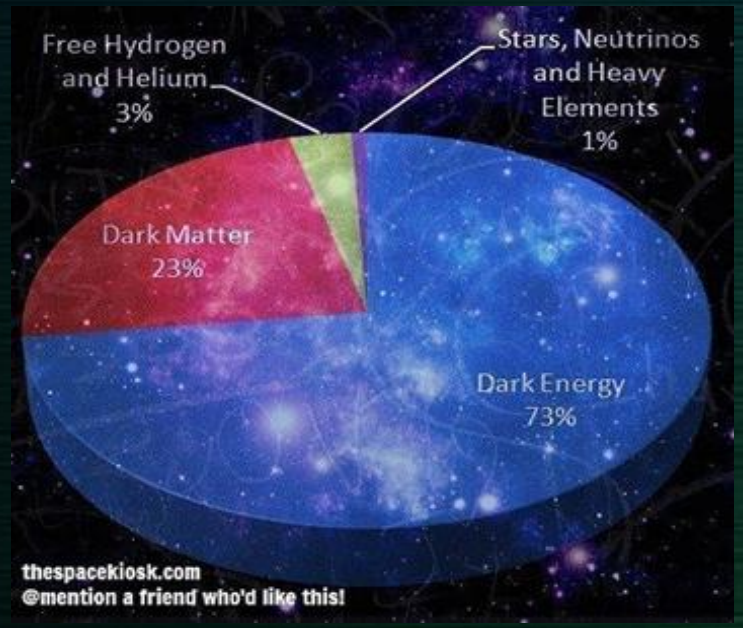
The XXV International Workshop-School
High Energy Physics and Quantum Field Theory

July 3, 2025, MSU, Moscow

Physics beyond the Standard Model at the LHC – is LLP signatures new or the last hope?



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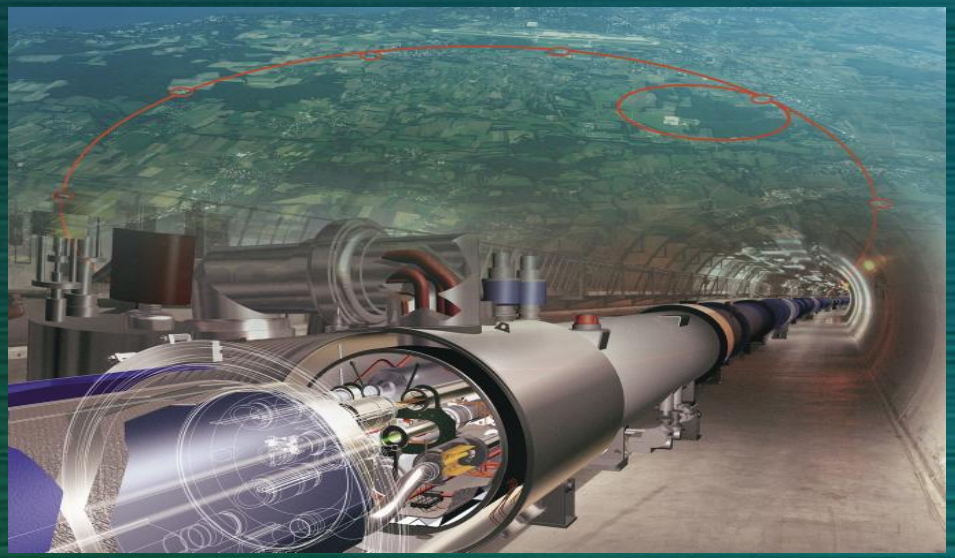


Search for a new physics ←→ frameworks ⟶ "full" theories vs "portals"

Dark matter example

"Full" theories:

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

superpartners, HNL, KK-modes etc.

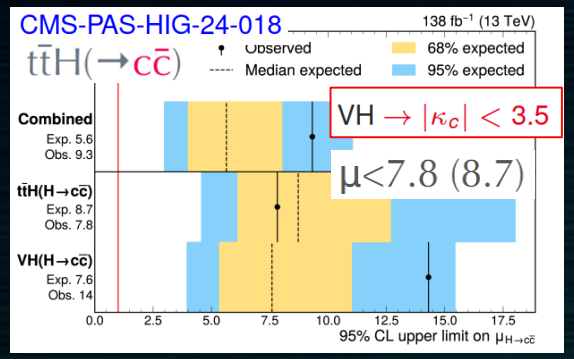
"Portals":

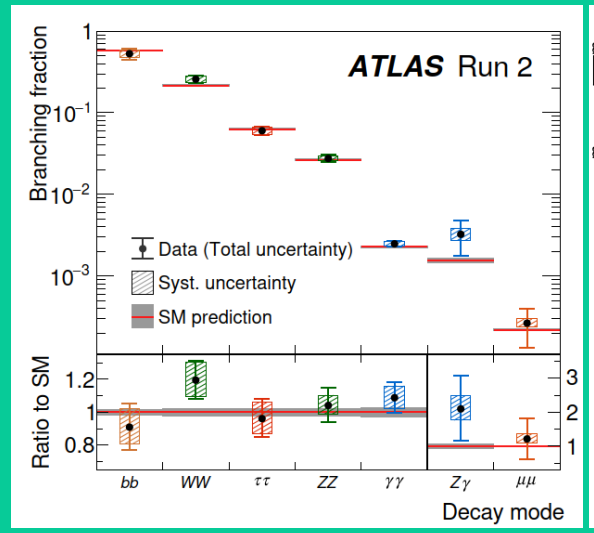
scalar/vector/fermionic

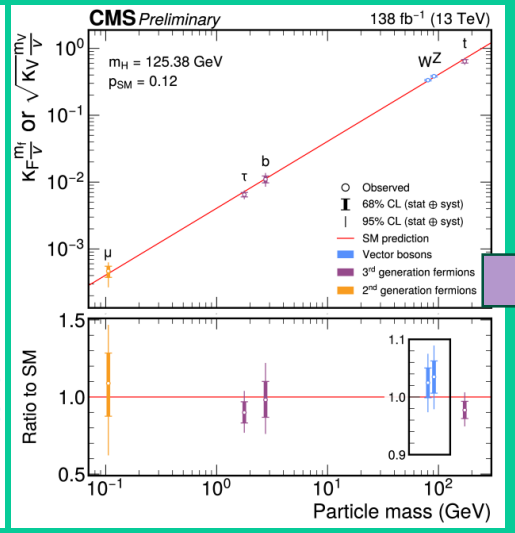
the h_{125} properties, h → invisible, flavor-violating processes, extra higgses/gauge bosons, new resonant/non-resonant deviations from the SM, ALPs, MET etc.

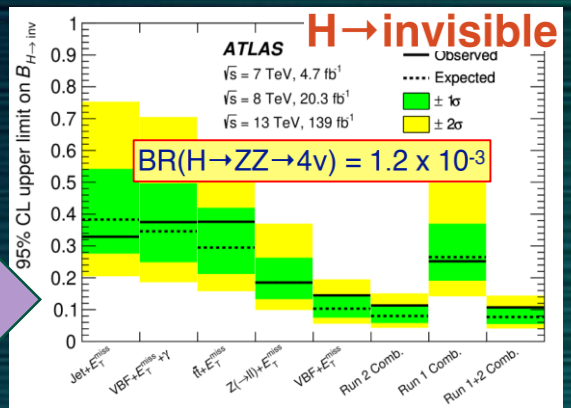
No NP signals – only limits on model parameter space !!

Higgs couplings to the 2nd generation + rare decays (LHCP 2025)









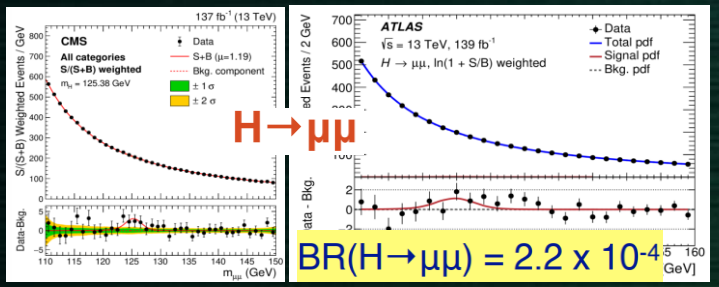
ATLAS: 0.107 (0.077) observed (expected) limit

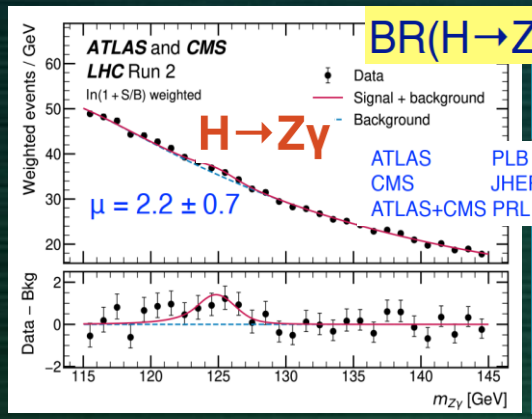
CMS: 0.15 (0.08) observed (expected) limit

ATLAS PLB 842 (2023) 137963
CMS EPJC 83 (2023) 933/PAS-HIG-21-018

ATLAS PLB 812 (2021) 135980 CMS JHEP 01 (2021) 148		ATLAS	CMS
Theoretical input	BR(H→μμ)	2.17±0.04×10⁻⁴	2.18±0.04×10⁻⁴
	mH	125.09 GeV	125.38 GeV
Measurement	Signal strength	1.2 ± 0.6	$1.19^{+0.44}_{-0.42}$
	Observed significance	2.0σ	3σ
	Expected significance	1.7σ	2.5σ

0.59 (0.85) < κμ < 1.50 (1.29) at 95% (68%) CL





BR(H→Zγ) = 1.6 x 10⁻³

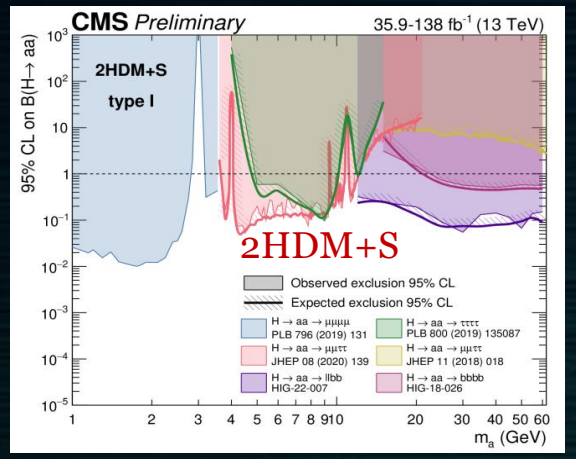
ATLAS PLB 809 (2020) 135754
CMS JHEP 05 (2023) 233
ATLAS+CMS PRL 132 (2024) 021803

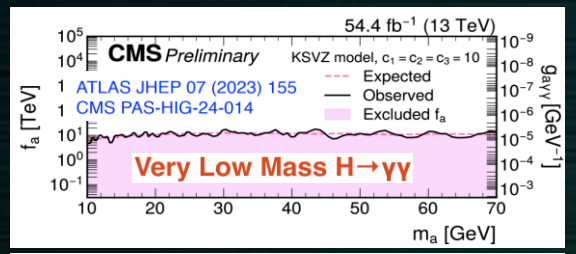
		ATLAS	CMS
Theoretical input	BR(H→Zγ)	1.54±0.09×10⁻³	1.567±0.09×10⁻³
	mH	125.09 GeV	125.38 GeV
Measurement	Signal strength	$2.0^{+1.0}_{-0.9}$	$2.4^{+0.9}_{-0.9}$
	Observed significance	2.2σ	2.7σ
	Expected significance	1.2σ	1.2σ
	95% CL obs(esp) limit	3.6 (1.7)	4.1 (1.8)
	σ(pp→H)×BR(H→Zγ)	305 fb (95%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

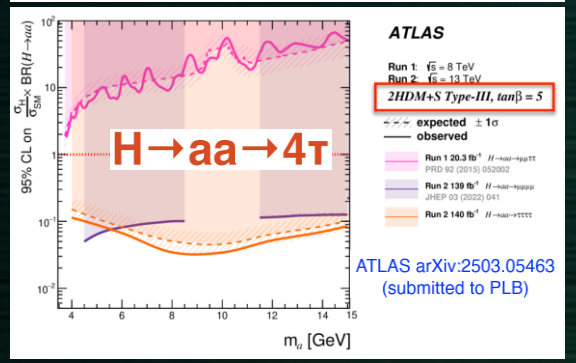
Extra higgses, PS light/heavy states (LHCP 2025)

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

→ decoupling limit?







Two complex scalar doublets, Φ_1 and Φ_2, 8 real d.o.f, after SSB –
5 physical scalar states:

- neutral CP-even h,H
- neutral CR-odd A
- charged H^+, H^-

2 non-zero VEVs: v_1 (Φ_1) and v_2 (Φ_2):

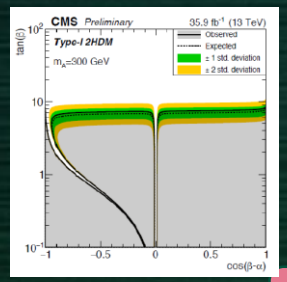
$$v_1^2+v_2^2 = v^2 \equiv (246\ GeV)^2,\ \frac{v_1}{v_2} \equiv tan\beta$$

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

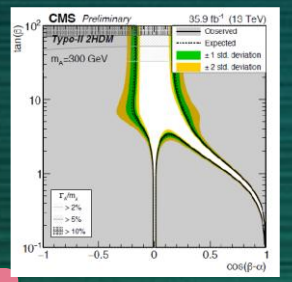
$$h_{SM} = \phi_1 cos\beta + \phi_2 sin\beta = h sin(\alpha-\beta) - H cos(\alpha-\beta)$$

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

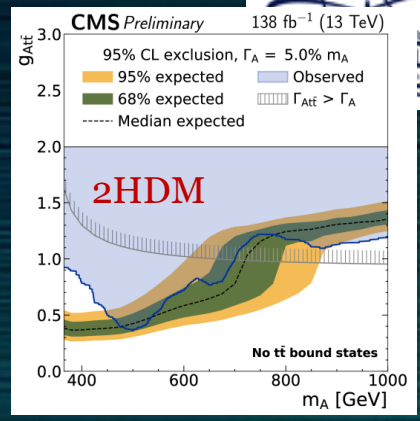
Most of the LHC studies, including for dark matter, are performed for this limit

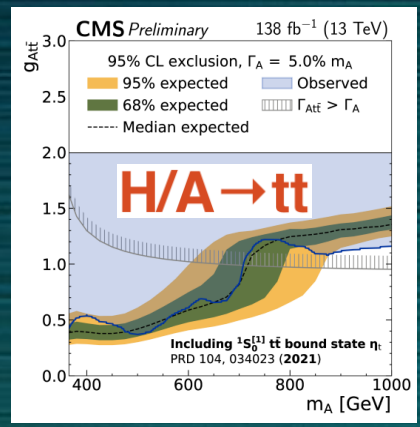


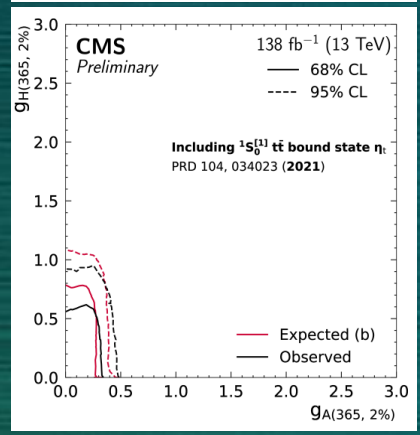
Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2



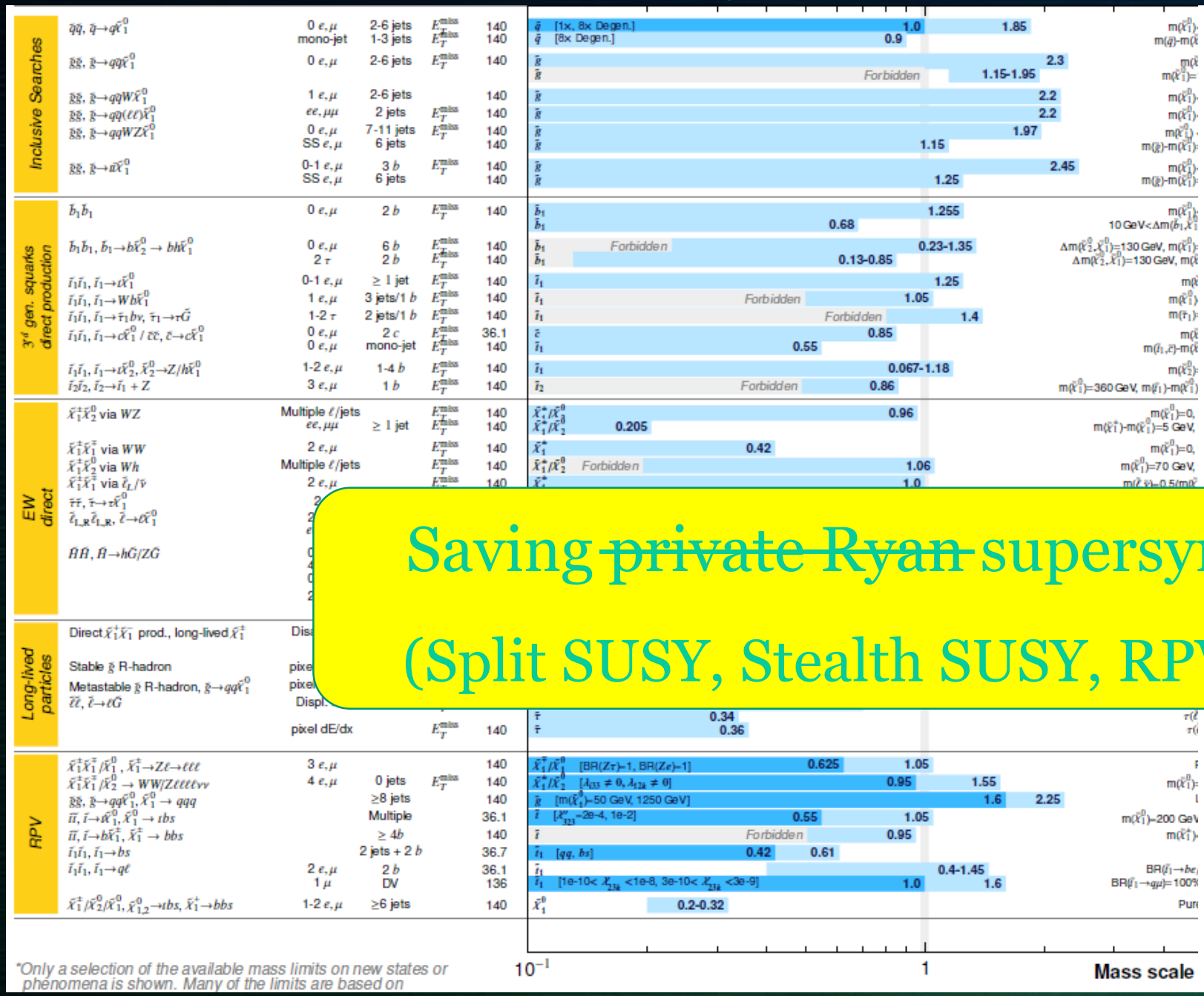
Still no signals from extra higgses

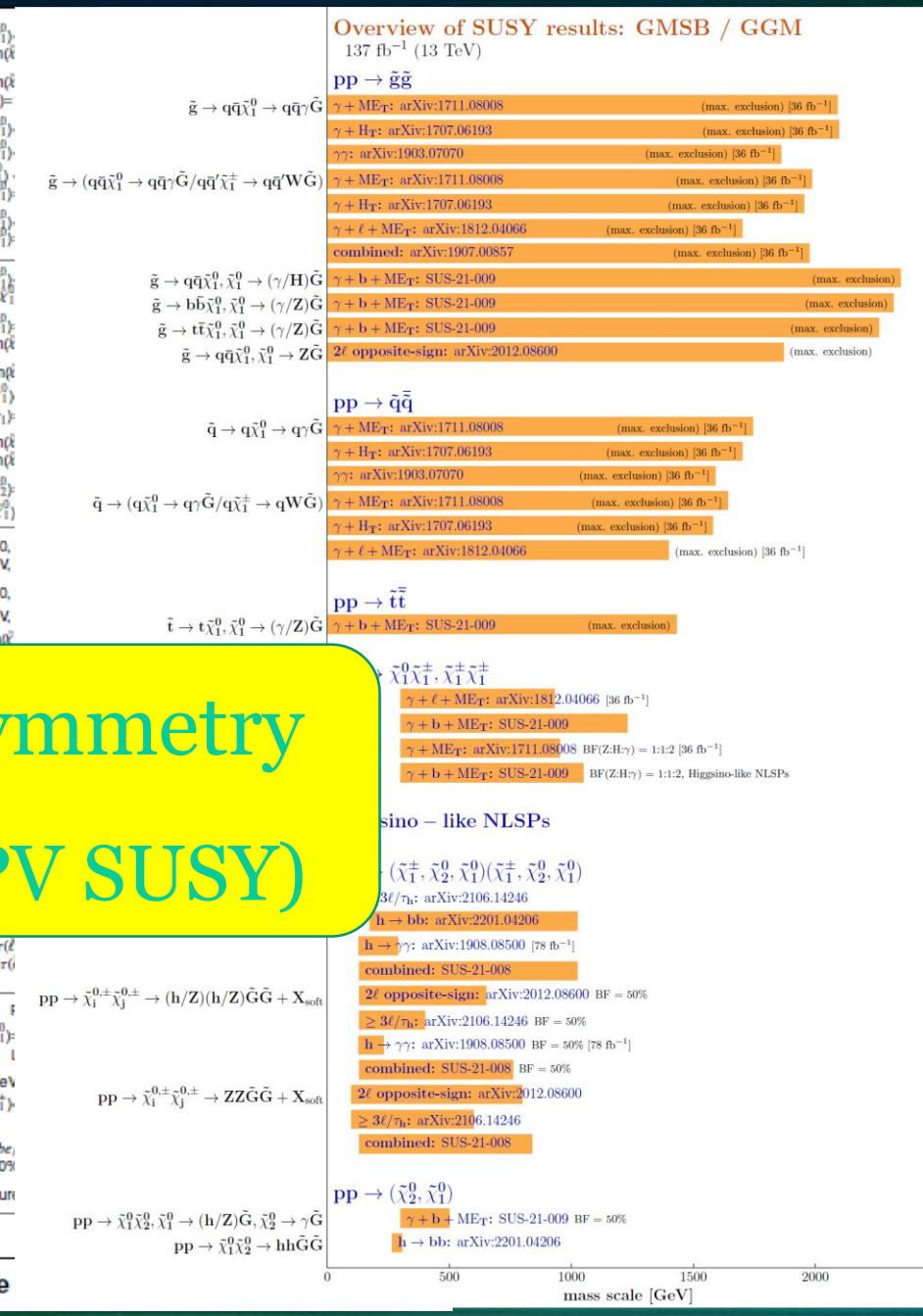






ATLAS/CMS SUSY Limits, 2023





Saving ~~private Ryan~~ supersymmetry

(Split SUSY, Stealth SUSY, RPV SUSY)

