Probing Baryogenesis with Displaced Vertices

- from the LHC to CLIC

Yanou Cui

University of California-Riverside

- Phys.Rev.D, 87,11603, YC and Raman Sundrum
- JHEP 1312 (2013) 067, YC
- JHEP 1502 (2015) 049, YC and Brian Shuve
- Ongoing cooperation with ATLAS LLP working group
- Phys.Rev. D94 (2016) YC and Takemichi Okui, Arash Yunesi
- Work in progress, YC and Aniket Joglekar, Brian Shuve, Yuhsin Tsai

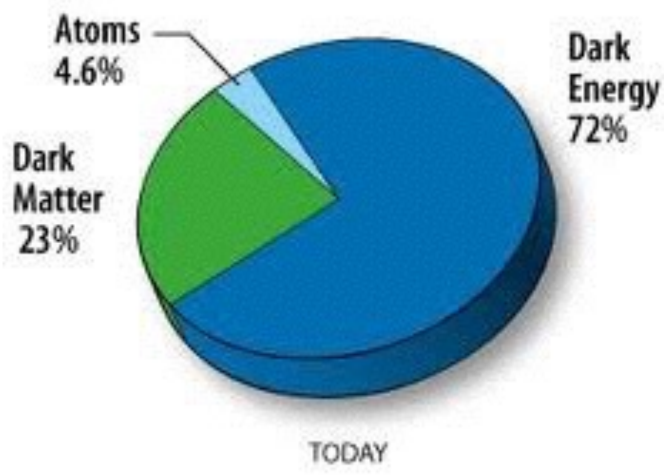
BSM Searches@CLIC meeting,
Feb 21, 2018

Cosmological Motivation for LLP Searches

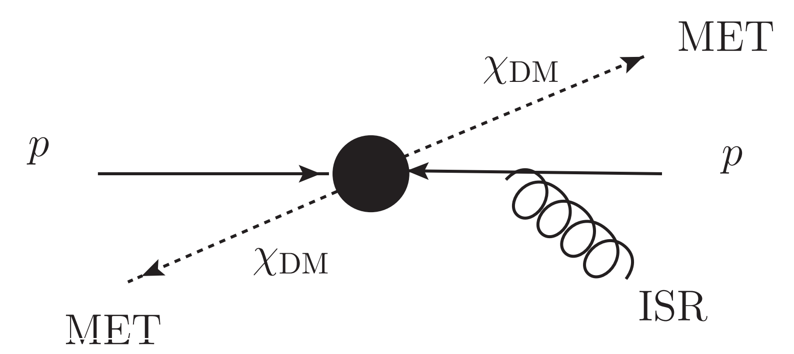
- Baryogenesis from Metastable Weak-scale New Particle

Could collider experimentents shed light on prominent puzzles in modern cosmology?

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



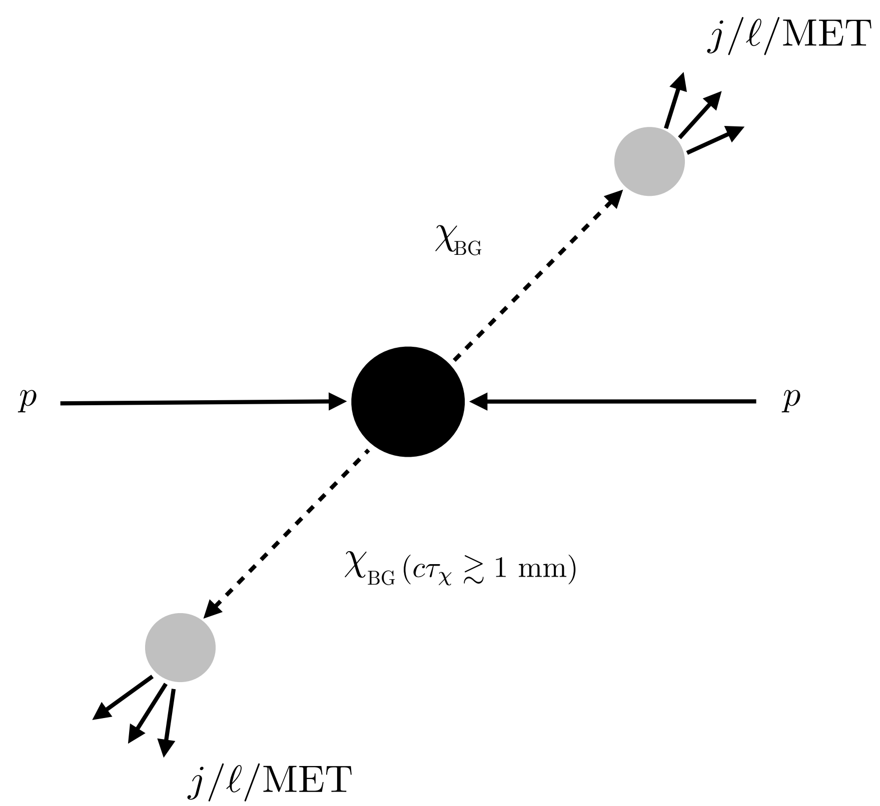
- Familiar/well-studied case: WIMP dark matter (Ω_{DM})
  - Stable, weak-scale mass, can be produced within E_{LHC} =14 TeV
  - Pair produced (Z_2),
  - Invisible, MET + X



Cosmological Motivation for LLP Searches

- Baryogenesis from Metastable Weak-scale New Particle

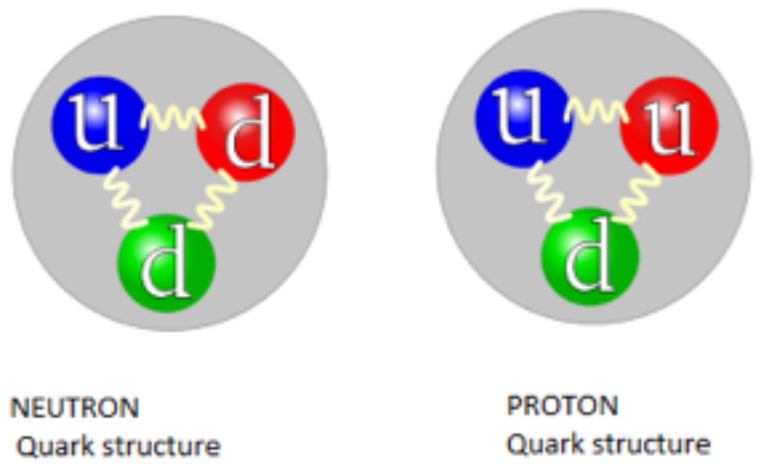
- **New opportunity**: baryogenesis (address Ω_B , possibly + $\Omega_B \sim \Omega_{DM}$)
  - New metastable particle (baryon parent), weak scale mass
  - Pair produced (approx. Z_2)
  - Displaced decay to $j/\ell/\mathrm{MET}$ by cosmological condition!



Baryon $\Omega_B \approx 5\%$
— The Unknown Aspects of the Known

- **Baryon**: proton, neutron ➡ atoms, stars, ourselves!
- **Where does Ω_B come from?**

= Where do we ourselves come from?



Baryon $\Omega_B \approx 5\%$
— The Unknown Aspects of the Known

- **Baryon**: proton, neutron ⇨ atoms, stars, ourselves!
- **Where does Ω_B come from?**

= Where do we ourselves come from?

We do not know!

NEUTRON
Quark structure

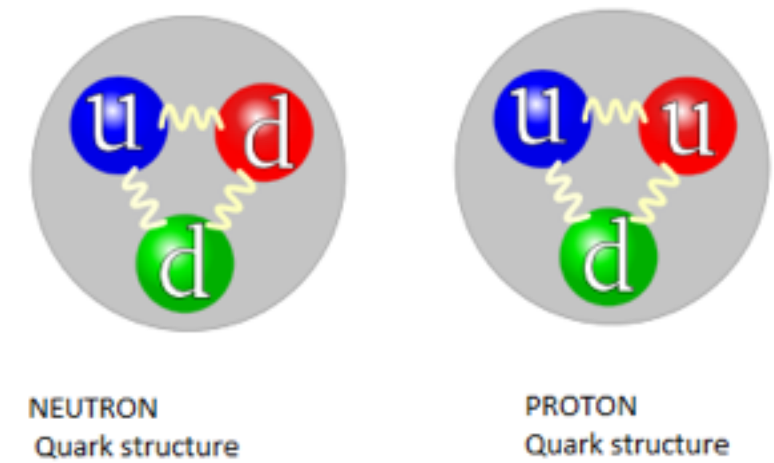
PROTON
Quark structure

Baryon $\Omega_B \approx 5\%$
— The Unknown Aspects of the Known

- **Baryon**: proton, neutron ⇨ atoms, stars, ourselves!
- **Where does Ω_B come from?**

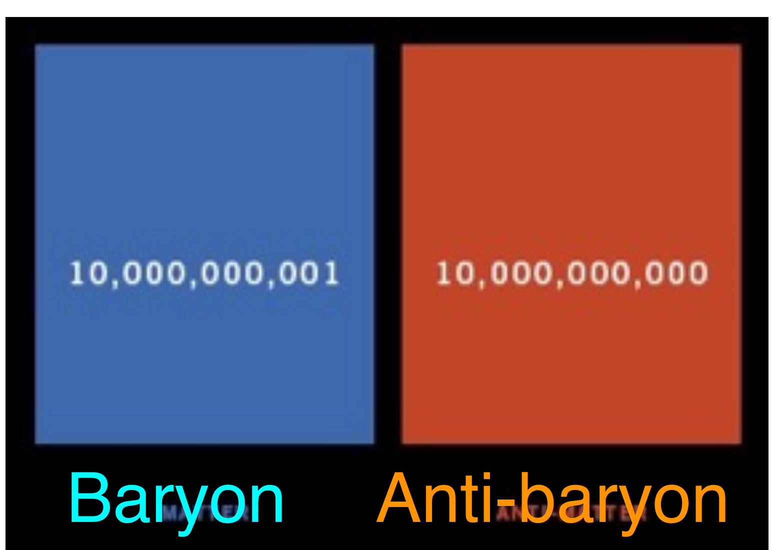
= Where do we ourselves come from?

We do not know!



