Emerging jet probes of strongly interacting dark sector

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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, JHEP 01 (2024) 034.

8th Red LHC Workshop, 29.05.2024

Outline

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

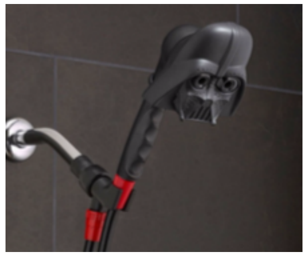
Strongly interacting dark sectors

Motivation

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

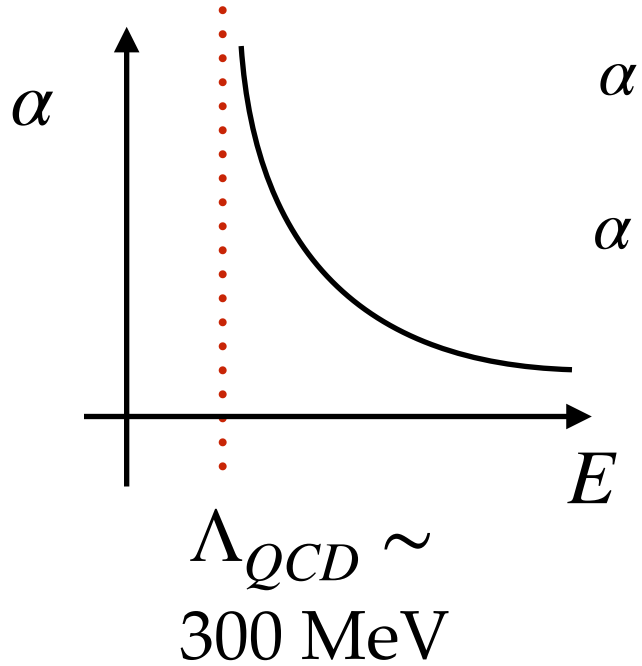
Strassler, Zurek, hep-ph/0604261

- 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 highly dependent on $m_{q_D}, \Lambda_D, \sqrt{s}$ hierarchies



Mass hierarchy		Signatures
1. $m_{q_D} \lesssim \Lambda_D \ll \sqrt{s}$	→	Dark showers: This talk!
2. $m_{q_D} \lesssim \Lambda_D \approx \sqrt{s}$		Dark bound states: resonances
3. $m_{q_D} \gg \Lambda_D \lesssim \sqrt{s}$		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) $E \lesssim \Lambda_{QCD}$

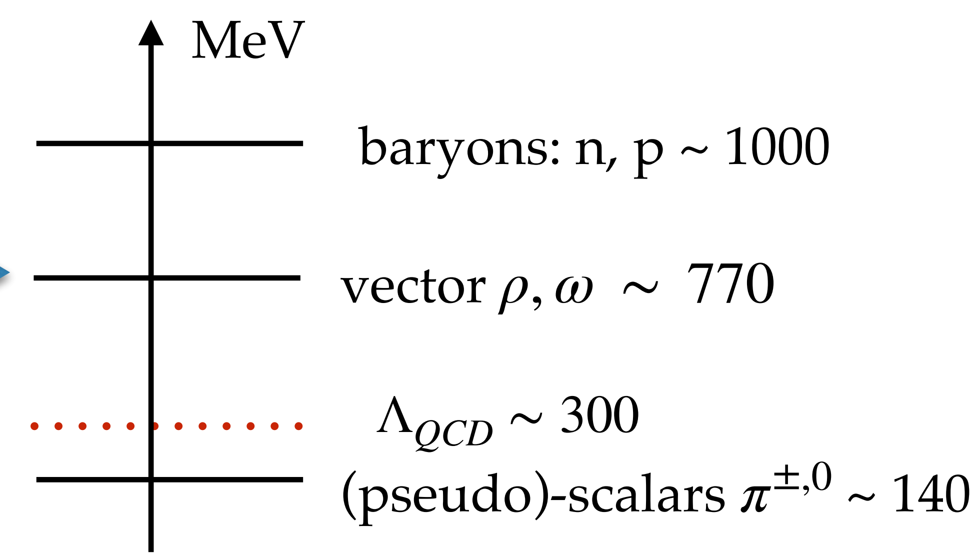
From the Lagrangian parameters m_{q_D}, g_D (α_D) one cannot reliably (perturbatively) compute hadron masses: lattice QCD

IR perspective:

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

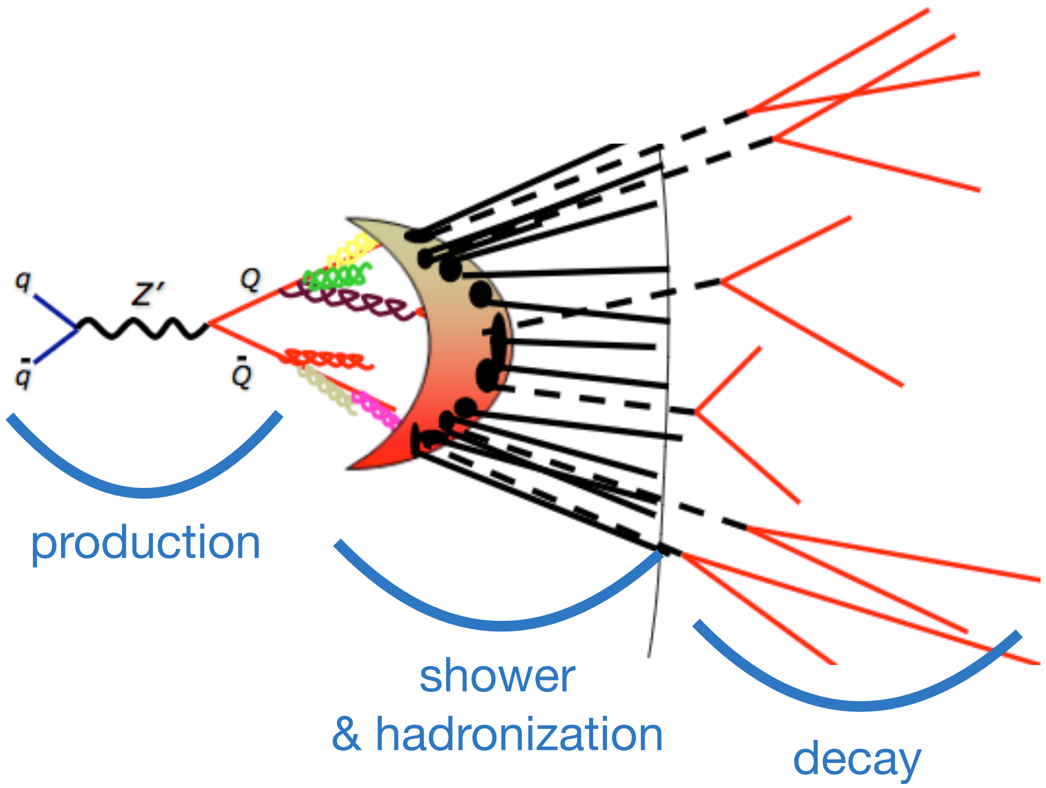
Expect $N_f^2 - 1$=3 mass degenerate "π, ρ" with same lifetime (but we can't turn off QED!)