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on

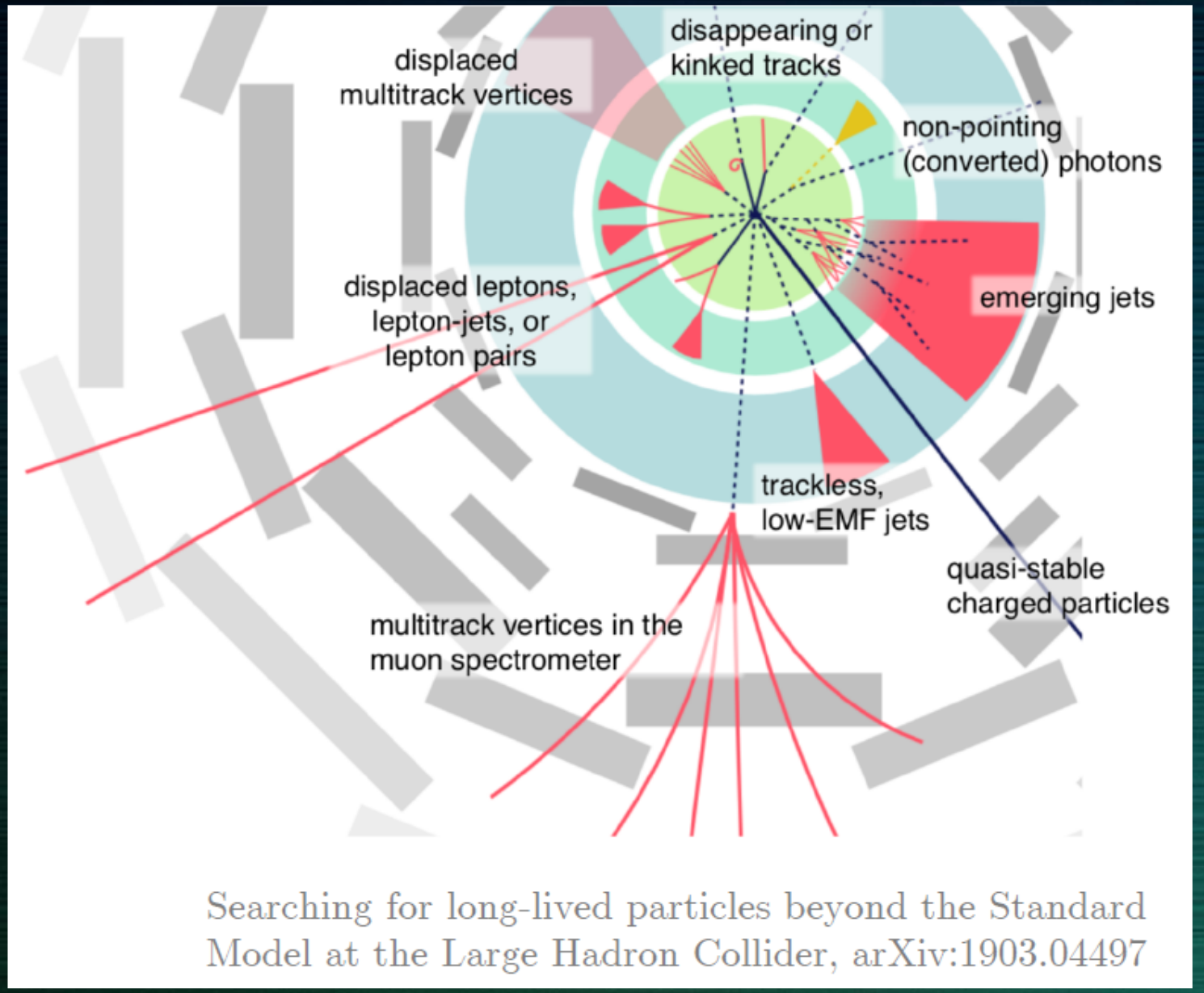
Long-Lived Particles at the LHC

LLP:
a proper lifetime $c\tau_0$ is greater than or comparable to the characteristic size of the (sub)detectors

✓ small $c\tau_0$ that comparable to the inner tracker size, no displaced tracks → "standard" prompt decay

✓ intermediate $c\tau_0$ → LLP (> 100 μm)

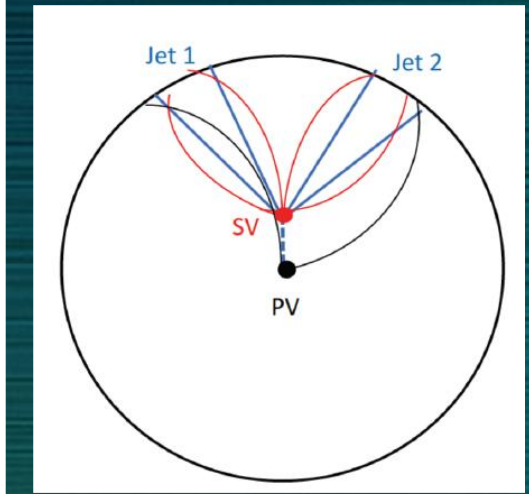
✓ very large/infinite large $c\tau_0$ → stable particles, "standard" MET signatures

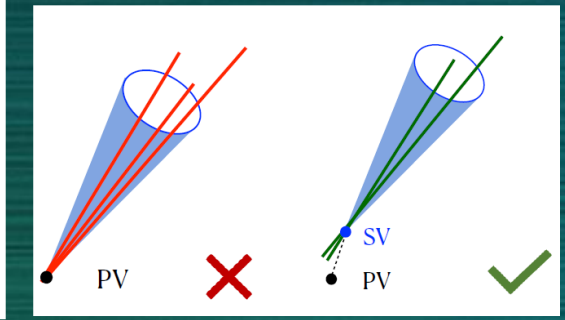


Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

LLP White Paper: arXiv:1903.04497

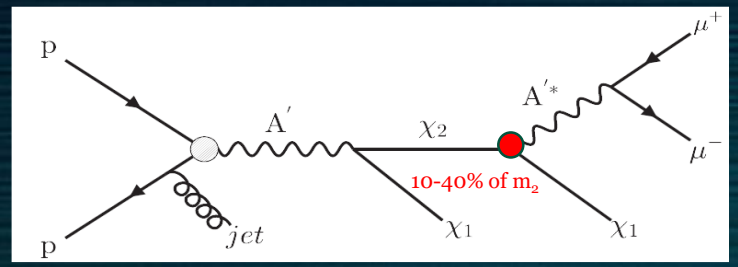
LLP theory motivations: arXiv:1806.07396

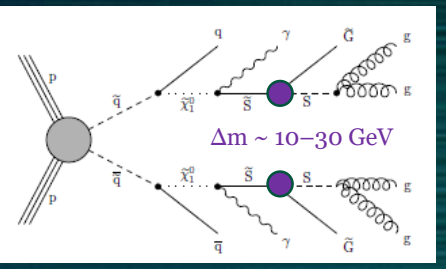




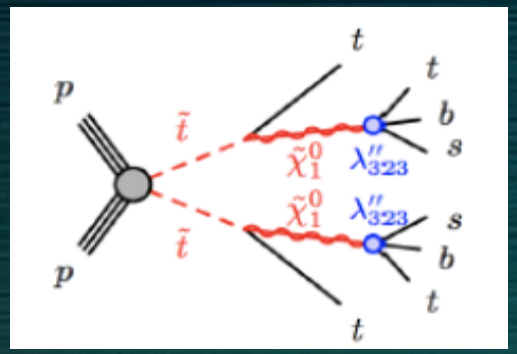
LLP – where are they from?

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

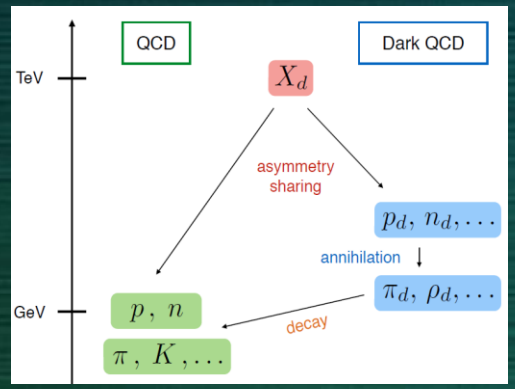




- ✓ Delayed decays because of small/very small coupling values (f. e. RPV SUSY)

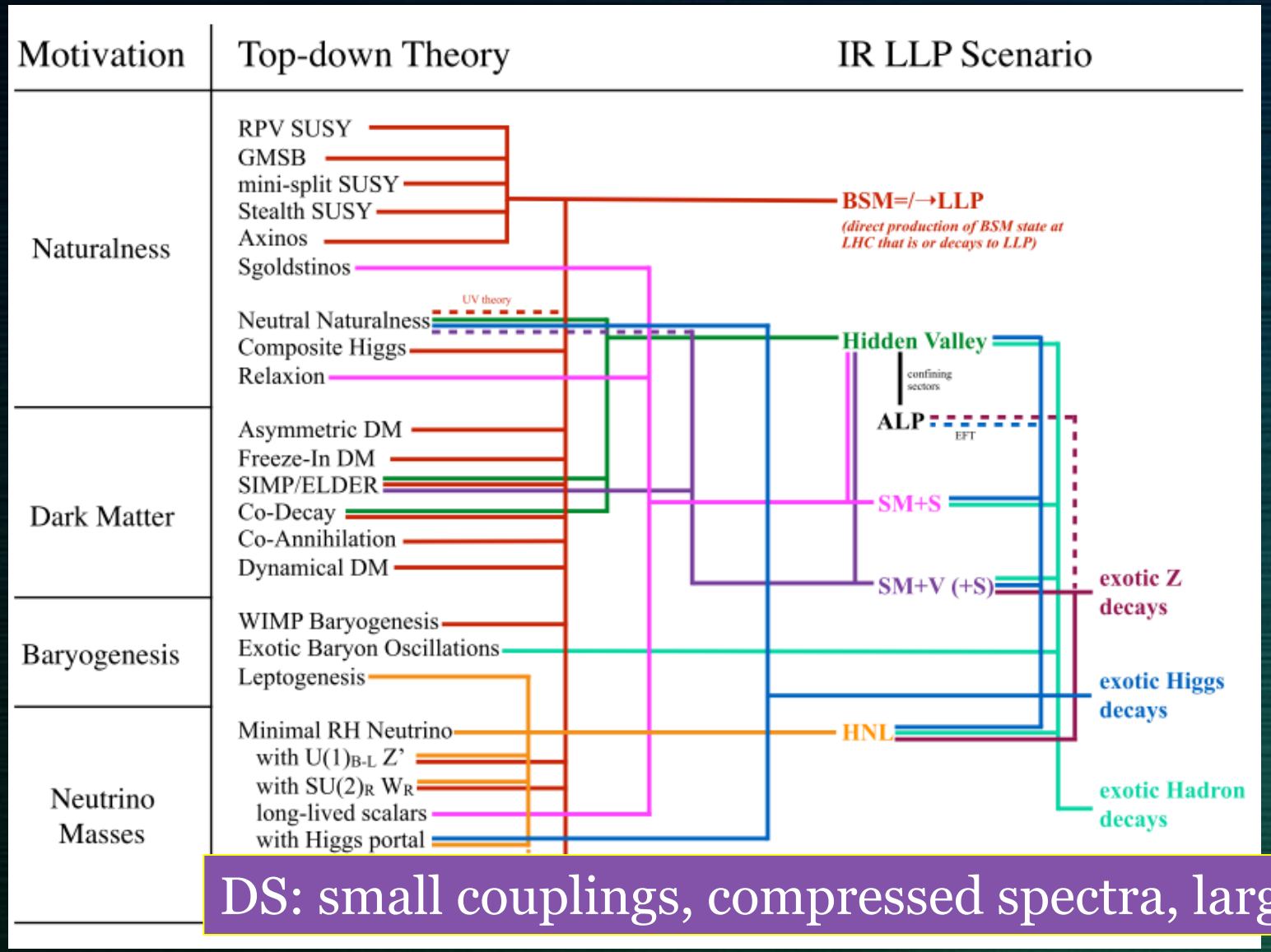


- ✓ Hidden valleys (dark QCD) concept: transitions between dark and visible sectors are suppressed by a high mediator mass scale → prompt/LLP decays



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

DS: small couplings, compressed spectra, large hierarchy → large cτ

GMSB, low scale SSB: a basis

SM+SP, ~~SUSY~~

messenger sector
$(\Phi_i, \overline{\Phi_i}, ..., i = 1,..N_f)$

$X, \qquad \langle X \rangle = M + \theta^2 F$

one(two)loop suppressed interactions with MS , soft SP masses, no flavor violation enhancement from soft terms, LSP – gravitino!

chiral scalar superfield(s), fund. rep. 5+anti-5 (also 10+anti-10) of SU(5) or 16+anti-16 of SO(10) for the GUT group

tree level interaction goldstino-MS

$$W = \lambda_{ij} \bar{\Phi}_i X \Phi_j$$

$$\delta\alpha_{GUT}^{-1} = -\frac{N}{2\pi} \ln \frac{M_{GUT}}{M} \qquad N \lesssim 150 / \ln \frac{M_{GUT}}{M}$$

Masses are depend on *F, M, N*

$$\mathcal{L}_{\text{soft}} = -\frac{1}{2}\left(\tilde{M}_\lambda \lambda_g \lambda_g + \text{h.c.}\right) - m_{\tilde{Q}}^2 Q^\dagger Q - \left(\sum_i A_i Q_i \partial_{Q_i} W(Q) + \text{h.c.}\right)$$

$$\tilde{M}_\lambda(t) = -\frac{1}{2}\frac{\partial \ln S(X,t)}{\partial \ln X}\bigg|_{X=M} \frac{F}{M},$$

$$m_{\tilde{Q}}^2(t) = -\frac{\partial^2 \ln Z_Q(X, X^\dagger, t)}{\partial \ln X \, \partial \ln X^\dagger}\bigg|_{X=M} \frac{FF^\dagger}{MM^\dagger},$$

$$A_i(t) = \frac{\partial \ln Z_{Q_i}(X, X^\dagger, t)}{\partial \ln X}\bigg|_{X=M} \frac{F}{M}.$$

physical scalar states : $\dfrac{(\Phi \pm \bar{\Phi})}{\sqrt{2}}$ ⇒ $M^2_{\Phi\bar{\Phi}} \sim (\lambda M)^2 \pm (\lambda F)$

M – SUSY mass scale, F – SSB energy scale !!

(limits:
F ~ M² or F << M²)

GMSB, gravitino as DM in the MSSM sector

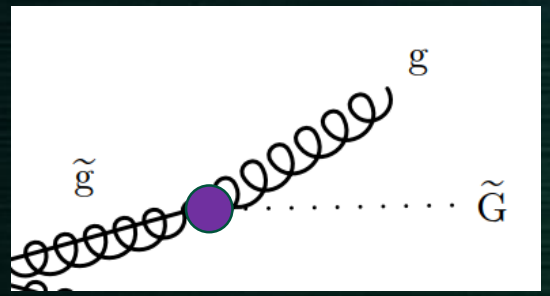
Gravitino mass

$$m_{3/2} = \frac{F}{k\sqrt{3}M_P} = \frac{1}{k}\left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^2 2.4\ \mathrm{eV}$$

$$\kappa = \frac{F}{F_0} < 1 \quad \Rightarrow \quad m_{3/2} \geq keV$$

- "warm" DM - OK
- no direct search – not OK

Gravitino effective action



$$\mathcal{L} = -\frac{1}{F_0} J_Q^\mu \partial_\mu \tilde{G}$$

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

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

1/F suppressed !

GMSB, HS/MS stable states as DM candidates

S. Dimopoulos, G. F. Guidice, 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)

$$\Omega_{B_\varphi} h^2 \gtrsim (m_{B_\varphi}/300\ \mathrm{TeV})^2$$

cold unobservable DM (highly suppressed HS-MSSM interactions)

superheavy DM

- **MS neutral scalar**

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

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

$$x_f = \frac{m_\varphi}{T_f}$$

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

$F << M^2$ or $M^2 - F \sim 1$

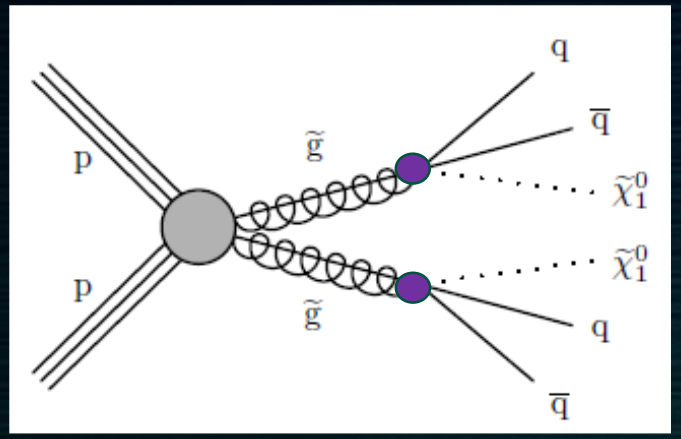
conditions for the stable lightest neutral scalar

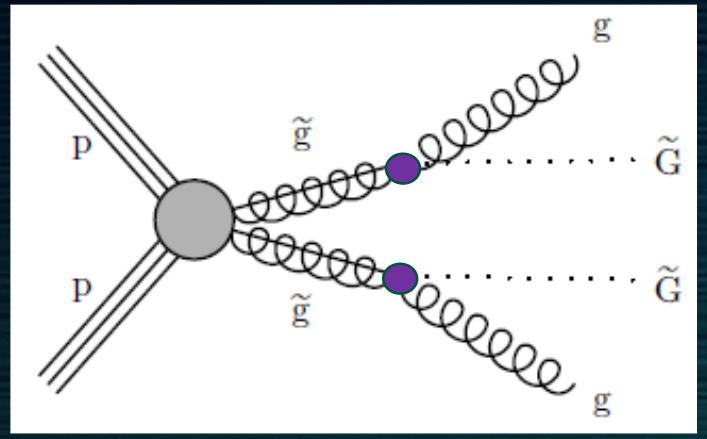
$$\sum_{i=1}^{n} m_{\varphi_i}^2 \lesssim (5\ \mathrm{TeV})^2$$

cold observable DM

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

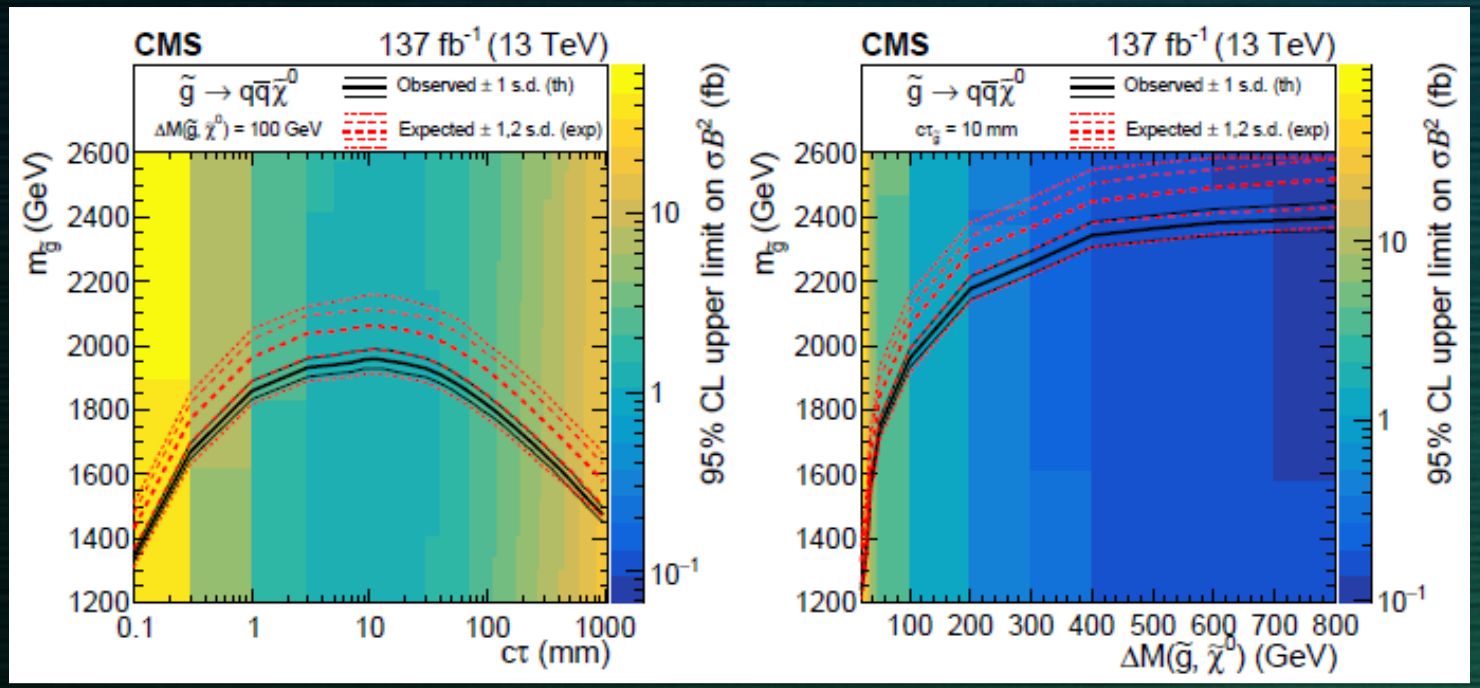
Split/GMSB SUSY, LLP decays, displaced vertices plus MET

