Reinterpretation of CMS emerging jets for Higgs-mediated dark showers

José Francisco Zurita

Roadmap of Dark Matter Models for Run 3, 17.05.2024

Outline

- Strongly interacting dark sectors

- Dark Showers: collider signatures

- Reinterpreting the CMS Emerging Jet search: bounding Exotic Higgs decays

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Strongly interacting dark sectors

Motivation

- What if New Physics arises from a strongly coupled dark/hidden sector?

  Strassler, Zurek, hep-ph/0604261

- New matter fields (*dark quarks, q_D*) and gauge fields (*dark gluons*).

- The SM and dark sector coupled through *portals:* scalars, gauge bosons, ...

- Parameters: number of *colors* (Nc_D), *flavors* (Nf_D), confinement scale (Λ_D)

- Collider phenomenology <u>highly dependent</u> on $m_{q_D}, \Lambda_D, \sqrt{s}$ hierarchies

<u>Mass hierarchy</u>

$$1. \, m_{q_D} \lesssim \Lambda_D \ll \sqrt{s}$$

$$2. \, m_{q_D} \lesssim \Lambda_D \approx \sqrt{s}$$
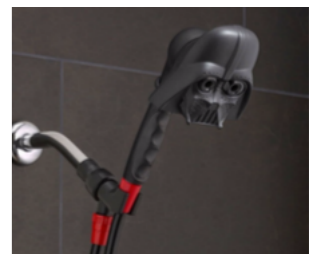
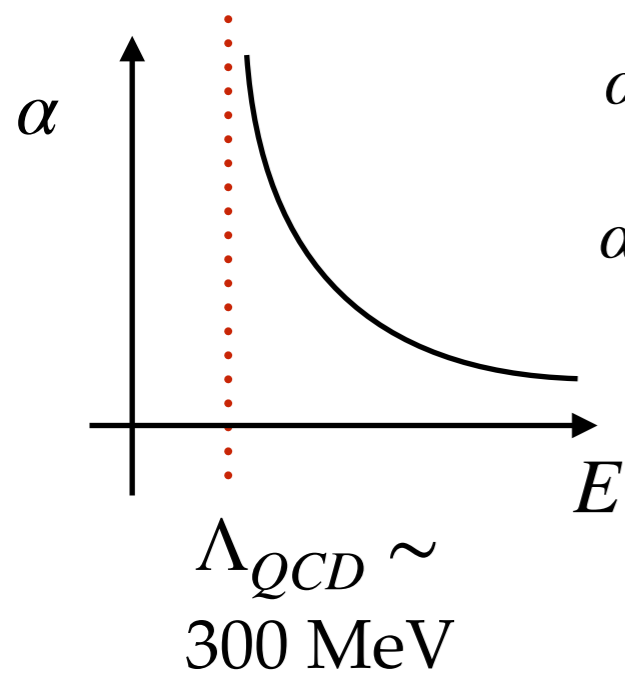$$3. \, m_{q_D} \gg \Lambda_D \lesssim \sqrt{s}$$

<u>Signatures</u>

Dark showers: This talk!

Dark bound states: resonances

Quirks

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QCD: The known strong sector

$\alpha \to 0, E \to \infty$ Asymptotic freedom: Perturbative (NN...LO/L)

$\alpha \to \infty, E \to \Lambda_{QCD}$ Confinement: bound states (hadrons) $E \lesssim \Lambda_{QCD}$

$\Lambda_{QCD} \sim$ 300 MeV
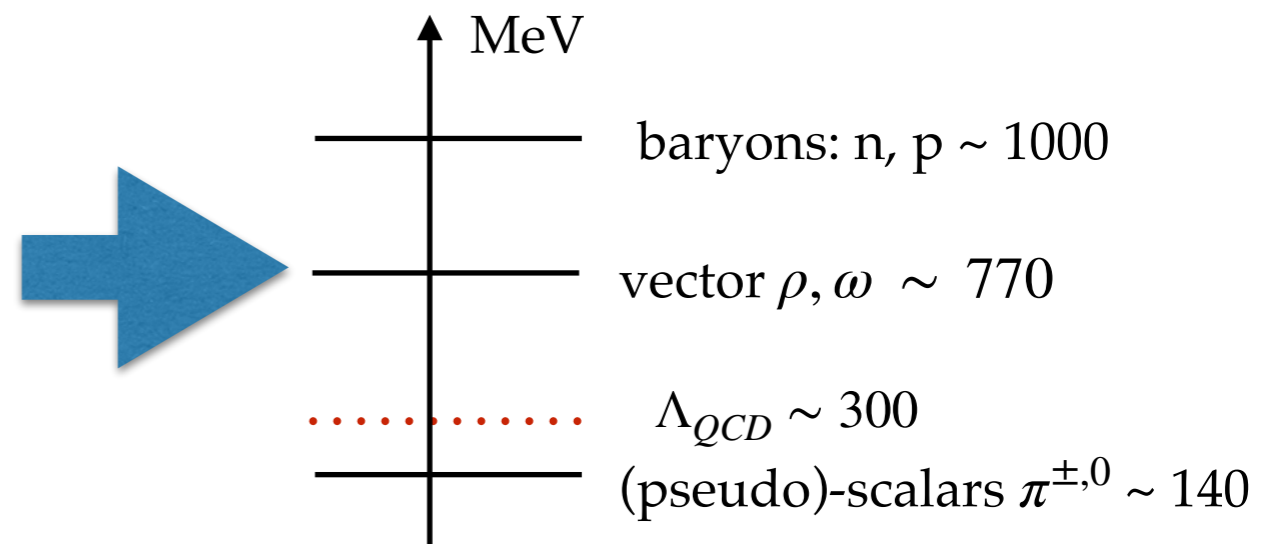
From the Lagrangian parameters m_{q_D}, g_D (α_D) one cannot reliably (perturbatively) compute hadron masses: lattice QCD

IR perspective:
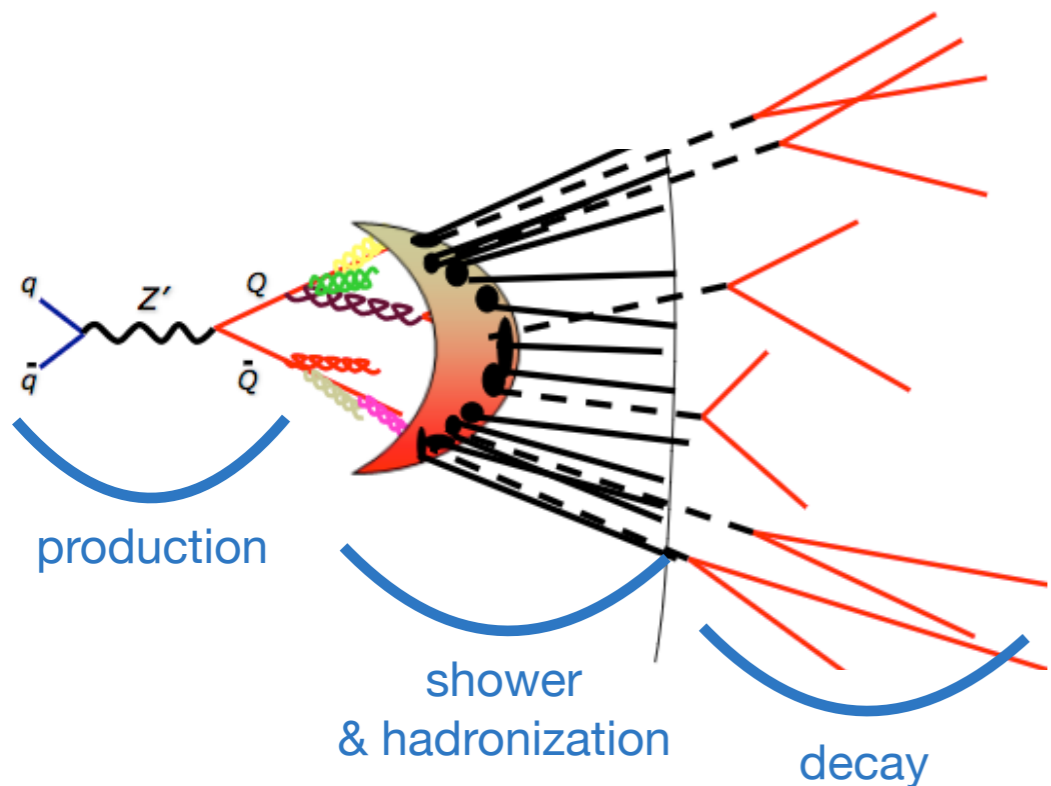
$N_f = 2$ ($m_s \sim$ 100 MeV, K~500 MeV are missing)

