Exploring strongly interacting dark matter

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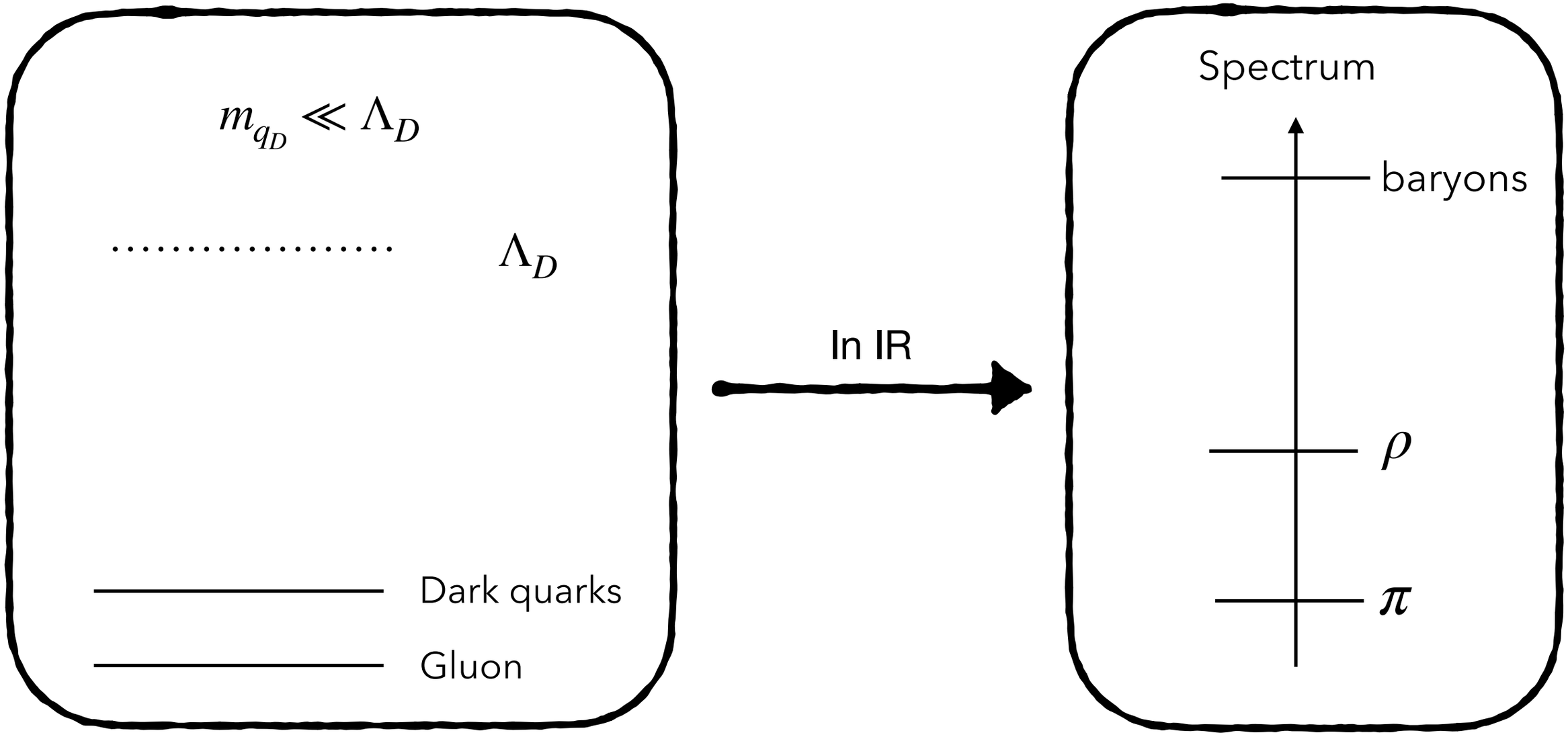
UNI GRAZ

Can dark matter be composite instead of elementary?



Can dark matter be composite instead of elementary?

- Composite Higgs: dark sector (DS) scale related to SM

Nussinov Phys.Lett.B 165 (1985) 55-58, Chivakula et al, Nucl.Phys. B329 (1990) 445, Hietanen et al., arXiv:1308.4130, Cacciapaglia et al arXiv:2002.04914

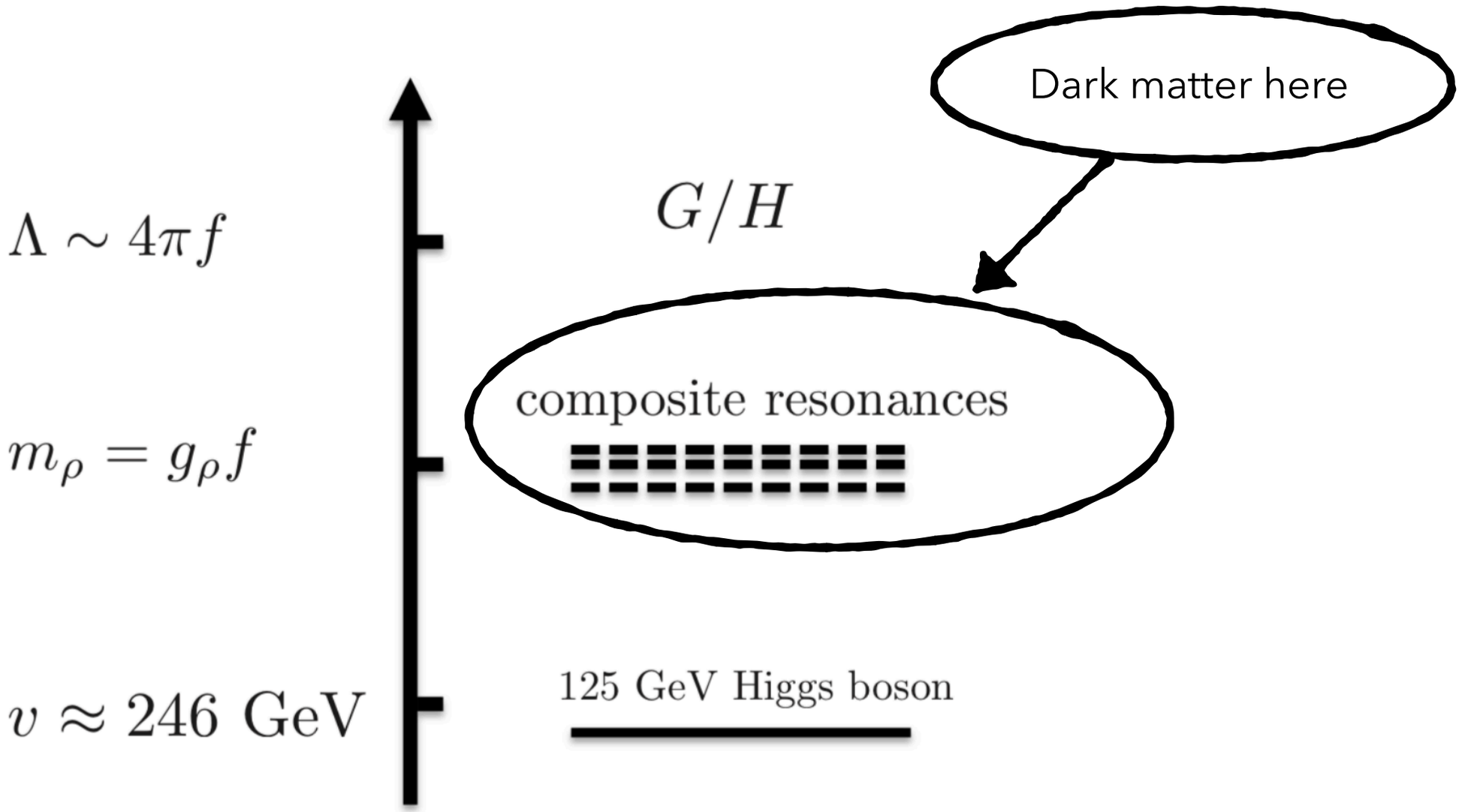


Figure from Liu et. al. arXiv:1904.00026

Strongly interacting dark matter

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

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:1610.10068 , 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 previously unexplored signatures

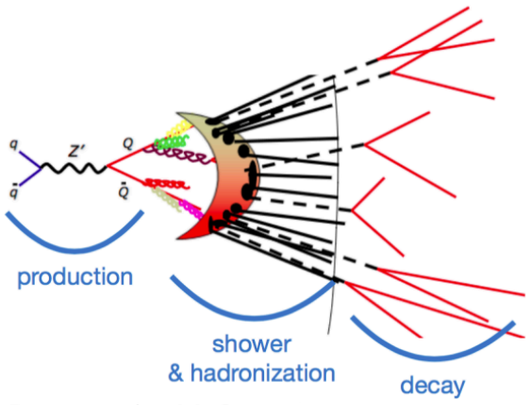
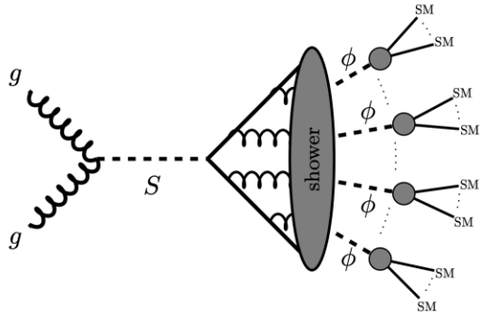
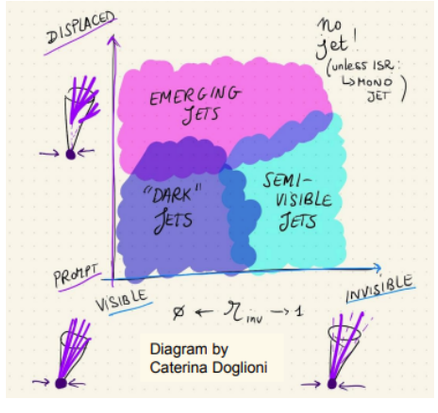


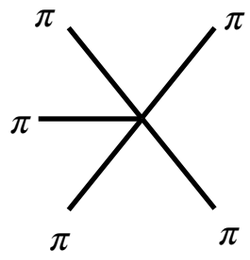
Diagram by M. Strassler

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

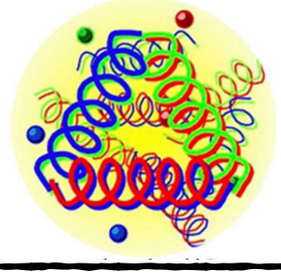


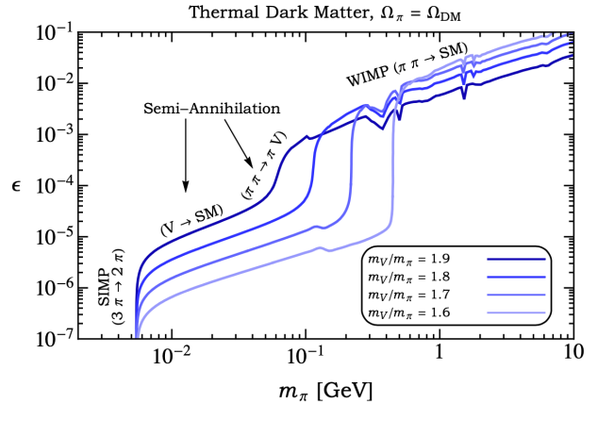


New dark matter candidates



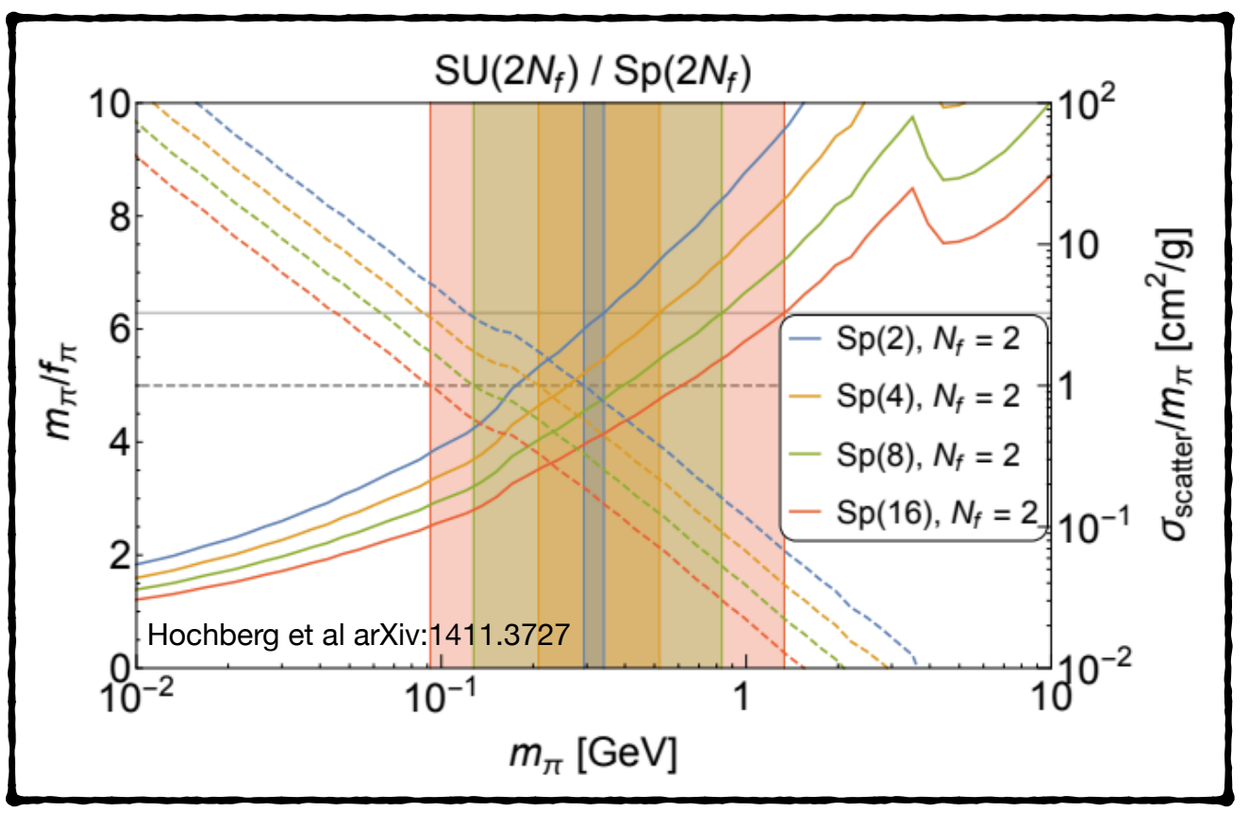
Hochberg et al arXiv:1512.07917
Kribs et al arXiv: 1604.04627
Cline et al arXiv:2108.10314
Beriln et al arXiv:1801.05805

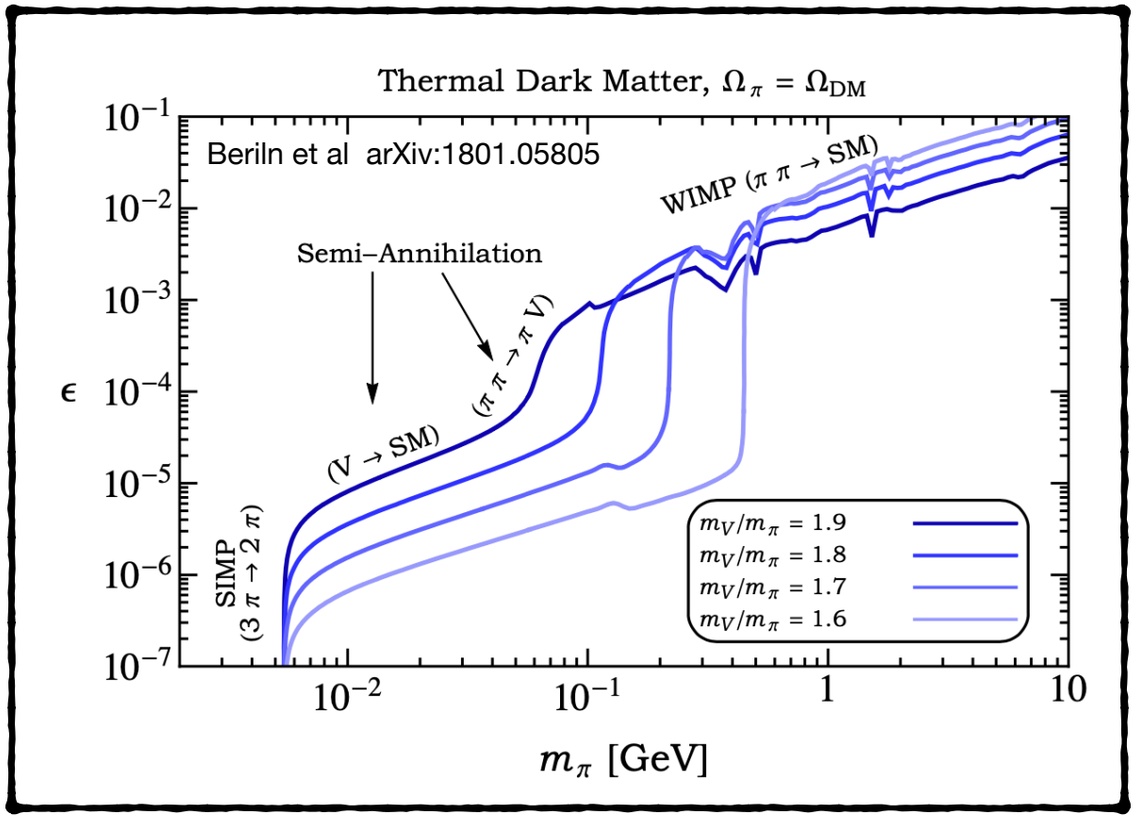




Strongly interacting “dark matter”

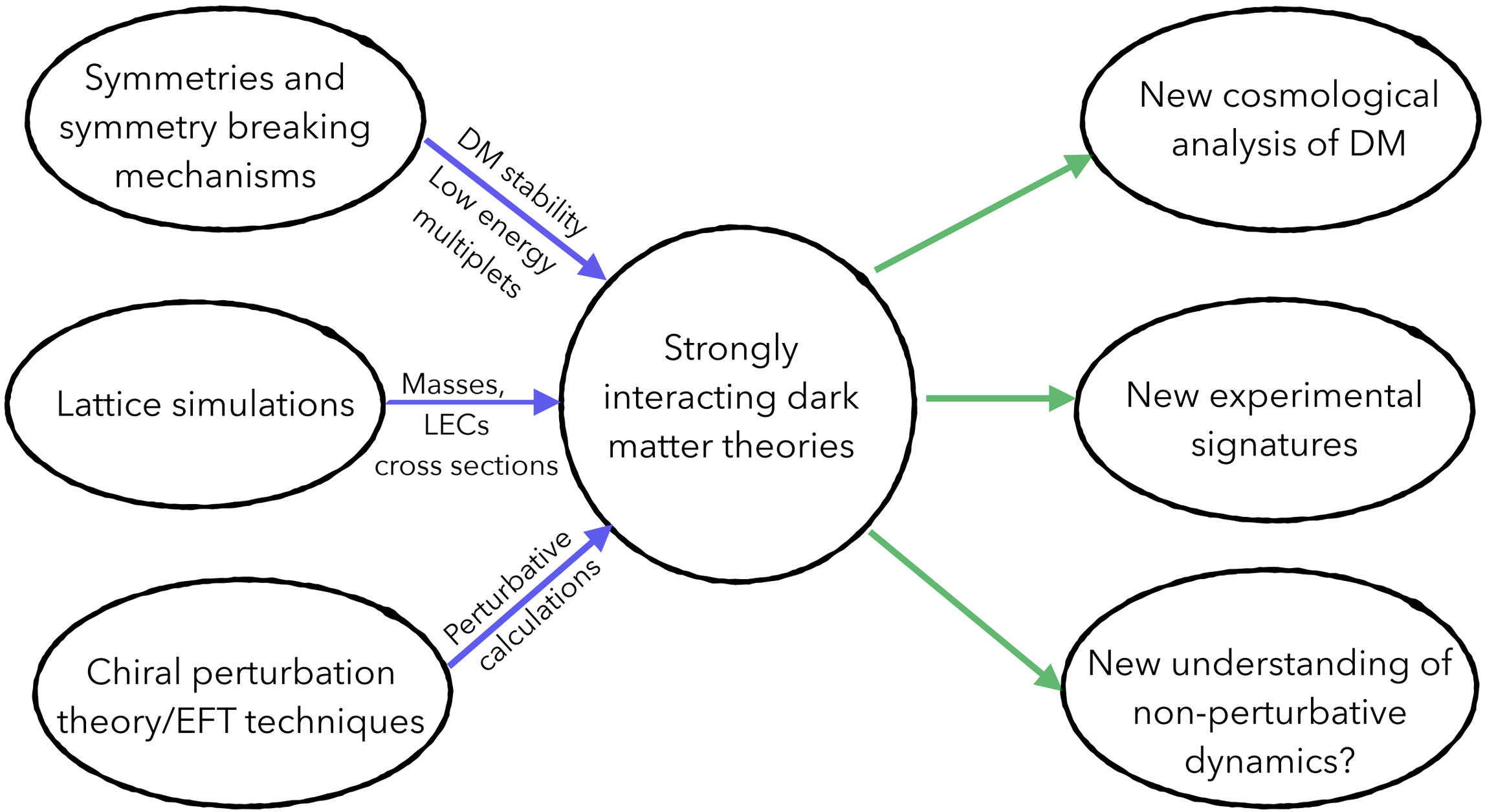
- We need a stable or extremely long-lived state or multiplet
  - Baryons: stable by virtue of baryon number
  - Pions: stabilised by careful model building
- We need to understand relic density mechanisms and detection prospects
  - Pions: several mechanisms possible including cannibalisation and semi-annihilation
  - Baryons: need to generate some dark matter - antimatter asymmetry to keep ‘leftover’ baryons





