A flavour of dark flavours

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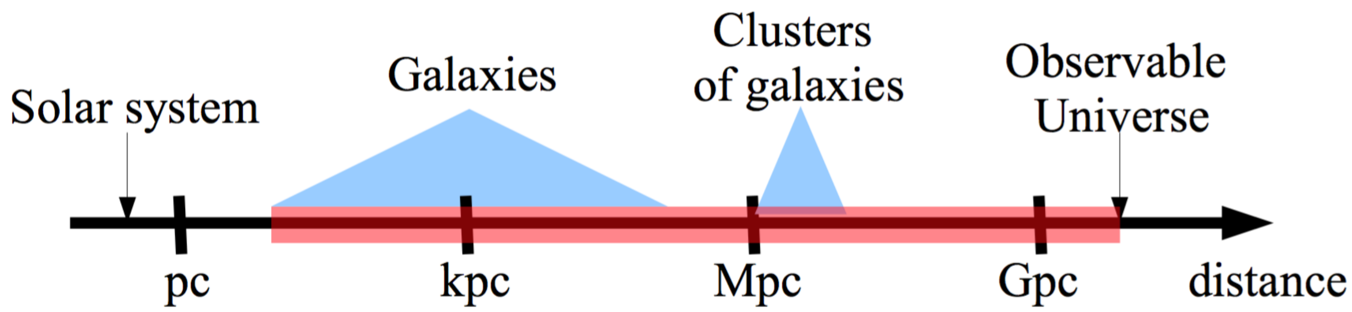
FWF Austrian Science Fund

UNI GRAZ

Dark matter: where are we?

By A. Ibarra

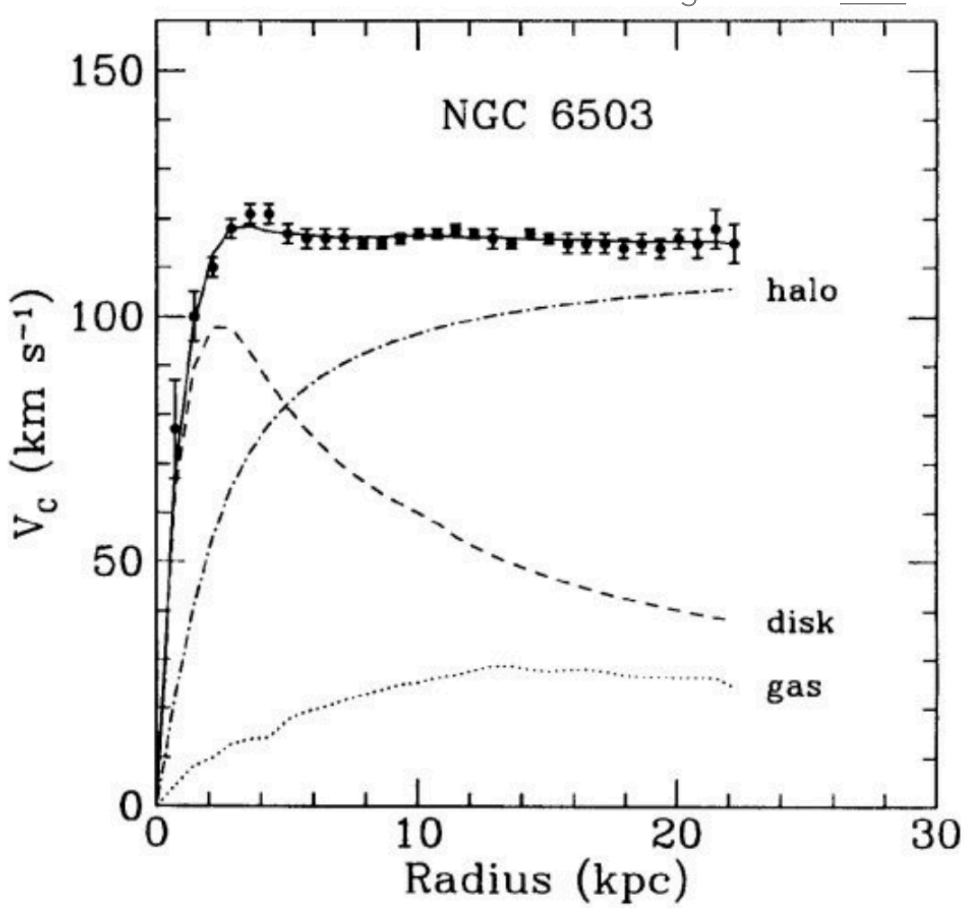
- Strong evidence on all scales

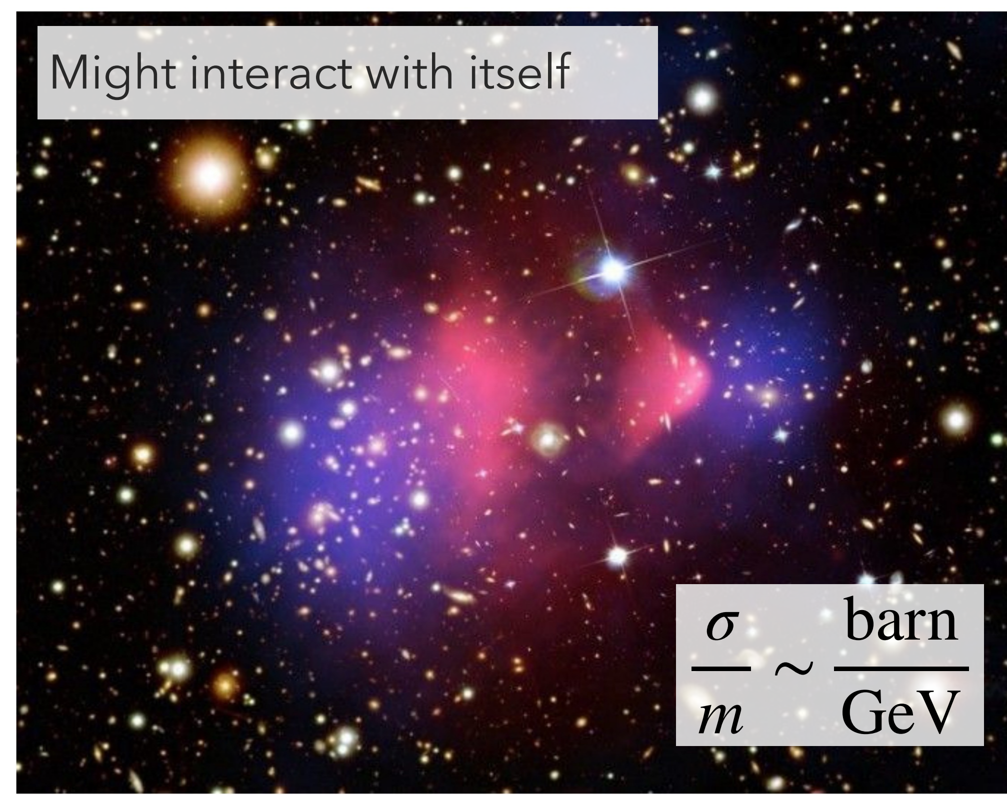


$$\Omega_{DM} h^2 \approx 0.11$$

- Four times more abundant than visible matter
- Does not directly interact with photons
- Mostly non-relativistic, charge neutral, very long lived/stable
- No such particle in the Standard Model
- No evidence at experiments so far

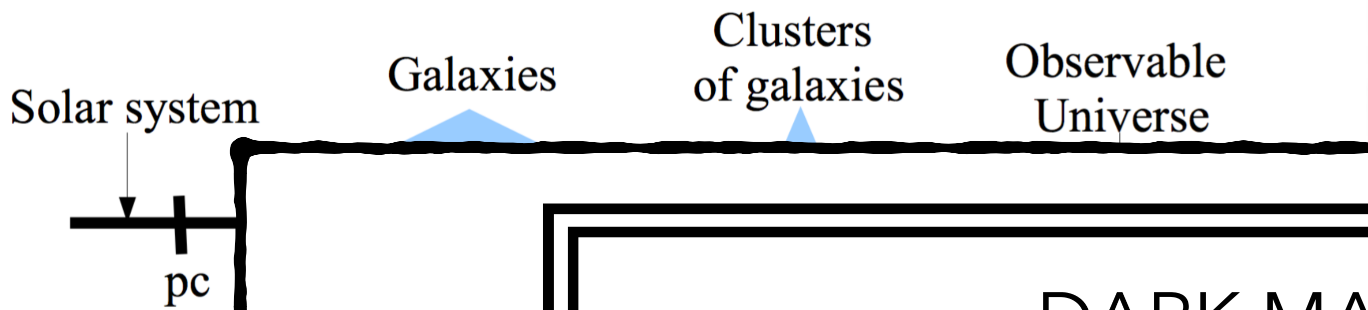
Diagram from here





By A. Ibarra

- Strong evidence on all scales



$$\Omega_{DM} h^2 \approx 0.11$$

- Four times more abundant than visible matter

hotons
eutral,

Model
far

By A. Ibarra

DARK MATTER

J = ?

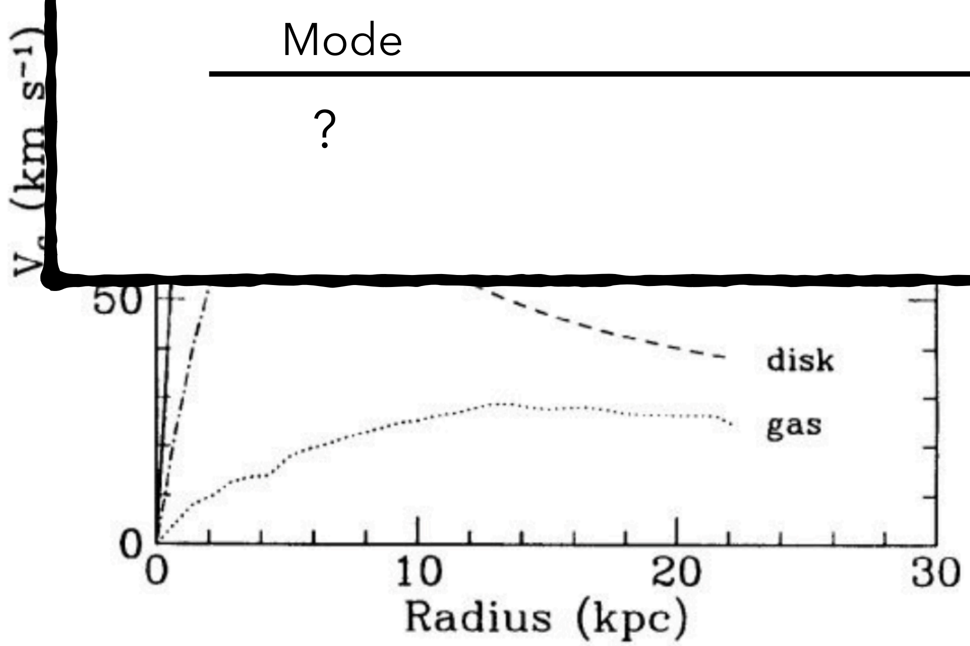
Diagram from here

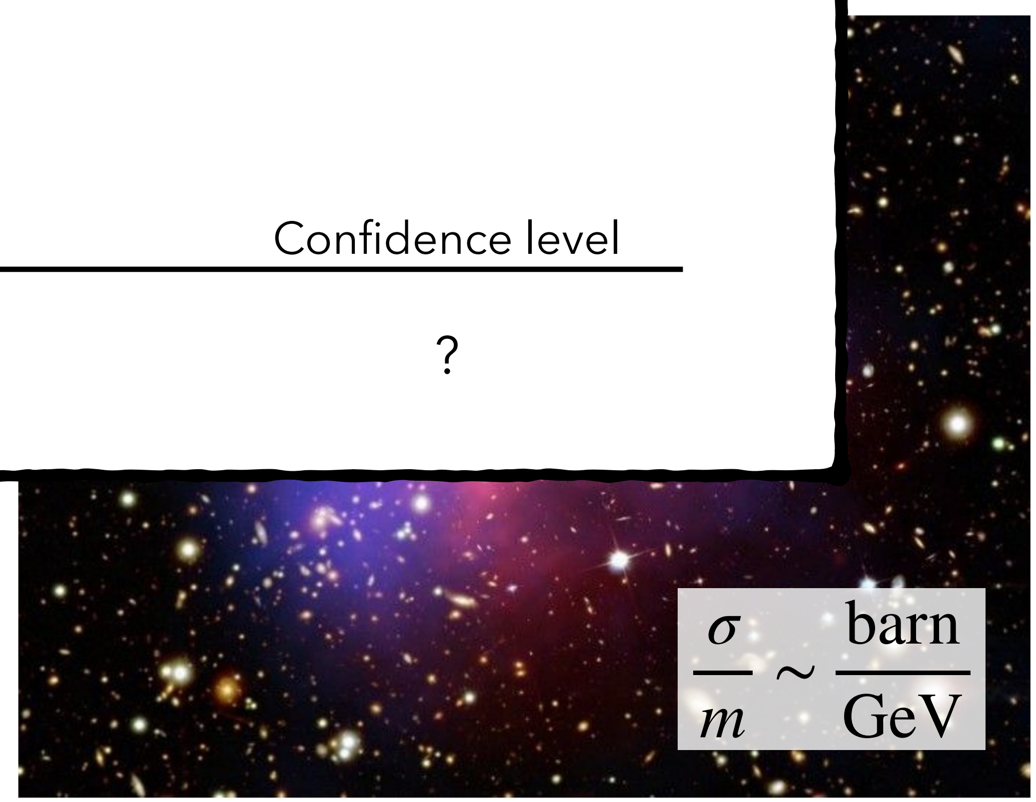
Mass = ?

Mean lifetime = ?

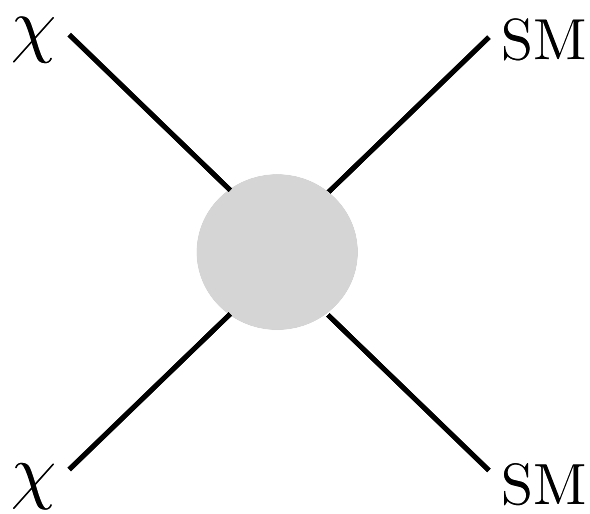
Decay modes

Mode	Fraction	Confidence level
?	?	?





Dark matter: connecting to particle physics



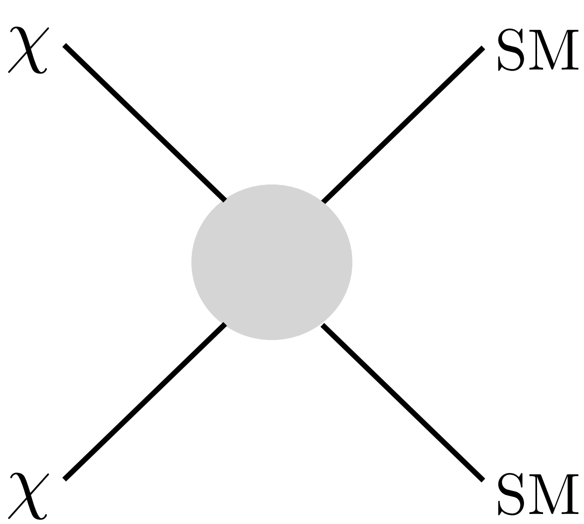
$$\Omega_\chi h^2 \sim \frac{10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \simeq 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m}{100\ \mathrm{GeV}}\right)^2$$

Weak scale coupling

Weak scale mass

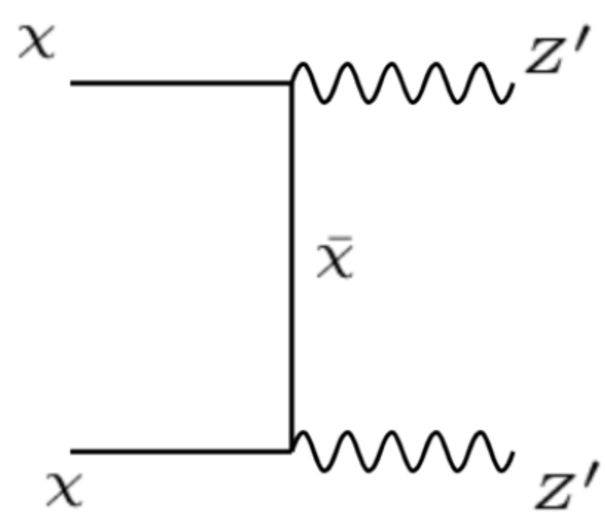
DM relic density mechanism needs a number changing interaction

