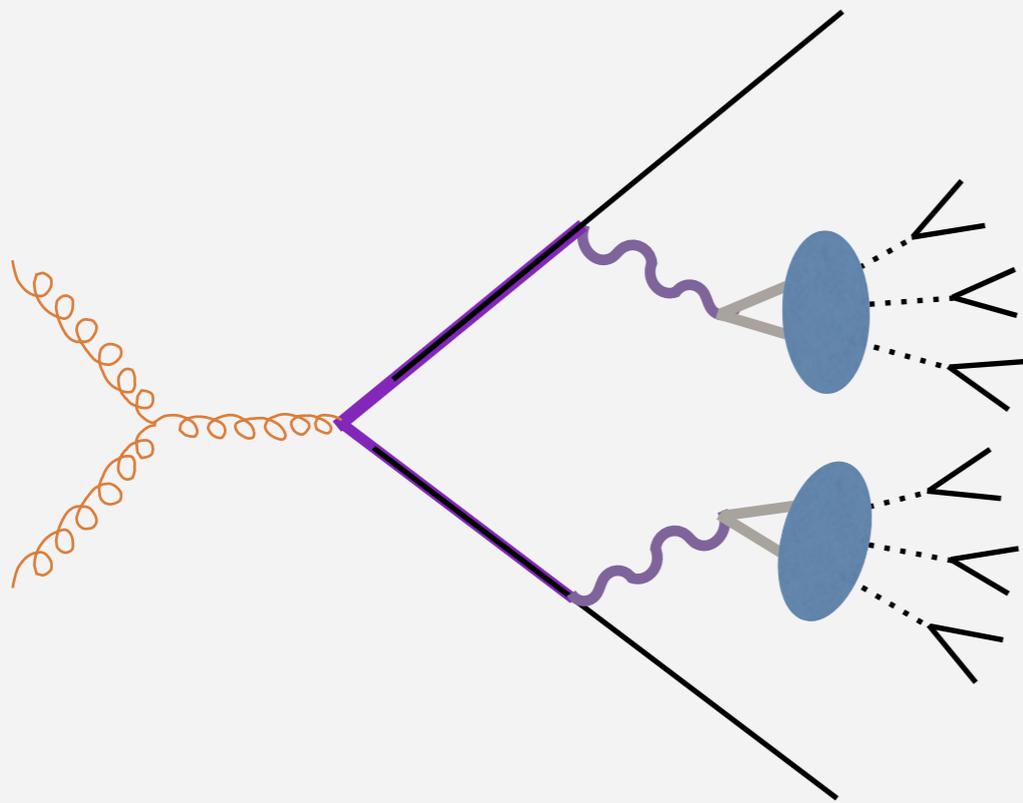


# Topologies for $X$ +Displaced Searches

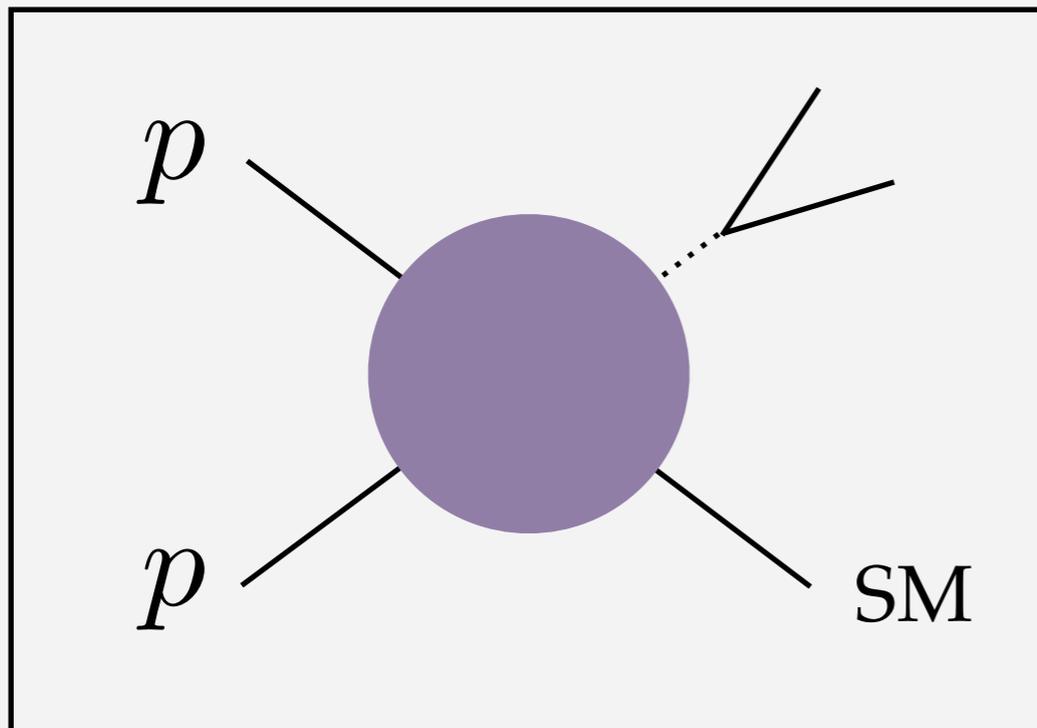


Yuhsin Tsai

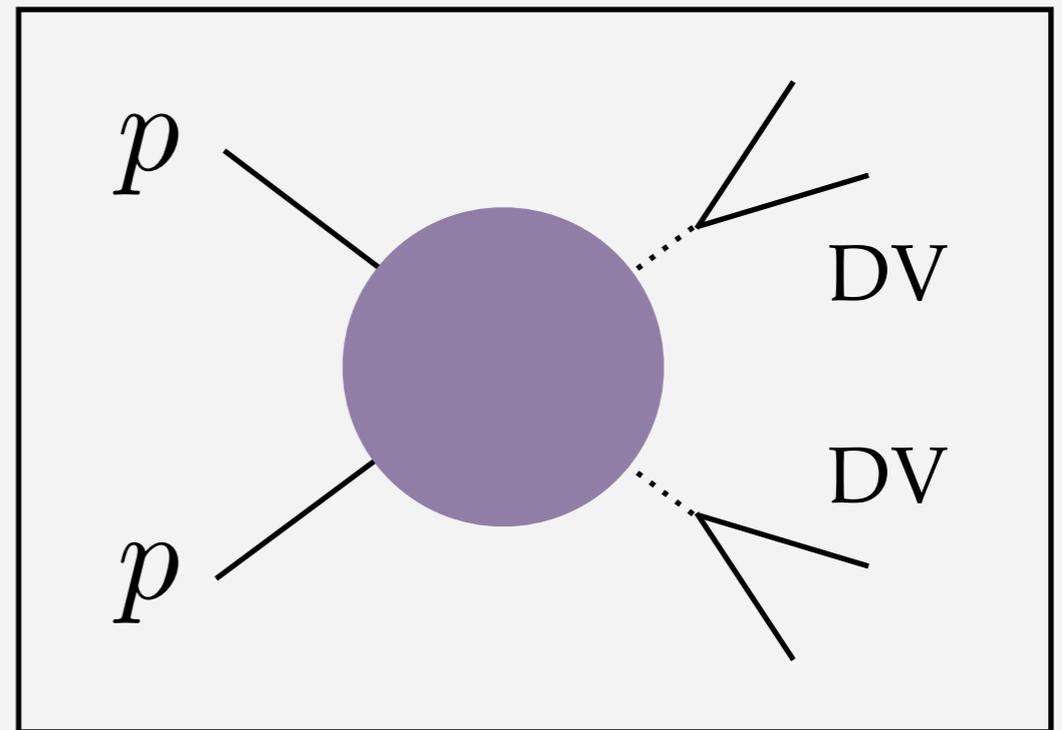
University of Maryland

Triggering on Long-Lived Particles, LBL, April 18, 2017

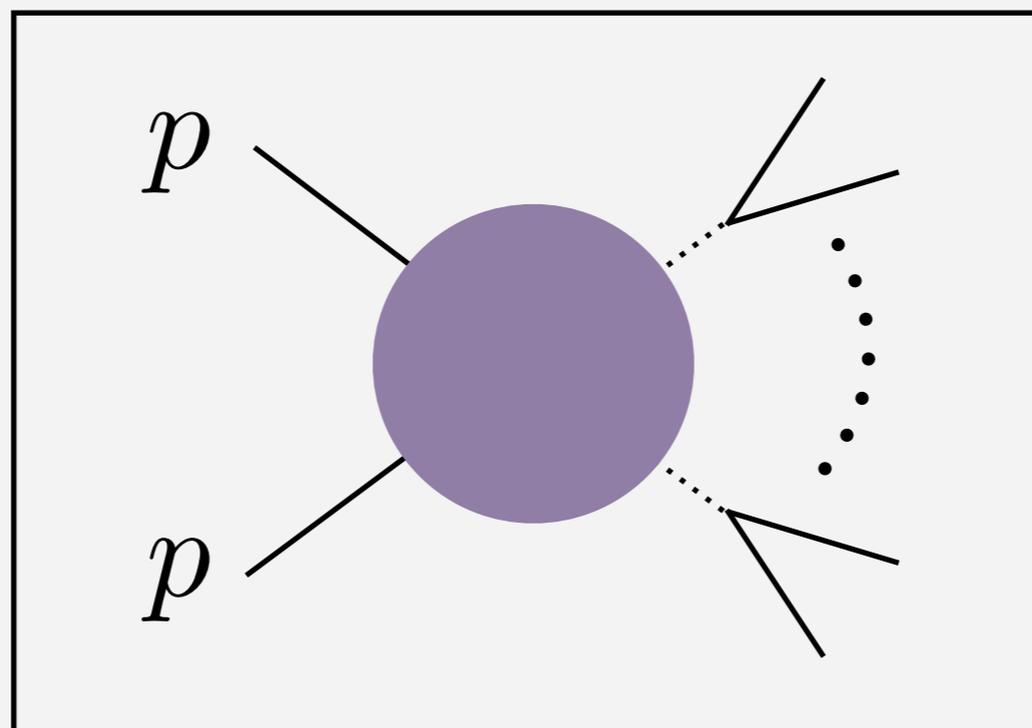
DV + SM



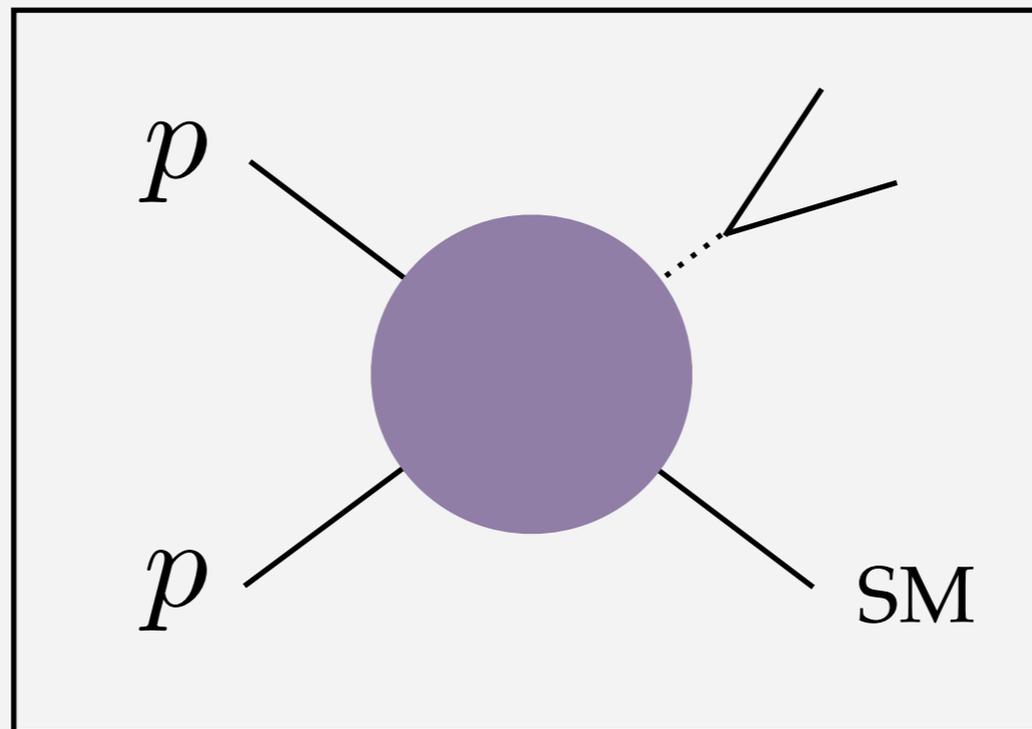
DV + DV



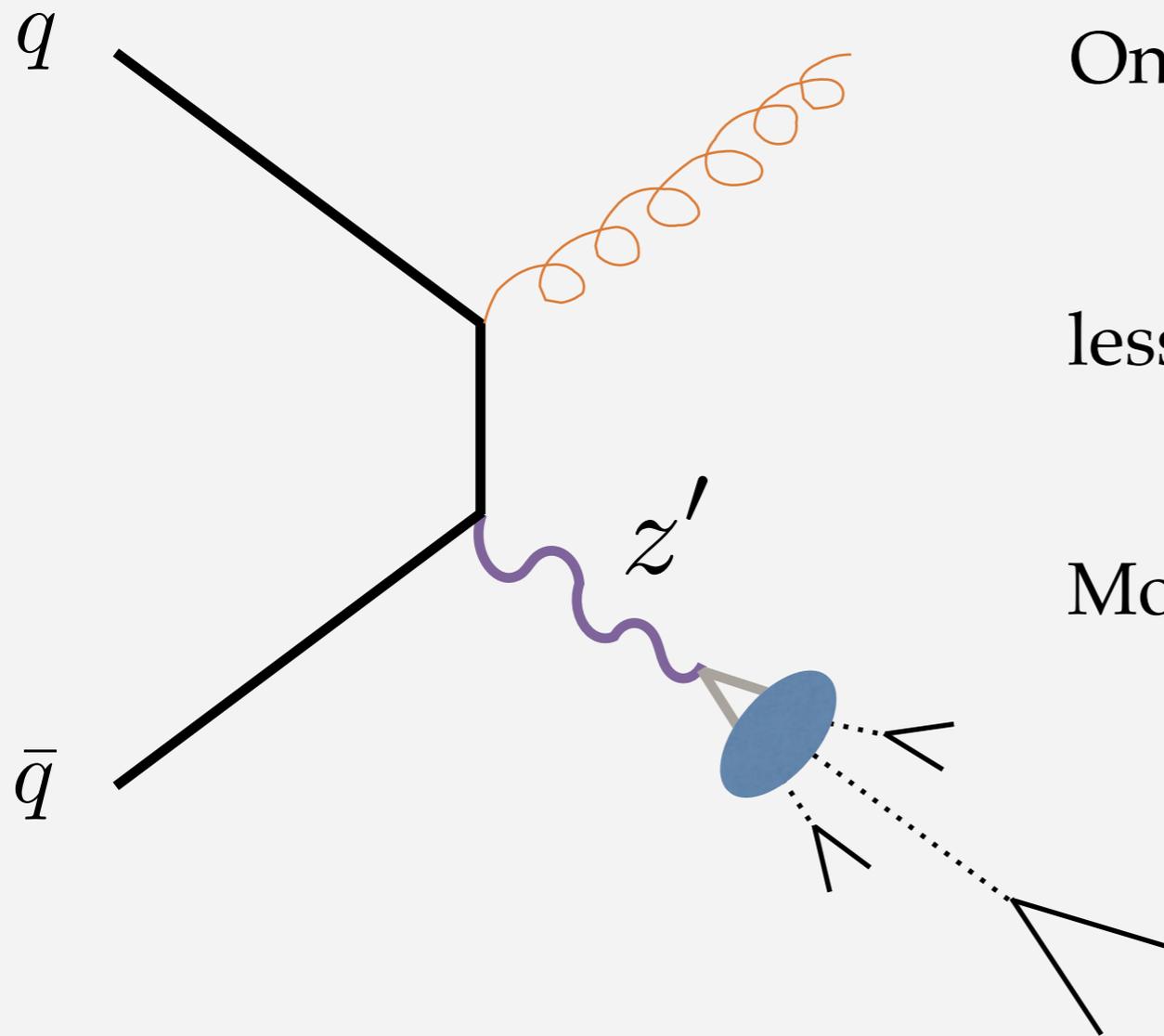
DV + DV + ...



1 or more DV + SM



# Hidden Valley + ISR



Displace jets, leptons, or photons

One way to trigger soft HV signal

less number of decays => larger MET

More decays => multi-jets or leptons

e.g. ATLAS displaced jets  
(1504.03634)

Trigger requires: MET > 75 GeV,  
and leading jet  $p_T > 110$  GeV

