Dark Matter and Baryon Asymmetry

- Probing the Cosmic Origin of Matter at the LHC

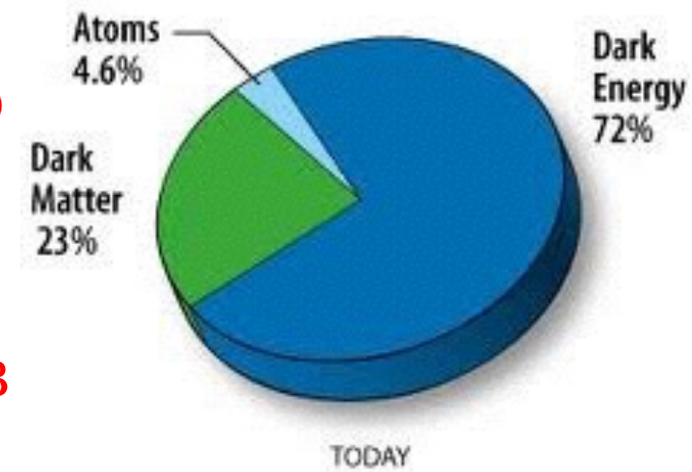
Yanou Cui

UC Riverside

DM@LHC workshop,
UCI, Apr 3 2017

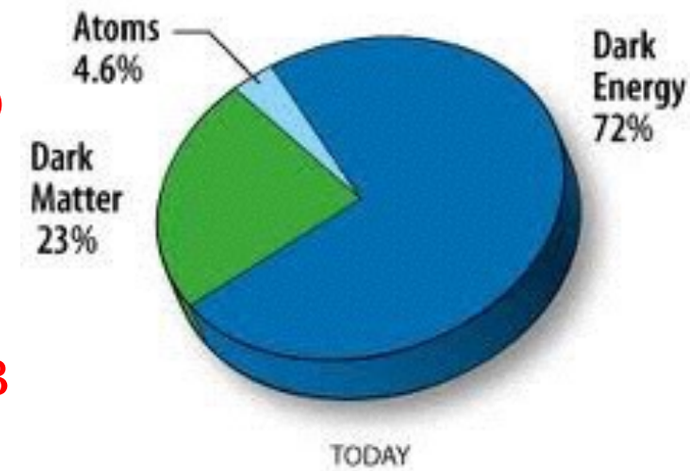
Probing the Origin of Matter with the LHC?

- **Baryon (atomic matter):** $\Omega_B \approx 4\%$
- **Dark Matter:** $\Omega_{\rm DM} \approx 23\%$
- **Coincidence/Similarity:** $\Omega_{\rm DM} \sim \Omega_{\rm B}$



Probing the Origin of Matter with the LHC?

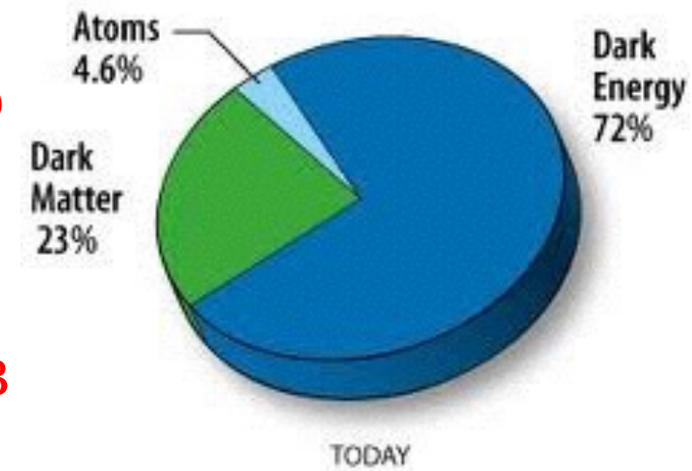
- **Baryon (atomic matter):** $\Omega_B \approx 4\%$
- **Dark Matter:** $\Omega_{\rm DM} \approx 23\%$
- **Coincidence/Similarity:** $\Omega_{\rm DM} \sim \Omega_{\rm B}$



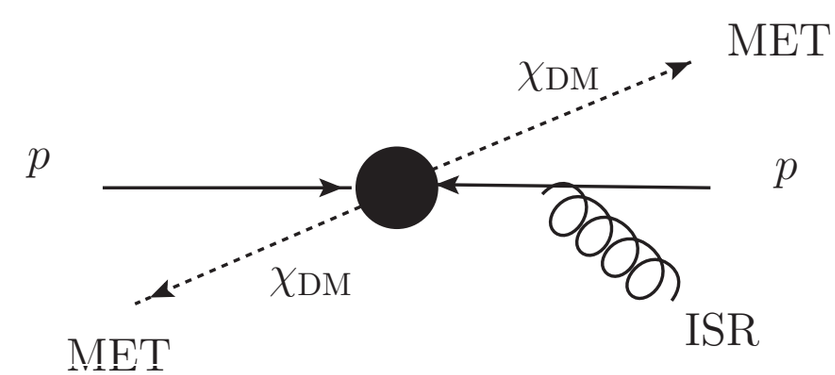
- Familiar/well-studied case: WIMP dark matter ($\Omega_{\rm DM}$)
  - Stable, mass ~O(10-100) GeV, can be produced within E_{LHC} =14 TeV
  - Pair produced (Z_2),
  - Invisible, MET + X

Probing the Origin of Matter with the LHC?

- **Baryon (atomic matter):** $\Omega_B \approx 4\%$
- **Dark Matter:** $\Omega_{\rm DM} \approx 23\%$
- **Coincidence/Similarity:** $\Omega_{\rm DM} \sim \Omega_{\rm B}$

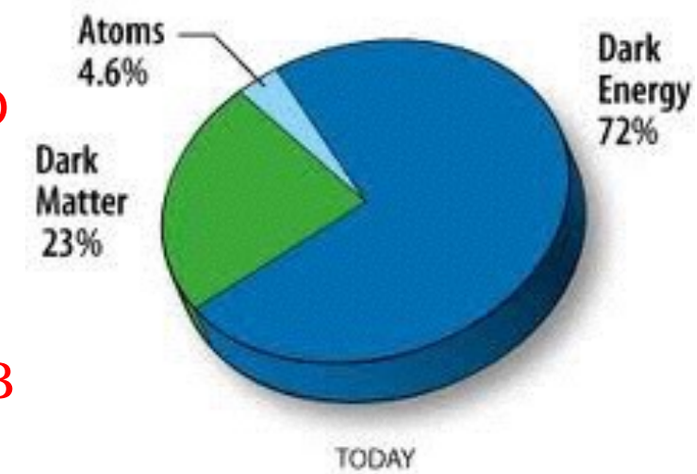


- Familiar/well-studied case: WIMP dark matter ($\Omega_{\rm DM}$)
  - Stable, mass ~O(10-100) GeV, can be produced within E_{LHC} =14 TeV
  - Pair produced (Z_2),
  - Invisible, MET + X

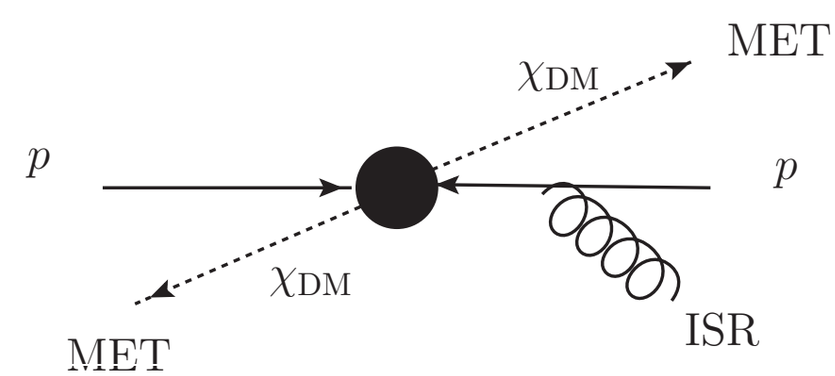


Probing the Origin of Matter with the LHC?

- **Baryon (atomic matter):** $\Omega_B \approx 4\%$
- **Dark Matter:** $\Omega_{\rm DM} \approx 23\%$
- **Coincidence/Similarity:** $\Omega_{\rm DM} \sim \Omega_{\rm B}$



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



- *Direct* test for $\Omega_{\rm B}$, $\Omega_{\rm B} \sim \Omega_{\rm DM}$ @LHC?

$$\Omega_{\rm DM} \sim \Omega_{\rm B} \quad (\Omega_{\rm DM}/\Omega_{\rm B} \approx 5)$$

— A mere cosmic coincidence or deep connection?

- DM and atomic matter almost decoupled today!
- $\Omega_{\rm B}$, $\Omega_{\rm DM}$ often explained by separate physics mechanisms

⇨ *Naive expectation*: evolve independently, drastically different today!

$$\Omega_{\rm DM} \sim \Omega_{\rm B} \quad (\Omega_{\rm DM}/\Omega_{\rm B} \approx 5)$$

— A mere cosmic coincidence or deep connection?

- DM and atomic matter almost decoupled today!
- Ω_B, Ω_{DM} often explained by separate physics mechanisms

⇨ *Naive expectation*: evolve independently, drastically different today!

Candidate theories addressing the "coincidence":

- *Asymmetric* Dark Matter (Kaplan 1982; Nussinov 1985; Kaplan, Luty, Zurek 2009…): no WIMP miracle, asymmetry to be explained

$$\Omega_{\rm DM} \sim \Omega_{\rm B} \quad (\Omega_{\rm DM}/\Omega_{\rm B} \approx 5)$$

— A mere cosmic coincidence or deep connection?

- DM and atomic matter almost decoupled today!
- Ω_B, Ω_{DM} often explained by separate physics mechanisms

⇨ *Naive expectation*: evolve independently, drastically different today!

Candidate theories addressing the "coincidence":

- *Asymmetric* Dark Matter (Kaplan 1982; Nussinov 1985; Kaplan, Luty, Zurek 2009…): no WIMP miracle, asymmetry to be explained
- Alternatives: compatible with WIMP DM! + new BG mechanism
  - **WIMPy baryogenesis**: BG from WIMP DM freezeout (**YC**, Randall, Shuve 2011)
  - **Baryogenesis from metastable WIMPs** (**YC**, Sundrum 2012)

$$\Omega_{\rm DM} \sim \Omega_{\rm B} \quad (\Omega_{\rm DM}/\Omega_{\rm B} \approx 5)$$

— A mere cosmic coincidence or deep connection?

- DM and atomic matter almost decoupled today!
- Ω_B, Ω_{DM} often explained by separate physics mechanisms

⇨ *Naive expectation*: evolve independently, drastically different today!

Candidate theories addressing the "coincidence":

- *Asymmetric* Dark Matter (Kaplan 1982; Nussinov 1985; Kaplan, Luty, Zurek 2009…): no WIMP miracle, asymmetry to be explained
- Alternatives: compatible with WIMP DM! + new BG mechanism
  - **WIMPy baryogenesis**: BG from WIMP DM freezeout (**YC**, Randall, Shuve 2011)
  - ✓ **Baryogenesis from metastable WIMPs** (**YC**, Sundrum 2012)

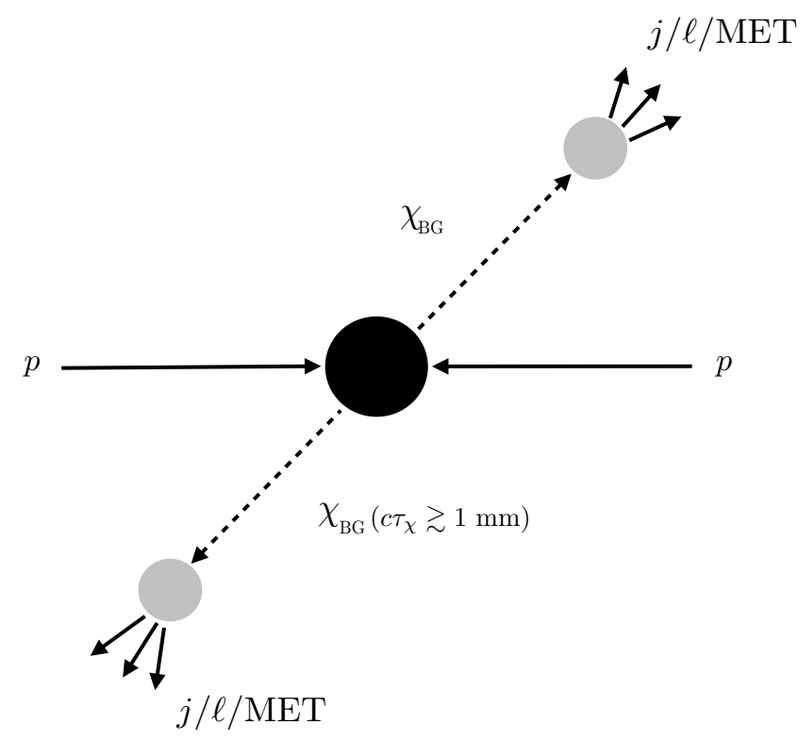
Spectacular signals at the LHC!

Probing the Cosmic Origin of Baryons with Displaced Vertices at the LHC

- **New opportunity**: baryogenesis
  (address Ω_B , possibly + $\Omega_B \sim \Omega_{DM}$)
  - New weak scale <u>metastable</u> particle (e.g. long-lived WIMP) as baryon parent
  - Pair produced (approx. Z_2)
  - Displaced decay to $j/\ell/\mathrm{MET}$ by cosmological conditions!

    Generic event topology

    (analogy to WIMP DM search!)



$L_{dec} \gtrsim 1$ *mm*

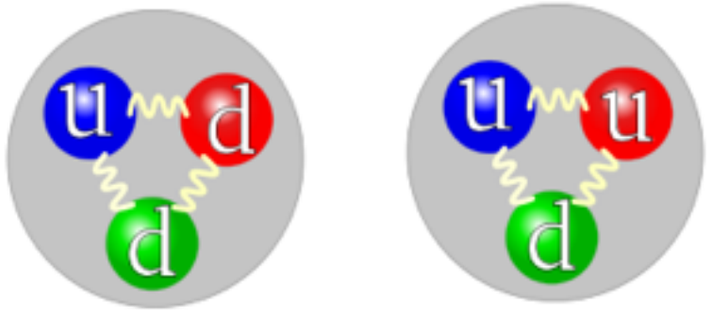
Baryogenesis 101

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?



NEUTRON
Quark structure

PROTON
Quark structure

Baryon $\Omega_B \approx 5\%$

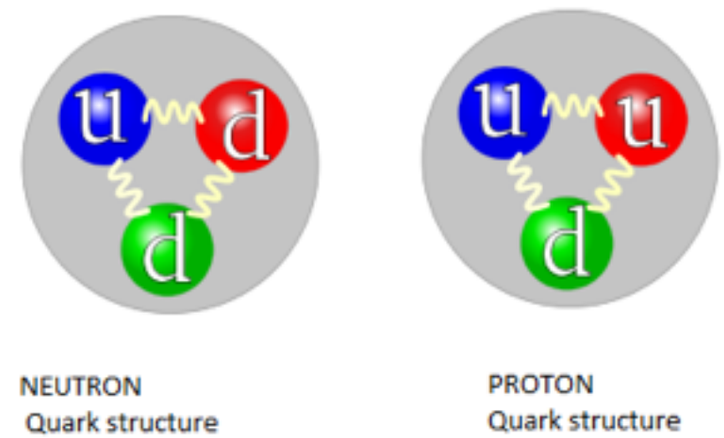
— The Unknown Aspects of the Known

- **Baryon**: proton, neutron ⇨ atoms, stars, ourselves!

