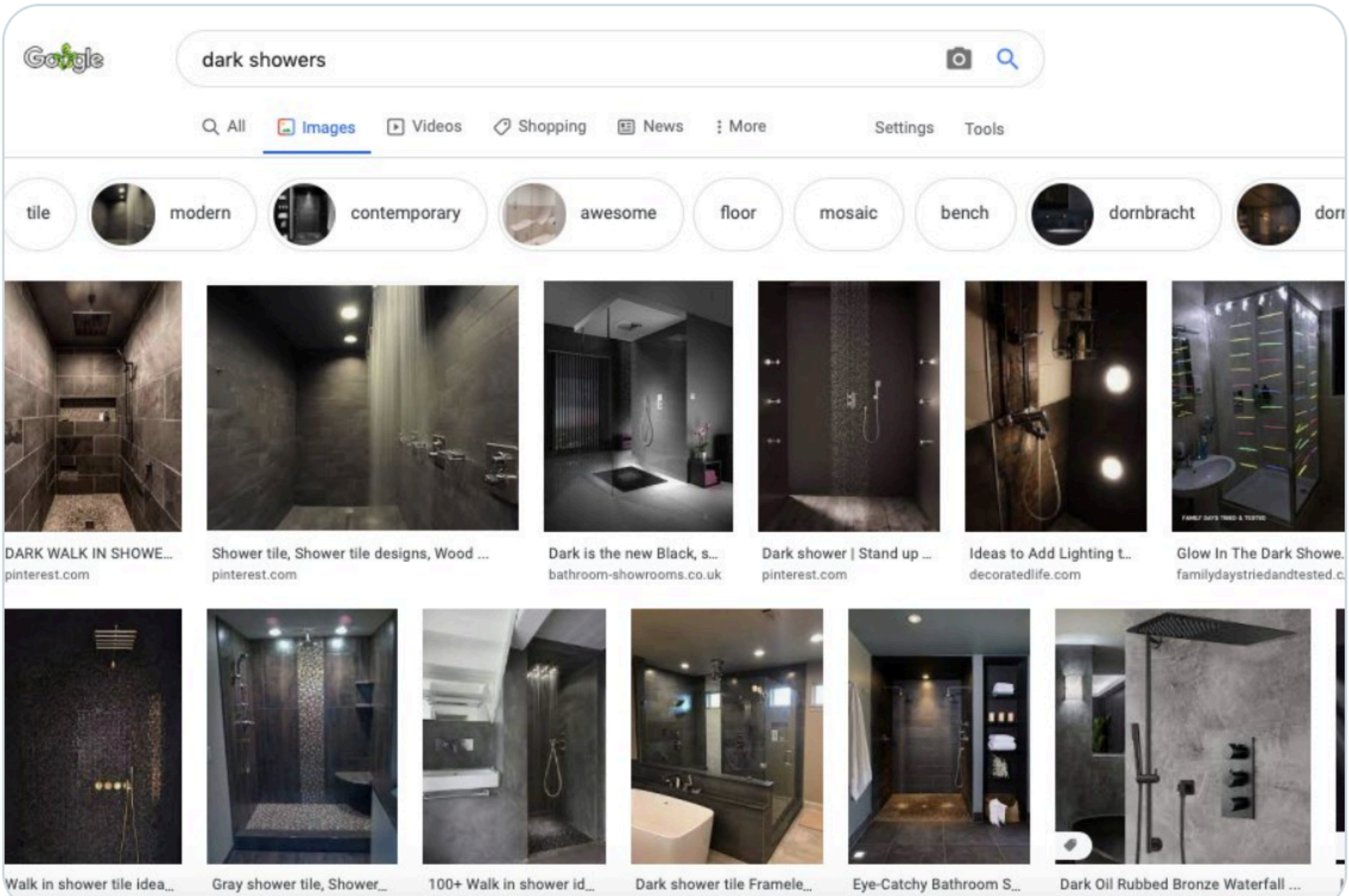
Tweet

Caterina Doglioni
@CatDogLUofM

this is what happen when one is tired and tries to find scientific illustrations in the laziest possible way @suchi_kulkarni



6:26 PM · Apr 22, 2021

Darkshowers a.k.a semivisible jets – Theory perspective

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Based on Snowmass darkshowers arXiv:2203.09503

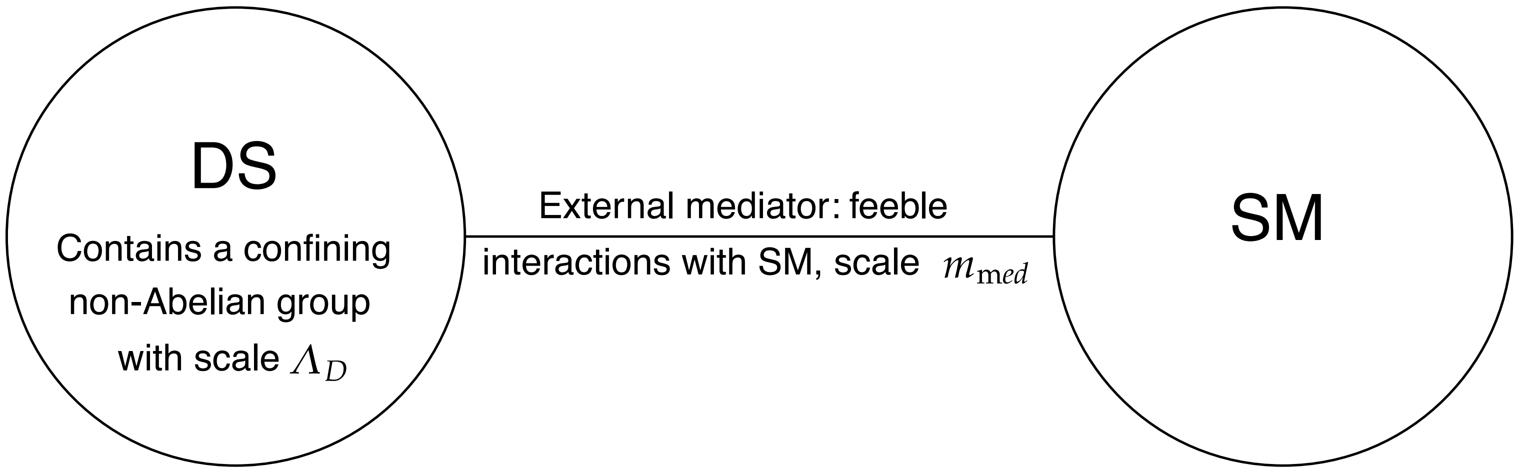
NAWI Graz Natural Sciences

FWF Der Wissenschaftsfonds.

UNI GRAZ

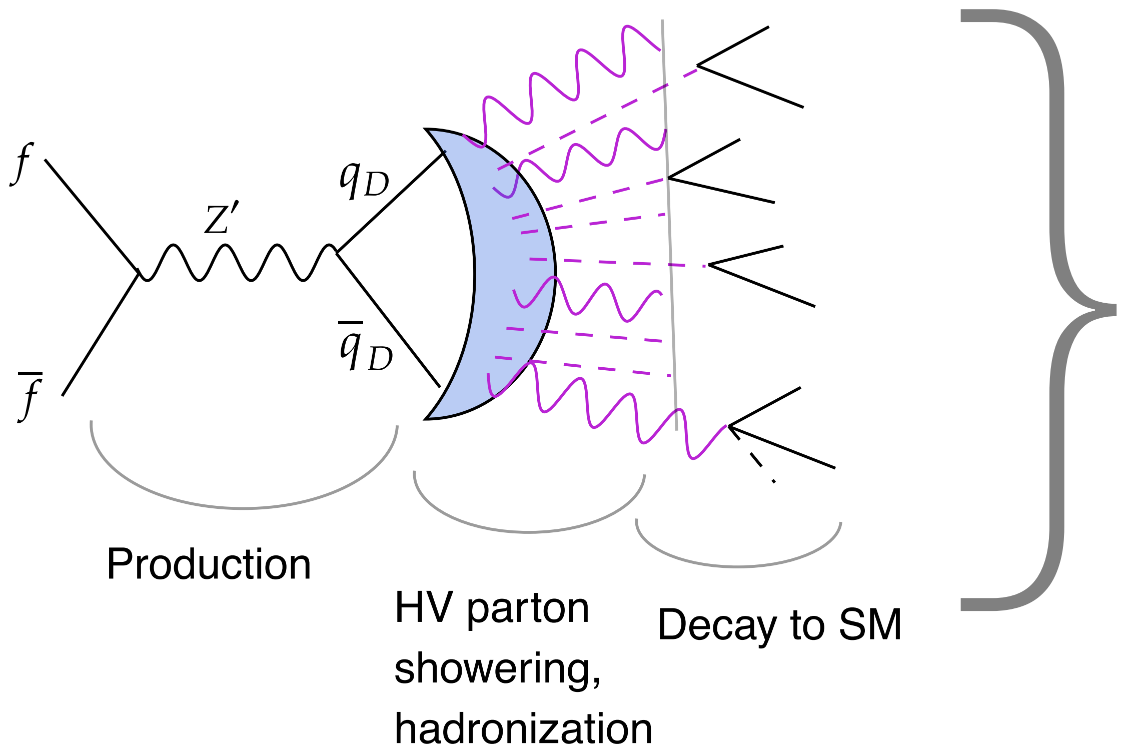
What we have in mind

- Only thinking about new $SU(N_c)$ gauge group uncharged under the SM with s-channel DS - SM mediators



See S. Sinha's talk for experimental aspects

⇒ Darkshowers



- Jets with large MET inside
- Jets with displaced vertices
- Jets with too many or too few tracks

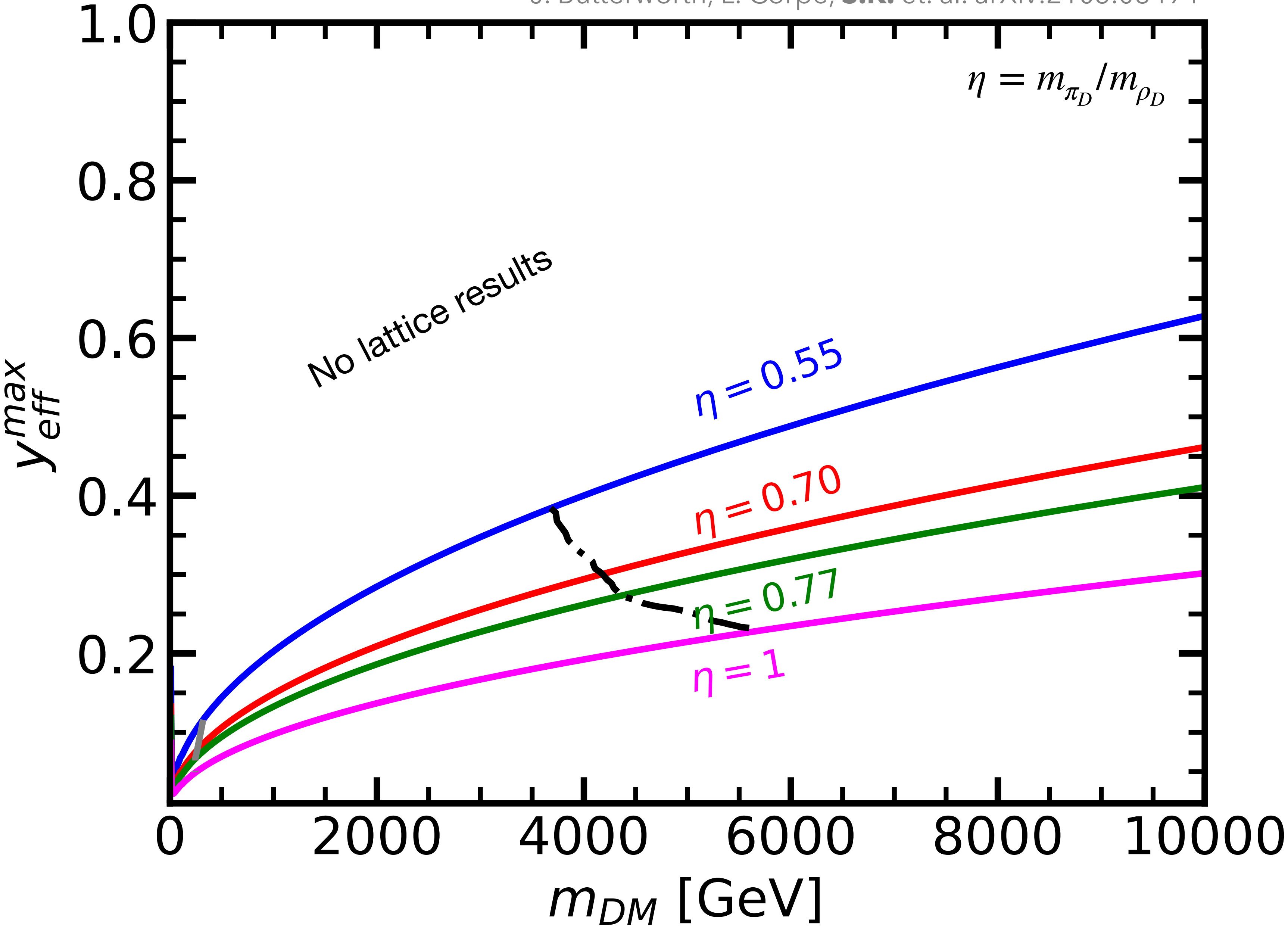
Semi-visible jets correspond to jets with large MET without displaced vertices

(Side remark SM mediators)

