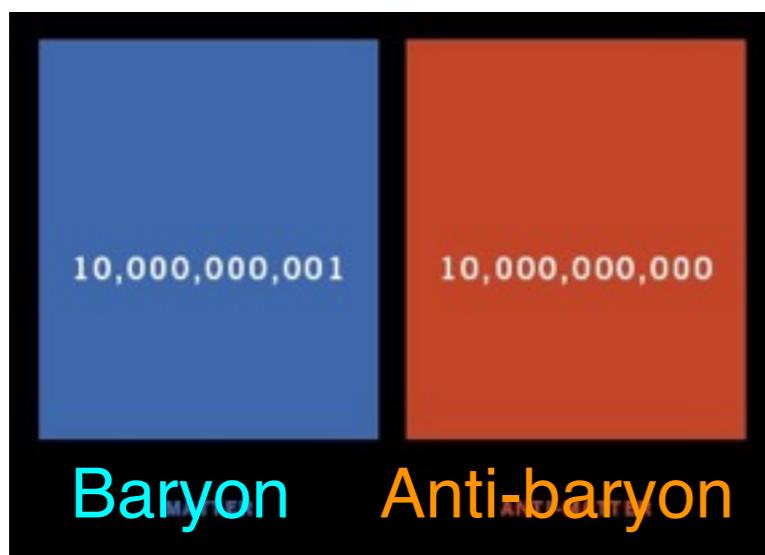


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Today



symmetric
annihilation



Baryogenesis

Sakharov Conditions (1967):

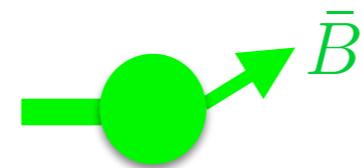
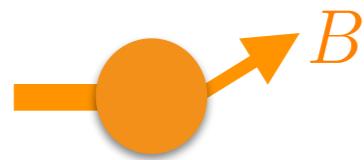


Baryogenesis



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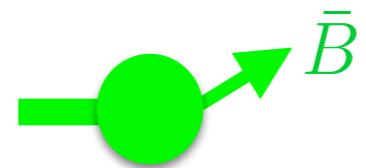
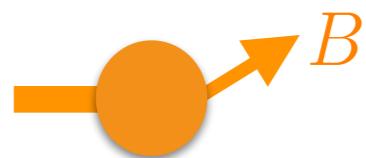
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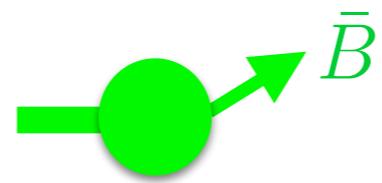
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- **Require C-, CP-symmetry violation**



\neq

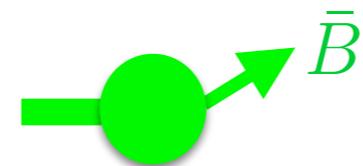


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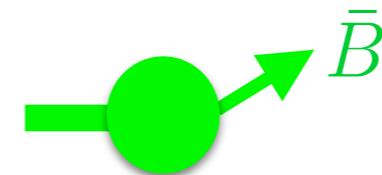


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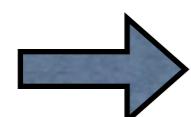


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- **Require departure from equilibrium!**

Thermal equilibrium + CPT symmetry



$$\langle B \rangle_{\text{eq}} = 0$$

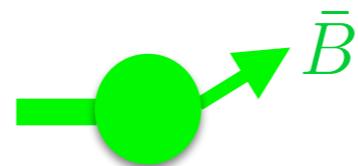


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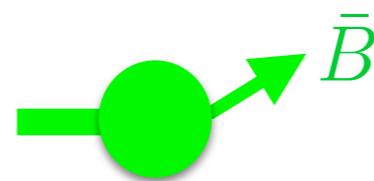


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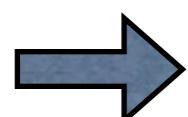
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Need beyond the
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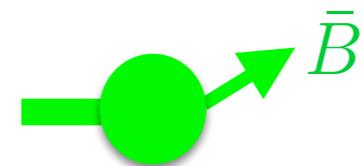


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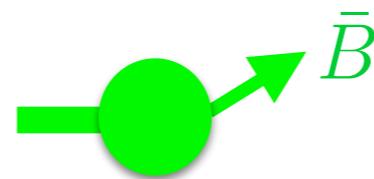


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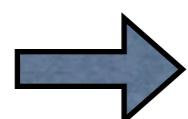
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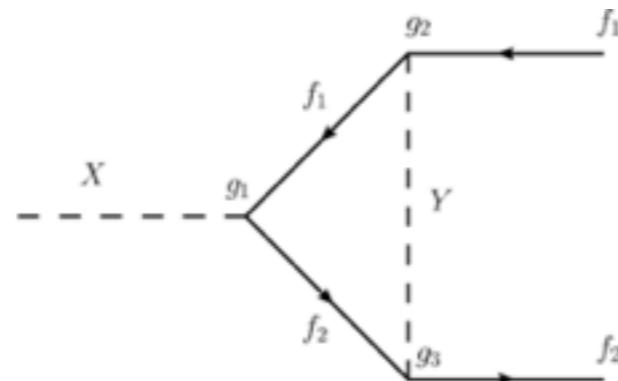
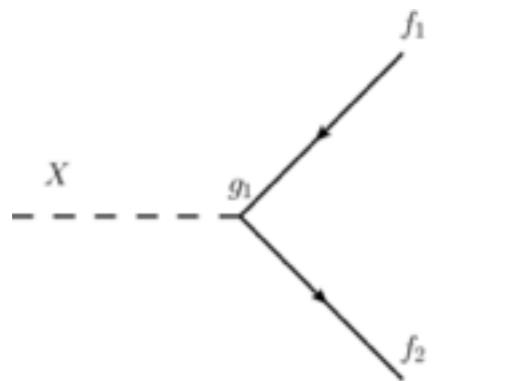


- ❖ Most existing BG mechanisms: high M or/and T, direct experimental test impossible (contrast: WIMP DM for Ω_{DM})

Baryogenesis from Out-of-Equilibrium Decay

A general class of baryogenesis models

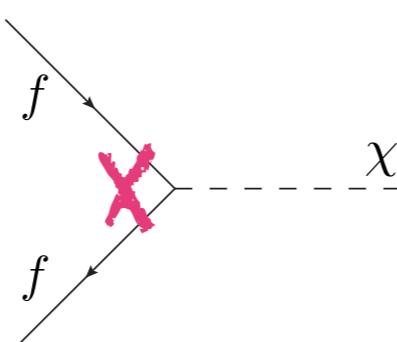
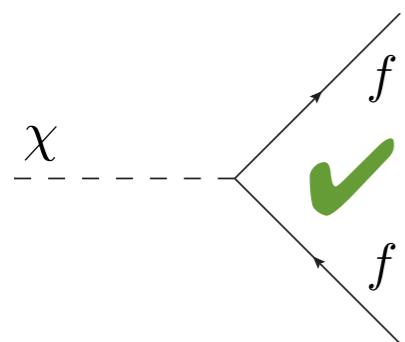
- Assume a massive neutral particle χ
- Baryon asymmetry can be produced in its decay (B-, CP-violation)



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

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

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

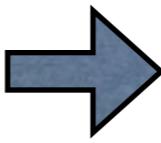


Inverse decay: $(H: \text{Hubble}$
Boltzmann suppressed expansion rate)

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



Out-of-equilibrium decay



Sakharov conditions ✓

Baryogenesis from Out-of-Equilibrium Decay

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

- If χ has weak scale mass:

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

- A generic connection between cosmological slow rates at $T \sim 100 \text{ GeV}$ and displaced vertices at colliders!