Initial $B - \bar{B}$ asymmetry

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

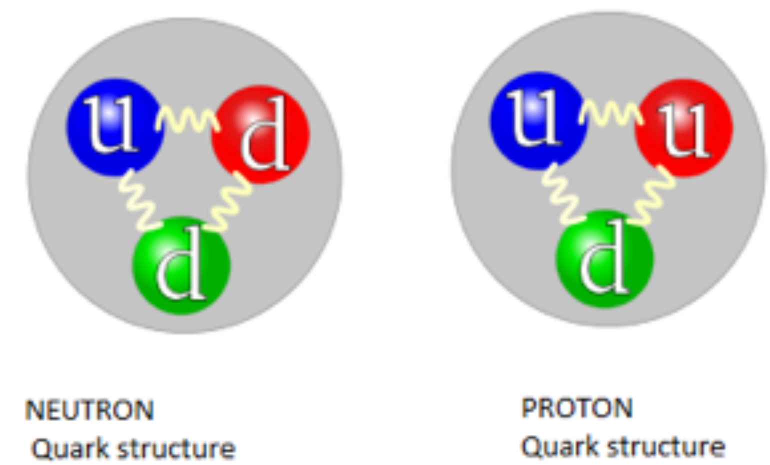


Baryon $\Omega_B \approx 5\%$
— The Unknown Aspects of the Known

- **Baryon**: proton, neutron ➡ atoms, stars, ourselves!
- **Where does Ω_B come from?**

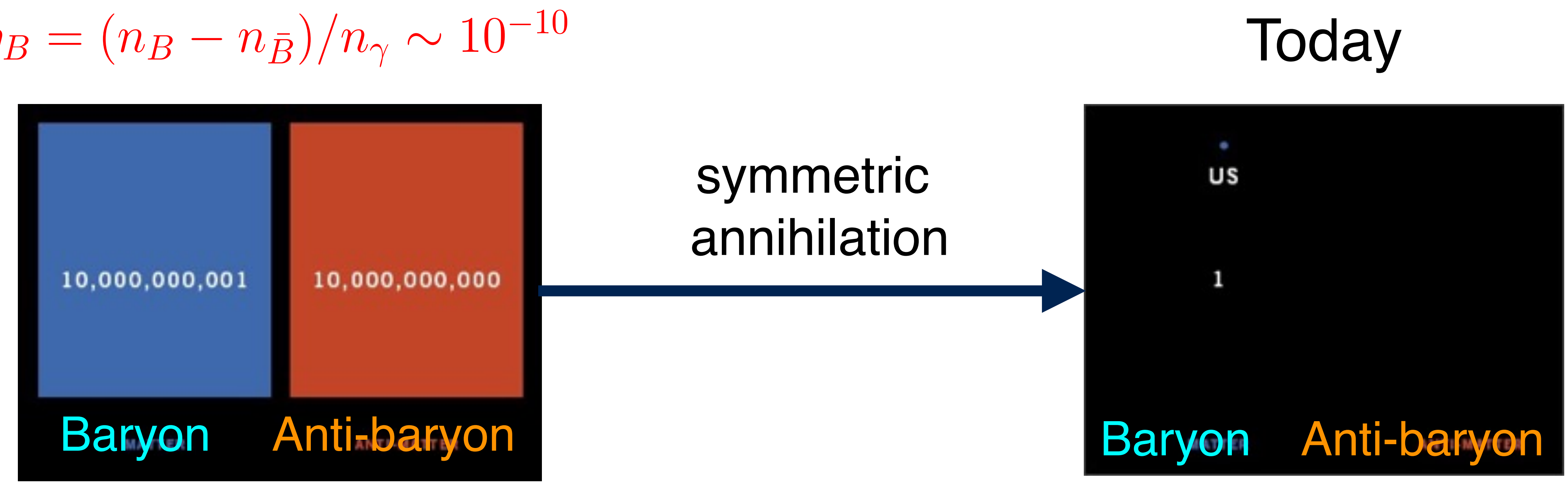
= Where do we ourselves come from?

We do not know!



Initial $B - \bar{B}$ asymmetry

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



Baryon $\Omega_B \approx 5\%$
— The Unknown Aspects of the Known

- **Baryon**: proton, neutron ⇨ atoms, stars, ourselves!
- **Where does Ω_B come from?**

= Where do we ourselves come from?

We do not know!

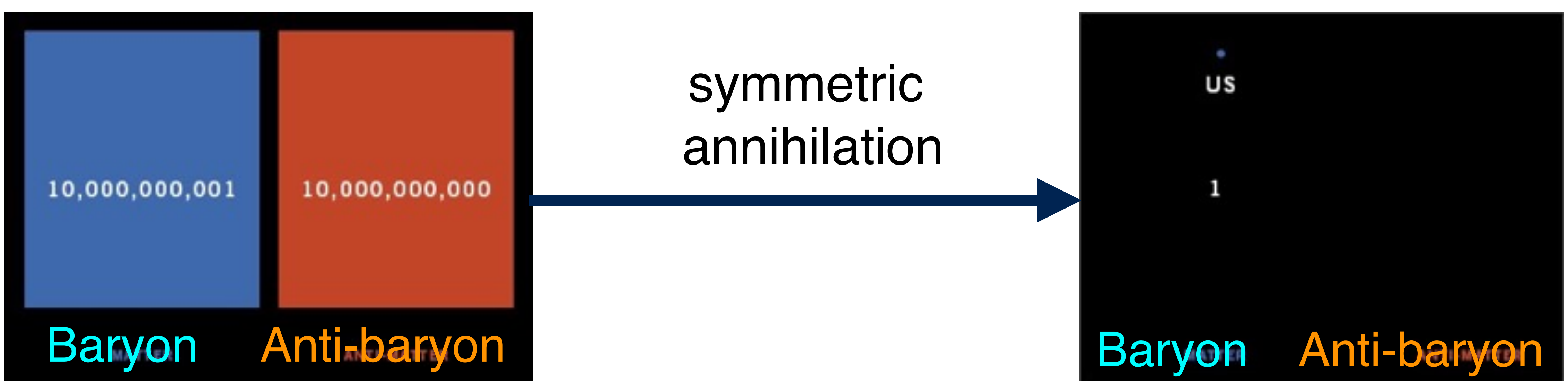
NEUTRON
Quark structure

PROTON
Quark structure

Initial $B - \bar{B}$ asymmetry

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

Today



Baryogenesis

- the Origin of the Baryon Asymmetry

The Universe starts with $B = 0$, **?** → $B \neq 0$

$B - \bar{B}$ asymmetry

Matter Anti-matter asymmetry

Baryogenesis

- the Origin of the Baryon Asymmetry

The Universe starts with $B = 0$, ? → $B \neq 0$

$B - \bar{B}$ asymmetry

Matter Anti-matter asymmetry

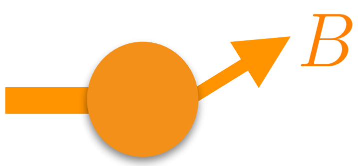
Baryogenesis

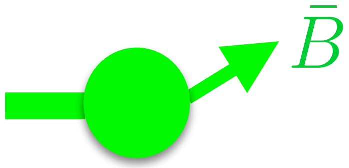
Sakharov Conditions (1967):

Baryogenesis

Sakharov Conditions (1967):

- **Require baryon number violation**



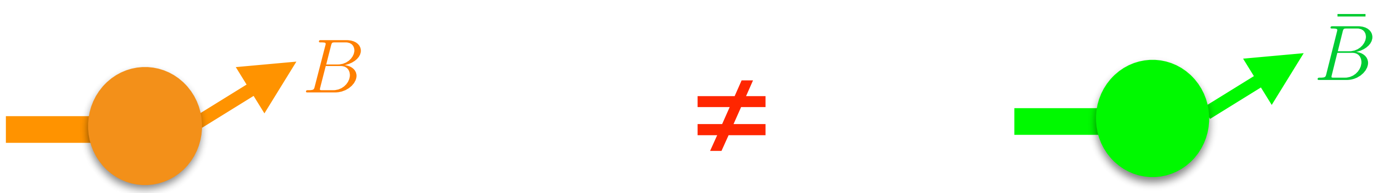


Baryogenesis

Sakharov Conditions (1967):

- **Require baryon number violation**

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

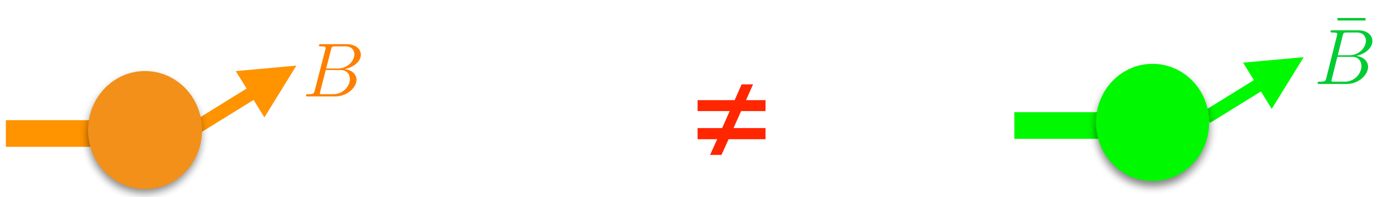


Baryogenesis

Sakharov Conditions (1967):

- **Require baryon number violation**

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



- **Require departure from equilibrium!**

Thermal equilibrium + CPT symmetry

$\Rightarrow$ $\langle B \rangle_{\rm eq} = 0$

Baryogenesis

Sakharov Conditions (1967):

- **Require baryon number violation**

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

- **Require departure from equilibrium!**

Thermal equilibrium + CPT symmetry

⇒ $\langle B \rangle_{\rm eq} = 0$

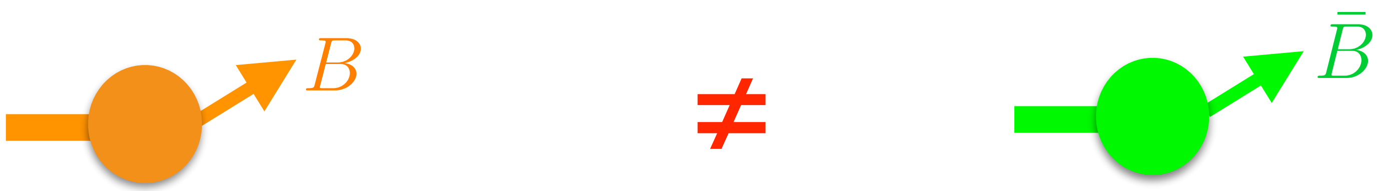
$\Omega_B \approx 5\%$:
Need beyond the Standard Model Particle Physics!

