Emerging jet probes of strongly interacting dark sectors

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Largely based on:

Theory, phenomenology and experimental avenues for dark showers: a Snowmass 2021 report, G.Albouy et al, arXiv 2203.09503.

Emerging jet probes of strongly interacting dark sectors, J. Carrasco, JZ, arXiv:2307.04847 (sent to JHEP)

The 20th Workshop of the LHC Higgs Working Group, 15.11.2023

Outline

- Strongly interacting dark sectors
- Dark Showers: collider signatures
- Reinterpreting the CMS Emerging Jet search: bounding Exotic Higgs decays

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)

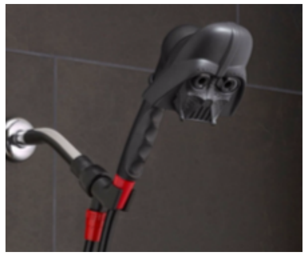
- Collider phenomenology <u>highly dependent</u> on $m_{q_D}, \Lambda_D, \sqrt{s}$ hierarchies

<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>

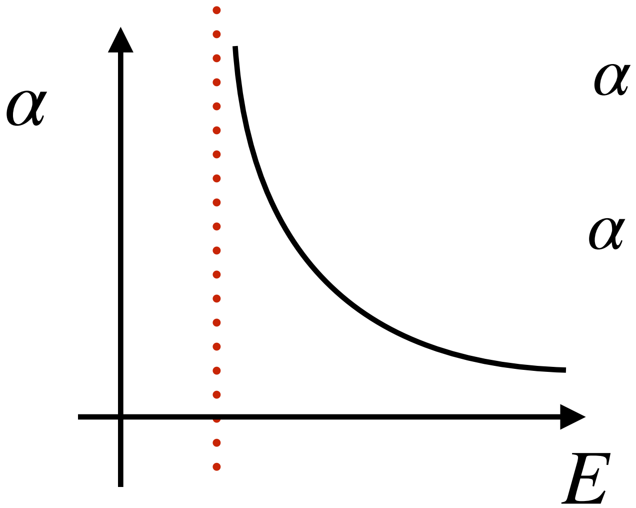


Dark showers: This talk!

Dark bound states: resonances

Quirks

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) $E \lesssim \Lambda_{QCD}$

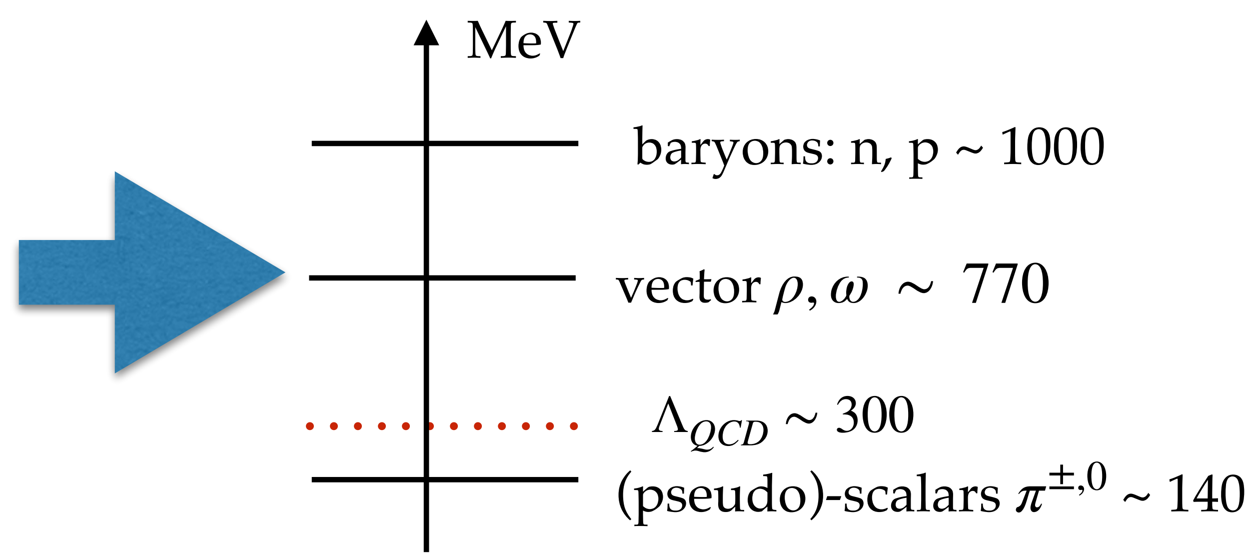
From the Lagrangian parameters m_{q_D}, g_D (α_D) one cannot reliably (perturbatively) compute hadron masses: lattice QCD

IR perspective:

$N_f = 2$ (m_s~ 100 MeV, K~500 MeV are missing)

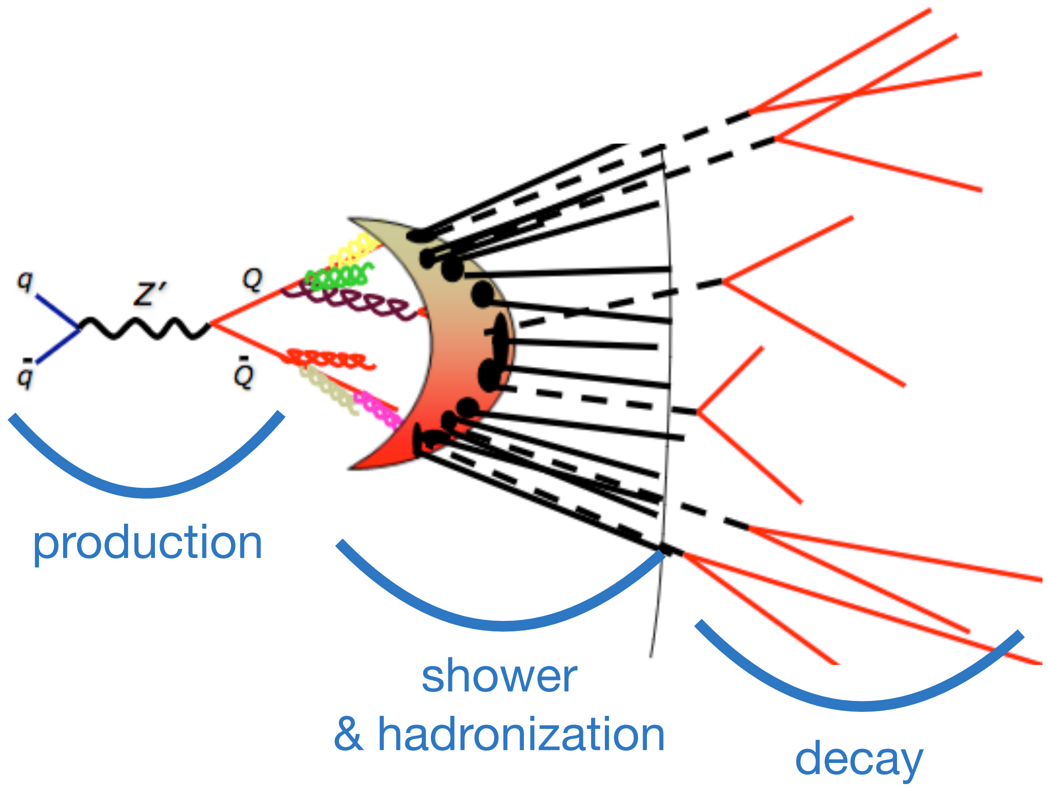
Expect $N_f^2 - 1$=3 mass degenerate "π, ρ"
with same lifetime (but we can't turn off QED!)