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



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

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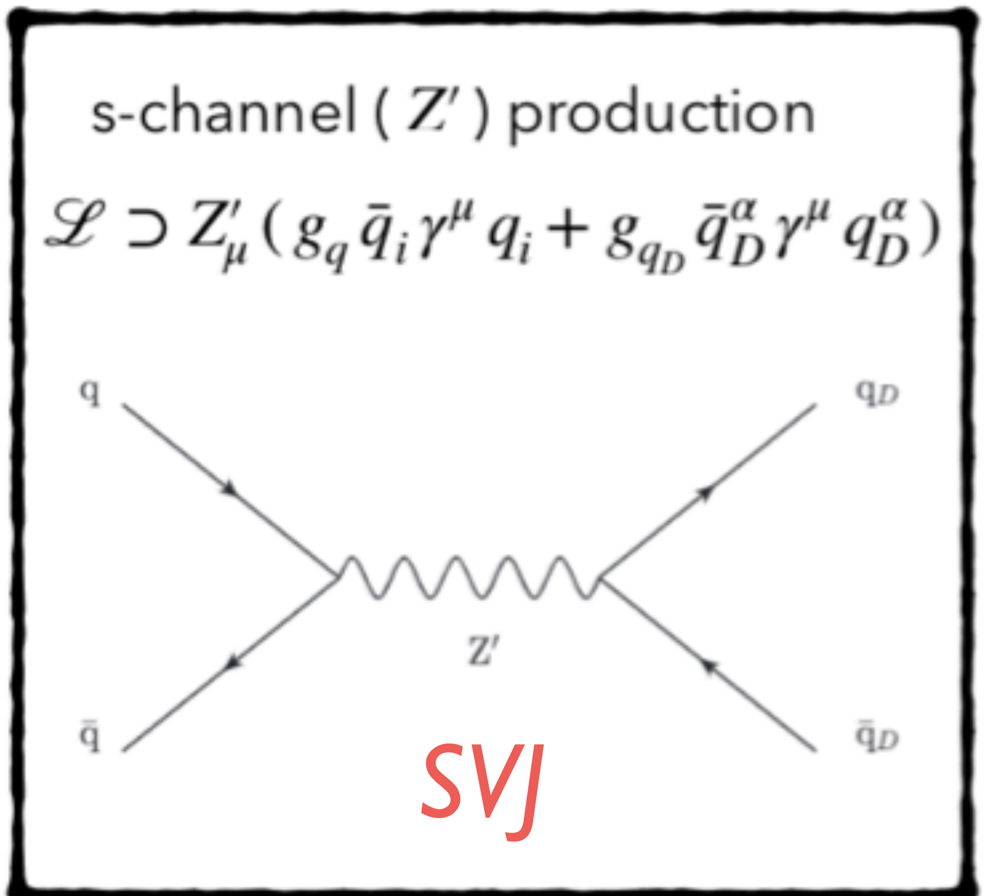
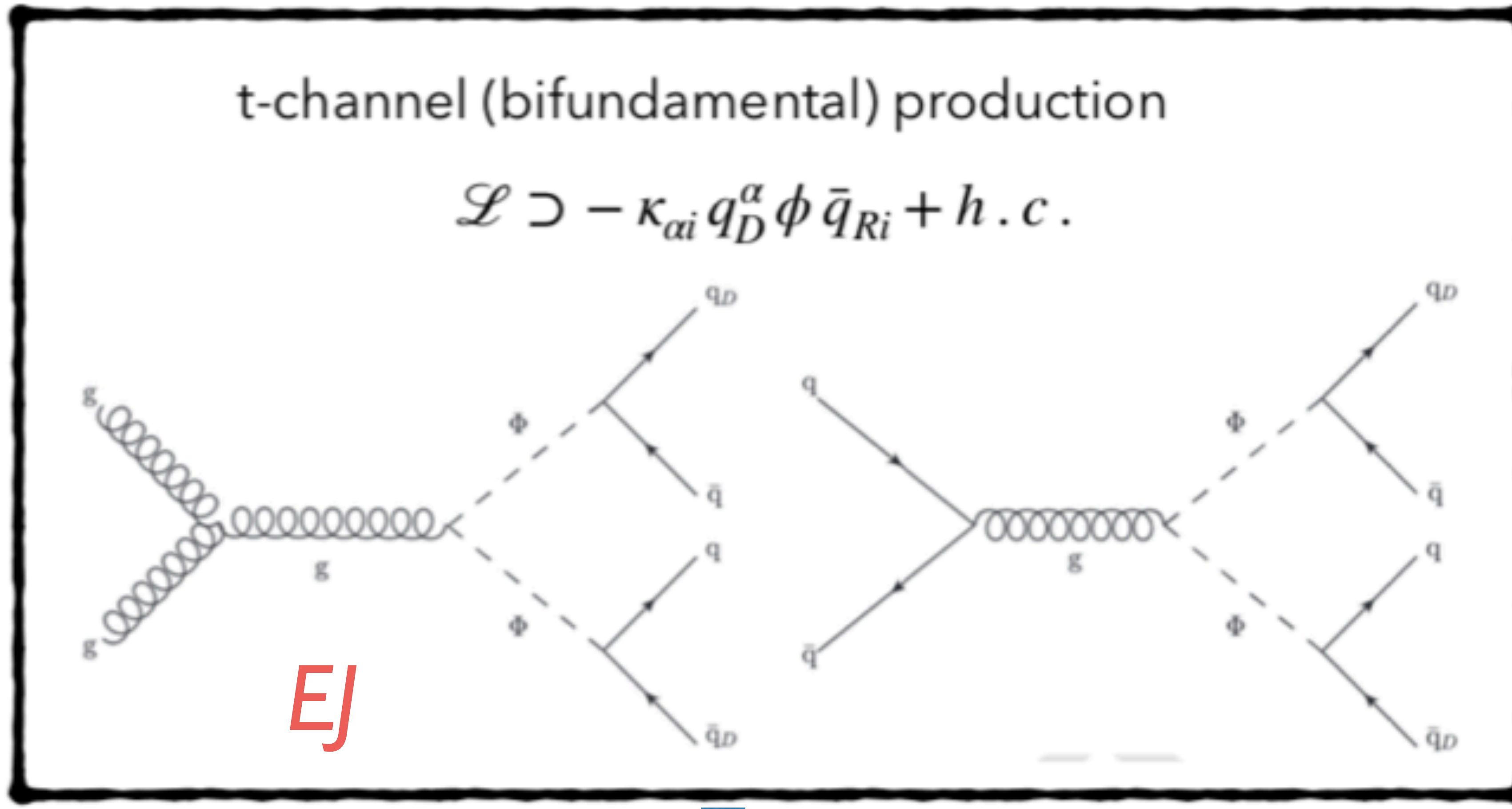
DS production: models

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





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 , updated in 2403.01556 for different flavour structures [not included here!]