Too many to add



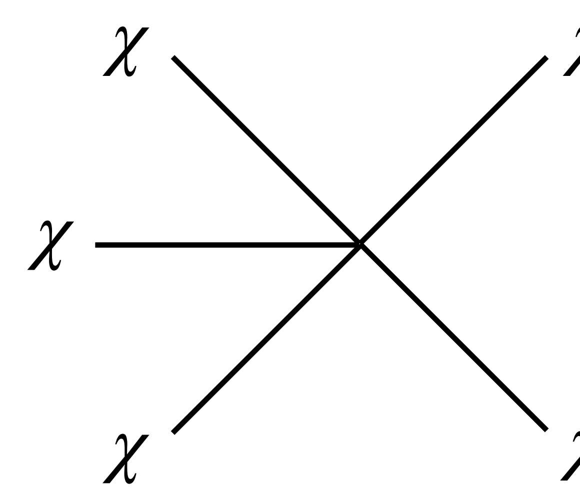
WIMP
$\mathcal{O}(100)$ GeV

Refer to original forbidden DM paper
Fitzpatrick et al. arXiv:2011.01240



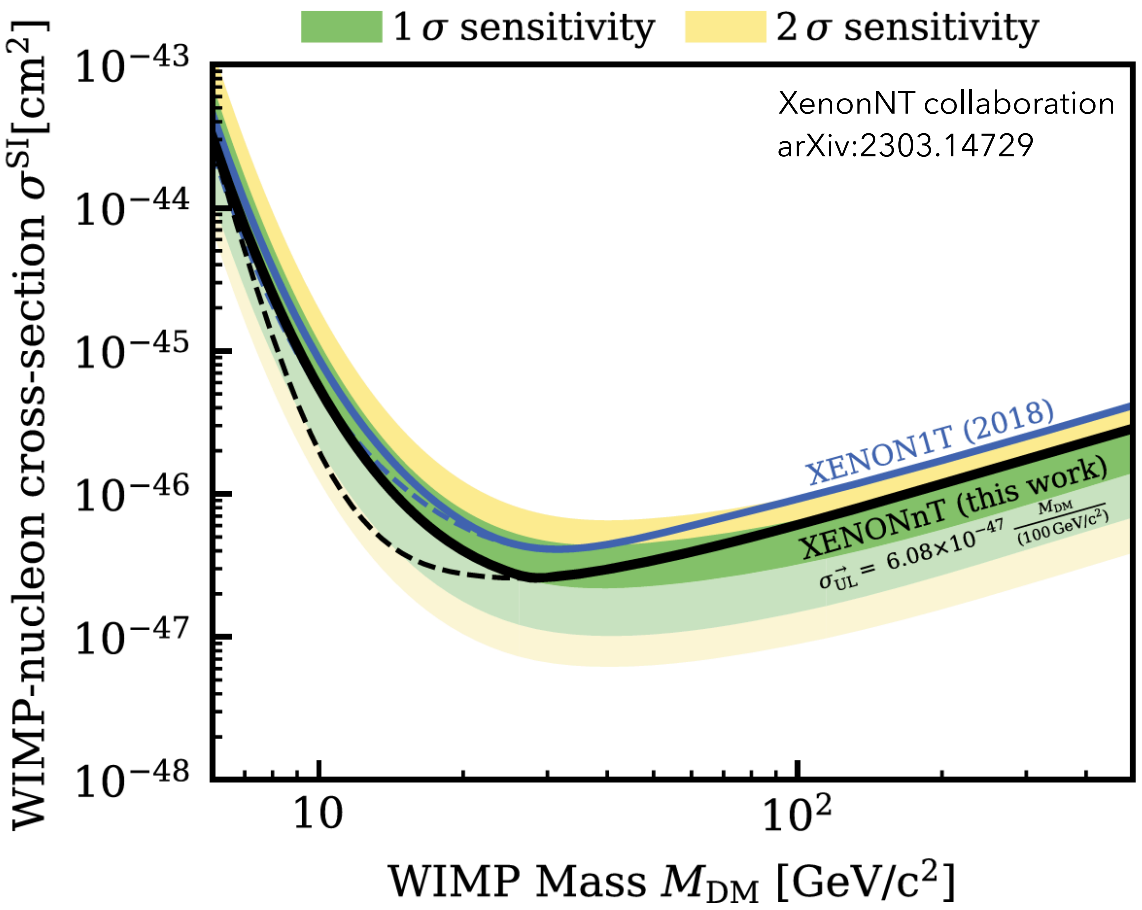
Light mediators
$\mathcal{O}(1) - \mathcal{O}(100)$ GeV

Hochberg et al. arXiv:1402.5143

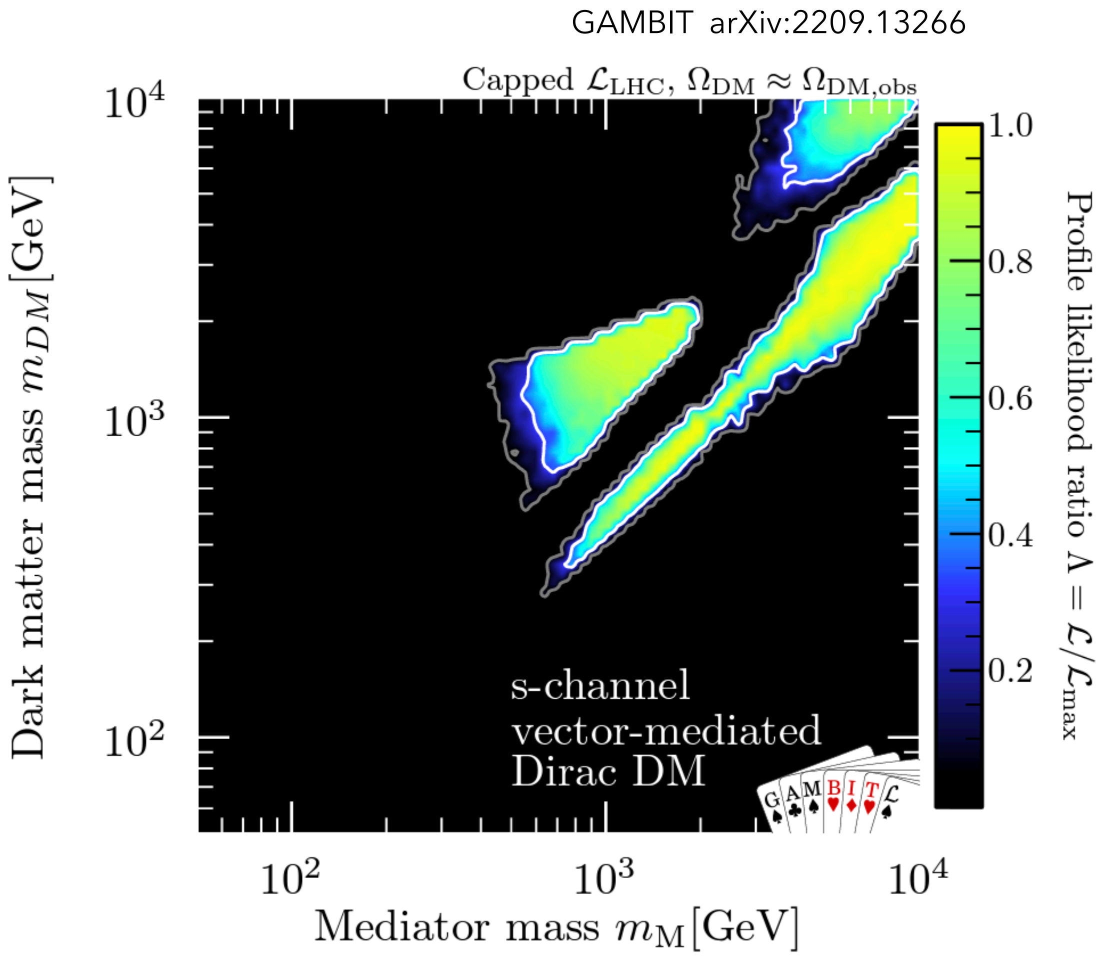


3 →2 annihilations
$\mathcal{O}(100)$ MeV

WIMP dark matter

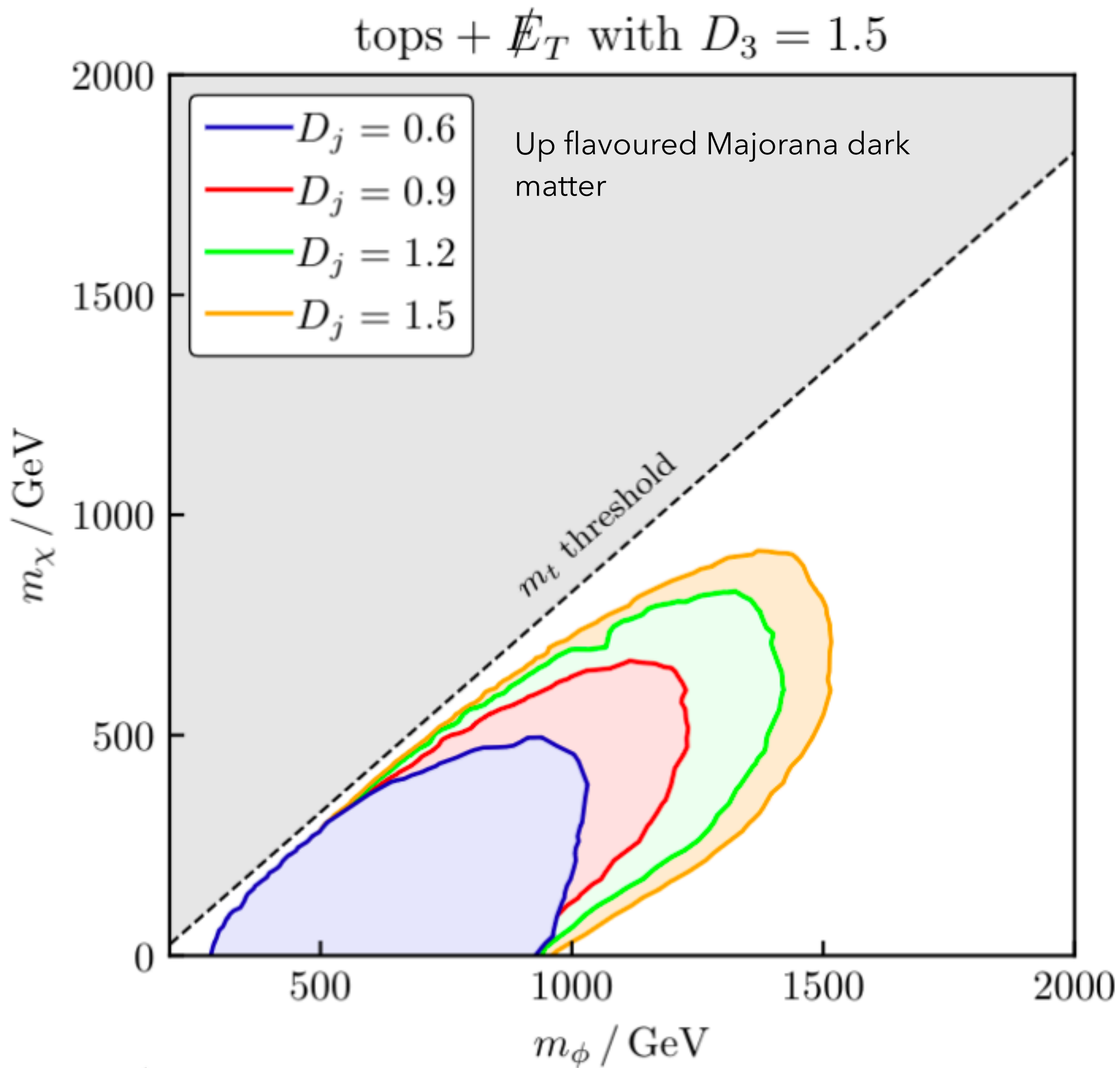


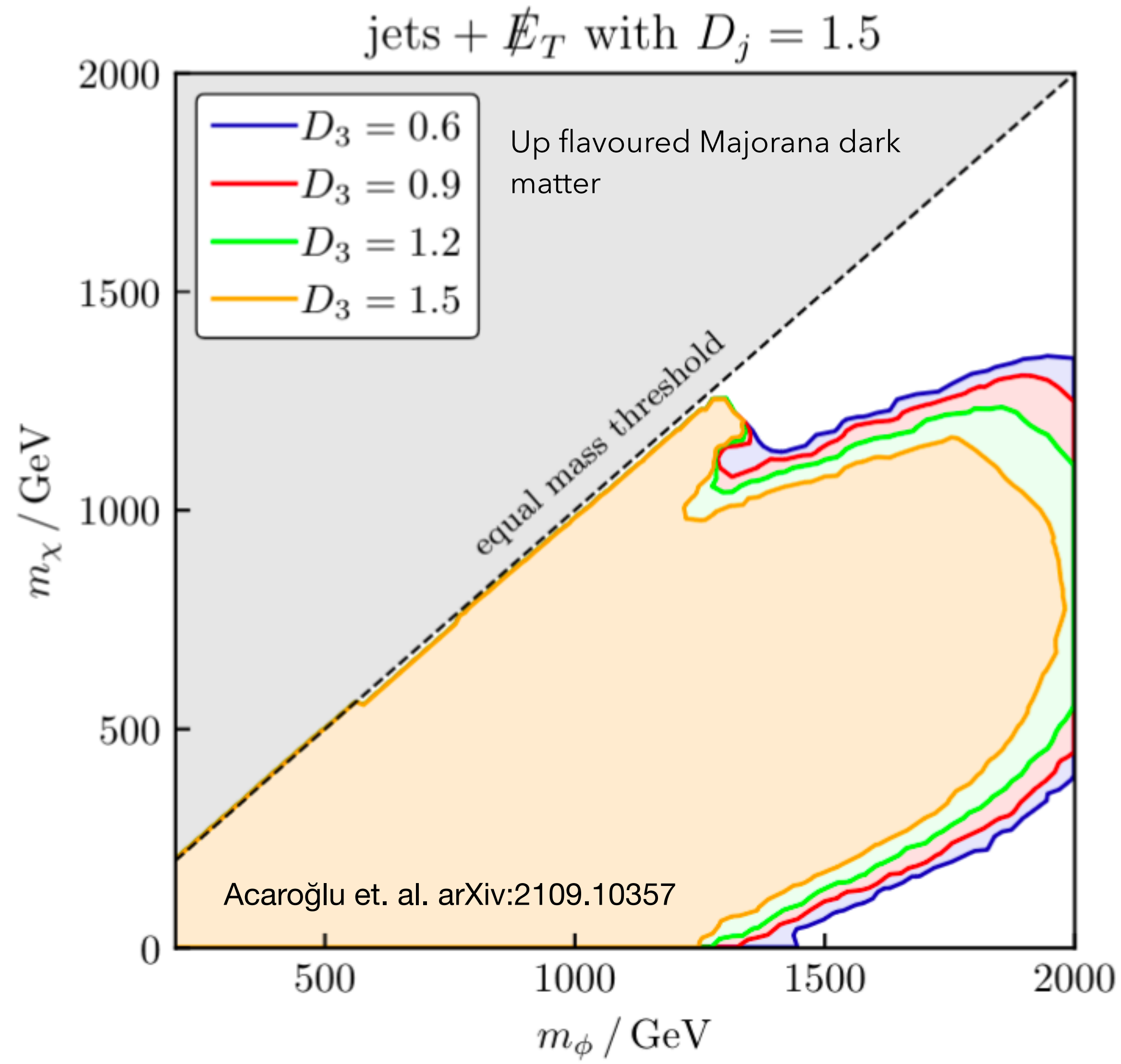
- Limits on Spin-Independent DM - nucleus scattering are being pushed to neutrino floor

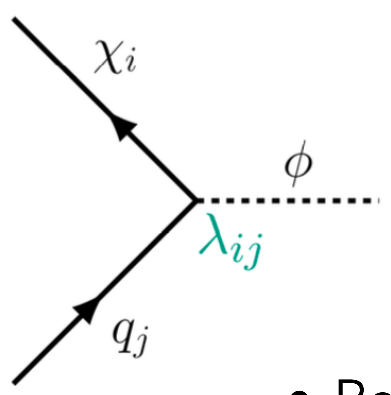


- Global fits performed by taking into account collider, direct detection and indirect detection constraints
- For simplest WIMP DM, the scales are pushed higher

Flavoured DM







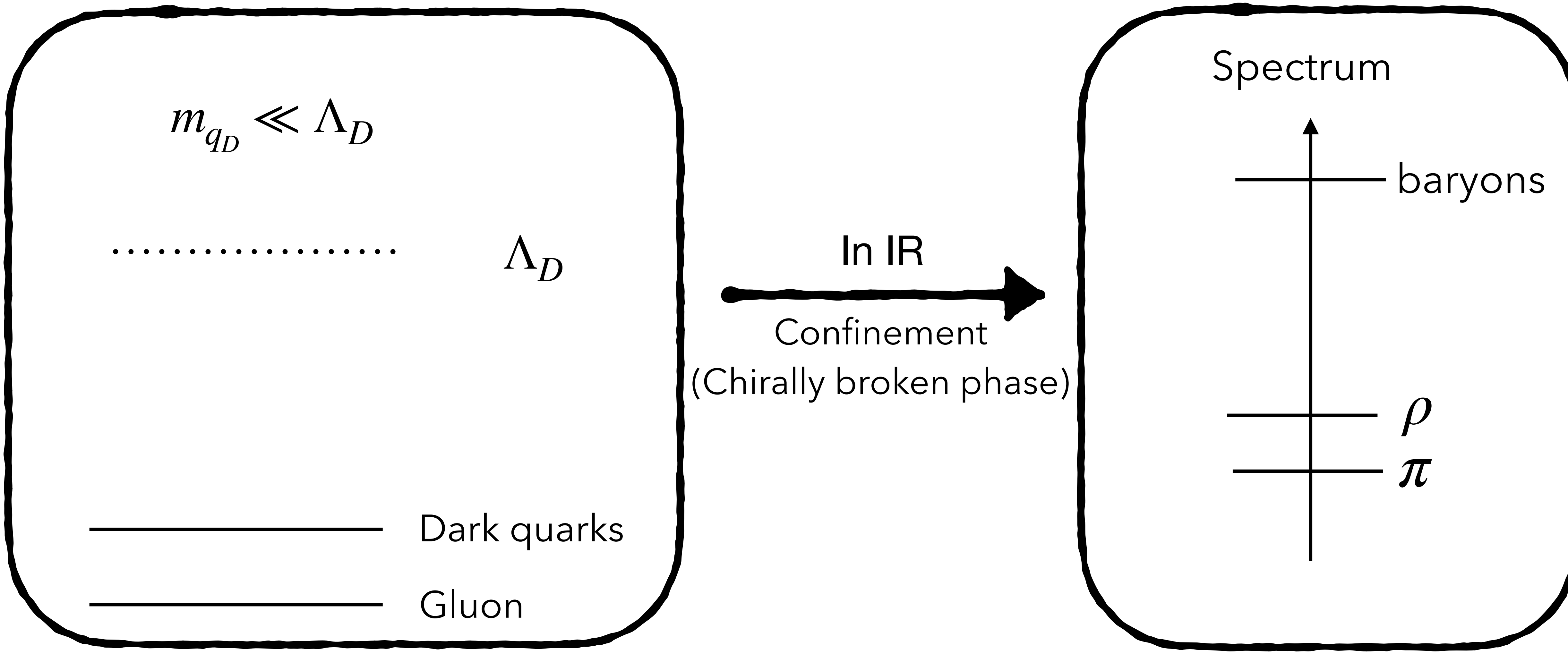
χ_3 DM candidate, λ_{ij} new CP and flavour violation

