Collider and cosmological implications of strongly interacting dark sectors

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Based on completed and ongoing works with J. Lockyer, S. Mee, N. Hemme, E. Bernreuther, D. Stafford, F. Kahlhoefer S. Plätzer, M. Strassler

NAWI Graz
Natural Sciences

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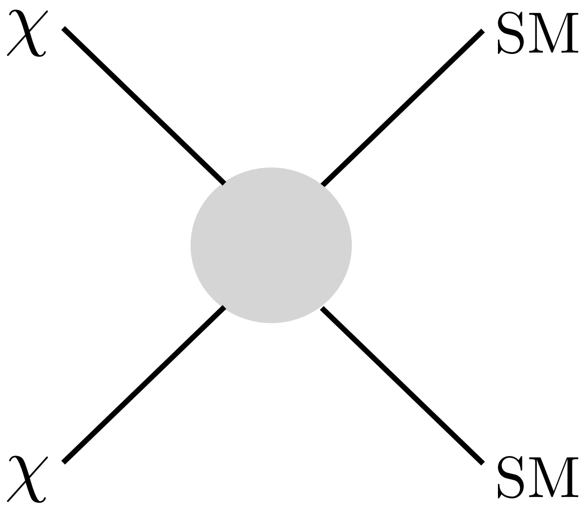
UNI GRAZ

Dark matter: connecting to particle physics



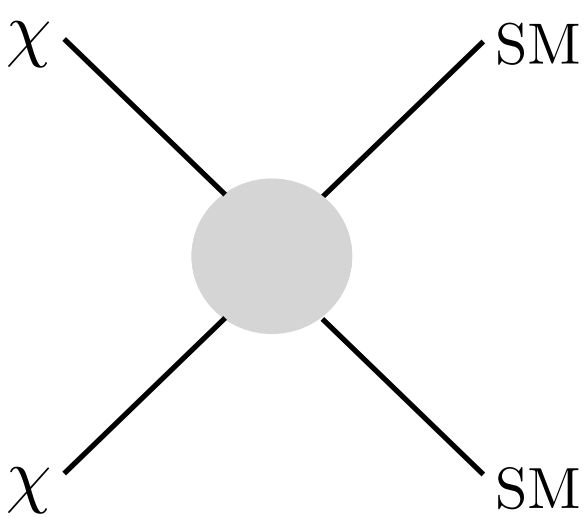
$$\Omega_\chi h^2 \sim \frac{10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \simeq 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m}{100\ \mathrm{GeV}}\right)^2$$

Weak scale coupling

Weak scale mass

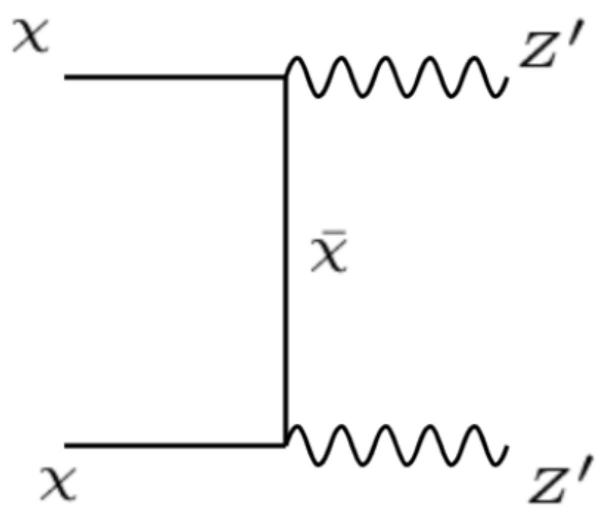
DM relic density mechanism needs a number changing interaction

Too many to add



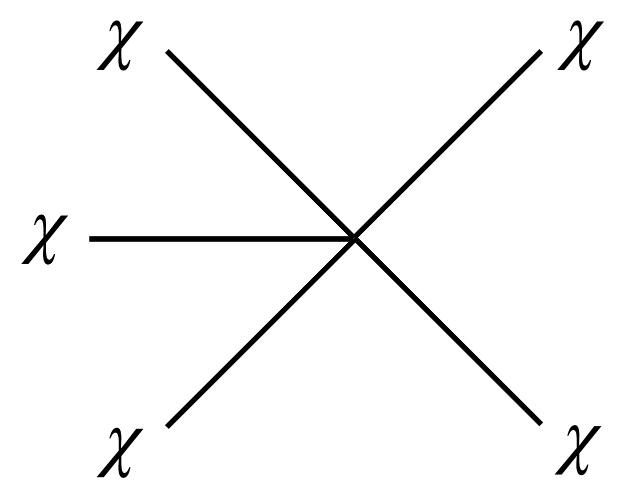
WIMP
$\mathcal{O}(100)$ GeV

D'Agnolo et al. arXiv:1505.07107
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

Dark matter: connecting to particle physics

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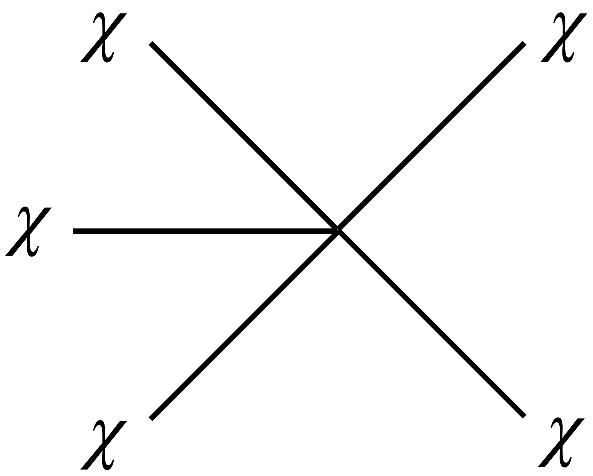
$$\Gamma_{3\to2} \sim H$$



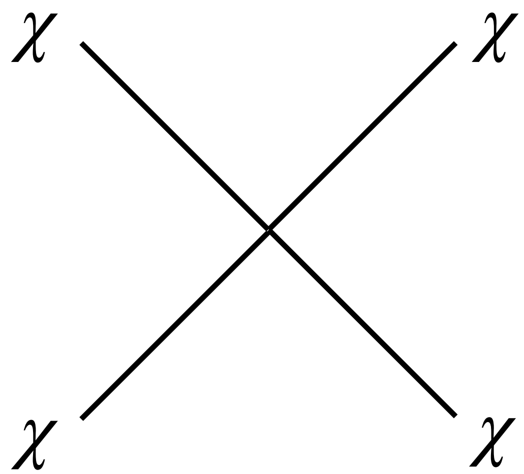
3 →2 annihilations

$$n_\chi^2 \langle \sigma v^2 \rangle_{3\to2} \sim \frac{T_{eq}^2 m_\chi^4}{x_F^6} \times \frac{\alpha_{eff}^3}{m_\chi^5} \sim H_F \sim \frac{T_F^2}{M_{\rm Pl}}$$

$T_{eq} \sim 0.8\,\mathrm{eV}$

$x_F \sim 20$

$$m_\chi \sim \alpha_{eff} \left(T_{eq}^2 M_{\rm Pl} \right)^{1/3} < \alpha_{eff} \times \mathcal{O}(100)\,\mathrm{MeV}$$



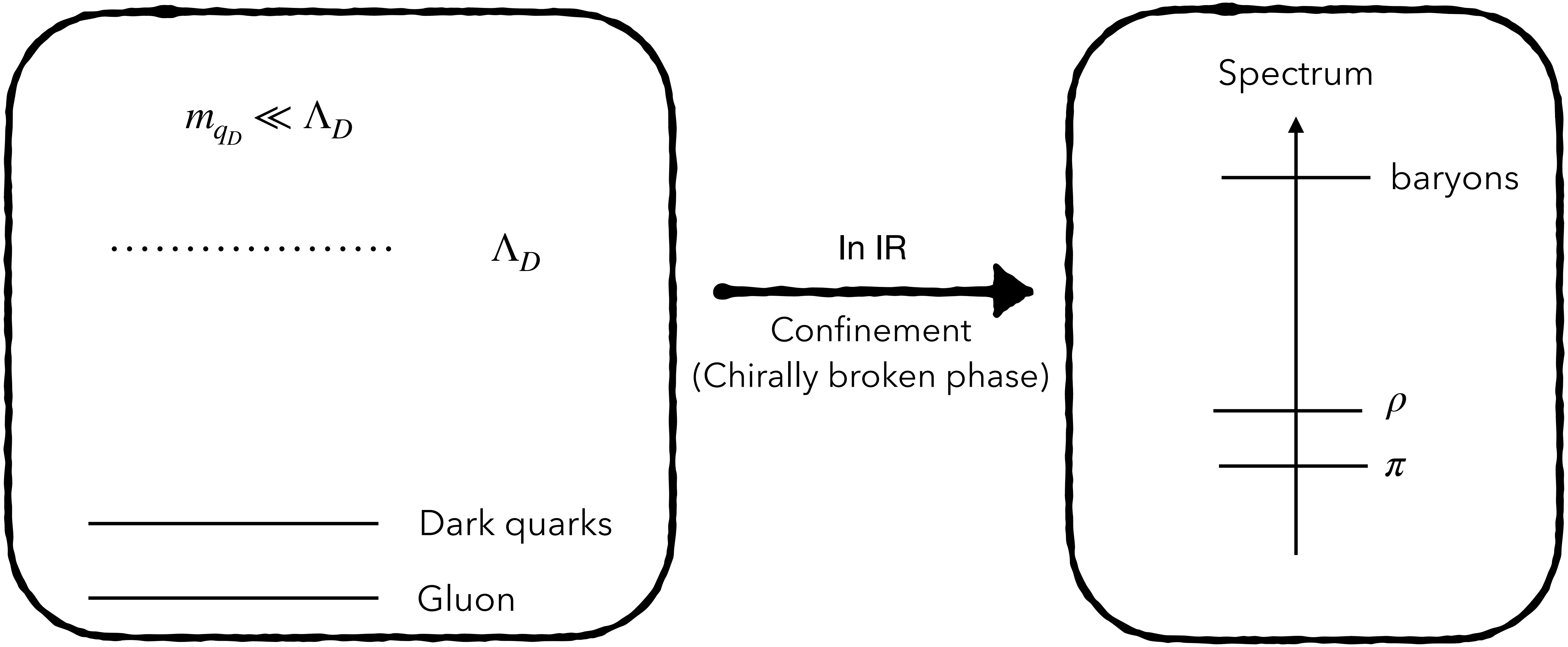
2 →2 self-interactions

$$\frac{\sigma_{\chi\chi}}{m_\chi} \sim a_{\rm int} \frac{\mathrm{barn}}{\mathrm{GeV}} \sim \frac{\alpha_{\rm eff}}{m_\chi^3}$$

$$m_\chi \geq 10 \left(\frac{a_{\rm int}}{\alpha_{\rm eff}} \right)^{1/3} \mathrm{MeV}$$

- Relic density and self-interactions require non-perturbative couplings and sub-GeV DM mass
- Very small region to reconcile both

Strongly Interacting Dark Matter



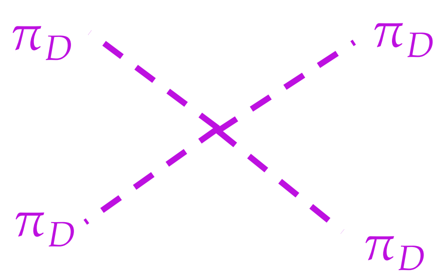
- One kind of theories where both of these may be possible are new QCD-like theories
- Also SIMP scenarios or (confining) Hidden Valleys or darkshowers/darkjets

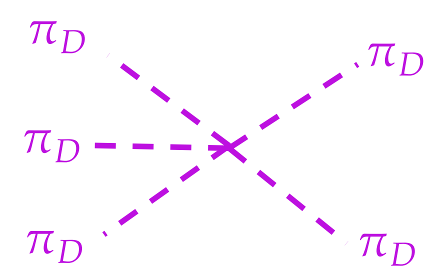
Strassler hep-ph/0607160

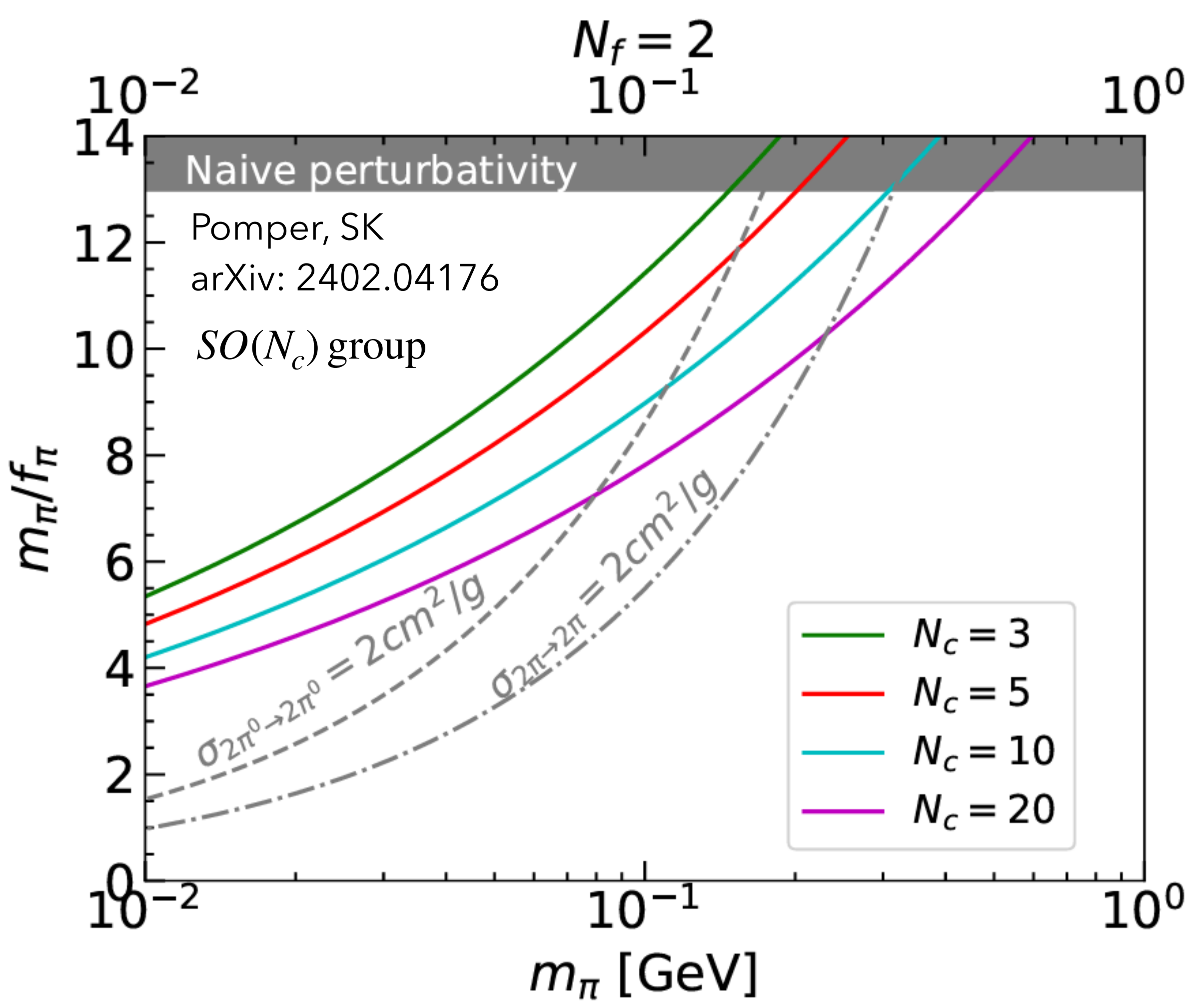
New avenues

- Dark pions being the lightest states can be dark matter candidates

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



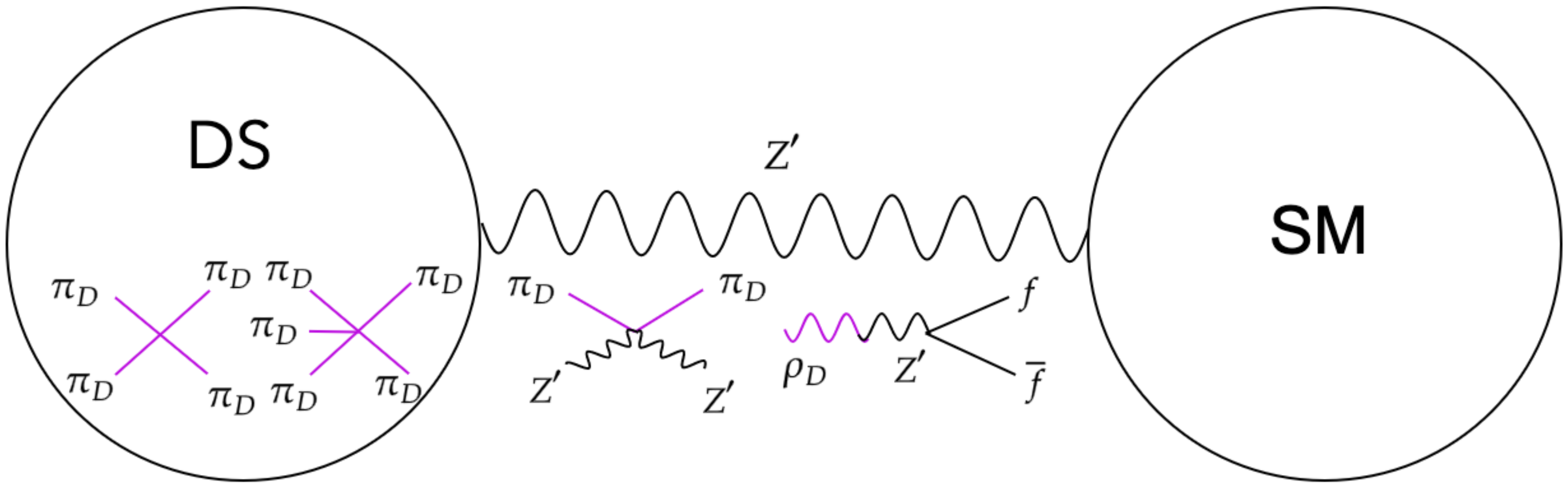




Hochberg et al arXiv:1512.07917, Kribs et al arXiv: 1604.04627, Cline et al arXiv:2108.10314, Beriln et al arXiv:1801.05805

- Relic density $\quad n_{\pi_D}\langle\sigma v\rangle_{3\to 2} \sim H \implies \dfrac{m_{\pi_D}}{f_{\pi_D}} \propto m_{\pi_D}^{3/10}$
- 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}

New avenues



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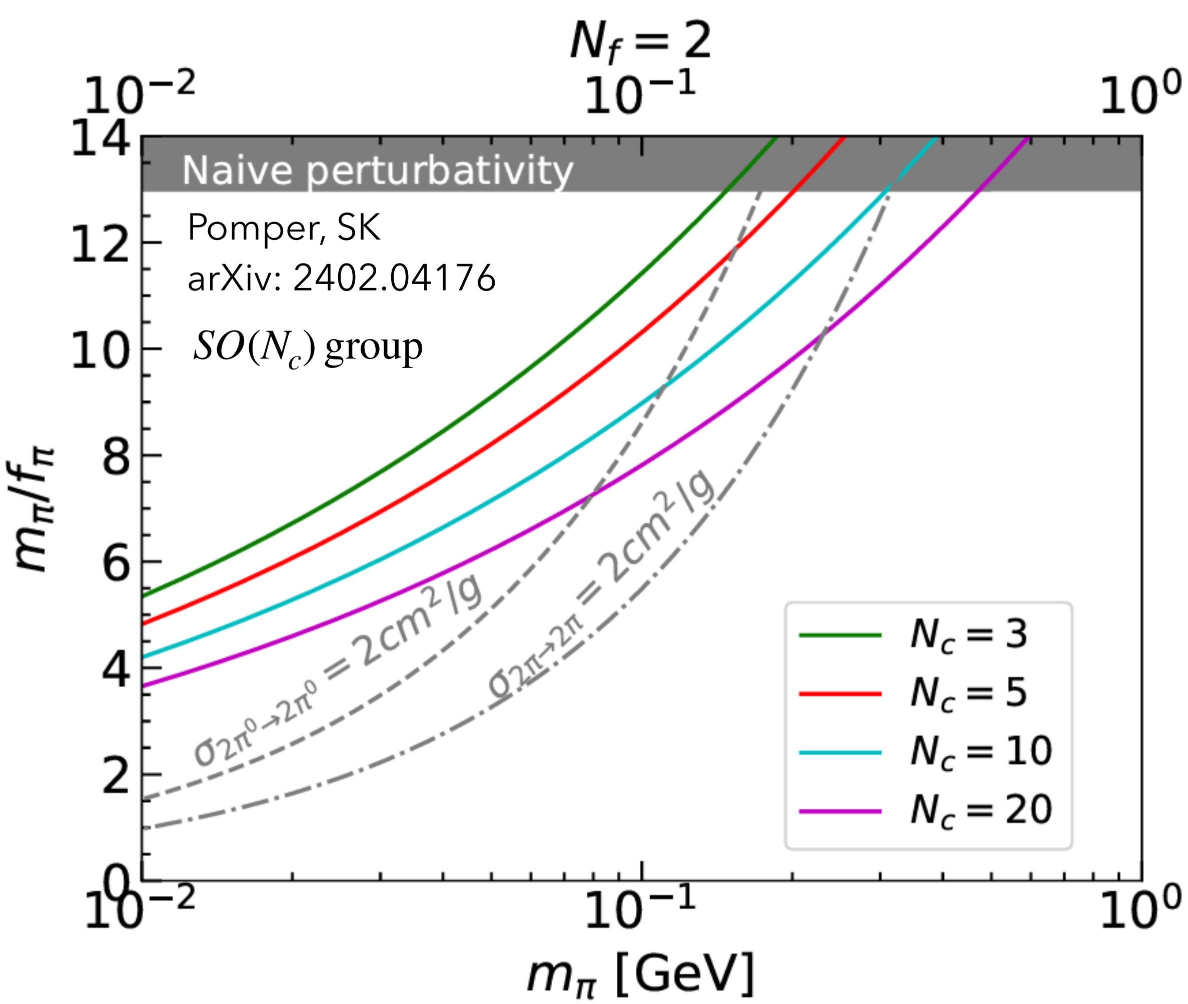