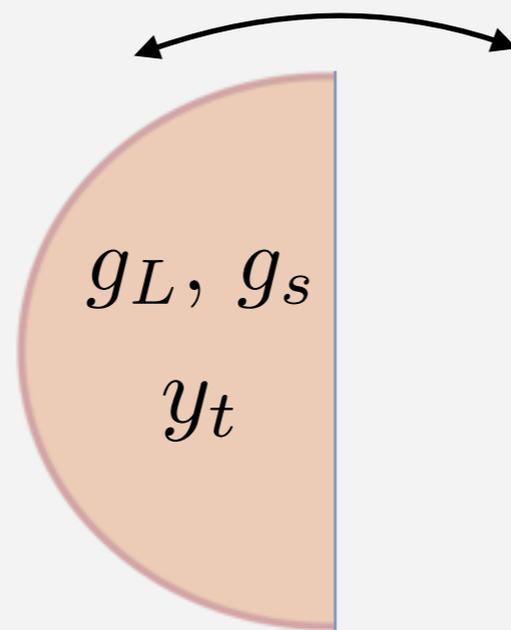
# Neutral Naturalness: Twin Higgs model

In composite Higgs model  $h \sim \pi$

light, because of symmetry protection

not massless, because the protection symmetry is explicitly broken

Explicitly breaking of the protection symmetry



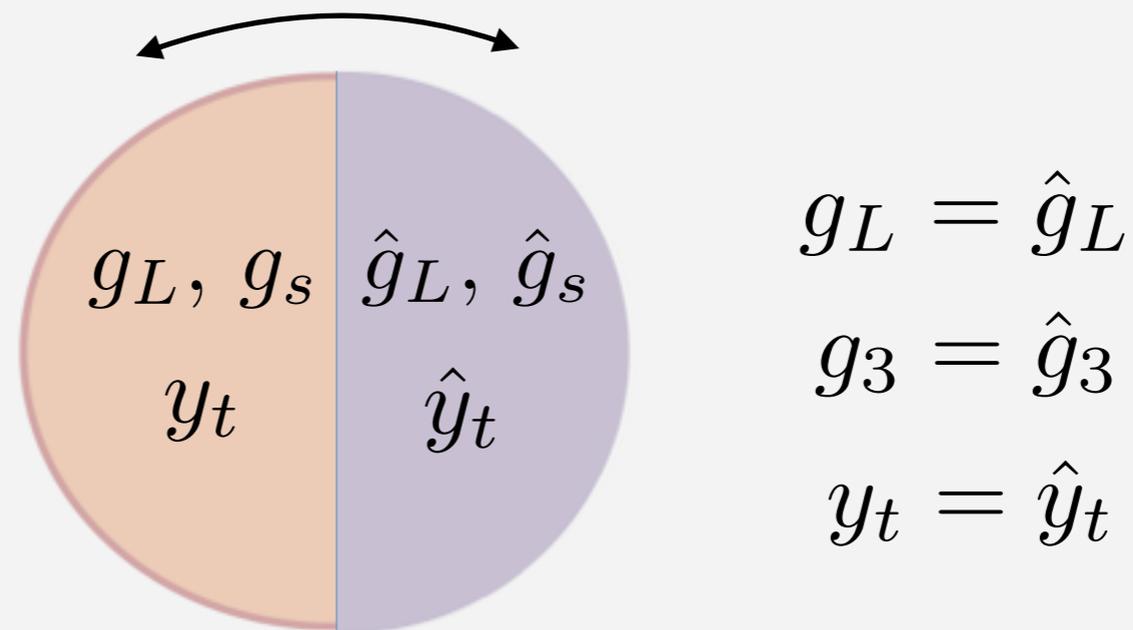
# Neutral Naturalness: Twin Higgs model

In composite Higgs model  $h \sim \pi$

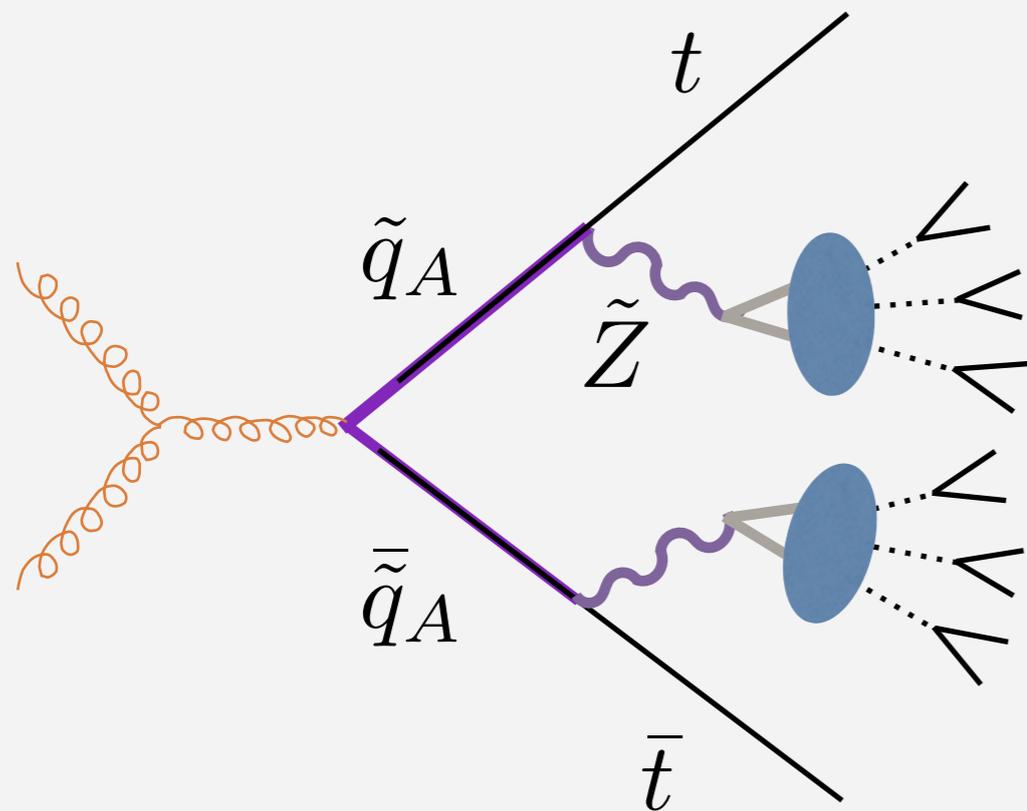
light, because of symmetry protection

not massless, because the protection symmetry is explicitly broken

Use a mirror symmetry to recover the protection symmetry



# DV from cascade decays



Exotic-quarks in Twin Higgs model  
Cheng, Jung, Salvioni, YT (15')

