BARYOGENESIS FROM WIMPS

Y. Cui, L. Randall, and BS, arXiv:1112.2704 (JHEP)
Y. Cui and BS, arXiv:1409.6729 (PRD)

Brian Shuve
SLAC

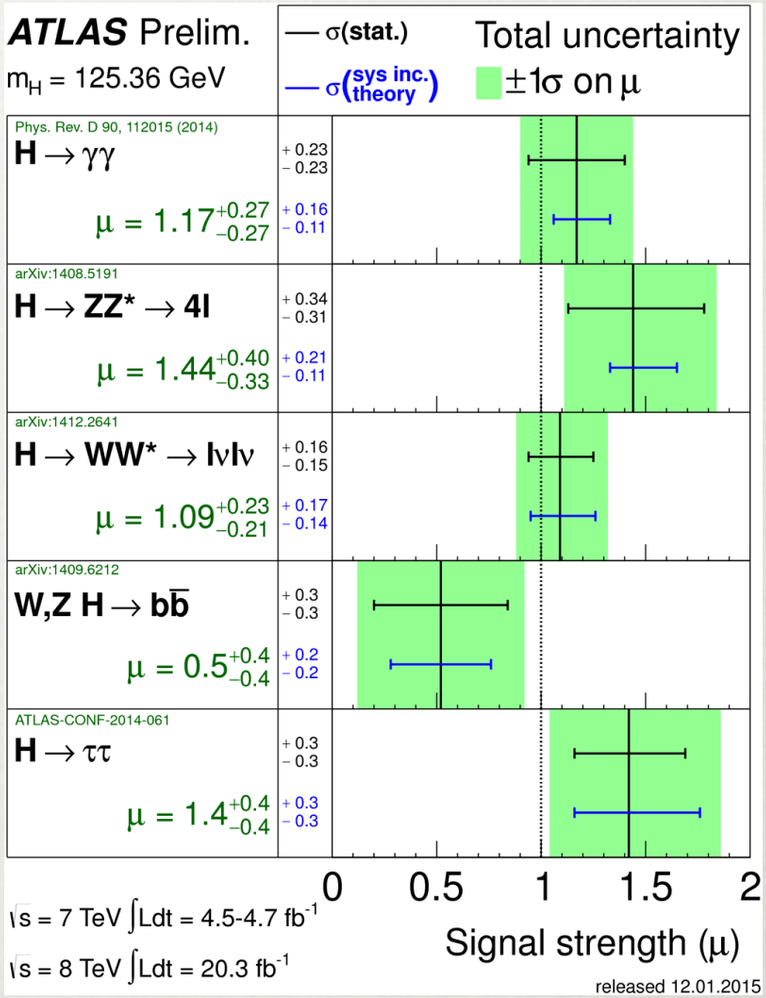
Probing the Electroweak Phase Transition with a Next-Generation pp Collider

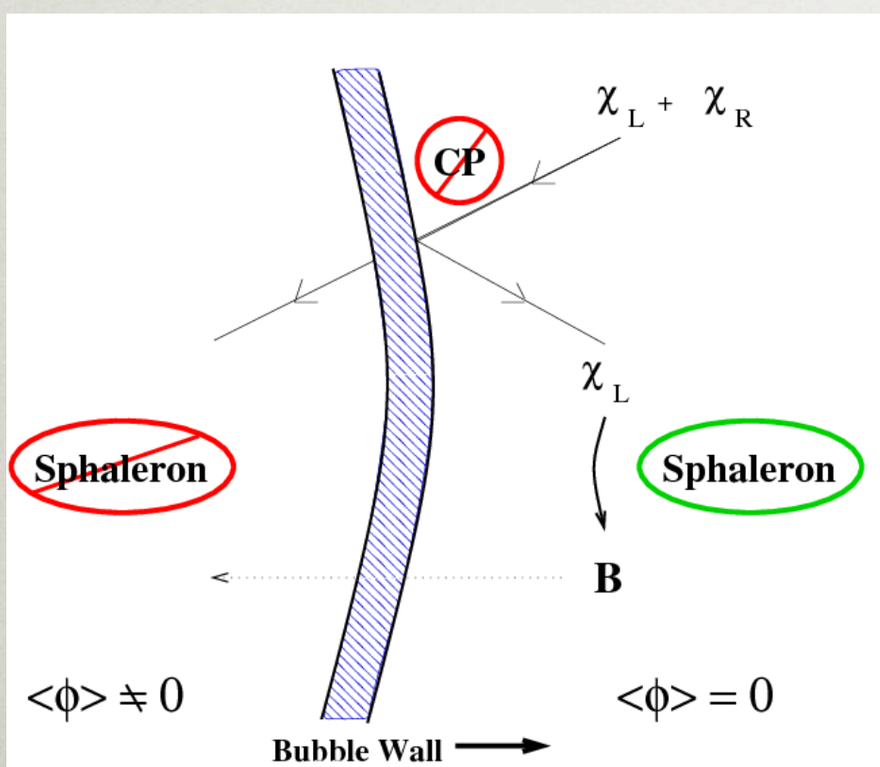
AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

19 September 2015

Cosmology at the Weak Scale

We have a **new scale** in particle physics

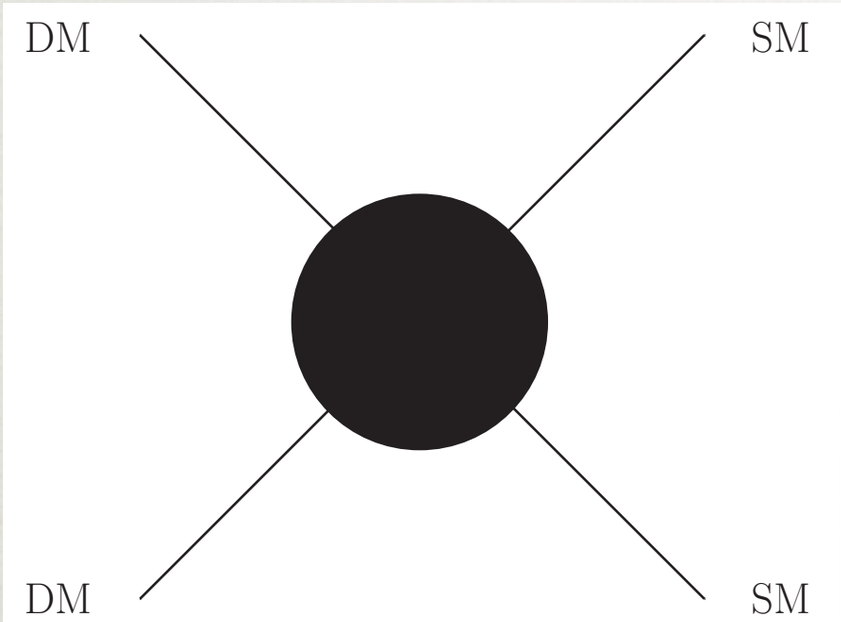




Electroweak baryogenesis links the baryon asymmetry to this new scale (but need new dynamics!)

Cosmology at the Weak Scale

Coincidentally, we also see this scale imprinted in cosmology



$$\Omega_{\rm DM} \sim \frac{1}{\langle \sigma\, v_{\rm DM} \rangle} \sim 0.27 \left(\frac{\alpha_{\rm W}}{\alpha_{\rm DM}}\right)^2 \left(\frac{M_{\rm DM}}{\rm TeV}\right)^2$$

perturbative unitarity: $M_{\rm DM} \lesssim 100\ \text{TeV}$

Griest, Kamionkowski 1990

What does this have to do with baryogenesis? Some hints....

1) Comparable energy densities of baryons and DM $\Omega_{\rm DM} \approx 5\,\Omega_{\Delta B}$

see also Asymmetric Dark Matter models (recent renewal of interest: ex. Kaplan, Luty, Zurek 2009)

2) Common features in DM/baryogenesis dynamics

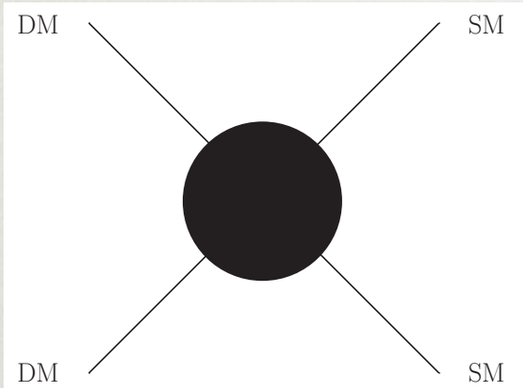
- Out-of-equilibrium dynamics, CPV, self-conjugate particles

Baryogenesis-WIMP connections

I will briefly review two possible WIMP baryogenesis mechanisms, focusing on connections between cosmology and weak-scale probes

Baryogenesis from WIMP Annihilation ("WIMPy Baryogenesis"):

