



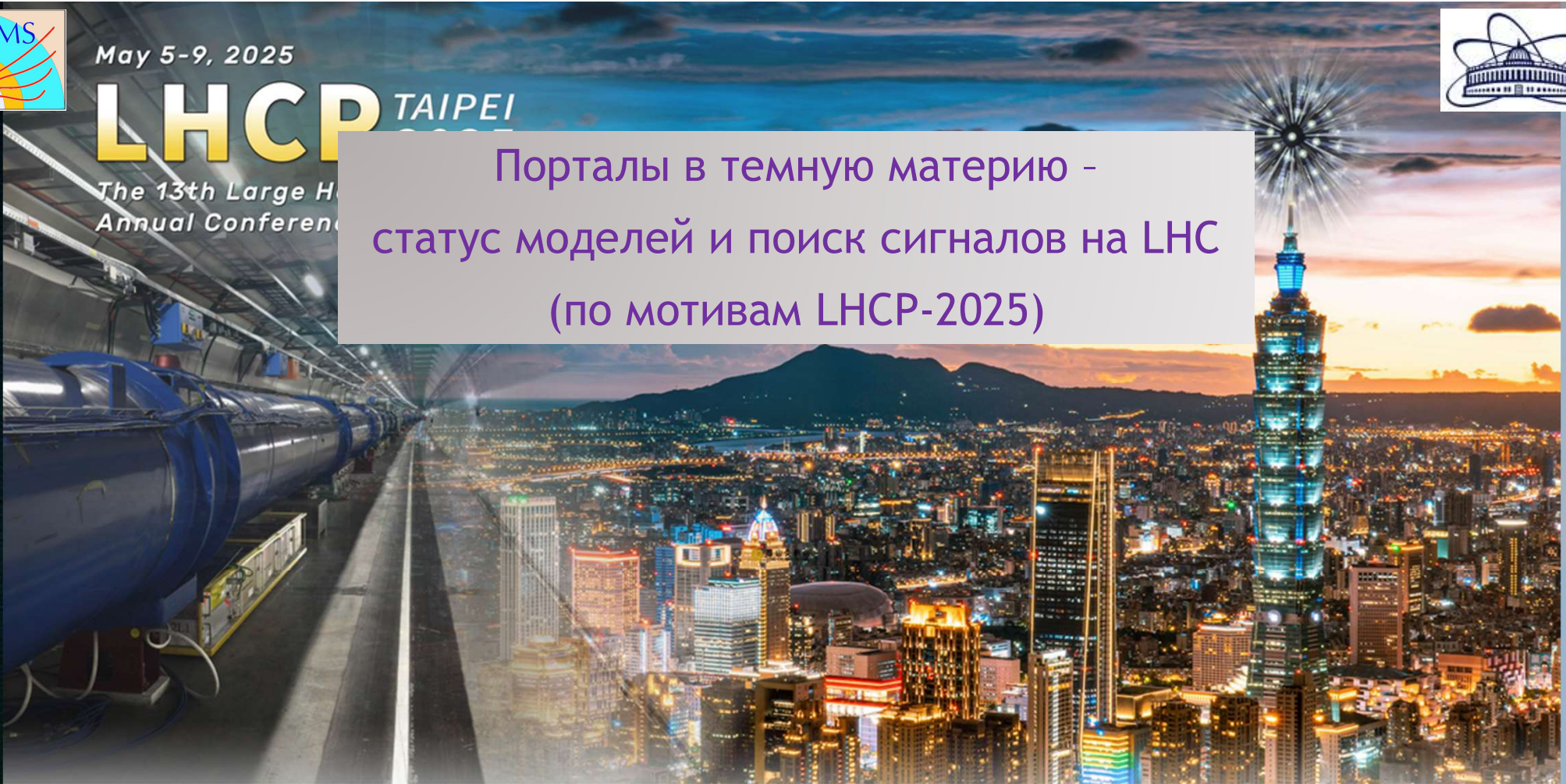
May 5-9, 2025

# LHCP TAIPEI

The 13th Large Hadron Collider  
Annual Conference

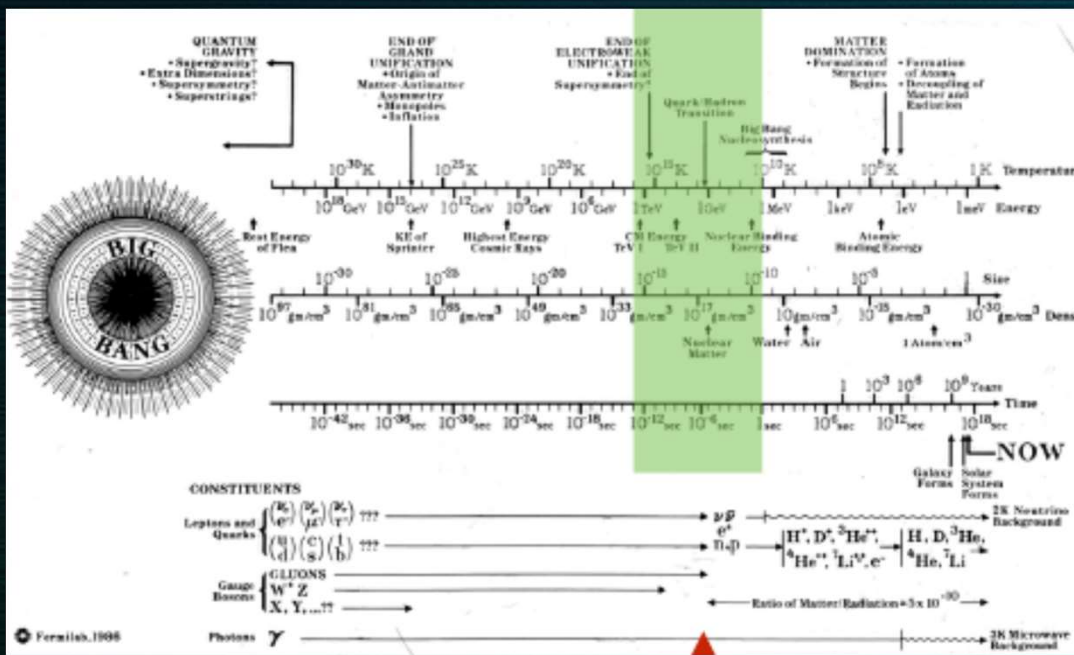


Порталы в темную материю -  
статус моделей и поиск сигналов на LHC  
(по мотивам LHCP-2025)





# The LHC RUN 3 is the era of LLP !!



$$c\tau \sim 0.1 \text{ mm} \Rightarrow \tau \gtrsim 10^{-13} \text{ s}$$

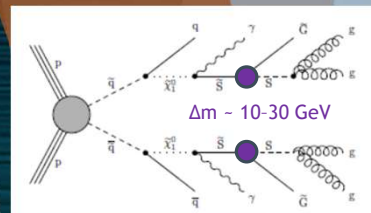
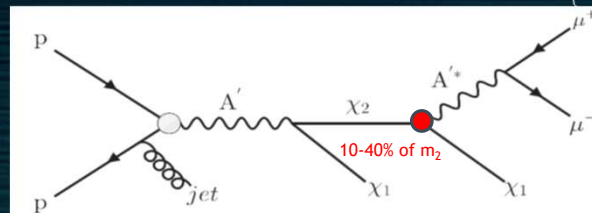
$$\text{To not disrupt BBN} \Rightarrow \tau \lesssim 1 \text{ s}$$



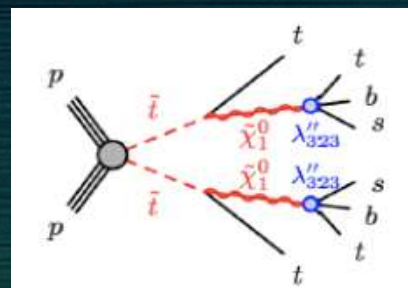
# LLPs - where are they from?



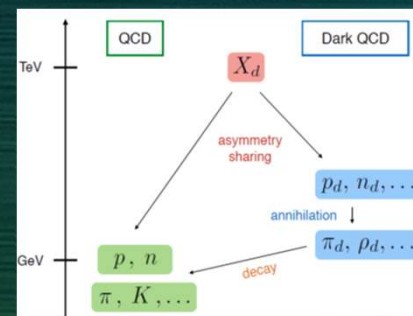
✓ Delayed decays because of small phase volume: states in the dark/visible sector are closely degenerated by masses



✓ Delayed decays because of small/very small coupling values (f. e. RPV SUSY)



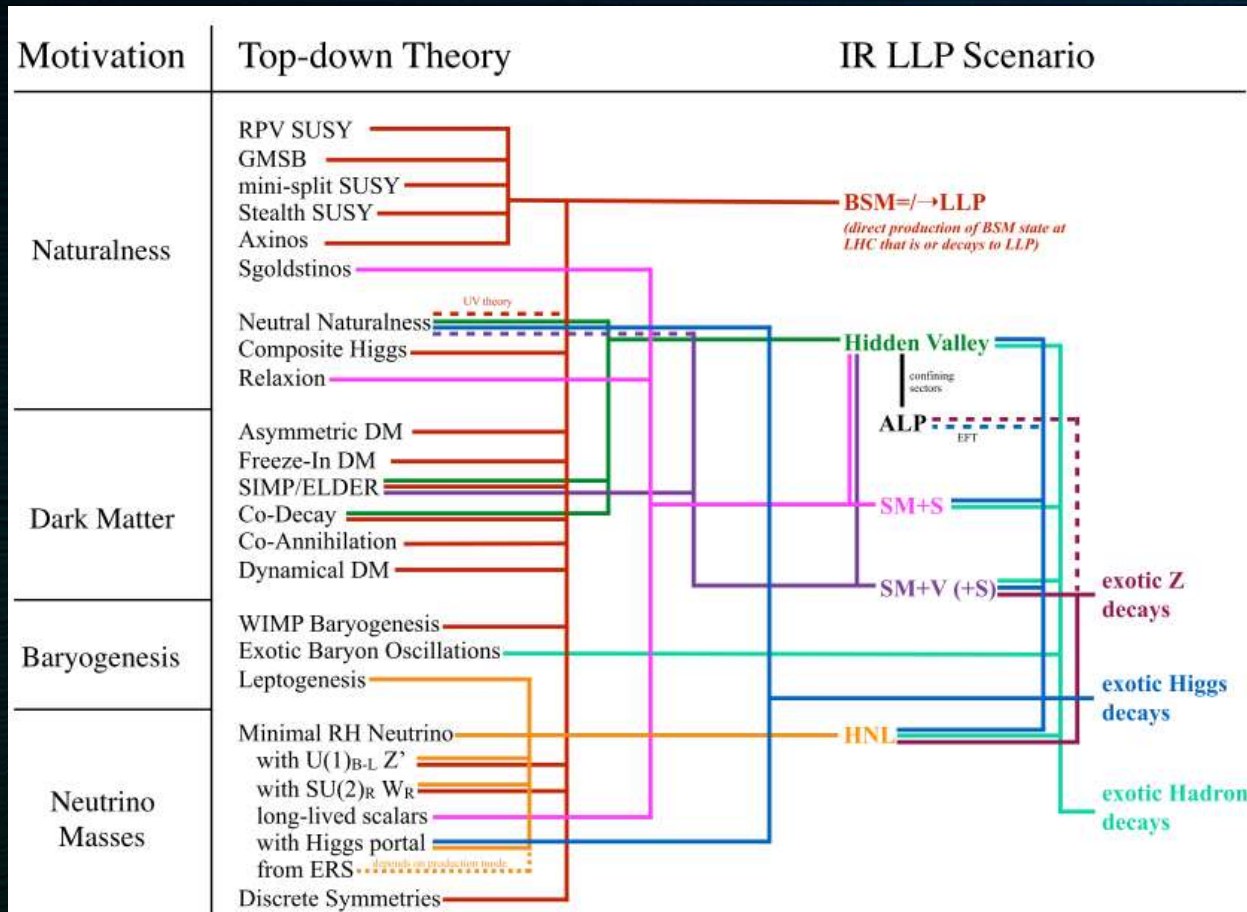
✓ Hidden valleys/dark QCD concept: transitions between dark and visible sectors are suppressed by a high mediator mass scale → prompt/LLP decays



# LLP at the LHC: physics motivations



<https://arxiv.org/abs/1901.04040>



- ✓ Dark photon
- ✓ Heavy neutral leptons (quarks)
- ✓ Dark GB and/or Higgs(es)...

- ✓ Higgs/GB/gluon/SUSY portals

- ✓ (Asymmetric DM/ Baryogenesis)
  - Dark SUSY
  - Dark QCD
- ✓ Twin Higgs
- ✓ ALPs (CP-violation)...

**DS: small couplings, compressed spectra, large hierarchy  $\rightarrow$  large  $ct$**



DM search  $\leftrightarrow$  a framework  $\longrightarrow$  “full” theories vs “portals”

“Full” theories:

SUSY/dark SUSY, hidden valleys, see-saw, extra dimensions...

superpartners, HNL, KK-modes etc.

“Portals”:

scalar/vector/fermionic

$h_{125}$  properties,  $h \rightarrow$  invisible, flavor-violating processes, extra higgses/gauge bosons, new resonant/non-resonant deviations from the SM, ALPs, MET etc.

No NP signals - only limits on model parameter space !!

# Portals to hidden sector

Possible portals at lowest order:

$$L_{\text{mix}} = -\frac{\chi_{\text{elec}}}{2} F_{\mu\nu} F^{\prime\mu\nu} - \frac{\chi_{\text{mag}}}{2} F_{\mu\nu} \tilde{F}^{\prime\mu\nu}$$

Vector portal

$$\propto \frac{\alpha}{\Lambda} \bar{\chi} \chi (H^\dagger H)$$

Fermion portal

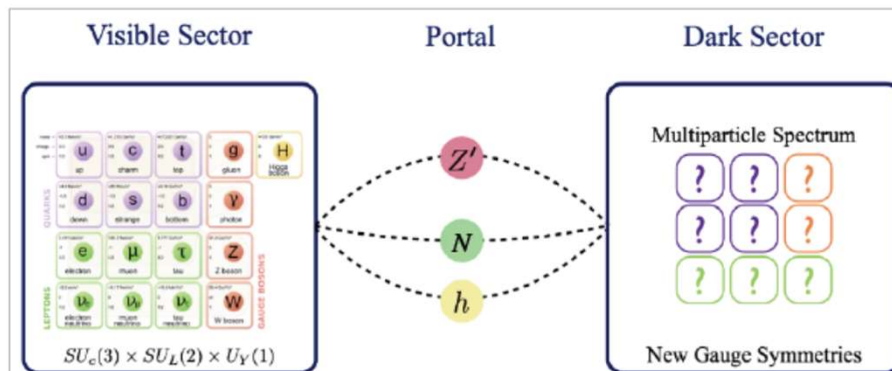
$$\mathcal{L}_{\text{int}} \ni \lambda_P |H(x)|^2 \phi(x)^2$$

Higgs portal

## Portals = Simplified Models

Nuclei for BSM models

Augment Lagrangian by term(s) that allow to access new/hidden sector

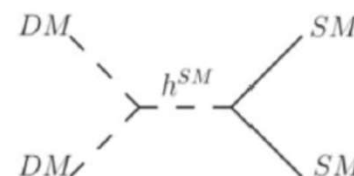




# Higgs portal to DM



- The Higgs mediates interactions with DM or dark sector
- Can naturally explain DM relic abundance via thermal freeze-out, and appear in many extensions (scalar singlet DM, Higgs-mixed dark vectors, etc.)
- Additional scalars can give rise to first-order EWPT (baryogenesis)



## Search strategies:

ZH, WBF, ttH, H+jet  $\rightarrow$  with Higgs decay into dark matter

## Current limits:

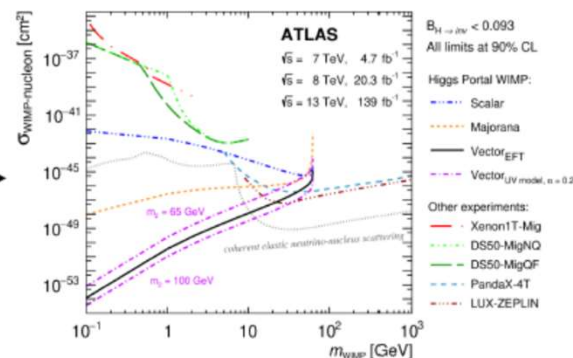
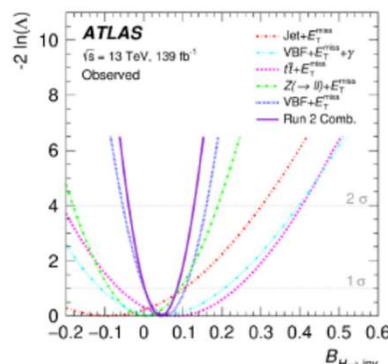
ATLAS:  $BR(H \rightarrow inv) < 0.15$

CMS:  $BR(H \rightarrow inv) < 0.18$

## HL-LHC limits:

Combination of ATLAS and CMS results in  $BR(H \rightarrow inv) < 0.025$  at 95% CL

- ➔ For **DM** below 62.5 GeV, probes Higgs-portal coupling constant  $\lambda$  to order  $10^{-2}$   $\rightarrow$  **excludes observed DM relic abundance** through Higgs-mediated interactions
- ➔ Can probe spin-independent DM-nucleon scattering CS down to  $10^{-48} \text{ cm}^2$   $\rightarrow$  **reaches neutrino floor** for DM masses around 50 GeV





# Fermion portals to DM



- DM interacts with SM predominantly via neutrino or lepton sector couplings, e.g. sterile neutrino DM candidate (often keV-GeV masses) that mixes feebly with active neutrinos.
- Introduce heavy neutral fermions  $N$  (e.g. right-handed neutrinos in seesaw models) that connect the SM and dark sector.  $N$  can serve as mediators or as DM themselves.

**Search strategies:** Neutrino-portal signatures often involve **heavy neutral leptons (HNL)**

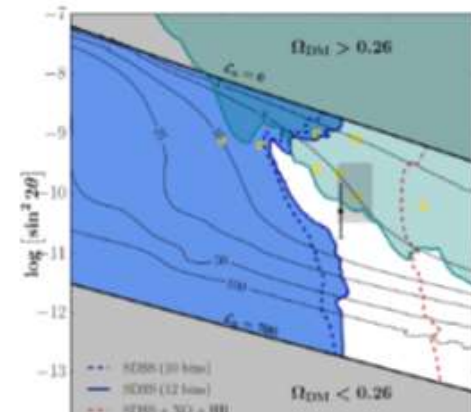
- (1) **Heavy Majorana  $N$**  via  $W$  exchange, e.g.  $pp \rightarrow W \rightarrow N\ell$
- (2) **HNL** from meson decays for  $m_N \sim \text{GeV}$ , e.g.  $B \rightarrow \ell N$
- (3) **Tri-lepton signatures** for  $10 < m_N < 1000 \text{ GeV}$ ,  $W \rightarrow N\ell \rightarrow \ell\ell\nu$
- (4) Long-lived HNL decays - if  $N$  long-lived

## HL-LHC limits:

- ➔ HL-LHC will mostly close window for a thermal heavy neutrino mediator (with elw-scale mass and  $\mathcal{O}(0.1)$  couplings)

Upcoming intensity-frontier experiments (DUNE, SHiP) and cosmic probes will tackle the lighter mass regime:

- ➔ DUNE can constrain HNL mixings in the sub-GeV range by orders of magnitude
- ➔ JWST/Euclid observations of dwarf galaxies will tighten sterile neutrino DM constraints.





# Vector portals to DM



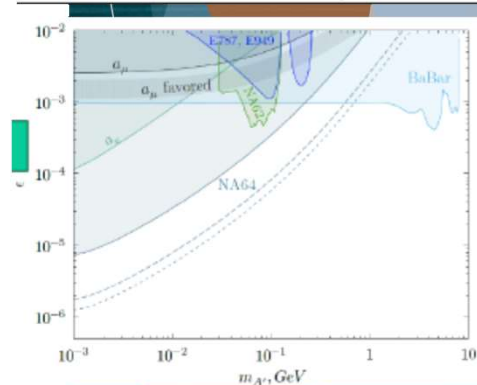
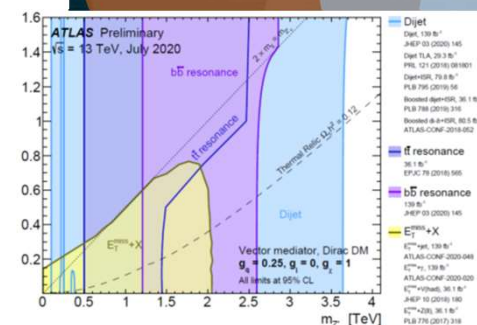
- VP features a **new gauge boson that kinetically mixes with the photon or Z boson**
- This arises naturally if there's an extra  $U(1)$  symmetry in the dark sector.
- Kinetic mixing of a dark photon ( $A'$ ) with the SM photon by a small parameter  $\epsilon$  is a minimal scenario, predicting a light vector that couples weakly to electric charge. Alternatively, many models include heavy  $Z'$  bosons (e.g. from  $U(1)_{B-L}$  or grand unified groups)

## Search strategies:

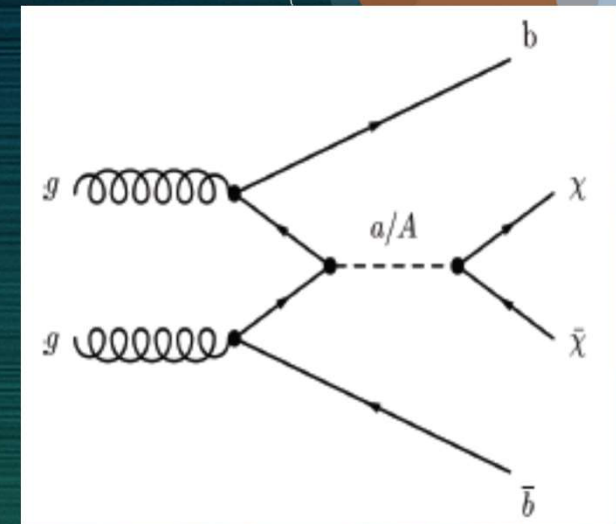
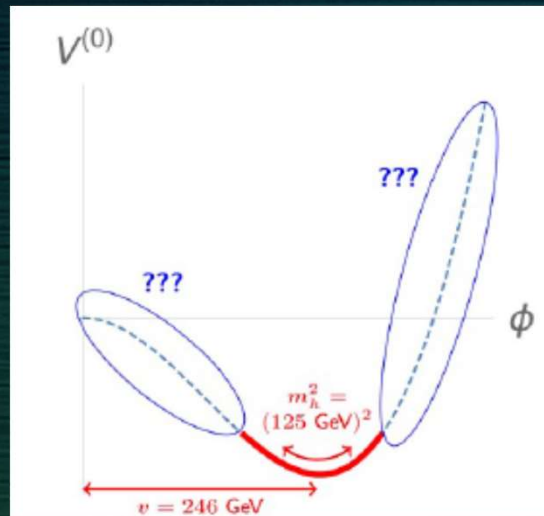
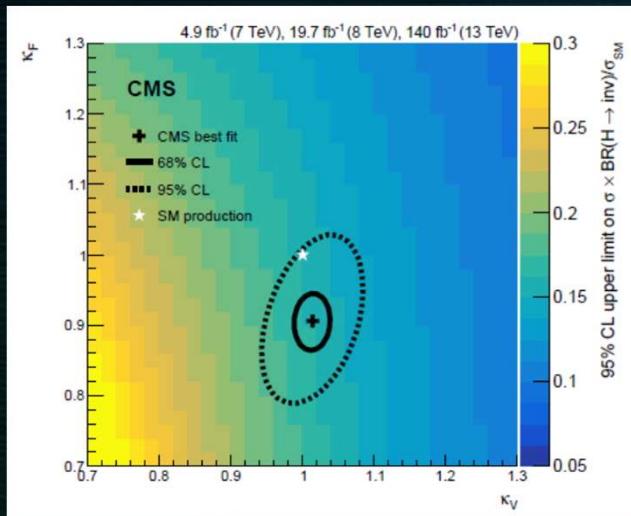
- (1) **High-Mass  $Z'$ :** Look for resonances in dilepton or dijet spectra
- (2) **Mono-X searches:** If  $Z'$  DM mediator - events with recoiling jet, photon etc
- (3) **Low-Mass Dark Photon:** For  $\mathcal{O}(0.1 - 10 \text{ GeV}) \rightarrow$  CMS dimuon data limits
  - $\rightarrow$  Combining these results with those from BABAR, NA64, and Belle II, kinetic mixings  $\epsilon > 10^{-3}$  now excluded for all  $A'$  masses from 1 MeV to 200 GeV

## HL-LHC limits:

- $\rightarrow$   $Z'$  Mass Reach: Exclusion limits could extend up to  $\sim 6 \text{ TeV}$  for  $Z'$  bosons with electroweak-scale couplings.
- $\rightarrow$  For mid mass  $Z'$  bosons, the HL-LHC aims to probe kin. mixing parameters down to  $\epsilon \sim 10^{-4}$
- $\rightarrow$  Moreover, experiments like FASER2 and Belle II will hunt for visibly decaying dark photons in the MeV–GeV range, down to  $\epsilon^2 \sim 10^{-8}$  (expl. thermal freeze-out target for light DM).