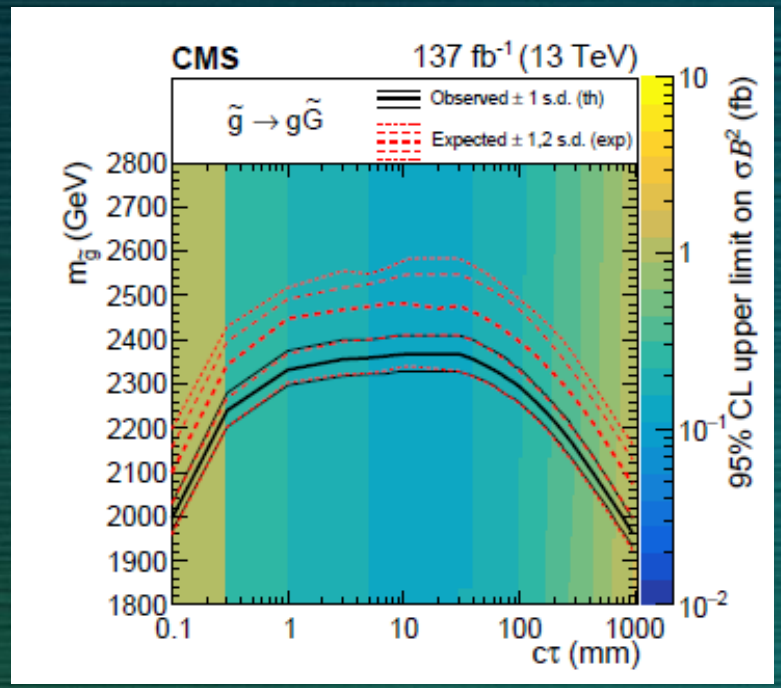




CMS EXO-22-020;
arXiv:2402.15804 [hep-ex]

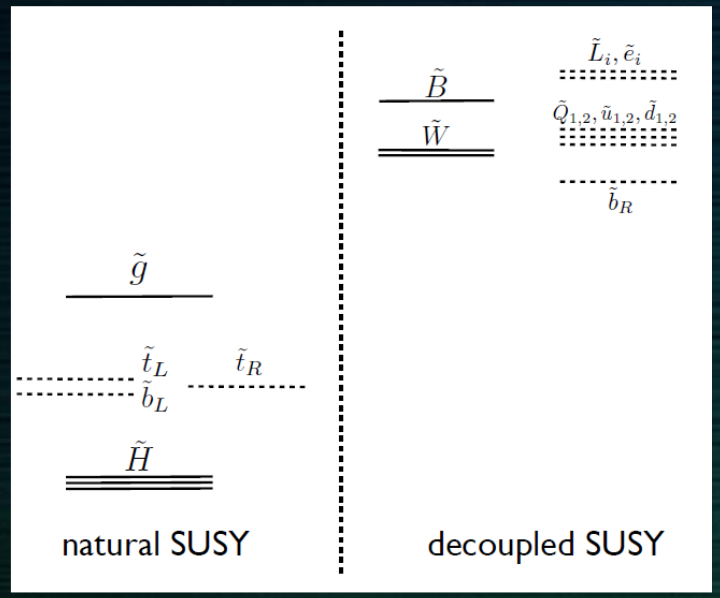
$$\tau \simeq 8 \left(\frac{m_{\mathrm{SUSY}}}{10^6\ \mathrm{TeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \mathrm{s}$$



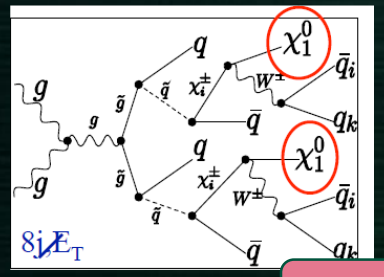


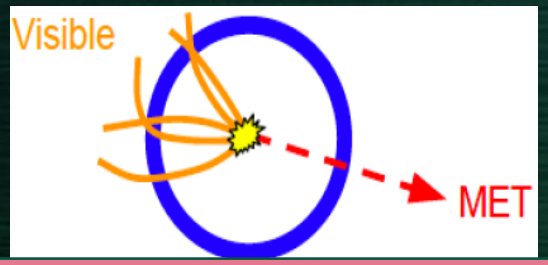
Saving SUSY : low(zero) p_T^{mis} signatures

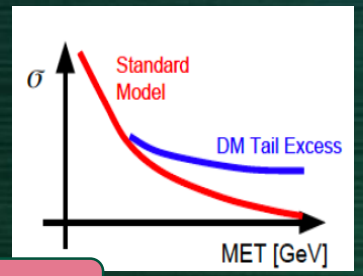
"natural" mass spectrum



typical expected signature: high p_T^{mis}







LHC search found no signal evidence

From prompt production to LLP:

1. Stealth SUSY

   JiJi Fan, Matthew Reece, Joshua T. Ruderman

   arXiv:1105.5135 [hep-ph]

   arXiv:1201.4875 [hep-ph]

   arXiv:1512.05781 [hep-ph]

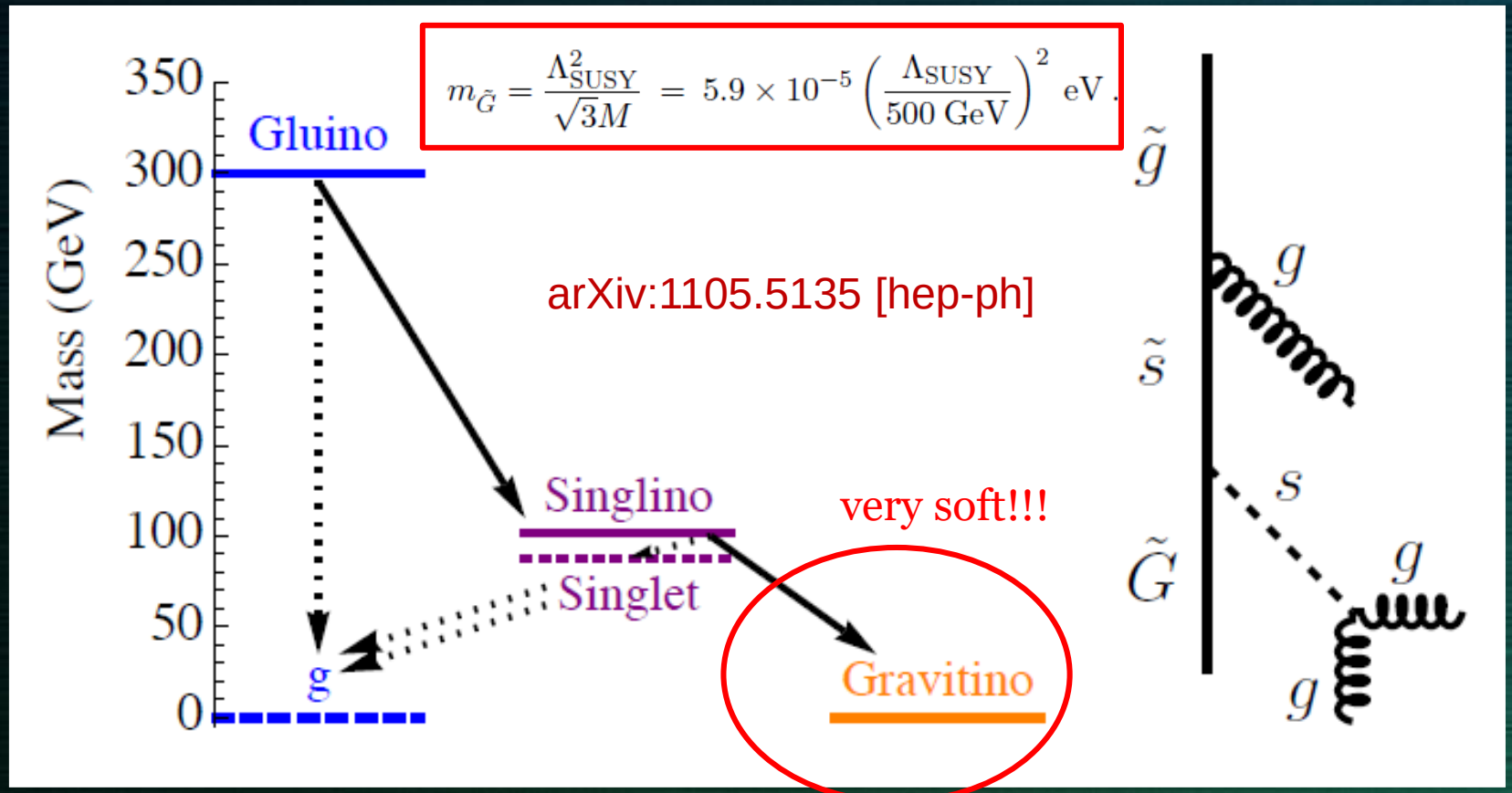
2. RPV SUSY

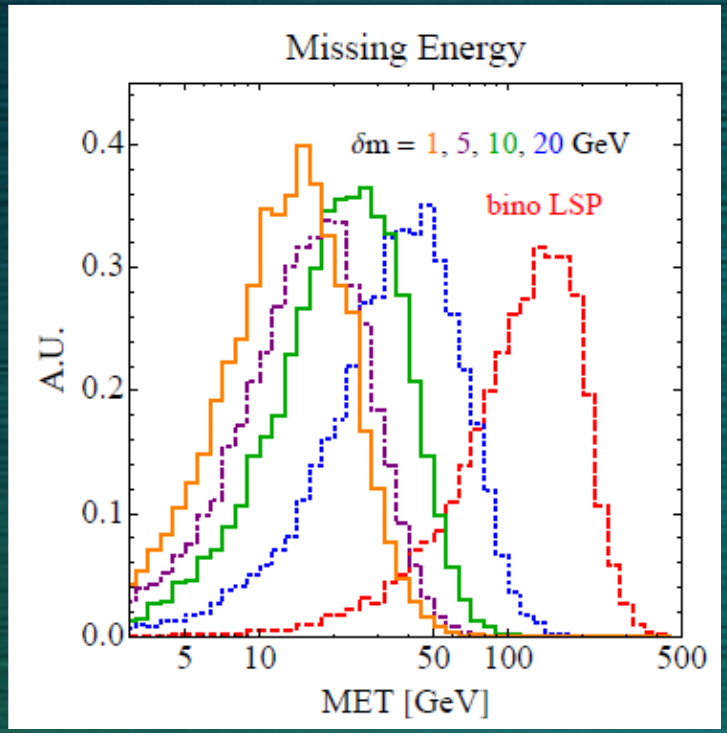
   Csaba Csaki, Yuval Grossman, and Ben Heidenreich

   arXiv:1111.1239 [hep-ph]

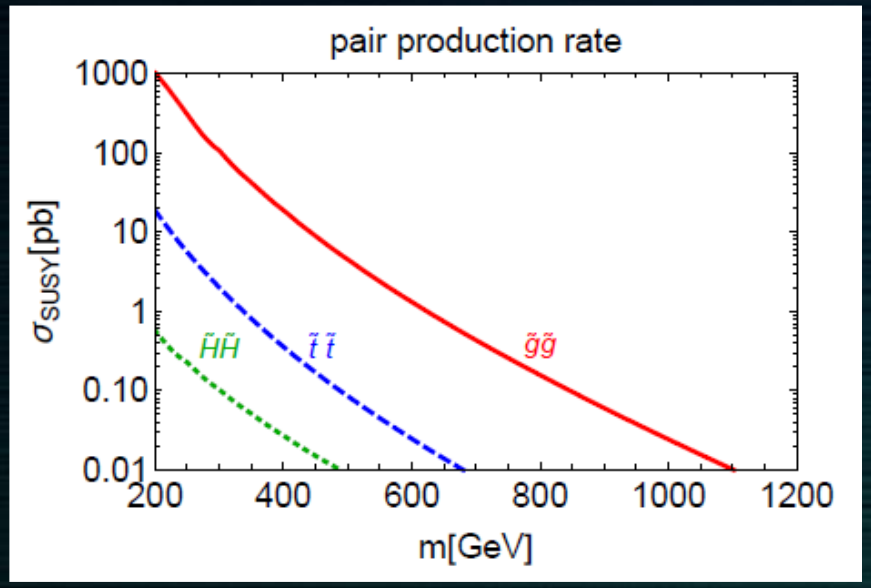
Stealth SUSY basis

SUSY is natural, low-scale SUSY breaking, hidden sector with (at least) one chiral singlet supefield (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 << M) – closely degenerated by masses.
Suppression of large missing E_T at the end of decay chain (gravitino assosiated).





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

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

NLSP gluino decay width

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

Typically LLP signatures in a wide parameter space region!! ($c\tau_0 > 8\,mm$ for F ~ 10 GeV)

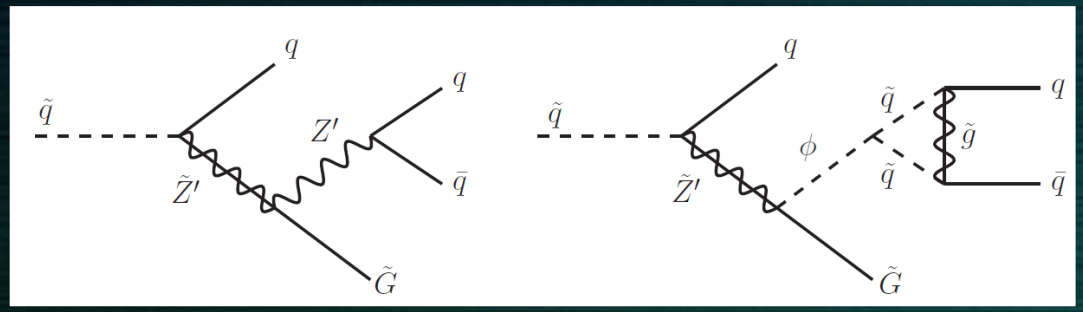
Portals between MSSM and stealth sector

- Neutral (uncharged under all MSSM gauge symmetries)

  - superpotential term λSO_{neut} (SH_uH_d /$SY\bar{Y}$ - exactly GMSB setup for the case F<<M)

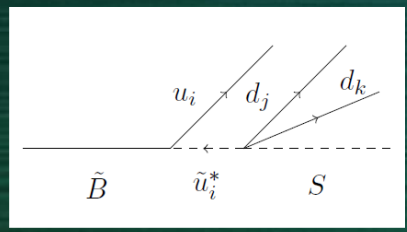
  - (pseudo)Goldstone fermion model – axino instead of gravitino

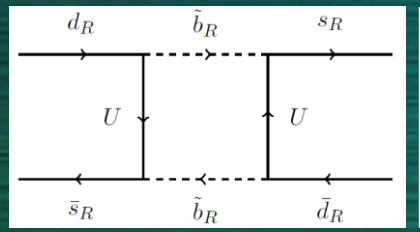
  - vector Z', kinetic mixing of U(1)

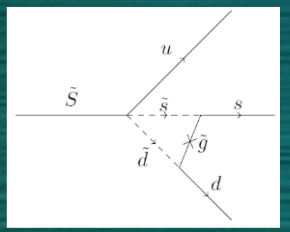


- Charged (not under gauge group because of large SUSY breaking mediation) – baryon/lepton number.
  RPV SUSY:

$$\mathcal{L}_{\text{eff}} \sim \lambda_{ijk} g' \frac{1}{M m_{\tilde{q}}^2} \tilde{B} u_i d_j d_k S + h.c.$$





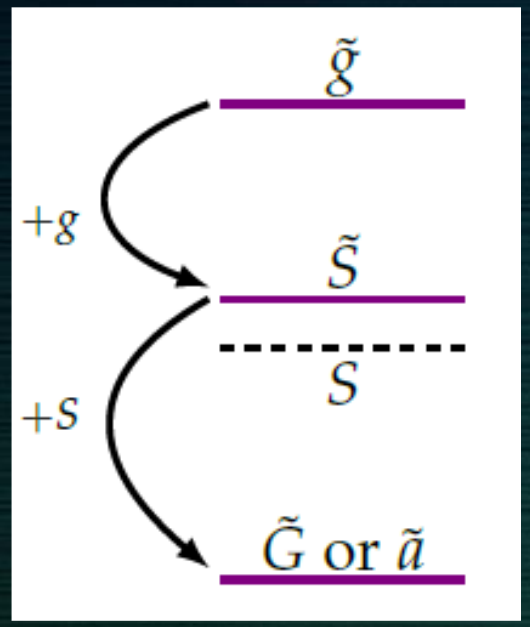


SLH_u, *Sudd* (the "baryon" portal), *SQLd*, *SLLE*

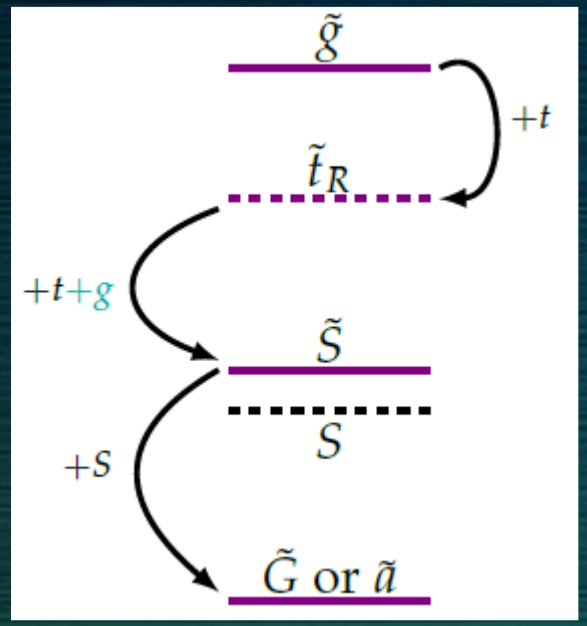
Stealth SUSY, gluino pair production, gluino/stop as NLSP

$SY\bar{Y}$: GMSB-like: messengers in $5, \bar{5}$ of SU(5), $m_S \sim 100$ GeV, $m_Y \sim$ TeV – supersymmetric soft masses

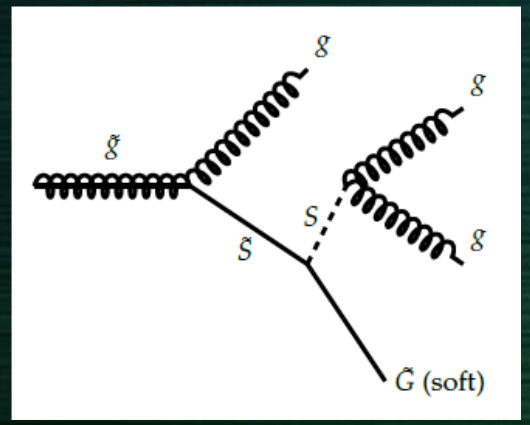
$\tilde{g} \to \tilde{S} \to \tilde{G}$

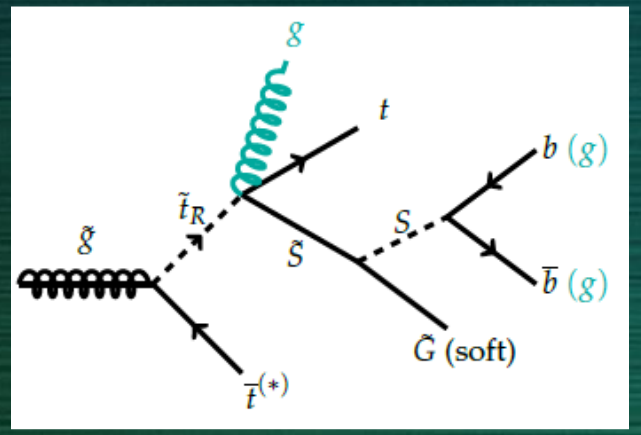


$\tilde{g} \to \tilde{t} \to \tilde{S}S\tilde{G}$



3g → 6 jets FS (mostly light flavors for small m_S)