Baryogenesis

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

- **Require baryon number violation**

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



- **Require departure from equilibrium!**

$\Omega_B \approx 5\%$:
Need <u>beyond</u> the Standard Model Particle Physics!

Thermal equilibrium + CPT symmetry

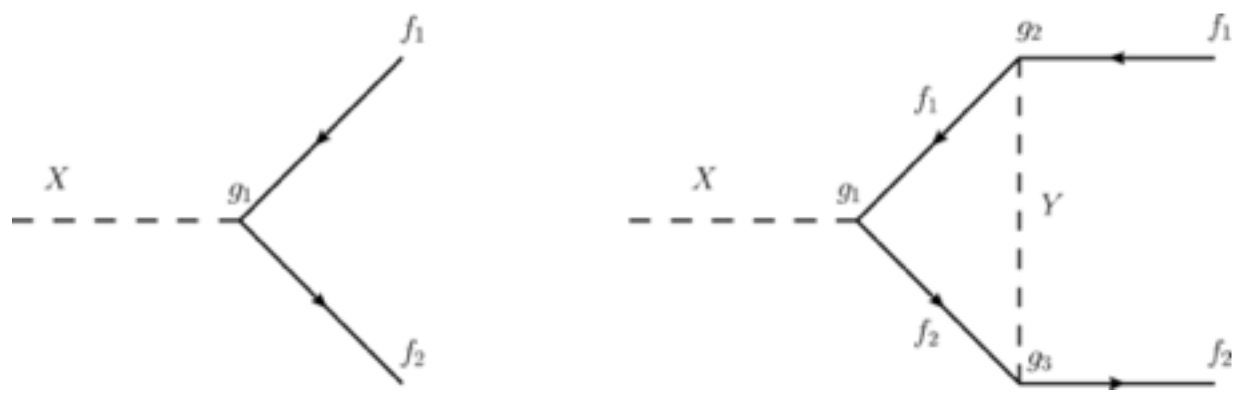
⇒ $\langle B \rangle_{\mathrm{eq}} = 0$

❖ Most existing BG mechanisms: high M or/and T, *<u>direct</u>* 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)

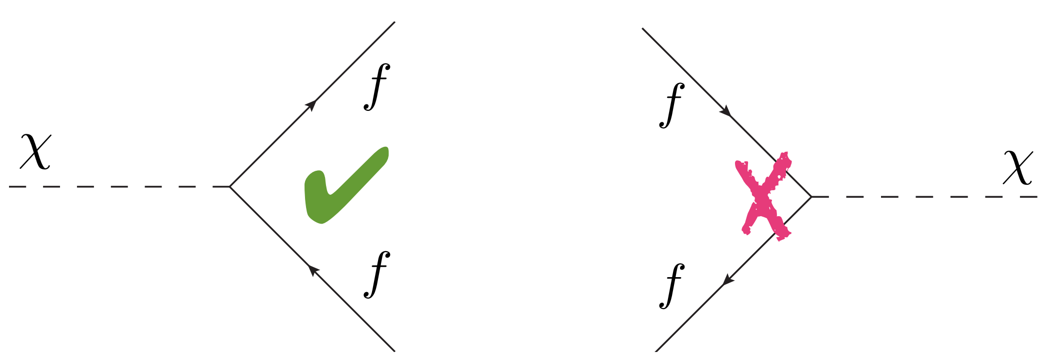


$$\Gamma(\chi \to f) \neq \Gamma(\chi \to \bar{f})$$

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

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

(*H*: Hubble expansion rate)



Inverse decay:
Boltzmann suppressed

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

☞ **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:

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

- A **generic connection** between cosmological slow rates at *T ~100 GeV* and displaced vertices at colliders!

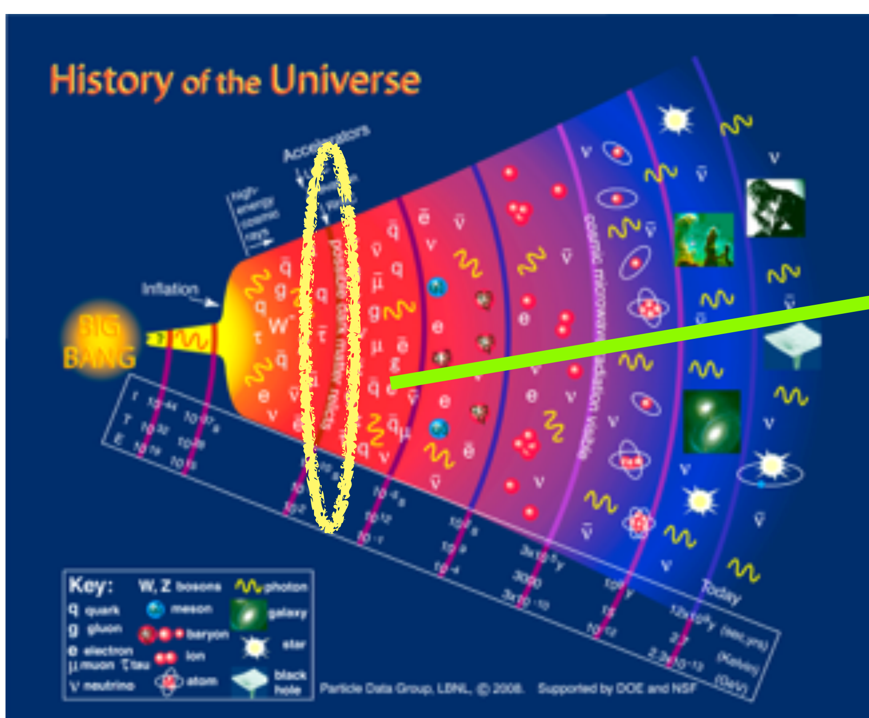
Baryogenesis from Out-of-Equilibrium Decay

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

- If χ has weak scale mass:

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

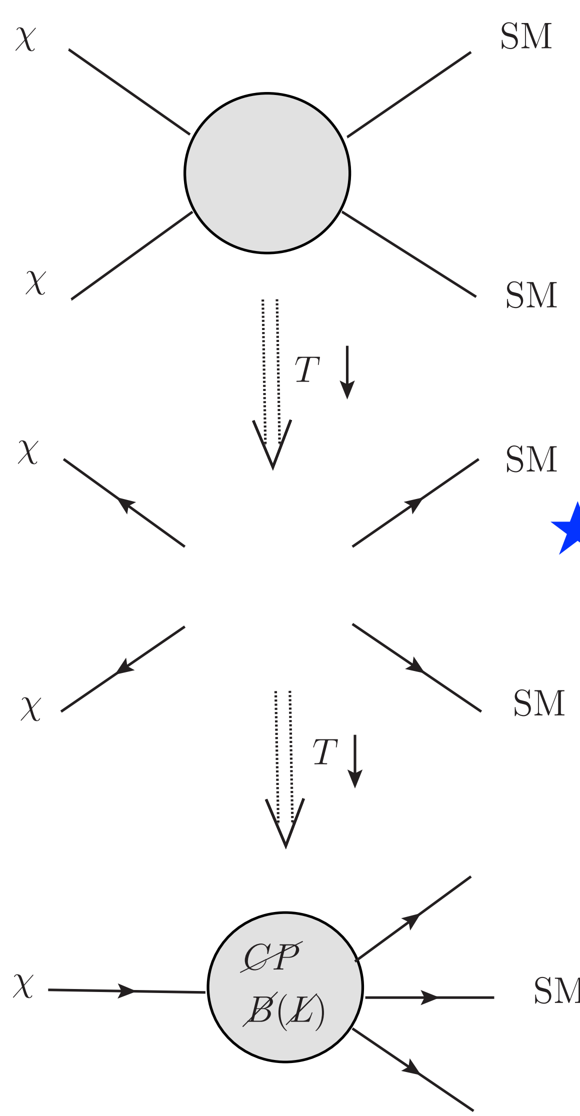
- A **generic connection** between cosmological slow rates at *T ~100 GeV* and displaced vertices at colliders!



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 2016)



★ Thermal freezeout

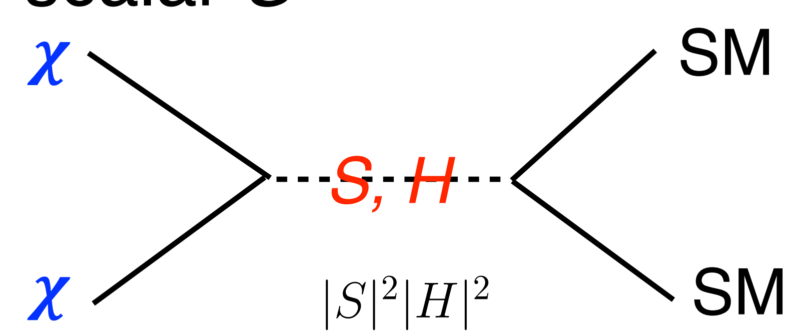
$$\Omega^{\tau\to\infty}_{\rm WIMP}$$

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

★ Baryogenesis from decay

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

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

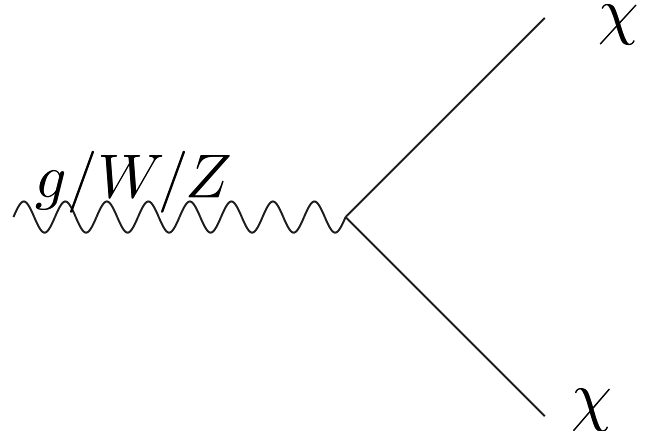
Simplified Model Approach for LHC Pheno

(**YC** and Shuve, 2014)

