Overview of the theory landscape for dark QCD models with focus on viable DM candidates

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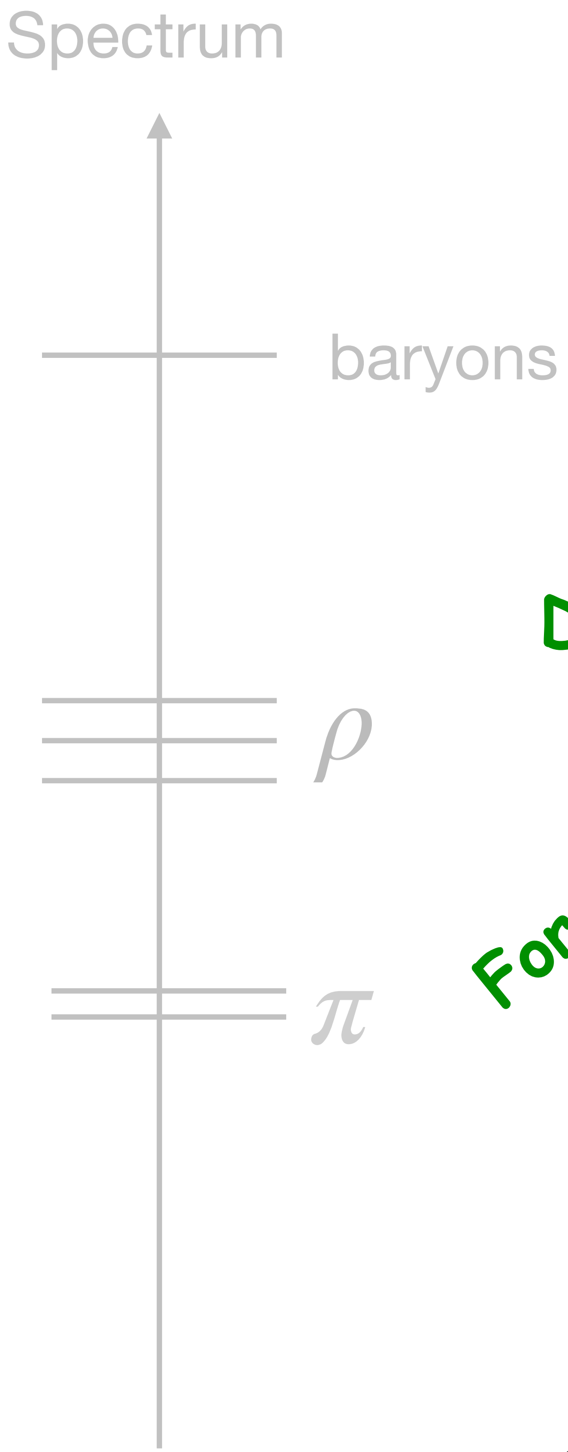
DMWG meeting

NAWI Graz
Natural Sciences

FWF
Der Wissenschaftsfonds.

UNI GRAZ

Dark matter: composite dark matter



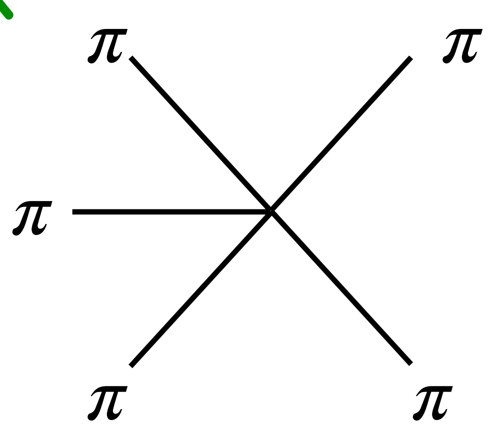
What if dark matter is result of non-Abelian dynamics in dark sector?

Important theory considerations

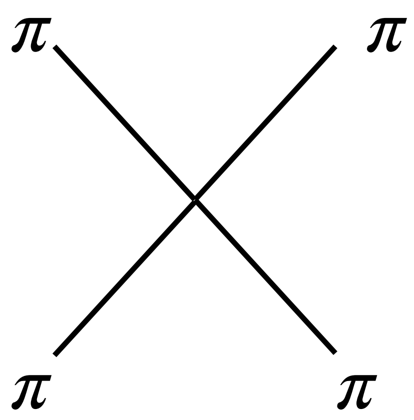
- What is the UV realisation of non-Abelian theory?
- What is the resulting IR dynamics?
- What is the DM - SM mediator mechanism?
- What stabilises DM?

DM stability: (Mostly) For free!

For free!



3 →2 annihilations



Self-interactions

New signatures!

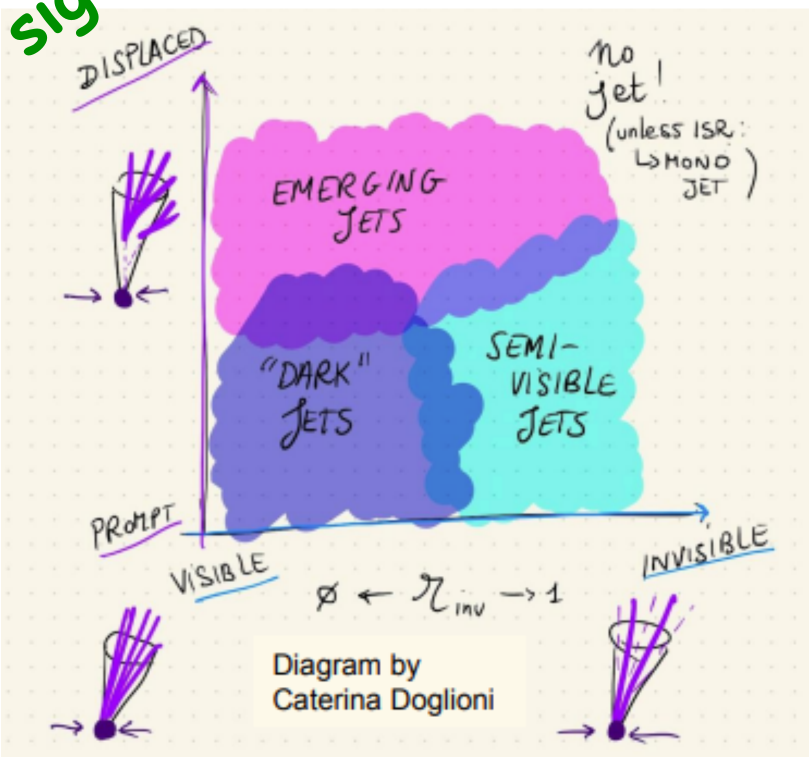
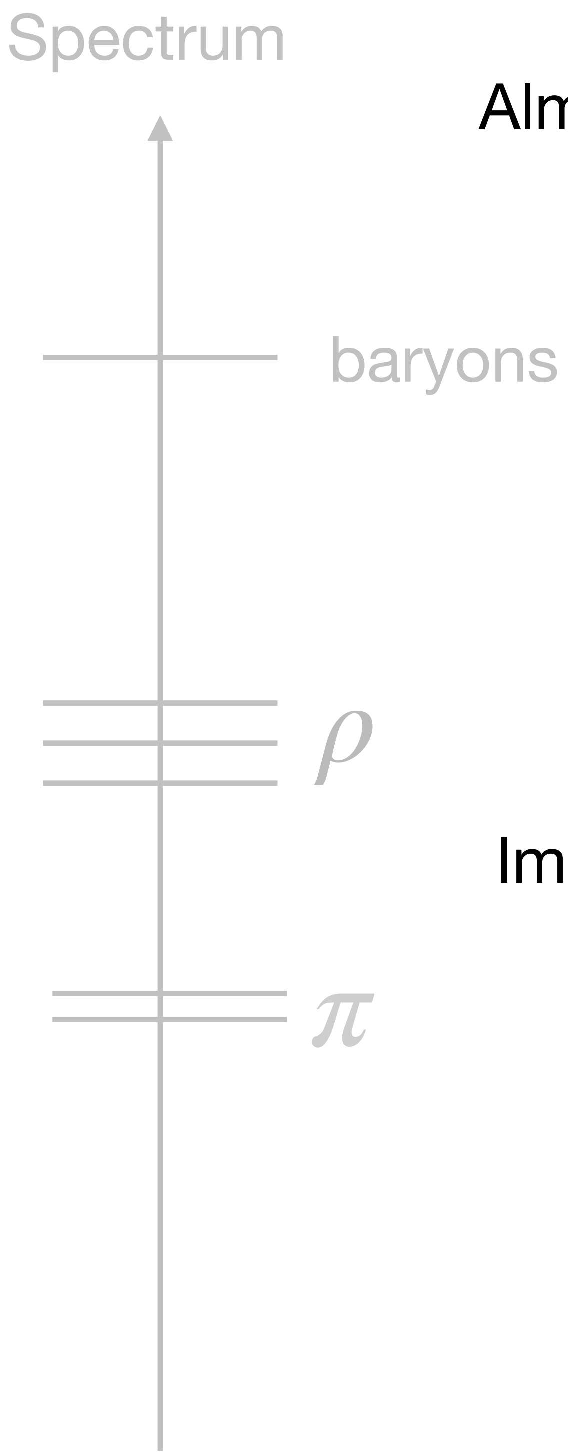