Expect $N_f^2 - 1 = 3$ mass degenerate "π, ρ" with same lifetime (but we can't turn off QED!)

$c\tau(\pi^0)[\mathrm{m}] \approx 2.5 \times 10^{-8}, c\tau(\pi^{\pm})[\mathrm{m}] \approx 7.8$

baryons: n, p ~ 1000

vector $\rho, \omega \sim$ 770

$\Lambda_{QCD} \sim$ 300

(pseudo)-scalars $\pi^{\pm,0} \sim$ 140

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Dark Showers: Collider Signatures

Dark showers: anatomy

production

shower
& hadronization

decay

Factorization: prod. x shower&had x decay

- Potentially large multiplicity

- Hierarchy of lifetimes (as in QCD pions!)

- Non-isolated (in general)

$\alpha_D N_{C_D}$	Small: *QCD-like* Dark Jets are formed [~ 0.3 in SM QCD]	Large: No dark jets *-Glueballs* *-Soft Unclustered Energy Patterns* (SUEP)
[QCD-like] $c\tau(\pi_D)$	Small (prompt): *Semivisible Jets* (SVJ) Cohen, Lisanti, Lou 1503.00009	Large (long-lived): *Emerging Jets* (EJ) Schwaller, Stolarski, Weiler 1502.05409

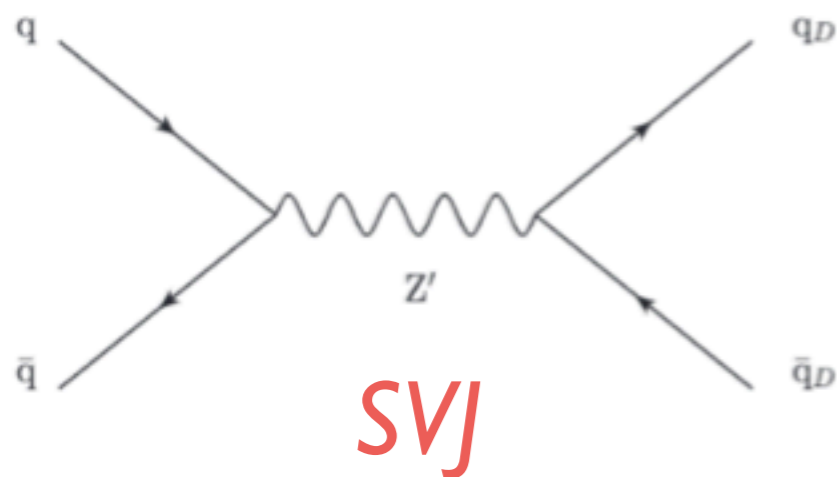José Zurita

DS production: models

Production requires* a *portal* connecting the dark and the visible (SM) sectors.

Two popular options: s-channel Z′ and t-channel bifundamental ϕ .

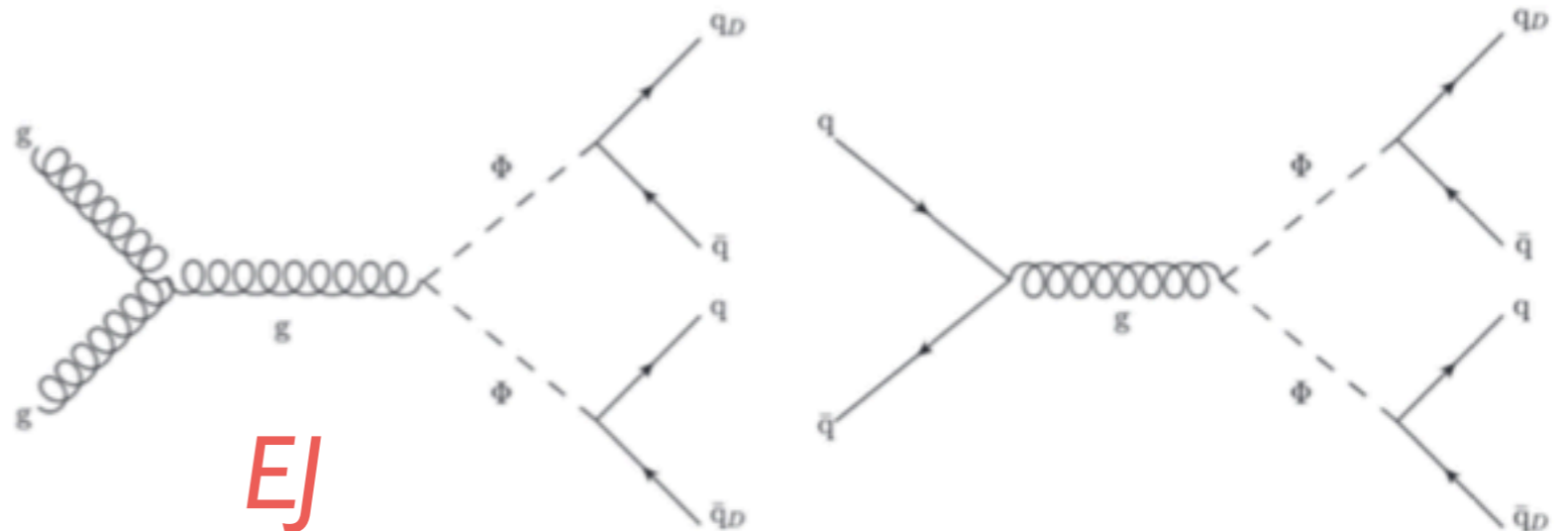<u>Only</u> MC available: Pythia Hidden Valley Module: Carloni, Sjöstrand et al 1006.2911, 1102.3795

s-channel (Z') production

$$\mathscr{L} \supset Z'_\mu (g_q \bar{q}_i \gamma^\mu q_i + g_{q_D} \bar{q}^\alpha_D \gamma^\mu q^\alpha_D)$$

SVJ

t-channel (bifundamental) production

$$\mathscr{L} \supset - \kappa_{\alpha i} q^\alpha_D \phi \bar{q}_{Ri} + h.c.$$

EJ

Aachen: Bernreuther, Kahlhöfer, Krämer,
Tunney 1907.04346
Cohen: Cohen, Listanti, Lou, 1503.00009