Soft unclustered energy patterns (SUEPs):

- ✦ CMS: *Search for soft unclustered energy patterns in proton-proton collisions at 13 TeV*, arXiv:2403.05311.

- EXP: More to come from ATLAS, CMS and LHCb!!!
  PHENO: MITP Colours in Darkness workshop summary report, arXiv:2311.16330

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

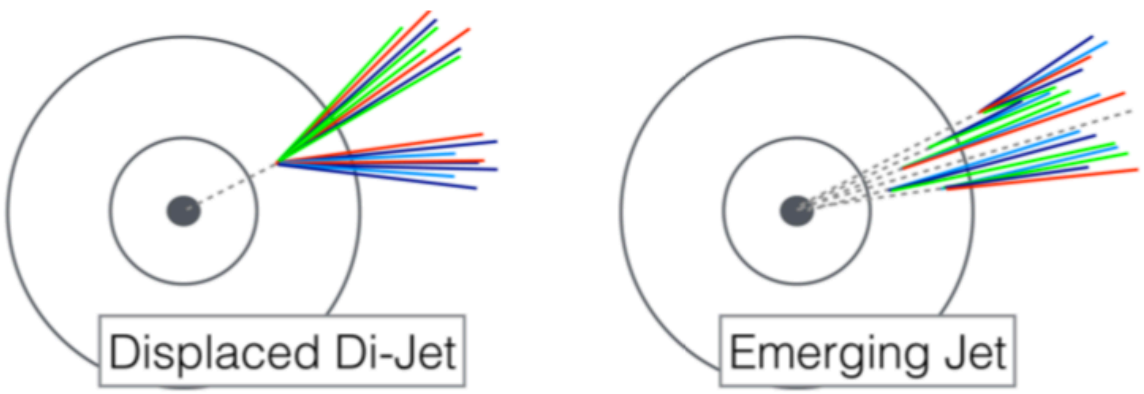
Reinterpreting CMS EJ search: bounding Exotic Higgs decays

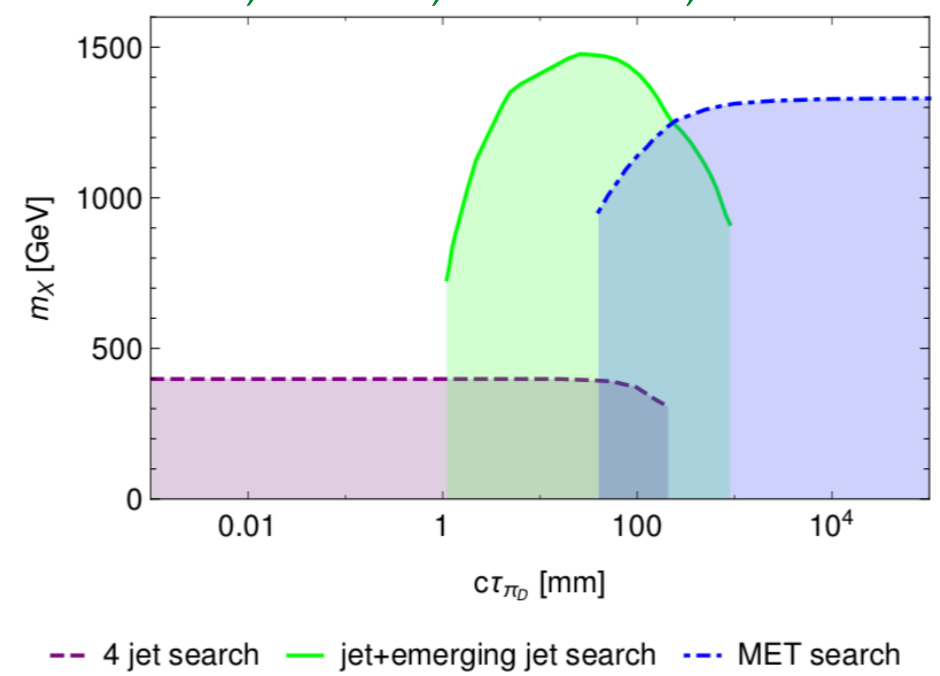
Emerging jets

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

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

Mies, Scherb, Schwaller, 2011.13990





unflavoured: single lifetime Schwaller, Stolarski, Weiler, 1502.05409

flavoured: lifetime hierarchy Schwaller, Renner, 1803.08080

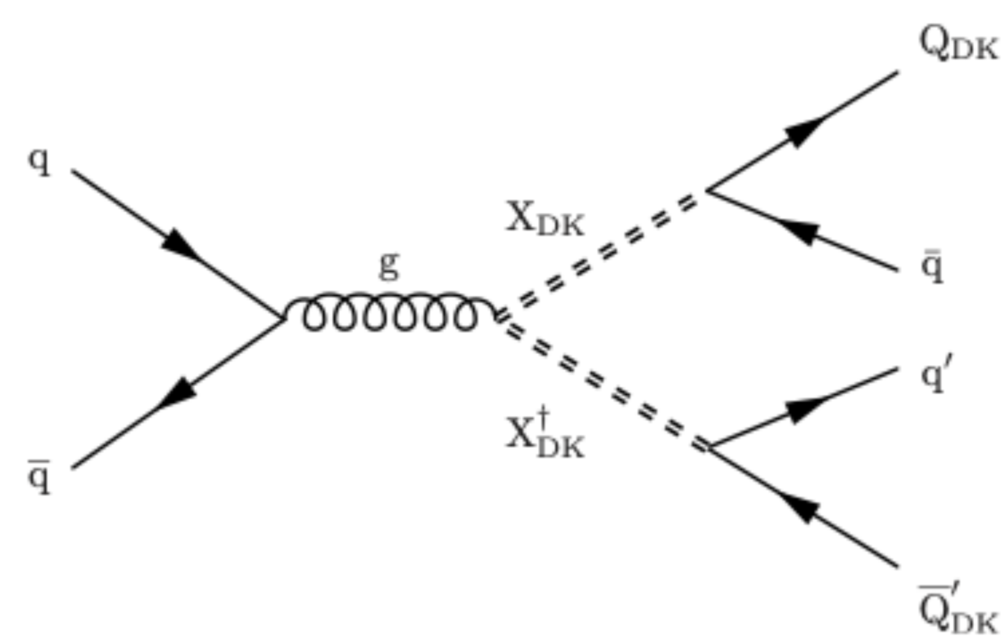
<u>CMS search:</u> CMS Collaboration, 1810.10069*