See talk by E. Raynolds for new ATLAS results

If dark sector if charged under the Standard Model, there are typically no jets

J. Butterworth, L. Corpe, **S.K.** et. al. arXiv:2105.08494



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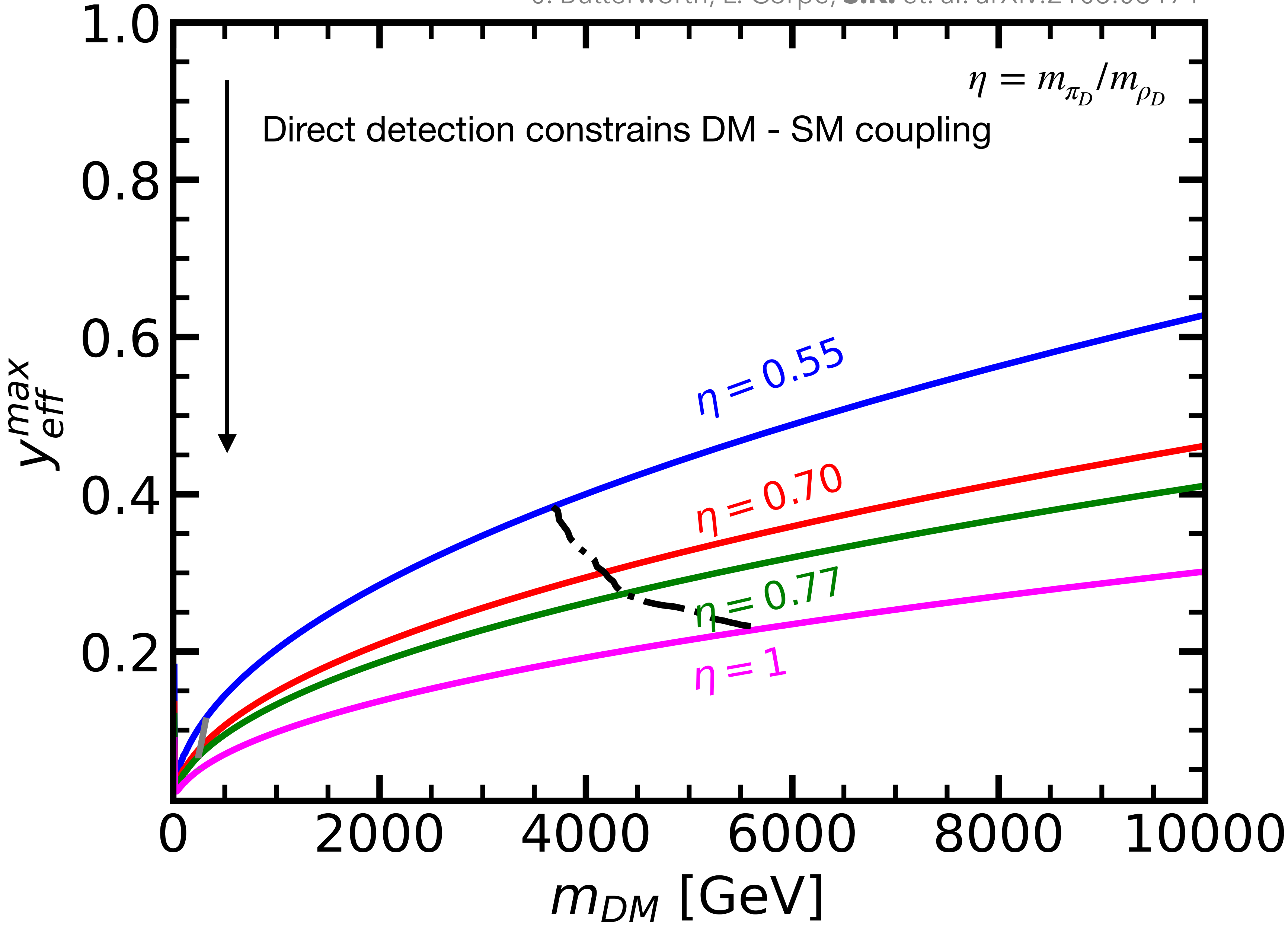

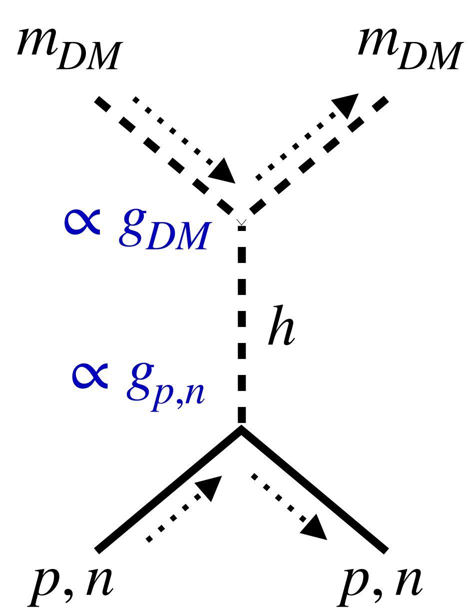

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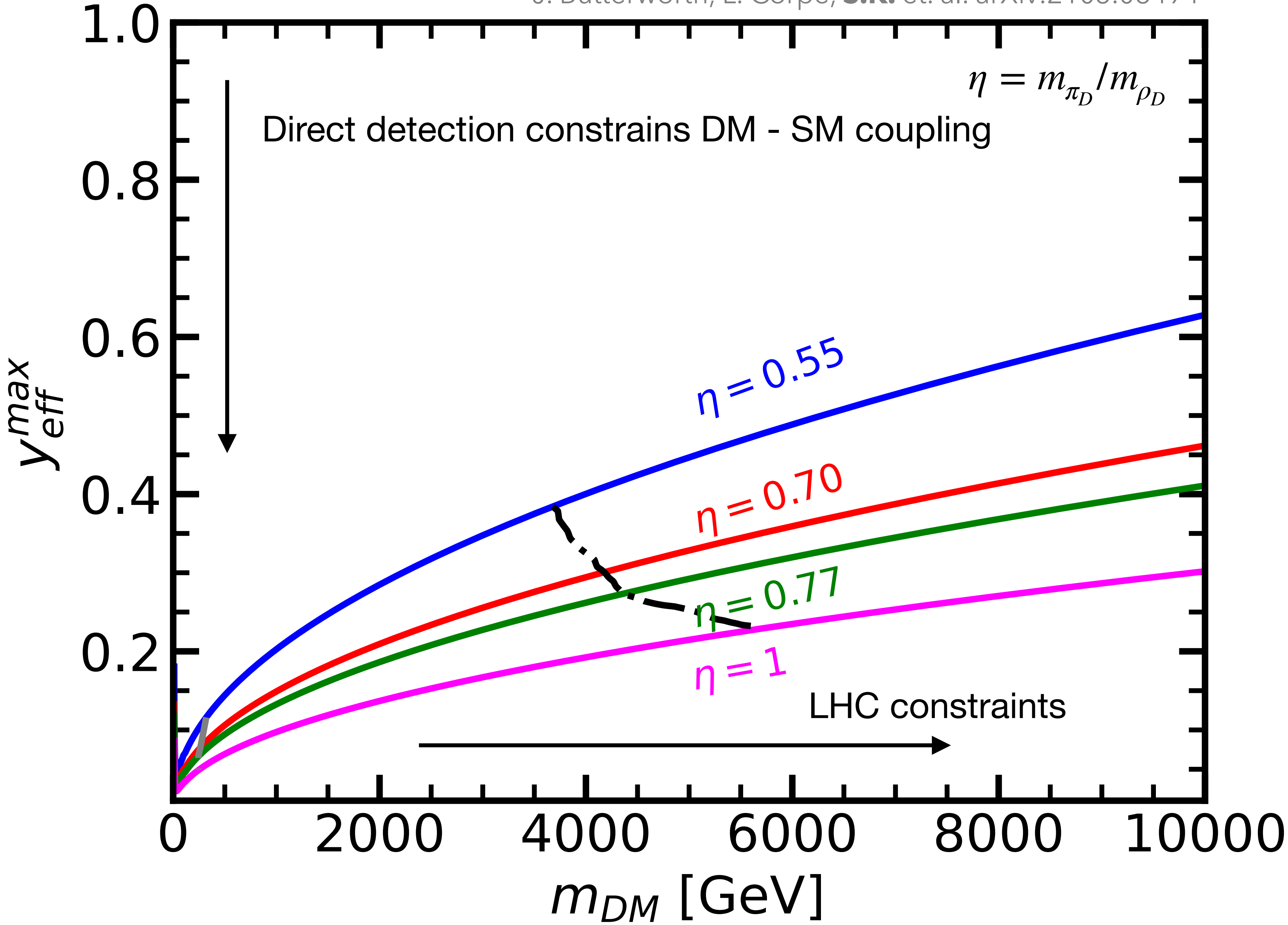
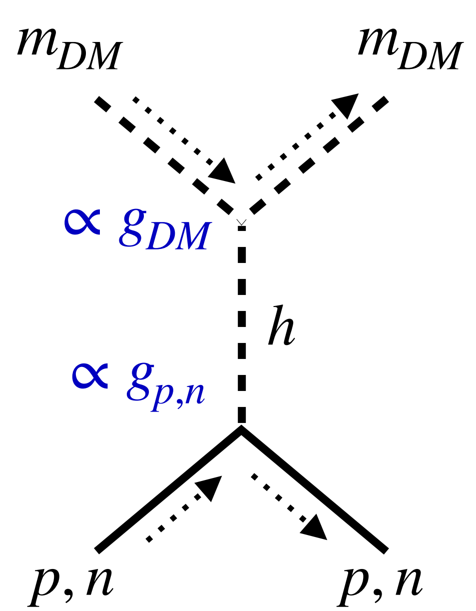
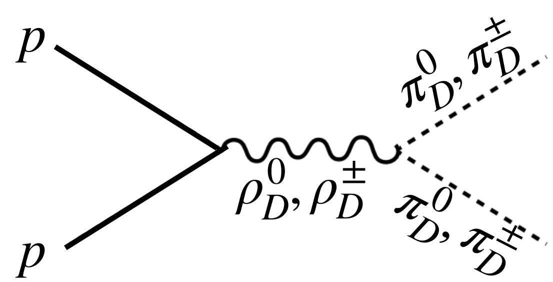






What we have in mind

Twin Higgs see e.g. Chako, Goh, Harnik hep-ph/0506256

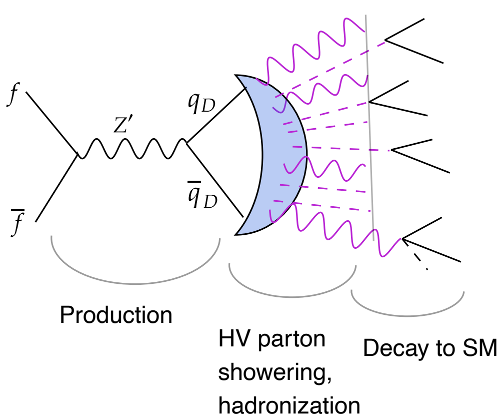
Why strongly interacting theories

- Composite Higgs: dark sector (DS) scale related to SM
- This talk: no relation between DS and SM scales

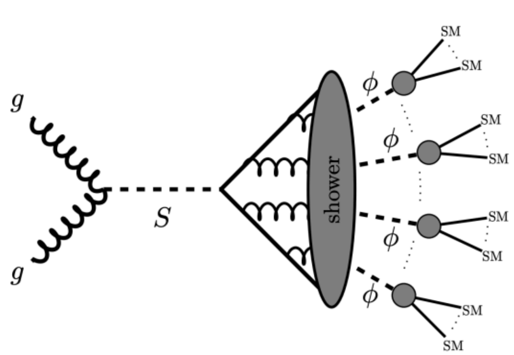
Talks by G. Durieux, J.M. Lizana

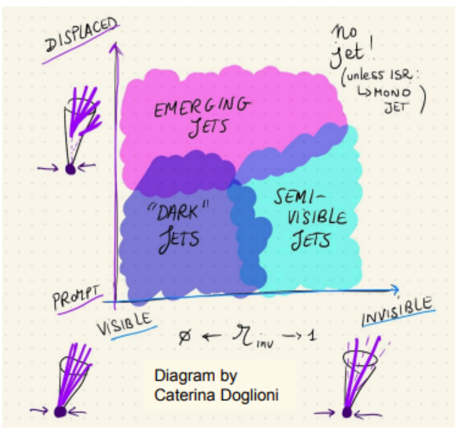
Nussinov Phys.Lett.B 165 (1985) 55-58, Chivakula et al, Nucl.Phys. B329 (1990) 445, Hietanen et al., arXiv:1308.4130, Kribs et al.,arXiv:0909.2034, Buckley et al,arXiv:1209.6054 , Francis et al.,arXiv:1809.09117 , LSD, arXiv:1301.1693, Boddy et al., arXiv:1402.3629 , Detmold et al. arXiv:1406.2276 , Farrar et al arXiv:2007.10378, Kaplan et. al. arXiv:0909.0753

New class of signatures

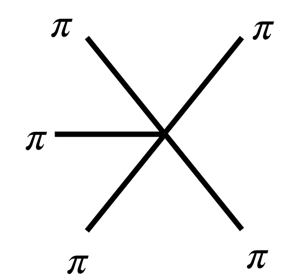


Strassler et al hep-ph/0604261
Cohen et al arXiv:1503.00009
Schwaller et al arXiv:1502.05409
LLP community report arXiv:1903.04497
Kahlhoefer et.al. arXiv:1907.04346
Hofman et al arXiv:0803.1467
Strassler arXiv:0801.0629
Knapen et al arXiv:1612.00850