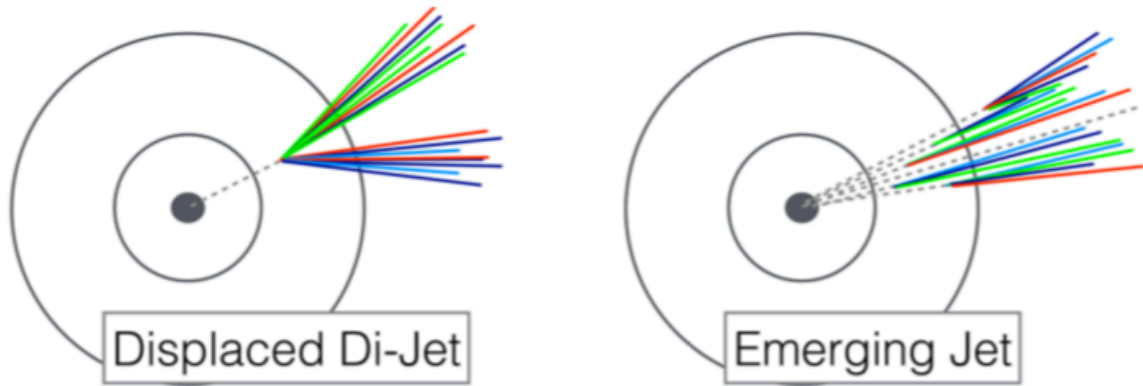unflavoured: single lifetime Schwaller, Stolarski, Weiler, 1502.05409
flavoured: lifetime hierarchy Schwaller, Renner, 1803.08080

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* for LHC-friendliness

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Reinterpreting CMS EJ search: bounding Exotic Higgs decays
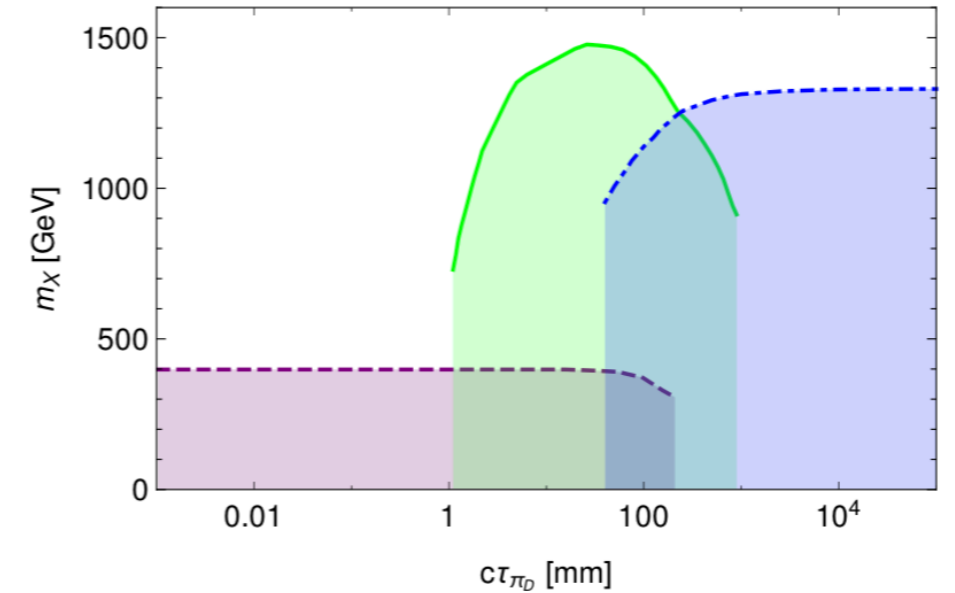
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Emerging jets

Dark mesons have a macroscopic lifetime, $c\tau \sim 10^{-3} - 1$ m.

For shorter (longer) lifetimes, multi-jet (missing energy) searches apply.

Displaced Di-Jet

Emerging Jet

unflavoured: single lifetime Schwaller, Stolarski, Weiler, 1502.05409
flavoured: lifetime hierarchy Schwaller, Renner, 1803.08080