- Relic density generation mechanisms depend on mass scales of χ_i
- Unexplored signatures include same-sign tops from Majorana DM

Acaroğlu et. al. arXiv:2312.09274

Towards dark flavours

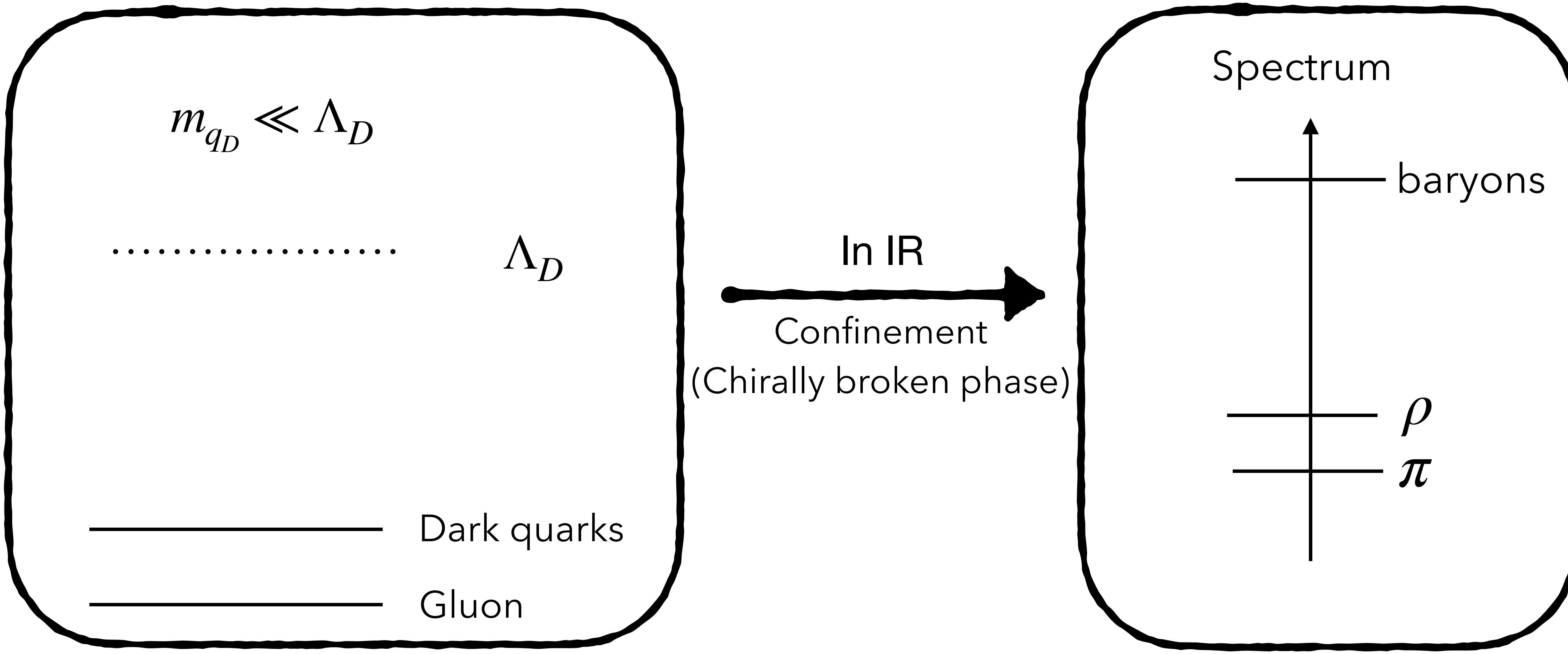
Dark flavoured dark matter



- If this is the reality of nature how do we look for it?
- Interesting scenarios due to possibility to obtain dark matter
- Generically known as (confining) Hidden Valleys or darkshowers/darkjets or SIMPs (for DM)

Strassler hep-ph/0607160

Dark flavoured dark matter



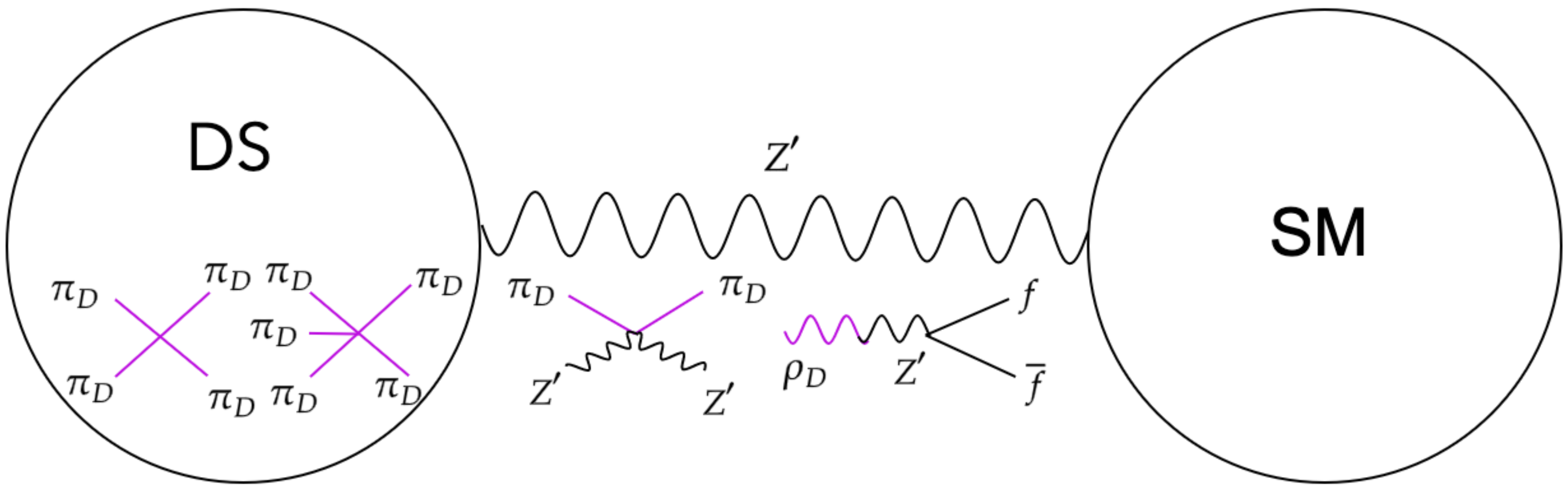
UV physics contains

- Gauge fields (gluons)
- Matter fields i.e. Dirac/Majorana fermions, Scalars (in representation N_r)
- This talk: **mass degenerate** Dirac fermions in fundamental representation

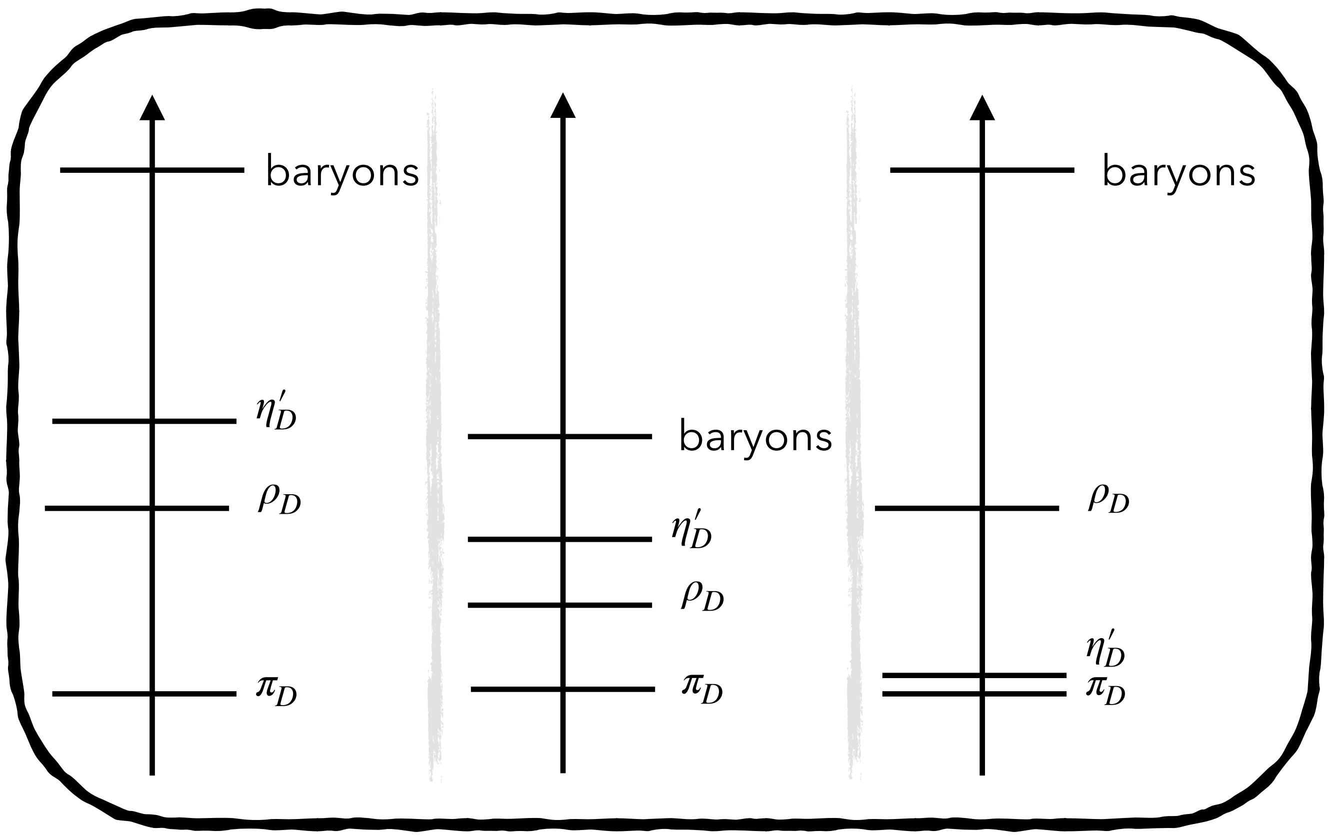
- Two discrete parameters N_{c_D}, N_{f_D}
- Two continuous parameters $m_{q_D}, \alpha_D(\mu)$ (UV)
  - $\Lambda_D, m_{\pi_D}/\Lambda_D$ or $m_{\pi_D}, m_{\pi_D}/m_{\rho_D}$ (IR)
- $N_{c_D} = 2$ and/or $N_{f_D} = 1$ for $SU(N_{c_D})$ special cases Francis et. al. arXiv:1809.09117,
- $N_{f_D} < 3\,N_{c_D}$ to be chirally broken

Towards dark flavoured dark matter

Diagram modified from Hochberg et al arXiv:1402.5143

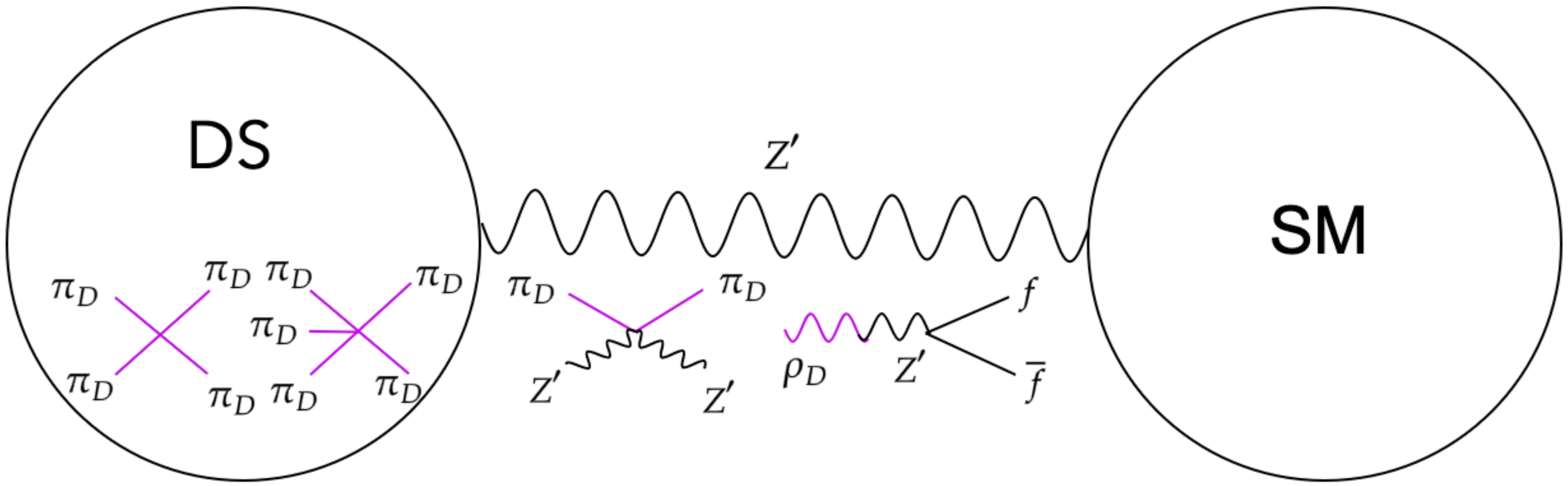


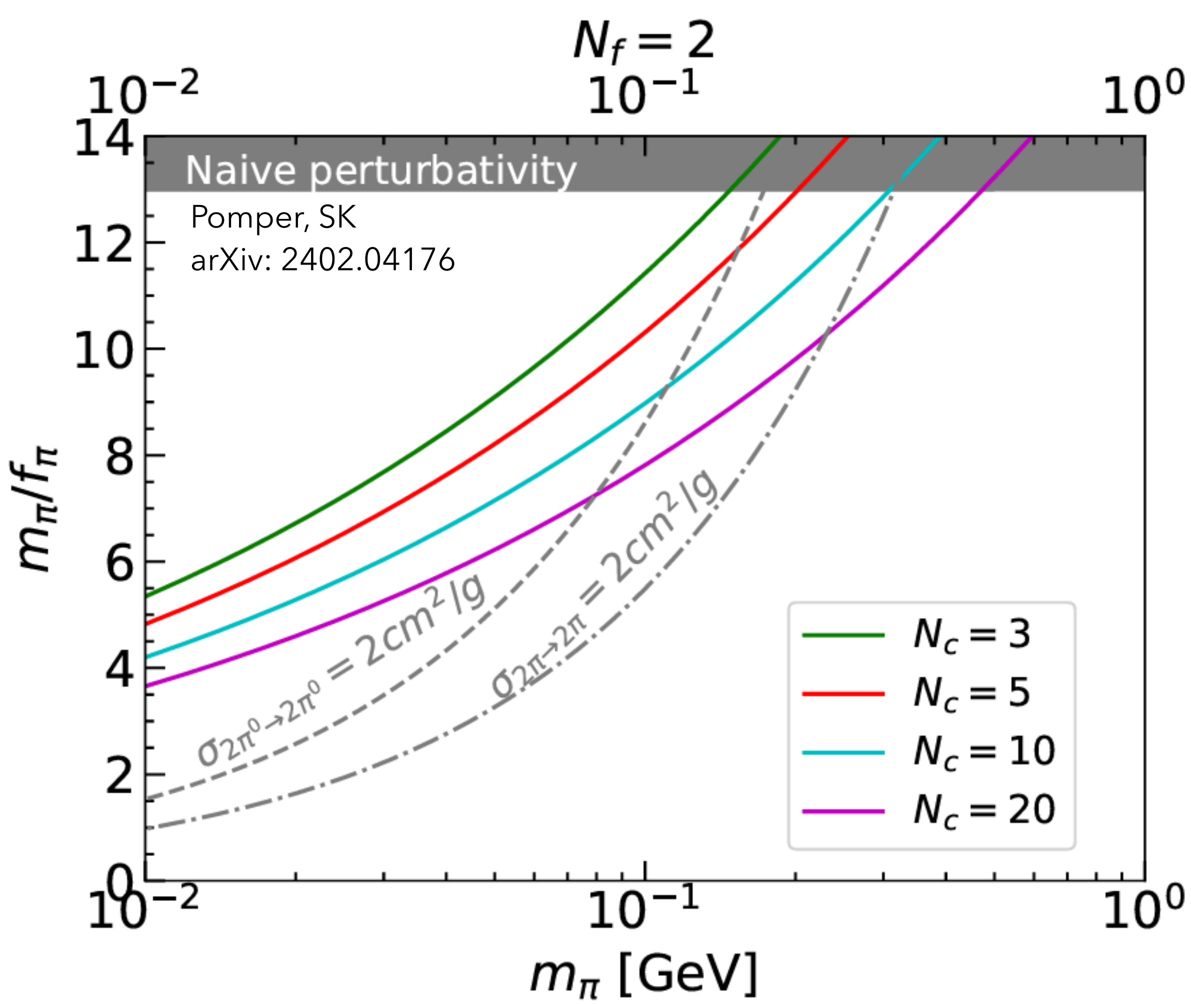
- Novel scenarios
- Cosmologically viable dark matter theories
- New experimental signatures; potential discovery at hand
- Necessitates careful analysis