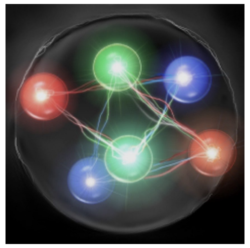


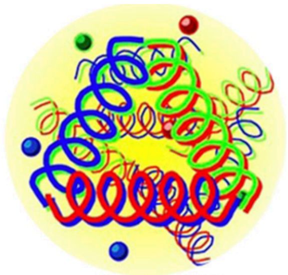


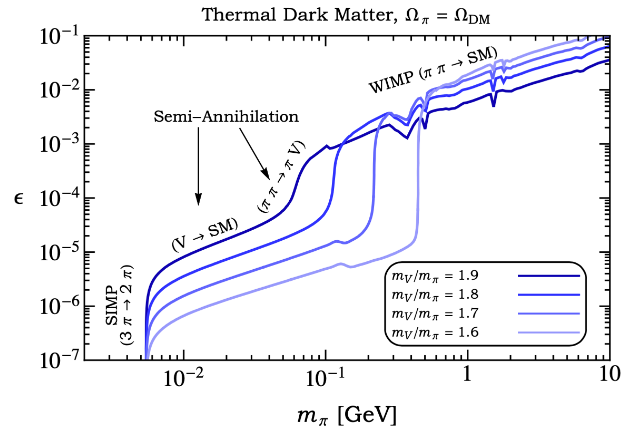
New dark matter candidates



Hochberg et al arXiv:1512.07917
Kribs et al arXiv: 1604.04627
Cline et al arXiv:2108.10314
Beriln et al arXiv:1801.05805
Fransden et al. arXiv:1103.4350
Soni et al arXiv:1602.00714, 1610.06931, 1704.02347

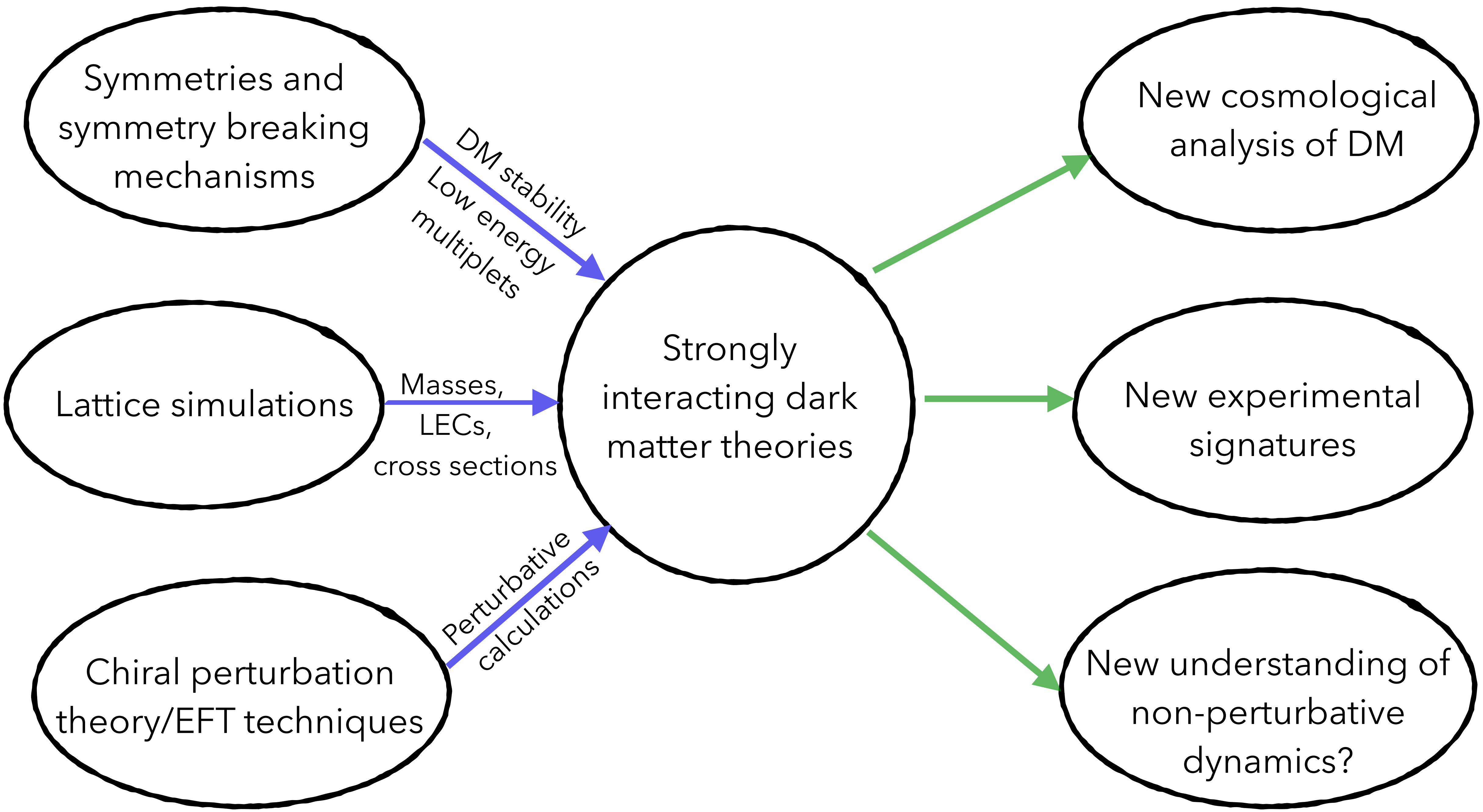






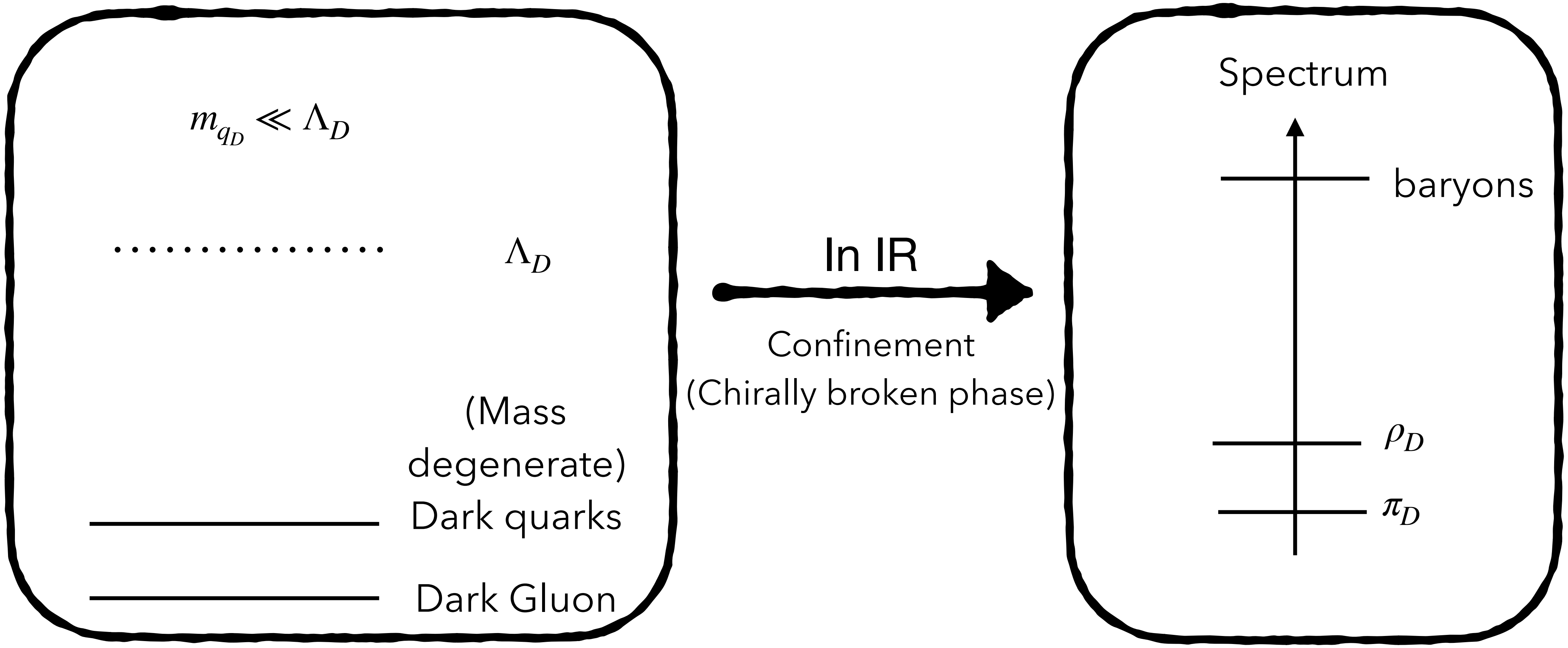
Strongly interacting theories: pathways

How to make systematic progress in the landscape of darkshowers?



N.B. All calculations can be done on lattice, but they are expensive, perturbative analysis is pragmatic way out

Dark sector: composition



UV physics contains

- Gauge fields (gluons)
- Matter fields i.e. Dirac/Majorana fermions, Scalars (in representation N_r)
- This talk: **mass degenerate Dirac fermions in fundamental representation of** $SU(N_{C_D})$ (event generators limitation)

- Two discrete parameters N_{c_D}, N_{f_D}
- Two continuous parameters $m_{q_D}, \alpha_D(\mu)$ (UV)
  - $\Lambda_D, m_{\pi_D}/\Lambda_D$ or $m_{\pi_D}, m_{\pi_D}/m_{\rho_D}$ (IR)
- $N_{c_D} \neq 2$: fundamental representation in SU(2) gauge group is pseudo-real
- $N_{f_D} \neq 1$: 1 flavour theory has no pions

Flavour, parity, CP conserving $SU(N_{C_D})$ theories

Non-$SU(N_{C_D})$ gauge groups

Snowmass dark shower incl. **S.K.**, S. Mee, M. Strassler arXiv:2202.09053
S.K., A. Maas, S. Mee, M. Nikolic, J. Pradler, F. Zierler arXiv:2202.05191
S.K., J. Pomper (in preparation)

See also Hochberg et al arXiv:1512.07917

complex	*pseudo – real*	*real*
2 – Flavor QCD	$Sp(4)$ – Fund.	$SO(N_C)$ – Vector
$U(2) \times U(2)$	$U(4)$	$U(4)$
↓	↓	↓ Axial anomaly
$SU(2) \times SU(2) \times U(1)_B$	$SU(4)$	$SU(4)$
↓	↓	↓ Chiral condensate $\chi_c \neq 0$; deg. mass $m_{(1)} = m_{(2)} \neq 0$
$SU(2) \times U(1)$	$Sp(4)$	$SO(4)$

- Number of pions and rho mesons in 2 flavour theories
  - Complex: $N_{\pi_D} = 3, N_{\rho_D} = 3$
  - Pseudo-real: $N_{\pi_D} = 5, N_{\rho_D} = 10$
  - Real: $N_{\pi_D} = 9, N_{\rho_D} = 6$
- Colour flows are different for pseudo-real and real gauge groups; not encoded in current event generators

$SU(N_{C_D})$ collider signatures

Few different regimes in signature space

Theories make (dark) jets
(QCD-like theories)
$\alpha_D N_{c_D}$ small

Theories don't make (dark) jets
They make
Soft Unclustered Energy Patterns (SUEPs)
$\alpha_D N_{c_D}$ large

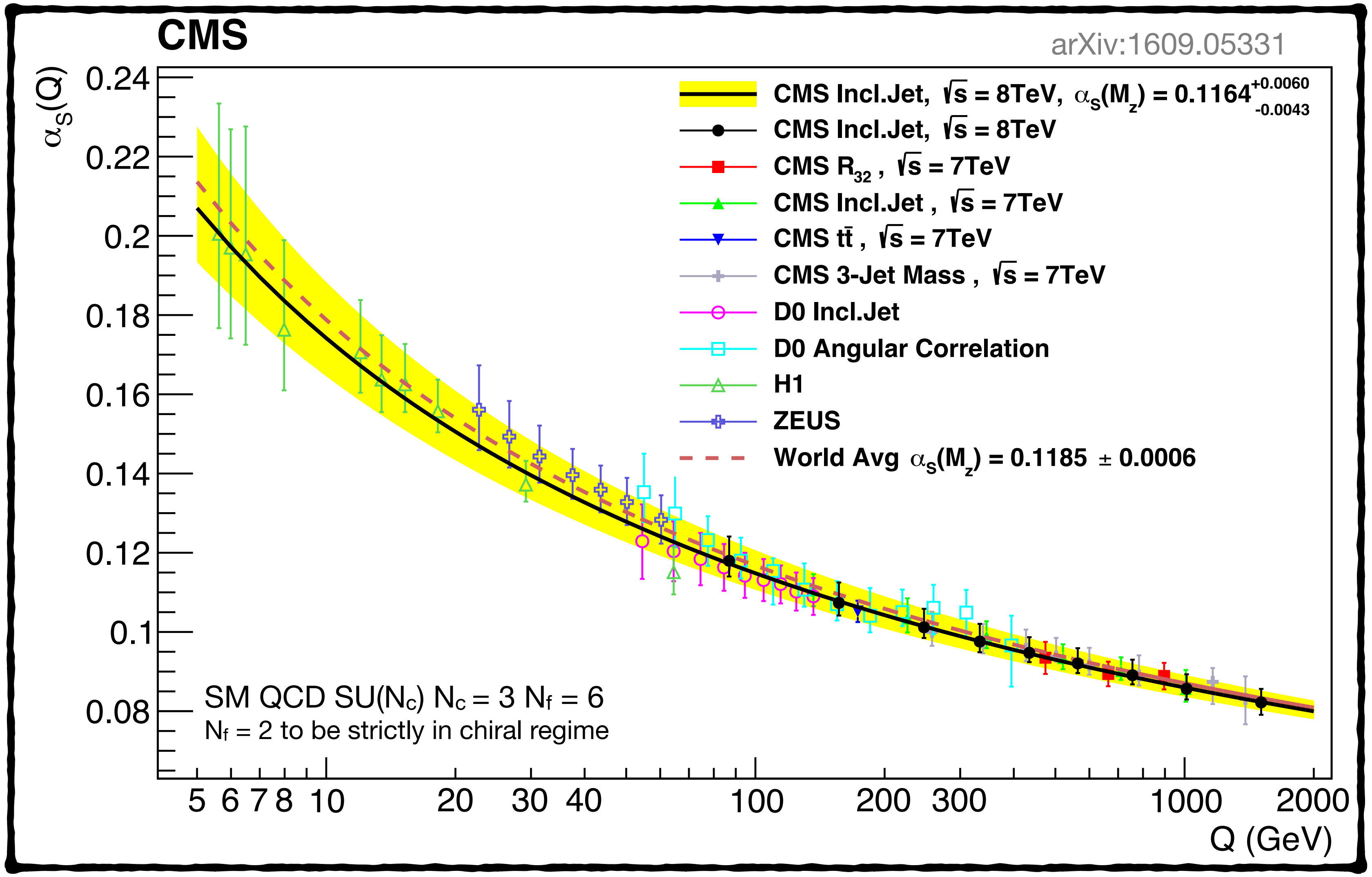
In this talk
Can simulate with PYTHIA8

Event shapes in between

Not in this talk
Out of scope of current event generators
Few special tools exist