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



Dark Showers:
Collider Signatures

Dark showers: anatomy



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

DS production: models

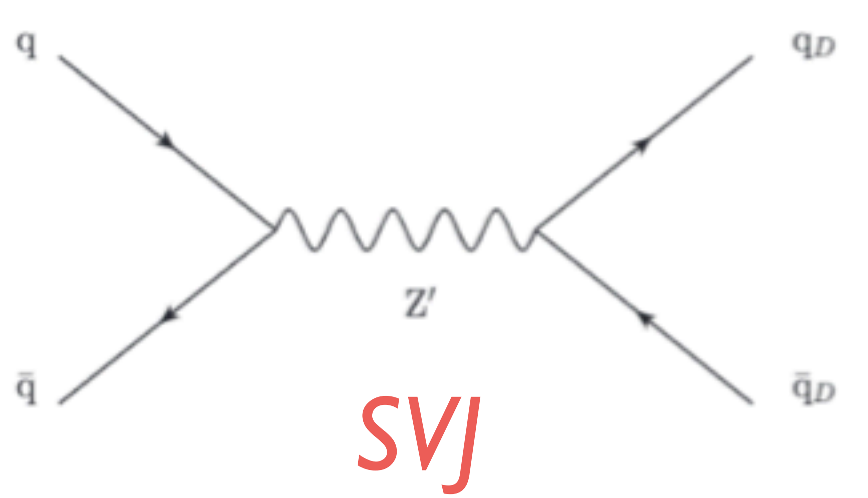
Production requires* a *portal* connecting the dark and the visible (SM) sectors.

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

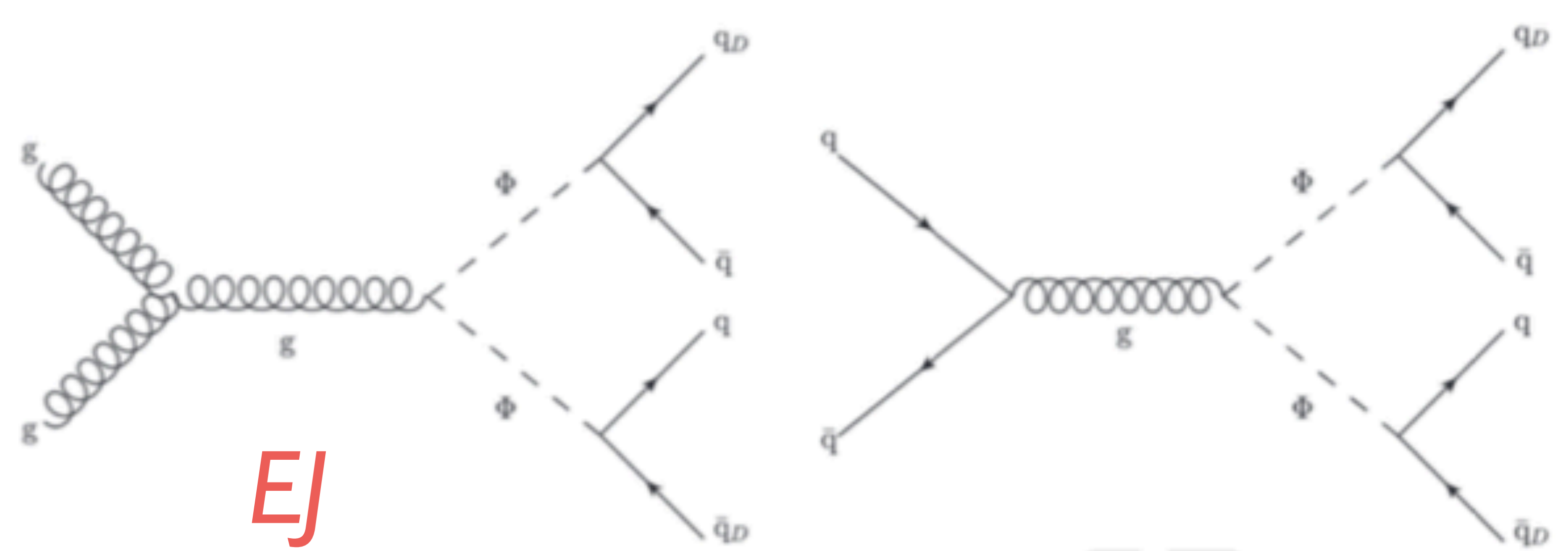
s-channel (Z') production

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



t-channel (bifundamental) production

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



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

* for LHC-friendliness

Dark showers@LHC

Semi-visible jets (SVJ):

- ✦ CMS: *Search for resonant production of strongly coupled dark matter in proton–proton collisions at 13 TeV*, JHEP 06 (2021) 156, arXiv: 2112.11125
- ✦ ATLAS (I): *Search for non-resonant production of semi-visible jets using Run 2 data in ATLAS*, arXiv: 2305.18037
- ✦ ATLAS (II): *Search for Resonant Production of Dark Quarks in the Dijet Final State with the ATLAS Detector*, arXiv:2311.03944

Emerging jets (EJs):

- ✦ CMS: *Search for new particles decaying to a jet and an emerging jet*, JHEP 02 (2019) 179, arXiv: 1810.10069

- EXP: More to come from ATLAS, CMS and LHCb!!!
  PHENO: MITP Colours in Darkness workshop summary report, arXiv:2311.vsoon