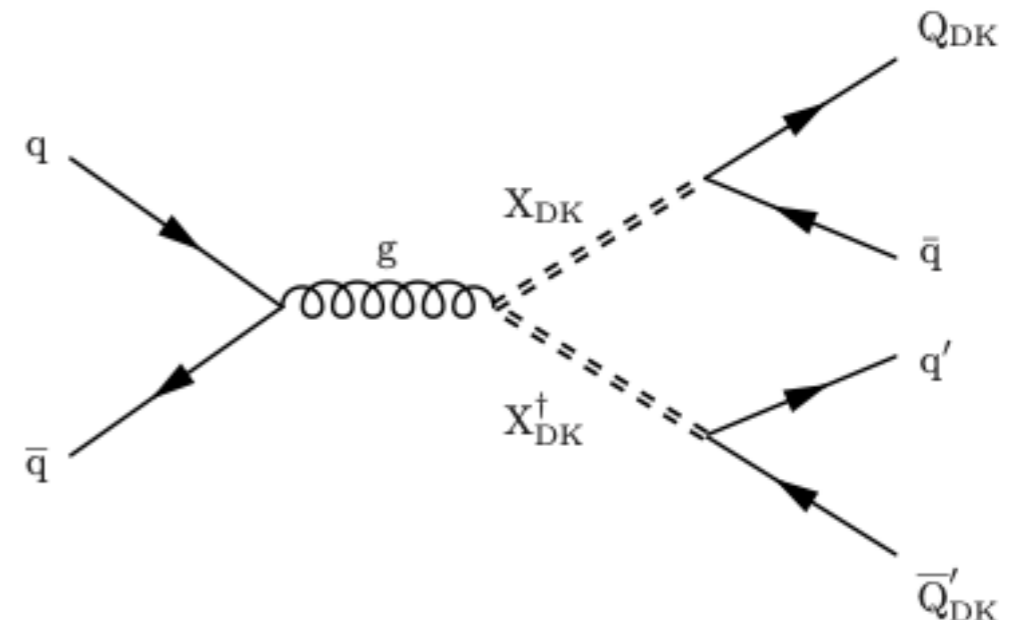Mies, Scherb, Schwaller, 2011.13990

-- - 4 jet search — jet+emerging jet search -- - MET search

CMS search: CMS Collaboration, 1810.10069*

Benchmark model SSW: $X_{DK} \rightarrow q\, Q_{DK}$

Trigger on $H_T > 900$ GeV

$m_{Q_{DK}} = \Lambda_D = 2m_{\pi_d} = 1/2 m_{\rho_d}$

Free parameters: $m_X, c\tau_{\pi_d}, m_{\pi_d}$

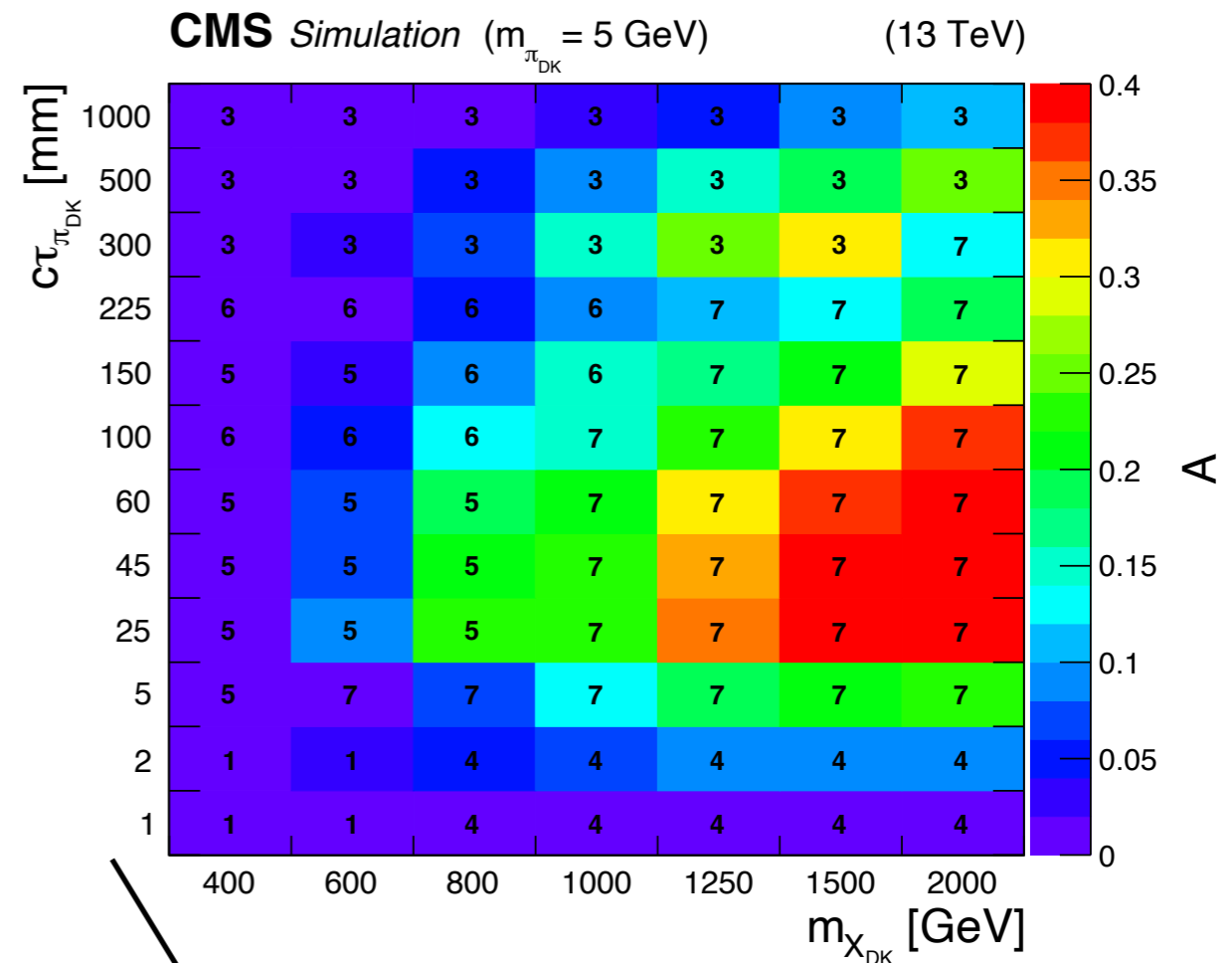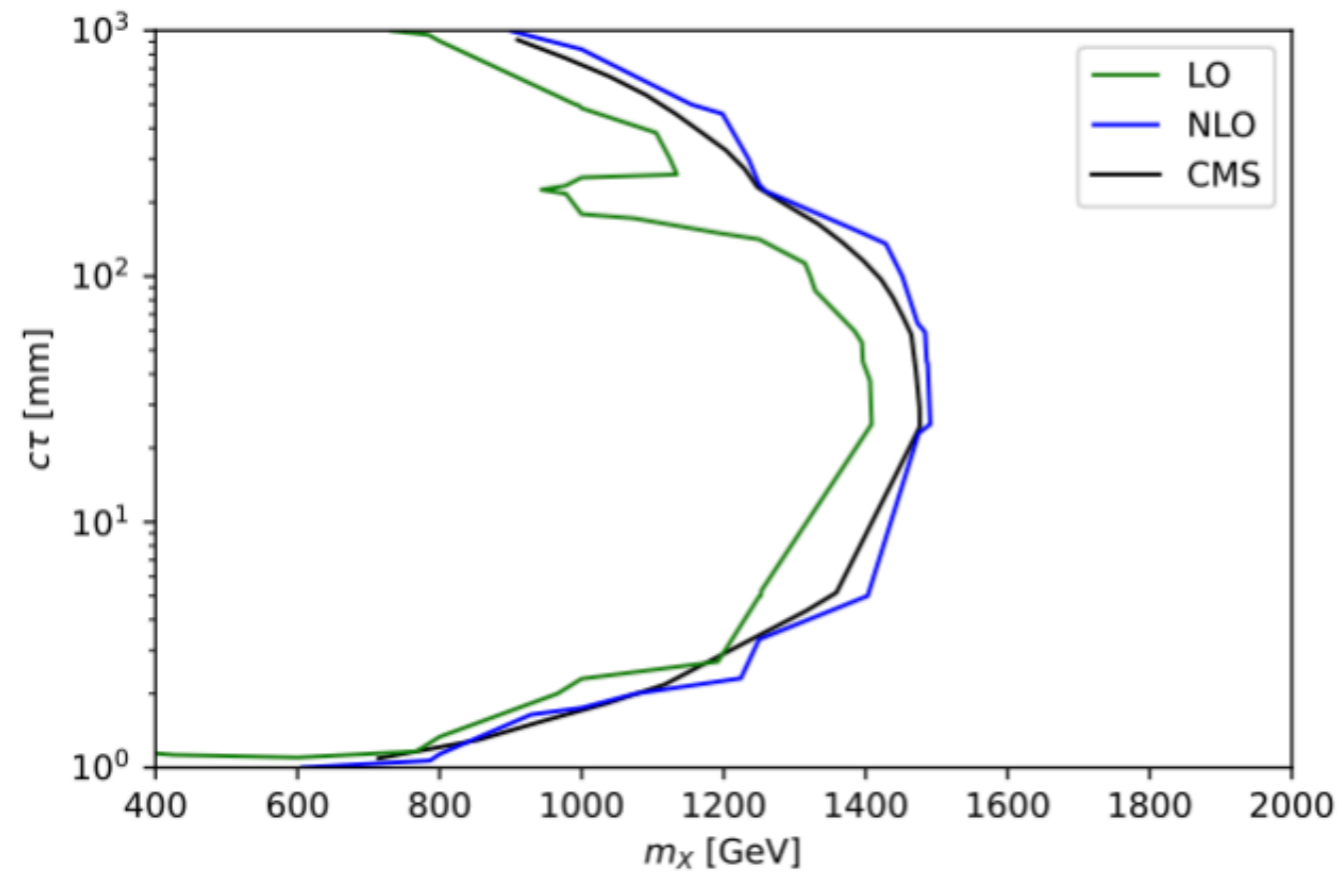José Zurita   *updated in 2403.01556 for different flavour structures [not included here!]

