Long-lived New Particles through the Higgs Portal

— Theoretical Motivations & LHC Searches

Yanou Cui

Perimeter Institute for Theoretical Physics

Exotic Higgs Decay Workshop
FermiLab, May 21 2015

Outline

- **Theoretical motivations for displaced Higgs decay:**
  - **Hidden Naturalness:** Twin Higgs (hidden valley)
  - **Cosmology at weak scale:** baryogenesis (NEW)
- **Recast existing LHC analyses with theorists' tools:**

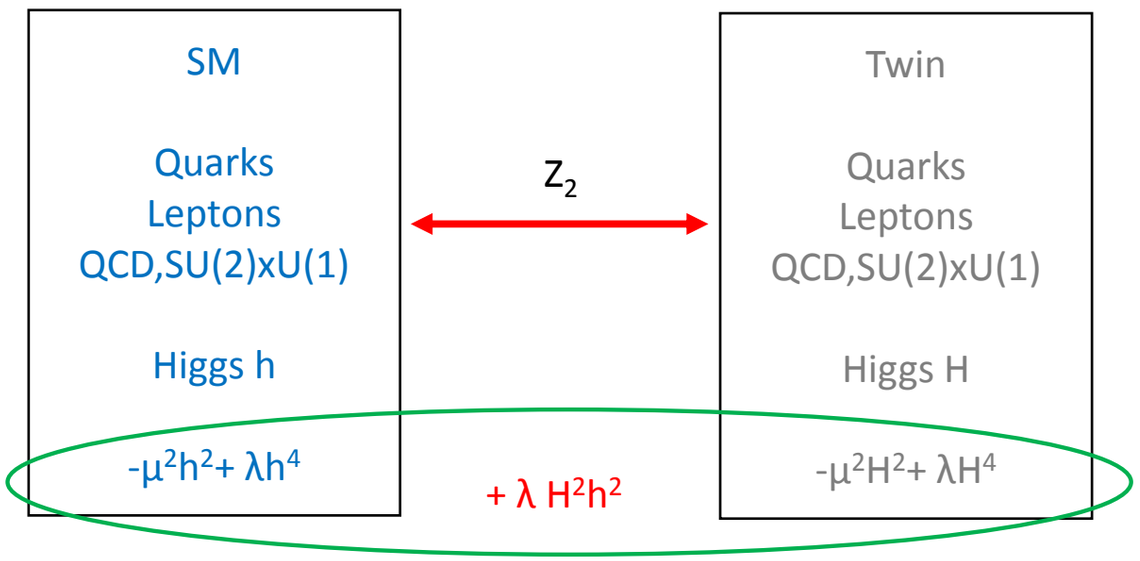
  Baryogenesis as an example, easy to generalize!
- **Summary, Suggestions for future development**

  (discussion session!)

Theoretical Motivations-1:

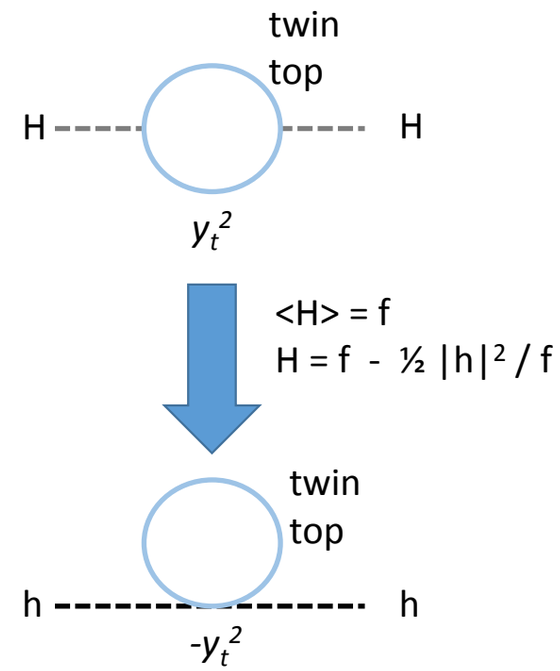
Hidden Naturalness

- **Naturalness Puzzle**
  - (So far) No sign of conventional favorite solutions
    (SUSY, little Higgs, extra dim…)
  - Hidden naturalness? Twin Higgs (Chacko, Goh, Harnik, 2005)



SU(4)

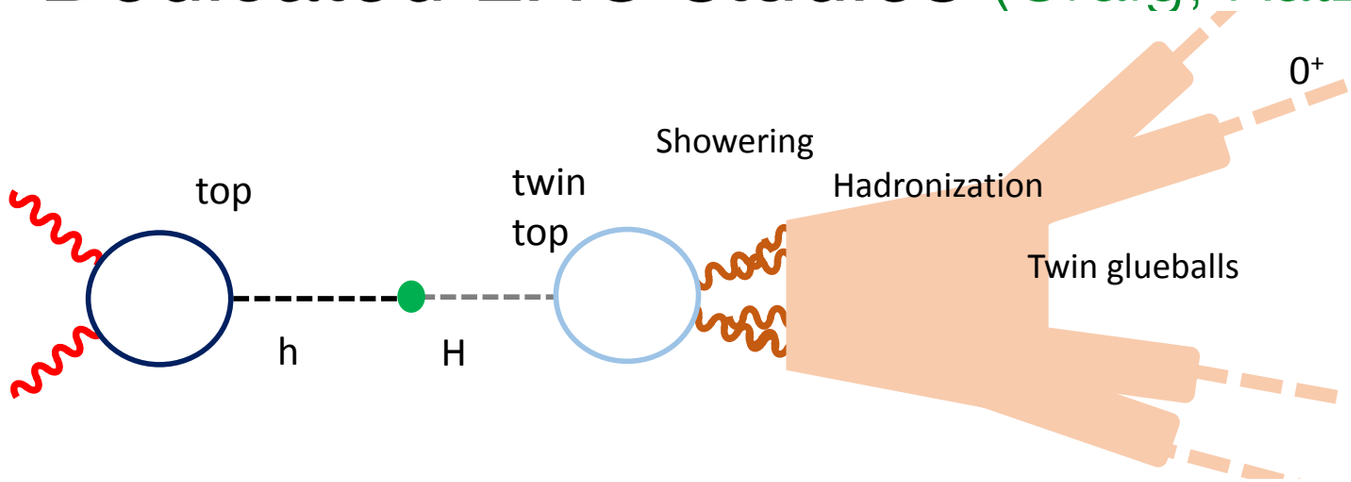
Quadratic divergence canceled by SM-singlet twin top:



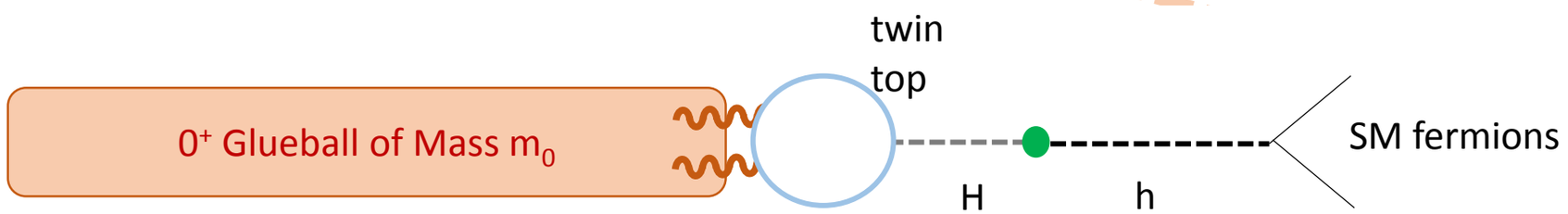
- SM higgs h is a portal to hidden, twin sector
  <H> = f » <h> = v

(More detail see M. Strassler's talk at an earlier exotic-h decay meeting, refs.)

- Hidden valley type phenomenology (Strassler, Zurek 2006)
- Dedicated LHC studies (Craig, Katz, Strassler, Sundrum 2015)



Br (h→ twin gluons) ~ 0.1% for f = 3 v



- Unlucky case: twin glueball decay invisible or prompt visible (large bkg); LHC sensitivity only Br≈10% (possible), hope: future e^+e^- collider (invisible: e.g. Chacko, **YC**, Hong, 2013)
- Lucky case: twin glueball decays into spectacular visible final states w/low bkg; few examples ∋ **Displaced decay!**

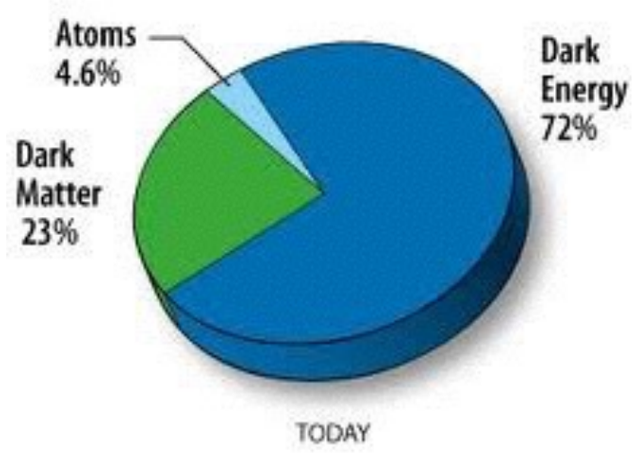
☞ **Displaced Higgs decay: Rare opportunity for LHC to probe generic param space of Hidden Naturalness!**

Theoretical Motivations-2:

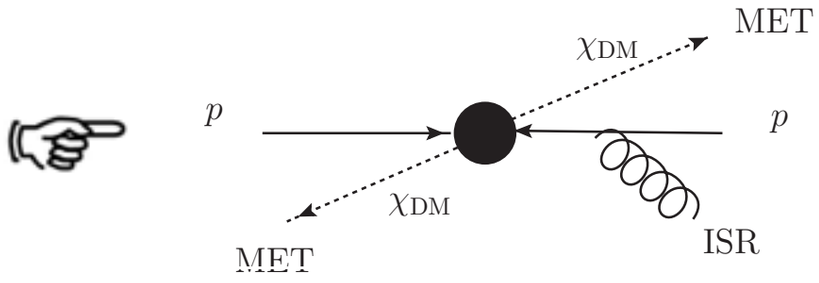
Baryogenesis from Metastable Weak-scale New Particle

Could LHC 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})
  - Mass ~O(10-100) GeV, can be produced within E_{LHC} =14 TeV
  - Pair produced (Z_2), invisible, MET + X



- **New opportunity**: baryogenesis (Ω_B , possibly + $\Omega_B \sim \Omega_{DM}$)
  - New <u>metastable</u> particle, w/mass ~O(10-100) GeV
  - Pair produced (approx. Z_2), Higgs portal production in general
  - Displaced decay to $j/\ell/\mathrm{MET}$ by cosmological condition!

Mini-Review of Baryogenesis

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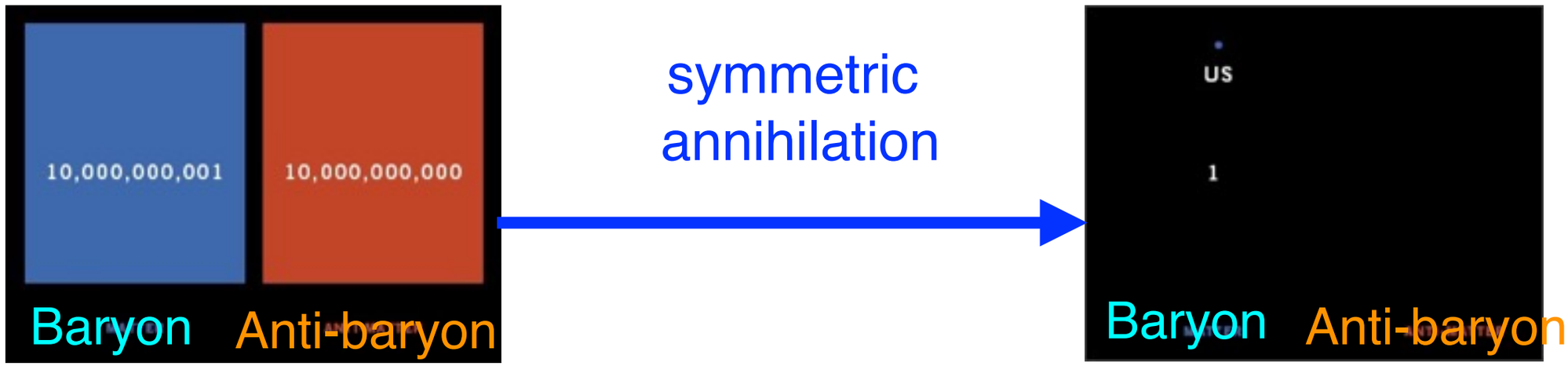

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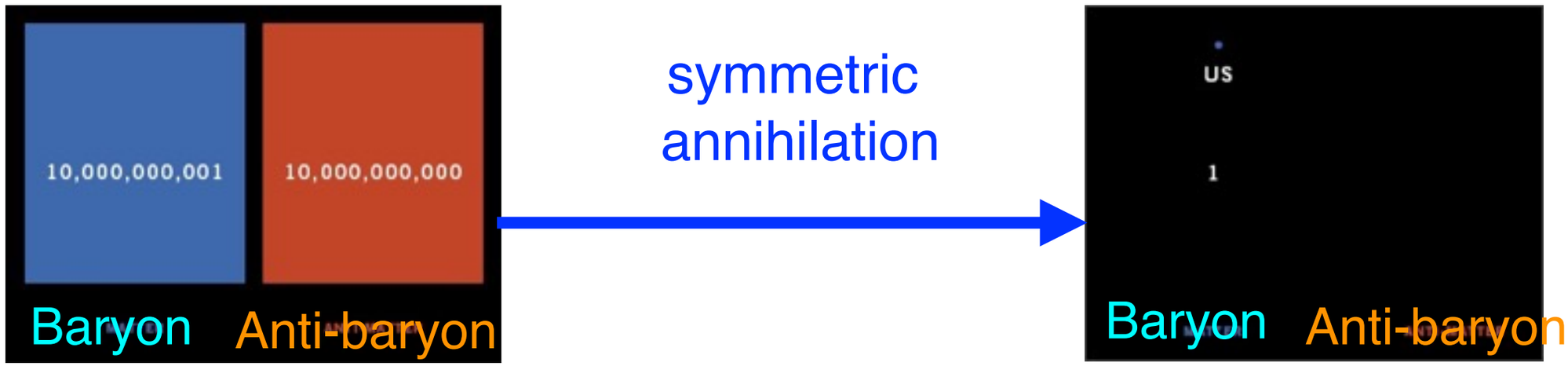
$$\eta_B = (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$$