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

Charged under SM gauge interactions:

wino/gluino-like (states in interference loop)



- Classify decay modes (unlike DM search)

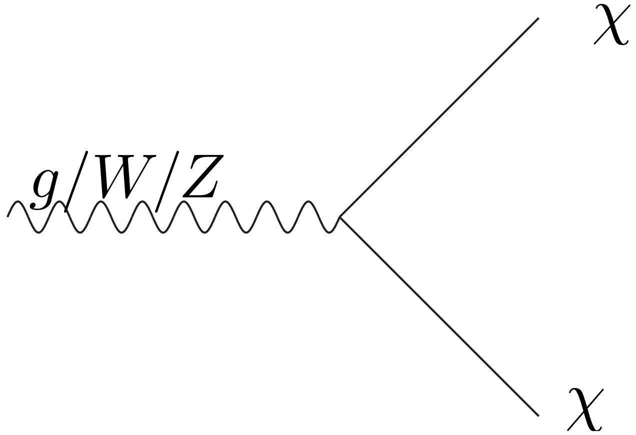
Simplified Model Approach for LHC Pheno

(**YC** and Shuve, 2014)

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

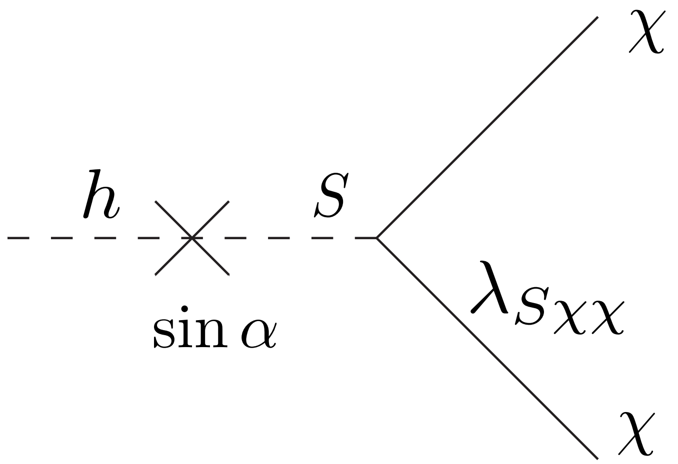
Charged under SM gauge interactions:

wino/gluino-like (states in interference loop)



Higgs portal:

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



- Classify decay modes (unlike DM search)

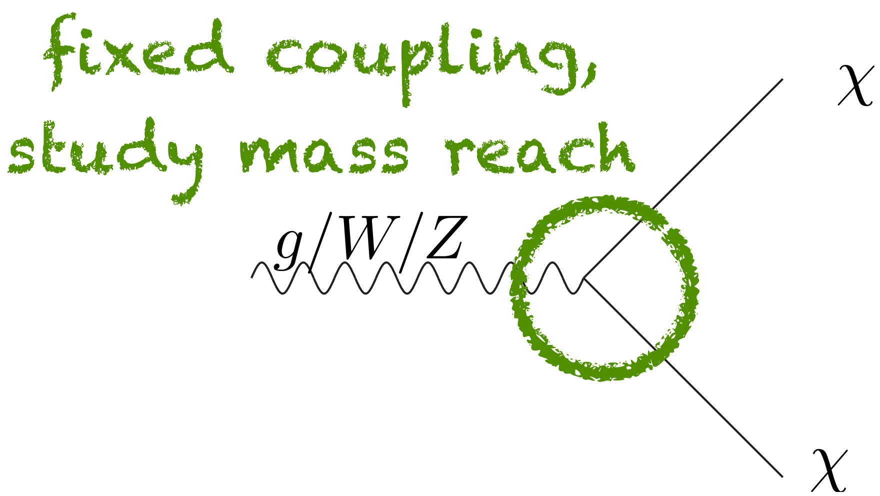
Simplified Model Approach for LHC Pheno

(**YC** and Shuve, 2014)

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

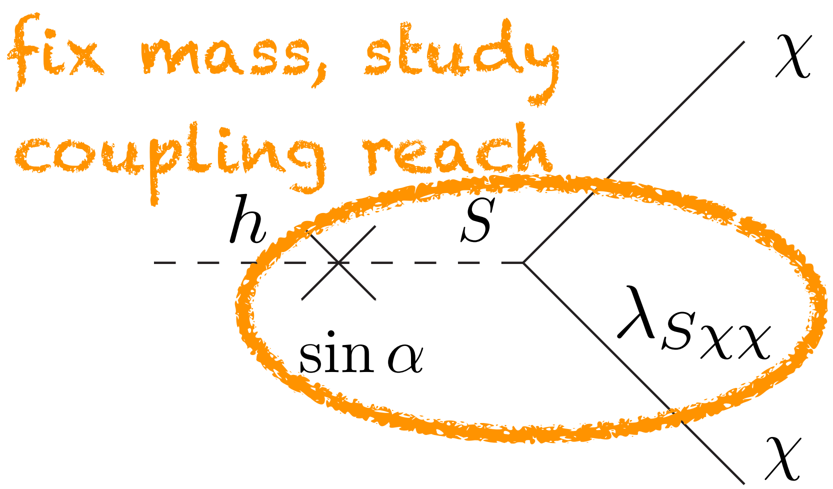
Charged under SM gauge interactions:

wino/gluino-like (states in interference loop)



Higgs portal:

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



- Classify decay modes (unlike DM search)

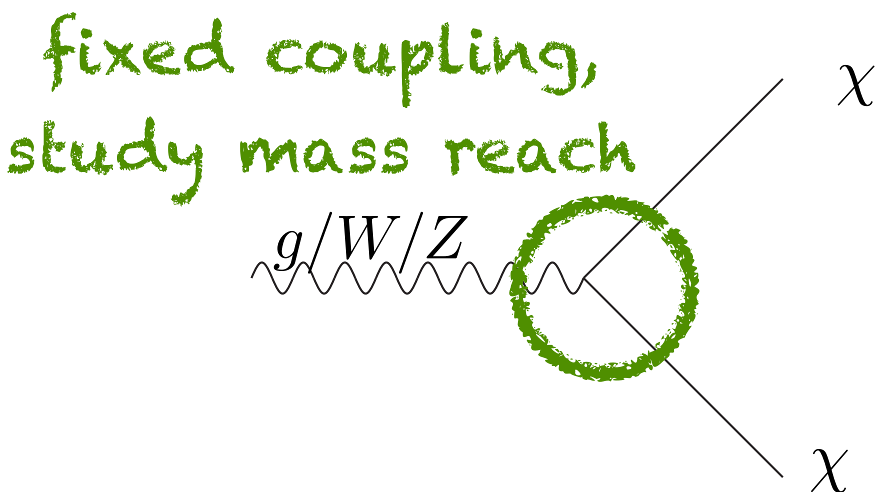
Simplified Model Approach for LHC Pheno

(**YC** and Shuve, 2014)

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

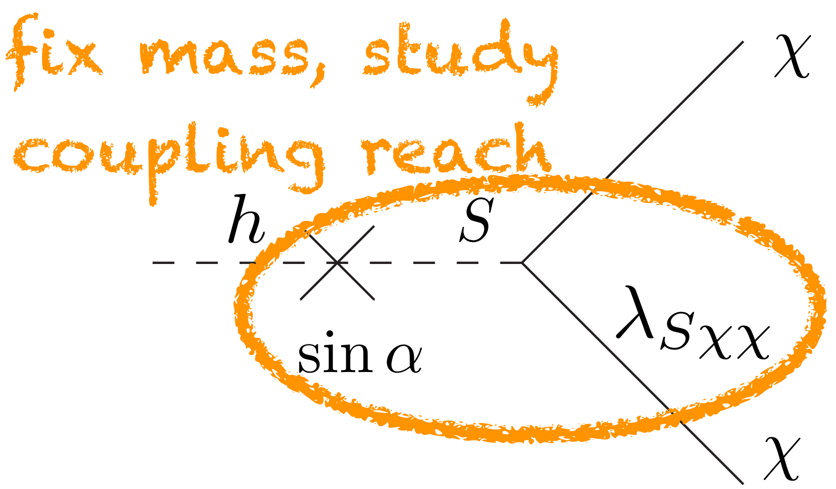
Charged under SM gauge interactions:

wino/gluino-like (states in interference loop)



Higgs portal:

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



- Classify decay modes (unlike DM search)

Baryon number violating:

$$\chi \to u_i d_j d_k$$

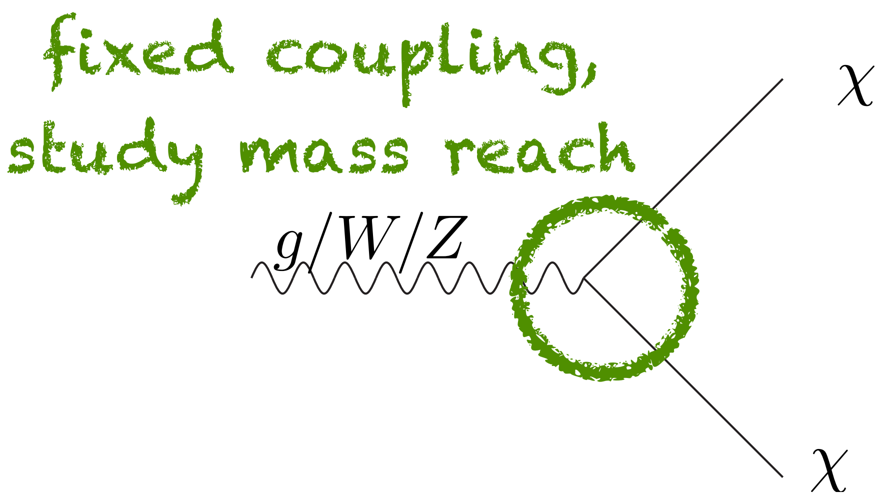
Simplified Model Approach for LHC Pheno

(**YC** and Shuve, 2014)