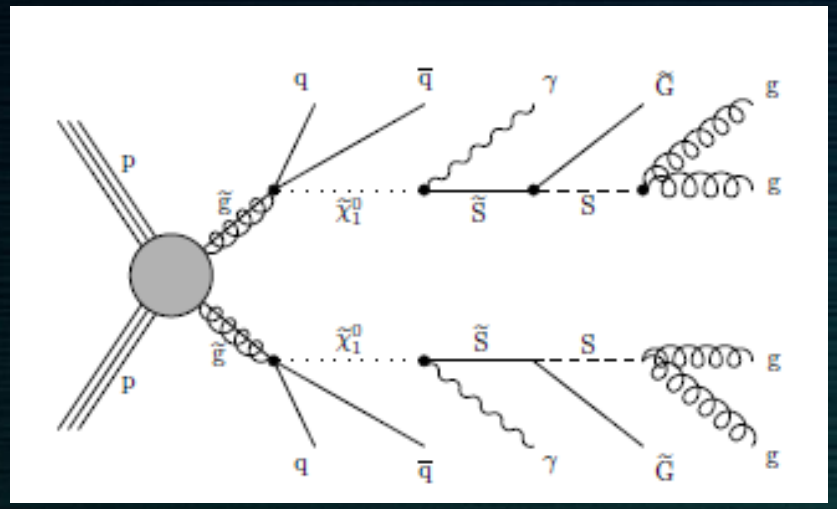


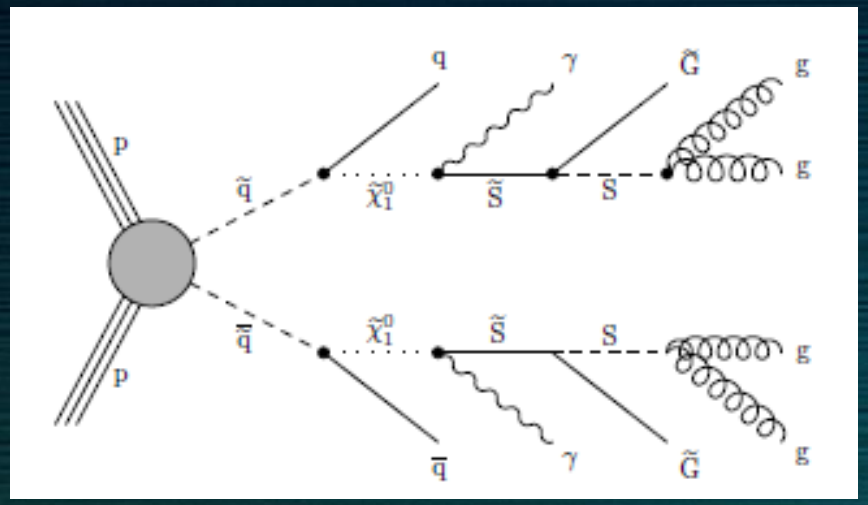
SS leptons or 3 leptons plus >4 jets (3 jets b-tagged)

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

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

$SY\bar{Y}$





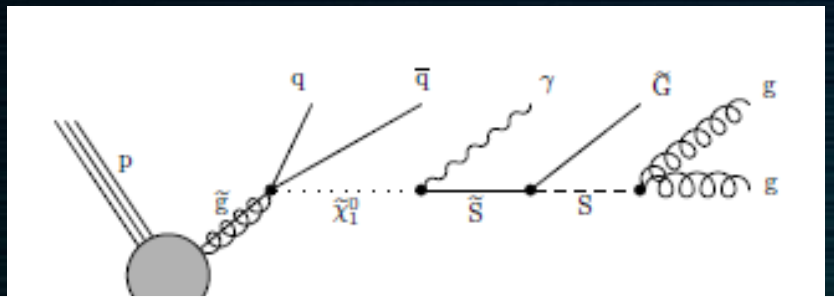
CMS SUS-19-001;
arXiv:2310.03154 [hepex];

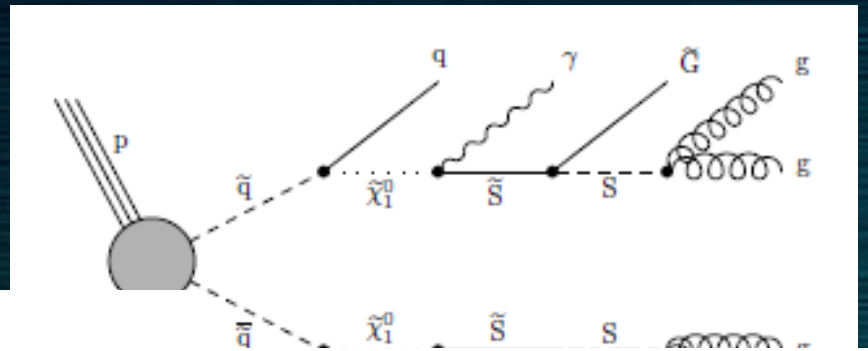
See also:
CMS SUS-23-001
for stealth /RPV SUSY
with DNN

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

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

$SY\bar{Y}$





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

See also:
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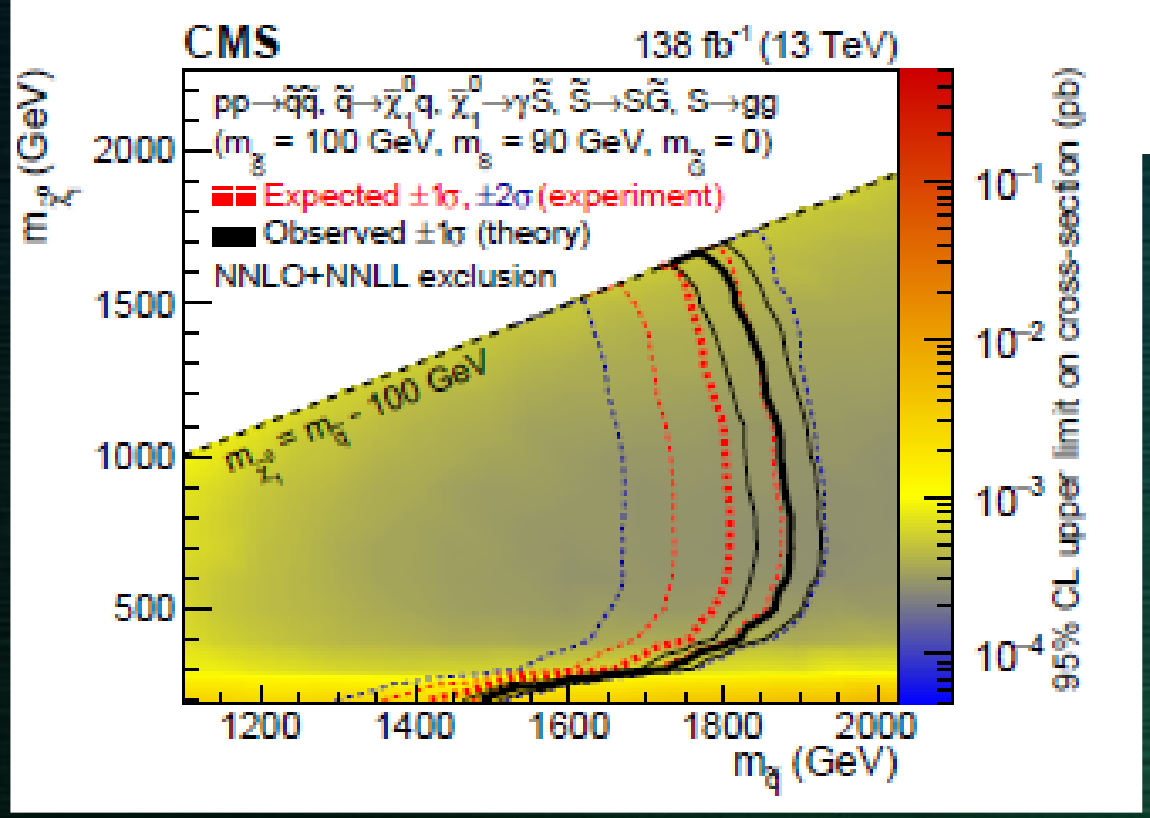
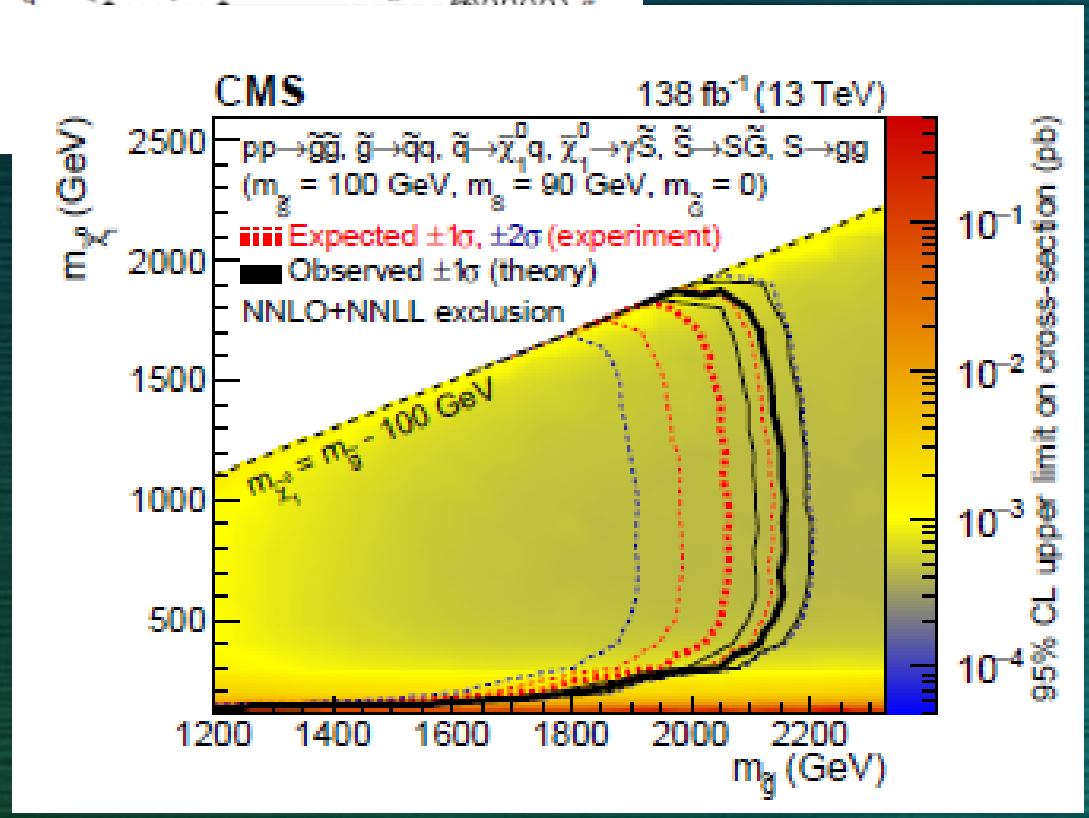




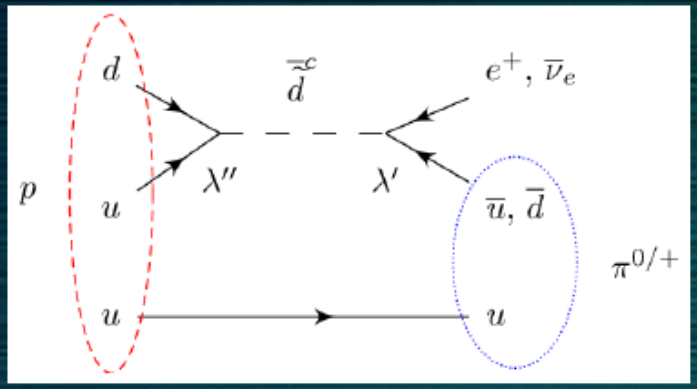
RPV SUSY

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

$$W_{\not R_p} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$

Lepton number violating | Baryon number violating

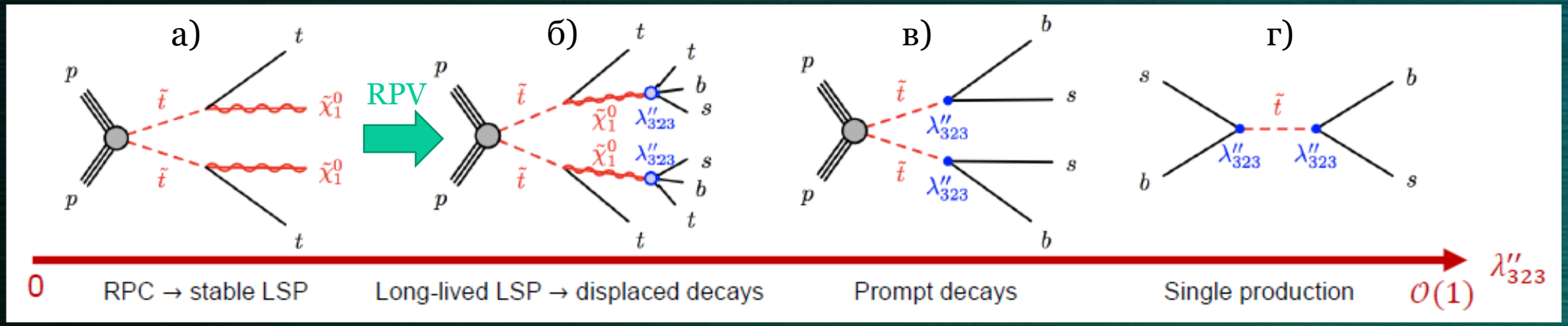
$$R = (-1)^{3(B-L)+2s}$$



too many free parameters!

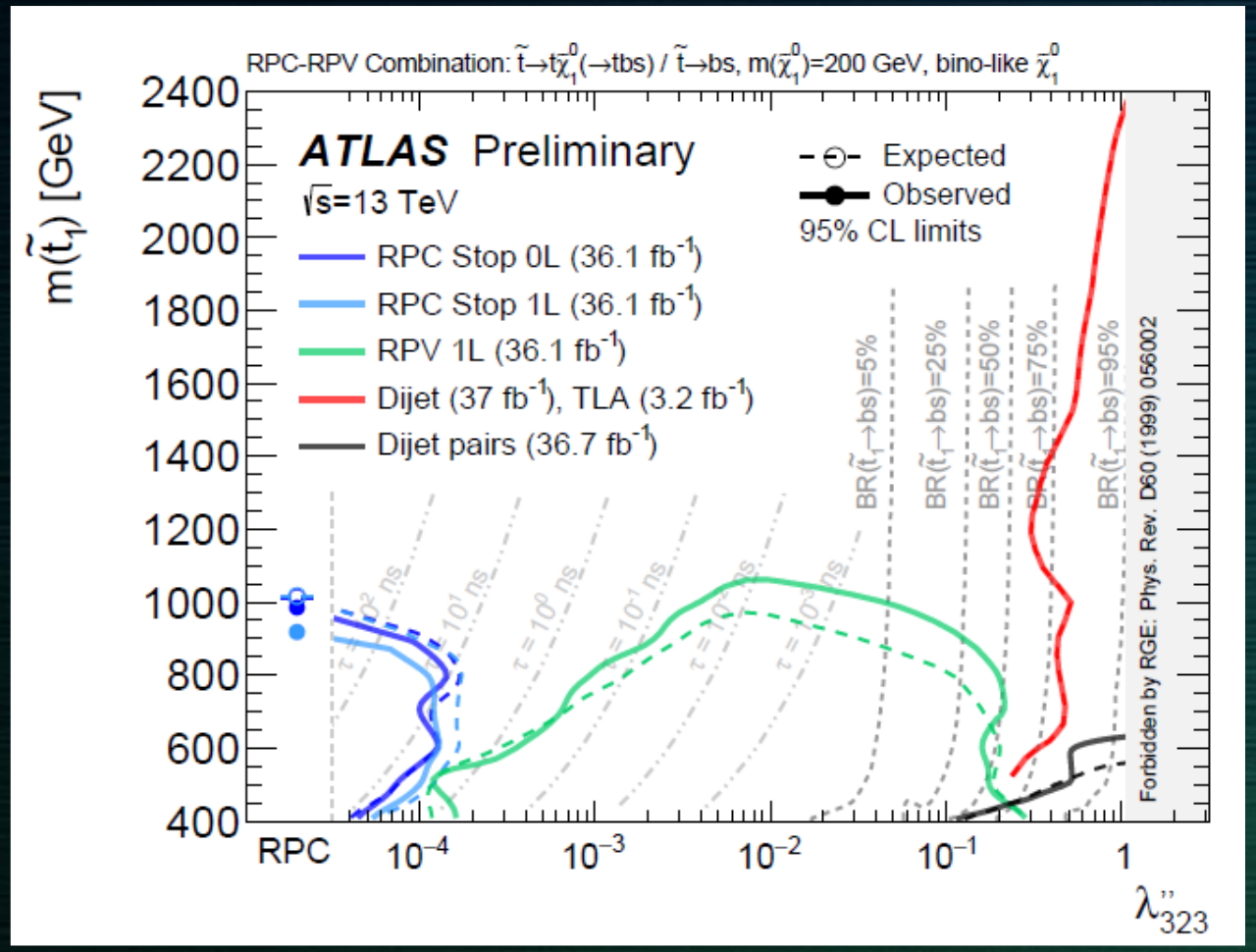
RPV:

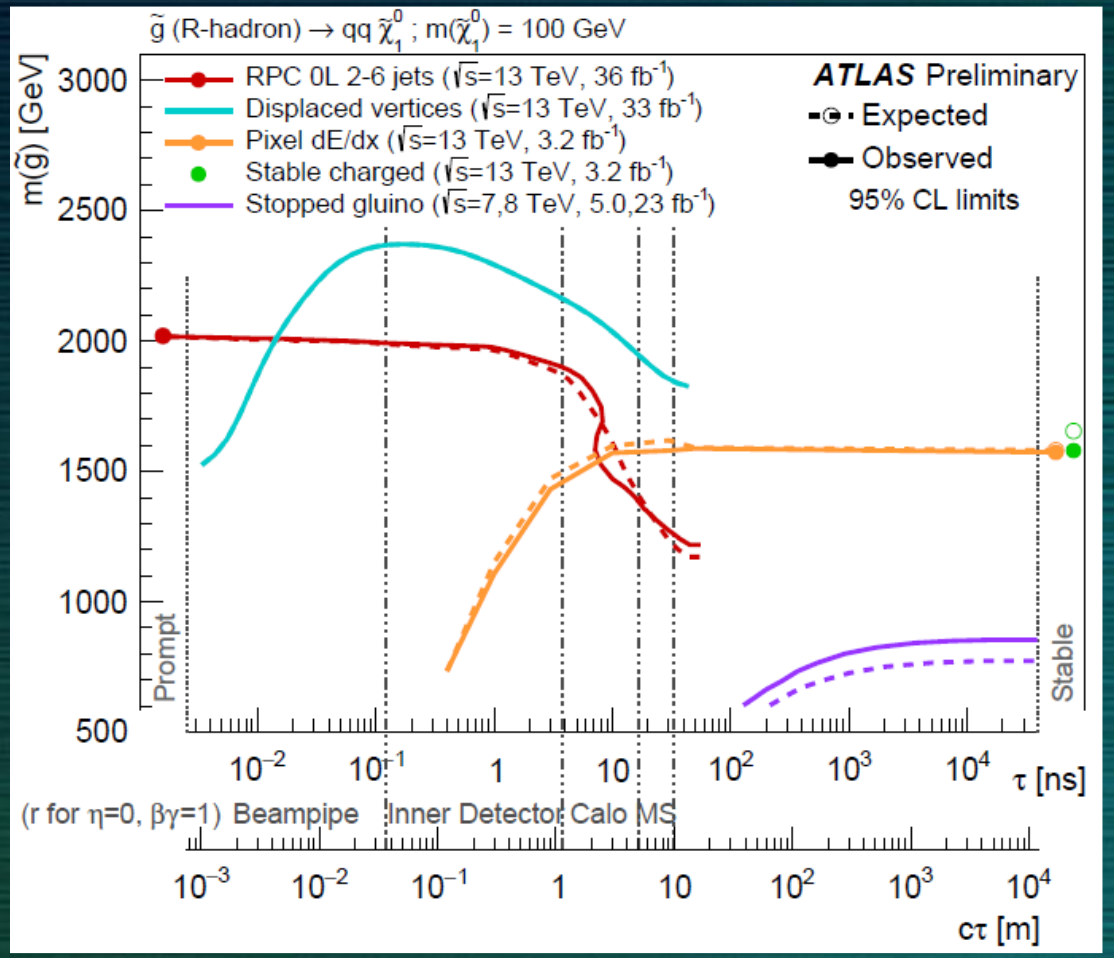
- L-volating terms – origin of light neutrino mass
- LSP can carry charge and decay to SM
- Various detector signatures depending on coupling strength (triple resonances, SS leptons, multijets..., LLP)
- DM candidate – gravitino, axino !!