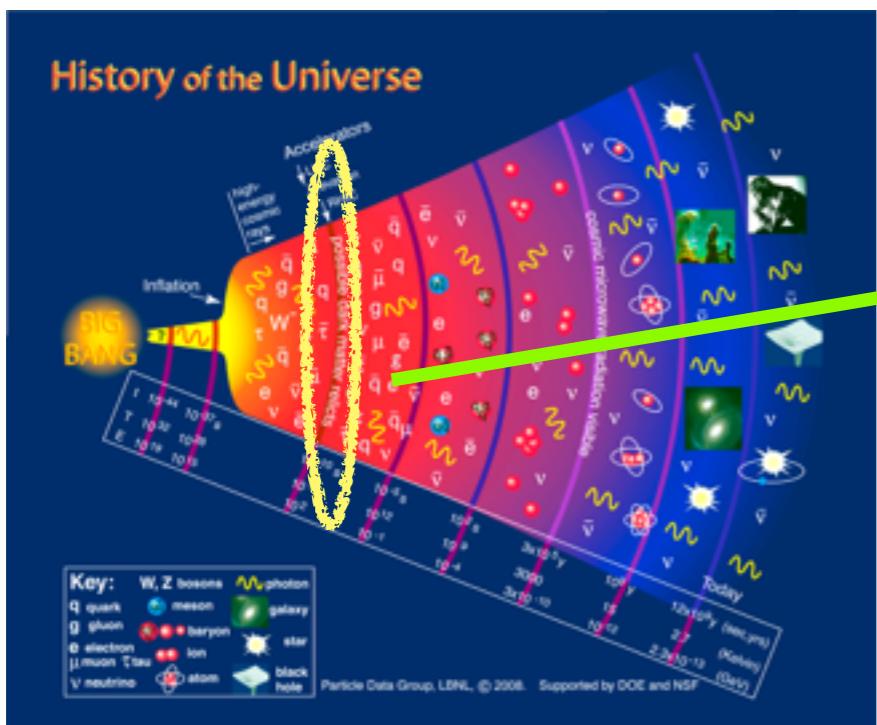
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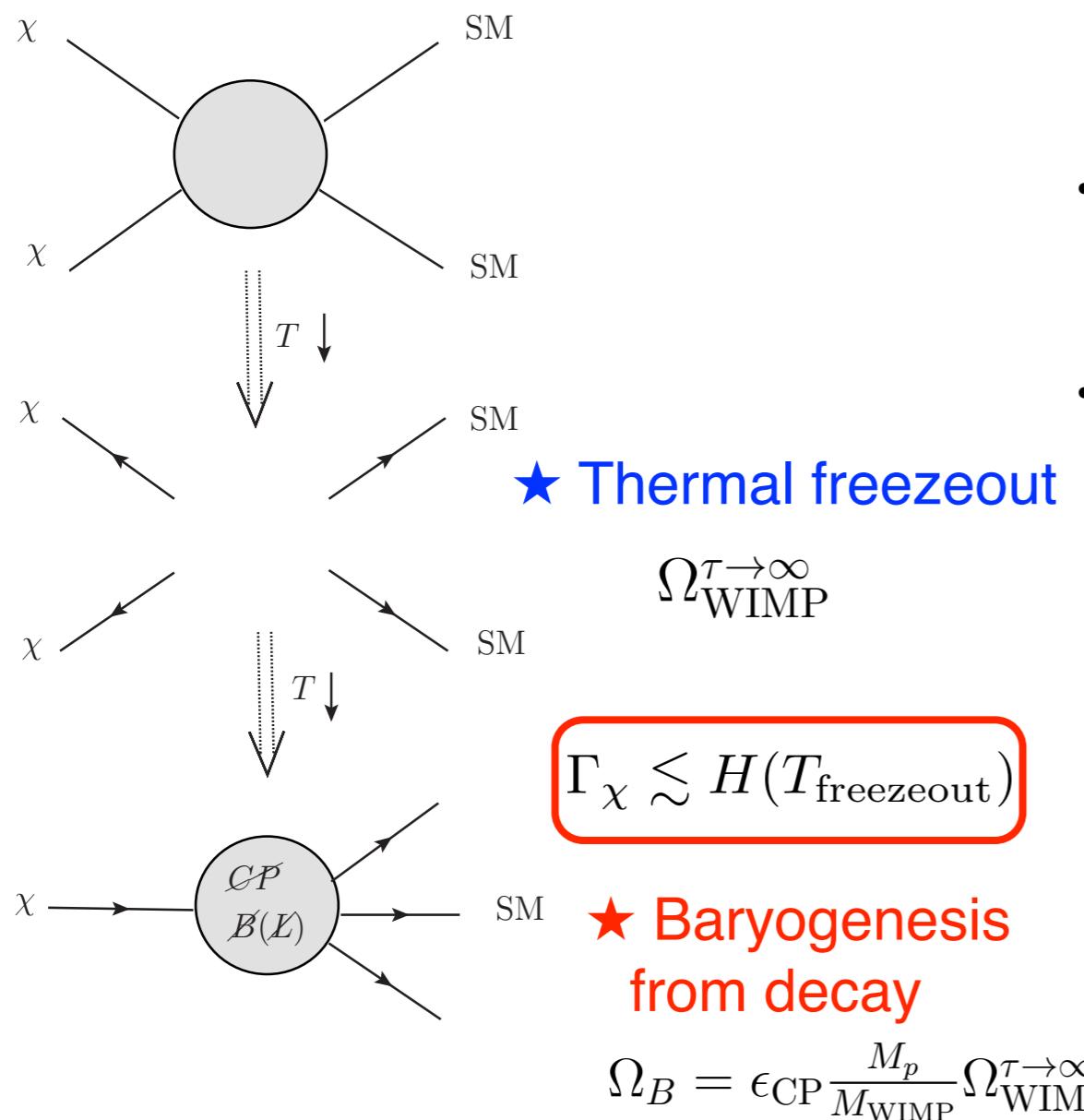


Our universe around EW phase transition was just slightly bigger than LHC tracking resolution!

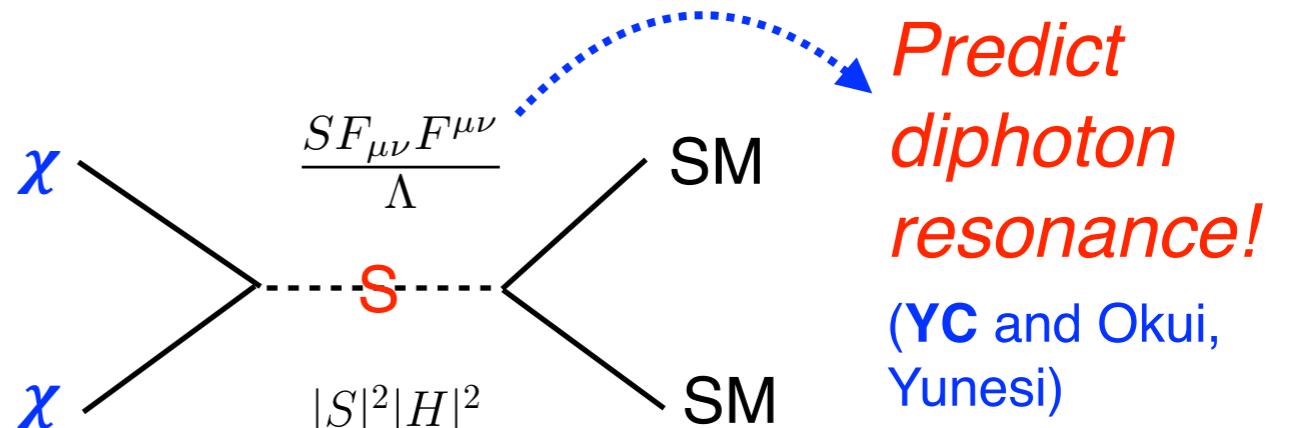
Baryogenesis from Meta-stable WIMP Decay

- concrete, motivated model examples

(YC and Sundrum 2012; YC 2014; YC and Okui, Yunesi, in prep)



- WIMP miracle prediction for Ω_B
+ new path addressing $\Omega_B \sim \Omega_{\text{DM}}$
- General mechanism, easy to embed in RPV SUSY (*natural or split*)
- Thermal annihilation of WIMP through a singlet scalar S



Pair production of long-lived baryon parent WIMP at the LHC!