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

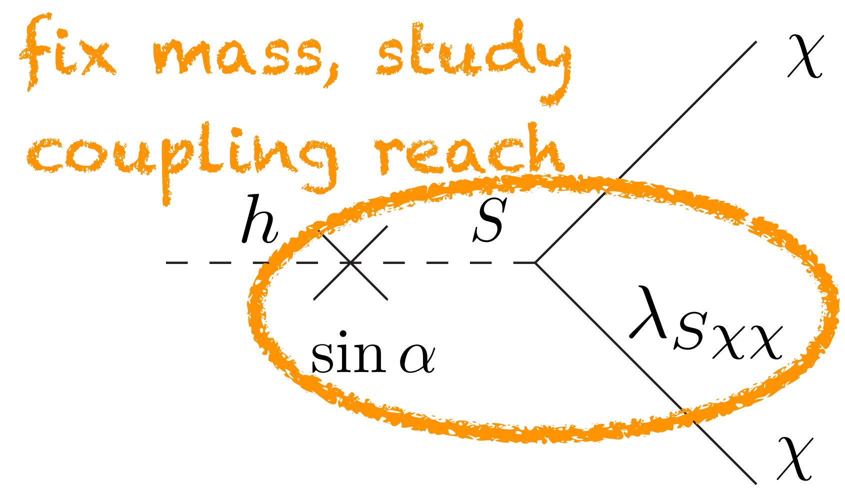
Charged under SM gauge interactions:

wino/gluino-like (states in interference loop)



Higgs portal:

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



- Classify decay modes (unlike DM search)

Baryon number violating:

$$\chi \to u_i d_j d_k$$

Lepton number violating:

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

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

Recast Existing LHC Searches

- Focus on displaced decay in tracking volume

Near lower bound $c\tau_\chi \gtrsim \mathrm{mm}$, better sensitivity to wide lifetime range, easier to model with theorists' tools!

(decay in other parts of detector important too!)

Recast Existing LHC Searches

- Focus on displaced decay in tracking volume

  Near lower bound $c\tau_\chi \gtrsim \mathrm{mm}$, better sensitivity to wide lifetime range, easier to model with theorists' tools!

  (decay in other parts of detector important too!)

- 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 + tracks

ATLAS-CONF-2013-092

Recast Existing LHC Searches

- Focus on displaced decay in tracking volume

  Near lower bound $c\tau_\chi \gtrsim \mathrm{mm}$, better sensitivity to wide lifetime range, easier to model with theorists' tools!

  (decay in other parts of detector important too!)

- 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 + tracks

ATLAS-CONF-2013-092

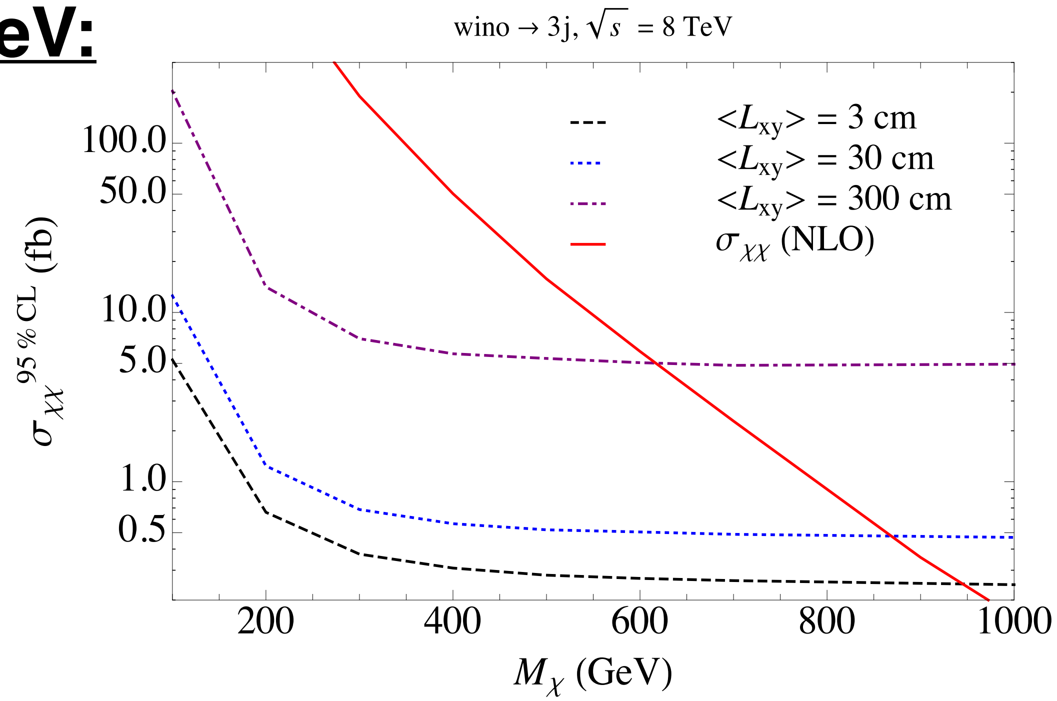
- **Goal of our analysis:**
  - What is the coverage for our simplified models based on benchmarks chosen by the collaborations?
  - What advice can we provide for general experimental improvement?

Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:

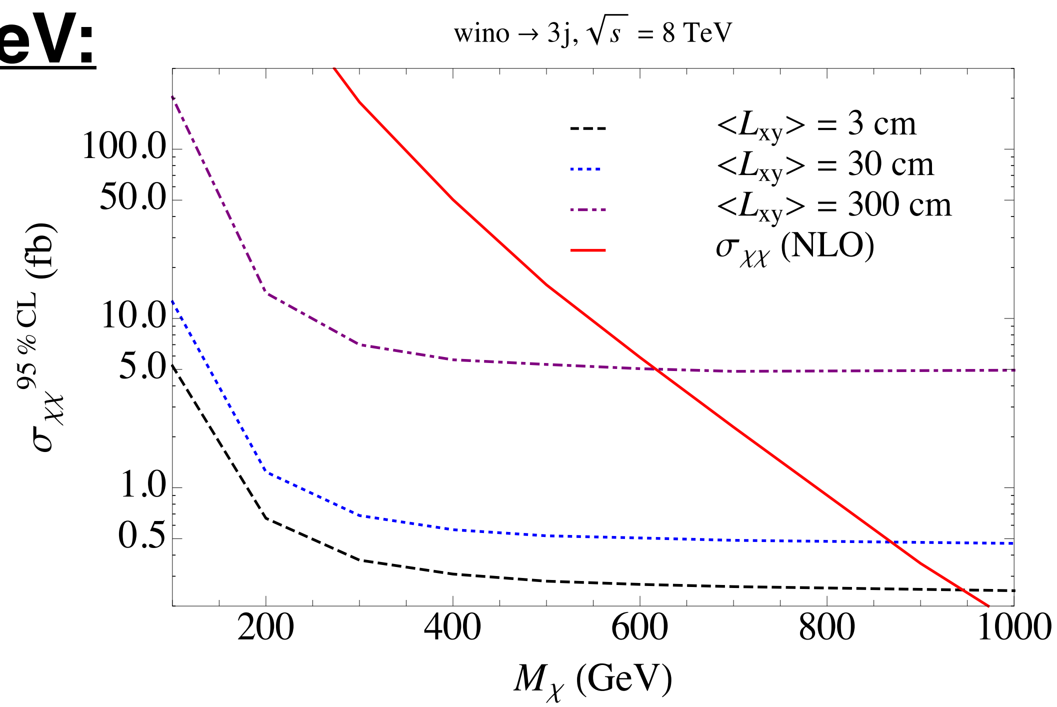


Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:



singlet-like (Higgs portal)

We studied a challenging case:

M_χ = 150 GeV, moderately off-shell!

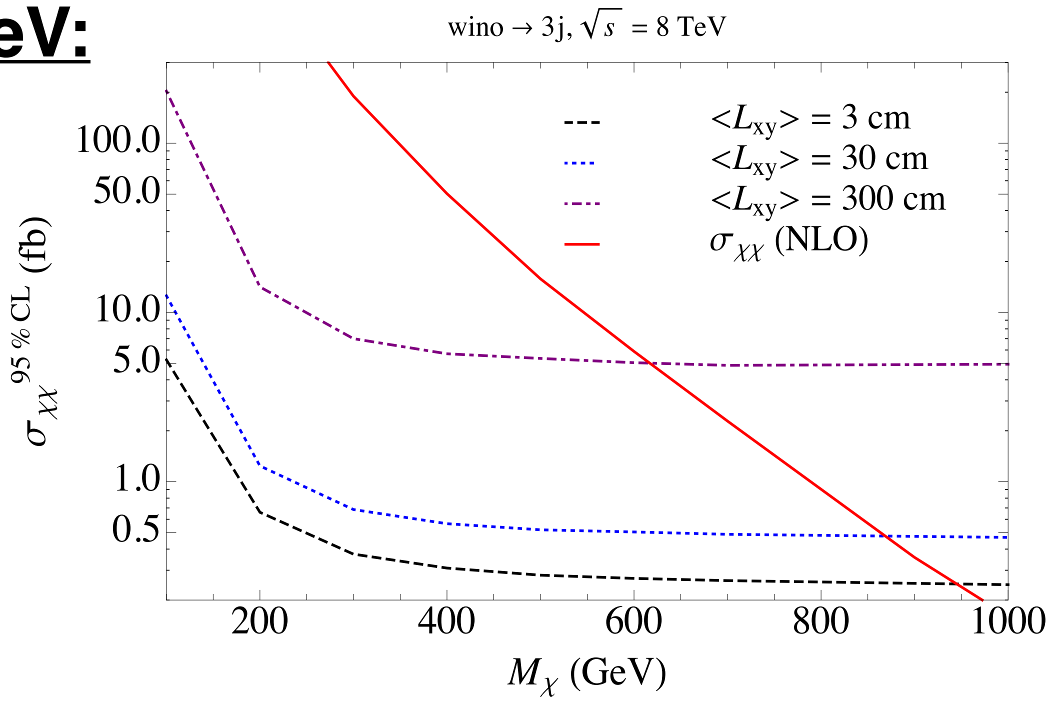
No bound @ 8 TeV 20 fb^{-1}!

Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:



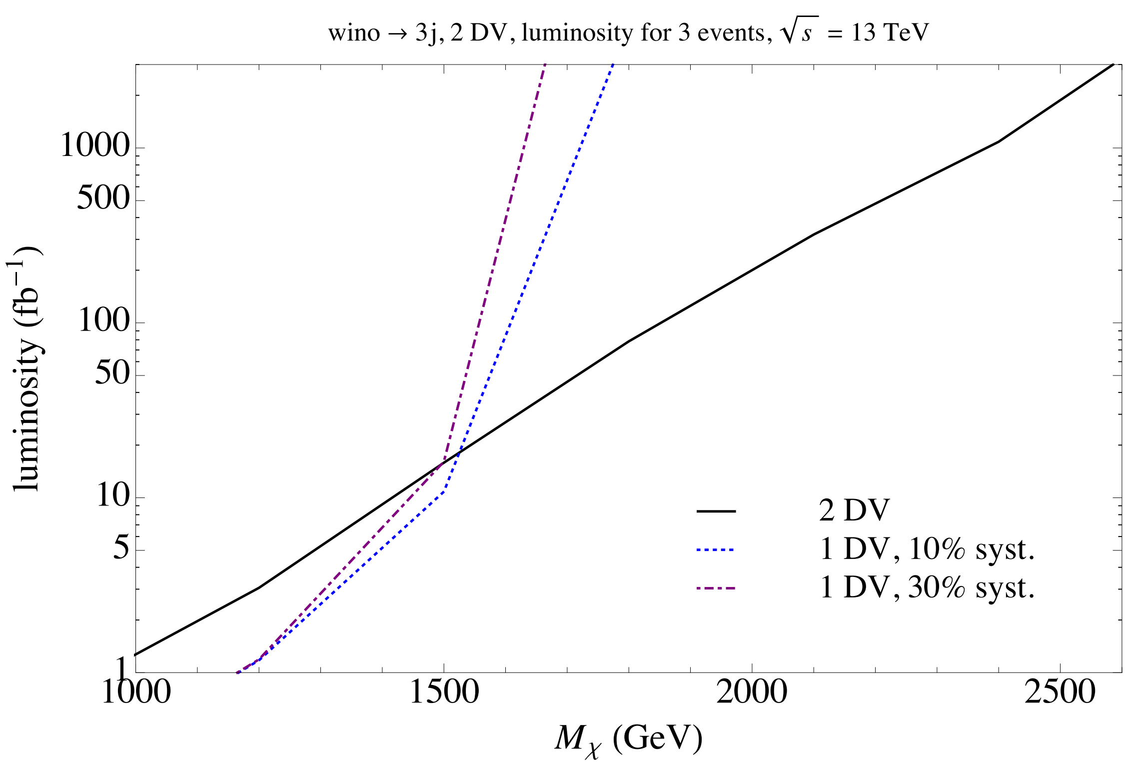
singlet-like (Higgs portal)

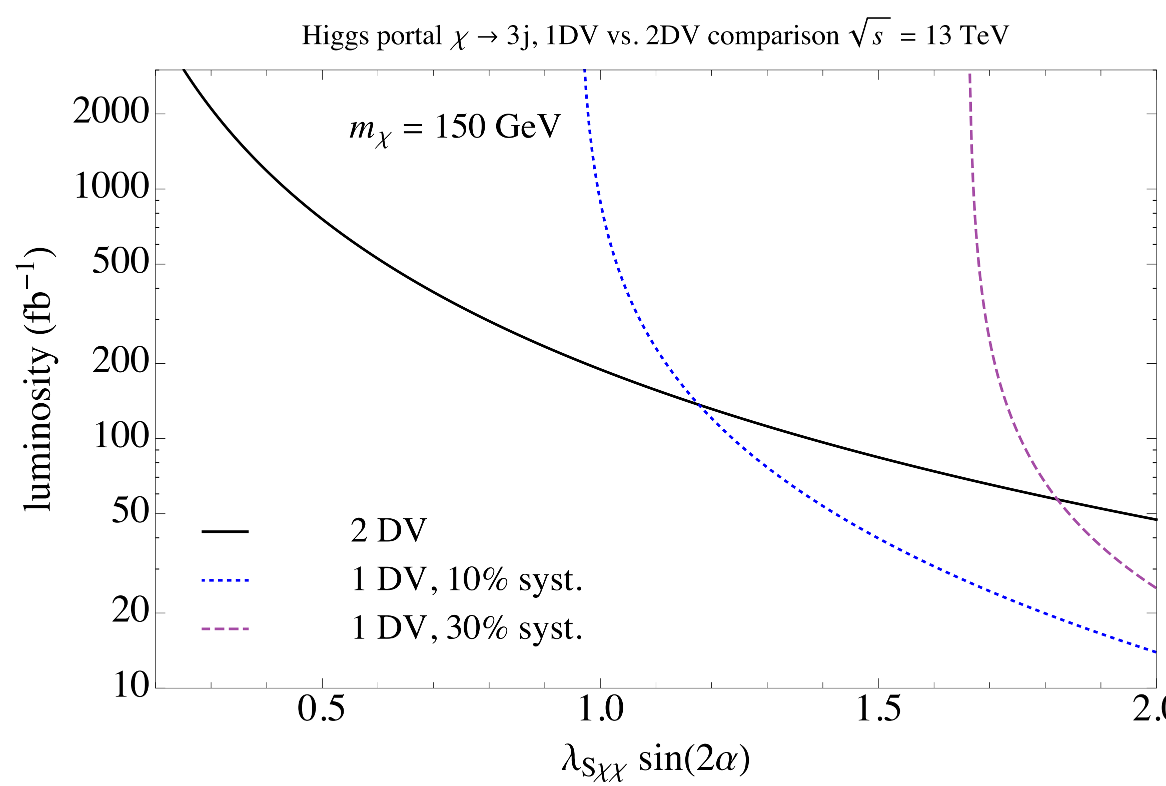
We studied a challenging case:
M_χ = 150 GeV, moderately off-shell!

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

13 TeV:

L_{xy} = 3 cm



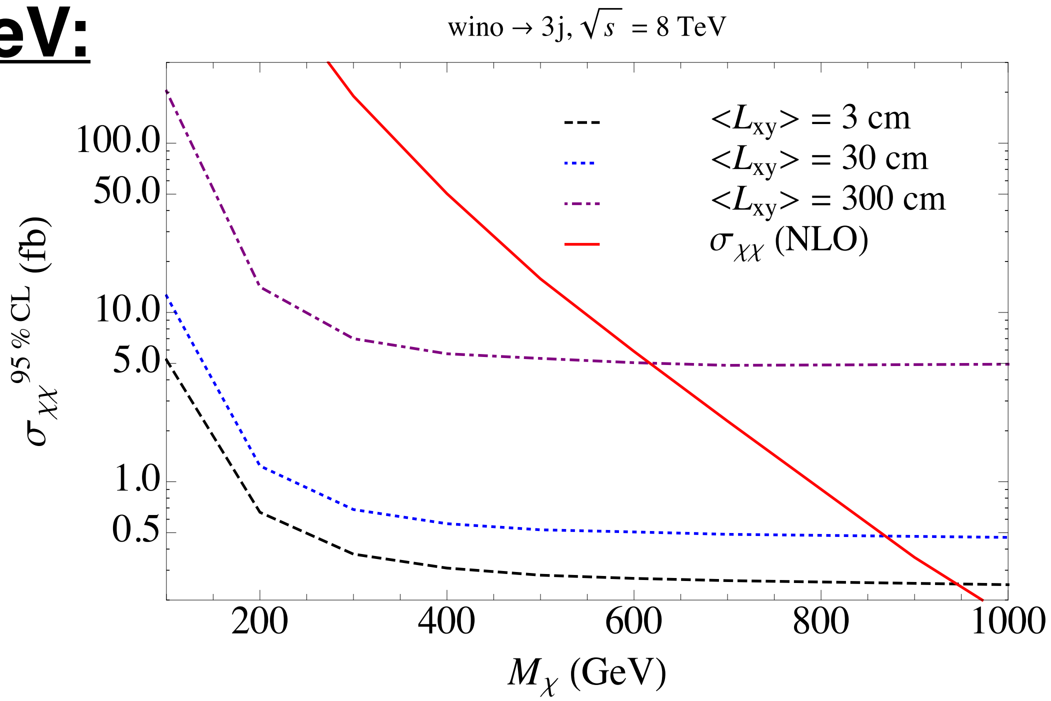


Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:



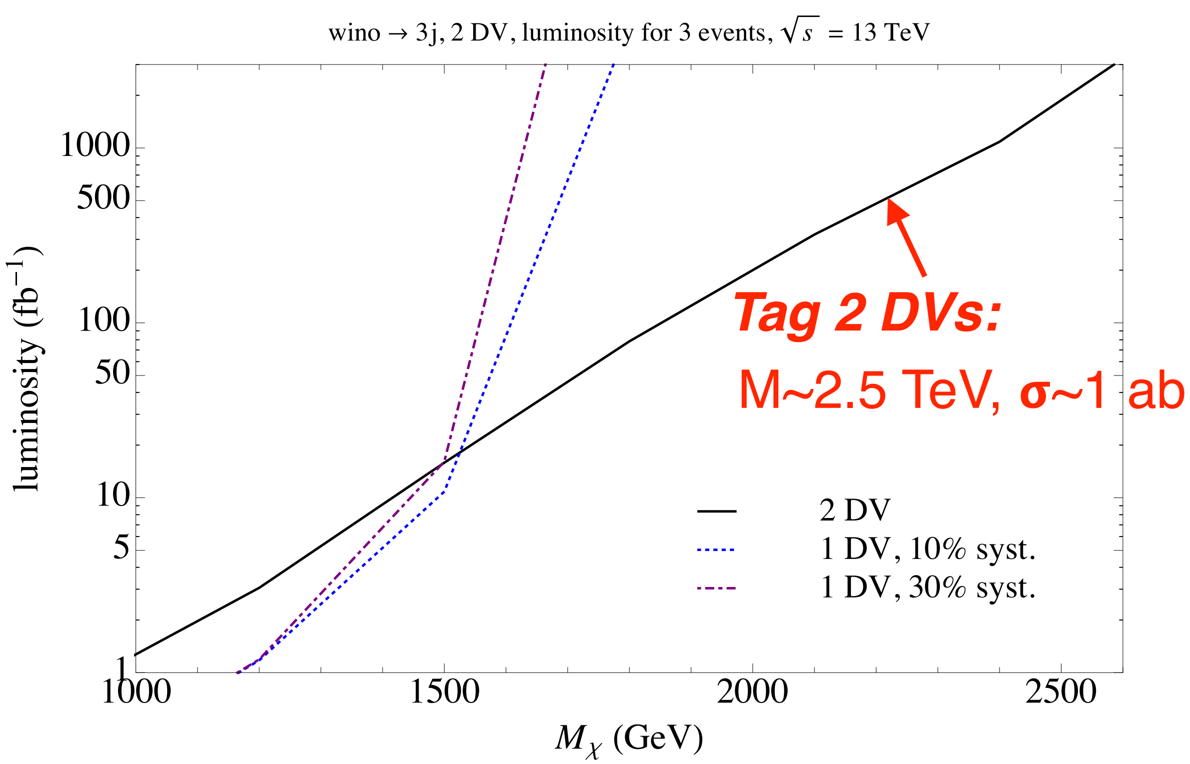
singlet-like (Higgs portal)