- **Where does Ω_B come from?**

= Where do we ourselves come from?

We do not know!



Baryon $\Omega_B \approx 5\%$

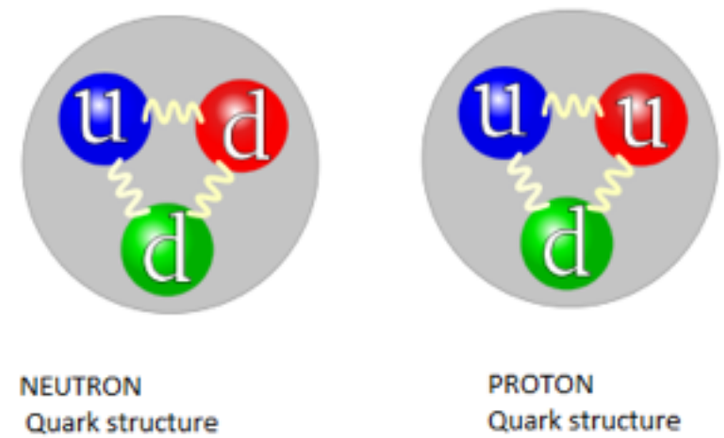
— The Unknown Aspects of the Known

- **Baryon**: proton, neutron ⇨ atoms, stars, ourselves!

- **Where does Ω_B come from?**

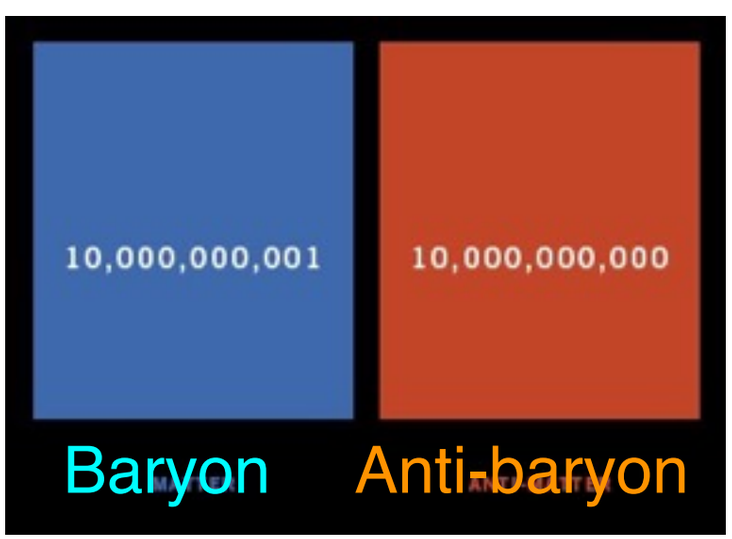
= Where do we ourselves come from?

We do not know!



Initial $B - \bar{B}$ asymmetry

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



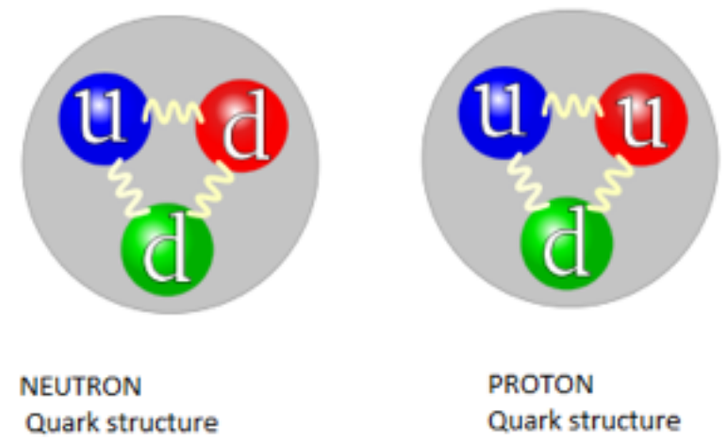
Baryon $\Omega_B \approx 5\%$

— The Unknown Aspects of the Known

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

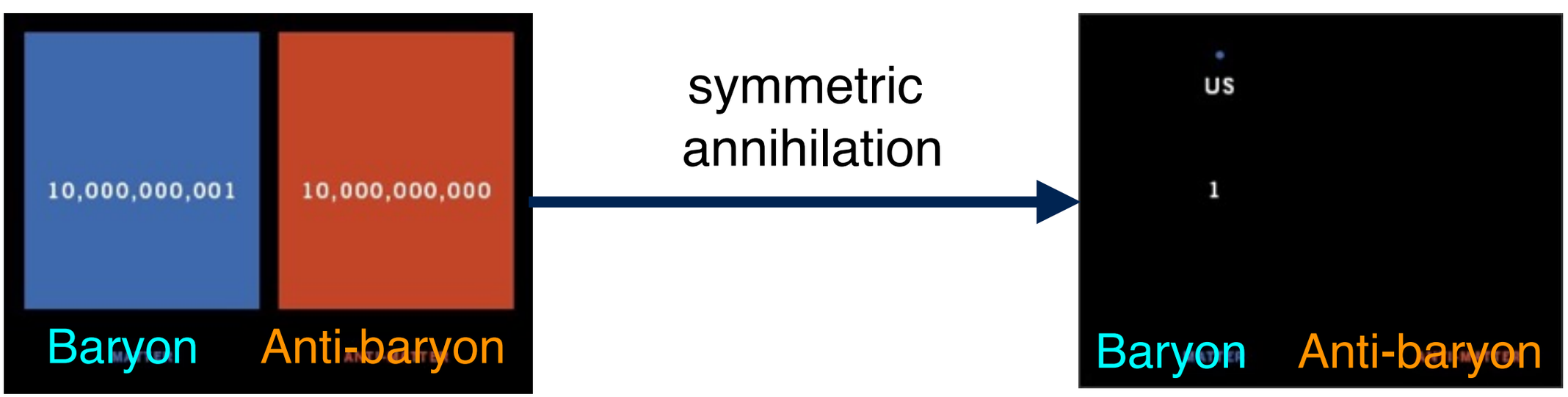
= Where do we ourselves come from?

We do not know!



Initial $B - \bar{B}$ asymmetry

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



Baryogenesis

- the Origin of the Baryon Asymmetry

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

$B - \bar{B}$ asymmetry

Baryogenesis

- the Origin of the Baryon Asymmetry

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

$B - \bar{B}$ asymmetry

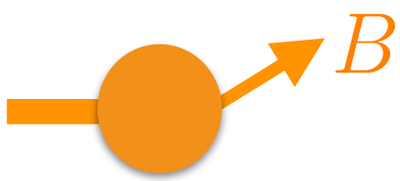
Baryogenesis

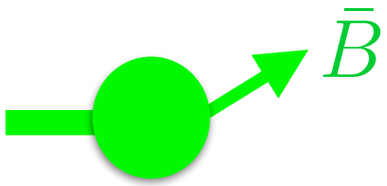
Sakharov Conditions (1967):

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

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

Baryogenesis

Sakharov Conditions (1967):

- **Require baryon number violation**

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

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

- **Require departure from equilibrium!**

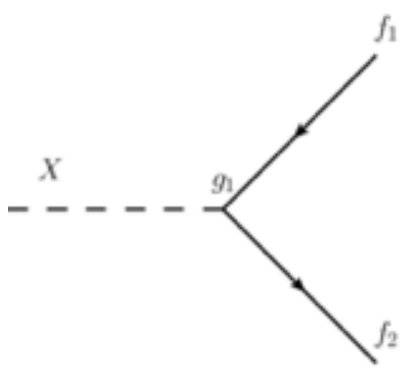
Thermal equilibrium + CPT symmetry

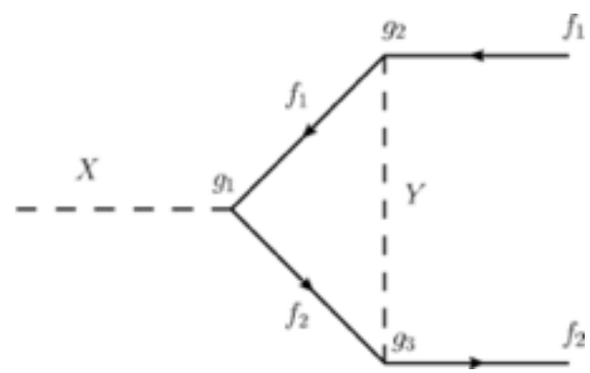
$$n_B^{\rm eq} = n_{\bar{B}}^{\rm eq}, \quad \boxed{\langle B \rangle_{\rm eq} = 0}$$

Baryogenesis from Out-of-Equilibrium Decay

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

- Consider an unstable massive neutral particle χ
- Baryon asymmetry produced in its decay (B-, C-, CP-violating)

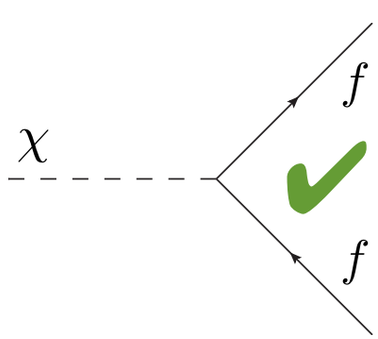


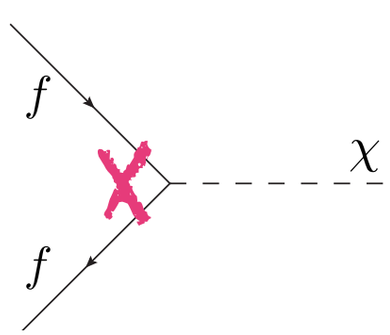


$$\Gamma(\chi \to f) \neq \Gamma(\chi \to \bar{f})$$

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

- 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

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

Baryogenesis from Out-of-Equilibrium Decay

☞ **Out-of-equilibrium decay** → Sakharov conditions ✔

An intriguing observation (**YC**, Sundrum; **YC**, Shuve):

If χ has weak scale mass,

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

Baryogenesis from Out-of-Equilibrium Decay

☞ **Out-of-equilibrium decay** → Sakharov conditions ✔

An intriguing observation (**YC**, Sundrum; **YC**, Shuve):

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

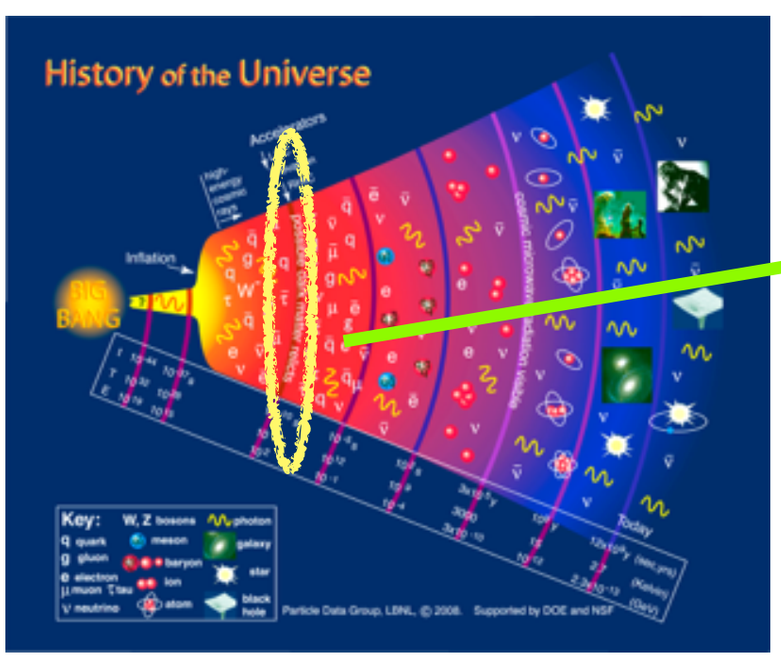
☞ **Out-of-equilibrium decay** → Sakharov conditions ✔

An intriguing observation (**YC**, Sundrum; **YC**, Shuve):

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!

Displaced Vertices at the LHC

- Nearly all SM particles decay **promptly**

  $\lesssim$ 100 μm - 1 mm (= *prompt*)

- Ubiquitous predictions from motivated new physics:

  long-lived particles, **displaced decay vertices** from all part of the detector ($L_{dec} \gtrsim 1\ mm$) (SUSY,twin-Higgs,hidden valley, sterile ν…)

☞ ✦ Spectacular signal! **low SM background**, sensitive to **rare signal events**

Displaced Vertices at the LHC

- Nearly all SM particles decay **promptly**

  $\lesssim$ 100 μm - 1 mm (= *prompt*)

- Ubiquitous predictions from motivated new physics:

  long-lived particles, **displaced decay vertices** from all part of the detector ($L_{dec} \gtrsim 1$ *mm*) (SUSY,twin-Higgs,hidden valley, sterile ν…)

✦ Spectacular signal! **low SM background**, sensitive to **rare signal events**

✦ *But, we could easily miss it entirely!…*

Conventional LHC searches impose "prompt" cuts (reject cosmic ray/mis-reconstruction), may not be triggered on!

Displaced Vertices at the LHC

- Nearly all SM particles decay **promptly**

  $\lesssim$ 100 μm - 1 mm (= *prompt*)

- Ubiquitous predictions from motivated new physics:

  long-lived particles, **displaced decay vertices** from all part of the detector ($L_{dec} \gtrsim 1$ *mm*) (SUSY,twin-Higgs,hidden valley, sterile ν…)

☞ ✦ Spectacular signal! **low SM background**, sensitive to **rare signal events** 

✦ *But, we could easily miss it entirely!…* 

Conventional LHC searches impose "prompt" cuts (reject cosmic ray/mis-reconstruction), may not be triggered on!

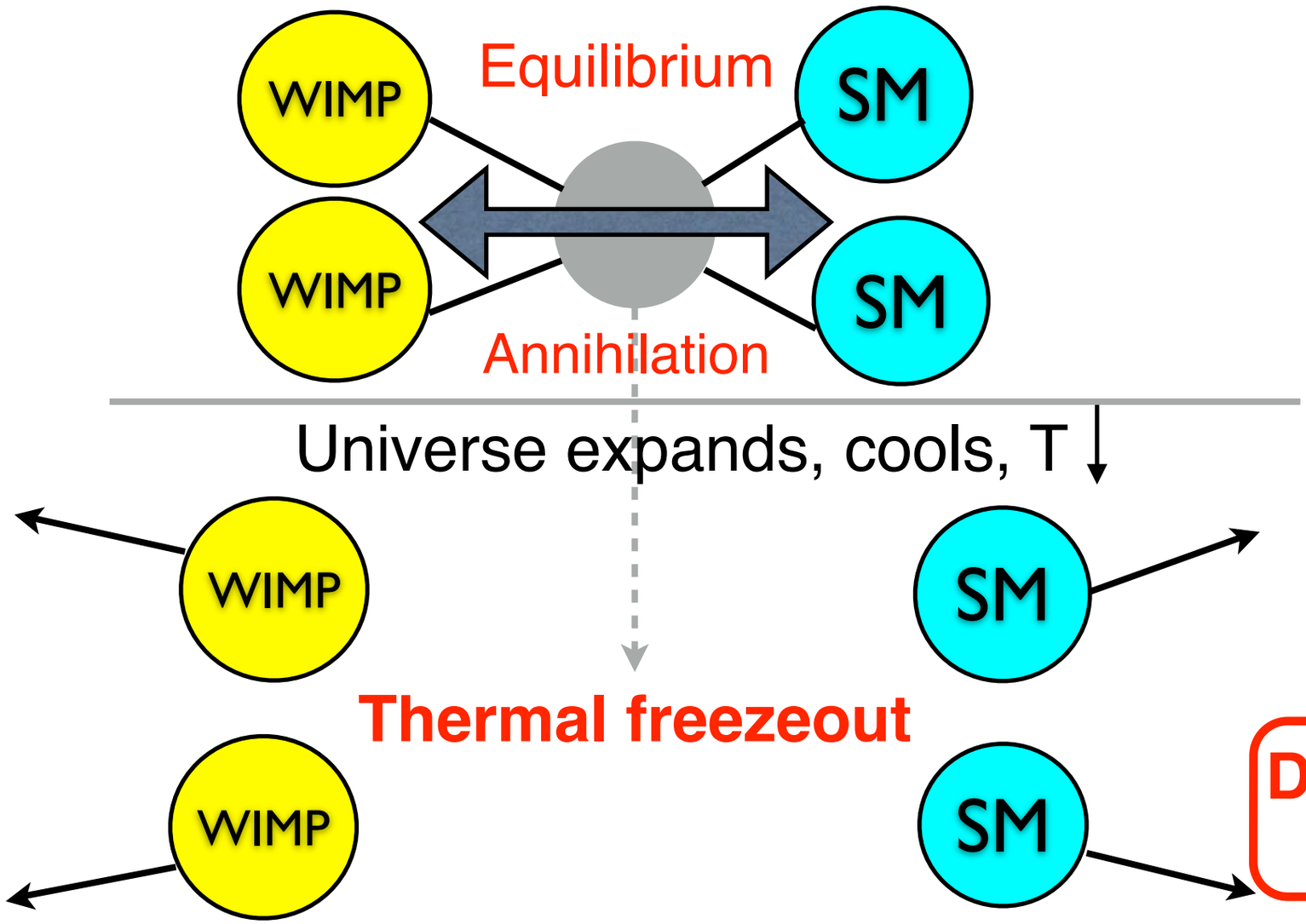
Impressive developments, dedicated studies in the past a few years (experimentalists + theorists)!