Simplified Model Approach for LHC Pheno

(YC and Shuve, 2014)

- Classify production modes (analogy to DM search @LHC!)
- Classify decay modes (unlike DM search)

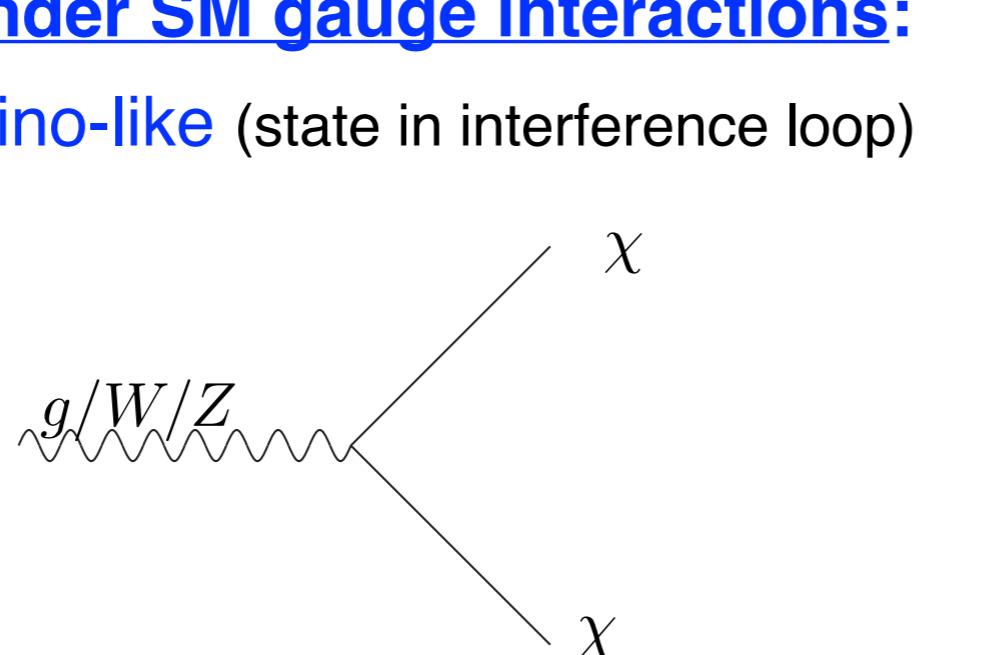
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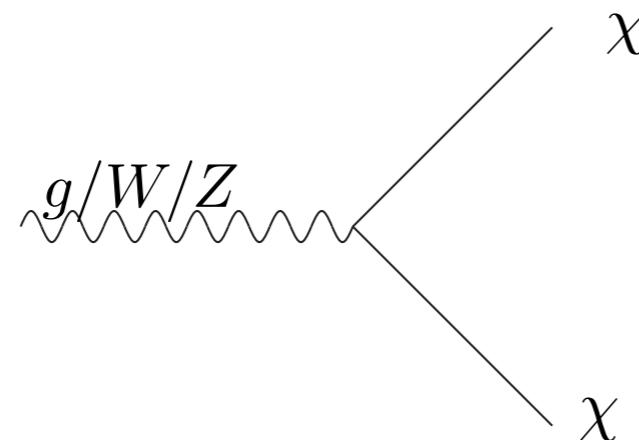
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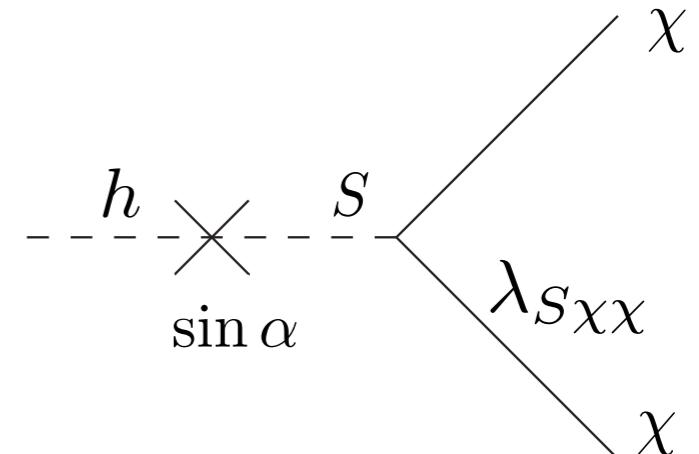
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singlet-like (e.g. $M_\chi = 150$ GeV)