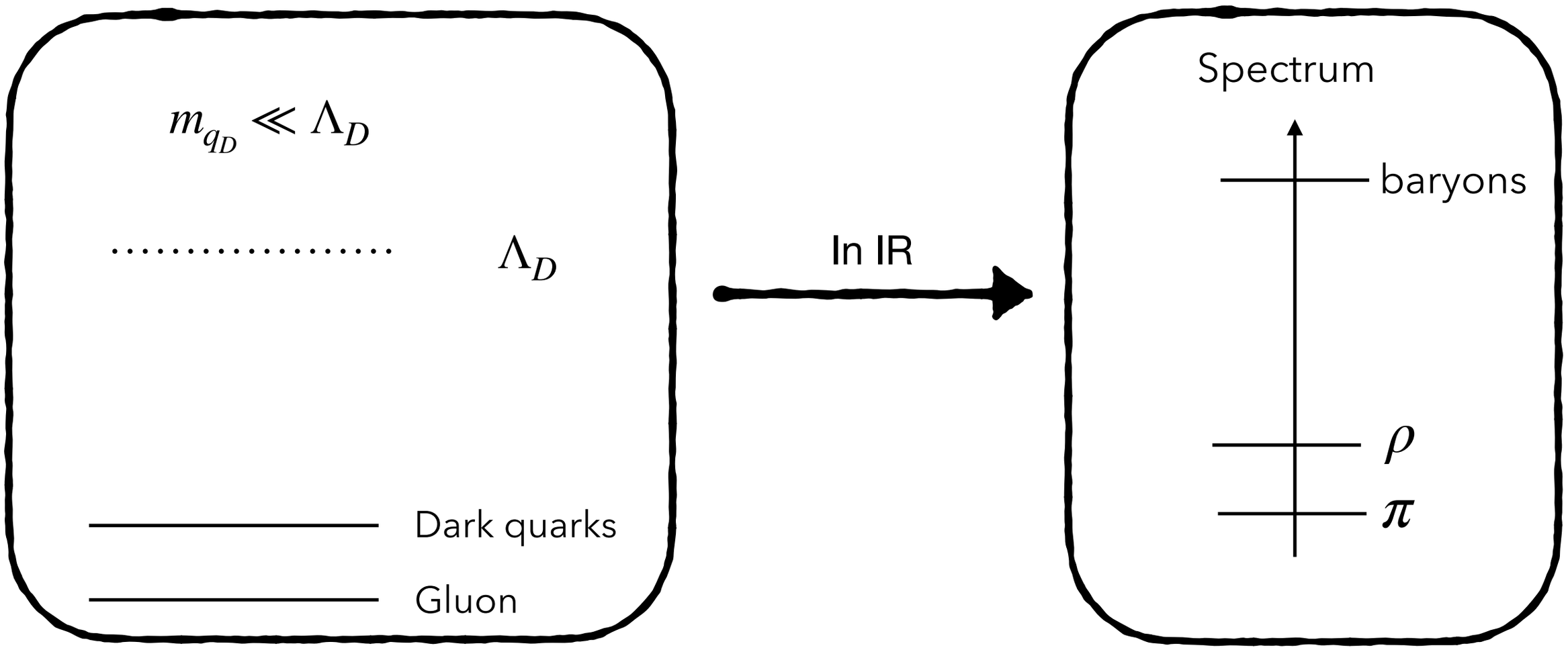
Strongly interacting theories: pathways

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



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

Strongly interacting theories: composition



UV physics contains

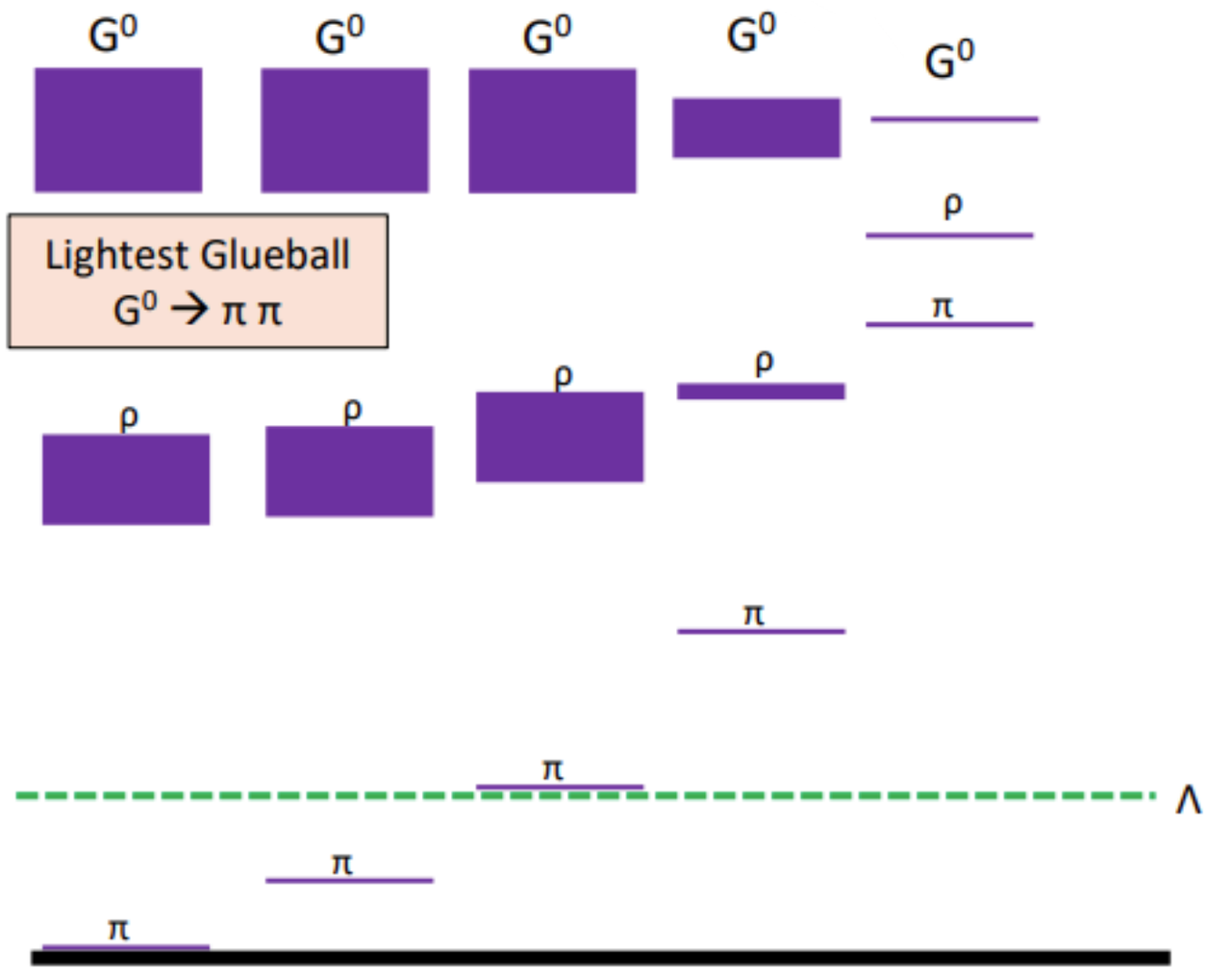
- Gauge fields (gluons)
- Matter fields i.e. Dirac/Majorana fermions, Scalars (in representation N_r)
- This talk: Dirac fermions in fundamental rep

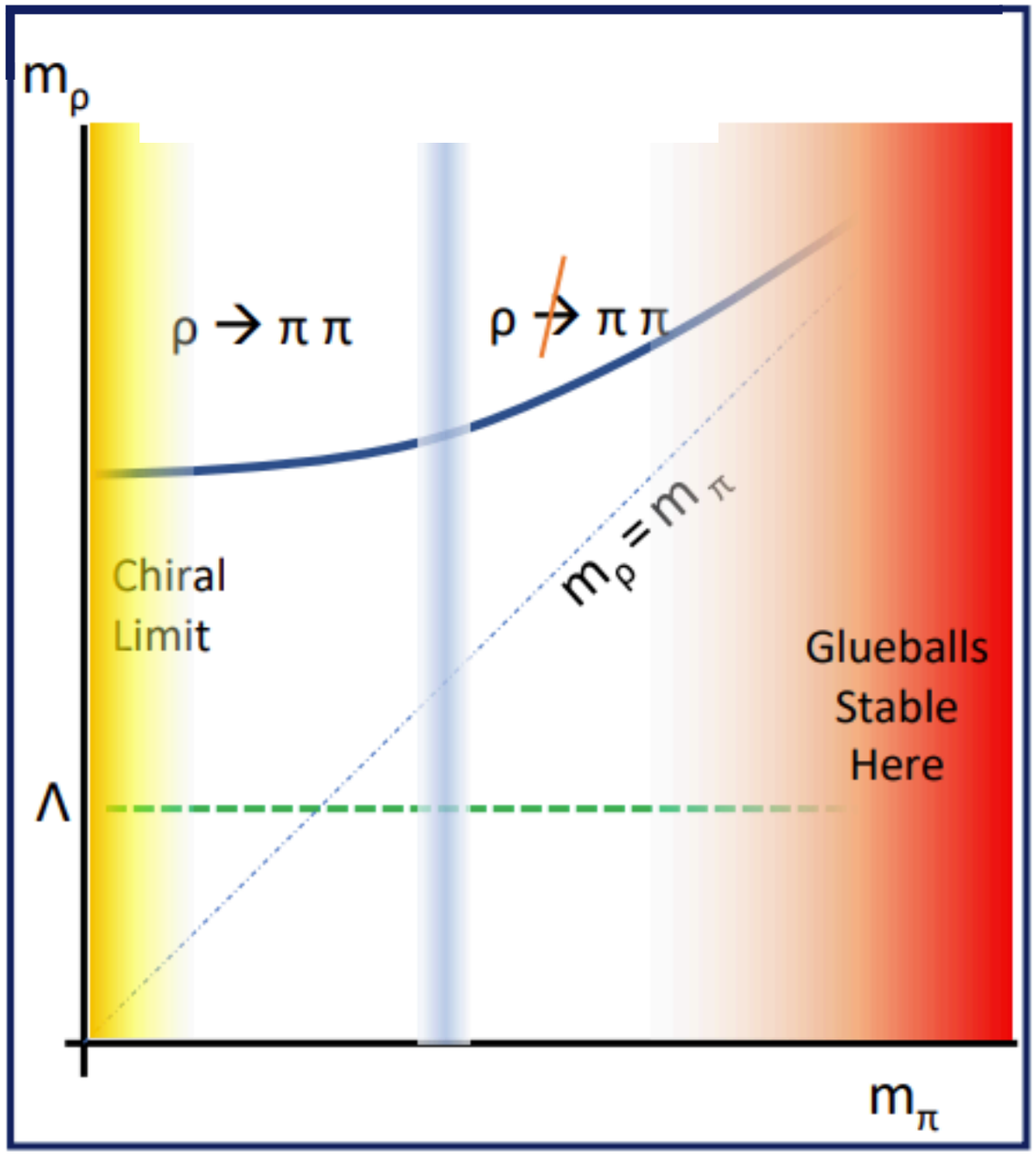
- Two discrete parameters N_{c_D}, N_{f_D}
- Two continuous parameters $m_{q_D}, \alpha_D(\mu)$ (UV)
  - $\Lambda_D, m_{\pi_D}/\Lambda_D$ or $m_{\pi_D}, m_{\pi_D}/m_{\rho_D}$ (IR)
- $N_{c_D} = 2$ and/or $N_{f_D} = 1$ special cases

Sketch QCD spectrum: m_π/Λ_D effect

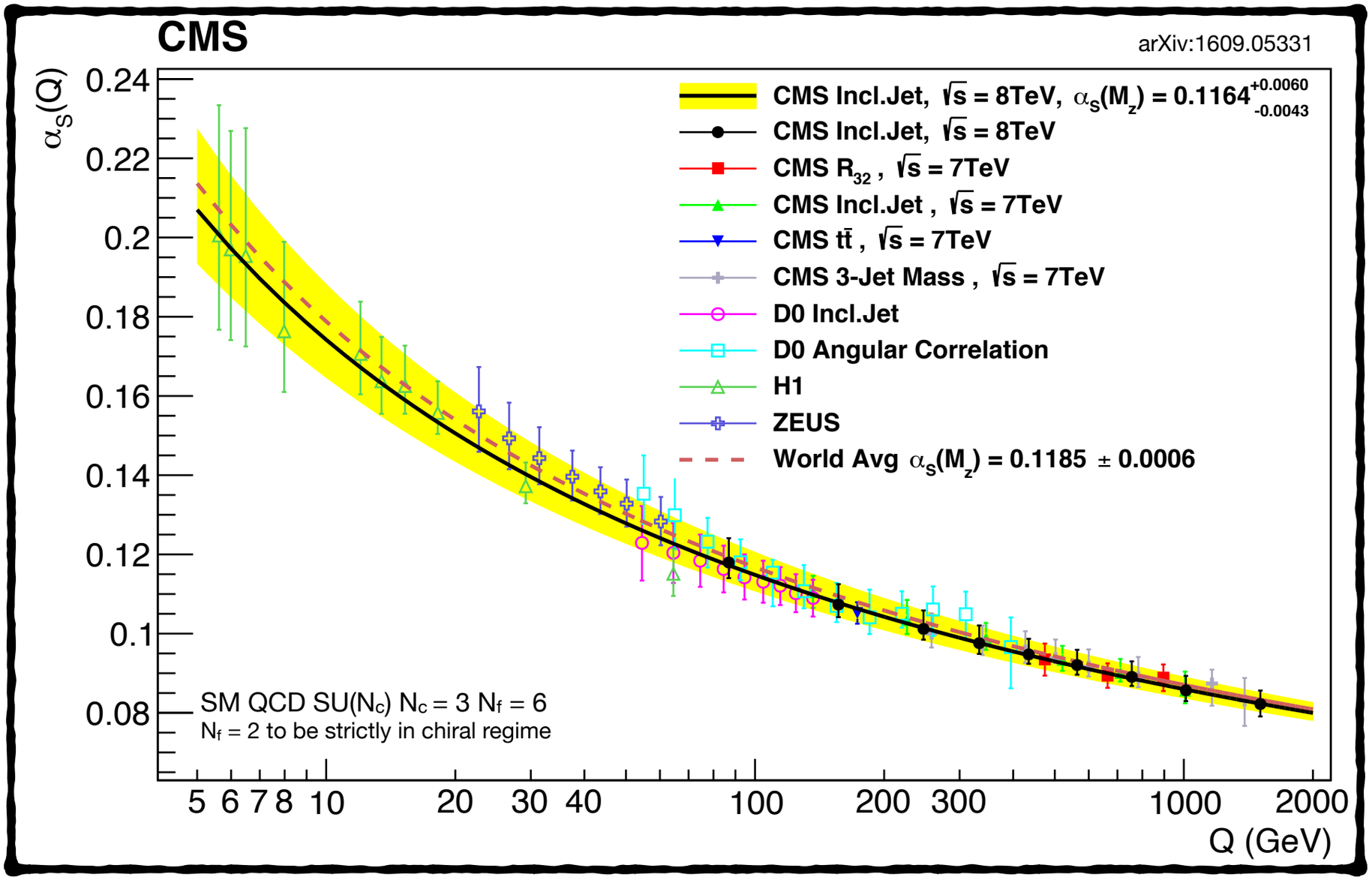
From M. Strassler's talk

$m_{q_D} \ll \Lambda_D$ $\quad$ $m_{q_D} \sim \Lambda_D$ $\quad$ $m_{q_D} \gg \Lambda_D$



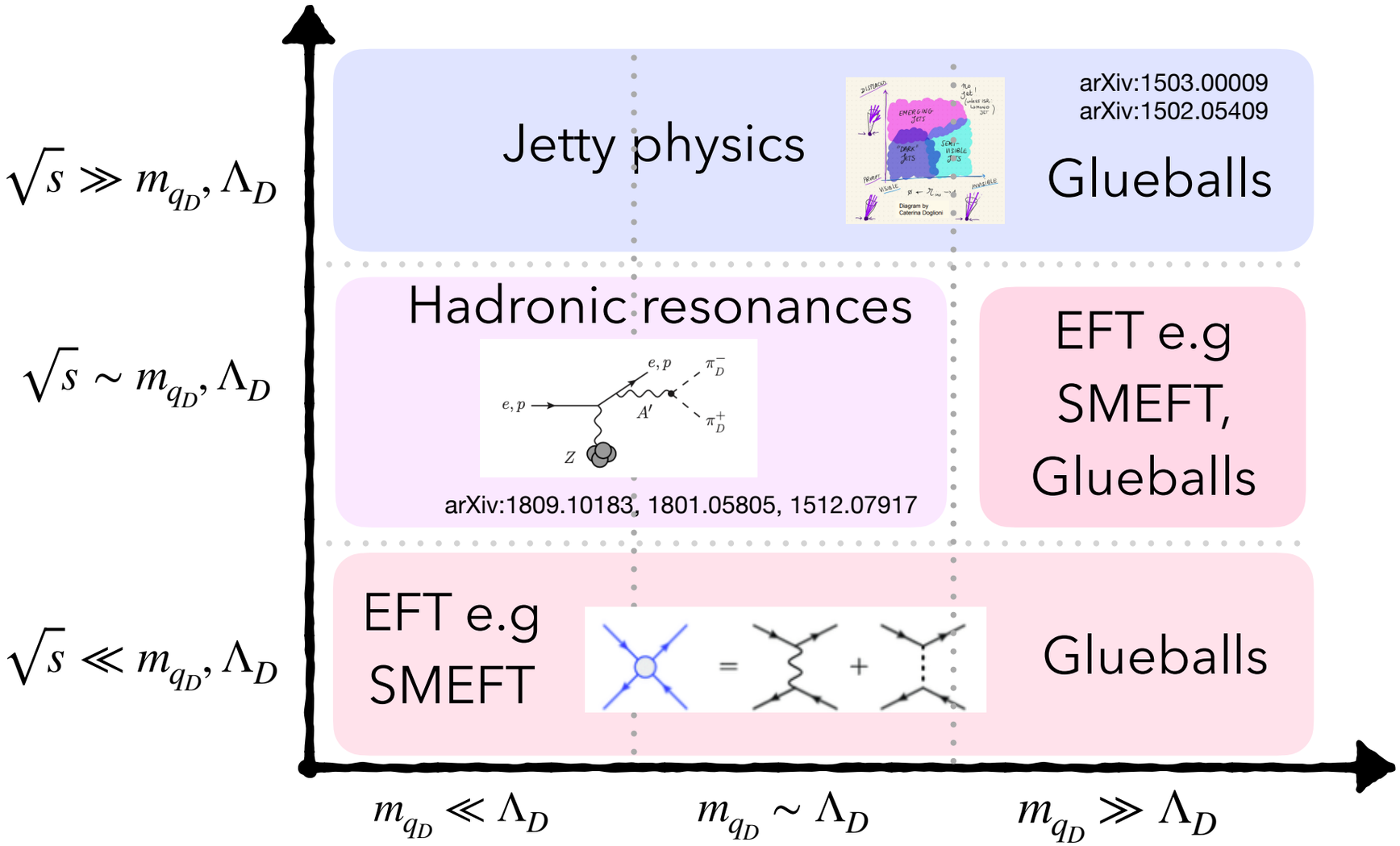


Effect of N_{f_D}, N_{c_D}



- QCD like theories: asymptotically free theories and in chirally broken phase (dark pions are Goldstones; chiral perturbation theory expected be valid)
- Choose N_{c_D}, N_{f_D} such that asymptotic freedom is achieved

Strongly interacting theories: signatures



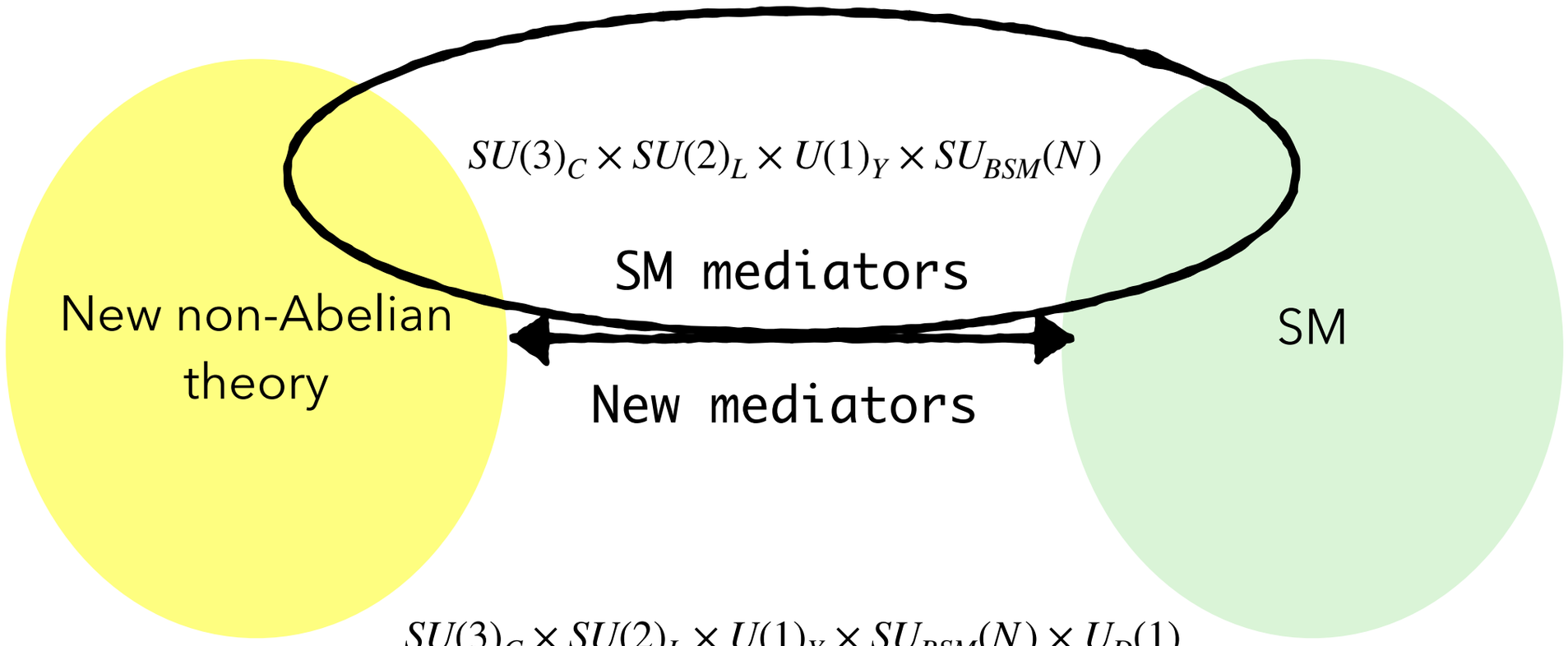
For an improved understanding of jetty physics see Snowmass darkshowers project arXiv:2202.05191