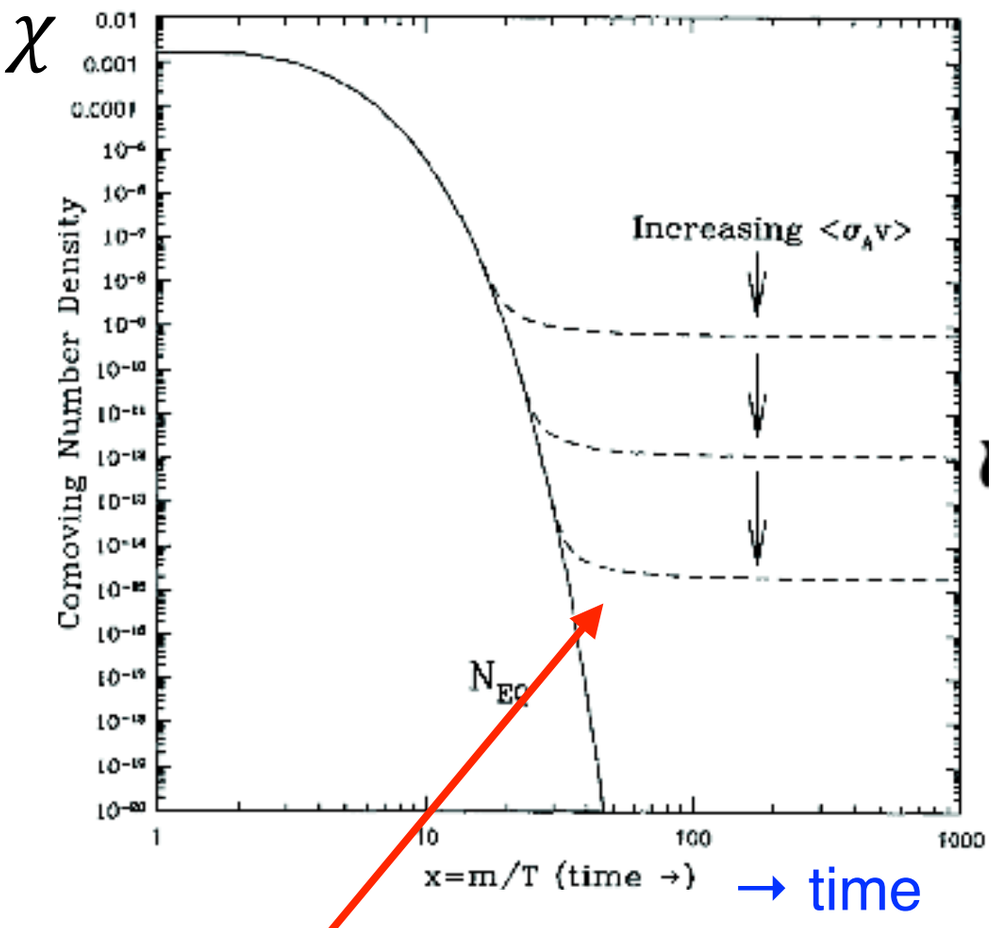
Baryogenesis from WIMPs

— A New Proposal to Address Ω_B, $\Omega_B \sim \Omega_{DM}$

- YC and Raman Sundrum, Phys.Rev. D87 (2013) 11
- YC, JHEP 1312 (2013) 067

· Cosmic Evolution of a <u>stable</u> WIMP χ

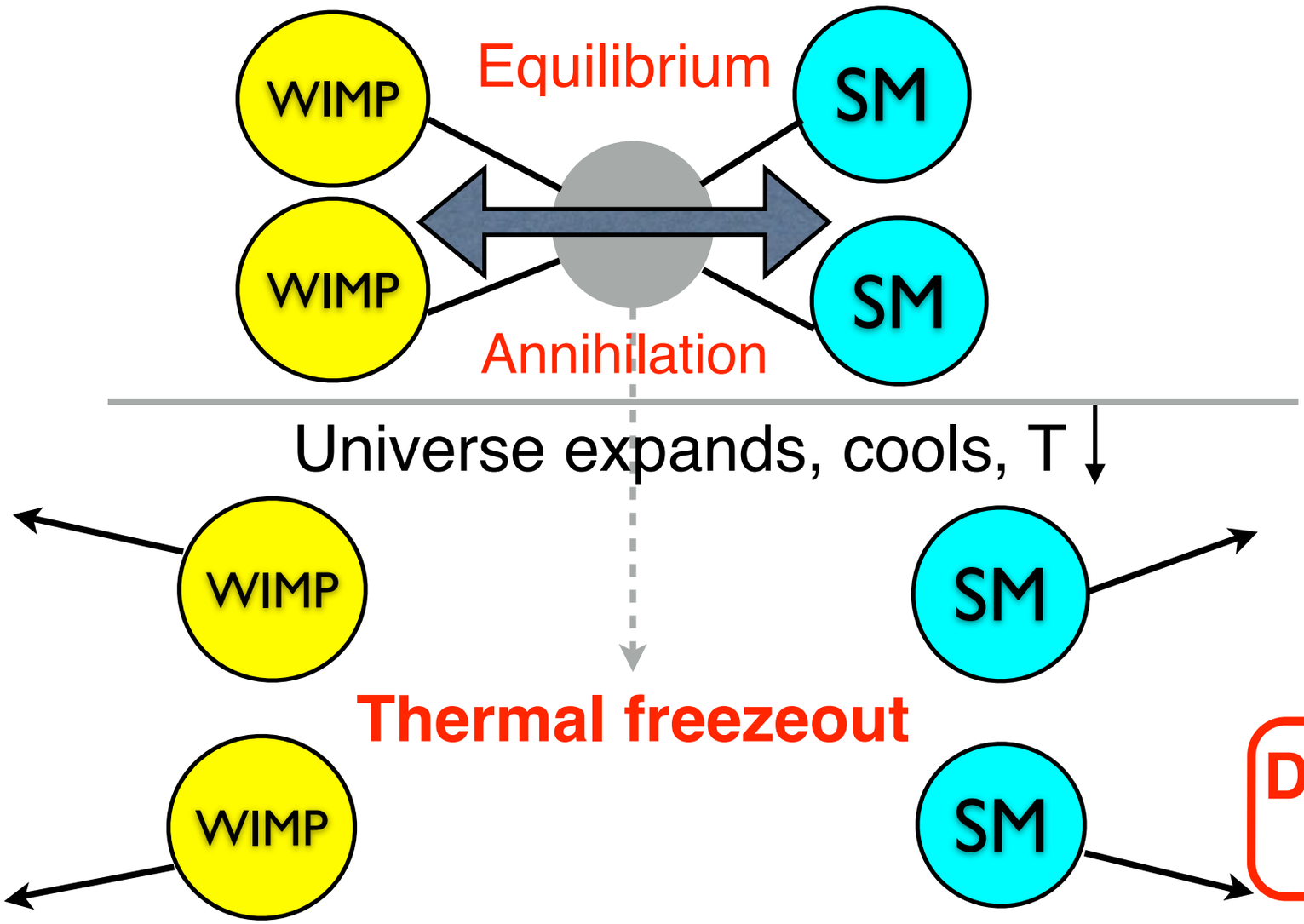


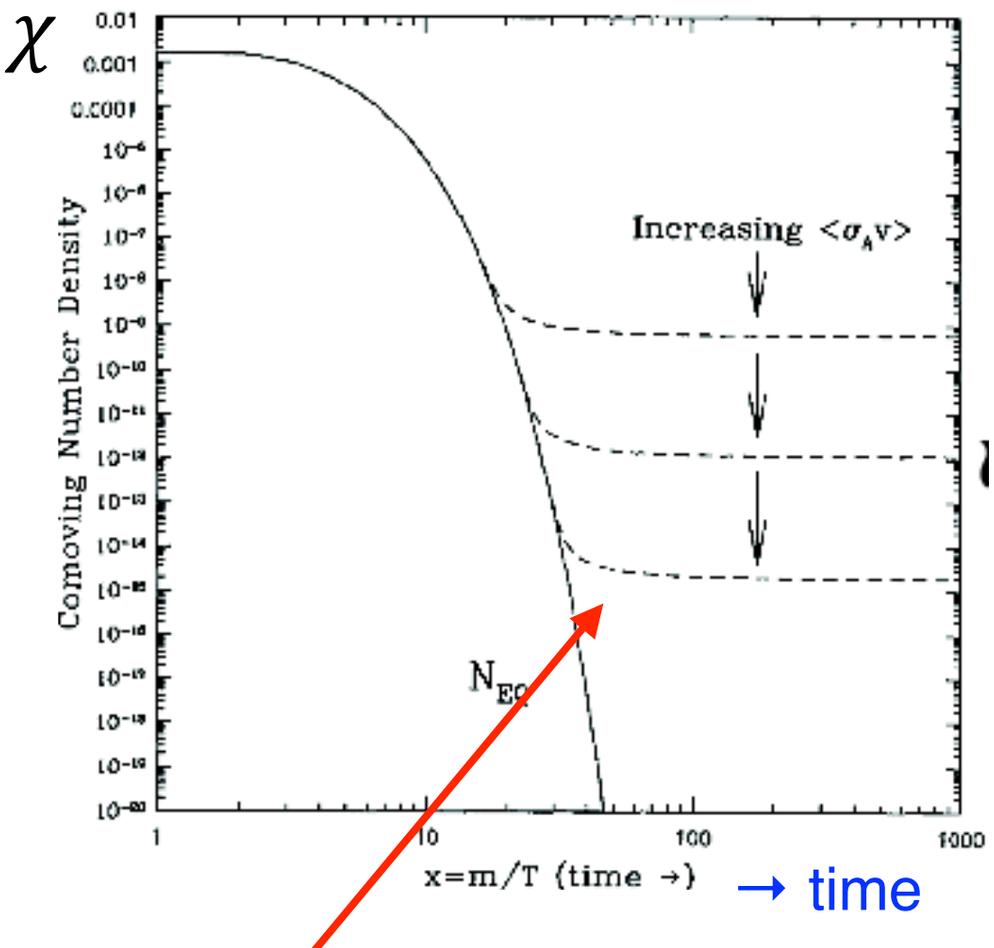


Departure from equilibrium: key to Ω_{WIMP} !

(recall Ω_B?)

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





Departure from equilibrium: key to Ω_{WIMP} !

(recall Ω_B?)

- **Relic abundance:**

$$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1}$$

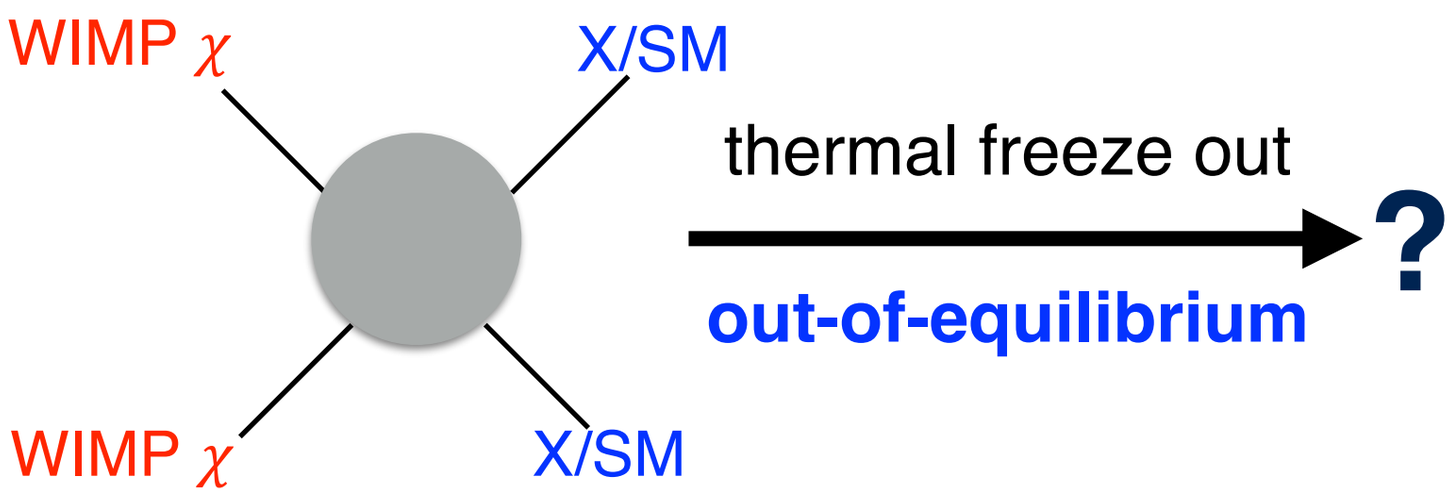
$$\sim 0.1 \left(\frac{G_{\rm Fermi}}{G_\chi} \right)^2 \left(\frac{M_{\rm weak}}{m_\chi} \right)^2$$

☞ **WIMP Miracle!**

WIMP Miracle for Baryons?