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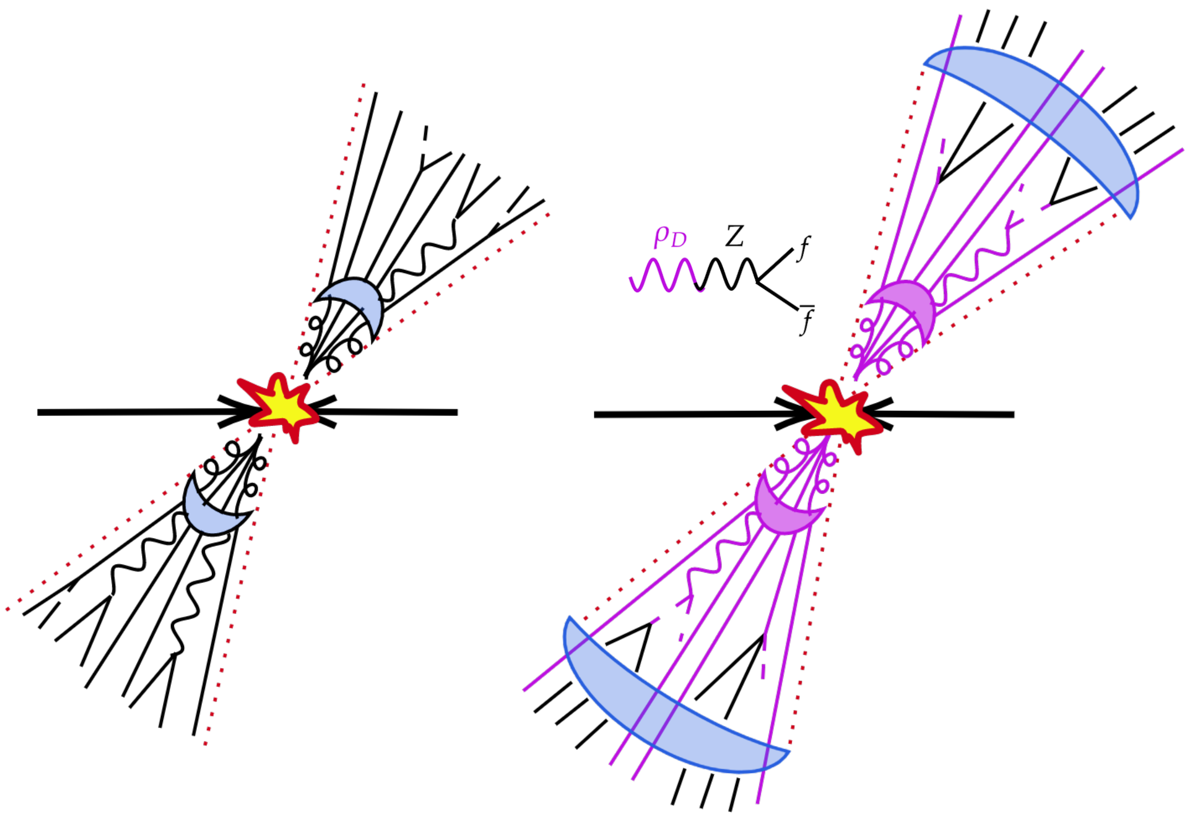
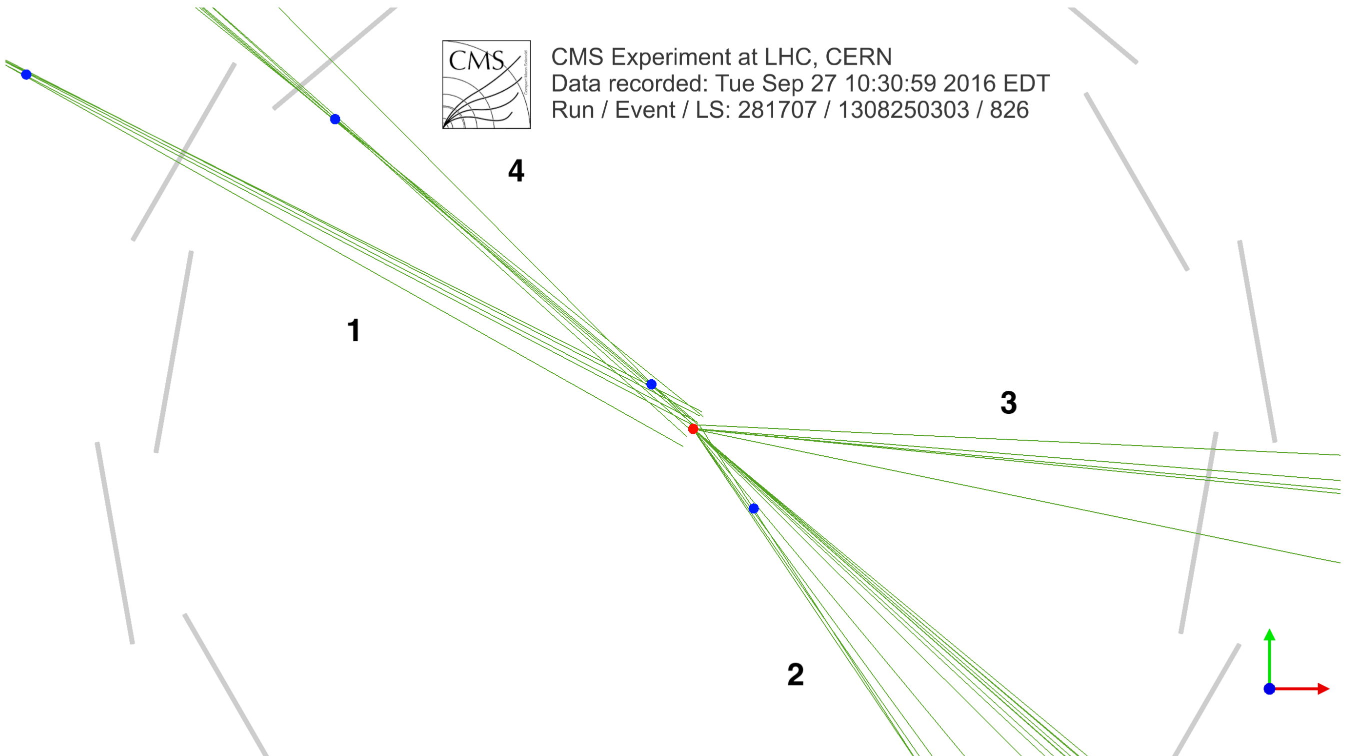
Experimental signatures

- 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

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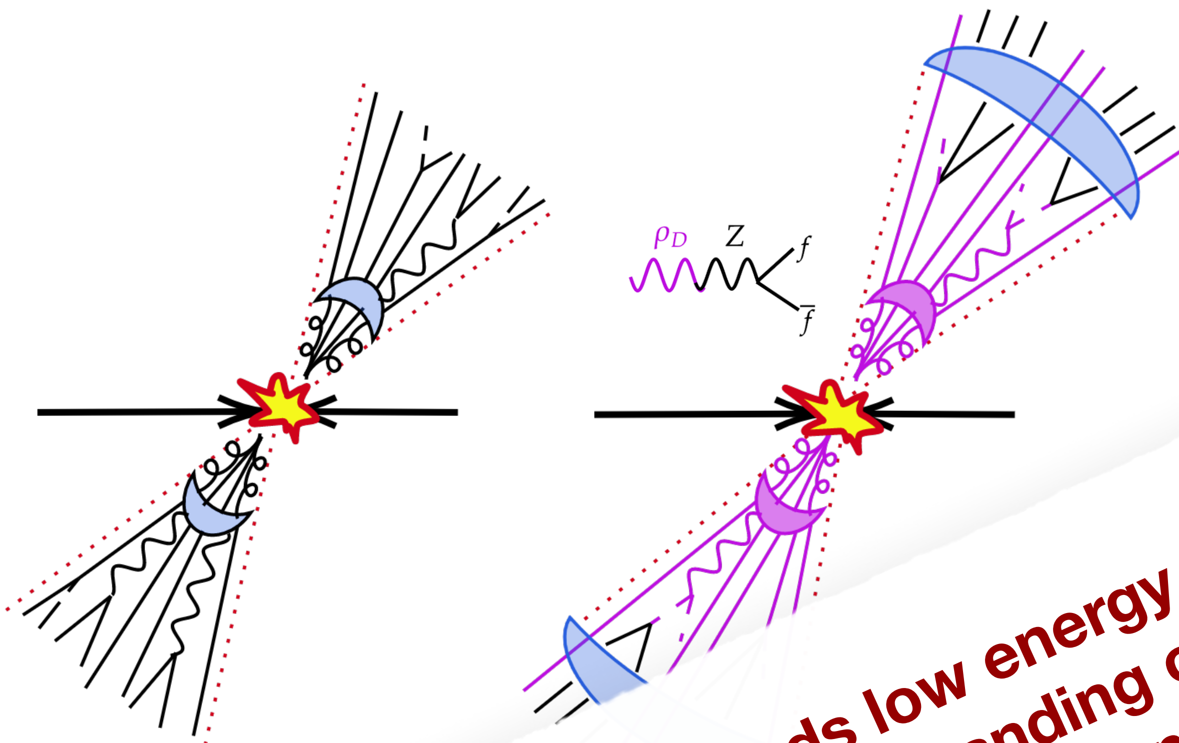

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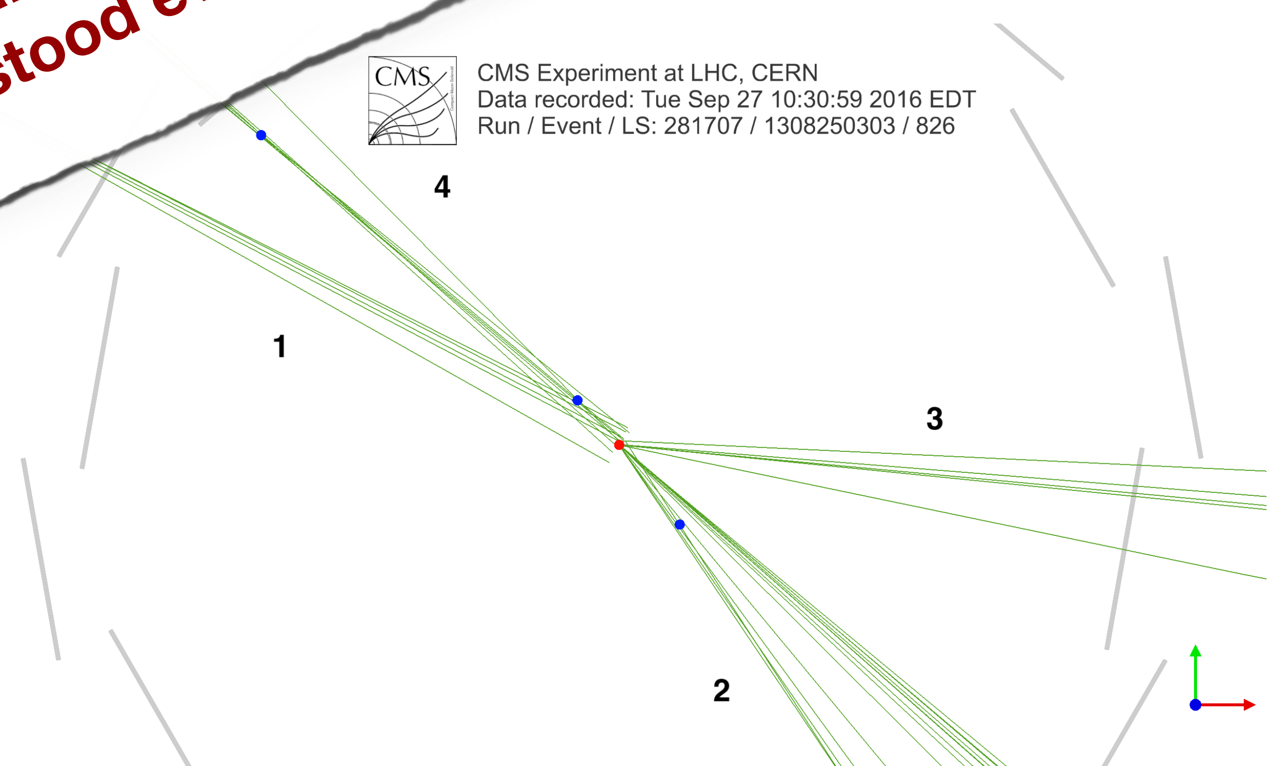
Needs low energy effective Lagrangian
Understanding of dark hadronization
Existence of well understood event generators

- 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



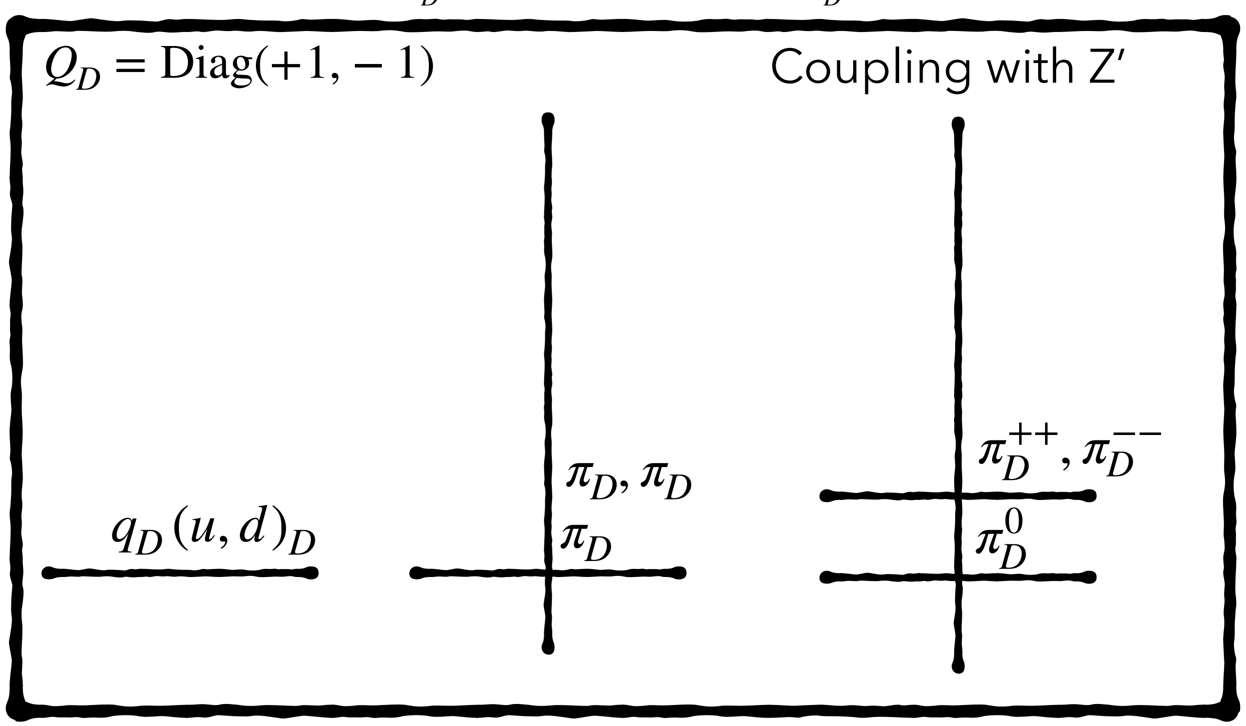
arXiv:1810.10069

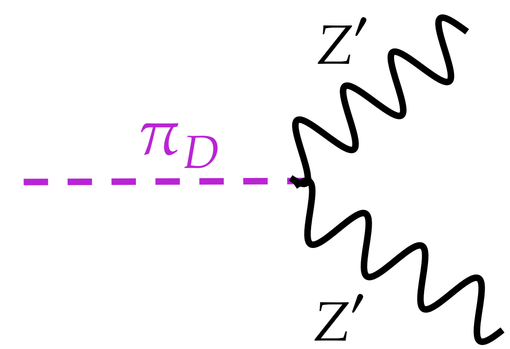
Primary obstacles in theory constructions

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

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





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

$\to Q_D^2 \propto 1$

Quantitative estimates from genuine non-perturbative physics are needed

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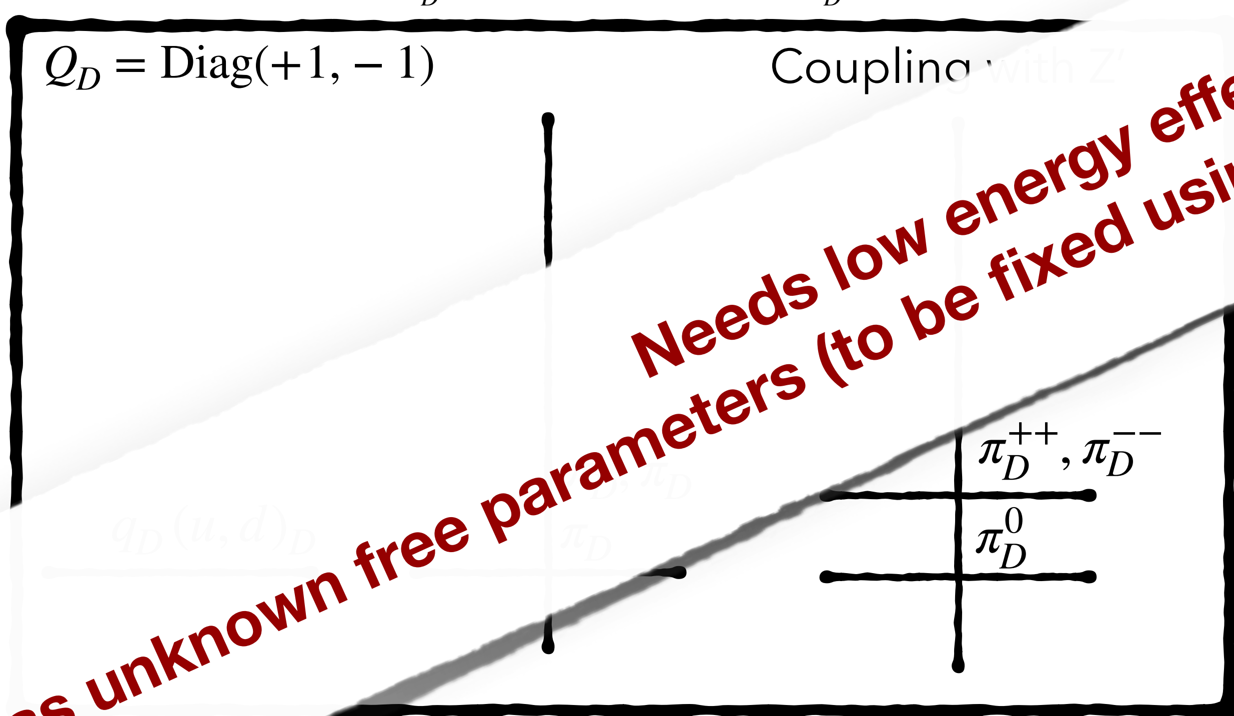
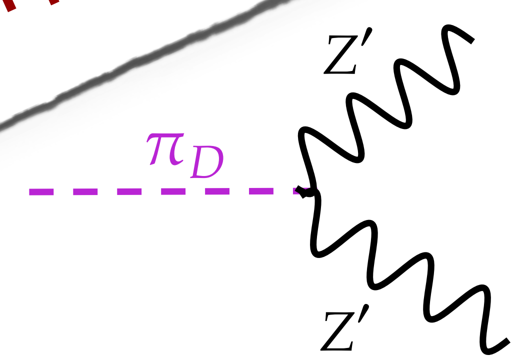