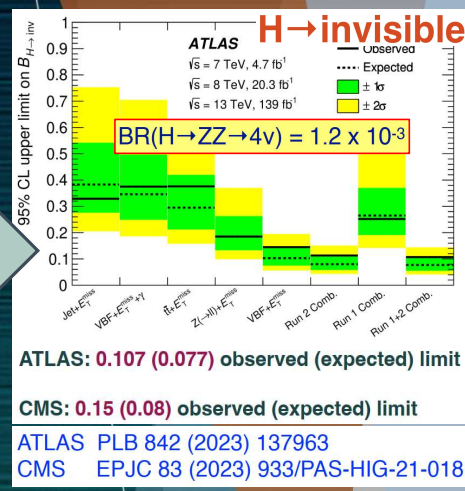
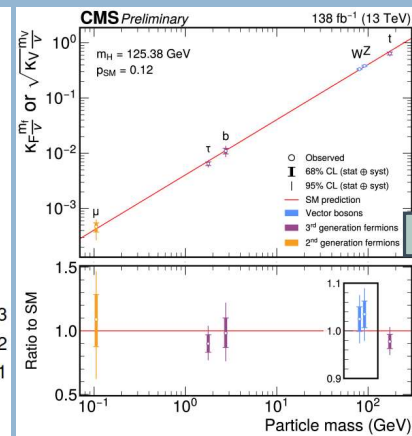
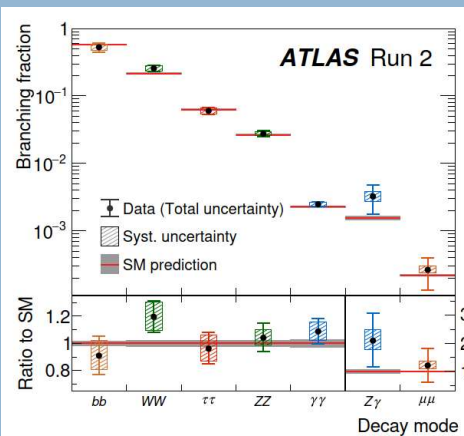
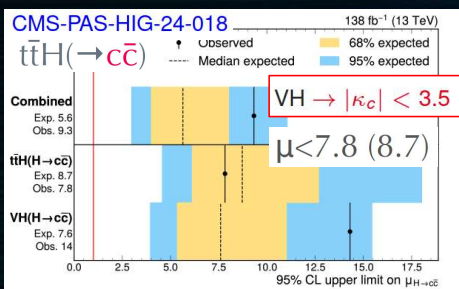


# Higgs portal



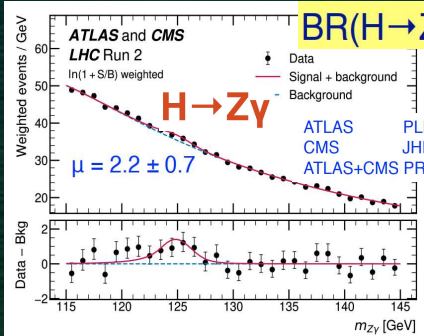
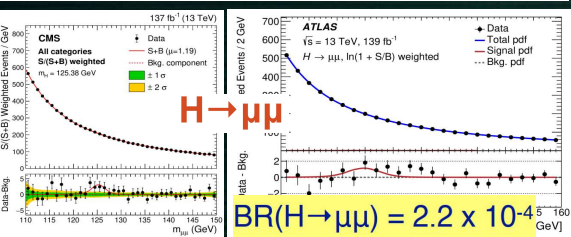


# Higgs couplings to the 2<sup>nd</sup> generation + rare/invisible decays



		ATLAS	CMS
Theoretical input	BR(H to mu mu)	$2.17 \pm 0.04 \times 10^{-4}$	$2.18 \pm 0.04 \times 10^{-4}$
	$m_H$	125.09 GeV	125.38 GeV
Measurement	Signal strength	$1.2 \pm 0.6$	$1.19^{+0.44}_{-0.42}$
	Observed significance	$2.0\sigma$	$3\sigma$
	Expected significance	$1.7\sigma$	$2.5\sigma$

**$0.59 (0.85) < \kappa_\mu < 1.50 (1.29)$  at 95% (68%) CL**



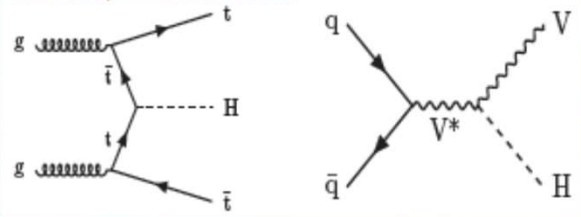
		ATLAS	CMS
Theoretical input	BR(H to Z gamma)	$1.54 \pm 0.09 \times 10^{-3}$	$1.567 \pm 0.09 \times 10^{-3}$
	$m_H$	125.09 GeV	125.38 GeV
Measurement	Signal strength	$2.0^{+1.0}_{-0.9}$	$2.4^{+0.9}_{-0.9}$
	Observed significance	$2.2\sigma$	$2.7\sigma$
	Expected significance	$1.2\sigma$	$1.2\sigma$
	95% CL obs(esp) limit	3.6 (1.7)	4.1 (1.8)
	$\sigma(pp \rightarrow H) \times BR(H \rightarrow Z\gamma)$	305 fb (95% CL UL)	352 fb (95% CL UL), 210 ± 80 fb (measured)
	Mass resolution	4.0 GeV	3.7 GeV



# Combination of $h_{125} \rightarrow$ invisible searches for $t\bar{t}$ and VH



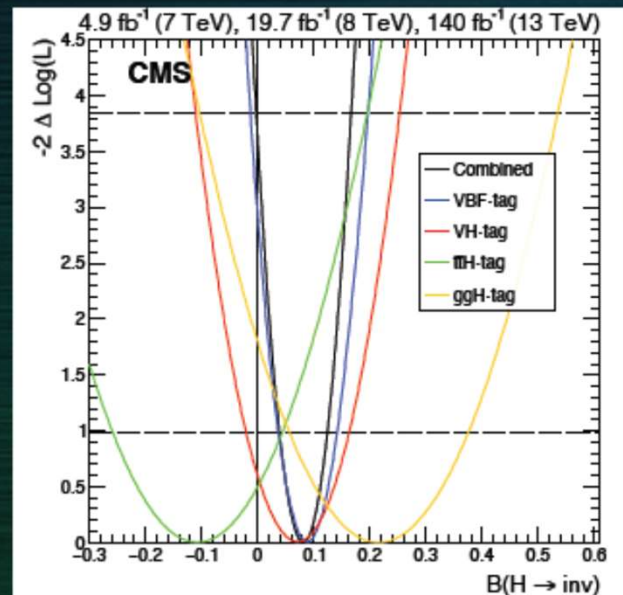
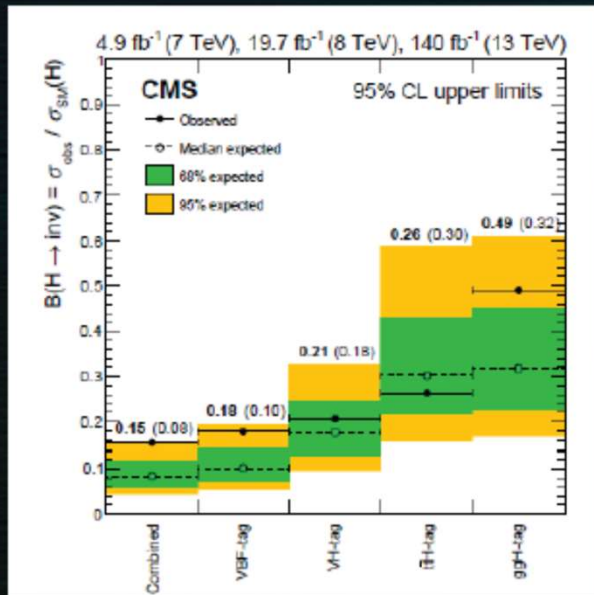
resolved/boosted  $t\bar{t}H$



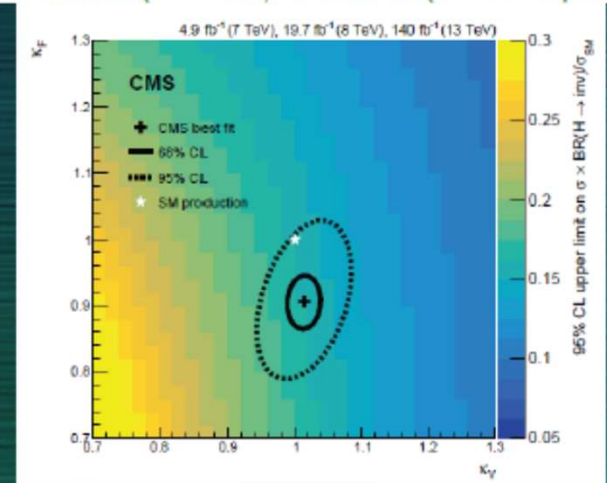
Higgs  $h_{125}$  with an admixture of a new CP-even neutral higgs state can decay into other higgs states from an extended scalar sector due to the mixing in the potential  $\leftrightarrow$  decay into a light PS pair  $\leftrightarrow$  decays of each PS into DM particles (invisible)

see further on 2HDM+a search

CMS HIG-21-007, arXiv:2303.01214 [hep-ex]



CMS:  $BR(H \rightarrow inv.) < 15\%$  (8% expected)  
ATLAS:  $BR(H \rightarrow inv.) < 10.7\%$  (7.7% expected)



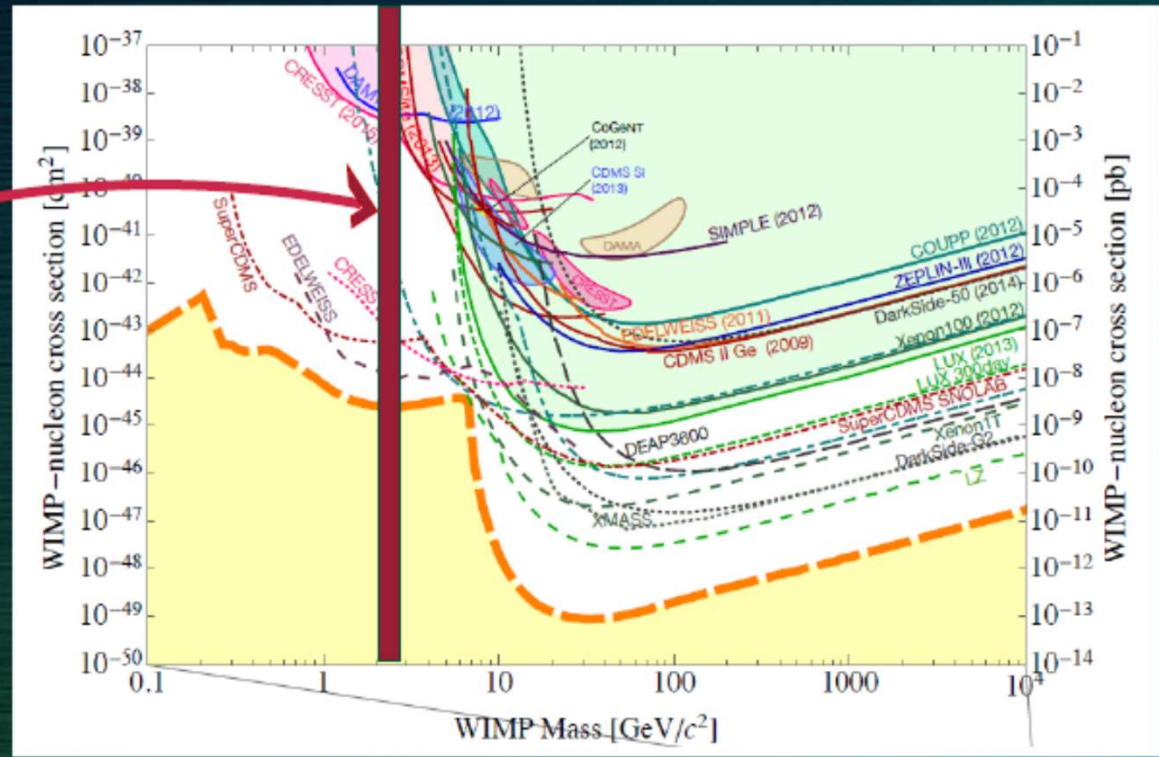
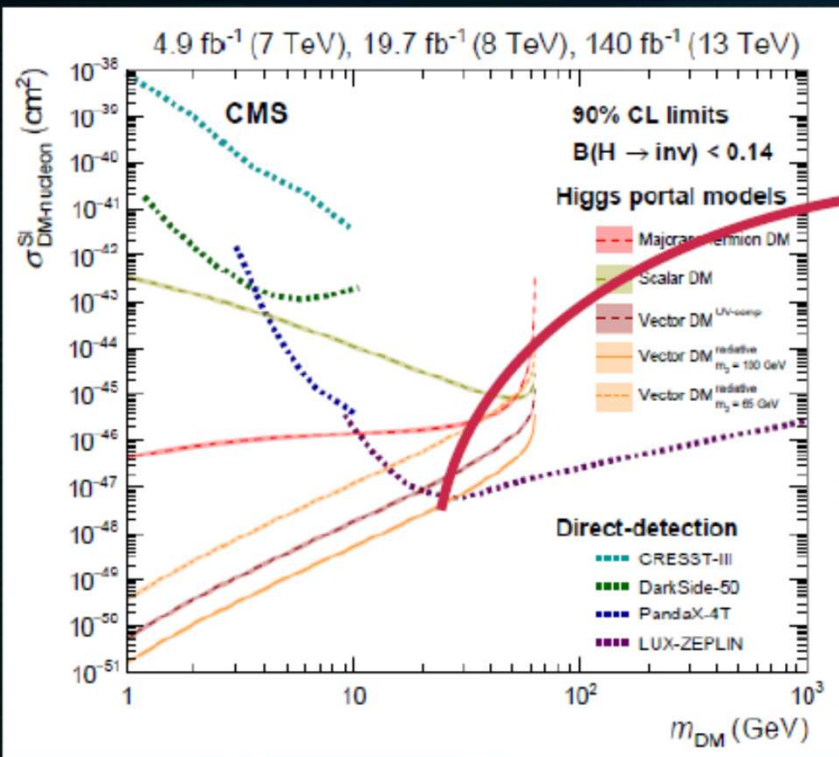


# Combination of $h_{125} \rightarrow$ invisible searches



The most stringent limit on WIMP-nucleon scattering cross section in the DM mass region up to  $\frac{1}{2} m(h_{125})$  for the scalar mediator!!

CMS HIG-21-007, arXiv:2303.01214 [hep-ex]





# Higgs potential and self couplings



Standard Model  
Higgs potential

$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4$$

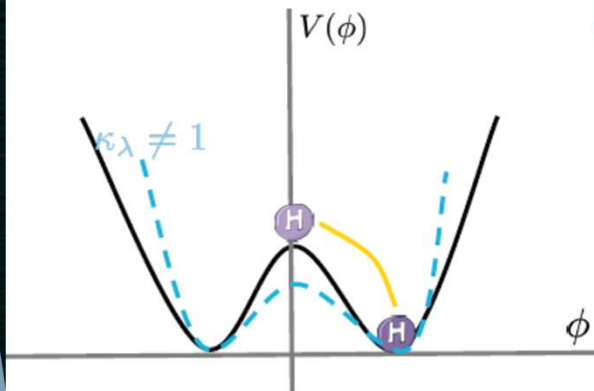
Our universe lives in  
the minimum:

$$V = V_0 + \frac{1}{2} m_H^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4} \lambda_4 h^4 - \frac{\lambda}{\nu^4}$$

In the Standard  
Model:

$$\lambda^{\text{SM}} = \frac{m_H^2}{2\nu^2}$$

$$\kappa_\lambda = \lambda / \lambda^{\text{SM}}$$

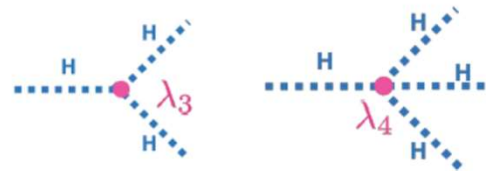


Non-resonant HH production searches probe the shape of the Higgs potential by measuring the Higgs self coupling:  $\kappa_\lambda$ .

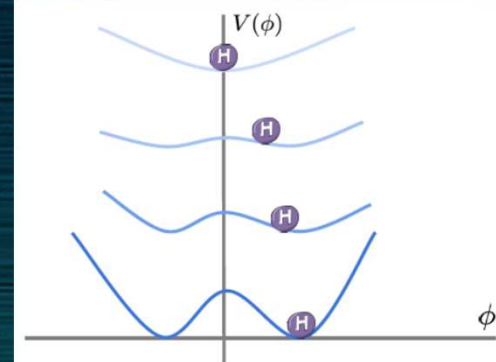
$\kappa_\lambda \neq 1$  could indicate beyond Standard Model physics.

Moreover, in the SM:

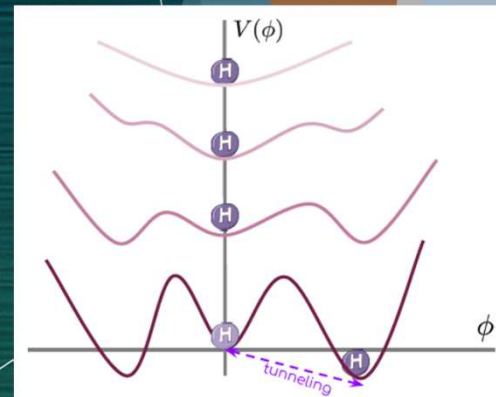
$$\lambda_3 = \lambda_4$$



We can use HHH searches to independently constrain  $\lambda_4$



SM: 2<sup>nd</sup> order phase transition. Continuous cross-over from one phase to the other.

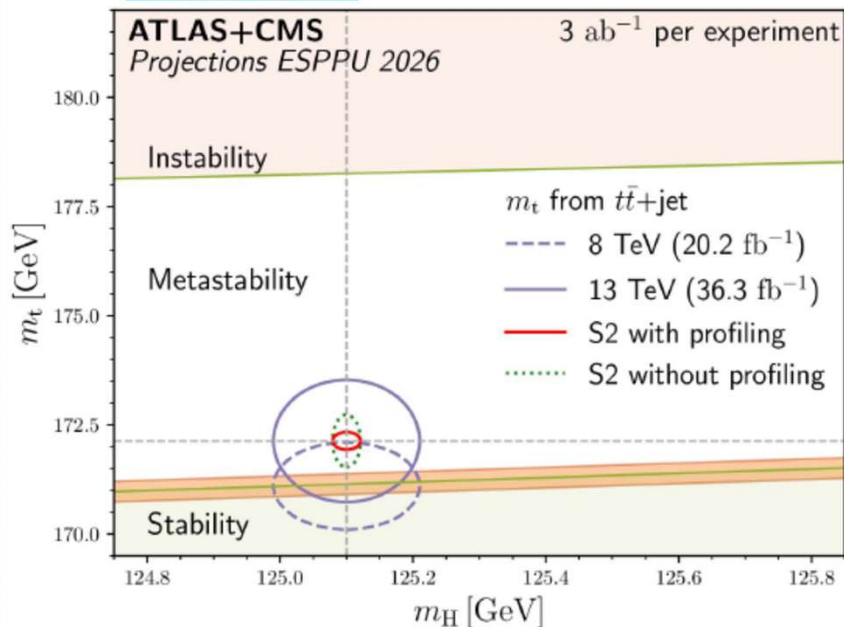


BSM: 1<sup>st</sup> order phase transition.

✓ minim

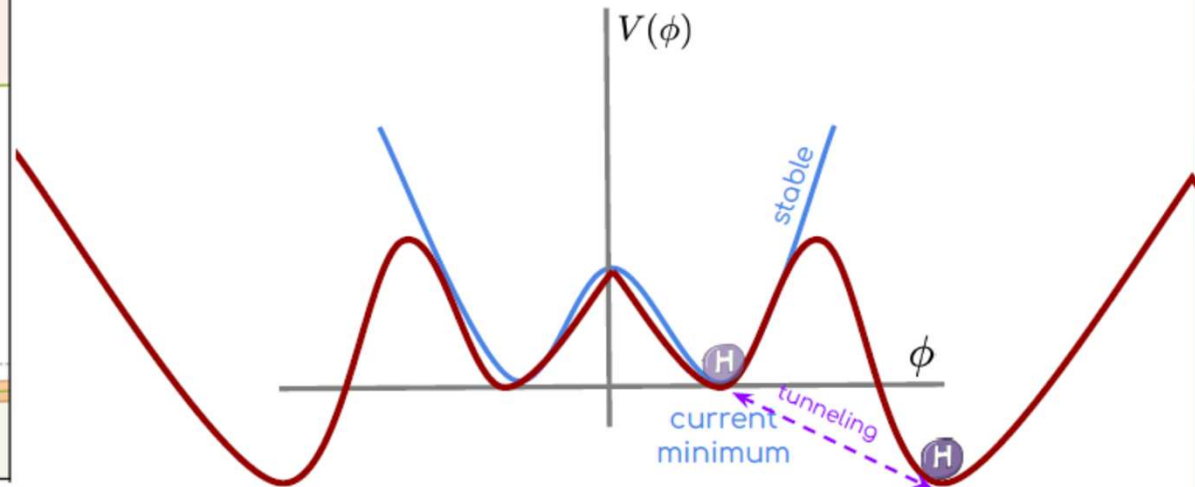
Precision on top mass is also fundamental to answer the question on the **metastability** of the universe.

[arXiv:1205.6497](https://arxiv.org/abs/1205.6497)

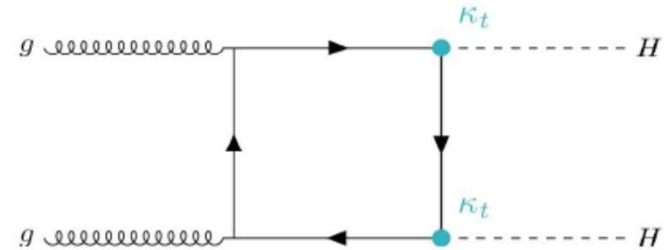
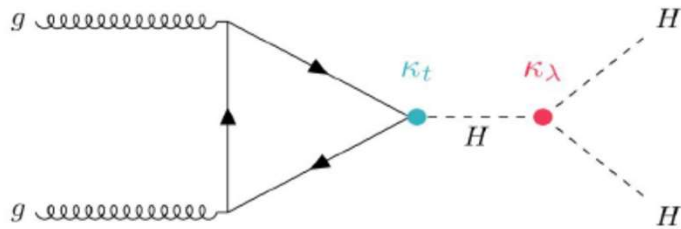


## Metastable universe

- Current minimum is a *false* vacuum.
- Lifetime is larger than the age of the universe, but eventually it will decay to the new minimum...

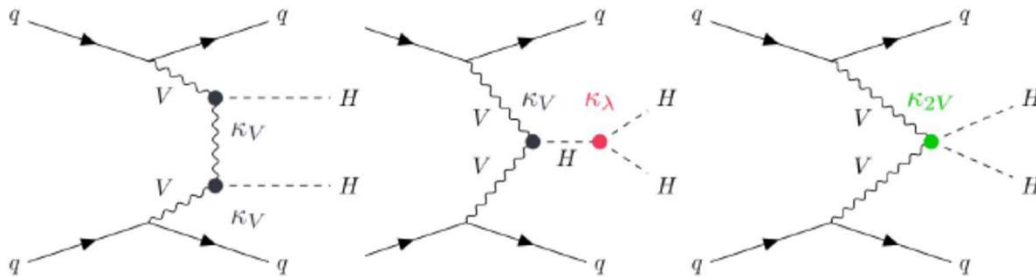


Measuring the self-coupling can provide discrimination between different scenarios, or different models. But, keep in mind that we will require to measure **triple-Higgs production** to fully describe the shape of the Higgs potential.



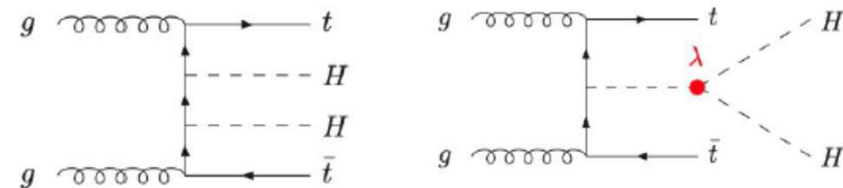
Other production mechanisms also allow us to probe different couplings:  $\kappa_{2V}$ ,  $\kappa_V$ .

## Vector boson fusion

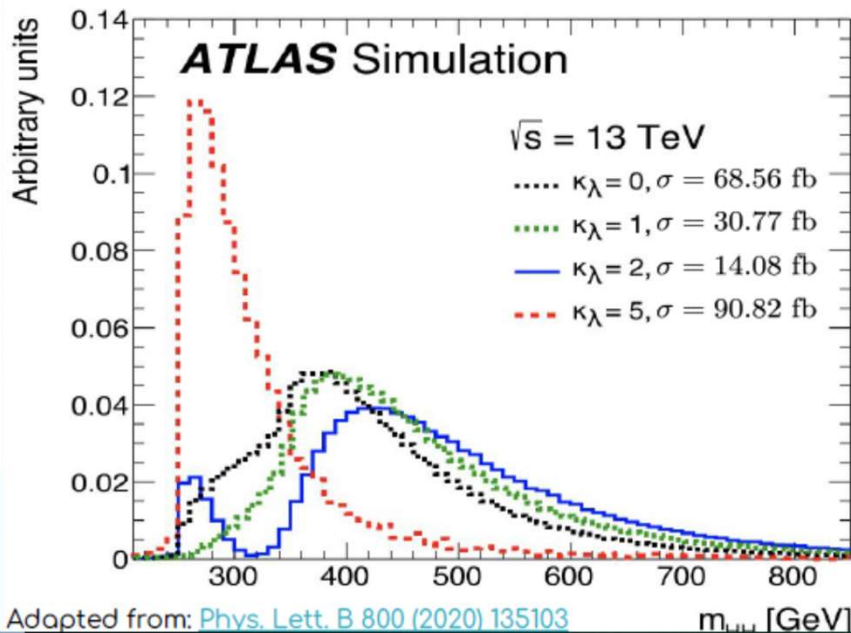
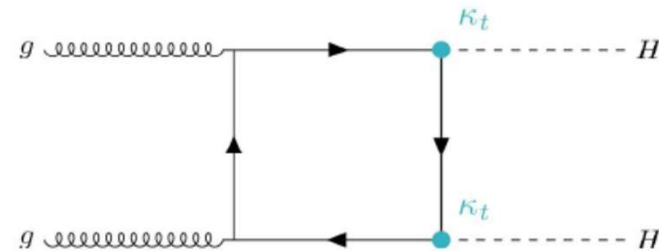
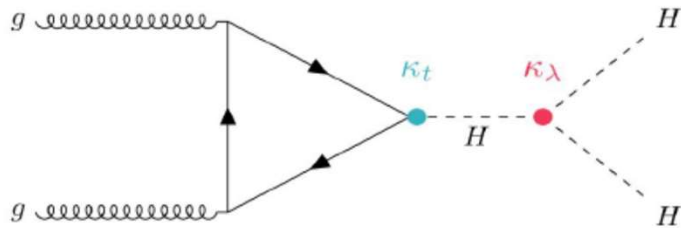


VVHH coupling modifier  
SM predicts  $\kappa_{2V} = 1$

## Associated production ttHH



VVH coupling modifier  
SM predicts  $\kappa_V = 1$



There is however destructive interference between the box and triangle diagrams, thus the **cross section is suppressed** ( $\sim 10^3$  times smaller than single Higgs cross section).

$$\kappa_\lambda = \lambda / \lambda^{\text{SM}}$$

SM predicts  $\kappa_\lambda = 1$

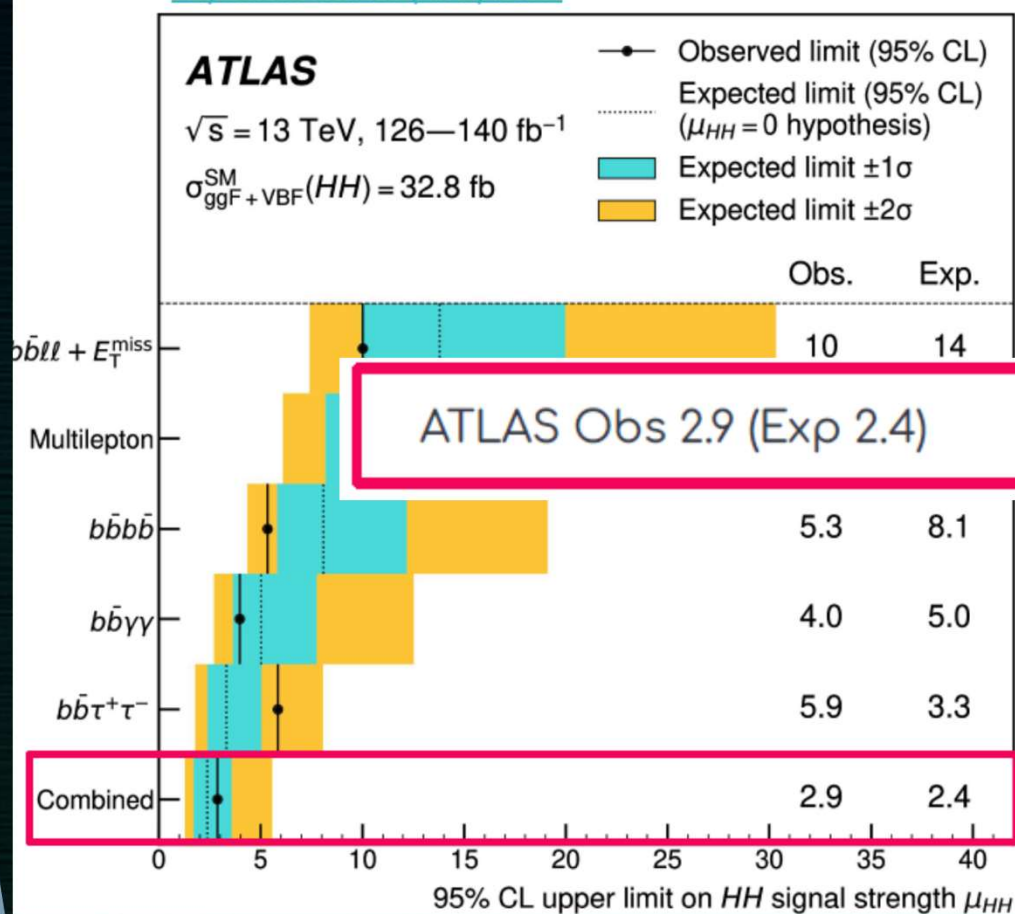
- $m_{HH}$  distribution depends on  $\kappa_\lambda$ .
- For large values of  $\kappa_\lambda$  the triangle diagram dominates.
- For values of  $\kappa_\lambda \neq 1$ , x-section can be enhanced.



