# Long-lived particles in BSM: A biased take on the subject

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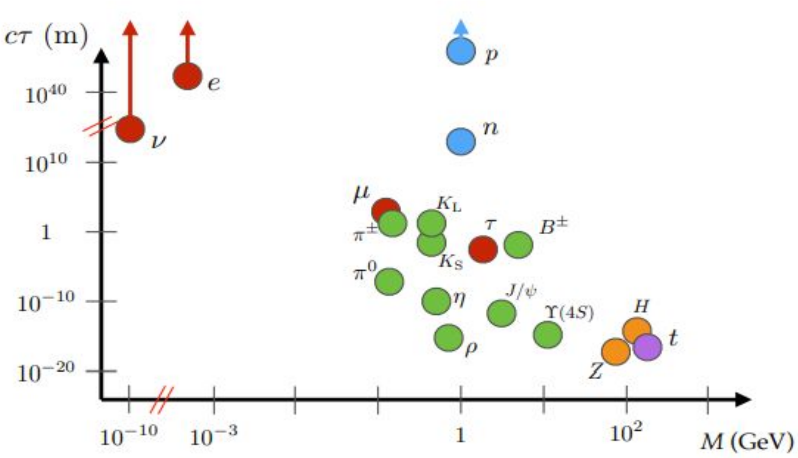
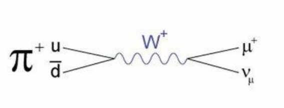
# Long-lived particles in the SM




arXiv: 1903.04497; Alimena et al.

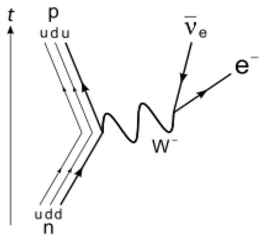
- In SM, Z-boson has **τ** ~ 2 x $10^{-25}$ s, e and **ν** are stable. *In the SM, proton is also stable*
- For a charged pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$




$$\Gamma_{\pi^+} \sim g_W^2 \left(\frac{M_\pi}{M_W}\right)^4 M_\pi$$

$$\tau_{\pi^+} \sim 2.6 \times 10^{-8} \text{ seconds}$$

- For a neutron decay, the neutron and proton are nearly degenerate. Lifetime is around 15 minutes.




- The lifetime of the muon is ~ 2.2 $\mu s$

# Long-lived particles in the SM

- SM particles can be long-lived if an approximate symmetry makes them stable

  **1. For protons: *Baryon Number Conservation*** (approximate symmetry in the SM). In some GUTs, a proton can decay with an extremely large decay lifetime **($\tau \geq 10^{34}$ years)**

  2. **For electrons and neutrinos:** Stable because ***Lepton Number*** is conserved in the SM

  **3. For neutrons: *Energy conservation within nuclei***

- Has to do with the ***weakness*** of weak couplings; ***hierarchies of scales*, etc.**

- **Mass degeneracies** $\longrightarrow$ suppress decay rates

- **Small symmetry breaking parameters** $\longrightarrow$ suppress decay rates

# What makes a particle ($X$) long lived?

- The lifetime of a particle, *X*, can be written as

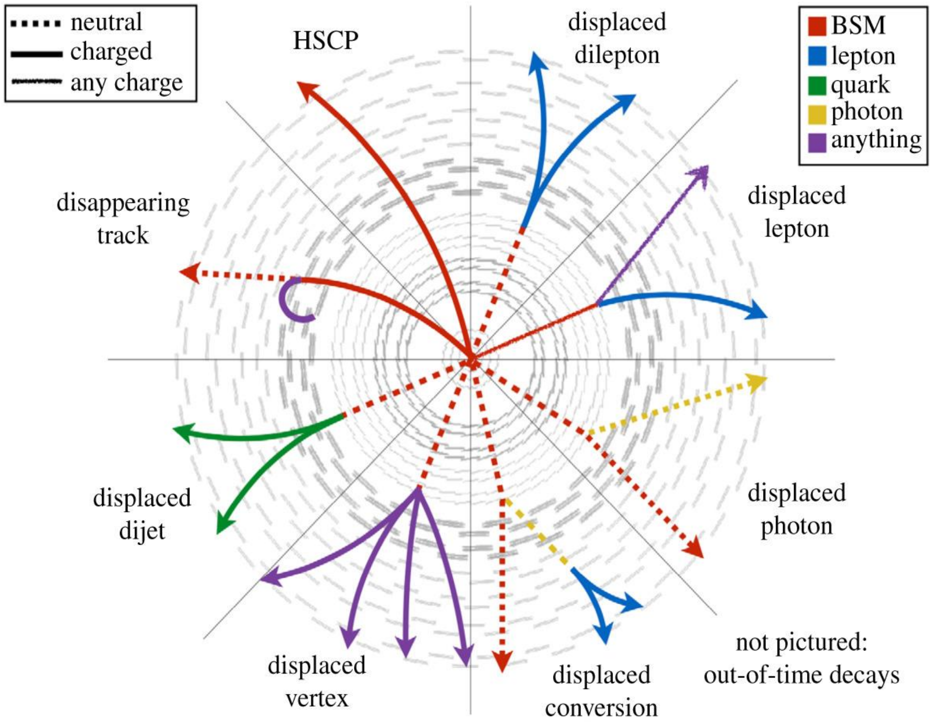
$$\tau^{-1} \sim \Gamma = \frac{1}{2m_X} \int \mathrm{dLIPS} |\mathcal{M}(m_X \to \{p_f\})|^2$$

- A particle, *X*, can be long-lived if any or all of the following criteria holds.