$\sim Tr[Q_D^2 T_0] = 0$

$\rightarrow Q_D^2 \propto 1$

Needs low energy effective Lagrangian

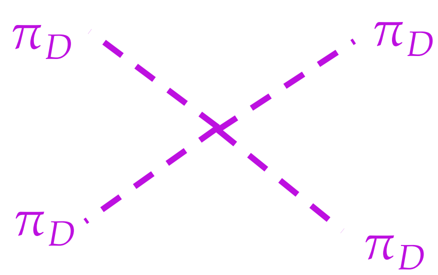
Has unknown free parameters (to be fixed using non-perturbative calculations e.g. lattice)

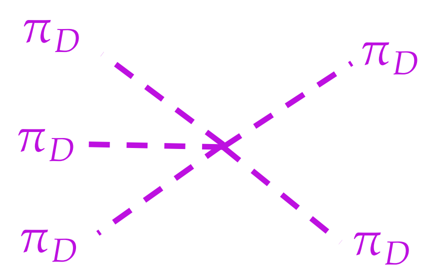
Quantitative estimates from genuine non-perturbative physics are needed

Chiral Lagrangian in isolation

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

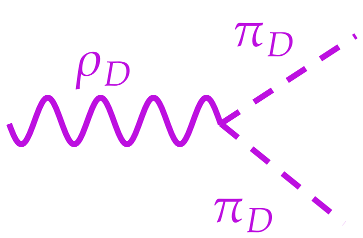
$\mathscr{L} = \mathscr{L}_{\text{non-anom}}$ $+\mathscr{L}_{\text{anom}}$ → Construction a la Witten

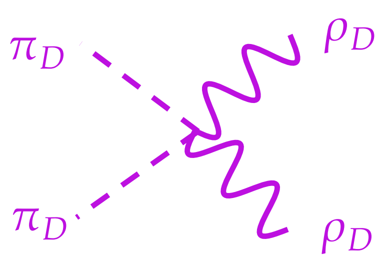


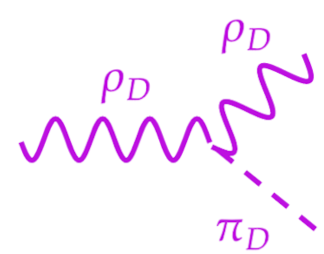


- $SU(N_{c_D})$ with $N_{f_D} = 2$ and $SO(N_{c_D})$ with $N_{f_D} = 1$ exhibit chiral symmetry breaking but no anomaly
- Witten construction needs certain homotopy conditions e.g. $\pi_4(SU(4)/SO(4)) = 0$

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







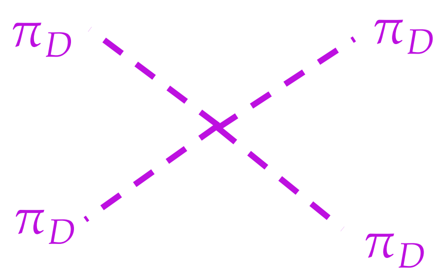
See **S.K.**, S. Mee, et al arXiv:2202.05191 for Sp(2N)
J. Pomper, **S.K.**, arXiv: 2402.04176 for SO(N)

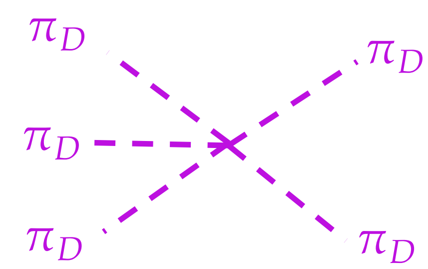
- Heavier states introduce new interesting dark matter and collider phenomenology

$U(1)_D$ 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





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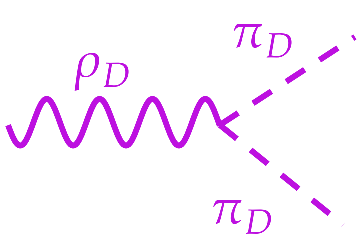
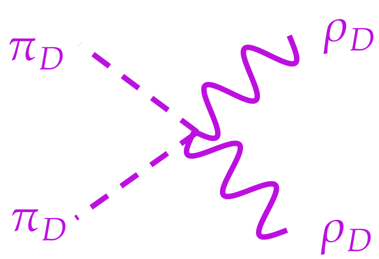
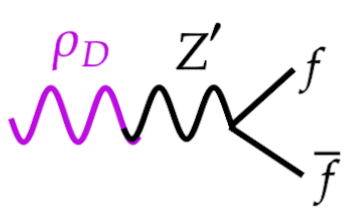
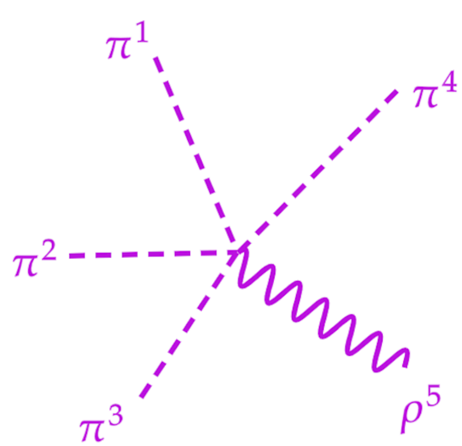
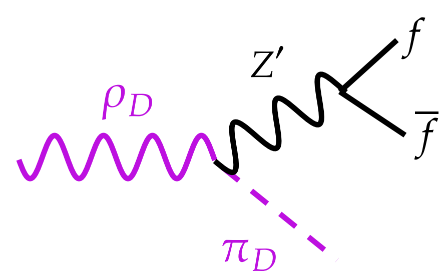
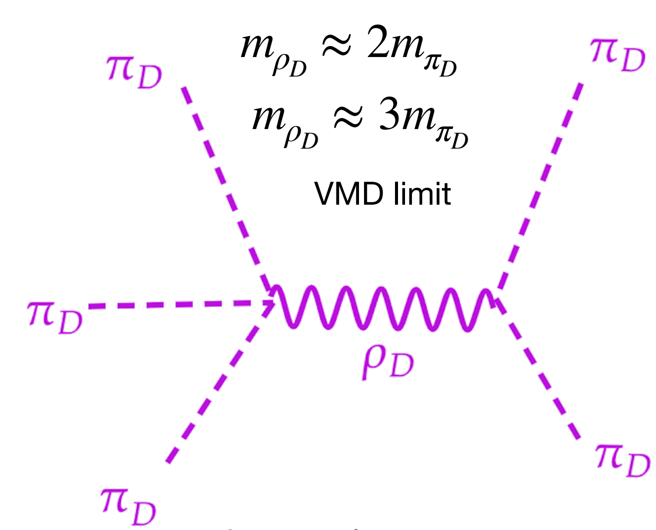












Choi et al., arXiv:1801.07726

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

Strongly Interacting Dark Matter

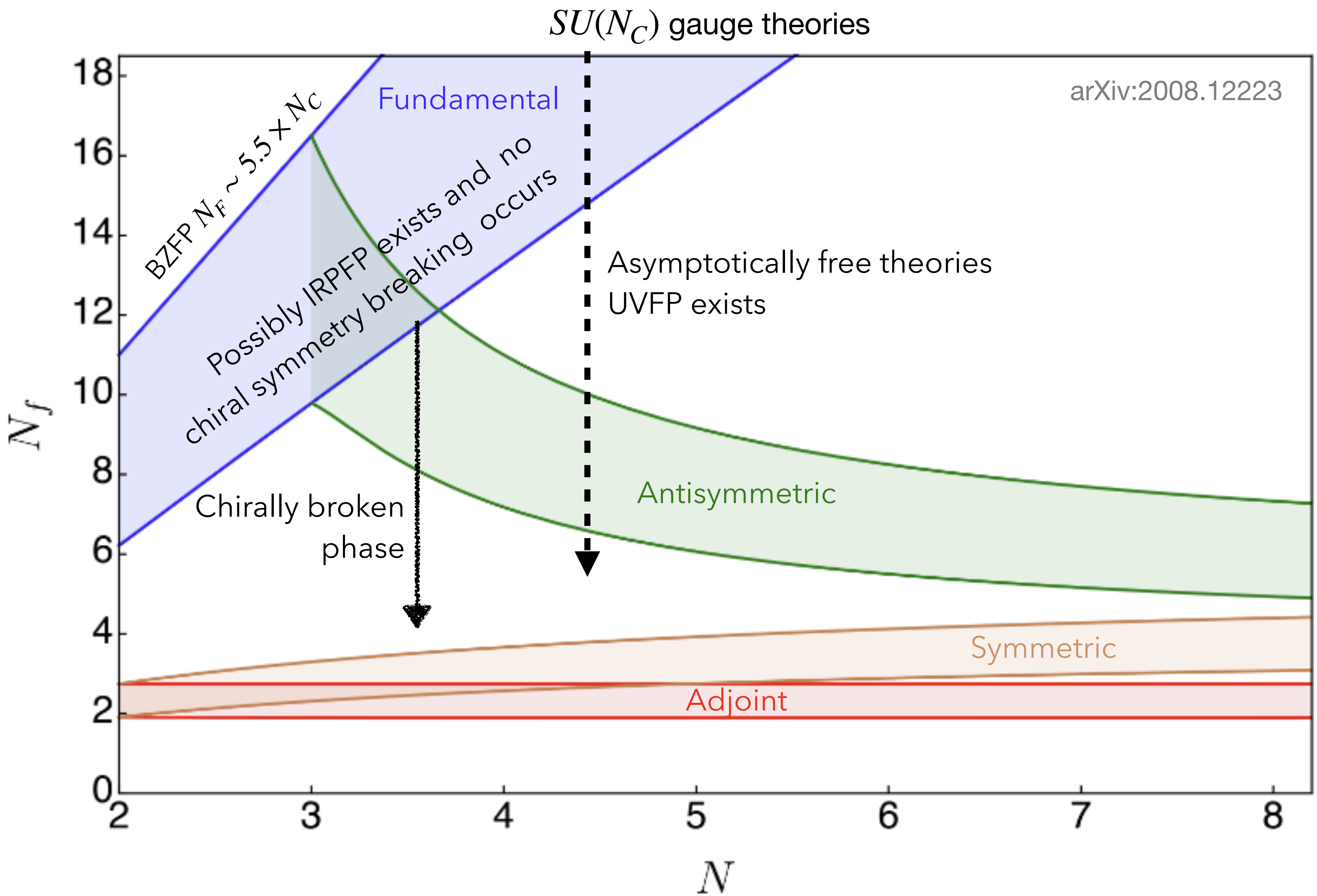
UV physics contains

- 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)

Strongly Interacting Dark Matter

UV



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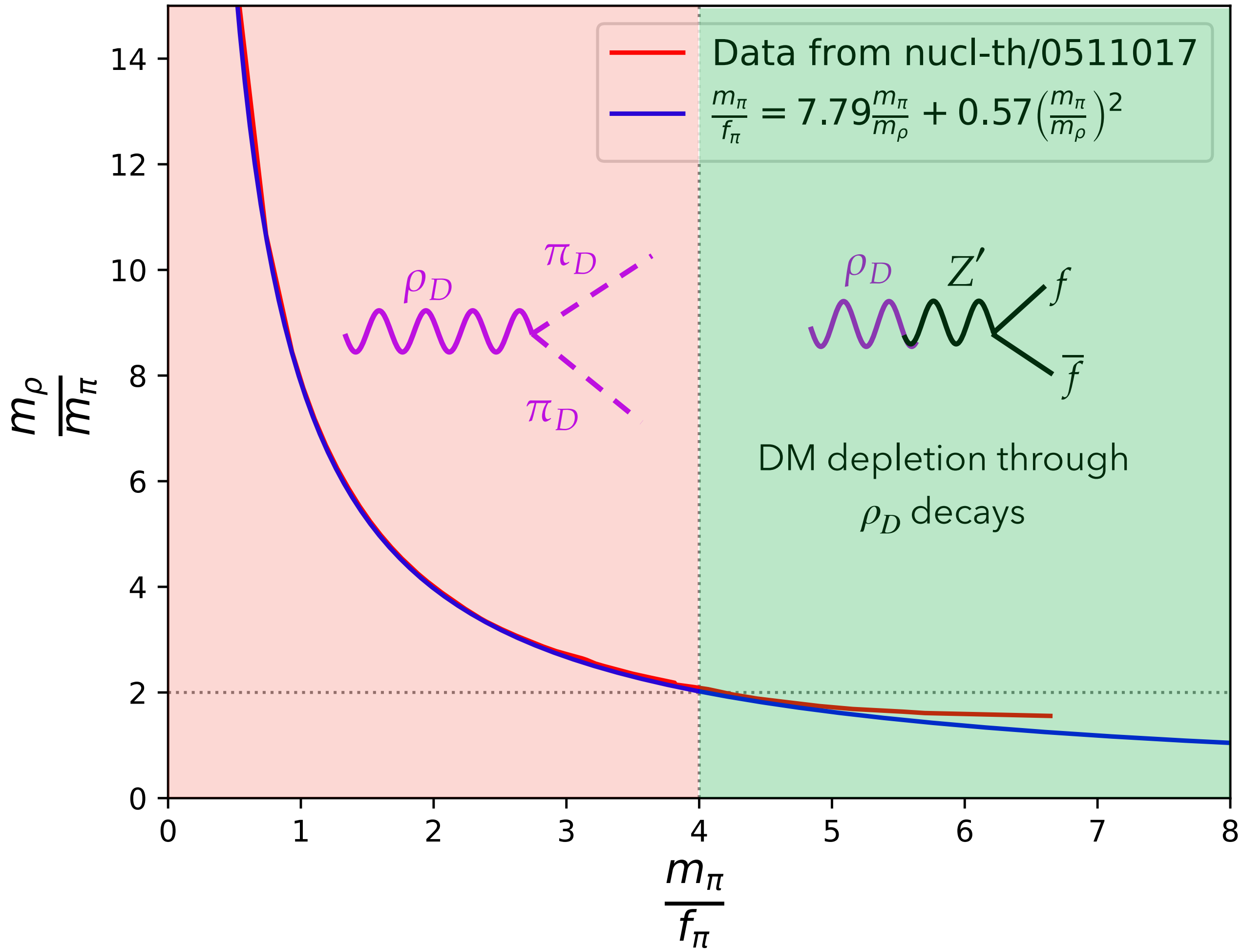


- Two discrete parameters N_{c_D}, N_{f_D}
- Two continuous parameters $m_{q_D}, \alpha_D(\mu)$ (UV)
  - $f_\pi, m_\pi/f_\pi$ or $\Lambda_D, m_{\pi_D}/\Lambda_D$ or $m_{\pi_D}, m_{\pi_D}/m_{\rho_D}$ (IR)

See also Snowmass report Kulkarni et al. arXiv:2203.09503

- Fits from non-perturbative calculations

$$\frac{m_\pi}{f_\pi} = 7.79\frac{m_\pi}{m_\rho} + 0.57\left(\frac{m_\pi}{m_\rho}\right)^2$$

- Need $m_\pi/f_\pi \gtrsim 4$ for interesting DM phenomenology involving vector mesons

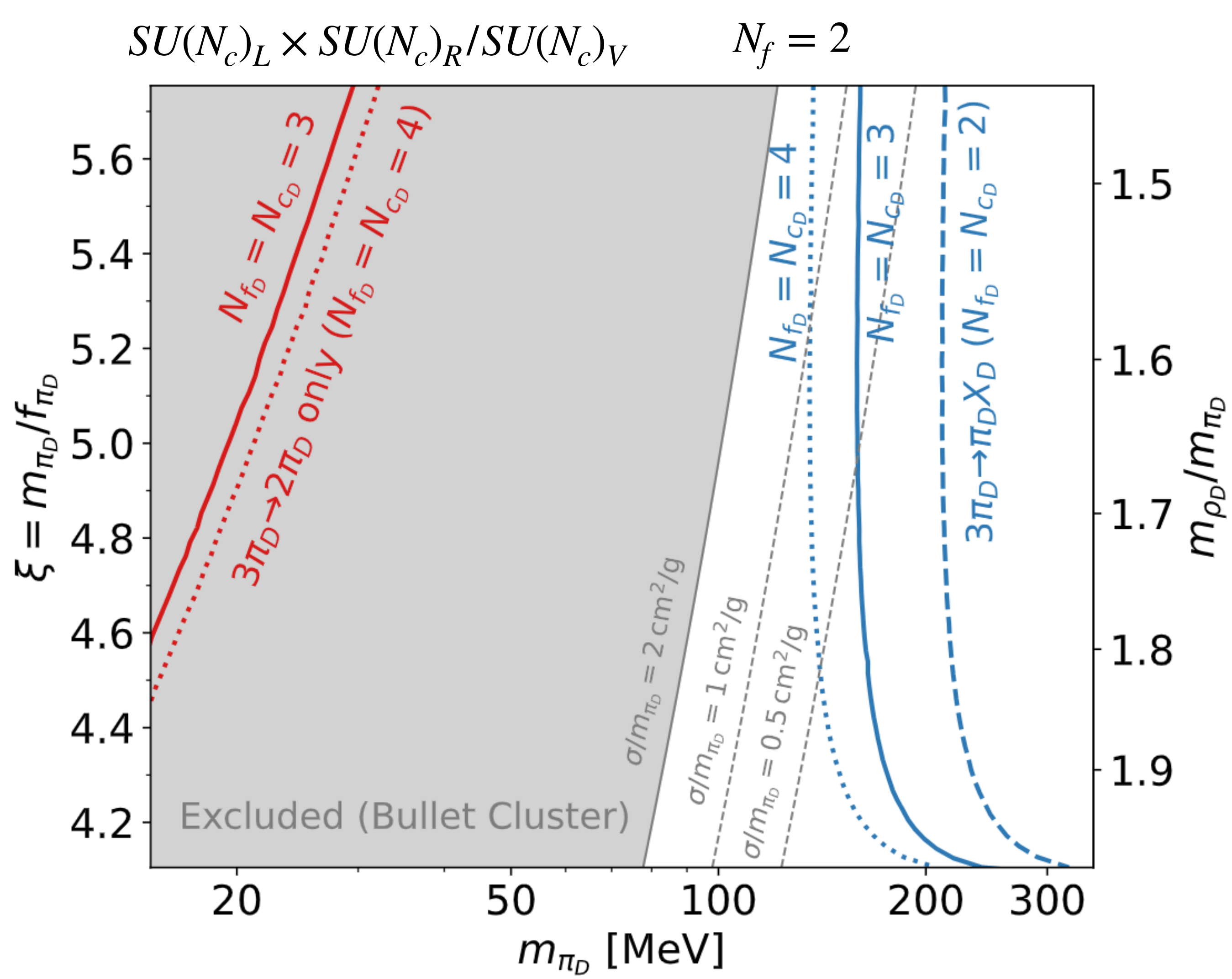
$N_{f_D} = 1$ and/or $\mathrm{N_{c_D}} = 2$ special cases