Validating CMS (I): Closure test

$$n_S^i = \sigma_{(pp \to XX)} \times BR(X \to qQ_D) \times \mathcal{A}_i \times L$$

NLO input
("LQ XS")

Set number	Expected			Observed	Signal	
1	168 $\pm$	15 $\pm$	5	131	36.7 $\pm$	4.0
2	31.8 $\pm$	5.0 $\pm$	1.4	47	(14.6 $\pm$	2.6)$\times 10^2$
3	19.4 $\pm$	7.0 $\pm$	5.5	20	15.6 $\pm$	1.6
4	22.5 $\pm$	2.5 $\pm$	1.5	16	15.1 $\pm$	2.0
5	13.9 $\pm$	1.9 $\pm$	0.6	14	35.3 $\pm$	4.0
6	9.4 $\pm$	2.0 $\pm$	0.3	11	20.7 $\pm$	2.5
7	4.40 $\pm$ 0.84 $\pm$ 0.28			2	5.61 $\pm$	0.64

For L =16.1fb^{-1}, $\sqrt{s}$ =13TeV

Good agreement with CMS!

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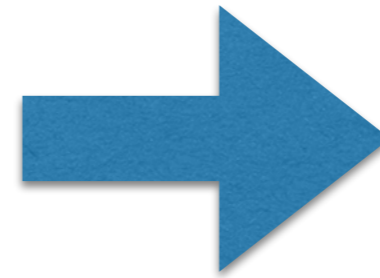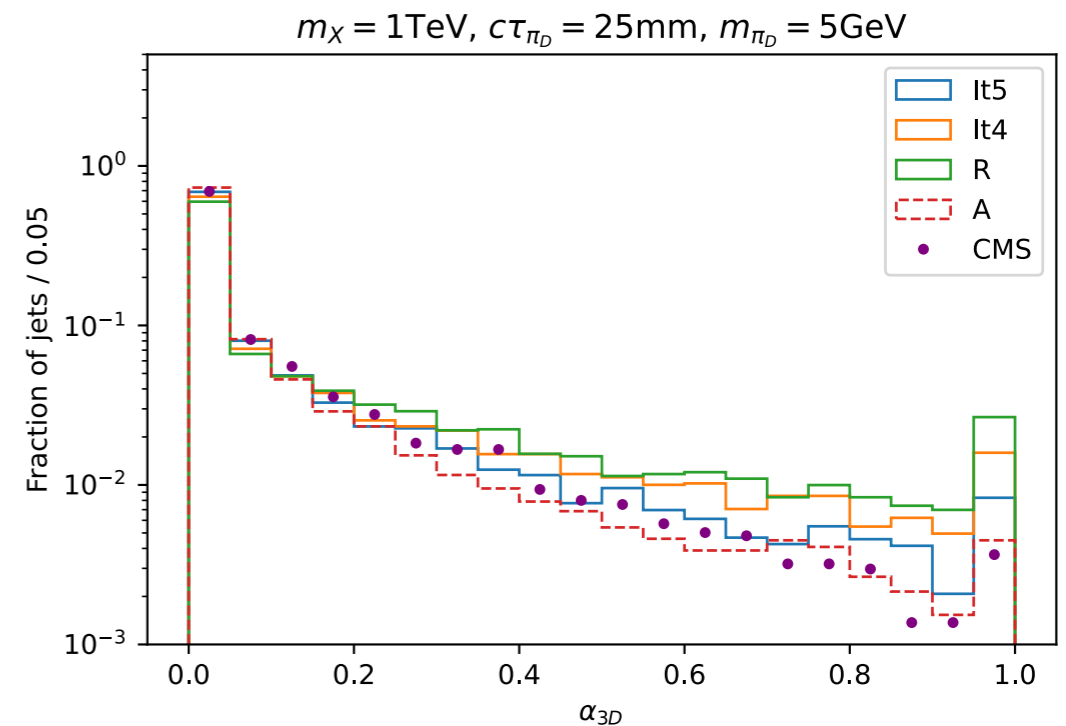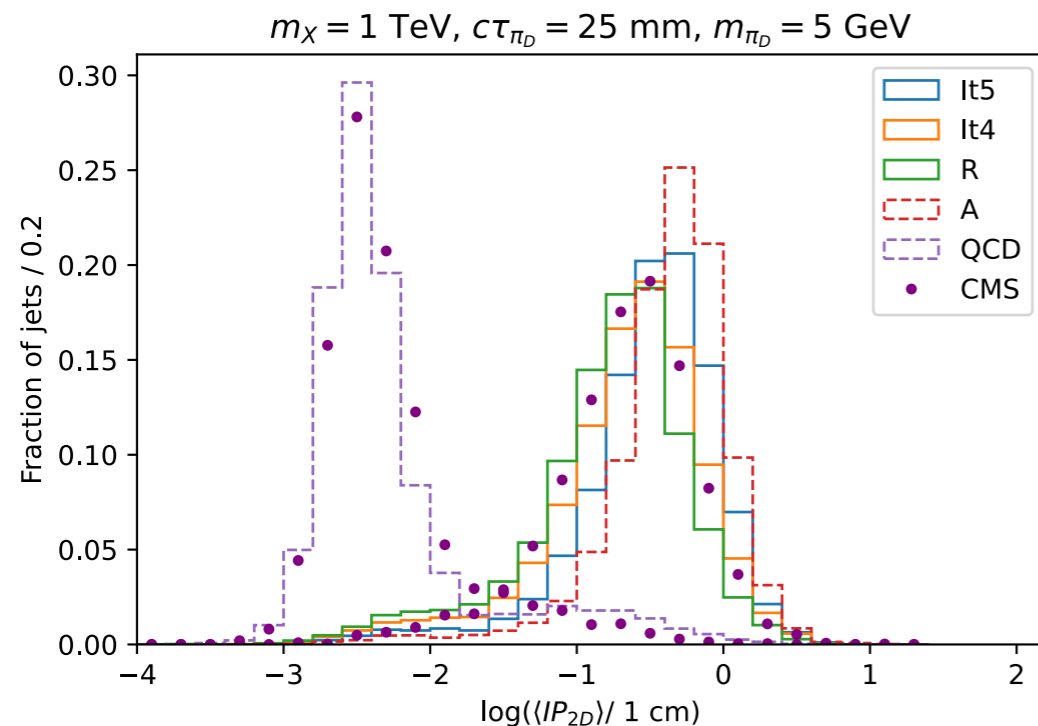
Please give us all SRs!

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Validating CMS (II): Kinematics

- Emerging Jet tagging variables:

  - $\langle IP_{2D} \rangle$: Median transverse impact parameter of associated tracks