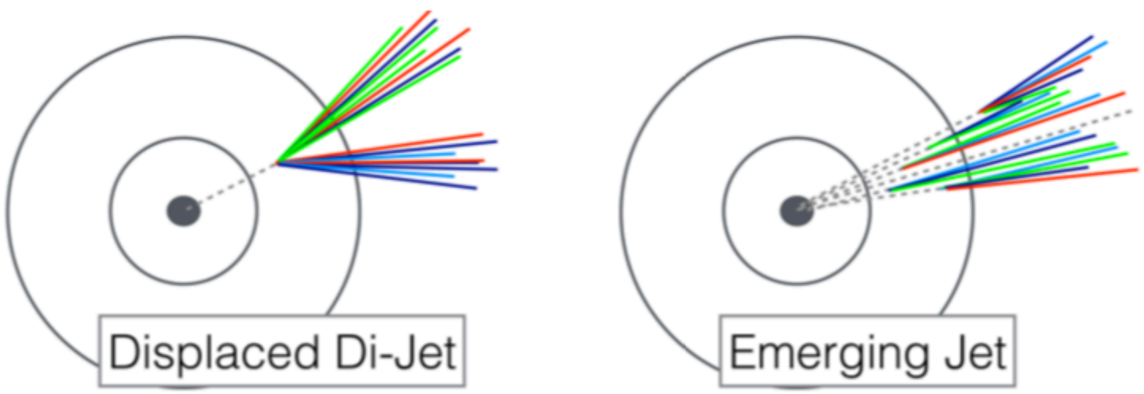
This talk: general reinterpretation of CMS EJ search, and application to Higgs-mediated dark showers.

Reinterpreting CMS EJ search: bounding Exotic Higgs decays

Emerging jets

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

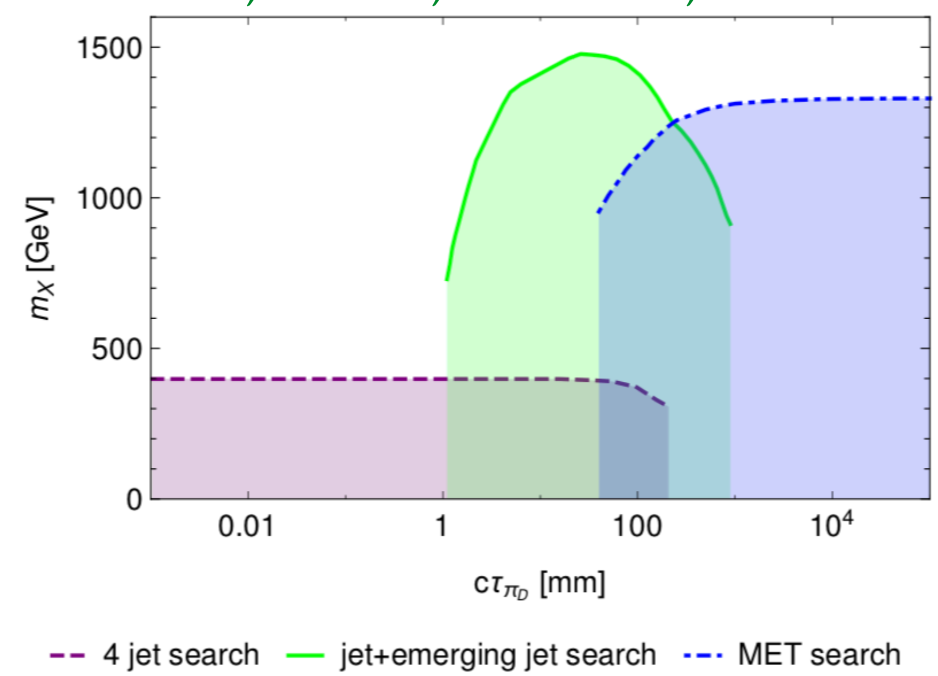
For shorter (longer) lifetimes, multi-jet (missing energy) searches apply.



unflavoured: single lifetime Schwaller, Stolarski, Weiler, 1502.05409

flavoured: lifetime hierarchy Schwaller, Renner, 1803.08080

Mies, Scherb, Schwaller, 2011.13990



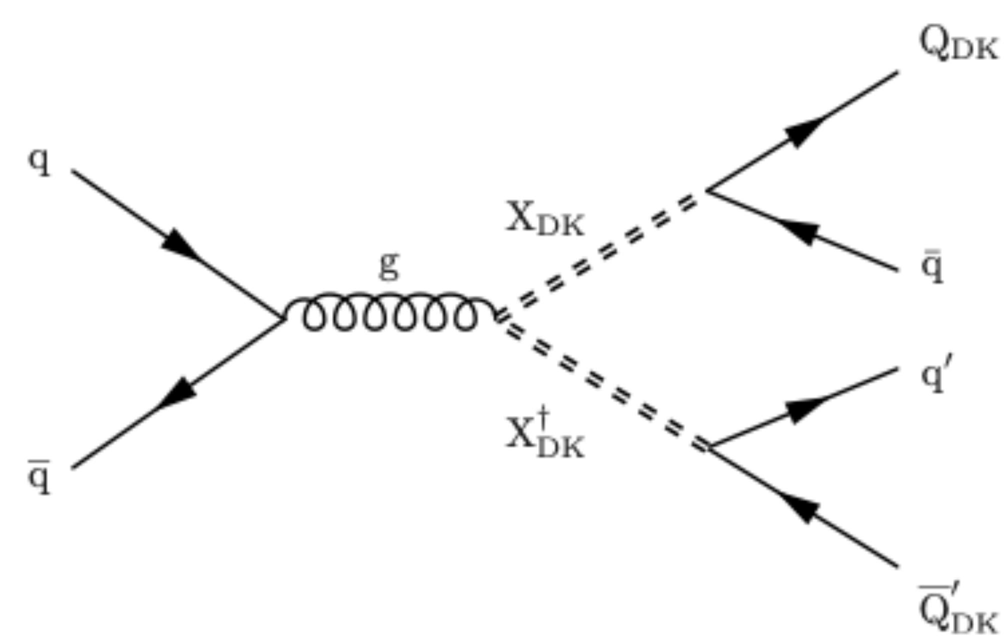
<u>CMS search:</u> CMS Collaboration, 1810.10069