Large mass gap

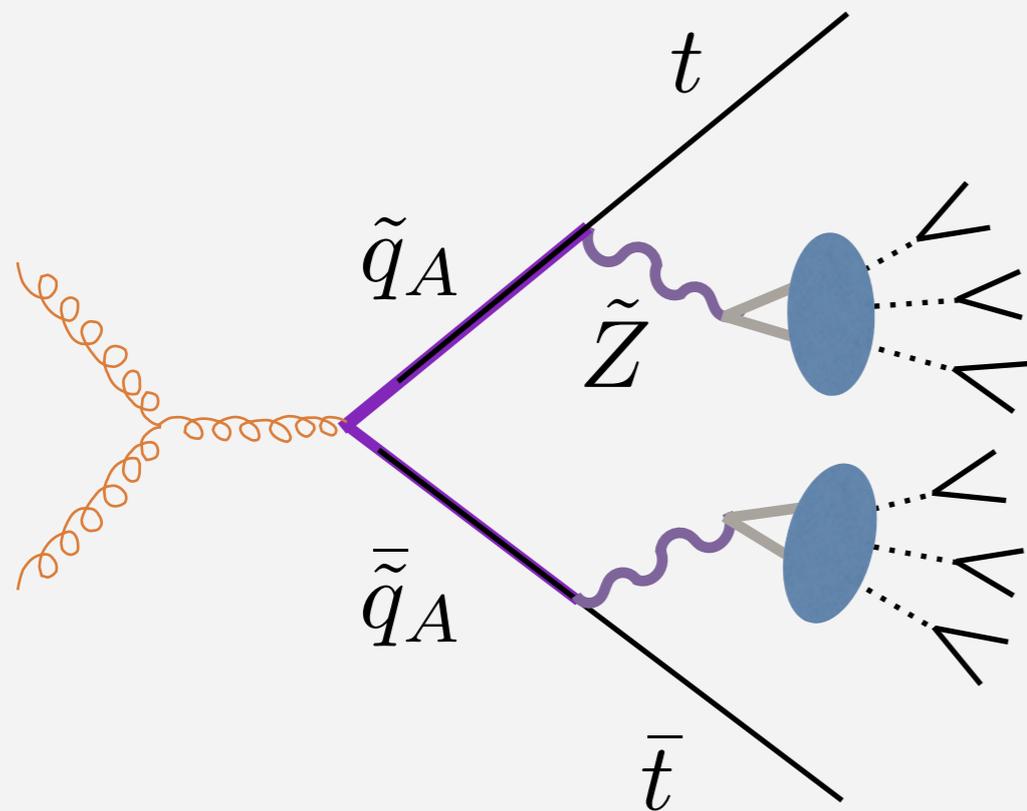
=> DV + high pT prompt signals

Smaller mass gap (off-shell top into SM)

=> how soft can the prompt objects be?

High pT leptons  
+ displaced jets or leptons

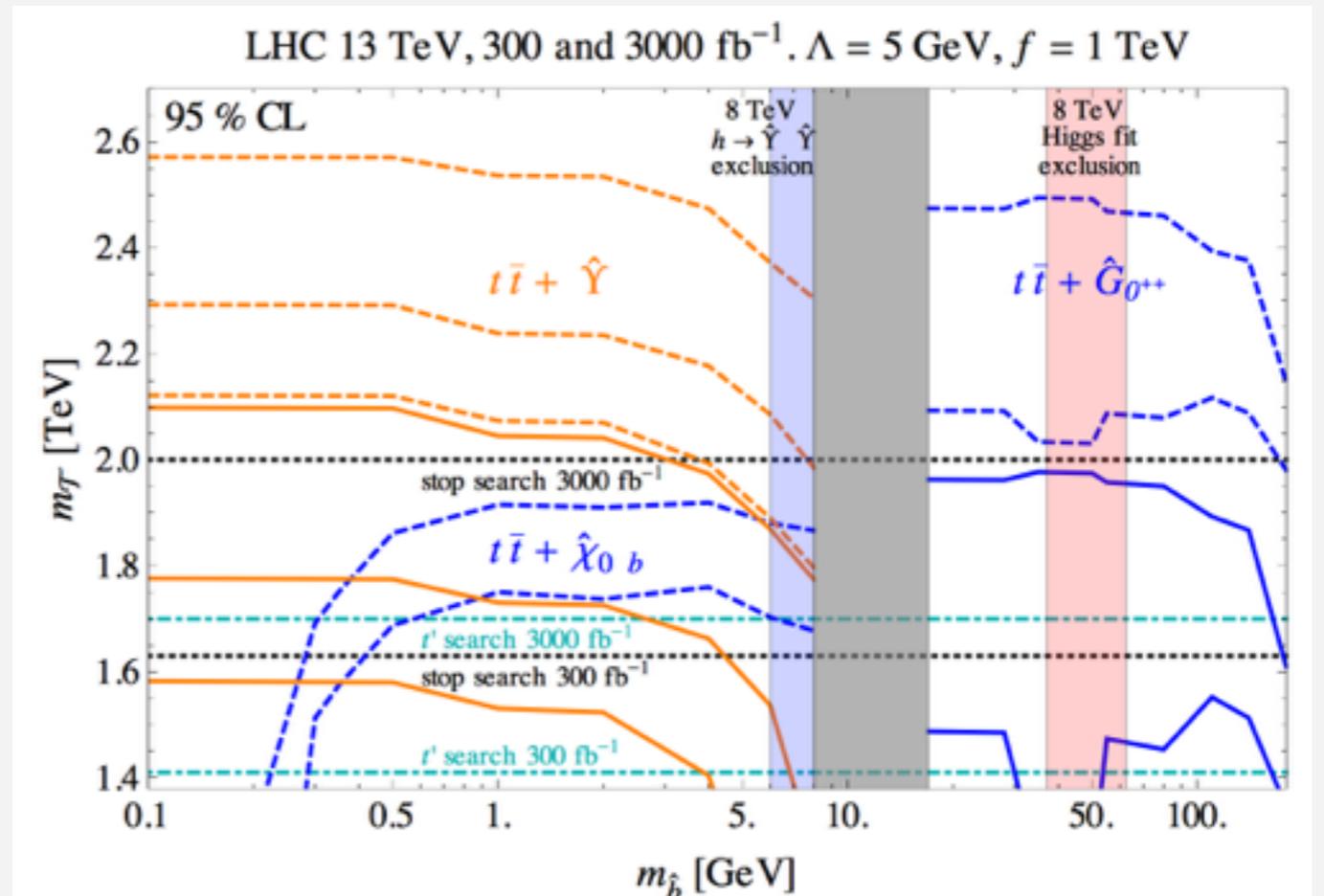
# DV from cascade decays



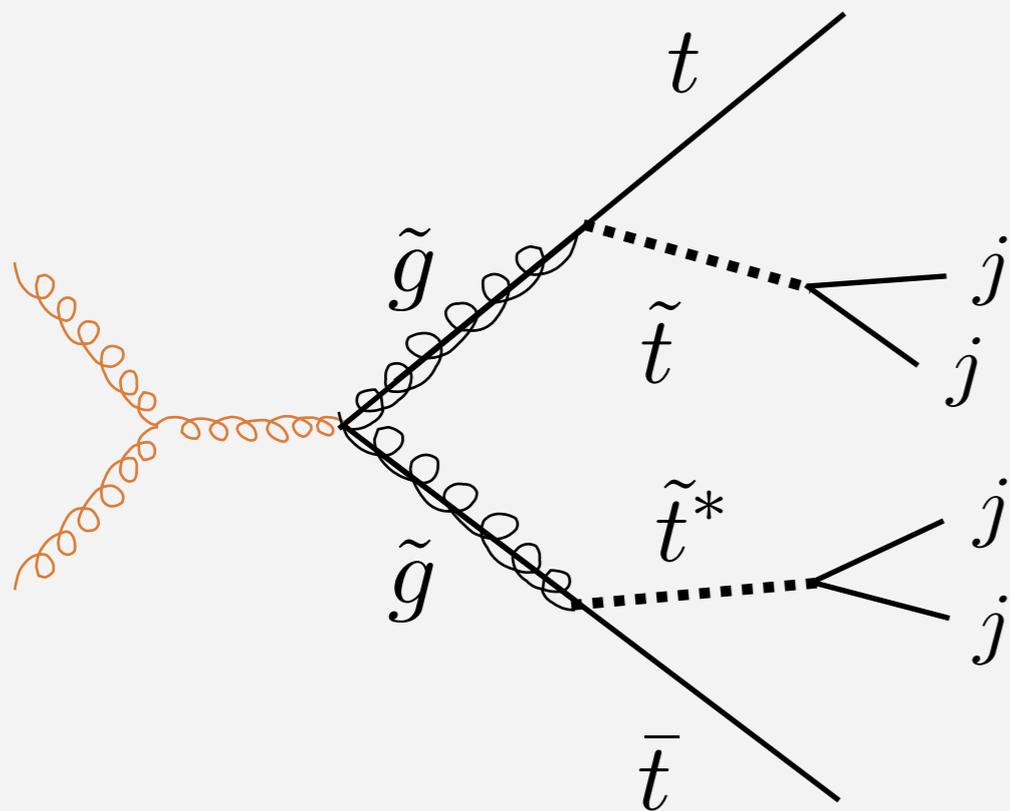
High  $p_T$  leptons  
+ displaced jets or leptons