$B - L = 0$

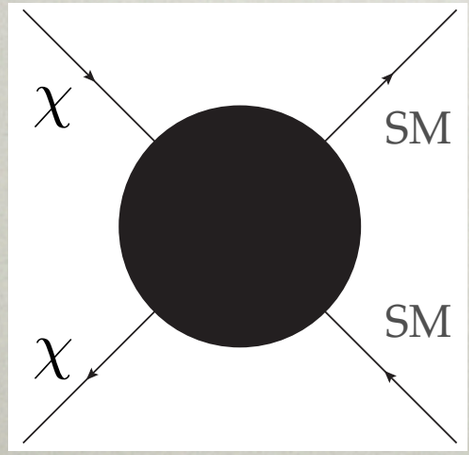


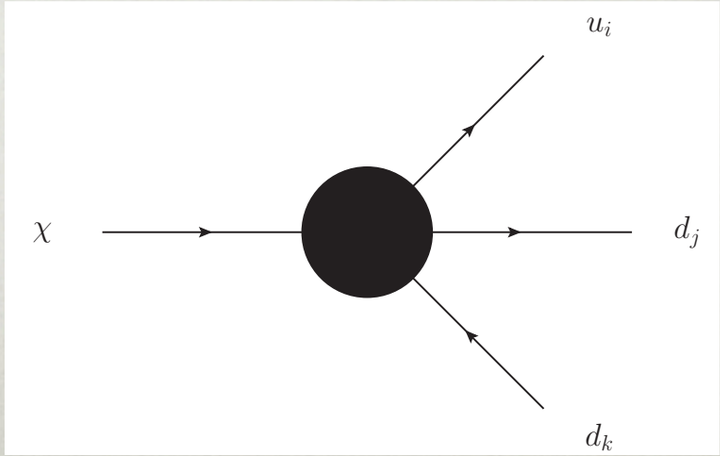
$B - L > 0$

- Typically predict new gauge-charged states
- Collider and DM probes

Cui, Randall, BS 2011

Baryogenesis from Meta-Stable WIMP Decay:



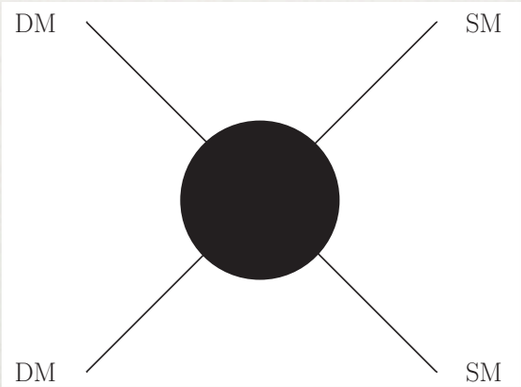


- Colliders (long-lived decays)

Cui, Sundrum 2012
Cui 2013
Cui, BS 2014

WIMPy Baryogenesis

$B - L = 0$



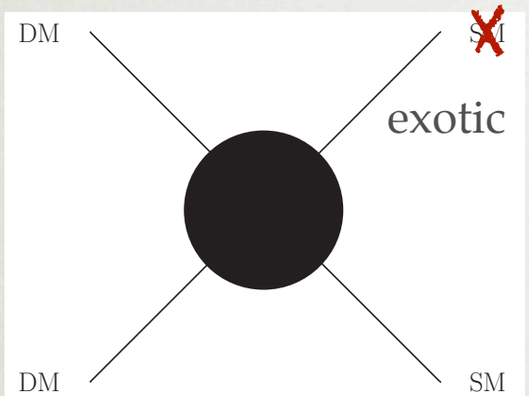
$B - L > 0$

WIMPy Baryogenesis

Sakharov conditions:

1. **Violation of *B-L***

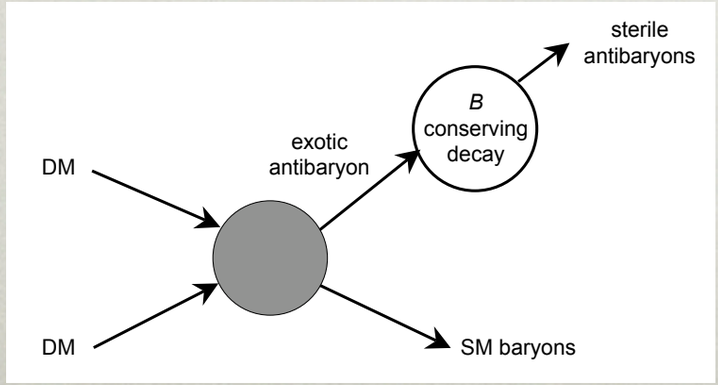
$B - L = 0$

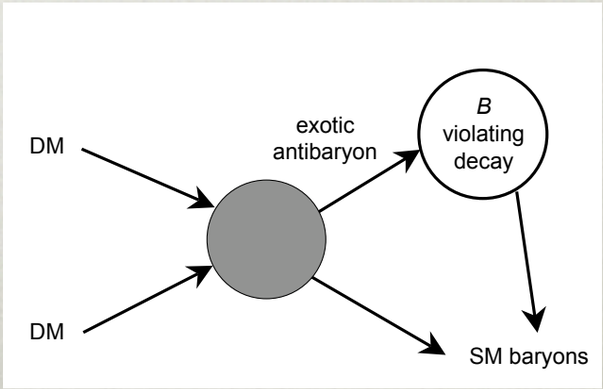


$B - L > 0$

- If DM is a colour singlet, no *B-L* violation allowed for pair of SM final states
- Need to couple to an **exotic** *B*/*L* charged state

- Equal and opposite asymmetries in regular baryons & exotic baryons
- Need asymmetries to be sequestered **or** for the exotic baryon to have additional couplings to quarks that change its effective baryon number

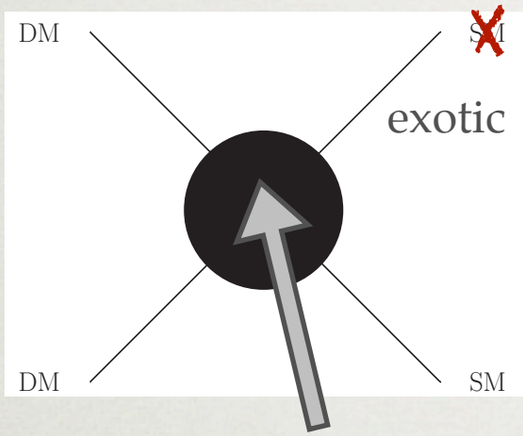




WIMPy Baryogenesis

2. Violation of *CP*

$B - L = 0$

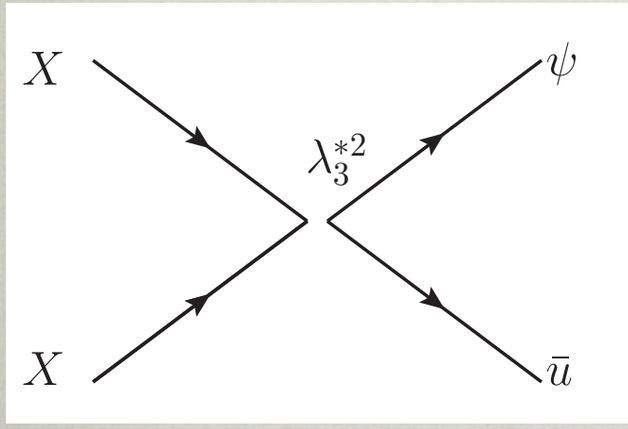


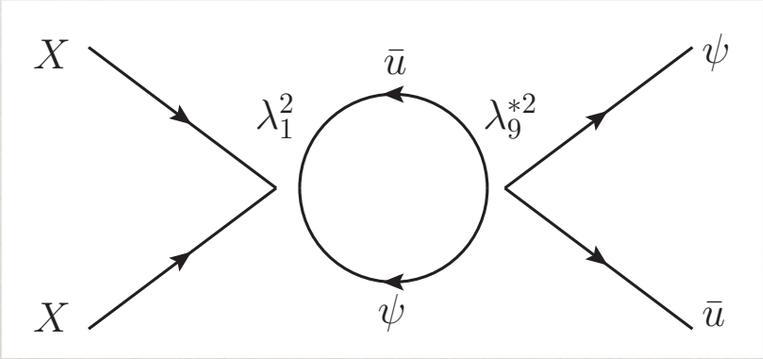
$B - L > 0$

new CP phases

- Generally have phases in new couplings
- Might provide phenomenological handle!