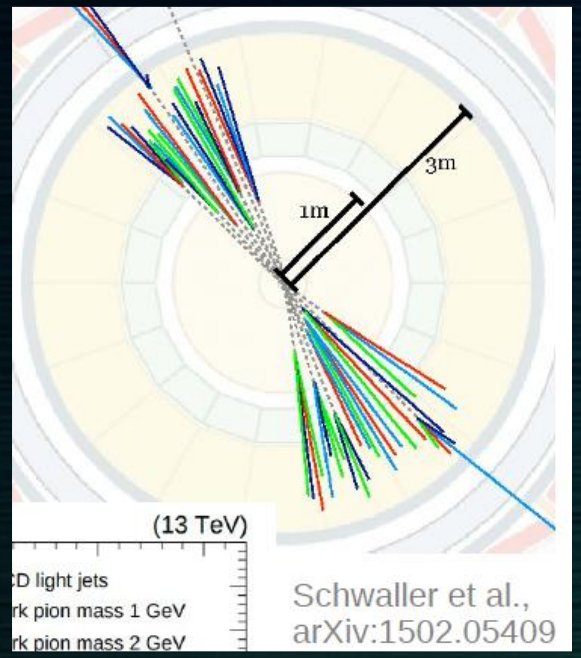
RPV SUSY, ATLAS RUN2, prompt/LLP

ATLAS-CONF-2018-003





Strongly coupled DS, dark showers, prompt/LLP



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

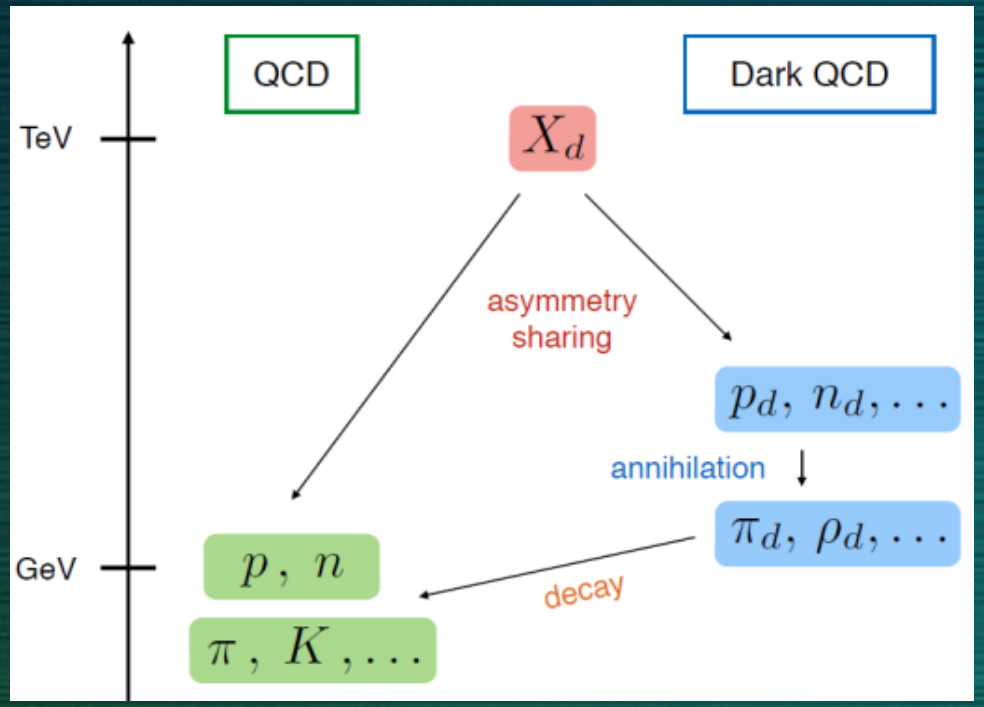
N_c, N_f, Λ_{dark},
m_{dark}, r_{inv}…

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

F^a: dark gluons (N_d colours)

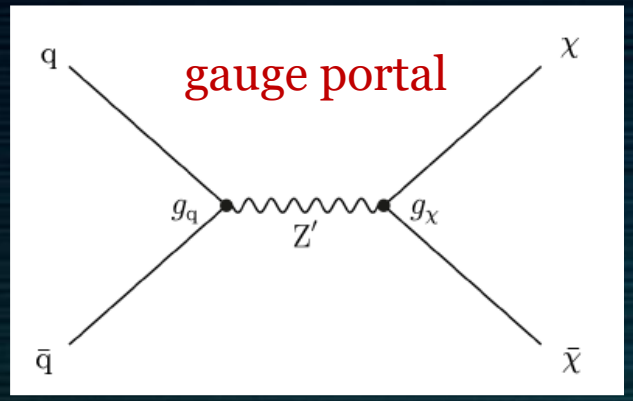
q_d: dark quarks (N_f flavours)

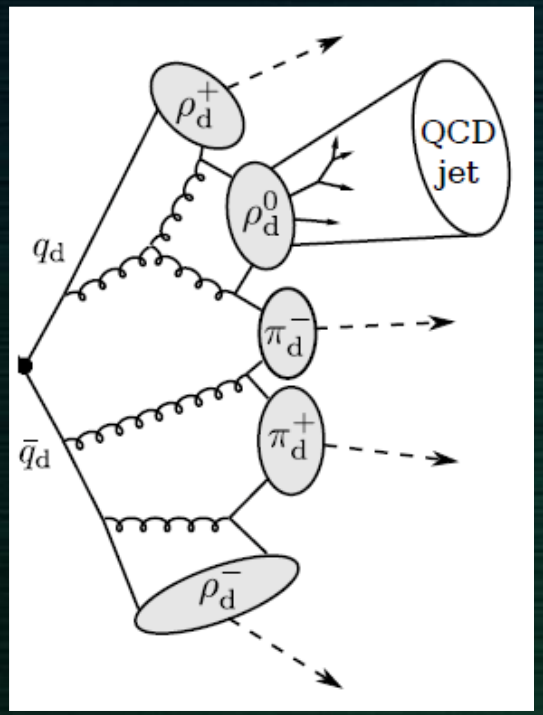
M_q: quark mass matrix



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

Dark QCD, dark showering, a part of the invisible



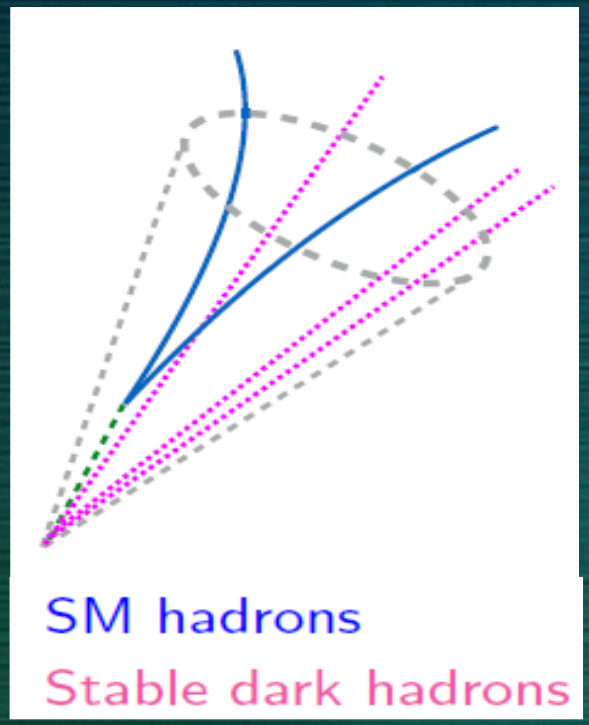


semivisible jets

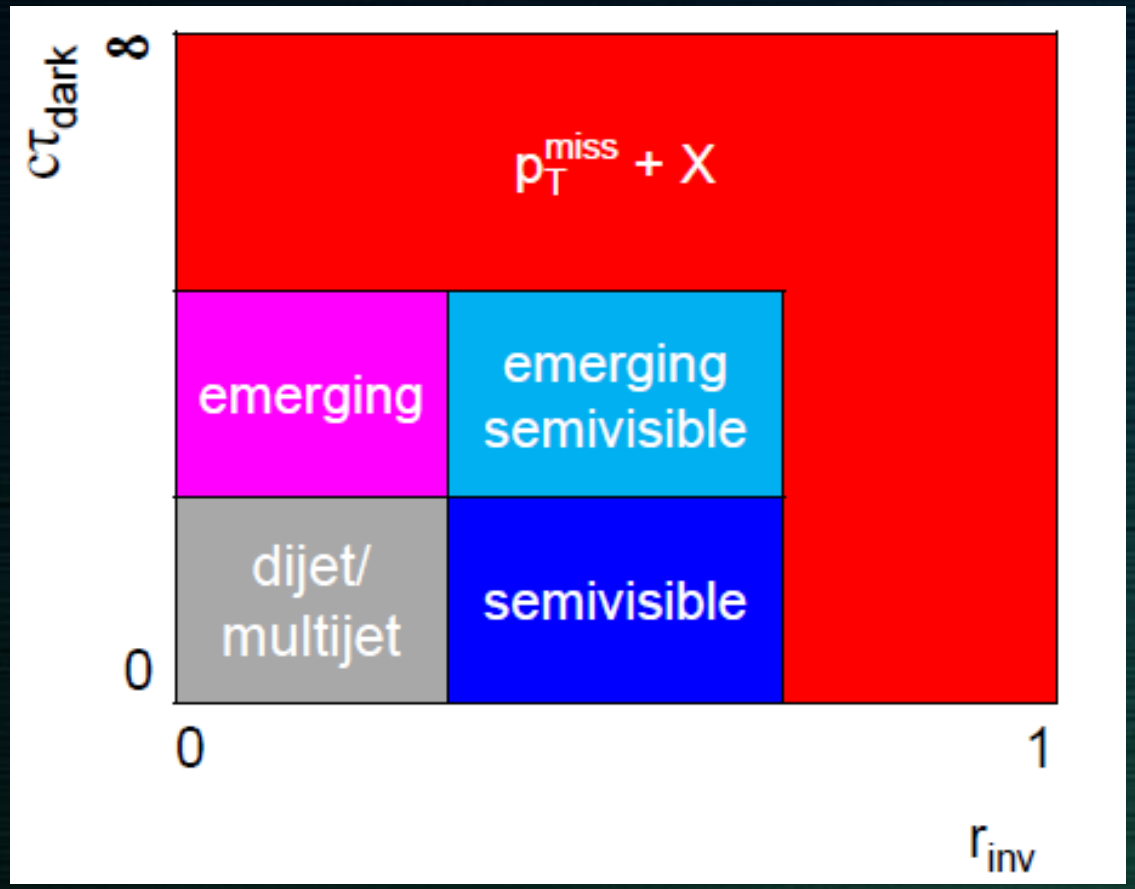
DM part (visible) +

SM part (invisible)

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

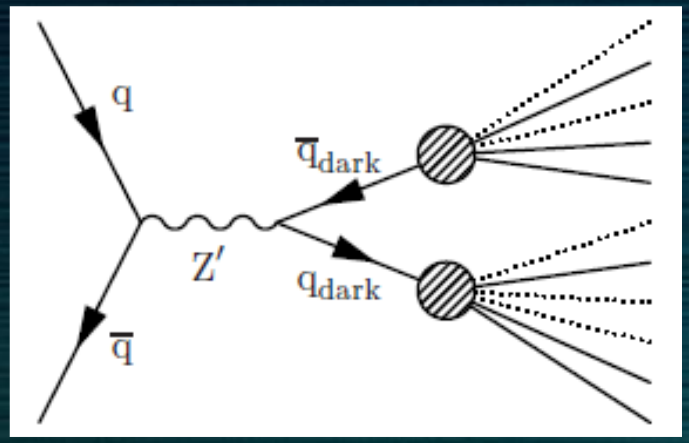


Strongly coupled DM: signatures, prompt/LLP

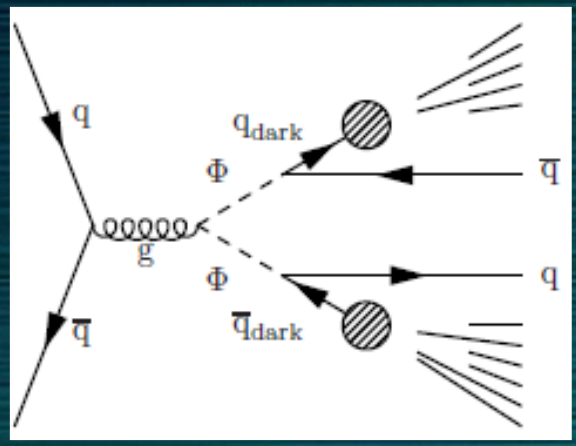


Tracks start near the edge of the tracker, in the ECAL and HCAL and even in the inner muon stations

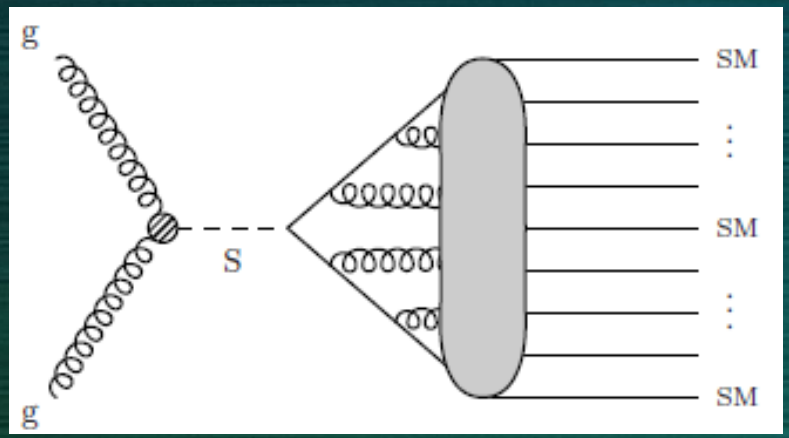
't Hooft coupling $\lambda = \alpha_{dark}^2 N_c^{dark} \ll 1$



semivisible jets



emerging jets



soft unclustered energy patterns (SUEP)

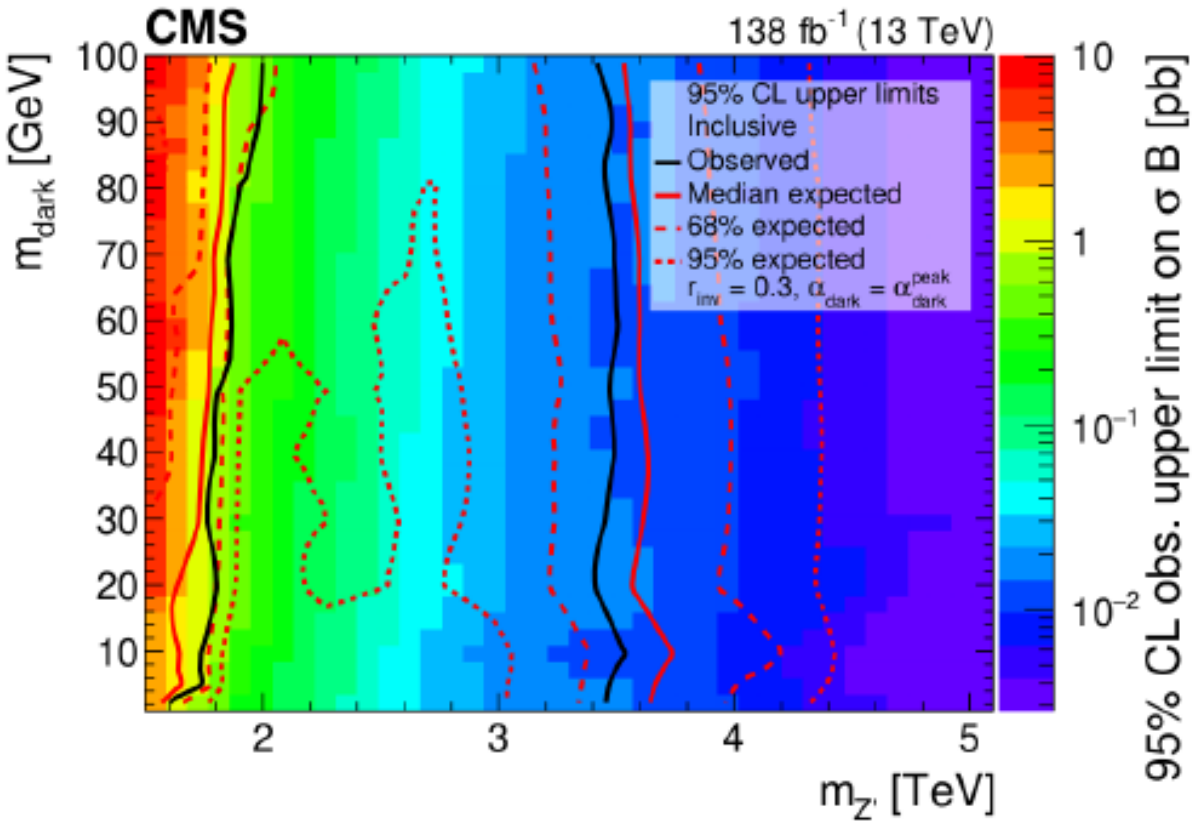
$\lambda \gg 1$

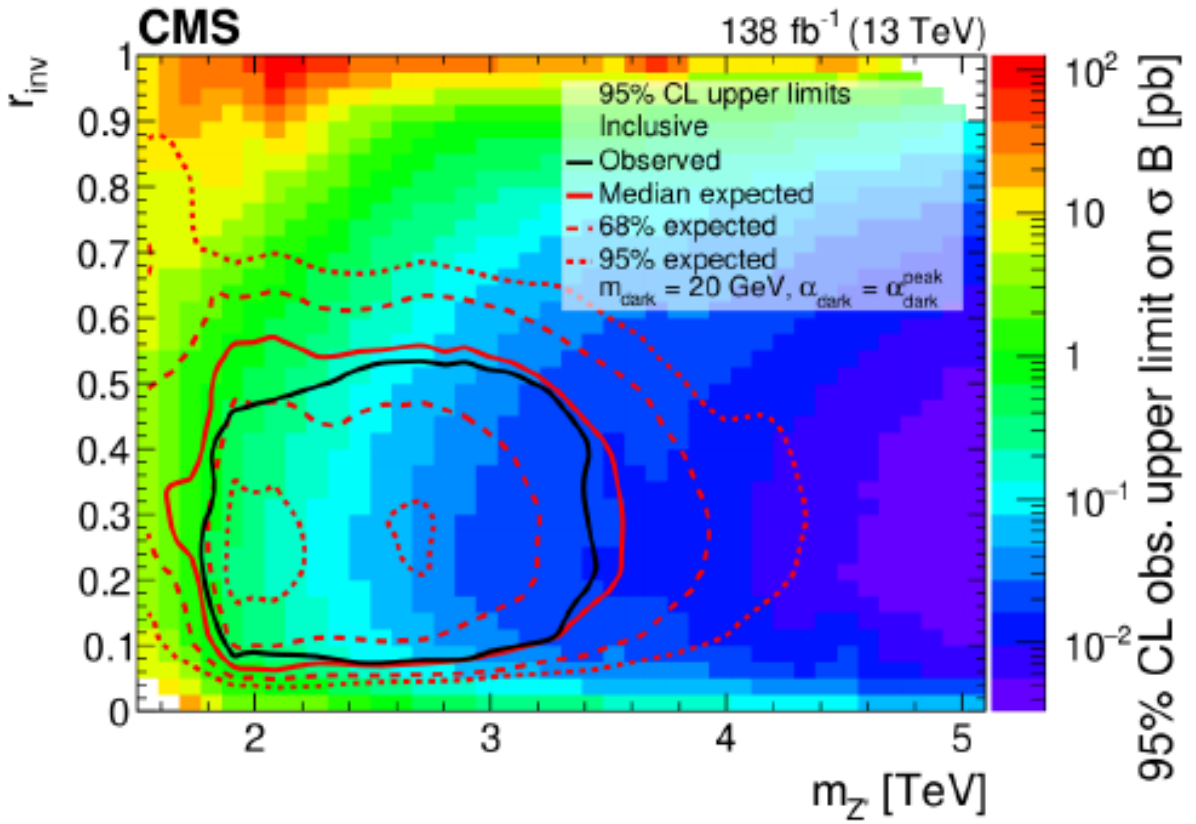
quasi-conformal spectra, dark "high-temperature QCD"

Dark QCD, prompt, semivisible jets

The first CMS study of jet ivsisible 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