## Exotic-quarks in Twin Higgs model

DV into  $bb$  or muons + lepton ( $p_T > 100$ )



# DV from cascade decays



High  $p_T$  leptons  
+ displaced jets

SUSY with R-Parity Violation

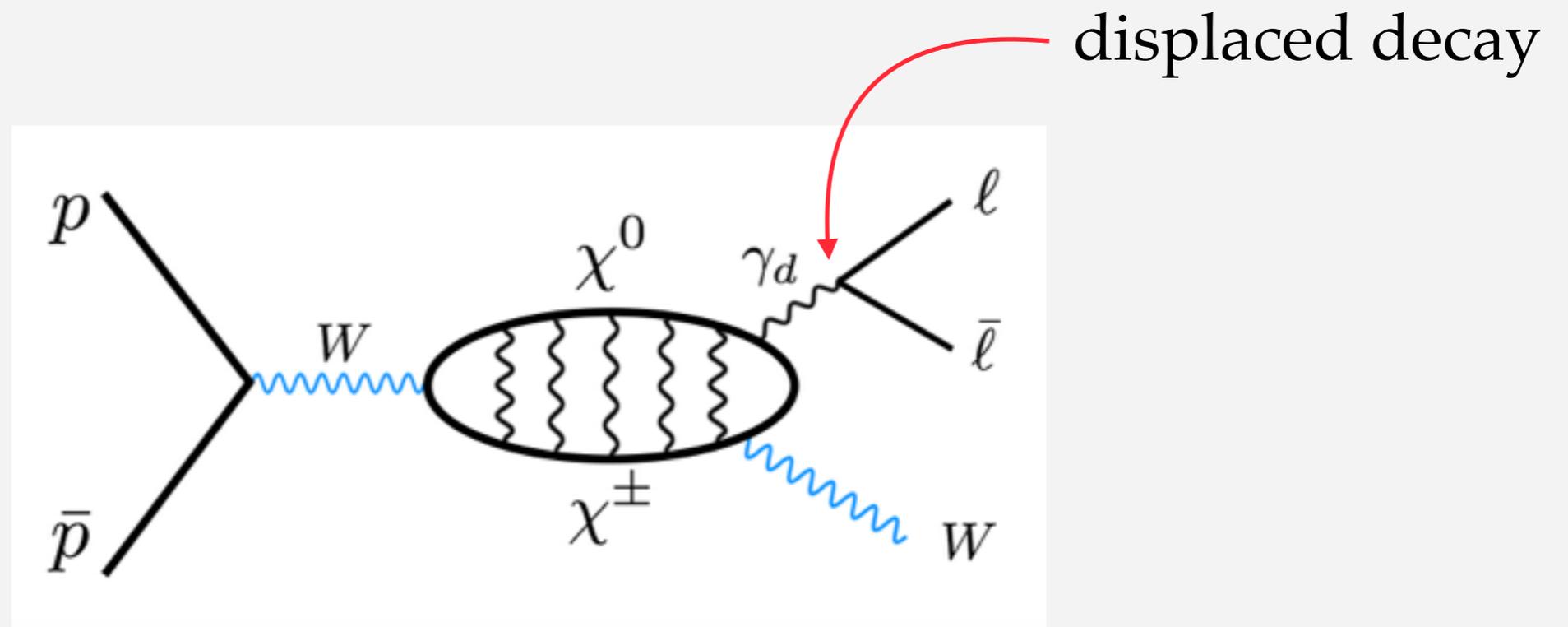
Large mass gap

=> DV + high  $p_T$  prompt signals

Smaller mass gap (off-shell top into SM)

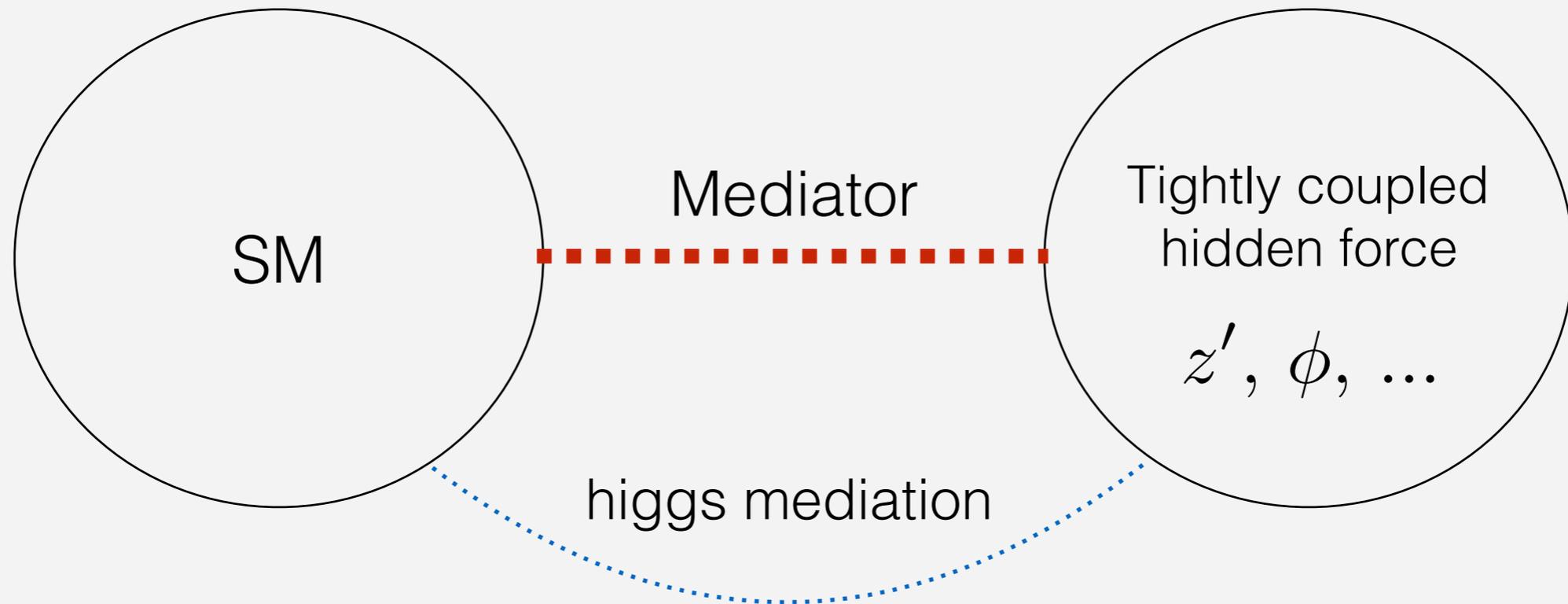
=> how soft can the prompt objects be?