QCD-like theories

- For mass degenerate fermions theory has four free parameters $N_{c_D}, N_{f_D}, m_{\pi_D}/\Lambda_D, \Lambda_D$



Nc	Nf
3	<< 9
4	<< 13
5	<< 16
6	<< 18

arXiv:2008.12223

$$\alpha_D(Q^2) = \frac{1}{\frac{11 N_{c_D} - 2 N_{f_D}}{6\pi} \log\left(\frac{Q}{\Lambda_D}\right)}$$

- QCD-like theories: asymptotically free theories and are in chirally broken phase

Mass spectrum

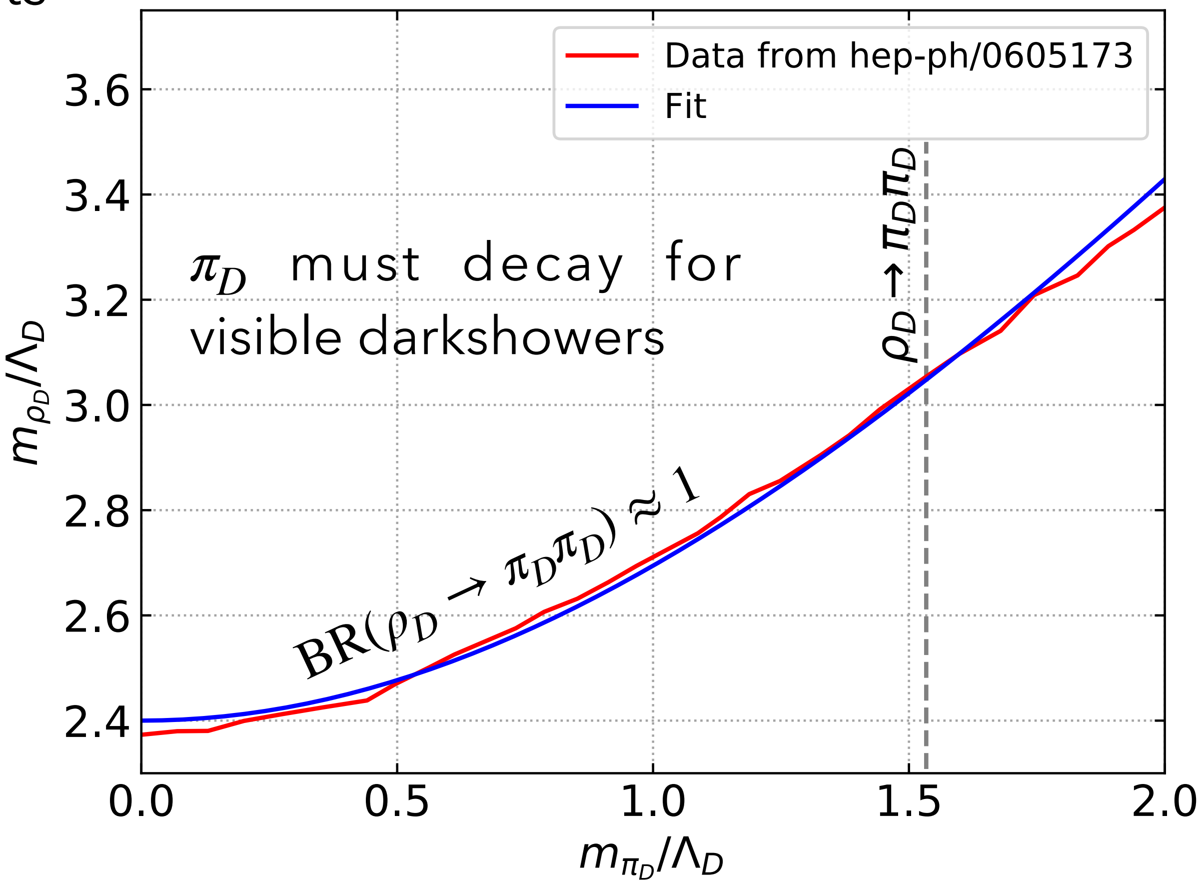
- $SU(N_{c_D}), N_{c_D} > 2$ theory with N_{f_D} mass degenerate quarks has $N_{f_D}^2 - 1$ mass degenerate dark rho, pions, plus 1 spin -0 and spin -1 singlet (just like the SM case)

$$\Pi^{SM} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\sqrt{\frac{2}{3}}\eta \end{pmatrix} + \eta' \qquad \rho^{\mu,SM} = \begin{pmatrix} \frac{\rho^0_\mu}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} & \rho^+_\mu & K^{*+}_\mu \\ \rho^-_\mu & -\frac{\rho^0_\mu}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} & K^{*0}_\mu \\ K^{*-}_\mu & \overline{K^{*0}_\mu} & -\sqrt{\frac{2}{3}}\omega_\mu \end{pmatrix} + \phi$$

- Lattice data used to derive (N_{c_D}, N_{f_D} independent) fits

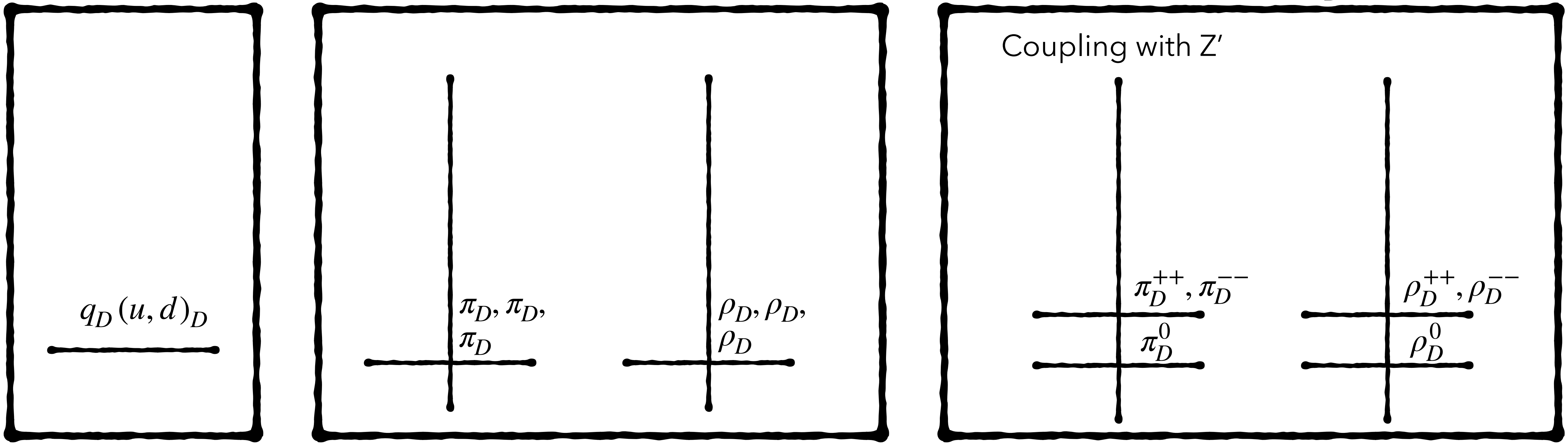
$$\frac{m_{\pi_D}}{\tilde{\Lambda}_D} = 5.5\sqrt{\frac{m_{q_D}}{\tilde{\Lambda}_D}}$$

$$\frac{m_{\rho_D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5\frac{m^2_{\pi_D}}{\tilde{\Lambda}^2_D}}$$



Flavour symmetry breaking leads to (dark)showers

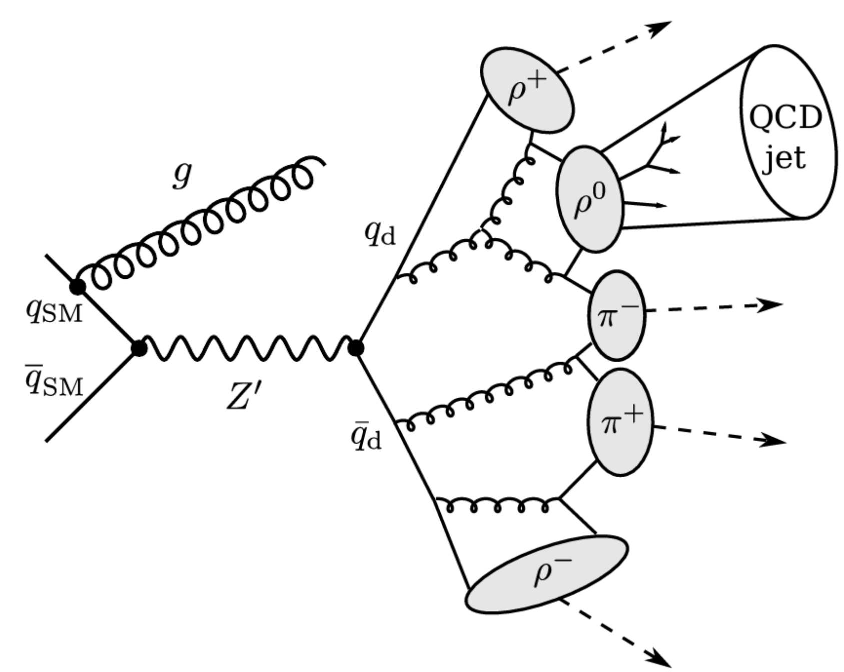
$SU(N_{C_D})$ Fund . rep . , $SU(N_{F_D}) = 2$, $Q_D = \text{Diag}(+1, -1)$



- Example 1: $N_{f_D} = 2$; $n_{\pi_D} = n_{\rho_D} = 3$; $Q_D = \text{Diag}(+1, -1)$;
  Doublet (π_D^{++}, π_D^{--}); $(\rho_D^{++}, \rho_D^{--})$
  Singlets (π_D^0); (ρ_D^0)
  $\rho_D^0 - Z'$ mixing leads to visible decays
  For charges of type Diag(+1… -1) only one diagonal ρ_D^0 mixes with Z'

- Example 2: $N_{f_D} = 4$; $n_{\pi_D} = n_{\rho_D} = 15$; $Q_D = \text{Diag}(-1, +1, -2, +2)$;
  All diagonal ρ_D^0 mix with Z'

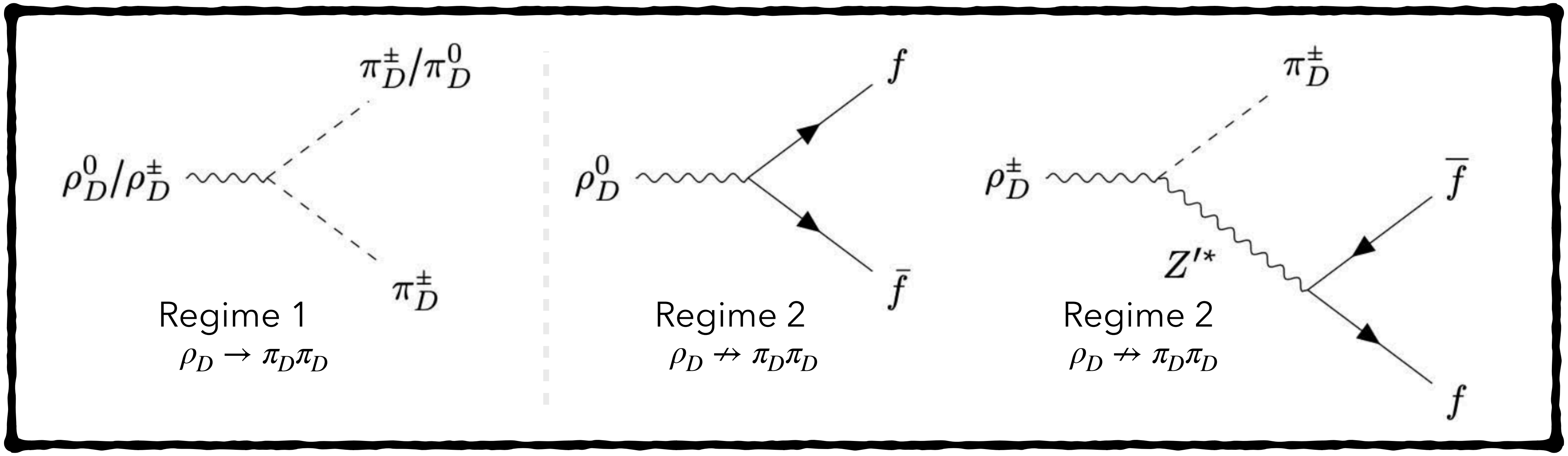
Fig. From Kahlhoefer et.al. arXiv:1907.04346