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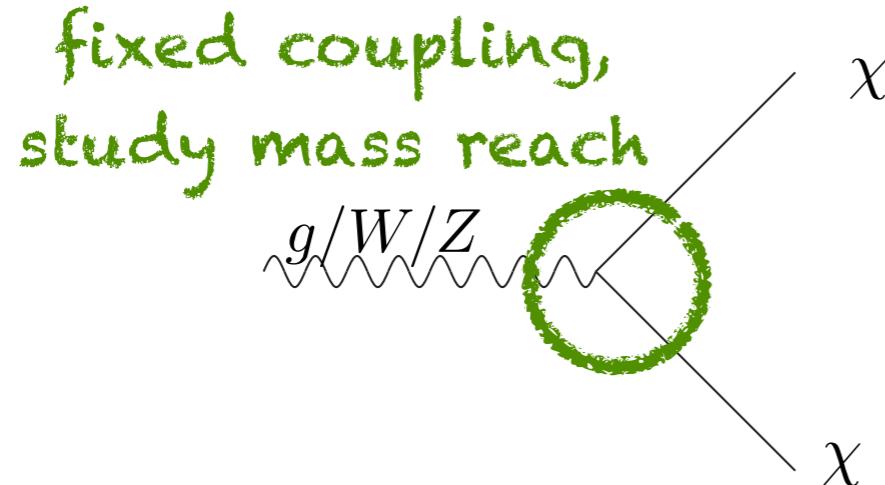
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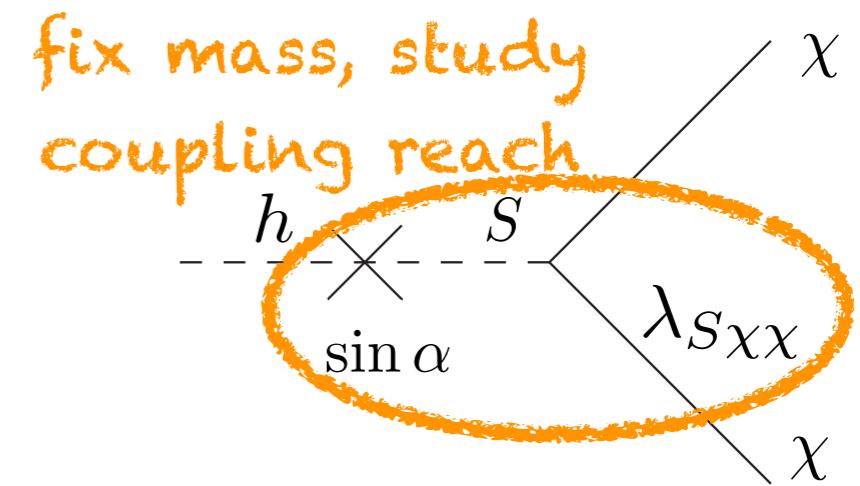
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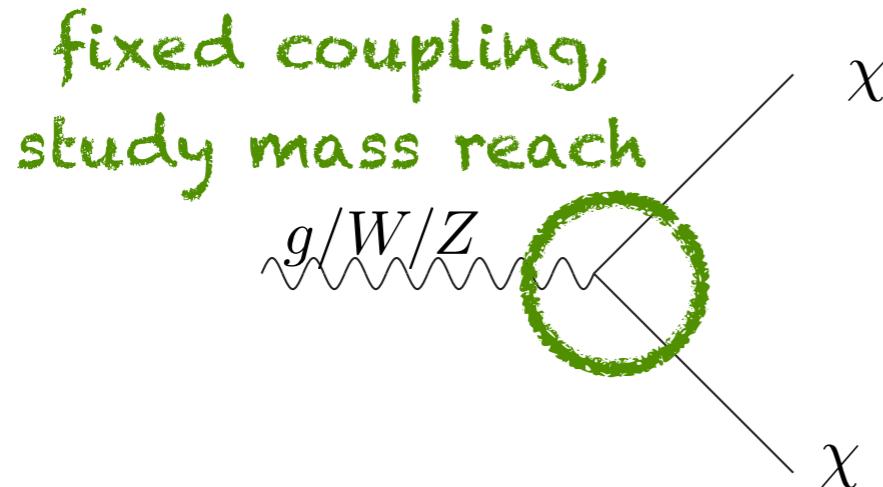
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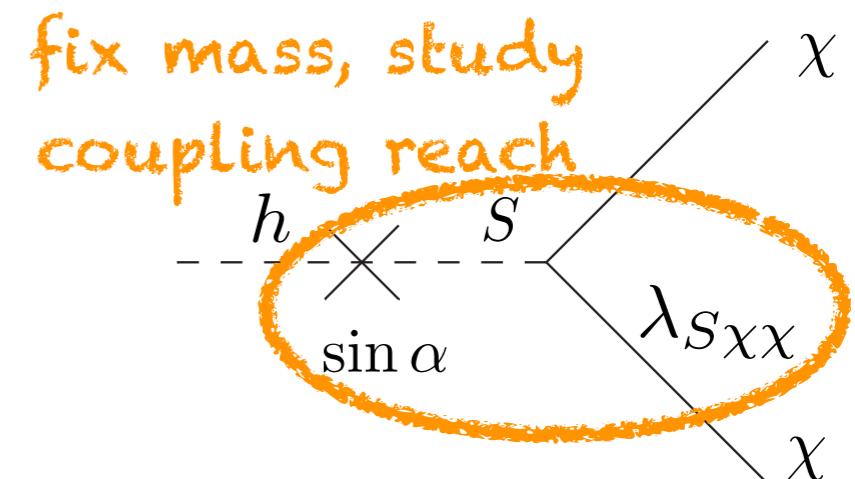
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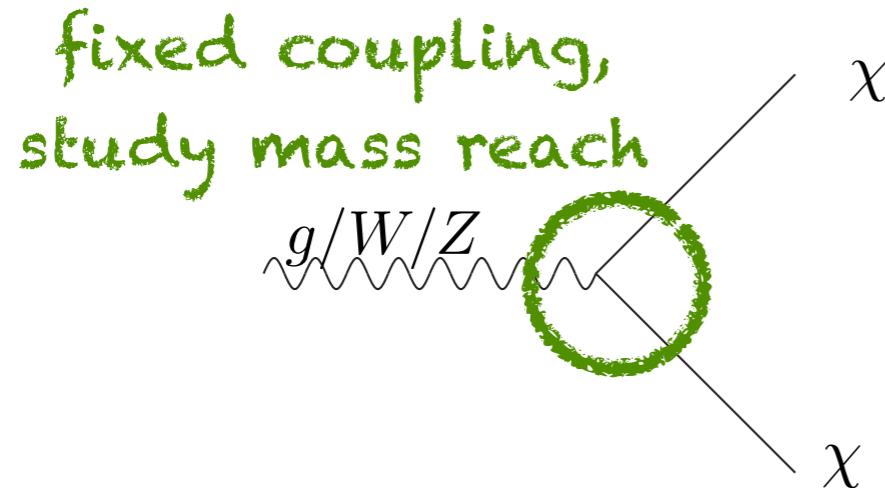
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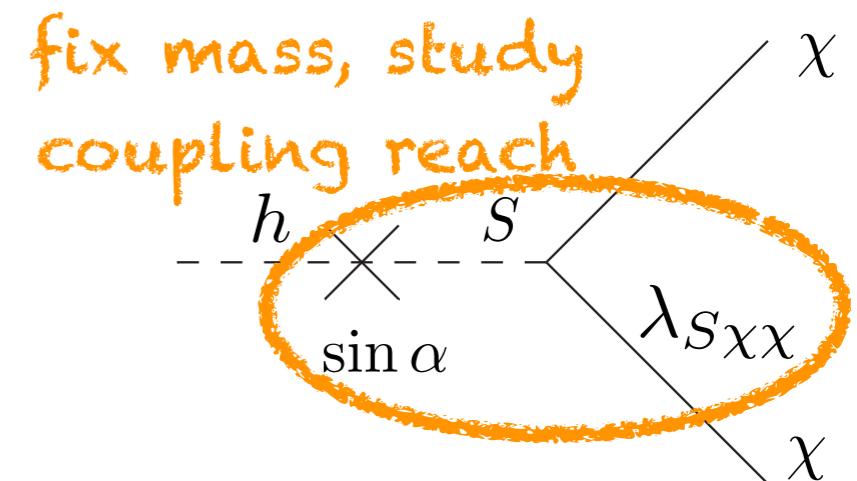
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Lepton number violating:

$$\begin{aligned}\chi &\rightarrow L_i Q_j \bar{d}_k \\ \chi &\rightarrow L_i L_j \bar{E}_k\end{aligned}$$

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:

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displaced muon + tracks

ATLAS-CONF-2013-092

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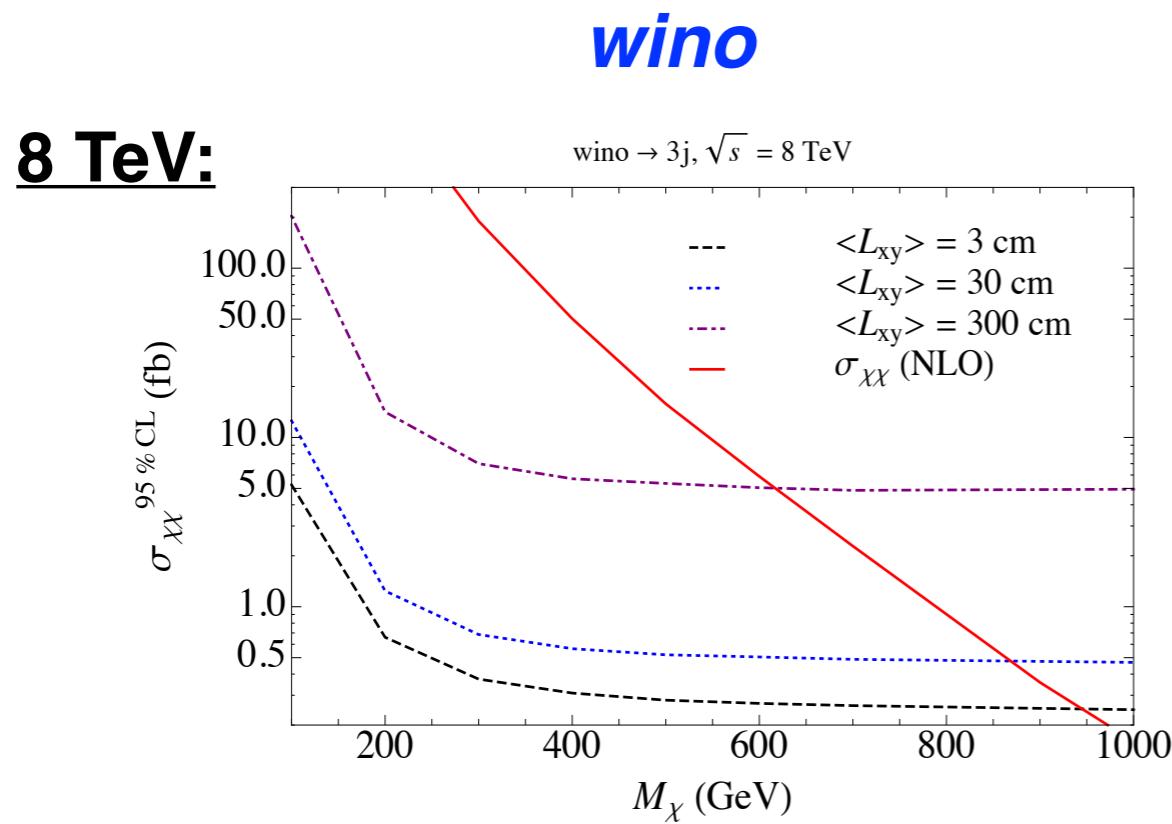
ATLAS-CONF-2013-092

- 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?