For a review c.f. arXiv:1604.04627

N.B.: things like SUEP are not strictly signatures of QCD-like theories

New non-Abelian theory

Portal phenomenology - I



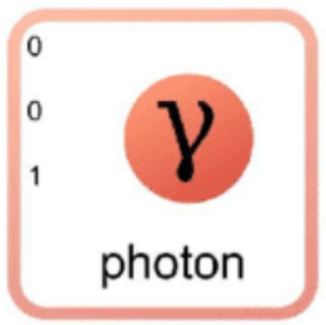
$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU_{BSM}(N) \times U_D(1)$$

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

SM mediators

Appelquist et al arXiv:1402.6656

Relevant if DS has SM color charges



Lowest dimensional operators:

- magnetic dipole (5)
- charge radius (6)
- polarizability (7)

Similar considerations for W/Z mediators, suppressed by masses

Most relevant interaction if constituents have Yukawa couplings

- Theory with $N_{c_D} = 4, N_{f_D} = 4$; contains scalar baryon
- Dark quarks get part of their masses from EWSB and partly vector-like

Model details

Field content

Field	$(SU(N_D), SU(2)_L, SU(2)_R)$
F_L	$(\mathbf{N}, \mathbf{2}, \mathbf{1})$
$\hat{F}_L$	$(\overline{\mathbf{N}}, \mathbf{2}, \mathbf{1})$
F_R	$(\mathbf{N}, \mathbf{1}, \mathbf{2})$
$\hat{F}_R$	$(\overline{\mathbf{N}}, \mathbf{1}, \mathbf{2})$

Vector masses $\mathscr{L} = M_{12} F_L \hat{F}_L + M_{34} F_R \hat{F}_R + h.c.$

EWSB masses $\mathscr{L} = y_{14} F_L \mathcal{H} \hat{F}_R + y_{23} \hat{F}_L \mathcal{H} F_R + h.c.$

Fermion masses split $M_u = M_d = \begin{pmatrix} M_{12} & y(1-\epsilon)v/\sqrt{2} \\ y(1+\epsilon)v/\sqrt{2} & M_{34} \end{pmatrix}$

$$\Sigma = \exp\left[\frac{i}{f}\begin{pmatrix} \pi_1^0 + \frac{\eta}{\sqrt{2}} & \sqrt{2}\pi_1^+ & K_A^0 & -\sqrt{2}K_B^+ \\ \sqrt{2}\pi_1^- & -\pi_1^0 + \frac{\eta}{\sqrt{2}} & -\sqrt{2}K_A^- & K_B^0 \\ \bar{K}_A^0 & -\sqrt{2}K_A^+ & \pi_2^0 - \frac{\eta}{\sqrt{2}} & \sqrt{2}\pi_2^+ \\ -\sqrt{2}K_B^- & \bar{K}_B^0 & \sqrt{2}\pi_2^- & -\pi_2^0 - \frac{\eta}{\sqrt{2}} \end{pmatrix}\right]$$

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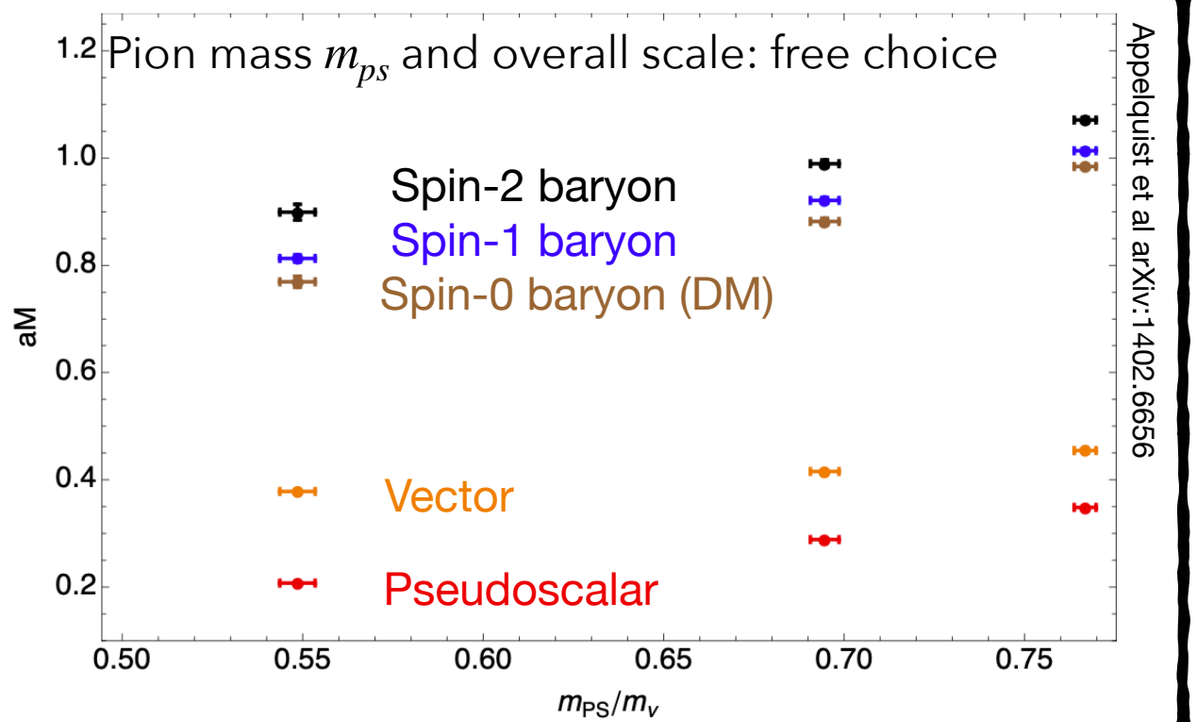
$$15 \to (3,1) \oplus (2,2)_a \oplus (2,2)_b \oplus (1,3) \oplus (1,1)$$

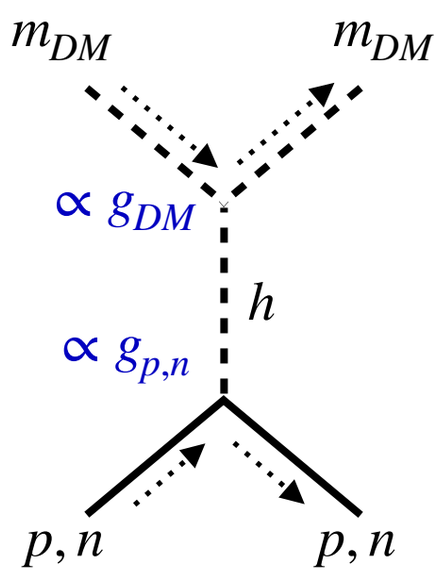
Pion π_1 Kaon Kaon Pion π_2 Singlet η

Phenomenology

- Necessary inputs for phenomenology
  - Bound state mass spectrum
  - Interaction with the SM sector
- LEP results $m_{\tilde{\tau}} > 86.6$ GeV directly applicable
  → dark proton mass > $\mathcal{O}(100)$GeV



DD phenomenology



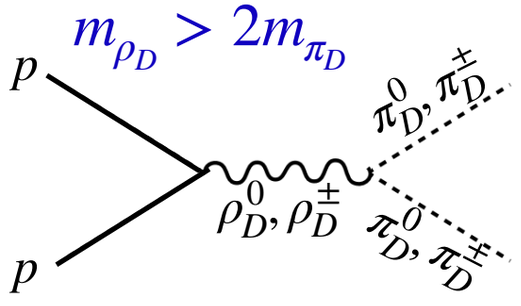
$$\mathcal{M}_{p,n} = \frac{g_{p,n}\, g_{DM}}{m_h^2}$$

$$g_{p,n} \propto f_q^{(p,n)}$$

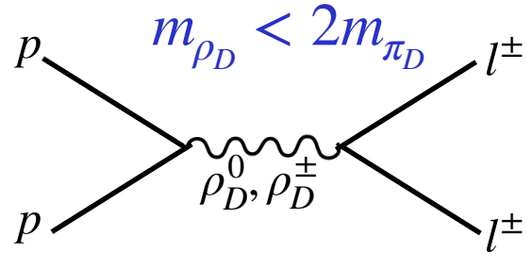
$$g_{DM} \simeq y_{eff} f_f^{DM}$$

Form factors f_q, f_f computed by lattice

LHC phenomenology



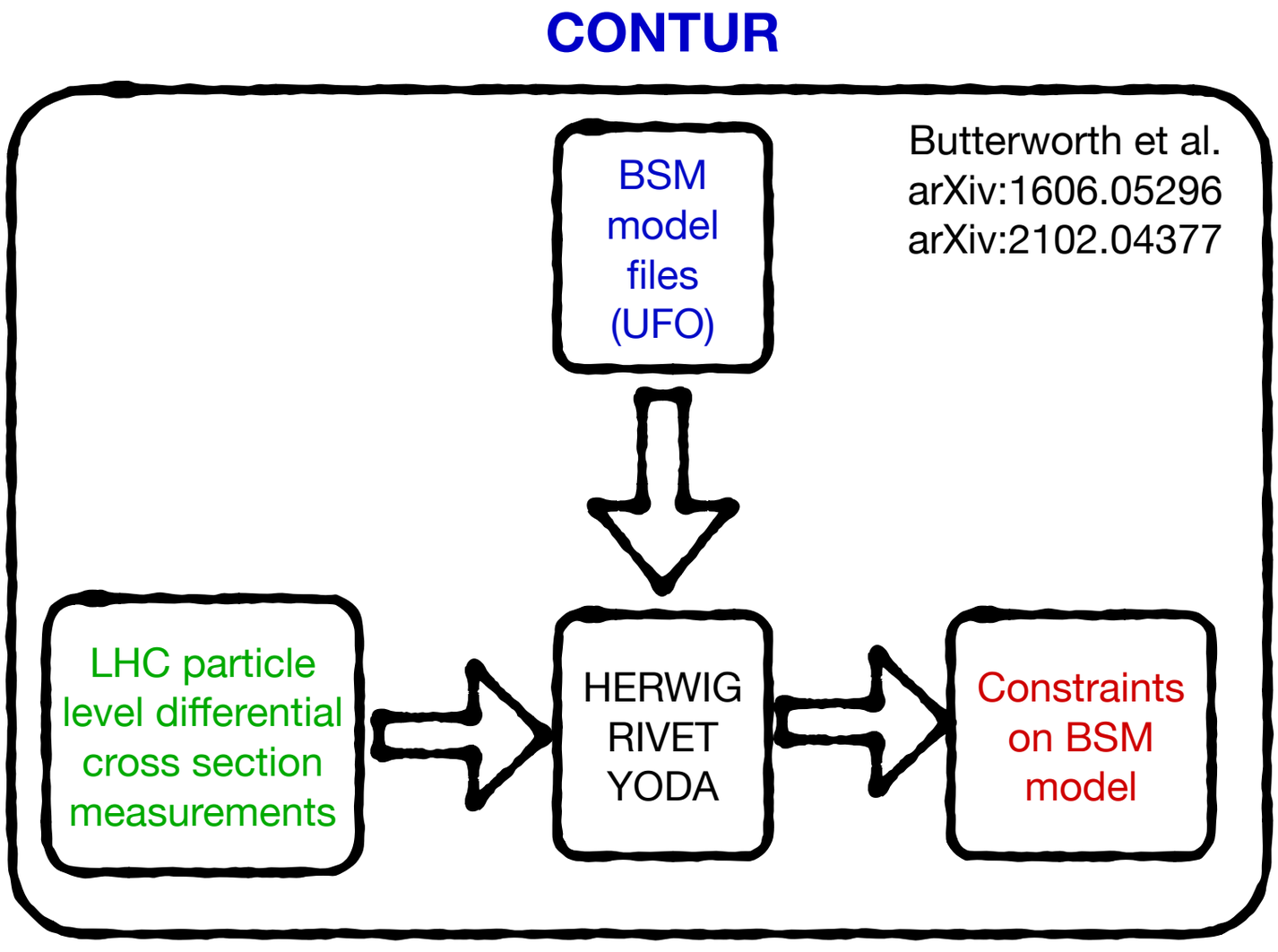
π_D decay to SM 3rd generation fermions/ Higgs → many searches

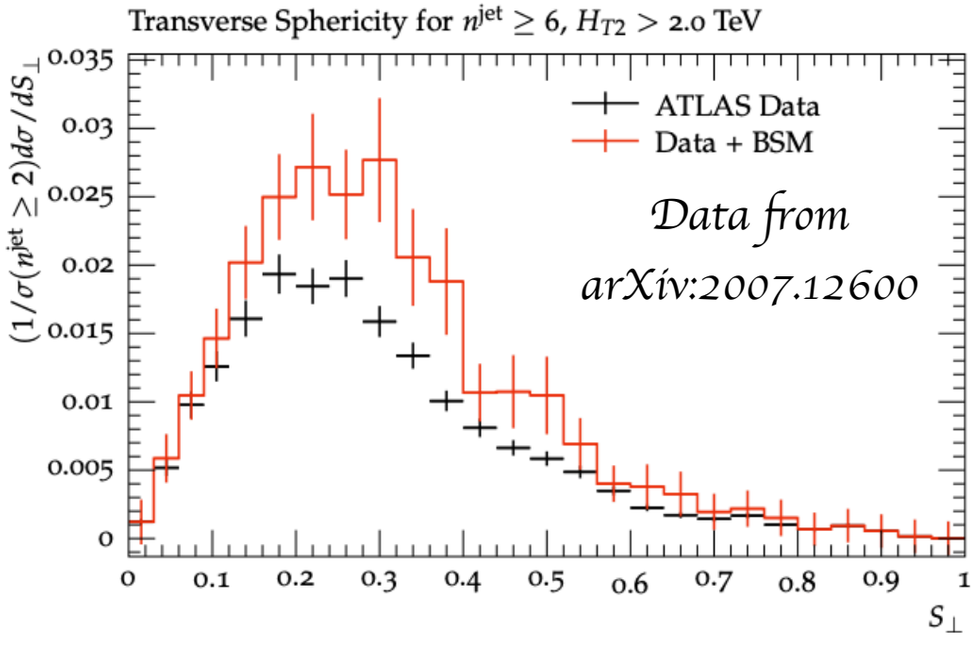


Dilepton searches

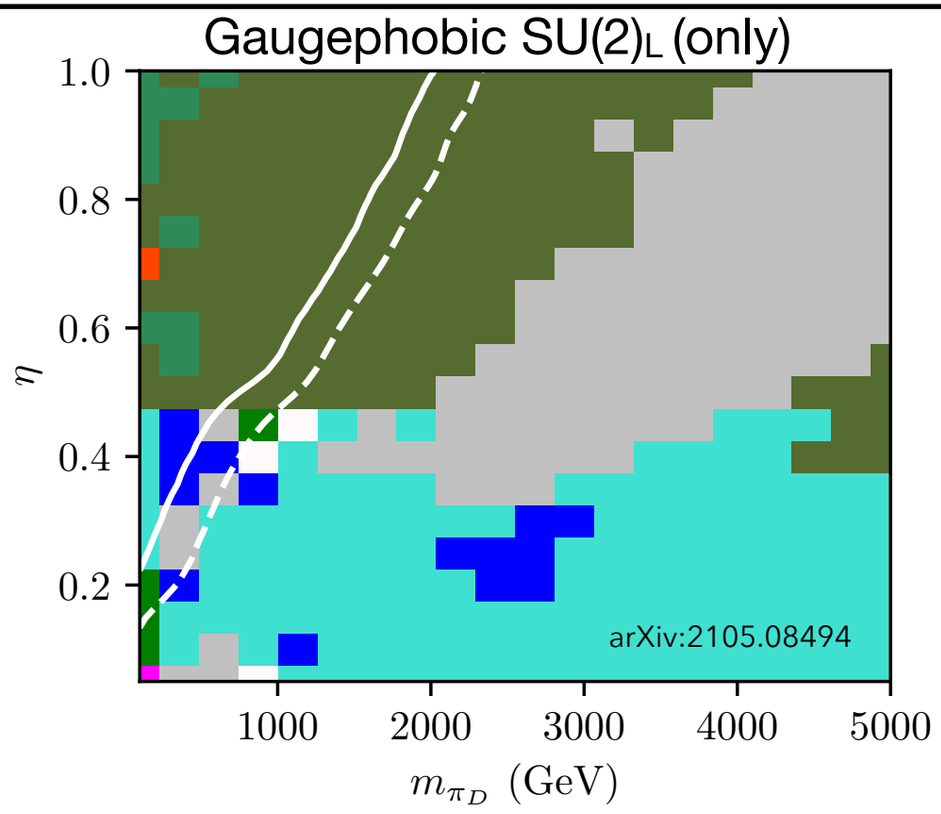
CONTUR

Use Standard Model differential cross-section measurements to exclude presence of signal in phase spaces already compatible with the SM calculations





LHC limits from CONTUR



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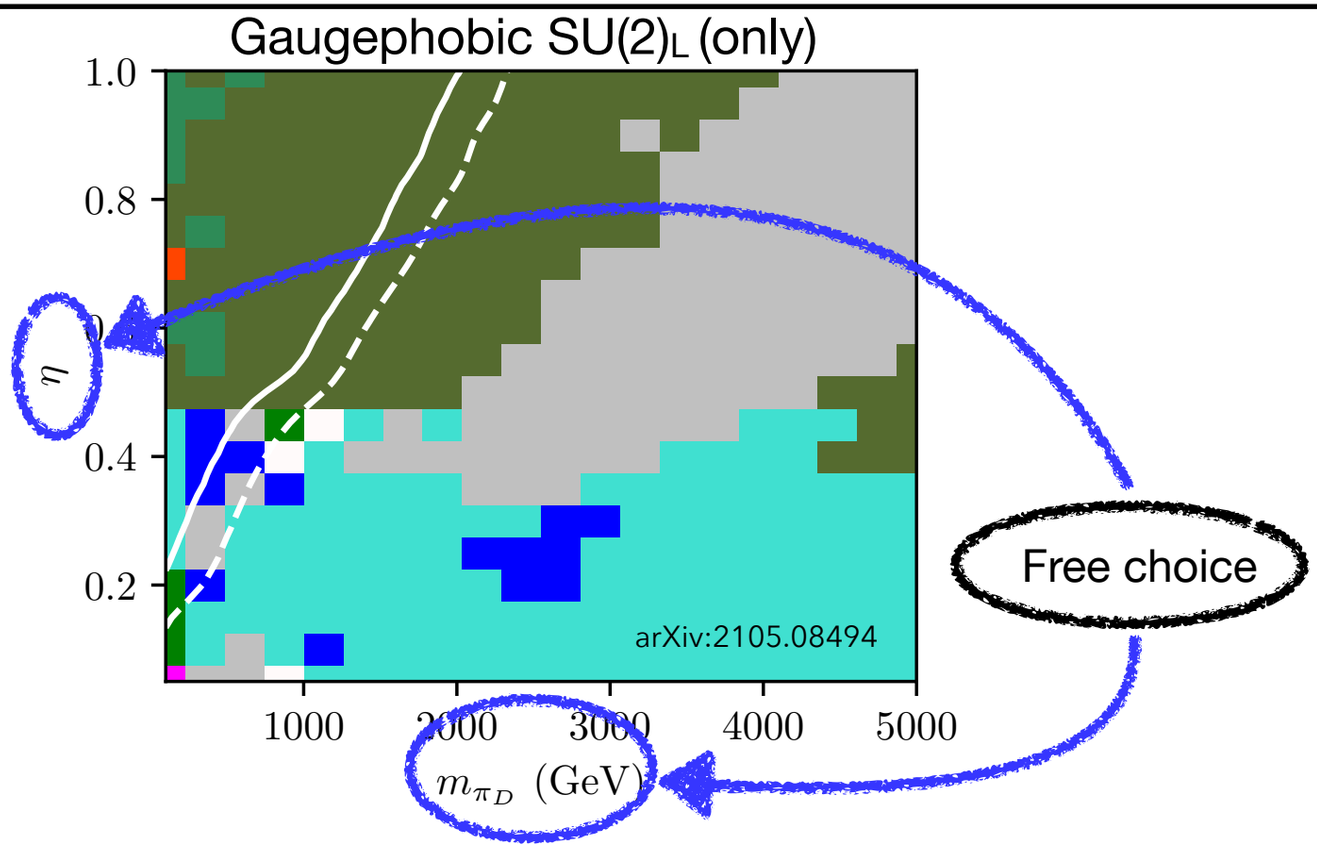