1. The matrix element is small $\longrightarrow$ small broken symmetry $\longrightarrow$ small coupling values
2. Small phase space $\longrightarrow$ nearly degenerate particle spectrum
3. Couplings suppressed by the scale of new physics

[See Shilpi’s slides]

# Long-Lived Particles: Search topologies




Roeck, 2019

Many models give rise to such signatures; example: RPV SUSY, AMSB SUSY (backup), gauge-mediated SUSY, split SUSY (backup), νCMSSM (backup), Hidden Valley models, dark QED, ALPs, and more.

All of these searches require dedicated algorithms, detector modifications/additions, etc.

See talks by Shilpi and Swagata!

# SUSY Example 1: R-parity violating SUSY

- ***R-parity*** defined as $R_p = (-1)^{3(B-L)+2S}$; B = Baryon number, L = Lepton number, S = particle spin
- **SM particles have $R_p = 1$** and **superpartners have $R_p = -1$**
- In ***R-parity*** conserving SUSY, LSP is stable and a potential dark matter candidate
- In ***R-parity*** violating SUSY, this type of particle can decay and **B and/or L may not be conserved**

$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk}\epsilon^{\alpha\beta}L_{i\alpha}L_{j\beta}E^c_k + \lambda'_{ijk}\epsilon^{\alpha\beta}L_{i\alpha}Q_{j\beta}D^c_k + \frac{1}{2}\lambda''_{ijk}\epsilon^{\alpha\beta\gamma}U^c_{i\alpha}D^c_{j\beta}D^c_{k\gamma}$$

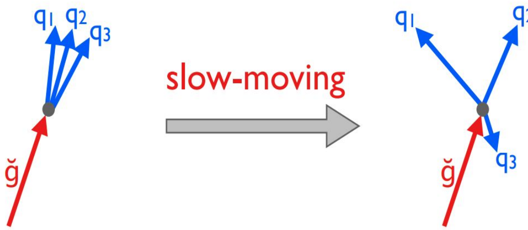
**$L$, $Q$, $E$, $D$, and $U$ are the superfields corresponding to the lepton doublet, quark doublet, charged lepton singlet, down-type quark singlet, and up-type quark singlet, respectively. The $\lambda$, $\lambda'$, and $\lambda''$ are the R-parity violating couplings. $\epsilon^{\alpha\beta}$, $\epsilon^{\alpha\beta\gamma}$ are totally antisymmetric tensors**

- **Example: Long-lived neutralino** $\tilde{\chi}^0_1 \rightarrow l^{\pm}_i + q_j + \bar{q}_k$

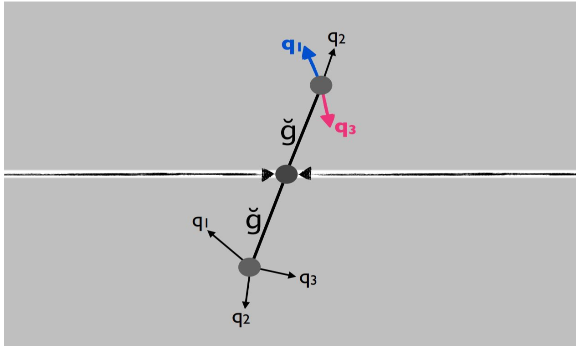
**Due to the smallness of the $\lambda'$ coupling, the decay width of the neutralino is small, leading to a long lifetime.** [arXiv: hep-ph/0406039; R. Barbier et al. [2005]]

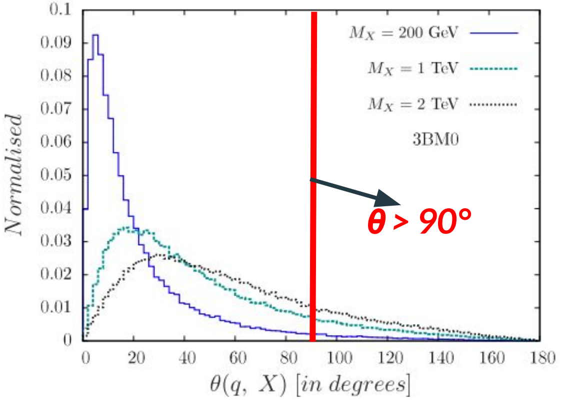
# SUSY Example 1: R-parity violating SUSY

- For an RPV scenario like $\tilde{\chi}_1^0 \rightarrow qqq$ a significant fraction of the decay particles can move in the **backward direction** ***(Backward Moving Objects)***




Pictures courtesy Swagata



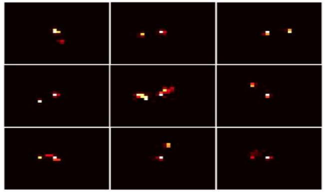




**Angle $\theta$ between the direction of $X$ and the 'massless' daughter (one of the quarks, $q$)**

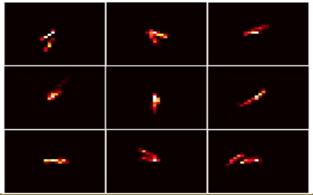
arXiv:1706.07407; SB, Bélanger, Bhattacherjee, Boudjema, Godbole, Mukherjee; PRD (2018)