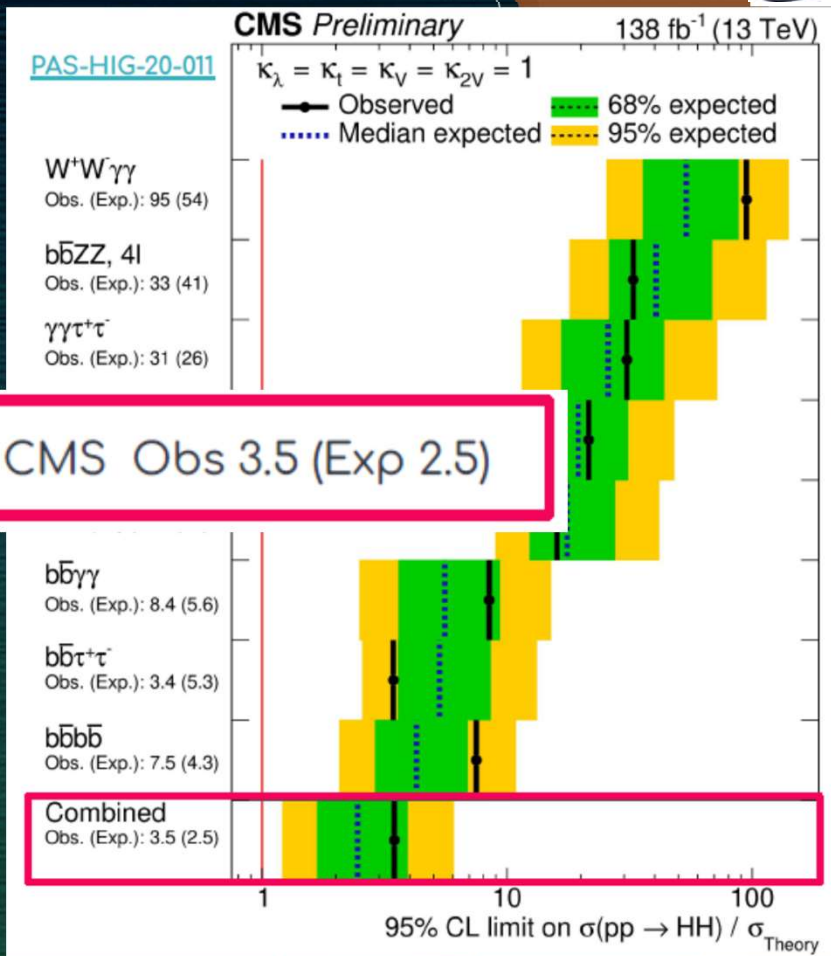
# HH production, observed upper limits, ATLAS/CMS



Phys. Rev. Lett. 133 (2024) 101801



ATLAS Obs 2.9 (Exp 2.4)      CMS Obs 3.5 (Exp 2.5)





# HH production, observed upper limits, ATLAS/CMS

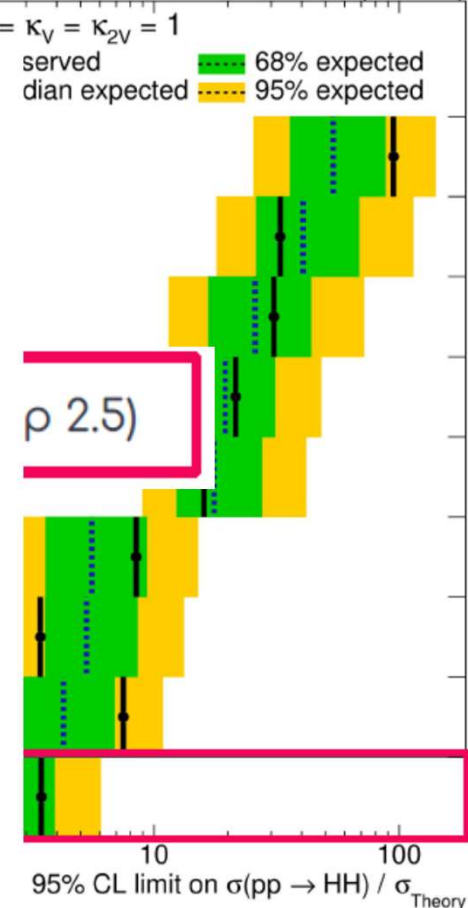
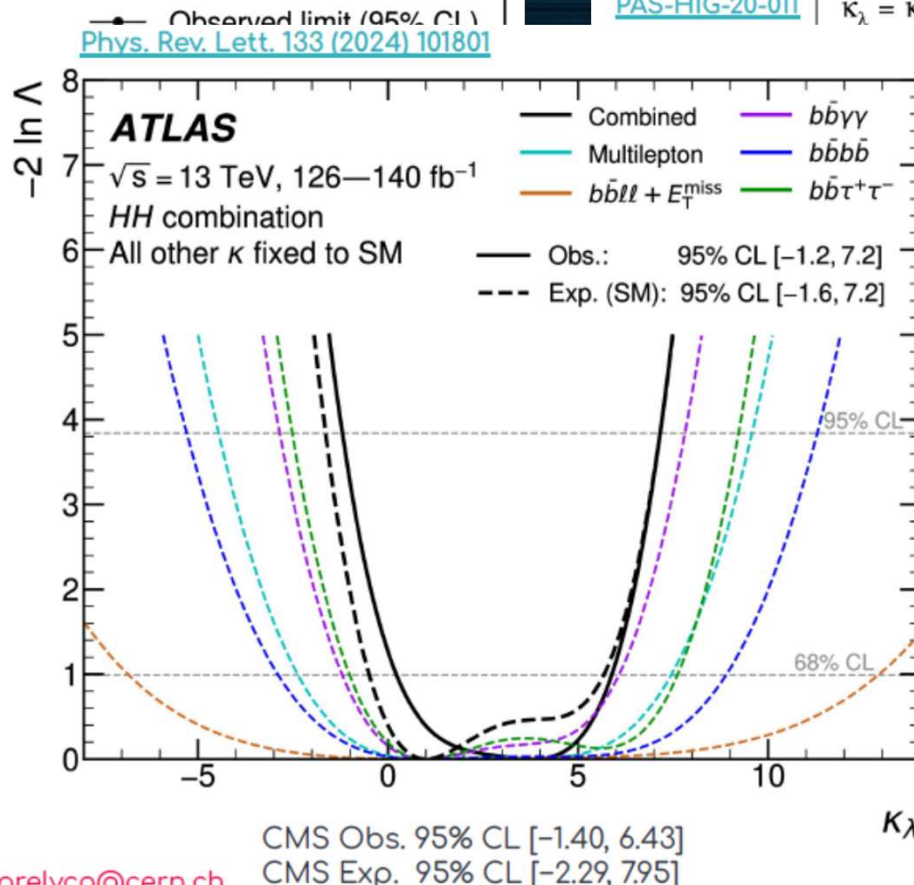
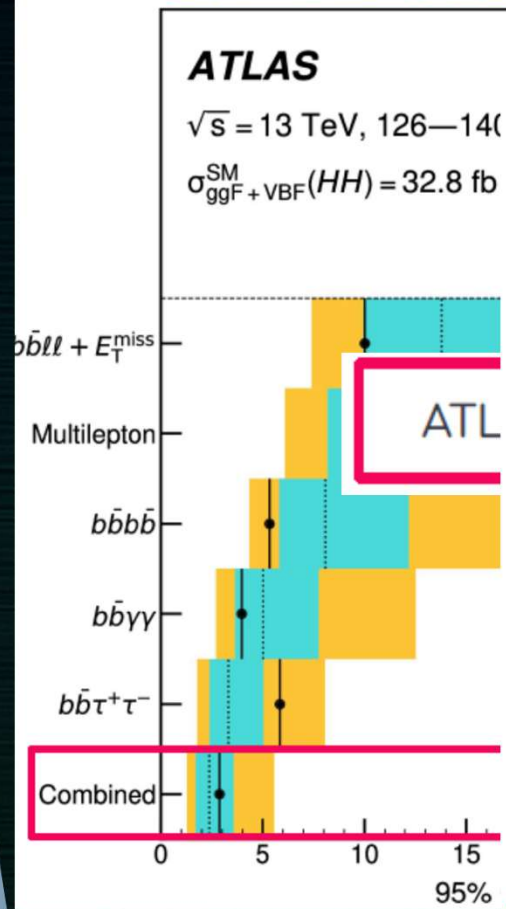


Phys. Rev. Lett. 133 (2024) 101801

PAS-HIG-20-011

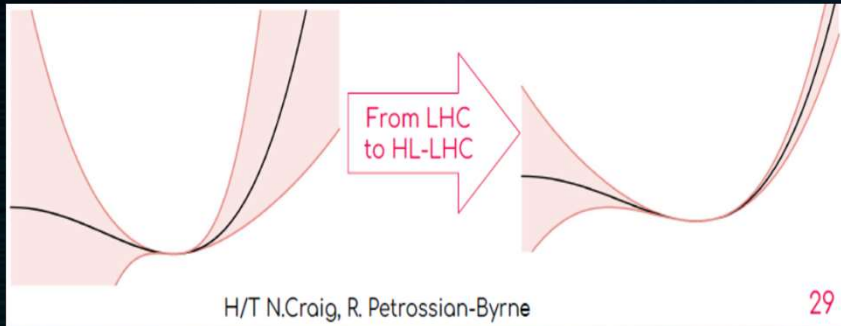
CMS Preliminary

138 fb<sup>-1</sup> (13 TeV)



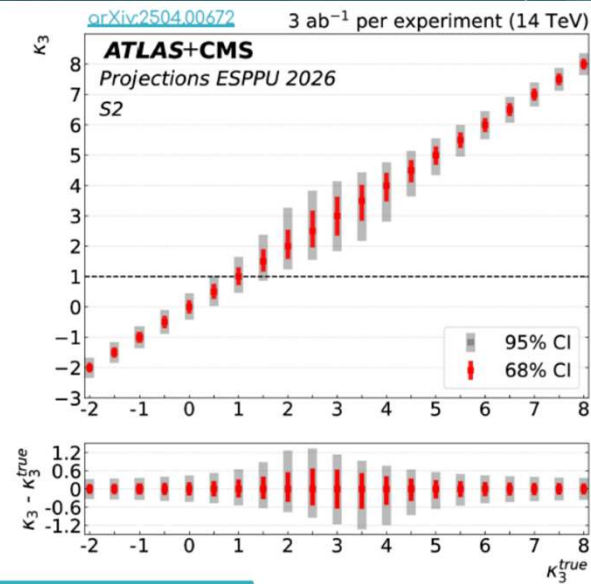
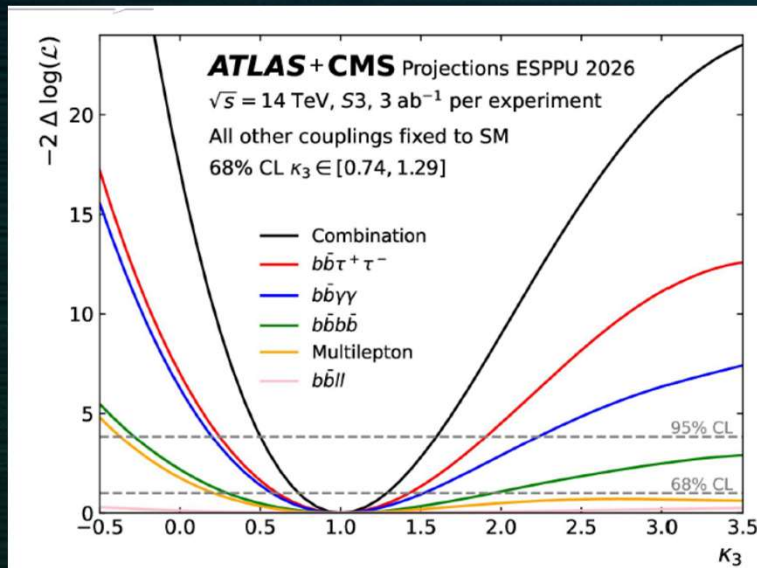
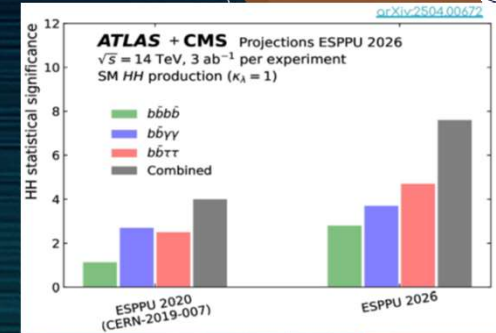


# Higgs self-coupling measuring: perspectives



HL LHC projection

HH pair production



S3 scenario:  $\kappa_\lambda$  is expected to be measured as  $1.0^{+0.29}_{-0.26}$ .

arelycg@cern.ch

M. Savina, BLTP JINR, Russia

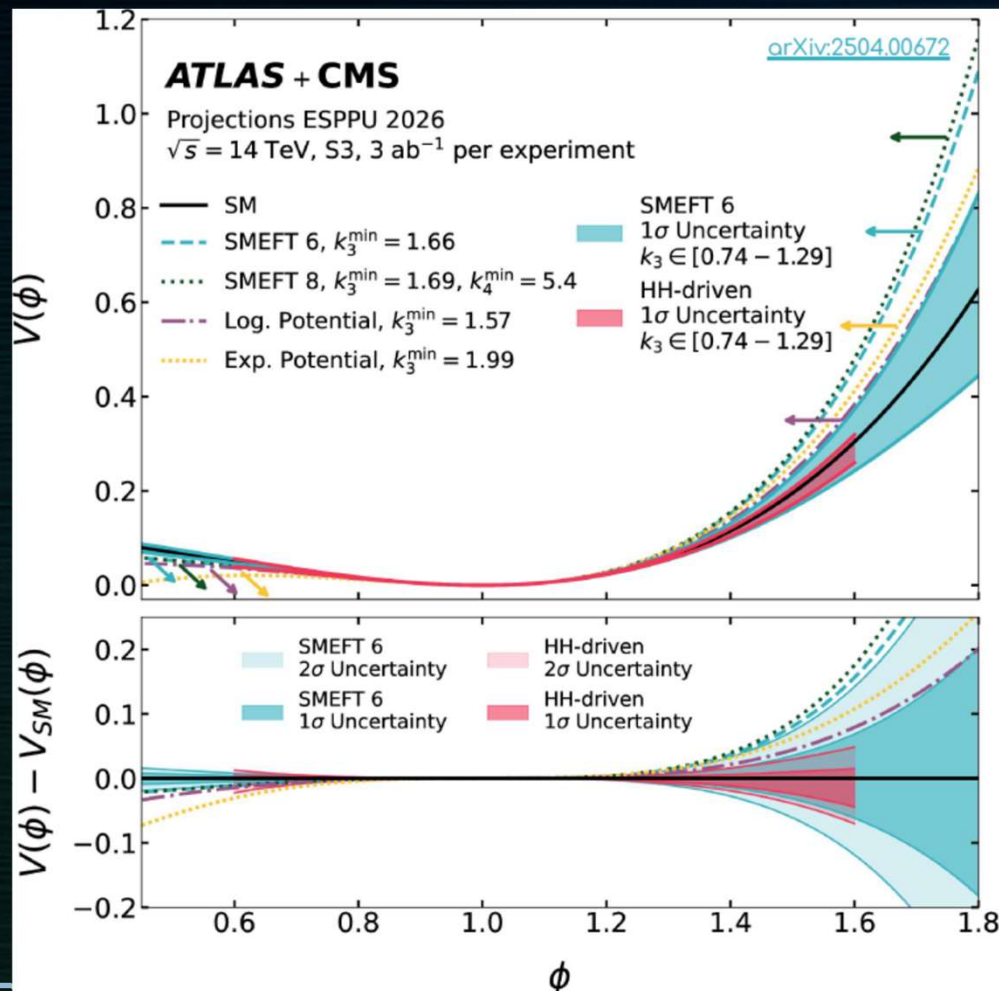
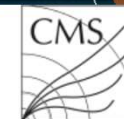
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25.09.2025

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# Higgs self-coupling measuring: perspectives



Measuring the self-coupling can provide discrimination between different potential scenarios or models.

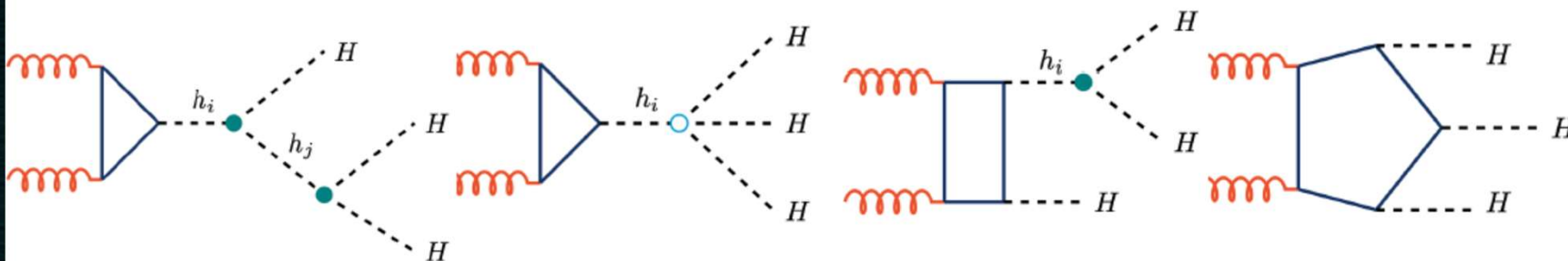
BSM scenarios where new heavy particles lie beyond a large energy scale cut-off, so cannot be produced at the LHC. The potential is then expressed as a deformation of the SM EWSB potential.

Scenarios considered are in the context of SMEFT (dim 6 and 8) and modifications of the low-energy SM Higgs potential by small term (logarithmic or exponential).

These scenarios predict a strong first-order phase transition in the early universe for  $\kappa_\lambda > \kappa_{\min}$ .

# Triple and quartic self couplings

- Triple Higgs production is extremely rare in the Standard Model ( $\sigma \approx 0.01$  fb)
- It is directly sensitive to:
  - Higgs self-couplings, including the quartic Higgs coupling
  - BSM enhancements
  - $h_i, h_j =$  any SM H or heavy scalar X, S



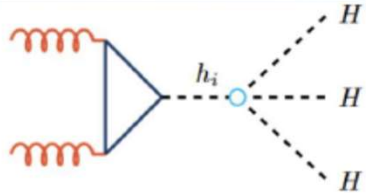
Results are interpreted in terms of three benchmark models:

- SM-like
- extending the SM by adding two real scalar bosons
- with resonant production of generic heavy spin-0 bosons



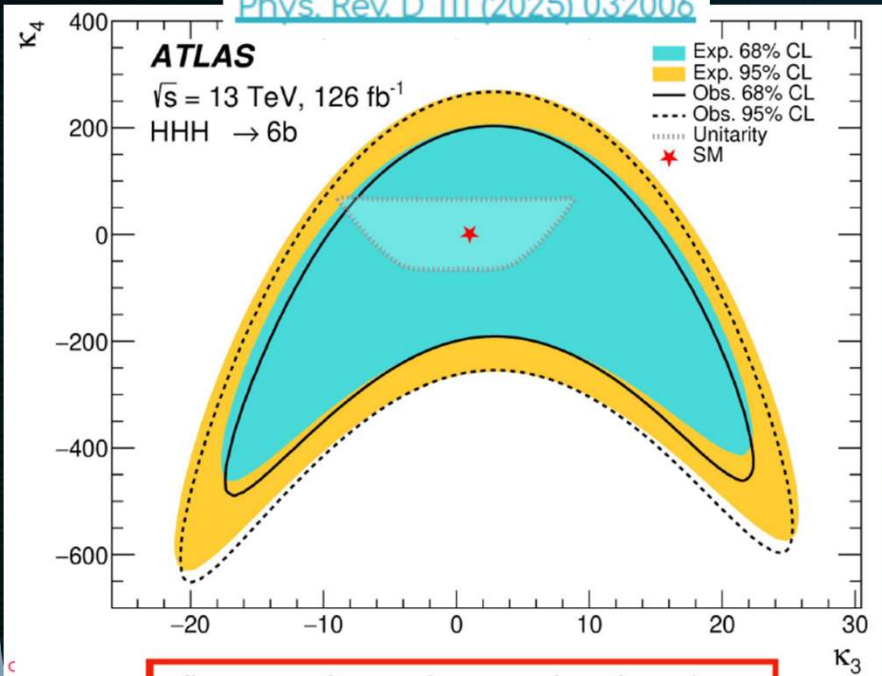
- Non Resonant:  $m_X > m_S + m_H, m_S \leq 2m_H$
- Resonant:  $m_X > m_S + m_H, m_S > 2m_H$ 
  - $325 \leq m_X \leq 575$  GeV,  $200 \leq m_S \leq 350$  GeV
- Heavy Resonant:
  - $550 \leq m_X \leq 1500$  GeV,  $275 \leq m_S \leq 1000$  GeV

# Triple and quartic self couplings

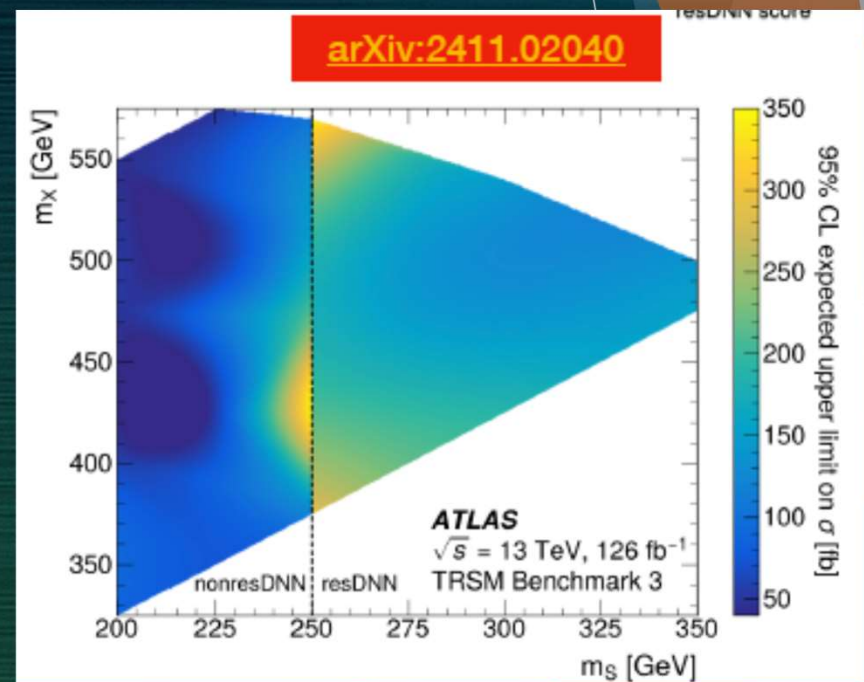


- Only direct access to quartic  $\lambda_4$  coupling.
- Production cross section lower than HH, thus an interesting channel for BSM searches

[Phys. Rev. D 111 \(2025\) 032006](#)



first experimental constraint placed on the quartic Higgs self-coupling ( $k_4$ )





# Extra higgses, PS light/heavy states (LHCP 2025)

The  $H_{125}$  tends to be closer and closer to the SM Higgs !!

→ decoupling limit?