Benchmark model SSW: X_{DK} -> q Q_{DK}

Trigger on $H_T > 900$ GeV

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

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



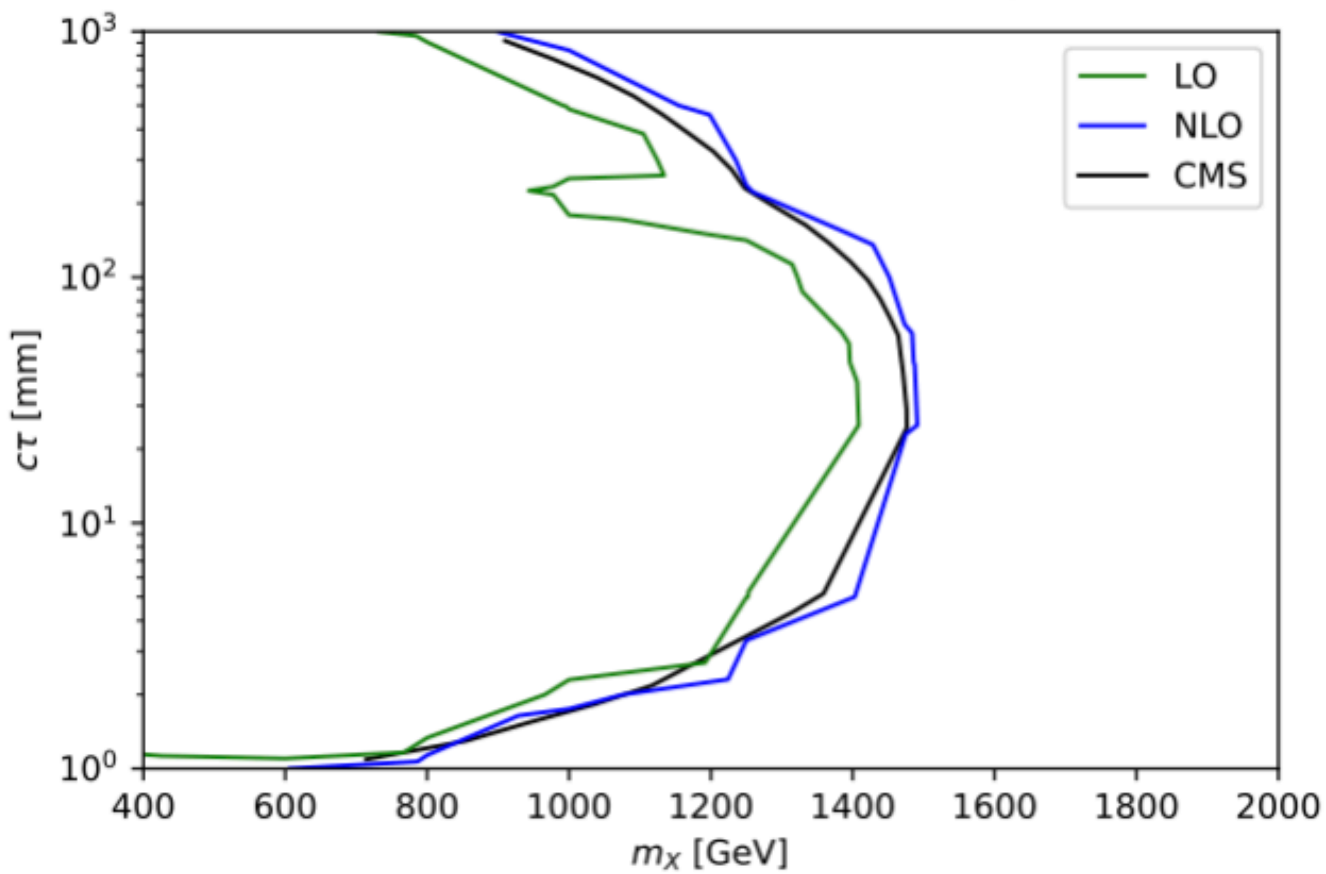
Validating CMS (I): Closure test

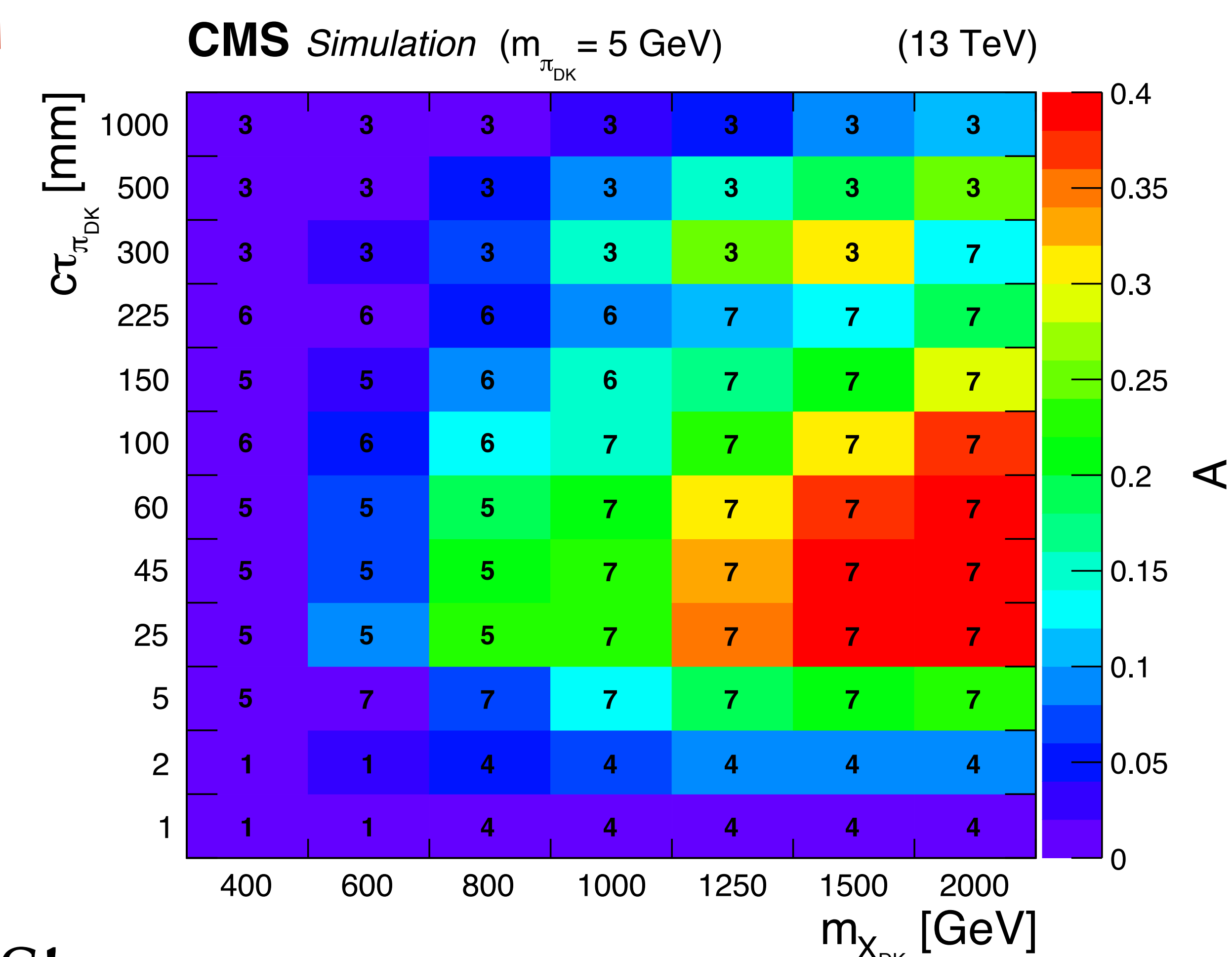
$$n_S^i = \sigma_{(pp \to XX)} \times BR(X \to qQ_D) \times \mathcal{A}_i \times L$$