# SUSY Example 2: Gauge Mediated SUSY Breaking

- **Gauge-Mediated Supersymmetry Breaking (GMSB)** $\longrightarrow$ SUSY breaking mediated through gauge interactions rather than gravitational interactions
- **SUSY broken in a hidden sector, and the breaking effects are transmitted (via "messengers") to the visible sector via gauge interactions**
- Model generates **soft SUSY breaking terms** in sector $\longrightarrow$ scalar masses, gaugino masses, A-terms $\longrightarrow$ determined by the gauge interactions of the messengers
- **Typically the gravitino is the LSP**
- **Example: Long-lived neutralino decaying to a gravitino and a Z-boson** $\tilde{\chi}_0^1 \rightarrow \tilde{G} + Z$
- **Signatures:** **Non-pointing Jets + missing transverse energy** [**Bhattacherjee, Mukherjee, Sengupta, 2019**], **displaced vertices**



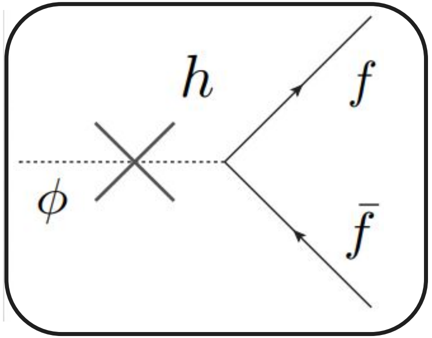
*Z* decaying to jets: no displacement



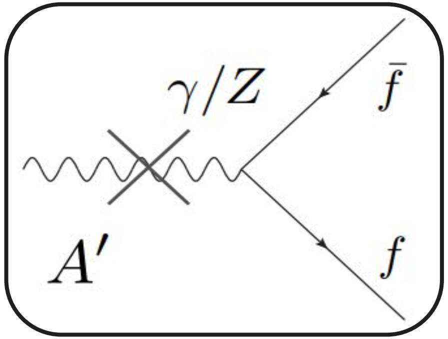
*Z* decaying to jets: transverse displacement of 200-220 cm (second)