- Physical *CP* violation comes from interference with on-shell states in loop:





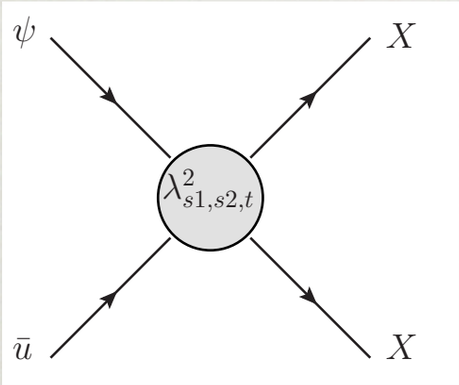
$$\epsilon \equiv \frac{\Gamma(XX \to \psi\bar{u}) - \Gamma(X^\dagger X^\dagger \to \psi^\dagger \bar{u}^\dagger)}{\Gamma(XX \to \psi\bar{u}) + \Gamma(X^\dagger X^\dagger \to \psi^\dagger \bar{u}^\dagger)}$$

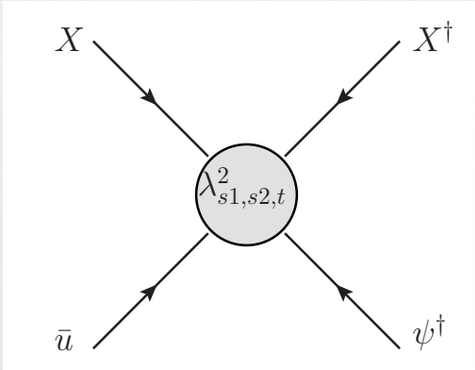
EFT diagrams from Bernal et al., *2012*

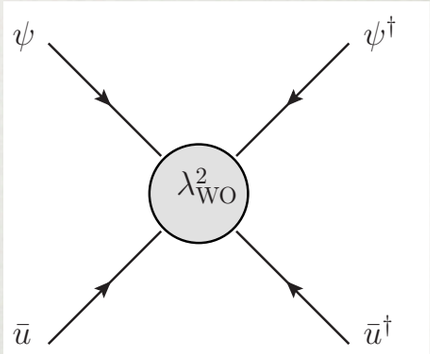
WIMPy Baryogenesis

3. Departure from Thermal Equilibrium

- Opening the loop gives rise to washout processes
- We want these to be inactive at some point during DM annihilation







$$\Gamma_{\rm washout} \sim \langle \sigma\, v_{\psi\bar{u}\to\psi^\dagger\bar{u}^\dagger}\rangle Y_\psi Y_u + \ldots$$

$$\Gamma_{\rm DM\,ann.} \sim \langle \sigma\, v_{XX\to\psi\bar{u}}\rangle Y_X$$

- Annihilation, asymmetry production and washout depend on same couplings
- Generally, washout only freezes out before DM annihilation for $M_X \lesssim M_\psi \lesssim 2M_X$ and ψ in equilbrium

Can be somewhat relaxed in EFT (Bernal et al.*, 2012)*

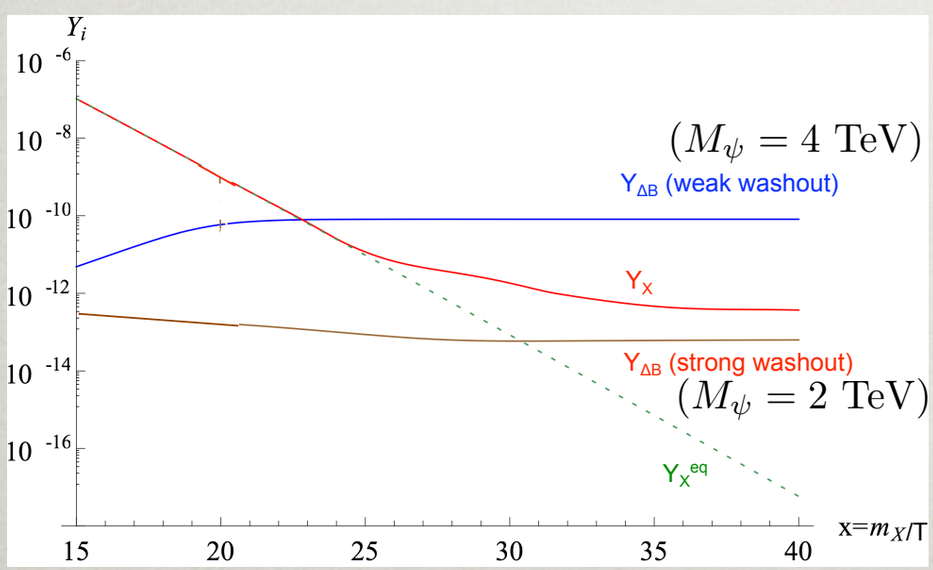
WIMPy Baryogenesis: Asymmetry

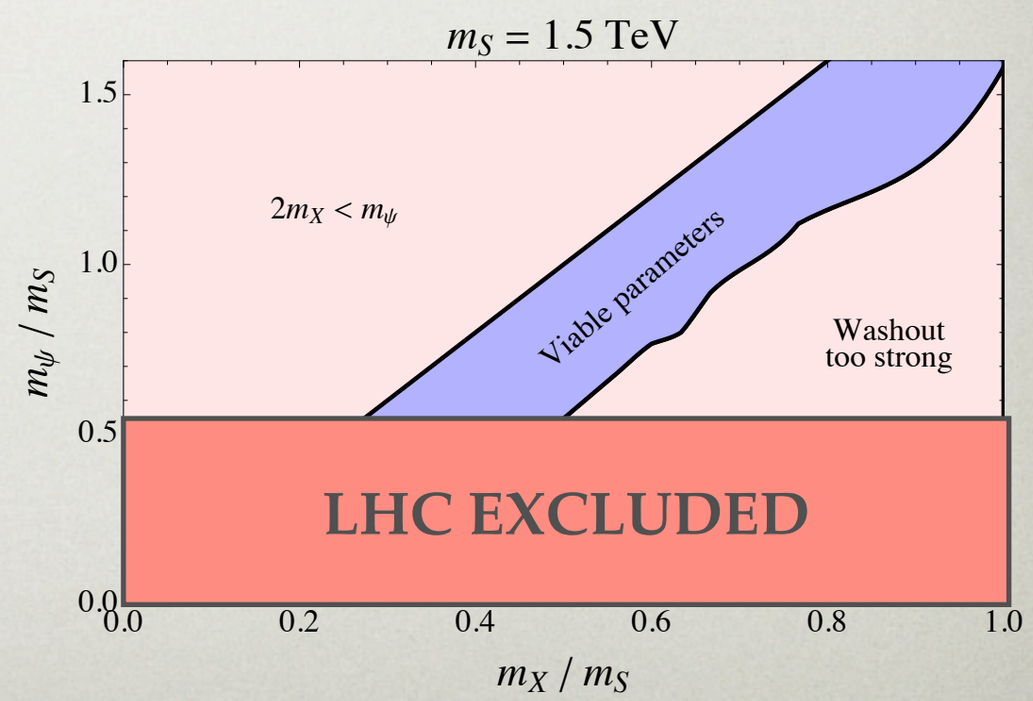
Example simplified model:

$$\mathcal{L} \supset \lambda_i \, S_i X^2 + y_i \, S_i \psi \bar{u} + \frac{1}{\Lambda^2} (\psi \, n)(\bar{u}^\dagger \bar{d}^\dagger) + \text{h.c.}$$

- *S* is real scalar mediator
- *n* is a Majorana singlet (can be dark radiation), keeps ψ in equilibrium
- Avoid ψ-quark mixing due to some discrete (or global) symmetry
- Can have **leptogenesis** if ψ instead couples to leptons

$M_S = 5$ TeV, $M_X = 3$ TeV



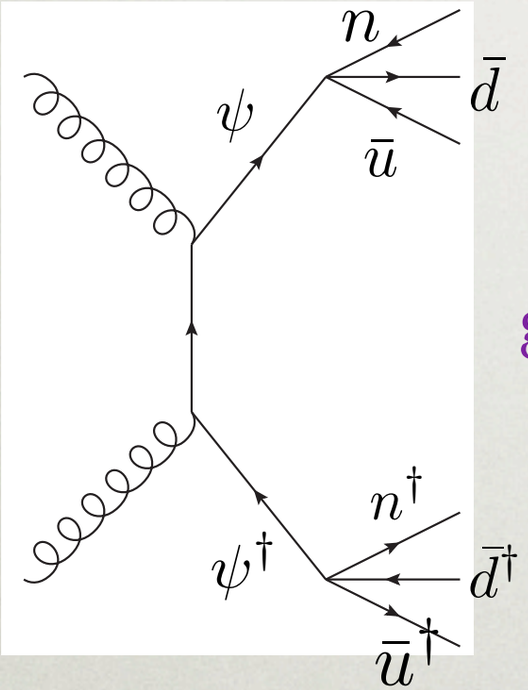


WIMPy Baryogenesis: Pheno

Colliders are the best way of probing WIMPy baryogenesis!

Direct Baryogenesis $(XX \to \bar{u}\psi)$

$$\Delta\mathcal{L} = \frac{1}{\Lambda^2}(\psi n)(\bar{u}^\dagger \bar{d}^\dagger)$$



gluino-like

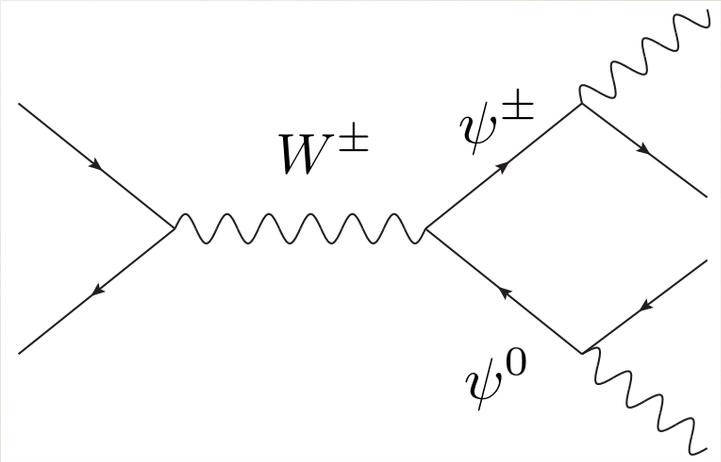
	M_ψ bound
8 TeV, 20/fb:	1.35 TeV
14 TeV, 3/ab:	2.5 TeV
100 TeV, 3/ab:	11.5 TeV