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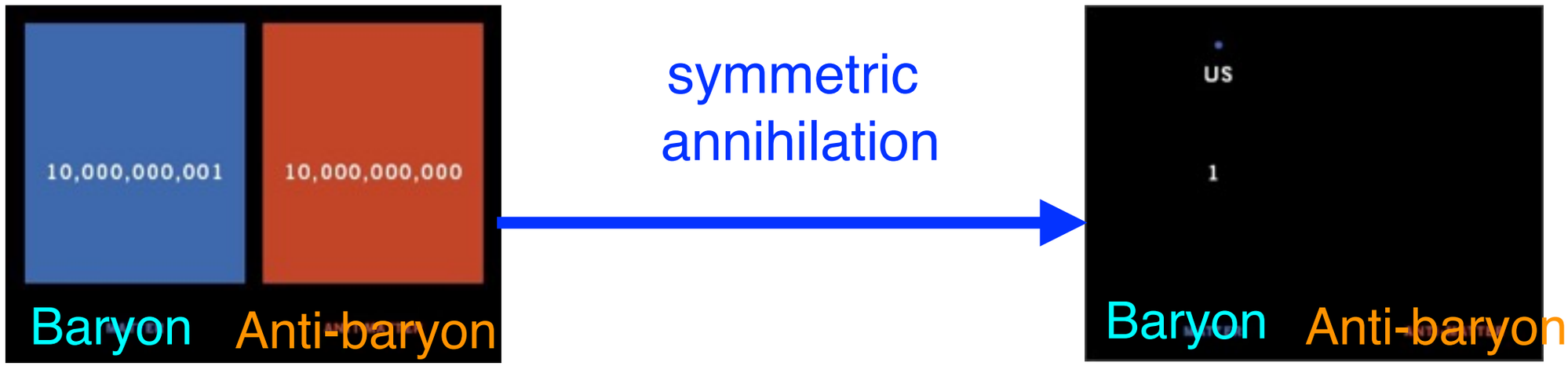

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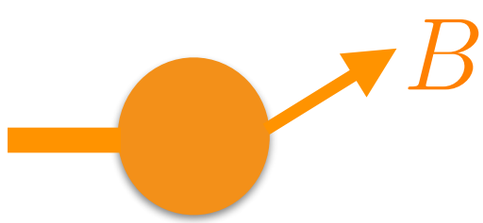

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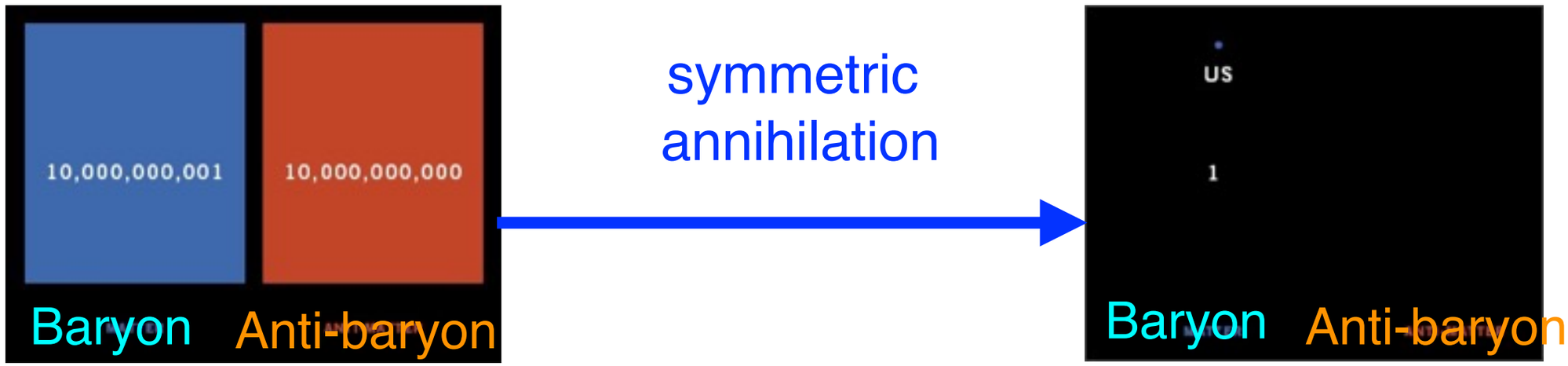

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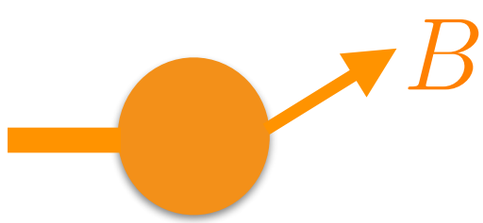
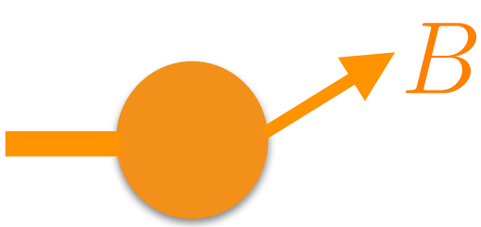


- **Require C-, CP-symmetry violation**



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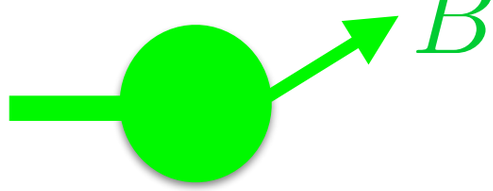

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Sakharov Conditions (cont.):

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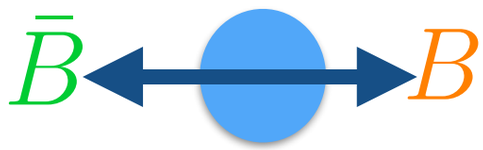

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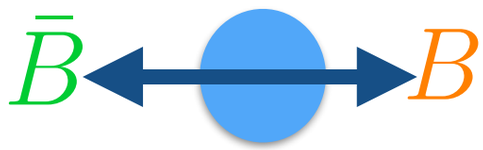

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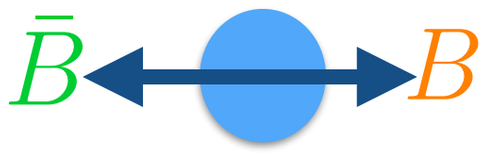

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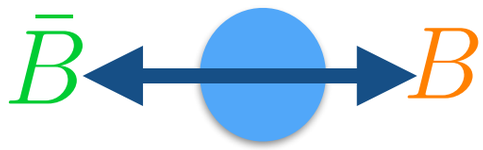

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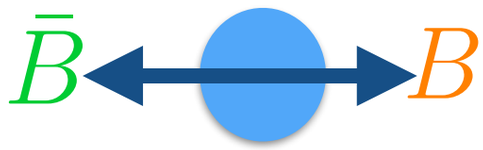

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- **Require departure from equilibrium!**

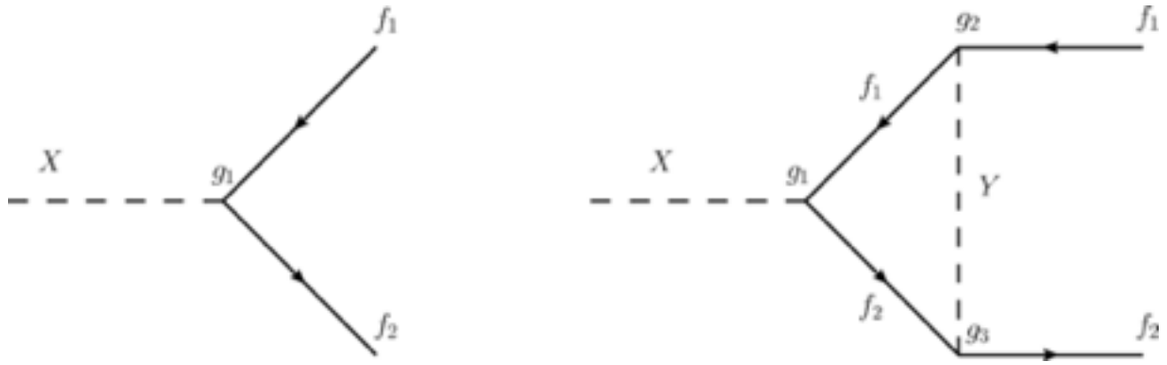
❖ Existing baryogenesis mechanisms: (leptogenesis, EWBG…)

Most involve high M or/and T, *direct* experimental test impossible (c.f. WIMP DM for $\Omega_{\rm DM}$)

Baryogenesis from Out-of-Equilibrium Decay

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

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



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

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

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

Inverse decay:
Boltzmann suppressed

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

☞ **Out-of-equilibrium decay** ⇨ Sakharov conditions ✓

Baryogenesis from Out-of-Equilibrium Decay

- Asymmetry is robustly preserved if (*H*: Hubble expansion rate)

$$\Gamma_\chi < H(T = M_\chi)$$ ☞ Weak washout scenario

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

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

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

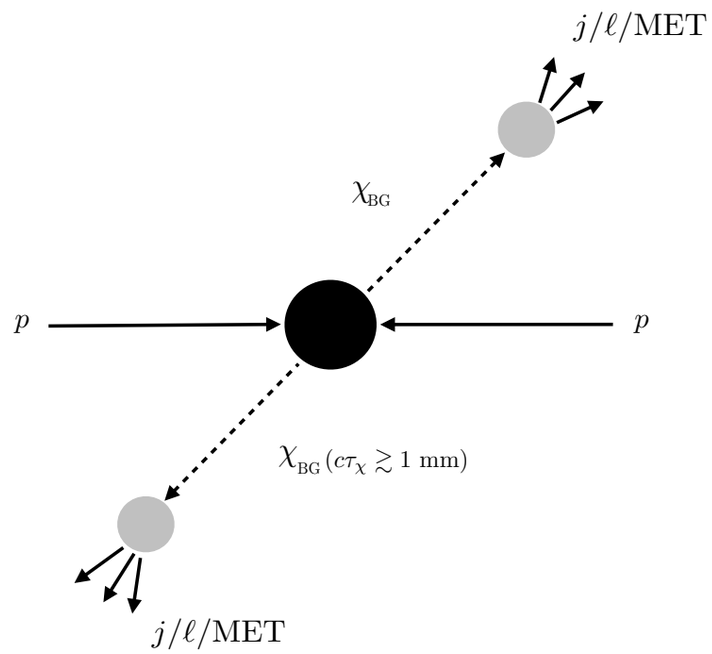
The universe around EW phase transition was just slightly bigger than LHC tracking resolution!

Displaced Vertices Motivated by Baryogenesis

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

- A **generic connection** between cosmological slow rates at *T ~100 GeV* and displaced vertices at colliders
- **Production at the LHC?**

No conflict between a **small** decay rate and a **large** production rate



- Long lifetime due to approximate symmetry (e.g. Z_2 parity)
- Recover MET signal for DM in the limit of exact symmetry!

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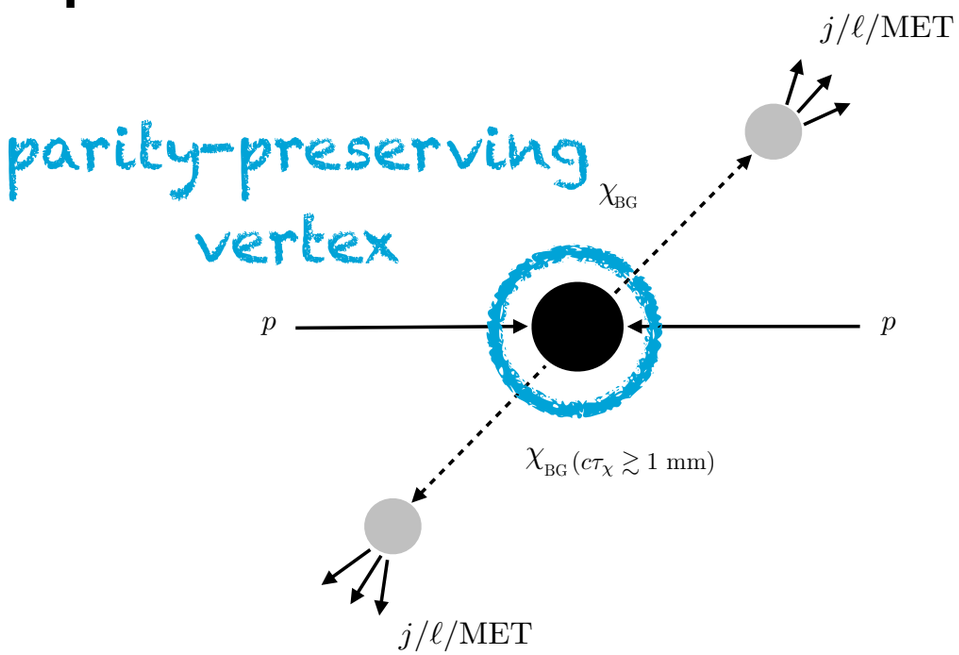

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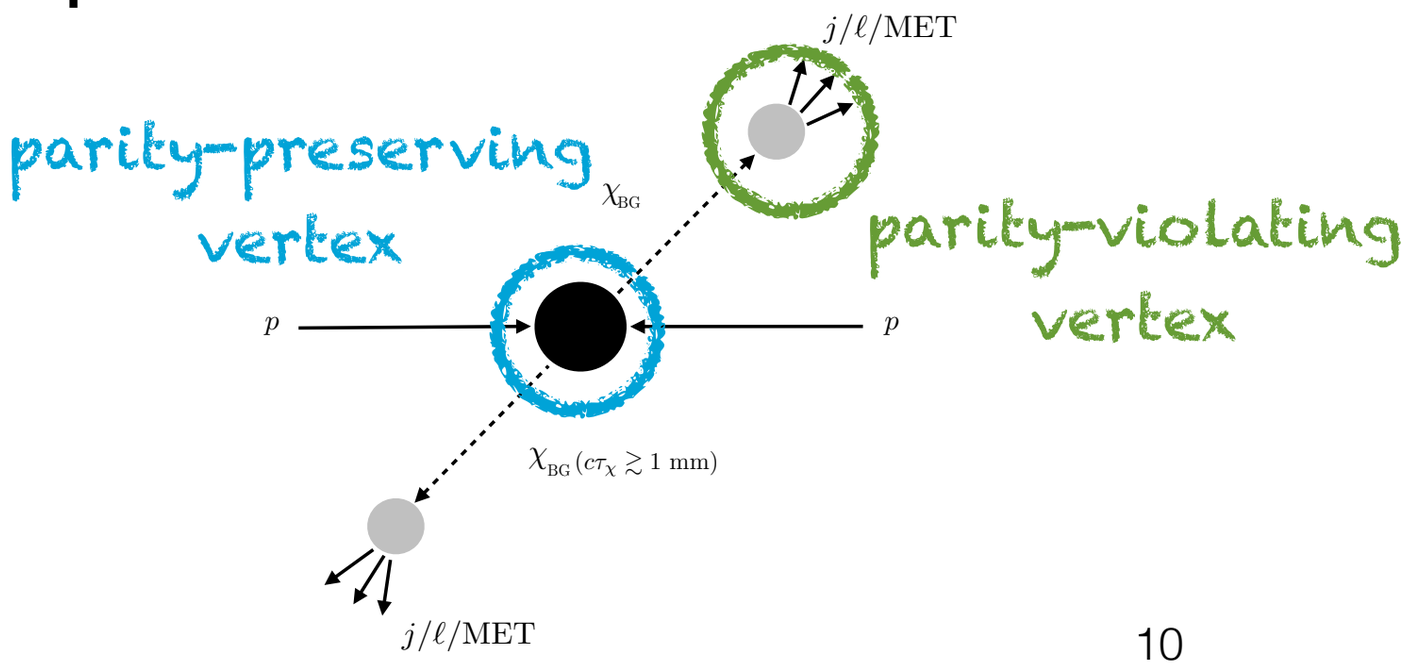