Diagram by Caterina Doglioni

Composite dark matter: candidates



Candidates are stable if they are the lightest particles with nothing to decay to OR they are part of (unbroken) multiplets i.e. symmetry protected

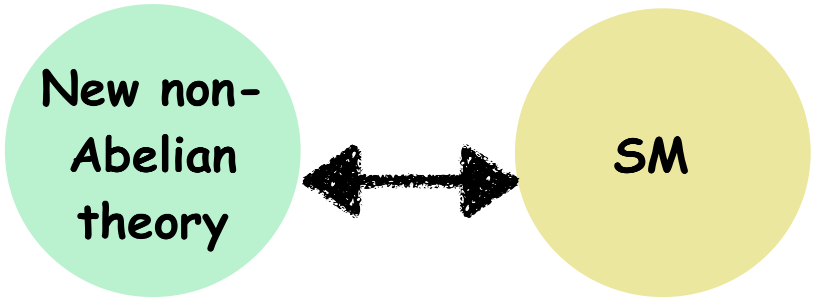
Almost all candidates can lead to self-interactions in the right mass range

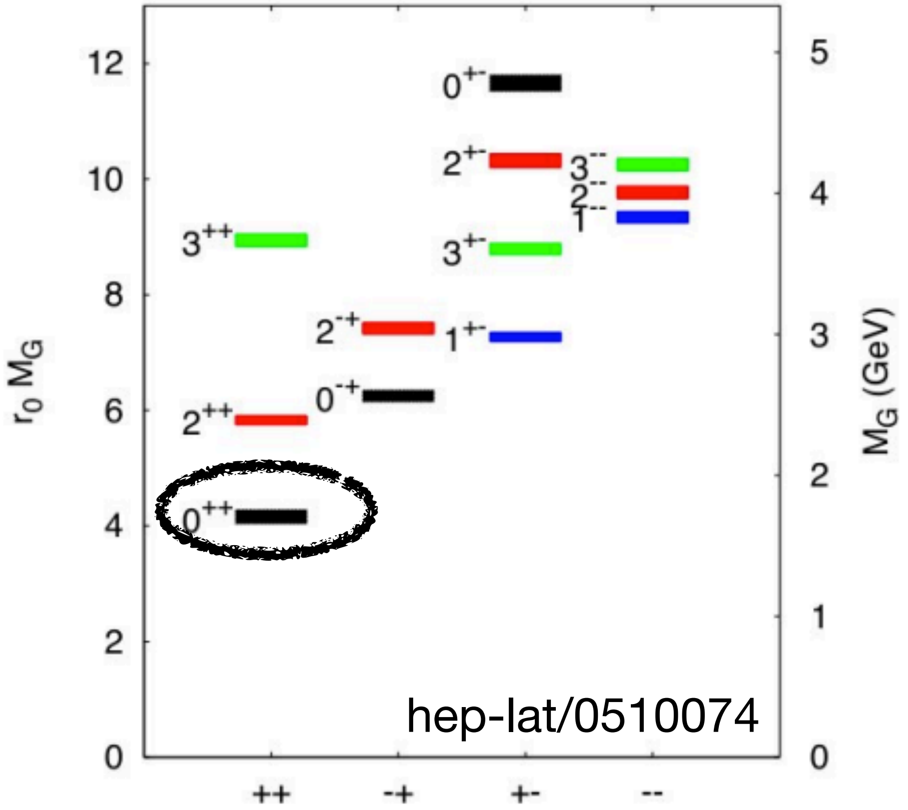
- Dark glueballs: unavoidable if $m_{q_D} \gg \Lambda_D$, simplest non-abelian theory realisation, stability tricky
- Dark mesons: dark pions famous, stability tricky
- Dark baryons: stability guaranteed
- Dark atoms: stability for free

Important dark sector considerations:

- Stability, longevity (no-trivial)
- Relic density generation (not always WIMP)
- Cosmological constraints (important for light DM)

Glueballs dark matter





hep-lat/0510074

Unavoidable in:

- Non-Abelian theory with no matter fields
- Theory with $m_{q_D} \sim 7\Lambda_D$
- 0^{++} lightest state unstable if SM - DS mediator present

arXiv:2108.10314

$$\mathcal{O} = \frac{1}{M^3} G_{\mu\nu} G^{\mu\nu} \bar{f} f$$

$$\langle f\bar{f} | \mathcal{O} | \phi \rangle \sim \frac{\Lambda_D^4}{M^3} \qquad \langle f\bar{f} | \mathcal{O} | \phi\phi \rangle \sim \frac{\Lambda_D^3}{M^3}$$

$$\Gamma \sim \frac{\Lambda_D^7}{M^6} \sim 3 \times 10^{26} cm^3/s \qquad \langle \sigma v \rangle \sim \frac{\Lambda_D^4}{M^6} > \frac{1}{\tau_{universe}}$$

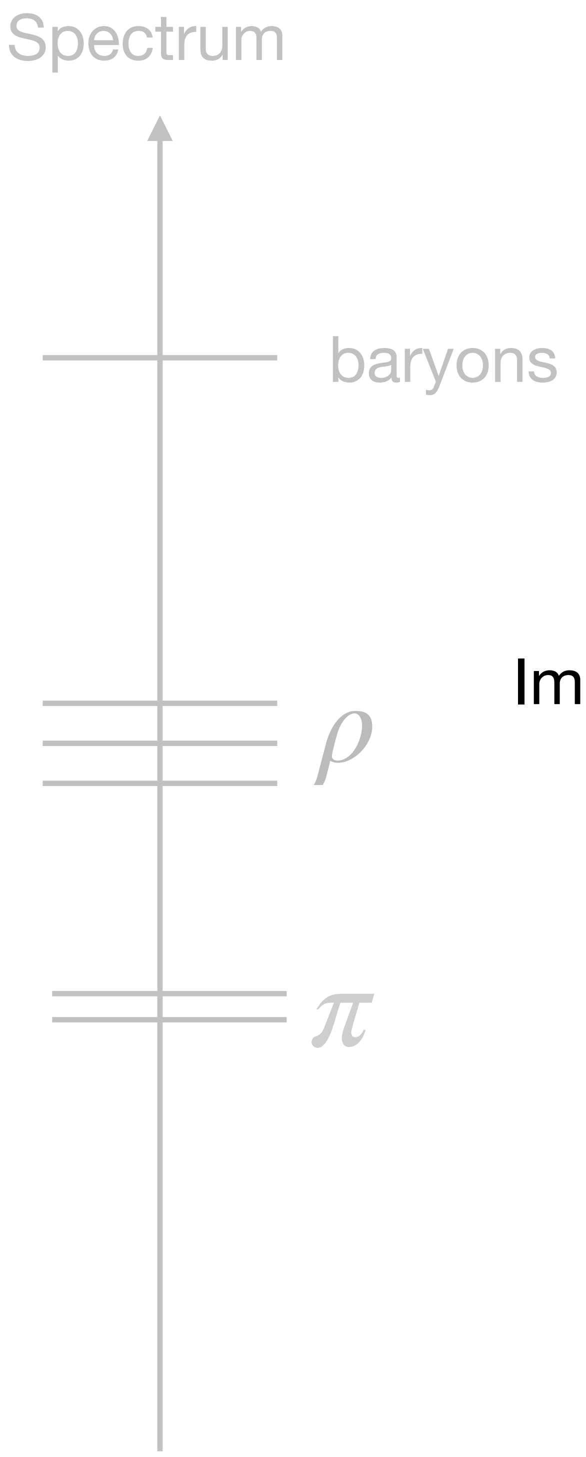
$$M \sim 1\mathrm{keV} \qquad \Lambda_{\mathrm{D}} \sim 0.01\mathrm{eV}$$