Two complex scalar doublets,  $\Phi_1$  and  $\Phi_2$ , 8 real d.o.f, after SSB - 5 physical scalar states:

- neutral CP-even  $h, H$
- neutral CP-odd  $A$
- charged  $H^\pm, H^\mp$

2 non-zero VEVs:  $v_1(\Phi_1)$  and  $v_2(\Phi_2)$ :

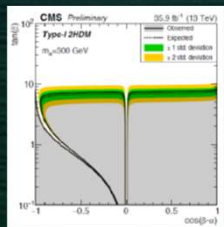
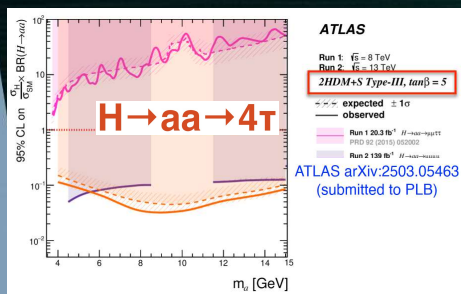
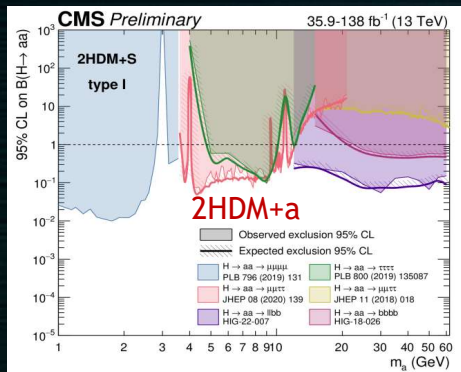
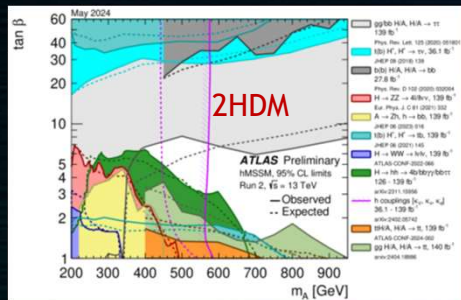
$$v_1^2 + v_2^2 = v^2 \equiv (246 \text{ GeV})^2, \quad \frac{v_1}{v_2} \equiv \tan\beta$$

Mass hierarchy is not fixed exactly, but the state  $h$  considered light and the rest 4 are considered heavy

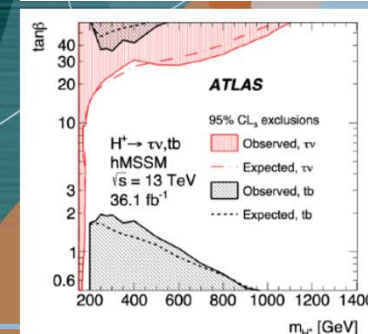
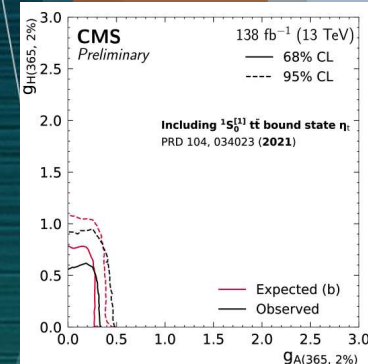
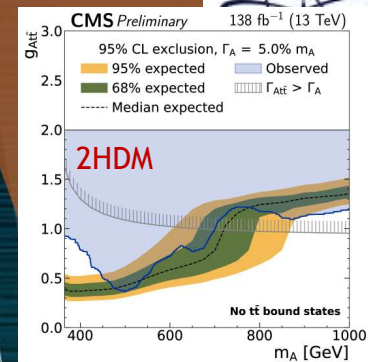
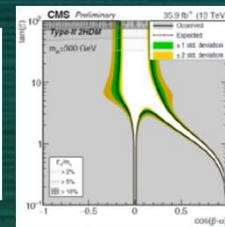
$$h_{SM} = \phi_1 \cos\beta + \phi_2 \sin\beta = h \sin(\alpha - \beta) - H \cos(\alpha - \beta)$$

Decoupling limit:  $\alpha \rightarrow \pi/2 - \beta$  (H does not contribute)

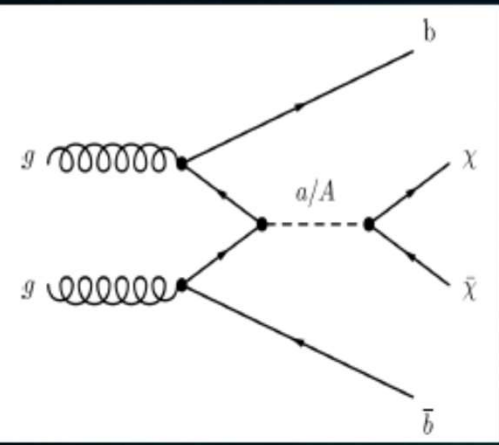
Most of the LHC studies, including for dark matter, are performed for this limit



Model	$u_R^i$	$d_R^i$	$e_R^i$
Type I	$\Phi_2$	$\Phi_2$	$\Phi_2$
Type II	$\Phi_2$	$\Phi_1$	$\Phi_1$
Lepton-specific	$\Phi_2$	$\Phi_2$	$\Phi_1$
Flipped	$\Phi_2$	$\Phi_1$	$\Phi_2$



# Pseudoscalar 2HDM+a: MET DM in association with $bb$ -pair



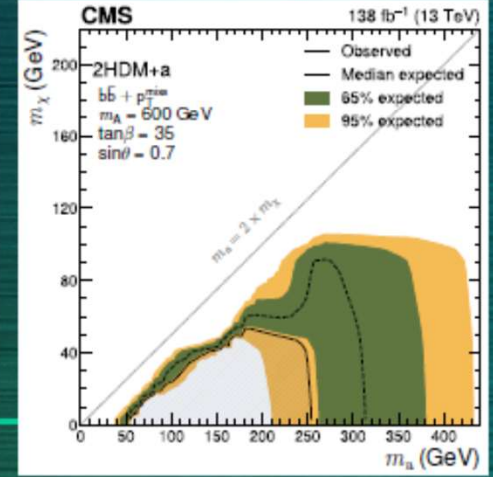
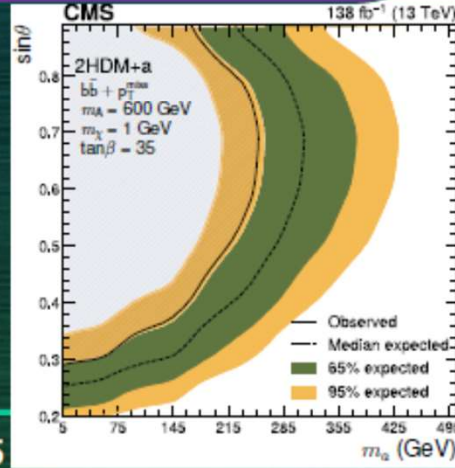
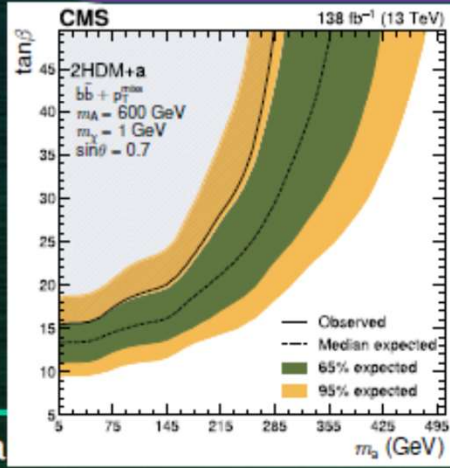
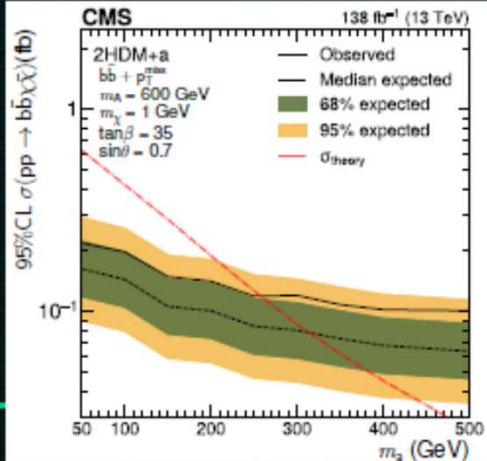
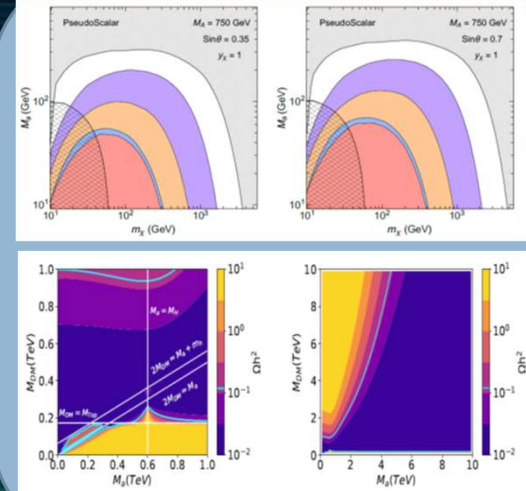
$$V_H^{2HDM} = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - m_{12}^2 (\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1) + \frac{\lambda_1}{2} (\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2} (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1) + \frac{\lambda_5}{2} [(\phi_1^\dagger \phi_2)^2 + (\phi_2^\dagger \phi_1)^2]$$

- 2HDM is near or in the decoupling limit ( $h$  becomes very SM-like):  $\alpha \rightarrow \beta - \pi/2$
- Add one complex scalar singlet  $S = \frac{1}{\sqrt{2}}(S_R + iS_I)$ :

$$V_{2HDM+S}(H_1, H_2, S) = V_{2HDM}(H_1, H_2) + \lambda S H_1 H_2 + \frac{\kappa}{3} S^3 + \dots$$

✓  $a$  (the mostly-singlet-like pseudoscalar)

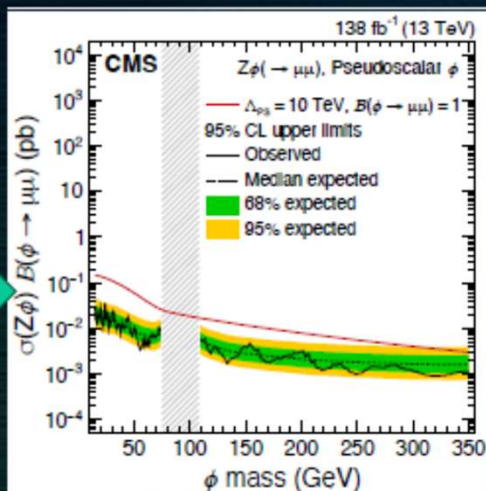
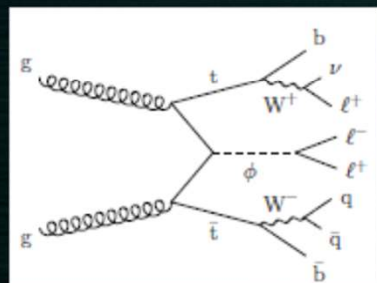
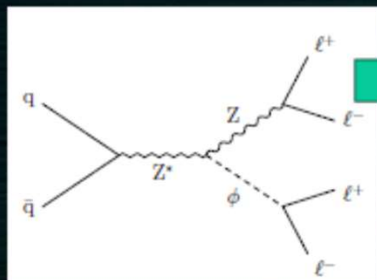
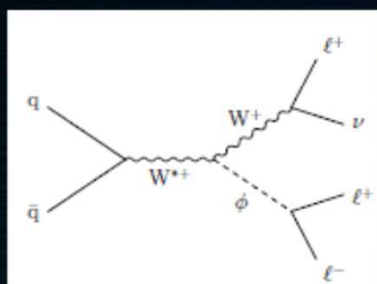
$$a = \cos \theta_a S_I + \sin \theta_a A \quad (\theta_a \ll 1)$$



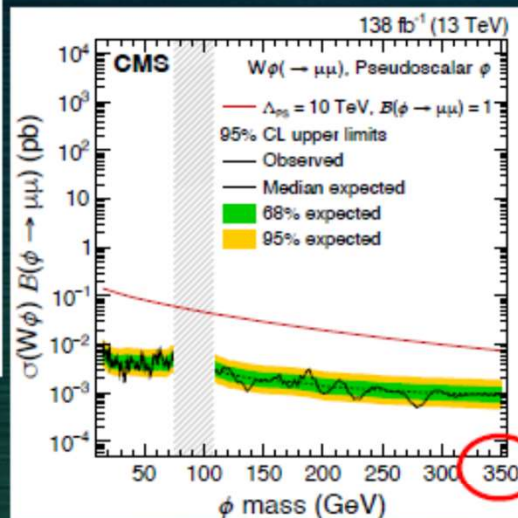


# (Pseudo)scalar: dilepton resonance in association with $V/t\bar{t}$ -pair

- ✓ Scalar, pseudoscalar (axion-like) and Higgs-like  $X\phi$  interactions ( $X=V/t\bar{t}$ )
- ✓ Scaled by  $\sin\Theta$  / Dim5 op. for S(PS)/Higgs-like interactions

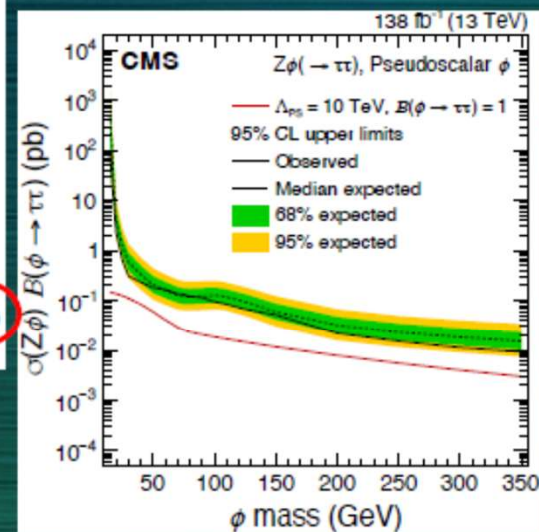


Z decays leptonically to all 3 generations  
W decays leptonically/hadronically for Higgs-like coupling



Higher mass limit of about 300 GeV because of non-negligible axion branching to top-antitop

CMS EXO-21-018,  
arXiv:2402.11098 [hep-ex]

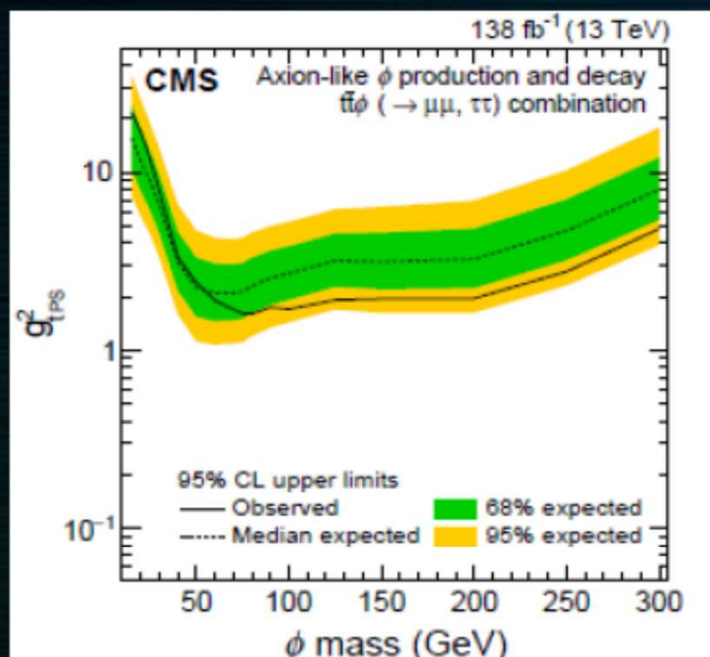




# (Pseudo)scalar: dilepton resonance in association with $V/t\bar{t}$ -pair

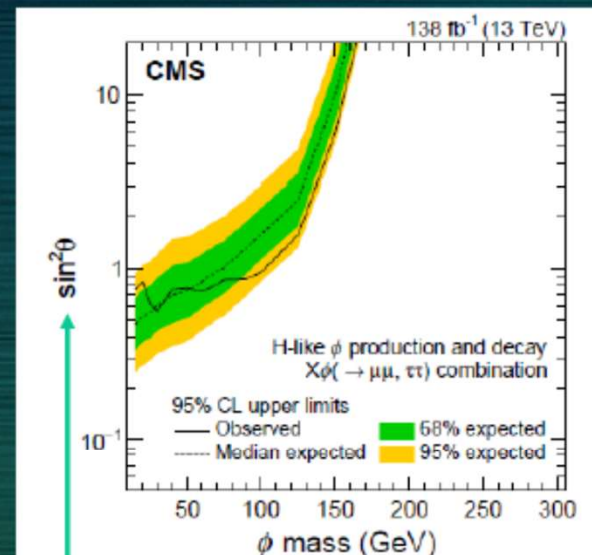
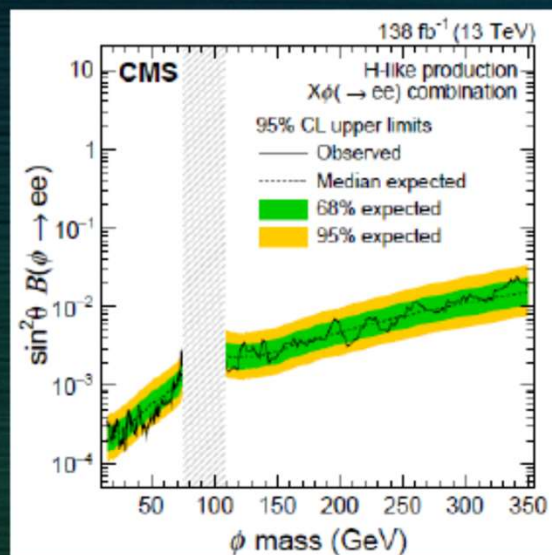


CMS EXO-21-018,  
arXiv:2402.11098 [hep-ex]



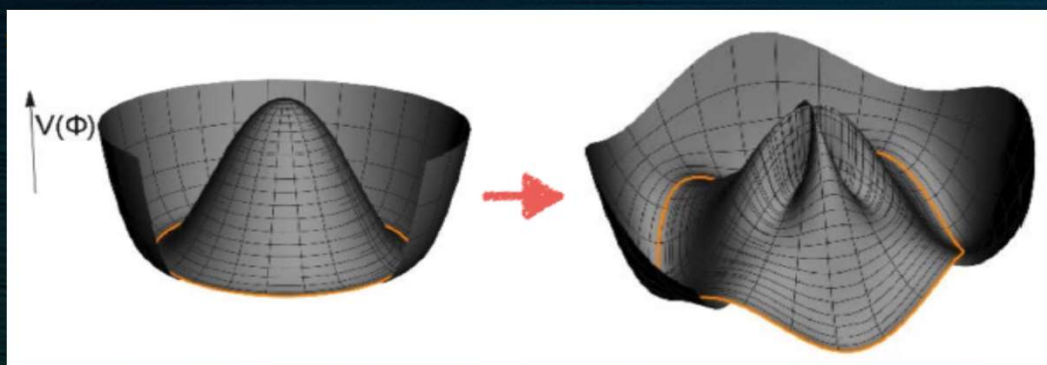
$$\mathcal{L} \subset -2 \sin\theta \frac{\phi_H}{v} \left( m_W^2 W^{+\mu} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu \right)$$

for Higgs-like,  
 $\Theta$  – mixing angle



For  $\phi$  branchings as for the SM Higgs

## PNGB - Axion-like particles



$$\mathcal{L}_{\text{anomaly}} \supset \frac{C_{GG}}{f_a} a G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{C_{\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \dots$$

$$\delta\mathcal{L} = \mu^2 \Phi^2 + \text{h.c.} = \mu^2 f_a^2 \cos\left(\frac{2a}{f_a}\right) + \dots \longrightarrow m_a^2 \sim \frac{\mu^2}{f_a^2}$$



# Electroweak-scale ALPs?



## Composite Higgs Models with Extended Cosets

In composite Higgs models, the Higgs is a pNGB from a spontaneous breaking of a global symmetry in a strong sector:  $G \rightarrow H$  with  $G \supset SU(2)_L \times SU(2)_R$ .

By enlarging the coset  $G/H$ , one often gets additional pseudo-Goldstone bosons, which can play the role of ALPs

Example:  $SO(6)/SO(5)$

[Gripaios, Pomarol, Riva, Serra '09]

- This coset gives 5 pNGBs: 4 Higgs components and 1 ALP-like state.
- The fifth pNGB is a singlet under the SM gauge group, and has a shift symmetry inherited from  $SO(6)$ .
- It couples to SM fermions and gauge bosons via partial compositeness or anomalies.

→ natural  $m_a$  few GeV to 100 GeV, depending on details of the strong sector,

## Relaxion and Clockwork models

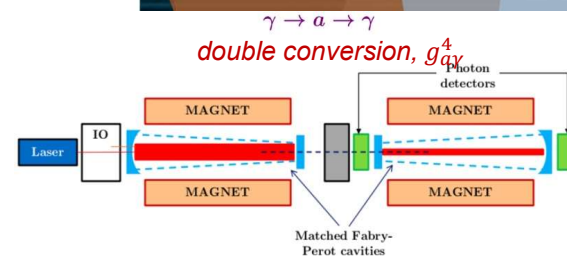
The relaxion mechanism involves an ALP-like field that dynamically relaxes the Higgs mass. Usually requires mild explicit breaking of shift symmetry over many periods — can be engineered using clockwork.

### Clockwork ALPs

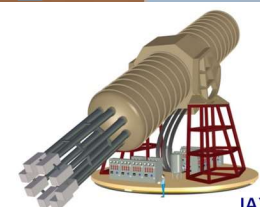
[Giudice, McCullough '16]

- A chain of  $N$  fields with nearest-neighbor interactions can give rise to a light ALP with exponentially suppressed couplings at one end.
- The mass of the ALP depends on the explicit breaking scale at the far end:  $m_a \sim \Lambda_{\text{br}}^2 / f_a$
- You can engineer  $m_a \sim 1 - 100$  GeV with  $\Lambda_{\text{br}} \sim \text{TeV}$  and  $f_a \sim \text{TeV}$ .

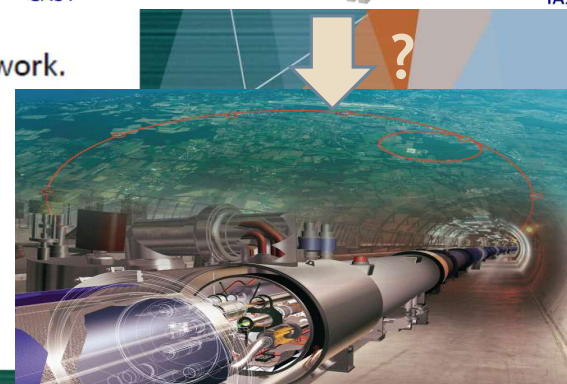
M. Savina, BLTP JINR, Russia



CAST



IAXO



23.07.2023

29770



# Electroweak-scale ALPs?



## Anomalous U(1) Extensions with Heavy Fermion Loops

Consider a UV model with:

- A global U(1) symmetry broken by  $\langle \Phi \rangle = f_a$
- Heavy vector-like fermions  $\Psi$  charged under both U(1) and SM gauge groups

Integrating out  $\Psi$  generates anomalous ALP couplings:  $\frac{a}{f_a} F\tilde{F}, \frac{a}{f_a} G\tilde{G}$

You can then introduce hard breaking terms like  $\mu^2 \Phi^2 + \text{h.c.}$  to give the ALP a mass:  $m_a \sim \mu \ll f_a$

With  $\mu \sim 10$  GeV and  $f_a \sim 1$  TeV, you get  $m_a$  in the collider-accessible regime

## Higgs-Portal ALP models

You can write an EFT with a Higgs-ALP portal:  $\mathcal{L} \supset \frac{c_{a\Phi}}{f_a} a H^\dagger H$  or  $\frac{c_{ah}}{f_a} a h^2$

After electroweak symmetry breaking, this mixes  $a$  and  $h$  and generates:

- A mass for  $a$  proportional to  $v$  (or  $v^2/f_a$ )
- Exotic decays like  $h \rightarrow Za, h \rightarrow aa$ .

EFT model, but can be UV-completed via:

- Extended scalar sectors (e.g. singlet extensions of 2HDMs) or mixing with other singlet scalars



# Electroweak-scale ALPs?



## Effective ALP couplings and role of shift symmetry

The shift symmetry  $a \rightarrow a + \text{const}$  strongly constrains ALP couplings. Allowed terms must involve derivatives of  $a$  or be associated with anomalous current divergences. The lowest-dimension couplings are:

### (a) Fermionic couplings (derivative):

The ALP couples derivatively to fermion axial currents:

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \sum_\psi C_\psi \bar{\psi} \gamma^\mu \gamma^5 \psi \xrightarrow{\text{IBP + EOM}} \mathcal{L} \supset i \frac{C_\psi m_\psi}{f_a} a \bar{\psi} \gamma^5 \psi \quad \text{pseudoscalar Yukawa coupling}$$

### (b) Gauge couplings (anomalous):

The ALPs can couple to gauge bosons via dim-5 operators: Arise from integrating out heavy fermions in triangle diagrams

$$\mathcal{L} \supset \frac{C_{FF}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \text{with} \quad \tilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}.$$

Interactions violate shift symmetry due to quantum anomalies, but are controlled by  $f_a$

So, up to dim-5 we have the following interactions:

$$\mathcal{L}_{\leq \text{dim}5} = \frac{1}{2} (\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2} a^2 + i \frac{C_\psi m_\psi}{f_a} a \bar{\psi} \gamma^5 \psi + \frac{C_{GG}}{f_a} a G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{C_{BB}}{f_a} a B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{C_{WW}}{f_a} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

# Electroweak-scale ALPs?

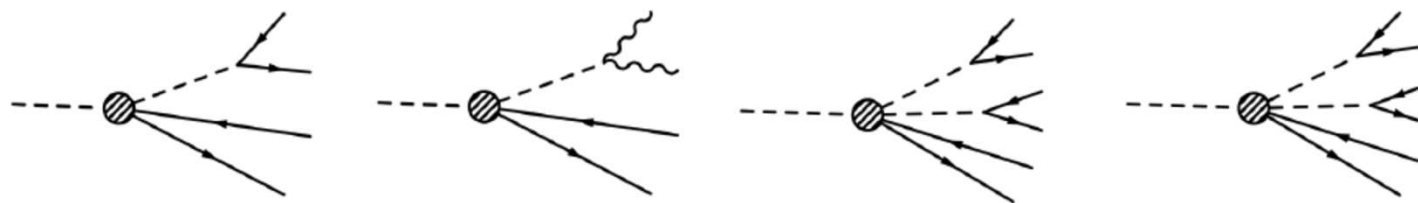
(c) Couplings involving Higgs boson and gauge bosons:

$$\mathcal{L}_{\geq \text{dim}6} \supset \frac{C_{ah}}{\Lambda^2} (\partial_\mu a)(\partial^\mu a) \phi^\dagger \phi + \frac{C_{Zh}^{(7)}}{\Lambda^3} (\partial^\mu a)(\phi^\dagger iD_\mu \phi + \text{h.c.}) \phi^\dagger \phi + \dots$$

(d) Couplings involving Higgs boson and fermions:

$$\mathcal{L}_{\geq \text{dim}6} \supset i \frac{C_\psi m_\psi}{f_a} a \bar{\psi} \gamma^5 \psi \phi^\dagger \phi + \frac{C_y}{f_a} a^2 \phi \bar{\psi} \psi + \dots$$