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



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

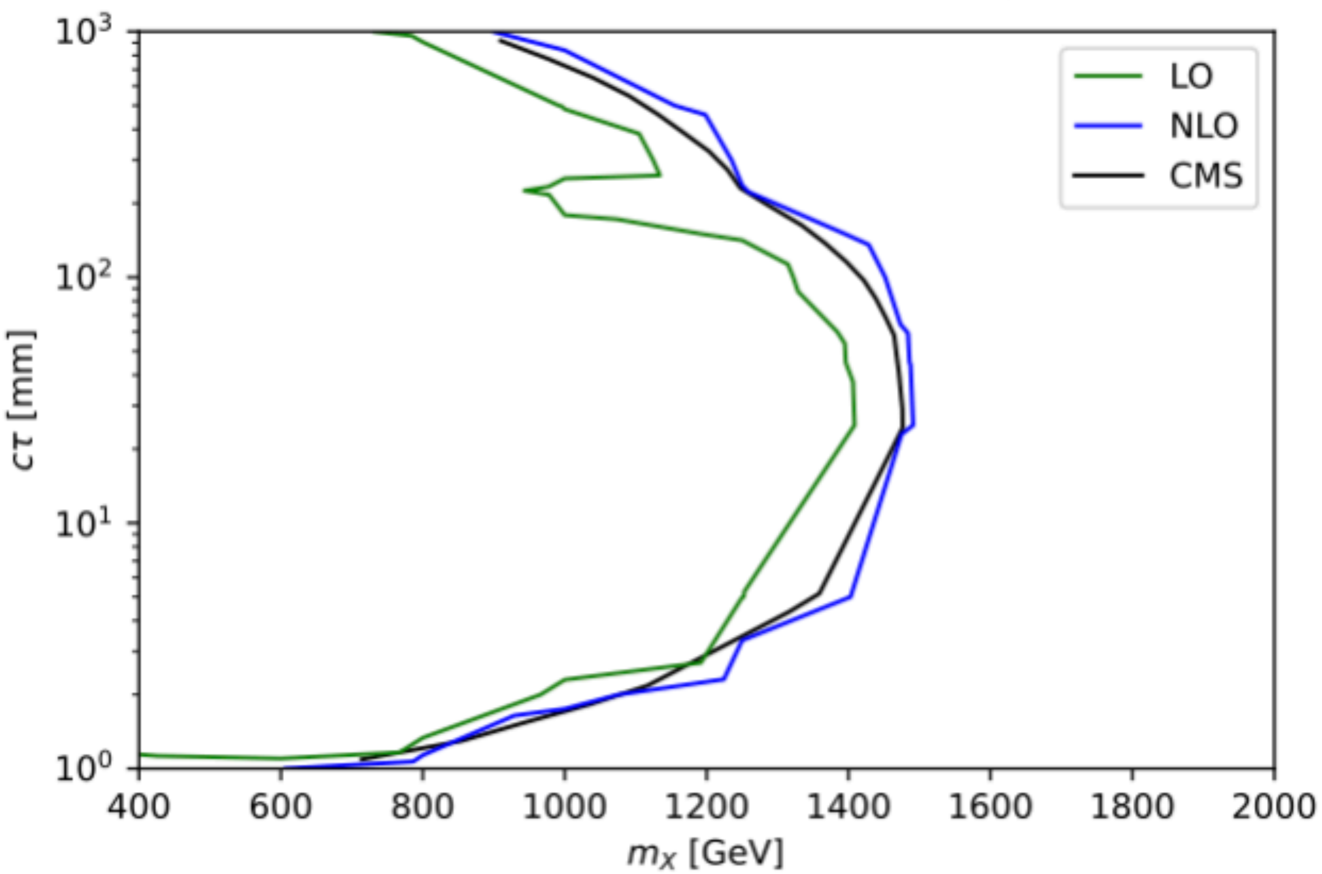
Validating CMS (I): Closure test

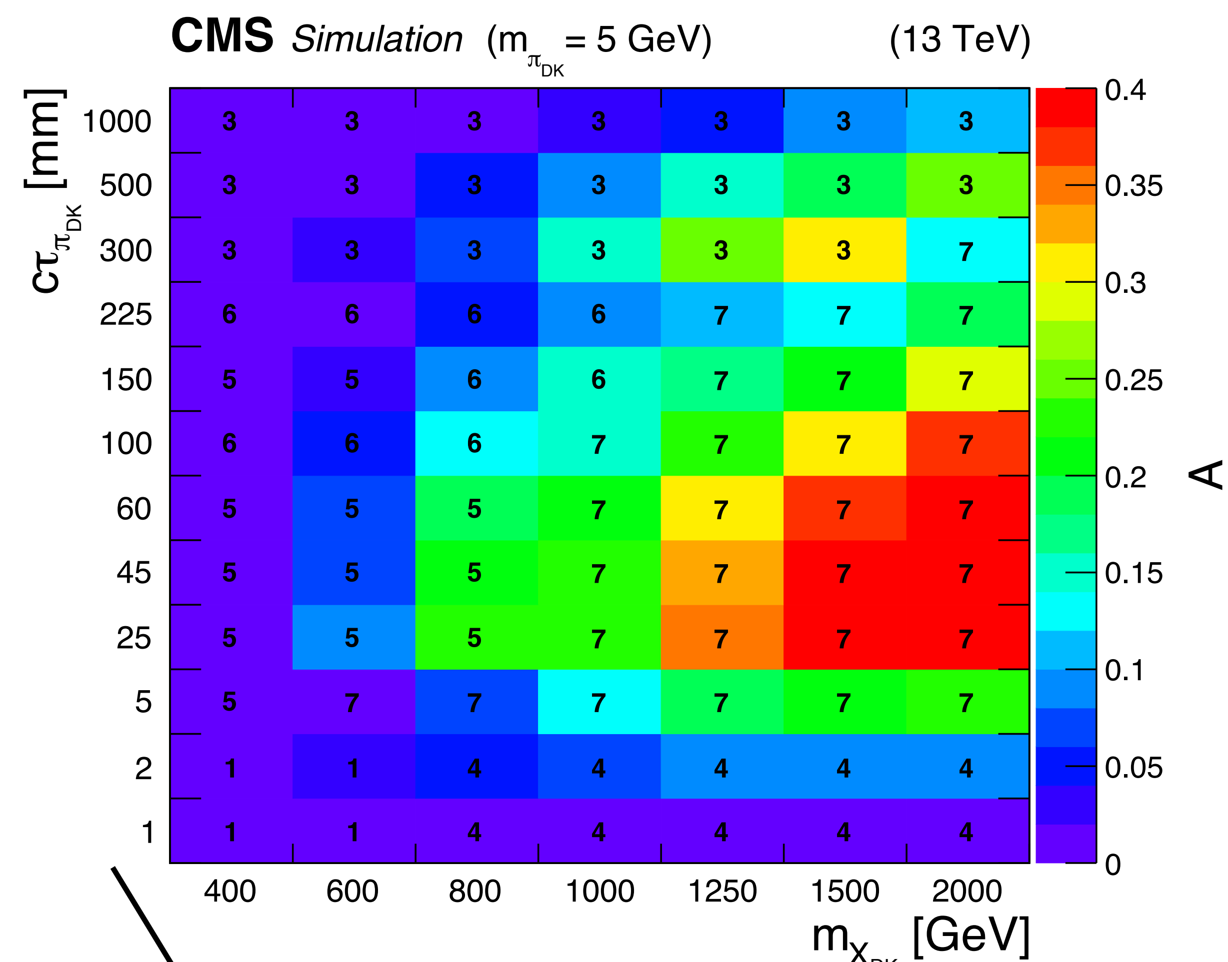
$$n_S^i = \sigma_{(pp\to XX)} \times BR(X \to qQ_D) \times \mathcal{A}_i \times L$$