# LLP through portals

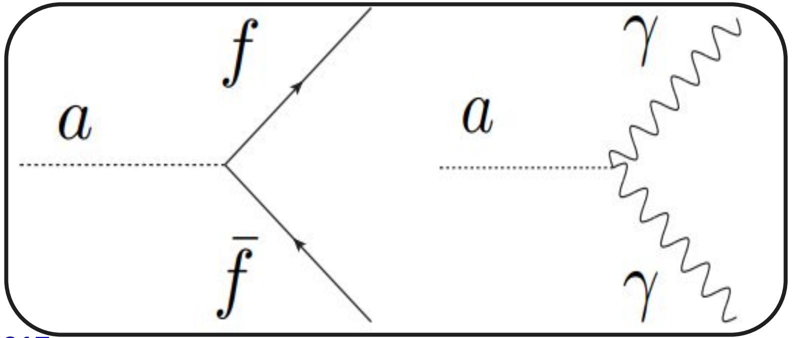
Higgs portal



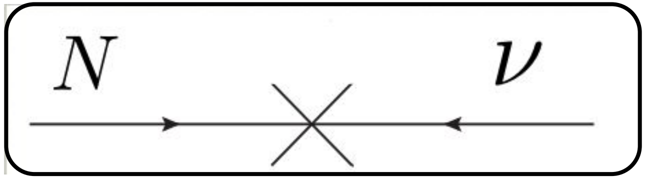

Vector Portal




Axion portal



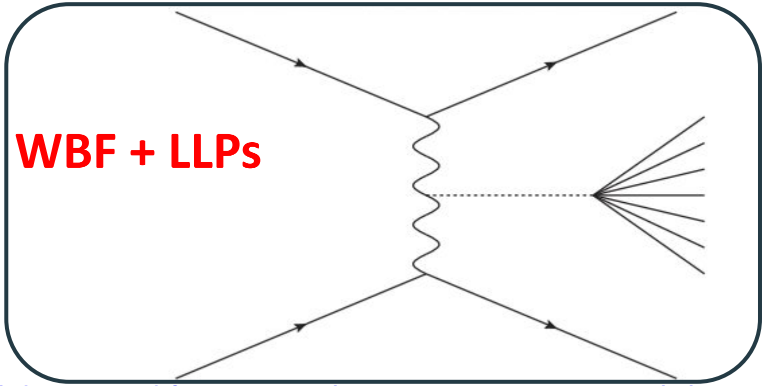

Neutrino portal

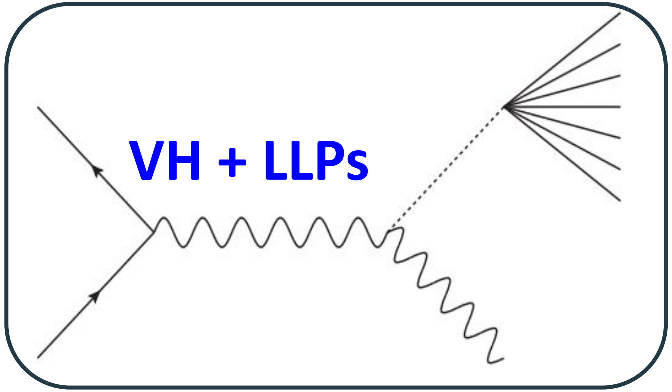



Slide adapted from Brian Shuve; LHC-LLP CERN Workshop — April 24, 2017

# Portal Example 1: The Higgs portals

- LLPs couple predominantly to SM-like Higgs
- SM Higgs field $\longrightarrow$ one of the leading renormalisable portals for new gauge-singlet particles to couple to SM
- Much scope for couplings of the Higgs to BSM physics
- Most striking signatures $\longrightarrow$ exotic Higgs decays to low-mass particles $\longrightarrow$ Useful for trigger and reconstruction $\longrightarrow$ detailed discussions on triggers by Swagata!




(jets, leptons, MET, …)

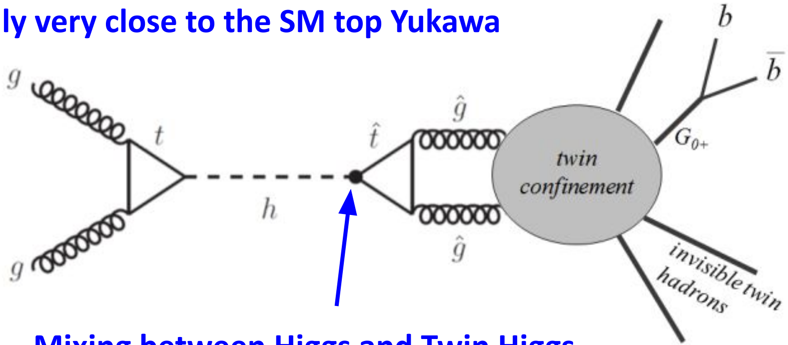
Slide inspired from Brian Shuve; LHC-LLP CERN Workshop — April 24, 2017

# The Higgs portals: Example 1: Minimal Twin Higgs

- Additional twin Higgs doublet and an approximately *SU(4)*-symmetric potential. SM-like Higgs is a pseudo Goldstone boson of this approximate global symmetry

$$V = \lambda(|\mathcal{H}|^2 - f^2/2)^2, \langle\mathcal{H}\rangle = f/\sqrt{2}$$

- Twin tops and a twin top Yukawa $\rightarrow$ numerically very close to the SM top Yukawa
- Twin weak bosons from the gauged *SU(2)*
- Twin glue $\rightarrow$ a gauged *SU(3)* symmetry
- Twin bottoms and twin taus
- Twin neutrino from the twin tau doublet

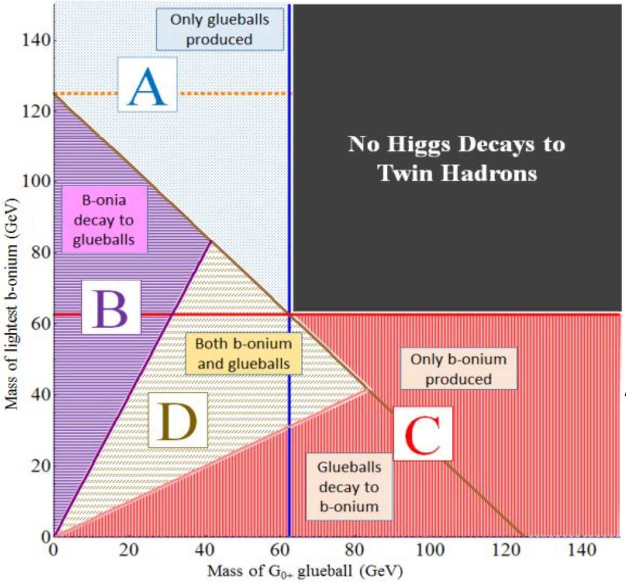



Mixing between Higgs and Twin Higgs

- Br(h $\rightarrow$ twin hadrons) > $10^{-4}$ everywhere that is not kinematically forbidden
- **Twin confinement** works in a similar way for hidden sectors, where twin gluons are confined and hadronise into twin glueballs, analogous to how regular gluons form glueballs in our visible universe

[arXiv:1501.05310; Craig et al.]

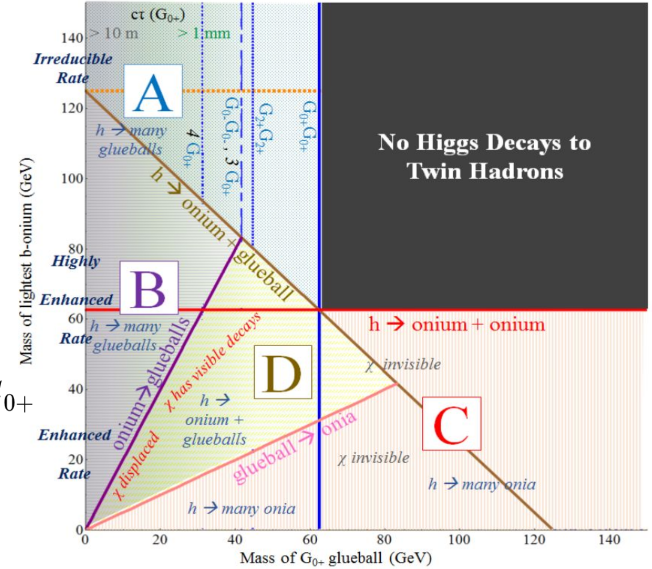
# The Higgs portals: Example 1: Minimal Twin Higgs




arXiv:1501.05310; Craig et al.