- A generalization/variation of WIMP miracle

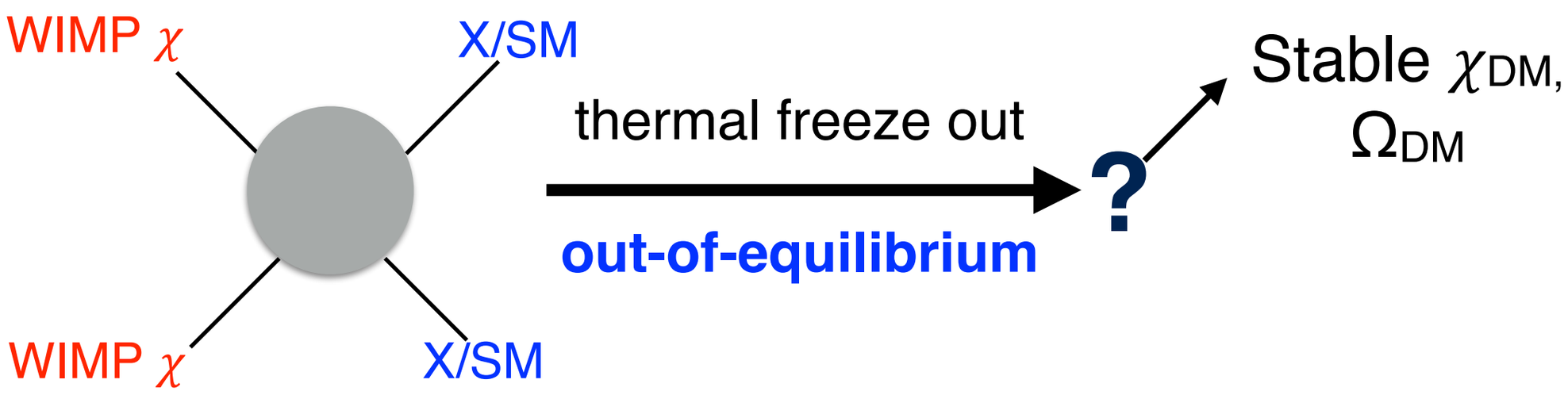
(**YC,** w/Sundrum)



WIMP Miracle for Baryons?

- A generalization/variation of WIMP miracle

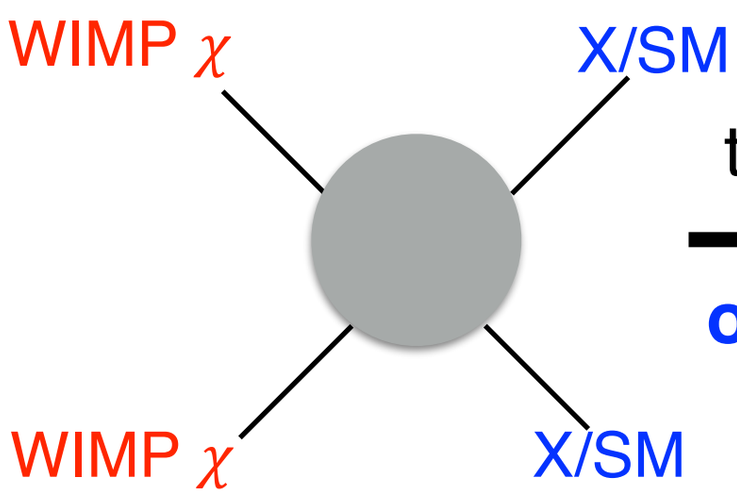
(**YC,** w/Sundrum)



WIMP Miracle for Baryons?

- A generalization/variation of WIMP miracle

(**YC,** w/Sundrum)



thermal freeze out

out-of-equilibrium

?

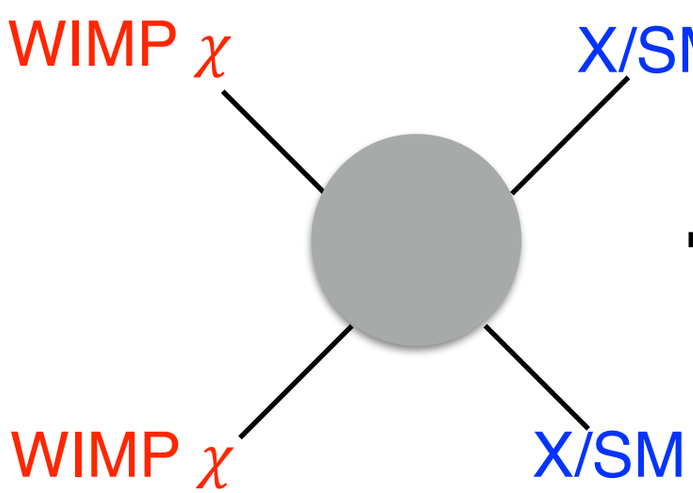
Stable χ_{DM}, Ω_{DM}

Metastable χ_B (later decay)

WIMP Miracle for Baryons?

- A generalization/variation of WIMP miracle

(**YC,** w/Sundrum)



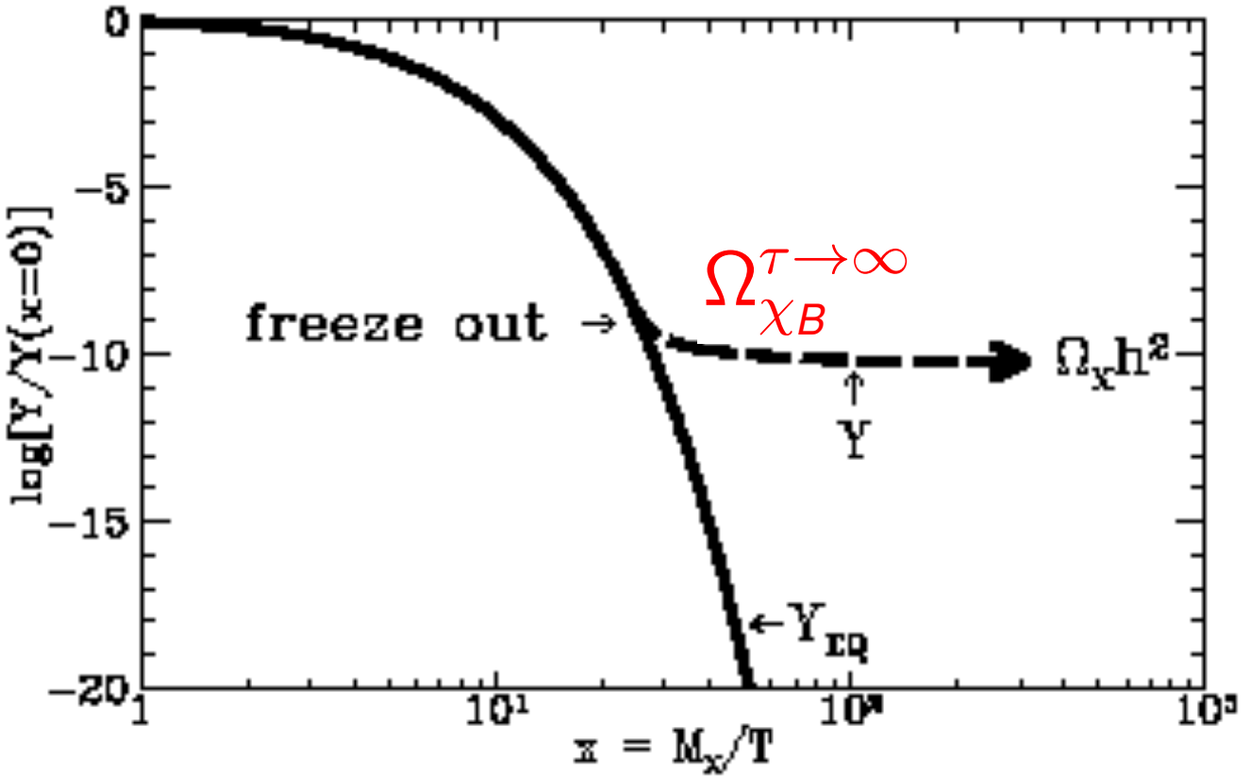
thermal freeze out

out-of-equilibrium

?

Stable χ_{DM}, Ω_{DM}

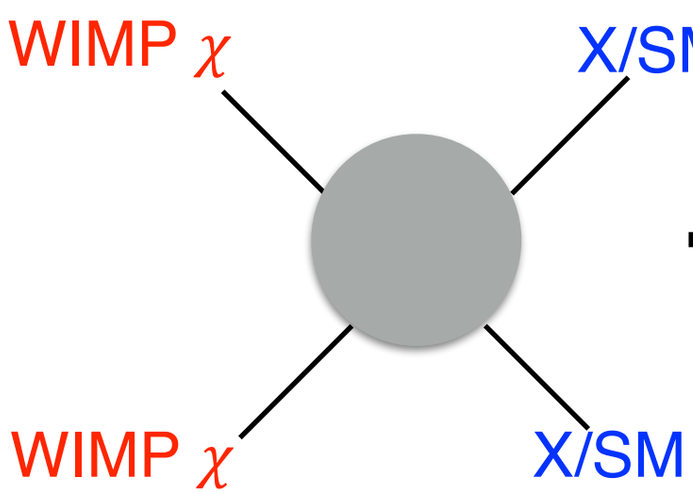
Metastable χ_B (later decay)



WIMP Miracle for Baryons?

- A generalization/variation of WIMP miracle

(**YC,** w/Sundrum)



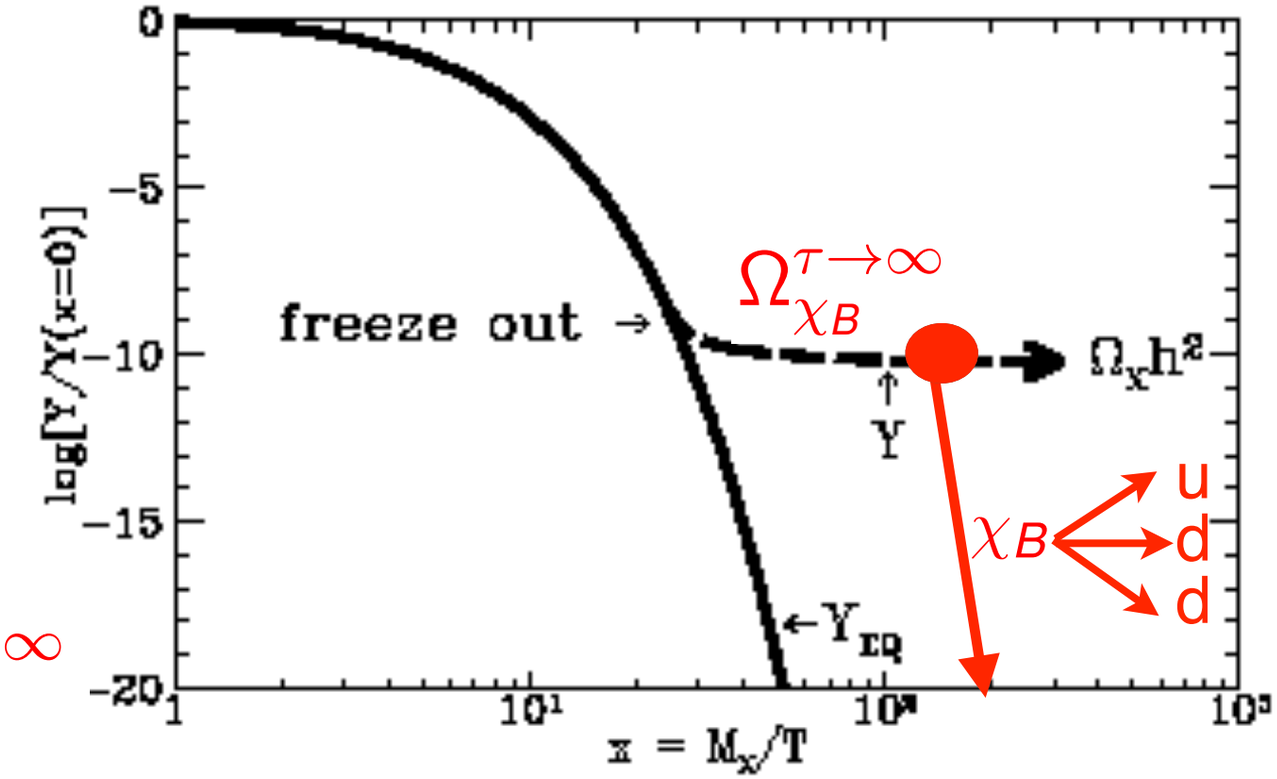
thermal freeze out

out-of-equilibrium

?

Stable χ_{DM}, Ω_{DM}

Metastable χ_B (later decay)

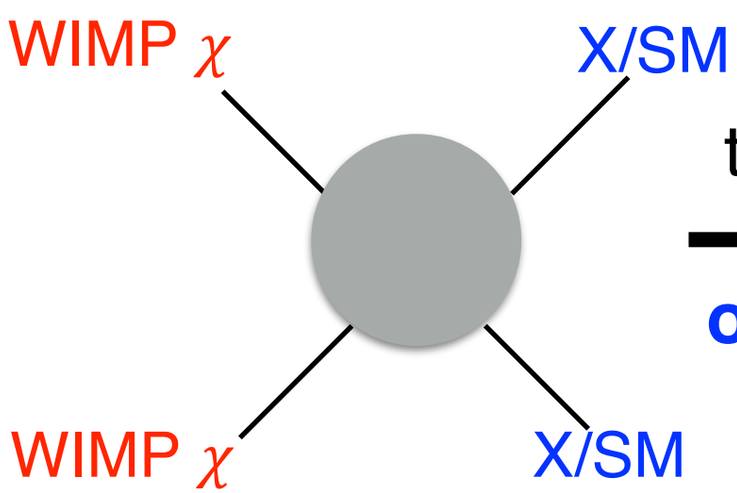


$$\Omega_B = \epsilon_{CP} \frac{m_p}{m_{\chi_B}} \Omega_{\chi_B}^{\tau\to\infty}$$

WIMP Miracle for Baryons?

- A generalization/variation of WIMP miracle

(**YC,** w/Sundrum)



thermal freeze out

out-of-equilibrium

?