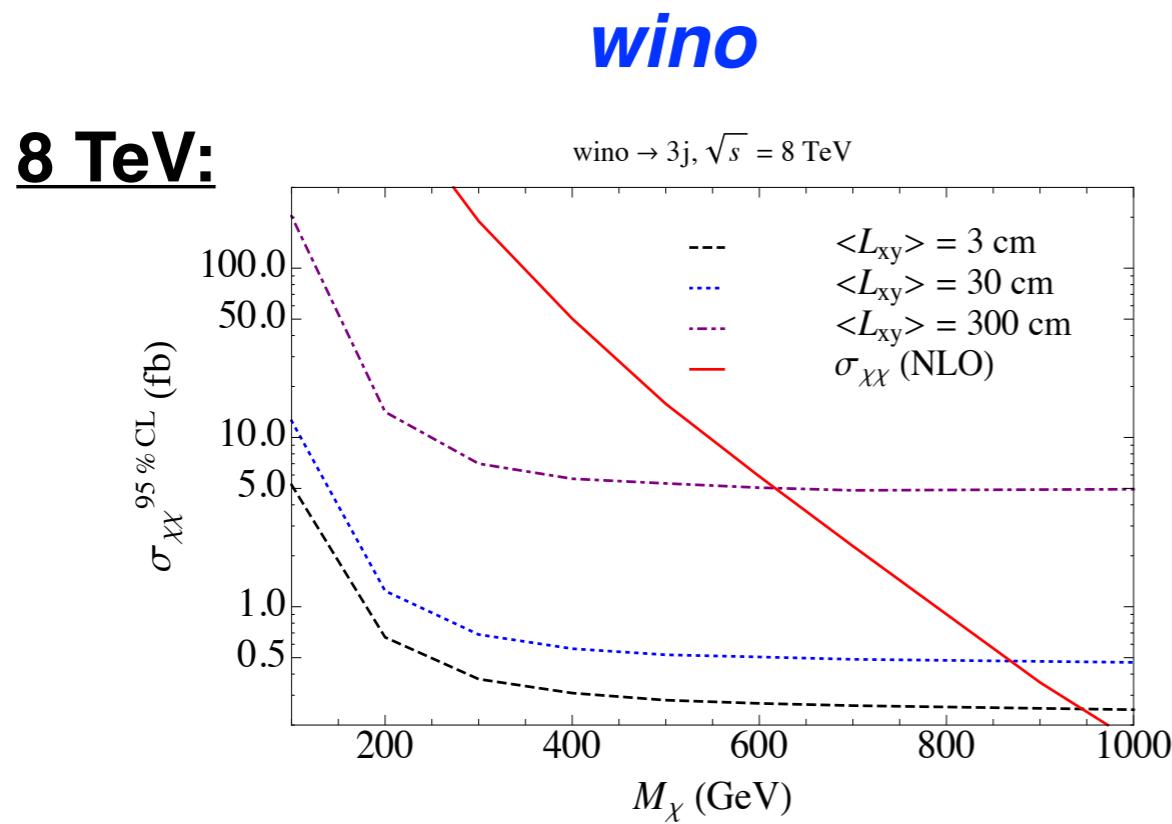
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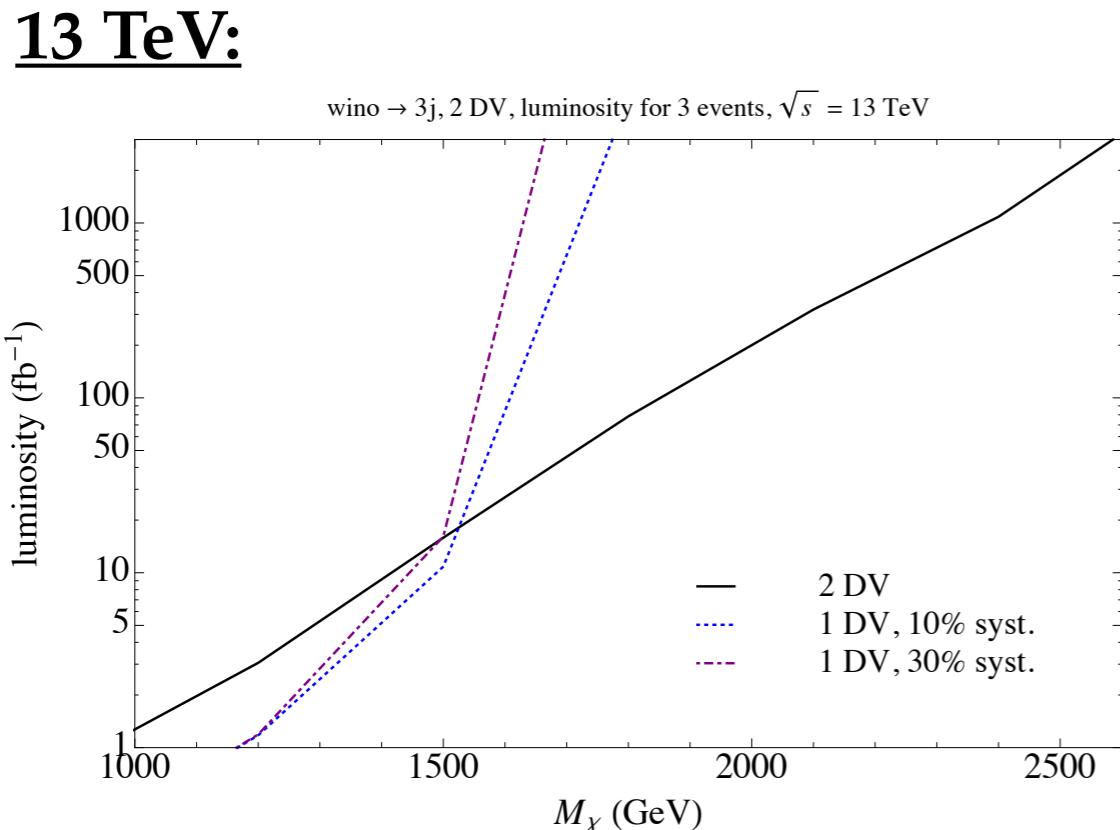
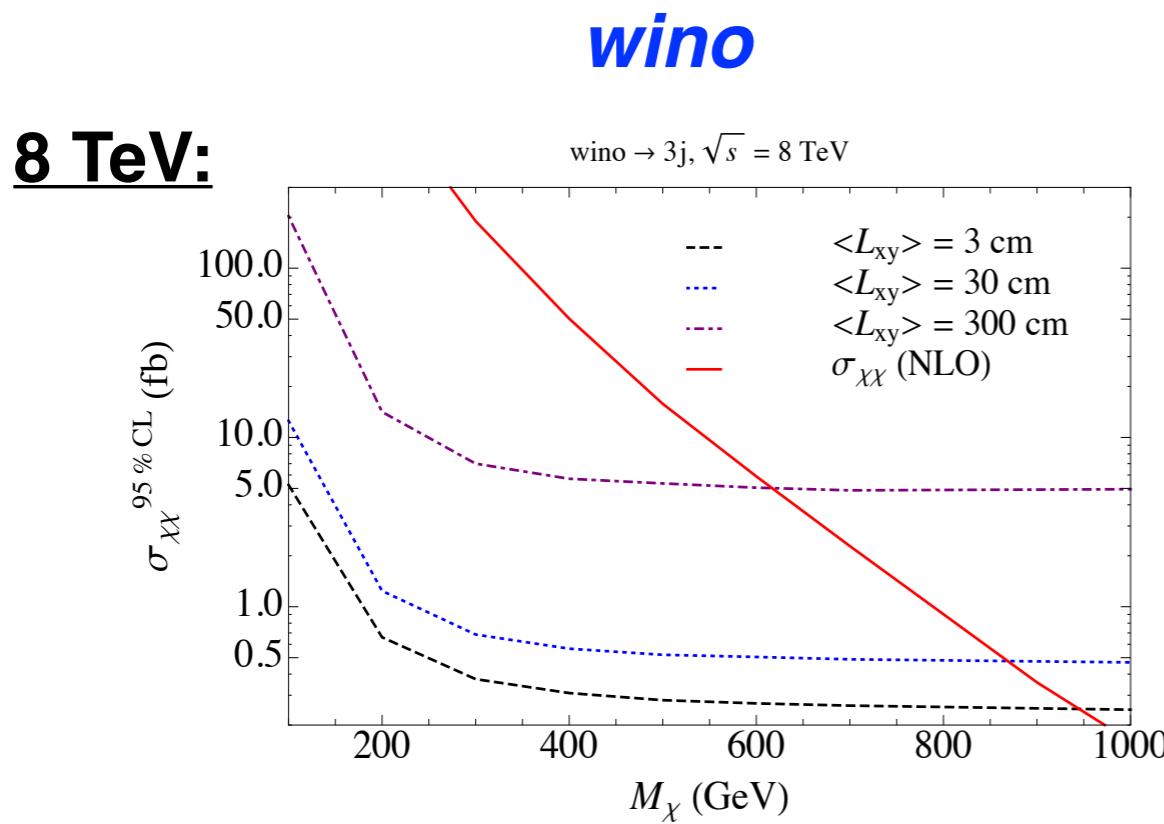
singlet-like (Higgs portal)