Dark rho meson decays

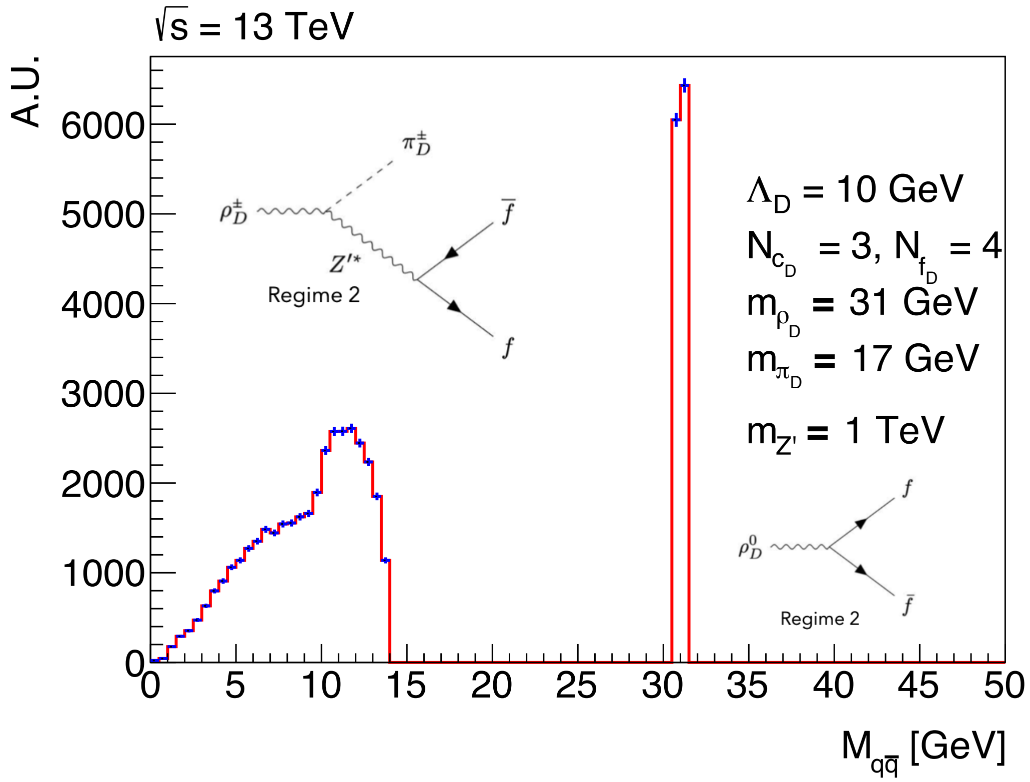
Beriln, Blinov, Gori, Schuster, Toro arXiv:1801.05805

- Analysis of broken symmetries and chiral Lagrangian set dark meson decays



See also Born, Karur, Knapen, Shelton arXiv:2303.04167

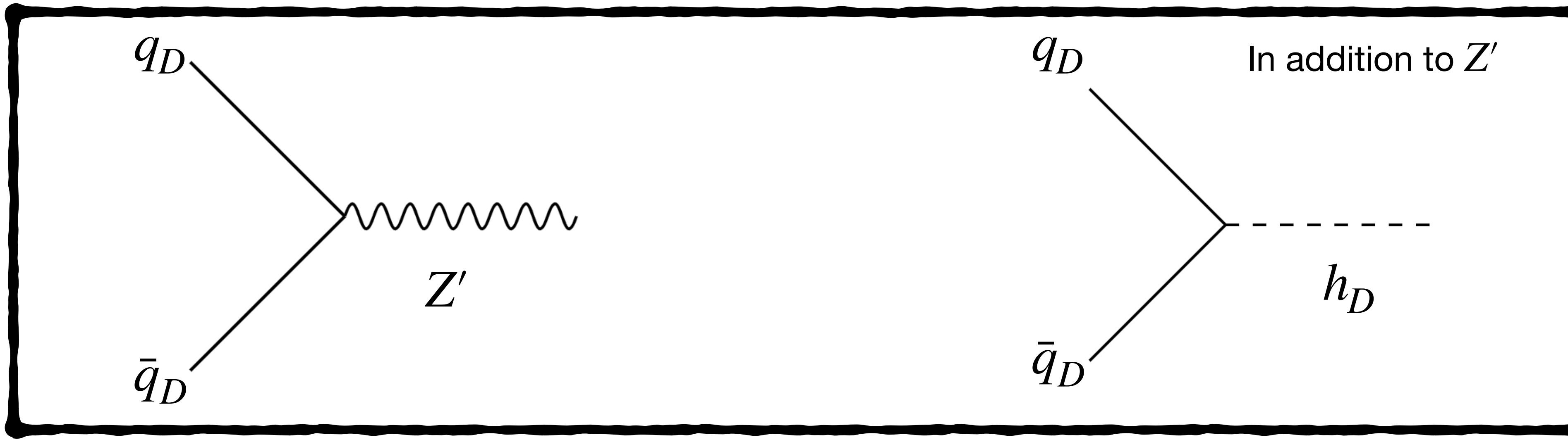
- Regime 2, $m_{\rho_D} < 2m_{\pi_D}$:
  - $\Gamma(\rho_D \to \pi_D f\bar{f}) \propto \dfrac{m_{\rho_D}^{11}}{\Lambda_D^6\, m_{Z'}^4}$ $\Rightarrow$ Potential LLPs!
  - Not captured in previous LHC phenomenology
- Example 1: $N_{f_D} = 1$ both off-diagonal ρ_D decay via three body
- Example 2: $N_{f_D} = 4$ seven ρ_D decay via three body



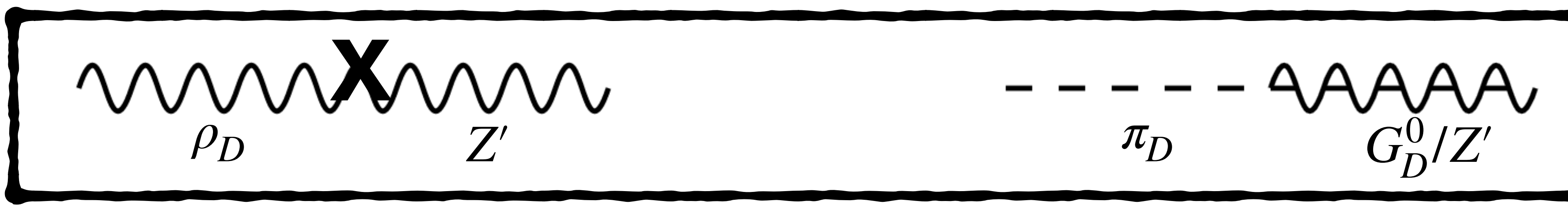
Dark pion decays

See Strassler, Zurek hep-ph/0604261

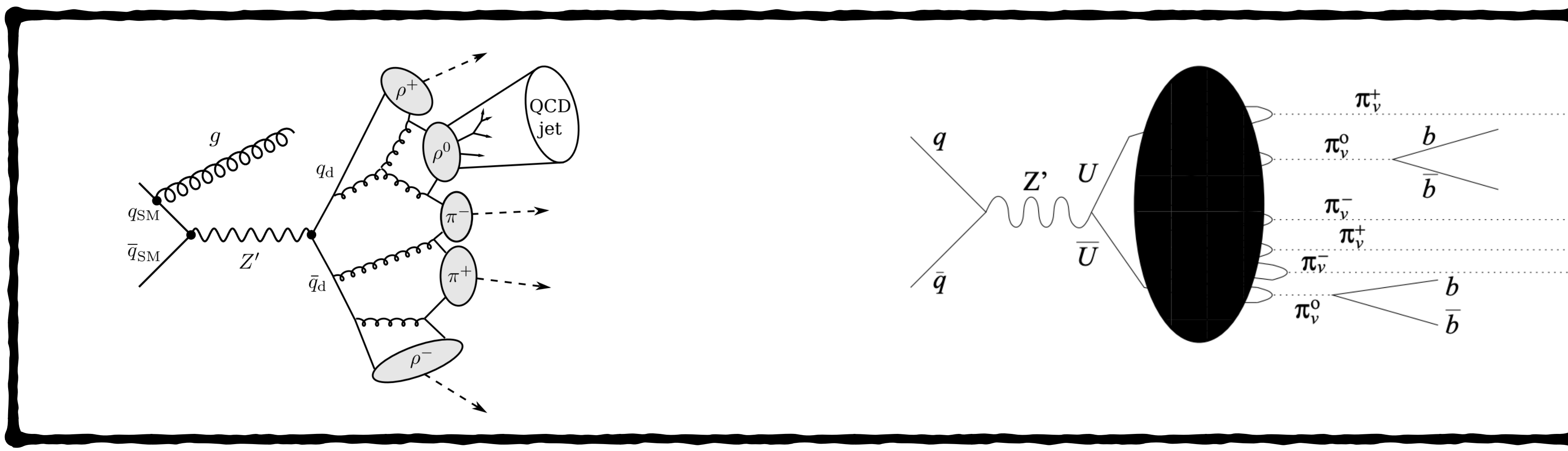
UV theories



IR portals



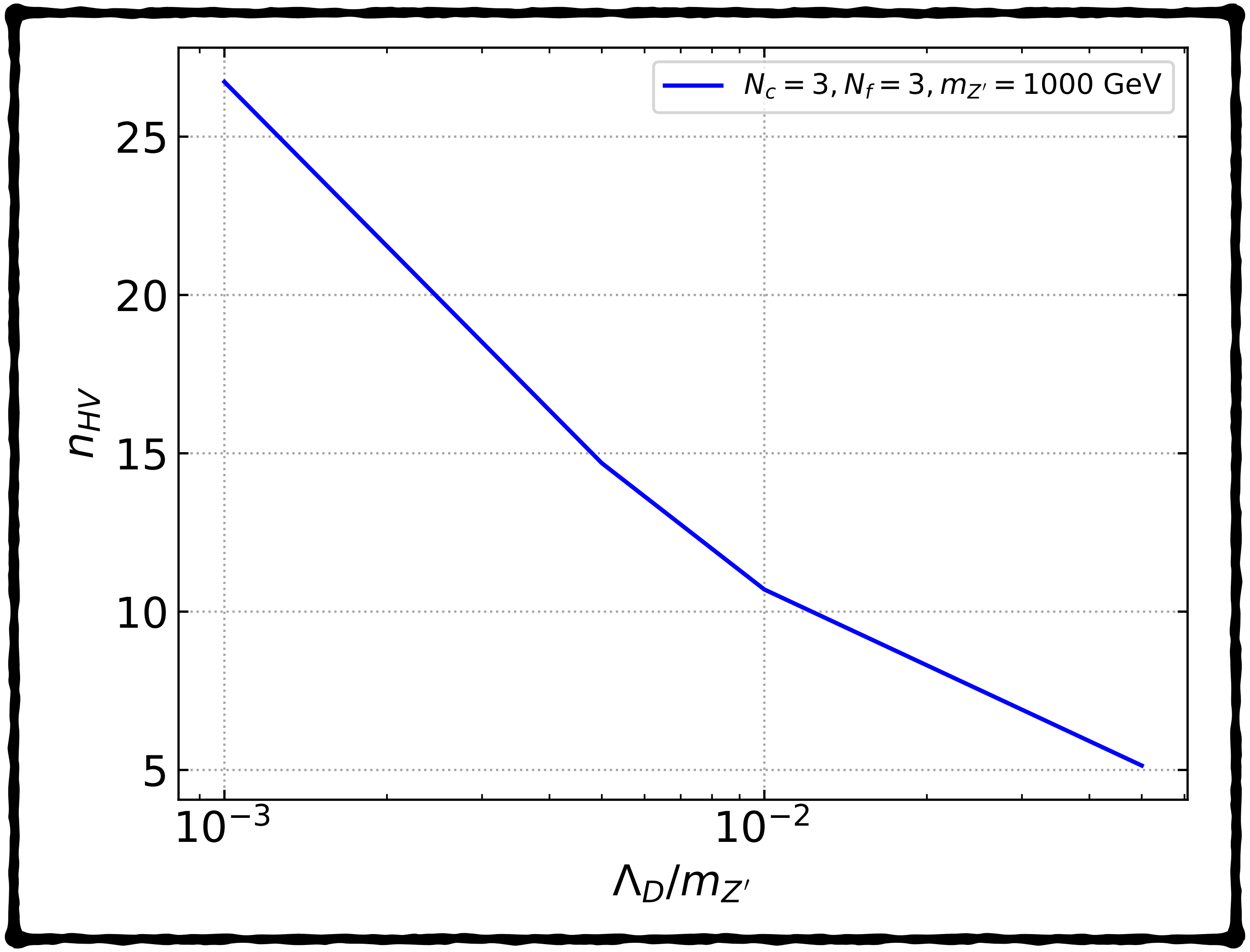
LHC signatures



SVJ composition depends on Z' properties

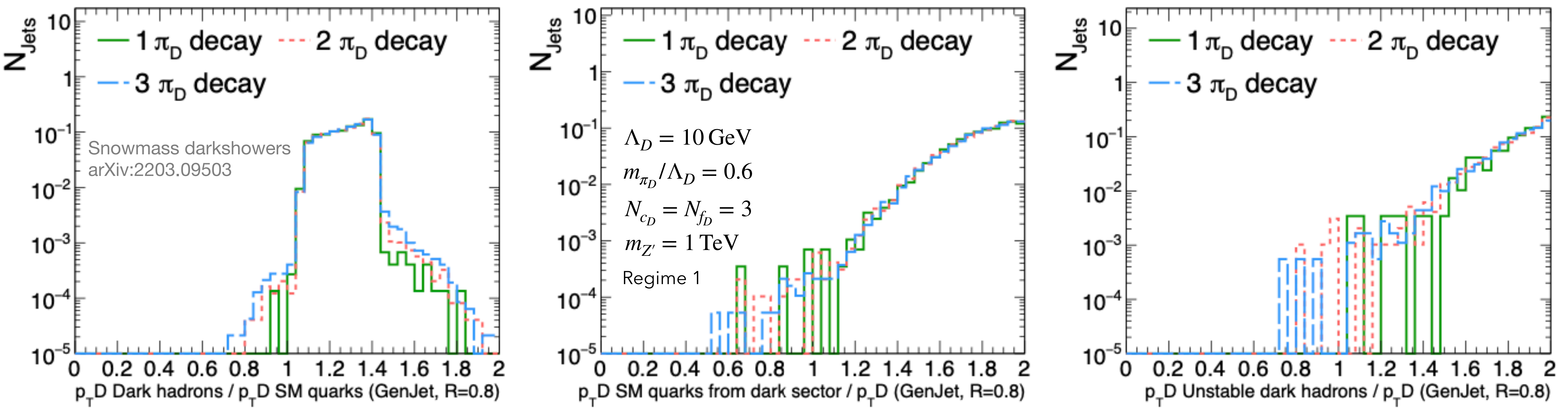
SVJ typically rich in HF

Choosing $m_{Z'}$



- For $m_{Z'} \gg \Lambda_D$ hard production is followed by dark parton shower and hadronization, for $m_{Z'} \sim \Lambda_D$ dark shower and hadronization shuts down → dark hadron production
- First approximate quantitive study to establish these regimes → pick $m_{Z'} \gtrsim 30\Lambda_D$