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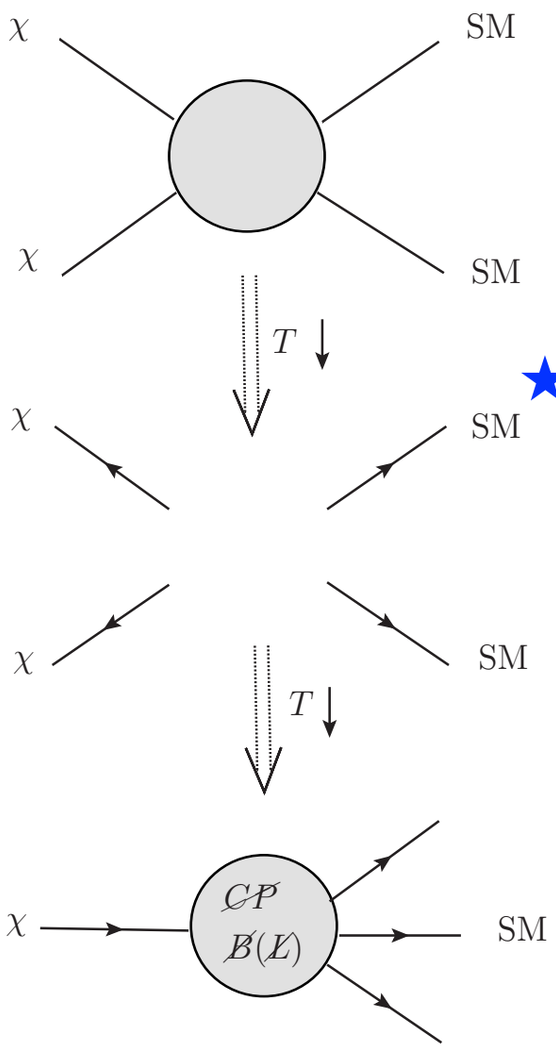
Example Theory Framework

- **Baryogenesis from Meta-stable WIMP Decay**

(**YC** and Sundrum, arxiv:1212.2973; **YC** arXiv:1309.2952)



★ Thermal freezeout

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

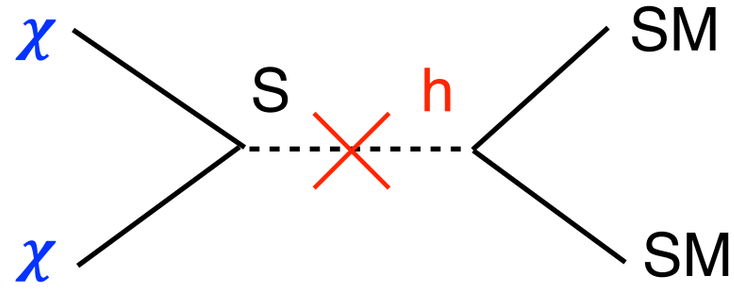
$$\Gamma_\chi \lesssim H(T_{\rm freezeout})$$

★ Baryogenesis from decay

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

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

☞ **Pair production of baryon parent WIMP at the LHC via Higgs-portal!**



Simplified Models

- Classify parity-invariant production modes (analogy to DM search @LHC!), e.g.

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

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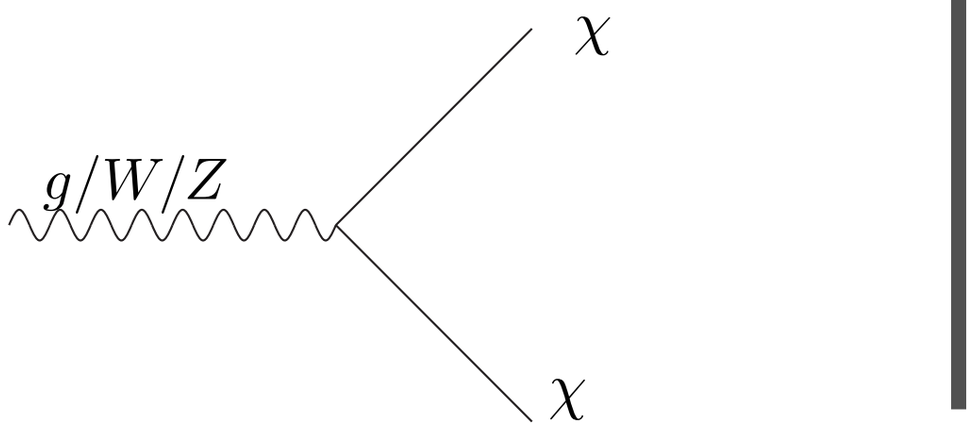
Charged under SM gauge interactions:

wino/gluino-like (state in interference loop)



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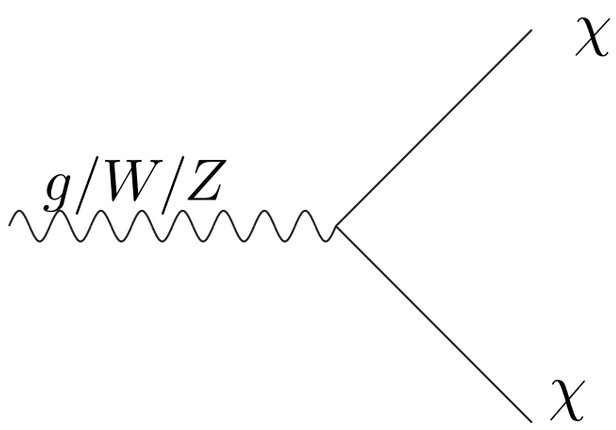
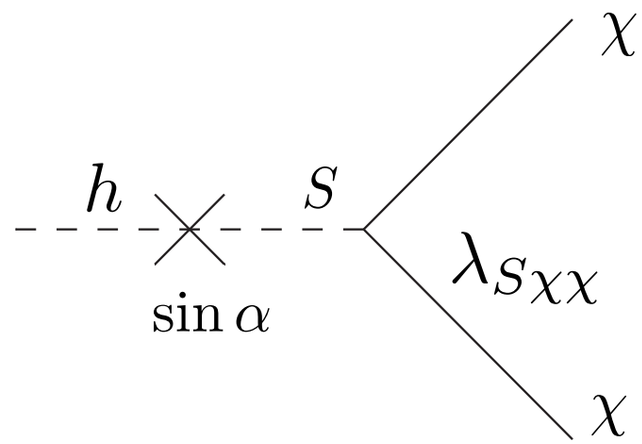


Higgs portal:

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



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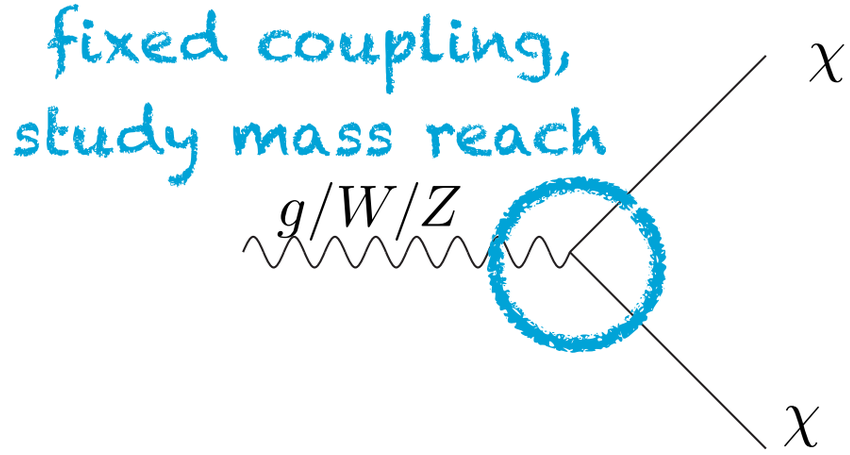

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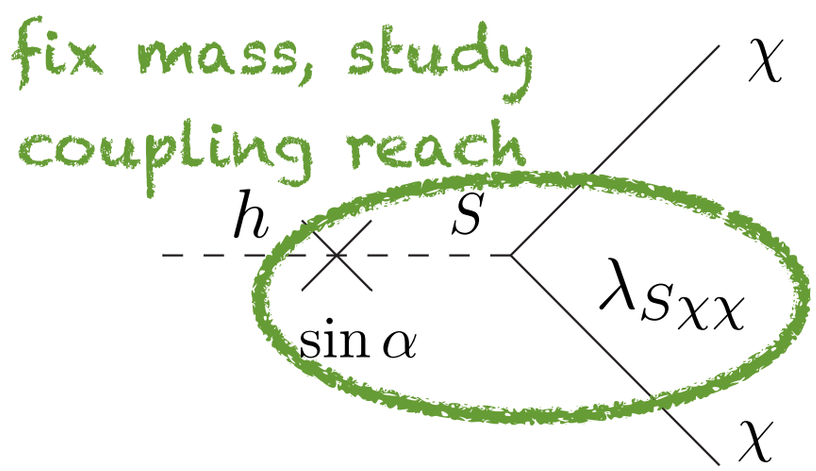

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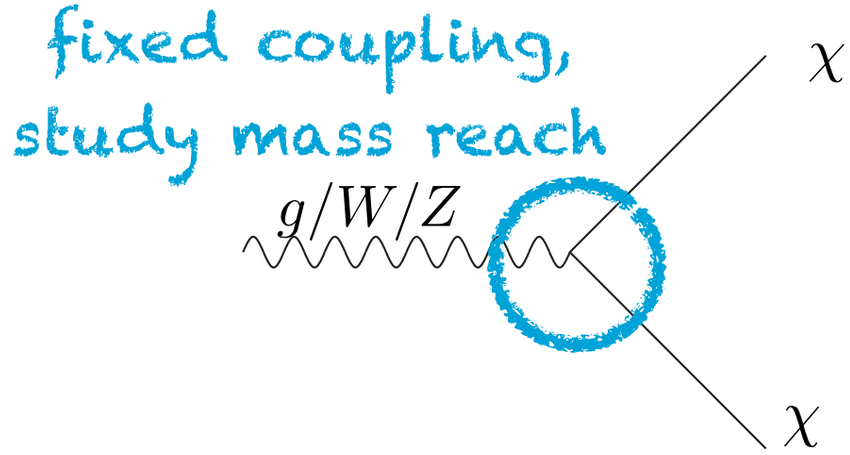

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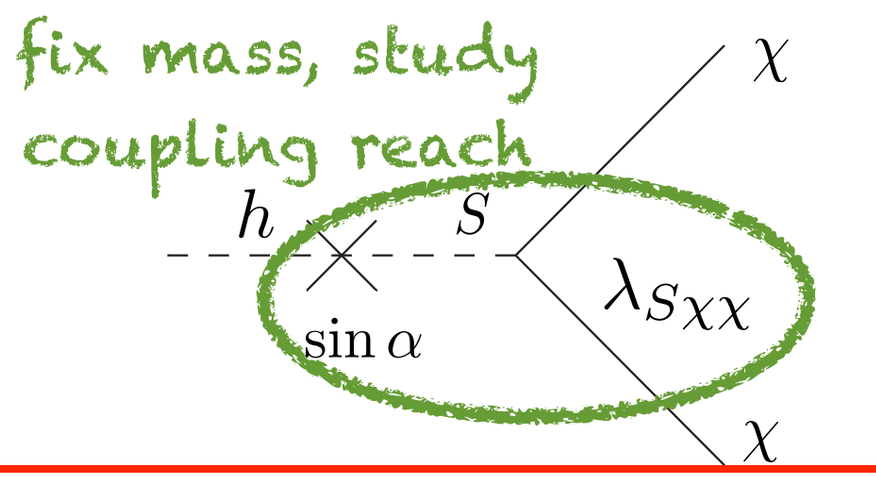

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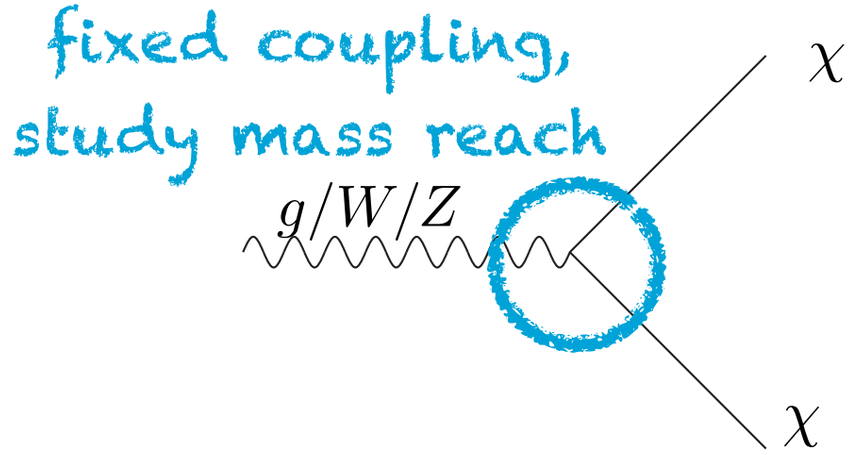

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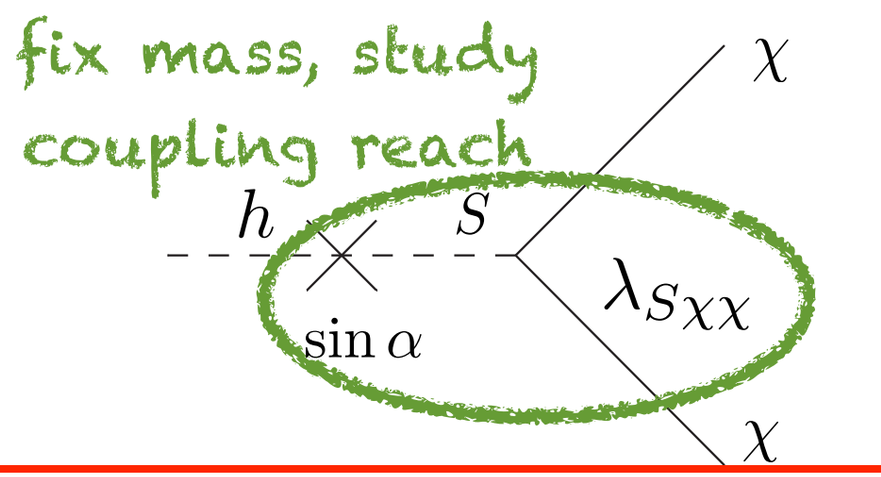