NLO input
("LQ XS")

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

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





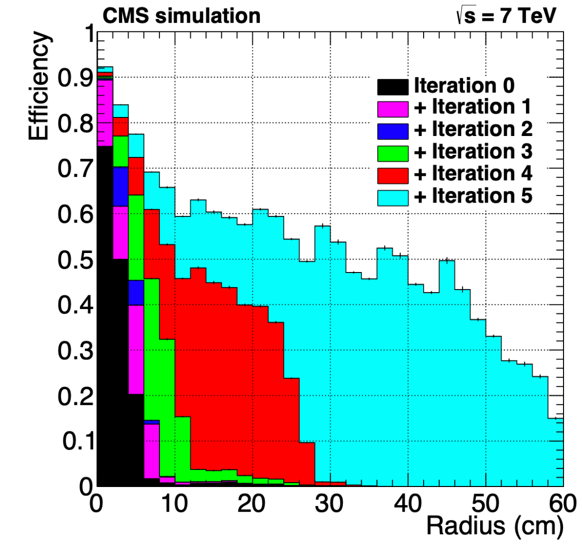
Good agreement with CMS!

Please give us all SRs!

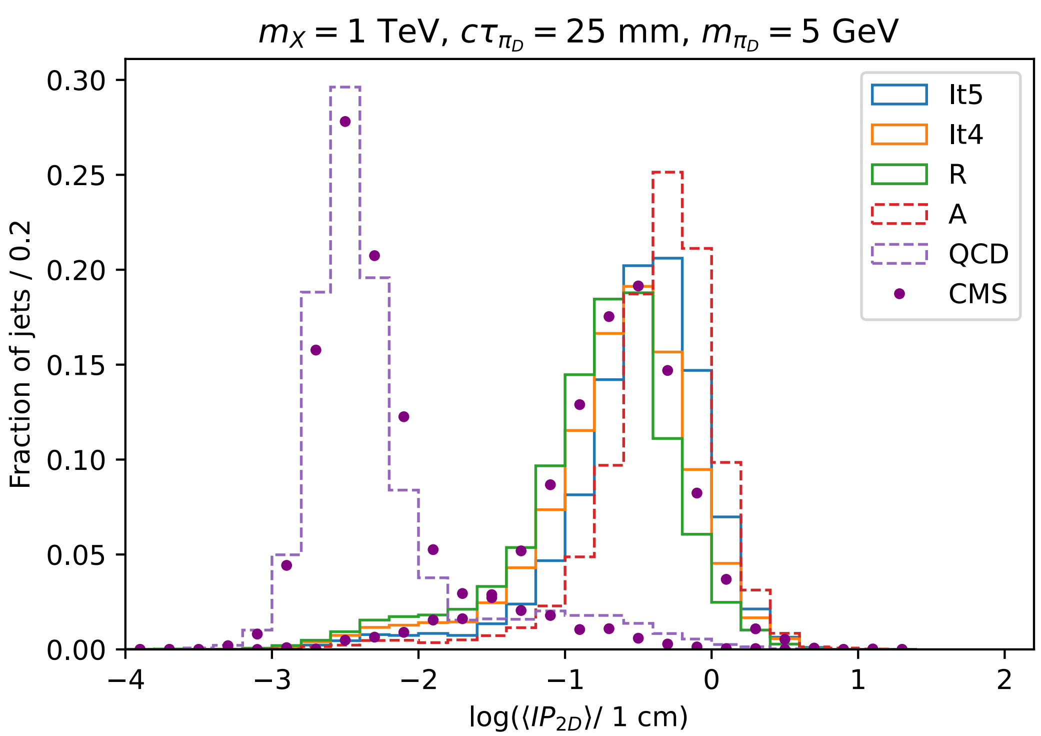
Validating CMS (II): Kinematics

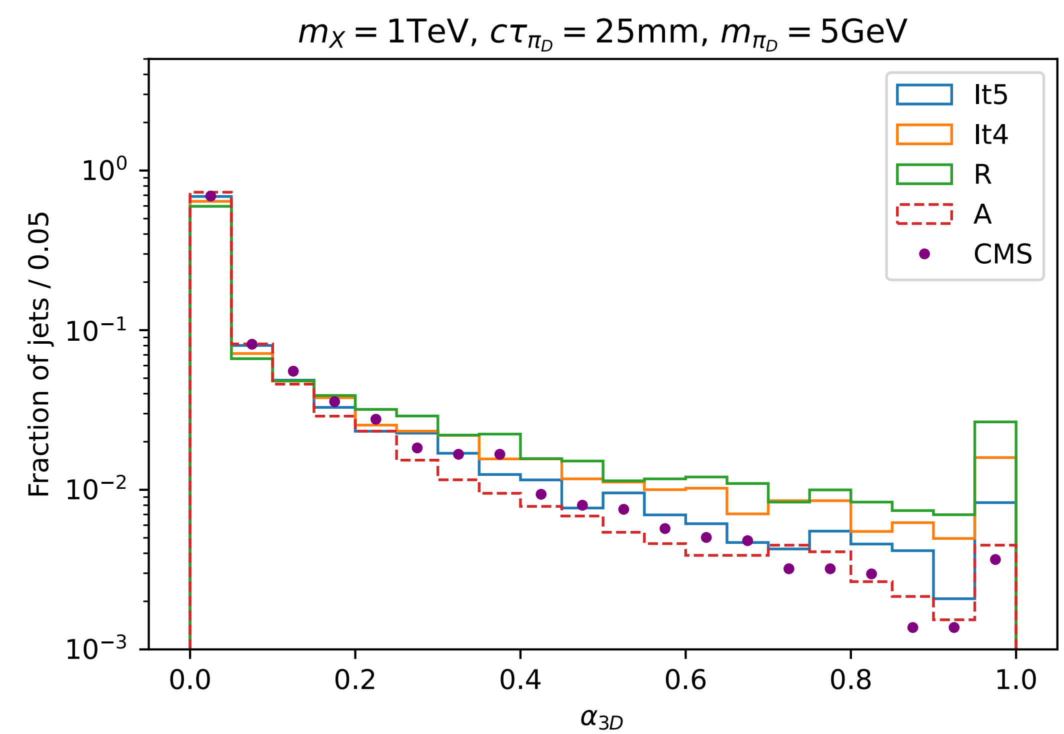
- Emerging Jet tagging variables:
  - $\langle IP_{2D} \rangle$: Median transverse impact parameter of associated tracks
  - α_{3D}: jet pT fraction associated to prompt tracks

Need to consider different tracking efficiencies, often hard to parametrise



CMS Collaboration, 1405.6569





Agreement with CMS kinematic distributions

Other masses, lifetimes?