Impact on SM final states



- Number of decaying pions can lead to differences in jet substructure variables
- Some of the jet substructure variables (e.g. pT_D) are not IRC safe, care should be taken while using them
- Regime - II scenarios, not yet explored
- (Dark) Hadronization uncertainties can be significant, did not explore in details

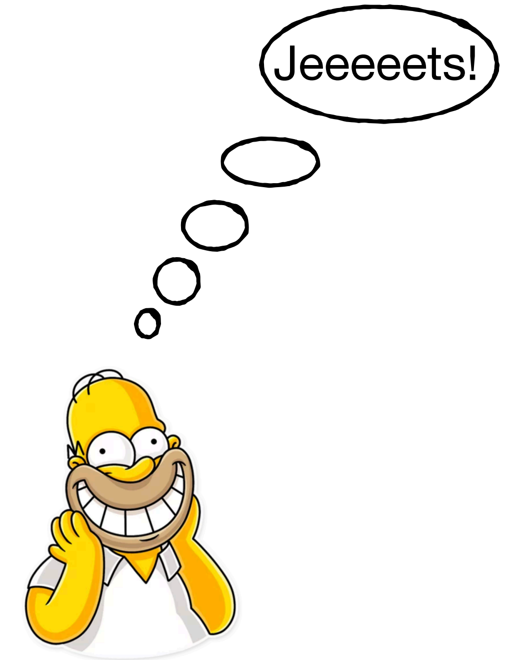
Conclusions

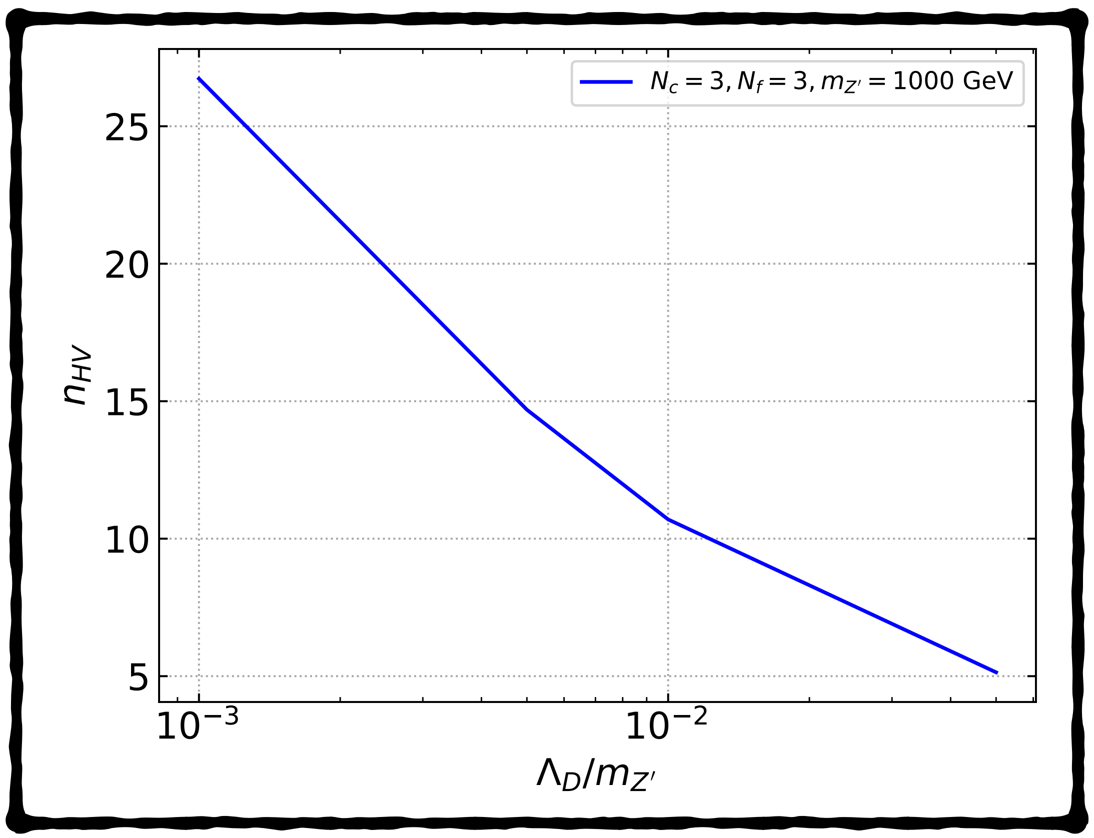
- Strongly interacting dark sectors can explain a variety of SM shortcomings and present interesting opportunities at the experiments
- A strong phenomenological and experimental program exists
- A successful exploration of strongly interacting sectors benefits from understanding the theories in UV and IR and is further complemented by lattice simulations
    - Defined theoretically consistent darkshowers scenarios for dark quark mass degenerate regime
    - Identified less explored spin-1 meson decays
    - Demonstrated need to carefully study IRC safety of jet substructure variables
    - Performed first validation of PYTHIA8 for simulating darkshowers (not presented in the talk)
- Did not consider mass split scenarios
    - More theory work necessary
    - PYTHIA8 validation necessary
- More SM - DS portals can be constructed and can lead to more exotic dark showers
- If you want to design a search for darkshowers talk to (more than one) theory friends before choosing your favourite model

Backup

How to get jets?

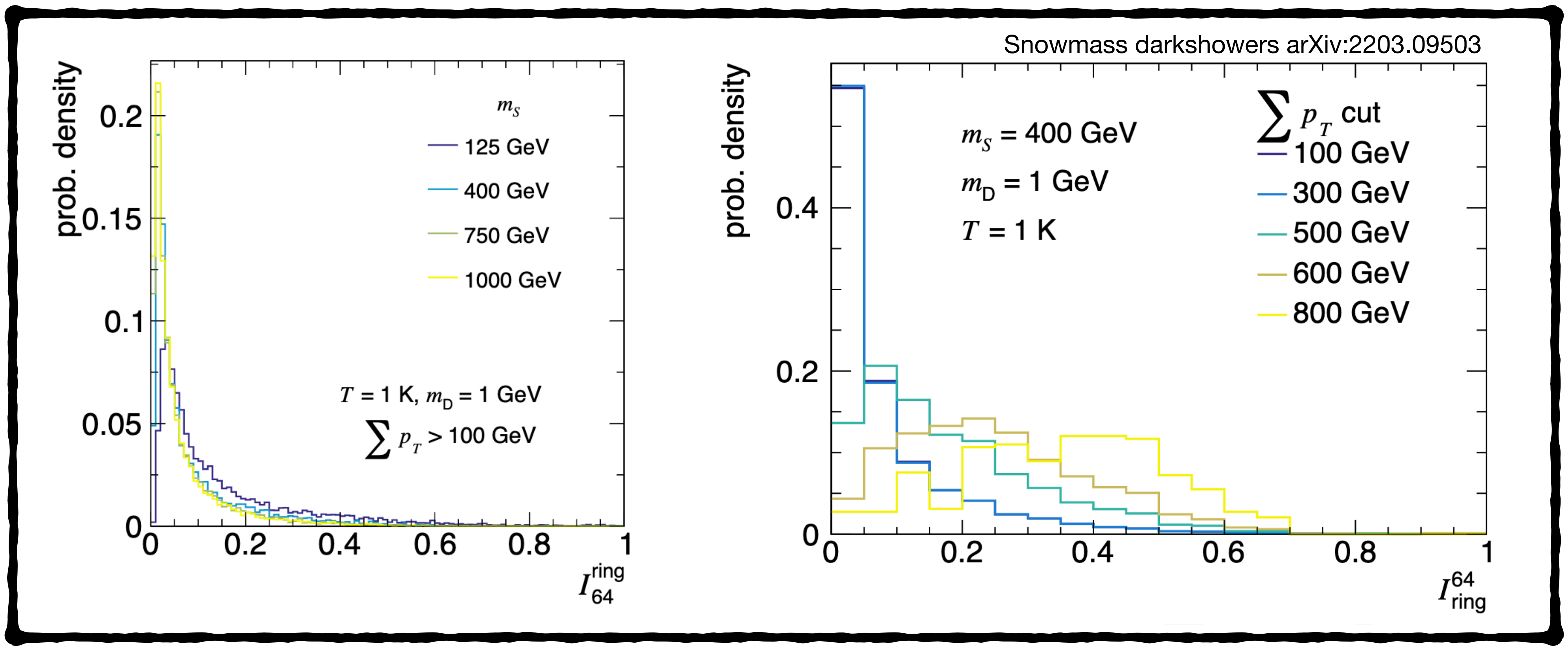
- Choose $N_{c_D} > 2$ and $N_{f_D} > 1$, $\Lambda_D > 1\,\mathrm{GeV}$, stay within asymptotically free region
- Pick $0.25 < m_{\pi_D}/\Lambda_D < 2$ and set mass spectrum
  - NB: This mass spectrum will provide current quark mass (NOT the same as PYTHIA8 HV 4900101:m0 parameter
  - Set constituent quark mass 4900101:m0 as $m_{q_{const}} \equiv m_{q_D} + \Lambda_D$ (this is not an exact relation)
- Pick $m_{Z'} \gtrsim 30\Lambda_D$ to get jets
- Neglect special treatment for singlets for now
- Assume baryons are heavy thus irrelevant
- Depending on m_{π_D}/Λ_D and portal, set the dark meson decay modes
  - Note: $m_{\pi_D}/\Lambda_D < 1.53 \Rightarrow \rho_D \to \pi_D\pi_D$ open!





Beyond QCD-like theories: SUEP

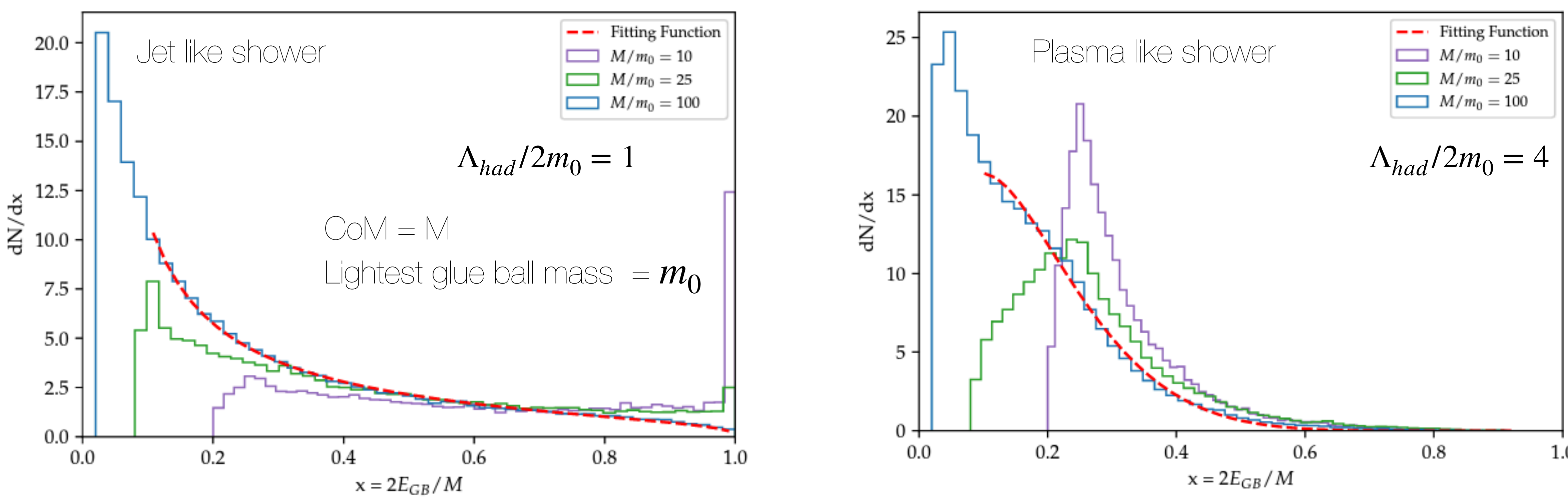
- Large 't Hooft coupling $\lambda = \alpha_D N_{c_D}$: unsuppressed large- angle radiation → wide, spherical showers; small class of theories have been proven to exist
- No dedicated simulation tools, at best some idealised approximations exist
- Common underlying feature is global radiation pattern, event shape observables can serve as useful analysis tool
- New variables to quantify event isotropy for SUEP benchmark models
- Experimental avenues being investigated; care in handling tools necessary
- Trigger strategies create bias towards less spherical events