New avenues

Hochberg et al arXiv:1512.07917, Kribs et al arXiv: 1604.04627,
ł, Beriln et al arXiv:1801.05805





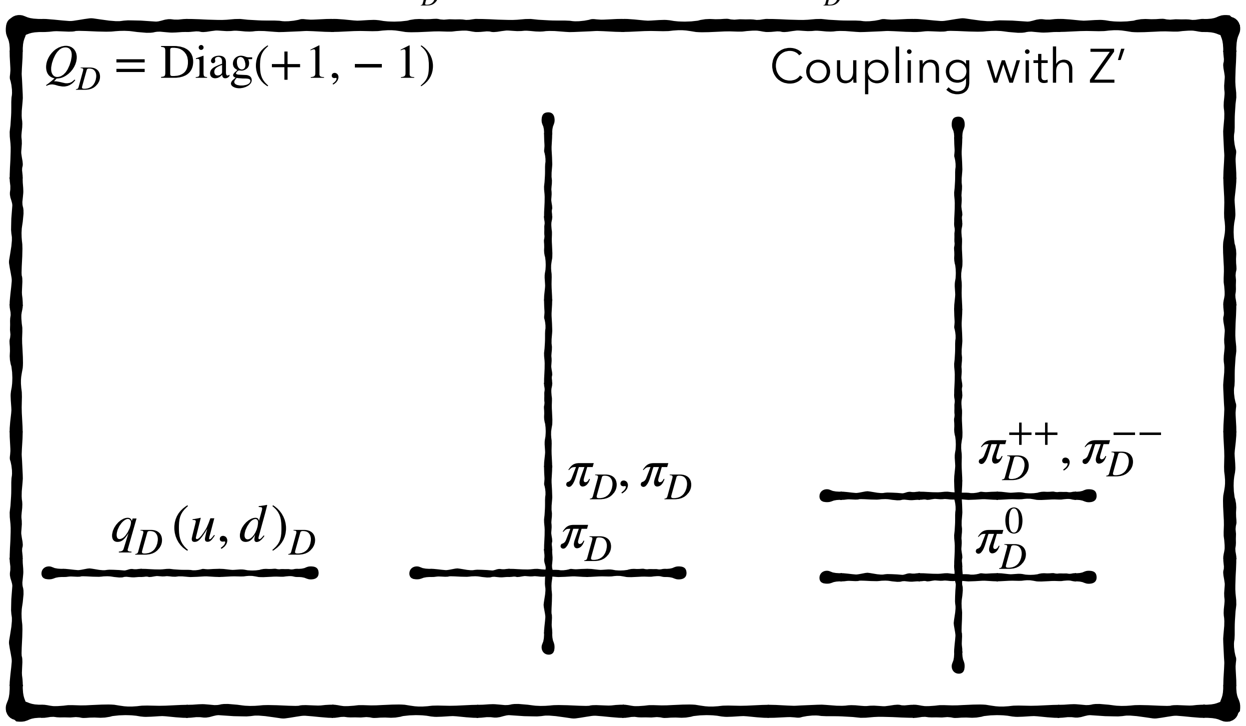
- Relic density $\quad n_{\pi_D}\langle\sigma v\rangle_{3\to2} \sim H \implies \dfrac{m_{\pi_D}}{f_{\pi_D}} \propto m_{\pi_D}^{3/10}$
- Self-scattering $\quad \dfrac{\sigma_{\pi_D\pi_D\to\pi_D\pi_D}}{m_{\pi_D}} \propto \left(\dfrac{m_{\pi_D}}{f_{\pi_D}}\right)^4 \times \dfrac{1}{m_{\pi_D}^3}$
- Needs m_{π_D}/f_{π_D} near perturbative unitarity: uncomfortable for validity of underlying effective theory
- Typically needs large N_{c_D}

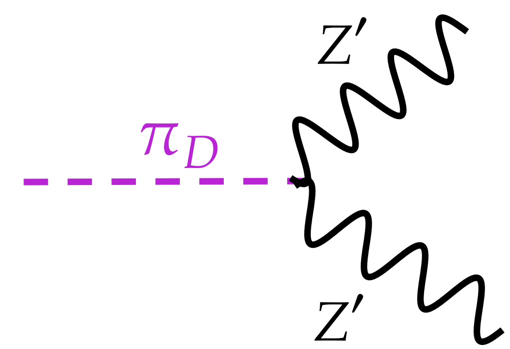
Primary obstacles in theory constructions

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 (needs asymmetry in dark sector) Cline and Perron arXiv:2204.00033
- Engineer models to ensure stability

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





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

$\rightarrow Q_D^2 \propto 1$

Quantitative estimates from genuine non-perturbative physics are needed

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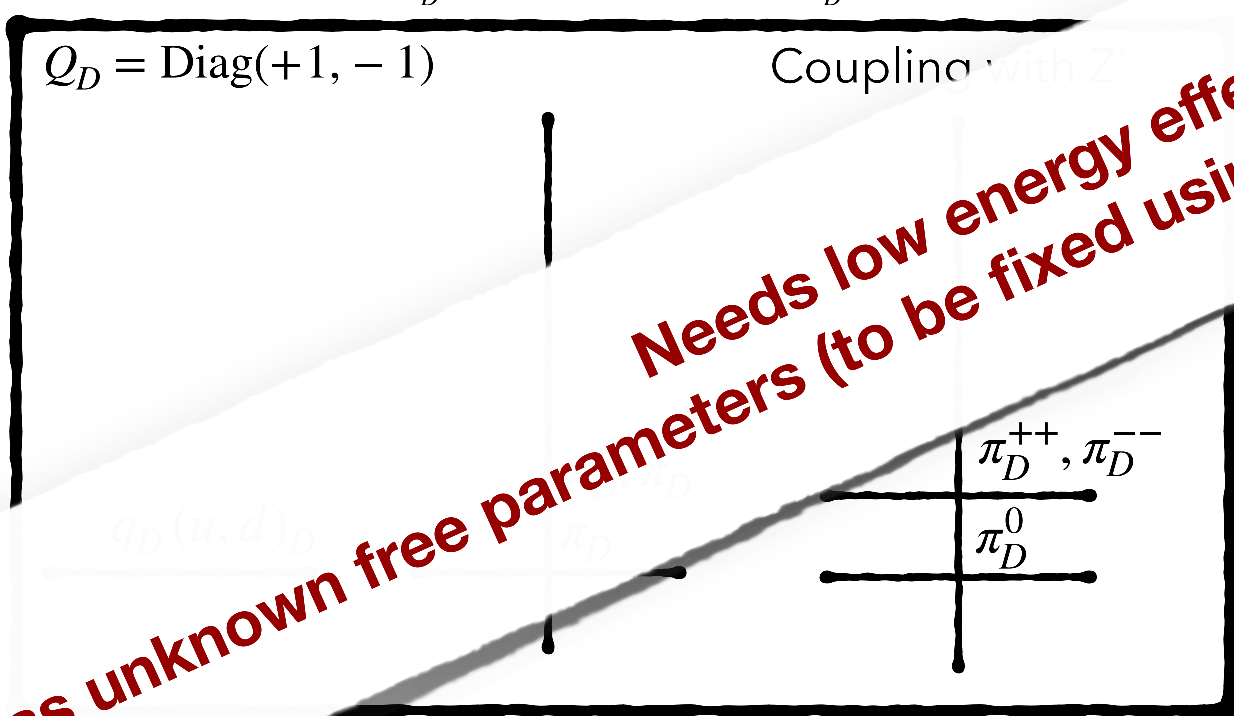
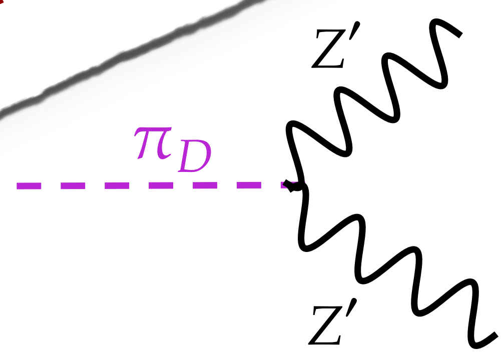




$\sim Tr[Q_D^2 T_0] = 0$

$\rightarrow Q_D^2 \propto 1$

Needs low energy effective Lagrangian

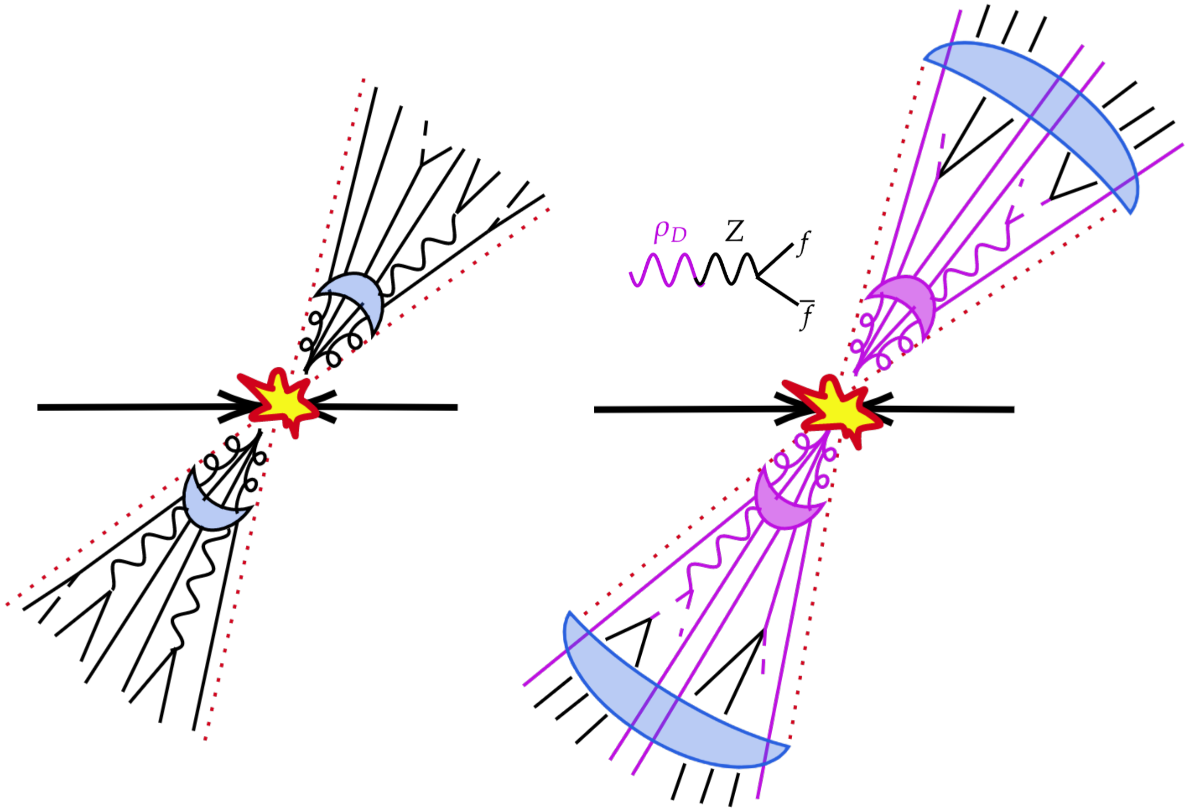
Has unknown free parameters (to be fixed using non-perturbative calculations e.g. lattice)

Quantitative estimates from genuine non-perturbative physics are needed

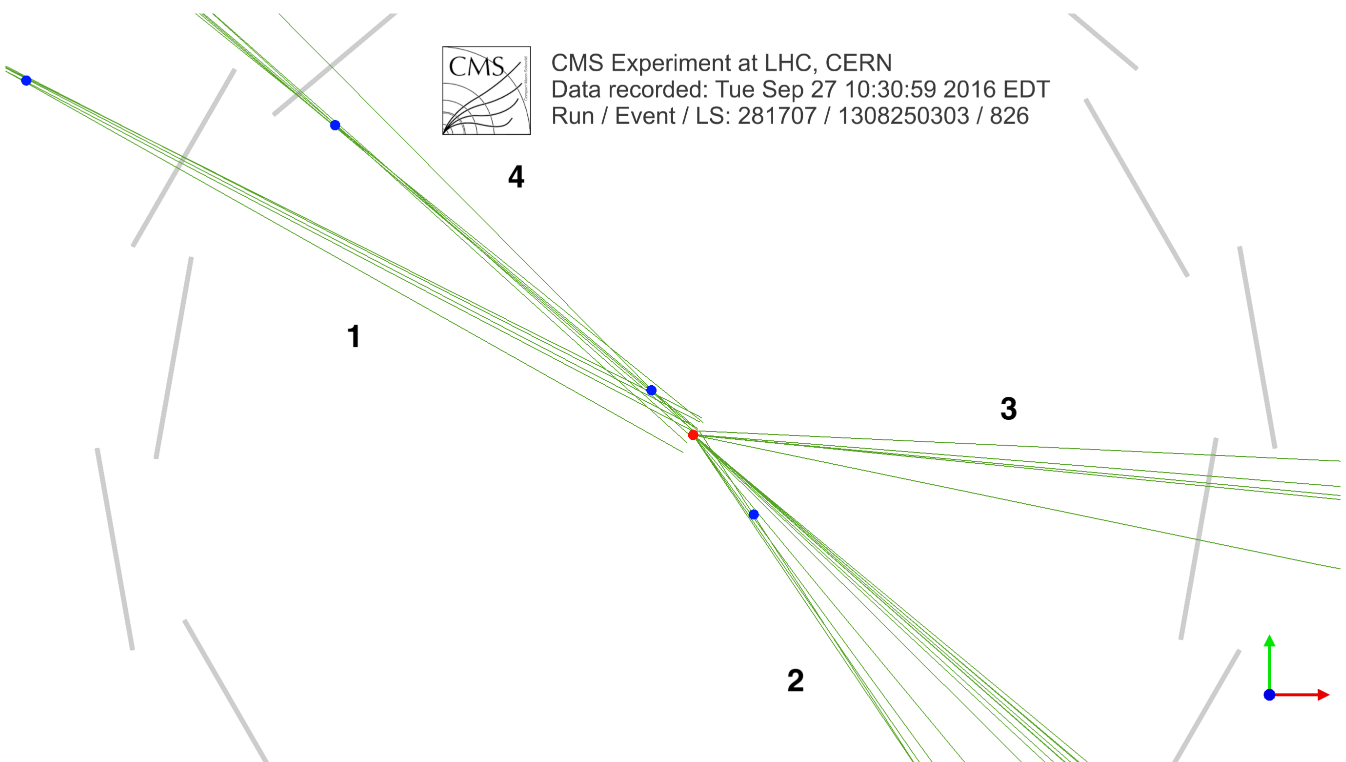
Experimental signatures

- Lead to new experimental 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



- Jets containing large missing energy
- Jets containing displaced vertices
- Jets with too many or too few tracks



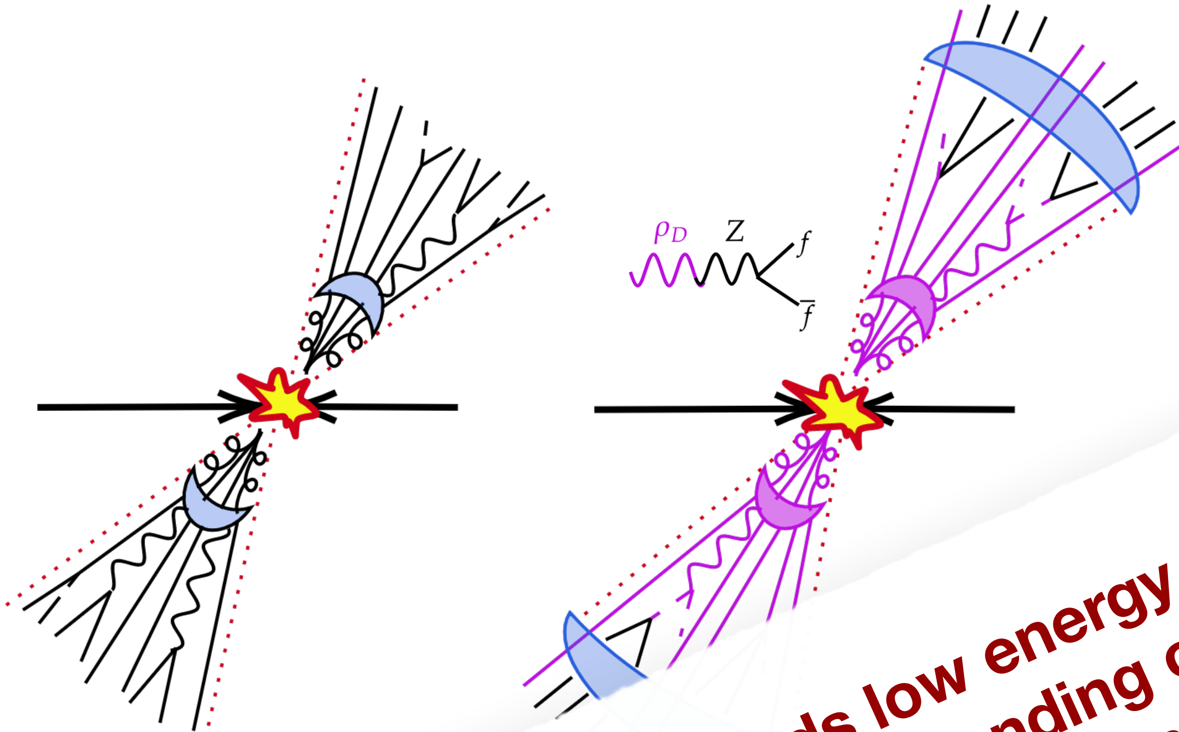
arXiv:1810.10069

- Experimental program to look for such signatures is just beginning
- Lack of understanding between theory space and experimental signatures
- Portals to the Standard Model play an important role

Experimental signatures

- Lead to new experimental 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:0903.1467, Strassler arXiv:0801.0629, Knapen et al arXiv:1612.00850