Stable χ_{DM}, Ω_{DM}

Metastable χ_B (later decay)

- **Novel baryogenesis**

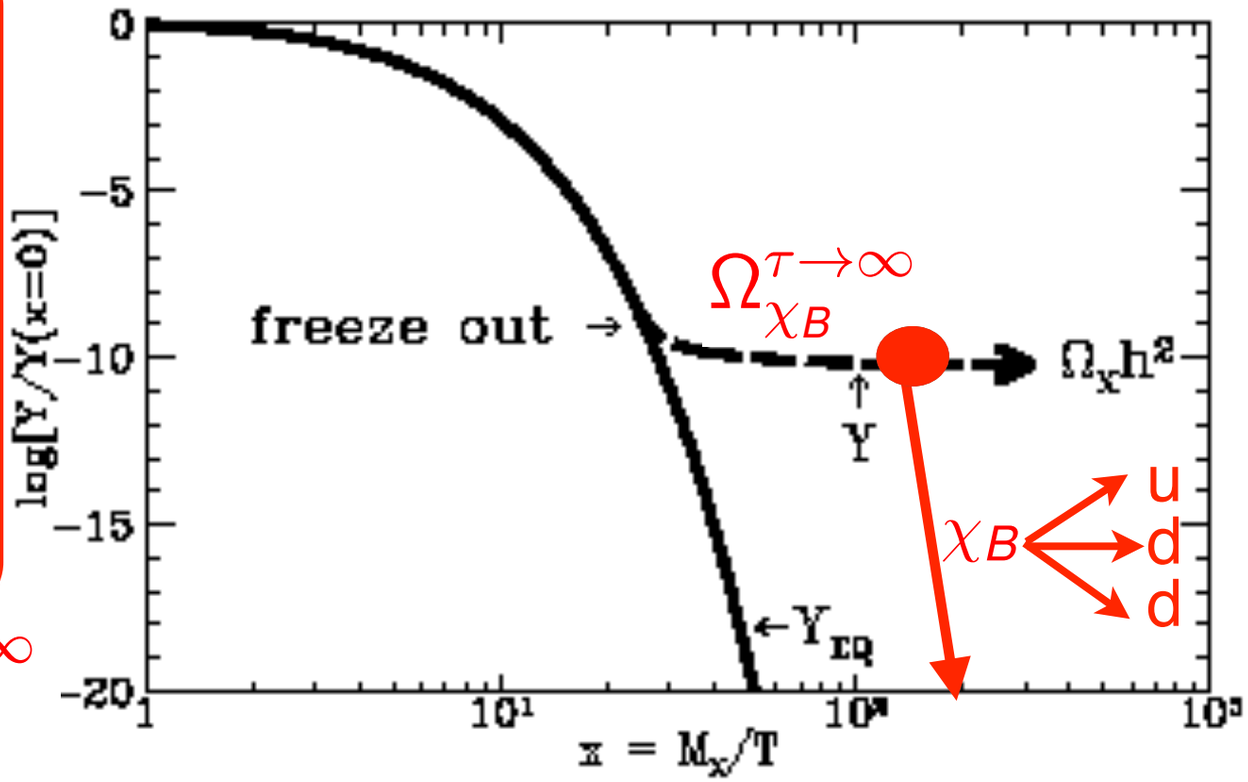
  Ω_B ✅

- **Generalized WIMP miracle**

  (+ stable WIMP DM Ω_{DM} ✅)

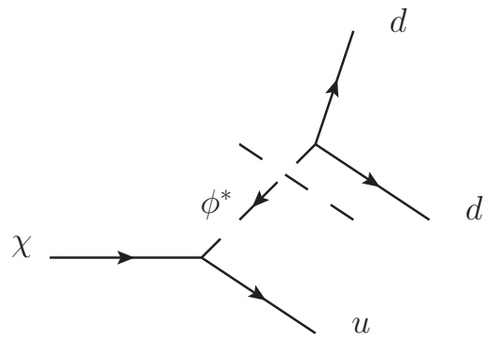
  $\Omega_B \sim \Omega_{DM}$ ✅

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

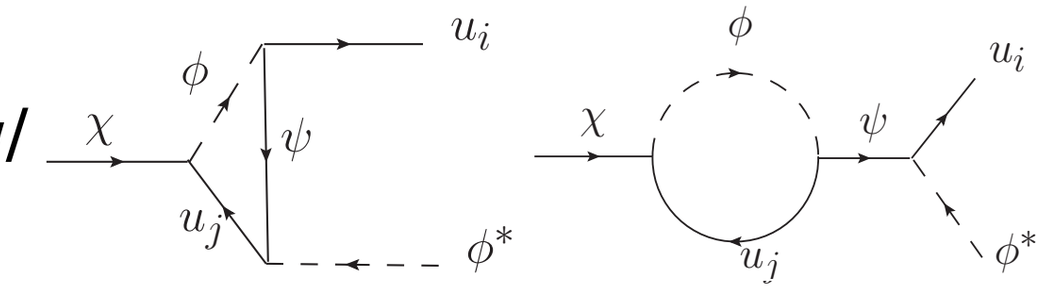


- **Minimal model example** (Phys.Rev. D87 (2013) 11, **YC** w/Sundrum)

CP asymmetry from:



interfere w/

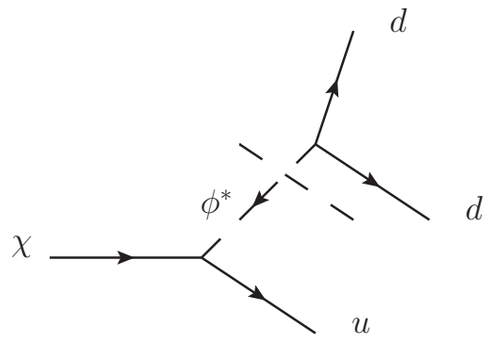


Easy embedding in RPV natural SUSY (+singlet)! ($\phi \to \tilde{t}$)

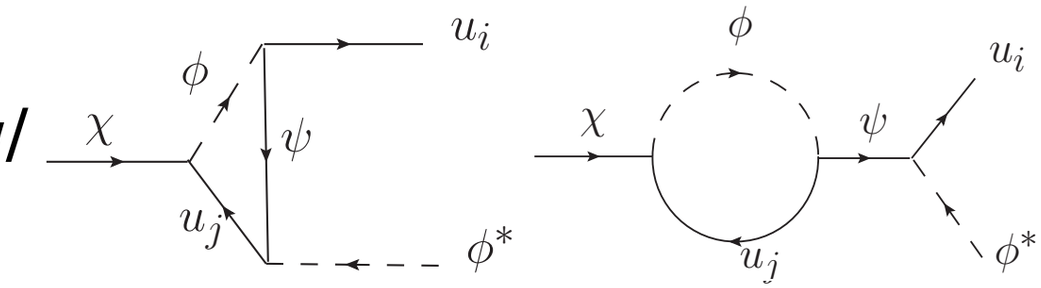
★ Late-time baryogenesis; a remedy for a potential cosmological crisis with RPV SUSY: RPV washout of existing Ω_B

- **Minimal model example** (Phys.Rev. D87 (2013) 11, **YC** w/Sundrum)

CP asymmetry from:



interfere w/



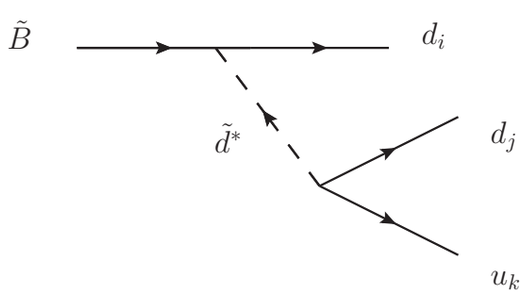
Easy embedding in RPV natural SUSY (+singlet)! ($\phi \to \tilde{t}$)

★ Late-time baryogenesis; a remedy for a potential cosmological crisis with RPV SUSY: RPV washout of existing Ω_B

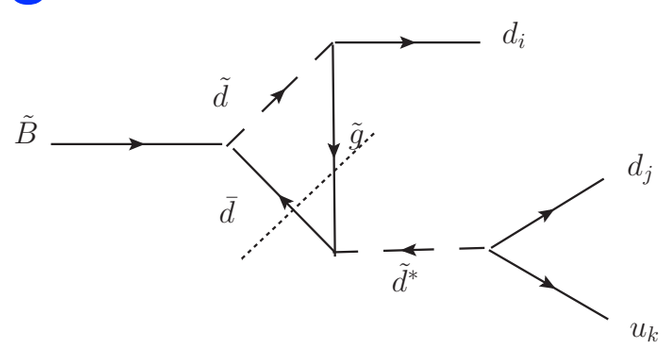
- **Baryogenesis with Minimal SUSY model!**

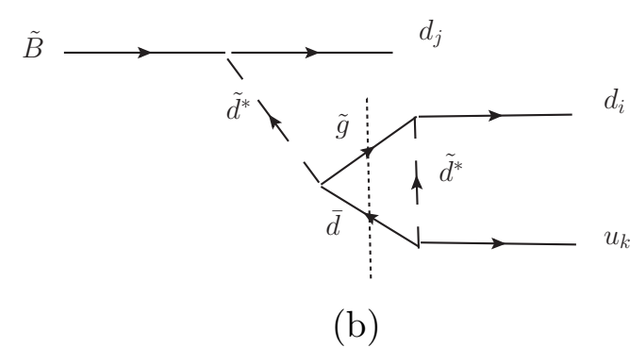
(**YC**, JHEP 1312 (2013) 067)

Bino $\tilde{B} \to \Delta B$! Cosmological motivation for mini-split SUSY!



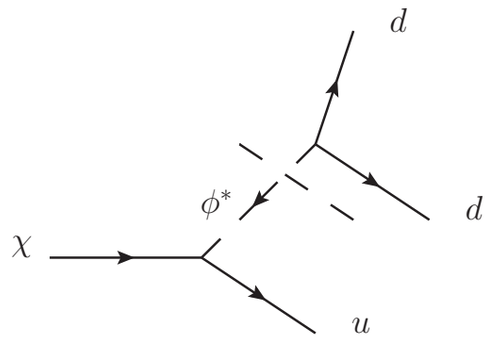
interfere w/



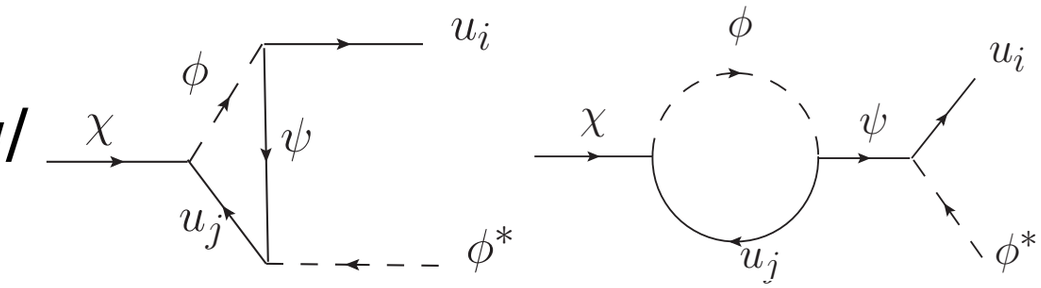


- **Minimal model example** (Phys.Rev. D87 (2013) 11, **YC** w/Sundrum)

CP asymmetry from:



interfere w/



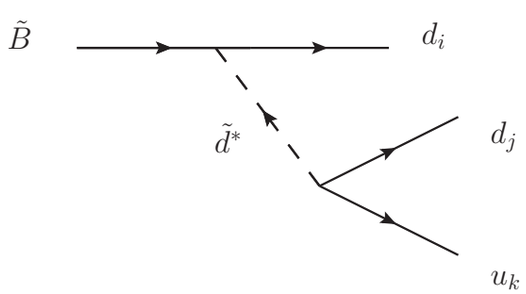
Easy embedding in RPV natural SUSY (+singlet)! ($\phi \to \tilde{t}$)

★ Late-time baryogenesis; a remedy for a potential cosmological crisis with RPV SUSY: RPV washout of existing Ω_B

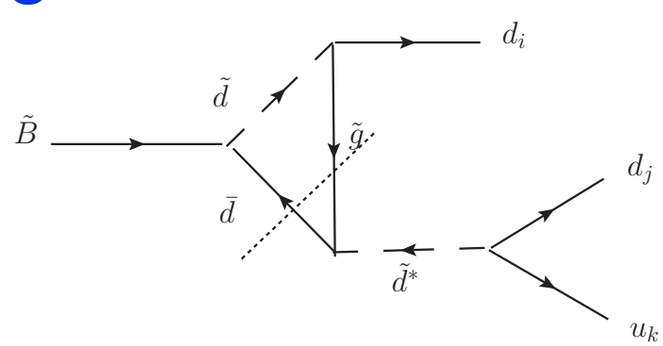
- **Baryogenesis with Minimal SUSY model!**

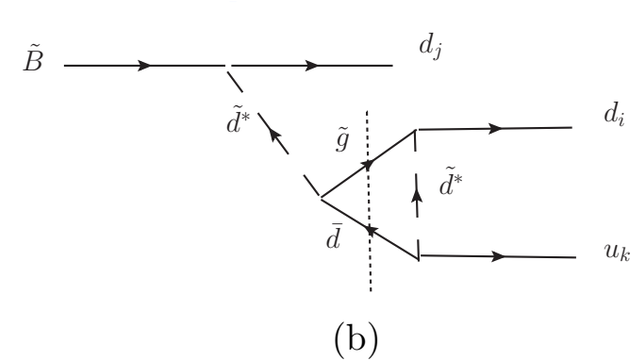
(**YC**, JHEP 1312 (2013) 067)

Bino $\tilde{B} \to \Delta B$! Cosmological motivation for mini-split SUSY!



interfere w/





Incorporate WIMP DM? Add a singlet $\chi_{\rm DM}$ protected by an exact Z_2

Baryogenesis from Out-of-equlibrium Decays

— Collider Phenomenology

YC and Shuve, JHEP 1502 (2015) 049

(**YC** and Okui, Yunesi, Phys.Rev. D94 (2016))

★ *Strategies/results generally applicable to other new physics searches via displaced vertices*

Reproduce Baryogenesis at the LHC!

(**YC** w/Sundrum; w/Shuve)

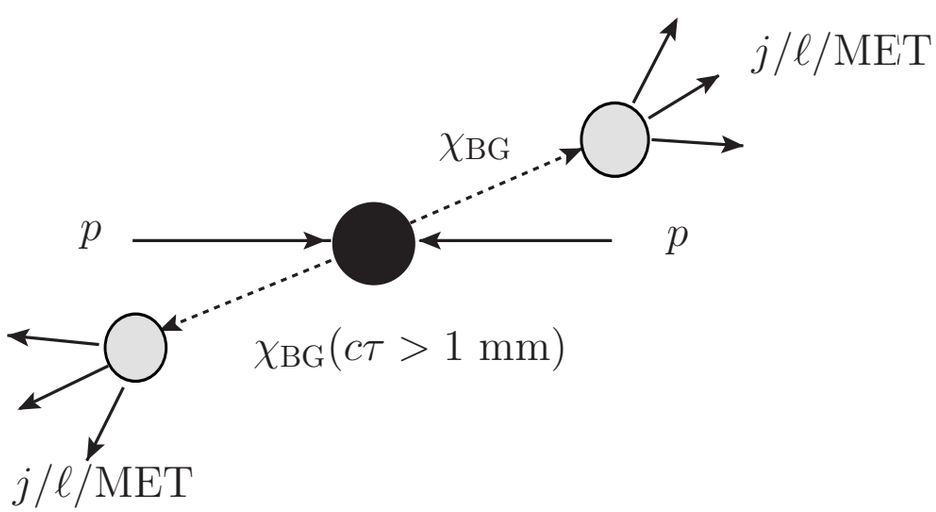
- WIMP $m_\chi \sim O(100\ GeV)$ can be produced within E_{LHC}=14 TeV!
- **Cosmological condition for baryogenesis:**

χ lives beyond its thermal freeze out time

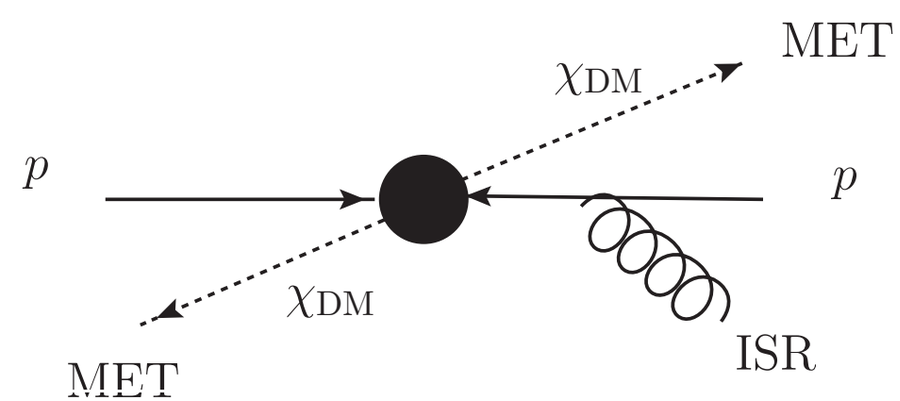
$$\Gamma_\chi < H_{\rm fo} \longleftrightarrow c\tau_\chi \gtrsim {\rm mm}$$

LHC tracking resolution!

- **Distinctive signal**: displaced decay vertex inside detectors —not well-covered, low bkg search channel, rising interest!