  - α_{3D}: jet pT fraction associated to prompt tracks

  Need to consider different tracking efficiencies, often hard to parametrise
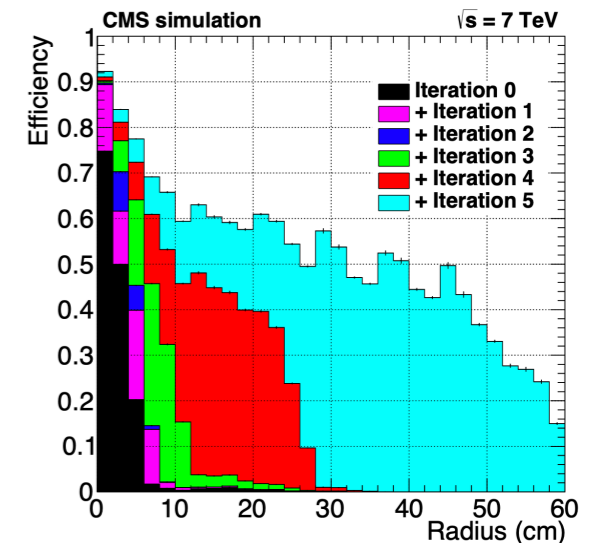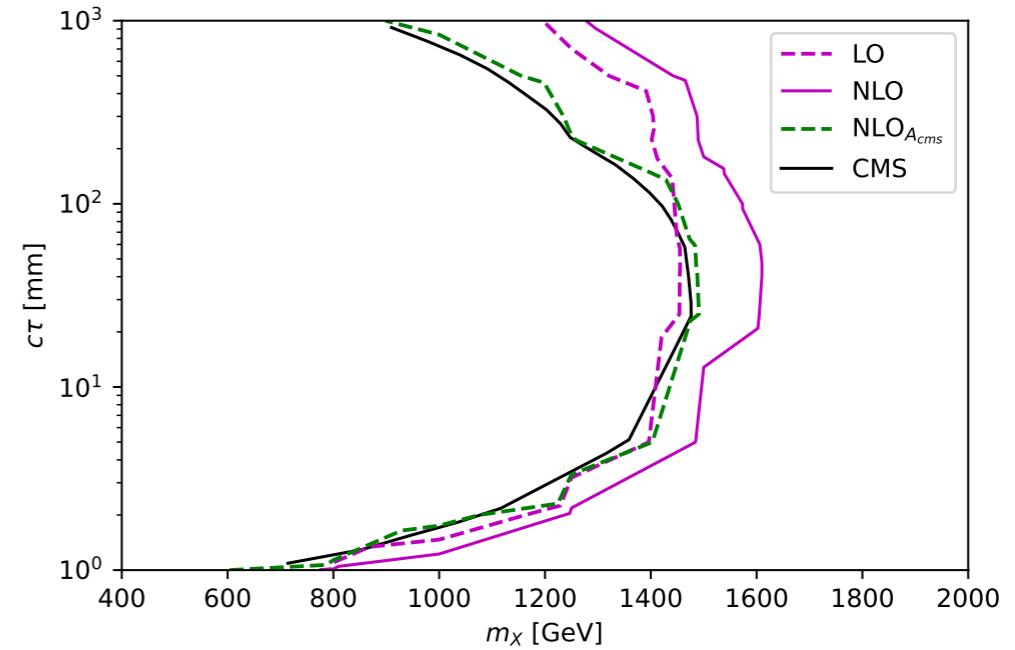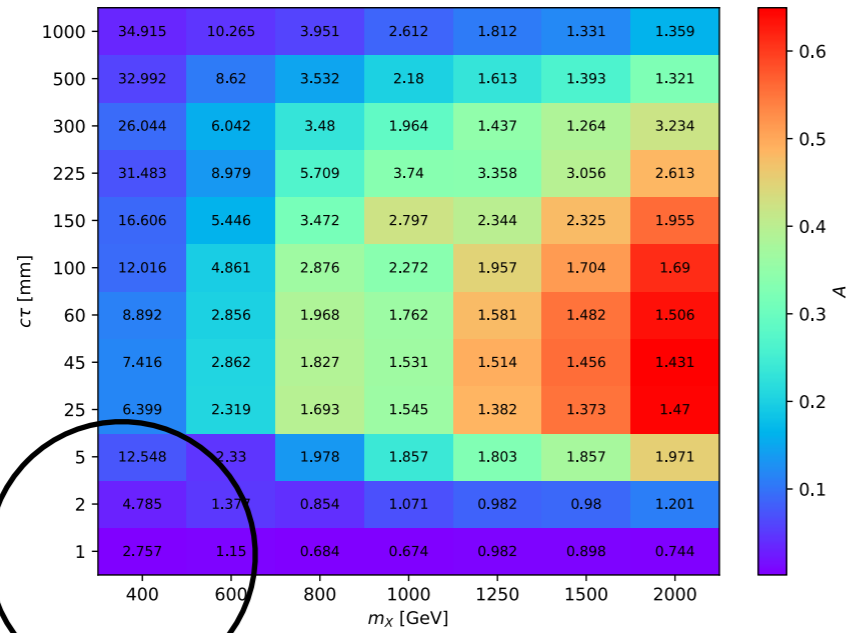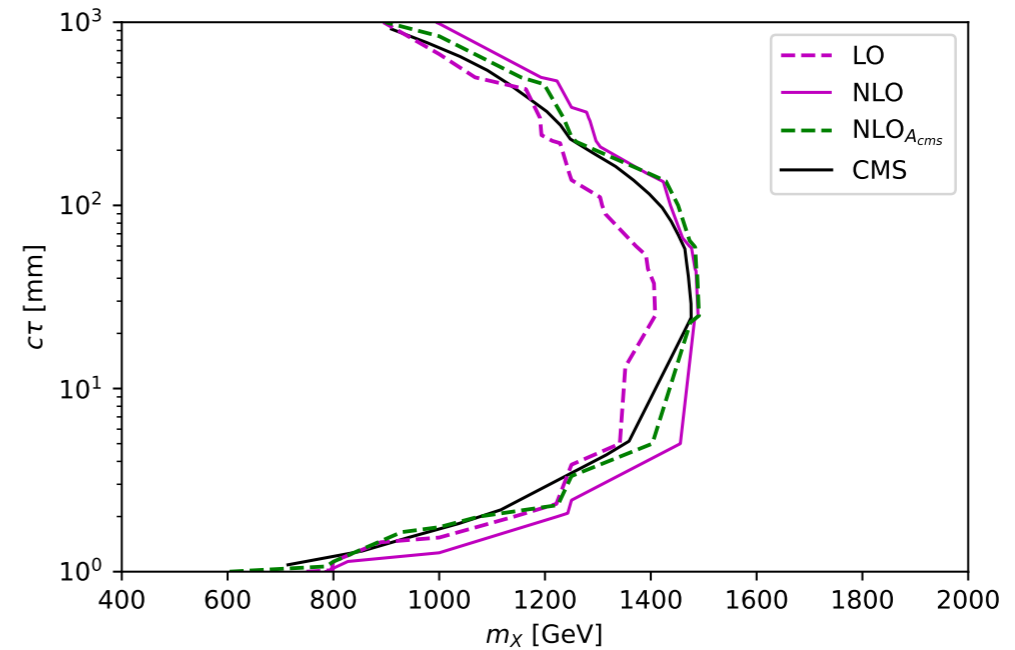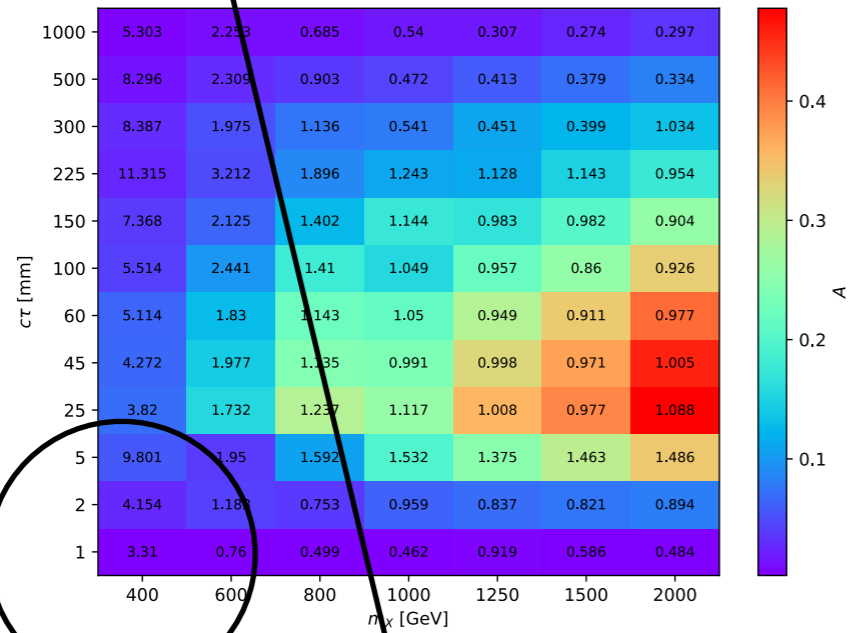

CMS Collaboration, 1405.6569

Agreement with CMS kinematic distributions

Validating CMS (III): Exclusion limits

It 5

R

ϵtrk(r) =
Θ(r− 102 mm).