$\hat{\eta} \equiv$ lightest $[\hat{b}\bar{\hat{b}}]$ state

$m_0 \equiv$ mass of lightest twin glueball, $G_{0+}$




Region A $m_h > 2m_0, m_h < 2m_{\hat{\eta}}, m_h < m_0 + m_{\hat{\eta}}$

Region B $m_h > m_0 + m_{\hat{\eta}}, m_{\hat{\eta}} > 2m_0$

Region C, either $m_0 + m_{\hat{\eta}} > m_h > 2m_{\hat{\eta}}$ or $m_0 > 2m_{\hat{\eta}}$

Region D $m_h > m_0 + m_{\hat{\eta}}, m_{\hat{\eta}} < 2m_0, m_0 > 2m_{\hat{\eta}}$

For $f = 3v, c\tau \sim 18\text{ m}\left(\frac{10\text{ GeV}}{m_0}\right)^7$

**Twin sector glueballs give rise to displaced decays on the length scale of the LHC detectors**

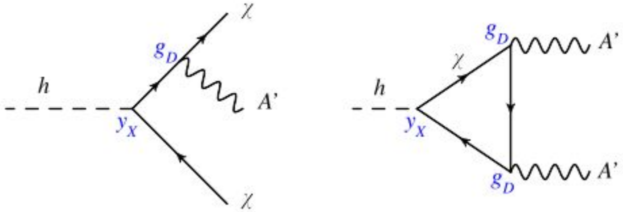
# The Higgs portals: Example 2: Higgs portal to dark QED

- Consider the following Lagrangian for the Higgs portal to dark QED

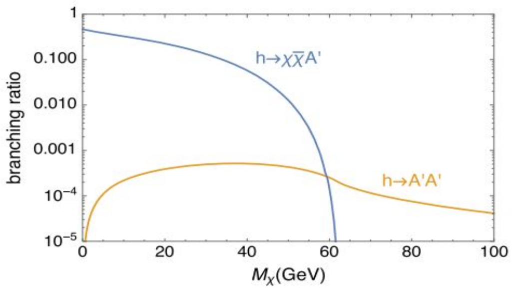
$$\mathcal{L} = \bar{\chi} i \not{D} \chi - m_\chi \bar{\chi}\chi + \frac{1}{\Lambda}\chi\chi^c(H^\dagger H - v^2/2) + \text{ H.c } - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu - \frac{\kappa}{2}F'_{\mu\nu}F^{\mu\nu}$$

$\chi \equiv$ Dirac fermion and dark matter candidate → couples to SM Higgs via dimension-5 interaction suppressed by $\Lambda$ → charged under dark $U(1)_D$ gauge symmetry with $V_\mu$ gauge boson

$A_\mu{}' \equiv$ dark photon, $D_\mu = \partial_\mu + igA'_\mu$




- If mixing, $\kappa$, between visible and dark photons is small, dark photon will be long-lived and could be via "monodark photon" channel