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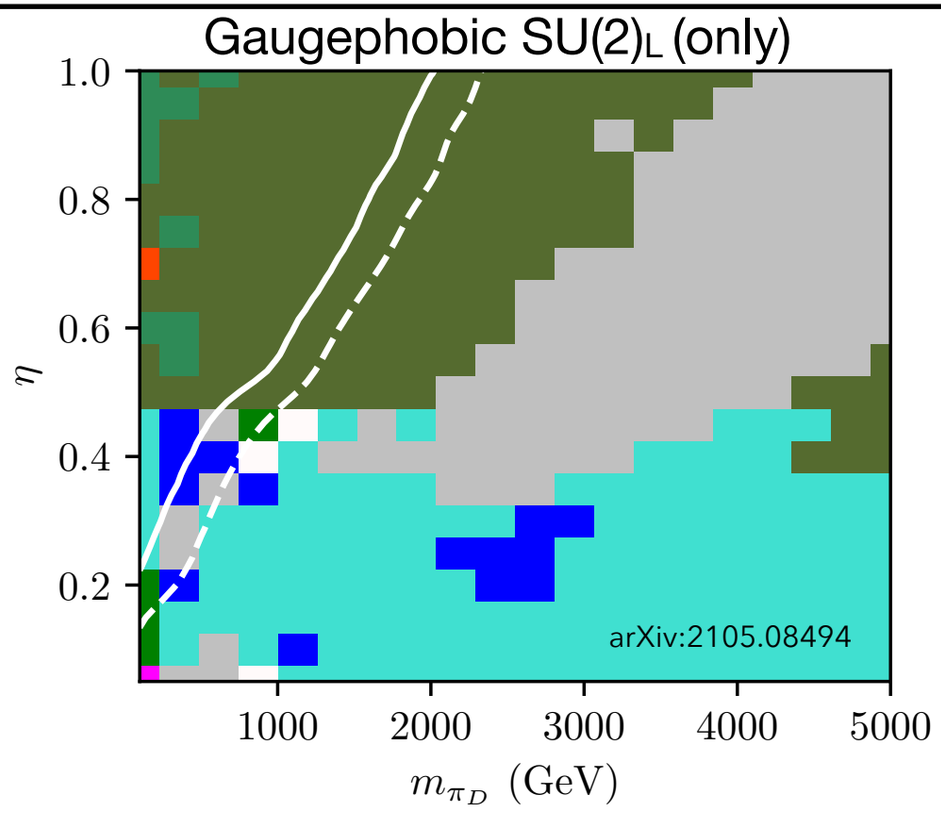

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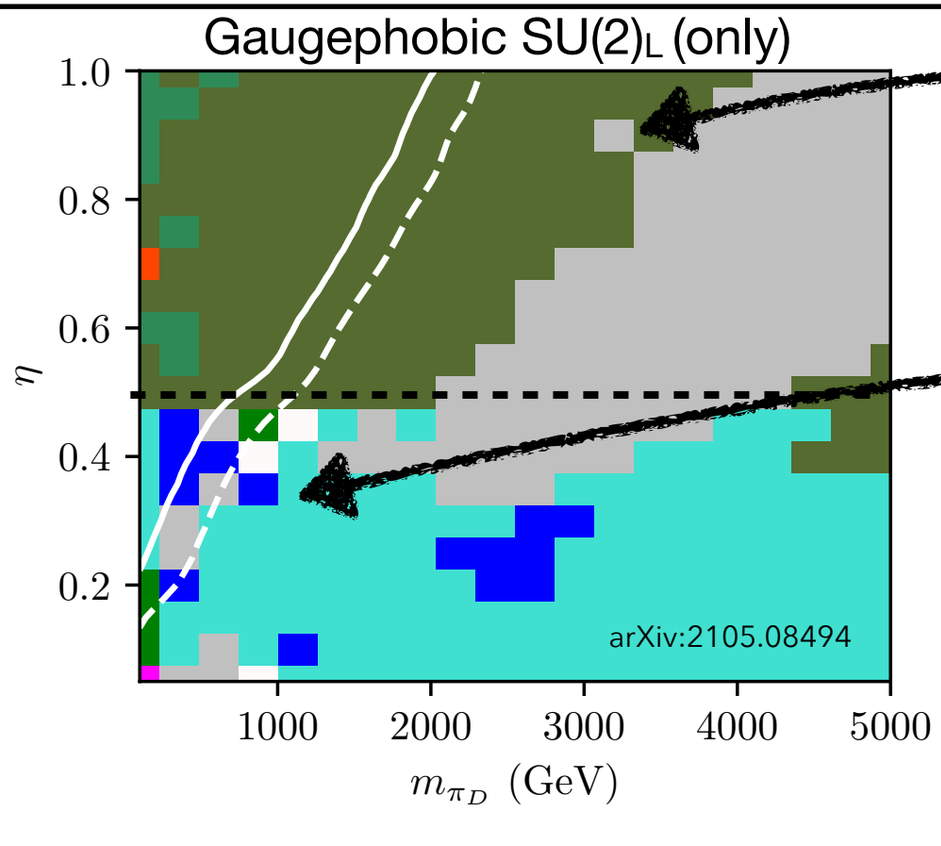

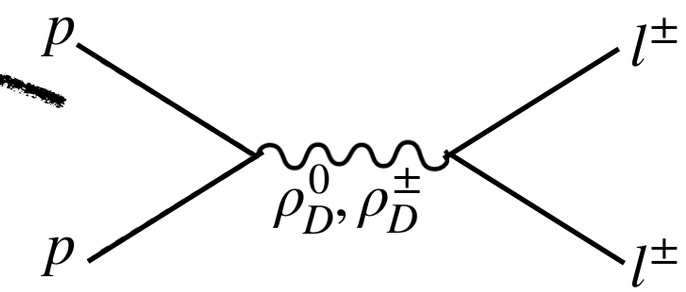

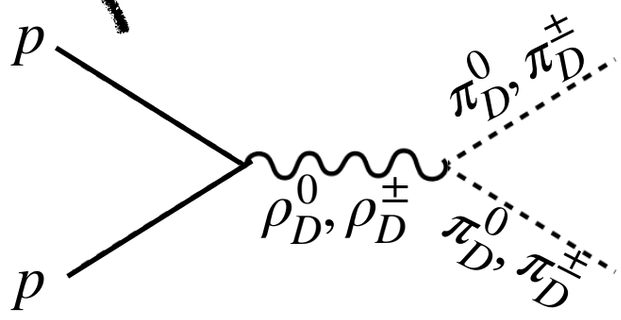

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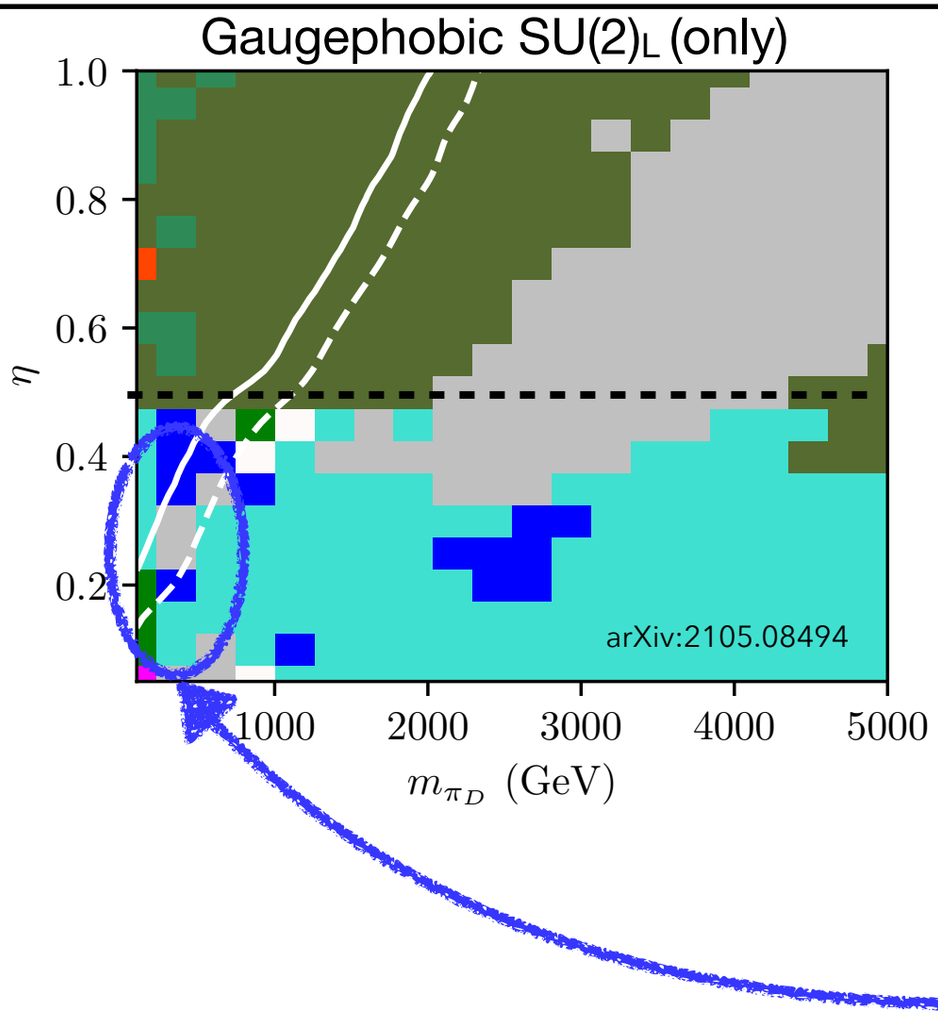
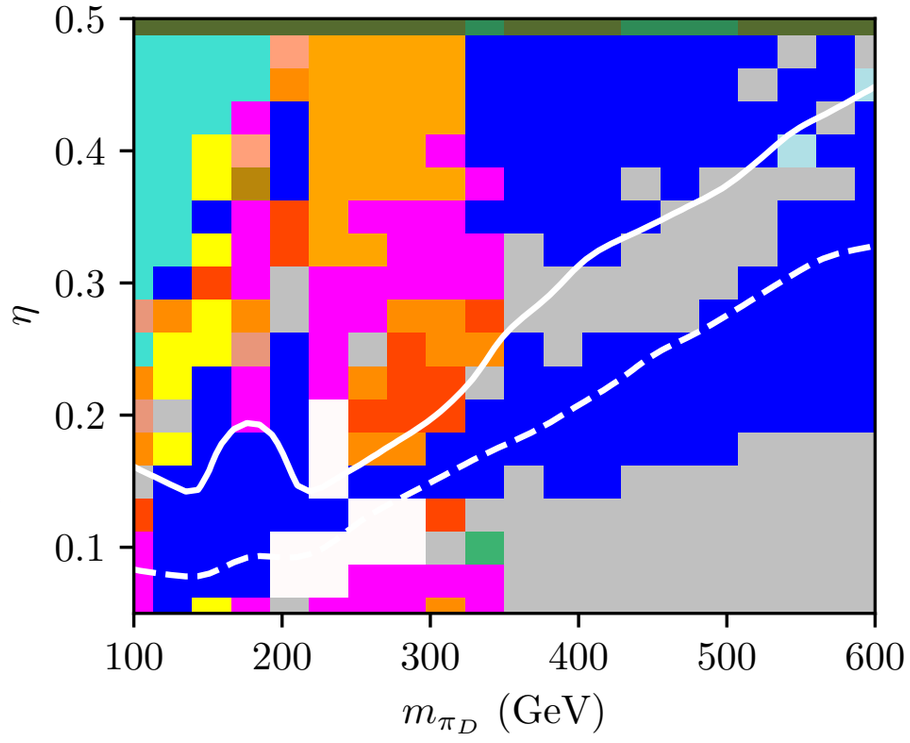
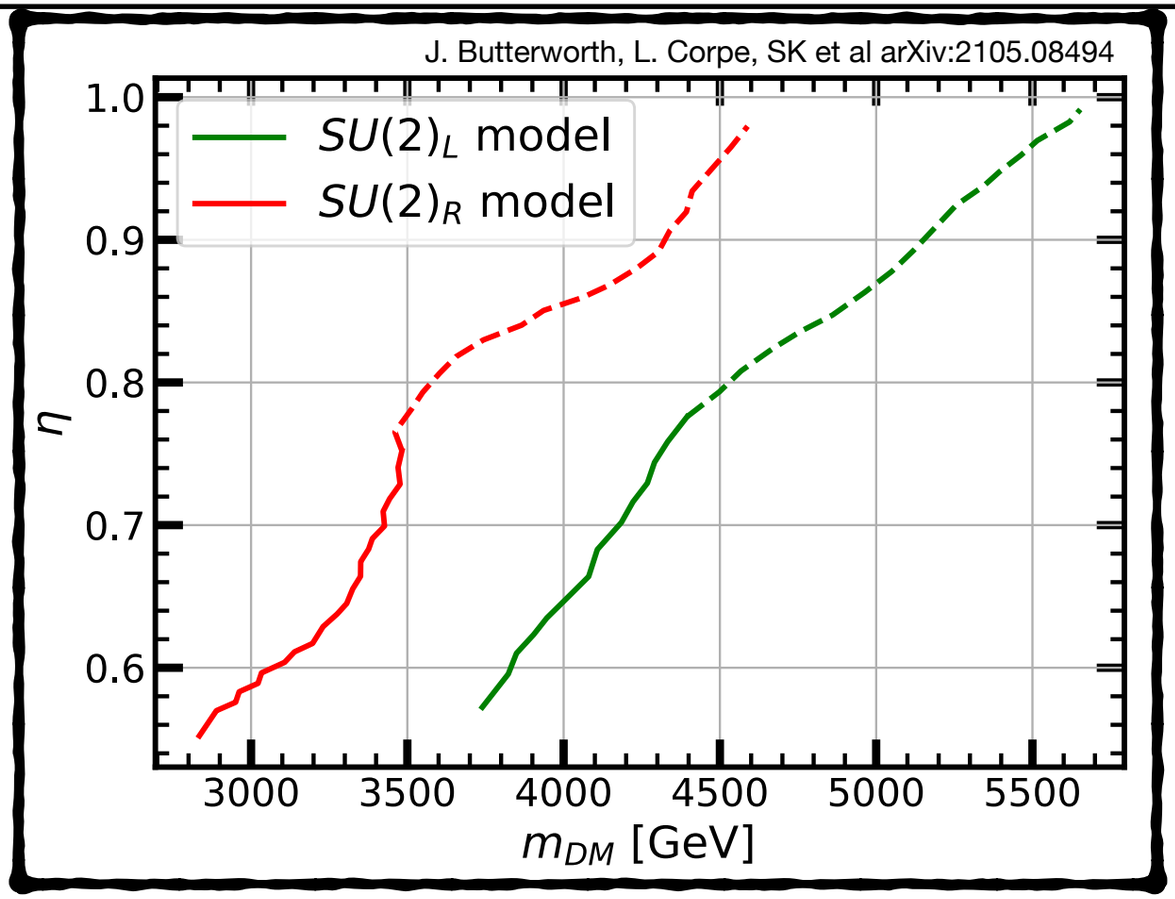




- Turn off resonance searches
- Turn off multi-jet analyses which suffers from QCD uncertainties
- Sensitivity to a variety of other SM differential measurements

CMS ee+jet
CMS $\mu\mu$+jet
ATLAS ee+jet
ATLAS $\ell\ell$+jet
ATLAS $\mu\mu$+jet
ATLAS ℓ+E_T^{miss}+jet
ATLAS μ+E_T^{miss}+jet
ATLAS e+E_T^{miss}+jet
CMS ℓ+E_T^{miss}+jet
ATLAS Hadronic $t\bar{t}$
ATLAS $\ell_1\ell_2$+E_T^{miss}+jet
ATLAS high-mass Drell-Yan $\ell\ell$
CMS high-mass Drell-Yan $\ell\ell$
ATLAS 4ℓ
ATLAS γ
ATLAS $\ell\ell\gamma$
ATLAS γ+E_T^{miss}
ATLAS jets

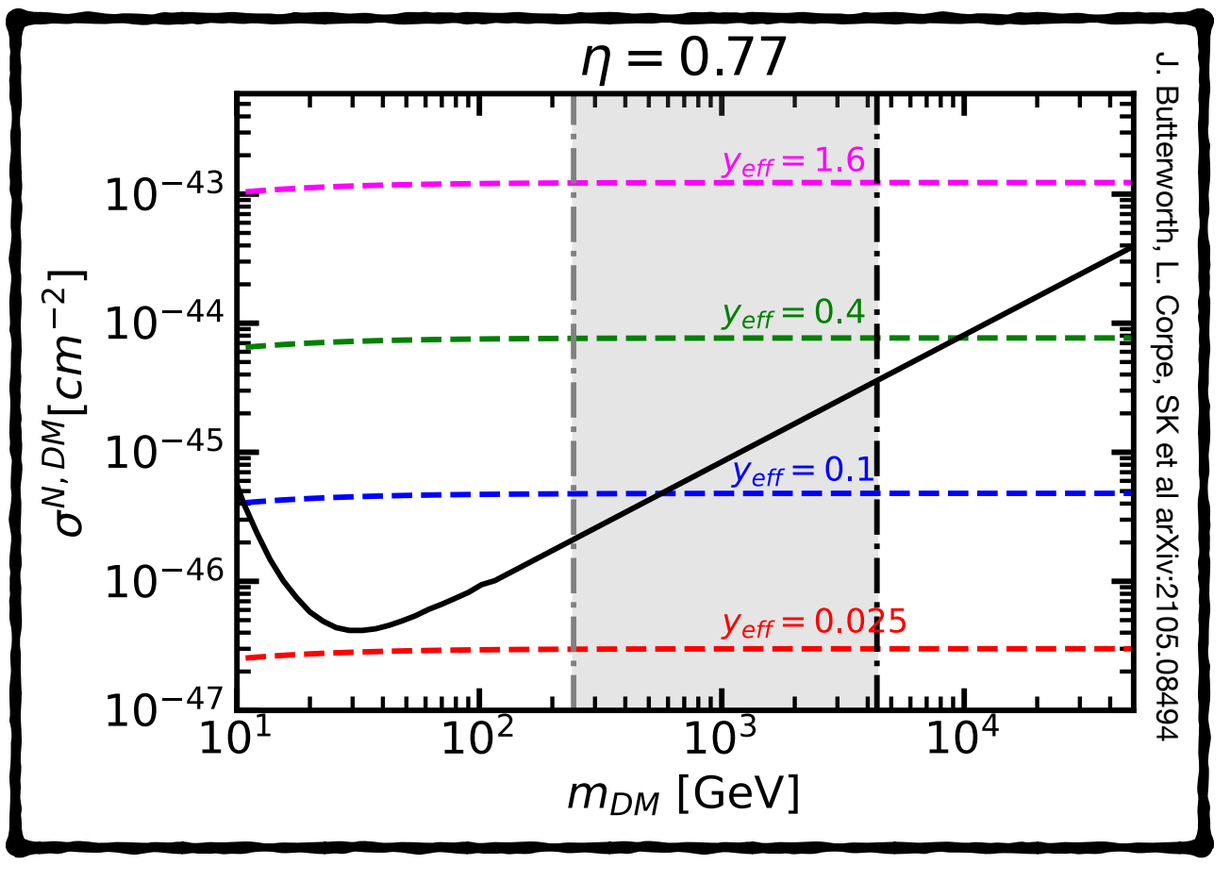
Constraints



See also Appelquist et al, arXiv:1503.04203

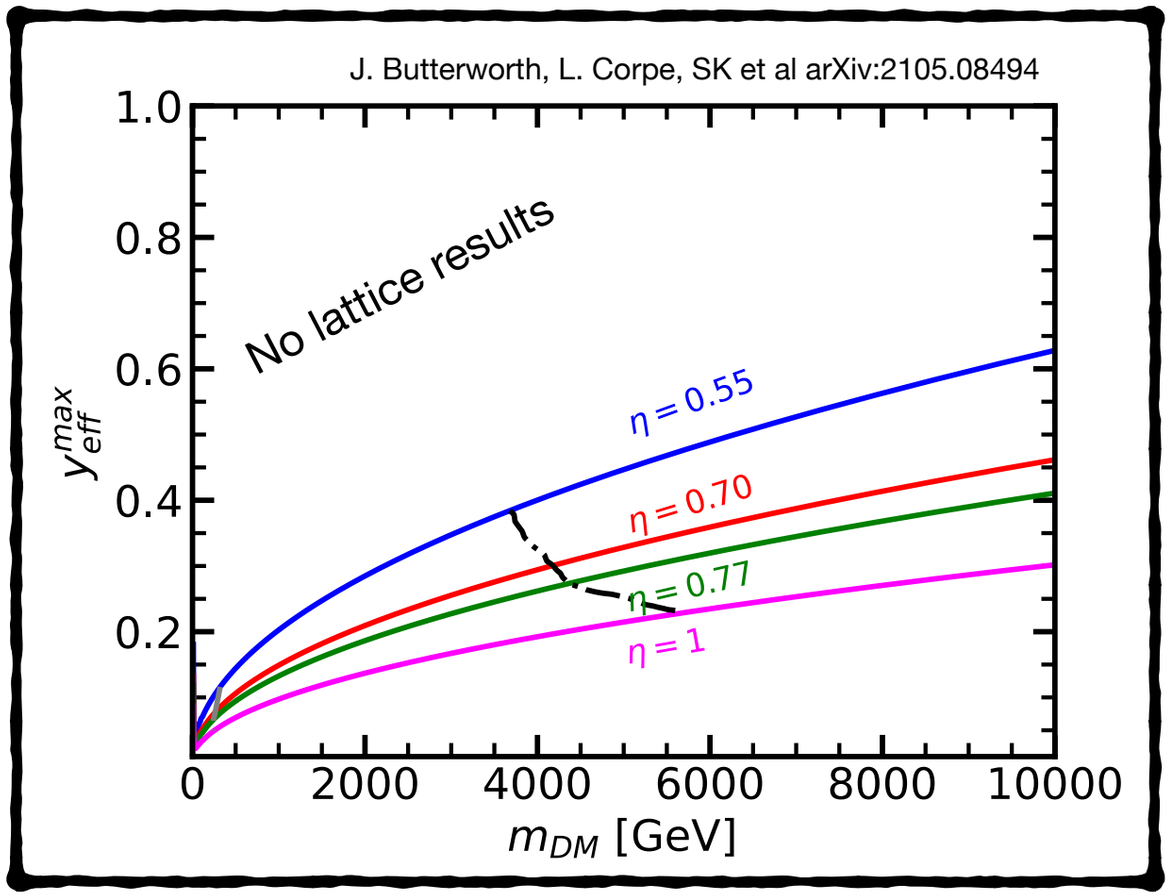
- Analysis with the help of CONTUR; constraints from SM precision measurements
- LHC exclusions together with the lattice results push the dark matter mass limits to multi-TeV mass range