- Jets containing large missing energy
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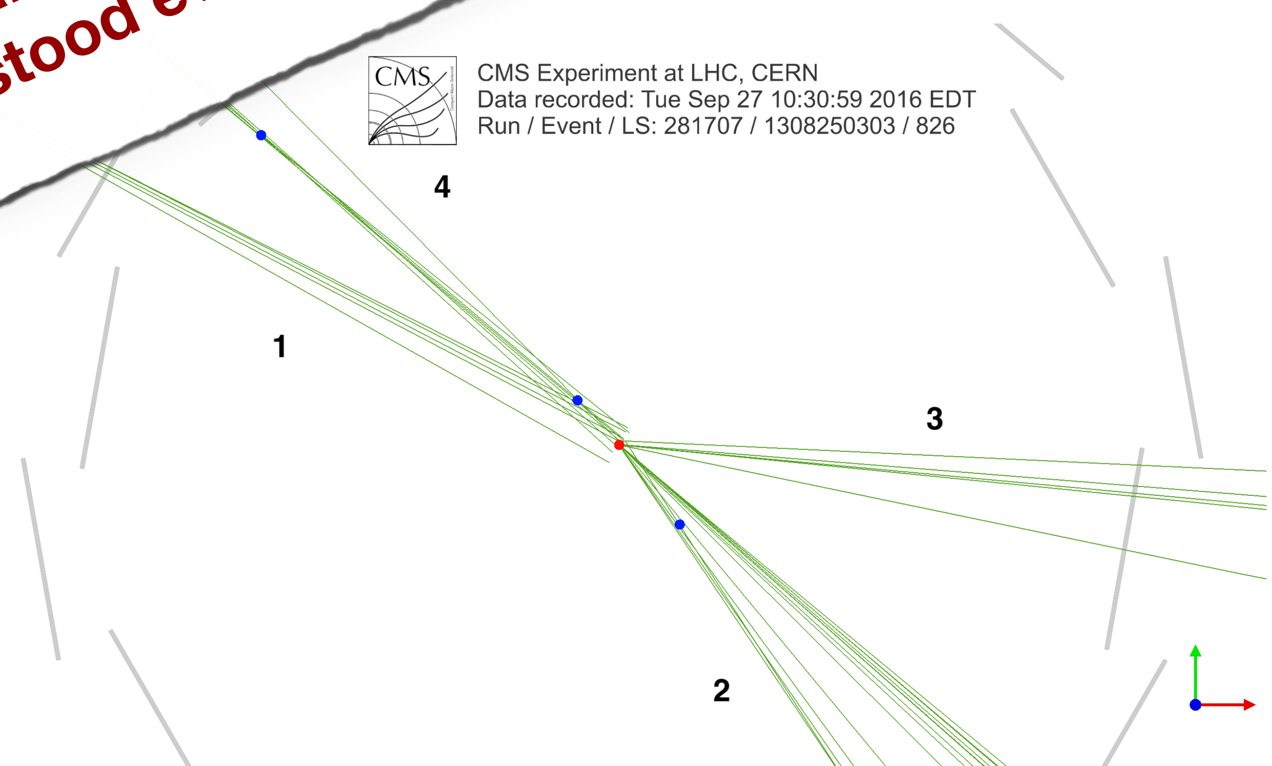
- Jets with too many or too few tracks

Needs low energy effective Lagrangian
Understanding of dark hadronization
Existence of well understood event generators

- Experimental program to look for such signatures is just beginning
- Lack of understanding between theory space and experimental signatures
- Portals to the Standard Model play an important role

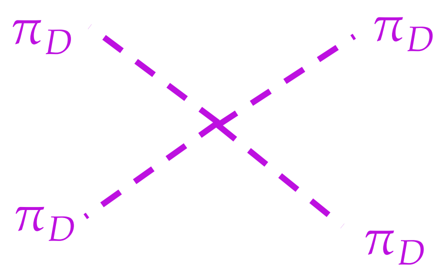


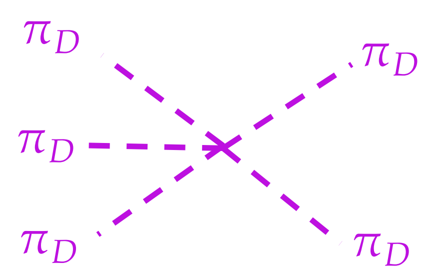
arXiv:1810.10069

Chiral Lagrangian in isolation

- Chiral Lagrangian contains non-anomalous and anomalous interactions (if $n_{\pi_D} > 4$)

$$\mathscr{L} = \mathscr{L}_{\text{non-anom}} + \mathscr{L}_{\text{anom}}$$ ⟶ Construction a la Witten

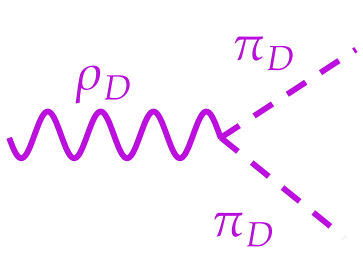


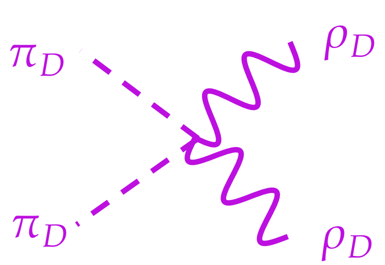


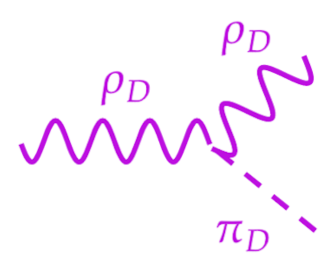
- $SU(N_{c_D})$ with $N_{f_D} = 2$ and $SO(N_{c_D})$ with $N_{f_D} = 1$ exhibit chiral symmetry breaking but no anomaly

- Witten construction needs certain homotopy conditions e.g. $\pi_4(SU(4)/SO(4)) = 0$

$$\mathscr{L}^{\text{gauged}} = \mathscr{L}^{\text{gauged}}_{\text{non-anom}} + \mathscr{L}^{\text{gauged}}_{\text{anom}}$$ ⟶ e.g. Hidden Local Symmetry





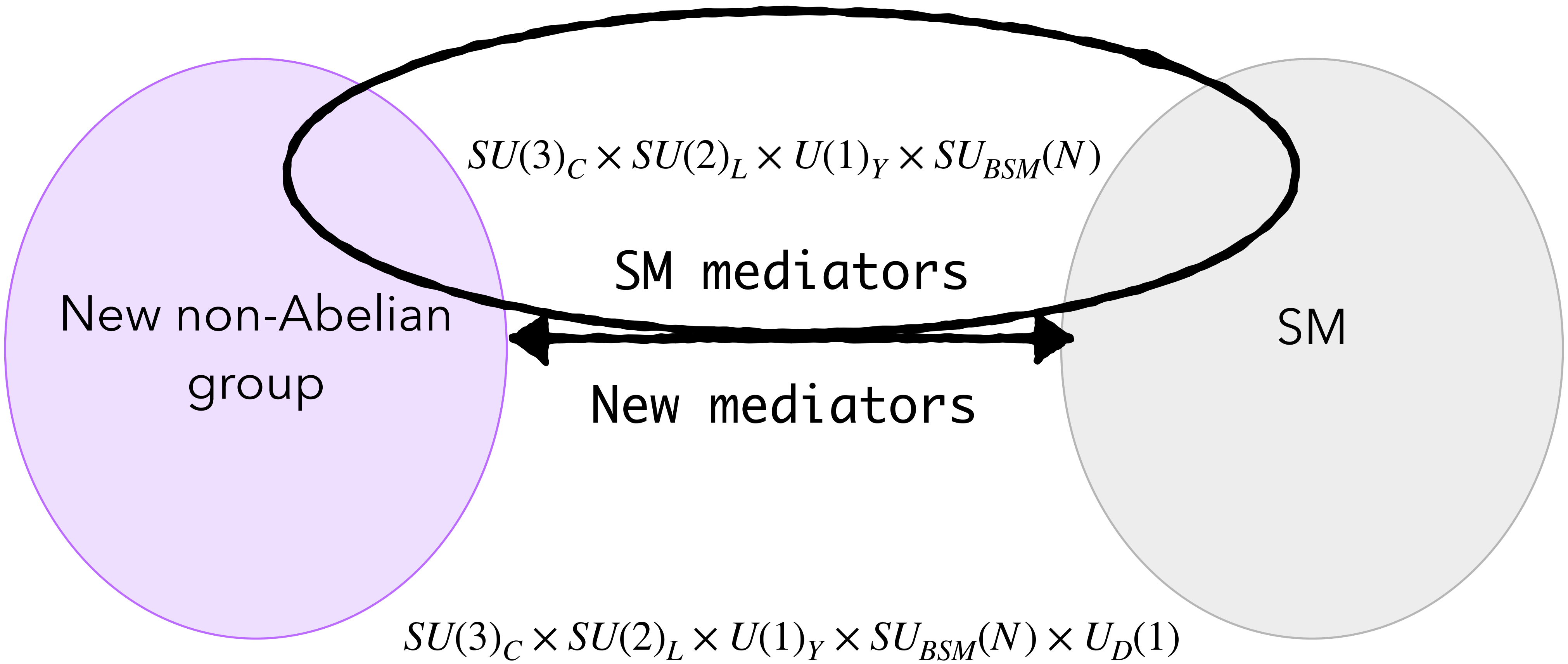


See **S.K.**, S. Mee, et al arXiv:2202.05191 for Sp(2N)
J. Pomper, **S.K.**, arXiv: 2402.04176 for SO(N)

- Heavier states introduce new interesting dark matter and collider phenomenology

New non-Abelian group

Portal phenomenology - I

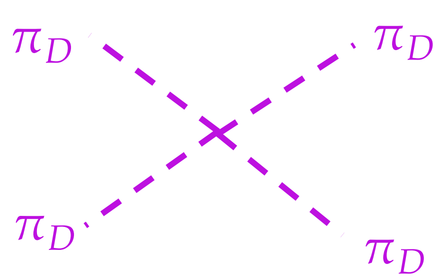


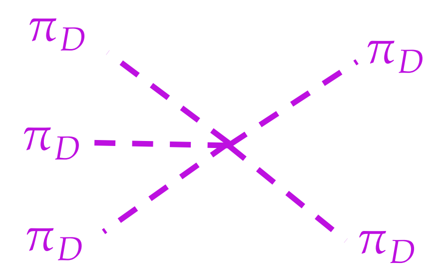
J. Butterworth, L. Corpe, **SK**., X. Kong, M. Thomas arXiv:2105.08494

Chiral Lagrangian

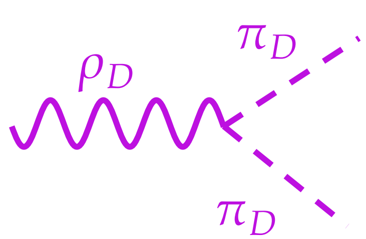
- Chiral Lagrangian contains non-anomalous and anomalous interaction terms

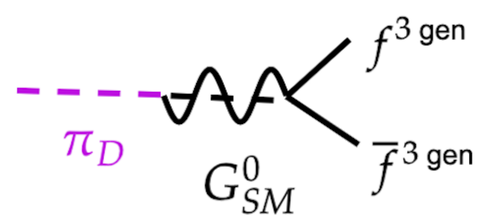
$$\mathscr{L} = \mathscr{L}_{\text{non-anom}} \qquad + \mathscr{L}_{\text{anom}}$$ → Construction a la Witten

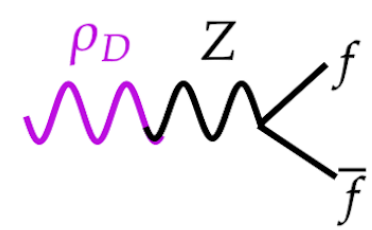




$$\mathscr{L}^{\text{gauged}} = \mathscr{L}^{\text{gauged}}_{\text{non-anom}} + \mathscr{L}^{\text{SM gauged}}_{\text{non-anom}}$$







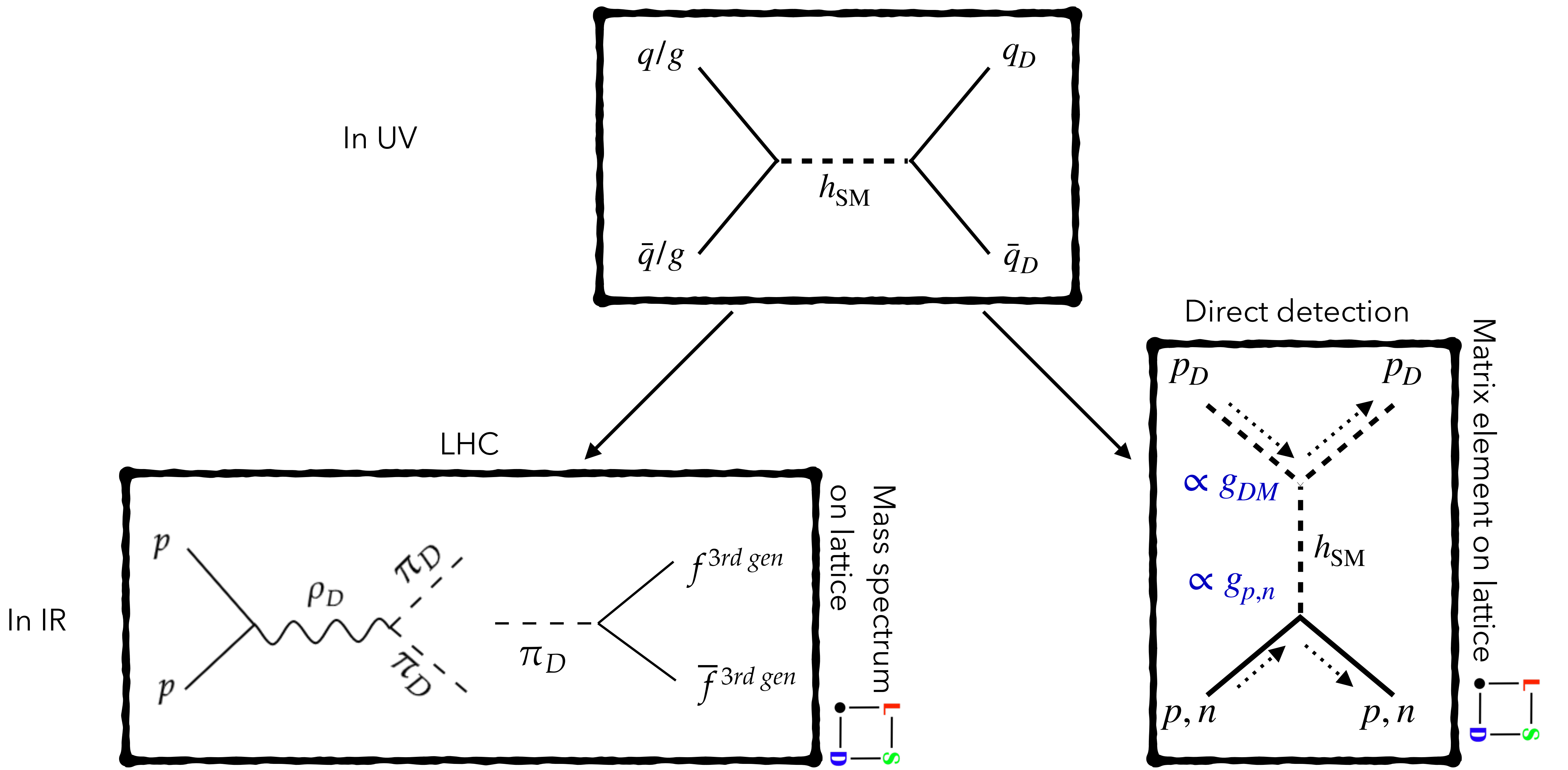
Heavy flavour dominated final states

Resonance searches

SM mediators

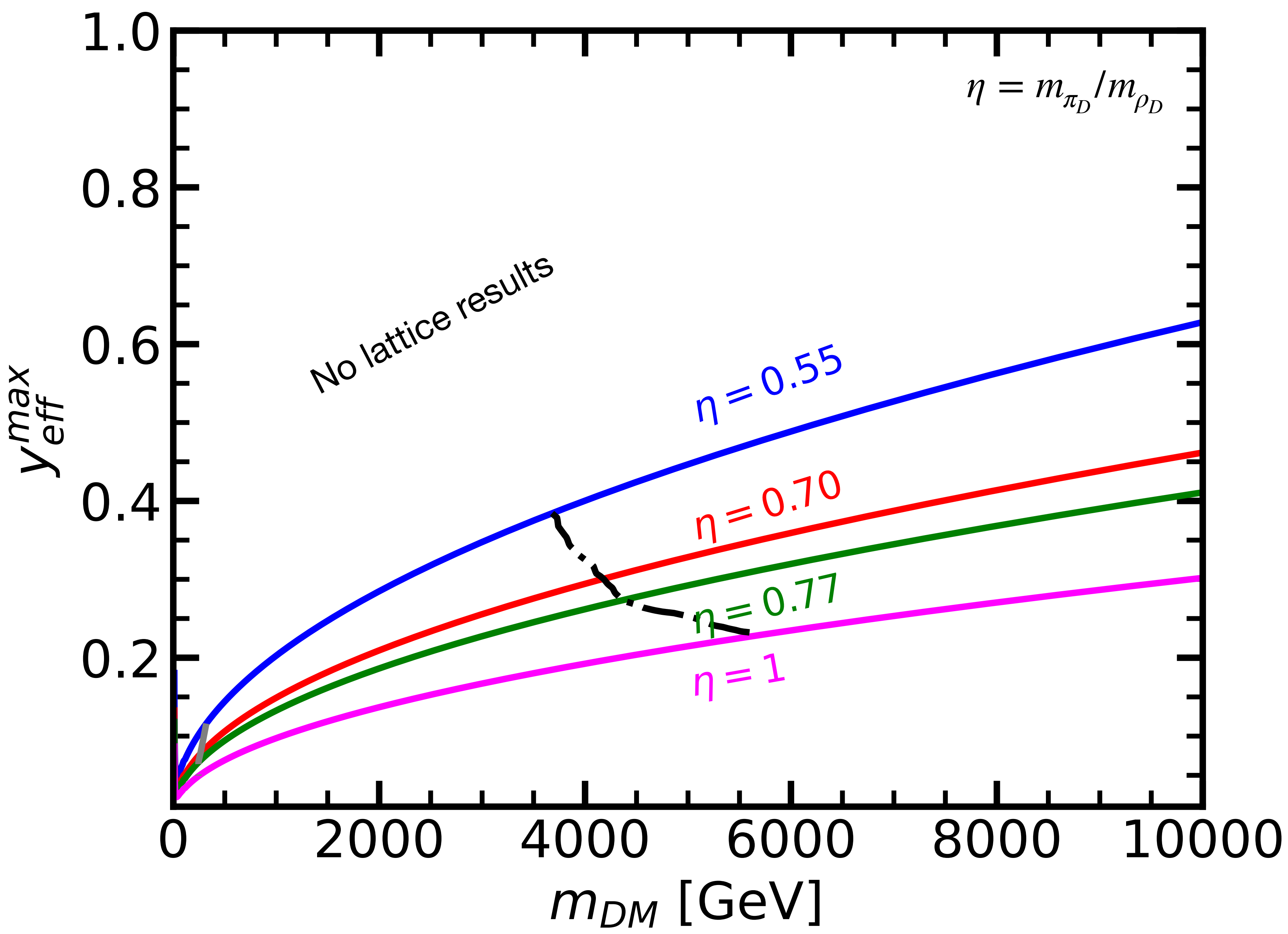
Appelquist et al arXiv:1402.6656
Bagnasco et. al. hep-ph/9310290