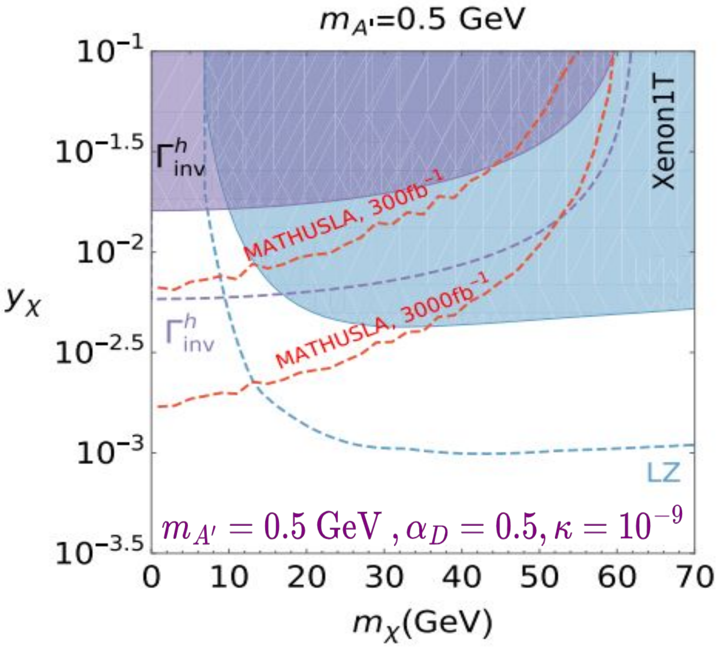


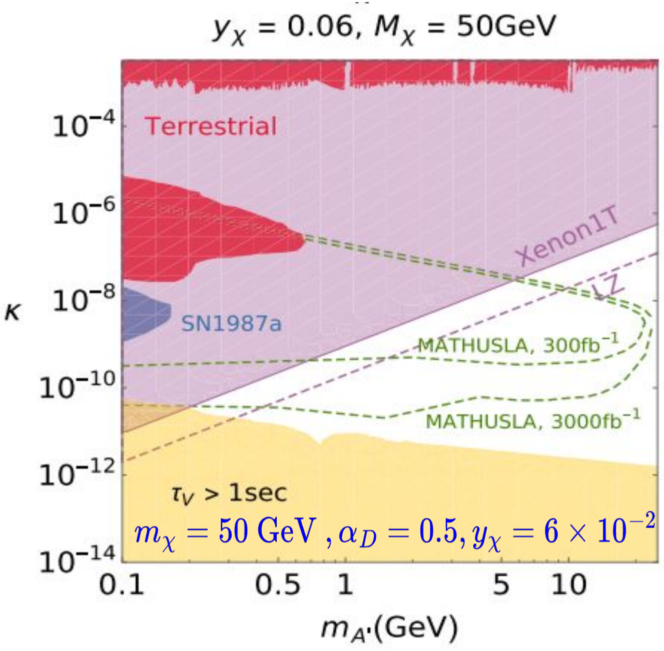

$$c\tau_{A'} = 10^7 \text{ cm} \left(\frac{10^{-9}}{\kappa}\right)^2 \left(\frac{1 \text{ GeV}}{m_{A'}}\right)$$

Typical dark photon decay length → longer than any existing and proposed detectors at LHC → detectors like MATHUSLA in non-forward directions

arXiv:1909.07987; Krovi et al.

# The Higgs portals: Example 2: Higgs portal to dark QED



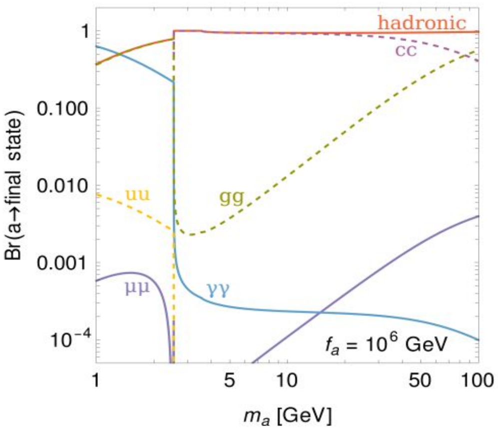



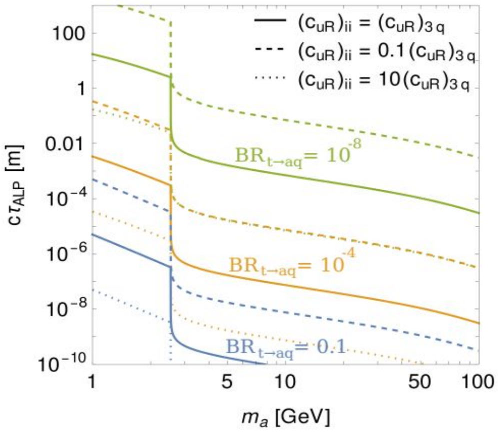

$$\alpha_D = g_D^2/(4\pi), y_\chi \equiv \frac{v}{\Lambda} \text{ dark yukawa coupling}$$

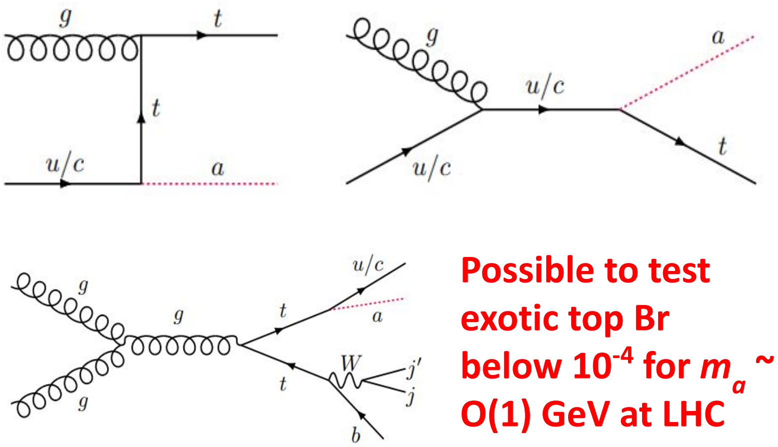
arXiv:1909.07987; Krovi et al.

# Portal Example 2: The ALP portal: Example: ALPs from exotic Top decays

- **Focusing on scenarios where ALPs only interact with up-type quarks at tree level**
- **Relevant EFT is given as** $\mathcal{L}_{\text{ALP,EFT}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}(c_{u_R})_{ij}\bar{u}_{Ri}\gamma^\mu u_{Rj}$
  **With $c_{uR}$ being a Hermitian matrix**
- **Examples of UV-completions: Dark QCD-like sectors with scalar mediators, Froggatt-Nielsen model**




**Possible to test exotic top Br below $10^{-4}$ for $m_a$ ~ O(1) GeV at LHC**

arXiv:2202.09371; Carmona et al.