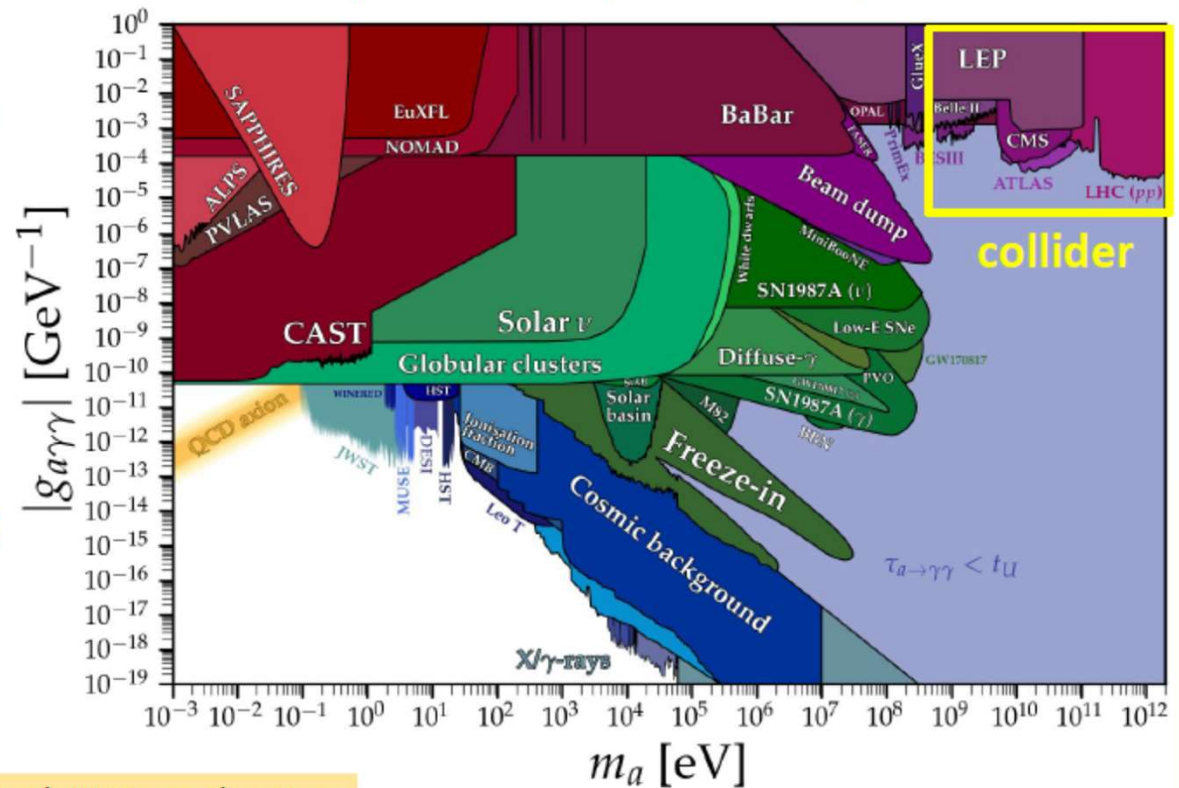
(a)-(d) result in many different decay channels and complex phenomenology at colliders



- Pseudoscalar in many BSM theories
- QCD axion: solution to **strong CP problem**
- ALP: Generalized axion with independent mass and coupling
- Nambu–Goldstone bosons from broken global U(1) symmetry
- Linked to **dark sector mediator**  
Explain anomalies (muon g-2, hierarchy ..)
- **Wide ( $m_a$ - $g$ ) parameter space**  
⇒ **diverse search strategies needed**

**LHC can act as an ALP factory**  
enabling  $\gamma$ -,  $g$ -, and **heavy boson**-mediated ALP production.

## ALP parameter space and experiments



[Image credit by caiohare](#)

- **Photon Couplings**

- **UPCs** : PbPb & pp collisions [arxiv:2412.15413](https://arxiv.org/abs/2412.15413) & [PRD110\(2024\)012010](https://arxiv.org/abs/2412.15413)

- **Top and Invisible Couplings**

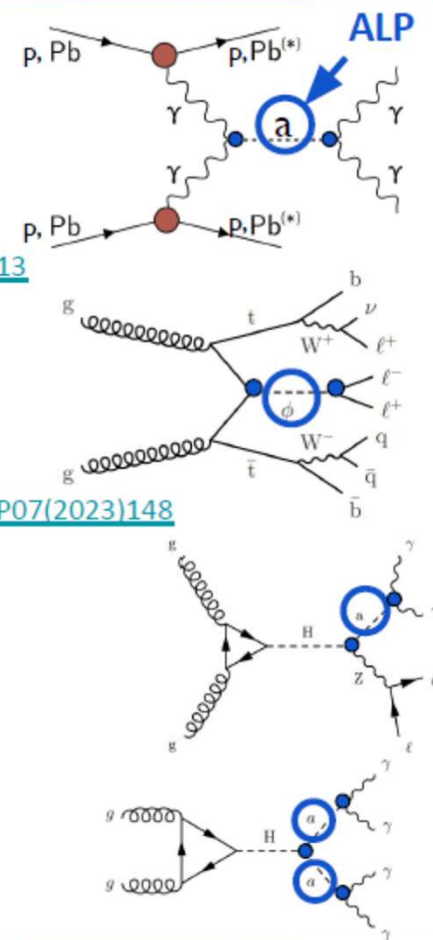
- **$t\bar{t}(t)+a$**  (invisible & leptonic decays) [CMS-PAS-EXO-22-014](https://arxiv.org/abs/2412.15413) & [PRD110\(2024\)012013](https://arxiv.org/abs/2412.15413)

- **Boson Couplings**

- **Mono-Z+a** (invisible decays) [EPIC81\(2021\)13](https://arxiv.org/abs/2412.15413)
- Higgs exotic decays :  $H \rightarrow Za \rightarrow 2l2\gamma$  &  $aa \rightarrow 4\gamma$  [PLB 852\(2024\)138582](https://arxiv.org/abs/2412.15413) & [JHEP07\(2023\)148](https://arxiv.org/abs/2412.15413)
- BSM Higgs X decays :  $X \rightarrow aa \rightarrow 2$  merged  $\gamma\gamma$  [PRL134\(2025\)04180110](https://arxiv.org/abs/2412.15413)

- **Displaced ALP signatures**

- Higgs exotic decays :  $H \rightarrow aa \rightarrow 2$  merged  $e^+e^-$  [CMS PAS EXO-24-031](https://arxiv.org/abs/2412.15413)
- Higgs exotic decays :  $H \rightarrow aa \rightarrow 4\mu$  [JHEP12\(2024\)172](https://arxiv.org/abs/2412.15413)



## Model

- Fermiophilic ALP: Pseudoscalar with Minimal Flavor Violation (MFV)  $\Rightarrow$  Higgs-like Yukawa couplings, enhanced top coupling

## Dataset and Signature

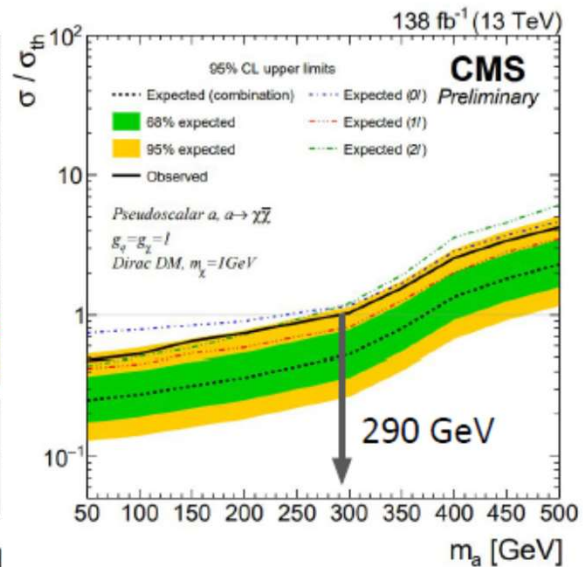
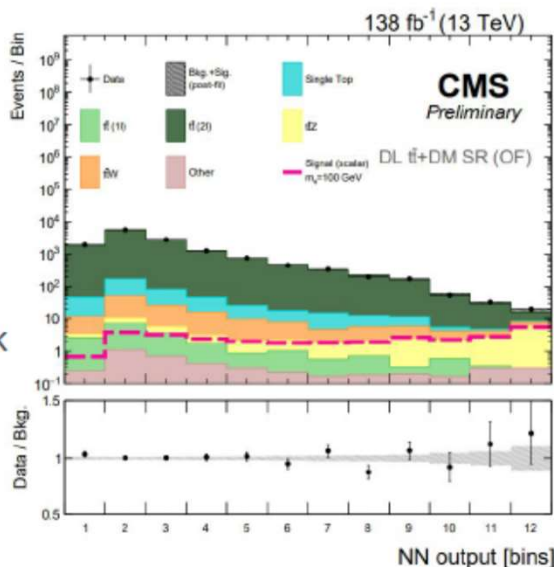
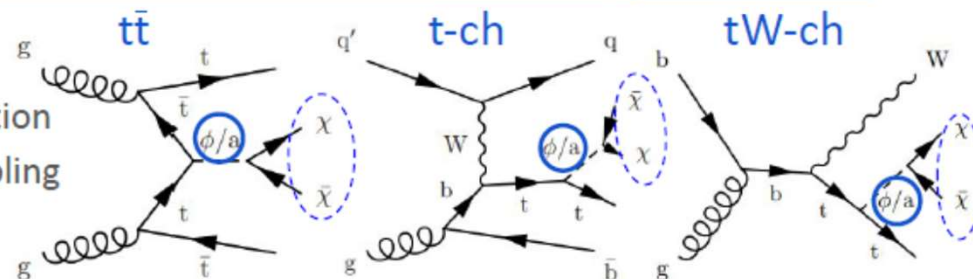
- 2016–2018 pp collisions at 13 TeV,  $\mathcal{L} \sim 138 \text{ fb}^{-1}$
- Signal:  $t\bar{t}/t/tW + a (a \rightarrow \chi\chi)$
- Channels: 0L (all-hadronic) 1L, 2L (dileptonic)

## Analysis Strategy

- 0-1L: Event categorization by  $N_L$ ,  $N_j$ , and  $N_b$  to increase sensitivity
- 2L: Sensitivity improved using a Neural Network

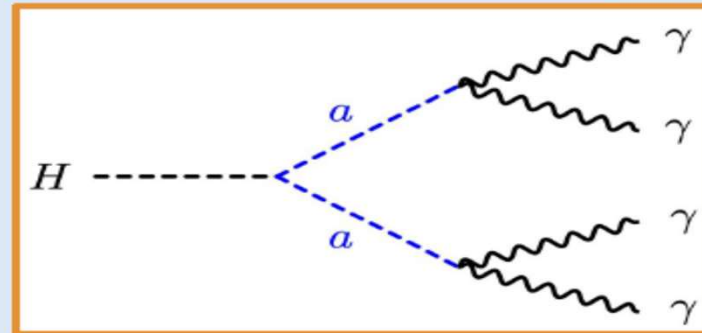
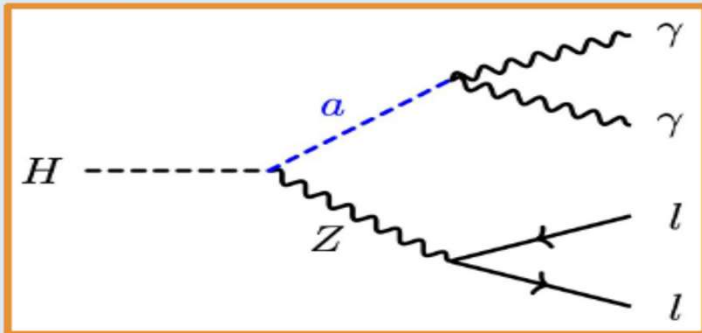
## Limits

- $m_a$  excluded  $< 290 \text{ GeV}$  (at fixed dark matter mass and coupling:  $m_\chi = 1 \text{ GeV}$ ,  $g_q = g_\chi = 1$ )





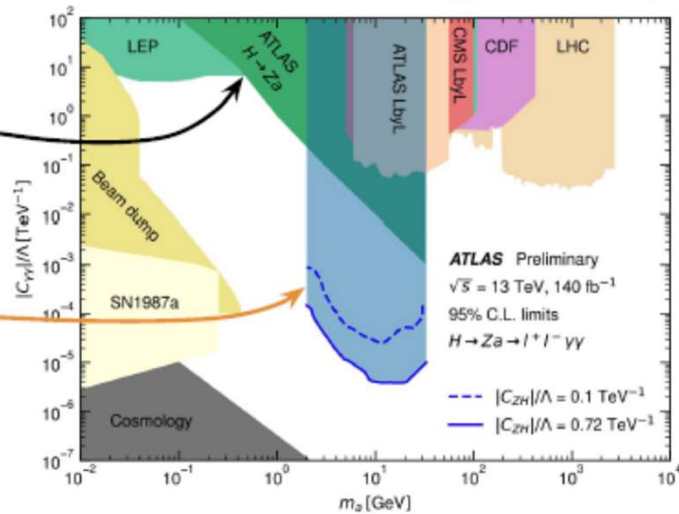
# ALP status



## H → Za (resolved photons)

Existing search

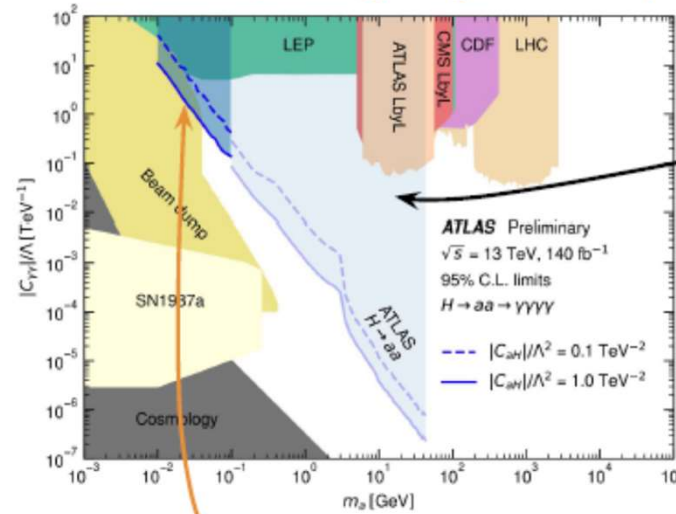
This paper



## H → aa (merged photons)

Existing search

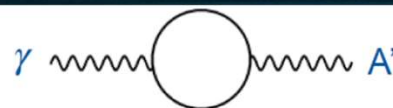
This paper



ATL-PHYS-PUB-2025-007

# Vector portals, dark photon / $Z_D$

The coupling to SM particles proportional to electric charge

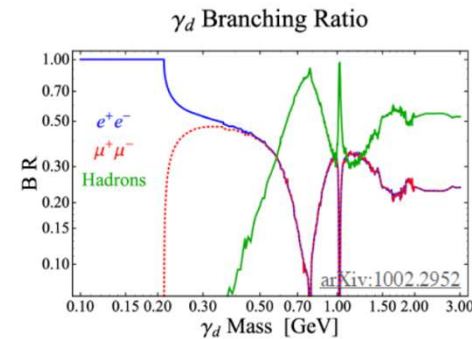
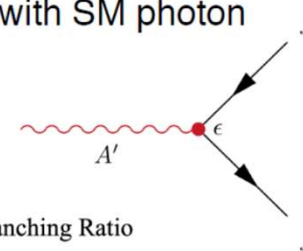
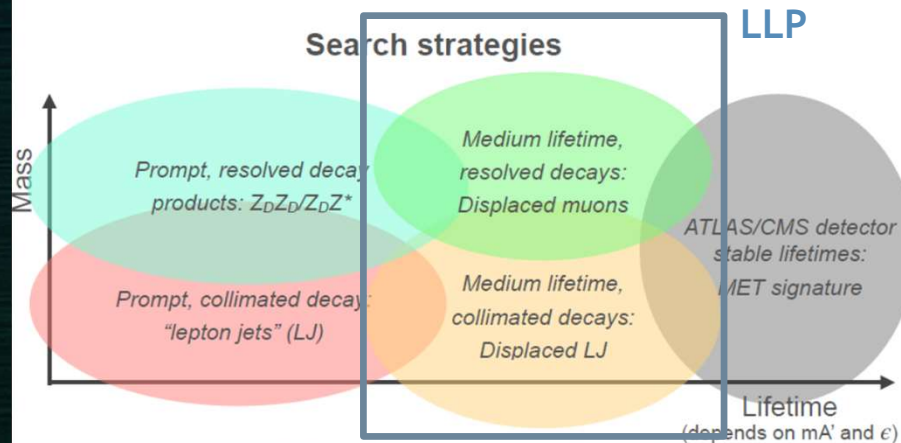


1 or 2 loops: naively  $10^{-5} \lesssim \epsilon \lesssim 10^{-3}$

$$\alpha' = \epsilon^2 \alpha_{EM}$$

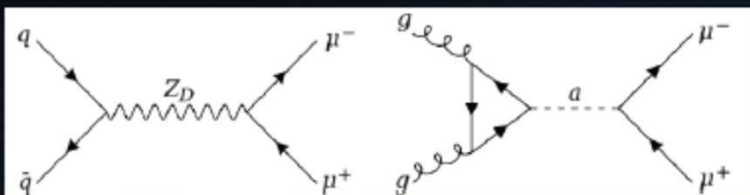
Add a  $U(1)_D$  where massive dark gauge boson ( $A'/Z_D/\gamma_D$ ) kinetically mix with SM photon

- Parameters: kinetic mixing term,  $\epsilon$ , and  $m_{A'}$



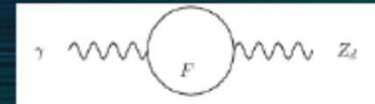


# Gauge/pseudoscalar: prompt GeV-scale dimuon resonance

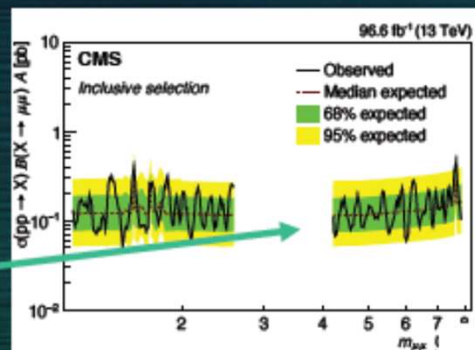
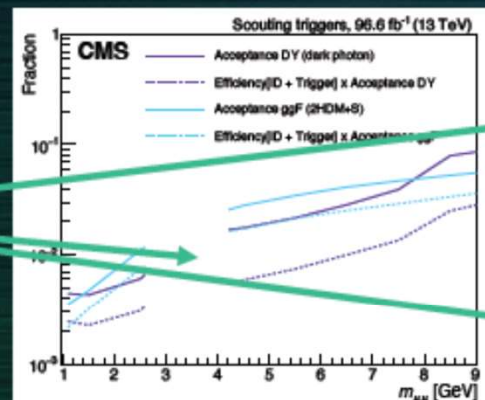
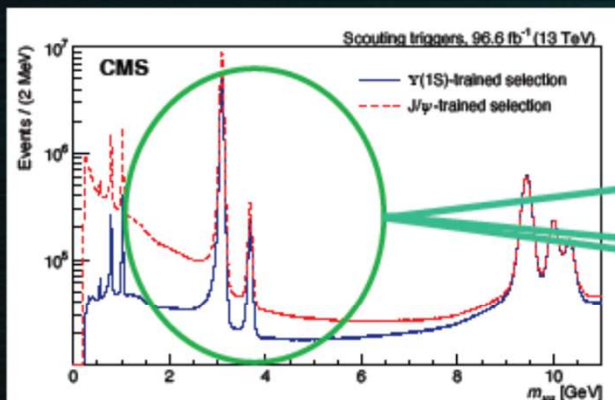


Reinterpretation in terms of two models :

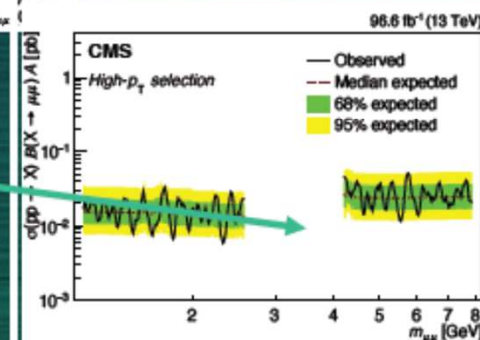
- ✓ minimal dark photon model  $U(1)_D$
- ✓ light pseudoscalar in 2HDM+S (7 Higgs states, CP-even/odd + charged)



The ability to search for light new resonances thanks to a sophisticated high-rate dimuon trigger trained on known SM resonances in the region below 10 GeV ( $J/\psi$  and  $Y(1S)$ )



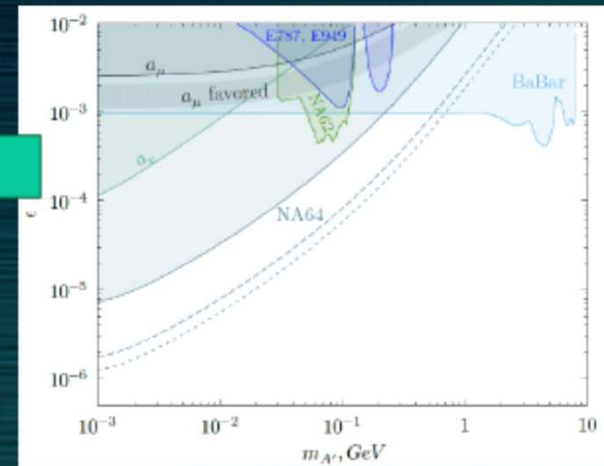
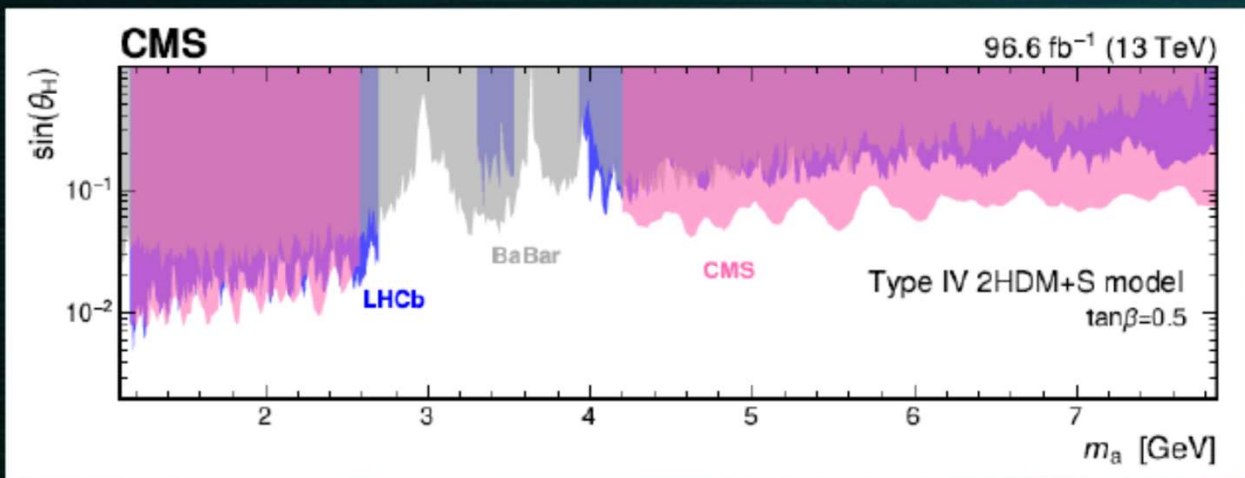
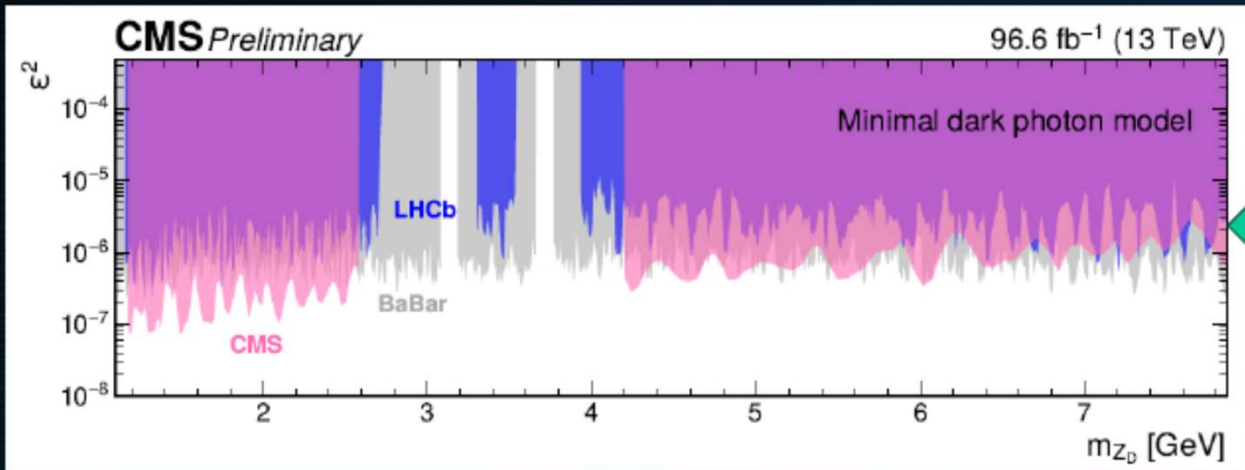
region 2.6 – 4.2 GeV is excluded due to the presence of  $J/\psi$  and  $\psi(2S)$



CMS EXO-21-005,  
arXiv:2309.16003 [hep-ex]



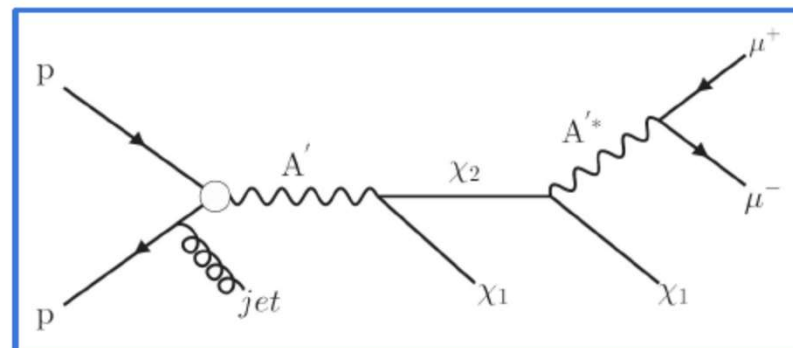
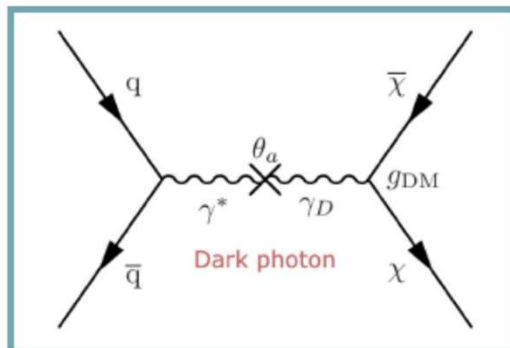
# Gauge/pseudoscalar: prompt GeV-scale dimuon resonance



CMS EXO-21-005,  
arXiv:2309.16003 [hep-ex]

# Connecting dark photon portal to other models

Under some assumptions on the mass and coupling of the dark matter candidate, other models like mono-X searches in  $Z'$  simplified model searches or IDM signatures can be used to set limits on the same parameter space extending coverage of the limits in terms of mass and lifetime



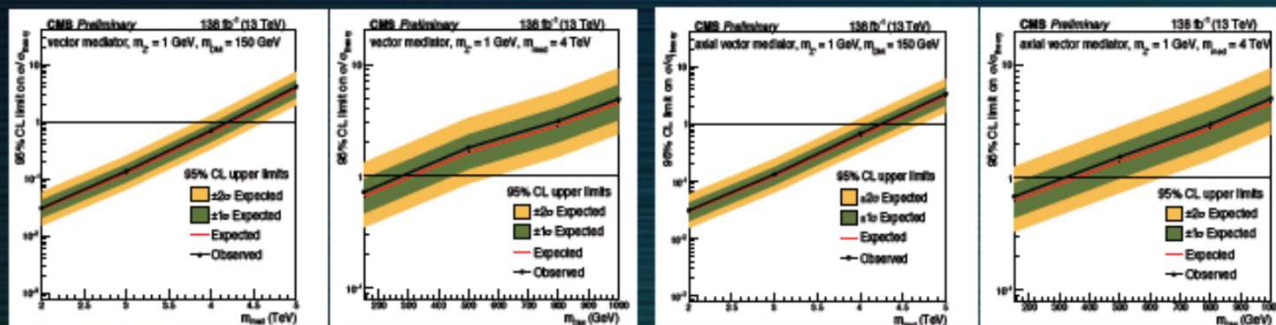
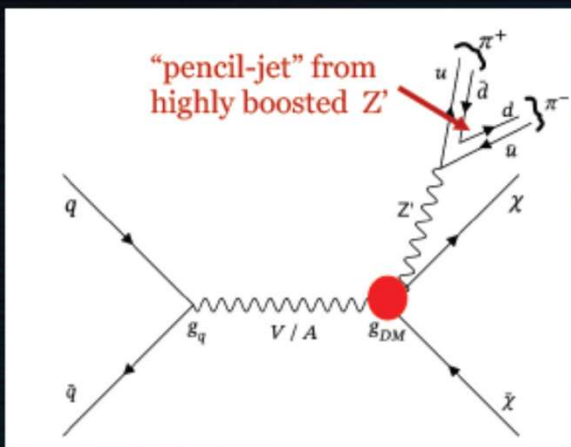


# Gauge SDM: MET+low-multiplicity jets



V/AV portal + additional Z'

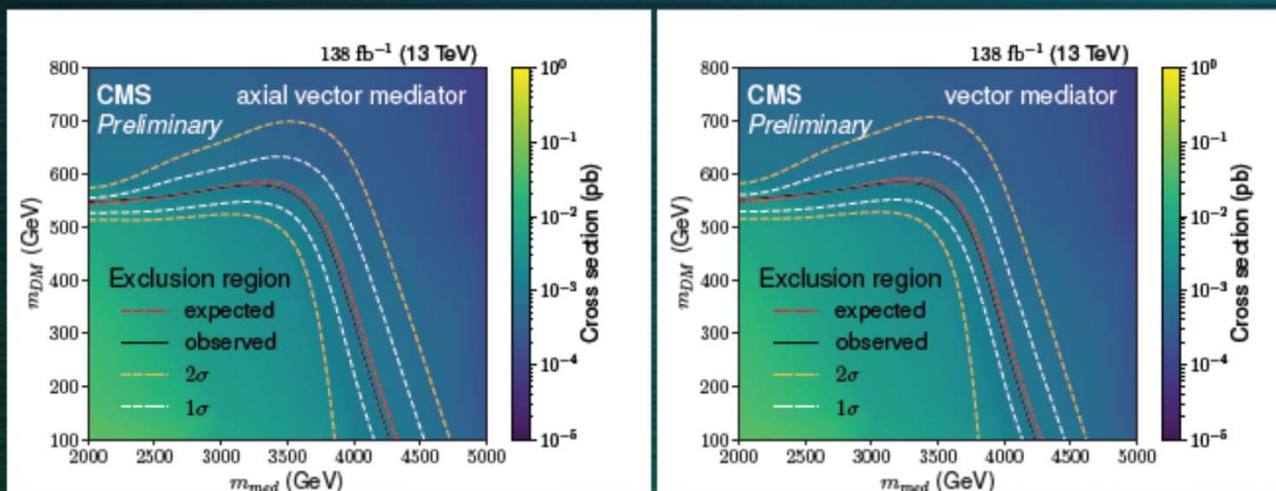
CMS PAS-SUS-23-017



“Double gauge” portal:

- ✓ heavy V/AV mediator (2 – 5 TeV)
- ✓ heavy DM (0.1 – 1 TeV)
- ✓ **light** additional Z' (0.3 – 3 GeV)

low multiplicity charged particles as decay product (hadronically decaying  $\tau$ -type rec.)