NLO input ("LQ XS")

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

Set number	Expected	Observed	Signal
1	$168 \pm 15 \pm 5$	131	36.7 ± 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 ± 1.6
4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0
5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0
6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5
7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64



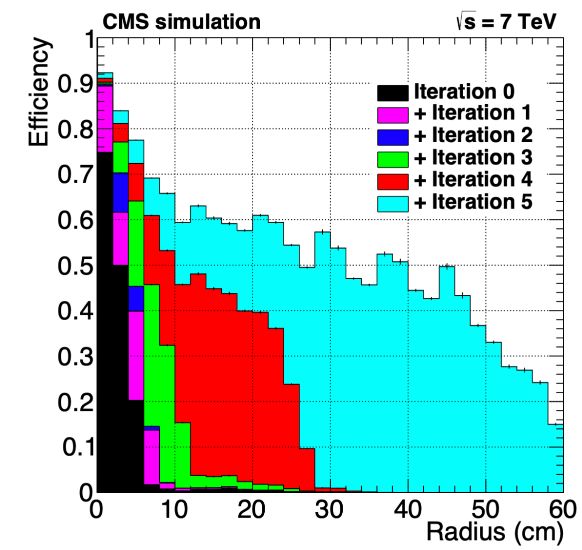


Good agreement with CMS!

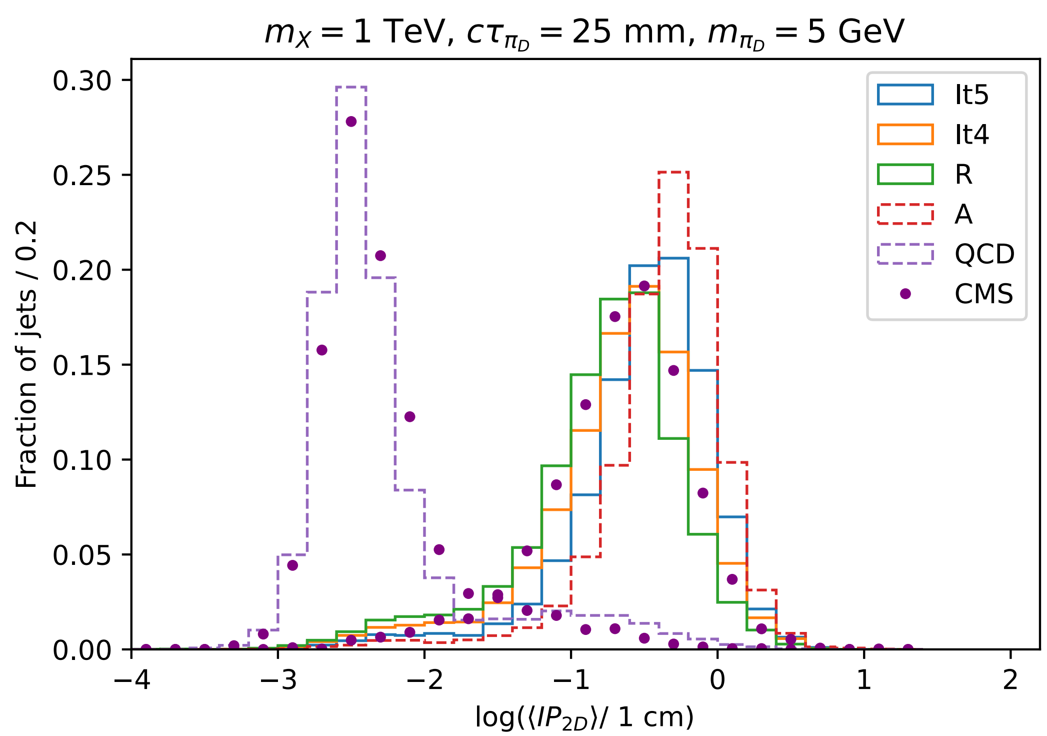
Validating CMS (II): Kinematics

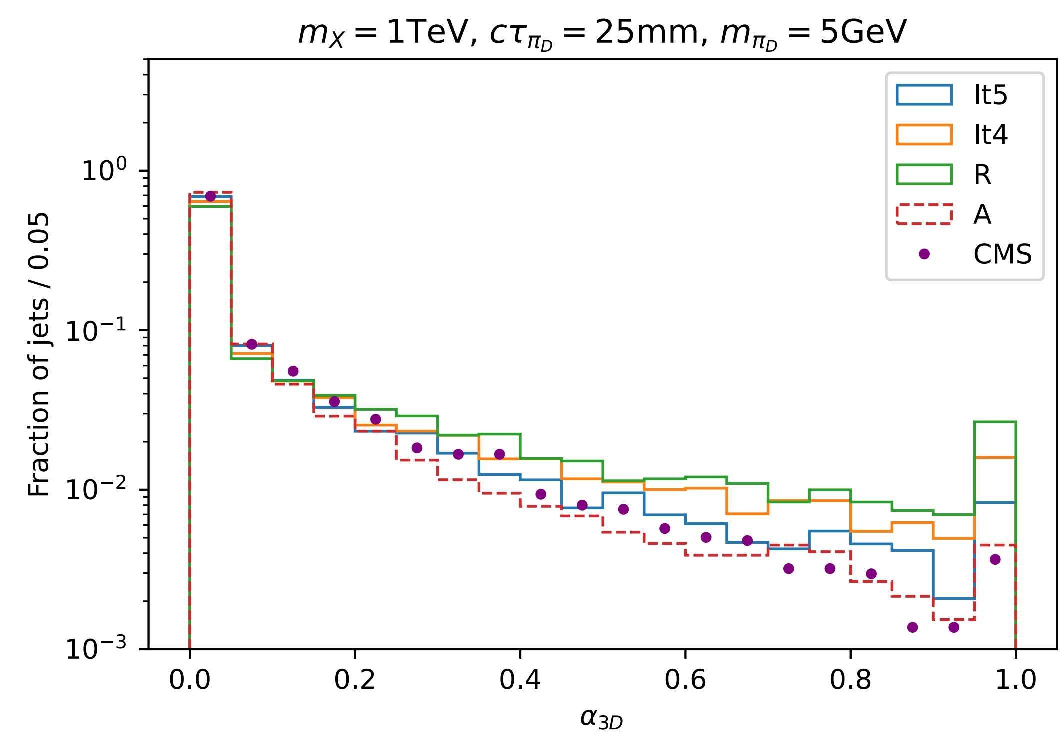
- Emerging Jet tagging variables:
  - $\langle IP_{2D} \rangle$: Median transverse impact parameter of associated tracks
  - α_{3D}: jet pT fraction associated to prompt tracks