Metastable WIMP baryon parent@LHC: displaced vertex



Stable WIMP DM@LHC: missing energy (analogy)

Simplified Model Approach for LHC Pheno

(**YC** and Shuve arxiv:1409.6729, JHEP)

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

- Classify decay modes (unlike DM search…)

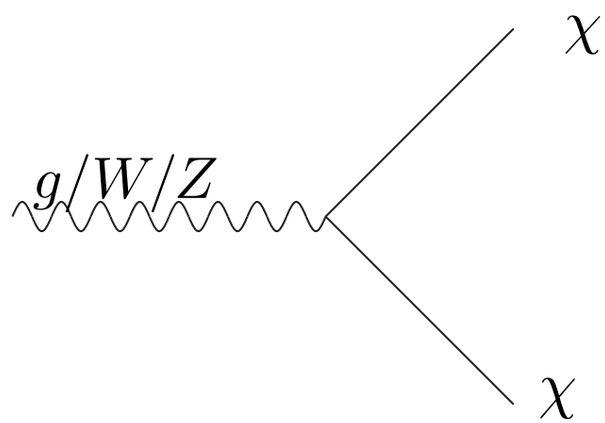
Simplified Model Approach for LHC Pheno

(**YC** and Shuve arxiv:1409.6729, JHEP)

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

Charged under SM gauge interactions:

wino/gluino-like (state in interference loop)



- Classify decay modes (unlike DM search…)

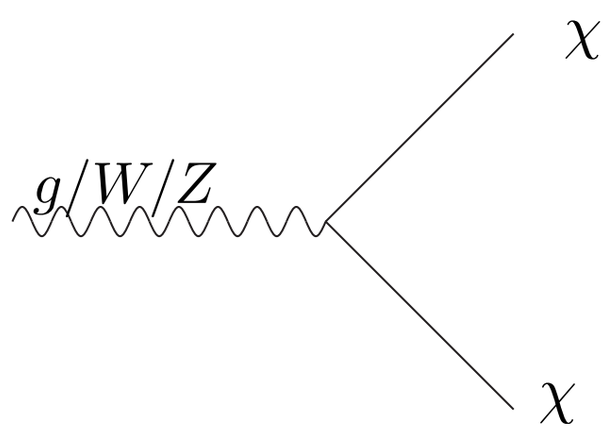
Simplified Model Approach for LHC Pheno

(**YC** and Shuve arxiv:1409.6729, JHEP)

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

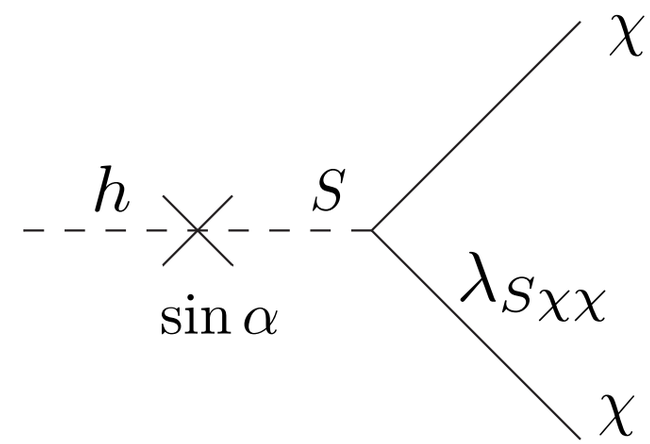
Charged under SM gauge interactions:

wino/gluino-like (state in interference loop)



Higgs portal:

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



- Classify decay modes (unlike DM search…)

Simplified Model Approach for LHC Pheno

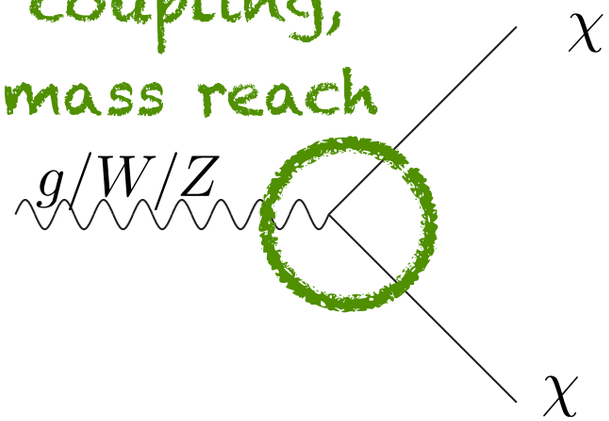
(**YC** and Shuve arxiv:1409.6729, JHEP)

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

Charged under SM gauge interactions:

wino/gluino-like (state in interference loop)

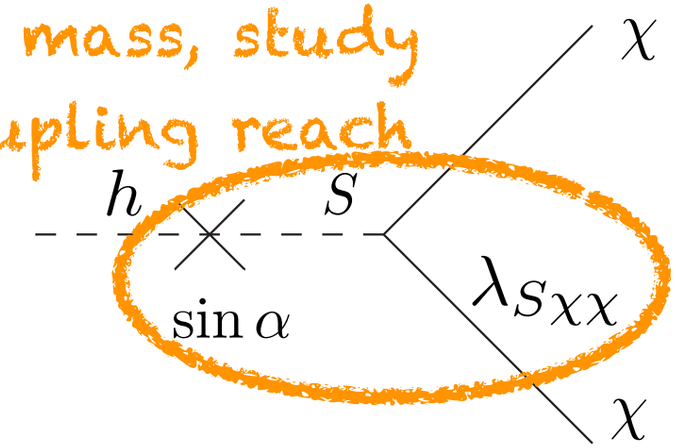
fixed coupling, study mass reach



Higgs portal:

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

fix mass, study coupling reach



- Classify decay modes (unlike DM search…)

Simplified Model Approach for LHC Pheno

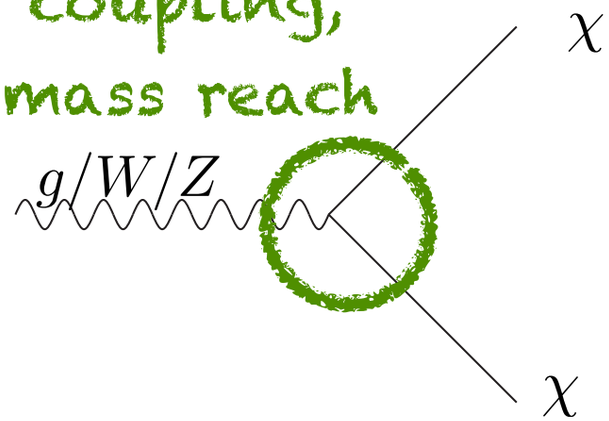
(**YC** and Shuve arxiv:1409.6729, JHEP)

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

Charged under SM gauge interactions:

wino/gluino-like (state in interference loop)

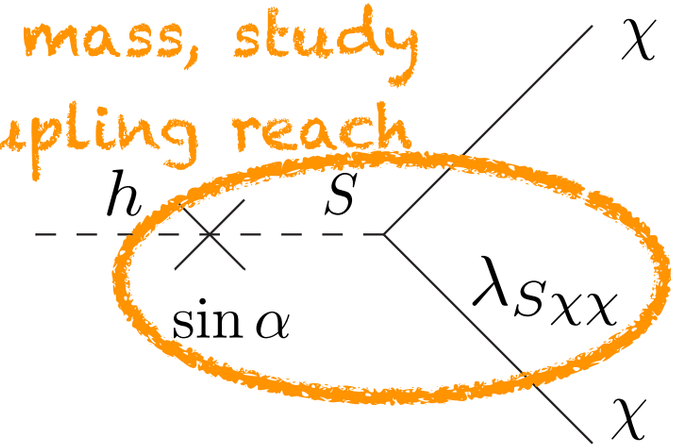
fixed coupling, study mass reach



Higgs portal:

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

fix mass, study coupling reach



- Classify decay modes (unlike DM search…)

Baryon number violating:

$$\chi \to u_i d_j d_k$$

Simplified Model Approach for LHC Pheno

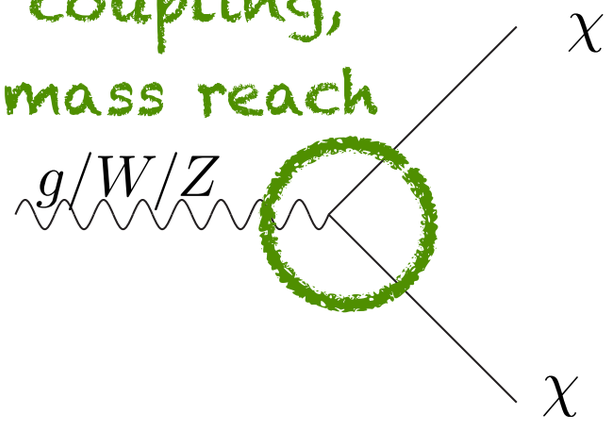
(**YC** and Shuve arxiv:1409.6729, JHEP)

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

Charged under SM gauge interactions:

wino/gluino-like (state in interference loop)

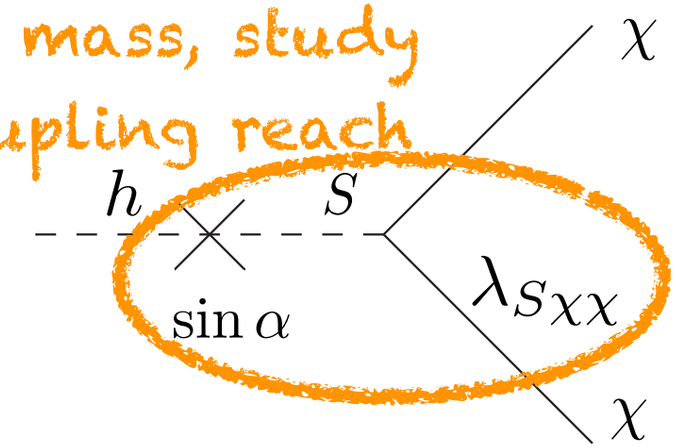
fixed coupling, study mass reach



Higgs portal:

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

fix mass, study coupling reach



- Classify decay modes (unlike DM search…)

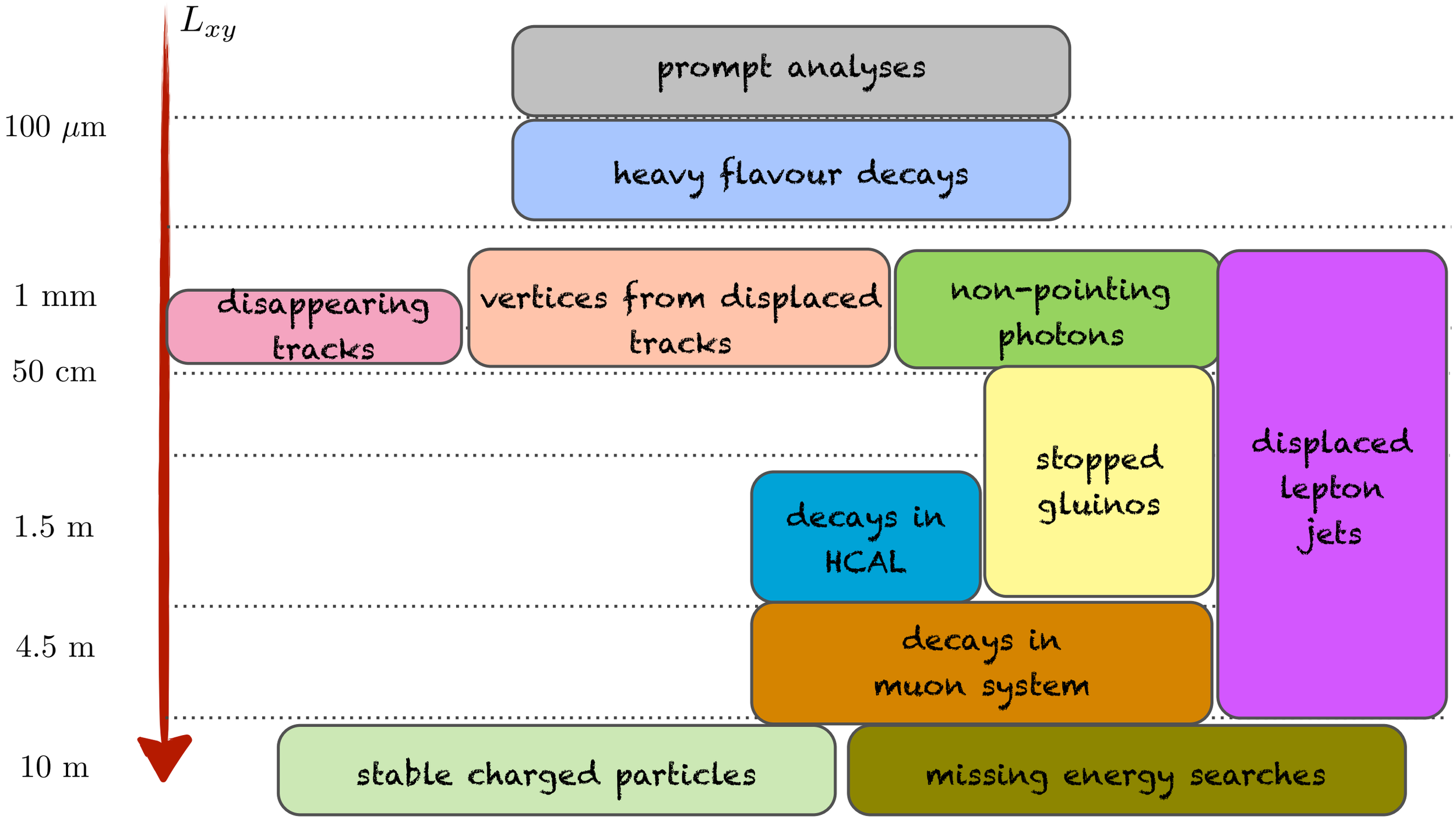
Baryon number violating:

$$\chi \to u_i d_j d_k$$

Lepton number violating:

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

LHC DV Search Possibilities



New detector: Mathusla? (Chou, Curtin, Lubatti +others)

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

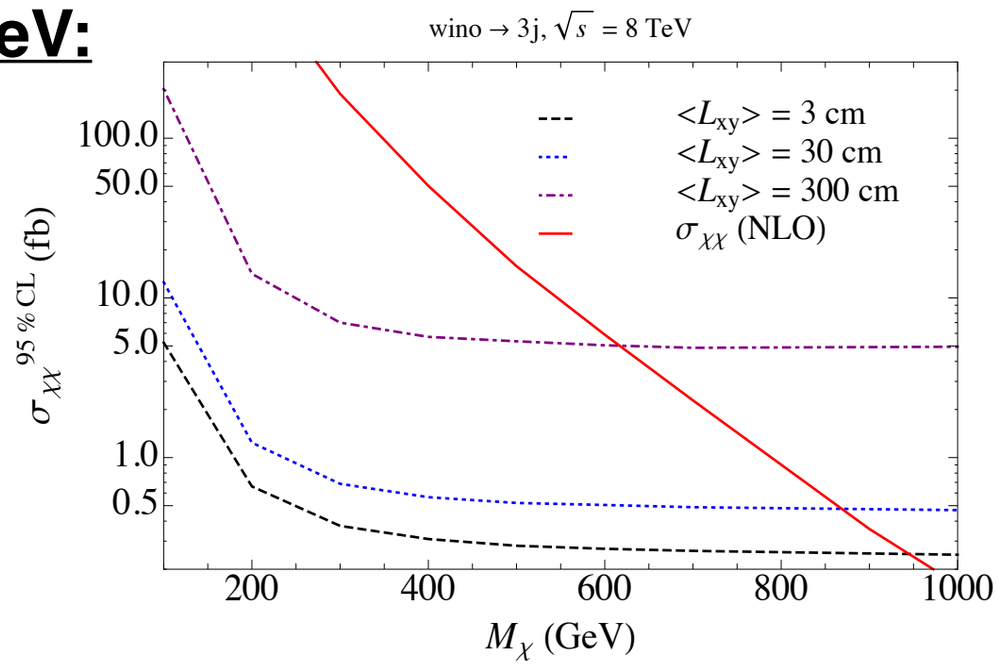
- **Goal of our analysis:**
  - What is the coverage for our simplified models based on benchmarks chosen by the collaborations?
  - What advice can we provide for general experimental improvement?

Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:

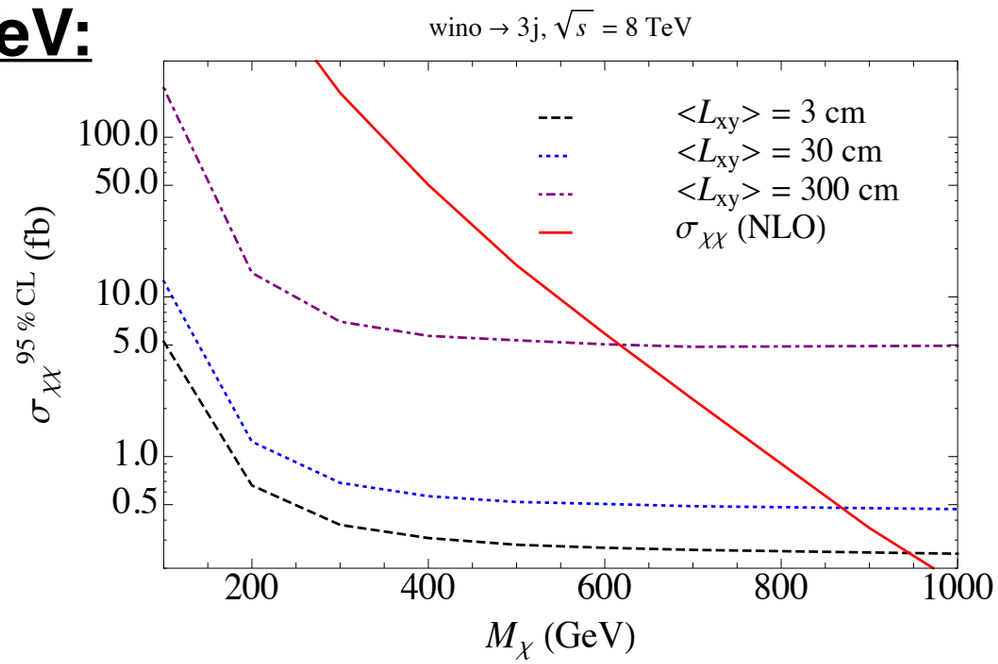


Fully hadronic displaced vertices

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!

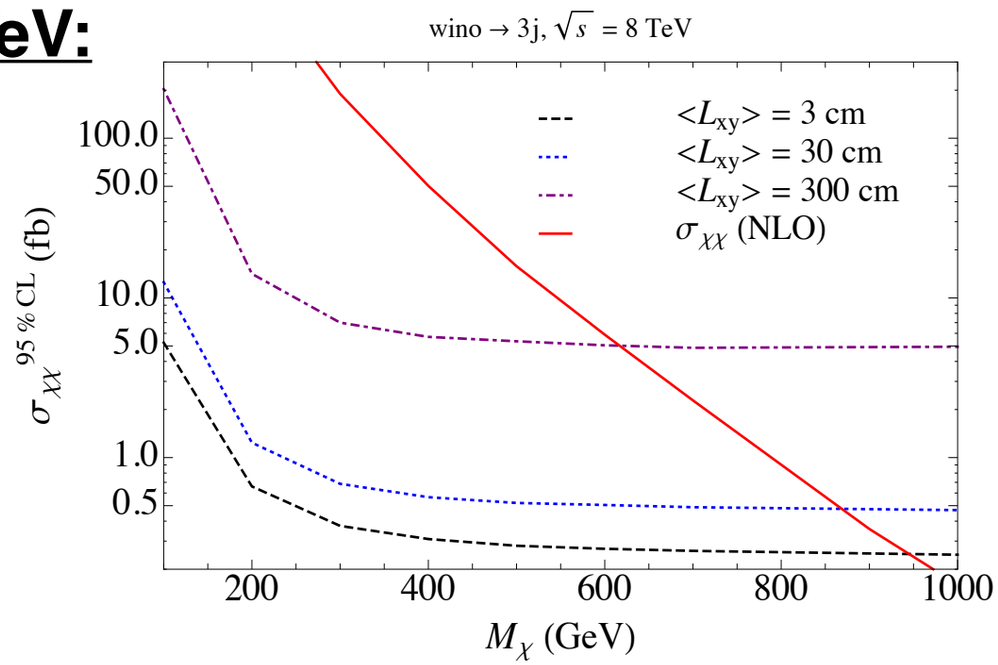
No bound @ 8 TeV 20 fb^{-1}!

Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:

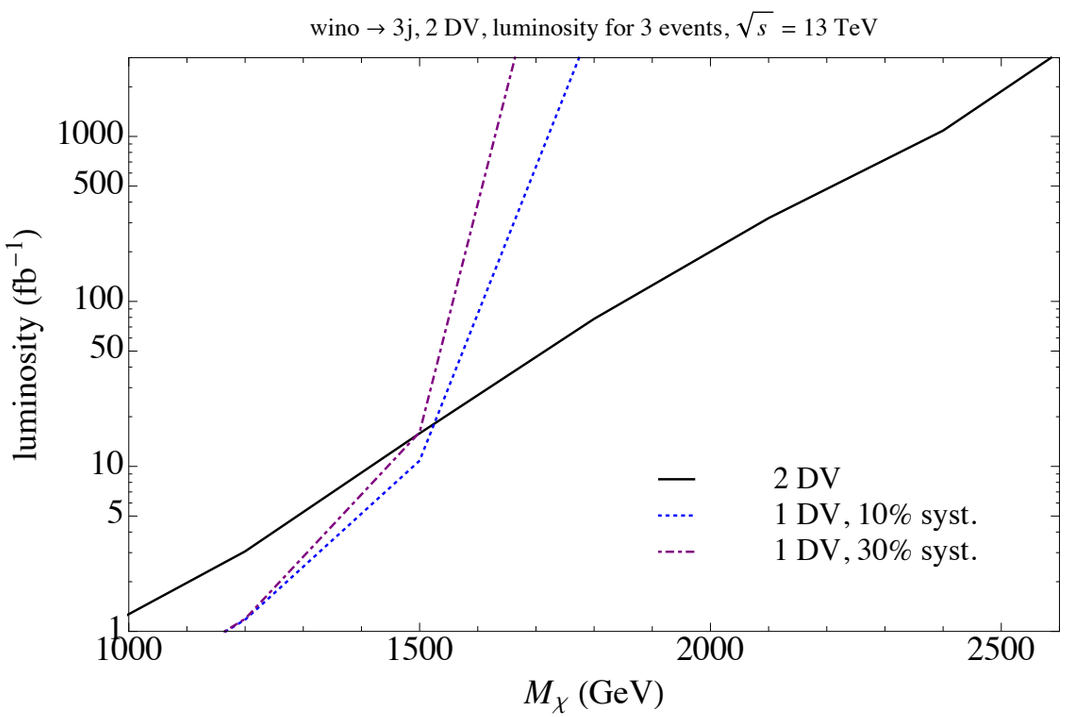


singlet-like (Higgs portal)

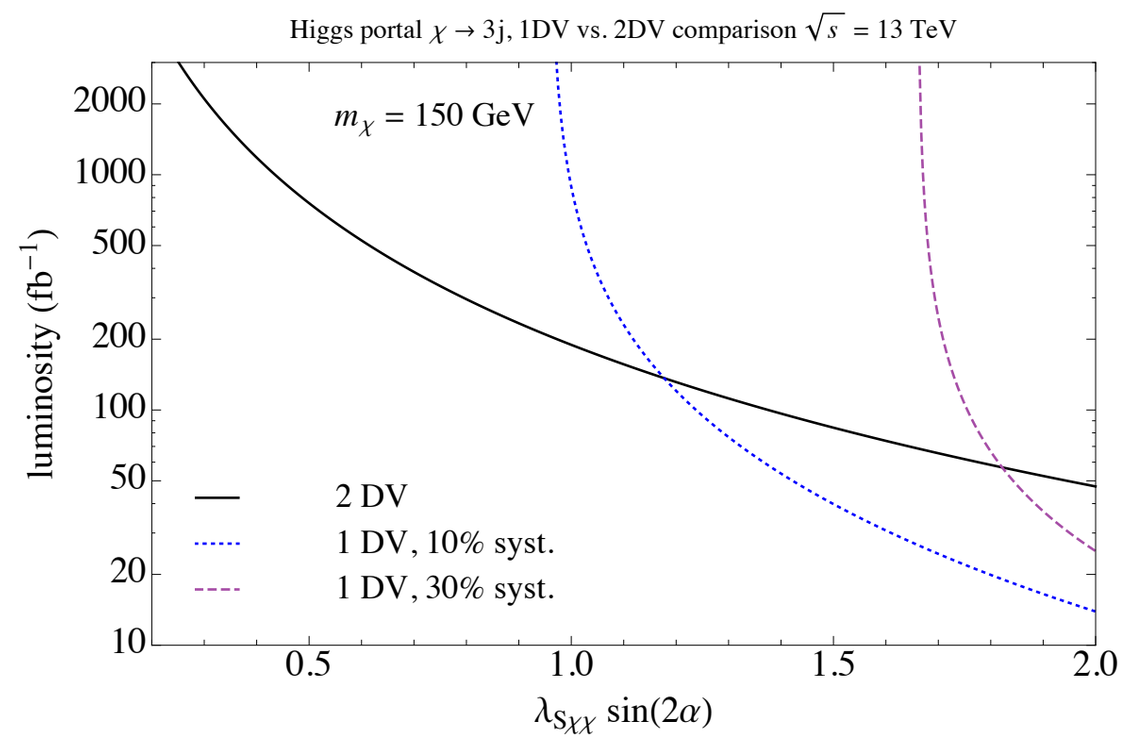
We studied a challenging case:
M_χ = 150 GeV, moderately off-shell!

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

13 TeV:



L_{xy} = 3 cm

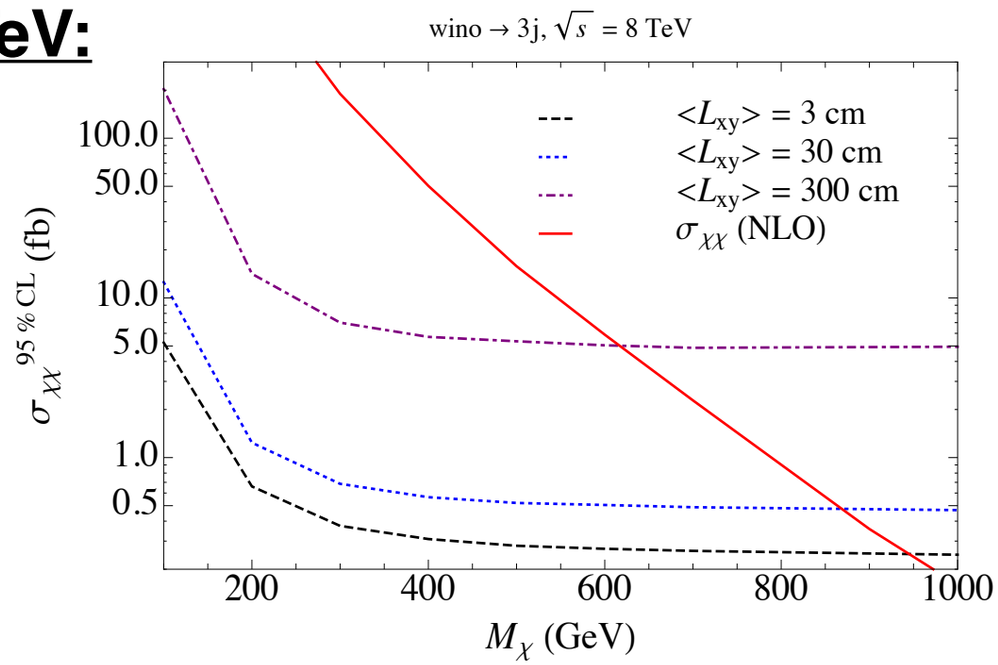


Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:

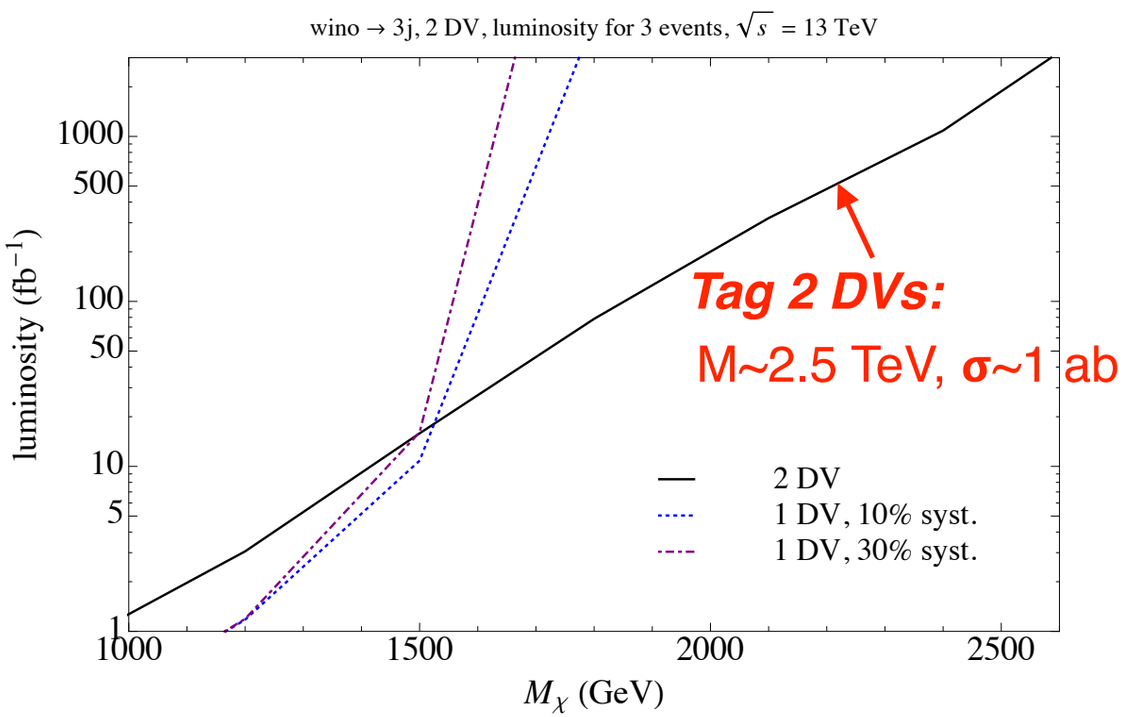


singlet-like (Higgs portal)

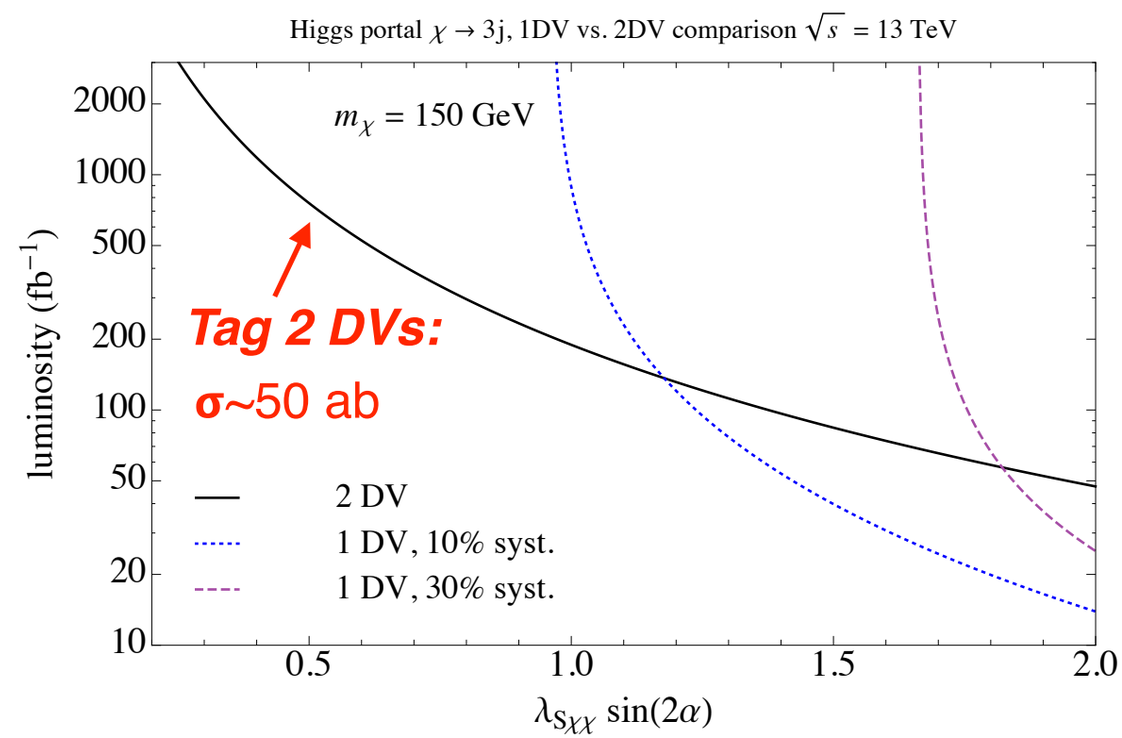
We studied a challenging case:
M_χ = 150 GeV, moderately off-shell!