- $N_{c_D} = N_{f_D} = 4$, in fundamental representation of $SU(N_{c_D})$; Lightest scalar baryon (dark proton) is dark matter
- In isolation, dark quarks are vector like; Higgs Yukawa breaks flavour symmetry



Higgs mediators

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



Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Higgs mediators

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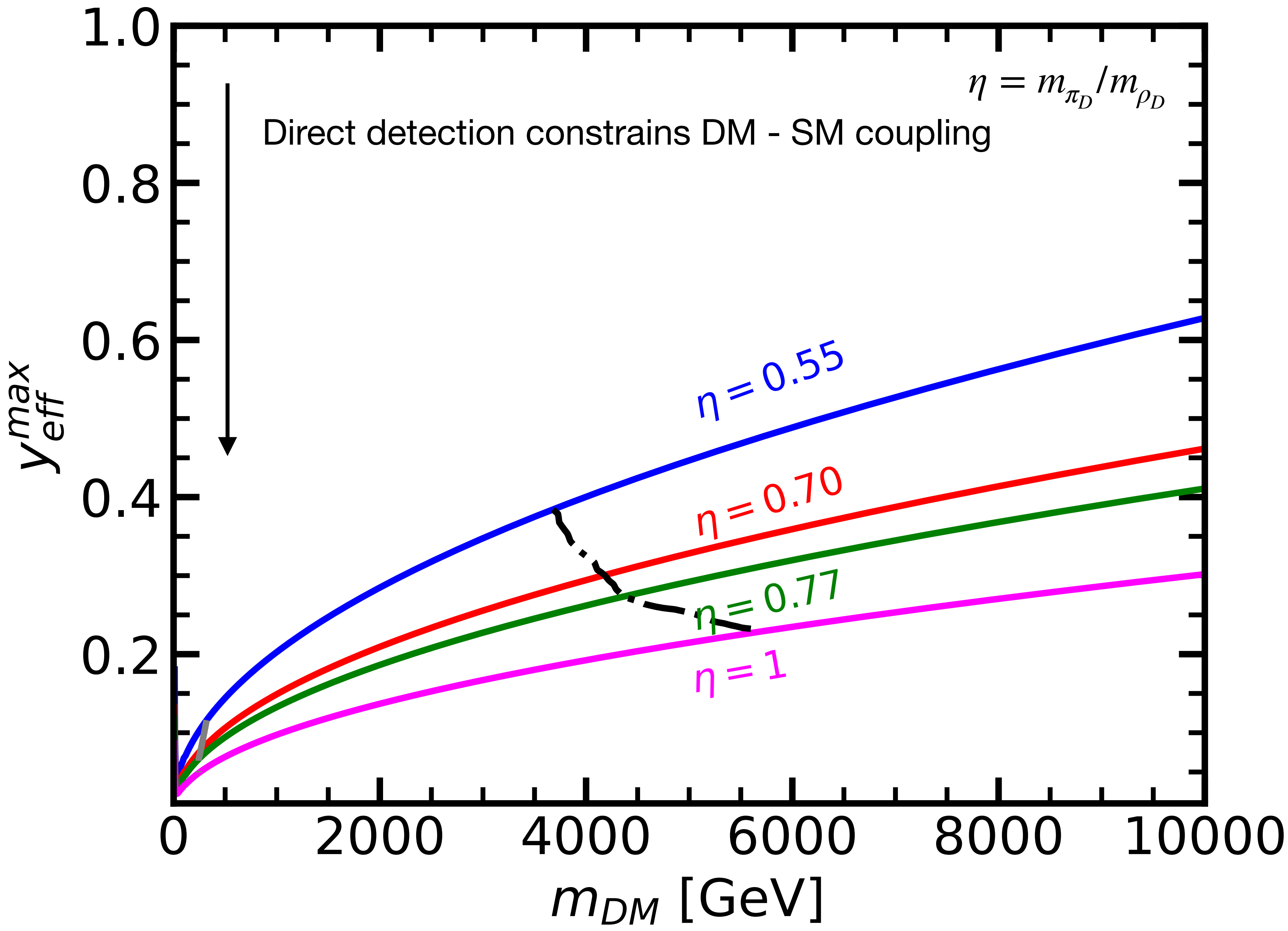

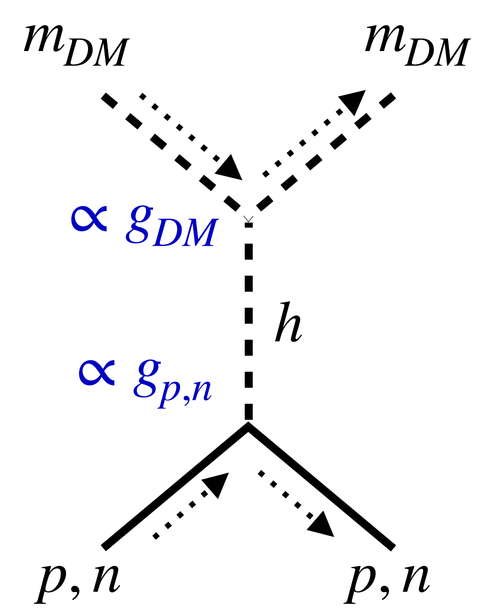

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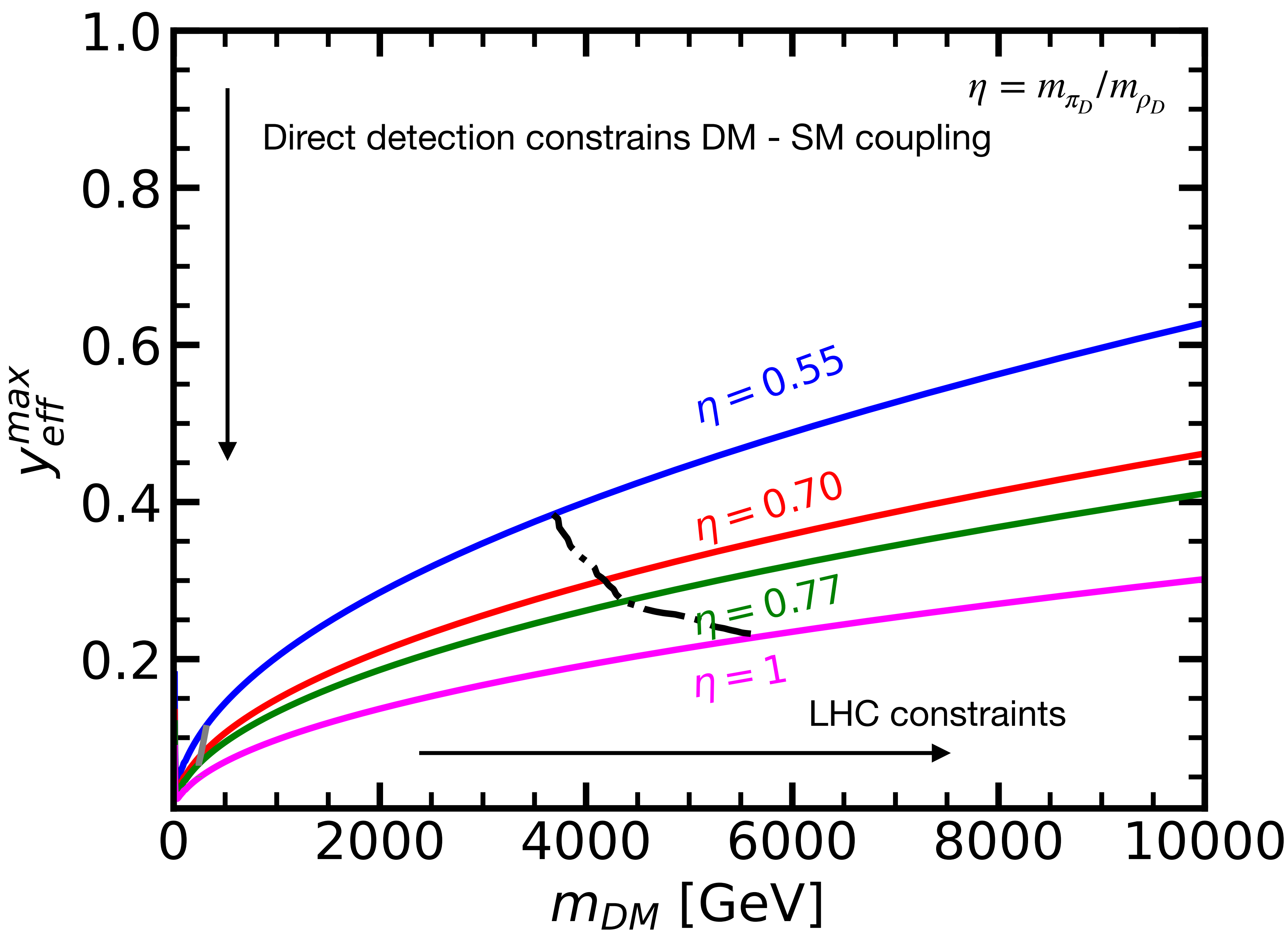

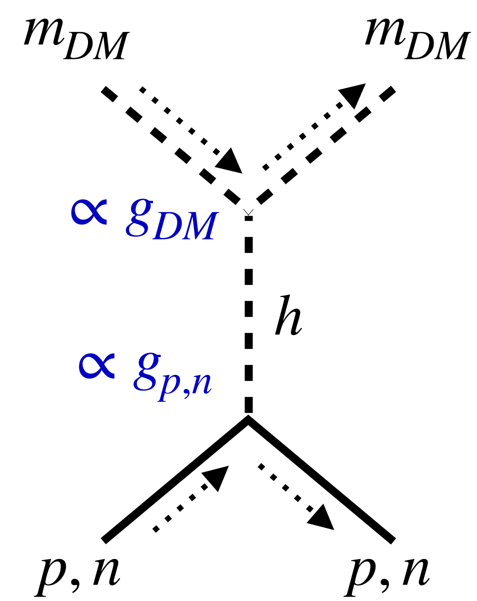

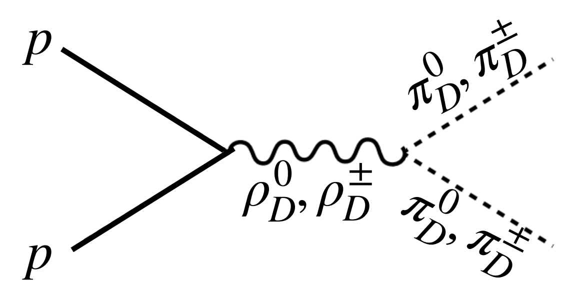

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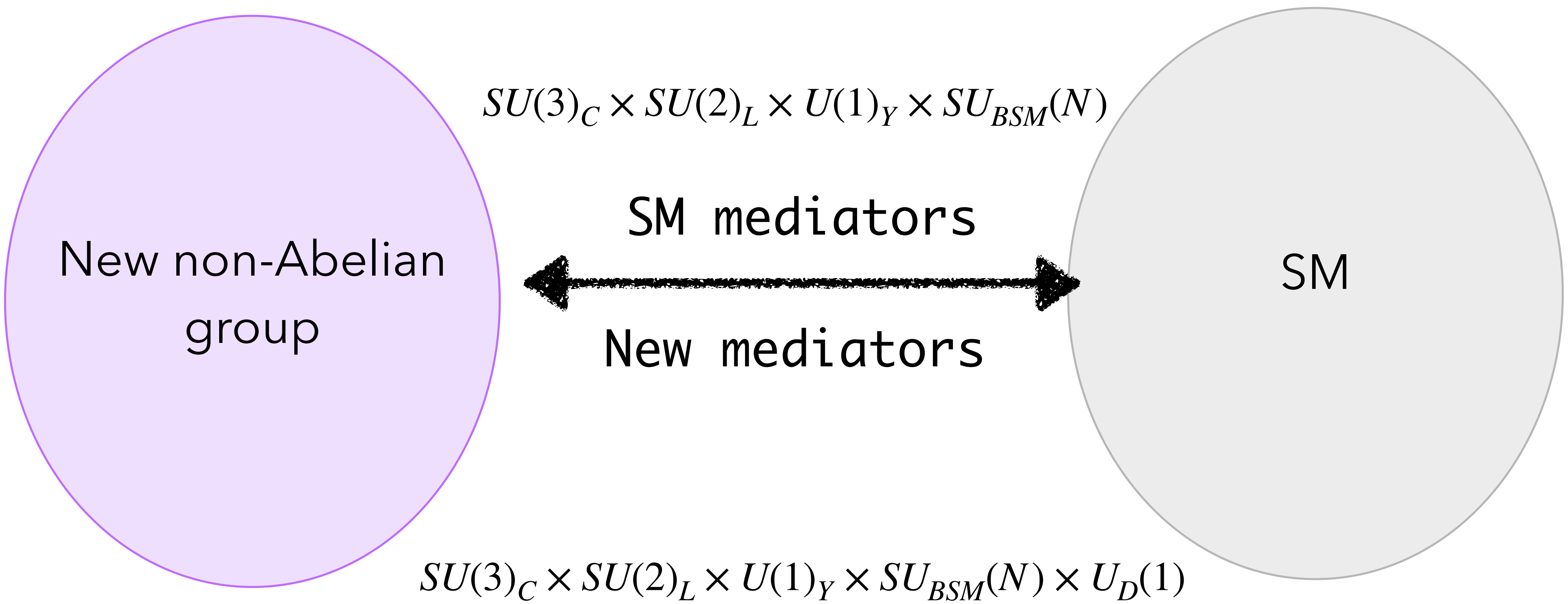
Portal phenomenology - II



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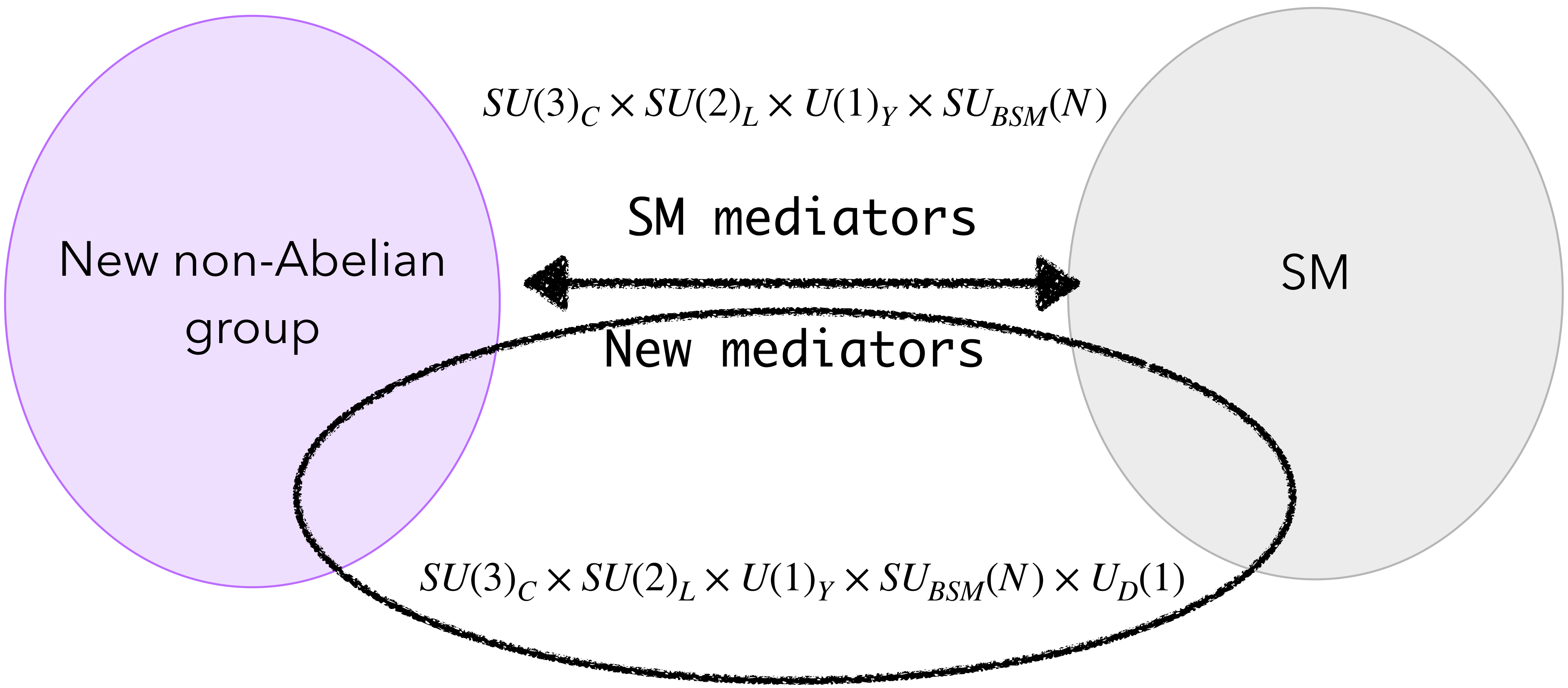