LHC and indirect detection phenomenology currently very restricted

Needs more understanding and simulation tools here

Typical early Universe phenomenology for non-thermal glueballs

Composite dark matter: candidates



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Theories with matter fields

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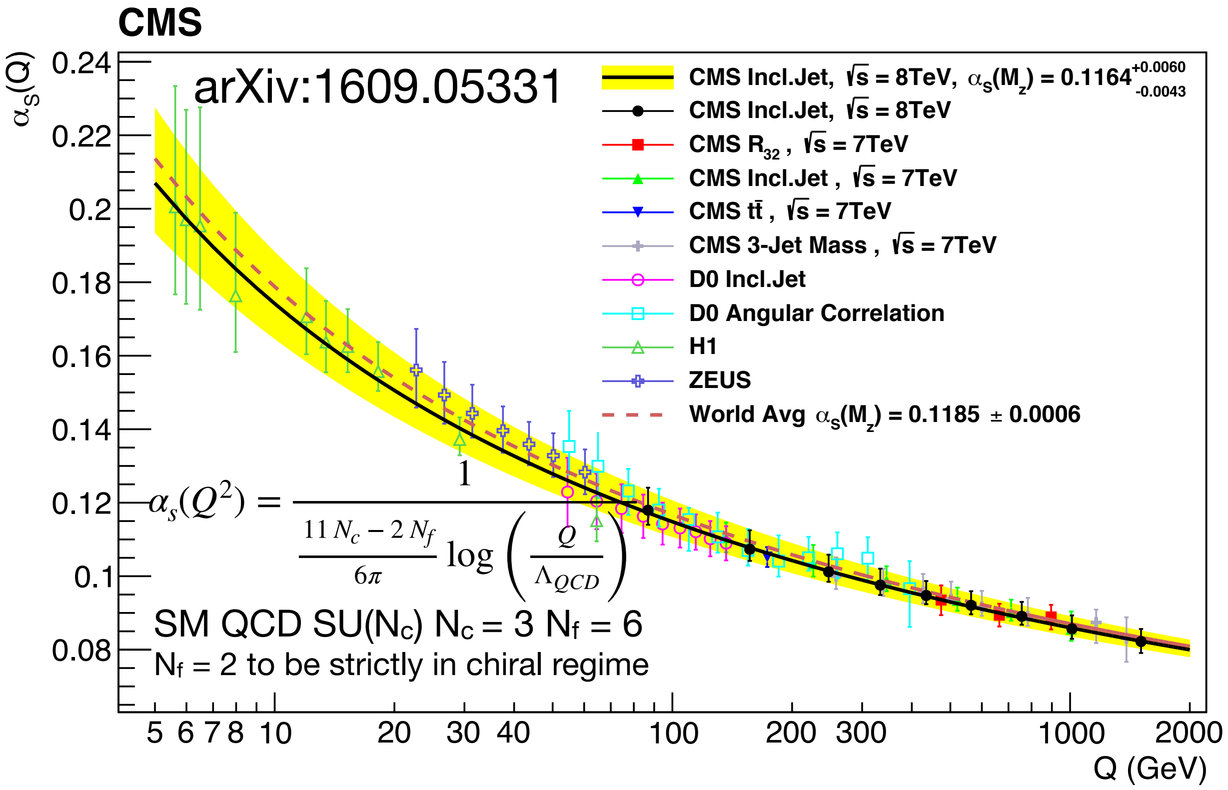
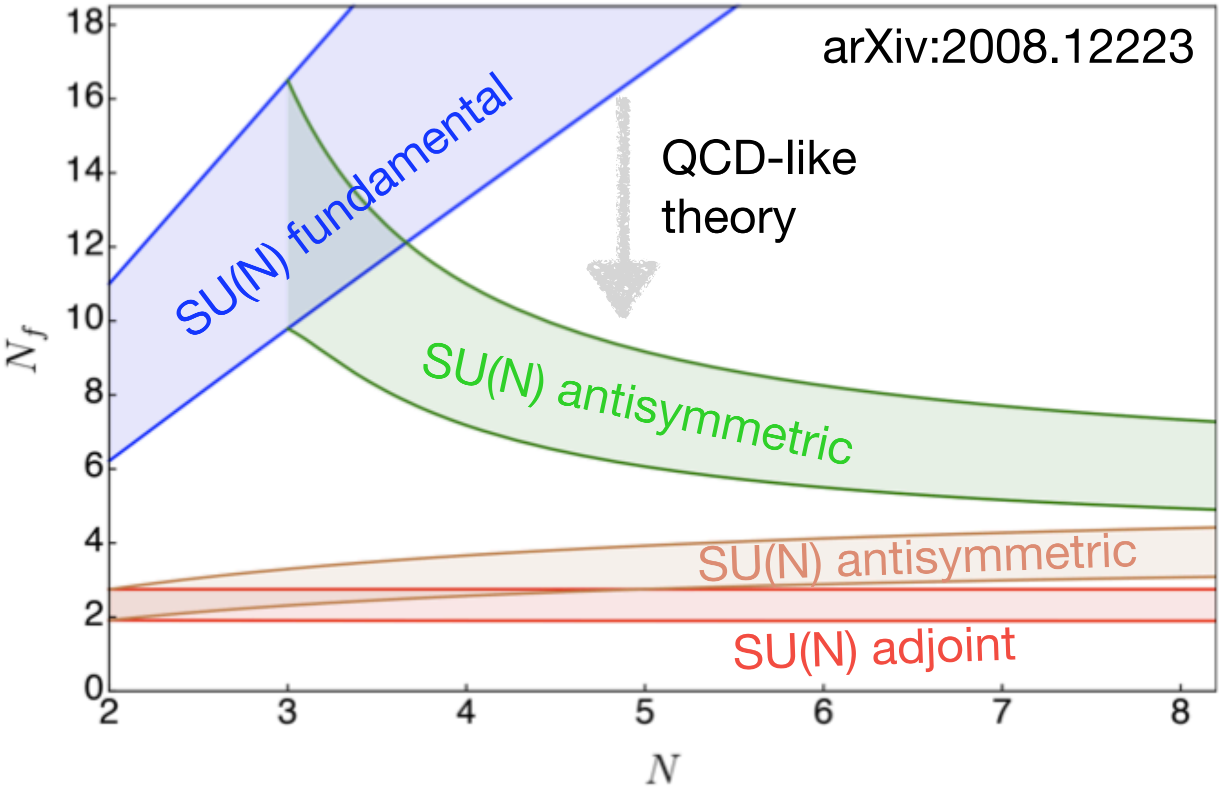
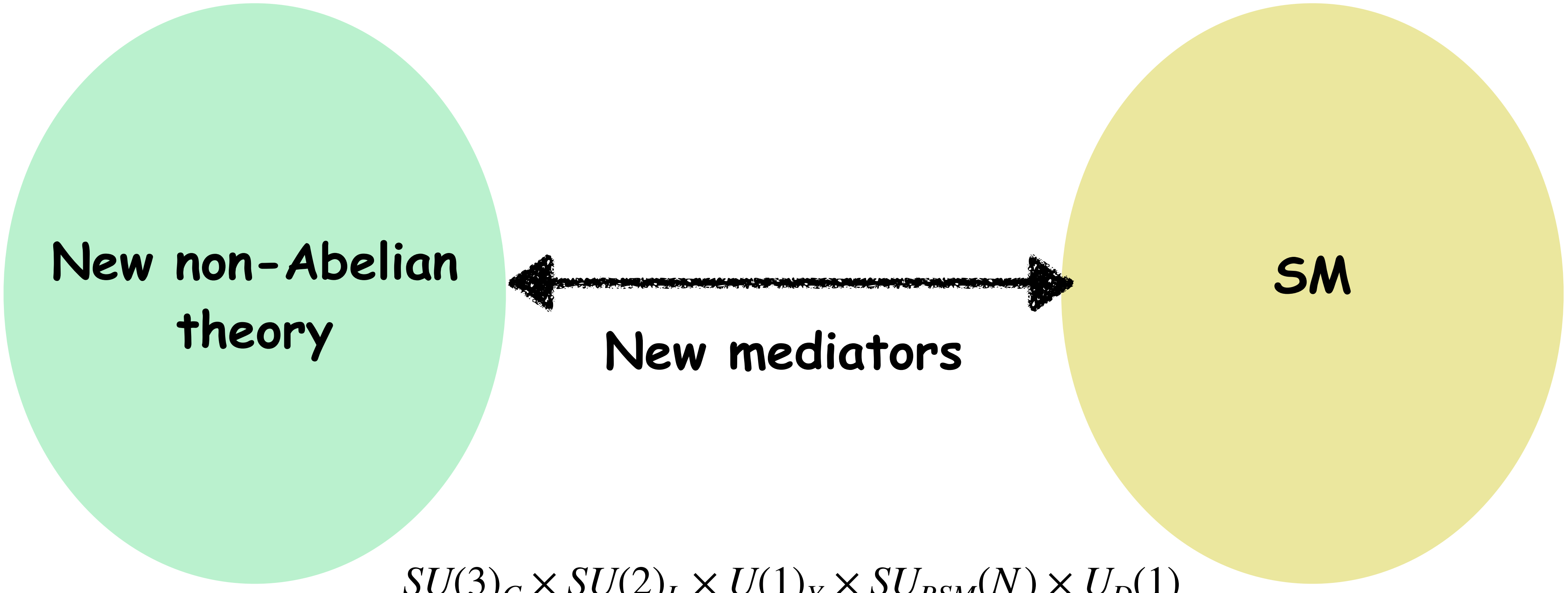
Strongly interacting theories: QCD-like