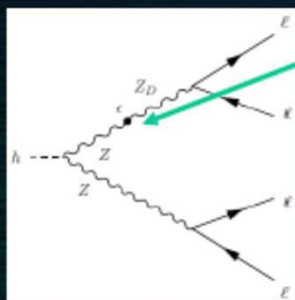




# Scalar/gauge portal: prompt pair of light dilepton resonances (4l)

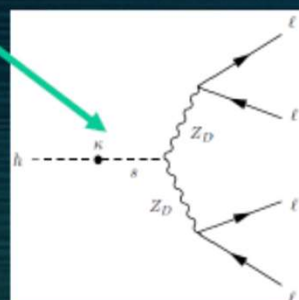


HAHM – Hidden Abelian Higgs Model, weakly coupled DS,  
dark Higgs, dark photon  $Z_D$  from  $U(1)_D$   
Gauge/higgs portal (kinetic/higgs mixing)



$$\kappa \gg \epsilon$$

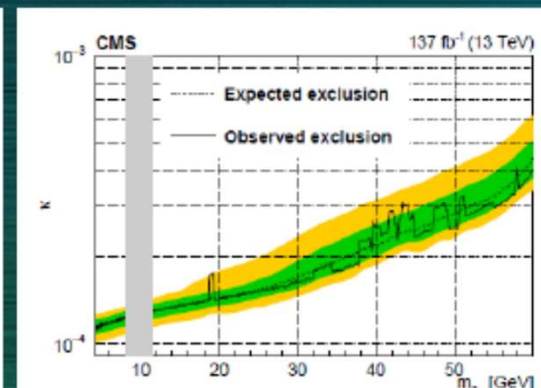
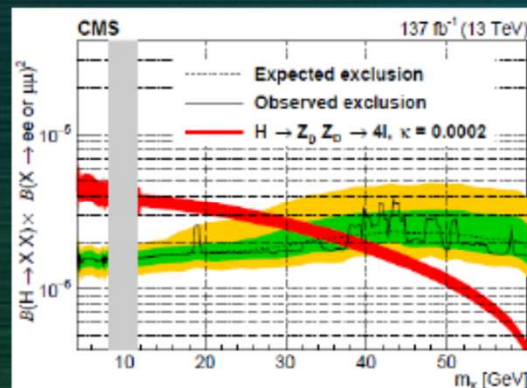
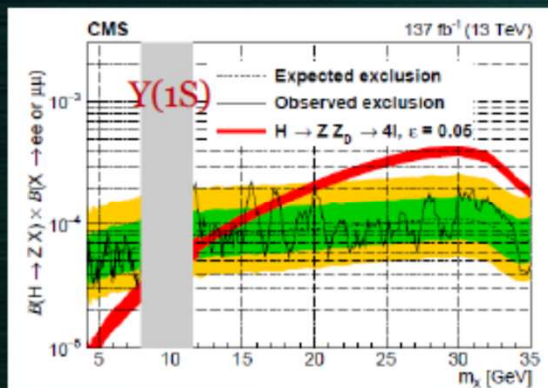
higgs mixing  
dominates over  
kinetic mixing



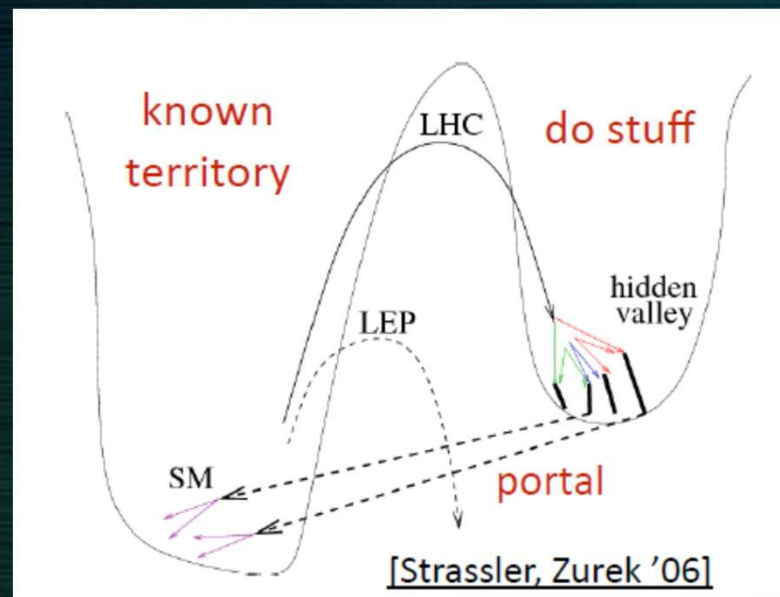
CMS-HIG-19-007,  
arXiv:2111.01299v2  
[hep-ex]

See a talk by  
Slava Valuev on  
LLP search

See also Backups  
for ALP  
interpretation



## Dark sector/hidden valleys





# Why “hidden” or “dark” physics?



## Data & Theory Both Motivate

- ▶ Dark matter
- ▶ Neutrino masses
- ▶ Supersymmetry breaking
- ▶ Cosmological phase transitions
- ▶ Baryogenesis
- ▶ String theory model building
- ▶ Neutral Naturalness

Also, experimental limits are weak

But accessible at the LHC?

Maybe, maybe not.

Still, cannot afford to ignore.

## Beyond Ordinary Signatures

### New Visible Particles

- Masses above 100 GeV (LEP)
- Lifetimes  $\sim 10^{-(15-27)}$  sec\*  
*\*with exceptions*
- Production singly or in pairs
- Decays: a few leptons, photons, jets

### Dark/Hidden Particles

- Masses may be below 100 GeV
- Lifetimes may be much longer
- Production & decay can be complex

Often requires specialized analysis



# What is a Hidden Valley?



MJS & Zurek 2006

A sector of SM-neutral particles which

1. can be produced in SM collisions with a reasonable rate  
(*not gravitationally-coupled hidden sectors*)
2. include states that can decay within 1 sec  
(*not sectors with massless final states or coupled too weakly*)
3. have self-interactions that complicate the dynamics  
(*i.e. not sectors of single dark photon or single free fermion*)

Often called "dark sectors" or "rich dark sectors" nowadays  
(*especially if sector contains dark matter*)



*Why useful to give this giant class of theories a single name?*

### Qualitative Predictions (alone or in combination)

- ▶ Multiple neutral particles decaying to SM particles (and often MET)
- ▶ High-multiplicity production
- ▶ Unusual clustering
- ▶ Displaced vertices

⇒ exotic jets: "dark", "displaced", "emerging", "semivisible"

### Potential Dramatic Impact:

- ▶ When added to existing theory, can completely change signatures
  - $SM + HV = \text{exotic decays of } h, W, Z, t$
  - $SUSY + HV = \text{reduced MET, exotic final states}$



## QCD vs “dark” QCD: SM



Quite a few adjustable parameters

- ▶  $SU(N_c)$  with  $N_c = 3$
- ▶ Quarks in **3** rep.
- ▶  $N_f^{light} / N_c = 1$ ,  $N_f^{heavy} / N_c = 1$
- ▶ Light quarks  $m_u, m_d \ll m_s < \Lambda_{QCD}$

Dynamics: Confinement, Chiral Symmetry Breaking

Light-quark hadrons

- ▶ masses range over an order of magnitude
- ▶ lifetimes range over 15 orders of magnitude
- ▶ many different decay modes (to hadrons, leptons, photons)
- ▶ produced in high-multiplicity clusters (“jets”) with no fixed mass

Predictions:

- Perturbation theory including resummation (showering)
- Lattice calculations (spectrum, decay constants, scales)
- Models of hadronization (Lund, Herwig, etc.)



## QCD vs “dark” QCD: HV/DS



Quite a few adjustable parameters

- ▶  $SU(N_c)$  with **other**  $N_c$ ; or **not**  $SU$  group
- ▶ Quarks in  $N_c$  and/or **other representations**
- ▶  $N_f/N_c$  (**much**) **larger or smaller than 1**
- ▶ Light quarks masses **smaller or larger** relative to  $\Lambda_{HV}$

Dynamics: Confinement?? Chiral Symmetry Breaking??

Light-quark hadrons

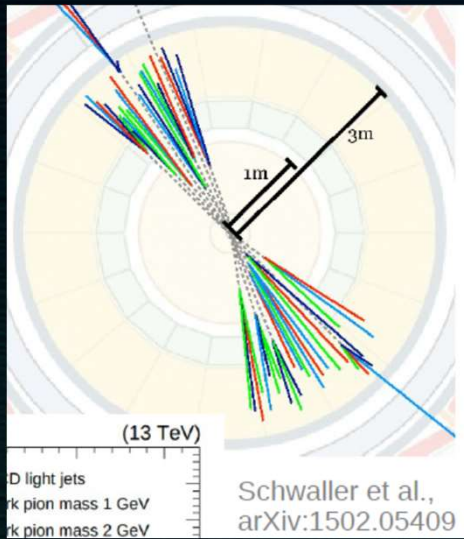
- ▶ masses range over an order of magnitude **or more**
- ▶ lifetimes range over **many** orders of magnitude
- ▶ many different decay modes (to **HV/DS hadrons, SM particles**)
- ▶ produced in high-multiplicity clusters (“jets”??) with no fixed mass

**Prediction methods can all potentially fail:**

- Perturbation theory including resummation (showering)
- Lattice calculations (spectrum, decay constants, scales)
- Models of hadronization (Lund, Herwig, etc.)



# Strongly coupled DS, dark showers, prompt/LLP



$N_c, N_f, \Lambda_{\text{dark}},$   
 $m_{\text{dark}}, r_{\text{inv}} \dots$

Hidden valleys, dark QCD,  $SU(N_c^{\text{dark}})$

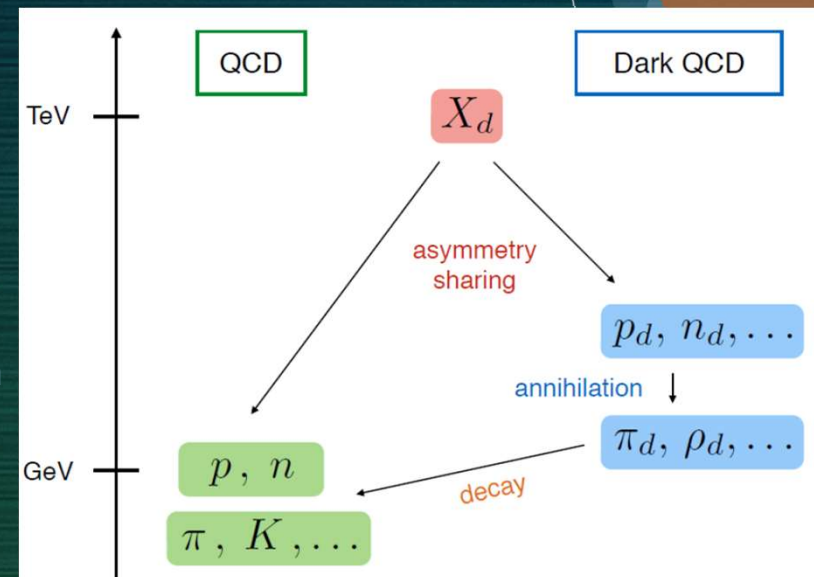
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu a} + \bar{q}_d i \not{D} q_d - \bar{q}_d M_q q_d$$

$F^a$ : dark gluons ( $N_d$  colours)

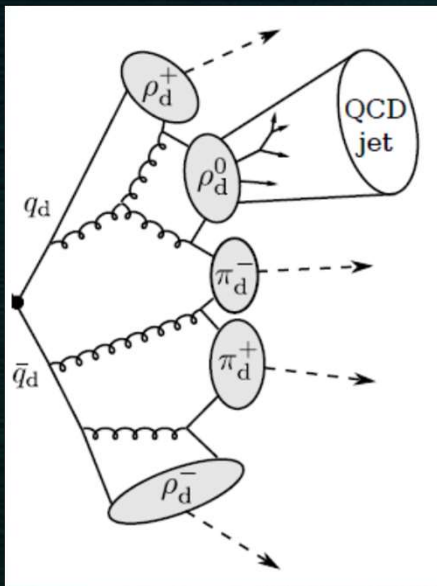
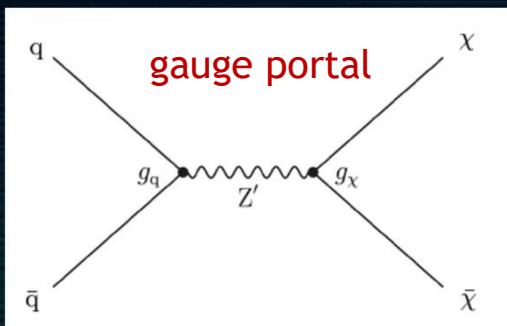
$q_d$ : dark quarks ( $N_f$  flavours)

$M_q$ : quark mass matrix

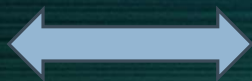
- ✓ One of the most striking DM-targeted signatures (dark QCD  $\rightarrow$  dark showers  $\rightarrow$  mediator  $\rightarrow$  SM transition)
- ✓ Broken  $U(1)_{\text{dark}}$ , kinetic  $U(1)_{\text{dark}} - U(1)_Y$  mixing, dark photon  $Z'$  as a messenger (also scalar portals)
- ✓ DS-SM transitions are suppressed by a high mediator mass scale  $\rightarrow$  prompt/LLP decays



# Dark QCD, dark showering, a part of the invisible

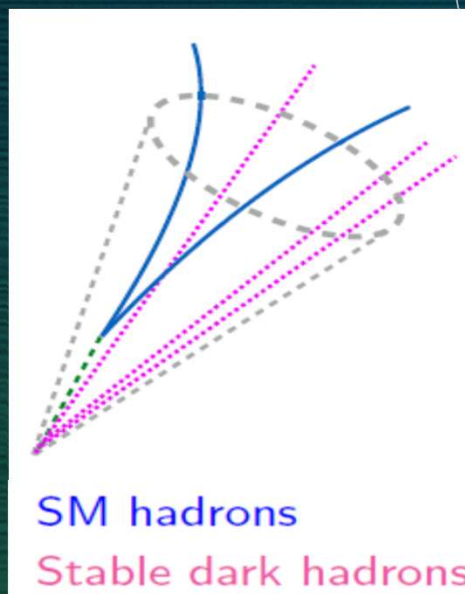


semivisible jets



DM part (visible) +  
SM part (invisible)

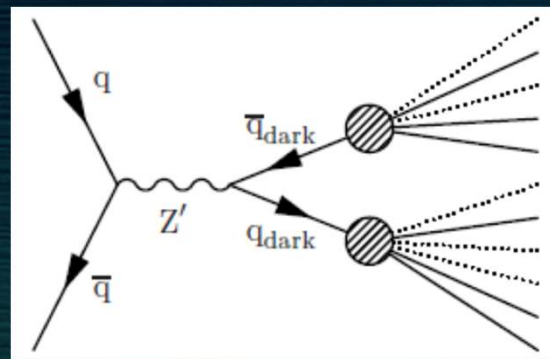
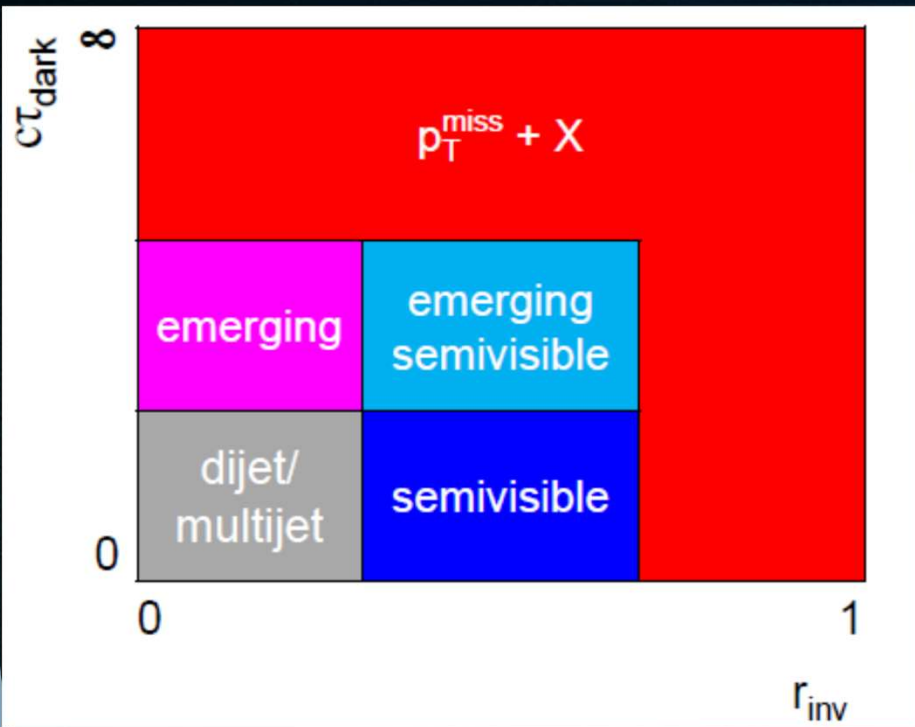
$x_{sec.}$ ,  $m_{Z'}$ ,  
 $m_{dark}$ ,  $g_{dark}$ ,  
 $r_{inv}$



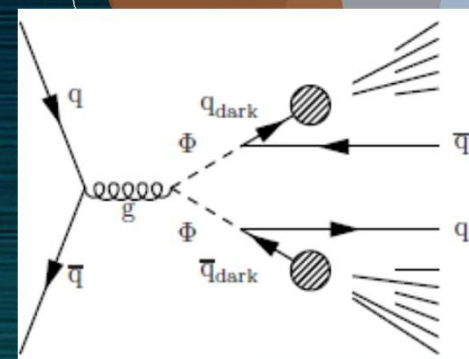


# Strongly coupled DM: signatures, prompt/LLP

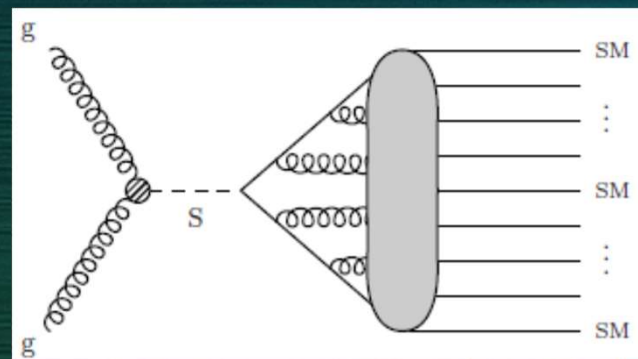
t Hooft coupling  $\lambda = \alpha_{dark}^2 N_c^{dark} \ll 1$



semivisible jets



emerging jets



soft unclustered energy patterns (SUEP)

$\lambda \gg 1$   
quasi-conformal spectra, dark "high-temperature QCD"

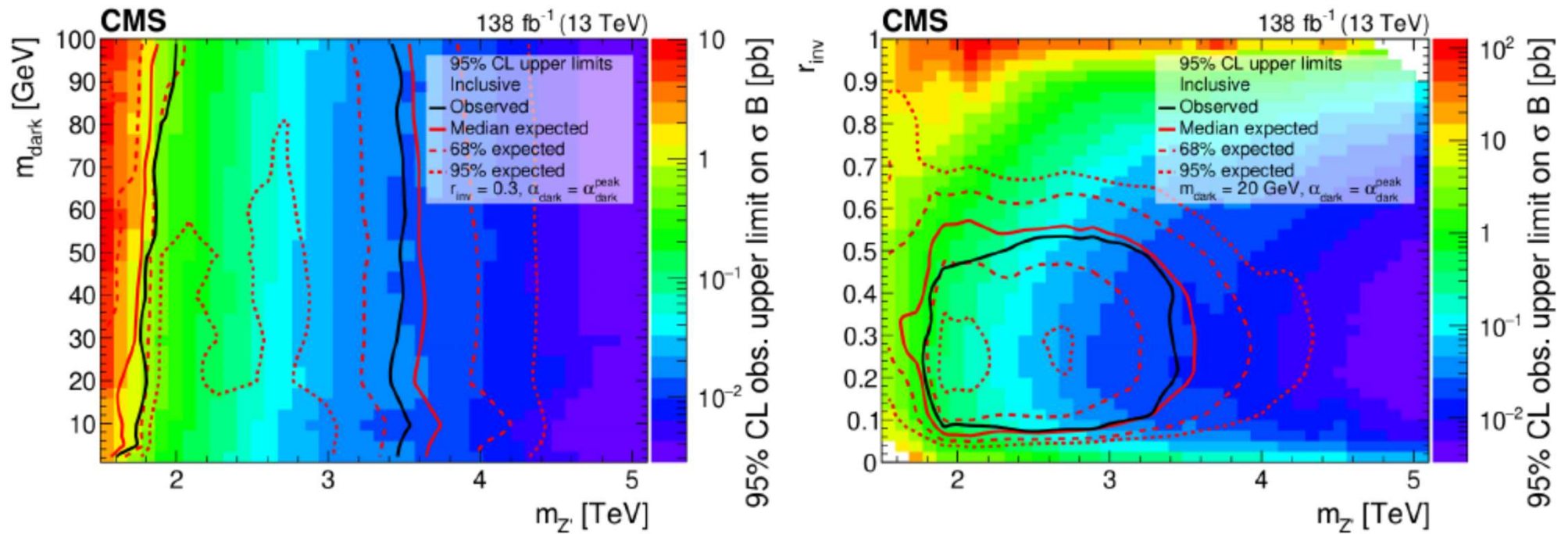
Tracks start near the edge of the tracker, in the ECAL and HCAL and even in the inner muon stations



# Resonant production of strongly coupled DM for semivisible jets

The first CMS study of jet invisible contribution with dark sector interpretation. The fraction  $r_{inv}$  of stable invisible dark hadrons in between 0 (dijet, small MET) and 1 (large MET)

JHEP 06 (2022) 156  
CMS EXO-19-020

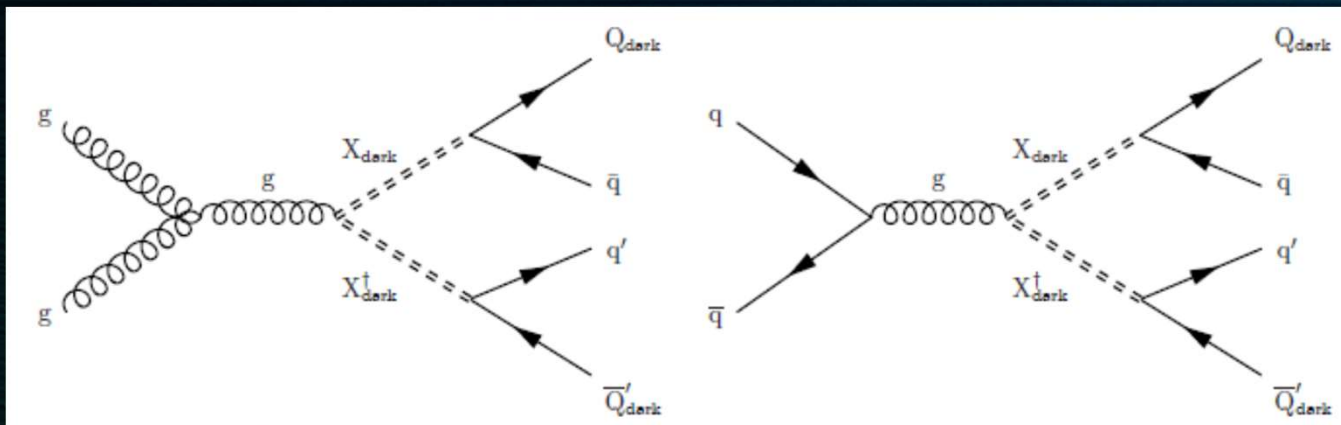




# LLP dark showers, LLP, emerging jets

CMS EXO-22-015;  
arXiv:2403.01556 [hep-ex]