Validating CMS (III): Exclusion limits

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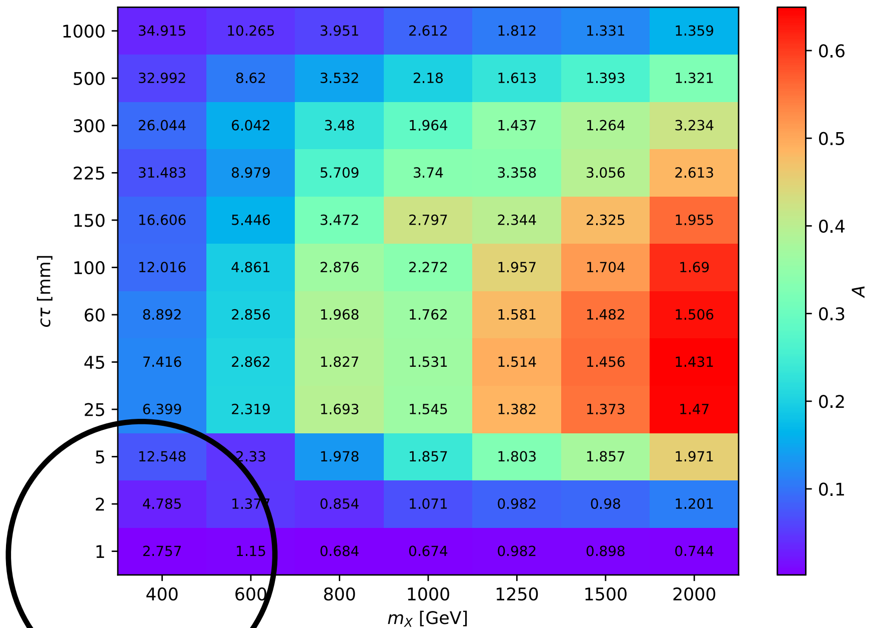

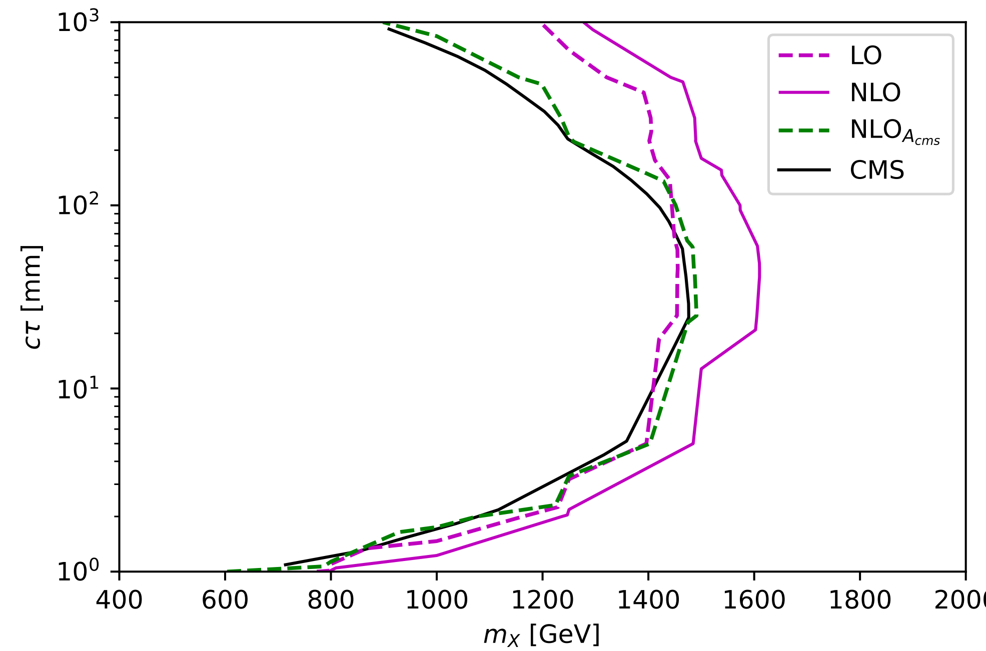

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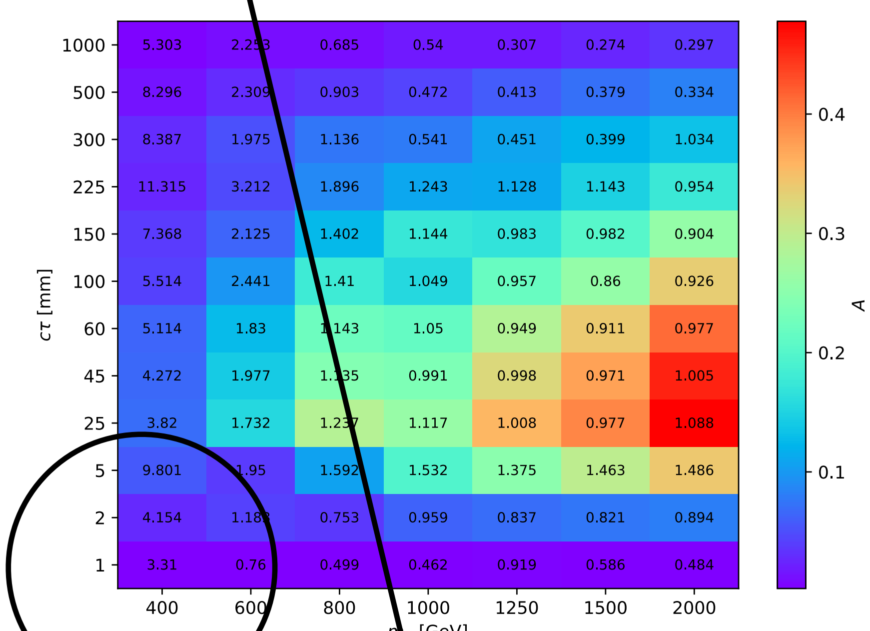
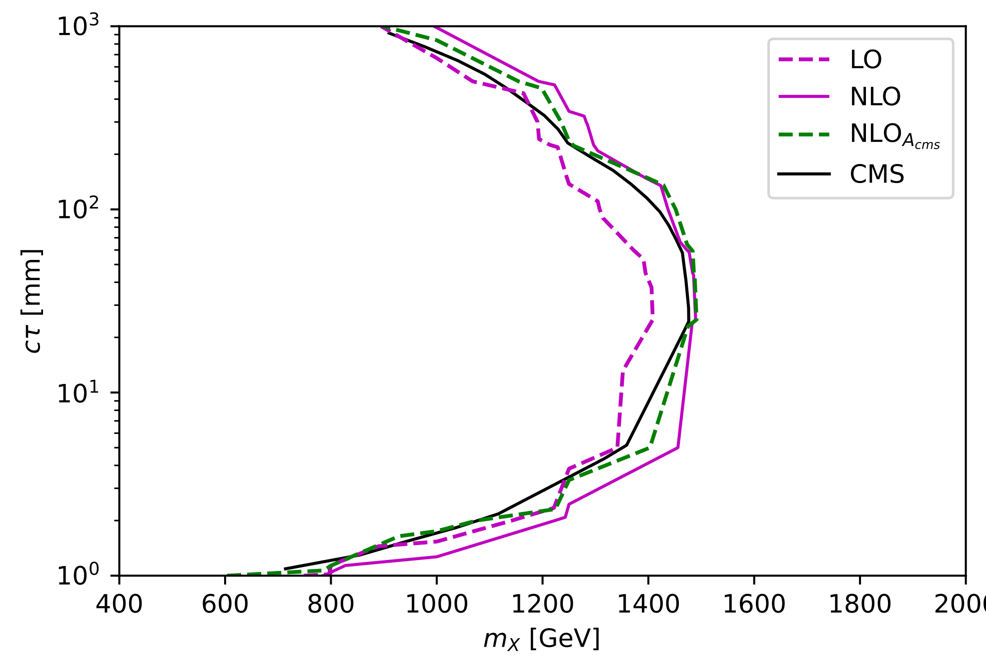