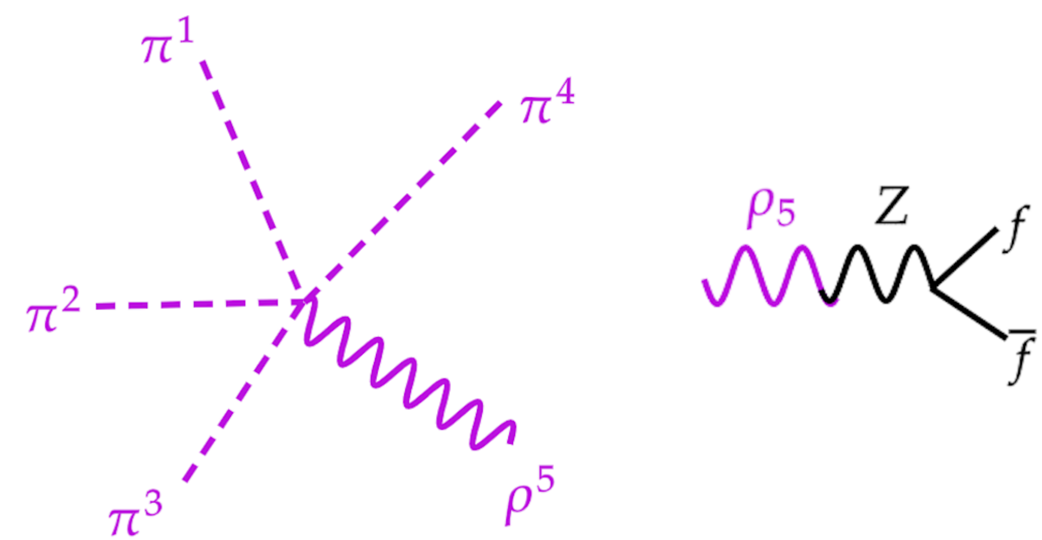
Francis et. al. arXiv:1809.09117

New relic density avenues

- Large self interactions consistent with relic density

Bernreuther, Hemme, Kahlhoefer, SK arXiv:2311.17157





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

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

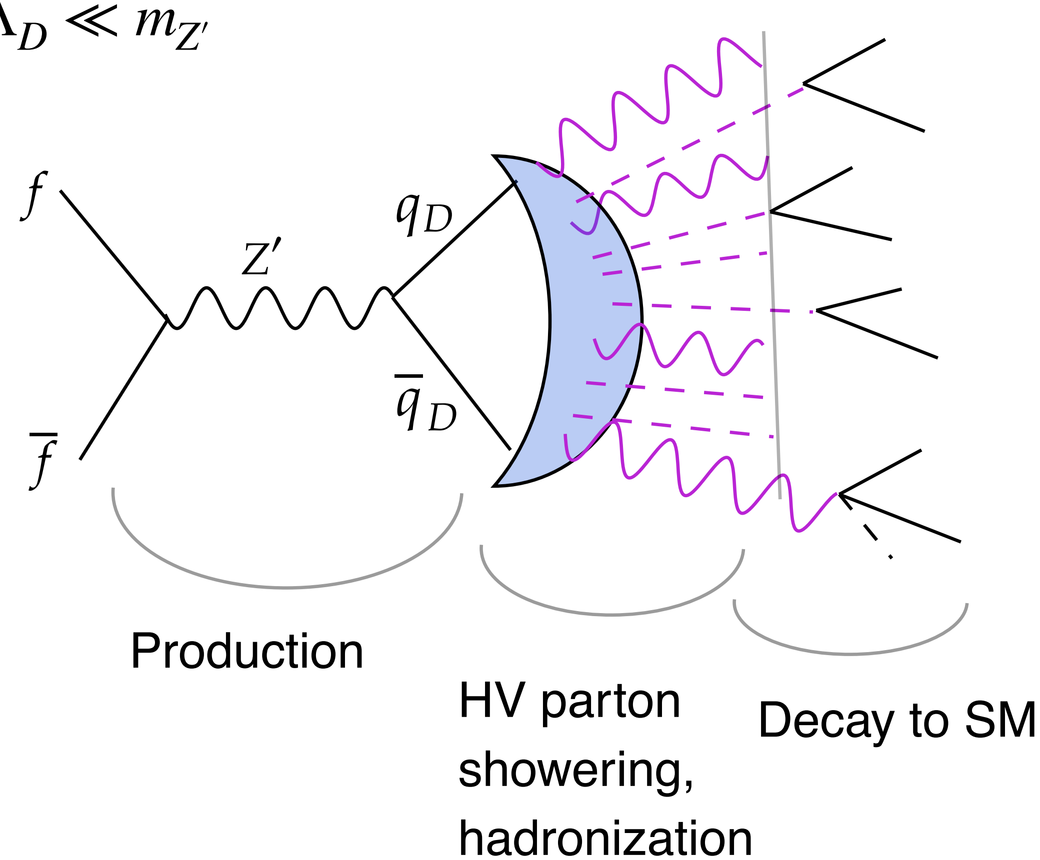
- Delayed freeze out allows for larger masses thus Bullet cluster constraints can be evaded

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

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

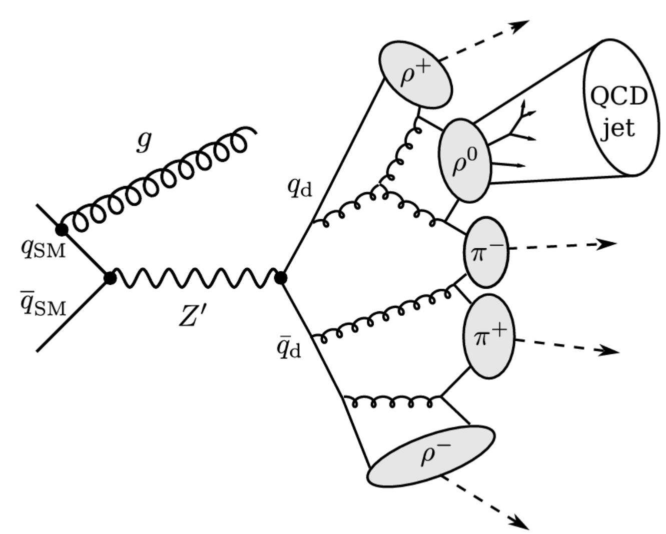
$m_{q_D} \ll \Lambda_D \ll m_{Z'}$



- 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

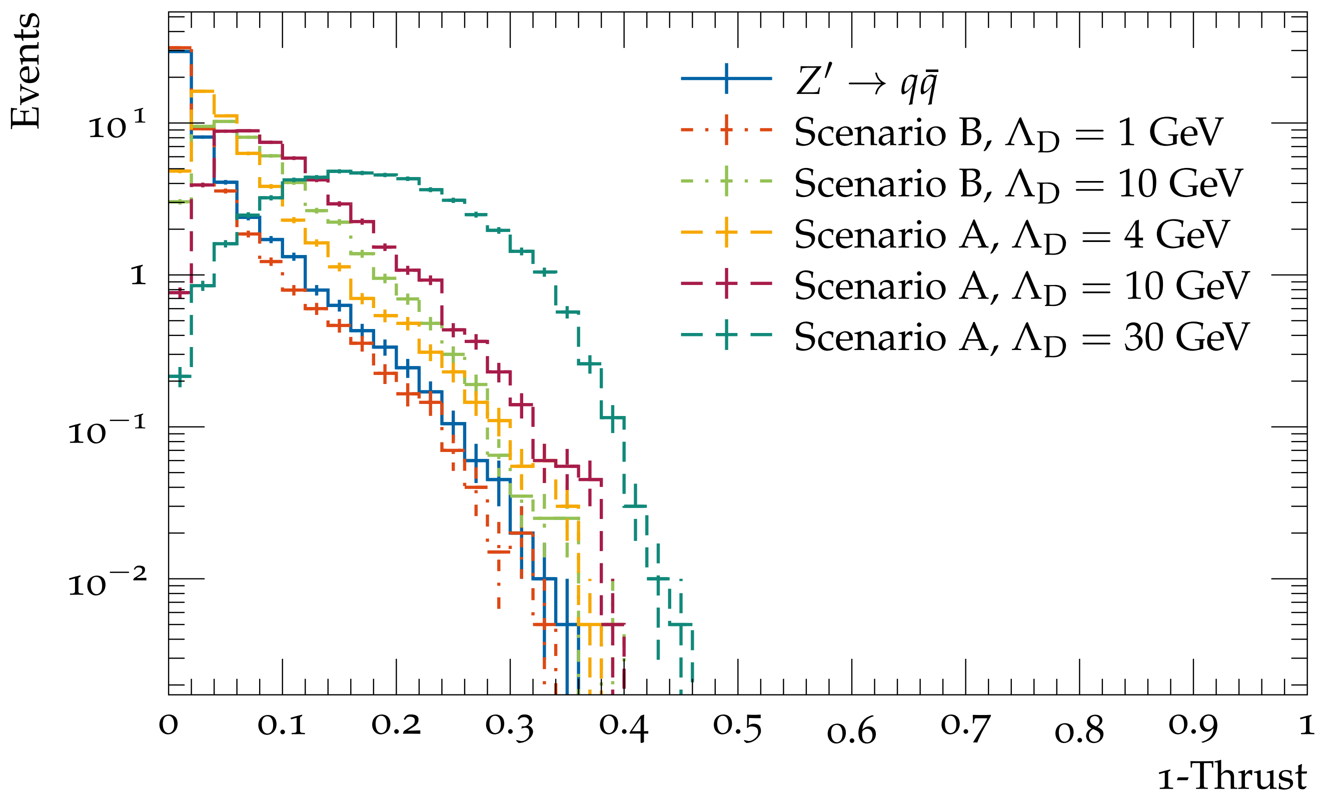
- Example: $N_{f_D} = 2$; $n_{\pi_D} = n_{\rho_D} = 3$;
  Doublet (π_D^{++}, π_D^{--}); $(\rho_D^{++}, \rho_D^{--})$
  Singlets (π_D^0); (ρ_D^0)
  $\rho_D^0 - Z'$ mixing leads to visible decays



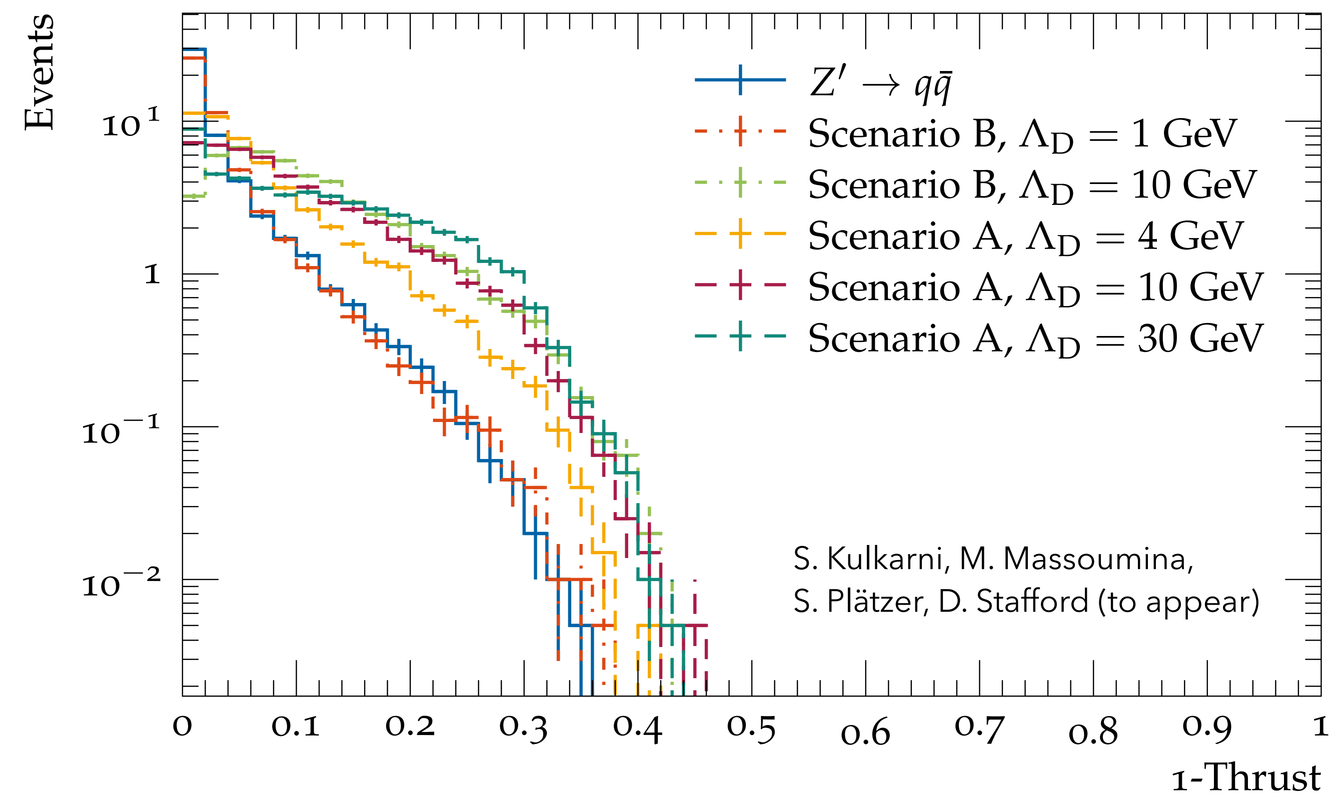
Darkshowers in Herwig7

- Overhauled PYTHIA8 HiddenValley module during snowmass process

1-Thrust distribution of dark hadrons



1-Thrust distribution of visible particles



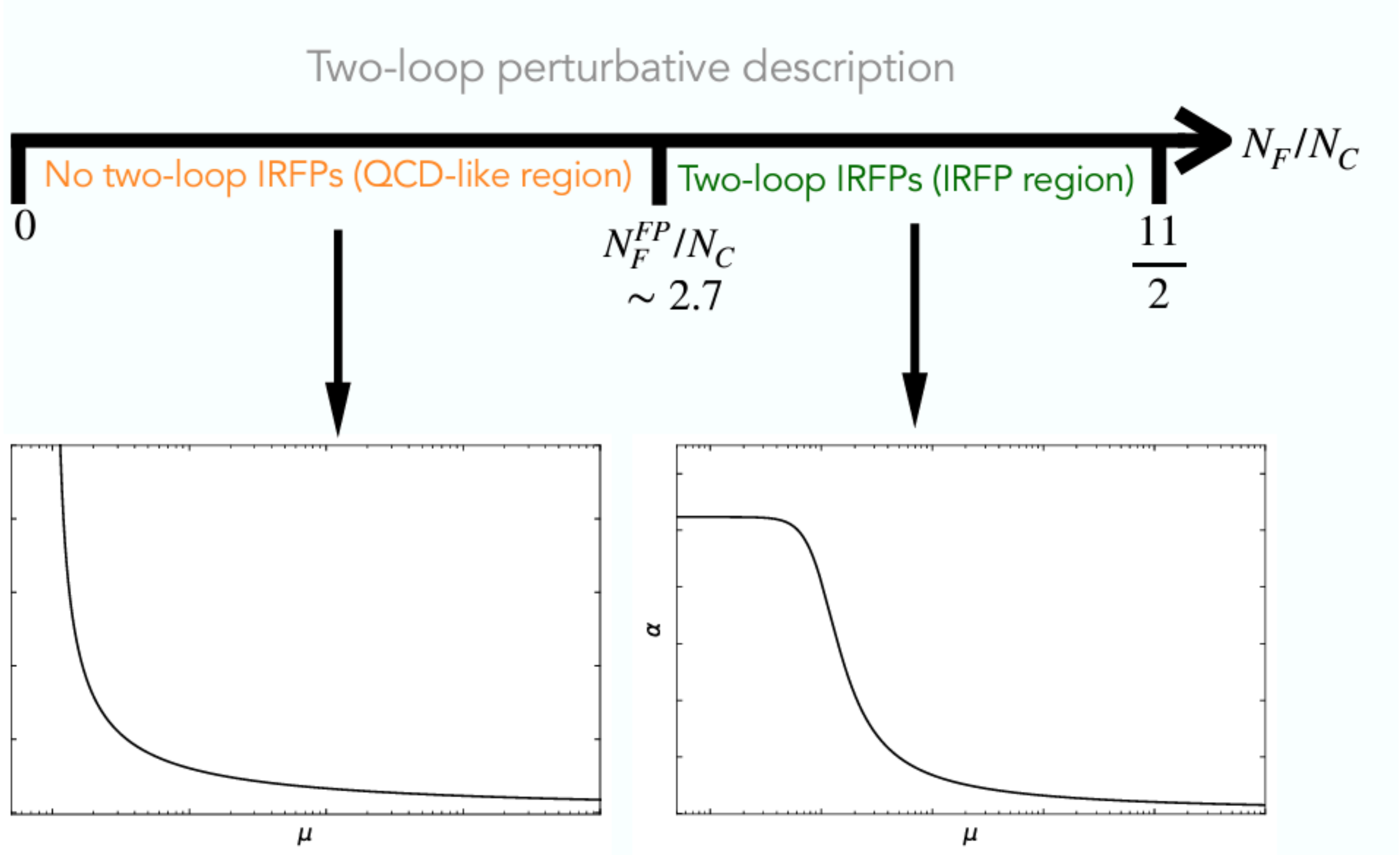
- Scenario A: $\rho \to \pi\pi$ open, π decays
- Scenario B: $\rho \to \pi\pi$ closed, $\rho \to f^{SM}\bar{f}^{SM}$ and $\rho \to f^{SM}\bar{f}^{SM}\pi$ with π stable
- More spherical events in isolation as Λ increases, decays to SM smear it out
- Understanding possible due to consistent mass scale settings

See also talk by Joon-Bin Lee

Beyond QCD-like theories: near conformal theories

- At larger N_f/N_c the two loop beta function of the running coupling can a non-trivial fixed point

$$\mu^2 \frac{d\alpha}{d\mu} = \beta(\alpha) = -\alpha^2(\beta_0 + \beta_1 \alpha) \qquad \alpha_* = -\frac{\beta_0}{\beta_1}; > 0 \text{ for } \frac{\mathrm{N_f}}{\mathrm{N_c}} \gtrsim 2.7$$