# Summary

- LLPs arise in SM as well
- In BSM LLPs arise when (i) Matrix Element is small, (ii) Phase space is small, (iii) Couplings are suppressed by the scale of new physics
- In SUSY, RPV scenarios give rise to interesting LLP signatures including (i) displaced vertices, (ii) backward moving objects
- In GMSB, one also gets interesting LLP signatures including non-pointing jets
- LLPs via portals (Higgs, vector, heavy neutrinos, ALPs) are very interesting to look at and are well-motivated
- LLPs mediated via Higgs portals include Hidden Valley Models like Twin Higgs, Higgs portal to dark QED, etc. These give rise to many interesting and rich signatures
- ALP portals give rise to striking signatures including exotic top decays

# Backup slides

# SUSY Example 3: Split SUSY

- **Split-SUSY** → hierarchy problem addressed by fine-tuning
- **Scales of fermionic superpartners (gauginos, Higgsinos) ~ TeV**; **Scalar superpartners (squarks, sleptons) ~ much heavier (typically around $10^{10}$ - $10^{12}$ GeV)**
- **Heavy scalar masses → suppresses certain decay channels → relatively long lifetimes for fermionic superpartners**
- **Example: Long-lived gluino** $\tilde{g} \to q\bar{q}\chi_1^0$
- **Lifetime is of the order:** $c\tau \approx 100\mu m \left(\frac{M_{\tilde{q}}}{10^3 \text{ TeV}}\right)^4 \left(\frac{\text{TeV}}{M_{\tilde{g}}}\right)^5$
- **Signatures: Non-pointing Jets + missing transverse energy, backward moving jets + missing transverse energy, displaced vertices, etc**

# SUSY Example 4: *νCMSSM* model

- **Assuming Lepton number conservation, MSSM superpotential extended by**

$$W_\nu^R = y_\nu \hat{H}_u \hat{L} \hat{\nu}_R^c$$

**$y_\nu \equiv$ neutrino Yukawa, $L$, $H_u$, $\nu_R$ are respectively the left-handed lepton, Higgs, right-handed neutrino superfields**

- **Small neutrino Yukawa couplings O($10^{-13}$) from neutrino oscillations + Planck + lensing + Baryon Acoustic Oscillation**

- **Sneutrino not thermalised in early universe but produced from decay of "MSSM-LSP" before or after Freeze-out**

$$\Omega_{\hat{\nu}_R}^{\rm FO} = \frac{m_{\hat{\nu}_R}}{m_{\tilde{\tau}_1}} \Omega_{\tilde{\tau}_1}, \Omega_{\hat{\nu}_R}^{\rm FI} h^2 \simeq \frac{1.09\times 10^{27}}{g^{*3/2}} m_{\tilde{\nu}_R} \sum_i \frac{g_i \Gamma_i}{m_i^2}$$

$$g^* \approx 106.75 : \text{ average number of effective d.o.f.s contributing to thermal bath}$$

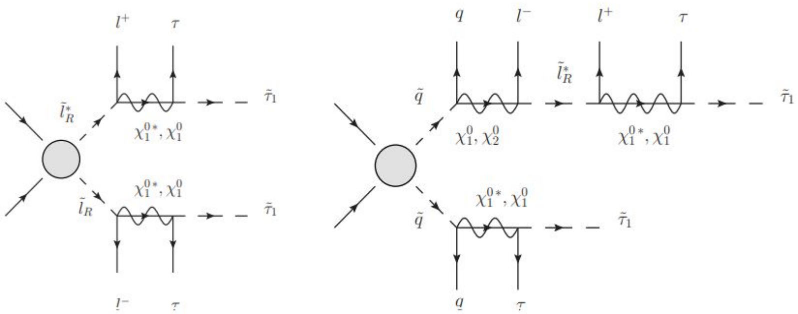
$$\Gamma_i, m_i, g_i \equiv \text{respectively decay to } \hat{\nu}_R, \text{ mass, and d.o.f. of the } i^{th} \text{superparticle}$$

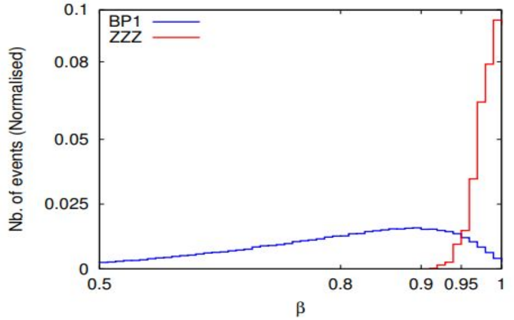
SB, Bélanger, Ghosh, Mukhopadhyaya; 2018

# SUSY Example 4: *νCMSSM* model

- Consider stau as "NLSP" → lives from second to minute → decays outside CMS/ATLAS

- LHC signatures: heavy stable charged particles (HSCP)
  Signatures: 2 stable charged tracks, 2 OSSF leptons, 1 τ-tagged jet, missing transverse energy
  2 stable charged tracks, 2 OSSF leptons, 2 τ-tagged jets, missing transverse energy






- Constraints from BBN: An LLP with hadronic decay modes can affect the Big Bang Nucleosynthesis → can cause overproduction of light nuclei like deuterium → we require stau NLSP lifetime doesn't exceed ~ 100 seconds
- Stable stau behaves like slow muons, □ = p/E < 1 → use ionisation properties and T.O.F. measurement to distinguish from muons → also use kinematic distributions

SB, Bélanger, Ghosh, Mukhopadhyaya; 2018

# SUSY Example 5: Anomaly-mediated Supersymmetry Breaking (AMSB)

- **Anomaly-mediated Supersymmetry Breaking (AMSB) → SUSY breaking mediated through anomalies in gauge interactions**