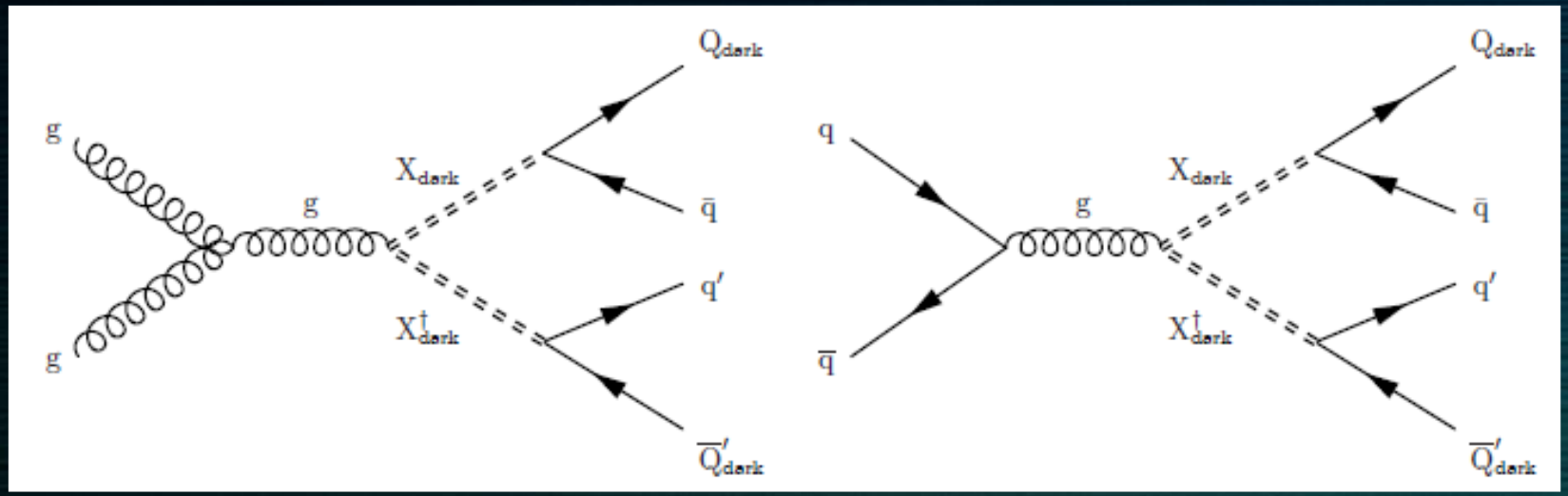




LLP dark showers, LLP, emerging jets

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

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

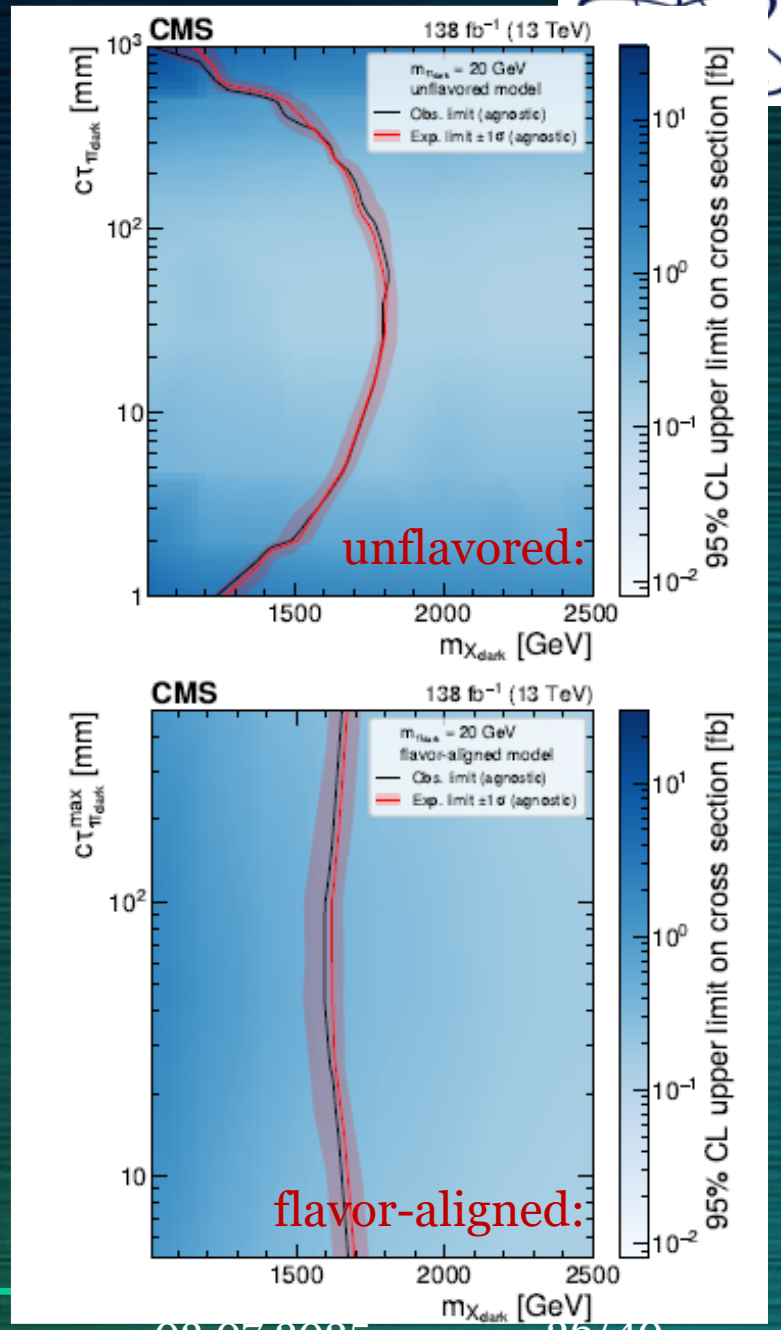


unflavored:

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

flavor-aligned:

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

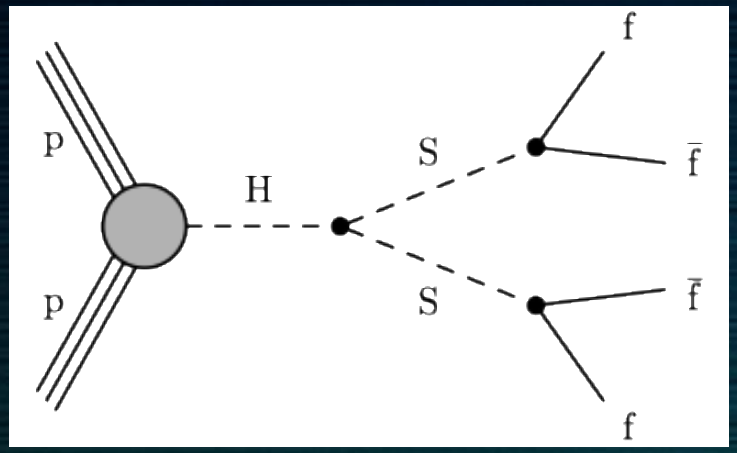


Weakly coupled DS, light LLP, displaced jets

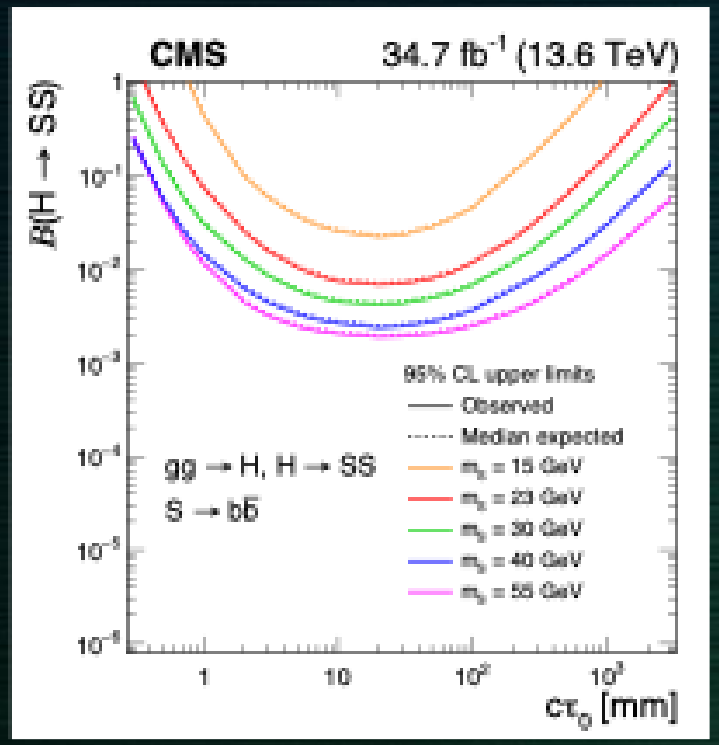
CMS EXO-23-013;
arXiv:2409.10806 [hep-ex]

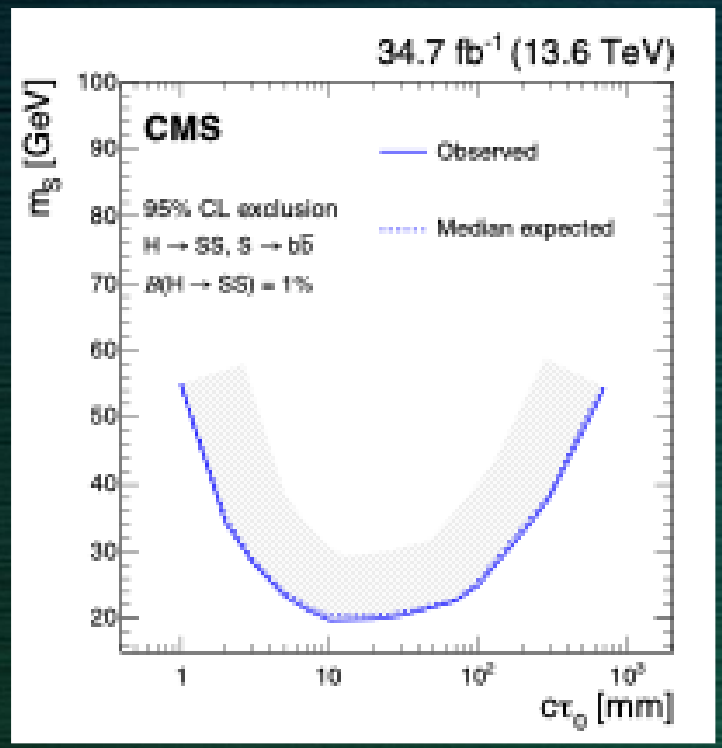
Neutral naturalness – a global SM-DS symmetry, protecting m_H

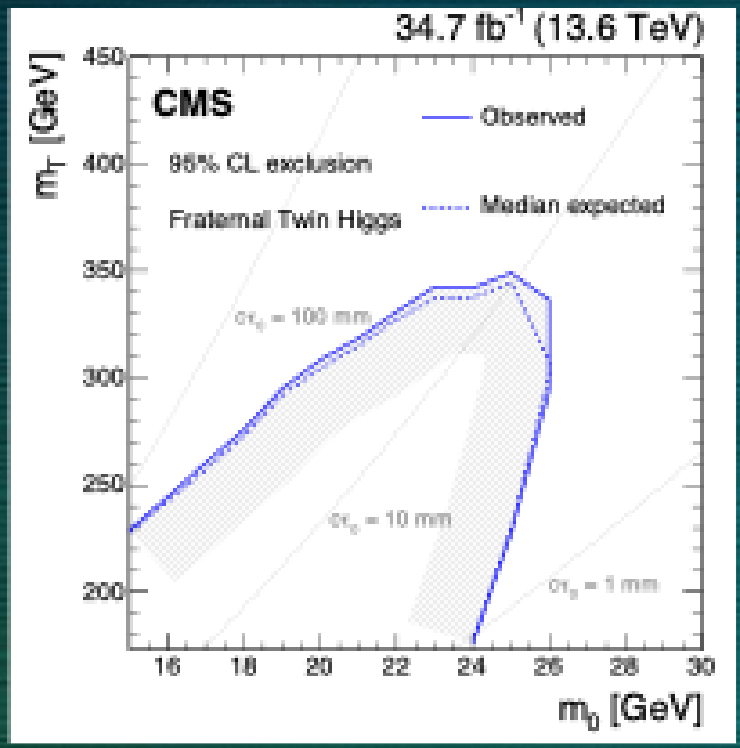
Fraternal twin higgs model and folded SUSY interpretations



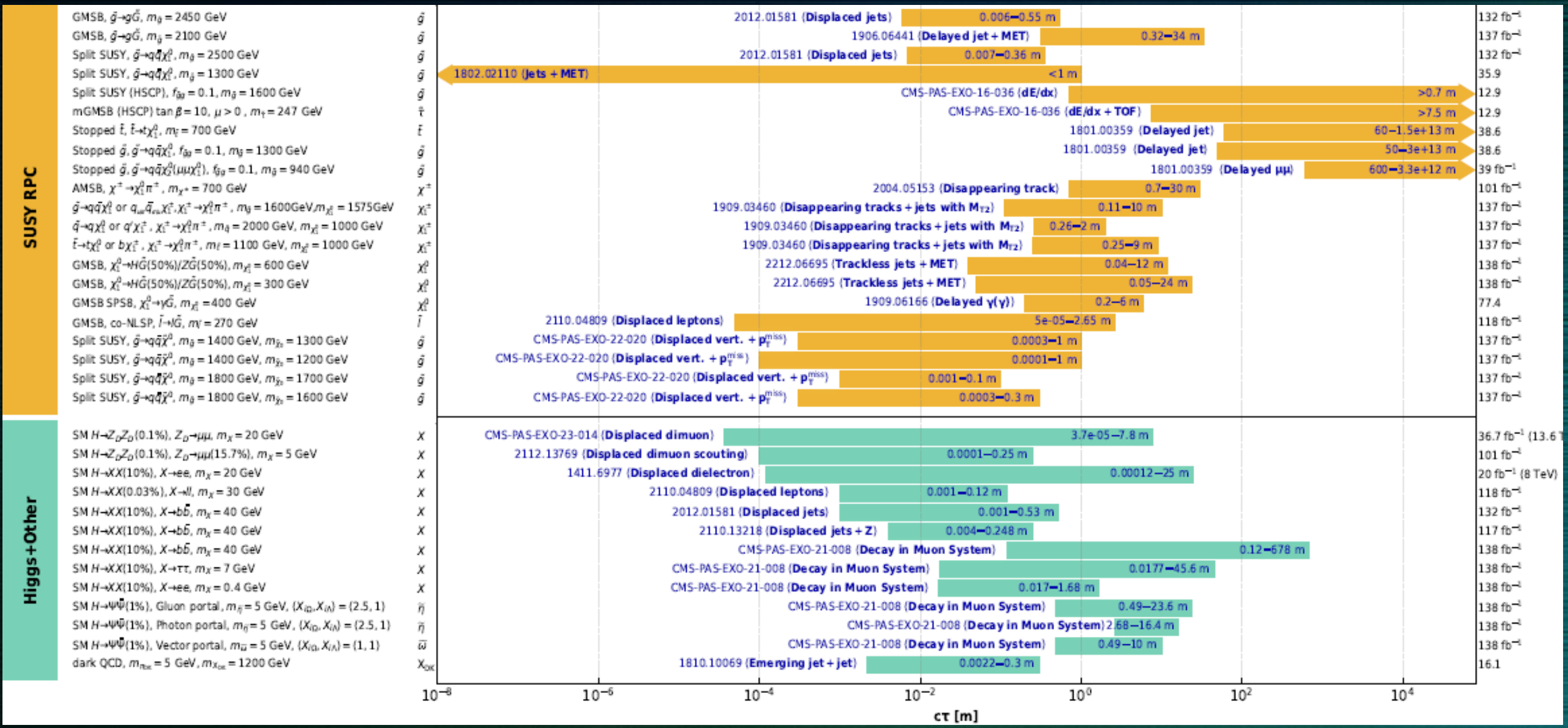
- the lightest DS state – dark glueball with strongly suppressed decays to SM
→ LLP
- light LLP with masses < 60 GeV
- LLP decays to b-/d- quarks and τ-leptons







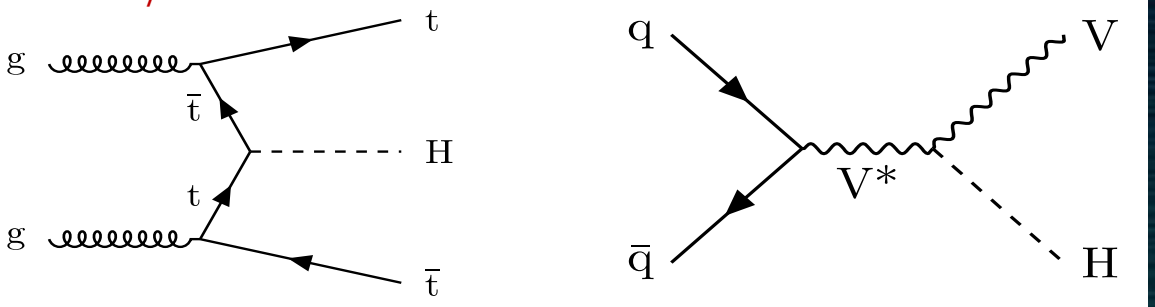
LLP summary plot, CMS, 2023



Backup slides

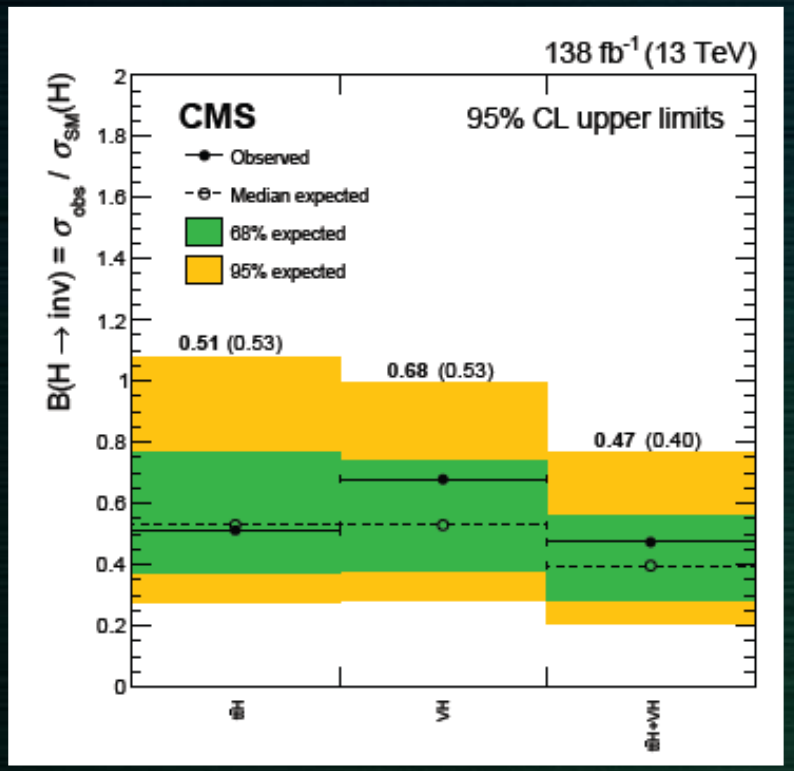
Combination of h_{125} → invisible searches for ttbar and VH

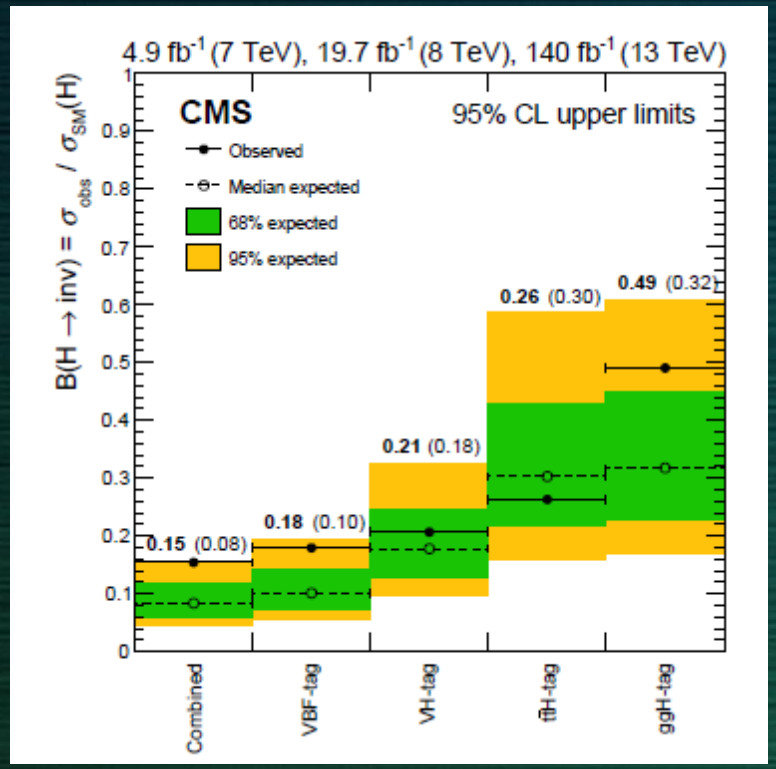
resolved/boosted ttbarH

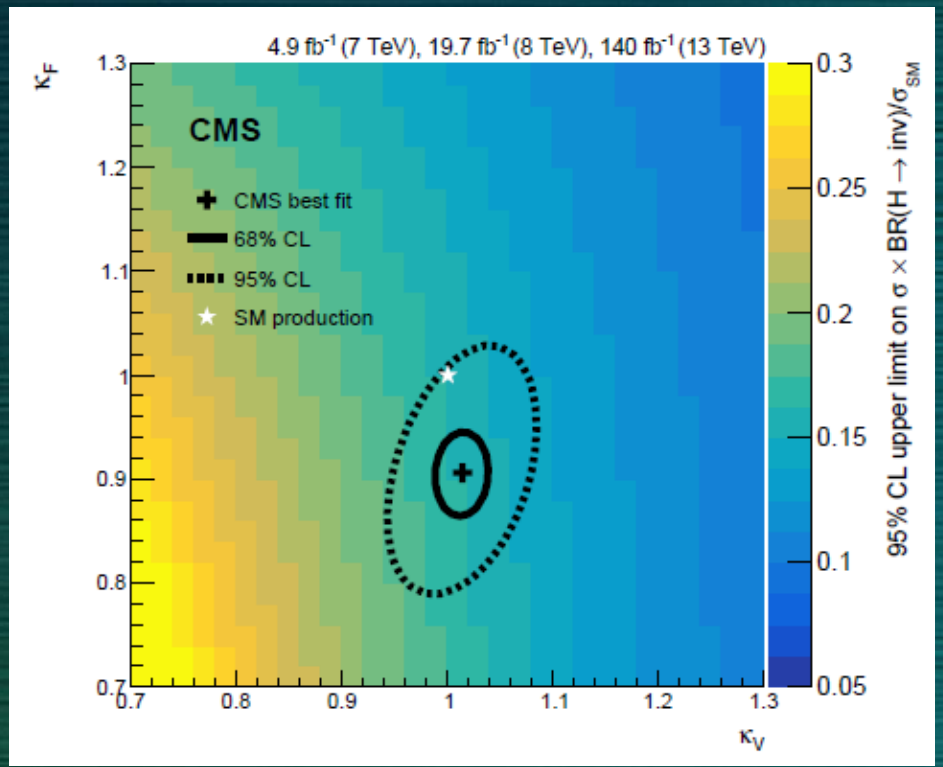


CMS HIG-21-007,
arXiv:2303.01214 [hep-ex]