Need to consider different tracking efficiencies, often hard to parametrise



CMS Collaboration, 1405.6569





Agreement with CMS kinematic distributions

Validating CMS (III): Exclusion limits

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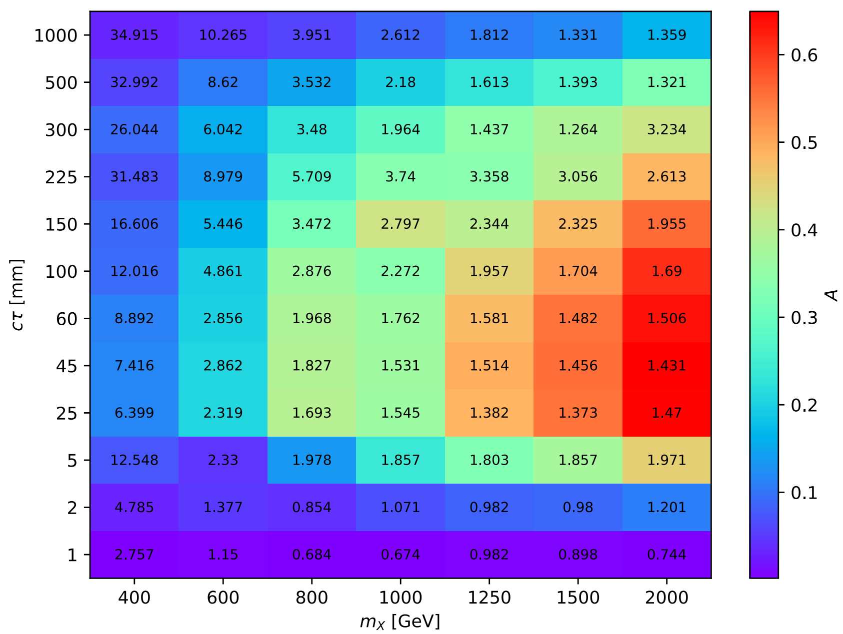