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$$\chi \to u_i d_j d_k$$

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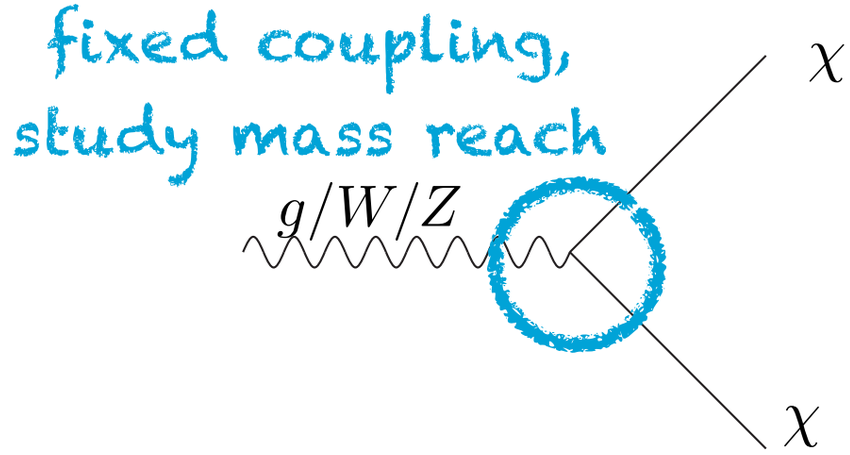
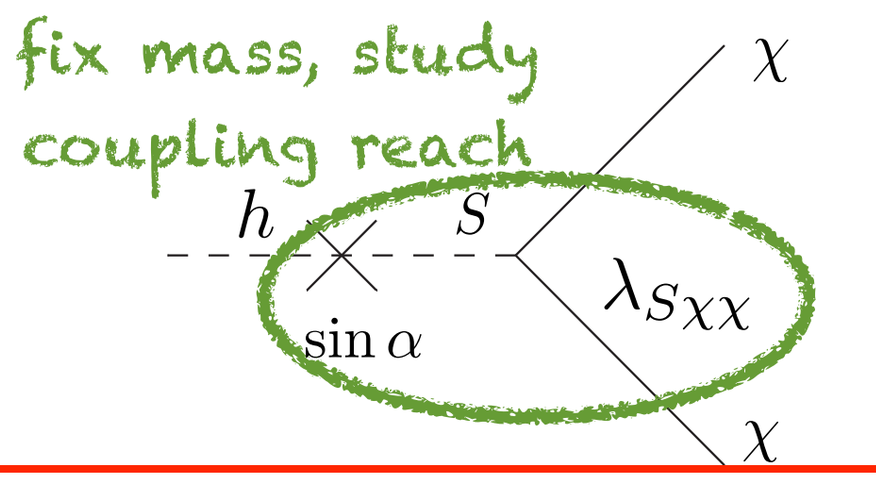
wino/gluino-like (state in interference loop)



Higgs portal:

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



★ **Three-folds of Higgs portal production:**

onshell or offshell (mostly) SM h; (heavy, mostly) singlet S mixed w/h

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

Baryon number violating:

$$\chi \to u_i d_j d_k$$

Lepton number violating:

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

Baryogenesis from Out-of-equlibrium Decays

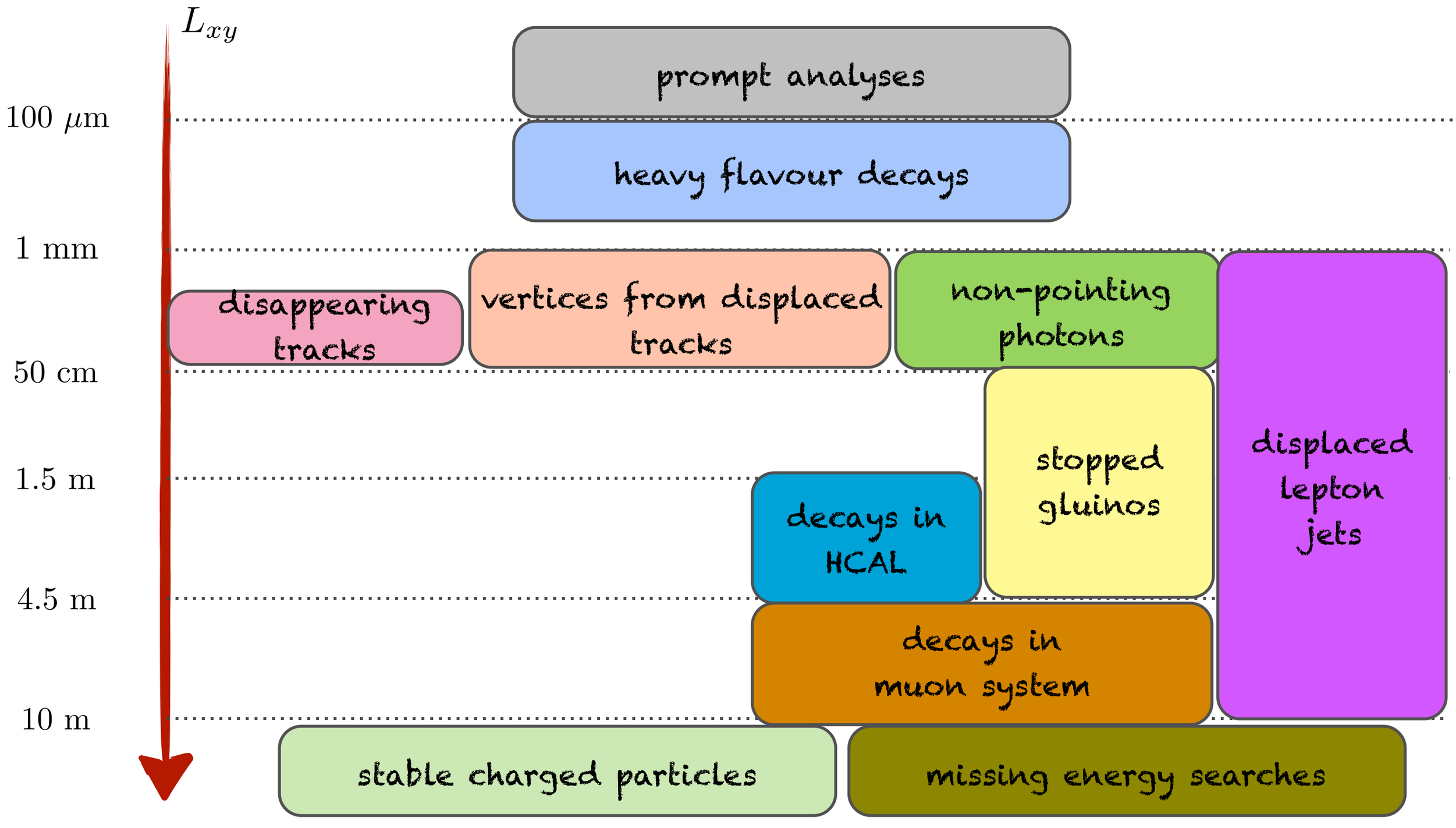
— Collider Phenomenology

YC and Shuve, arxiv:1409.6729, JHEP

★ *Strategy/results generally applicable to other new physics search via displaced vertices*

(in corporation with ATLAS displaced jets working group)

LHC Search Possibilities



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- Focus on displaced decay in tracking volume

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displaced jets (all-hadronic)

CMS, arXiv:1411.6530

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- **Goal of our analysis:**

  - What is the coverage for our simplified models based on benchmarks chosen by the collaborations?
  - Where are there blind spots/proposals for improvement?

Monte Carlo Methods

- Backgrounds: hopeless to simulate - use (scaled) values from expt. paper
- Signal: MadGraph5 + Pythia 8
  - Draw location of displaced vertex from an exponential distribution,
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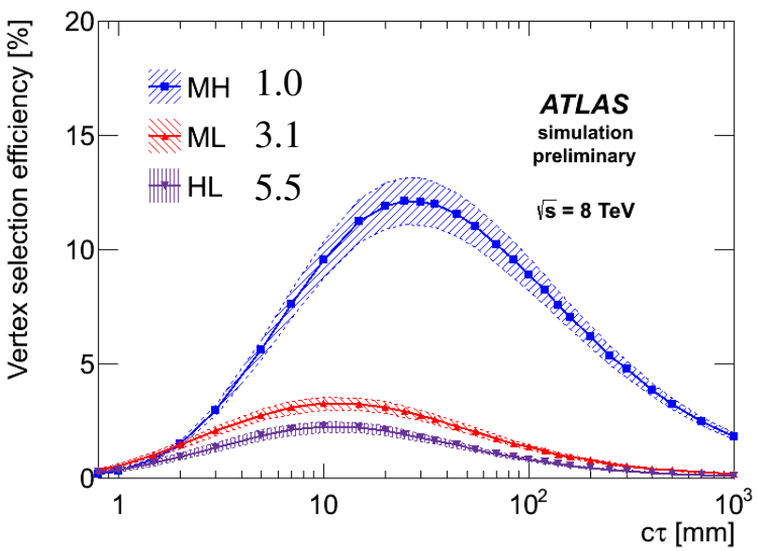
- Performance expected to **degrade with larger displacement** (L_{xy}), since the final-state particles pass through fewer tracking layers
- Some dependence on boost (changes collimation of tracks)



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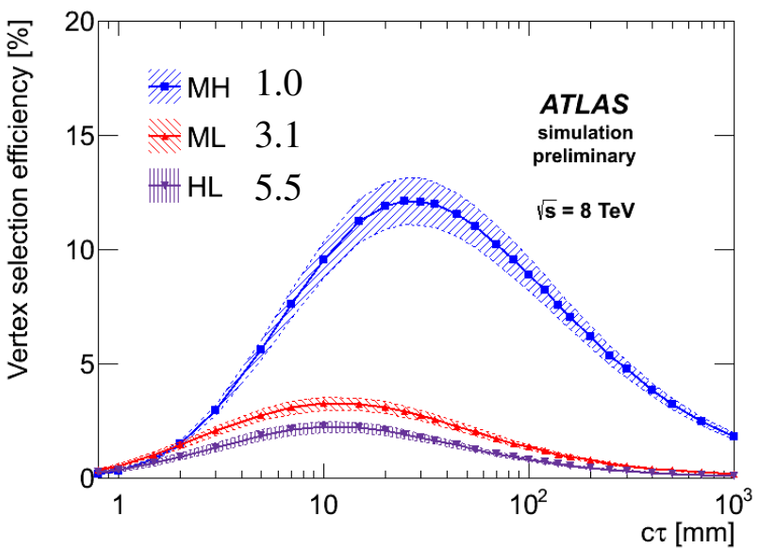


Conjecture:

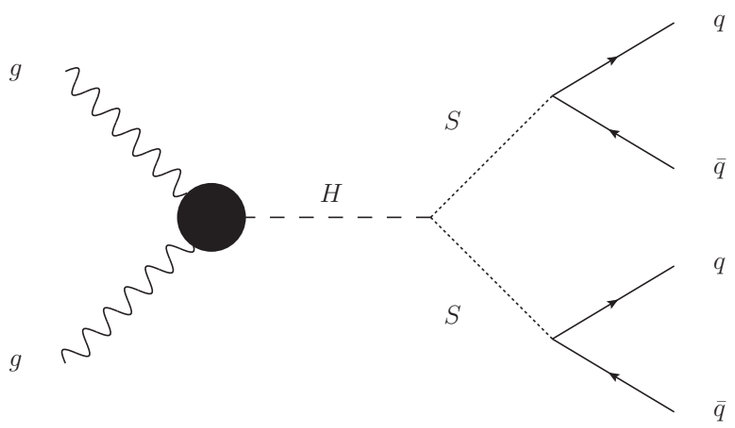
$$\epsilon_{\text{sig}} \approx \epsilon_{\text{MC selection}}(p)\, \epsilon_{\text{DV reconstruction}}(\langle L_{xy} \rangle)$$

holds to within ~50% for all analyses, more variance with very different boosts

Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

Example model in the CMS paper:



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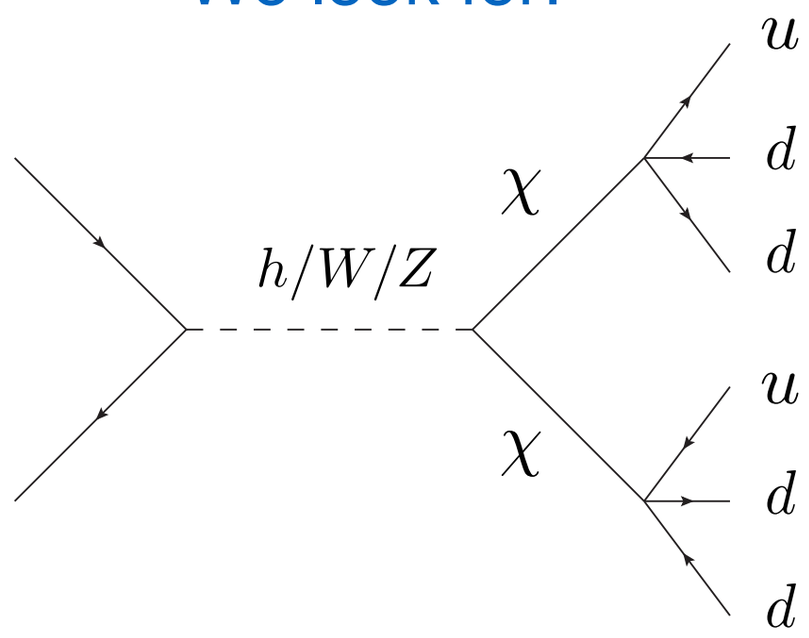

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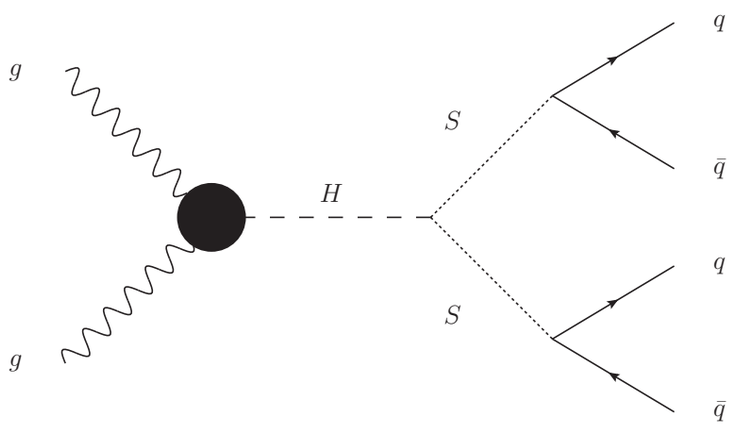

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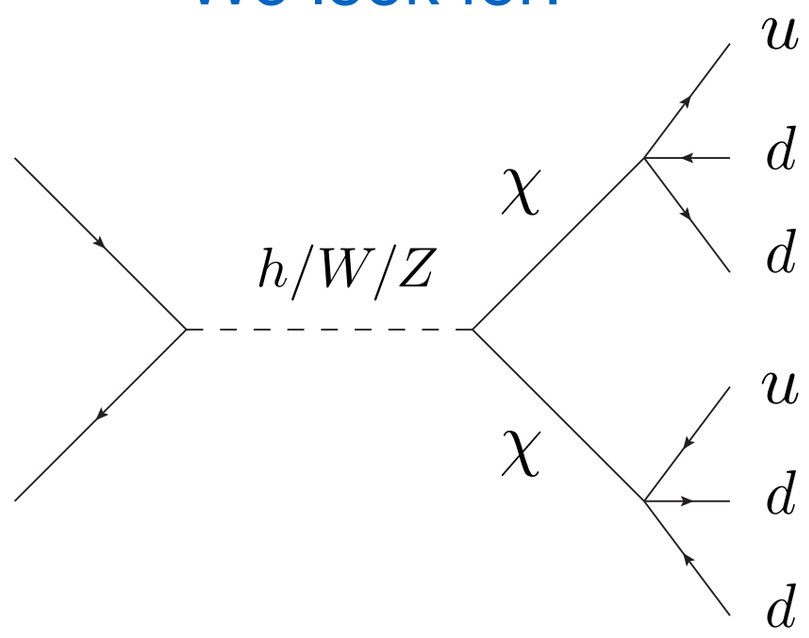

<u>Trigger</u>:

- $H_T > 325$ GeV
- at least 2 “displaced jets” with $p_T > 60$ GeV

☞ Effective at high mass, but very inefficient at low mass (e.g. higgs decay!)