We studied a challenging case:
 $M_\chi = 150$ GeV, moderately off-shell!

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

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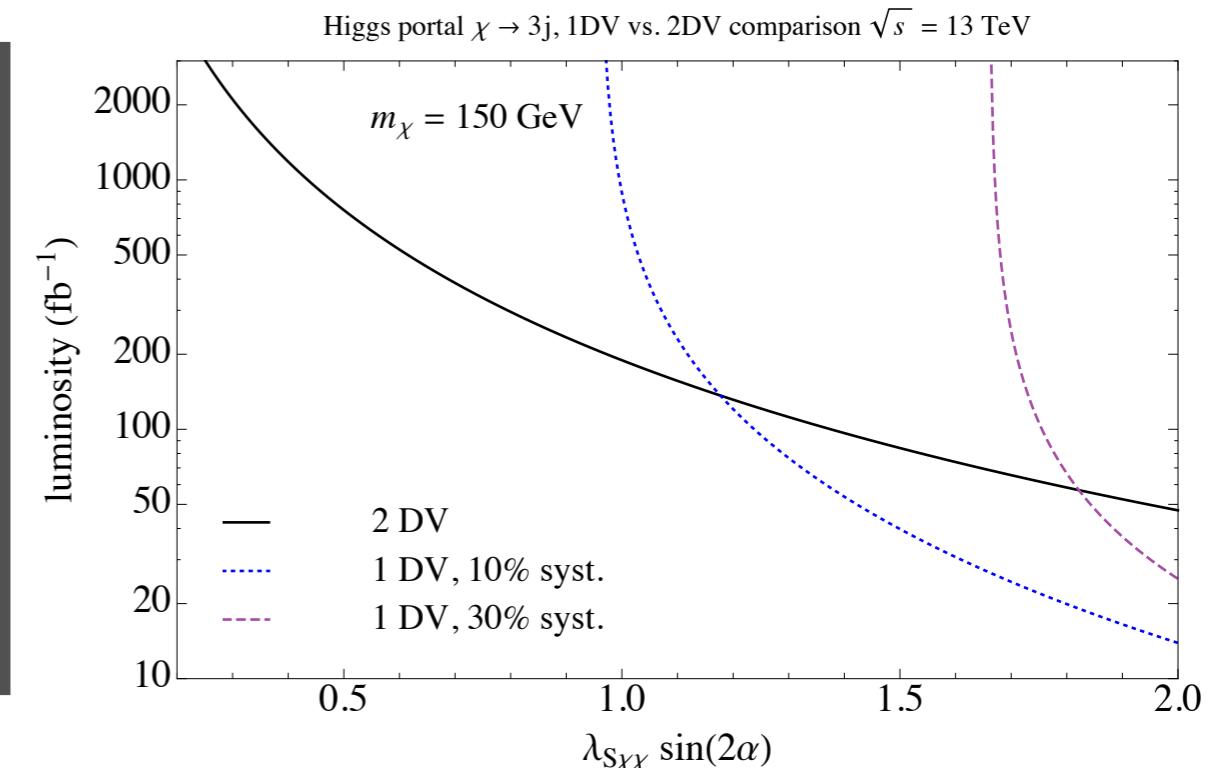


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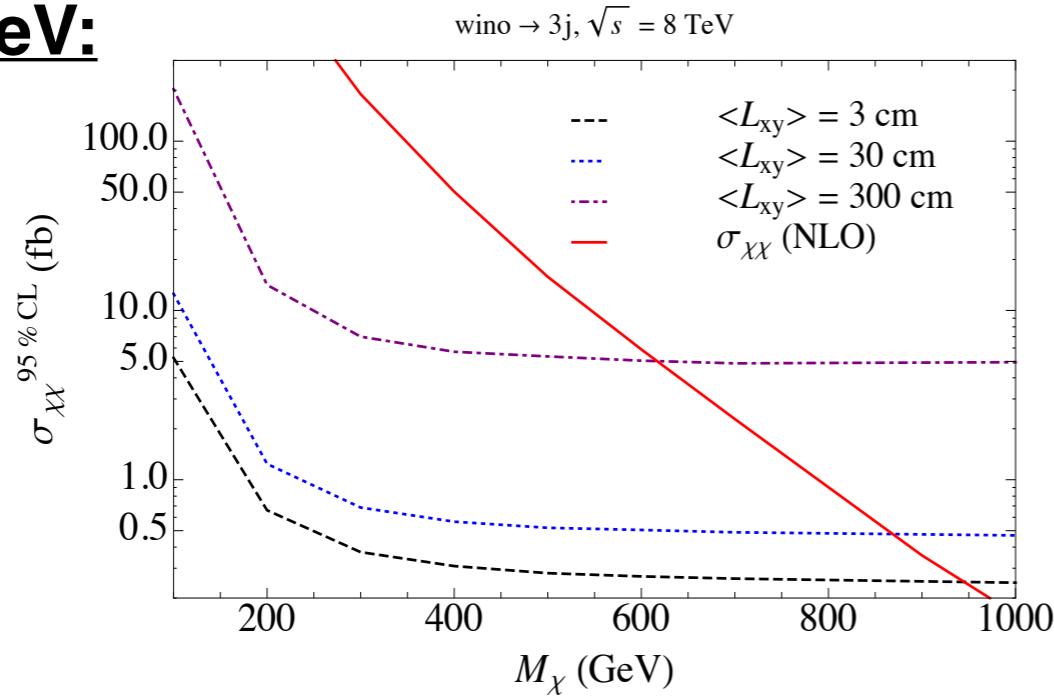