Beyond QCD-like theories: near conformal theories

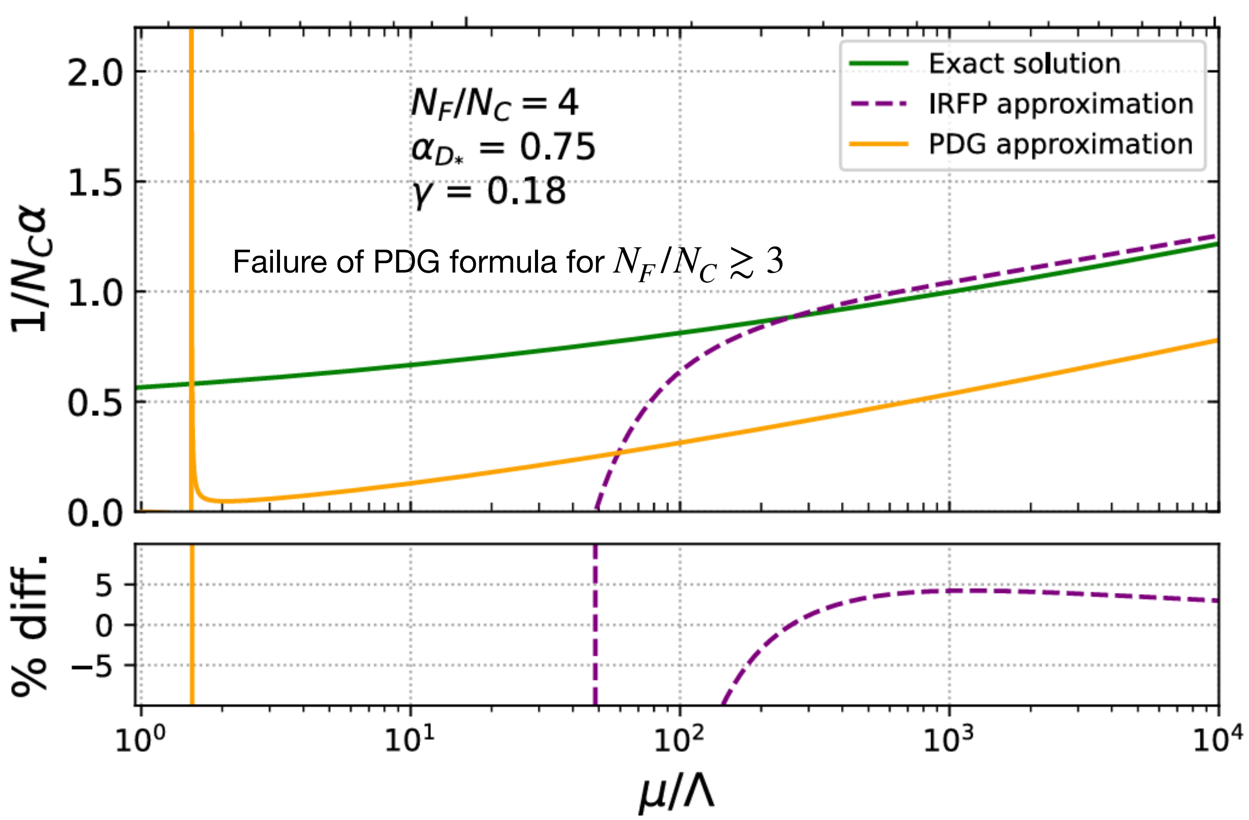
To appear with J. Lockyer, M. Strassler

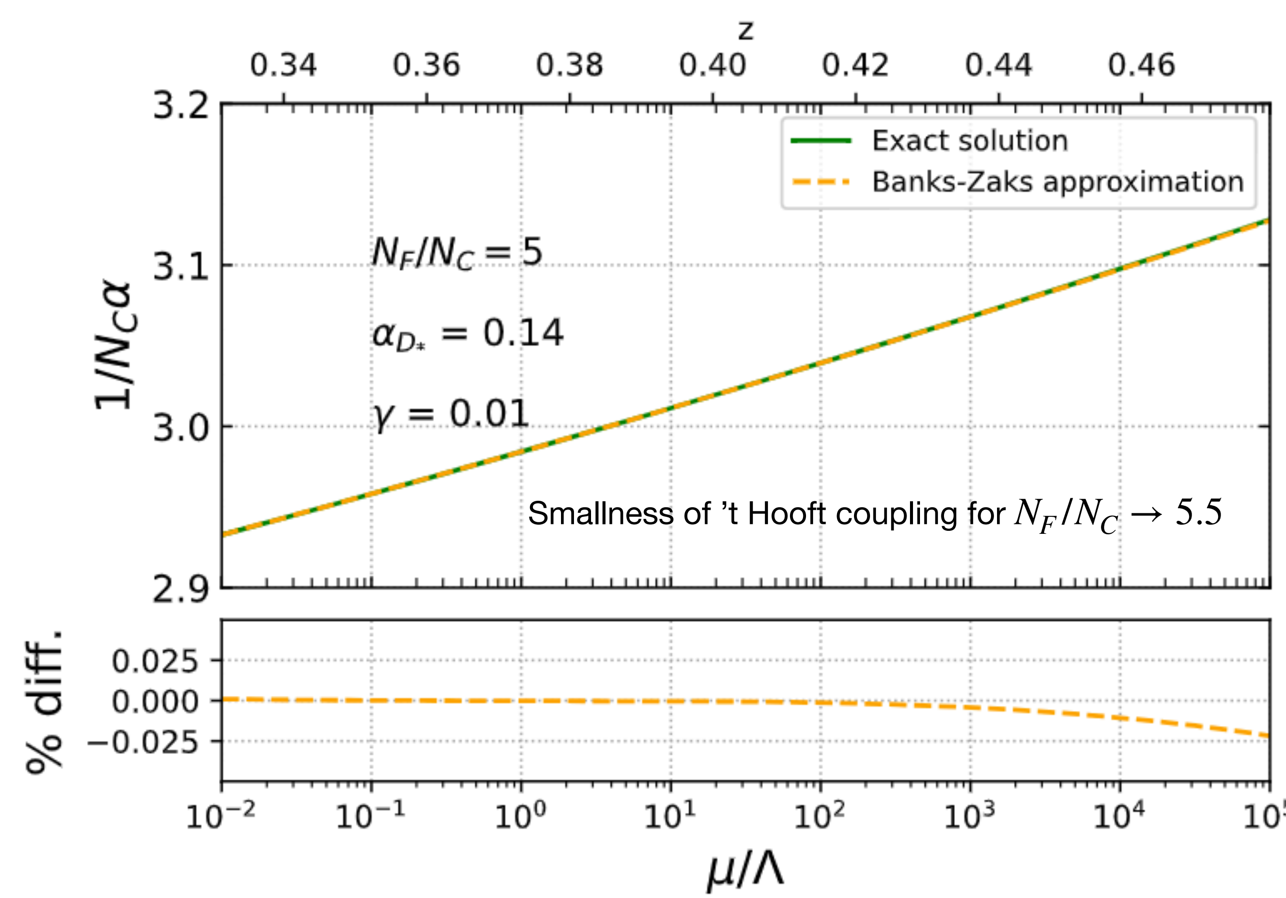
- Standard PDG formula derived under the assumption of occurrence of IR divergence does not work when fixed points occur
- New procedure to simulate theories containing infrared fixed points defined and validated

$$\alpha = \alpha_* \left[W_{-1}(-z) + 1\right]^{-1} \quad ; \quad \alpha = \alpha_* \left[W_0(z) + 1\right]^{-1} \quad ; \quad z = \frac{1}{e}\left(\frac{\mu^2}{\Lambda^2}\right)^{\beta_0 \alpha_*}$$

QCD-like (no IRFP) — IRFP-region

arXiv:9602385, T. Appelquist et al.
arXiv:1406.2337, D. Litim et al.
arxiv:9810192 - E. Gardi et al.



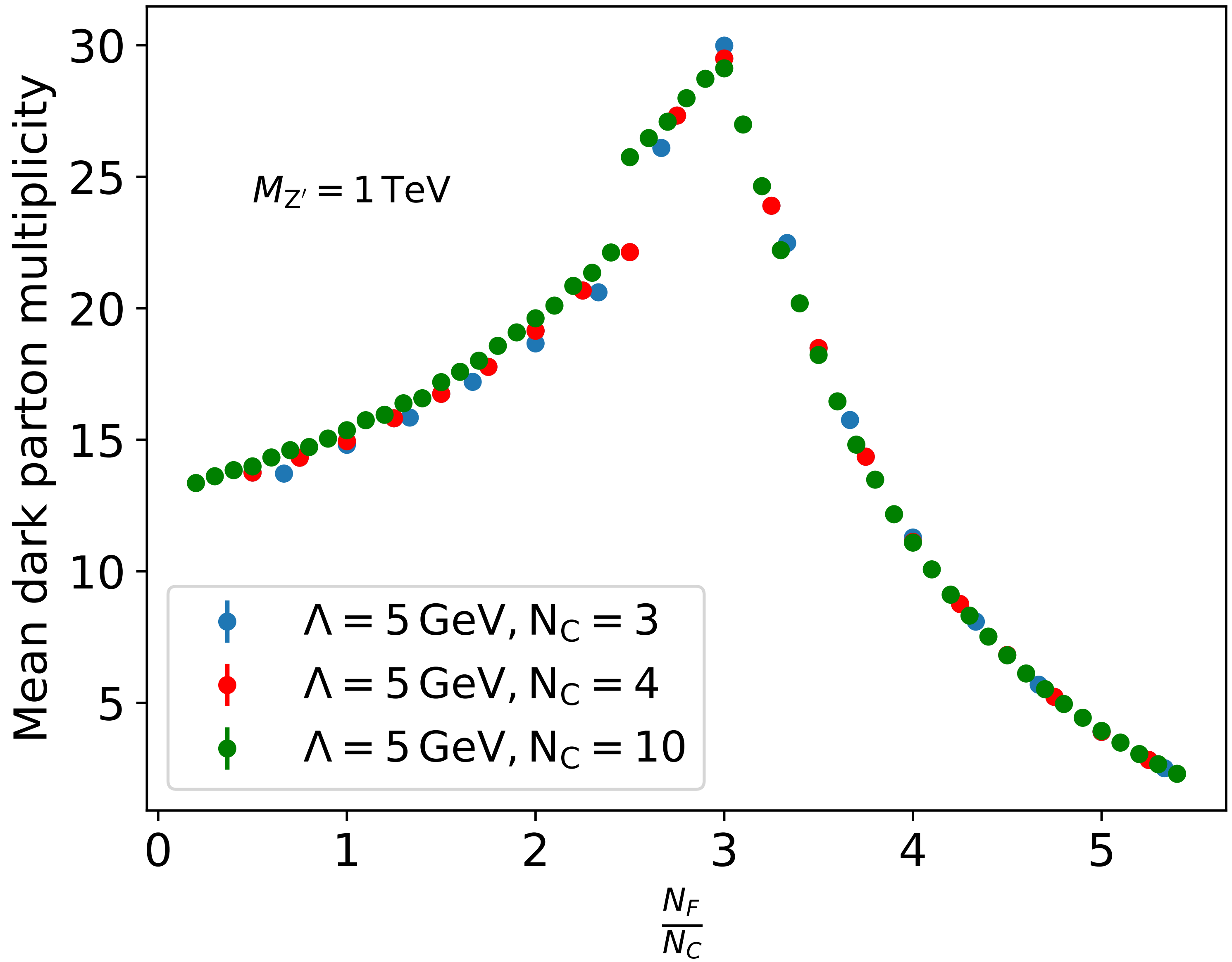


- Conformal theories do not always lead to SUEPs/Heavy Ion collision type events

Beyond QCD-like theories: near conformal theories

To appear with J. Lockyer, M. Strassler

- Drastic parton shower behaviour changes



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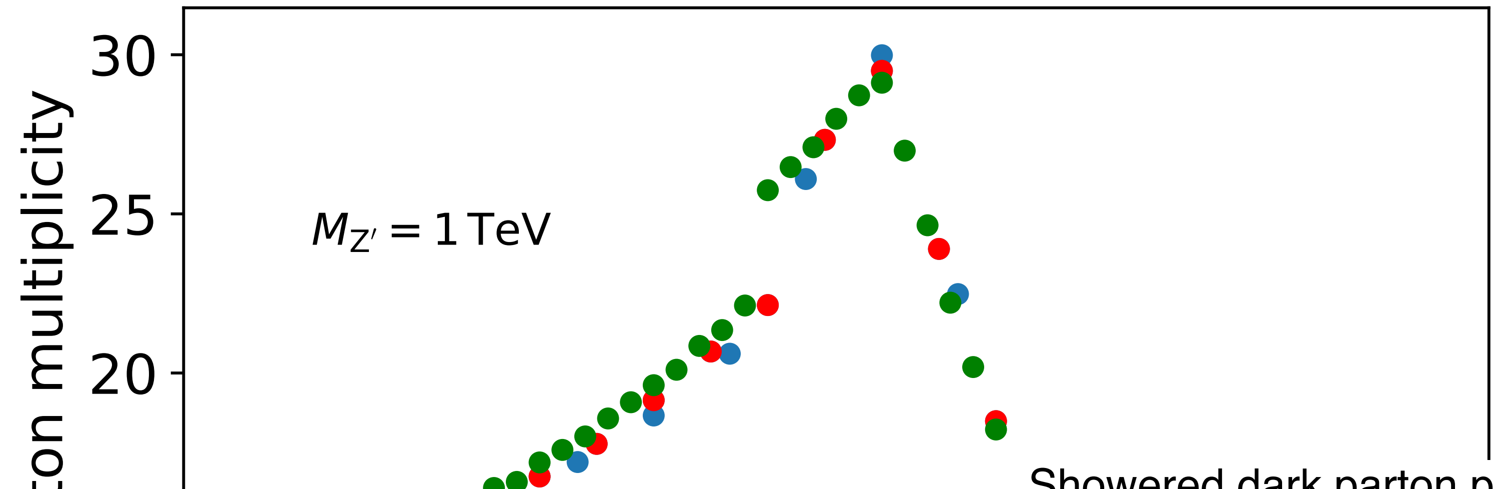
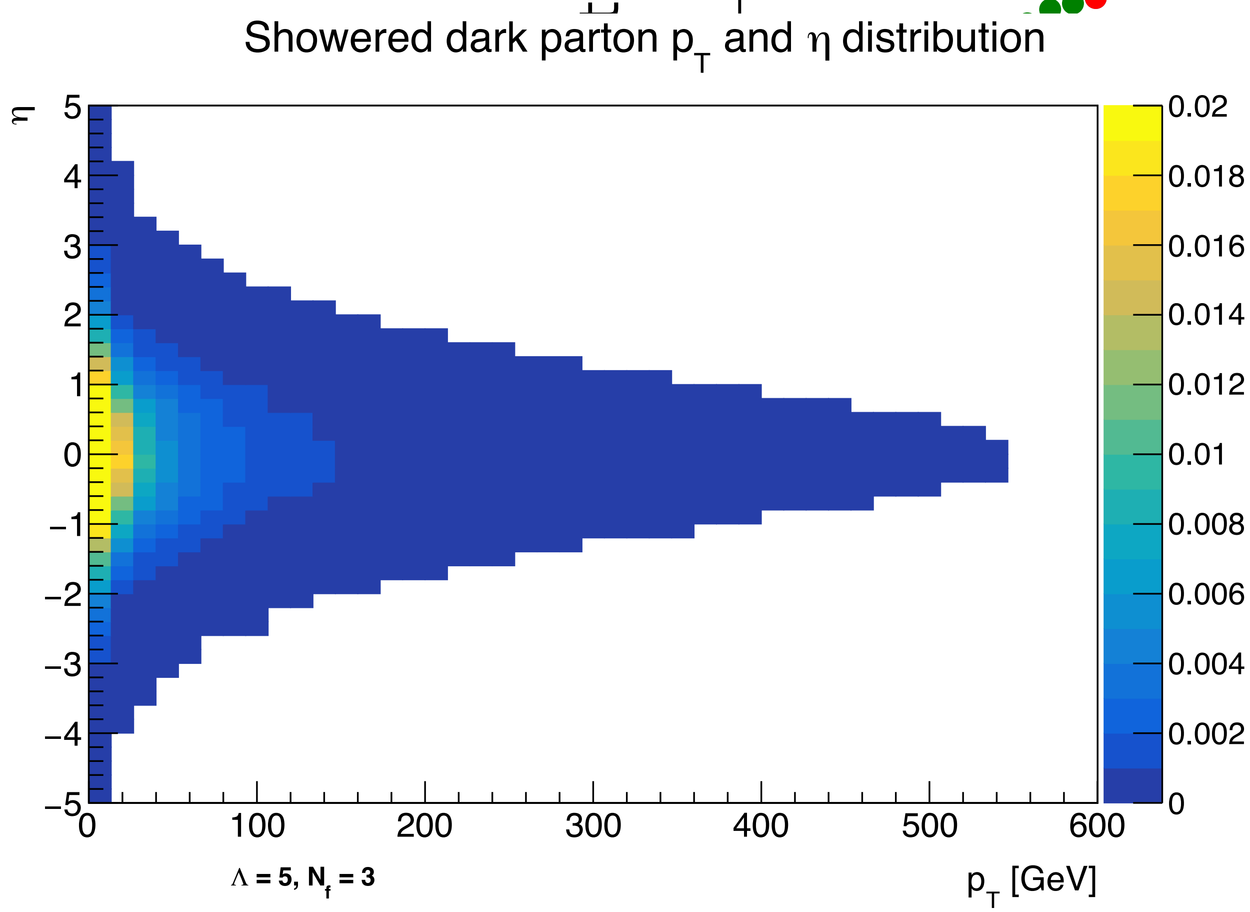
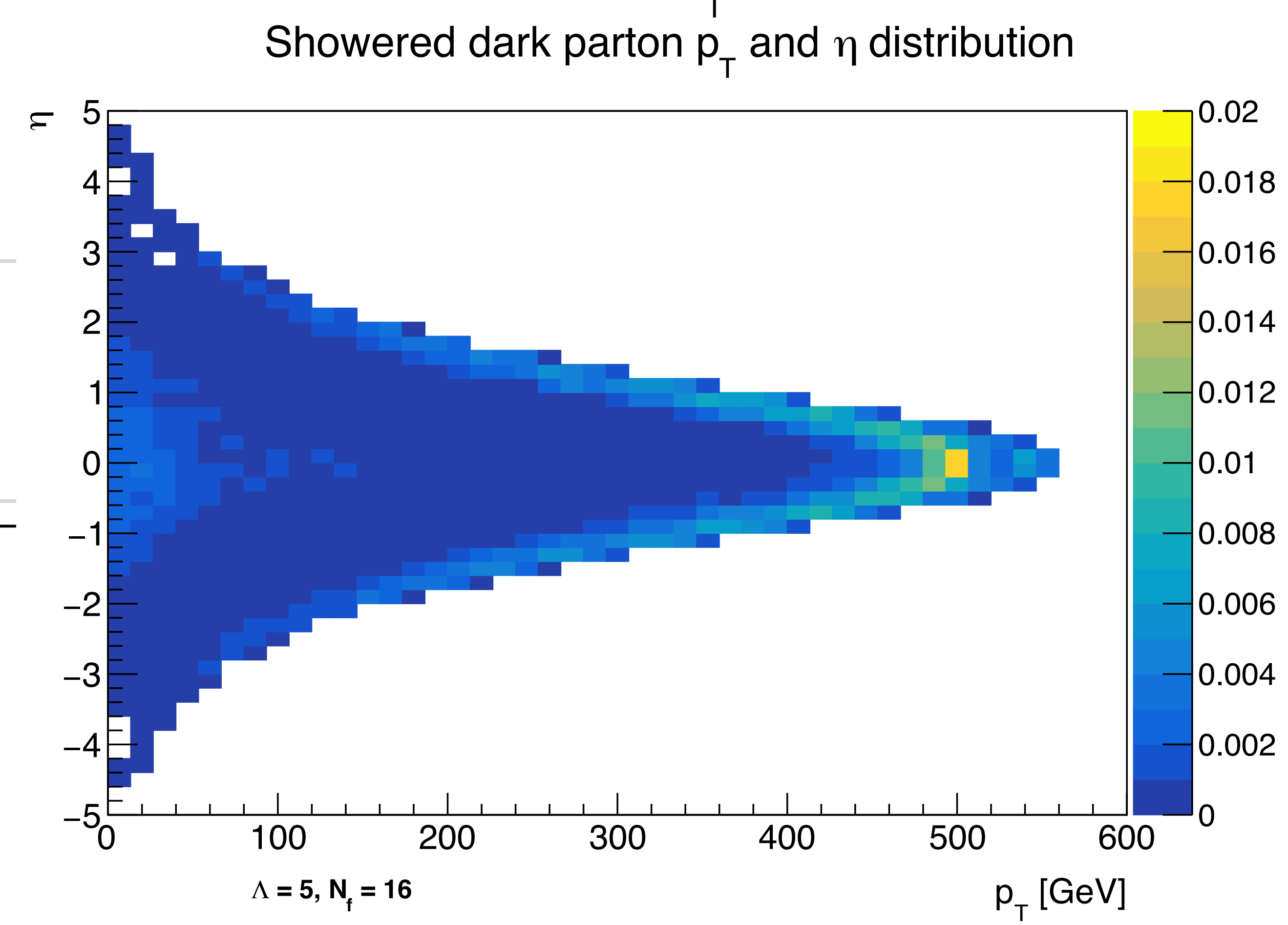
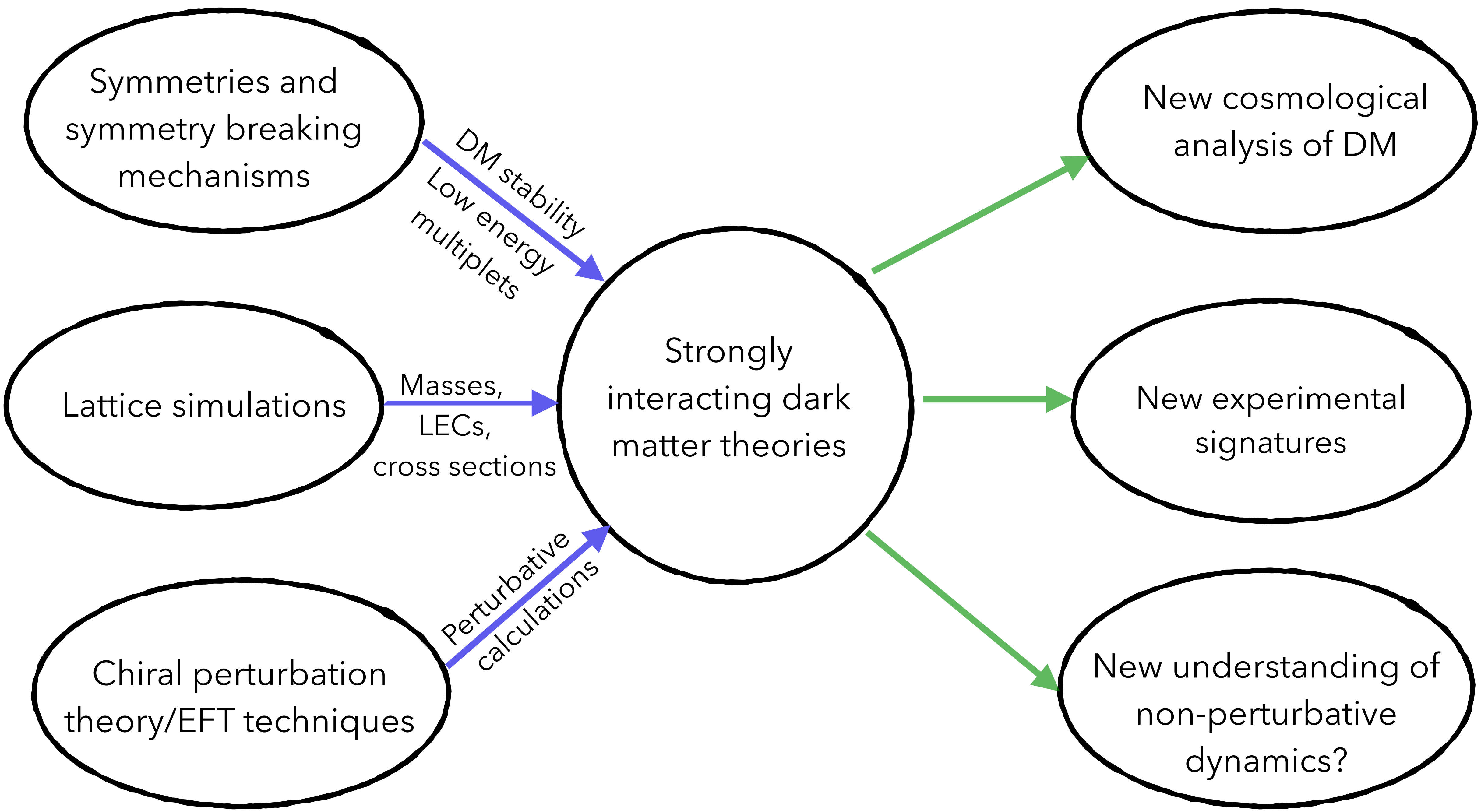






Conclusions

How to make systematic progress in the landscape of strongly interacting dark matter?