- This talk: QCD-like theories only, only Dirac fermion mass degenerate matter fields in fundamental representation
- QCD like theories: asymptotically free theories and are in chirally broken phase
- As a side note: the confinement scale Λ_{QCD} is free, fixed only by measuring coupling constant, conversely coupling constant is NOT a free parameter of the theory
- For such theories low energy calculations are done using chiral perturbation theory

Model parameter space



New non-Abelian theory

New mediators

SM

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

New non-Abelian sectors could also be SO(N), Sp(N) theories
Only concentrate on SU(N) theories

Strongly interacting theories: scales

Chiral $m_q \ll \Lambda$

SM QCD $N_f = 2 \ \ (u, d)$

$m_\pi \propto \mu$

Correction from small quark mass

Comparable scale: $m_q \sim \Lambda$

Is leading order χPT valid?

Quarkonia-like: $m_q \gg \Lambda$

SM QCD with charm, bottoms $N_f = 2 + 1 + 1$

$m_\pi \propto 2m_q$

Glue-balls live here

$\sqrt{s} \gg m_q, \Lambda$

Jetty physics

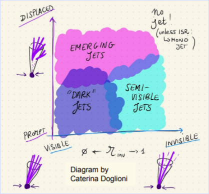


Diagram by Caterina Doglioni

arXiv:1503.00009
arXiv:1502.05409

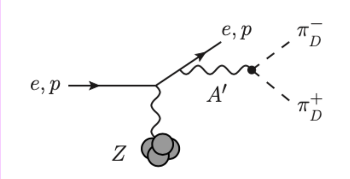
Glueballs

Snowmass darkshowers project

For a some issues related to jetty physics see M. Strassler's talk at LLP-X workshop

$\sqrt{s} \sim m_q, \Lambda$

Hadronic resonances



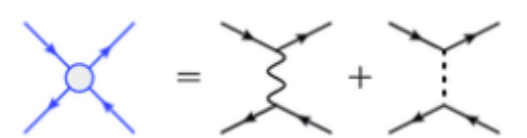
arXiv:1809.10183, 1801.05805, 1512.07917

EFT e.g SMEFT, Glueballs

For a review c.f. arXiv:1604.04627

$\sqrt{s} \ll m_q, \Lambda$

EFT e.g SMEFT



Glueballs

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

$m_q \ll \Lambda$ $\quad m_q \sim \Lambda$ $\quad m_q \gg \Lambda$

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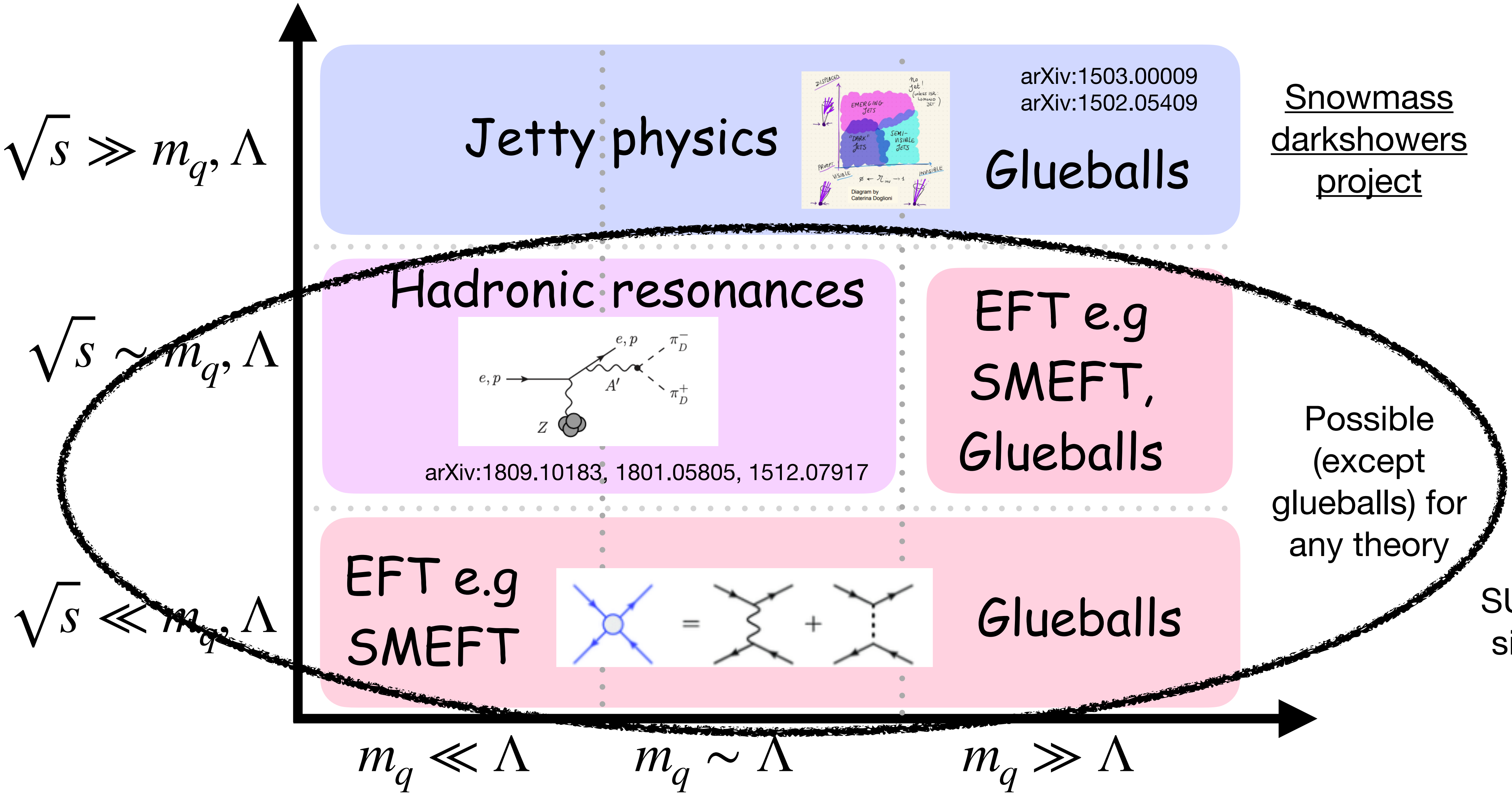