HV dark QCD, scalar portal,  
dark meson LLP decays, b-quark FS

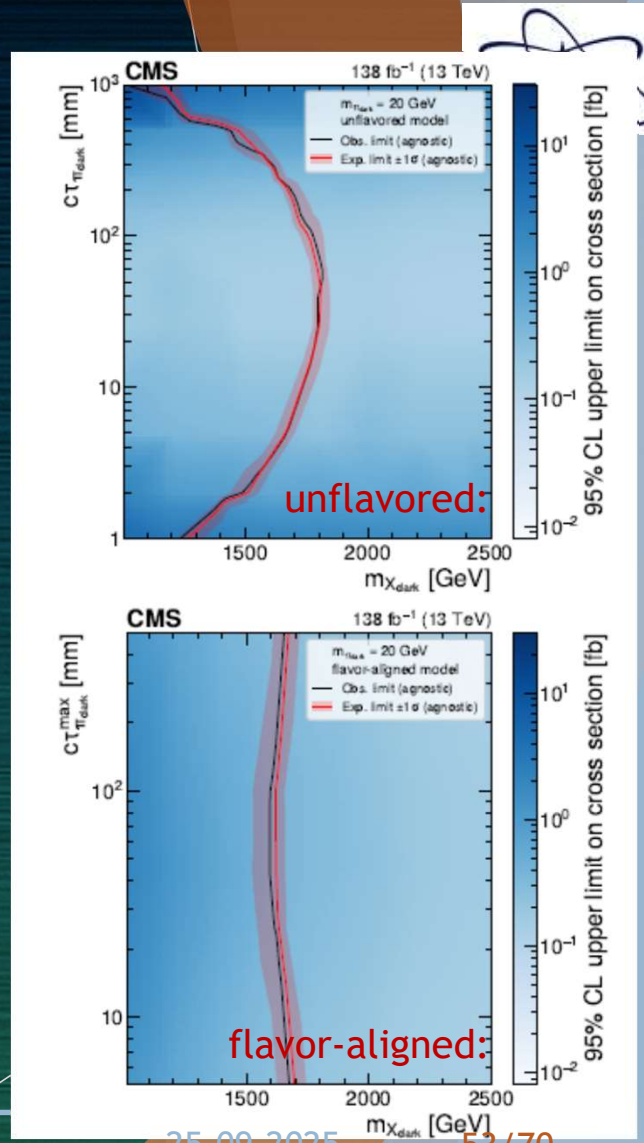


**unflavored:**

$$c\tau_{\pi_{\text{dark}}} = 80 \text{ mm} \left(\frac{1}{\kappa^4}\right) \left(\frac{2 \text{ GeV}}{f_{\pi_{\text{dark}}}}\right)^2 \left(\frac{100 \text{ MeV}}{m_d}\right)^2 \left(\frac{2 \text{ GeV}}{m_{\pi_{\text{dark}}}}\right) \left(\frac{m_{X_{\text{dark}}}}{1 \text{ TeV}}\right)^4$$

**flavor-aligned:**

$$c\tau_{\text{dark}}^{\alpha\beta} = \frac{8\pi m_{\Phi}^4}{N_c m_{\text{dark}} f_{\pi_{\text{dark}}}^2 |\kappa_{\alpha i} \kappa_{\beta j}^*|^2 (m_i^2 + m_j^2) \sqrt{\left(1 - \frac{(m_i + m_j)^2}{m_{\text{dark}}^2}\right) \left(1 - \frac{(m_i - m_j)^2}{m_{\text{dark}}^2}\right)}}$$





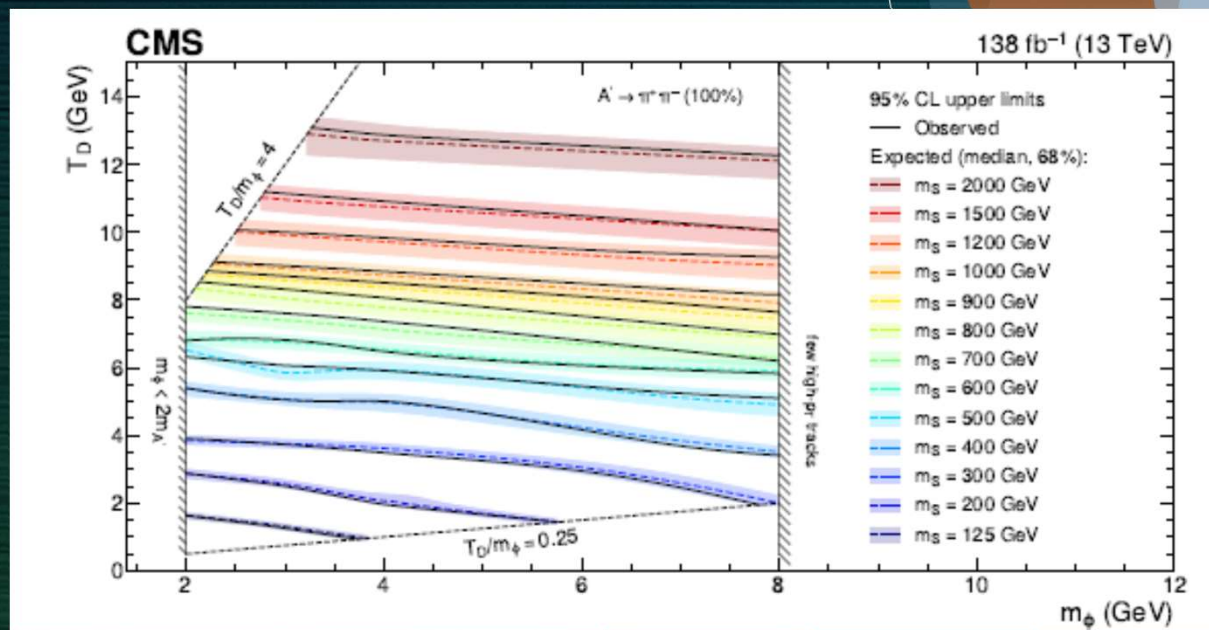
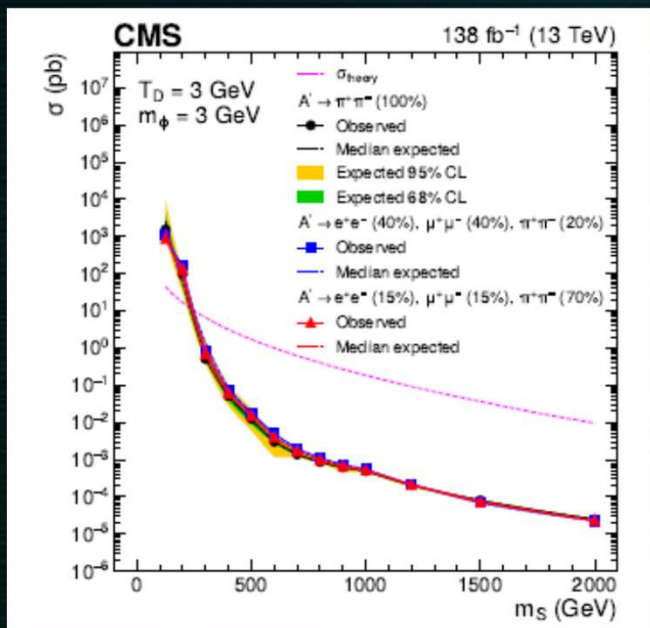
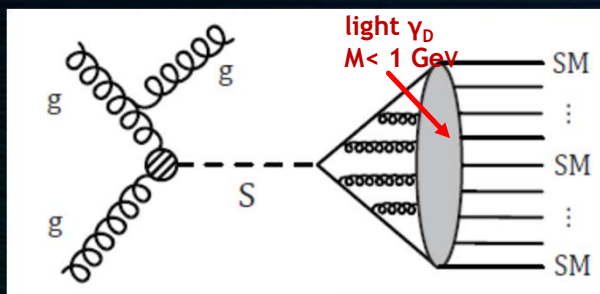
# Soft Unclustered Energy Patterns (SUEPs)



CMS EXO-23-002;  
arXiv:2403.05311 [hep-ex]

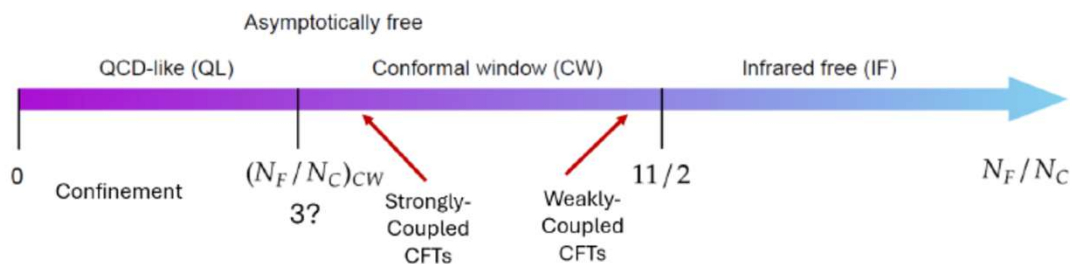
$$m_{qD} < \Lambda_D, \quad \Lambda_D \ll \sqrt{s}$$

- Scalar mediator  $S$ , quasi-conformal DS, dark mesons masses much smaller than  $m_S$ .  $S$  charged under both  $SU(3)$  and  $SU(3)_D$
- spherically symmetric FS distributions, high multiplicity of soft PS
- Boltzmann distr. for pseudoscalar  $p_T$ , depending on  $T_D$  ( $\Lambda_D$ ) and  $m_\phi$
- decay  $\phi \rightarrow \gamma_D \gamma_D \rightarrow SM$  FS trough  $\gamma$ - $\gamma_D$  mixing, prompt decays



# Showering in a dark QCD and SUEPs

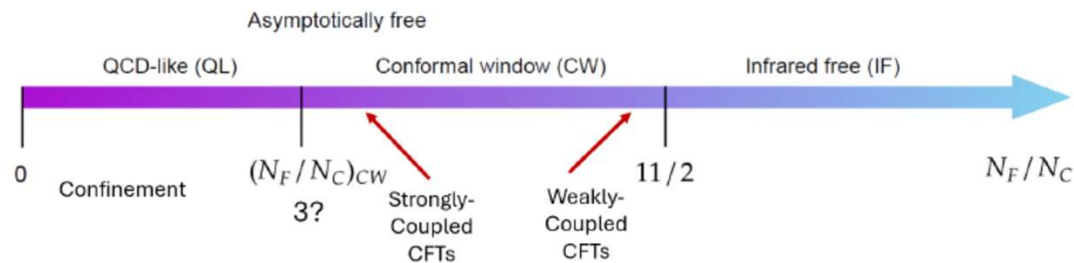
As we vary  $N_f^{light}/N_C$ , different behavior. For massless quarks:



- ▶ QCD-like: Ordinary shower with varying details;  $\Rightarrow$  confinement
- ▶ IF: Free gluons and quarks in IR; calculable at LL
- ▶ CW: Two-loop running balances one-loop running:
  - Leads to CFT; **Standard LL shower not always enough**
    - ▶ Narrow jets just below  $N_f/N_C = 5.5$
    - ▶ Fat jets for  $N_f/N_C \sim 3 - 4$  (Details?)
    - ▶ Not currently believed to give SUEP for any  $N_f/N_C$  (but not sure)

# Showering in a dark QCD and SUEPs

As we vary  $N_f^{light}/N_c$ , different behavior. For massless quarks:

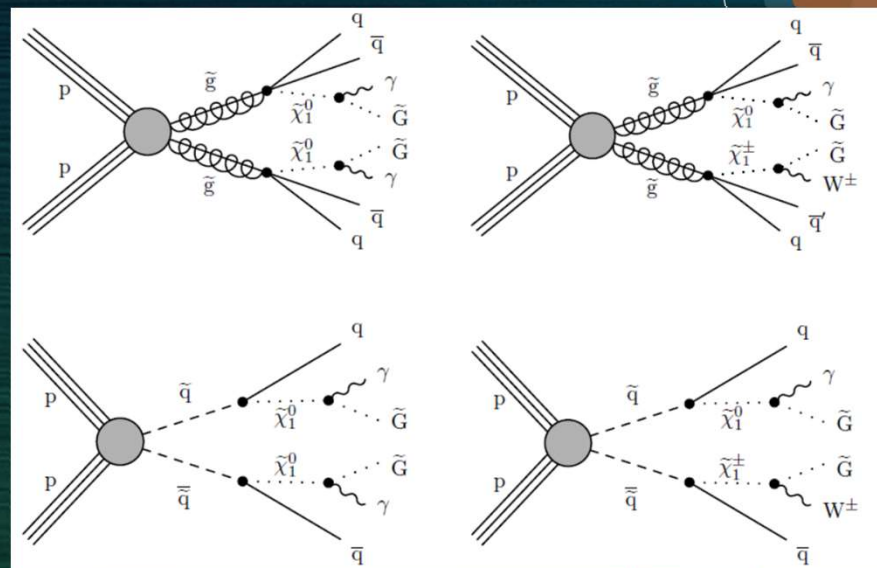
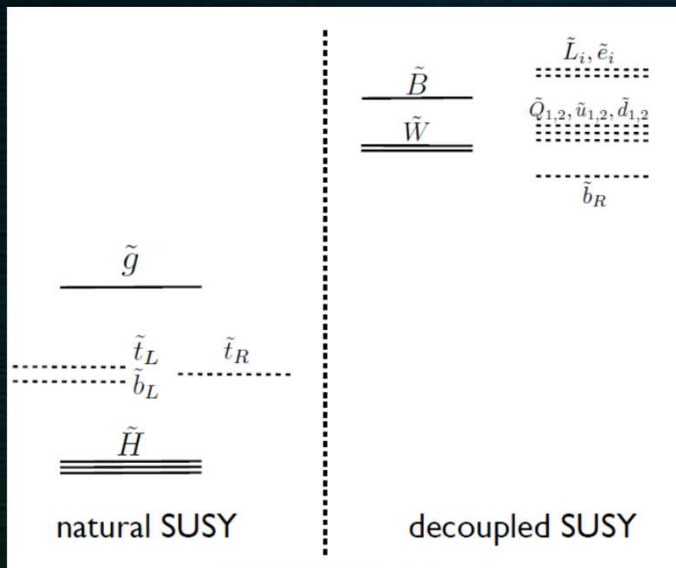


- ▶ QCD-like: Ordinary shower with varying details;  $\Rightarrow$  confinement

What creates SUEP? ~~Conformal Field Theory~~

- Only **extremely strongly-coupled CFTs** ( $\alpha_s N_c \gg 1$ ) make SUEP.
- Important: many QCD-like CFTs (and near-CFTs) have jets, not SUEP
  - ▶ Not currently believed to give SUEP for any  $N_f/N_c$  (but not sure)

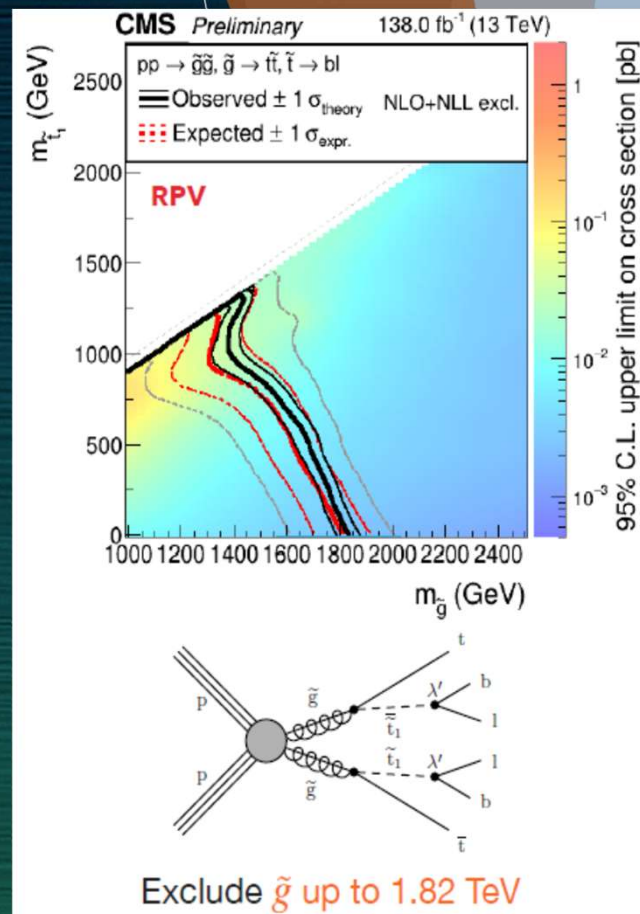
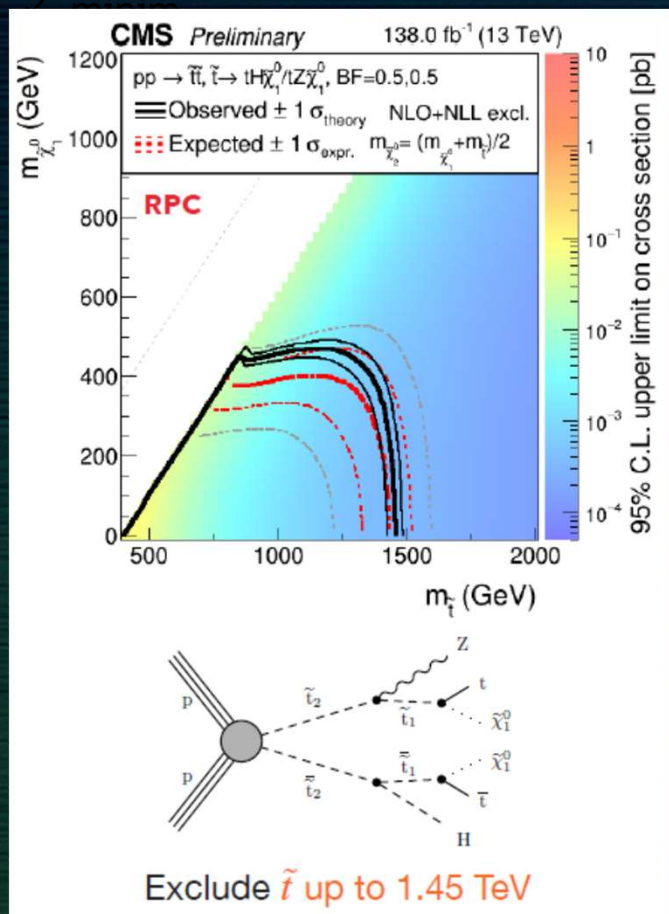
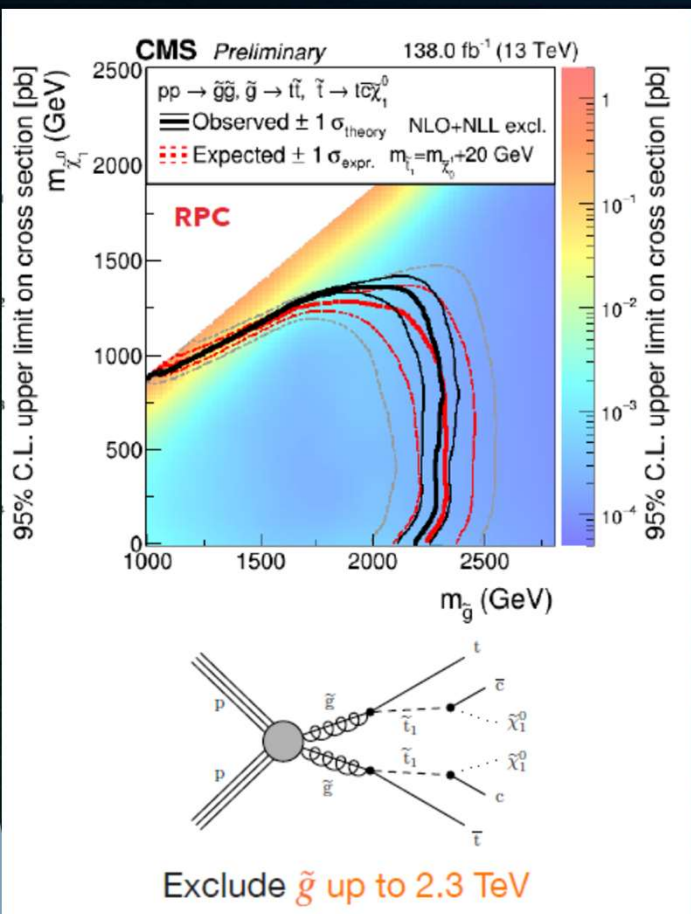
# Supersymmetry





# SUSY status

CMS SUS-23-014



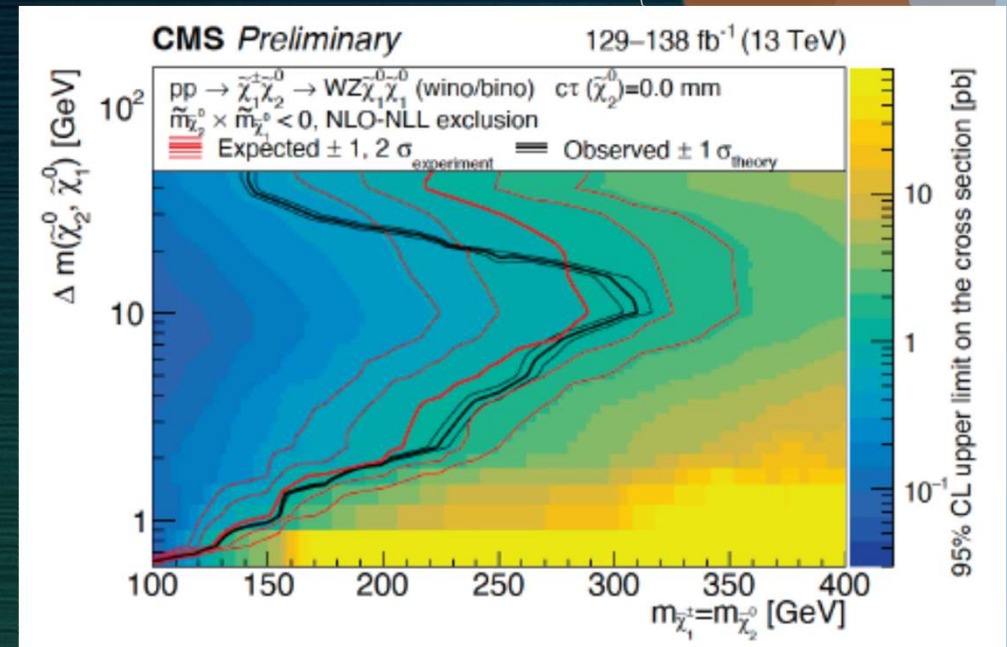
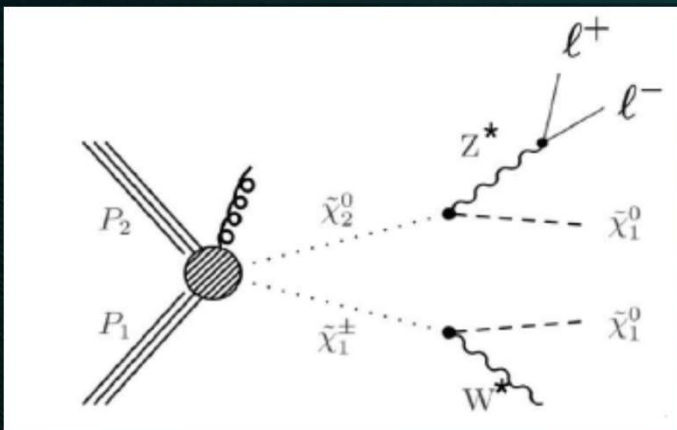
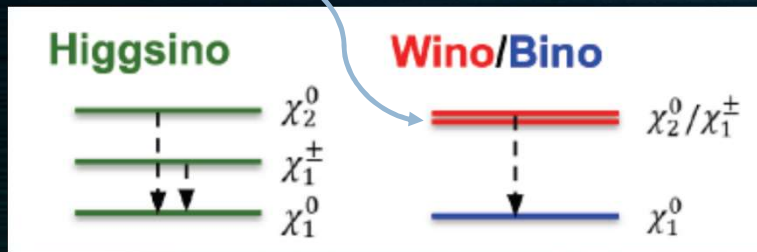


# SUSY status



CMS SUS-23-017

## Compressed electroweak



At  $\tilde{\chi}_2^0 = 100$  GeV, exclude  $\Delta m(\tilde{\chi}_{1,2}^0, \tilde{\chi}_1^\pm) \in [0.5, 25]$  GeV

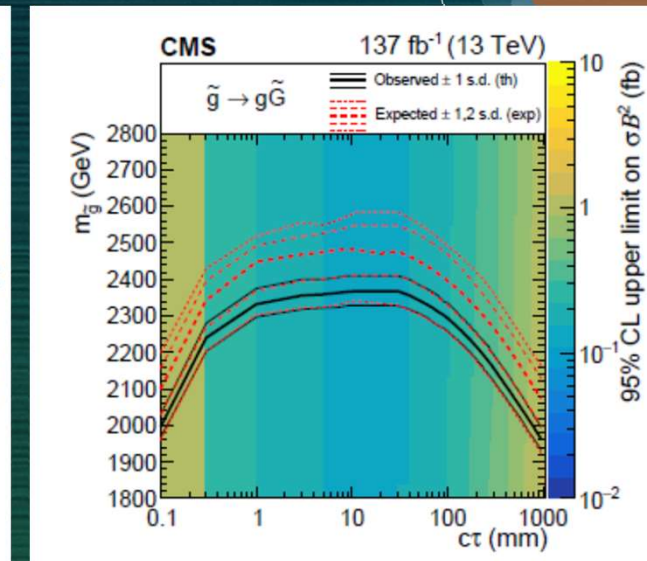
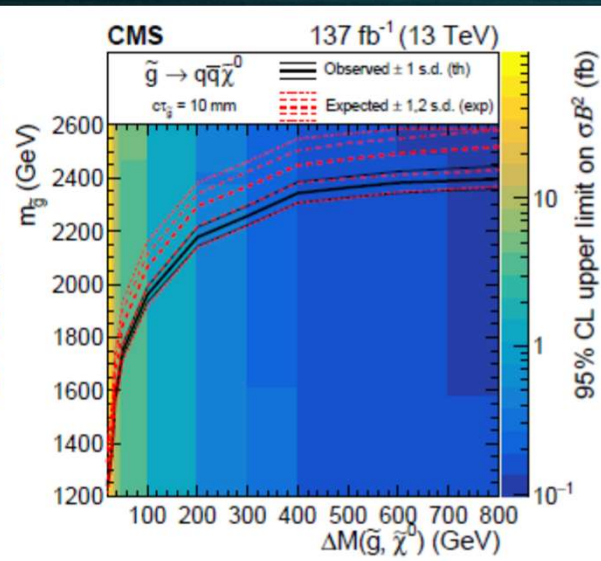
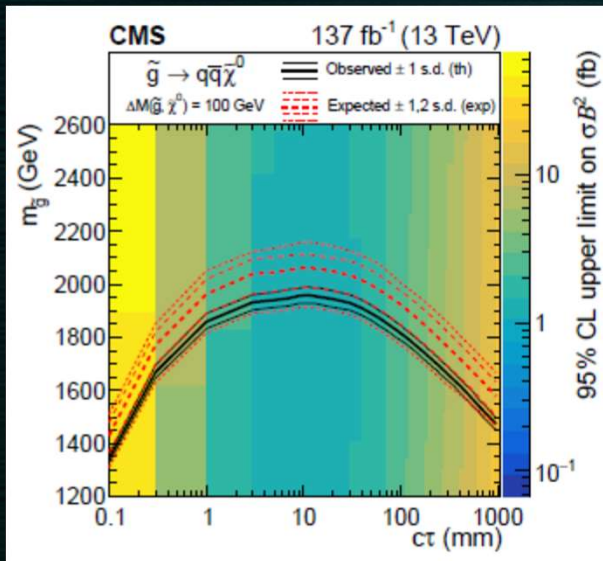
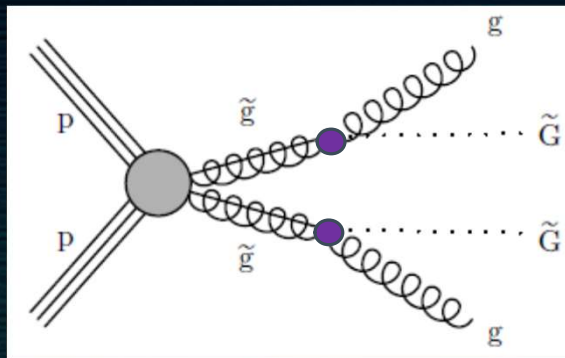
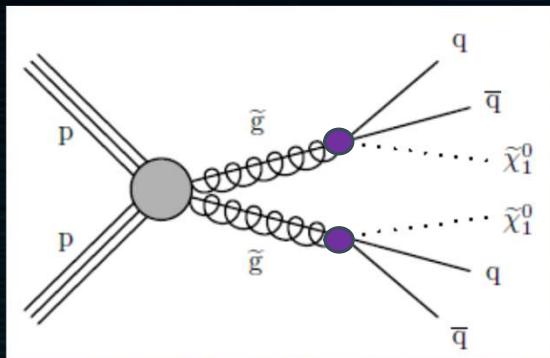


# Split/GMSB SUSY, LLP decays, displaced vertices plus MET



CMS EXO-22-020;  
arXiv:2402.15804 [hep-ex]

$$\tau \simeq 8 \left( \frac{m_{\text{SUSY}}}{10^6 \text{ TeV}} \right)^4 \left( \frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^5 \text{ s}$$





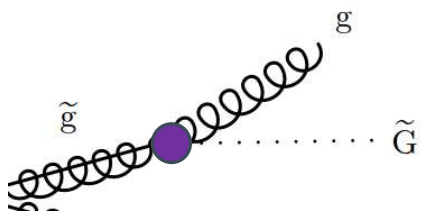
# GMSB, gravitino as DM in the MSSM sector

Gravitino mass

$$m_{3/2} = \frac{F}{k\sqrt{3}M_P} = \frac{1}{k} \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^2 2.4 \text{ eV} \quad \kappa = \frac{F}{F_0} < 1 \quad \Rightarrow \quad m_{3/2} \geq \text{keV}$$

“warm” DM - OK  
 no direct search - not OK

Gravitino effective action



$$\mathcal{L} = -\frac{1}{F_0} J_Q^\mu \partial_\mu \tilde{G} \quad \Rightarrow \quad \mathcal{L} = \frac{k}{F} \left[ (m_\psi^2 - m_\phi^2) \bar{\psi}_L \phi + \frac{M_\lambda}{4\sqrt{2}} \bar{\lambda}^a \sigma^{\nu\rho} F_{\nu\rho}^a \right] \tilde{G} + \text{h.c.}$$

$$\partial_\mu J_Q^\mu = -F_0 \gamma^\mu \partial_\mu \tilde{G}$$

1/F suppressed !