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

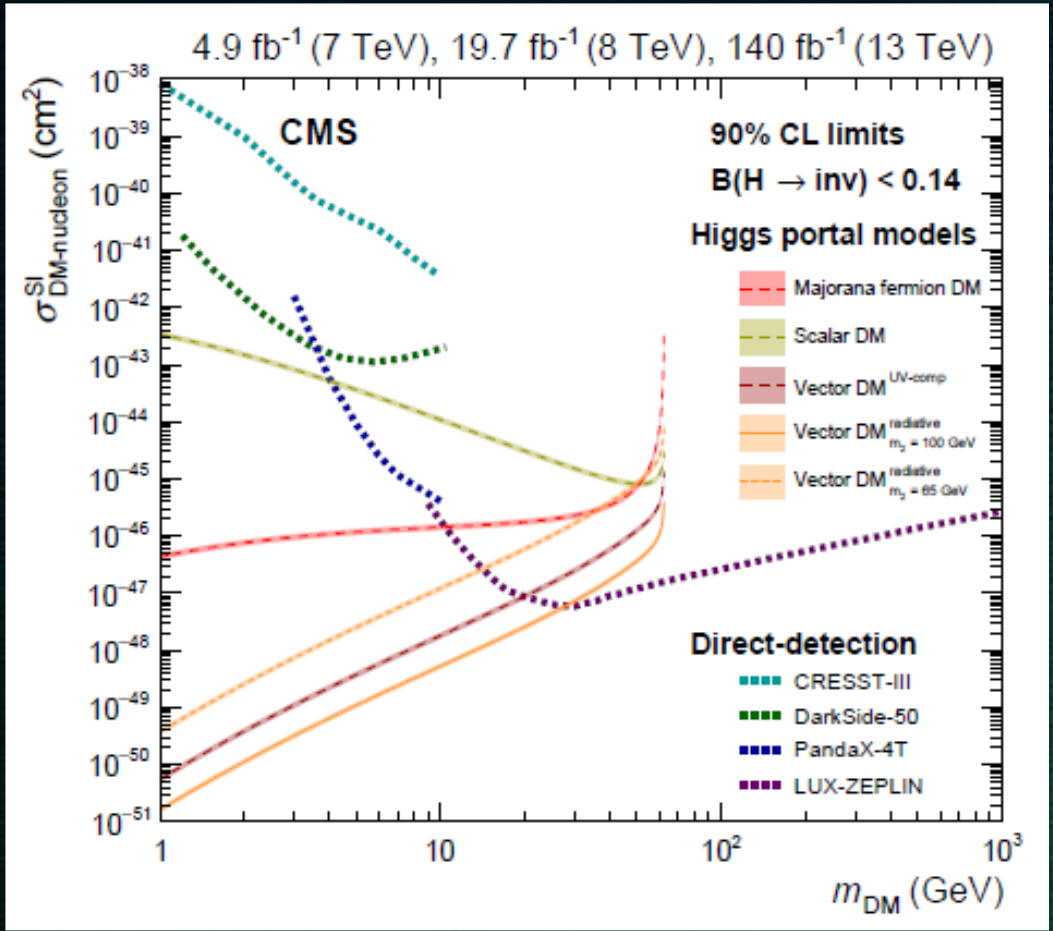


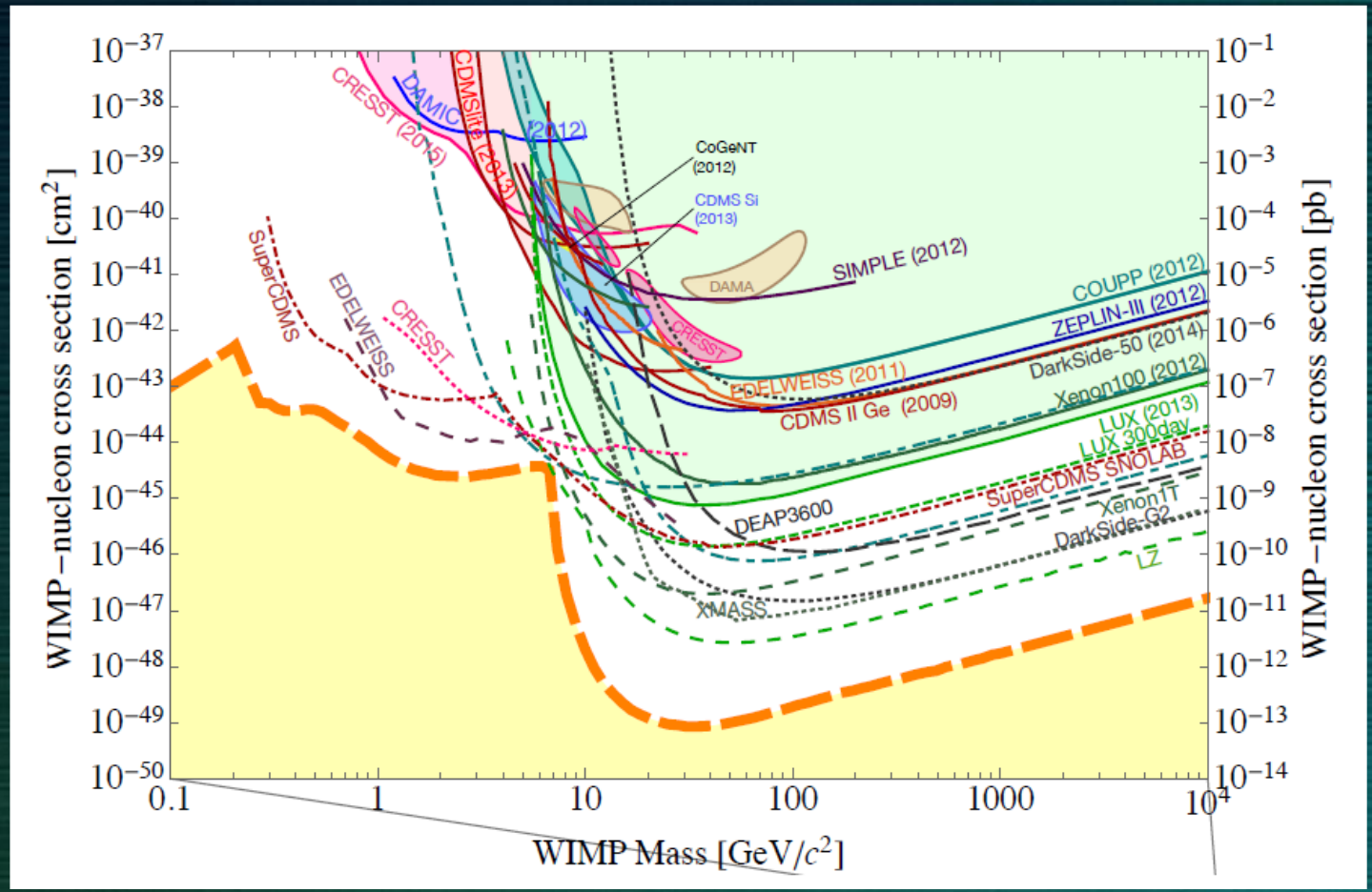




Combination of h_{125} → invisible searches

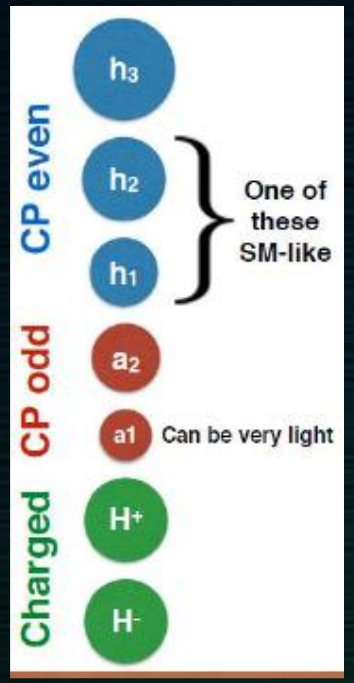
CMS HIG-21-007





2HDM+S extension

PRD 90, 075004 (2014)



Two Simple Assumptions ...

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

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

Light Boson Couplings

✓ a (the mostly-singlet-like pseudoscalar)

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

✓ could potentially be a light boson $\Rightarrow$ h exotic decays

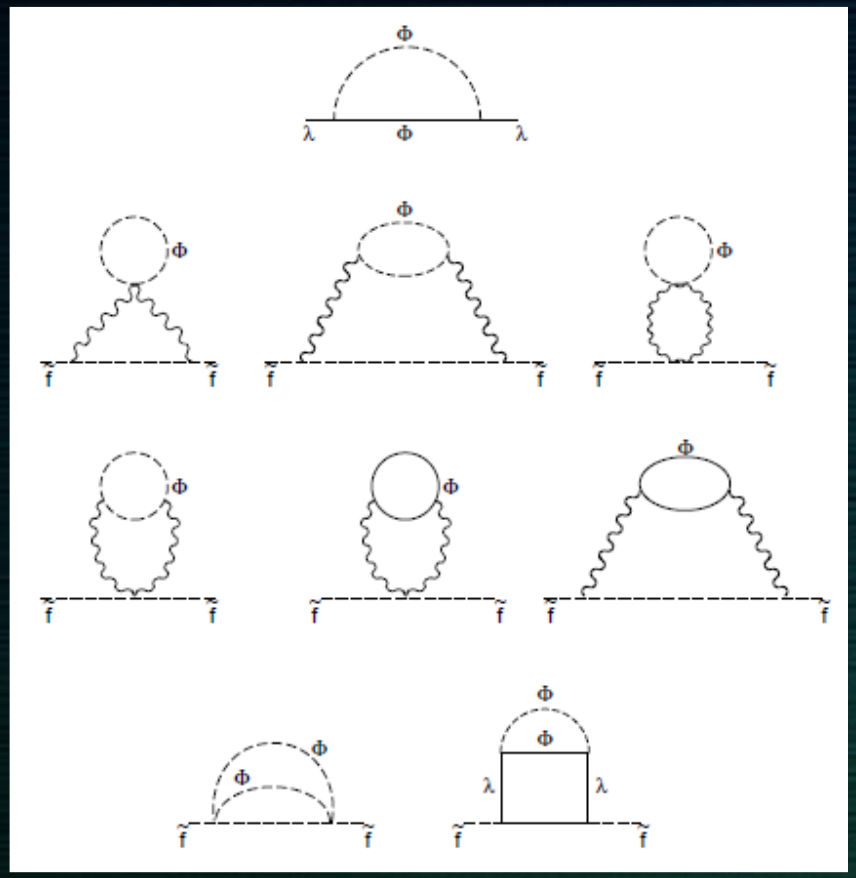
$$h \to aa \to X\bar{X}Y\bar{Y}(m_a < m_h/2) \;\mid\; h \to aZ \to X\bar{X}Y\bar{Y}(m_a < m_h - m_Z)$$

✓ with couplings to fermions driven by: $\xi_a \sim \sin\theta_a \cdot \xi_A$

Eigenstate	Coupling	Type-I	Type-II	Type-III	Type-IV
A	ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
	ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
	ξ_A^l	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

GMSB SUSY, soft mass terms and universal spectrum

1-loop for gauginos, 2-loops for squarks



$$\mathcal{L}_{\text{soft}} = -\frac{1}{2}\left(\tilde{M}_\lambda \lambda_g \lambda_g + \text{h.c.}\right) - m_{\tilde{Q}}^2 Q^\dagger Q - \left(\sum_i A_i Q_i \partial_{Q_i} W(Q) + \text{h.c.}\right)$$

$$\tilde{M}_\lambda(t) = -\frac{1}{2}\frac{\partial \ln S(X,t)}{\partial \ln X}\bigg|_{X=M} \frac{F}{M} ,$$

$$m_{\tilde{Q}}^2(t) = -\frac{\partial^2 \ln Z_Q(X,X^\dagger,t)}{\partial \ln X \, \partial \ln X^\dagger}\bigg|_{X=M} \frac{FF^\dagger}{MM^\dagger} ,$$

$$A_i(t) = \frac{\partial \ln Z_{Q_i}(X,X^\dagger,t)}{\partial \ln X}\bigg|_{X=M} \frac{F}{M} .$$

$$t = ln\, M^2/Q^2$$

F<<M²

$$\tilde{M}_{\lambda_r}(t) = k_r \frac{\alpha_r(t)}{4\pi} \Lambda_G \qquad (r = 1,2,3) ,$$

$$\Lambda_G = \sum_{i=1}^{N_f} n_i \frac{F_i}{M_i} \left[1 + \mathcal{O}(F_i^2/M_i^4)\right] ,$$

$$m_{\tilde{f}}^2(t) = 2\sum_{r=1}^{3} C_r^{\tilde{f}} k_r \frac{\alpha_r^2(0)}{(4\pi)^2} \left[\Lambda_S^2 + h_r \Lambda_G^2\right] ,$$

$$h_r = \frac{k_r}{b_r}\left[1 - \frac{\alpha_r^2(t)}{\alpha_r^2(0)}\right] ,$$

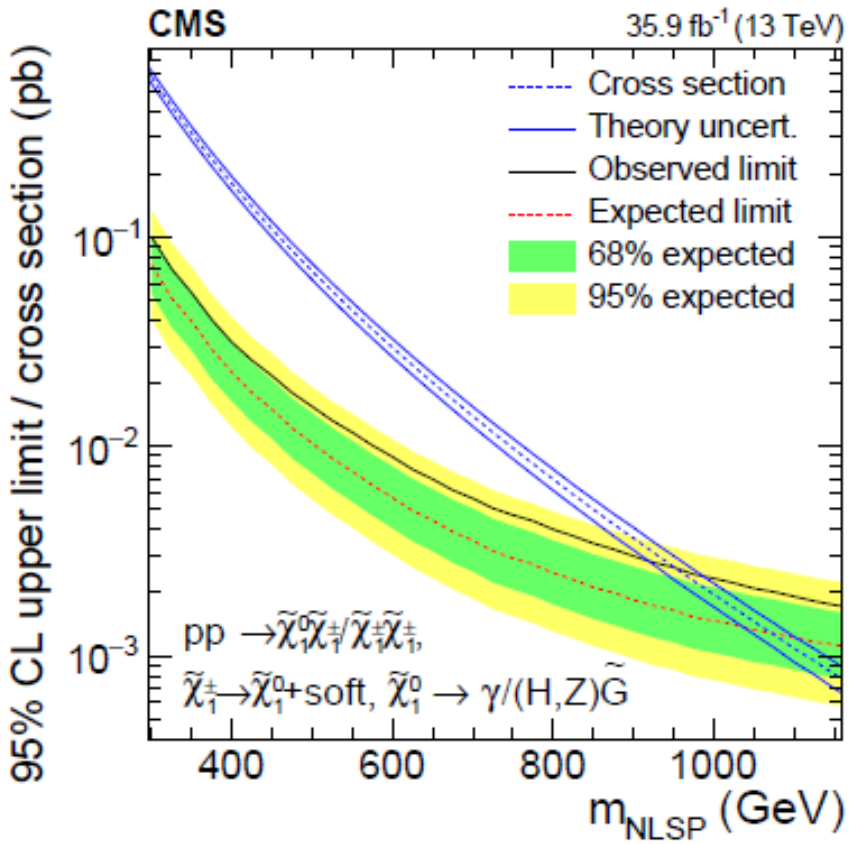
$$\Lambda_S^2 = N\frac{F^2}{M^2}\left[1 + \mathcal{O}(F^2/M^4)\right]$$

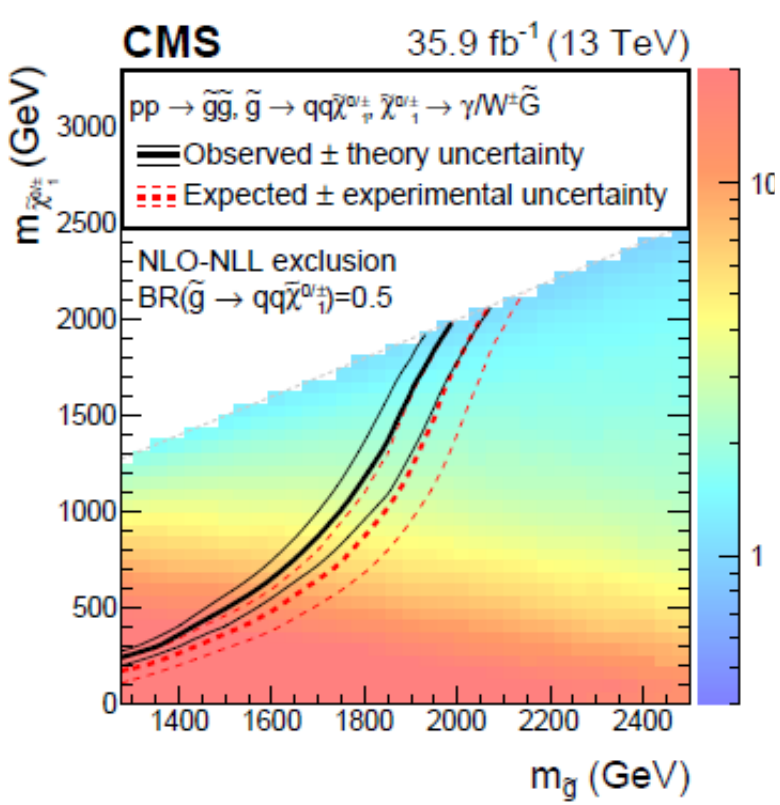
All soft masses are proportional to *NF/M*

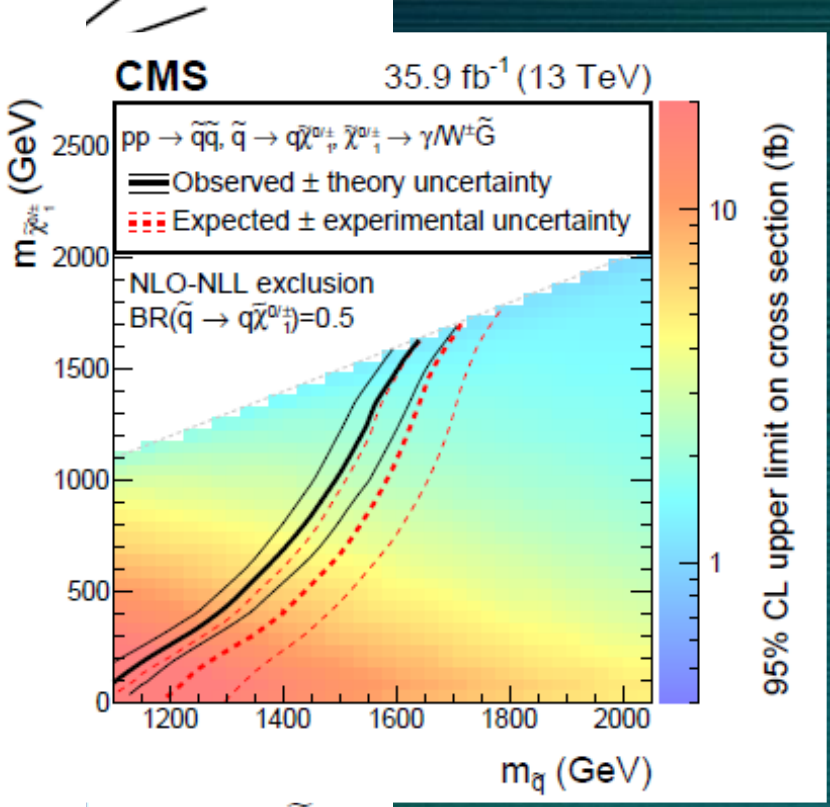
GMSB at the LHC, CMS RUN 2, prompt decays

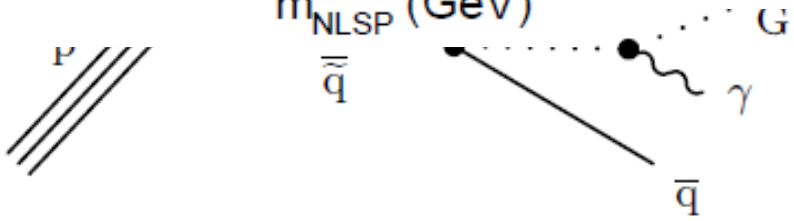
EWK production, neutralino as the NLSP, general GMSB

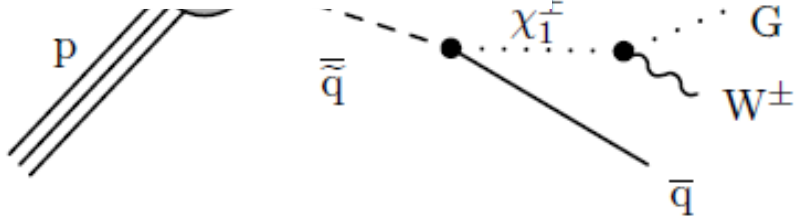
CMS SUS-16-046;
arXiv:1711.08008 [hep-ex]











MFV SUSY basis

Csaba Csaki, Yuval Grossman, and Ben Heidenreich "MFV SUSY: A Natural Theory for R-parity Violation", arXiv:1111.1239 [hep-ph]

Irreducible reps. of GUT for matter fields: $(q_L, u_R^c, d_R^c, l_L, e_R^c)_i$, $i = 1,2,3$

$U(3)^5$ symmetry in the limit of vanishing Yukawa couplings → breaking of flavor symmetry (FCNC + soft terms), scale of FSB?