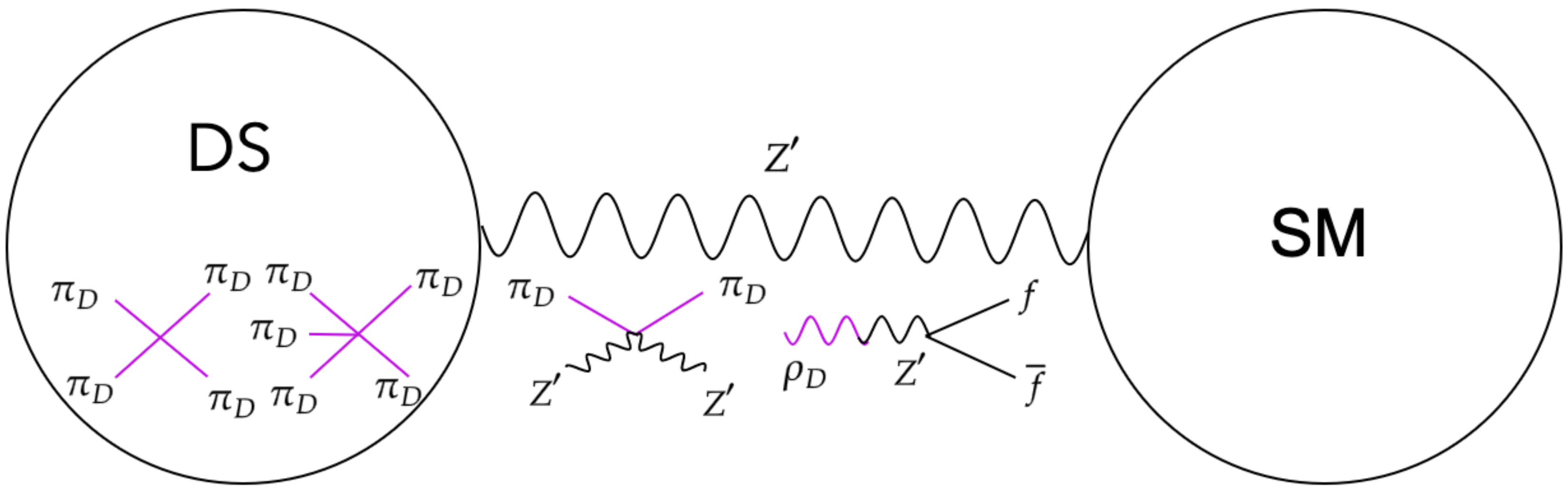


Thanks for listening

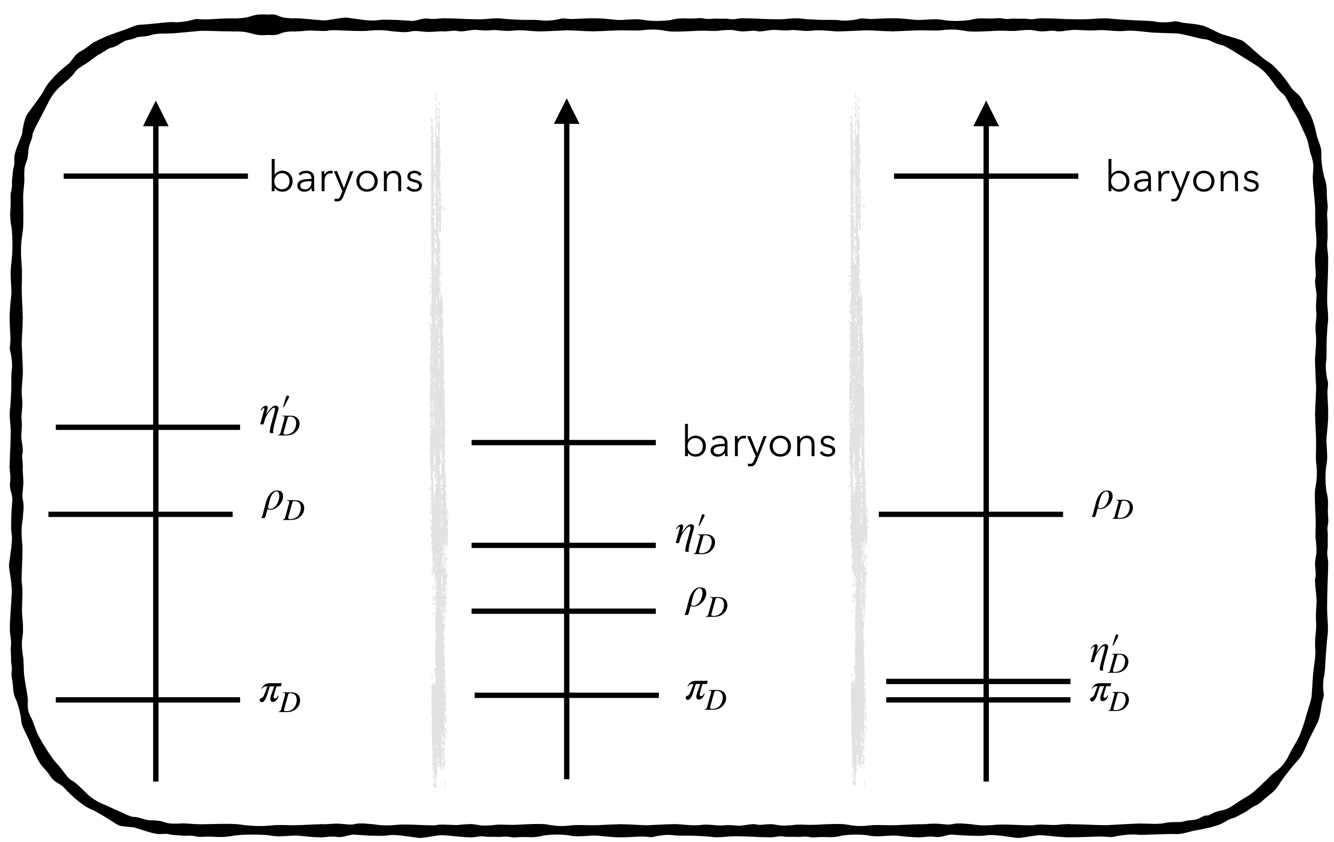
Questions?

Large N_C SIMPs

Diagram modified from Hochberg et al arXiv:1402.5143

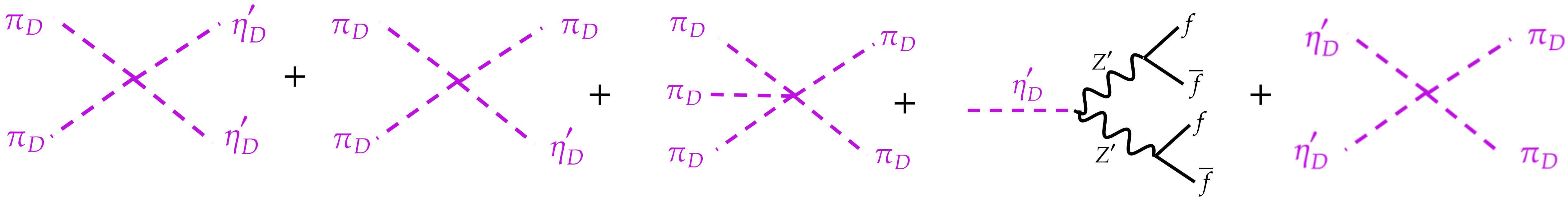


- At large N_C mass difference between π and the flavour singlet η' decreases
- Does η' play a role in relic density?

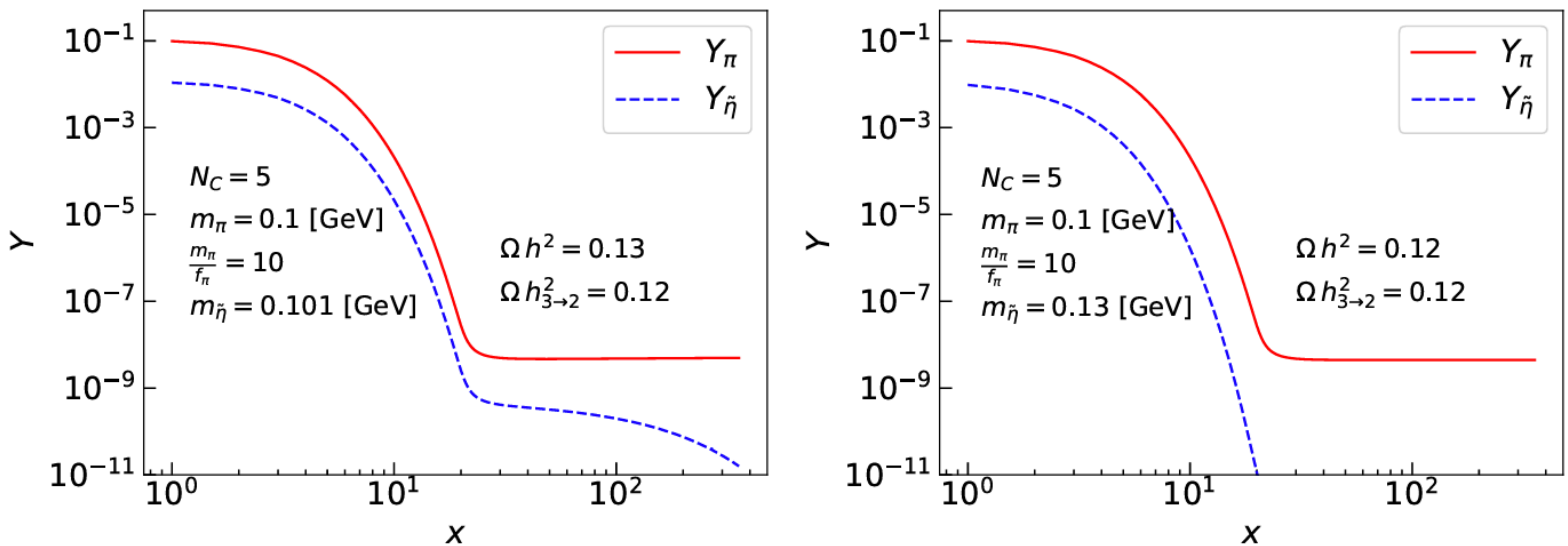


Large N_C SIMPs

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



Irrelevant $\Gamma_{\eta'} \gg 0$

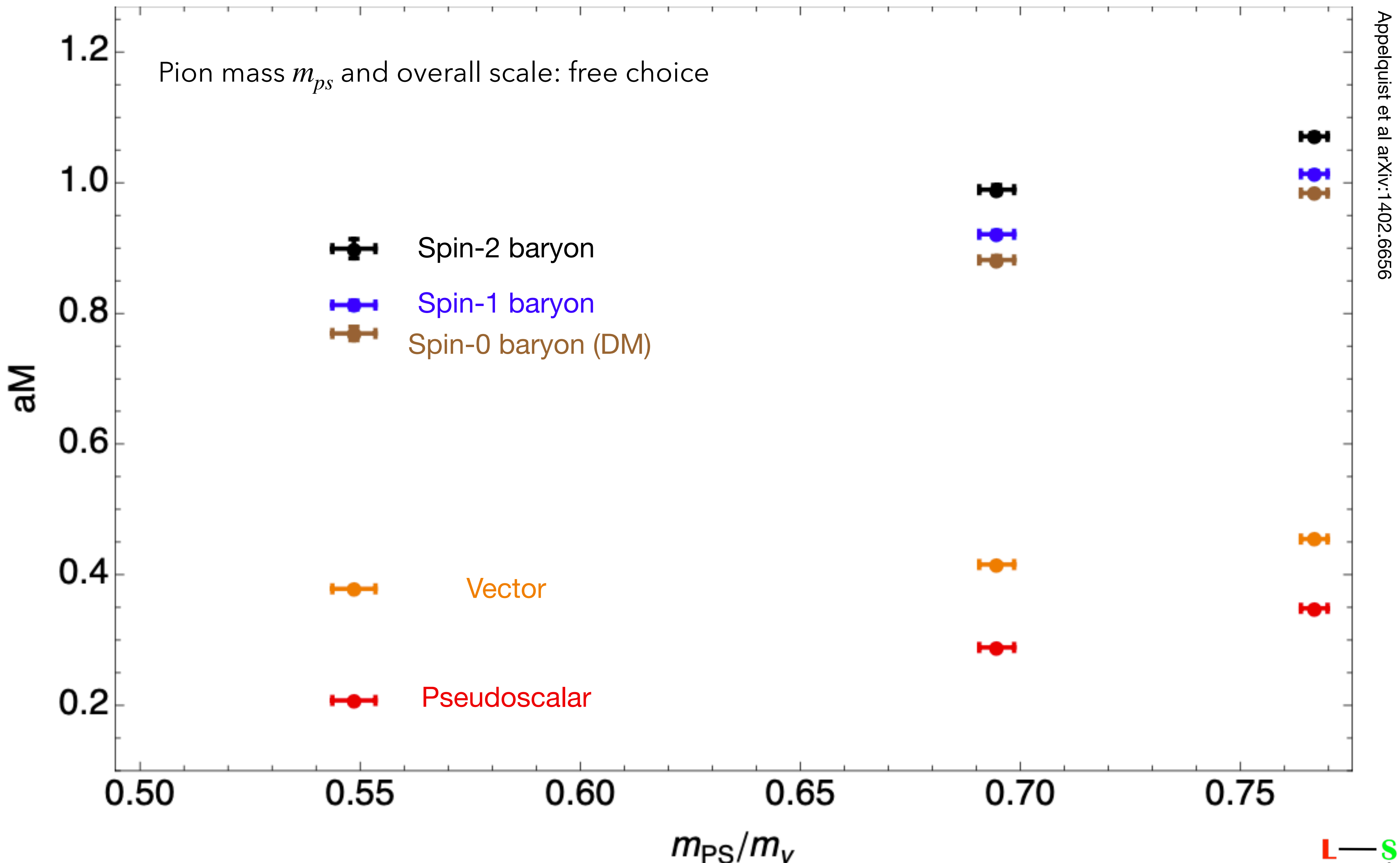


- Dark matter relic abundance can be affected if η'_D is very close to π_D

ÖPG Young Minds best thesis award

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

Stealth DM spectroscopy



Pseudo-real representations

S.K., A. Maas, S. Mee, M. Nikolic, J. Pradler, F. Zierler arXiv:2202.05191

- WZW needs at least five pions
- $SU(N_{c_D})$: coset $SU(N_{f_D})_L \times SU(N_{f_D})_R / SU(N_{f_D})$;

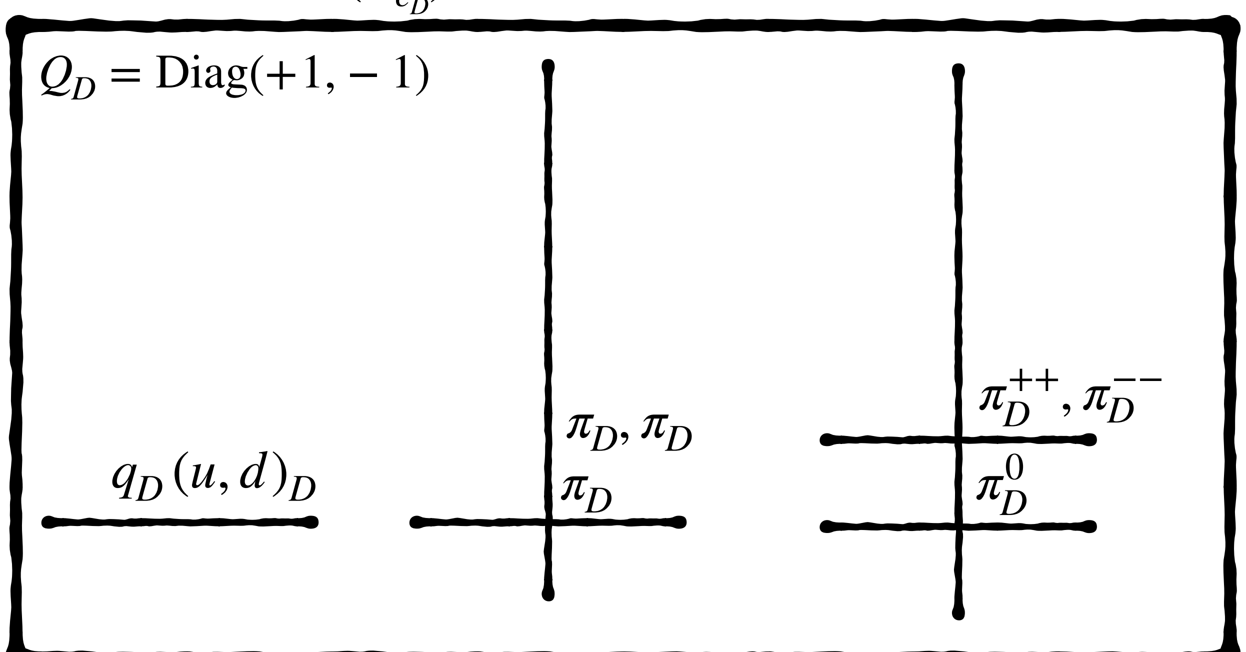
  $n_{\pi_D} = N_{f_D}^2 - 1 \rightarrow N_{f_D} = 3 \Rightarrow n_{\pi_D} = 8 \geq 5$

- $Sp(N_{c_D})$: coset $SU(2N_{f_D})/Sp(2N_{f_D})$

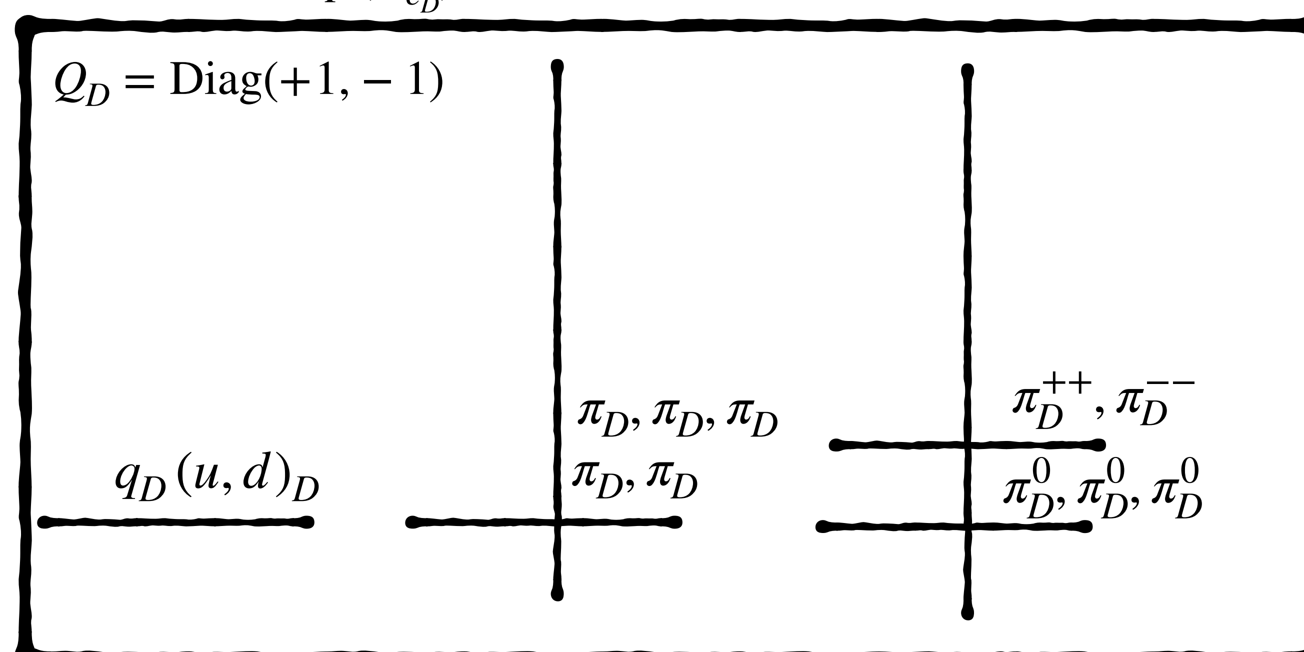
  $n_{\pi_D} = (2N_f + 1)(N_f - 1) \rightarrow N_{f_D} = 2 \Rightarrow n_{\pi_D} \geq 5$