$\sqrt{s} \gg m_q, \Lambda$

$\sqrt{s} \sim m_q, \Lambda$

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Jetty physics

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Glueballs

Hadronic resonances

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EFT e.g SMEFT, Glueballs

EFT e.g SMEFT

Glueballs

Possible (except glueballs) for any theory

$m_q \ll \Lambda$ $m_q \sim \Lambda$ $m_q \gg \Lambda$

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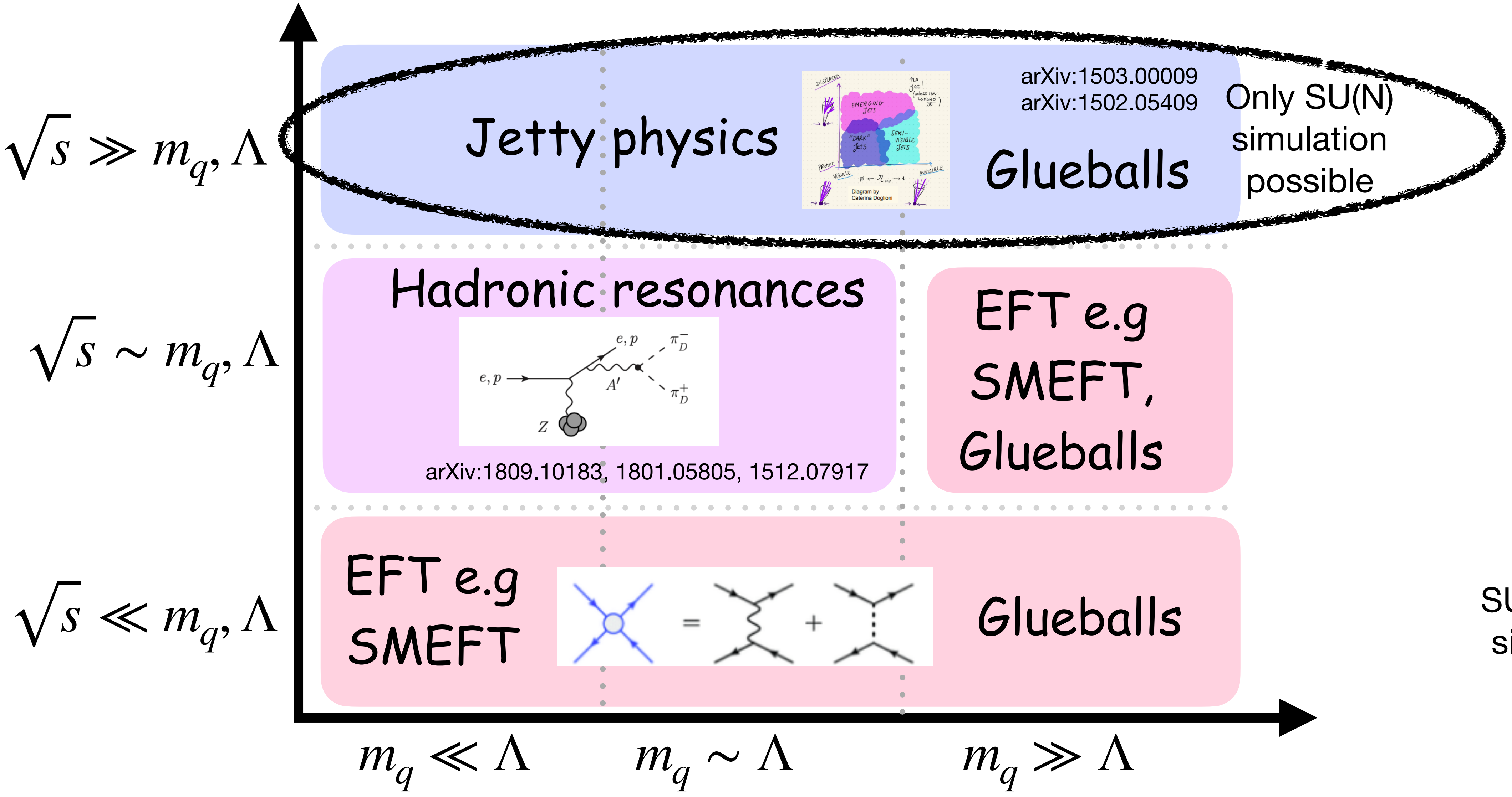

$\sqrt{s} \gg m_q, \Lambda$

Jetty physics

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Glueballs

Only SU(N) simulation possible

$\sqrt{s} \sim m_q, \Lambda$

Hadronic resonances

arXiv:1809.10183, 1801.05805, 1512.07917

EFT e.g SMEFT, Glueballs

$\sqrt{s} \ll m_q, \Lambda$

EFT e.g SMEFT

Glueballs

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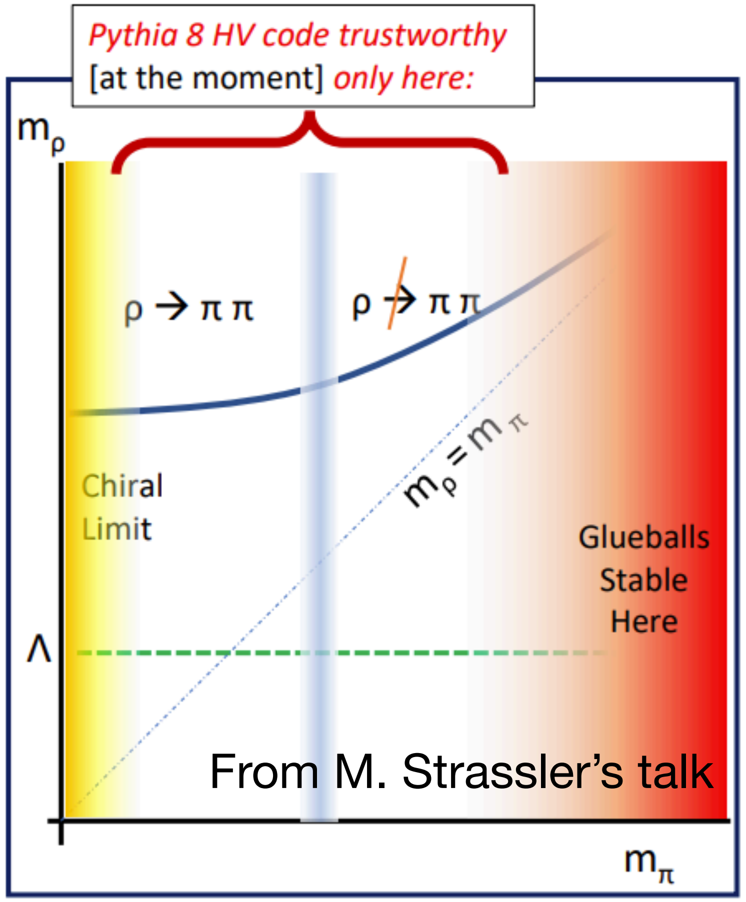
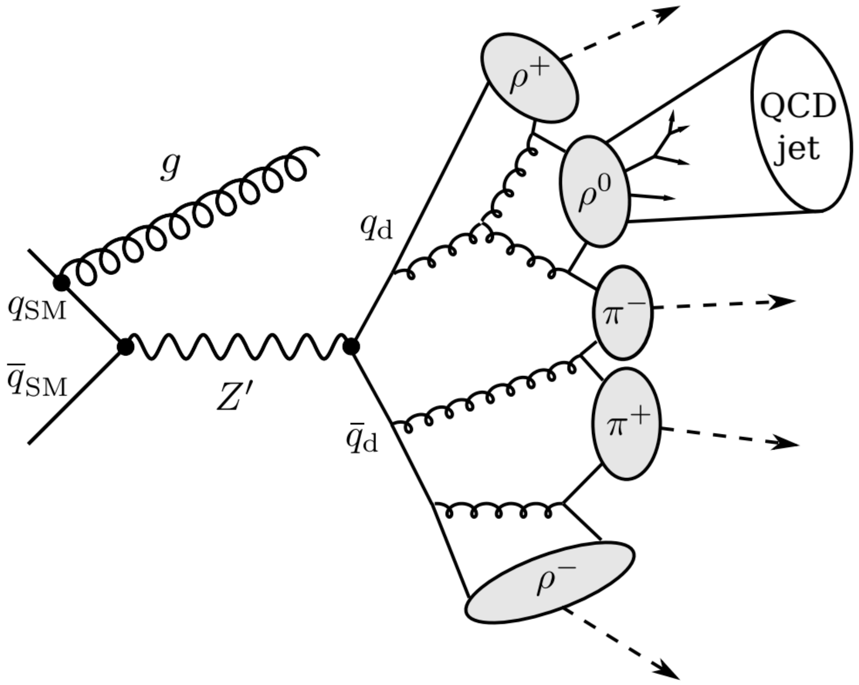
Jetty physics: too much ado about nothing?