$U(1)_D$ embedding well understood

See also Hochberg et al. arXiv:1512.07917

	$U(1)_D \subset H$ embedding	π representations
$Sp(N_c)$	$SU(N_f) \times U(1)_D \subset Sp(2N_f)$	$(\begin{smallmatrix}\square\\\square\end{smallmatrix}, +2) \oplus (\overline{\begin{smallmatrix}\square\\\square\end{smallmatrix}}, -2) \oplus (\text{adj}, 0)$
$SO(N_c)$	$SU(N_f/2) \times U(1)_D \subset SO(N_f)$	$(\square\square, +2) \oplus (\overline{\square\square}, -2) \oplus (\text{adj}, 0)$
$SU(N_c)$	$SU(N_1) \times SU(N_2) \times U(1)_D \subset SU(N_f)$	$(\square, \overline{\square}, 2) \oplus (\overline{\square}, \square, -2) \oplus (\text{adj}, 1, 0) \oplus (1, \text{adj}, 0) \oplus (1, 1, 0)$

- Introducing external mediator with non-trivial charges necessarily breaks multiples

  → unstable dark mesons → experimental signatures

- Rho mesons don't always share representation space with pions

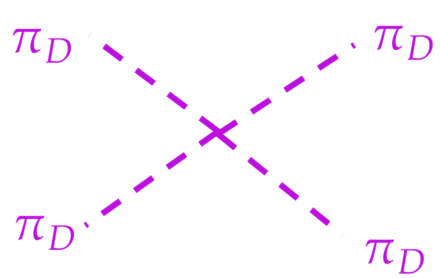
  Pions → broken generators; Rho → unbroken generators

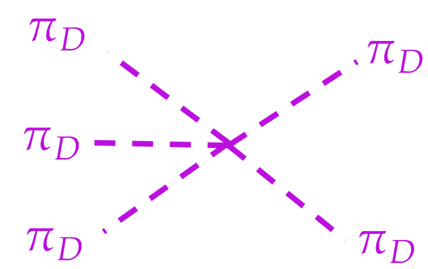
  $Sp(4)_c$ theories, pions 5-plet, rhos 10-plet representation

$U(1)_D$ gauged chiral Lagrangian

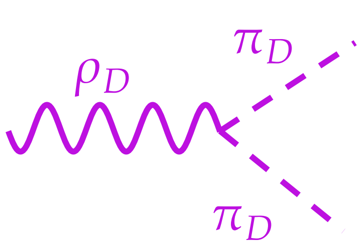
- Chiral Lagrangian contains non-anomalous and anomalous interaction terms

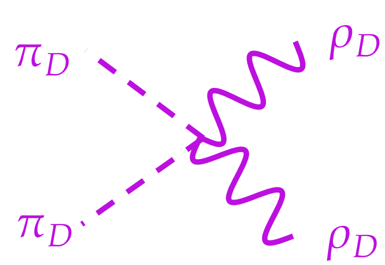
$\mathscr{L} = \mathscr{L}_{\text{non-anom}}$ $+\mathscr{L}_{\text{anom}}$ ⟶ Construction a la Witten

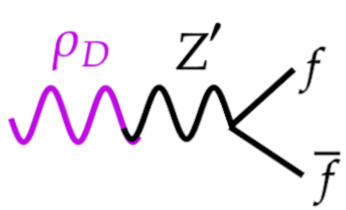


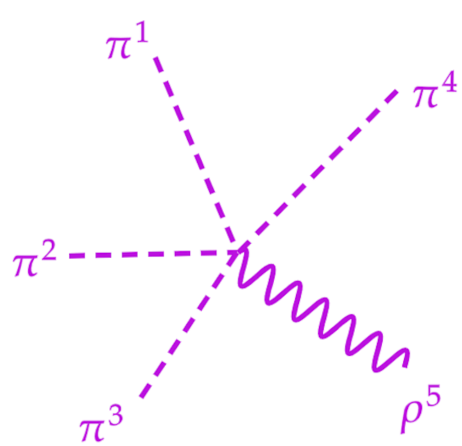


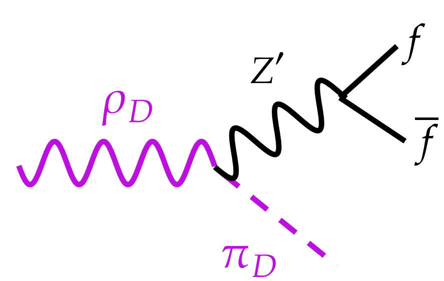
$\mathscr{L}^{\text{gauged}} = \mathscr{L}^{\text{gauged}}_{\text{non-anom}}$ $+\mathscr{L}^{\text{gauged}}_{\text{anom}}$ ⟶ e.g. Hidden Local Symmetry

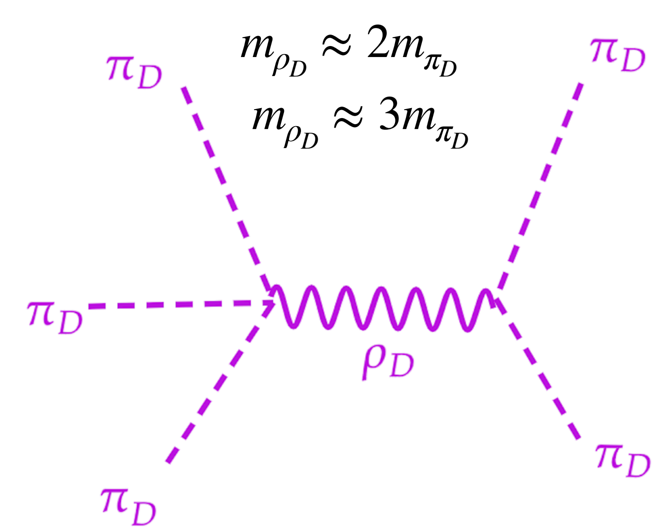












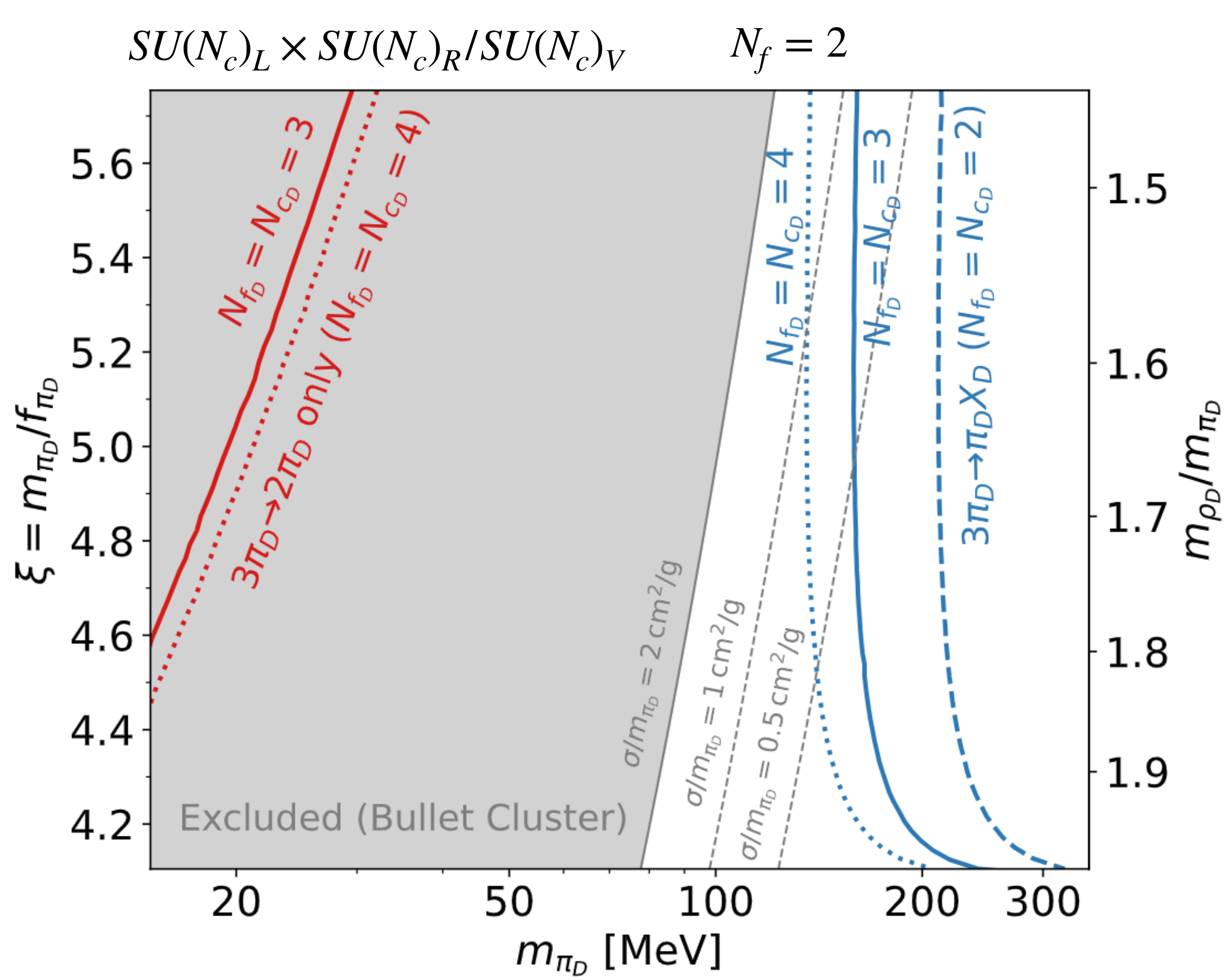
Choi et al., arXiv:1801.07726

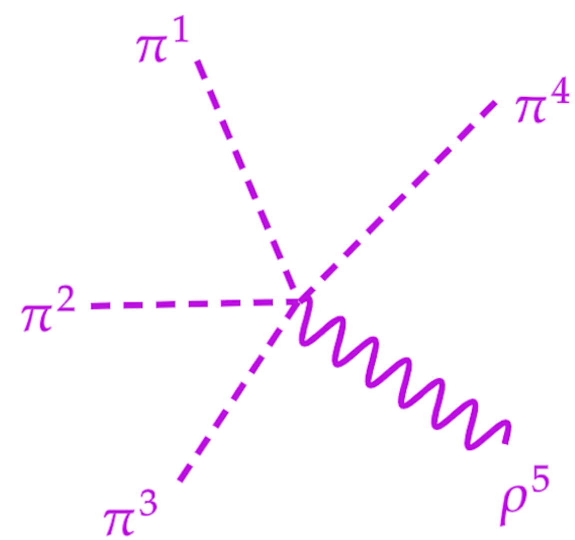
Absent for $SU(N_{c_D})$ with $N_{f_D} = 2$

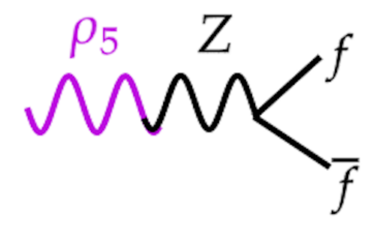
Dark flavoured DM: relic density

- Large self interactions consistent with relic density

Bernreuther, Hemme, Kahlhoefer, SK arXiv:2311.17157







$$R \equiv \frac{\langle \sigma v^2 \rangle_{3\pi_D \to \pi_D \rho_D}}{\langle \sigma v^2 \rangle_{3\pi_D \to 2\pi_D}} = \frac{\alpha^{\mathrm{eff}}_{3\pi_D \to \pi_D \rho_D}}{\alpha^{\mathrm{eff}}_{3\pi_D \to 2\pi_D}}$$

$$\approx (1800 - 8500) \times \frac{1}{N_{c_D}^2\, \xi^4} \frac{x^2}{\sqrt{1-y}}$$

- Inputs from non perturbative calculations in terms of prediction of dark rho mass as a function of dark pion mass
- Delayed freeze out allows for larger masses thus Bullet cluster constraints can be evaded

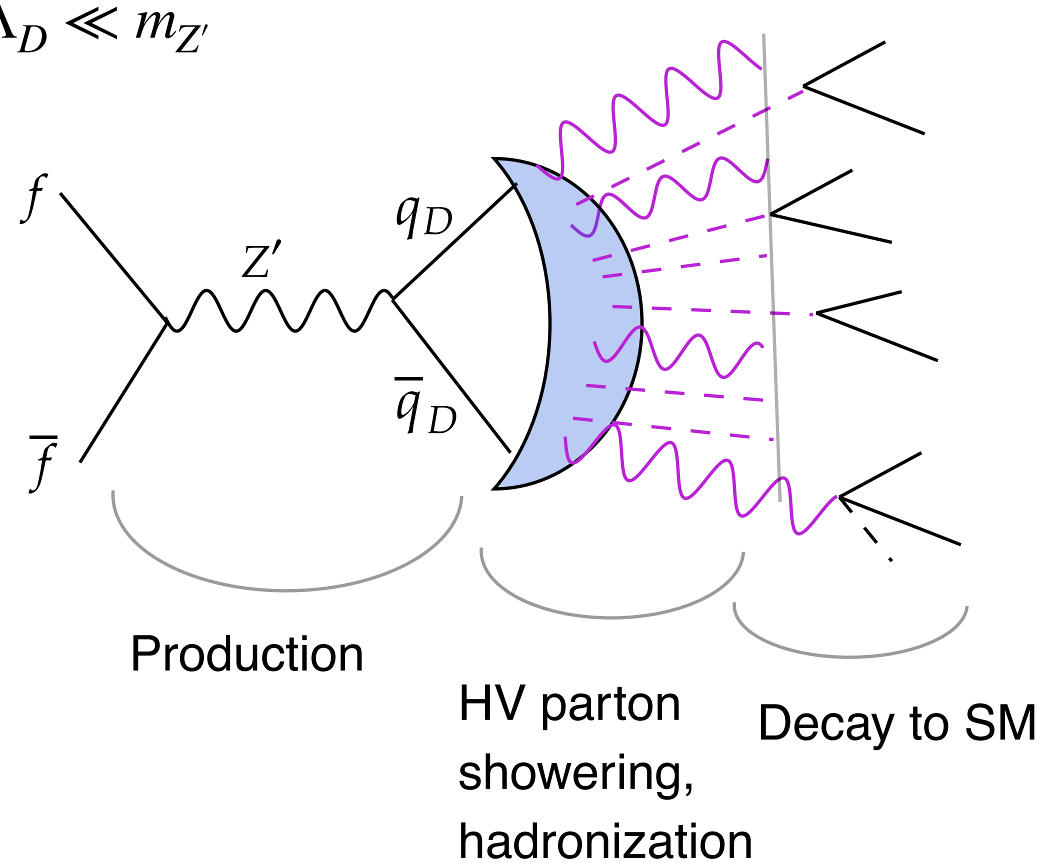
Implications for experiments

Snowmass darkshowers (incl. **S.K.**, S. Mee, M. Strassler) arXiv:2202.05191

- Anomalous jet production at the LHC
- Specific example for $SU(N_{c_D})$: coset $SU(N_{f_D})_L \times SU(N_{f_D})_R / SU(N_{f_D})$

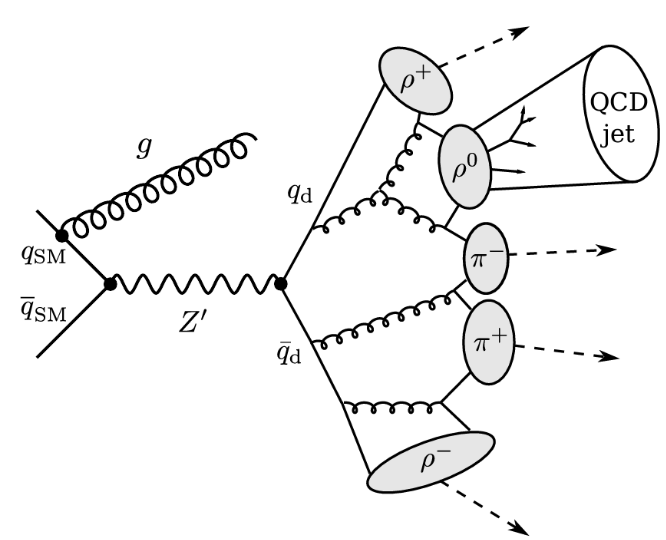
Strassler et al hep-ph/0604261
Cohen et al arXiv:1503.00009
Schwaller et al arXiv:1502.05409
LLP community report arXiv:1903.04497
Kahlhoefer et.al. arXiv:1907.04346
Hofman et al arXiv:0803.1467
Strassler arXiv:0801.0629
Knapen et al arXiv:1612.00850

$m_{q_D} \ll \Lambda_D \ll m_{Z'}$



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

Fig. From Kahlhoefer et.al. arXiv:1907.04346



- Example: $N_{f_D} = 2$; $n_{\pi_D} = n_{\rho_D} = 3$;
  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