- Coupling with Z′ preserves DM stability

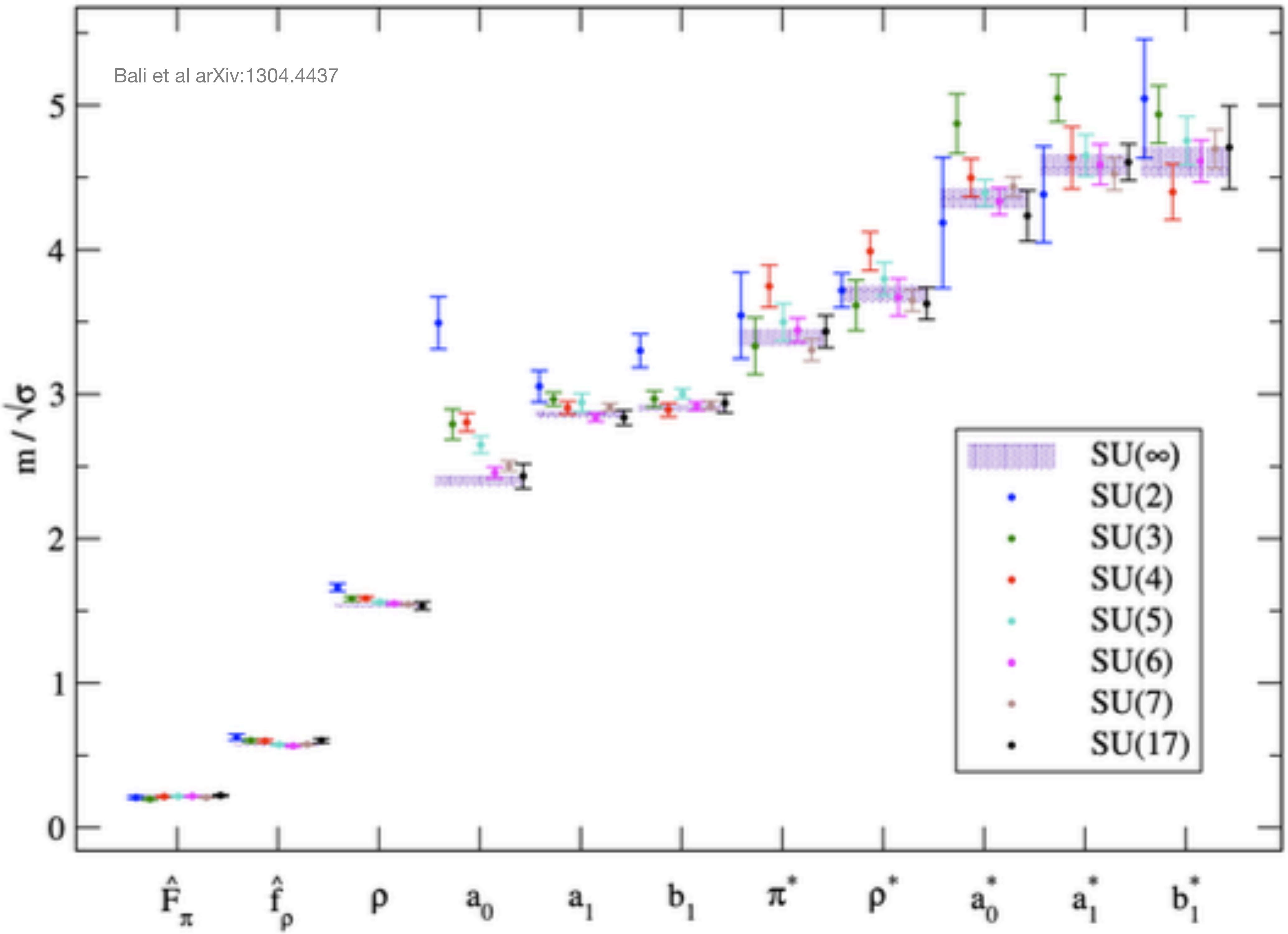
$SU(N_{c_D})$: 2 fermions in fundamental



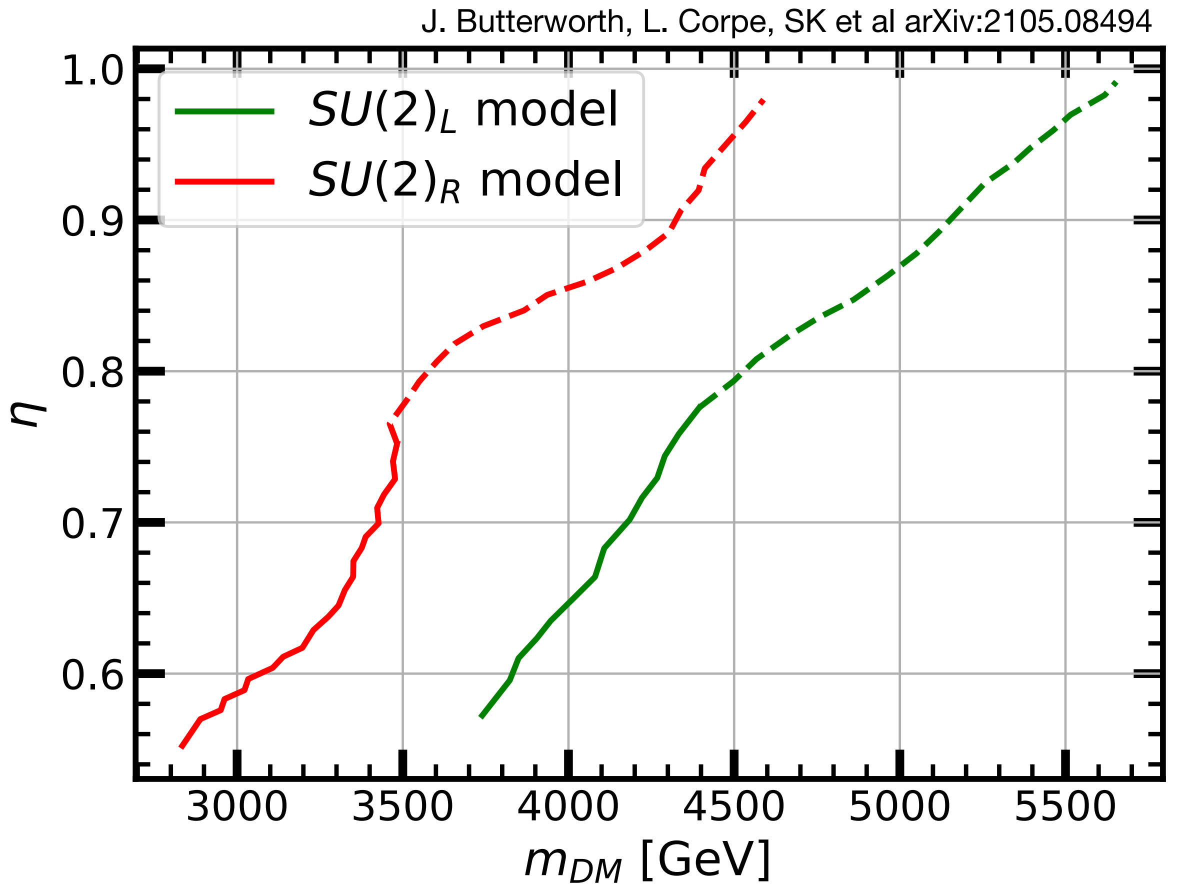
$Sp(N_{c_D})$: 2 fermions in fundamental



$SU(N_c)$ lattice simulations

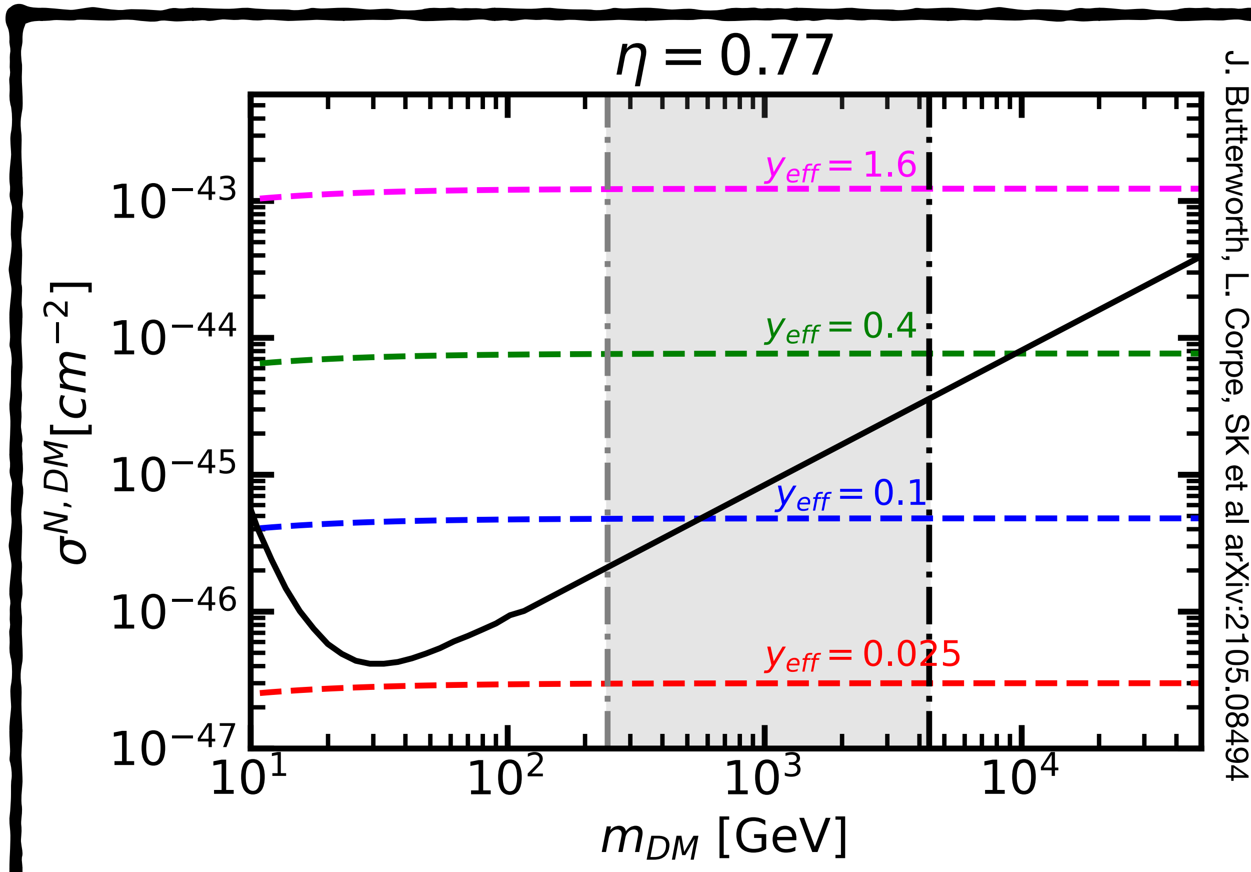


Constraints



See also Appelquist et al, arXiv:1503.04203

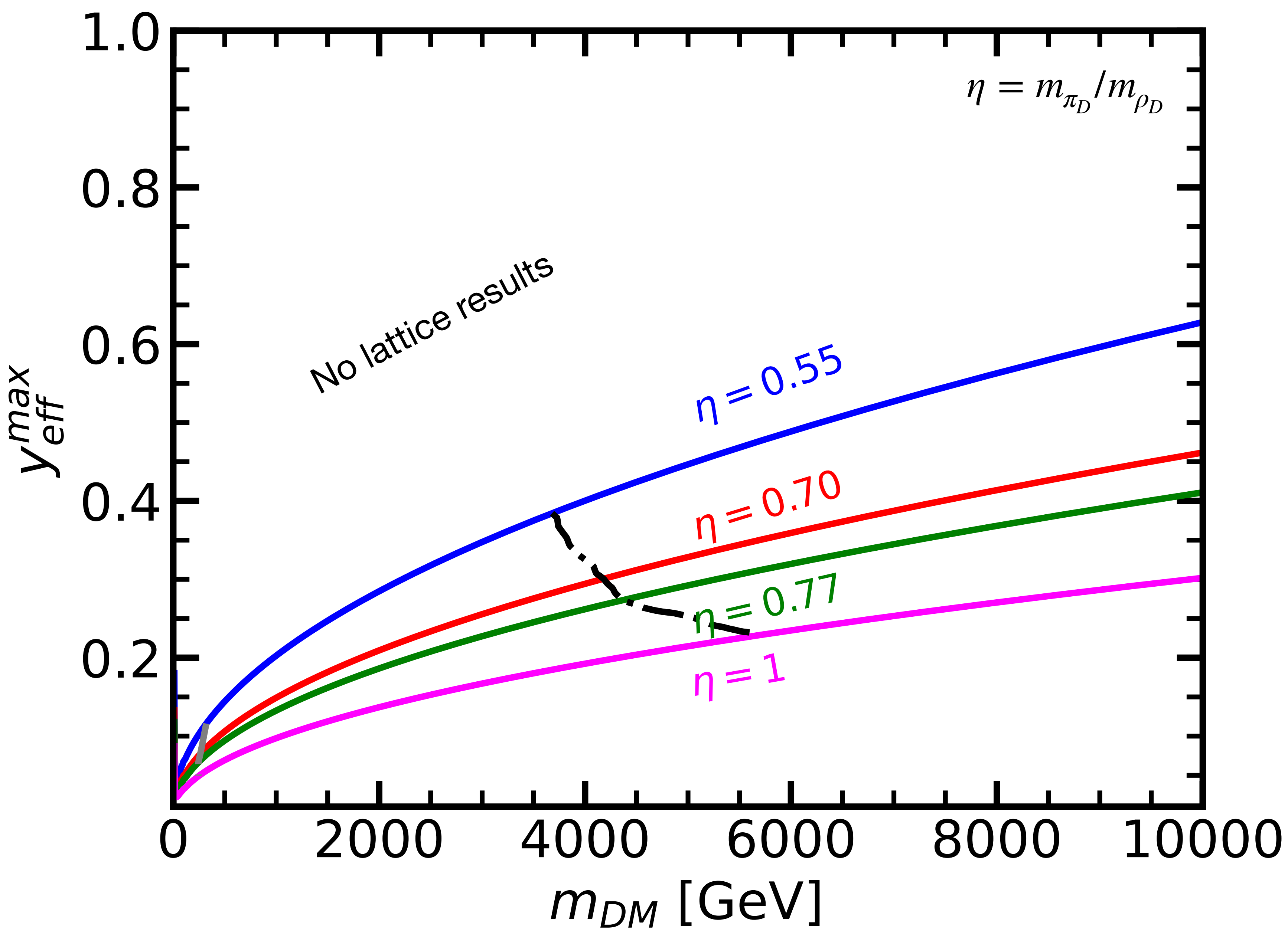
- Analysis with the help of CONTUR; constraints from SM precision measurements
- LHC exclusions together with the lattice results push the dark matter mass limits to multi-TeV mass range



- Direct detection limits push dark quark Yukawa coupling to lower values

Higgs mediators

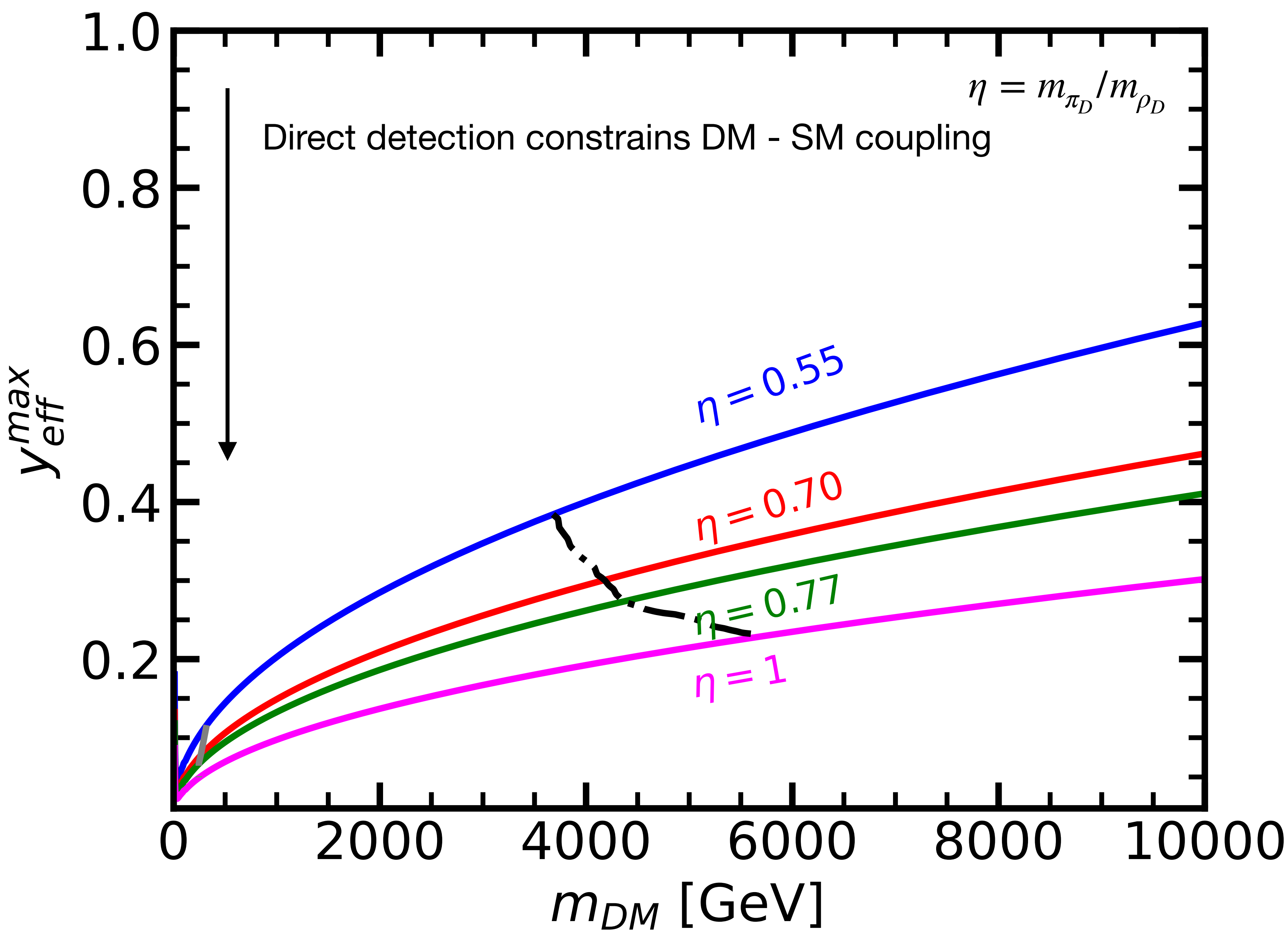
J. Butterworth, L. Corpe, **S.K.** et. al. arXiv:2105.08494