Pythia 8 HV code trustworthy [at the moment] *only here:*

From M. Strassler's talk

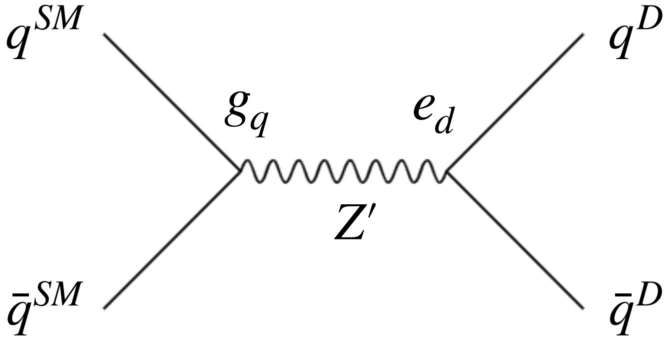
arXiv:1907.04346

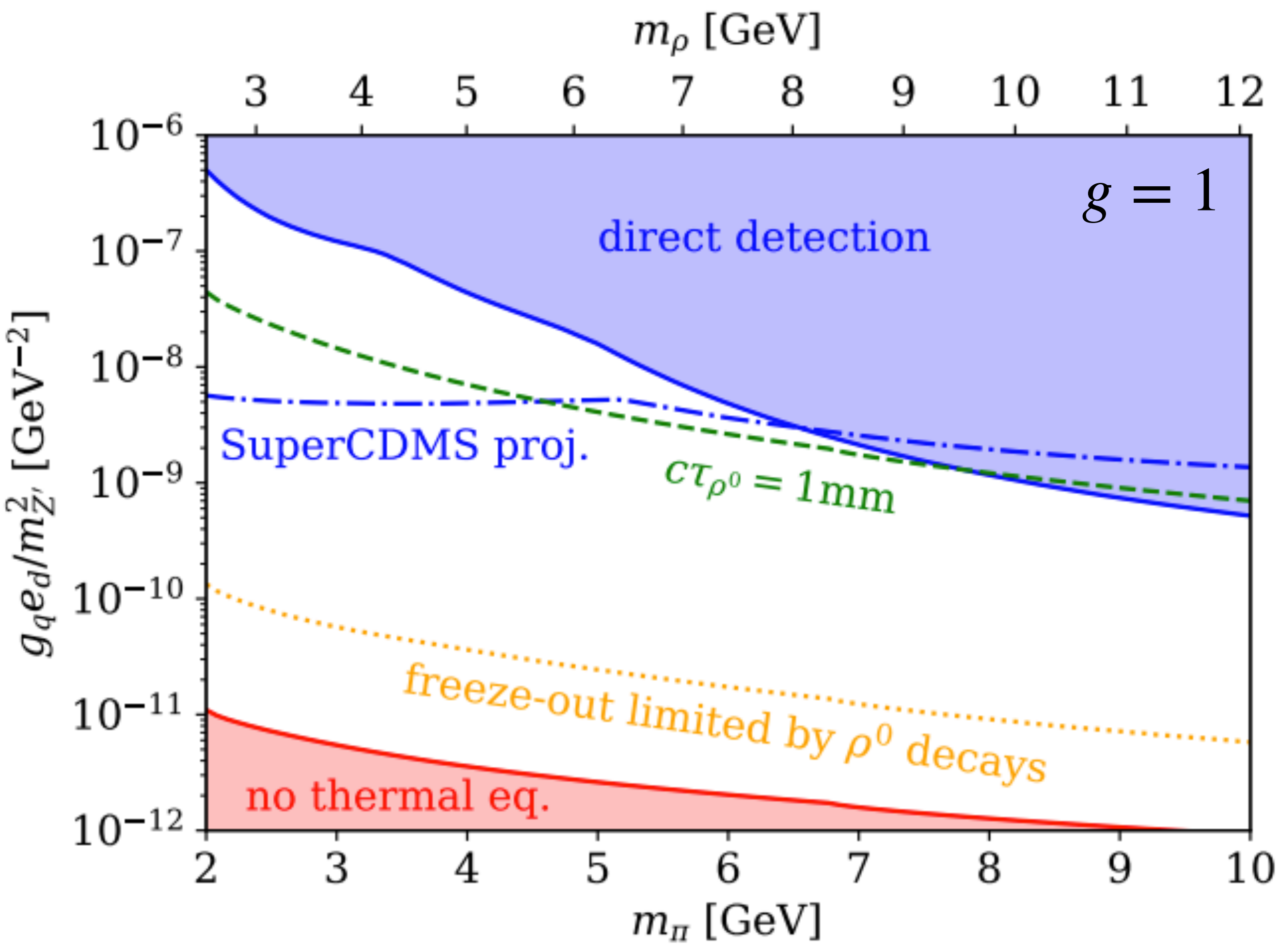


- LHC in jetty regime → sensitive to the UV physics → dark quark masses, Λ_D matter
- Due to high energies, LHC can be sensitive to higher excitations in the spectrum
- Theory has only four free parameters $N_c, N_f, m_\pi/\Lambda, \Lambda$ they need to be chosen carefully for chiral PT to be valid, 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 pions dark matter

$$m_{q_D} < \Lambda_D \ll m_{Z'}, \sqrt{s}$$

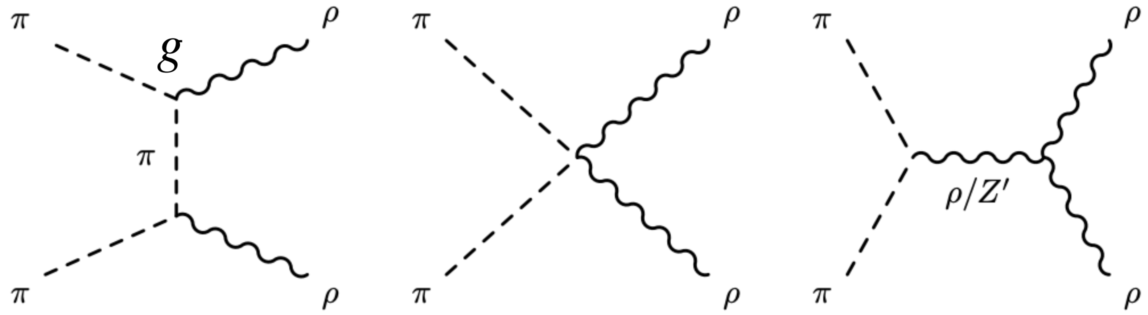




ρ mass chosen in order to satisfy relic

arXiv:1907.04346

Sector	Particles	Parameters
$SU(3)$	$q_{\mathrm{d},i}$ $(i = 1, 2)$, A_d (dark gluon)	m_q, Λ_d
Chiral EFT	$\pi^\pm$, π^0, $\rho^\pm$, ρ^0	m_π, m_ρ, g
$U(1)'$	Z'	$m_{Z'}$, e_d, g_q



- Relic driven by hidden sector parameters

$$\dot{n}_\pi + 3Hn_\pi = -\langle\sigma_{\pi\pi\to\rho\rho}v\rangle n_\pi^2 + \langle\sigma_{\rho\rho\to\pi\pi}v\rangle (n_\rho^{\mathrm{eq}})^2$$

$$\left(\frac{n_\rho^{\mathrm{eq}}}{n_\pi^{\mathrm{eq}}}\right)^2 \sim \exp(-2\Delta x) \qquad \langle\sigma v\rangle \sim \frac{g^4}{m_\pi^2}$$

- GeV pions lead to too small self-interactions

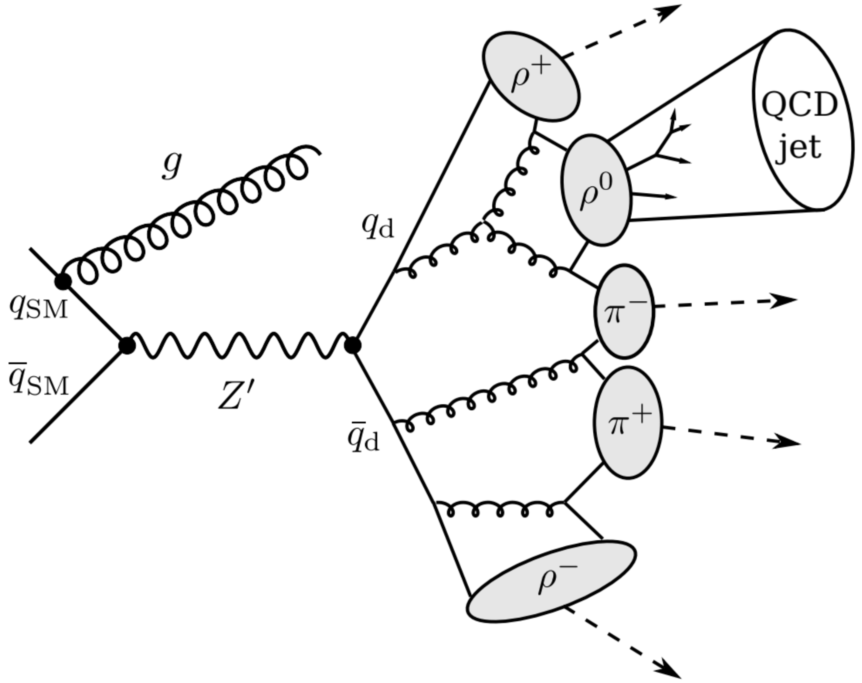
$$\frac{\sigma_{\mathrm{self}}}{m_\pi} = \frac{m_\pi}{4\pi f_\pi^4} \sim 10^{-3}\,\mathrm{cm}^2/\mathrm{g}\left(\frac{m_\pi}{1\,\mathrm{GeV}}\right)^{-3}\left(\frac{g}{\sqrt{4\pi}}\right)^4$$