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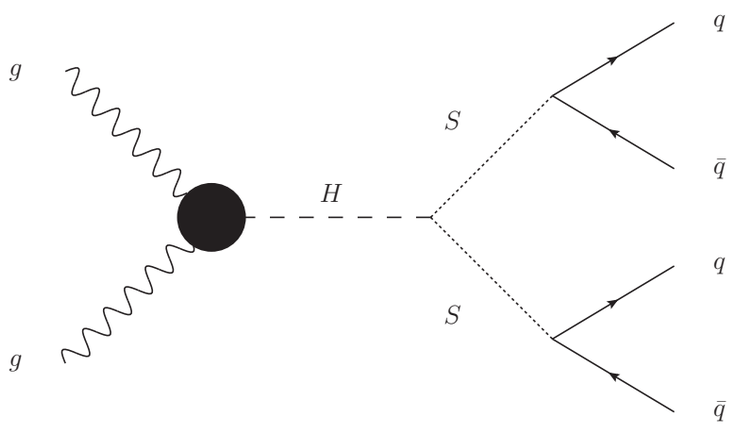

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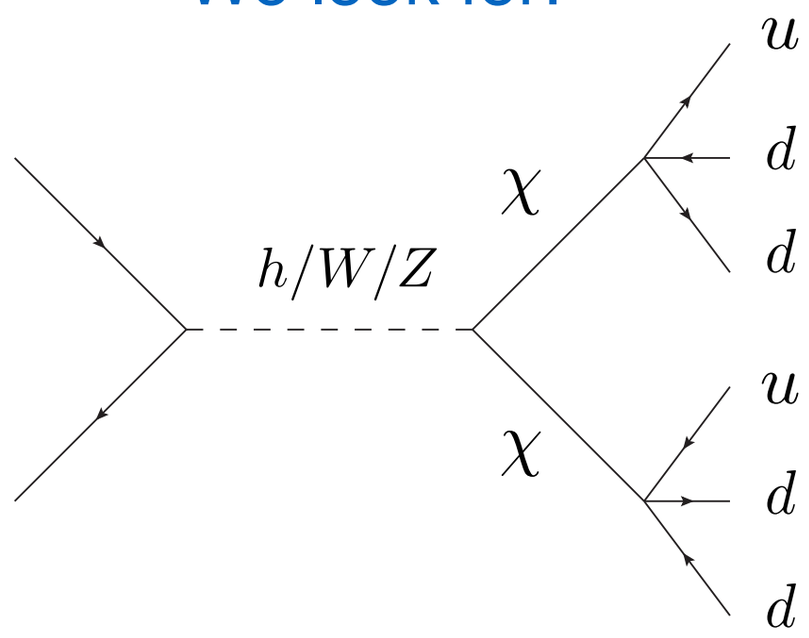

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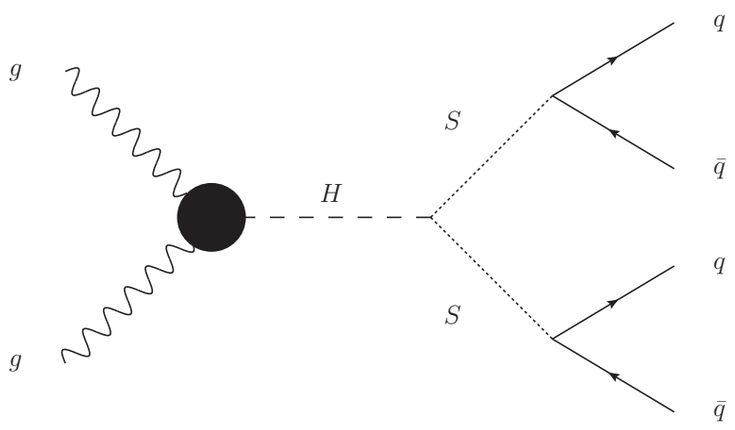

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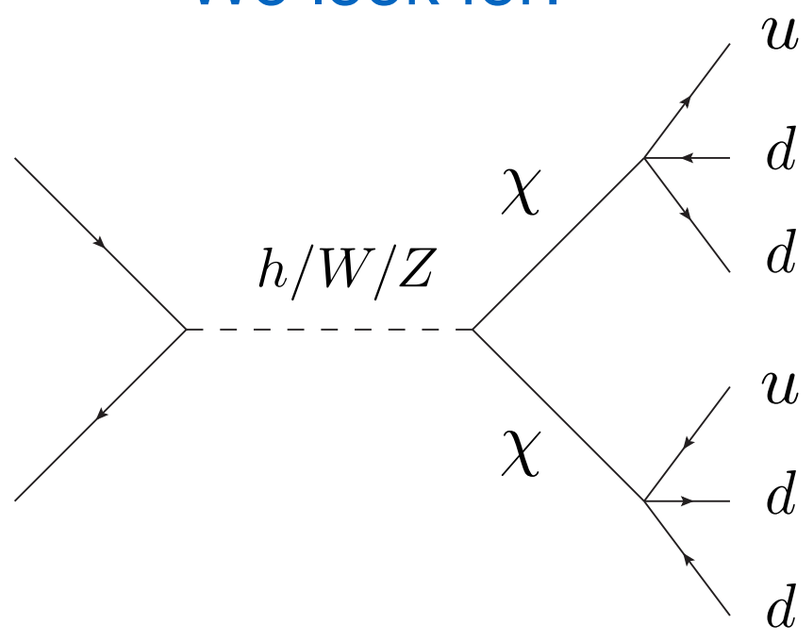

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Event Selection: Efficiency for 3-jet decay?

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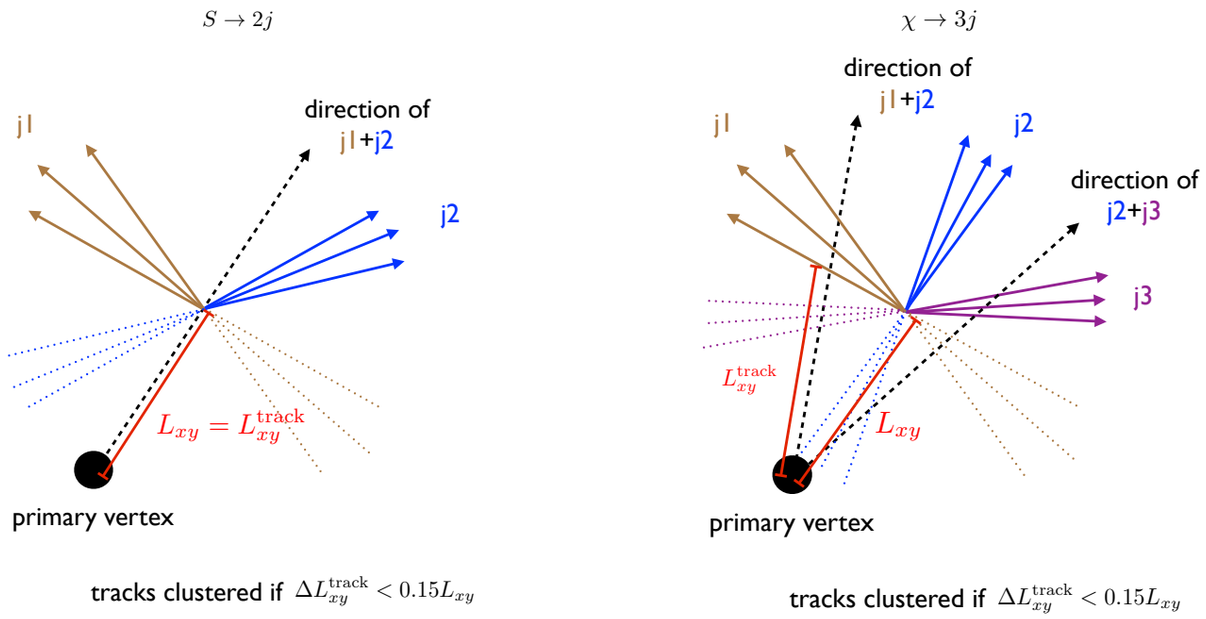
- Dijet requirement mostly comes in from “track clustering”



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  - Vertex track multiplicity
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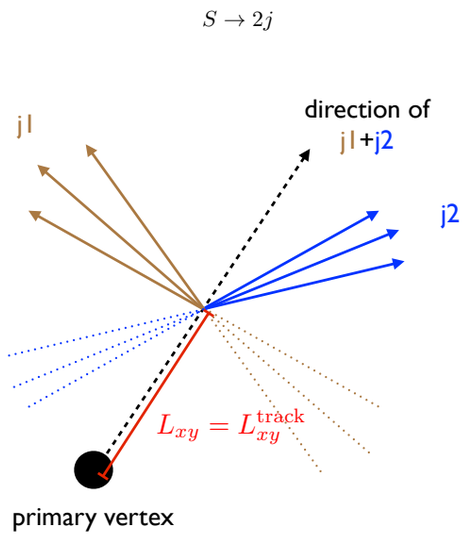

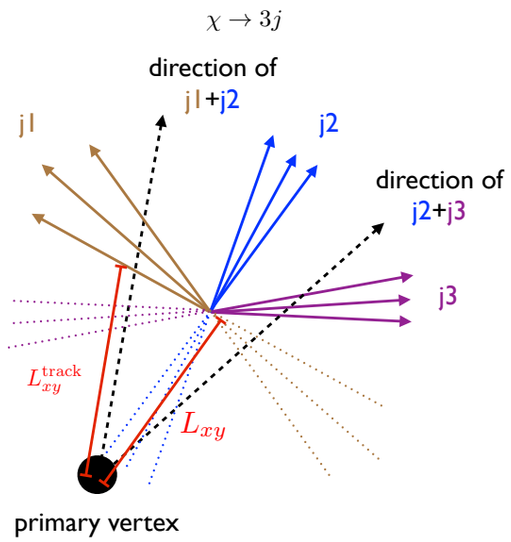

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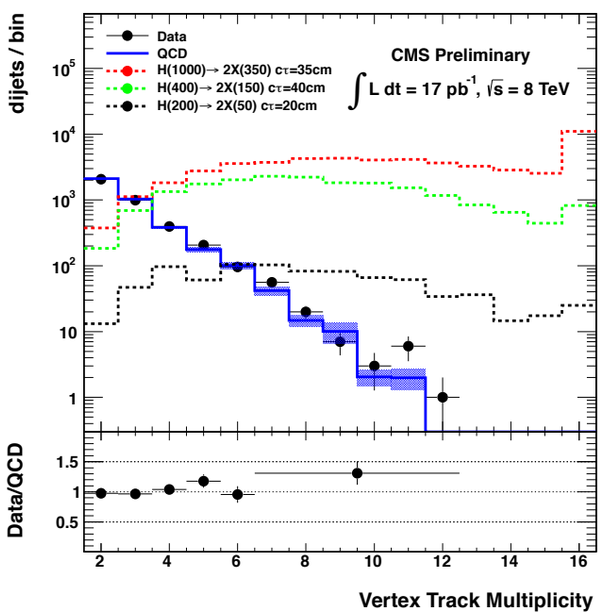
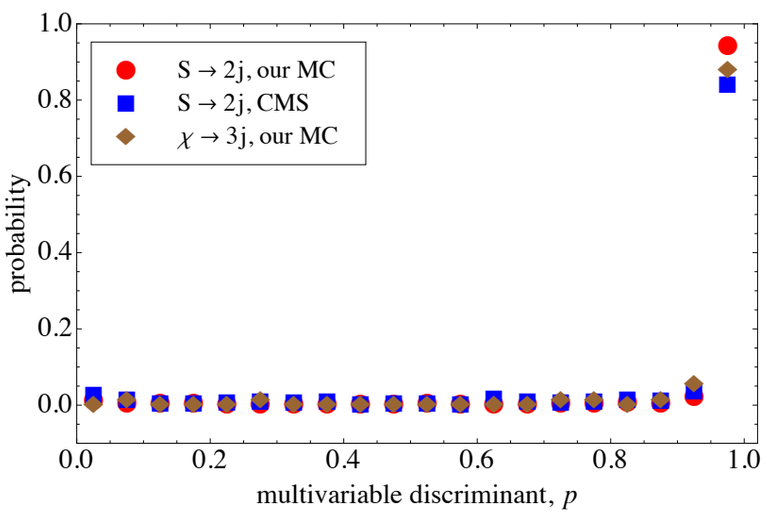
- Likelihood observable retains sensitivity if *at least one* observable still has significant signal/background discrimination (vertex multiplicity)





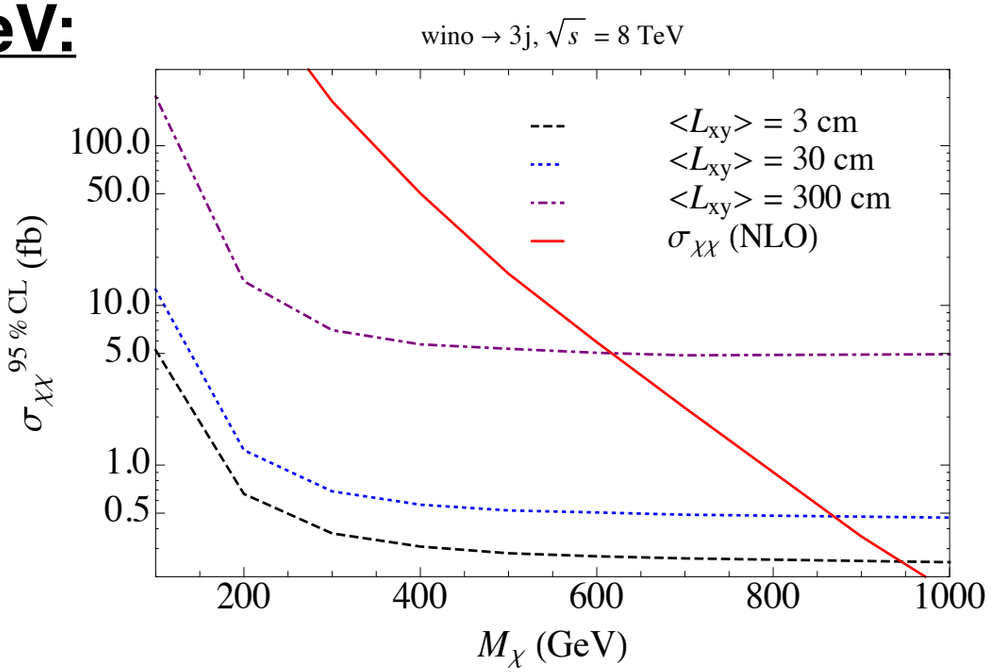
- 3-jet signal still peaked towards $p = 1$ (high signal likelihood)
- dijet search has good sensitivity to 3-jet signal!

Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:



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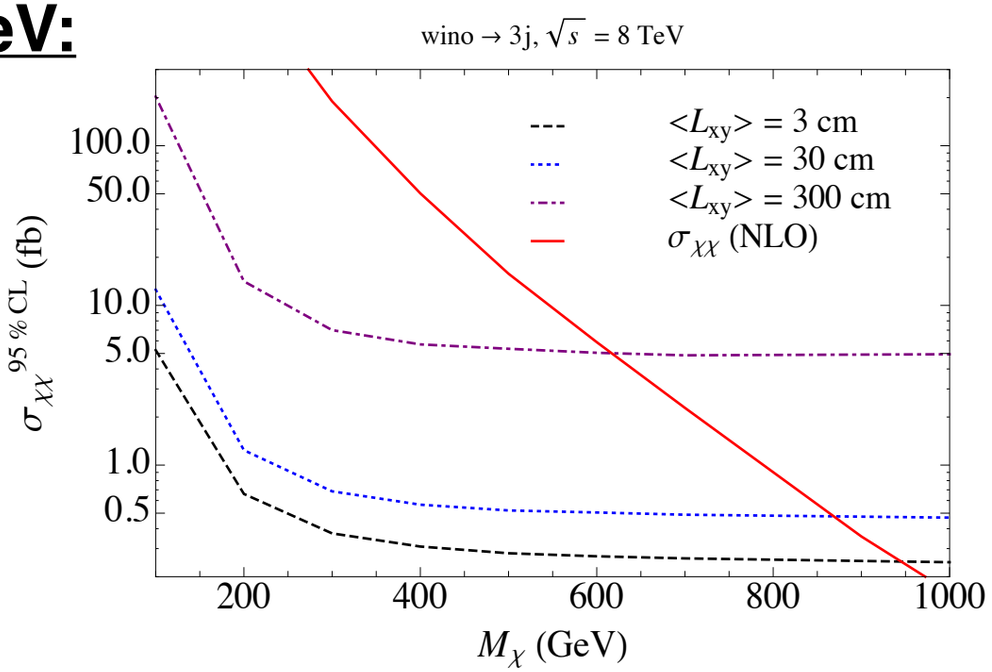

singlet-like (Higgs portal)

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

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

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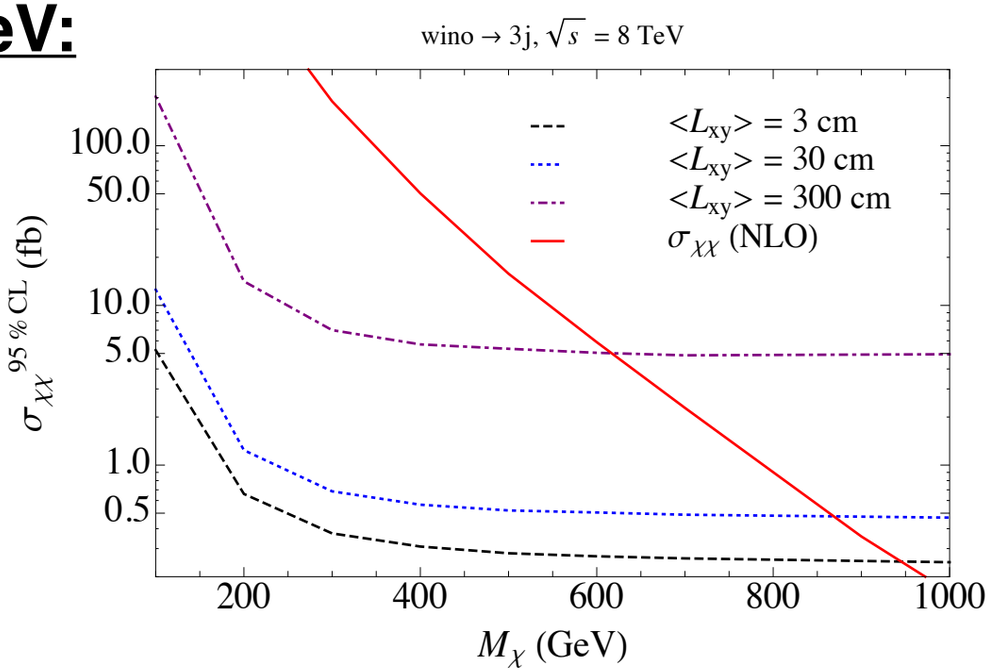

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13 TeV: Re-scale background with luminosity, pile-up, cross section; threshold for trigger increased to $H_T > 500$ GeV

Fully hadronic displaced vertices

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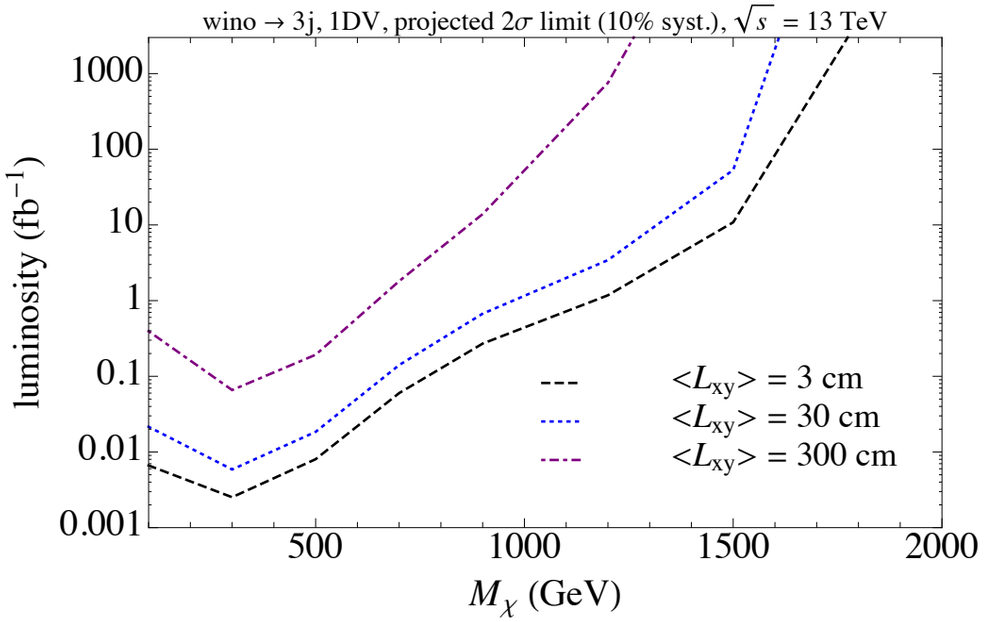
wino

13 TeV:

10% syst.



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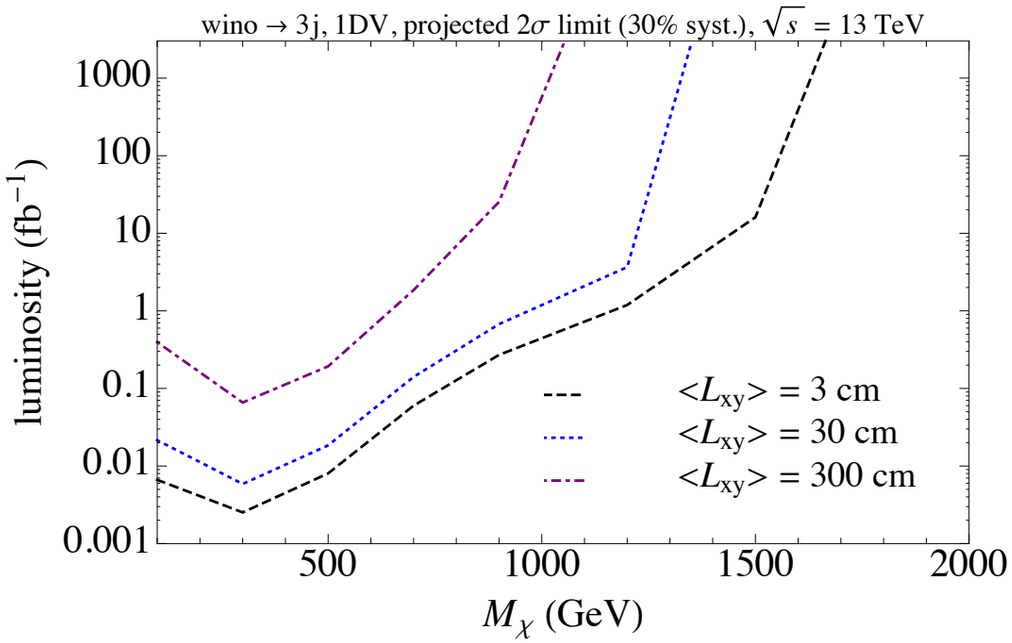

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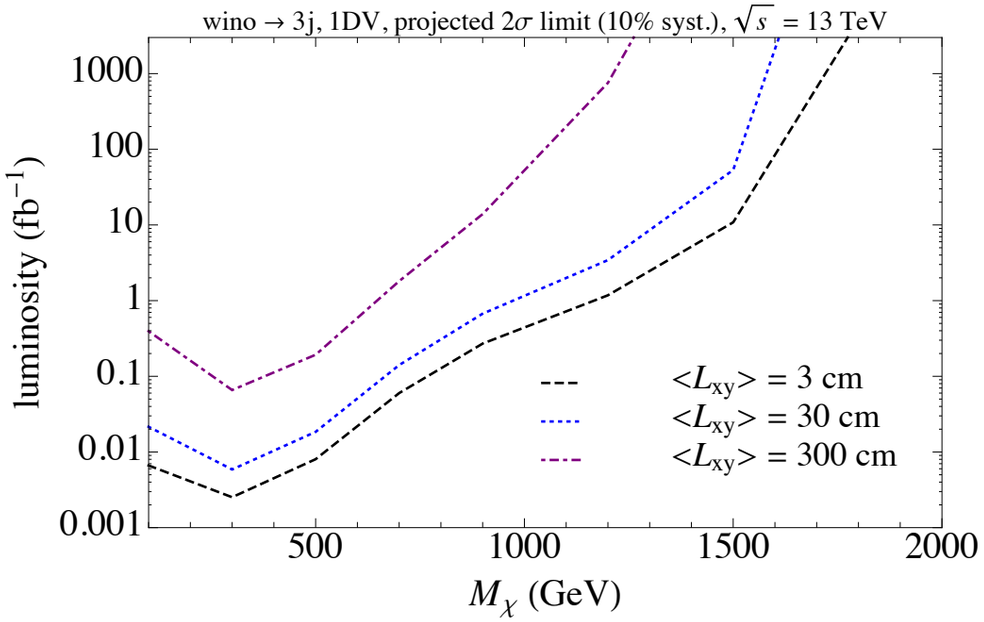

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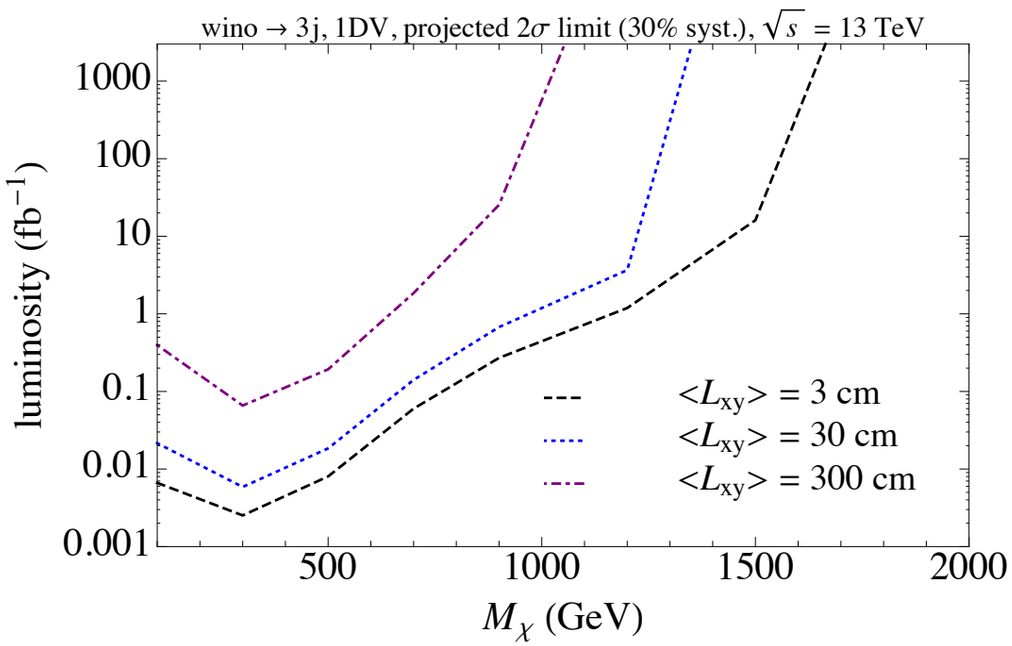
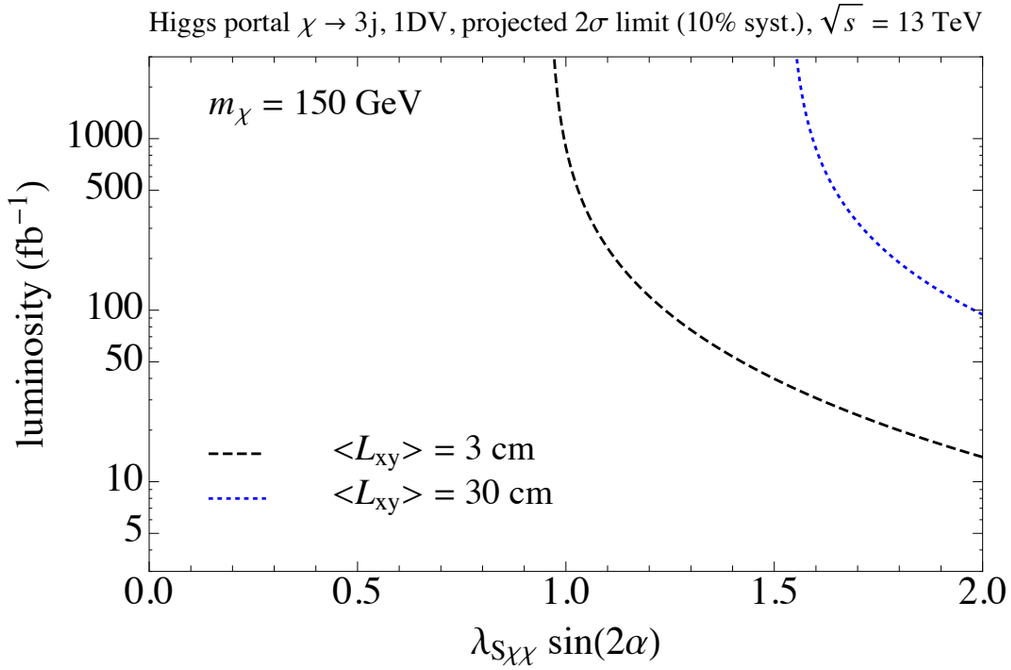
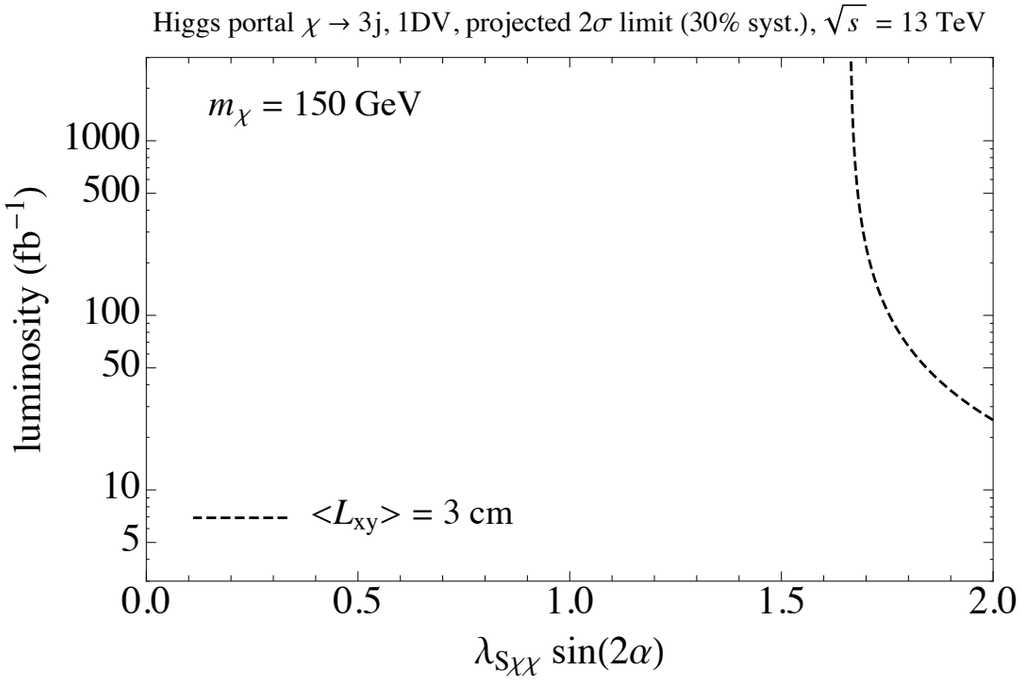