Beyond QCD-like theories: Glueballs

Curtin, Gemmell, Verhaaren
arXiv:2202.12899

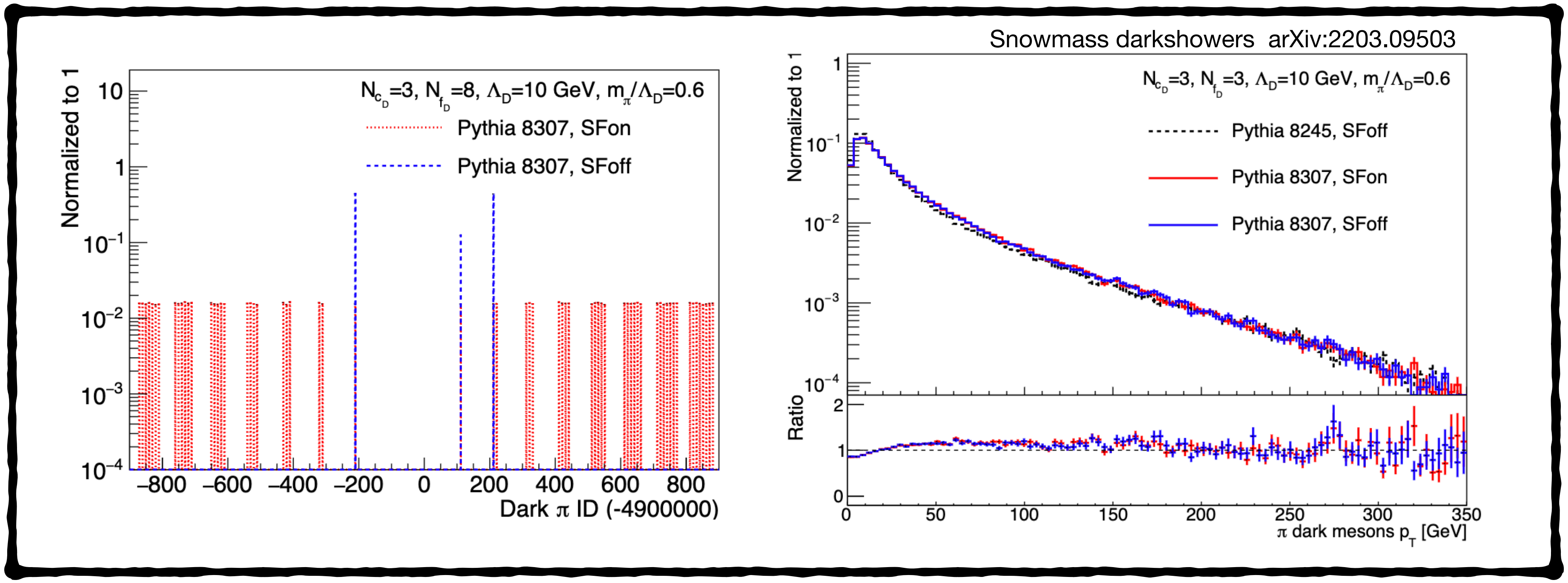
- Occur in simplest non-Abelian theories, theories containing no light fermions or scalars
- These refer to bound states of gluons, theories characterised entirely by confinement scale; spectrum computed on lattice
- First effort for creating Yang-Mills parton shower and hadronization
- First publicly available simulation tool with two different hadronization settings
  - Perturbatively motivated jet-like hadronization
  - More exotic SUEP like final state



PYTHIA8 improvements and validation

See also:
Mies, Scherb, Schwaller
arXiv:2011.13990

- Need to be able to control properties of individual hadrons in PYTHIA8 HV
- How should such mass degenerate dark quark theories look like in MC simulation?
- Do we reproduce SM QCD using PYTHIA8 HV module?



Pythia8.307
now available

- Adjustments in HV (mini)-string fragmentation so that it leads dark meson to p_T suppression to match with SM QCD; now available in PYTHIA8$_{(8.307)}$
- PYTHIA8$_{(8.307)}$ now has possibility to separately control properties of dark quark and mesons (separateFlav = on)
- Validated only for mass degenerate scenarios
- Hadronization module not validated however it reproduces SM QCD in appropriate regime

‘Hacking’ branching ratios in PYTHIA

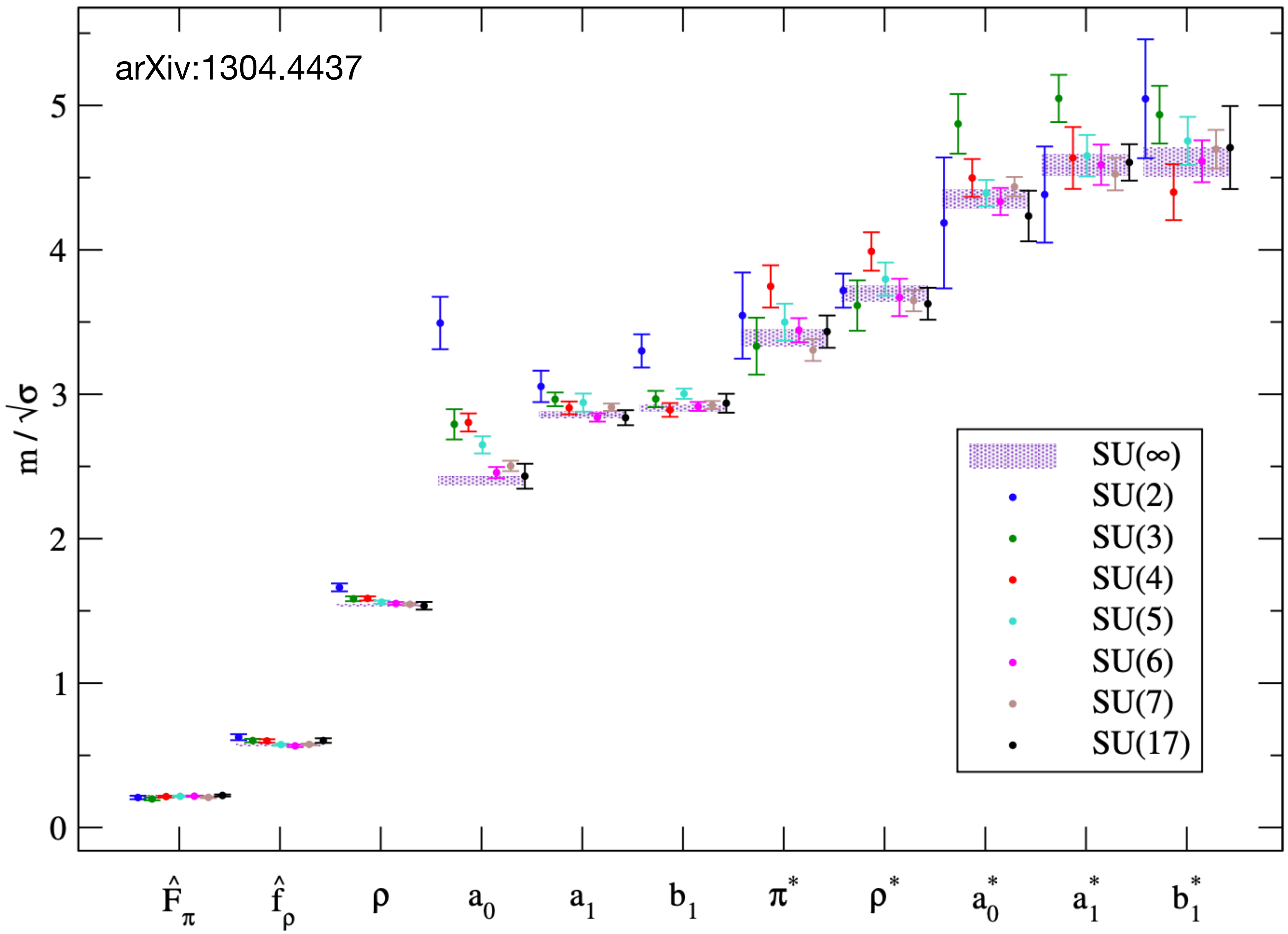
- For a theory with N_f flavours, number of pions are $N_f^2 - 1$
- Mass degenerate quarks imply mass degenerate pions (and rho)
- Out of these $N_f - 1$ are diagonal pions and $N_f(N_f - 1)/2$ off-diagonal pions
- Pythia models these diagonal and off-diagonal states using three pions, pythia assigns three pdg codes for these, one for diagonal, one for upper triangle and one for lower
- The number of pions/rhos that can decay depends on the specific theory
- Thus, one should rescale branching ratio of the pions by their multiplicity to account for the probability of decay
- If x number of diagonal pions decay then the rescale factor is $x/(N_f - 1)$
- Similarly for y number of off-diagonal pions decaying the probability is $y/(N_f(N_f - 1)/2)$

$$\Pi = \begin{bmatrix} \pi_D^0 & \pi_D^\pm & \cdots \\ \vdots & \ddots & \\ \pi_D^\pm & & \pi_D^0 \end{bmatrix}$$

- Theory dictates that equal number of diagonal and off-diagonal pions and rhos decay in any given theory (if rho to pi threshold is closed)

Meson masses

- Lattice simulations for a large number of (large N) SU(N) theories show that meson masses are more or less independent of the gauge group dimension

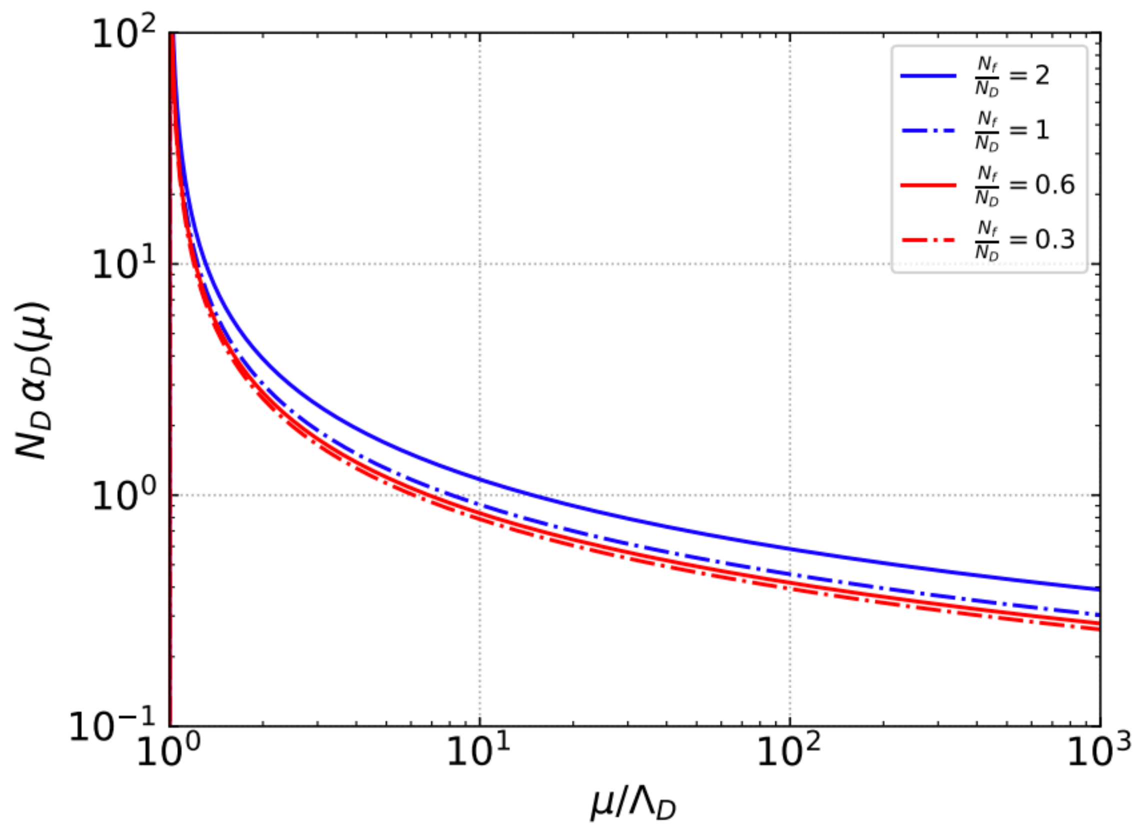


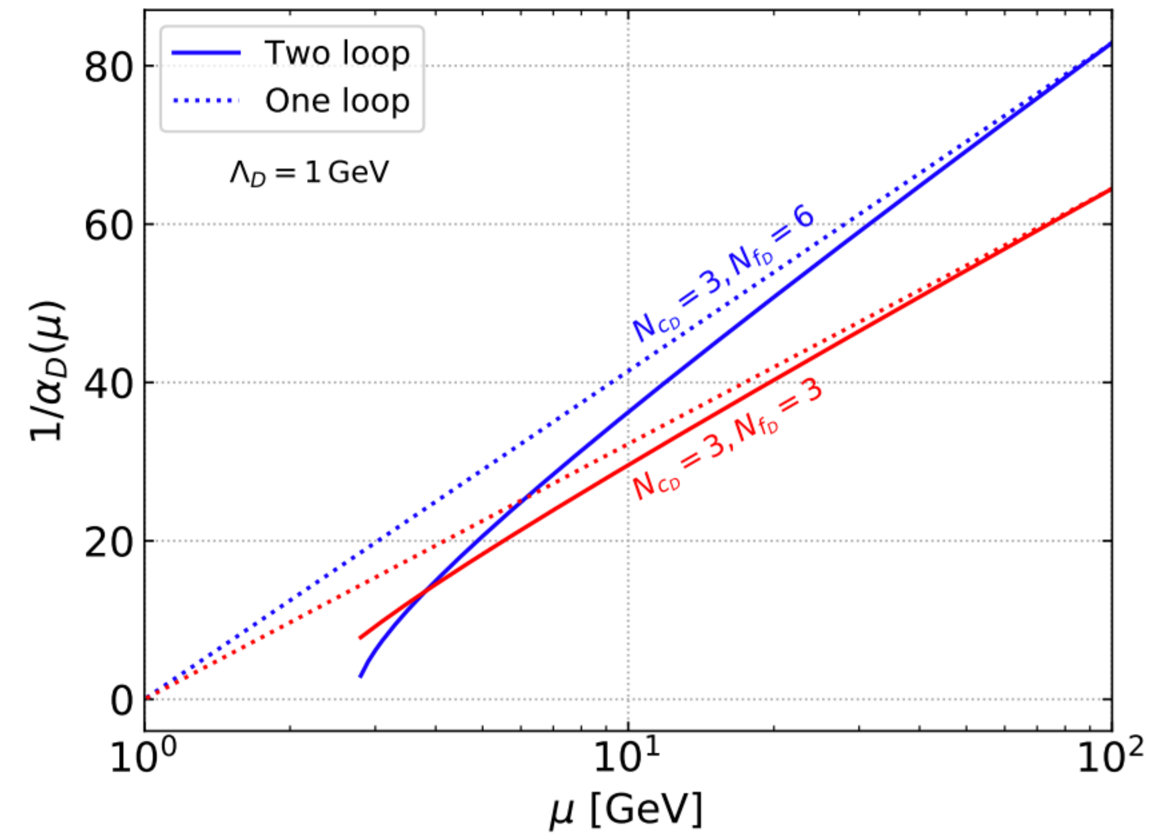
Benchmarks

- A few suggested first list of benchmarks in snowmass
- Applicable for s-channel vector mediated SM - DS interactions