Recast from Cohen et al., *2013 (Snowmass)*

Leptogenesis $(XX \to L\psi)$

$$\Delta\mathcal{L} = LH^* n$$

wino-like

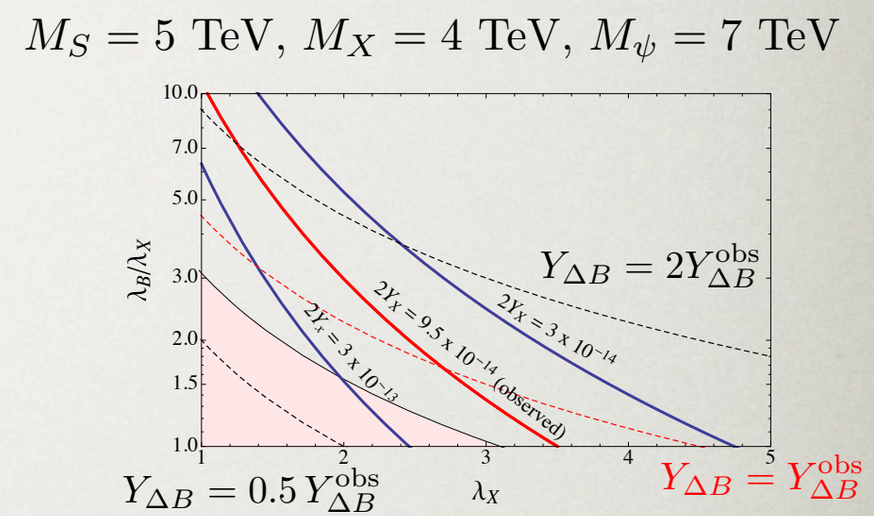


	M_ψ bound
8 TeV, 20/fb:	720 GeV
14 TeV, 3/ab:	1 TeV
100 TeV, 3/ab:	3.3 TeV

Gori, Jung, Wang, Wells 2014

WIMPy Baryogenesis: Pheno

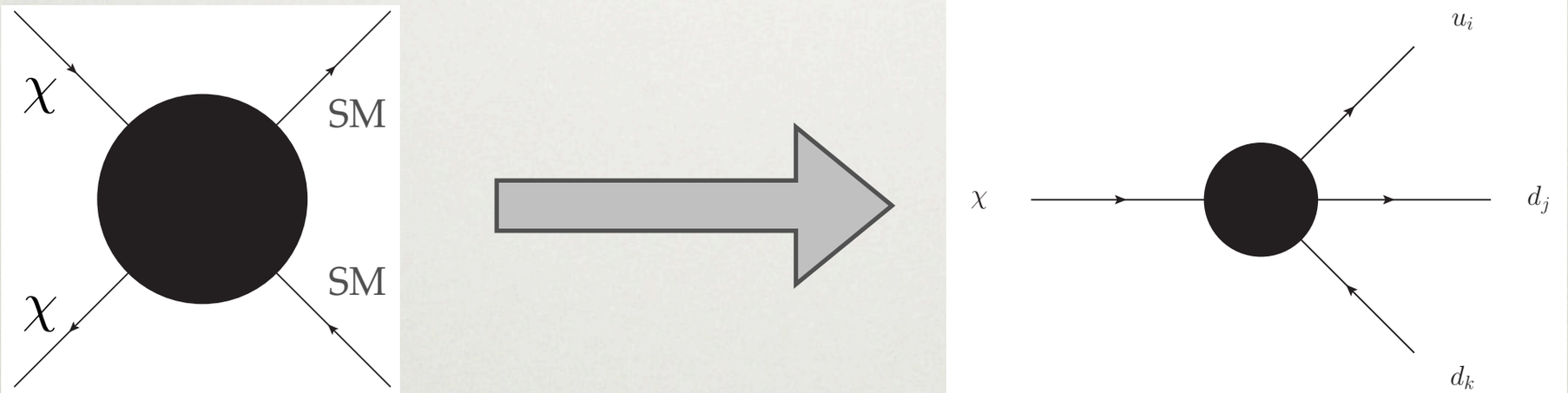
- Perturbative direct baryogenesis parameter space largely covered @ 100 TeV, 3/ab
- Leptogenesis more challenging near perturbativity limit
- In extended models, other signatures are possible (ex: RPV-like decays of charged states)



Other possible constraints:

1. EDMs
   - Naïve two-loop result cancels, giving suppressed EDMs in minimal model (may be larger in extended models)
2. Direct detection
   - Naïve one-loop result cancels, giving velocity-suppressed spin-independent rates
3. Indirect detection
   - Subdominant to collider constraints (but more model-independent)

Baryogenesis from WIMP Decay



Baryogenesis from WIMP Decay

- In WIMPy baryogenesis, baryogenesis comes from WIMP dynamics **but** the asymmetry is not directly related to the WIMP abundance

- Alternatively, if DM is produced through the decay of a meta-stable WIMP, the asymmetry is automatically proportional to a DM-like abundance

$$\epsilon = \frac{\Gamma(\chi \to B) - \Gamma(\chi \to \bar{B})}{\Gamma(\chi \to B) + \Gamma(\chi \to \bar{B})} \qquad \Omega_{\Delta B} \approx \epsilon \, \frac{M_{\rm nucleon}}{M_\chi} \Omega_\chi^{\tau_\chi \to \infty}$$

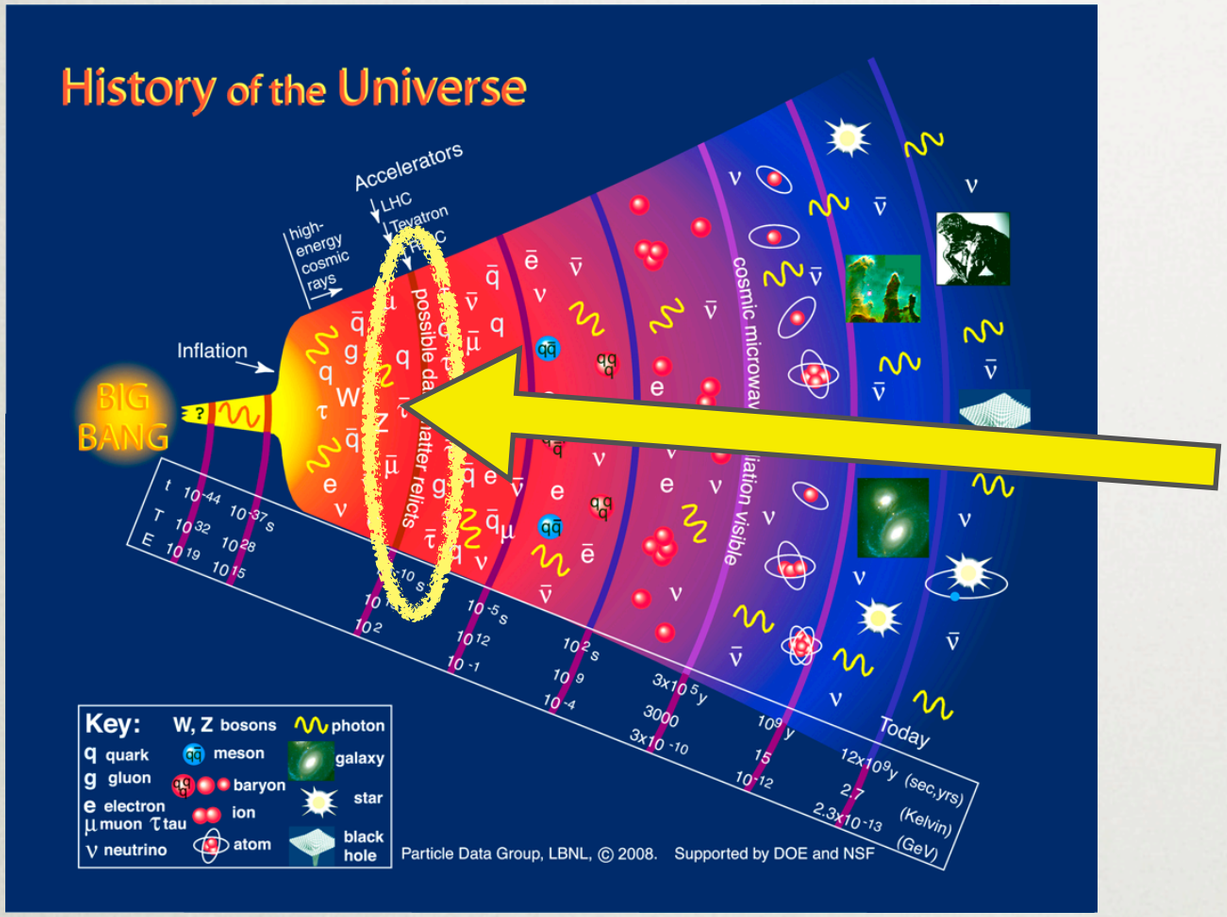
Cui, Sundrum 2012

- WIMP dynamics can give an **overabundance** of χ, compensating for the suppression factors

- To inherit the freeze-out abundance, $\Gamma_\chi \lesssim H(T_{\rm f.o.})$
  - Earlier decay can generate some asymmetry, but it is diluted due to rapid χ scattering

Baryogenesis from WIMP Decay

- How big was the universe around the weak scale?