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wino

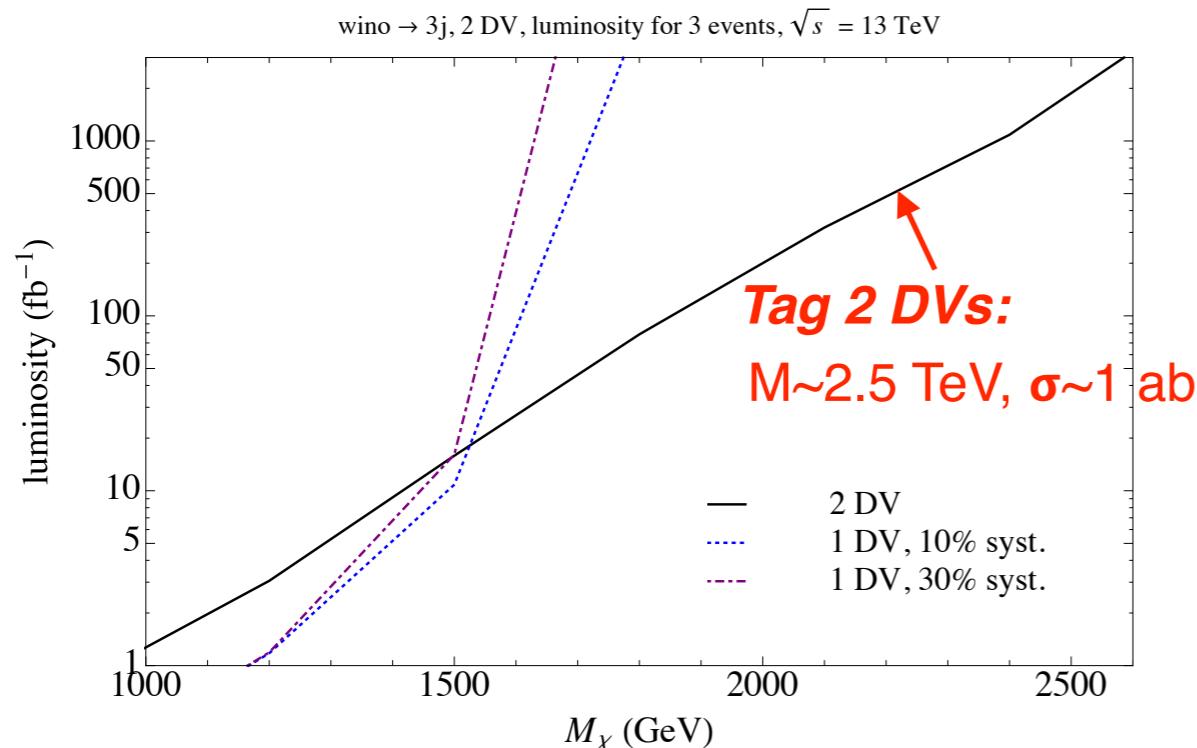
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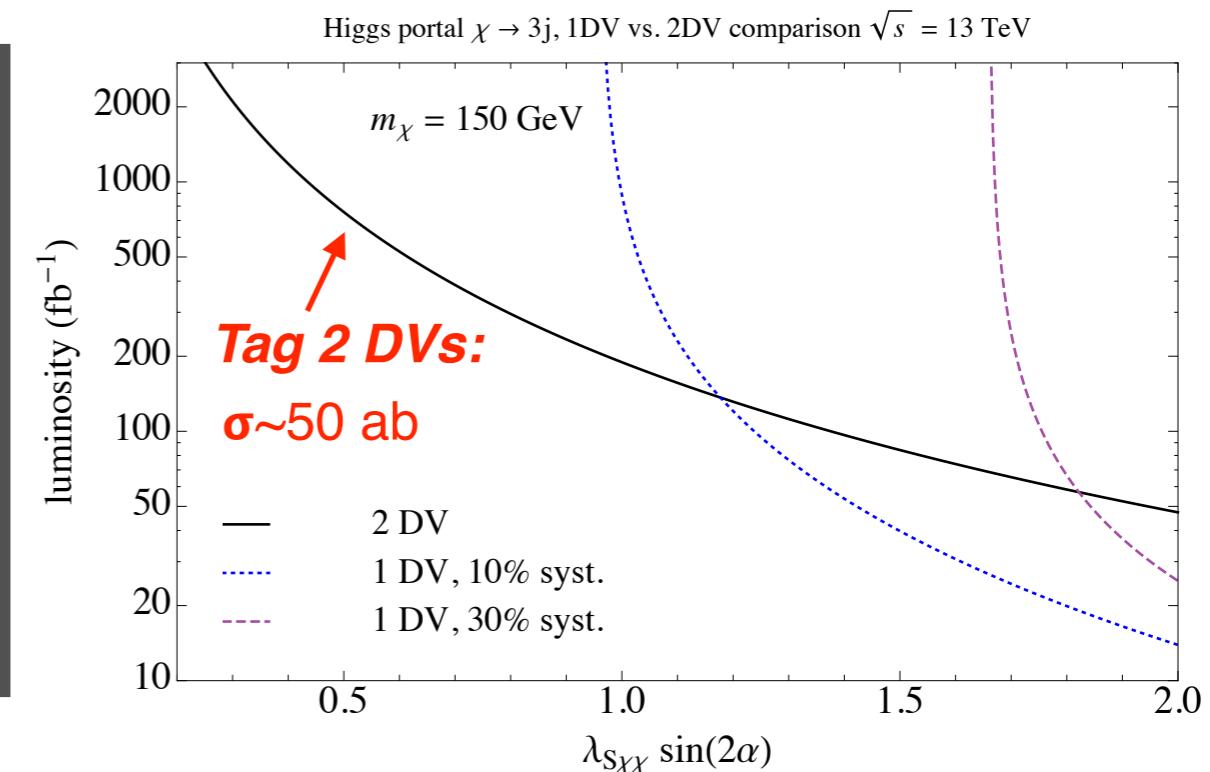
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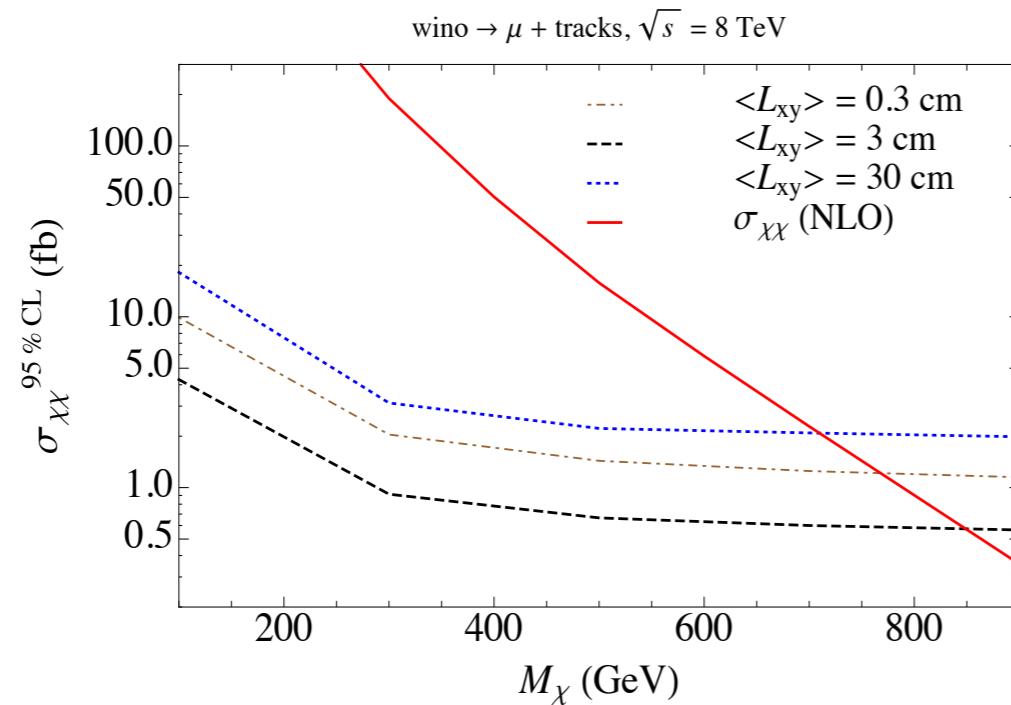