# DV from a decay of EW-charged bound state

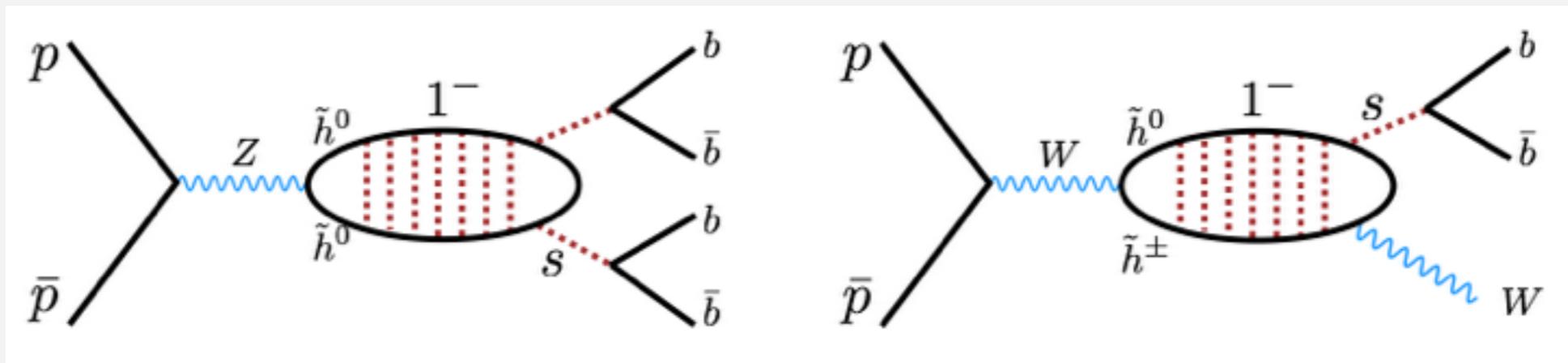


Li, Rui, Salvioni, YT, *in preparation*

# Probing a tightly coupled hidden force

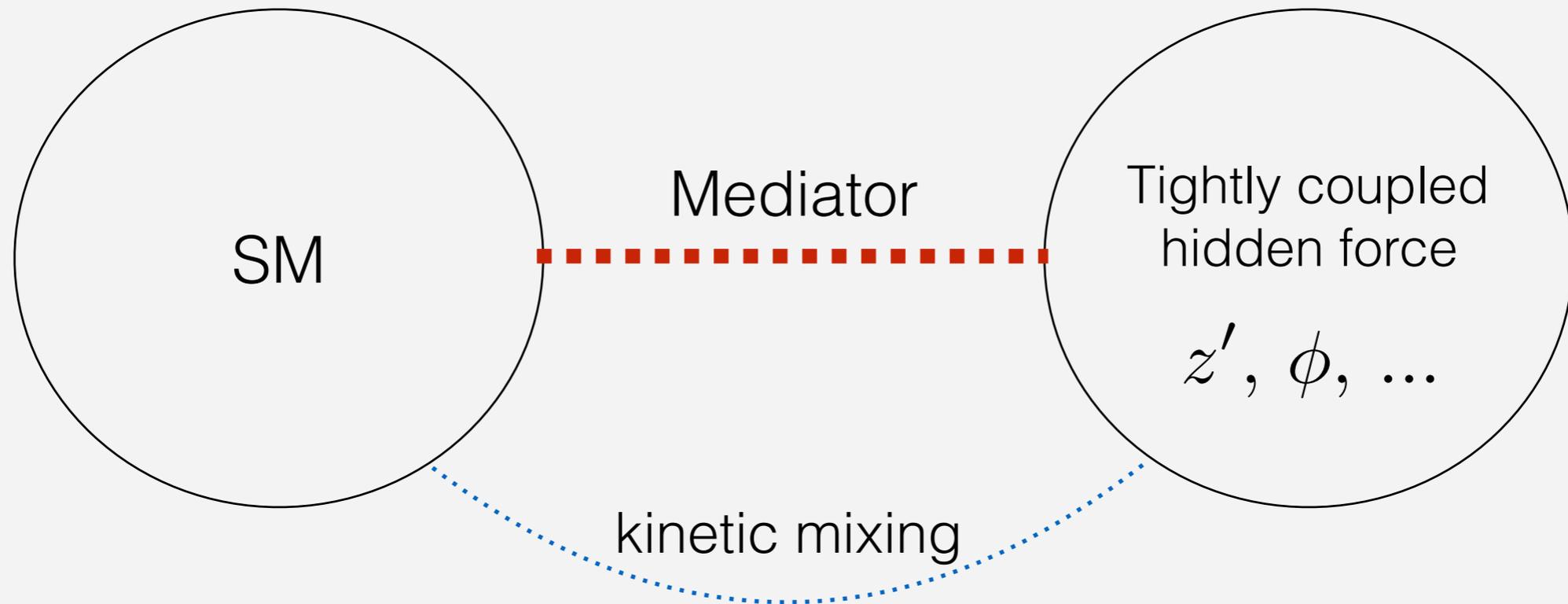


Lambda- SUSY

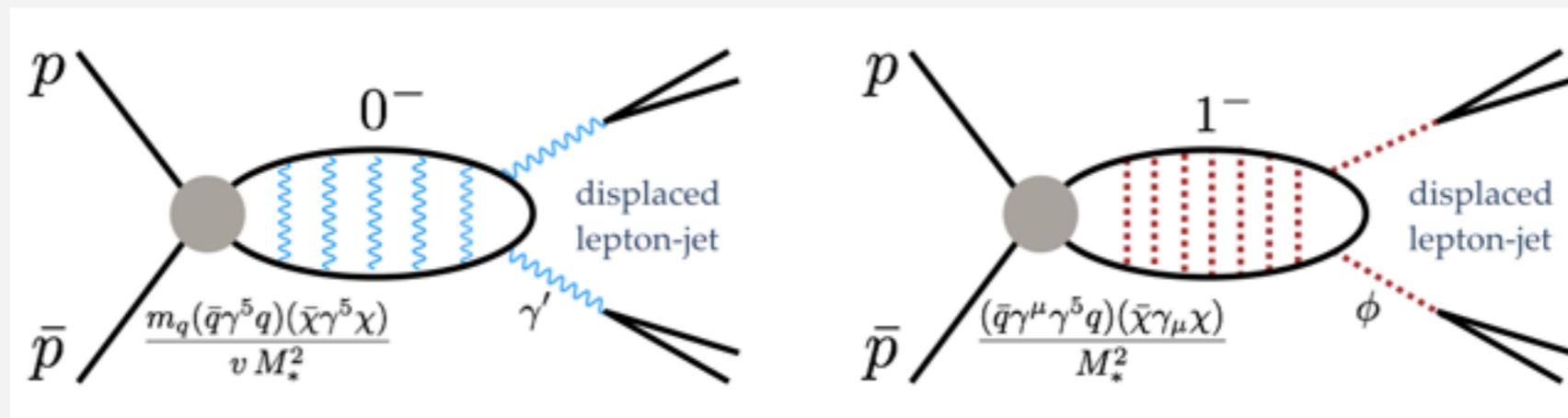


YT, Wang, Zhao (15')

# Probing a tightly coupled hidden force

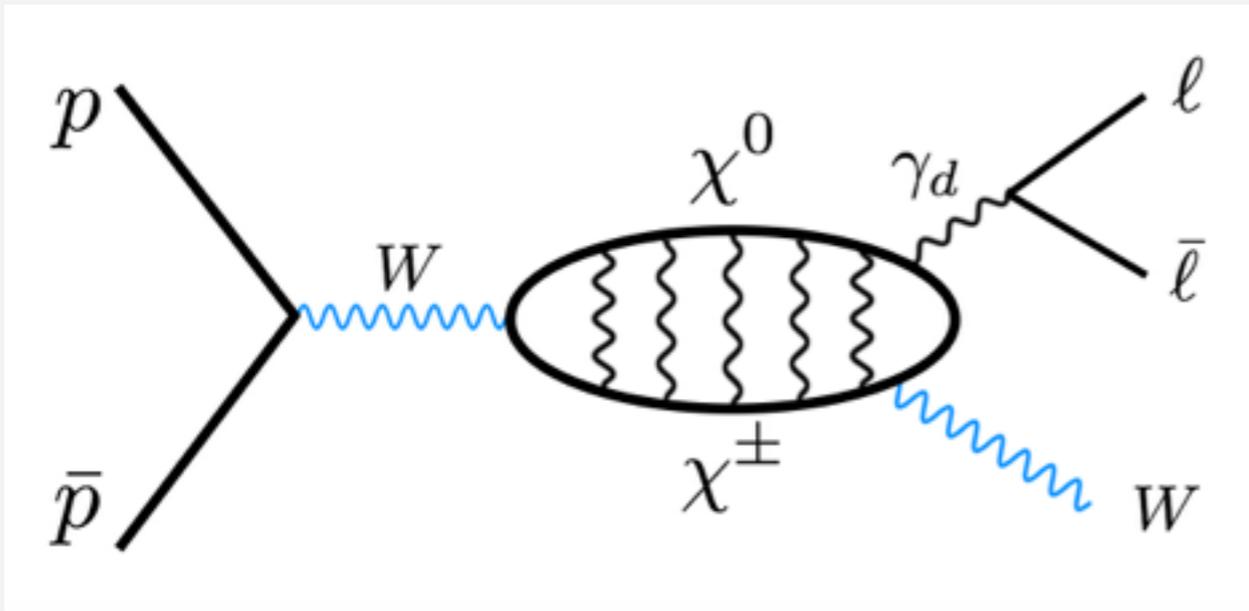


Self-Interacting DM



YT, Wang, Zhao (15')

# DV from a decay of EW-charged bound state



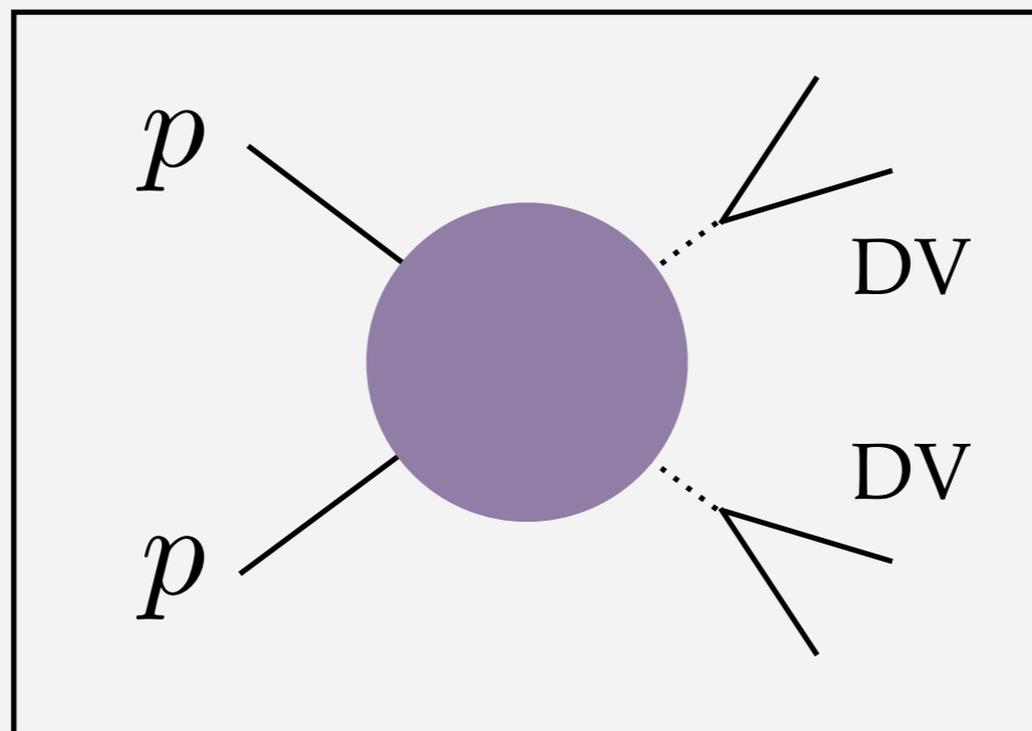
Resonance decays into SM + DV

Measure dark force coupling  
from cross section & masses

Trigger using the hard lepton

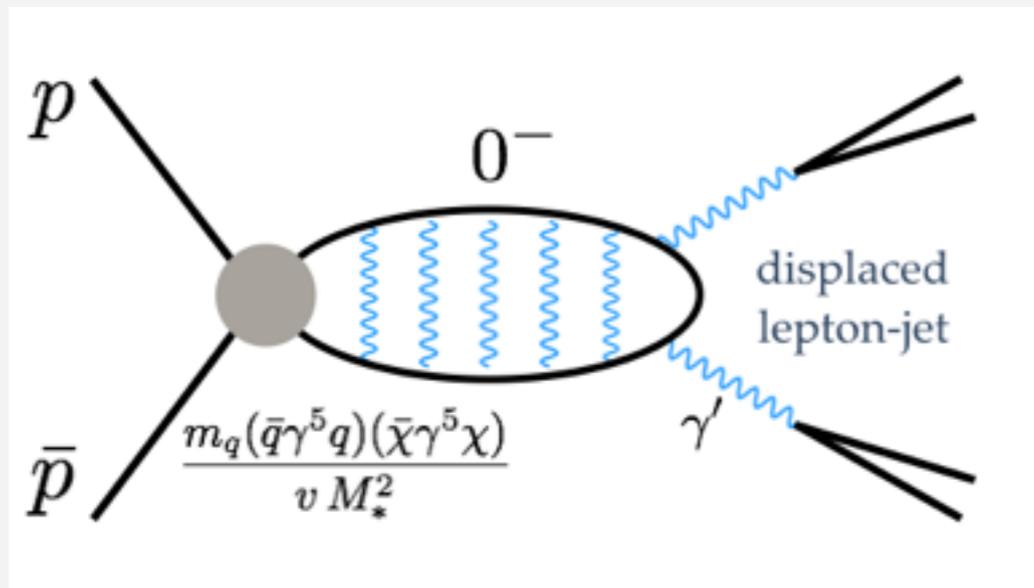
Dark photon can be highly boosted

DV + DV



Have a chance to reconstruct the resonance mass

# DV from heavy bound state decay



One of the final decays can be prompt, displaced, MET

DM annihilation at the LHC

Two displaced lepton-jets

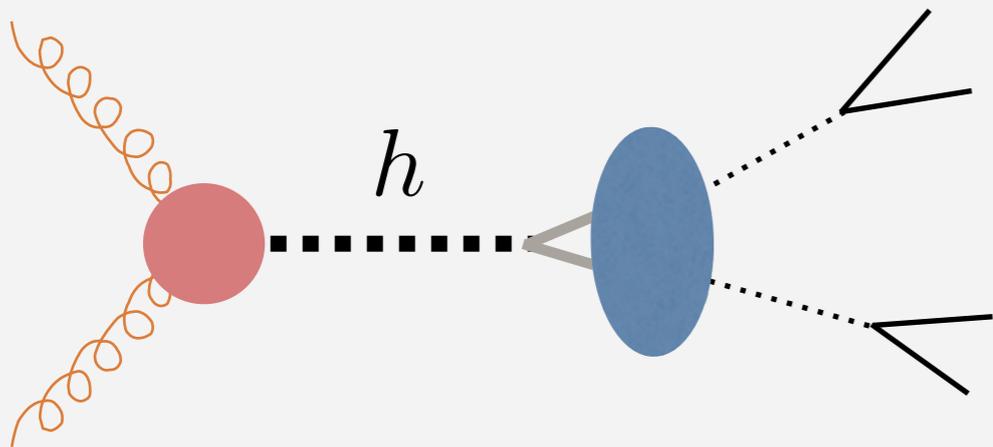
Dark photon can also be less boosted

e.g. ATLAS displaced lepton-jets  
(ATLAS-CONF-2016-042)