singlet (Higgs portal) (still loose!)





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CMS displaced dijet, arXiv:1411.6530

Can we further improve? How? *(esp. for Higgs-portal singlet)*

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→ Lowering the kinematic threshold **and** requiring 2 displaced vertices, Significant gain! To estimate:

- We choose as a trigger threshold: the ATLAS L1 4-jet, 20 GeV trigger

Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

- Assume: hadronic DVs are uncorrelated → the 2-DV search is **bkg-free**
- We look for a mean of 3 events ↔ 95% probability observing ≥1 event

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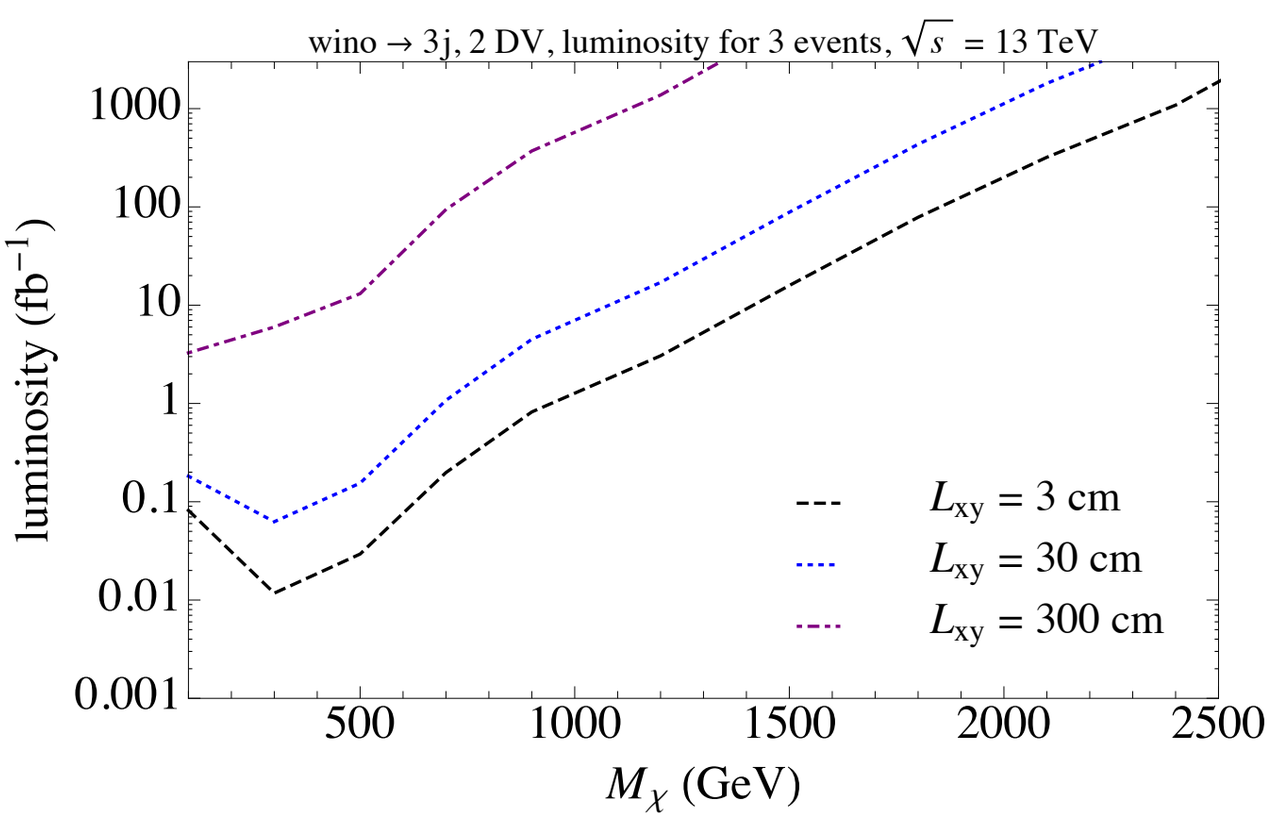

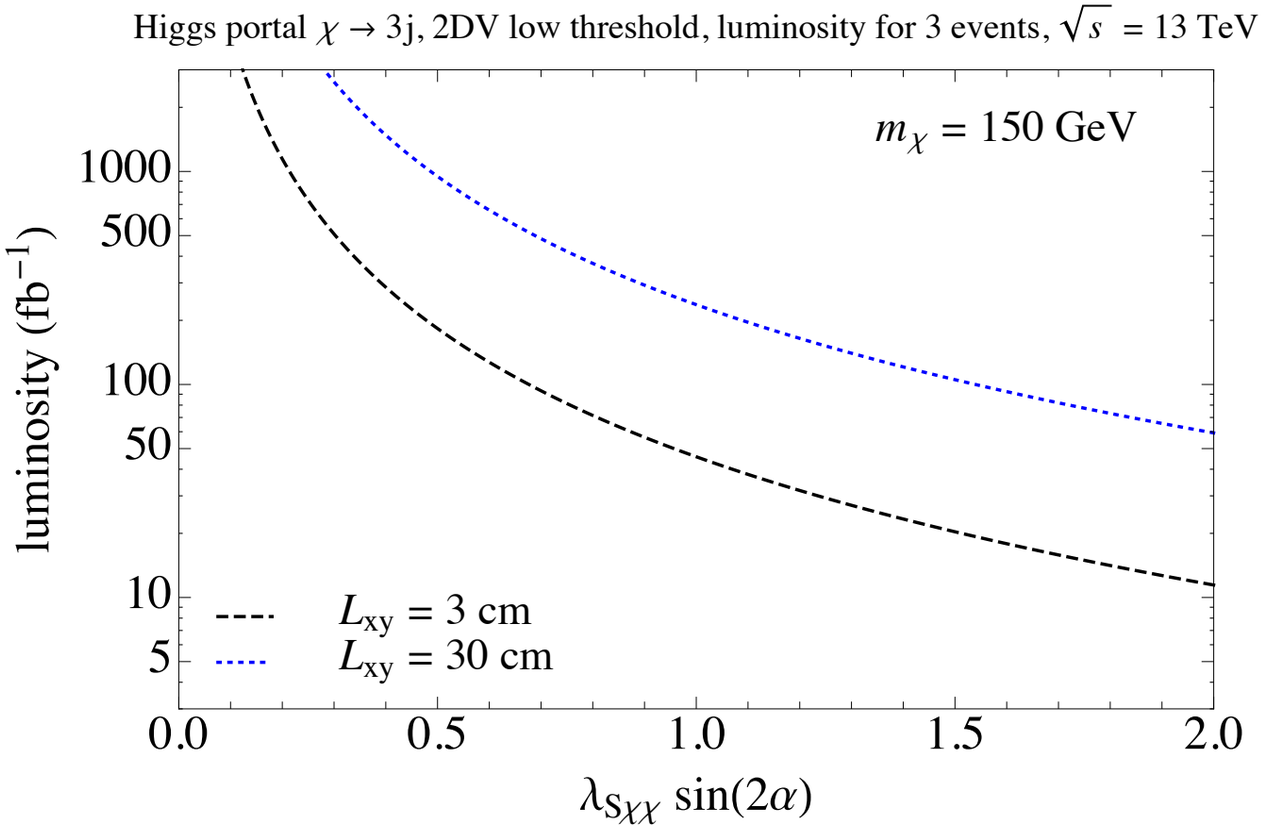

- Excellent prospects for **EW** production (M~2.5 TeV)!
- Significant improvement for **Higgs portal** singlets! (σ_S~10 ab for L_{xy}~1 cm!)

Displaced muon + hadrons

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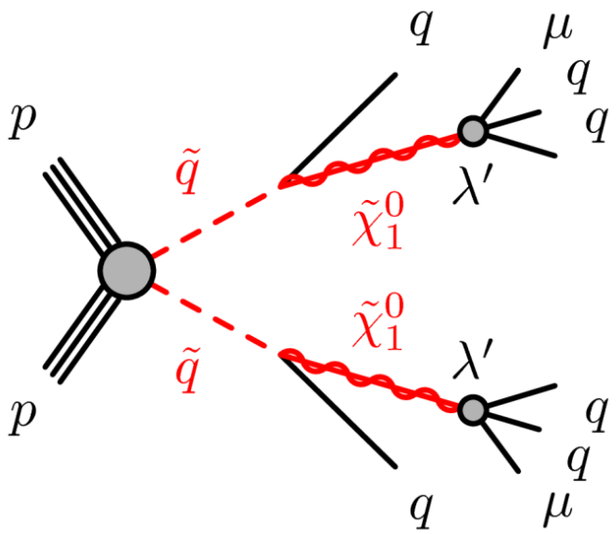
Example model in ATLAS paper



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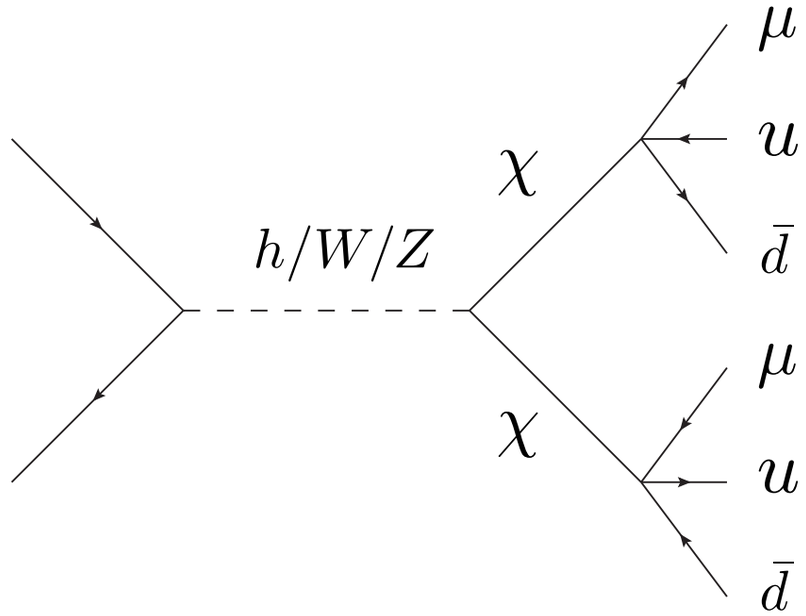

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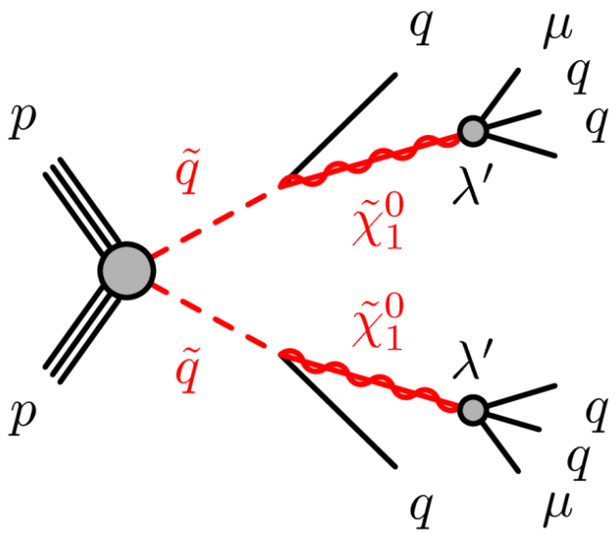

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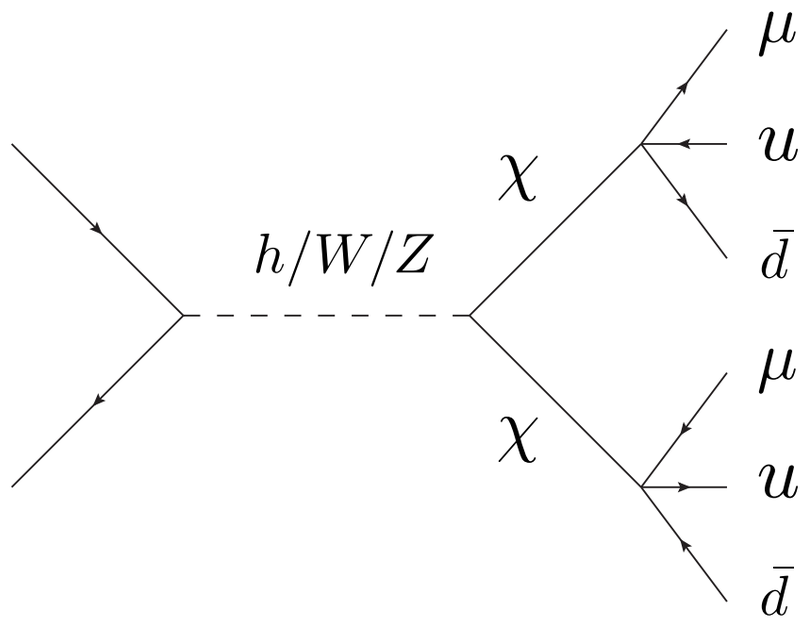