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



Combined limits

Combination of direct detection limits, LHC measurements and DY searches



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

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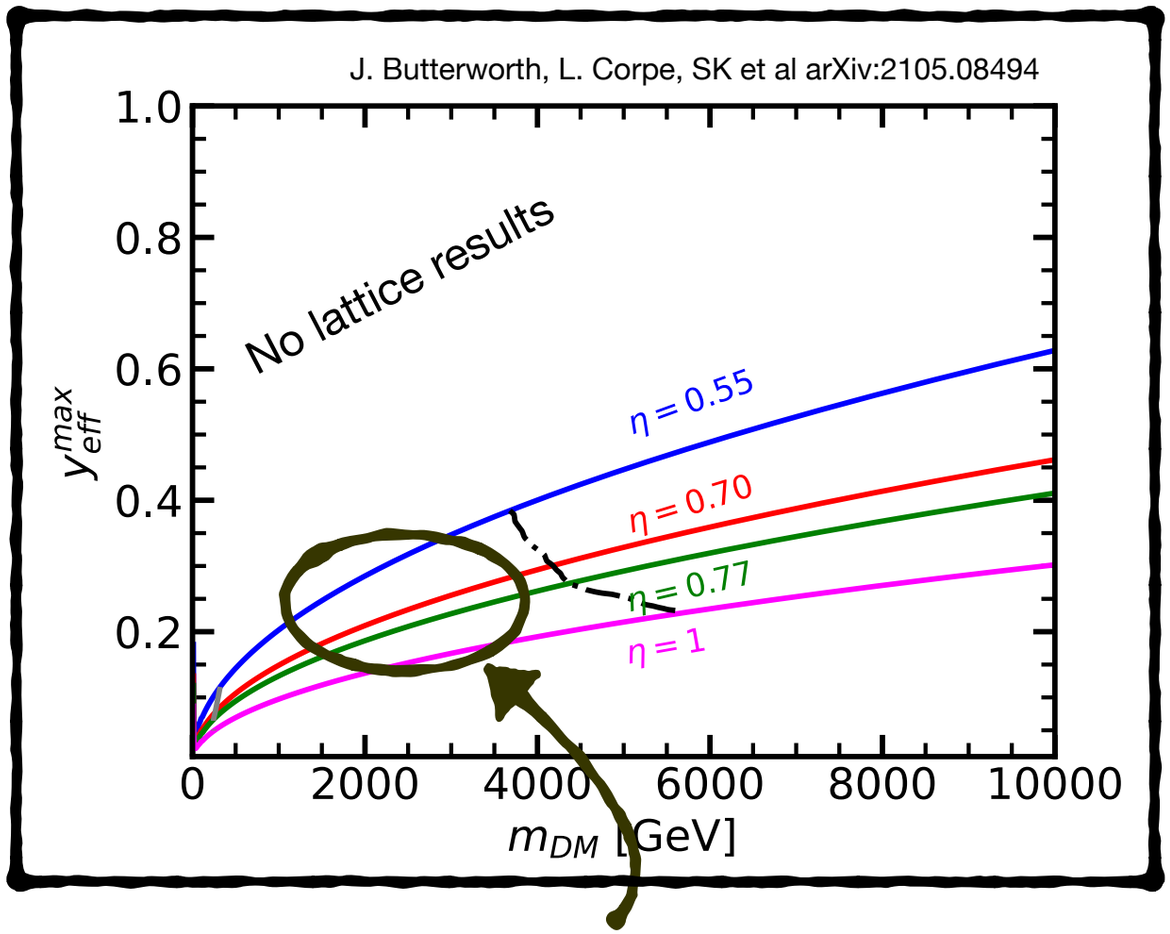

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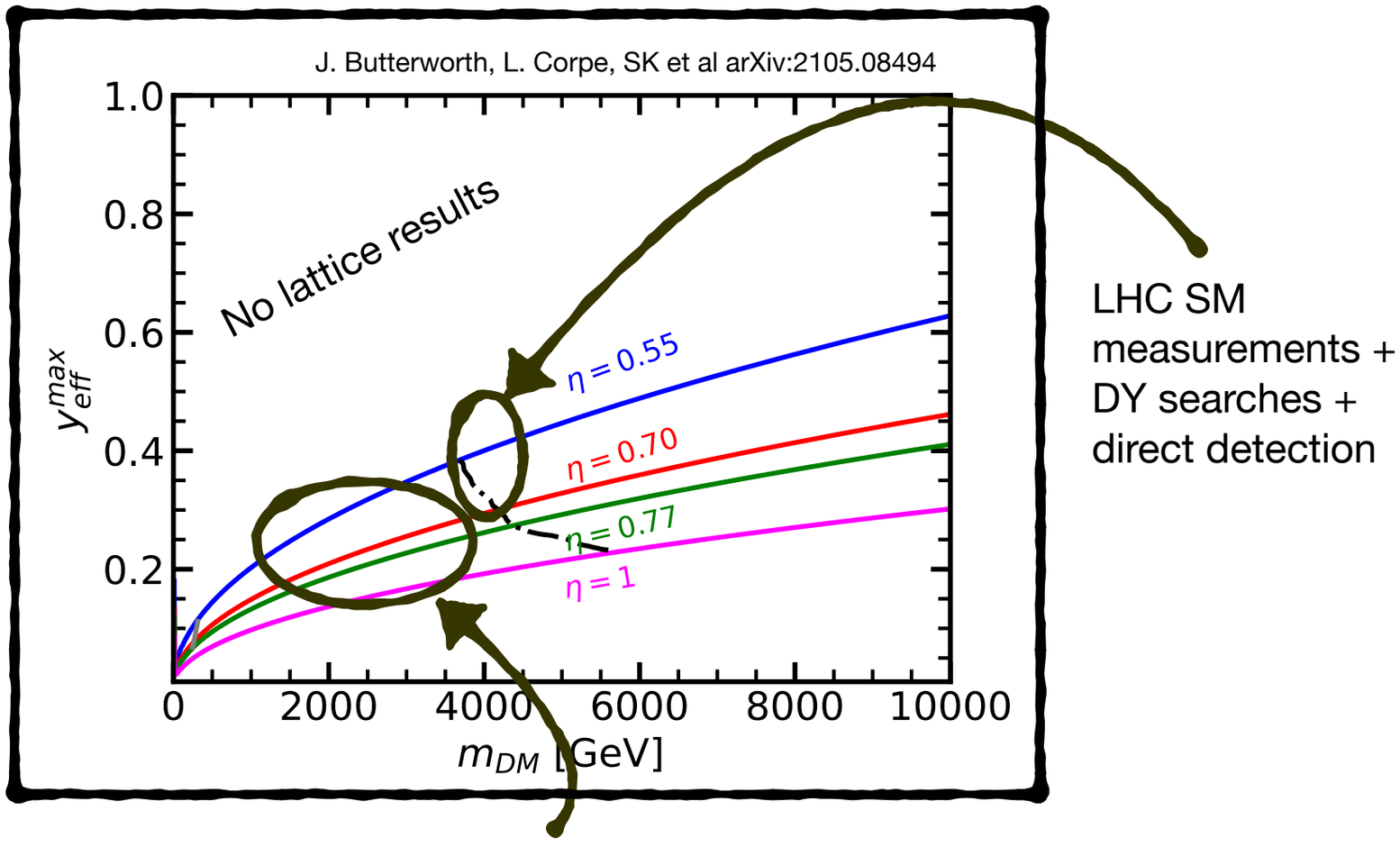
Combined limits

Combination of direct detection limits, LHC measurements and DY searches



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

Combined limits

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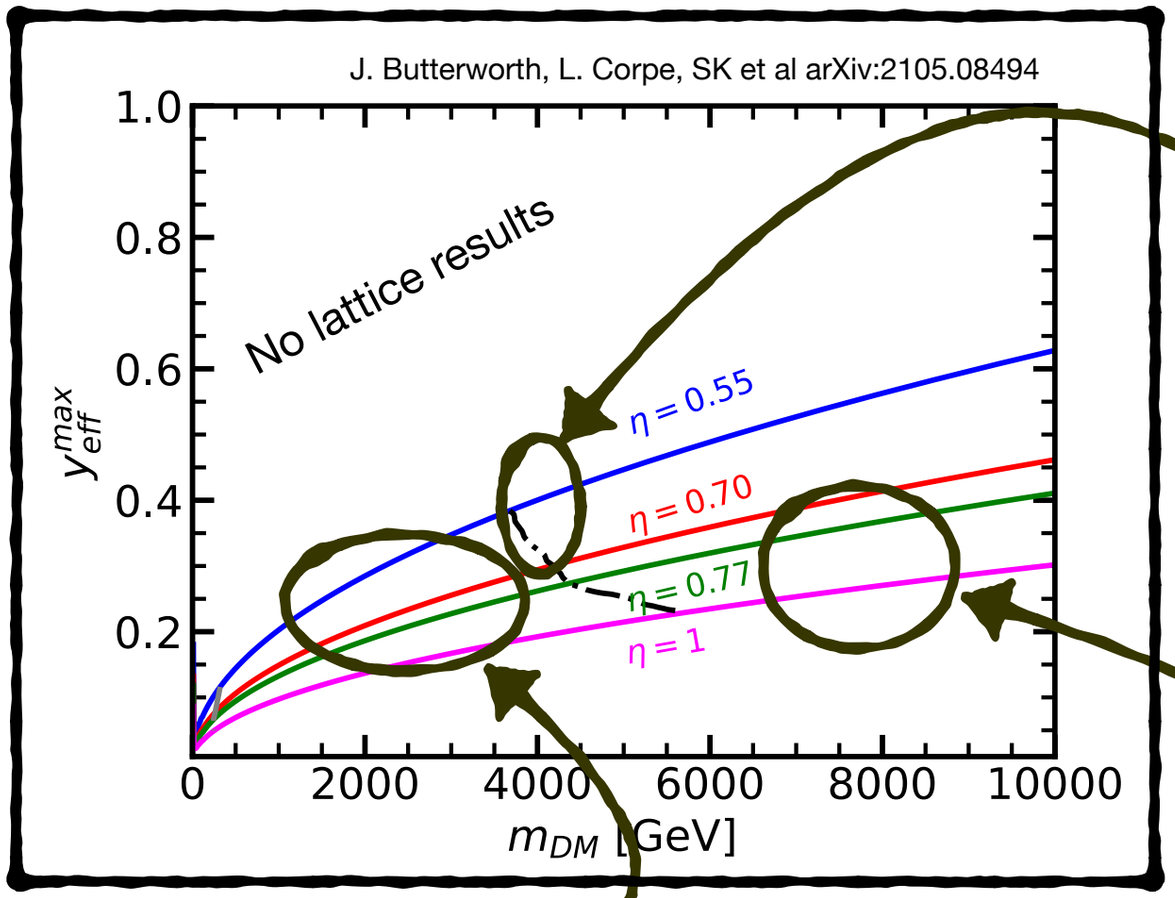


LHC SM measurements + DY searches + direct detection

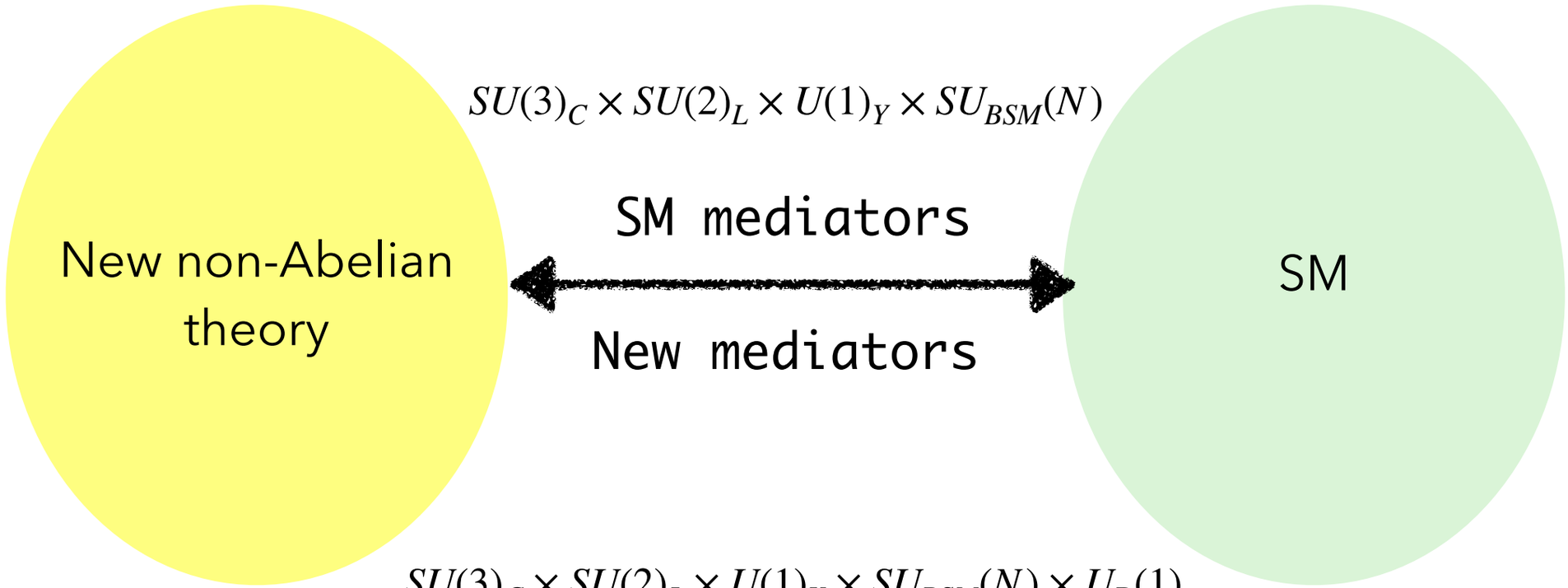
Direct detection only

Allowed region

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

Portal phenomenology - II

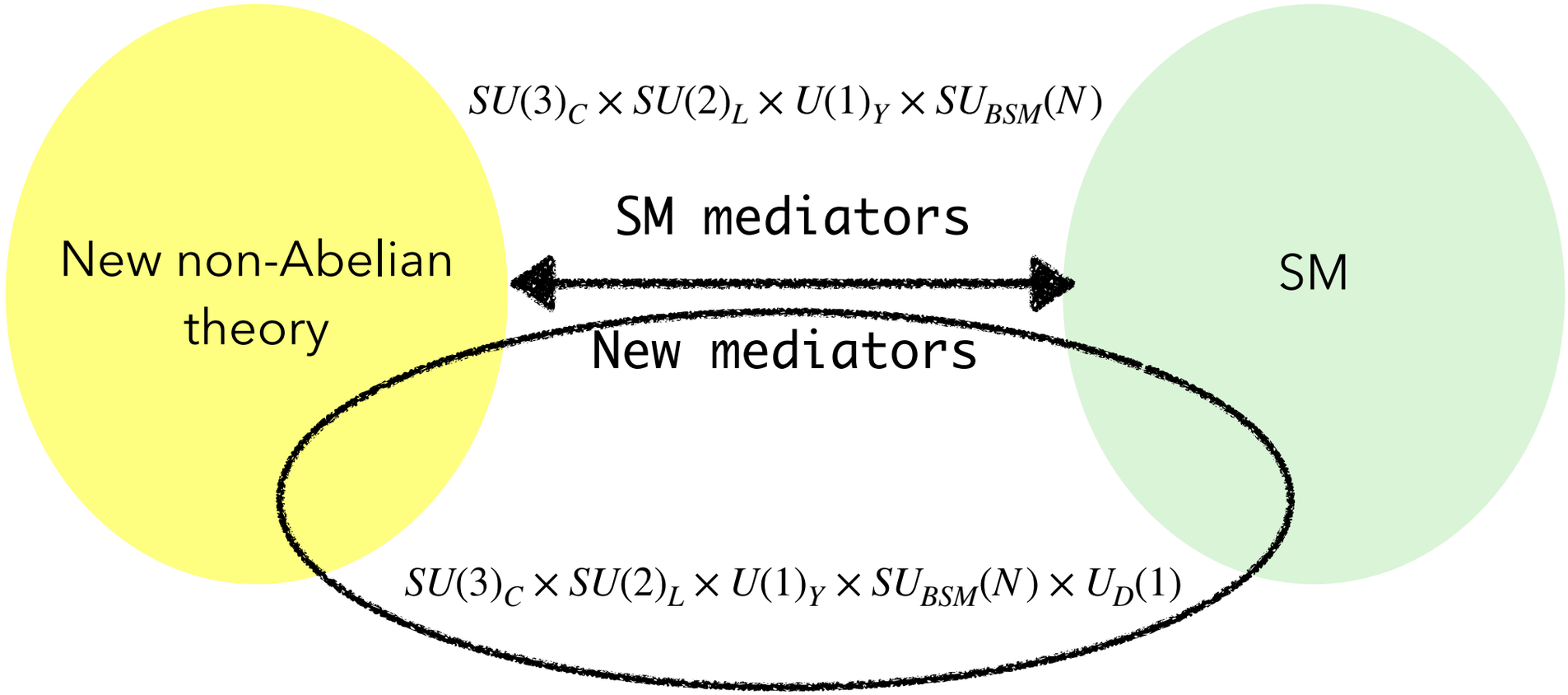
$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU_{BSM}(N)$$



$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU_{BSM}(N) \times U_D(1)$$

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

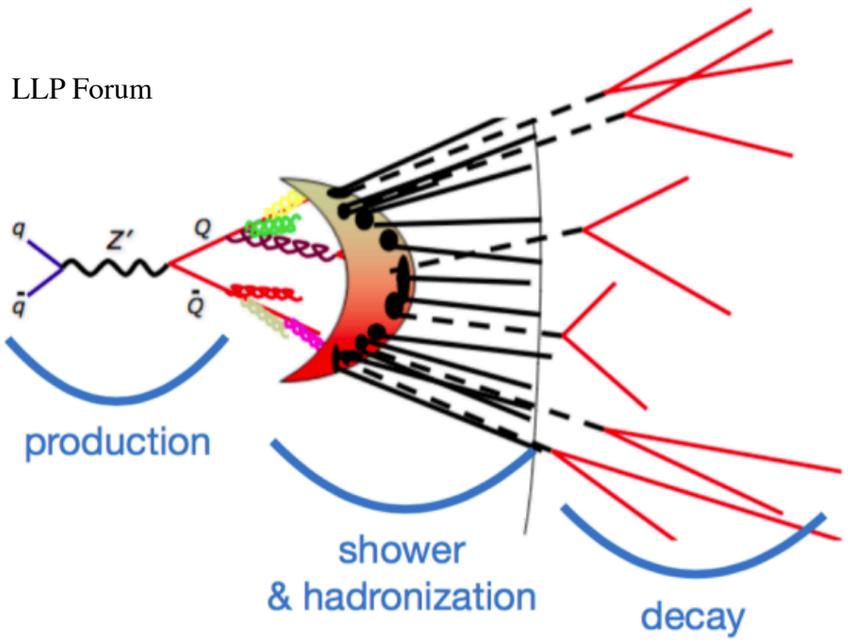
Portal phenomenology - II



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

Theory setup

$$\mathcal{L}_{\text{int}} \subset -e_D Z'_\mu \sum_i \bar{q}_{Di} Q_i \gamma^\mu q_{Di} - g_q \, Z'_\mu \sum_r \bar{q}_{SM,r} \gamma^\mu q_{SM,r}$$



- $m_{Z'} \gtrsim 30\Lambda_D \, , m_{q_D} \ll \Lambda_D \ll \sqrt{s}$ → production of dark quarks followed by rapid parton showering and hadronization → jets
- Z' coupling leads to decay of some of the dark hadrons back to the SM; details coupling dependent

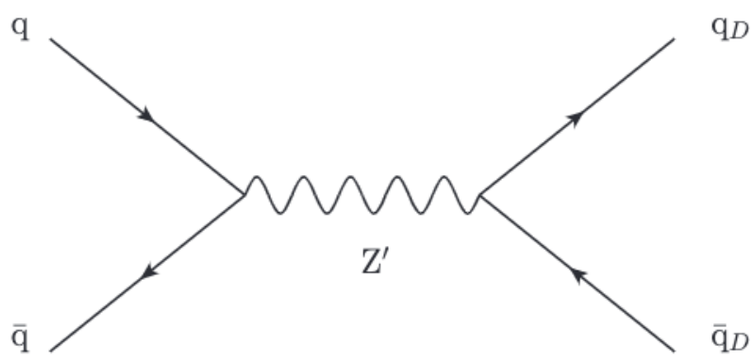
Theories with dark jets

- Traditionally signature based approach: $N_{c_D}, N_{f_D}, \Lambda_D, \alpha_D, m_{q_D}, m_{\pi_D}, m_{\rho_D}, m_{baryon_D}$ branching ratios along with mediator properties free variables
- Two primary portal analysis s-channel Z' and t-channel bifundamental ϕ
- Signature space with semivisible jets, emerging jets, trackless jets
- Treat dark rho and dark pions on same footing
- Simulation based on Pythia Hidden Valley module