Regime	N_{c_D}, N_{f_D}	Λ_D [GeV]	**Q**	m_{π_D} [GeV]	m_{ρ_D} [GeV]	Stable dark hadrons	Dark hadron decays
$m_{\pi_D} < m_{\rho_D}/2$	3,3	5	Various	3	12.55	$0/1/2\pi_D^0$	$\rho_D^{0/\pm} \to \pi_D^{0/\pm}\pi_D^{\mp}$ $\pi_D^0 \to c\bar{c}$
	3,3	10	Various	6	25	$0/1/2\ \pi_D^0$	$\rho_D^{0/\pm} \to \pi_D^{0/\pm}\pi_D^{\mp}$ $\pi_D^0 \to c\bar{c}$
	3,3	50	Various	30	125.5	$0/1/2\ \pi_D^0$	$\rho_D^{0/\pm} \to \pi_D^{0/\pm}\pi_D^{\mp}$ $\pi_D^0 \to b\bar{b}$
$m_{\pi_D} > m_{\rho_D}/2$	3,4	10	(-1,2,3,-4)	17	31.77	All π_D	$\rho_D^0 \to \mathrm{q\bar{q}}$ $\rho_D^{\pm} \to \pi_D^{\pm}\mathrm{q\bar{q}}$

Running of α_D



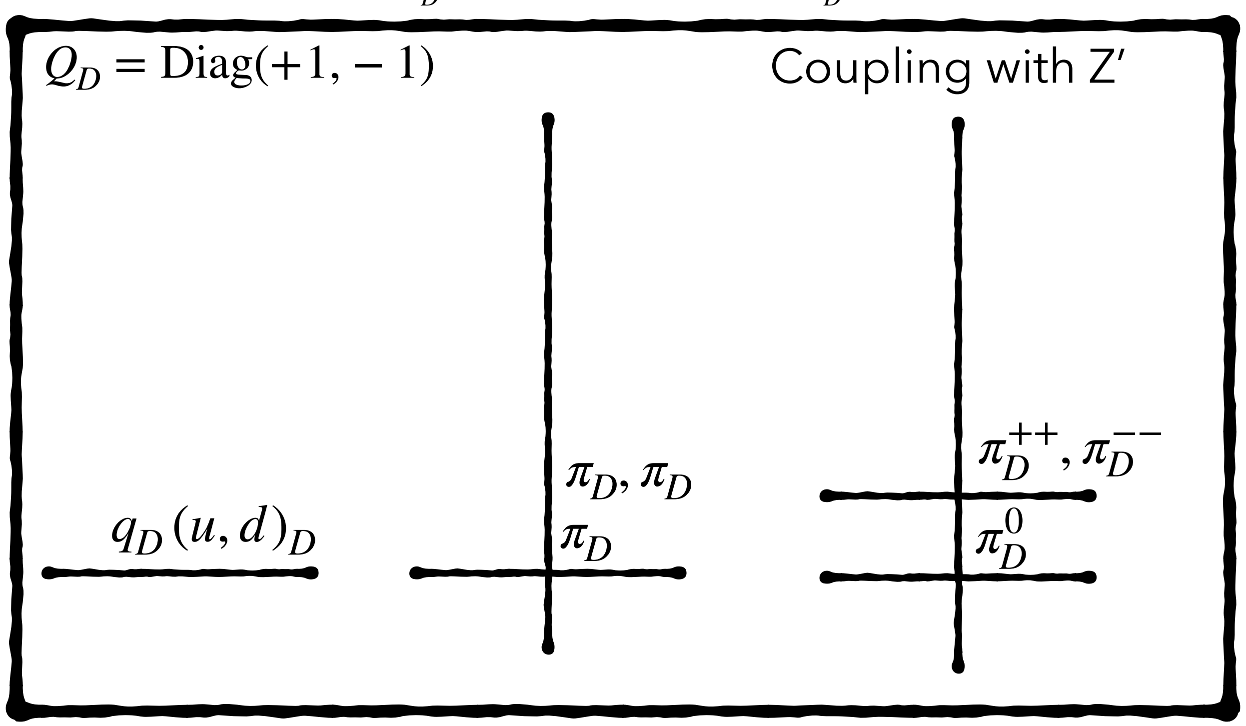


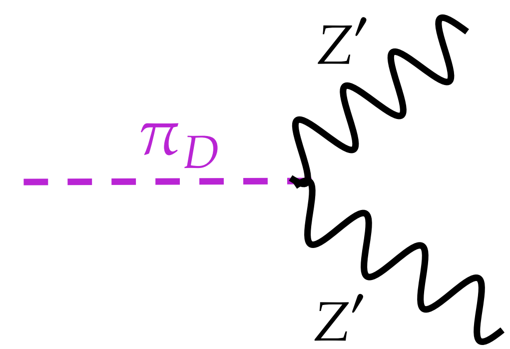
- Running depends on N_{f_D}/N_{c_D}
- Two loop corrections become important as N_{f_D}/N_{c_D} increases

Primary obstacles in getting DM candidate

- DM longevity needs to be ensured
  - Impose external symmetries
  - Use accidental symmetries e.g. lightest baryon (proton) is stable in the SM due to baryon number conservation
  - Engineer models to ensure stability

$SU(N_{C_D})$ Fund. rep., $SU(N_{F_D}) = 2$,





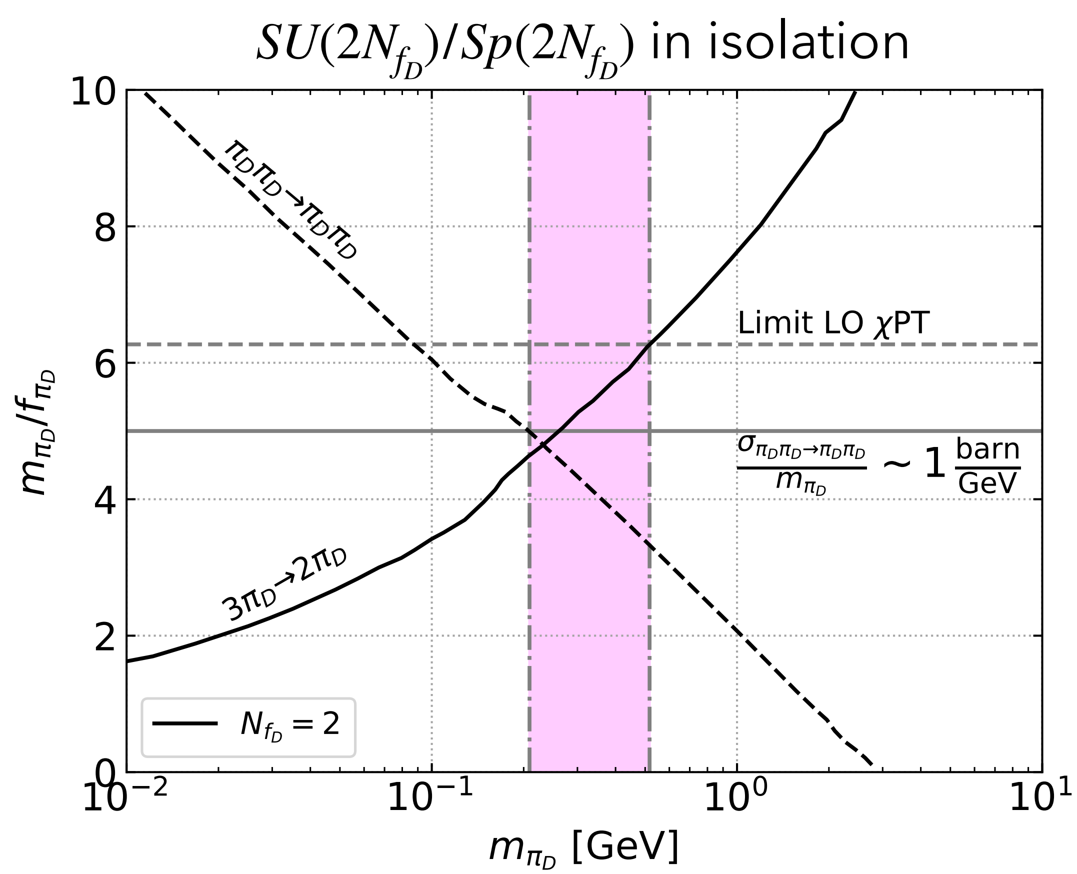
$$\sim Tr[Q_D^2 T_0] = 0$$

$$\rightarrow Q_D^2 \propto 1$$

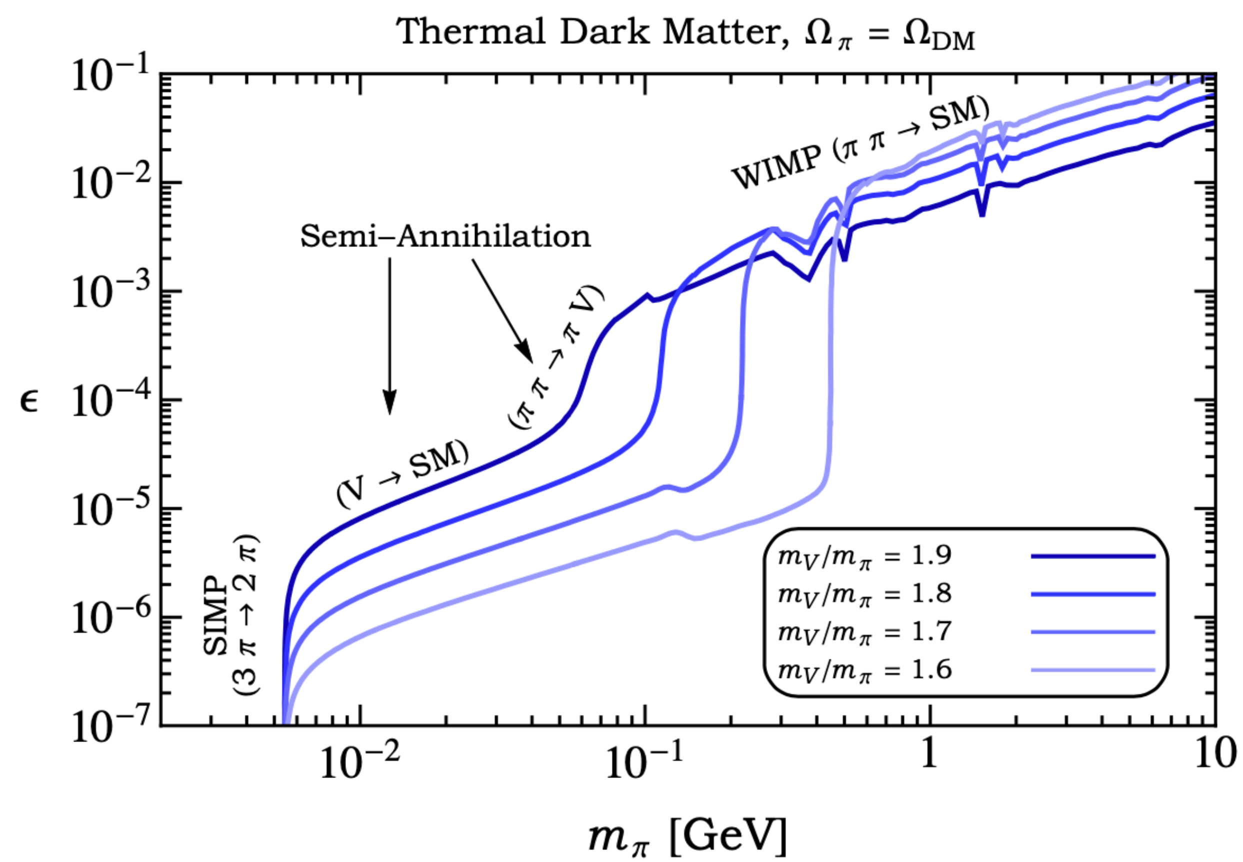
- Quantitative estimates from genuine non-perturbative physics are needed

New avenues

Hochberg et al arXiv:1512.07917, Kribs et al arXiv: 1604.04627, Cline et al arXiv:2108.10314, Beriln et al arXiv:1801.05805



- Relic density $$n_{\pi_D}\langle\sigma v\rangle_{3\to2} \sim H \implies \frac{m_{\pi_D}}{f_{\pi_D}} \propto m_{\pi_D}^{3/10}$$
- Self-scattering $$\frac{\sigma_{\pi_D\pi_D\to\pi_D\pi_D}}{m_{\pi_D}} \propto \left(\frac{m_{\pi_D}}{f_{\pi_D}}\right)^4 \times \frac{1}{m_{\pi_D}^3}$$



SIMP future prospects

Hochberg et al arXiv:1512.07917