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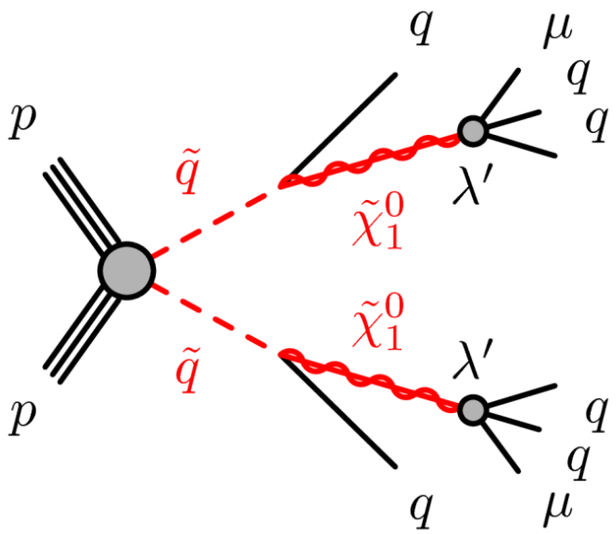

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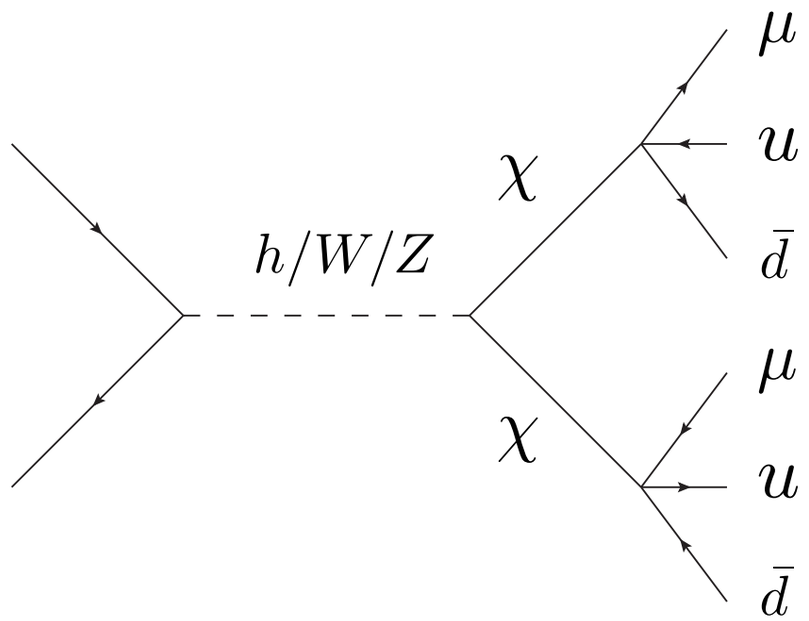

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<u>Event Selection</u>:

- Find displaced vertex with > 4 tracks, $m_{tracks\ @\ DV}$ > 10 GeV, L_{xy} < 20 cm
- Reject vertices with prompt tracks
- Muon associated with displaced vertex (< 0.5 mm away)

Displaced muon + hadrons

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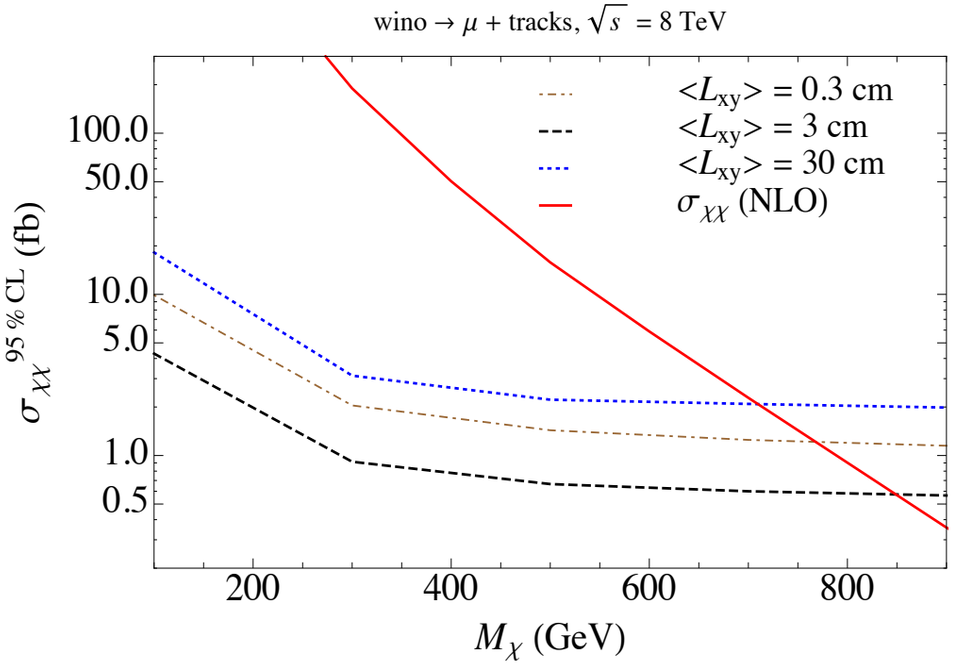
Strict requirement: a DV with 5 tracks AND a muon

☞ 0 bkd even without requiring the muon-DV association, even at high Lum!

wino

8 TeV



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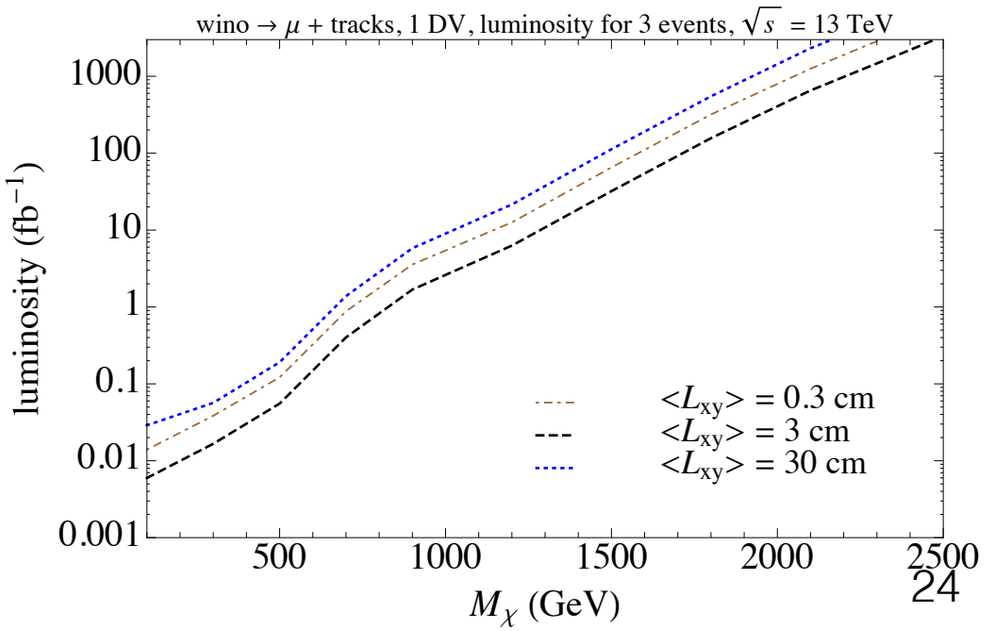
M~2.5 TeV



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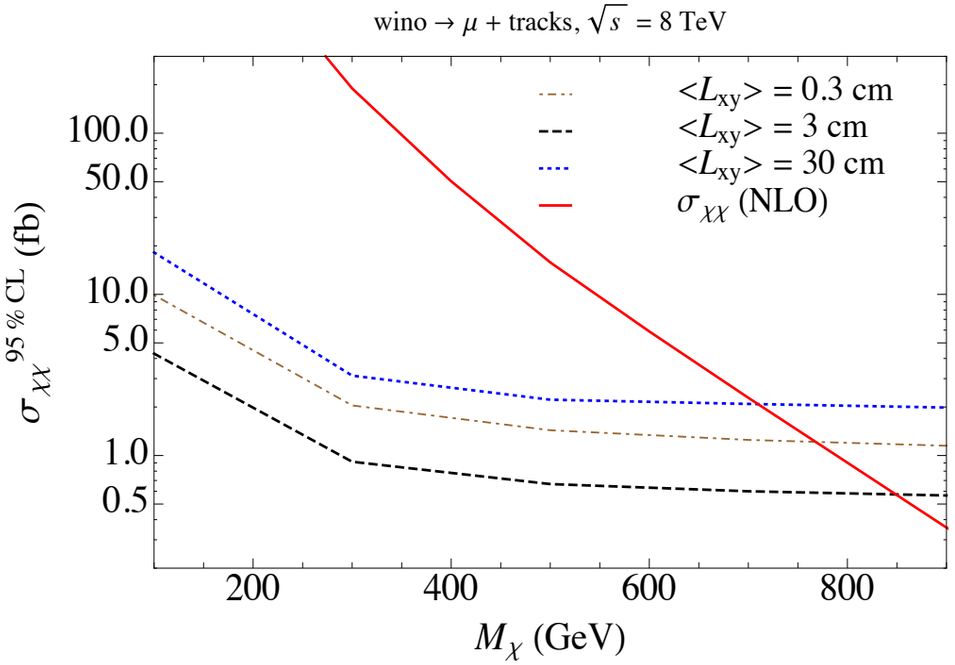
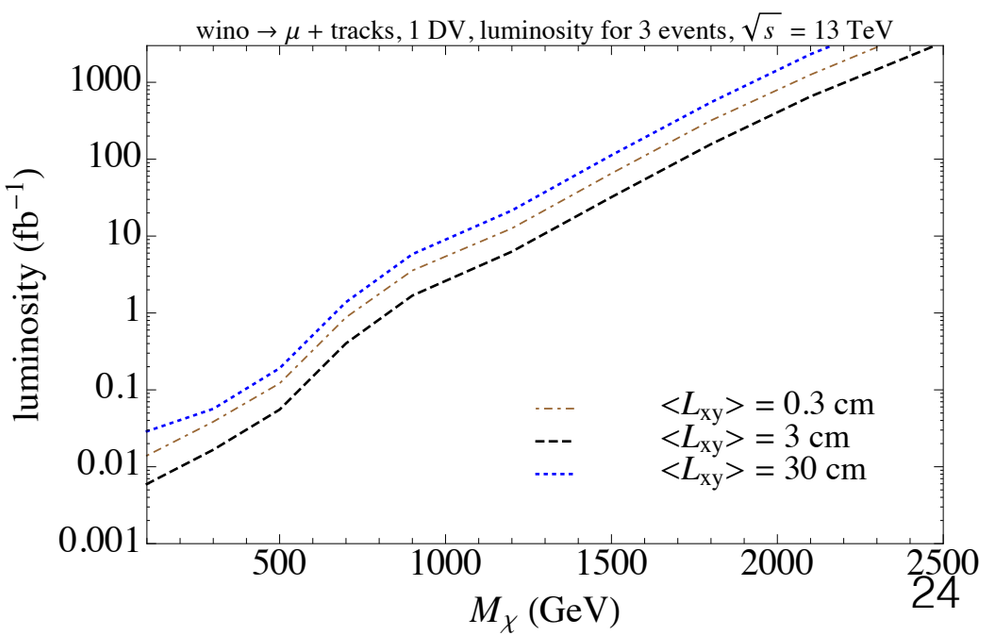


13 TeV:
M~2.5 TeV

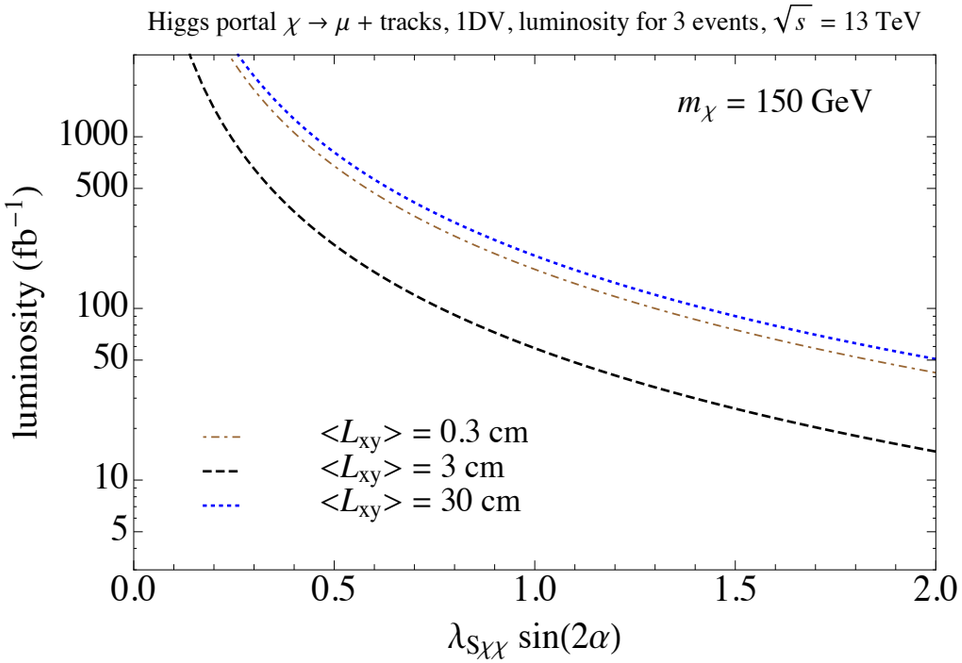


singlet (Higgs portal)

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

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

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



Summary/Outlook - 1

- **Strong theoretical motivations** for *displaced vertex signals through the Higgs portal*, e.g.
  - **Hidden naturalness** (twin Higgs)**:** prominent puzzle in particle physics frontier!
  - **Baryogenesis from out-of-equilibrium decay** (metastable WIMP): the cosmic origin of ourselves!

— Not a mere ("why not?") exotic!

Great opportunities, Worth our efforts!

- **Three-fold possibility of production:** different triggers/strategies…
  - On-shell Higgs decay
  - Off-shell Higgs decay
  - Heavy singlet S (mixed w/Higgs) resonance decay

  (Qs: How well can we reconstruct total invariant mass w/DVs?)

Summary/Outlook - 2

Looking ahead…

Summary/Outlook - 2

Looking ahead…

- **How to present results in a generic way?**

Summary/Outlook - 2

Looking ahead…

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Simplified models approach:

- Production channels *(3-fold for h-portal)*
- Final state topology *(number/combo of j, l, γ, MET…)*
- Lifetime (L_{xy} ,where in the detector it decays), boost factor

— *peculiarity for DV searches*

Summary/Outlook - 2

Looking ahead…

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- **How to further improve sensitivity?**

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- **How to further improve sensitivity?**

- Dedicated triggers (e.g. lower H_T/p_T threshold for all hadronic)
- Exploit signal properties: reduce bkg, increase ε_s (e.g. double DV tagging for long-lifetime due to parity)

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More brainstorm in discussion session!