Narrow-Scan trigger for  
muon signals

# Exotic Higgs decay in Fraternal Twin Higgs

Carig, Katz, Strassler, Sundrum (15')



$DV$  can be Glueball ( $> bb$ )  
or Twin-Upsilon ( $> leptons$ )

Two DV if the meson / glueball  
mass  $> \sim 30$  GeV

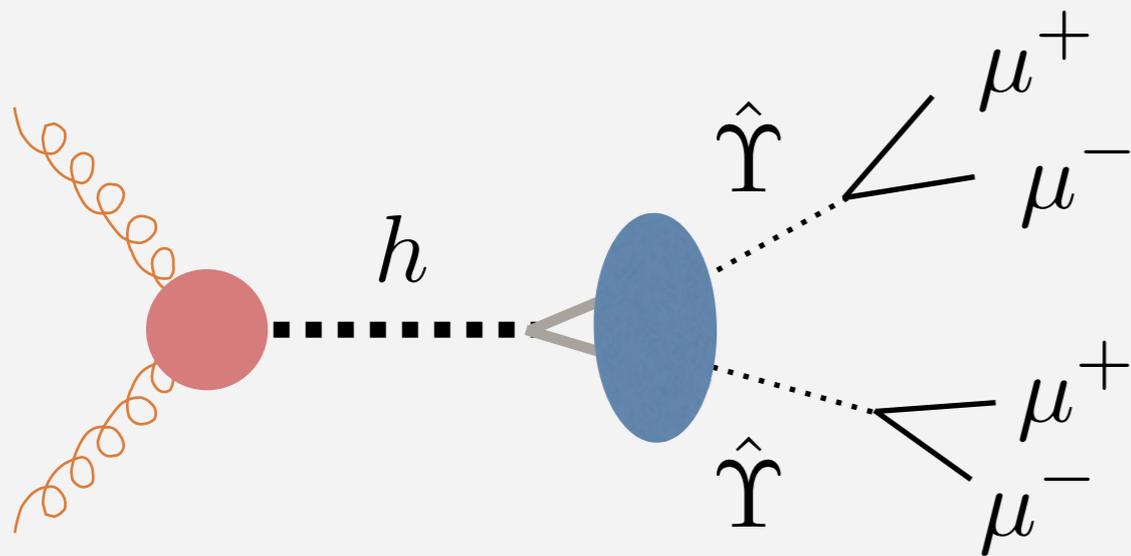
May reconstruct the Higgs mass

Can also come from associate  
Higgs productions

$\Rightarrow$  additional  $W/Z$ , forward jets

# Exotic Higgs decay in Fraternal Twin Higgs

Cheng, Jung, Salvioni, YT (15')



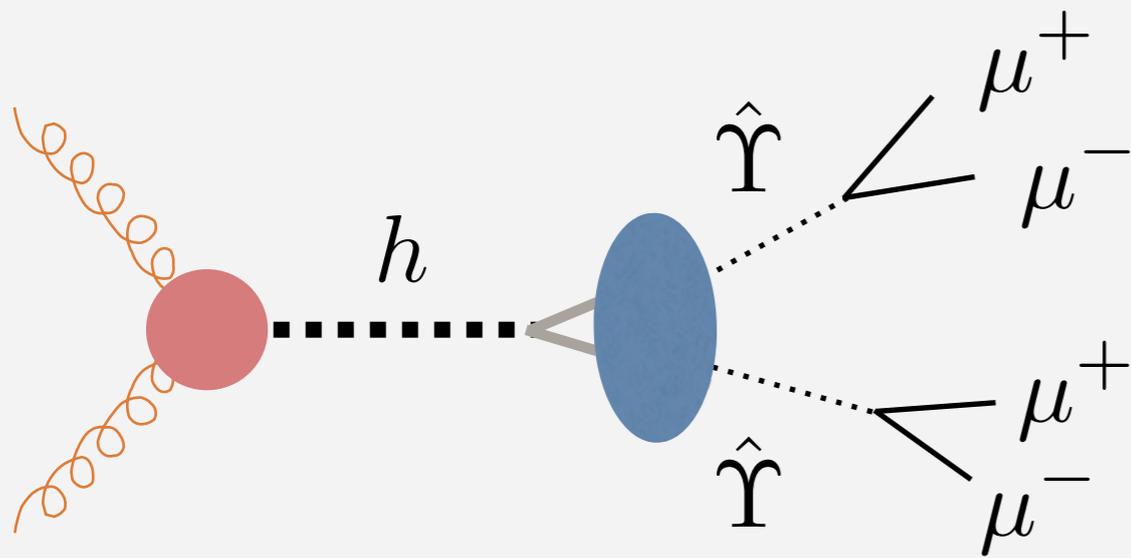
e.g. CMS displaced di-muon search  
(1411.6977)

Trigger: 2 muons, no PV constraint  
each with  $p_T > 23$  GeV

Twin-epsilon decay through kinetic mixing

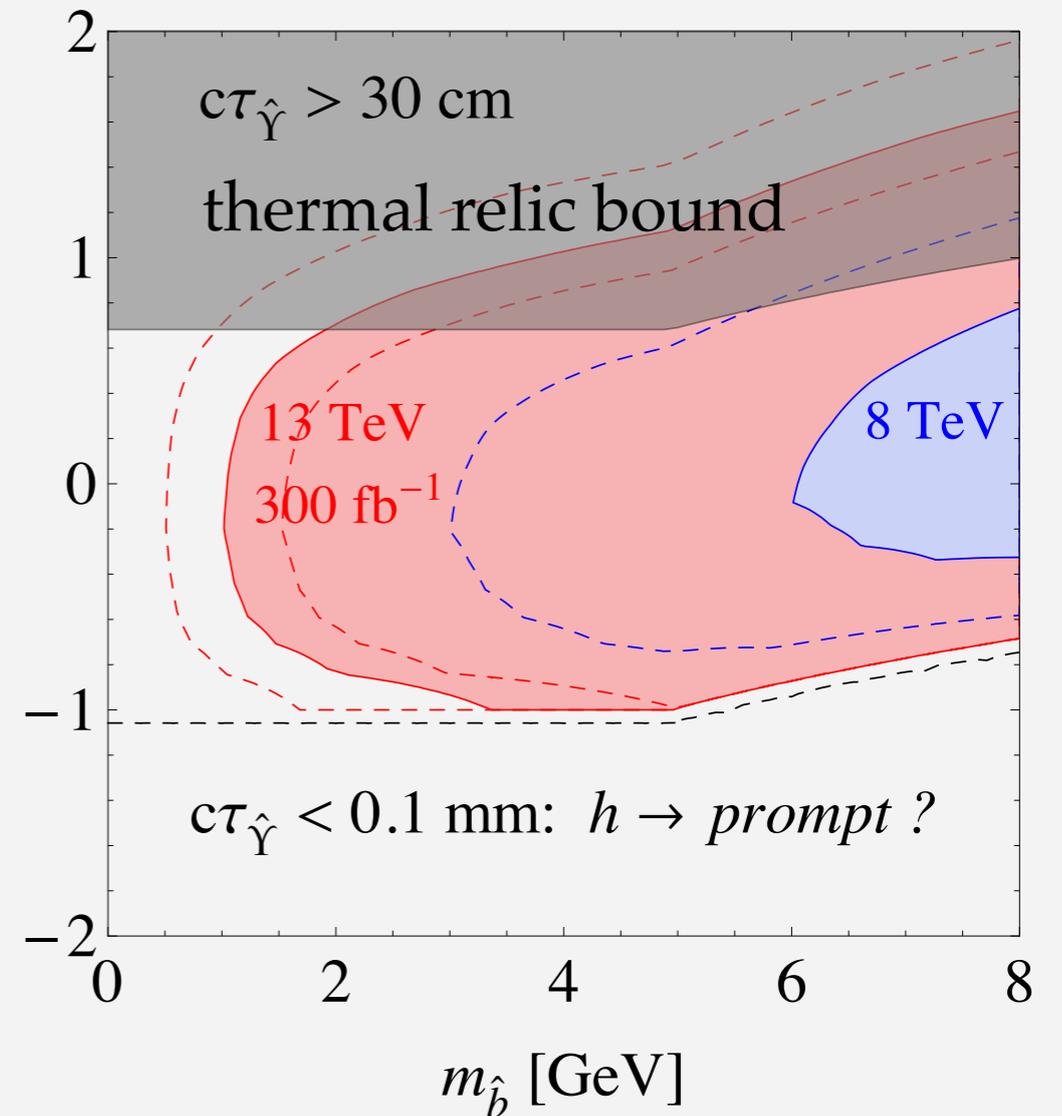
# Exotic Higgs decay in Fraternal Twin Higgs

Cheng, Jung, Salvioni, YT (15')

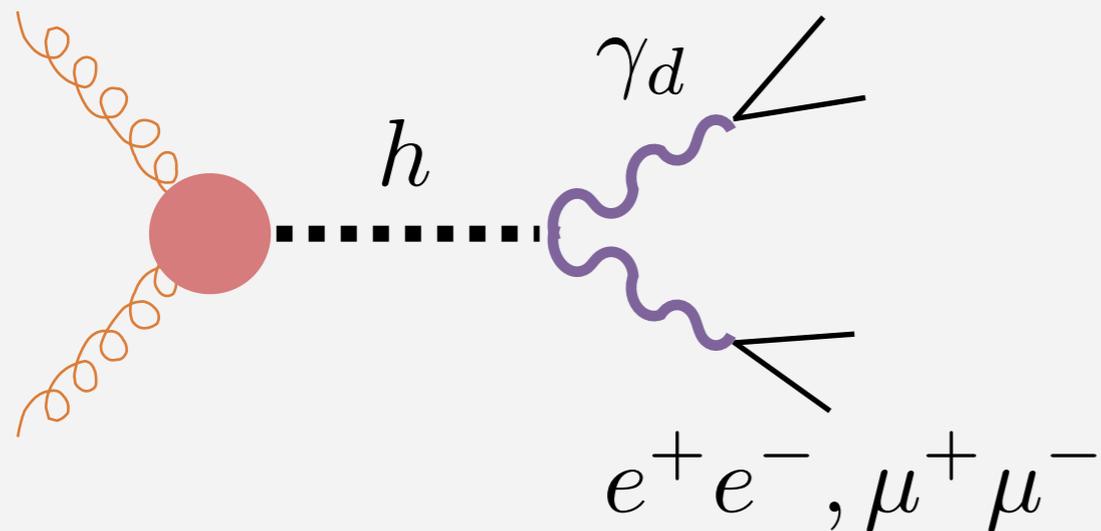


Mediation scale for  
Twin-Upsilon decay

$$\text{Log}_{10} \left[ \frac{m_A^2}{(100 \text{ GeV})^2} \frac{10^{-3}}{\epsilon} \right]$$