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

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

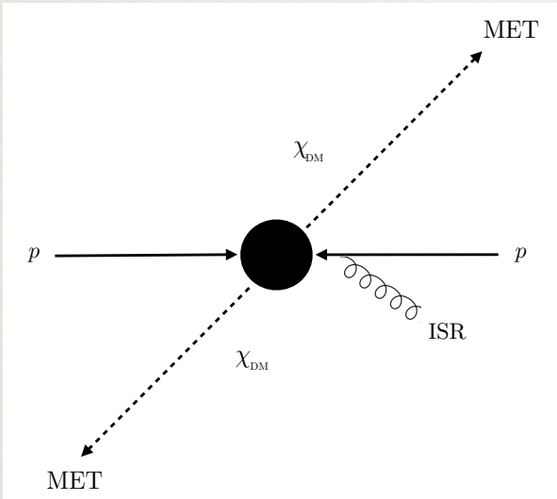
$$1\ \text{TeV} \to (0.13\ \text{mm})^{-1}$$

- Recall $z_{\text{f.o.}} \sim 20$
- For WIMP masses ~100 GeV-TeV, the particle is long-lived *if we can make it at a collider!*
- Heavier particles are closer to *B* lifetime, but mass discrimination is better

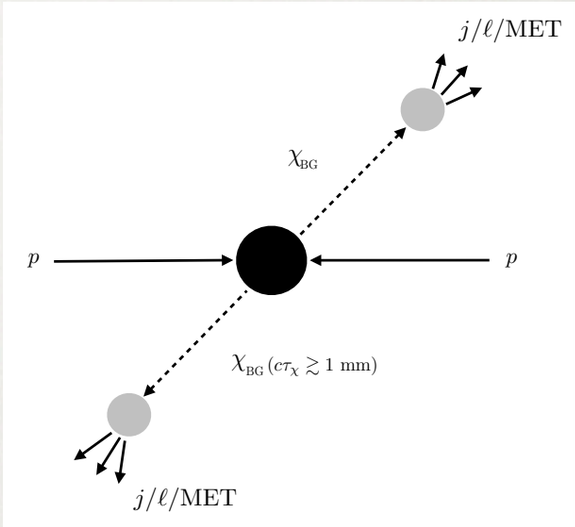
see also Barry, Graham, Rajendran 2013

Baryogenesis from WIMP Decay

- The method of collider production is similar to DM: cross the diagram



vs.



- Large production + late decay consistent with **approximate** stability symmetry
- Direct link between cosmological condition and collider signature
- Look at representative models to see possible production modes, and then use simplified models approach for collider study

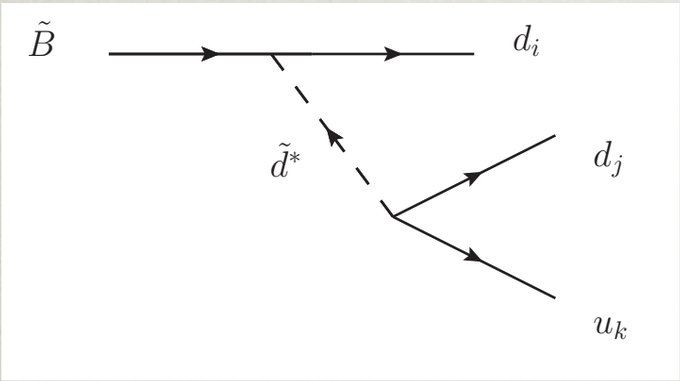
SUSY Model

- An RPV-SUSY model illustrates the possible long-lived particles
  - Many *CP* phases (ex. gaugino masses)
  - *B-L* violation can come from udd, QdL, LLE-type superpotential terms or RPV terms in Kähler potential
  - Mini-split spectrum alleviates EDM constraints, makes LSP long-lived

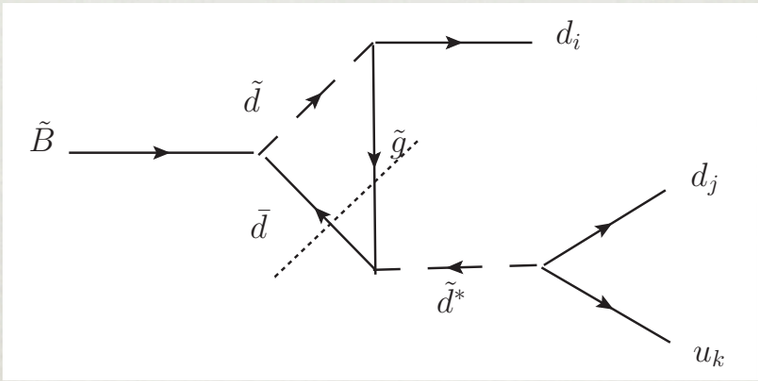
Cui 2013

- Bino typically gives overabundance, so it is a natural candidate for χ
  - Asymmetry is largest when there is some other on-shell Majorana state that can run in loop

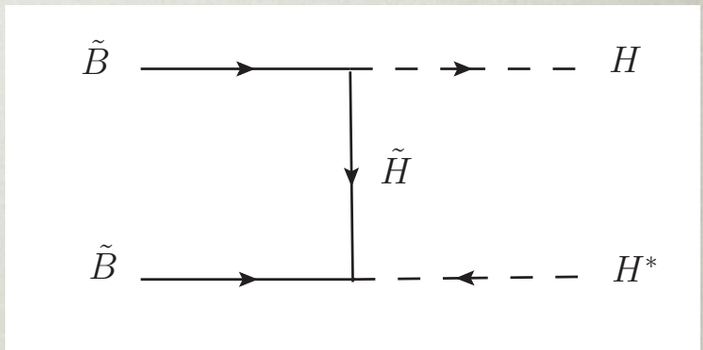
Tree-level Decay



Loop-level Decay



Freeze-out



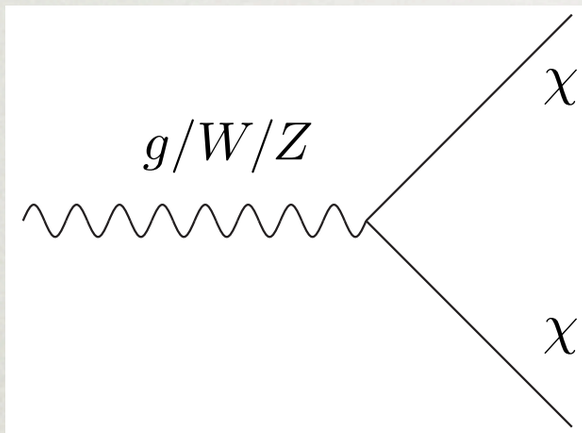
- Can also have light **gauge-charged** states with same parametric lifetime

WIMP decay baryogenesis: Pheno

Cui, BS 2014

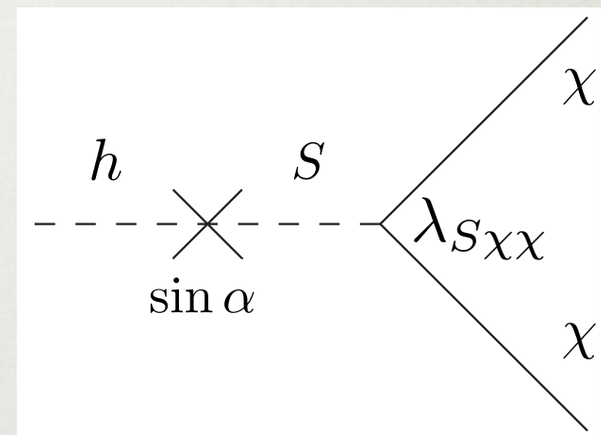
- Similar to EWBG, factorize CPV from equilibrium criterion
- By analogy with DM, classify pair production modes, such as...

SM gauge interactions:
Majorana = gaugino-like (wino)

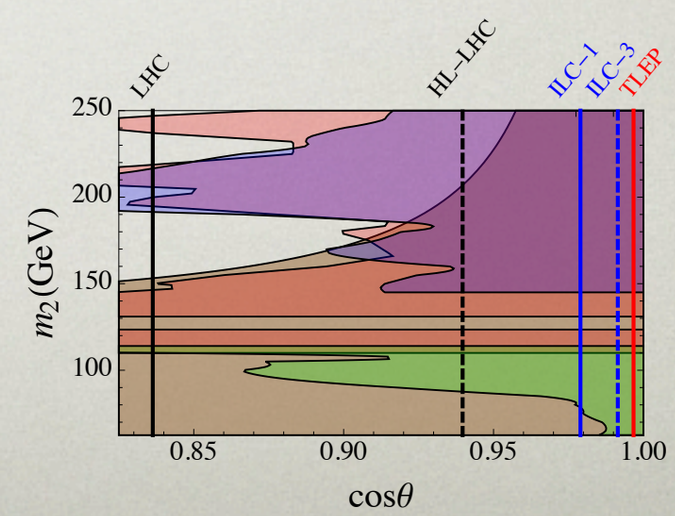


coupling fixed, can study **mass reach**

Higgs portal:
singlet-like



fix χ mass @ 150 GeV, study **coupling reach**



- Model-independent constraints on Higgs mixing relatively weak

Profumo, Ramsey-Musolf, Wainwright, Winslow 2014

WIMP decay baryogenesis: Pheno

- **Unlike** DM, we also have to specify decay modes (also two examples):

Baryon number violating:

$\chi \to u_i d_j d_k$ $\qquad$ $\chi \to Q_i Q_j (d_k^c)^\dagger$

displaced jets (all-hadronic)

CMS, arXiv:1411.6530

Lepton number violating:

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

displaced muon + hadrons

ATLAS-CONF-2013-092

- We specifically looked at inner-detector decays (consistent with saturating cosmological criteria), but decays in other components important too

- Very low SM backgrounds give good sensitivity even for small cross sections

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

In context of naturalness: Craig et al., *2015; Csaki* et al., *2015;*

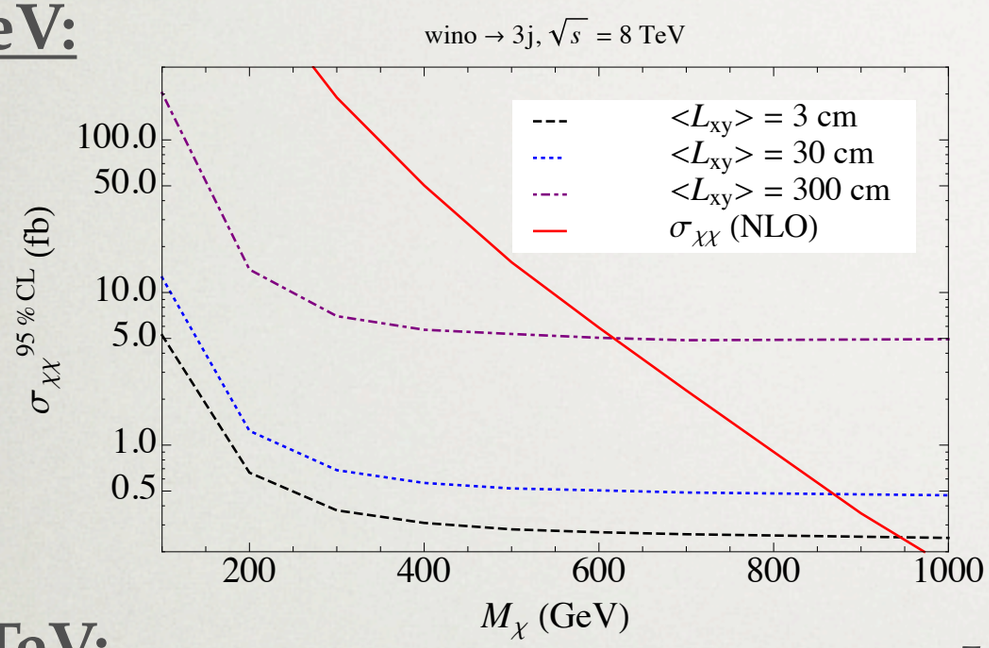
Fully hadronic displaced vertices

wino

singlet (Higgs portal)

(singlet-like, M_χ = 150 GeV)

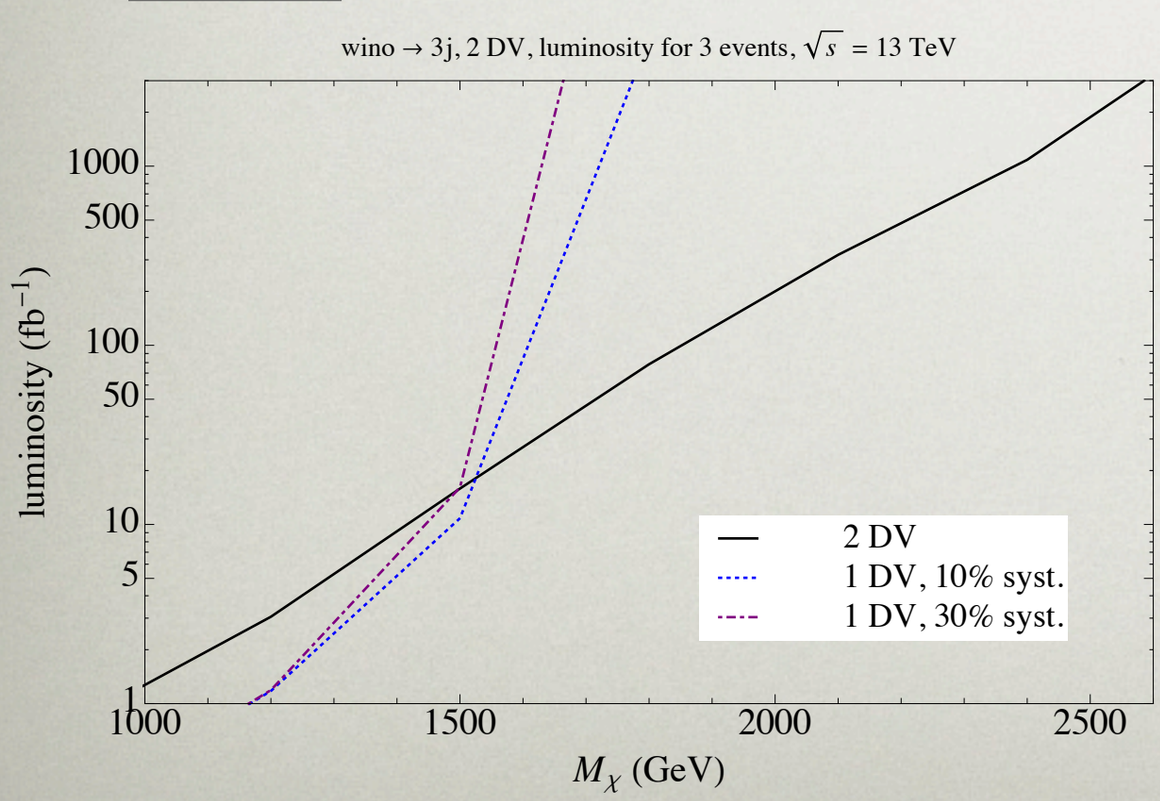
8 TeV:

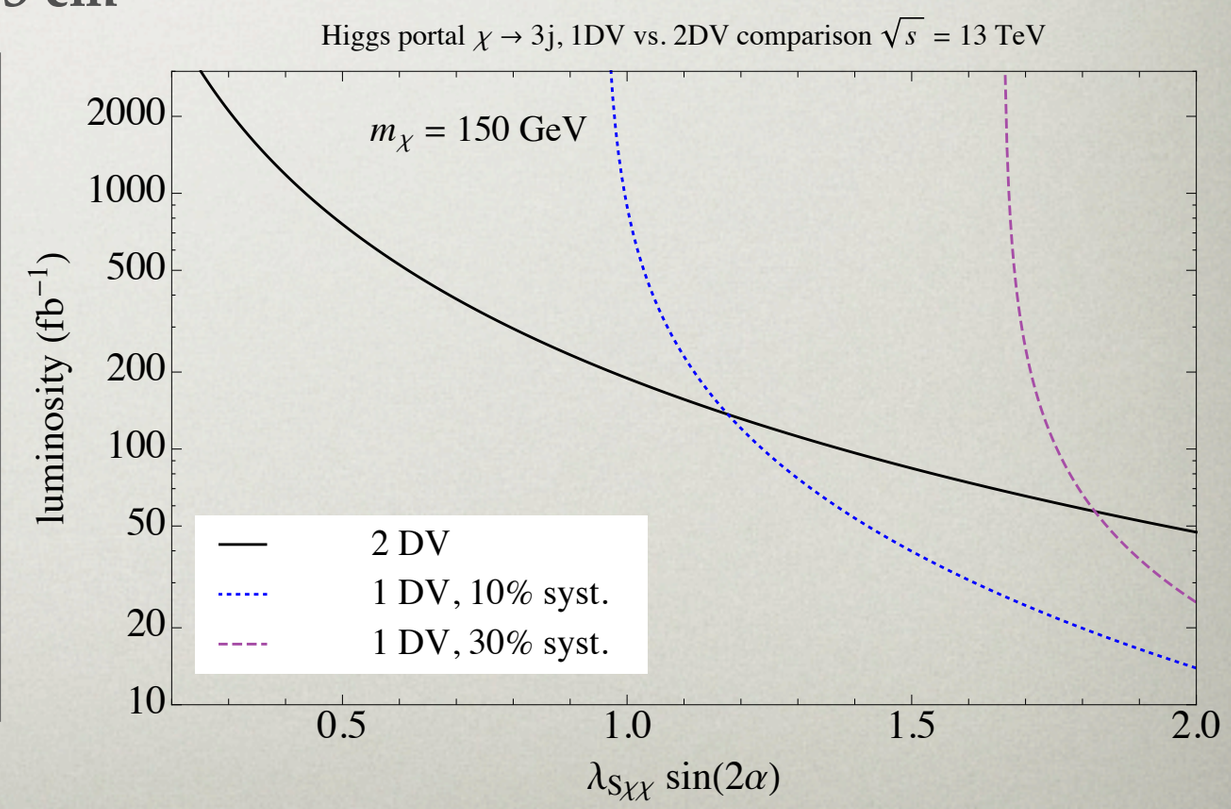


no bound

13 TeV:

L_{xy} = 3 cm





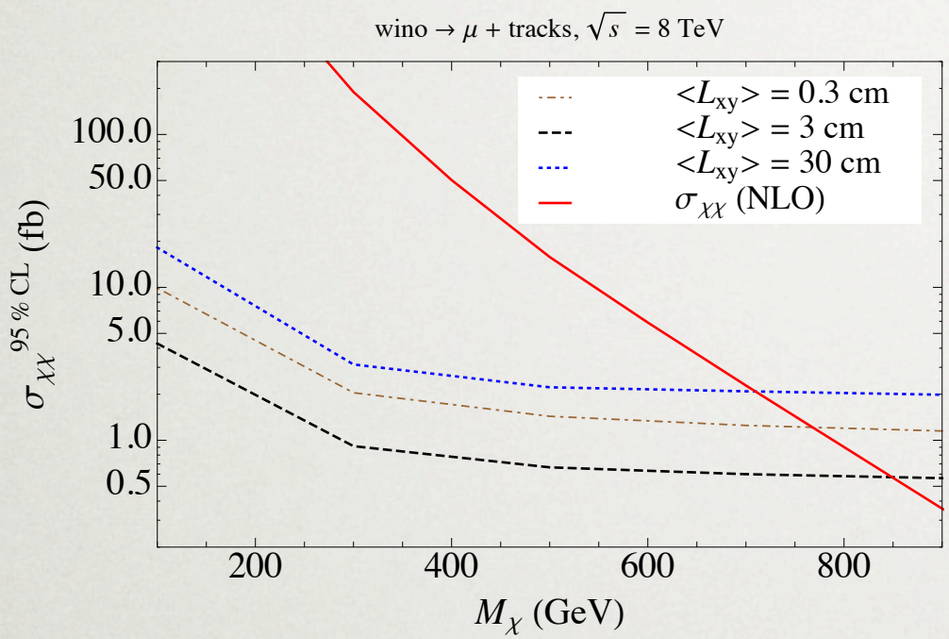
Displaced muon + hadrons

wino

singlet (Higgs portal)

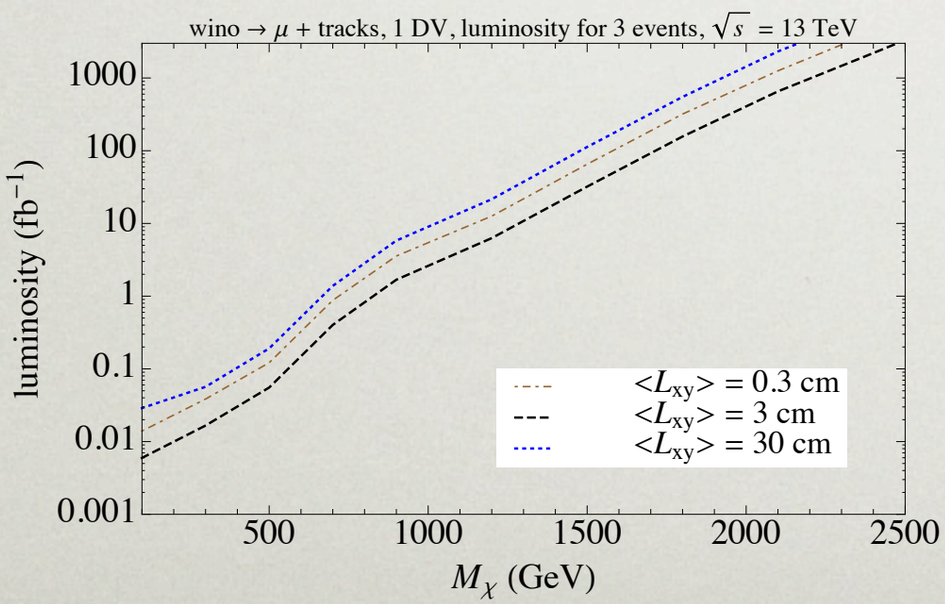
(singlet-like, $M_\chi = 150$ GeV)

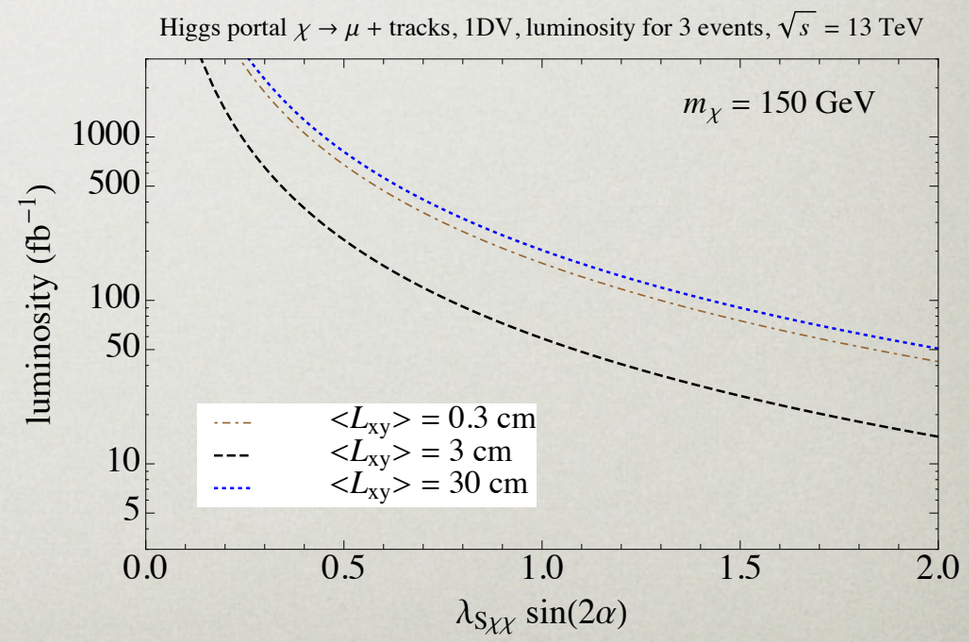
8 TeV



no bound

13 TeV





Prospects for HL/HE running

- Decays in other components: easy to trigger, harder to reconstruct
    - Best sensitivity ~3 orders of magnitude worse than inner detector
- High-mass physics: should have sensitivity up to kinematic limit!
- Main challenge is triggering on **all-hadronic**, **low-mass** new physics
    - Hidden valleys (Strassler, Zurek 2006)
    - Exotic Higgs decays (review: Curtin *et al.*, 2013)
    - Neutral naturalness (Craig *et al.*, 2015; Curtin, Verhaaren 2015)
- Other trigger options
    - Associated objects
    - "Volunteers"
    - Trackless jets or other use of tracking information
    - LHCb (better for high-multiplicity objects like emerging jets)

Schwaller, Stolarski, Weiler 2015

Implications of Phase Transition

- In neither scenario are there direct links to the EWPT
    - **Leptogenesis** must occur prior to EWPT, so modifying the transition can change the allowed parameter space

- Phase transitions change masses of fields
    - If fields get their mass from symmetry breaking, this can change particle abundances and asymmetries, generate out-of-equilibrium abundances

- Finally, let's not forget low-scale leptogenesis, which can be tested by:
    - SHiP
    - Exotic Higgs sectors *(BS, Yavin 2014)*
    - *B*-factories/LHCb
    - LHC + 100 TeV collider *(Izaguirre, BS 2015; Batell, Pospelov, BS in progress)*
    - ....

MANY , MANY REFERENCES!!

Conclusions

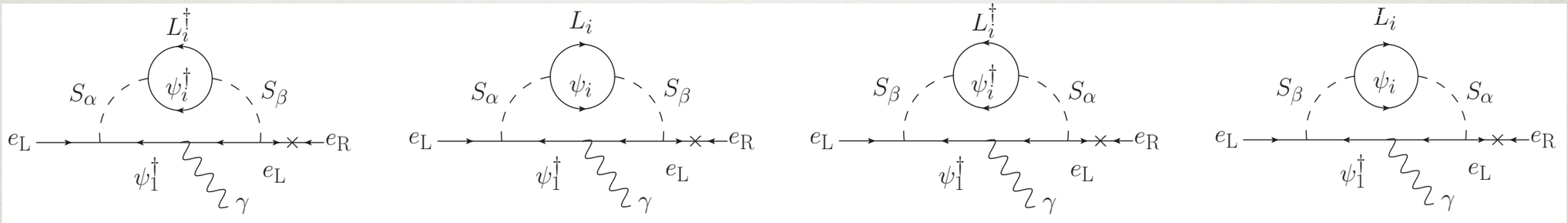
- WIMP-like dynamics can generate a baryon asymmetry in several ways, definitively linked to the weak scale
- Colliders serve as excellent probes of this new physics
- 100 TeV collider would allow the comprehensive study of the most favoured regions for WIMP-driven baryogenesis

Back-up slides

WIMPy Baryogenesis: Pheno

Other possible constraints:

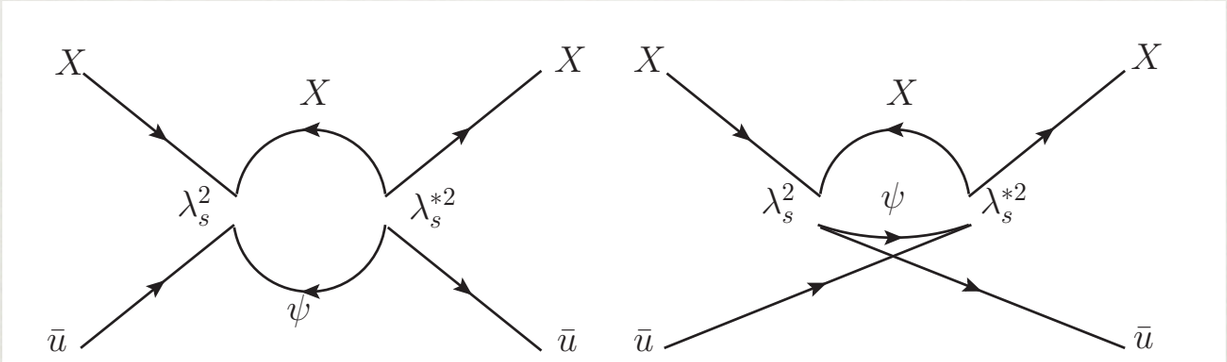
1. EDMs
   - In the minimal model, new physics only couples to one chirality of fermion
   - Gives cancellation when summing over diagrams at two loops
   - In the quark-coupled model, may have EDM at 10^{-31} e cm level
   - CPV can be very large in extended models