Lattice inputs and effects on (dark)jets

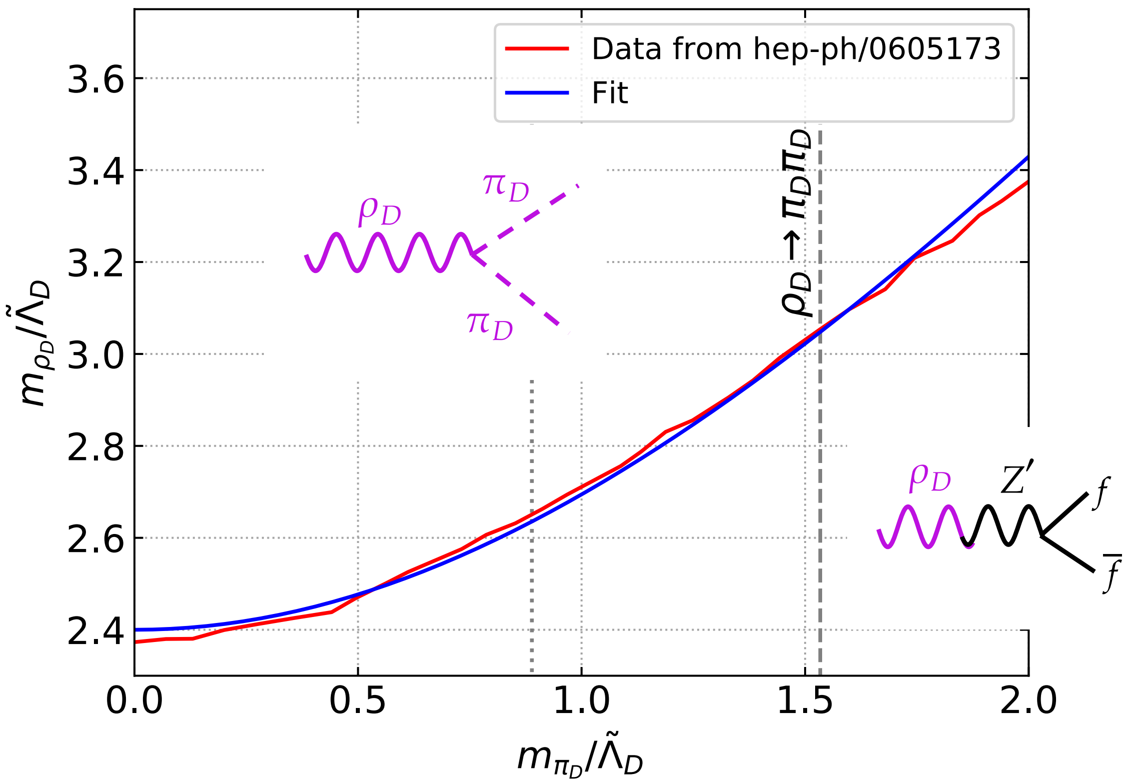
- First guidelines for collider simulations of strongly interacting theories
- Effects due to N_{c_D}, N_{f_D} ignored for now
- Dark meson mass fits from lattice results

$N_{f_D} = 1$ and/or $\mathrm{N}_{\mathrm{c_D}} = 2$
special cases

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

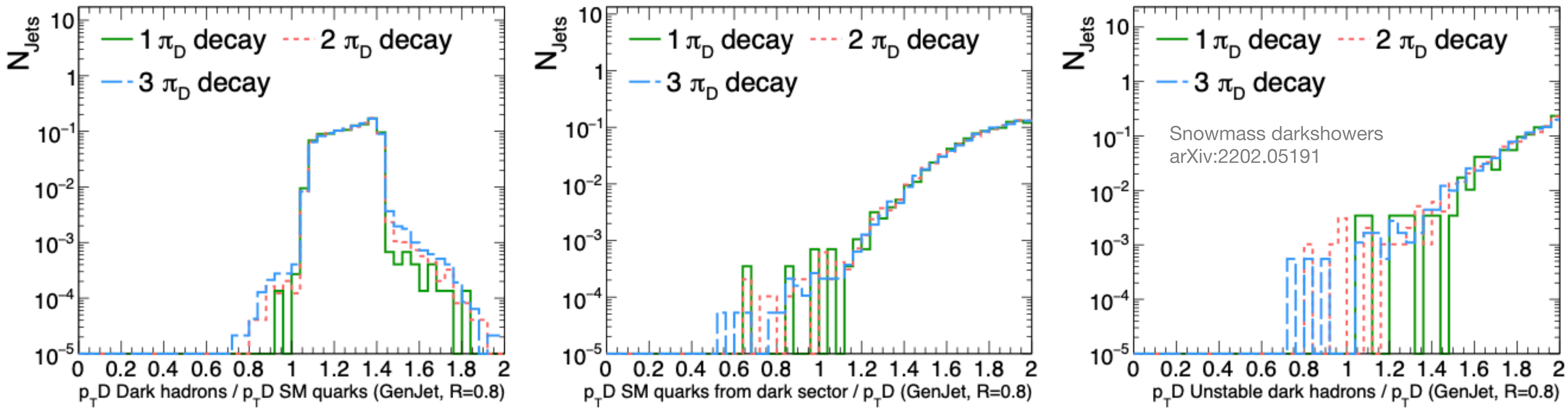
$$\frac{m_{\rho_D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5\,\frac{m_{\pi_D}^2}{\tilde{\Lambda}_D^2}}$$

Snowmass darkshowers arXiv:2202.05191



- Clear definitions for simulating semi-visible jets
- Possible light glueballs for $m_{\pi_D}/\tilde{\Lambda}_D > 2$
- Extensively tested and extended Pythia Hidden Valley module

Effects on jets



- $p_T D$: jet transverse momentum dispersion $p_T D \approx \sqrt{2p_T^2}/(2p_T)$
- The details of jet substructure depend on the details of the decay modes and number of stable/unstable particles
- Careful analysis design is necessary to circumvent too much dependence on jet properties

Real representations

S.K., J. Pomper (arXiv: 2402.04176)

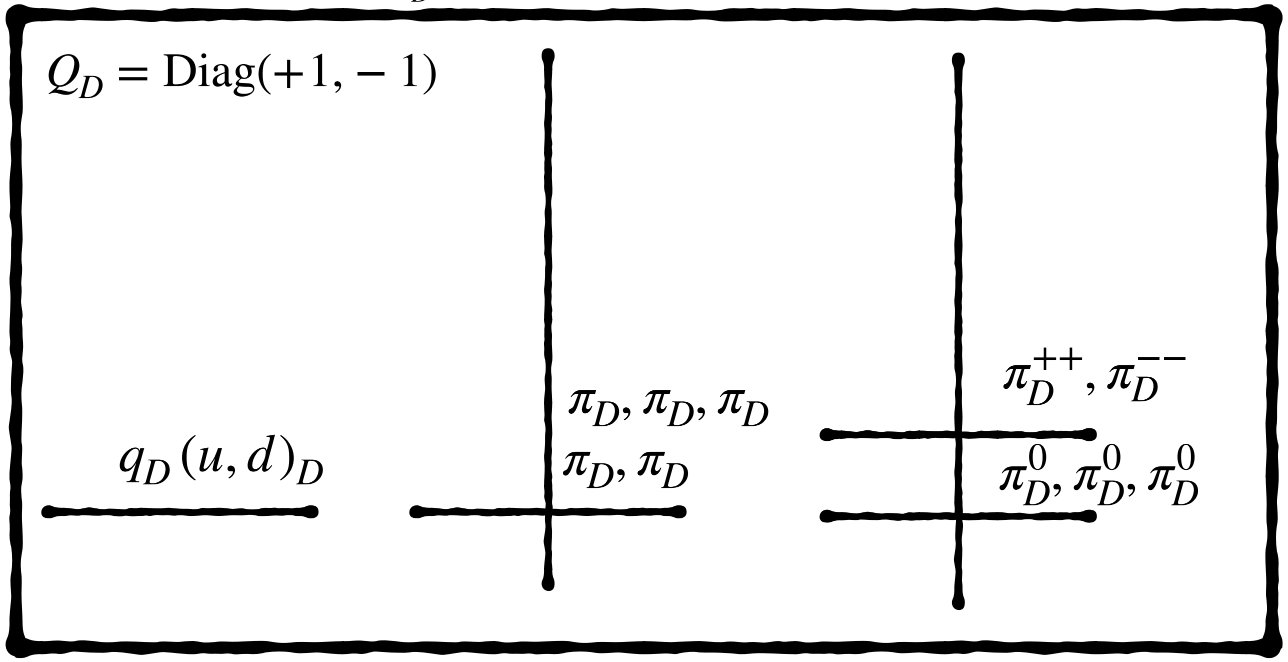
- $SU(N_{c_D})$: coset $SU(N_{f_D})_L \times SU(N_{f_D})_R / SU(N_{f_D})$;

$$n_{\pi_D} = N_{f_D}^2 - 1 \to N_{f_D} = 3 \Rightarrow n_{\pi_D} = 8$$

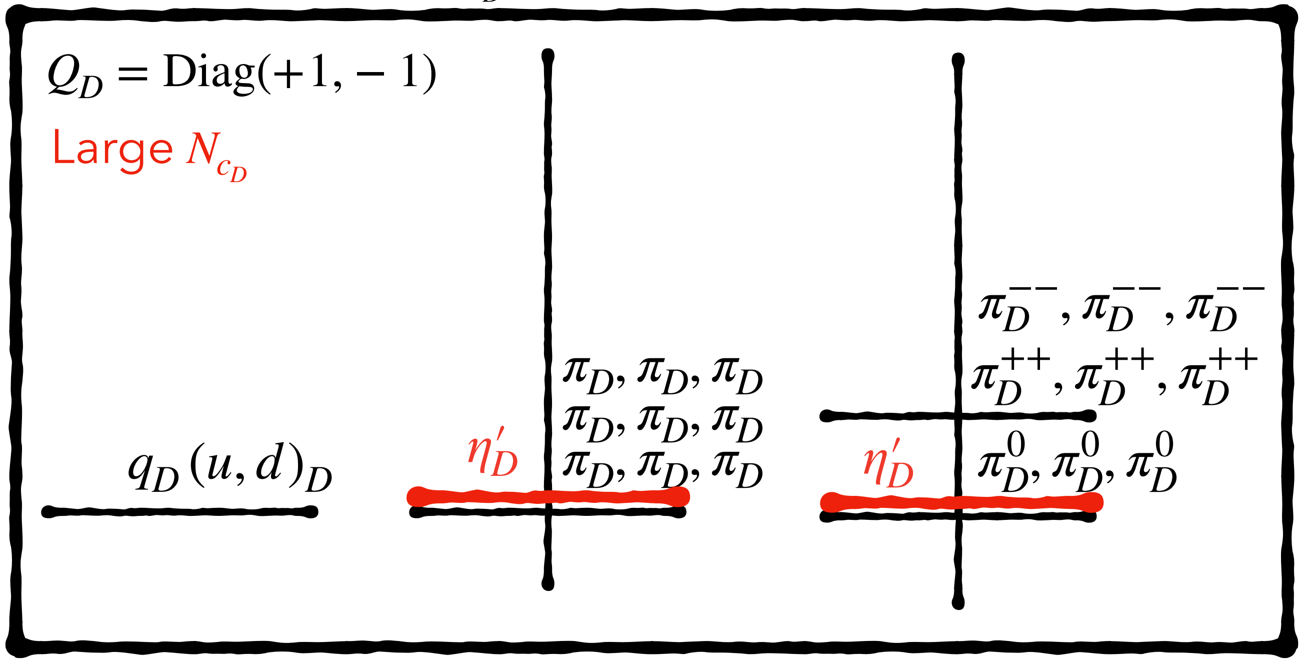
- $SO(N_{c_D})$: coset $SU(N_{f_D})/SO(N_{f_D})$;

$$n_{\pi_D} = \frac{1}{2}(N_{f_D} + 2)(N_{f_D} - 1) \to N_{f_D} = 2 \Rightarrow n_{\pi_D} = 9$$

$Sp(N_{c_D})$: 2 fermions in fundamental



$SO(N_{c_D})$: 2 fermions in vector



Insights from UV dynamics

S.K., J. Pomper (arXiv: 2402.04176)

Witten, Nucl. Phys. B 223 (1983)

- Can not fix WZW by considering IR dynamics alone $\pi_4(SU(4)/SO(4)) \neq 0$
- WZW can be written by considering detailed UV to IR anomaly relations (if anomaly is present in IR, it must be present in the UV → anomaly equation → solution is WZW term)

Chu, Ho, and Zumino, Nuclear Physics B 475 (1996)
Wess and Zumino, Physics Letters B 37 (1971)]

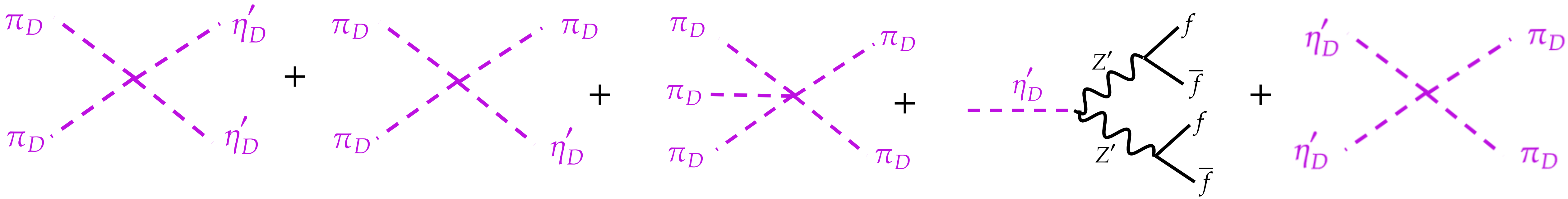
Wess-Zumino effective action

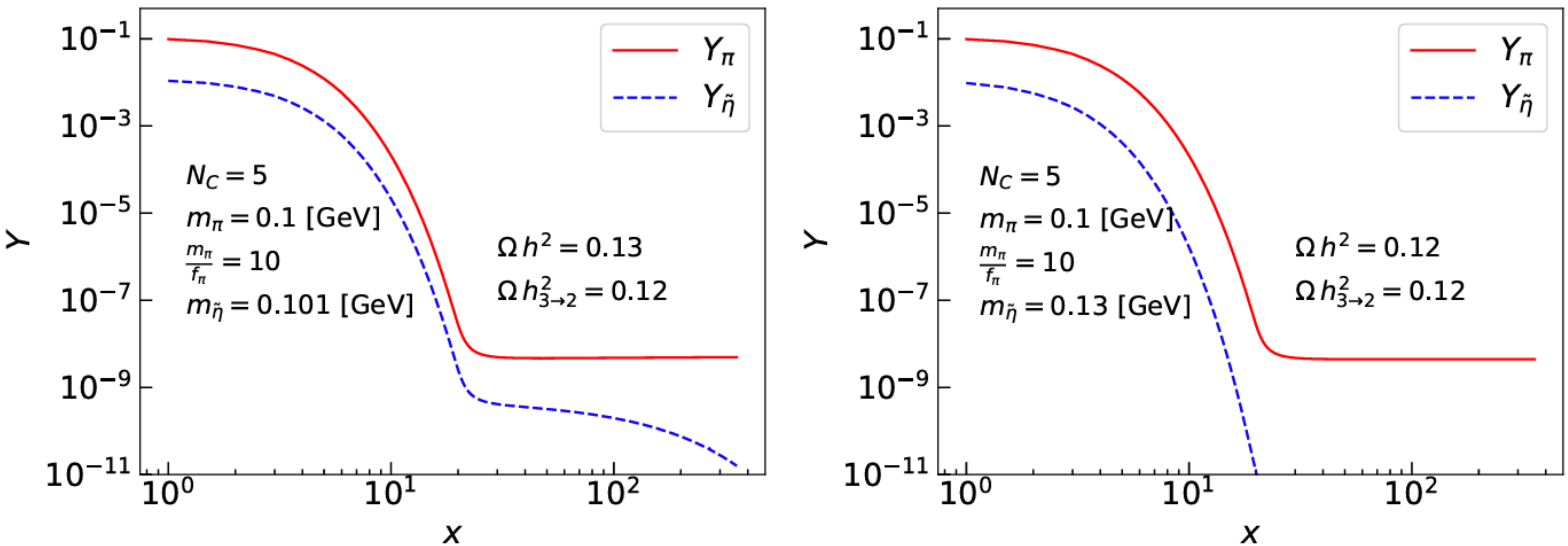
$$S_{WZ}[\xi = (\eta', \pi)] = \frac{D_C}{3\pi^2 f_\pi} \int_0^1 \mathrm{d}t \int_{S^4} \mathrm{Tr}\left\{\xi\left(\left(U[t\xi]\right)^{-1}\mathrm{d}U[t\xi]\right)^4\right\}$$

$$\approx \frac{D_C}{15 f_\pi \pi^2} \epsilon^{\mu\nu\sigma\rho} \int_{S^4} \mathrm{d}^4x\ \mathrm{Tr}\left\{\pi\partial_\mu\pi\partial_\nu\pi\partial_\sigma\pi\partial_\rho\pi\right\}$$

Effects on relic density

S.K., J. Pomper (arXiv: 2402.04176)





- Dark matter relic abundance can be affected if η'_D is very close to π_D

See also Choi et al arXiv:1801.07726, Hochberg et al arXiv:1805.09345, Toro et al. arXiv:1801.05805

Conclusions

- A systematic analysis of strongly interacting theories is possible using
  - Connections to non-perturbative calculations
  - Analysis of underlying symmetries and underlying effective Lagrangians
- Presented several examples containing dark baryon and dark pion dark matter candidates
  - Typically matter content charged under the SM gauge group leads to heavy dark matter
  - Multiple relic density generation mechanisms can be engineered
- Portals lead to new interesting phenomenology, in particular in terms of dark-jets are colliders
  - Development of reliable event generators is important
  - Needs some understanding of hadronization in the dark sector


The Future is
Wonderful
XX NCTS Future workshop
On the Menu
Dark matter mass measurements
Dark matter interaction characteristics
Dark matter global fits
Large scale structure and dark matter
Collider evidences and future prospects