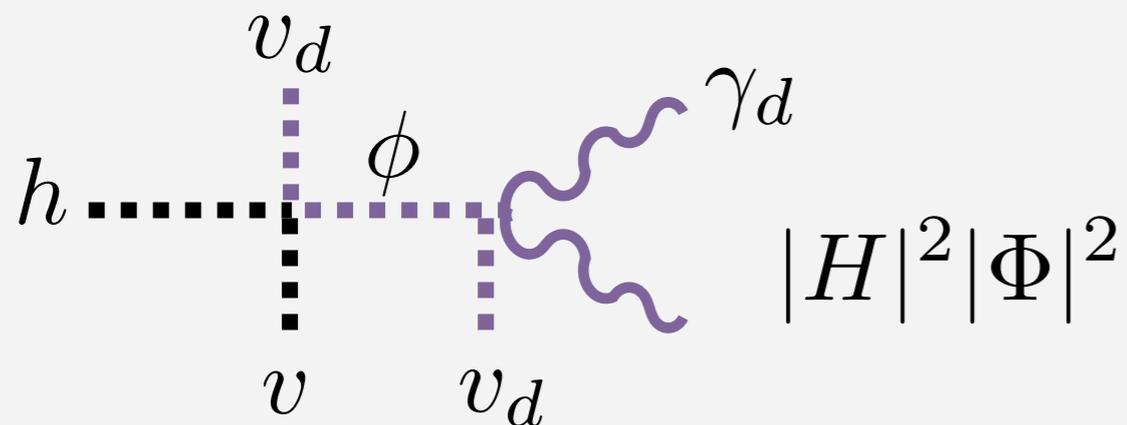
# Exotic Higgs decay into dark photons



Higgs decays through the mixing with dark U(1) Higgs

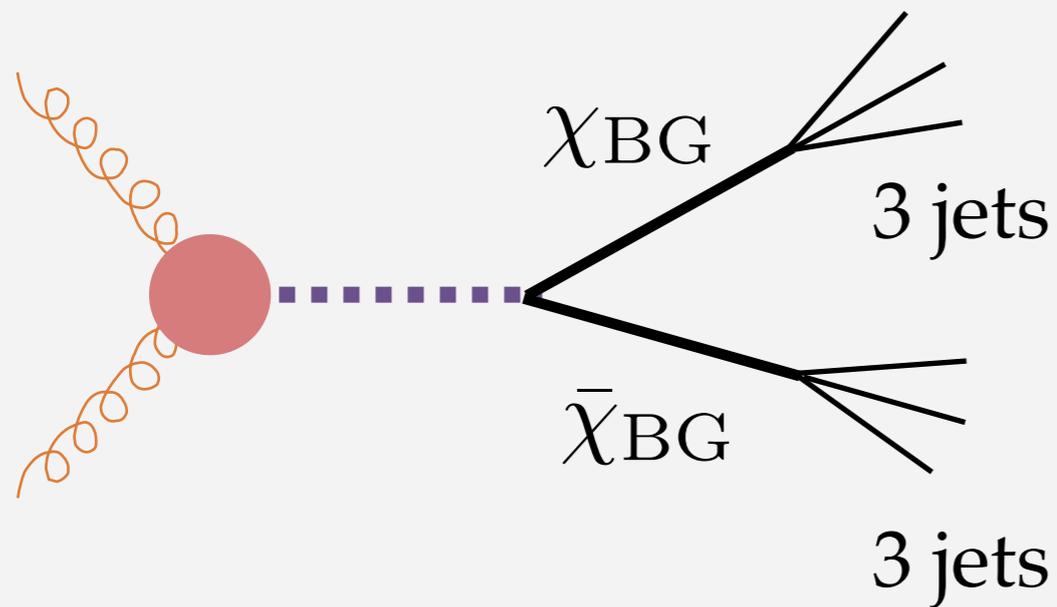
Dark photons can be highly boosted

Can also come from associate Higgs productions => additional W/Z, forward jets, or tops



# DV from WIMP Baryogenesis

Cui, Shuve (15')



Two sets of displaced jets

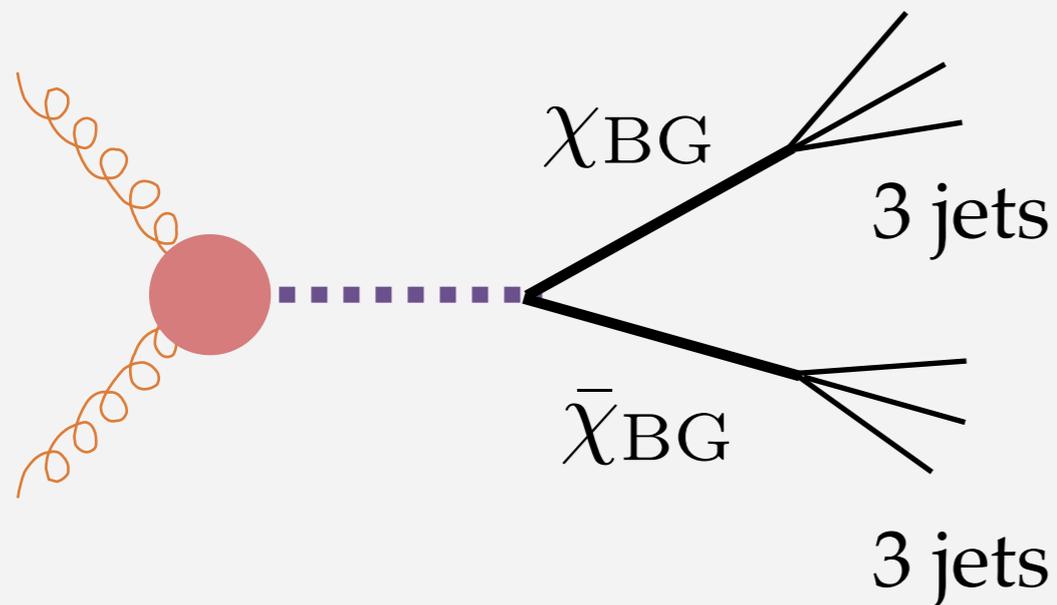
When the mother particle is **heavier than the EW scale**, they decay into jets/leptons with proper length  $\sim O(10)$  cm

e.g. ATLAS displaced di-jets  
(CMS-PAS-EXO-12-038)

Trigger: total jet HT  $> 300$  GeV,  
2 displaced jets  $> 60$  GeV

# DV from WIMP Baryogenesis

Cui, Shuve (15')



When the mother particle mass is **below the EW scale**, they decay into jets with proper length  $\sim O(10)$  cm

If both decays inside detector, 6 displaced jets, each has  $p_T < 30$  GeV

Two sets of displaced jets

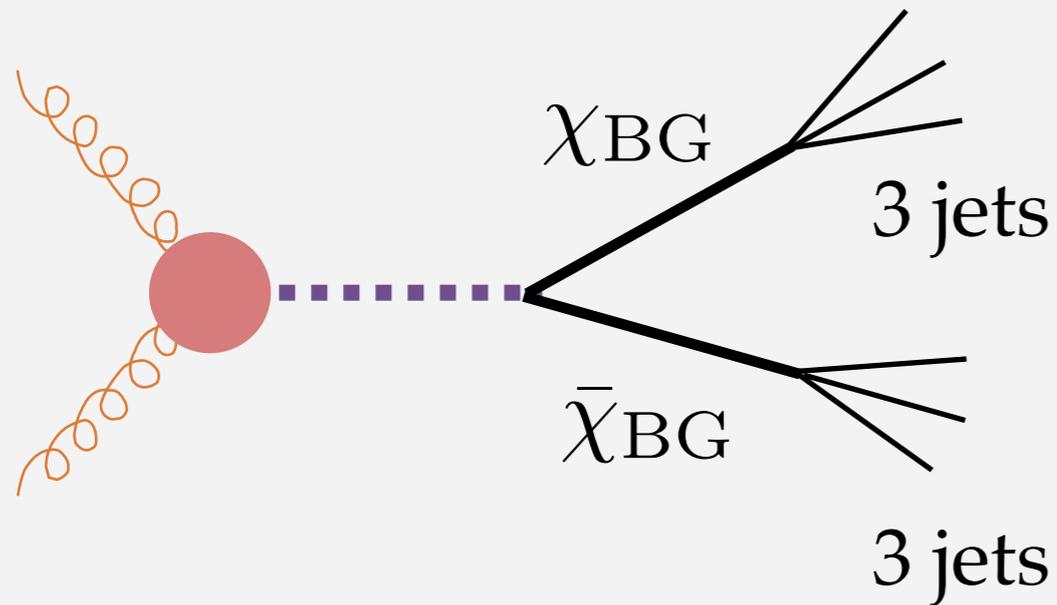
Need to lower trigger requirement

e.g. ATLAS displaced lepton-jets  
(ATLAS-CONF-2016-042)

Trigger: total jet HT  $> 300$  GeV,  
2 displaced jets  $> 60$  GeV

# DV from WIMP Baryogenesis

Cui, Shuve (15')



When the mother particle mass is **below the EW scale**, they decay into jets with proper length  $\sim O(10)$  cm

If both decays inside detector, 6 displaced jets, each has  $p_T < 30$  GeV

Two sets of displaced jets

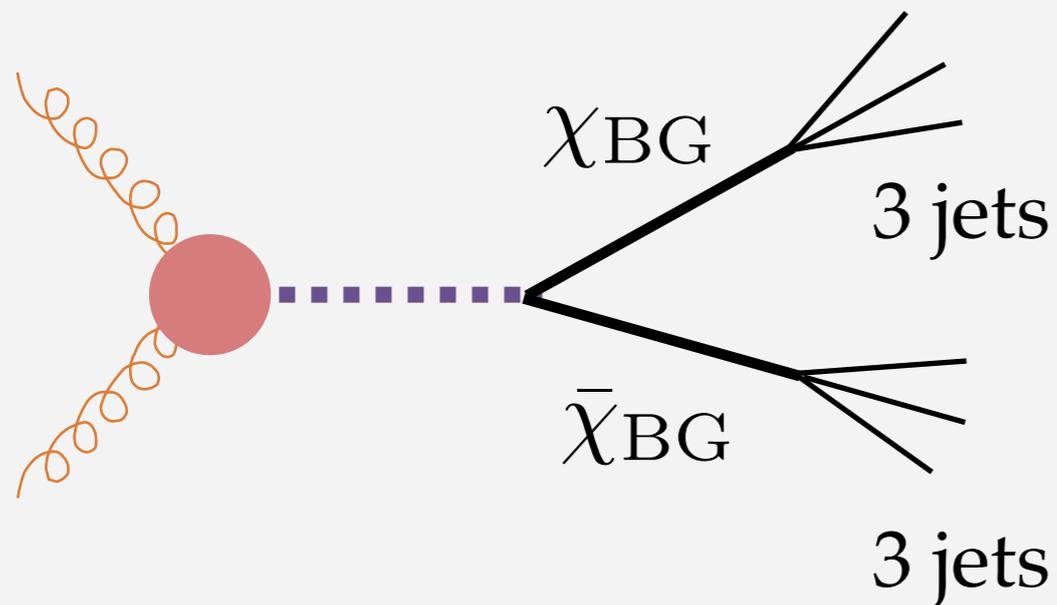
Need to lower  
the requirement

e.g. ATLAS displaced lepton-jets  
(ATLAS-CONF-2016-042)