WIMPy Baryogenesis: Pheno

Other possible constraints:

2. Direct detection
   - In the quark-coupled model, direct detection occurs naïvely at 1-loop
   - However, there is a cancellation among diagrams to give a v-suppressed rate
   - Again, this may be different beyond the minimal model

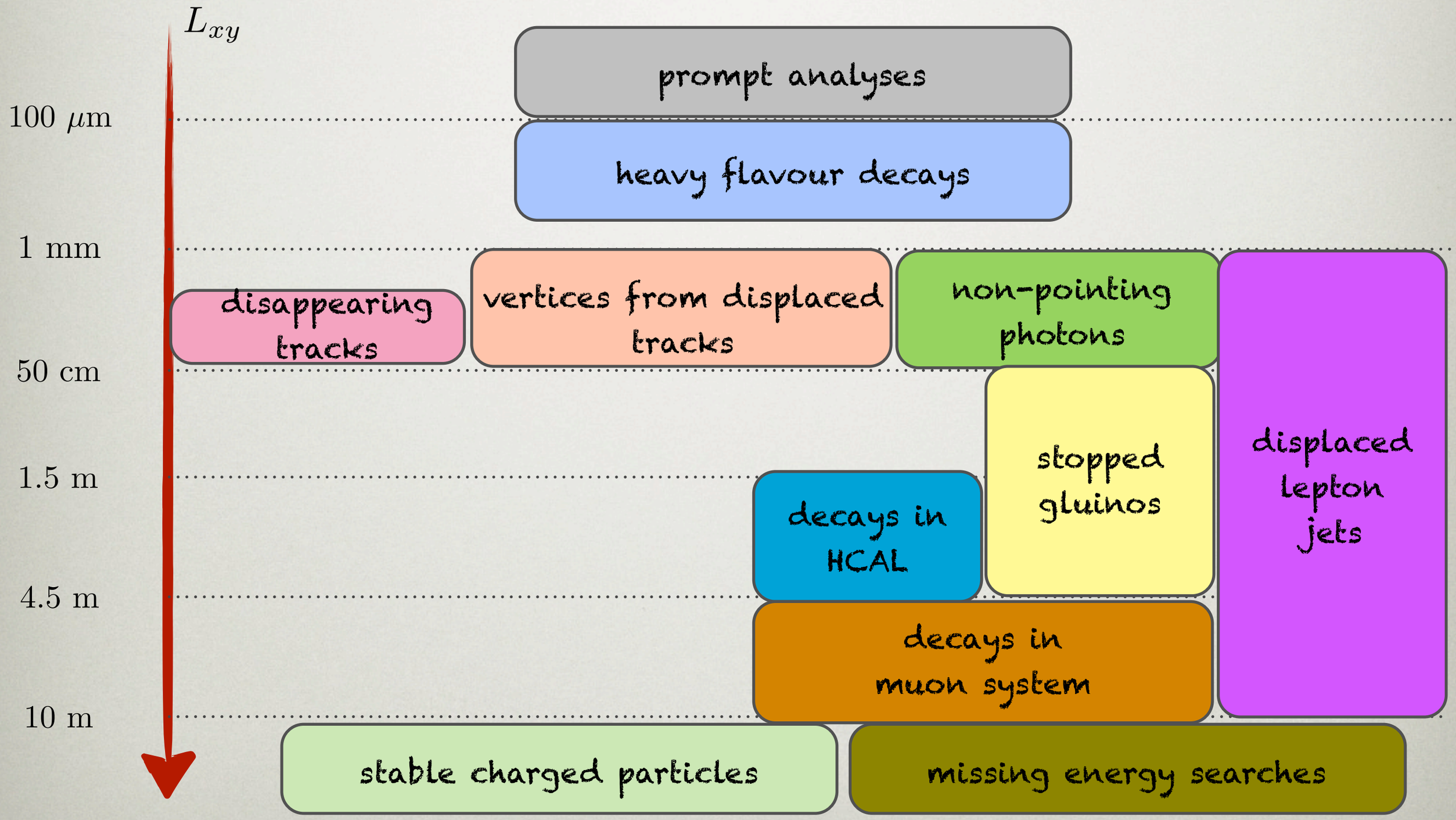


3. Indirect detection
   - Comparable to regular WIMPs annihilating to hadrons, gauge bosons, subdominant to collider constraints (but more model-independent)

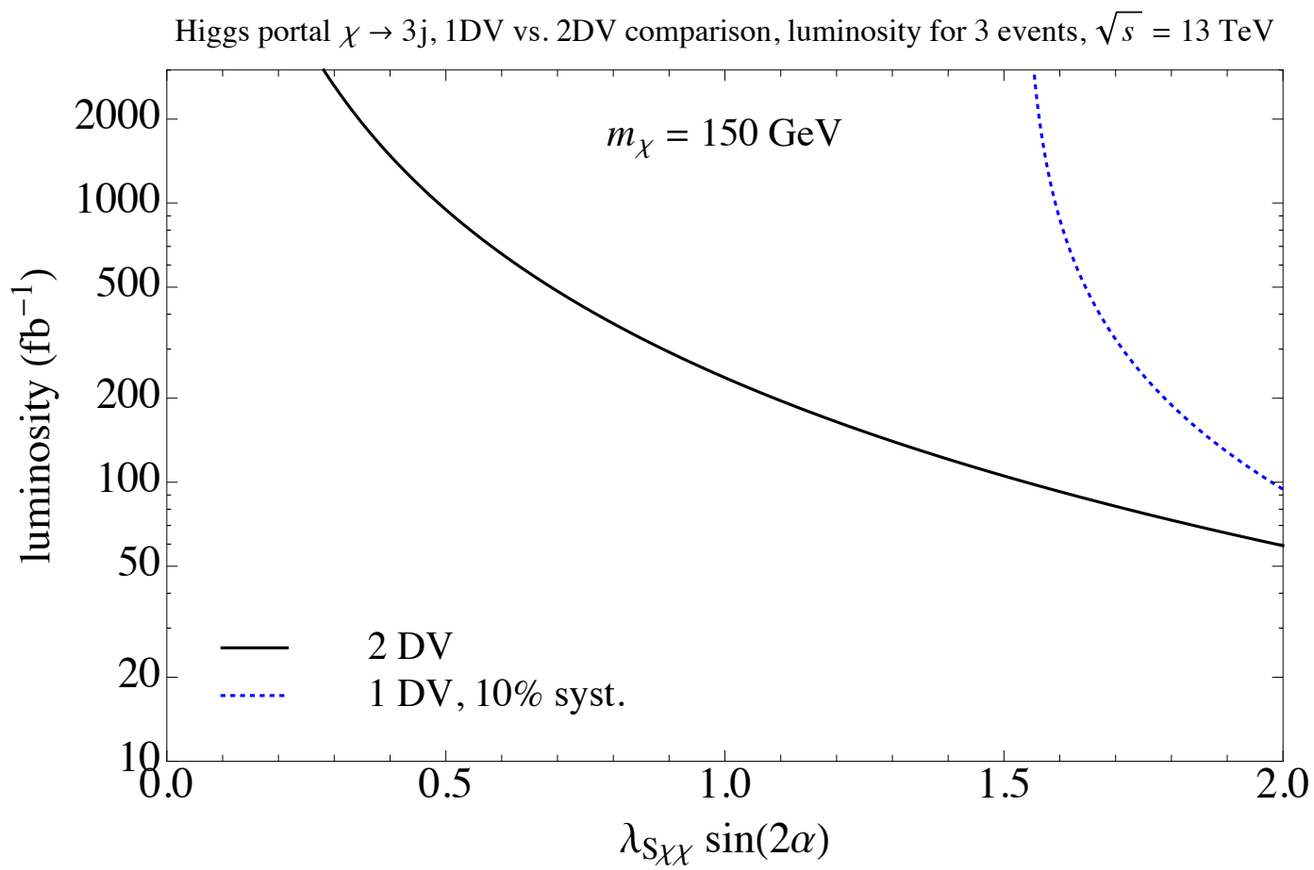
- Other bounds (flavour, n-nbar oscillation) could be large, are model-dependent

LHC Search Possibilities

exotica & SUSY



Displaced Jet Bounds



(b) $\langle L_{xy} \rangle = 30$ cm

Decays in Other Components

Can also have decays in calorimeters and muon system

HCAL **muon system (MS)**

(ATLAS - ar v:1504.03634)

trigger c on large,
no ECAL ivity in MS

2 long-live tracker
decaying or MS

- Commo
  - places
  - Need stringent criteria + 2DV to suppress backgrounds
  - Worse limits than tracker decays for high-mass objects, comparable for low-mass
  - Thresholds won't go up significantly for future running