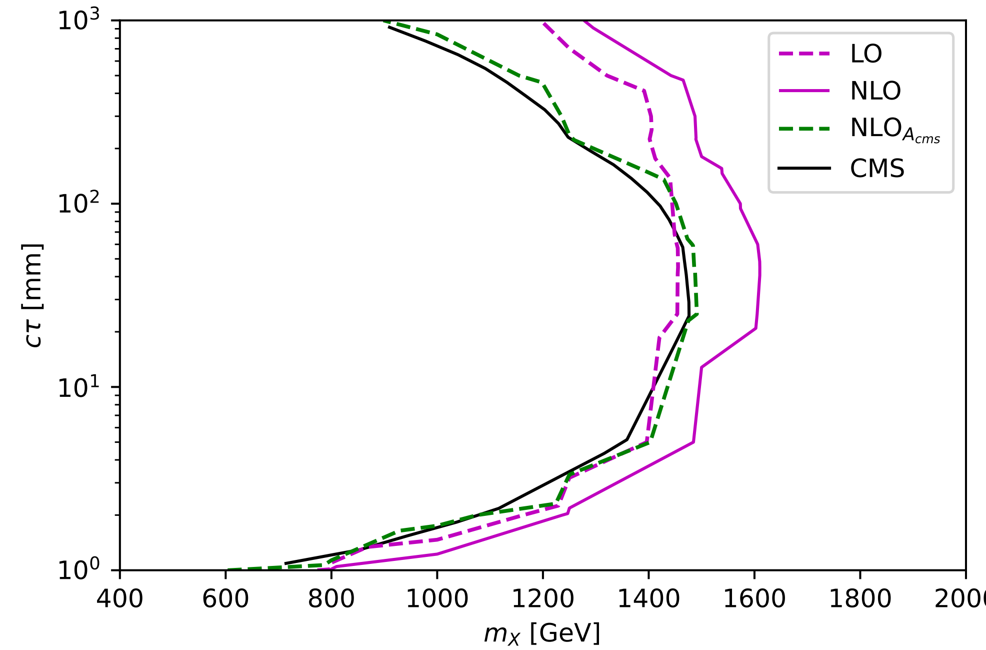

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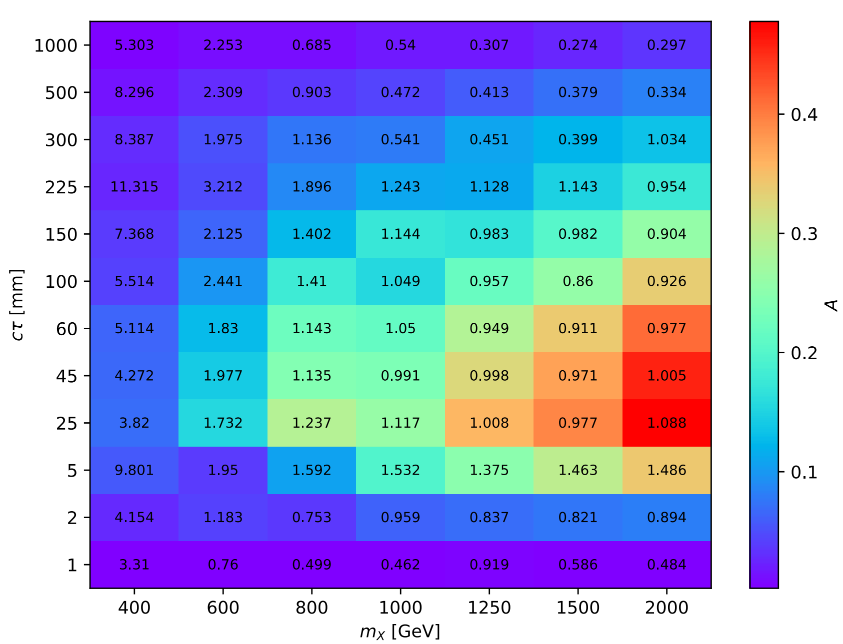
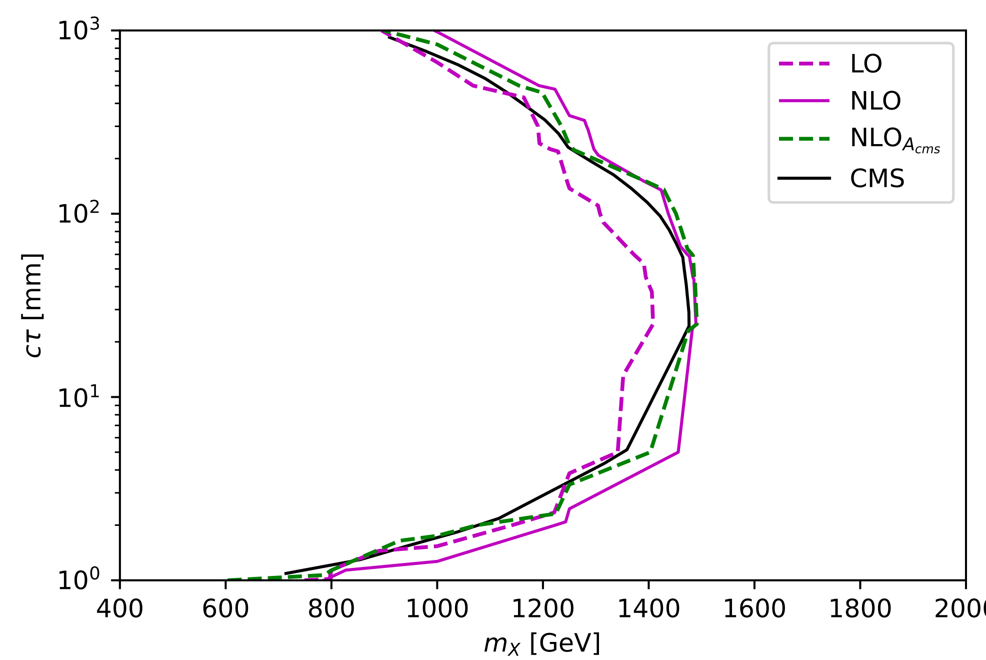




Reinterpretation: Exotic Higgs decays

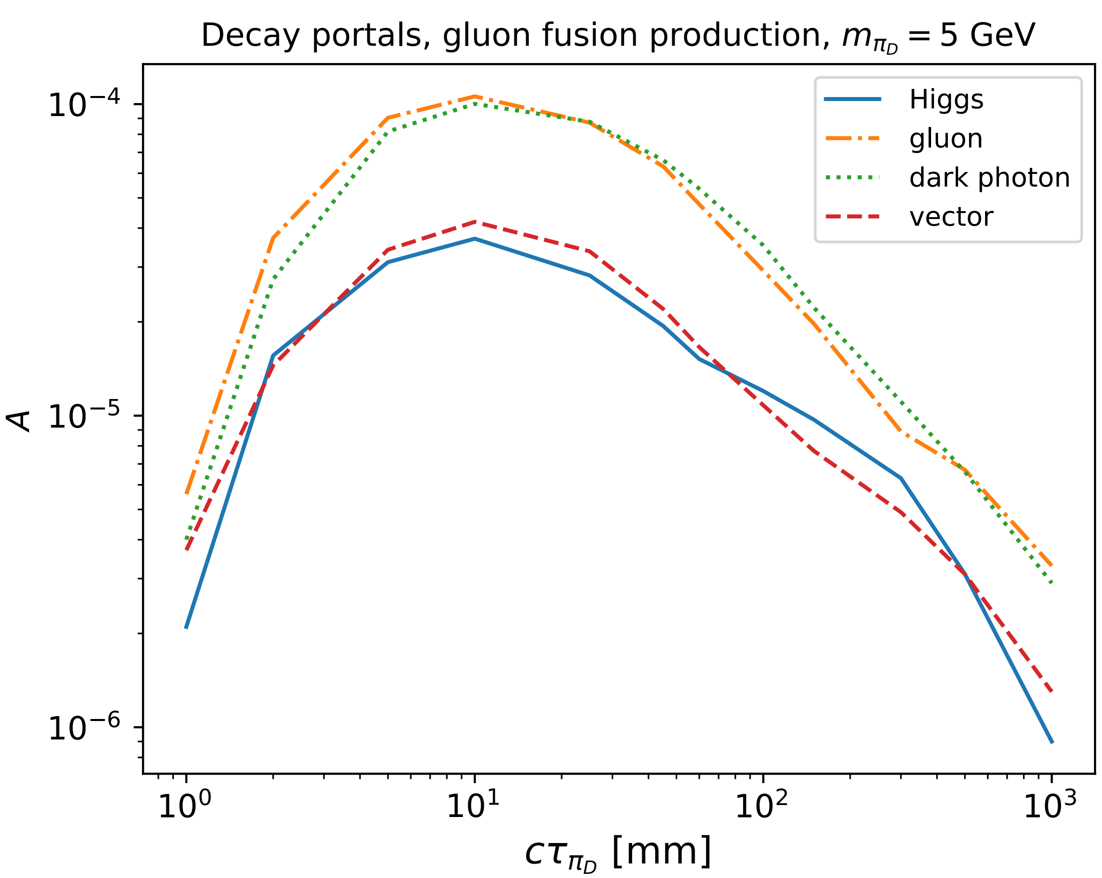
$$n_S^i = \sigma_{(pp \to h)} \times BR(h \to Q_D Q_D) \times \mathscr{A}_i \times L$$