Trigger: total jet HT  $> 300$  GeV,  
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# DV from WIMP Baryogenesis

Cui, Shuve (15')



When the mother particle mass is **below the EW scale**, they decay into jets with proper length  $\sim O(10)$  cm

If both decays inside detector, 6 displaced jets, each has  $p_T < 30$  GeV

Two sets of displaced jets

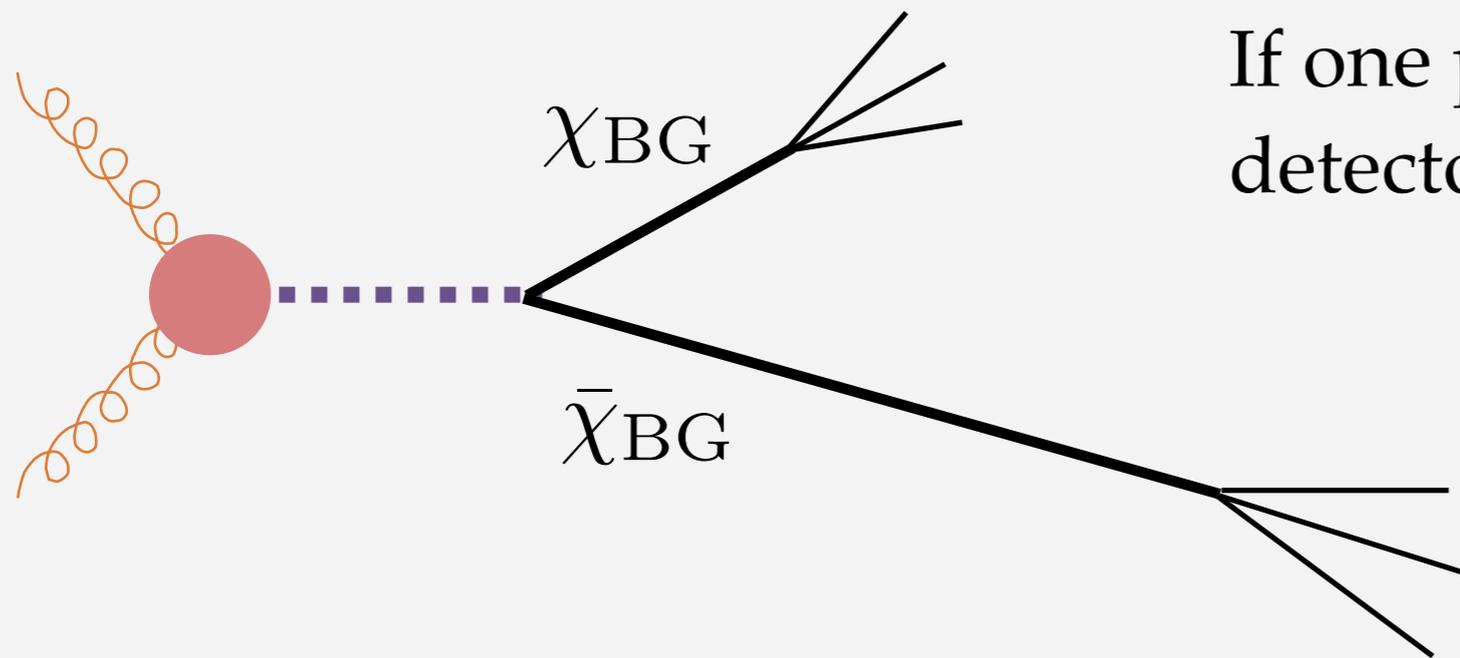
Still not easy



e.g. ATLAS multi-track DV  
(1504.05162)

Trigger: (4, 5, 6) jets with  
 $p_T > (80, 55, 45)$  GeV

# DV from WIMP Baryogenesis



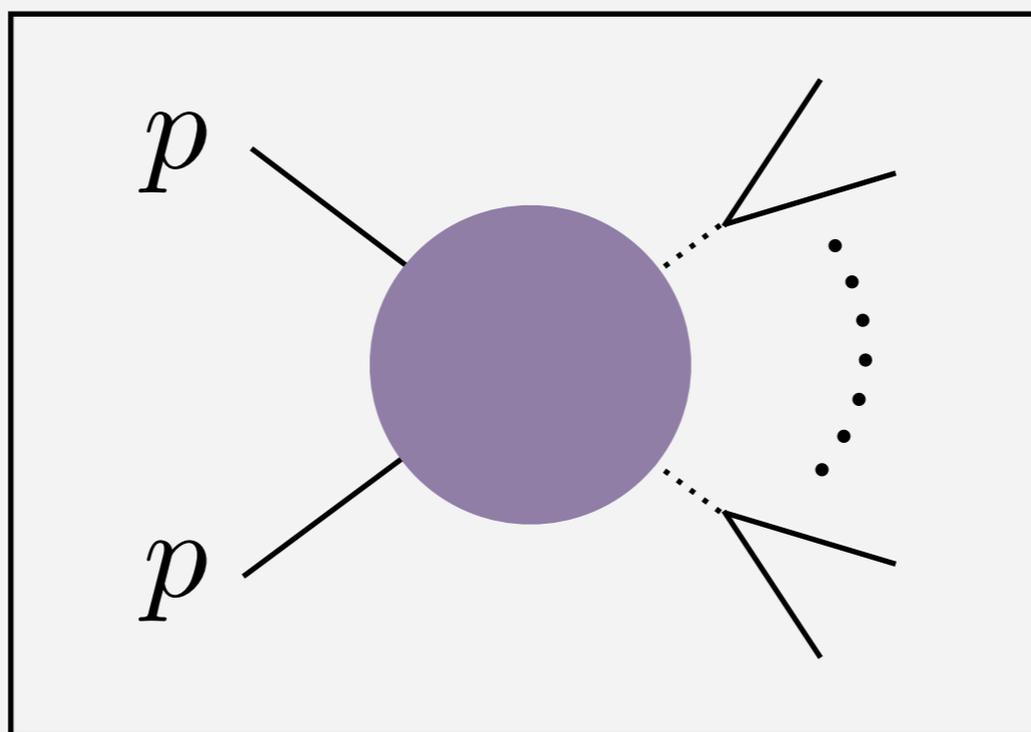
If one particle decays outside of the detector => displaced jets + MET

Can we search for this?

1 displaced jets + MET

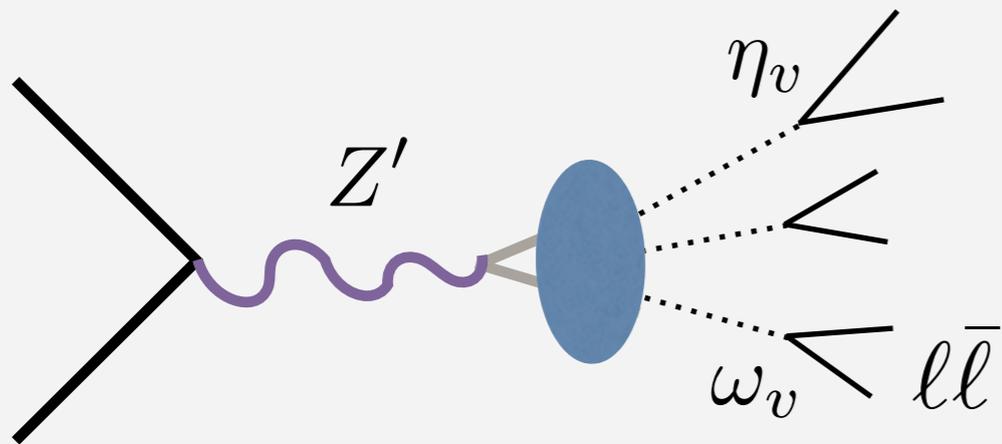
outside of detector

DV + DV + ...



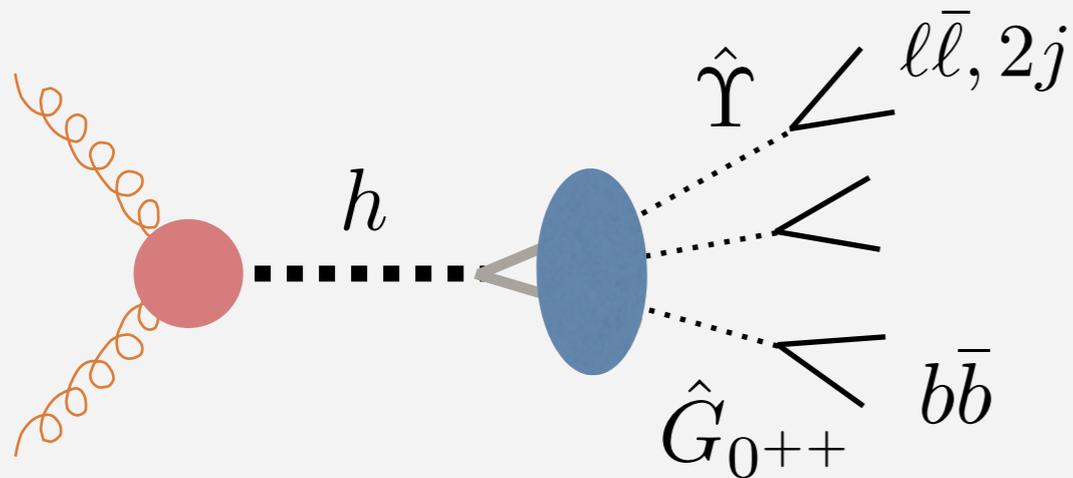
# Hidden Valley models

Strassler, Zurek (06')



LLP can be light and soft  
( $p_T \sim$  few GeV or event lower)

Need to trigger on soft objects with  
high multiplicity



Final states can be complicated

Displaced jets or leptons + MET

# Summary and outlook

- Displaced vertices can be accompanied by many different objects
- $X =$  tops, leptons, jets, W/Z, MET, additional DV('s)
- Provide a better chance to trigger/search for the soft & light LLP
- What's the priority?