$\epsilon_{trk}(r) = \Theta(r - 102\text{ mm})$.

Agreement less striking for low masses

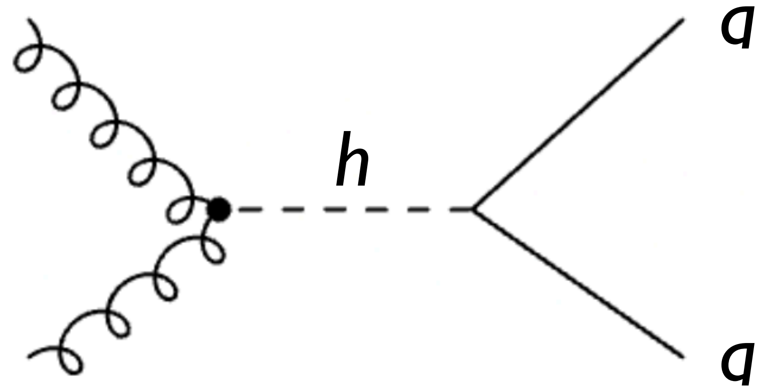
Reinterpretation: Exotic Higgs decays

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

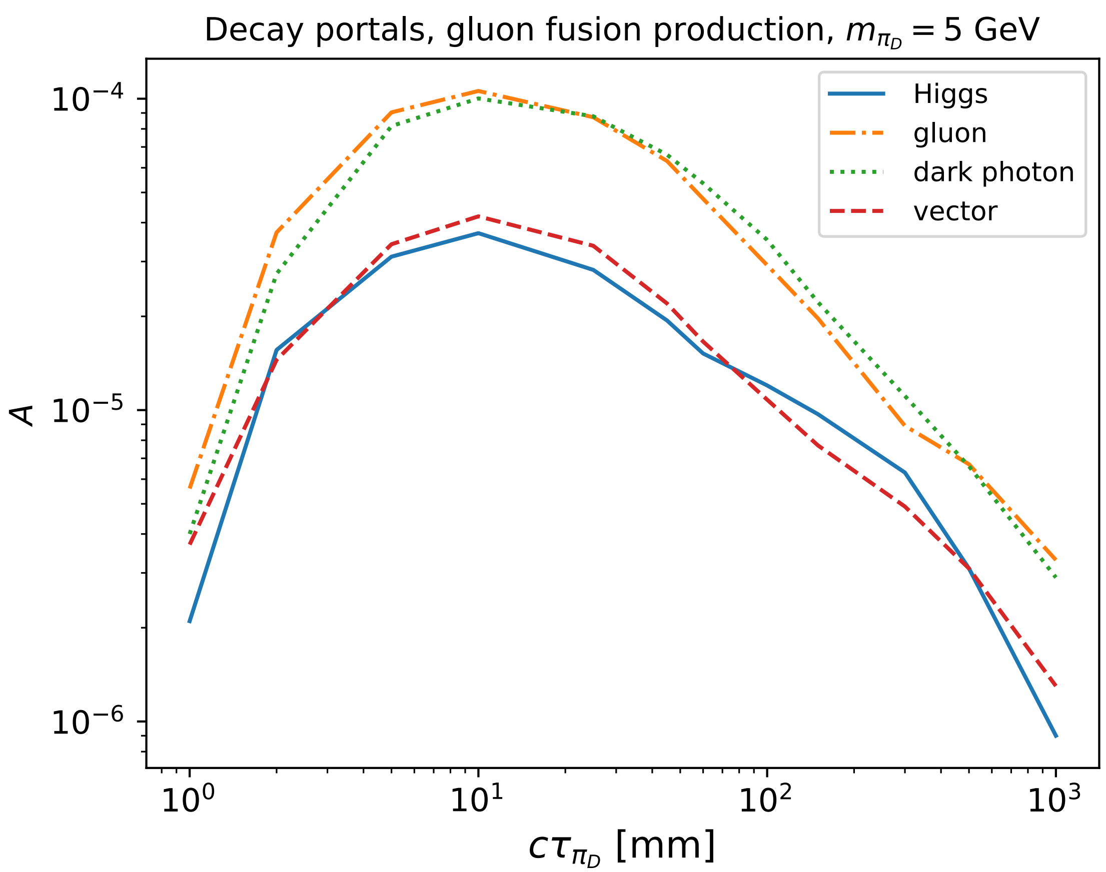
Our reinterpretation

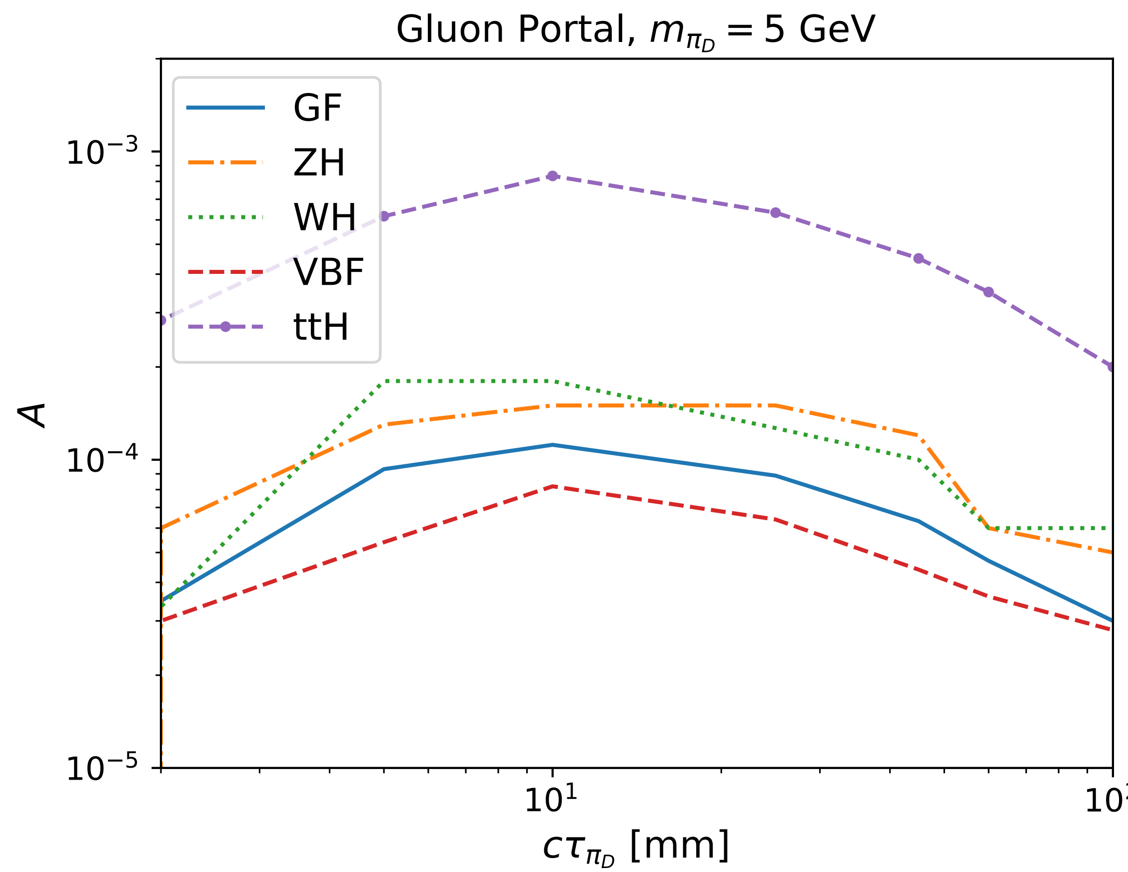