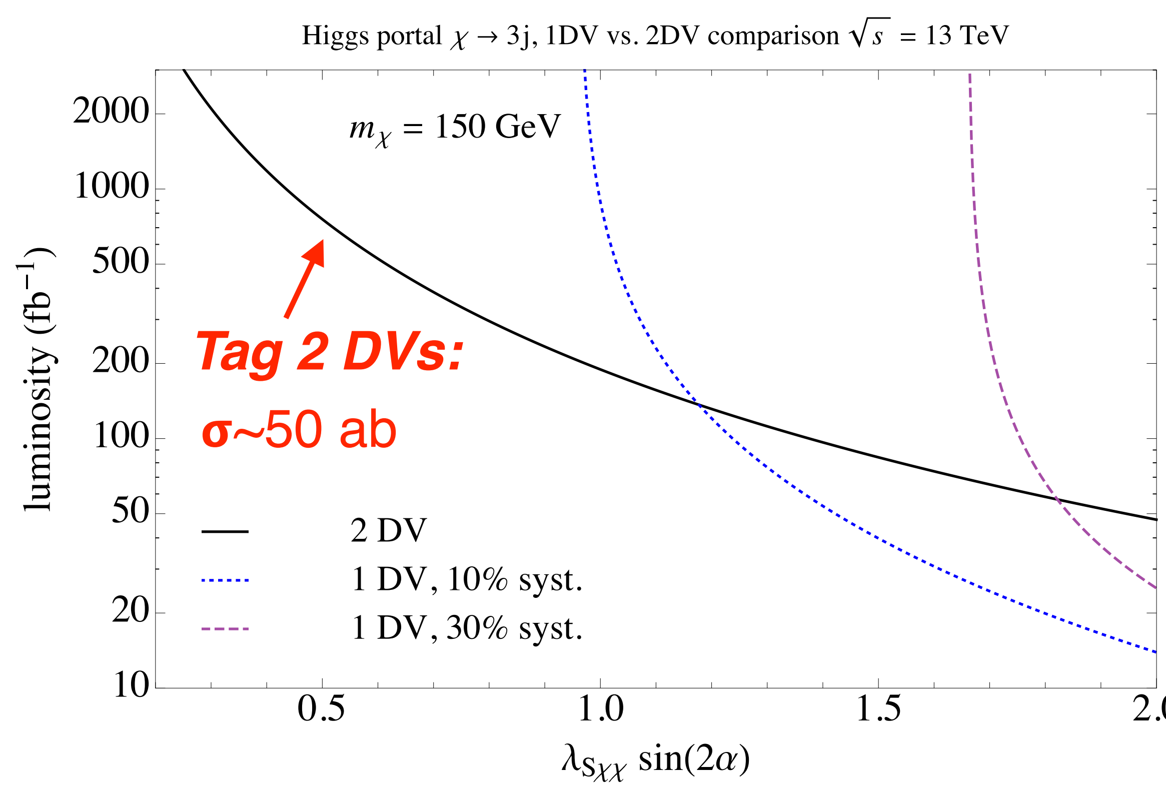
We studied a challenging case:
M_χ = 150 GeV, moderately off-shell!

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

13 TeV:

L_{xy} = 3 cm



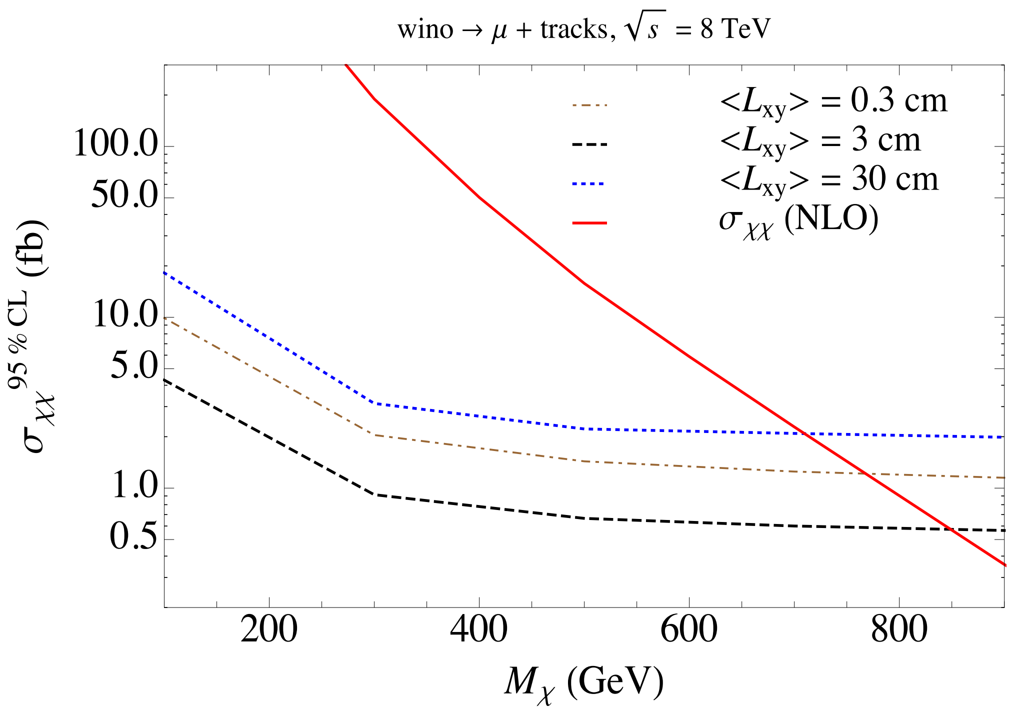


Displaced muon + Tracks

ATLAS-CONF-2013-092

wino

8 TeV

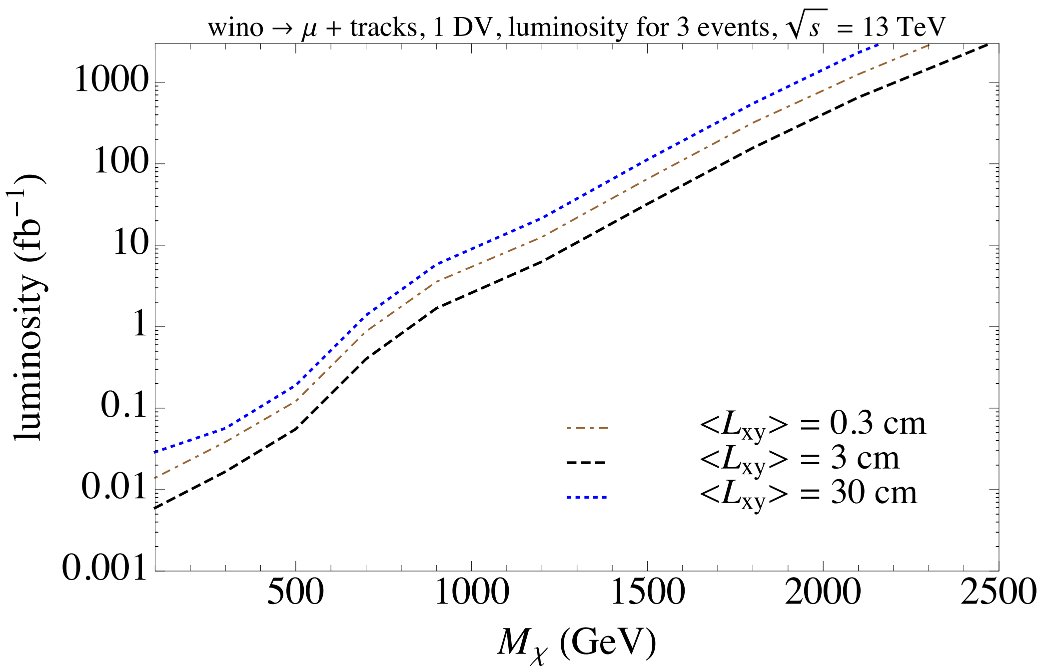


13 TeV:

Tag 1 DV

M~2.5 TeV

(lower bkg than all-hadronic)