Dark pions dark matter

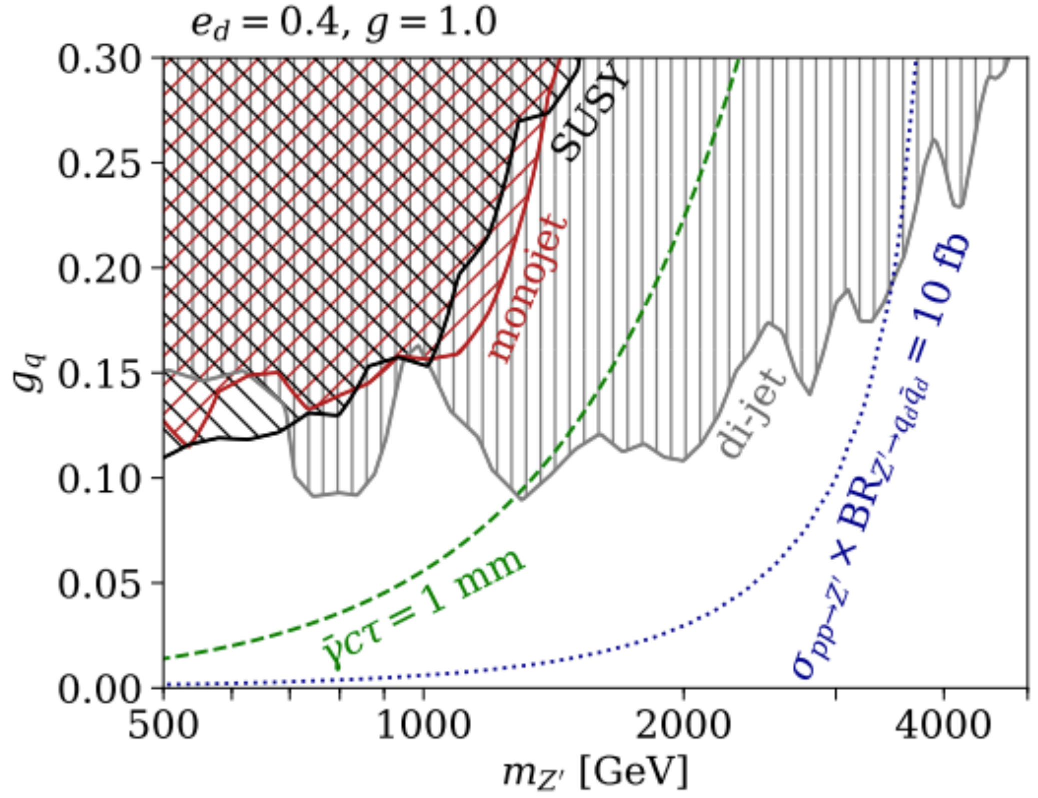
arXiv:1907.04346

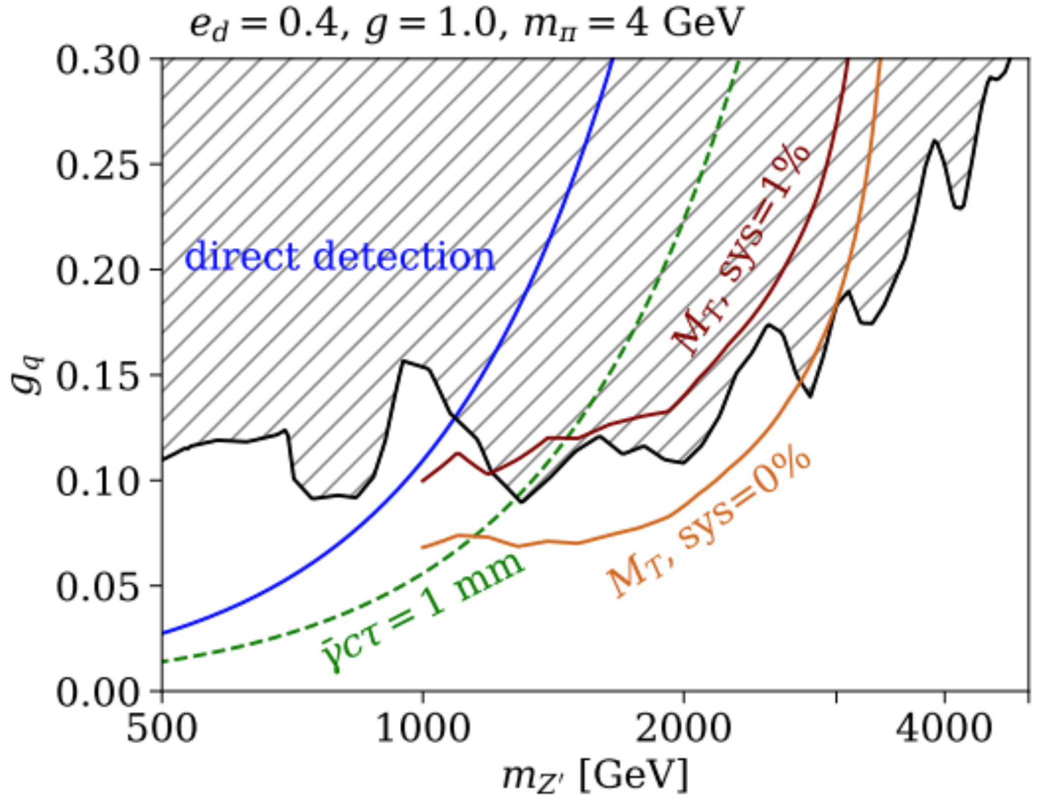
- At colliders the ρ^0 lifetime matters

$$\Gamma\left(\rho^0 \to q_{\rm SM}\bar{q}_{\rm SM}\right) = \frac{1}{\pi}\frac{g_q^2 e_{\rm d}^2}{g^2}\, m_\rho \left(\frac{m_\rho}{m_{Z'}}\right)^4 \left(1-4\frac{m_{q_{\rm SM}}^2}{m_\rho^2}\right)^{1/2} \left(1+2\frac{m_{q_{\rm SM}}^2}{m_\rho^2}\right)$$