See also:
Beauchenese, Bertuzzo, Di Cortana
arXiv:1712.07160
Bernreuther, Kahlhoefer, Krämer, Tunney
arXiv:1907.04346
Knapen, Shelton, Xu
arXiv:2103.01238

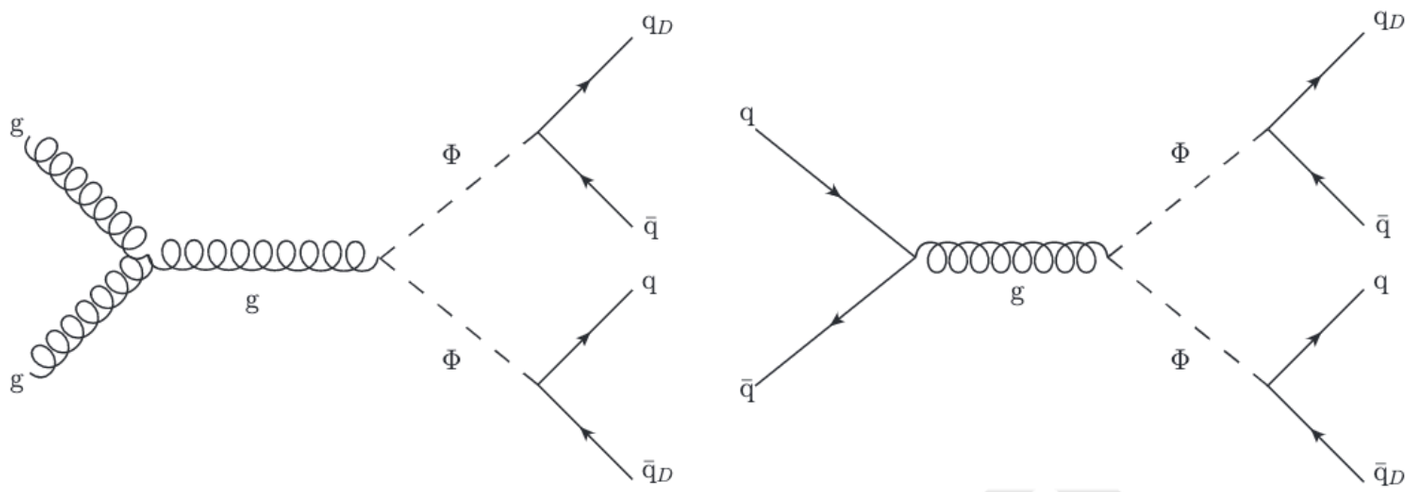
s-channel (Z') production

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



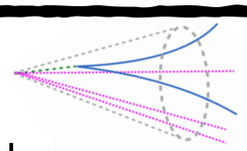
t-channel (bifundamental) production

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

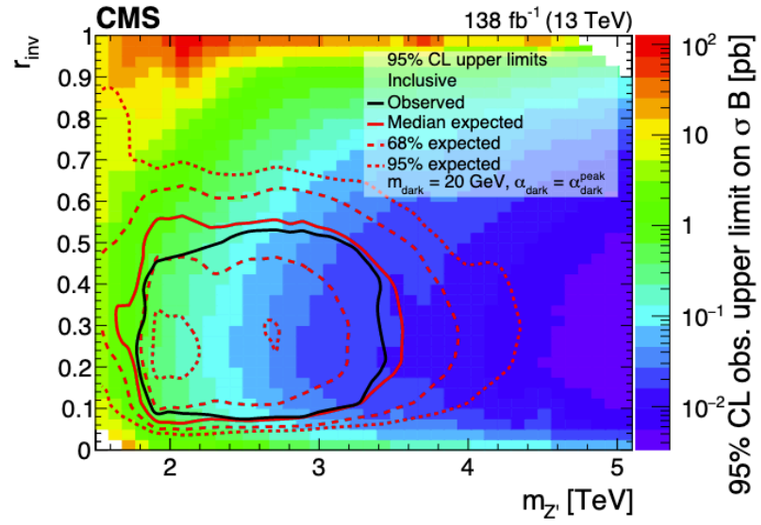


LHC phenomenology

Semivisible jets



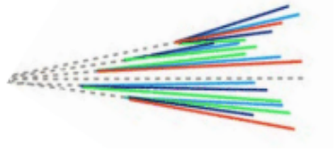
- Unstable dark mesons decay promptly via two body decays
- $r_{inv} = N_{stable}/(N_{stable} + N_{unstable})$ Cohen, Lisanti, Lou arXiv:1503.00009
- Small r_{inv}: dijet search strategy;
  Large r_{inv}: monojet searches;
  Intermediate r_{inv}: Dedicated searches



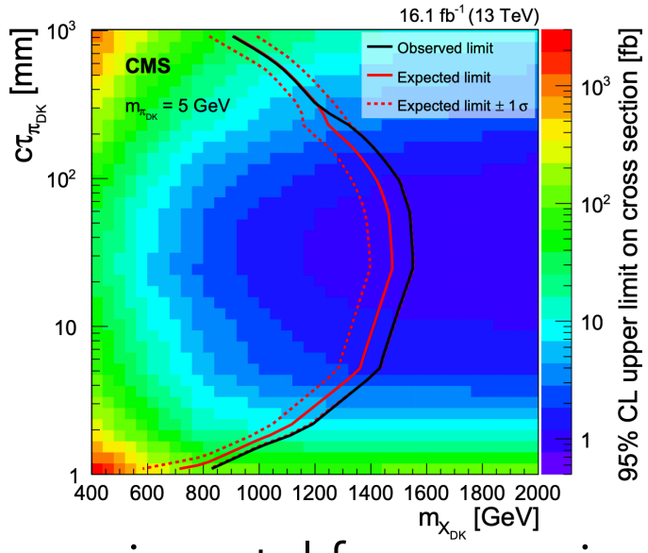
CMS collaboration arXiv:2112.11125

First experimental for semivisible jets

Emerging jets



- Dark mesons with finite lifetime: jet with multiple displaced vertices
- Unflavoured case: one lifetime for all dark hadrons Schwaller, Stolarski & Weiler arXiv:1502.05409
- Flavoured case: diagonal, off-diagonal dark hadrons have different lifetime



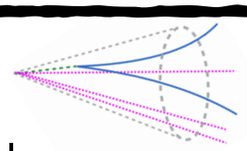
CMS collaboration arXiv:1810.10069

First experimental for emerging jets

Phenomenology has not always been realistic e.g. missing particles and symmetry constraints; now updated within snowmass study

LHC phenomenology

Semivisible jets



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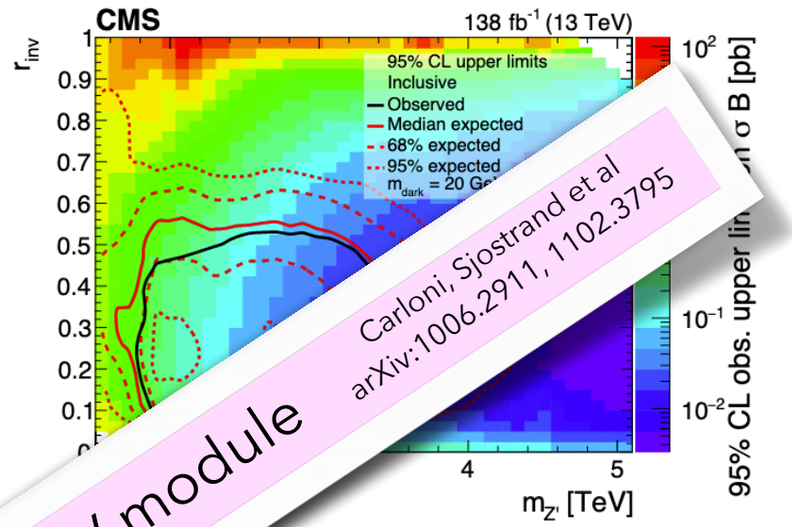
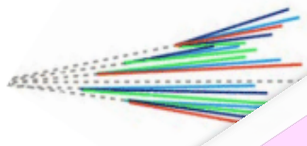


CMS collaboration
arXiv:2112.11125

…mental for semivisible jets

Emerging jets



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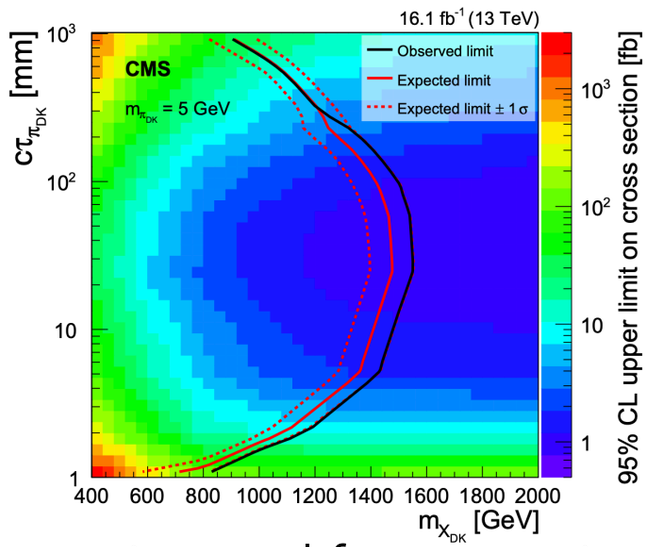
Schwaller, Stolarski & Weiler arXiv:1502.05409

- Flavour… …agonal, off-diagonal dark ha… …have different lifetime



CMS collaboration
arXiv:1810.10069

First experimental for emerging jets

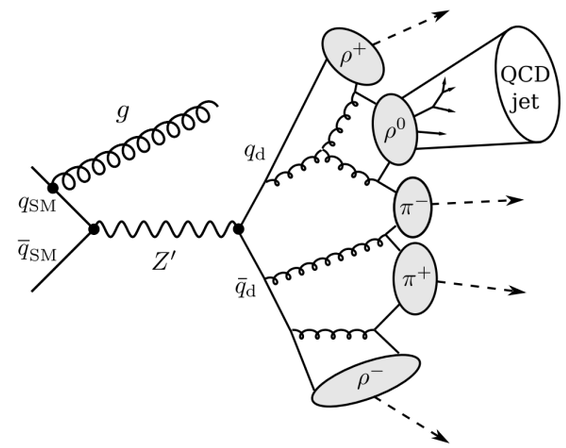
All studies use PYTHIA8(<8.307) HV module
Carloni, Sjostrand et al
arXiv:1006.2911, 1102.3795

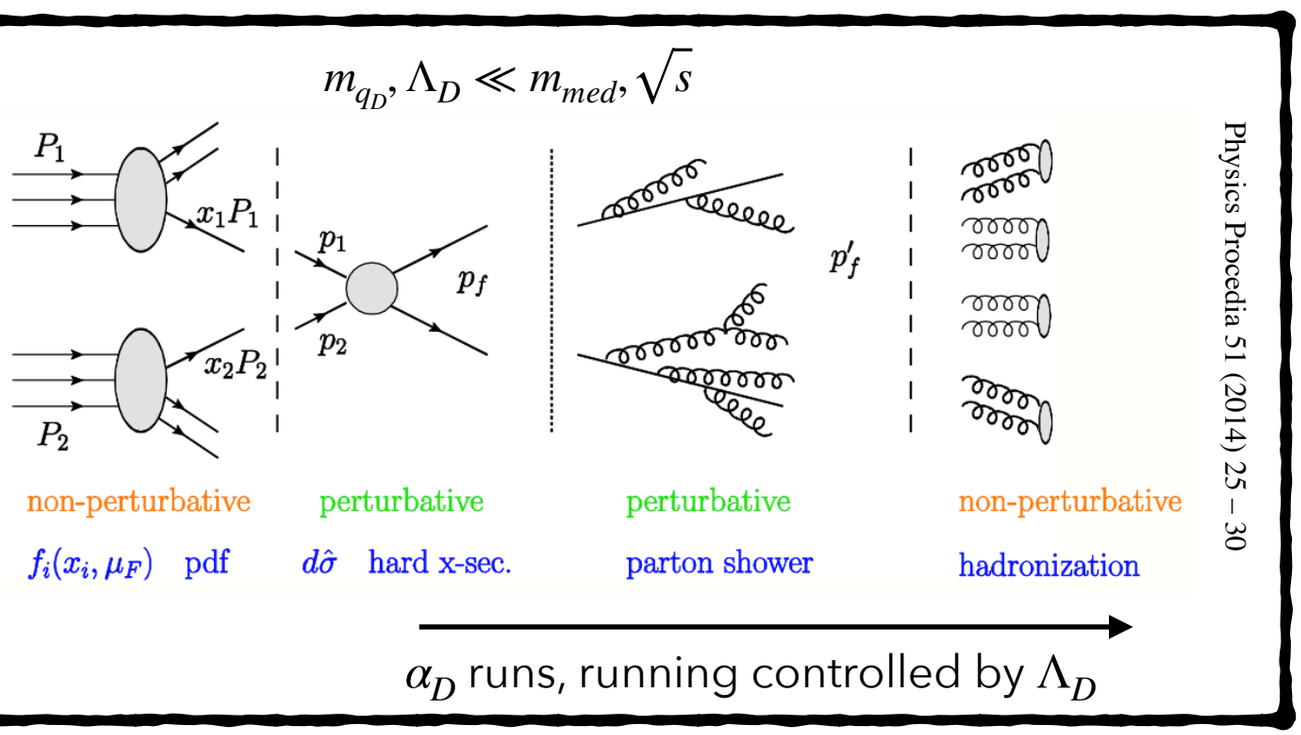
Phenomenology has not always been realistic e.g. missing particles and symmetry constraints; now updated within snowmass study

(LHC) phenomenology

- Depending on N_{c_D}, N_{f_D} a variety of DM candidates possible e.g. dark pions, dark baryon (NB: baryons could be spin 0,1/2)
- Stabilise pions with appropriate $U_D(1)$ charges → easier in even flavours than odd flavours
- Dark quark production followed by hadronization (similar to the SM at the LHC)
- Leads to new signatures, few constraints, many possibilities

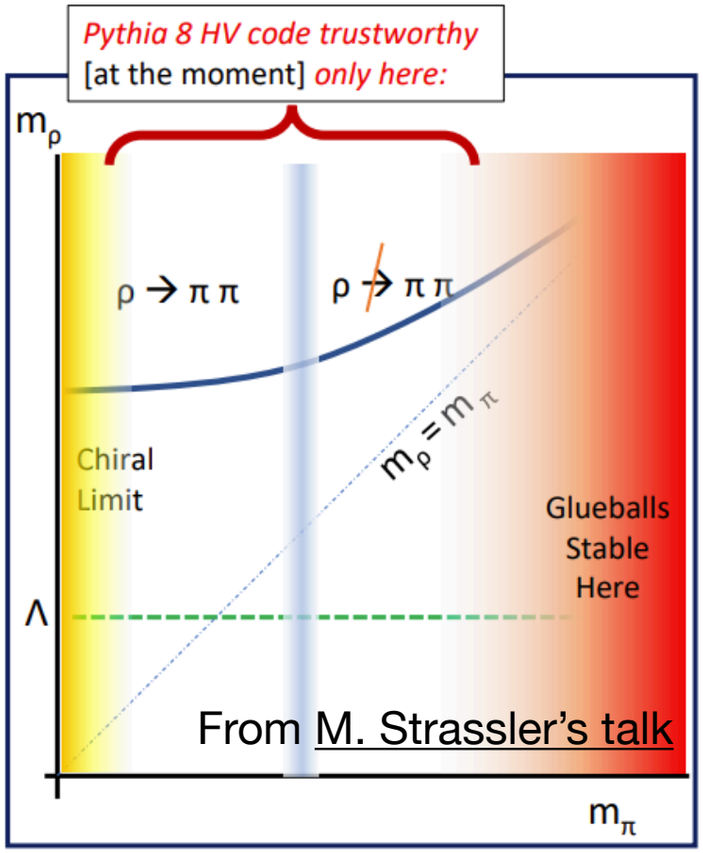
Kahlhoefer et.al. arXiv:1907.04346





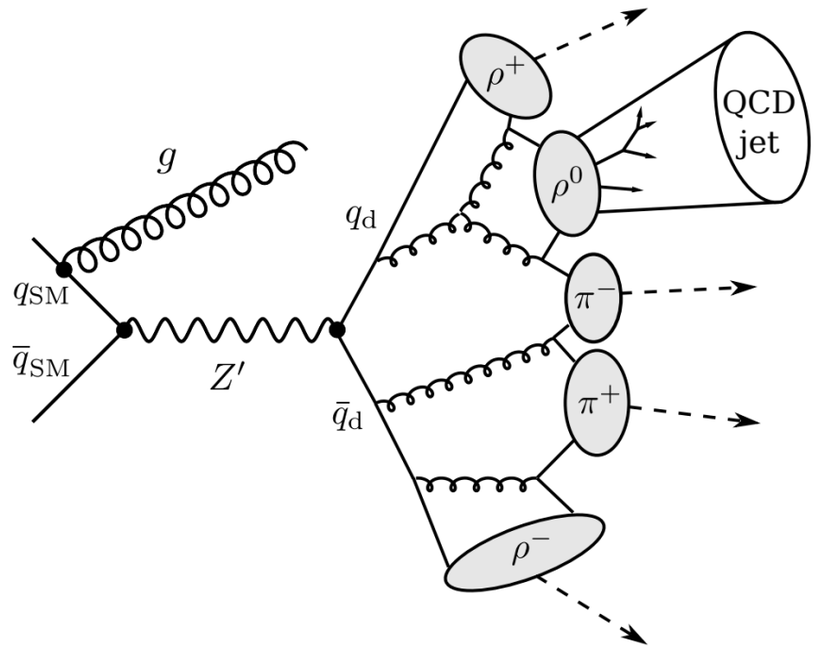
- Jet shapes and kinematics depends on consistency between UV and IR regimes
- It seems favourable to use Λ_D as external scale to define physical masses

‘Jetty’ physics: too much ado about nothing?



From M. Strassler’s talk

arXiv:1907.04346



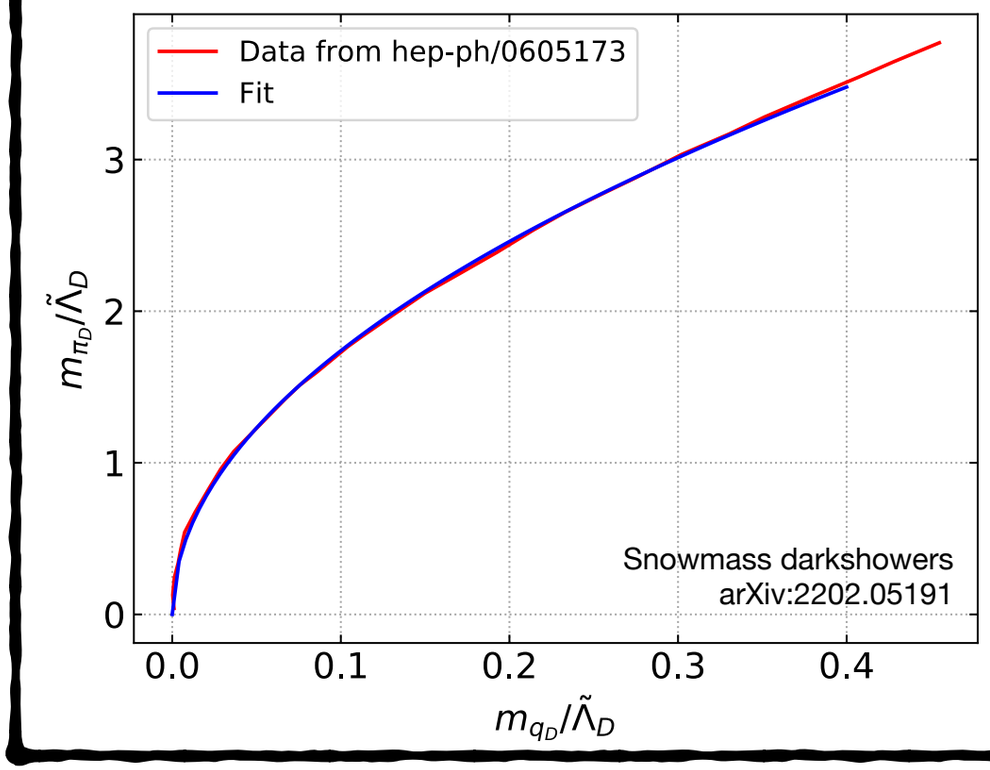
- LHC in jetty regime → sensitive to the UV physics → dark quark masses, Λ_D matter
- Due to high energies, LHC can be sensitive to higher excitations in the spectrum
- Theory has only four free parameters $N_c, N_f, m_\pi/\Lambda, \Lambda$ they need to be chosen carefully for chiral PT to be valid, for simulation tools to be valid
- Mediator mechanisms need to be constructed carefully for pions to remain stable
- Typically relic density driven by IR parameters, LHC phenomenology both UV and IR