Displaced muon + Tracks

ATLAS-CONF-2013-092

wino

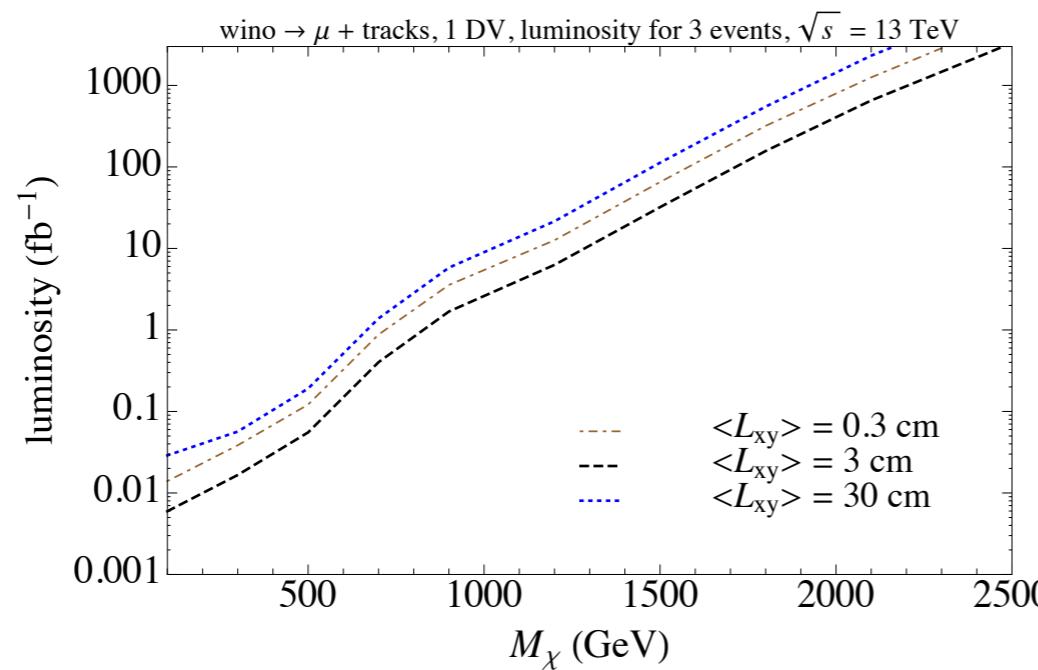
8 TeV



13 TeV:

Tag 1 DV
M~2.5 TeV

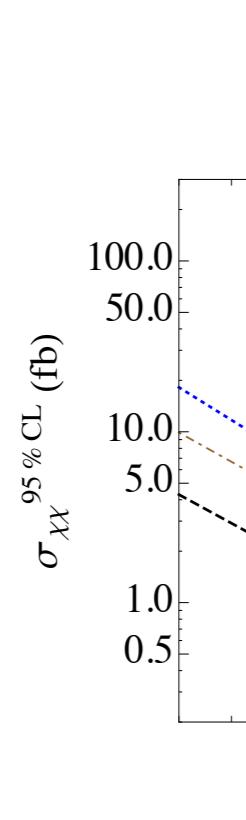
(lower bkg
than all-
hadronic)



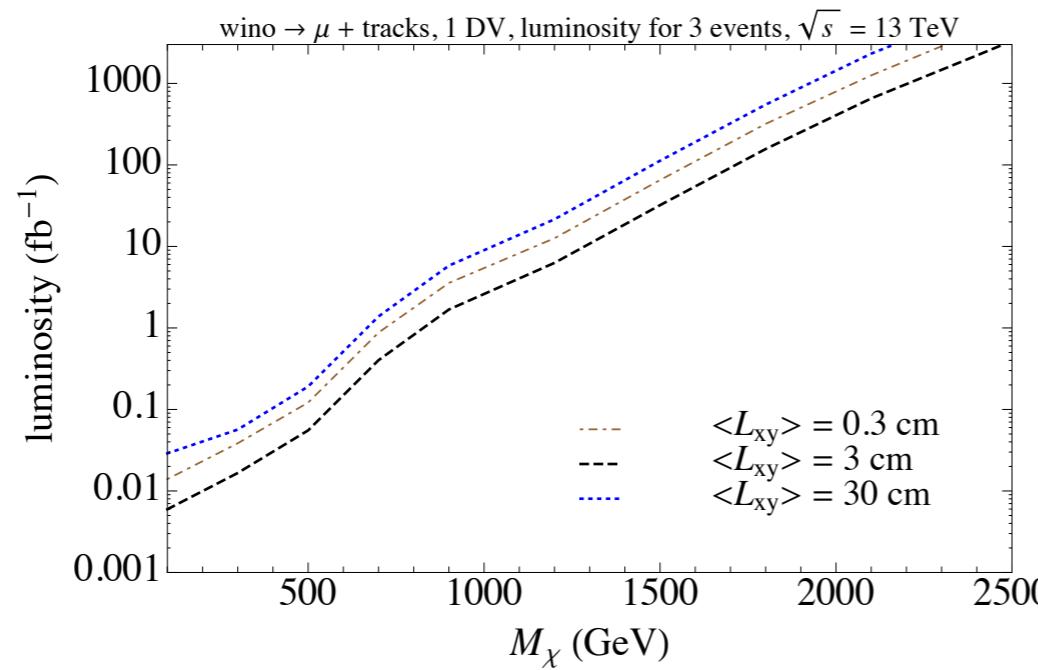
Displaced muon + Tracks

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8 TeV



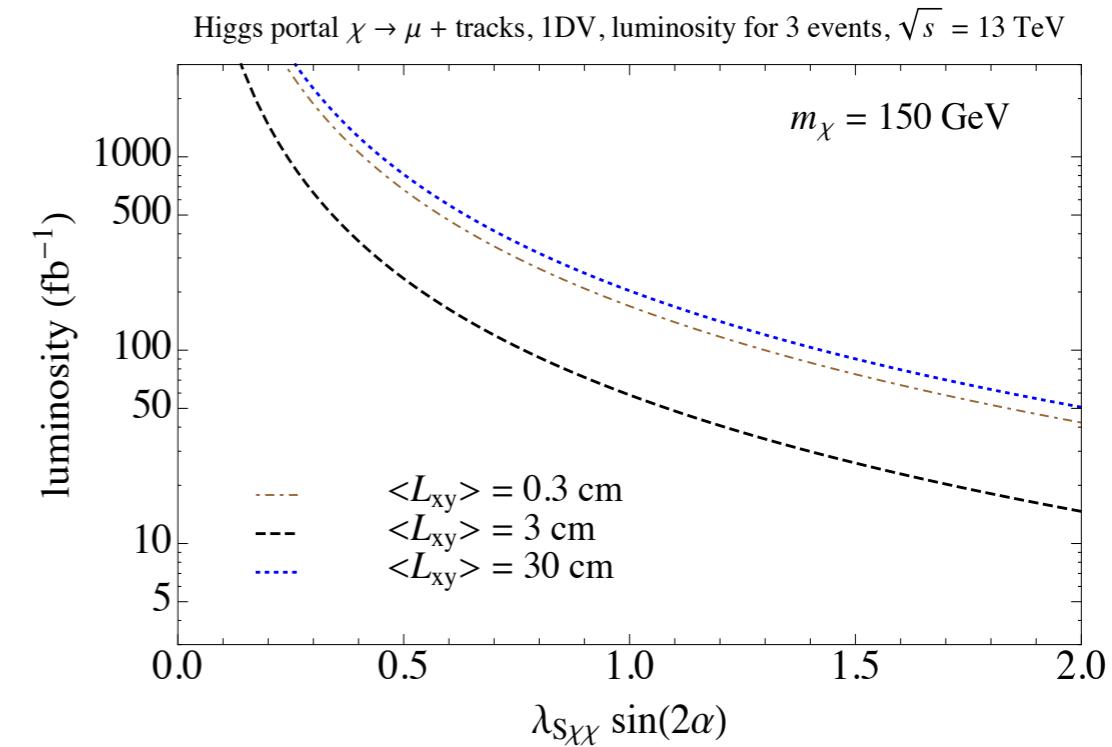
13 TeV:
Tag 1 DV
M~2.5 TeV
(lower bkg than all-hadronic)



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

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

- 13 TeV: $\sigma \sim 50 \text{ ab}$ for $L_{xy} \sim 1 \text{ cm}$
(Tag 1 DV)



Summary/Outlook

- **Baryogenesis from metastable weak scale particle decay:**
 - A **robust cosmological motivation** for DV searches
 - Exciting opportunity to reproduce and study the early universe BG @ LHC! (cf. WIMP DM search)
- **WIMP baryogenesis:** a motivated example, new mechanism addressing Ω_B (+) $\Omega_B \sim \Omega_{\text{DM}}$, natural embedding in SUSY
- Simplified models for LHC pheno: signal generator for **general DV searches** (*corporation with ATLAS displaced jets group*)

Some Food for Thought

- Two-DV tagging can significantly increase sensitivity to rare all-hadronic events at Run-2/High Lum LHC
- Best trigger/search strategy for low mass (low H_T) all-hadronic DV events (e.g. on-shell Higgs decay) ?
- DV reconstruction efficiency table helpful for theorists' recasting ...