Agreement less striking for low masses

EJ models beyond t-channel?

● Can we use the Z′ used in DMWG (and for SVJ)?
Z′ production and Z′ decay into qq given by the same coupling, so to have $Z' \rightarrow q_D \, q_D$ being long-lived the Z′ width must be feeble, rendering a production cross section absolutely negligible.

● But the SM Higgs works!
* Higgs production and the Higgs decay are not correlated
* Higgs data leaves room for O(10 %) non-SM (exotic) branching ratio.

Curtin et al, 1312.4992, Cepeda et al 2111.12751

+ SM Higgs XS ~ 50 pb
+ less free parameters (no mZ′, qqZ′ couplings)
o Must check how exotic Higgs decay searches impact!
- HT trigger is not ideal (~ 0.1 %)
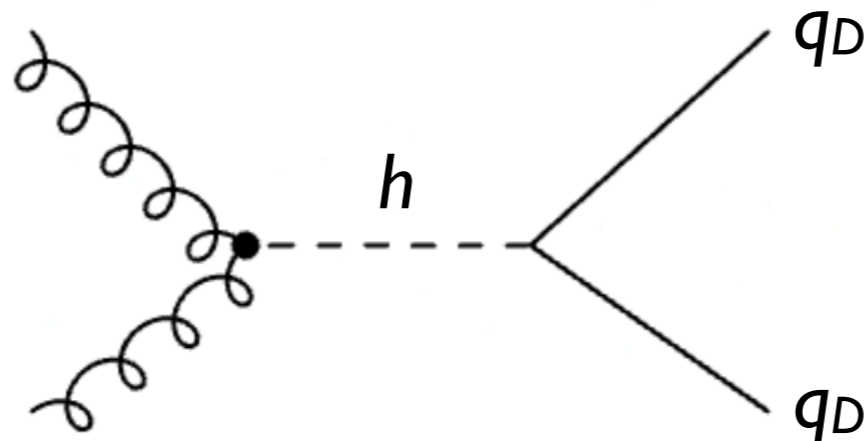
Reinterpretation: Exotic Higgs decays

$$n_S^i = \boxed{\sigma_{(pp \to h)}} \times BR(h \to Q_D Q_D) \times \boxed{\mathcal{A}_i} \times L$$
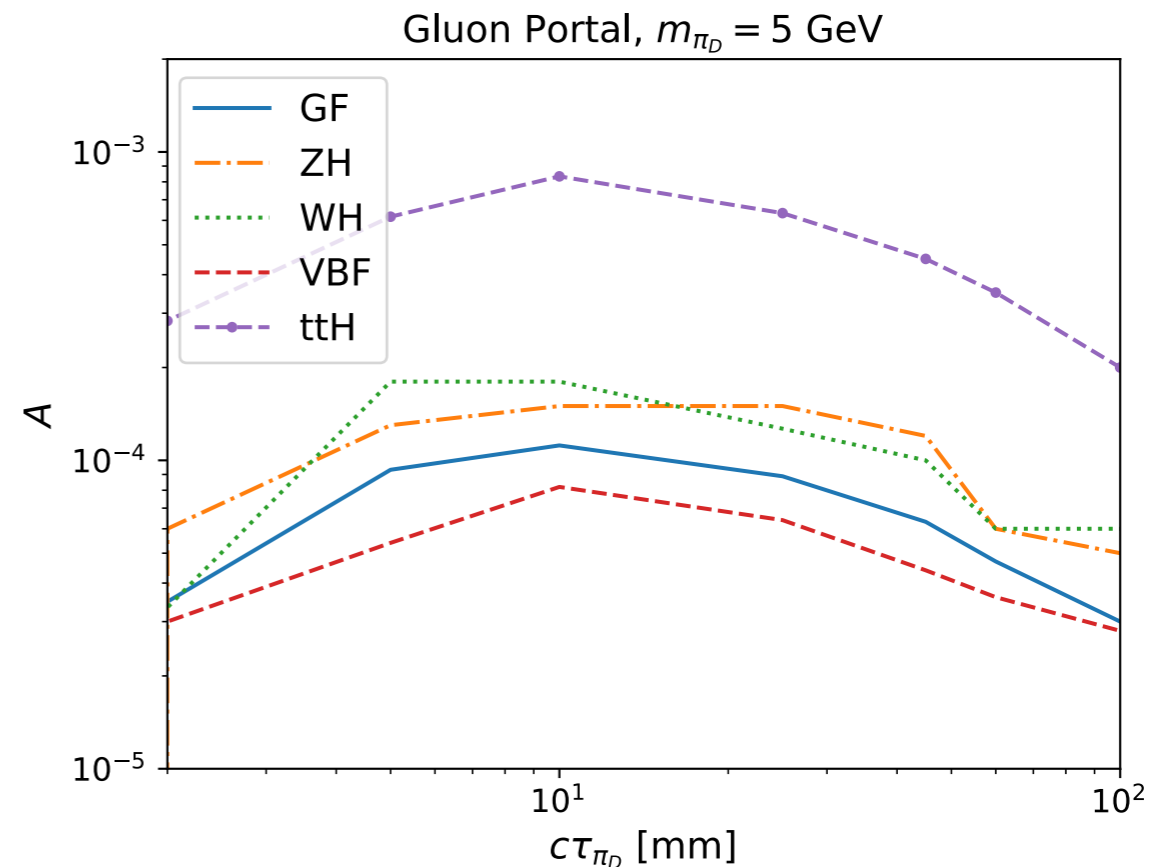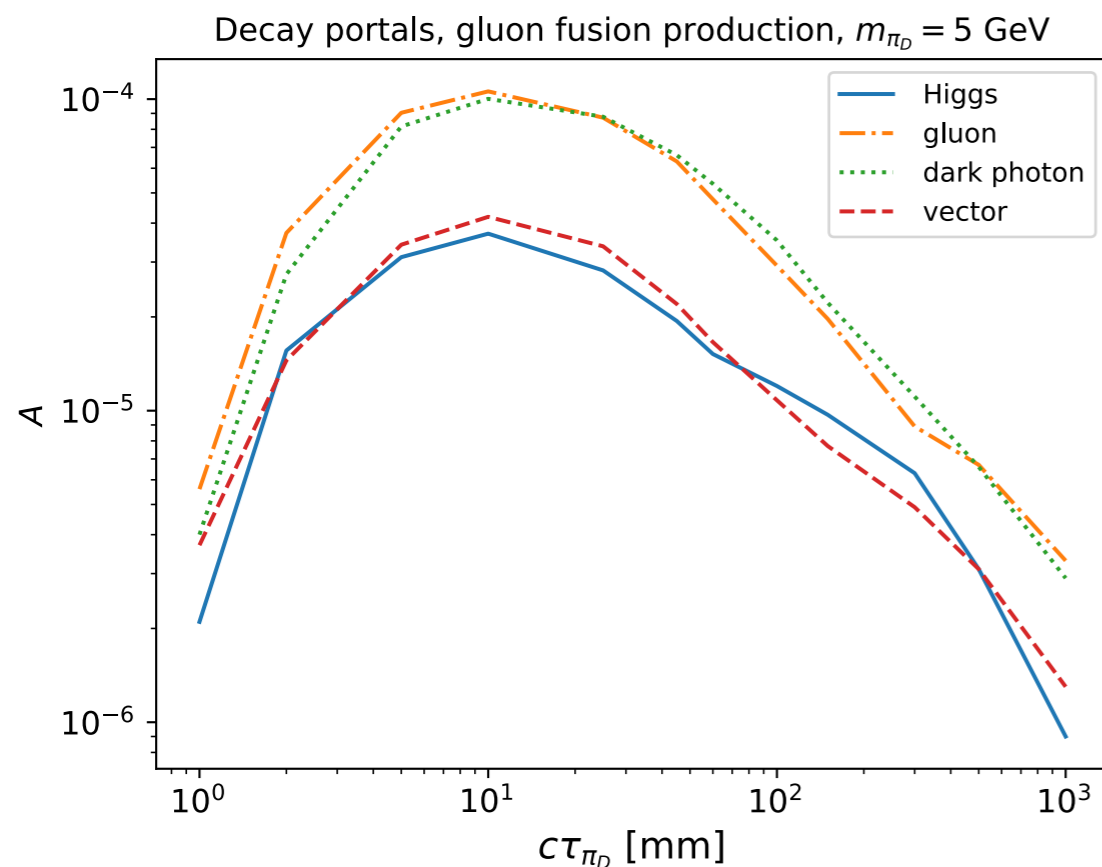
Our reinterpretation