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

13 TeV:



L_{xy} = 3 cm

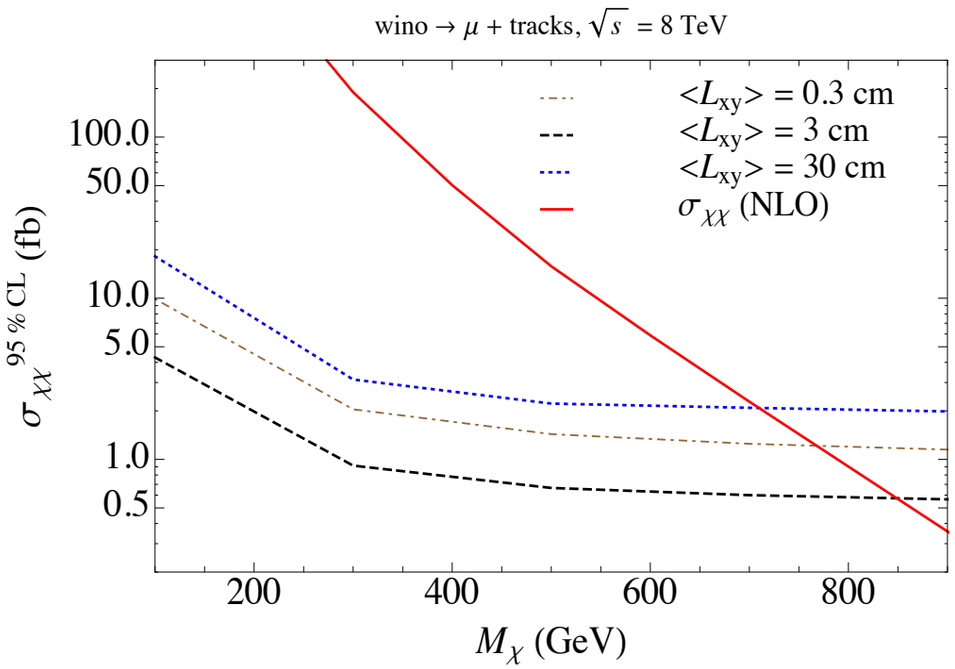


Displaced muon + Tracks

ATLAS-CONF-2013-092

wino

8 TeV

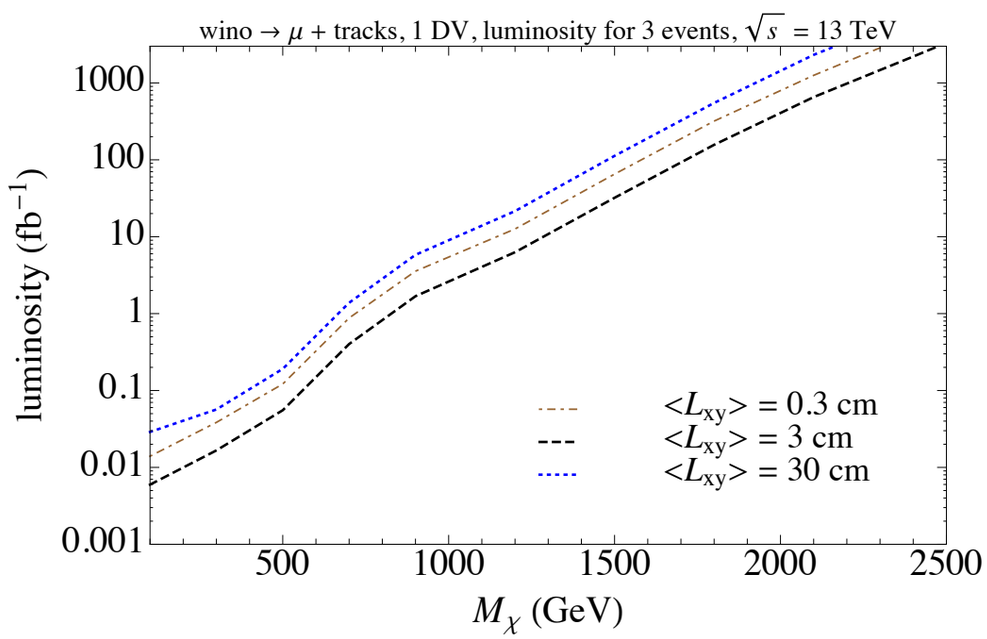


13 TeV:

Tag 1 DV

M~2.5 TeV

(lower bkg than all-hadronic)

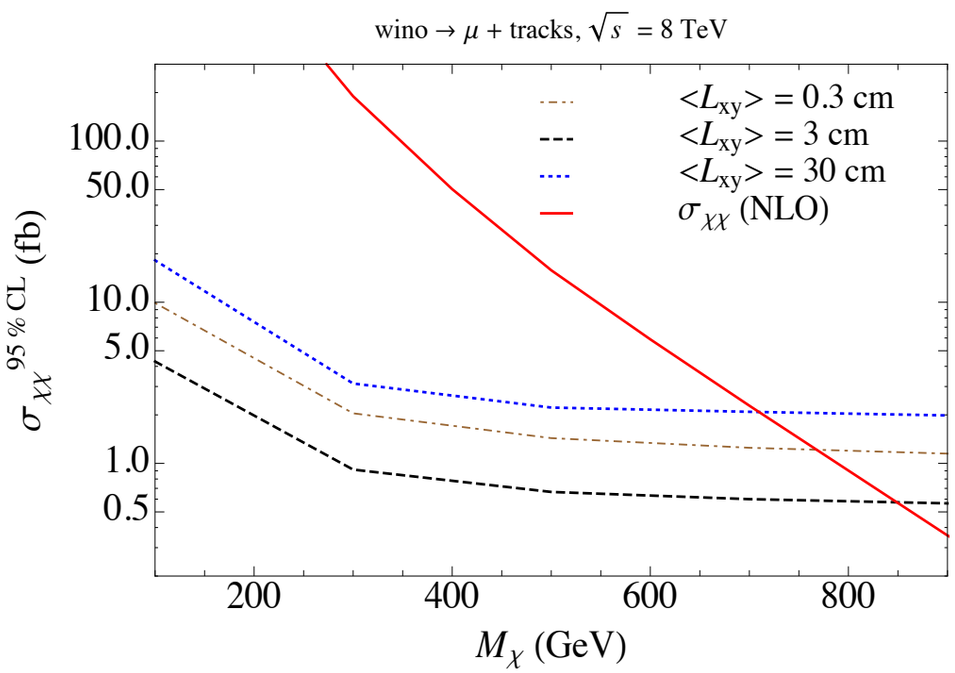


Displaced muon + Tracks

ATLAS-CONF-2013-092

wino

8 TeV

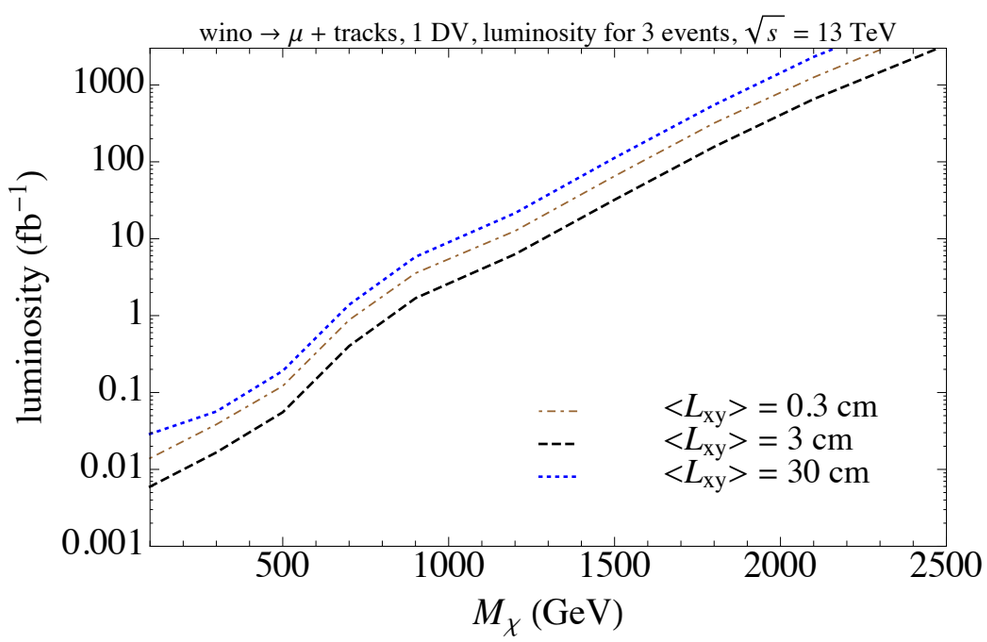


13 TeV:

Tag 1 DV

M~2.5 TeV

(lower bkg than all-hadronic)

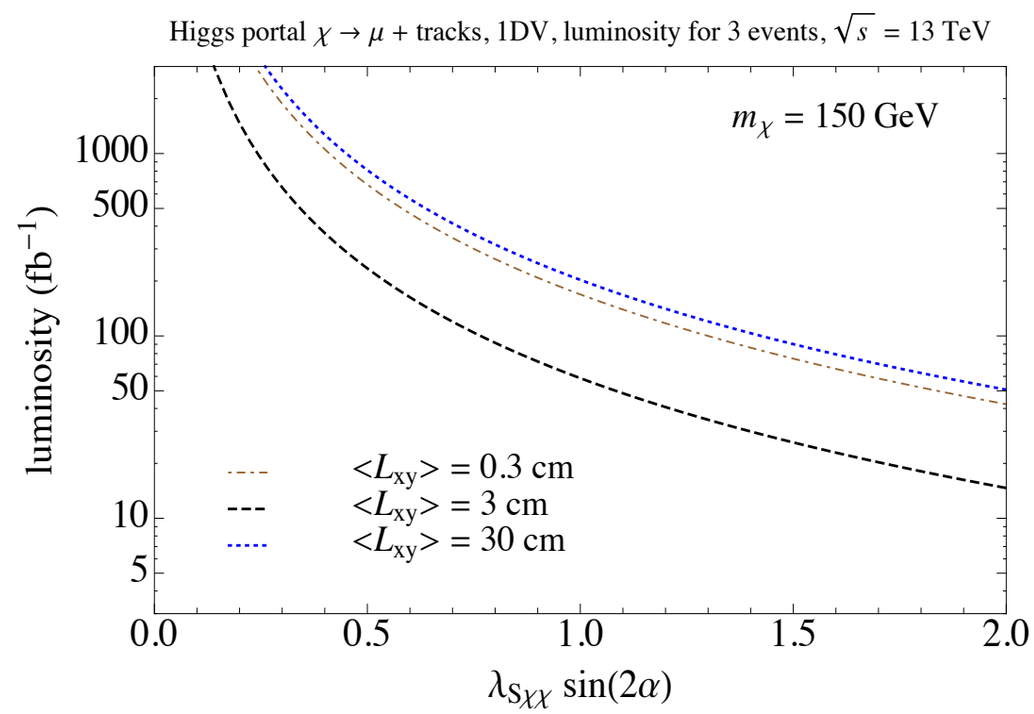


singlet (Higgs portal)

(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)



Summary/Outlook

- **Solution to the DM puzzle may relate to Ω_B !**

  - New opportunities @ LHC! (cf. WIMP DM search)

- **Baryogenesis from metastable weak scale particle decay (WIMP BG):** new mechanism addressing Ω_B (+) $\Omega_B \sim \Omega_{DM}$

Summary/Outlook

- **Solution to the DM puzzle may relate to Ω_B !**

  - New opportunities @ LHC! (cf. WIMP DM search)

- **Baryogenesis from metastable weak scale particle decay (WIMP BG):** new mechanism addressing Ω_B (+) $\Omega_B \sim \Omega_{DM}$

- **Simplified models for LHC pheno:** signal generator for **general** DV searches *(cooperation with ATLAS displaced jets group, officially approved as a new benchmark for Run-2 analysis)*

Summary/Outlook

- **Solution to the DM puzzle may relate to Ω_B !**

  - New opportunities @ LHC! (cf. WIMP DM search)

- **Baryogenesis from metastable weak scale particle decay (WIMP BG):** new mechanism addressing Ω_B (+) $\Omega_B \sim \Omega_{DM}$

- **Simplified models for LHC pheno:** signal generator for **general** DV searches *(cooperation with ATLAS displaced jets group, officially approved as a new benchmark for Run-2 analysis)*

- **Further pheno explorations:**
  - Other signal channels: diphoton resonance, multi-b/t events (YC and Okui, Yunesi arxiv:1605.08736, JHEP)
  - Challenging case for DV search: Light WIMP ($\lesssim$ *100 GeV*), longer lifetime, hadronic decay… ?

Summary/Outlook

- **Solution to the DM puzzle may relate to Ω_B !**

  - New opportunities @ LHC! (cf. WIMP DM search)

- **Baryogenesis from metastable weak scale particle decay (WIMP BG):** new mechanism addressing Ω_B (+) $\Omega_B \sim \Omega_{DM}$

- **Simplified models for LHC pheno:** signal generator for **general** DV searches *(cooperation with ATLAS displaced jets group, officially approved as a new benchmark for Run-2 analysis)*

- **Further pheno explorations:**
  - Other signal channels: diphoton resonance, multi-b/t events (YC and Okui, Yunesi arxiv:1605.08736, JHEP)
  - Challenging case for DV search: Light WIMP ($\lesssim$ *100 GeV*), longer lifetime, hadronic decay… ?

- **More opportunities@LHC inspired by $\Omega_B \sim \Omega_{DM}$, Ω_B? …**