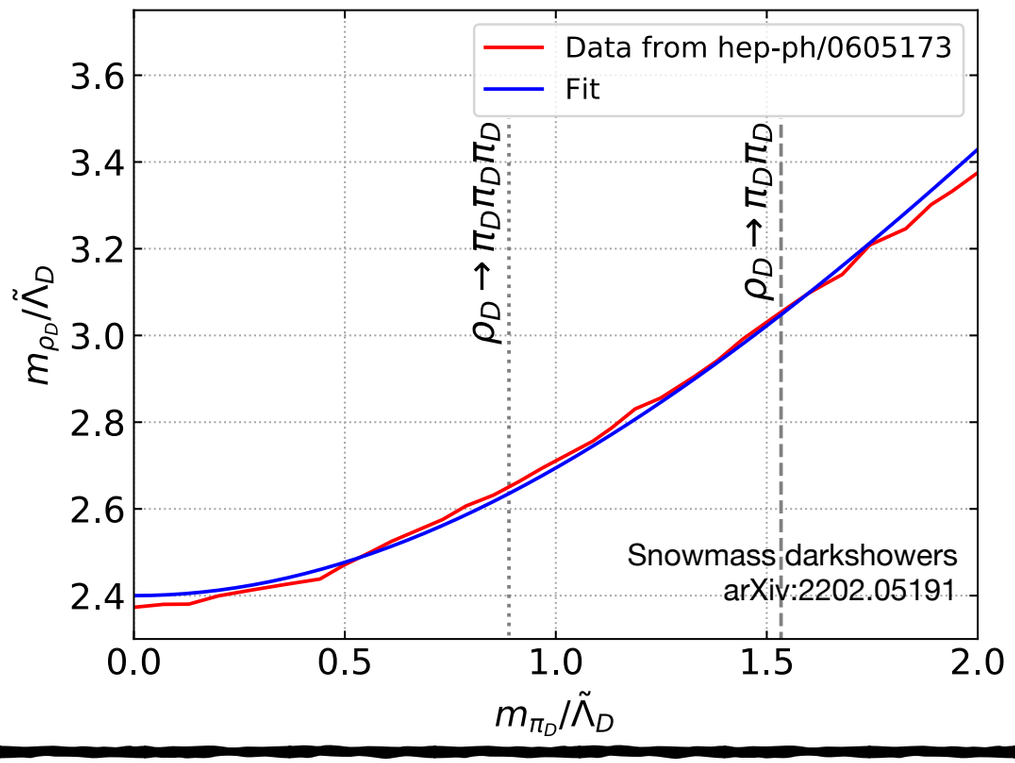
Dark meson masses

Snowmass darkshowers arXiv:2202.05191

- Effects due to N_{c_D}, N_{f_D} can be ignored for now
- Dark meson mass fits from lattice results

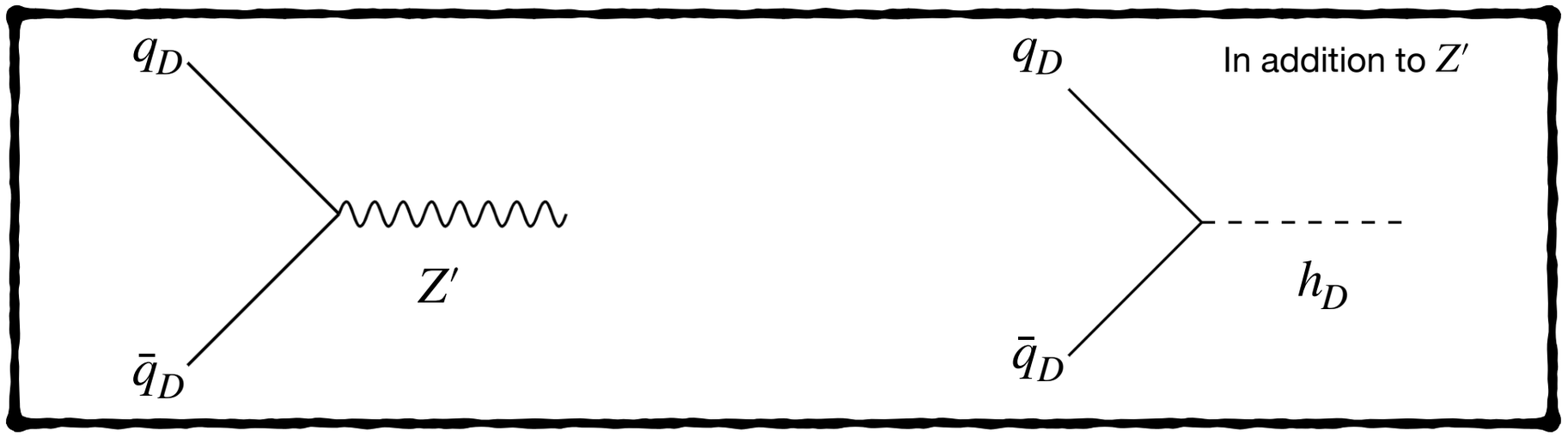
$$\frac{m_{\pi_D}}{\tilde{\Lambda}_D} = 5.5\sqrt{\frac{m_{q_D}}{\tilde{\Lambda}_D}} \qquad \frac{m_{\rho_D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5\frac{m_{\pi_D}^2}{\tilde{\Lambda}_D^2}}$$



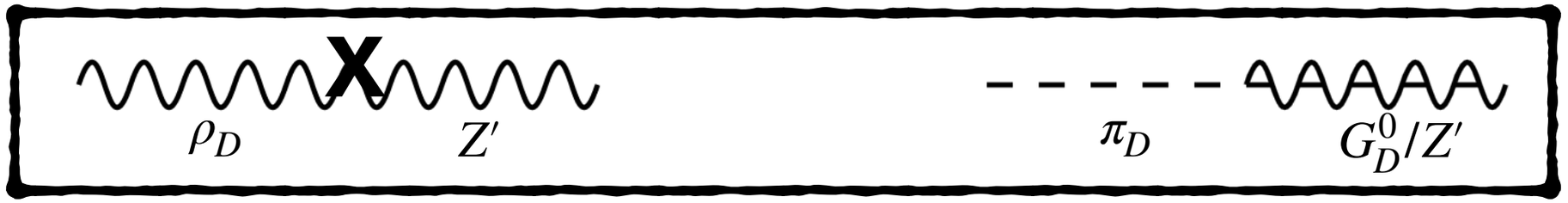


Mediators to the SM

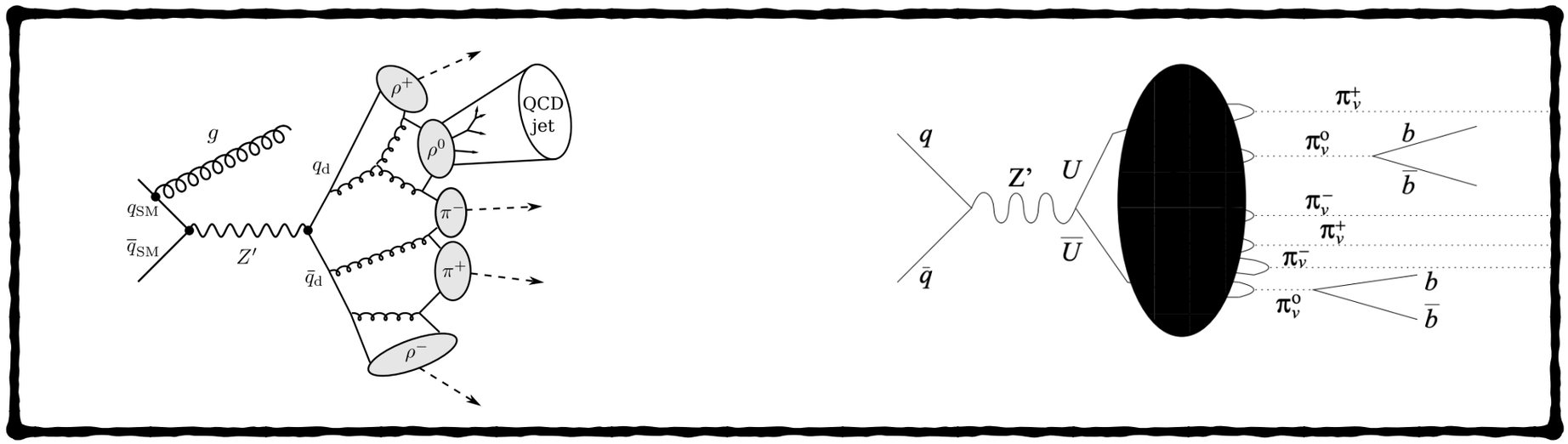
UV theories



IR portals



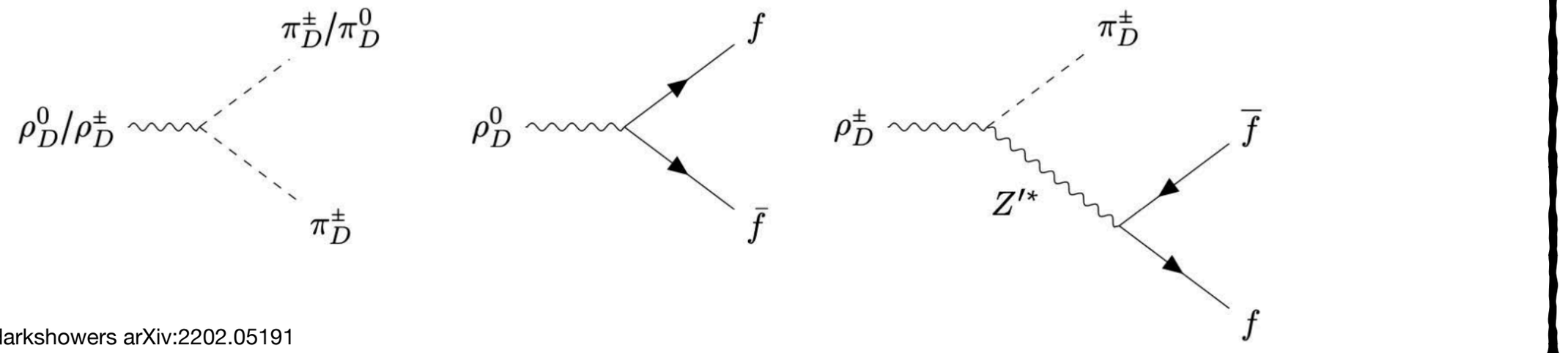
LHC signatures



SVJ composition depends on Z' properties

SVJ typically rich in HF

Dark meson decays

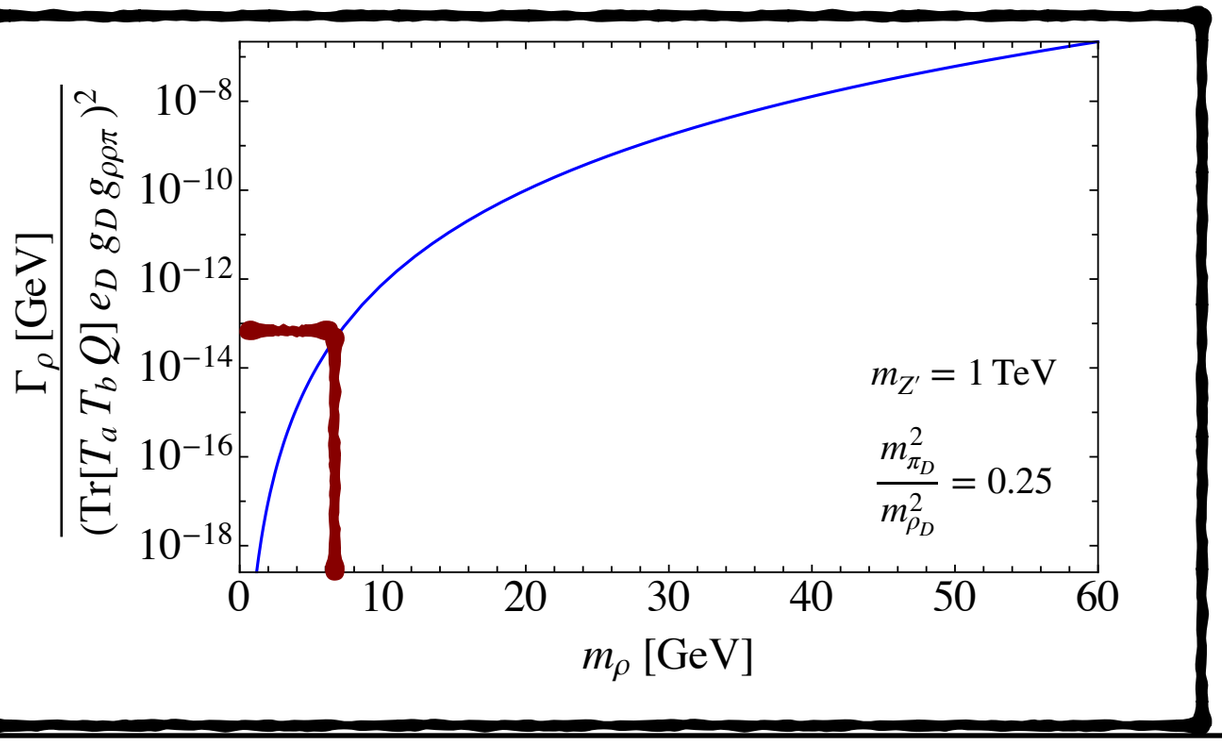


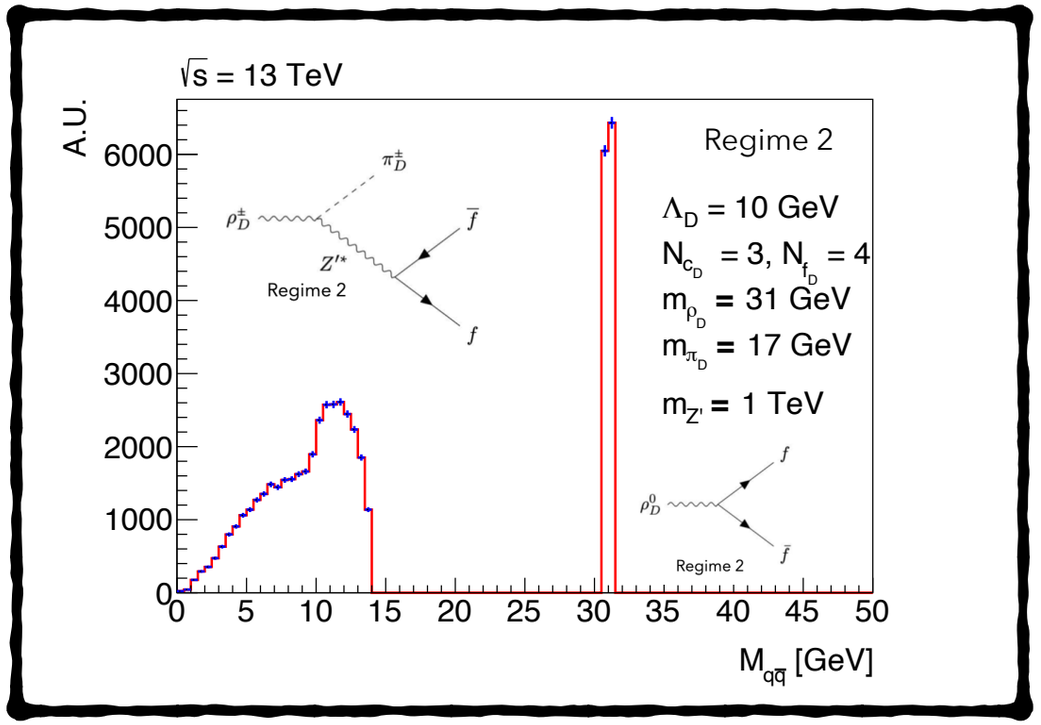
Snowmass darkshowers arXiv:2202.05191

- Off-diagonal dark rho can undergo three body decays; have been absent from much of LHC and DM phenomenology

See also Beriln et al arXiv:1801.05805,
Lee et al arXiv: 1504.00745

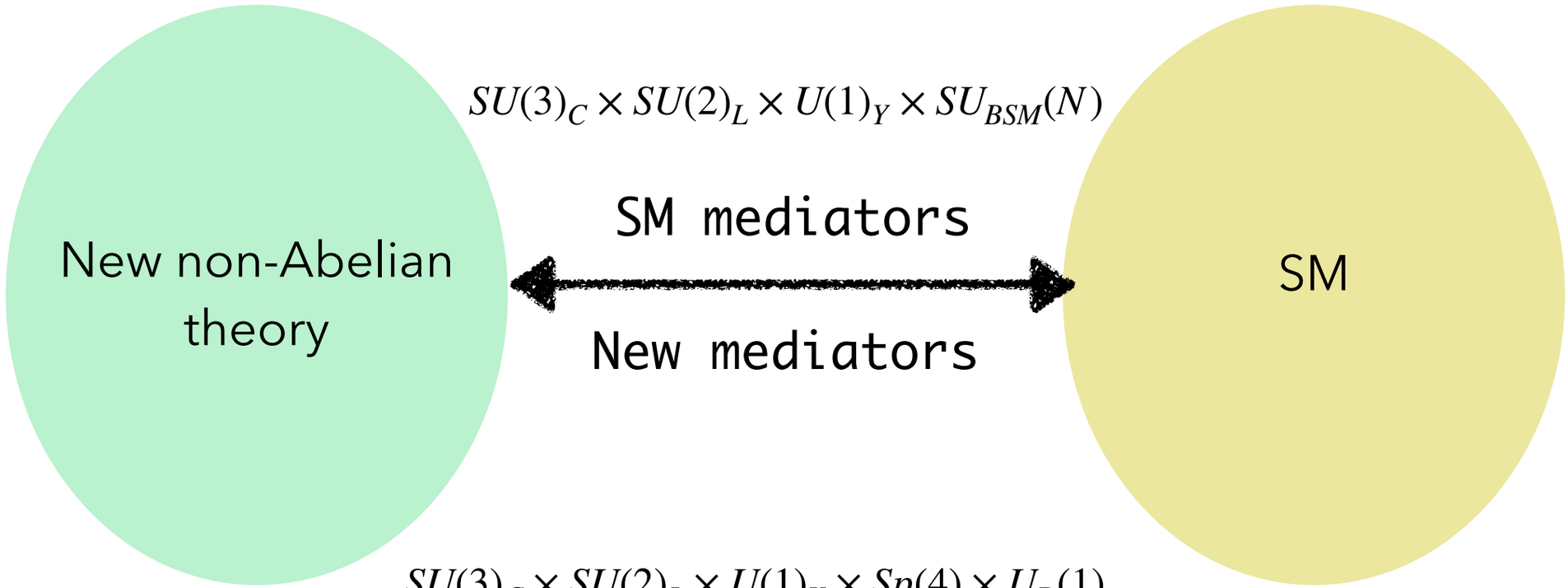
- Leads to LLPs → displaced vertices at the colliders, potential correlation with cosmology





Beyond SU(N)

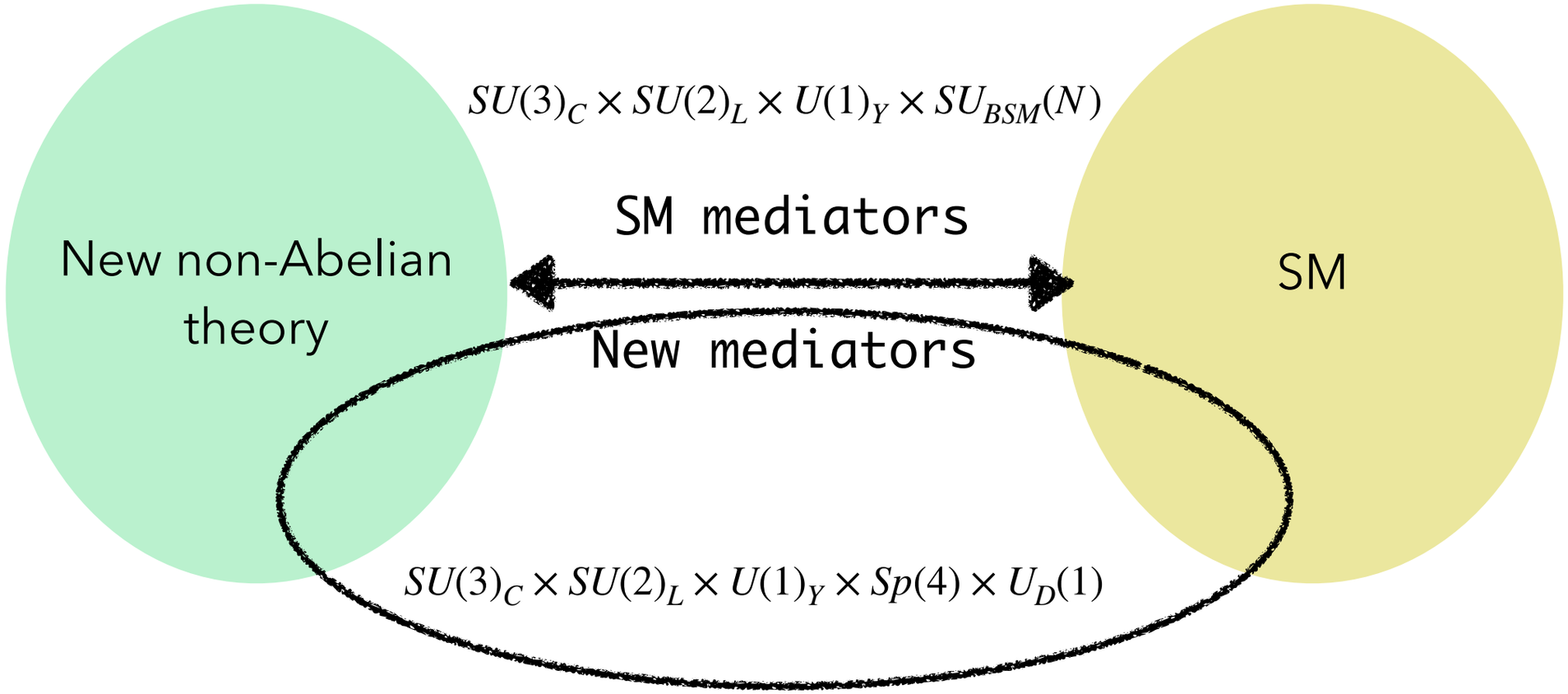
$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU_{BSM}(N)$$



$$SU(3)_C \times SU(2)_L \times U(1)_Y \times Sp(4) \times U_D(1)$$

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

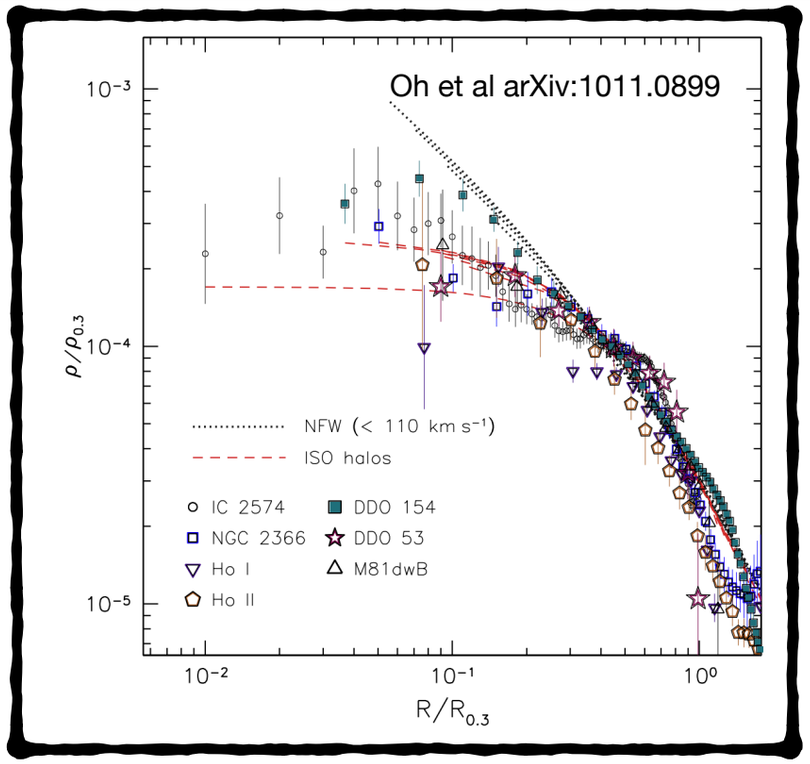
Beyond SU(N)