SM Higgs boson, different production mechanisms. Values from YR4.

π_D decay into SM through *gluon, higgs, dark photon and vector* portals (see Knapen et al. 2103.01238).

$\pi_D G^{\mu\nu} \tilde{G}_{\mu\nu}$, $\pi_D H^\dagger H$, $\pi_D F'^{\mu\nu} \tilde{F}_{\mu\nu}$, $\rho_D^{\mu\nu} F_{\mu\nu}$

Decay portals, gluon fusion production, $m_{\pi_D} = 5$ GeV

Legend: Higgs, gluon, dark photon, vector

Gluon Portal, $m_{\pi_D} = 5$ GeV

Legend: GF, ZH, WH, VBF, ttH

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Bounds on Exotic Higgs decays

Current indirect bounds on Exotic Higgs branching fraction, $BR(h \to Q_D Q_D) < 0.16$
at 95%CL with 139 fb^{-1}, and $\sqrt{s}$ =13TeV ATLAS-CONF-2021-053, CMS arXiv: 2207.00043

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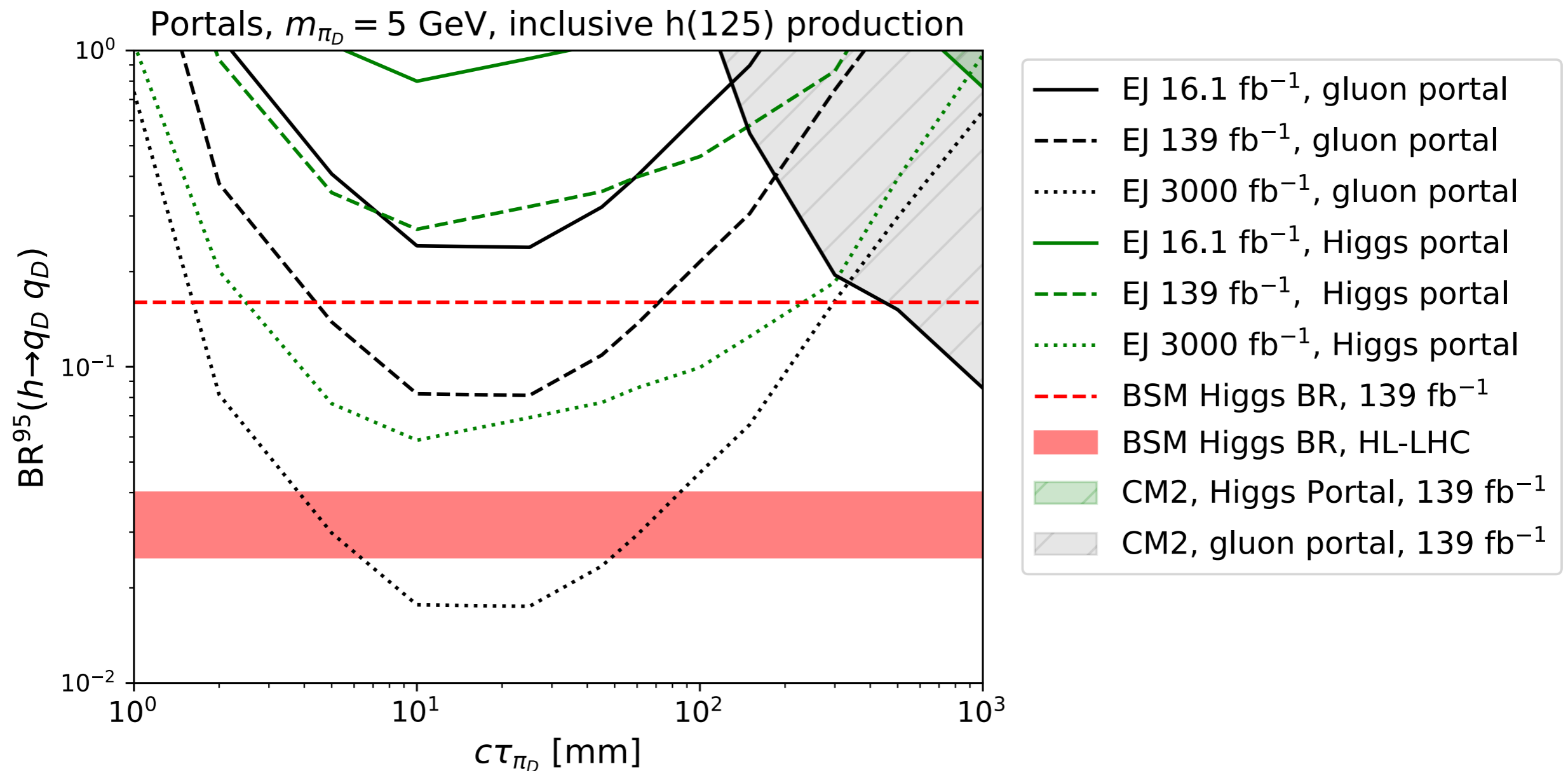
Conclusions

- Strongly interacting dark sectors are theoretically motivated scenarios with conspicuous signatures at colliders, such as semi-visible jets, emerging jets, soft-unclustered energy patterns, etc.

- Ongoing campaign on the theory, phenomenological and experimental fronts (G.Albouy et al, arXiv 2203.09503, J. Butterworth et al arXiv:2311.16330).

- I discussed our attempts to validate the CMS emerging jet search, reproducing the published limits.

- Reinterpretation procedure applied to Higgs mediated dark showers, and are competitive with model-independent Exotic Higgs decays bounds.

"All these theories, diverse as they are, have two things in common: they explain the observed facts, and they are completely and utterly wrong."

TERRY PRATCHETT, The Light Fantastic