- At colliders production cross-section controlled by UV parameters



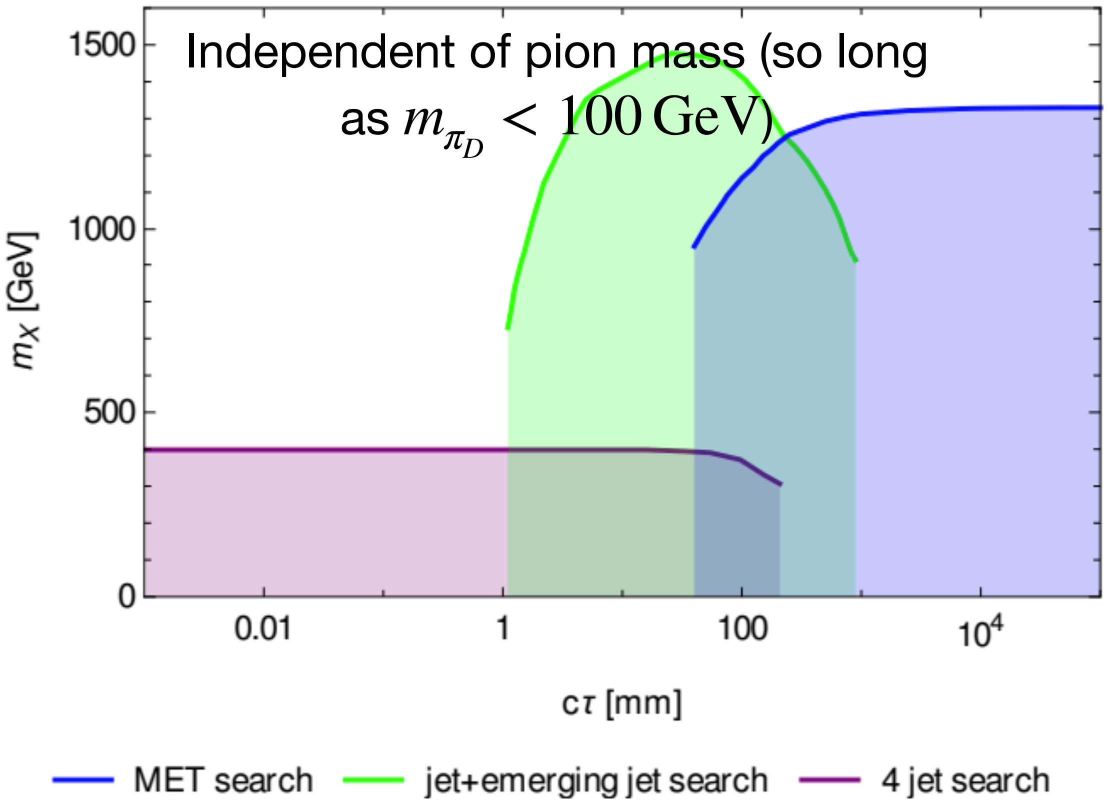


Baryon dark matter

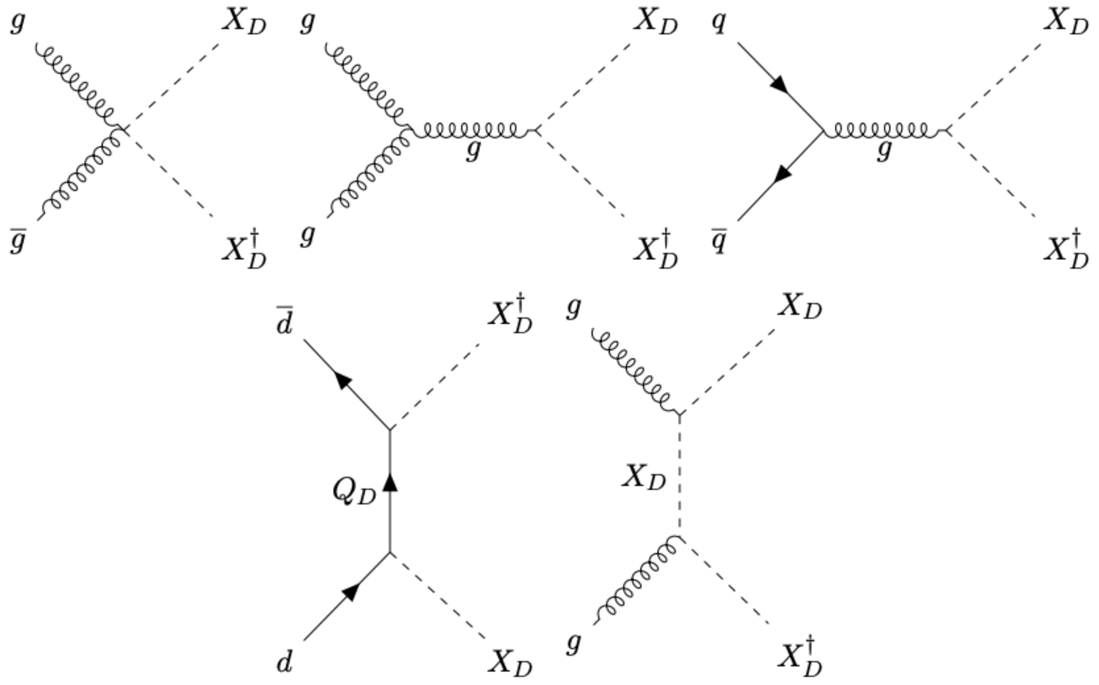
arXiv:2011.13990

- Need SU(N), N > 2, with $N_f > 1$ (number of flavours needed is a bit dependent on gauge group)
- Stability is guaranteed by baryon number (if conserved)
- Computing properties (e.g. masses and interactions) potentially more non-trivial (chi PT techniques may not be sufficient)
- Usually heavier than pions and rho → collider production typically suppressed; collider (LHC) potential reliant on ability to probe rho and pion state
- Advantage: pions decay allowed → possible to construct t-channel models

$$\mathcal{L}_{Yuk} = -\kappa_{ij}\bar{d}_{Rj}Q_{D_{Li}}X_D + h.c.$$



Independent of pion mass (so long as $m_{\pi_D} < 100\,\mathrm{GeV}$)



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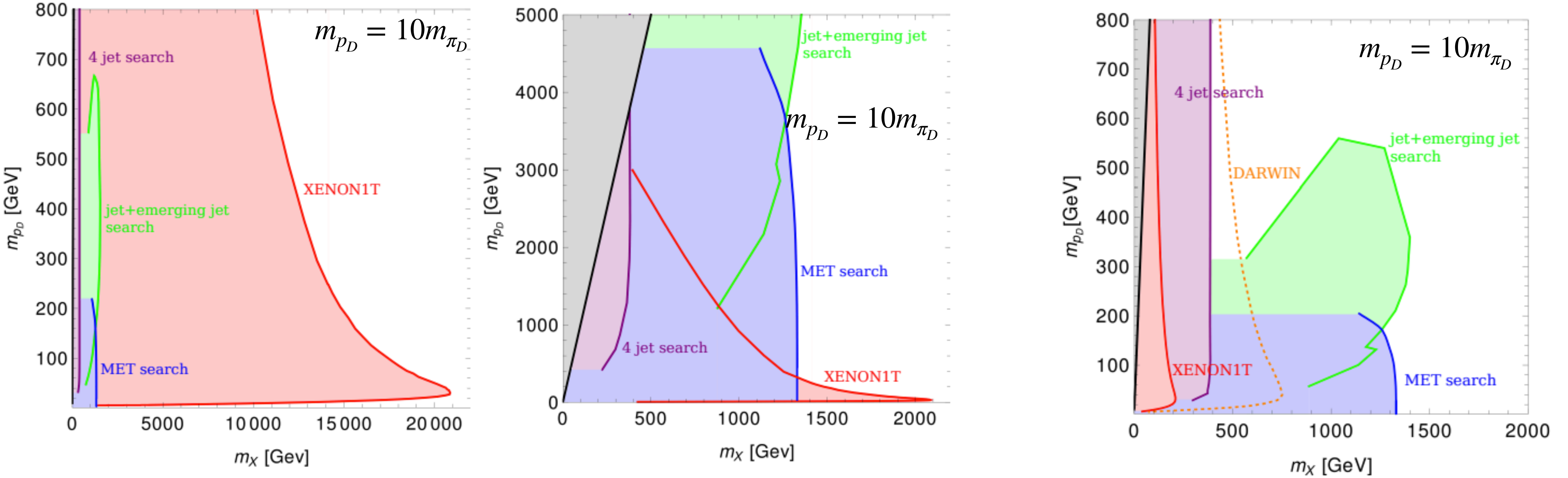

(a) $\kappa_0 = 1$

(b) $\kappa_0 = 0.1$

(c) $\kappa_0 = 1,\ \kappa_{11} = \frac{\kappa_0}{100}$

DD constraints strongest

DD constraints weaker

Note: $m_{\pi_D} > 100\,\mathrm{GeV}$

Suppressed couplings to light quarks, weaker DD constraints

$$\sigma^{SI}_{N-D} = \frac{1}{A}\sum_a \frac{(J^0_{Da})^2|\kappa^4_{\alpha 1}\mu^2_{n-D}}{32\pi m^4_X}(J^0_n(A-Z)+J^0_p Z)^2$$

$$= \frac{1}{A}\sum_a \frac{|\kappa^4_{\alpha 1}\mu^2_{n-D}}{32\pi m^4_X}(2(A-Z)+Z)^2,$$

DD scattering amplitudes assuming point-like dark proton

No statement on relic mechanisms

I did not talk about…

- Theories with split quark masses
- Dark resonances at LHC ($m_{q_D}, \Lambda_D \sim \sqrt{s}$)
- Non - SU(N) gauge theories
- Theories with composite Higgs and dark matter (theories where dark sector is charged under SM)
- Dark atom dark matter theories
- Connections to lattice
- …

Conclusions

- Strongly interacting dark matter theories is a young field (despite some very early works)
- Can lead to dark matter candidates which are automatically stable, are stabilised by external symmetries in form of composite baryons, atoms or mesons
- Huge interplay with cosmology but detailed understanding very much model dependent
- Relic density mostly a result of dynamics within dark sector than SM - DS mechanisms
- Cosmology independent of UV parameters most of the times i.e. deals directly with IR physics
- Collider (LHC) phenomenology depends on UV physics in jetty regime
- Direct detection phenomenology may involve computing dark form factors, exact effect currently unknown
- Still some understanding necessary to setup a generic mechanism for consistent top down theory treatment or for simplified model analysis
  - Involves understanding validity of assumptions on chirality
  - Involves understanding of hadronization procedures

Thanks for listening

Questions?