- **The gaugino masses are proportional to the beta-functions times the gravitino mass**

$$M_i = \frac{\beta_i}{g_i} m_{3/2}, \text{ where } \beta_i = \frac{g_i^3}{16\pi^2} b_i$$

- **The soft-breaking scalar terms are**

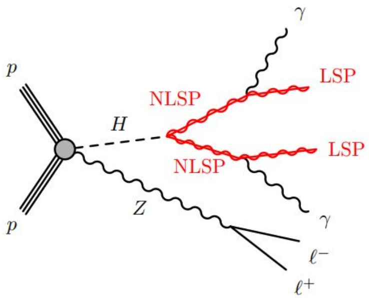
$$m_{\tilde{f}}^2 = -\frac{1}{4}\{\frac{d\gamma}{dg}\beta_g + \frac{d\gamma}{df}\beta_f\}m_{3/2}^2$$

- **The typical search channel is**

$$\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^0 + \pi^{\pm}$$

- **The signature is disappearing charged track where the chargino and the neutralino are nearly degenerate**

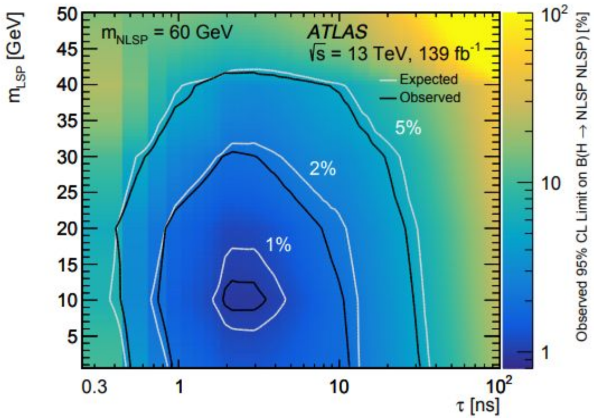
# Displaced photon

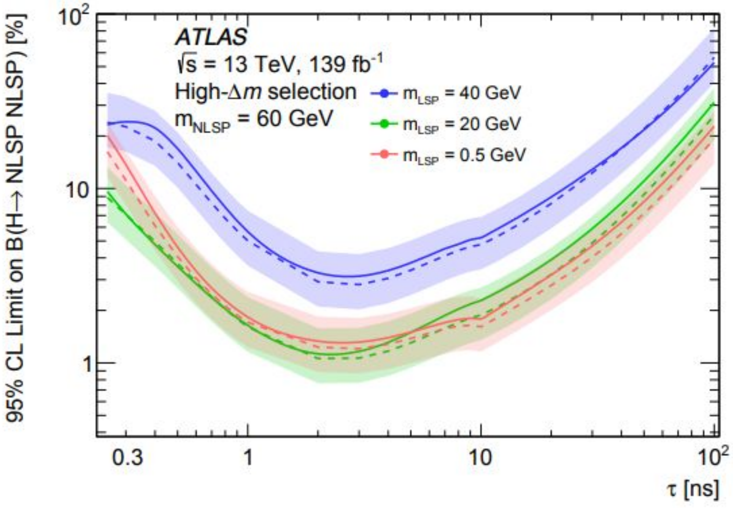



Signature: Displaced photon search

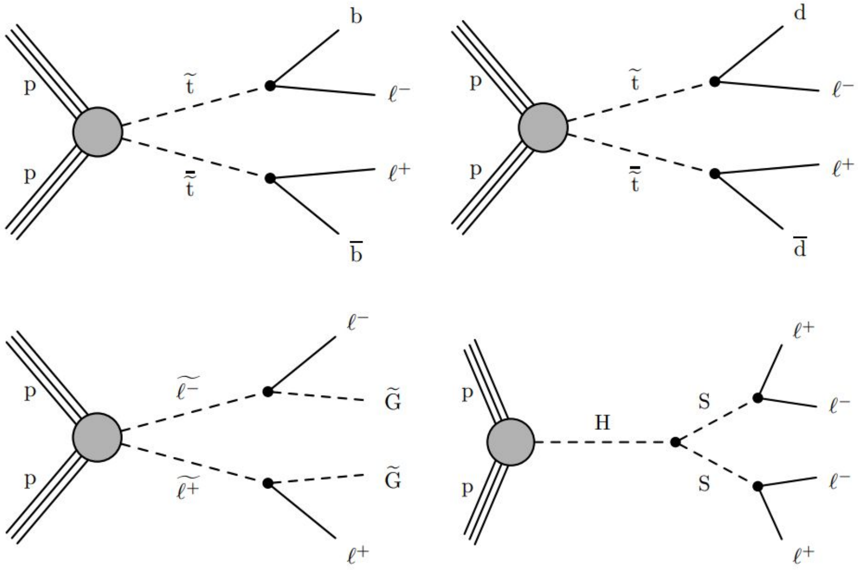
Possible scenario in GMSB: $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \gamma$, where $\tilde{\chi}_2^0$ is the NLSP

arXiv: 2209.01029 [ATLAS]



# Displaced leptons




$\tilde{t} \rightarrow b(d)\ell$ [RPV decay], $\tilde{\ell}^{\pm} \rightarrow \ell^{\pm} + \tilde{G}$ [GMSB]

arXiv: 2110.04809 [CMS]