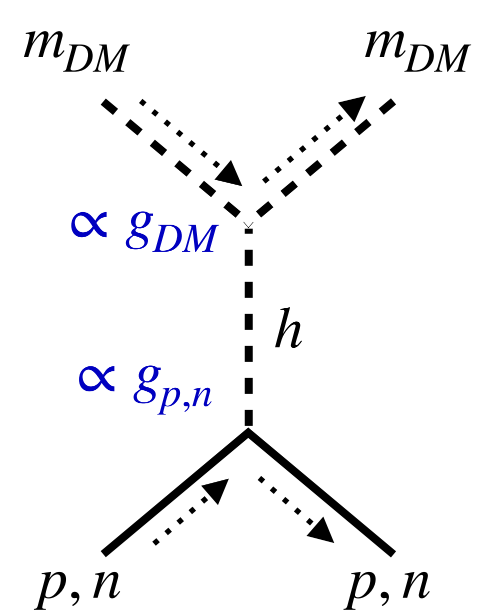


Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Higgs mediators

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





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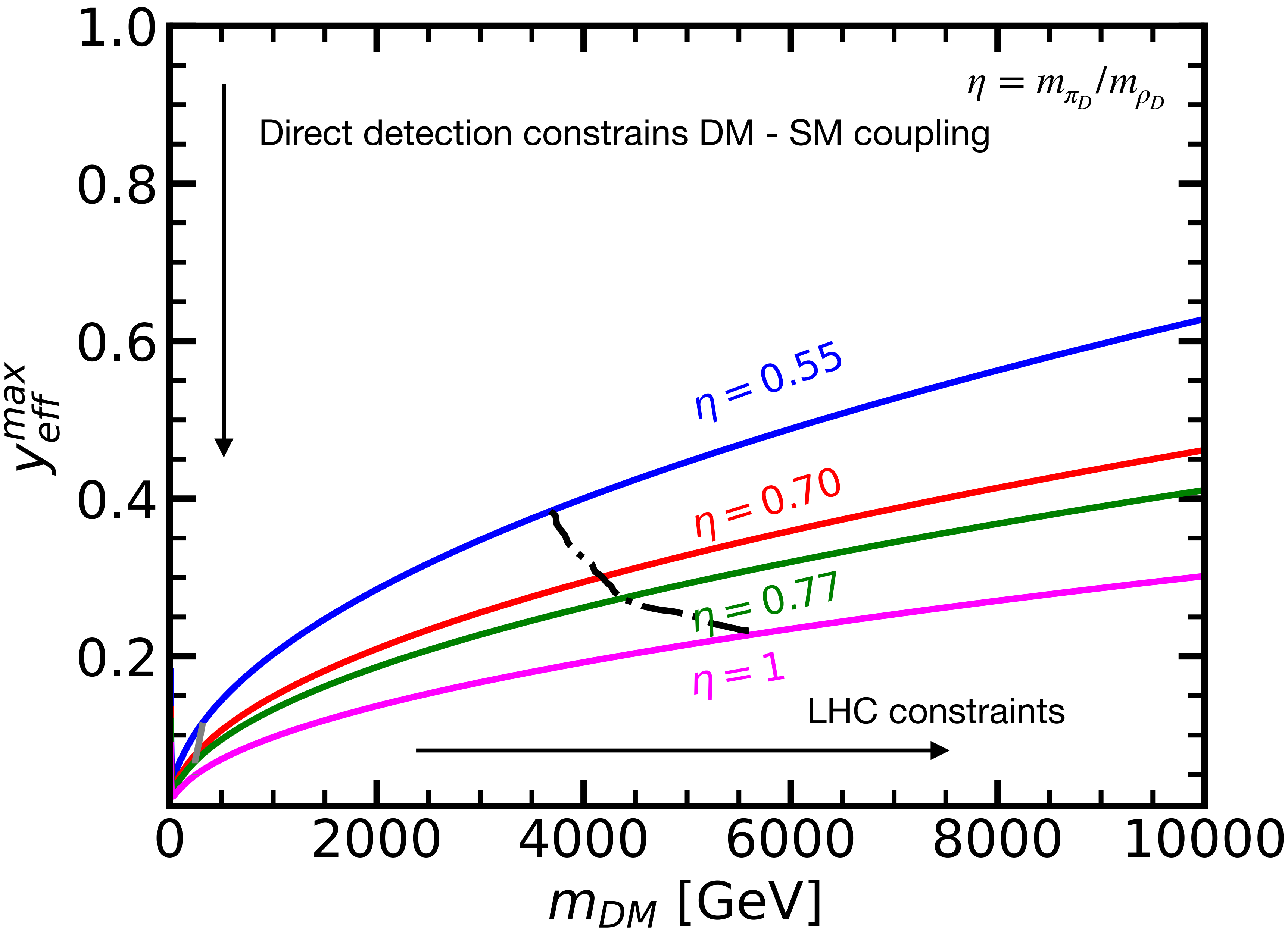
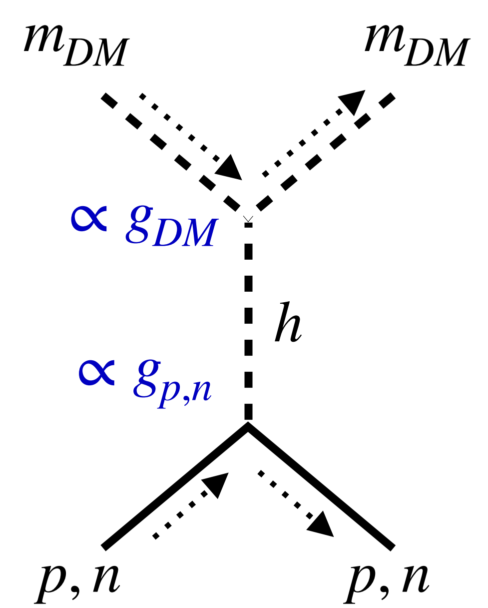
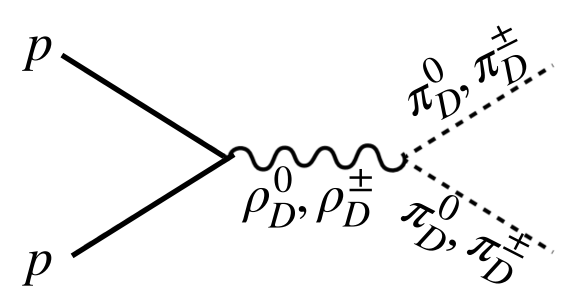


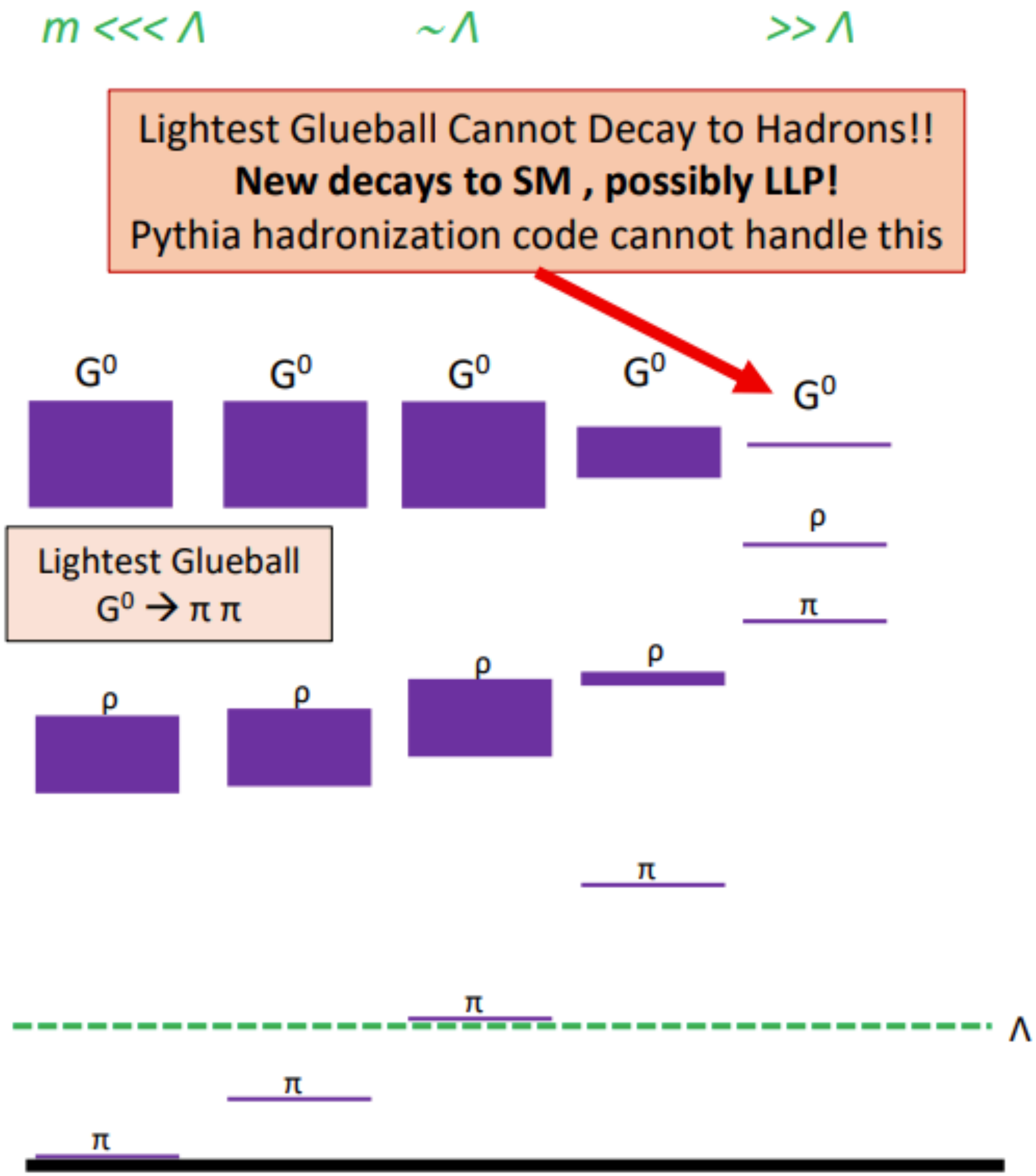


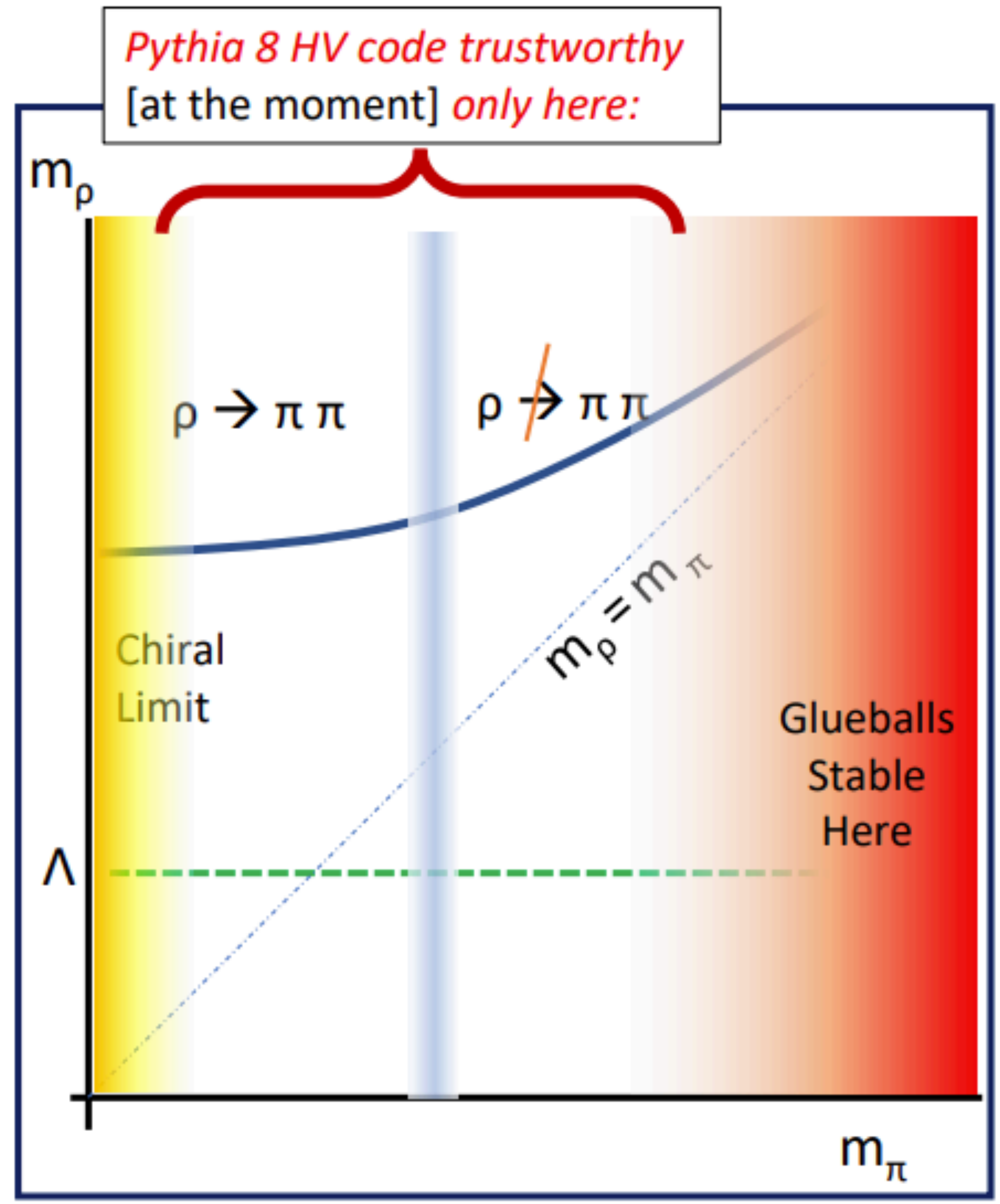


Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Sketch QCD spectrum

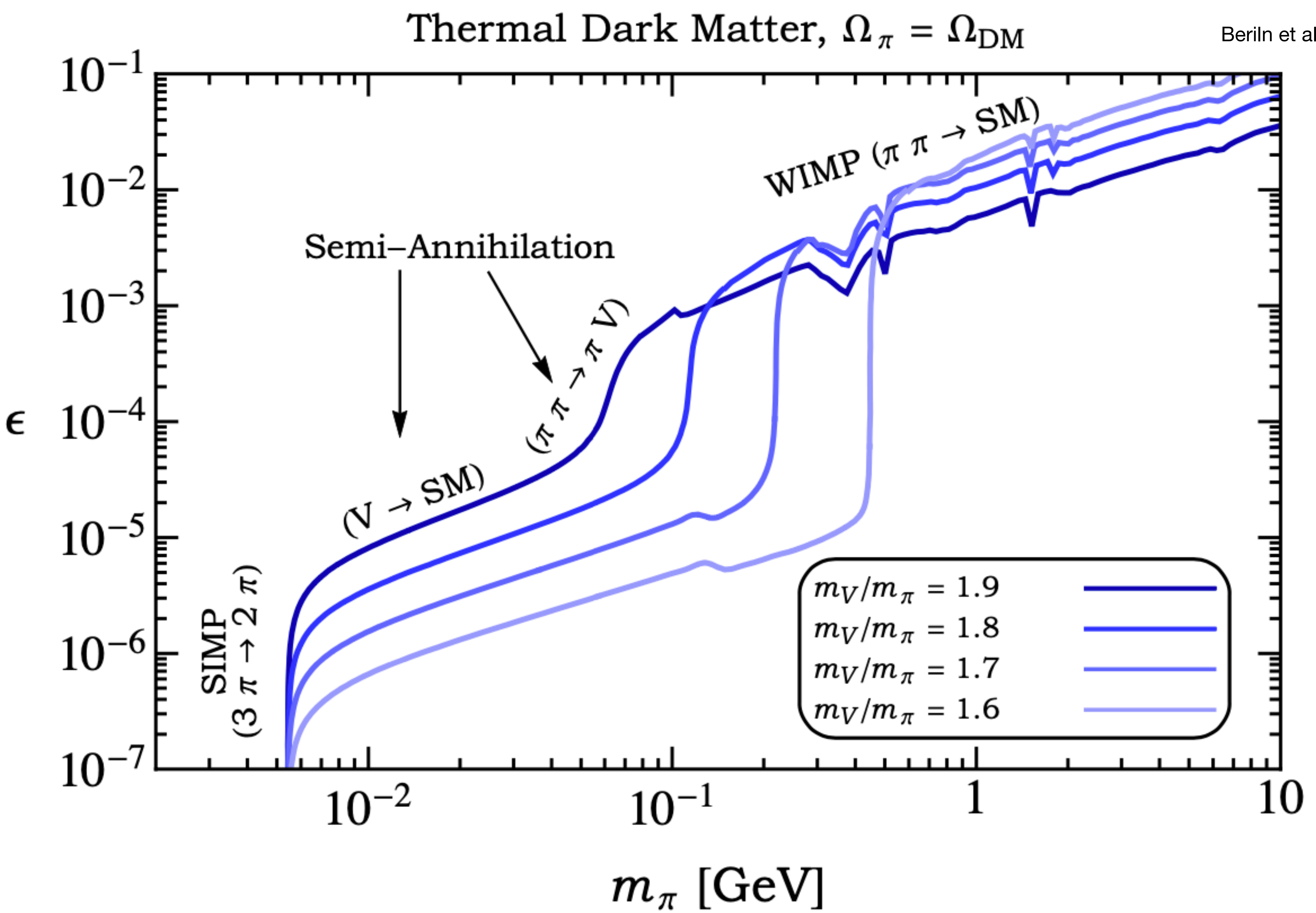
From M. Strassler's talk





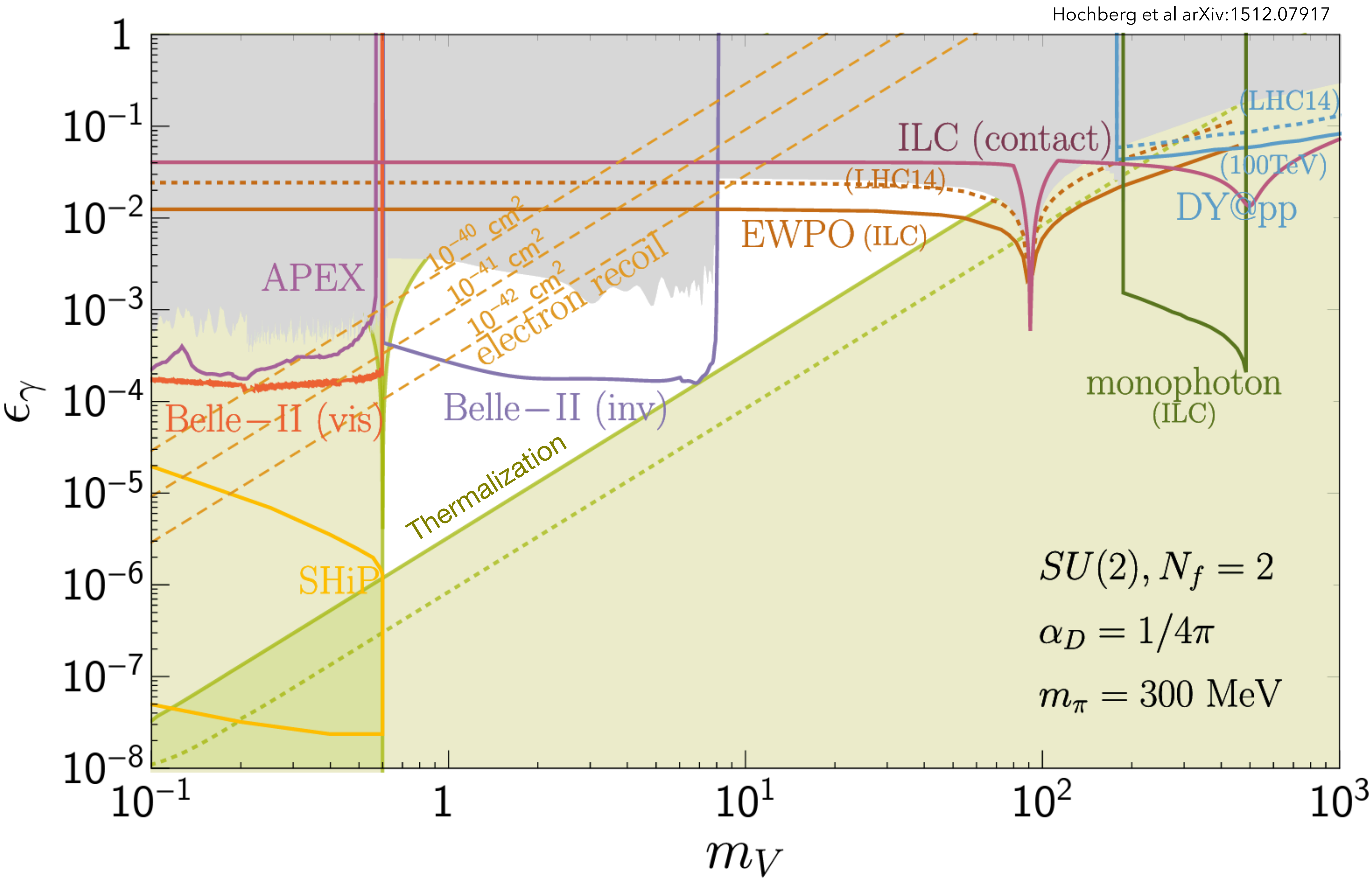
SU(N) theories relic density mechanisms

Beriln et al arXiv:1801.05805



- A number of possibilities to obtain relic density exists

SIMP future prospects



$U(1)_D$ embedding well understood

See also Hochberg et al. arXiv:1512.07917

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

- 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