SM Higgs boson. Values from YR4.

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

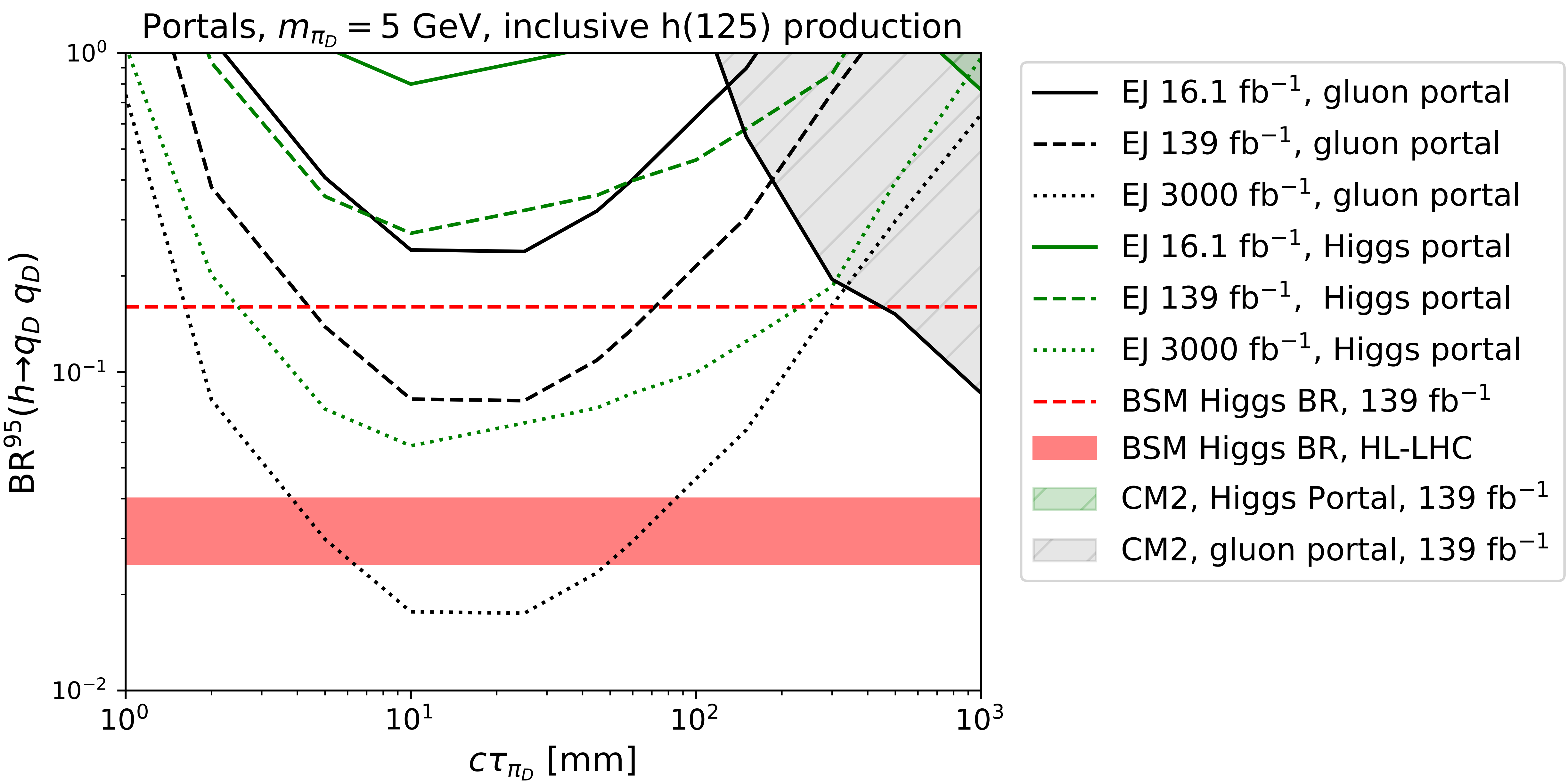


$$\pi_D G^{\mu\nu}\tilde{G}_{\mu\nu}\ ,\ \pi_D H^\dagger H\ ,\ \pi_D F'^{\mu\nu}\tilde{F}_{\mu\nu}\ ,\ \rho_D^{\mu\nu}F_{\mu\nu}$$





Bounds on Exotic Higgs decays



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