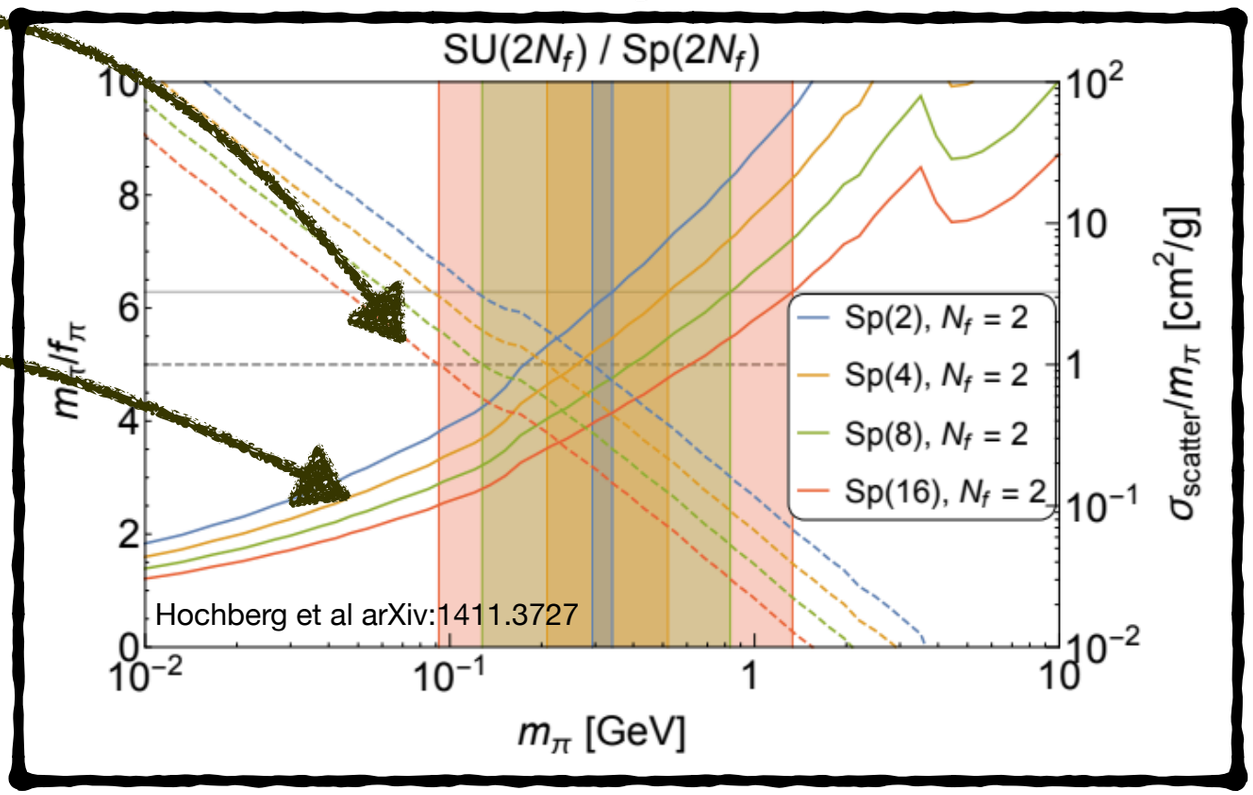


S.K., A. Maas, S. Mee, M. Nikolic, J. Pradler, F. Zierler arXiv:2202.05191

Dark pion dark matter

- Work in chiral regime, pions are pseudo-Goldstone bosons
- Chiral Lagrangian also contains Weiss-Zumino-Witten term
- In the SM: $K^+K^- \to \pi^+\pi^0\pi^-$ and $\pi^0 \to \gamma\gamma$

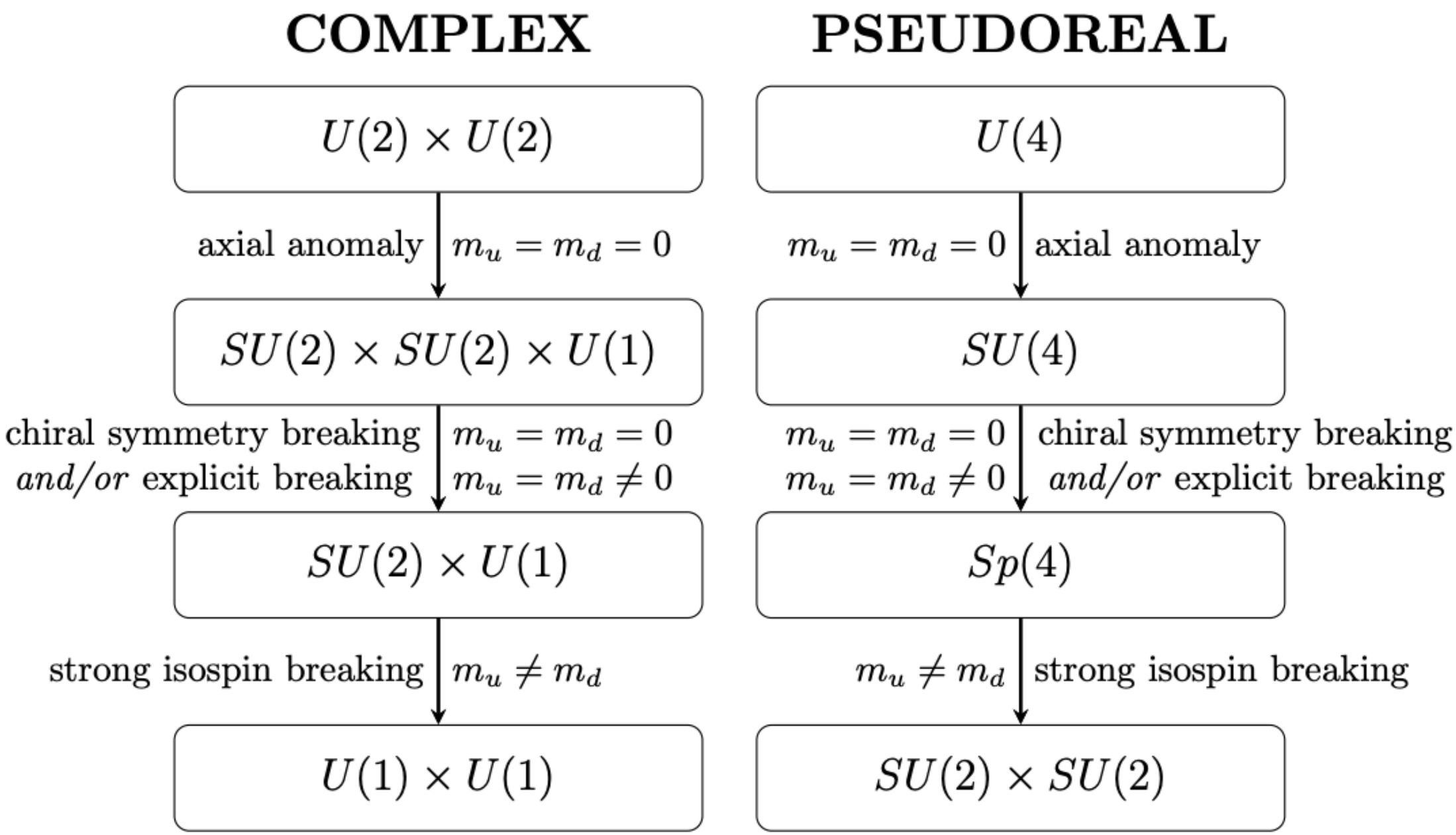




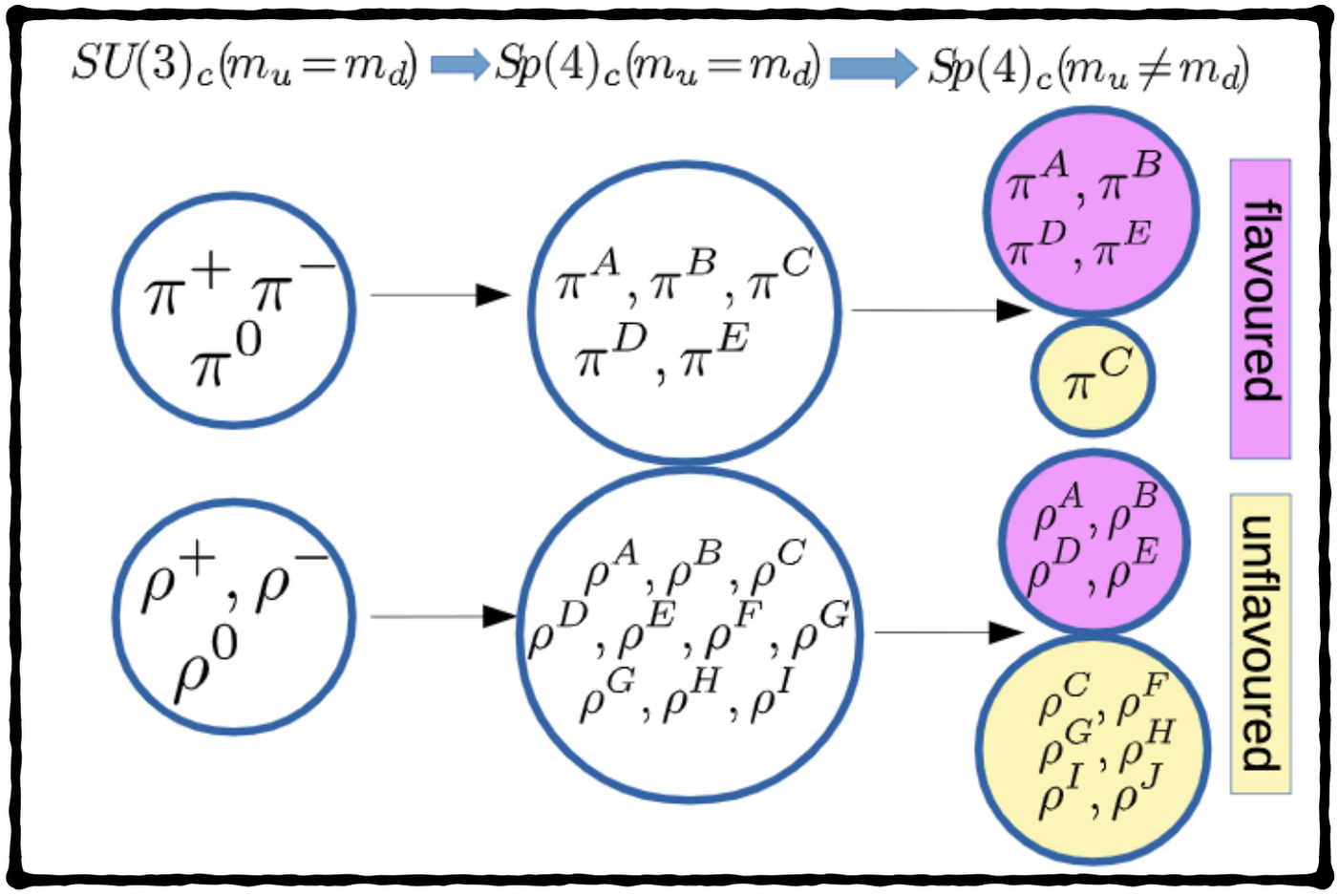
Symmetries

Any SU(N), N > 2 group $N_f = 2$

Sp(4)/symplectic group $N_f = 2$



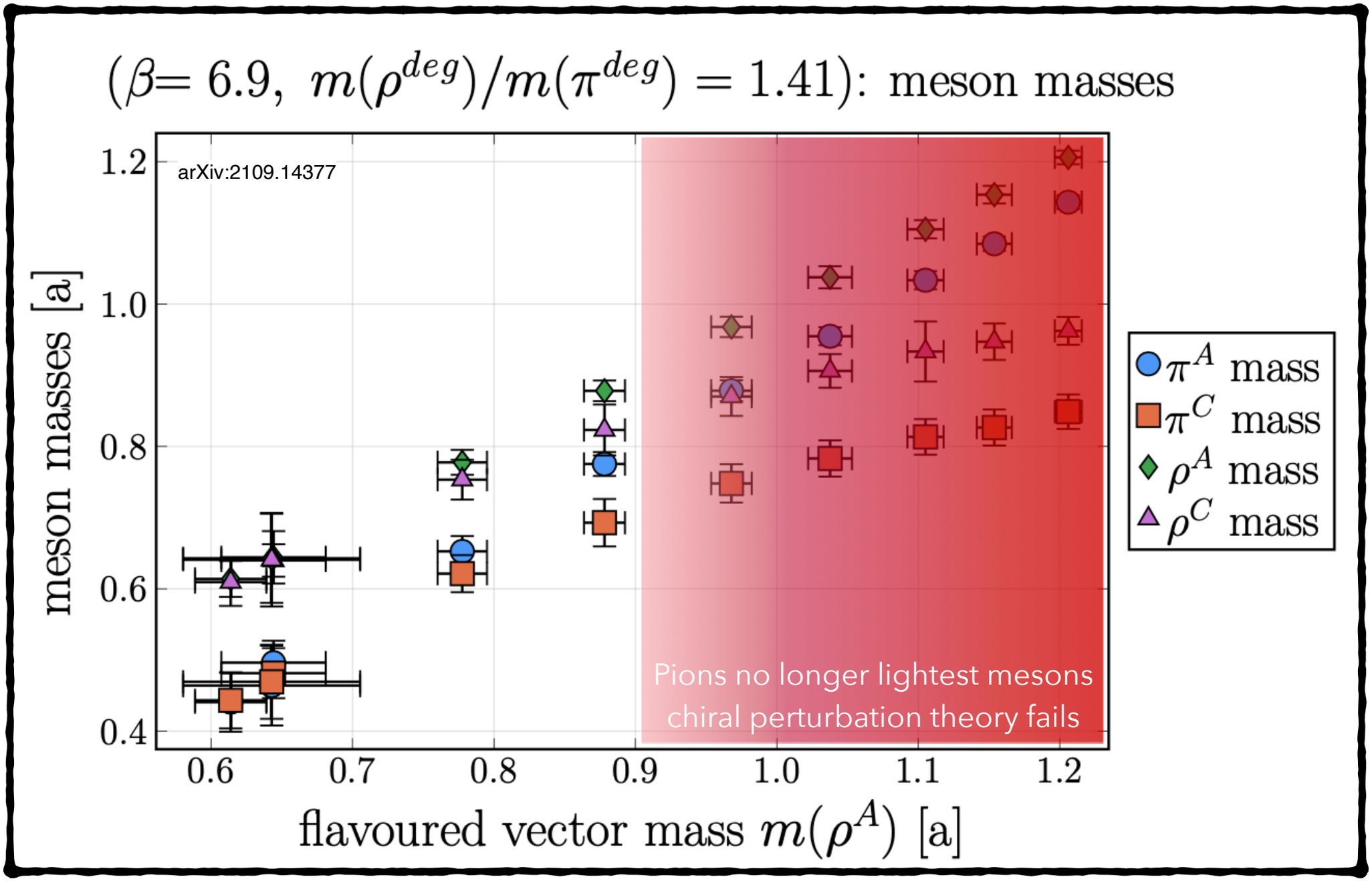
Phenomenological implications



- Theory contains 5 pions associated with broken generators of SU(4)/Sp(4)
- It contains 10 rho mesons associated with unbroken generators
- Can lead to characteristically different phenomenology in low energy
- Charging the theory under external U(1) keeps all pions stable

$$Sp(4) \to SU(2) \times U(1) \quad \begin{pmatrix} \pi^C \\ \pi^D \\ \pi^E \end{pmatrix}, \begin{pmatrix} \pi^A \\ \pi^B \end{pmatrix}$$

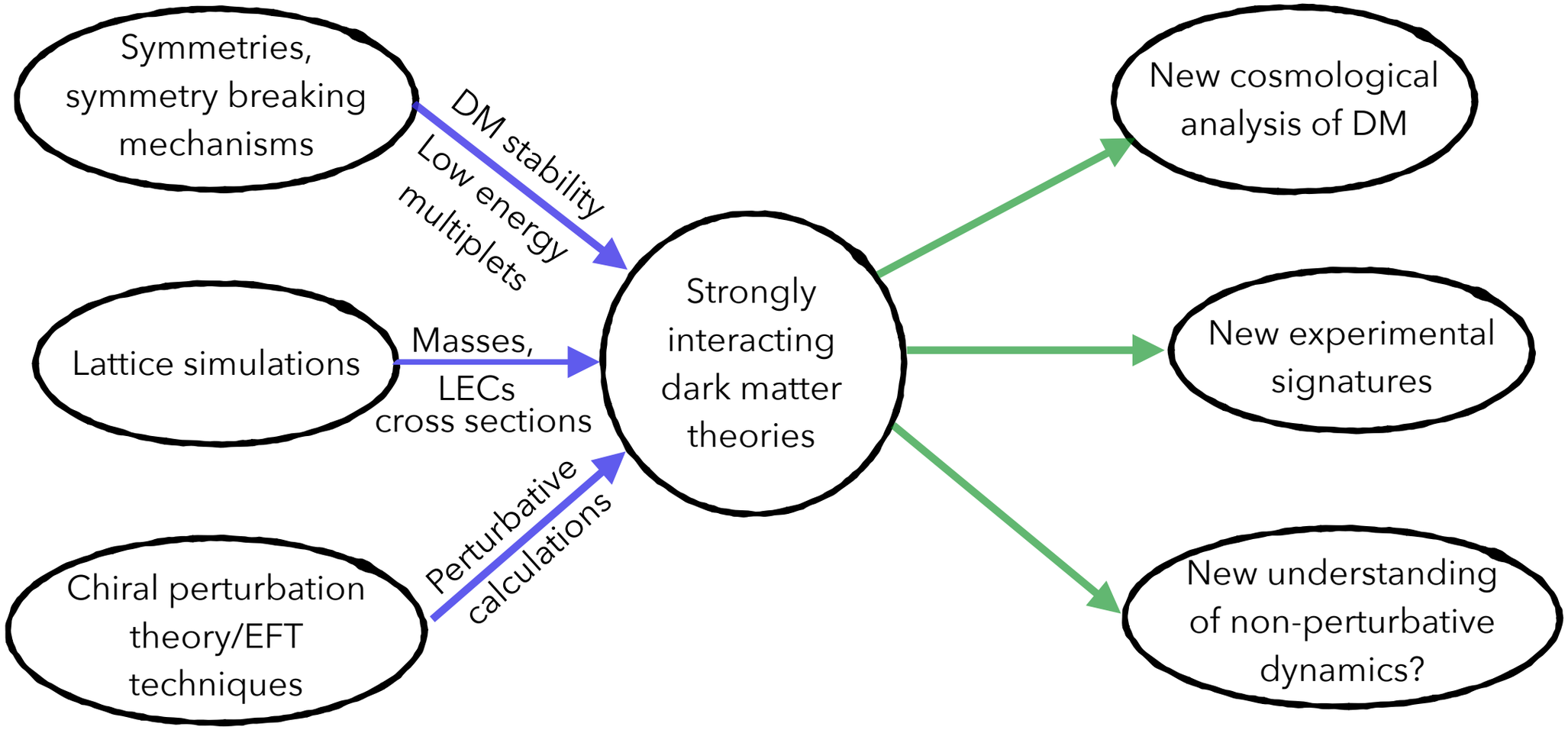
Lattice calculations $m_u \neq m_d$



- For the first time ever, lattice calculations available for non-degenerate dark quark masses

Conclusions

A systematic analysis of strongly interacting theories is possible



- Presented several examples containing dark baryon and dark pion dark matter candidates
- DM stability is ensured either via symmetries inbuilt in the theories or via careful choices of external charges
- Multiple relic density generation mechanisms can be engineered
- Portals lead to new interesting phenomenology

Thanks for listening

Questions?