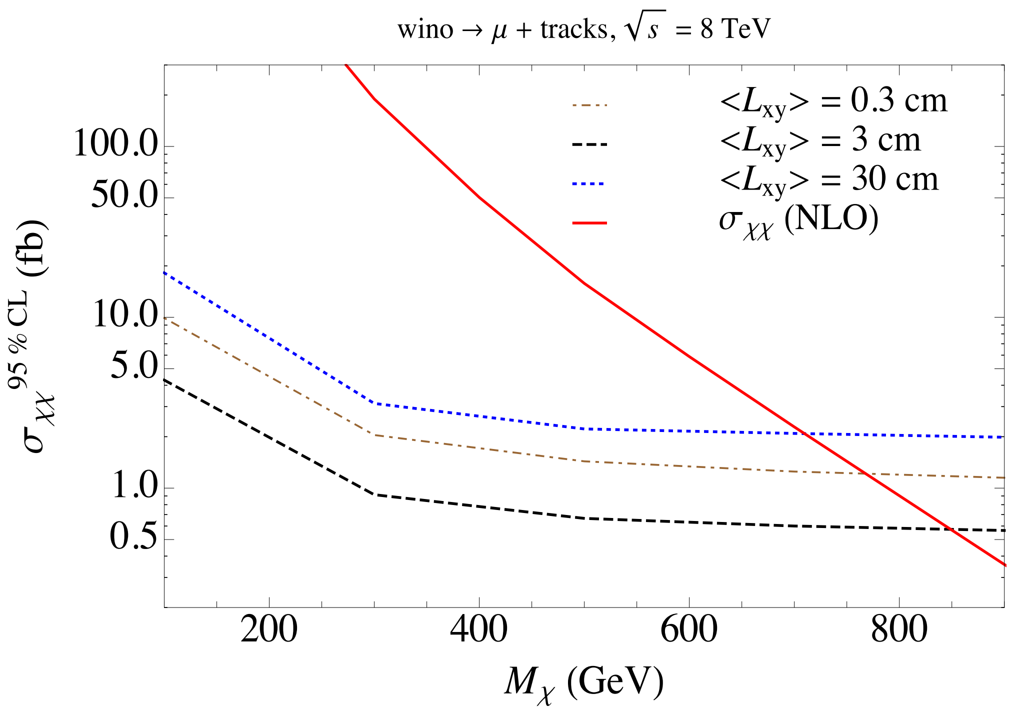


Displaced muon + Tracks

ATLAS-CONF-2013-092

wino

8 TeV

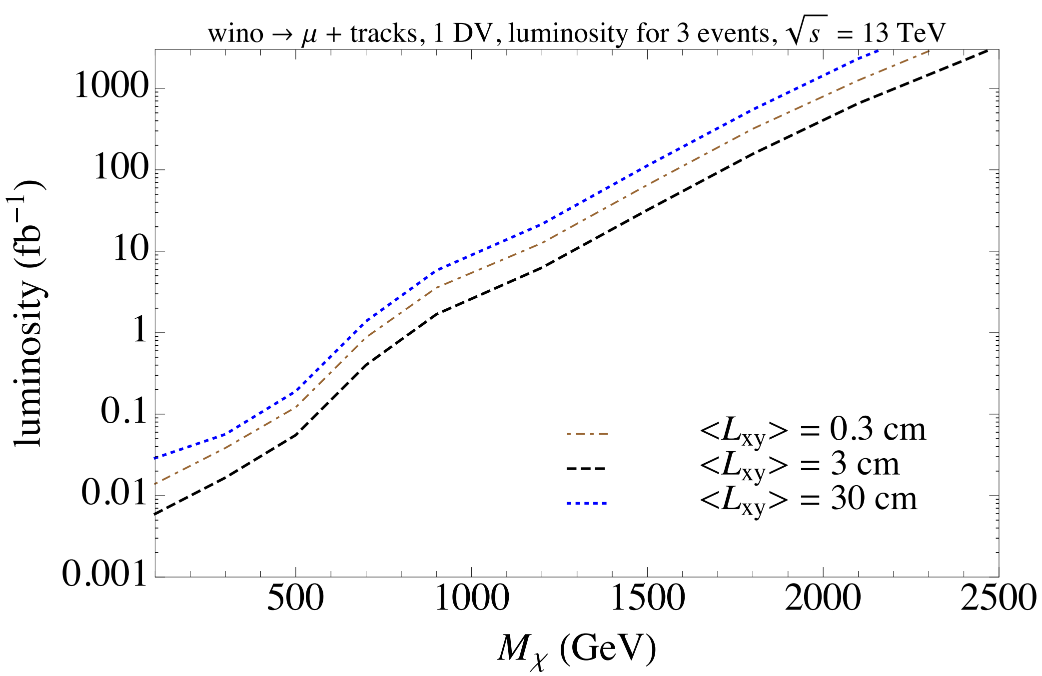


13 TeV:

Tag 1 DV

M~2.5 TeV

(lower bkg than all-hadronic)

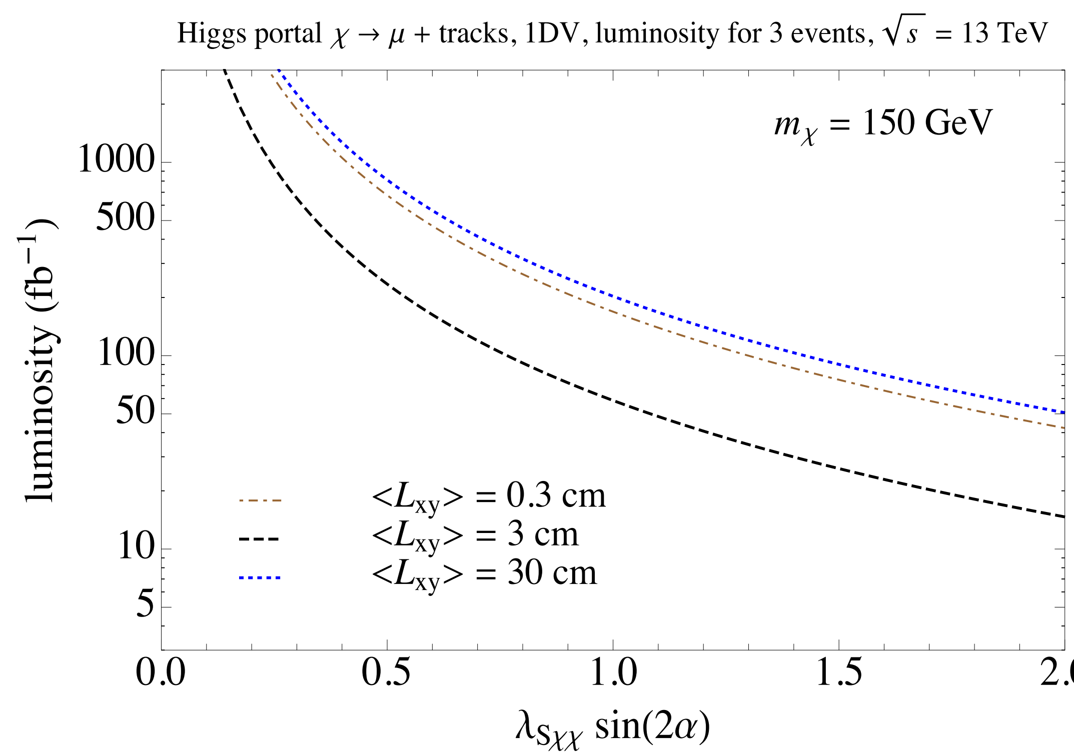


singlet (Higgs portal)

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

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

- 13 TeV: σ_S~50 ab for L_{xy}~1 cm (Tag 1 DV)



Opportunities for CLIC?

— Some Preliminary Thoughts

LHC has its limitations for DV searches,
there are opportunities for CLIC!

- **A general challenge at the LHC**: trigger for low mass all-hadronic DV events (overwhelmed by large QCD background at a hadron collider!)
  e.g. *L1* H_T trigger at 13 TeV: $H_T \gtrsim$ *500 GeV* ➜ a big loss of signals from Higgs-portal production

Opportunities for CLIC?

— *Some Preliminary Thoughts*

LHC has its limitations for DV searches,
there are opportunities for CLIC!

- **A general challenge at the LHC**: trigger for low mass all-hadronic DV events (overwhelmed by large QCD background at a hadron collider!)
  e.g. *L1* H_T trigger at 13 TeV: $H_T \gtrsim 500$ *GeV* ➜ a big loss of signals from Higgs-portal production

— This is particularly relevant for WIMP BG!

Out of equilibrium decay of low mass WIMP ($\lesssim$100 GeV) typically occurs well after EW phase transition when sphaleron process ($\Delta L \leftrightarrow \Delta B$) shuts off ➜

Has to be B-violating decay, i.e. hadronic final states!

Opportunities for CLIC?

— Some Preliminary Thoughts

- **Another general challenge at the LHC**: ultra long-lived particles (simply MET? motivate MATHUSLA…)

— **Relevance for WIMP BG**: wider range of lifetimes (from weak scale to BBN), light WIMPs typically decay later

Opportunities for CLIC?

— Some Preliminary Thoughts

- **Another general challenge at the LHC**: ultra long-lived particles (simply MET? motivate MATHUSLA…)

— **Relevance for WIMP BG**: wider range of lifetimes (from weak scale to BBN), light WIMPs typically decay later

- Optimizing the opportunity at the LHC to overcome/ relieve these challenges: worthwhile ongoing effort *(e.g. work in progress: YC with Joglekar, Shuve, Tsai)*

Opportunities for CLIC?

— Some Preliminary Thoughts

- **Another general challenge at the LHC**: ultra long-lived particles (simply MET? motivate MATHUSLA…)

— **Relevance for WIMP BG**: wider range of lifetimes (from weak scale to BBN), light WIMPs typically decay later

- Optimizing the opportunity at the LHC to overcome/ relieve these challenges: worthwhile ongoing effort *(e.g. work in progress: YC with Joglekar, Shuve, Tsai)*

- **CLIC has a clear edge vs. LHC!** Lepton collider, much cleaner for hadronic states, should be much easier to trigger low-mass events

Opportunities for CLIC?

— Some Preliminary Thoughts

Examples of CLIC's potential advantages over LHC:

- Singlet-like WIMP: limited sensitivity even after HL-LHC
  - Hadronically-decaying light WIMPs produced from light Z'
  - Hadronically-decaying light WIMPs produced from *H*-portal

    (caveat: the heavier Higgs in the S-H system may be easier to probe with the LHC)
- Wino-like WIMP: HL-LHC has excellent coverage for 1.5 TeV (or higher) mass wino with L_{xy}~1 cm, hard to beat; but not for much longer L_{xy}!

  - Advantages with CLIC: MET+mono-γ, suppressed bkg from jet punch-through for decay in μ-spectrometer

Dedicated consideration/design with CLIC certainly helps!

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 @ collider experiments today! (cf. WIMP DM search)

- **WIMP baryogenesis:** a motivated example, new mechanism addressing Ω_B (+) $\Omega_B \sim \Omega_{DM}$, natural embedding in SUSY

- Good reaches at HL-LHC for certain models/parameter regions, but still great potential for improvement with CLIC!