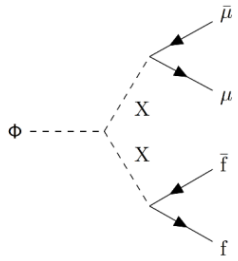
	$SU(3)_Q$	$SU(3)_u$	$SU(3)_d$	$SU(3)_L$	$SU(3)_e$	$U(1)_{B-L}$	$U(1)_H$
Q	$\bar{\square}$	1	1	1	1	1/3	0
$\bar{u}$	1	$\square$	1	1	1	−1/3	0
$\bar{d}$	1	1	$\square$	1	1	−1/3	0
L	1	1	1	$\bar{\square}$	1	−1	0
$\bar{e}$	1	1	1	1	$\square$	1	0
H_u	1	1	1	1	1	0	1
H_d	1	1	1	1	1	0	−1
Y_u	$\square$	$\bar{\square}$	1	1	1	0	−1
Y_d	$\square$	1	$\bar{\square}$	1	1	0	1
Y_e	1	1	1	$\square$	$\bar{\square}$	0	1

- "Spurions" Y_u, Y_d, Y_e – the only sources of FSB – VEVs of some heavy chiral superfields in the UV theory
- no Y^+ terms in the superpot. → very restrictive framework for possible RPV terms and couplings
- No suppositions about B- and L-number conservation, no R-parity conservation, FCNC suppression.

LLP – what and where

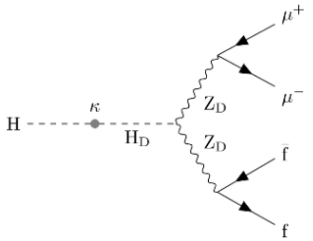
Portal	Mediated by
Vector	dark photon (Z_D or A')
Scalar	dark Higgs boson (H_D or S)
Fermion	heavy neutral lepton (HNL or N)
Pseudoscalar	axion-like particle (ALP or a)

Muon pair from DV



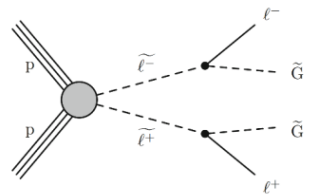
JHEP 05 (2023) 228

Low inv. mass muon pair from DV (data scouting)



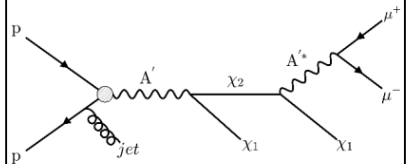
JHEP 04 (2022) 062

Two displaced leptons without common vertex



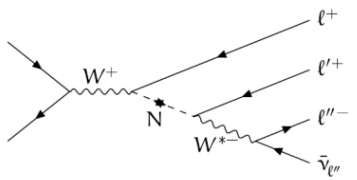
Eur. Phys. J. C 82 (2022) 153

Pair of soft muons from DV + MET + jet



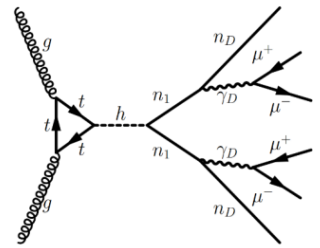
Phys. Rev. Lett. 132 (2024) 041802

Lepton pair from DV + prompt lepton



JHEP 07 (2022) 081

Two muon pairs from DVs



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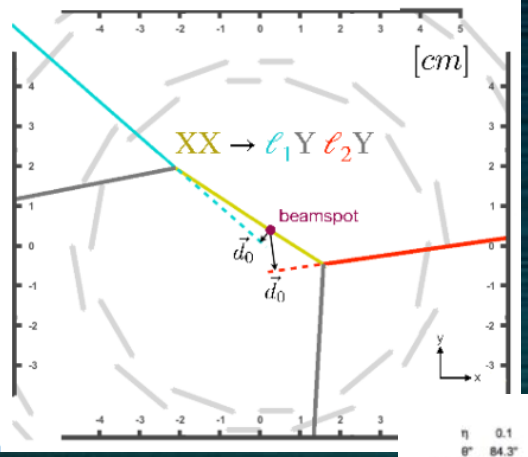
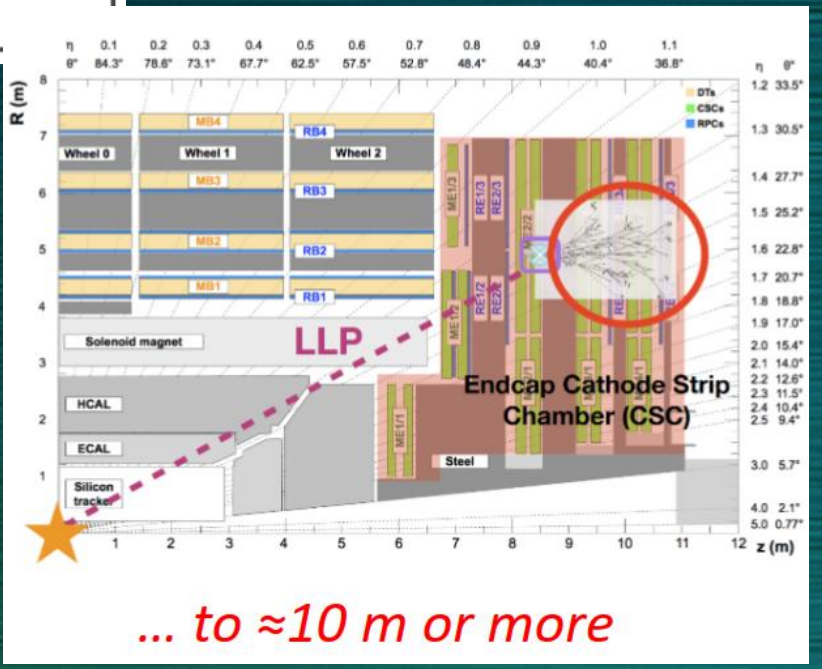
in ATLAS/CMS: from ≈100 μm



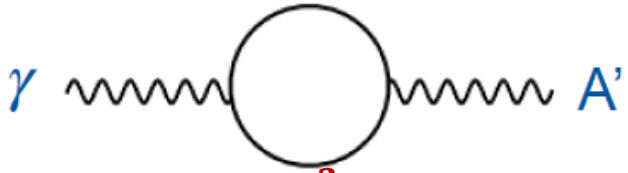
LHCP 2025, from a talk by Slava Valuev



... to ≈10 m or more

Search for dark photons, prompt/LLP

The coupling to SM particles proportional to electric charge

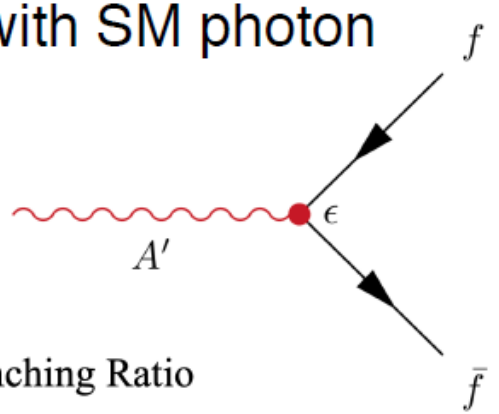


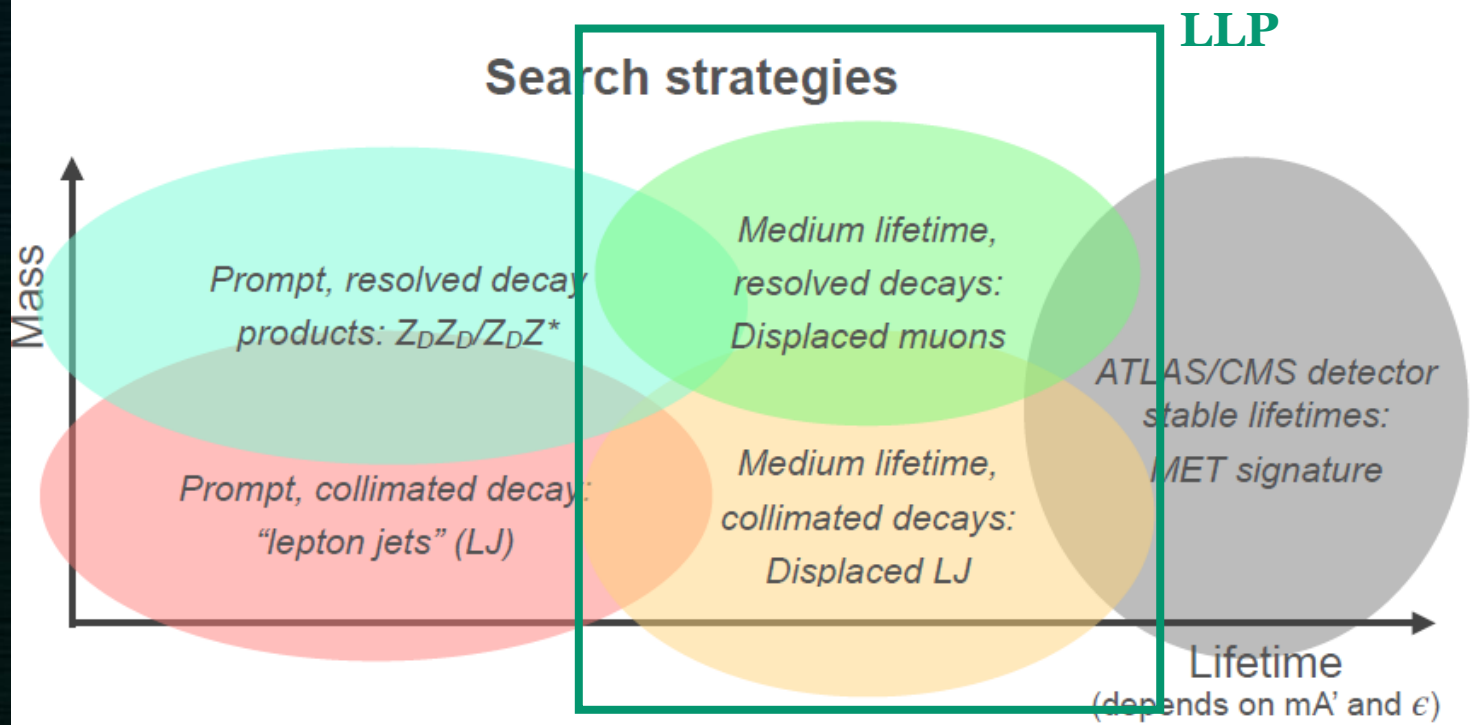
$\alpha' = \epsilon^2 \alpha_{EM}$

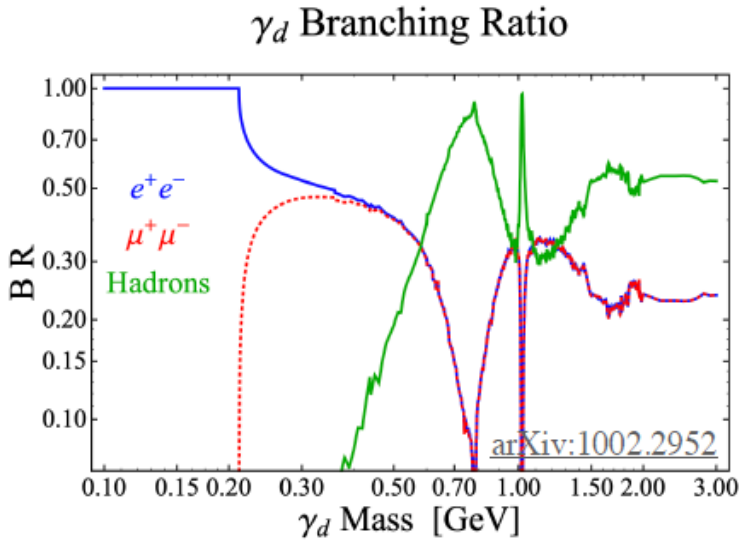
1 or 2 loops: naively $10^{-5} \lesssim \epsilon \lesssim 10^{-3}$

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

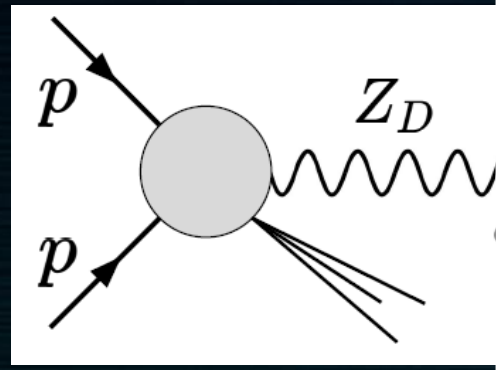
Parameters: kinetic mixing term, ϵ, and $m_{A'}$

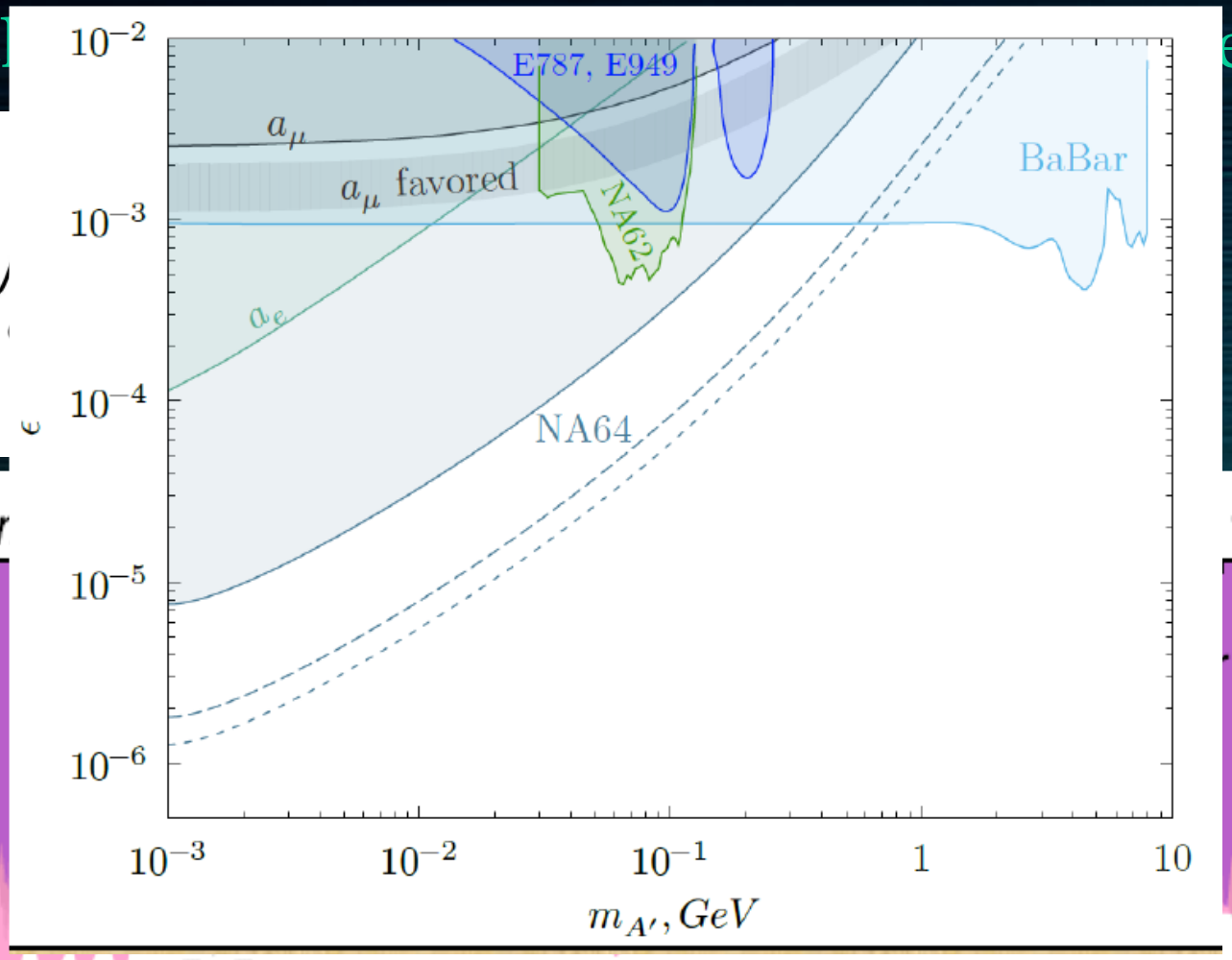






Searc e

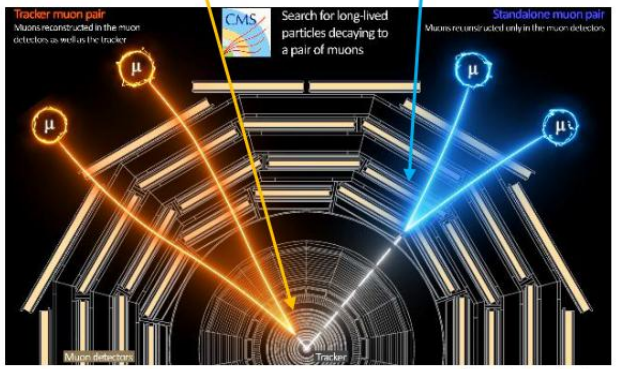




CMS EXO-21-005,
arXiv:2309.16003 [hep-ex]

Dark photon as LLP in displaced dimuons (LHCP 2025)

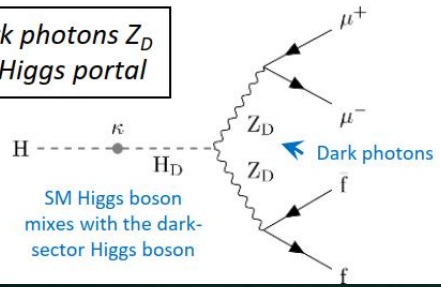
Targets LLP **decays** both **within** and **beyond** the CMS silicon tracker

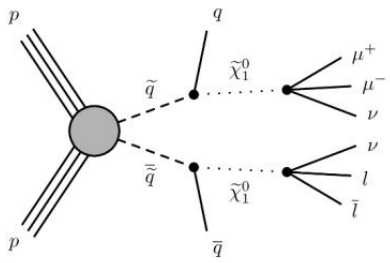


Signal simulation

Probes **numerous BSM models**, e.g.

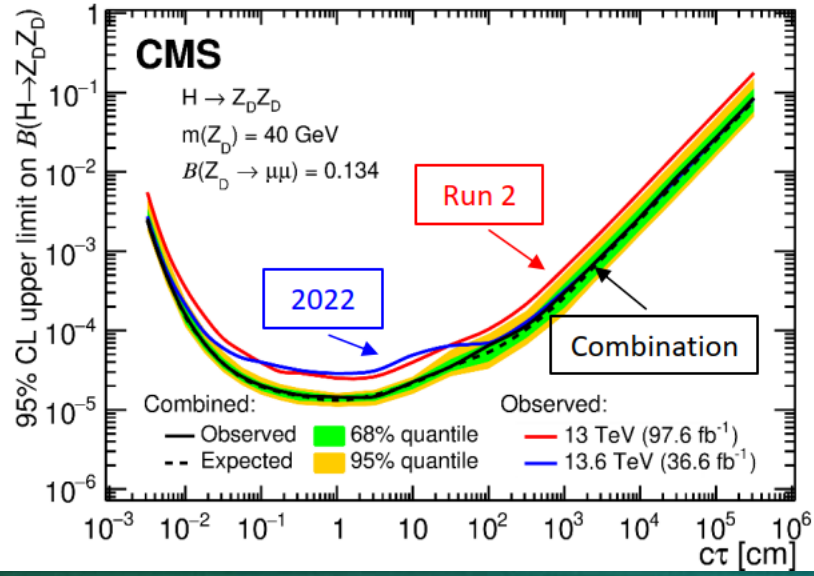
Long-lived dark photons Z_D produced via Higgs portal



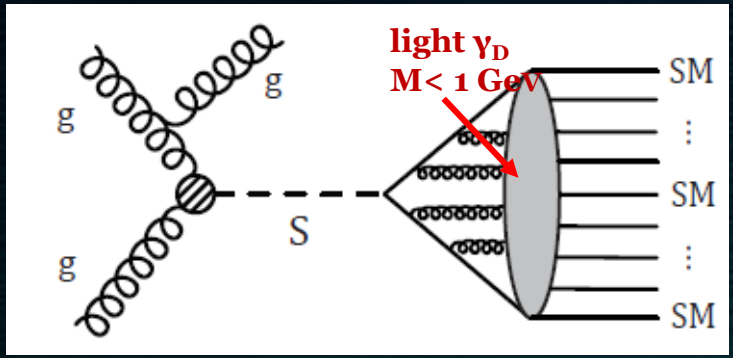


Long-lived RPV neutralinos $\tilde{\chi}_1^0$ produced in squark decays

2022: similar reach to Run 2 with only 1/3 of data



Soft Unclustered Energy Patterns (SUEPs)



$m_{q_D} < \Lambda_{dark}$, $\Lambda_{dark} \ll \sqrt{s}$

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

- ✓ HV, quasi-conformal DS, dark mesons masses much smaller than S mediator mass. The S charged under both SU(3) and $SU(3)_D$
- ✓ Spherically symmetric FS distributions, high multiplicity of soft PS
- ✓ Boltzmann distr. for PS p_T, depending on T_{dark} (Λ_{dark}) and m_φ
- ✓ Decay $\varphi \rightarrow \gamma_D\gamma_D$, → SM FS trough γ - γ_D mixing, prompt decays