# GMSB, HS/MS stable states as DM candidates



S. Dimopoulos, G. F. Giudice, and A. Pomarol, arXiv:hep-ph/9607225

- **HS neutral scalar** (singlets under SM group, loop level only, accidental global symmetry prevents hidden scalar interaction with MSSM sector, stable state - no DD of DM)

$$\Omega_{B_\varphi} h^2 \gtrsim (m_{B_\varphi}/300 \text{ TeV})^2 \quad \text{cold unobservable DM (highly suppressed HS-MSSM interactions)}$$

superheavy DM

- **MS neutral scalar**

$$\langle \sigma(\varphi\varphi^* \rightarrow \text{anything})v \rangle = \frac{1}{m_\varphi^2} \left( A + \frac{B}{x} \right)$$

$$\Omega_\varphi h^2 = \frac{8.5 \times 10^{-5}}{\sqrt{g_*}} \left( \frac{m_\varphi}{\text{TeV}} \right)^2 \frac{x_f}{A + \frac{B}{2x_f}} \quad x_f = \frac{m_\varphi}{T_f}$$

$$M_{\Phi\tilde{\Phi}} \sim (\lambda M)^2 \pm (\lambda F)$$

$$F \ll M^2 \quad \text{or} \quad M^2 - F \sim 1$$

conditions for the stable lightest neutral scalar

$$\sum_{i=1}^n m_{\varphi_i}^2 \lesssim (5 \text{ TeV})^2$$

cold observable DM

overestimated DM density !!  
(but - the LMSS can decay into gravitino)

# RPV SUSY

R-parity is not a symmetry of the most general MSSM Lagrangian!!

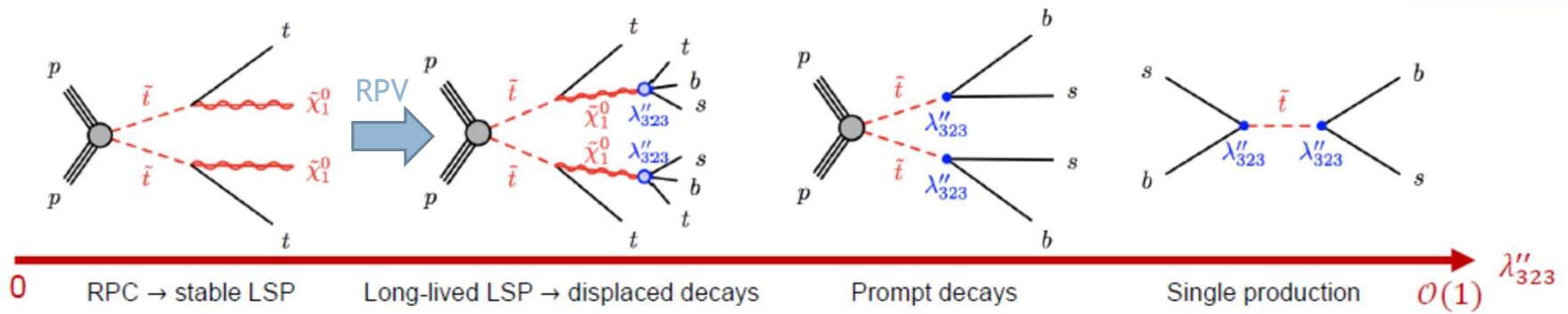
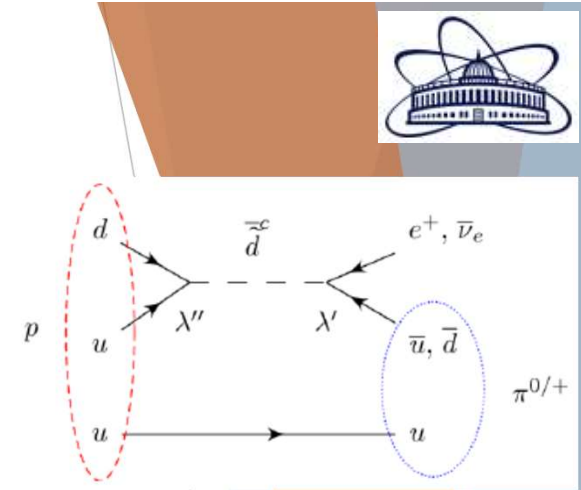
$$W_{RP} = \underbrace{\left[ \mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c \right]}_{\text{Lepton number violating}} + \underbrace{\left[ \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c \right]}_{\text{Baryon number violating}}$$

$$R = (-1)^{3(B-L)+2s}$$

too many free parameters!

RPV:

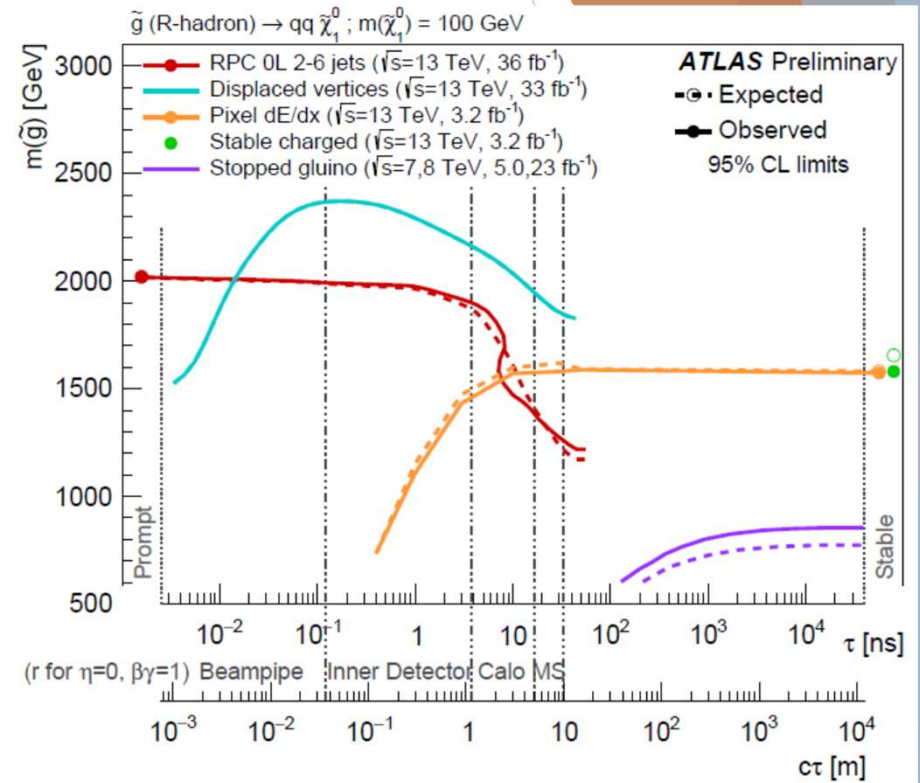
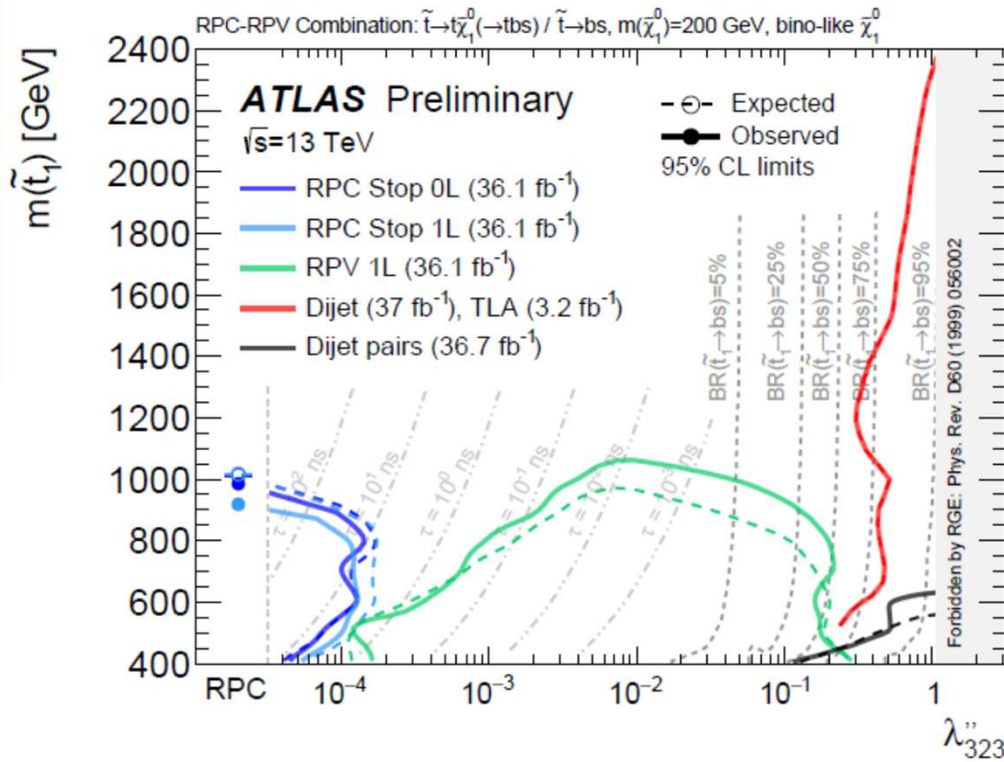
- L-violating terms - origin of light neutrino mass
- LSP can carry charge and decay to SM
- Various detector signatures depending on coupling strength (triple resonances, SS leptons, multijets..., LLP)
  - DM candidate - gravitino, axino !!



# RPV SUSY, ATLAS RUN2, prompt/LLP



ATLAS-CONF-2018-003

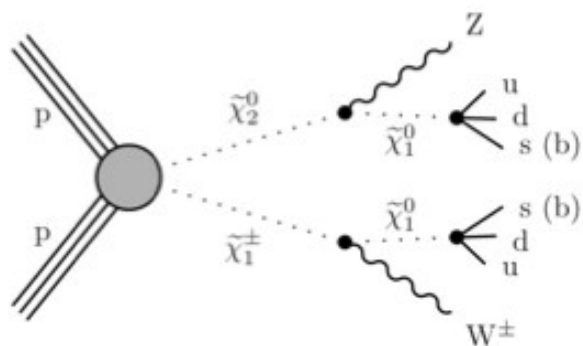




# RPV SUSY in three-lepton plus jets FS



CMS SUS-23-015



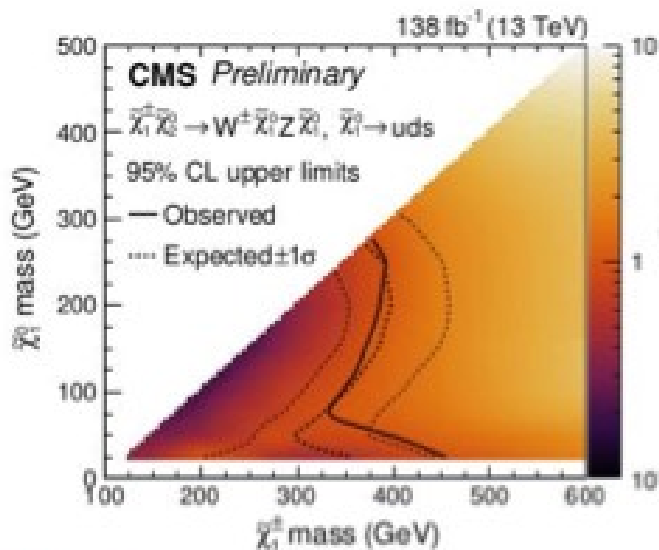
Degenerated by mass gaugino-like neutralino/chargino production with LSP (neutralino) RPV decay. FS with light/heavy quarks

$$\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0; \tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$$

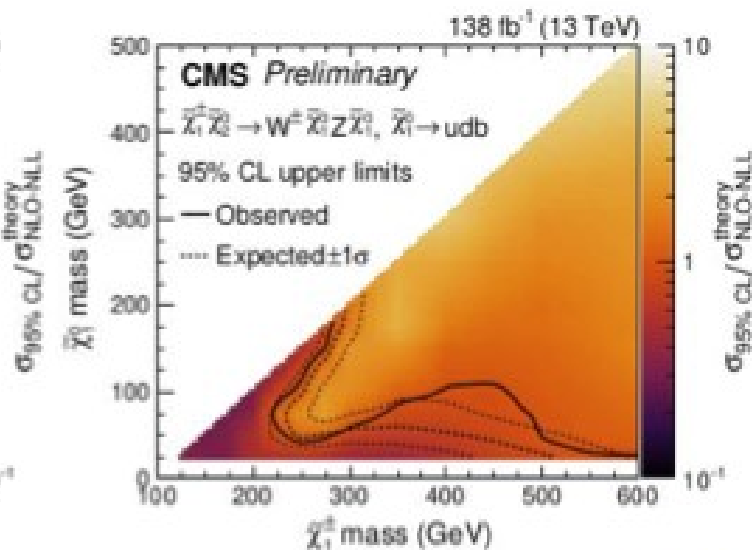
$$\tilde{\chi}_1^0 \rightarrow u \bar{d}$$

$$\tilde{\chi}_1^0 \rightarrow s \bar{d}$$

$$\tilde{\chi}_1^0 \rightarrow d \bar{u}$$



RPVq



RPVb

See also:

CMS-EXO-21-004;  
 arXiv:2402.02992  
 RPV SUSY in  
 pair-produced  
 multijet resonances



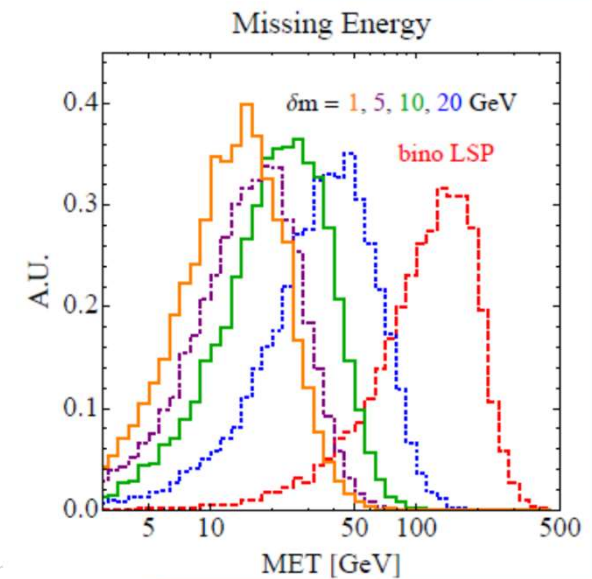
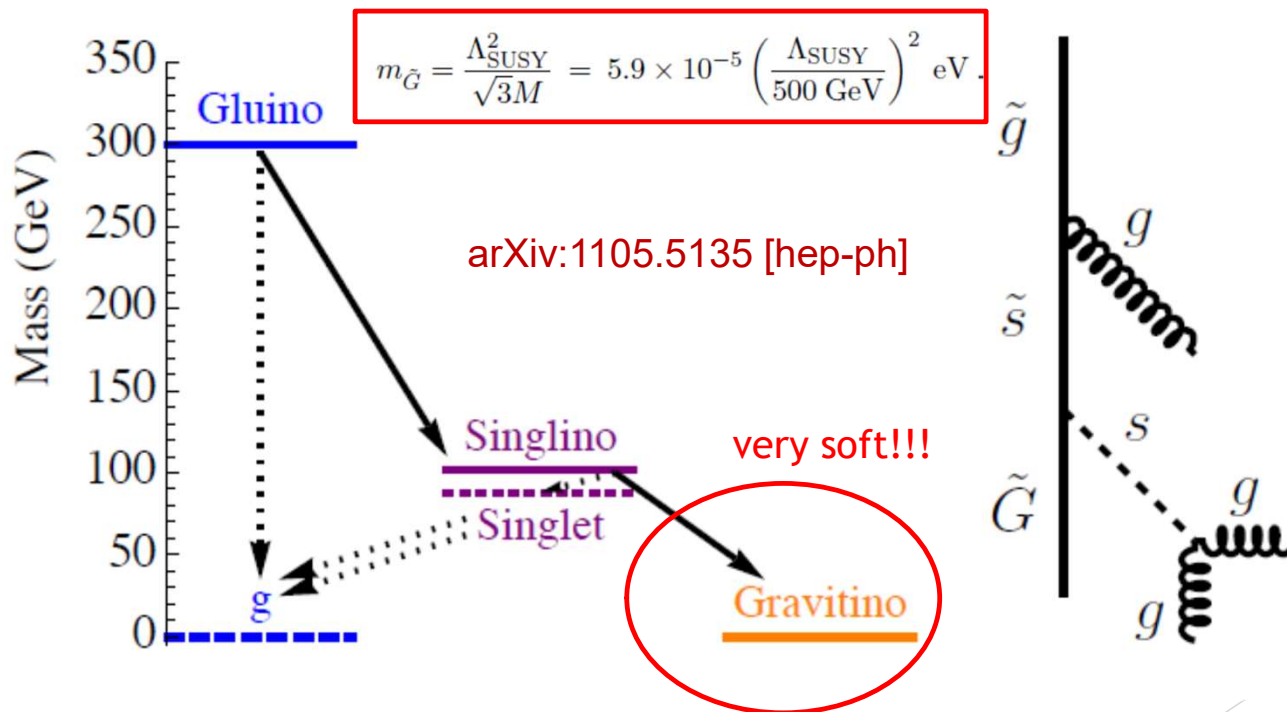
## Stealth SUSY basis

SUSY is natural, low-scale SUSY breaking, hidden sector with (at least) one chiral singlet superfield (R-odd singlino, R-even singlet). LSP - gravitino (GMSB),

NLSP decays to gravitino through a hidden sector.

HS states of order the EW scale, states approximately supersymmetric ( $F \ll M$ ) - closely degenerated by masses.

Suppression of large missing  $E_T$  at the end of decay chain (gravitino associated).

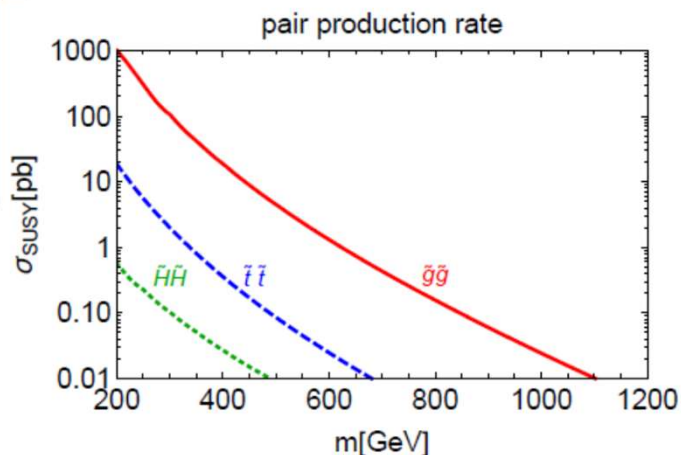




# Stealth SUSY simplified, prompt/LLP

JiJi Fan, Matthew Reece, Joshua T. Ruderman  
 arXiv:1105.5135 [hep-ph]  
 arXiv:1201.4875 [hep-ph]  
 arXiv:1512.05781 [hep-ph]

Field set: LOSP - gluino, stop, higgsino only  
 The lightest R-odd SUSY particle - gravitino/axino



NLSP neutralino decay width

$$\Gamma(\chi_1^0 \rightarrow \gamma \tilde{G}) = \frac{k^2 \kappa_\gamma m_{\chi_1^0}^5}{16\pi F^2} = k^2 \kappa_\gamma \left(\frac{m_{\chi_1^0}}{100 \text{ GeV}}\right)^5 \left(\frac{100 \text{ TeV}}{\sqrt{F}}\right)^4 2 \times 10^{-3} \text{ eV}$$

NLSP gluino decay width

$$\Gamma(\tilde{g} \rightarrow g \tilde{G}) = \frac{m_{\tilde{g}}^5}{48\pi M^2 m_{\tilde{G}}^2} = 1.1 \times 10^{-9} \text{ GeV} \left(\frac{m_{\tilde{g}}}{250 \text{ GeV}}\right)^5 \left(\frac{m_{\tilde{G}}}{1 \text{ eV}}\right)^{-2}$$

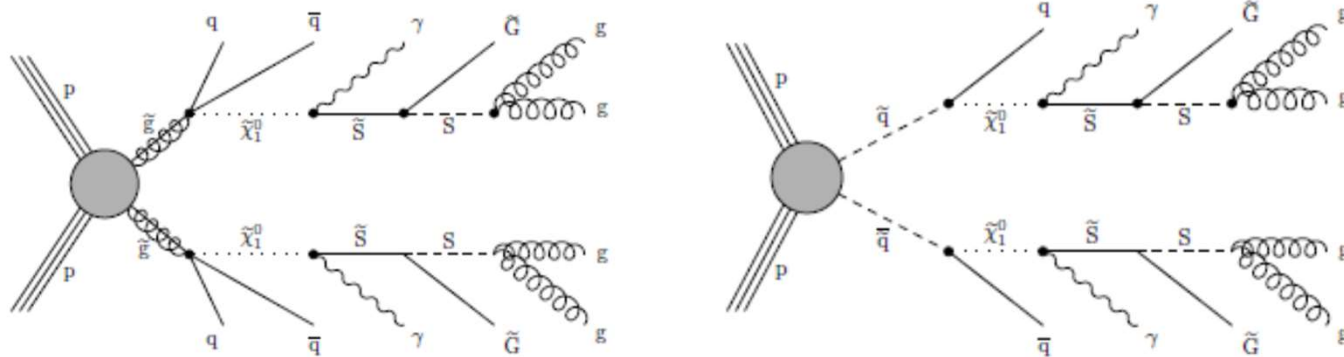
In dependence on a parameter space region NLSP decay can be prompt/LLP



# Gluino/stop PP, neutralino as NLSP, prompt, 2gamma + jets + low $E_T^{mis}$

$150 \text{ GeV} < M < m_{\tilde{g}}(m_{\tilde{q}}) - 100 \text{ GeV}$ ;  $m_{\tilde{q}}, m_{\tilde{g}}$ :  $1250 < M < 2350 \text{ GeV}$ ,  $1100 < M < 2000 \text{ GeV}$

SY $\bar{Y}$



CMS SUS-19-001;  
arXiv:2310.03154 [hepex];

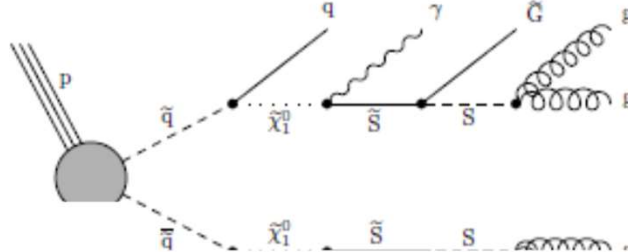
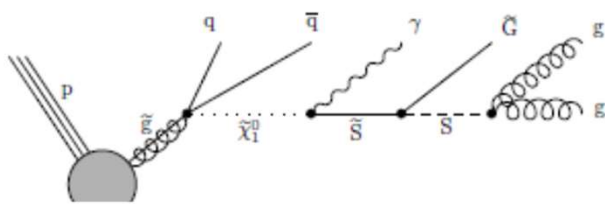
See also:  
CMS SUS-23-001  
for stealth /RPV SUSY  
with DNN



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