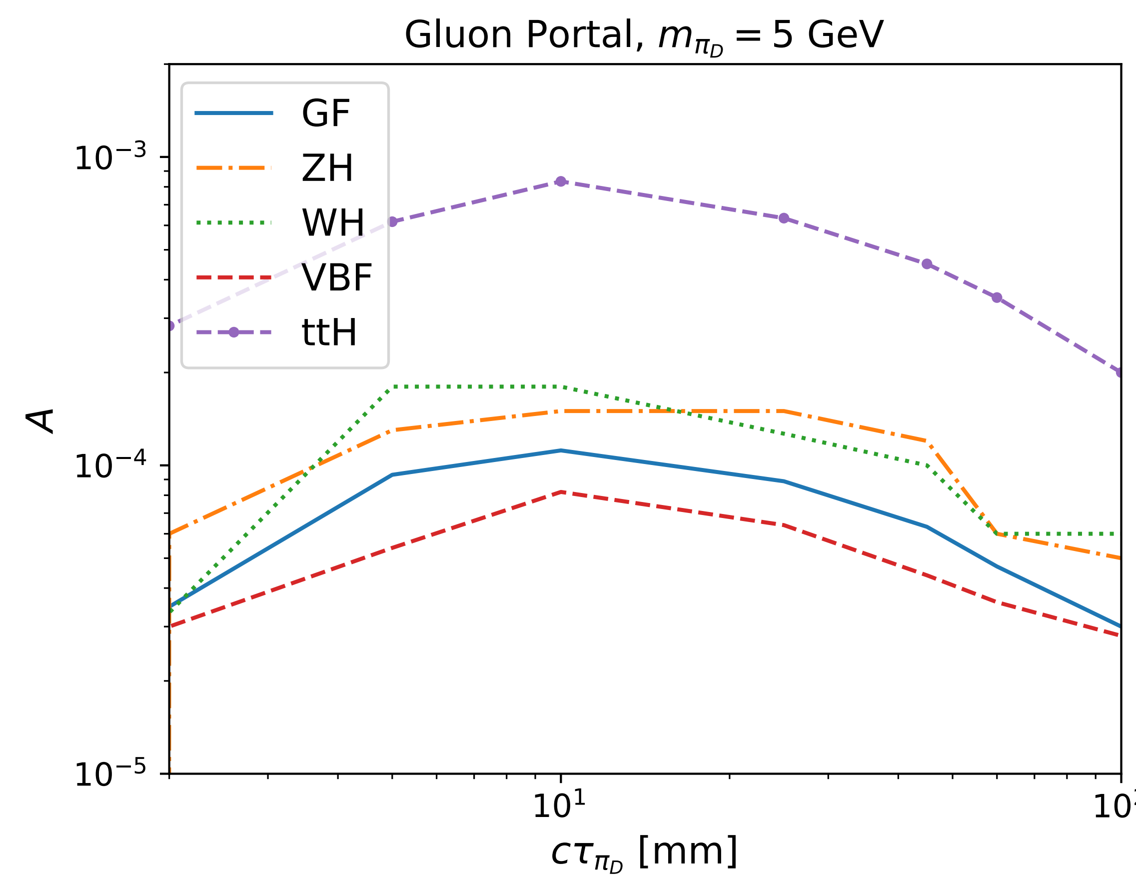
Our reinterpretation

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

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

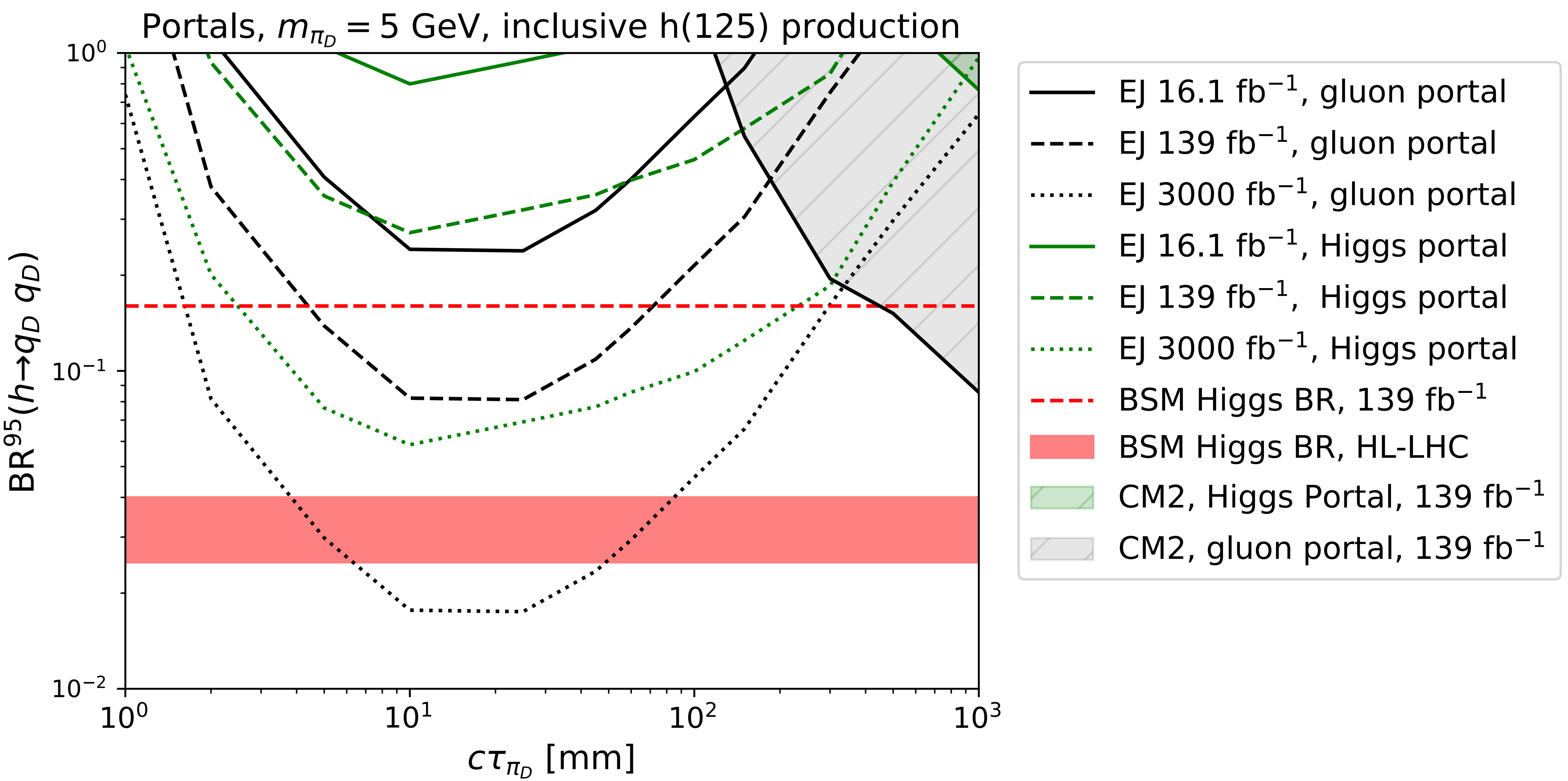
$$\pi_D G^{\mu\nu} \tilde{G}_{\mu\nu} \;, \pi_D H^\dagger H \;, \pi_D F'^{\mu\nu} \tilde{F}_{\mu\nu} \;, \; \rho_D^{\mu\nu} F_{\mu\nu}$$





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



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, S. Sinha et al arXiv:2311.vsoon)
- 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