Surprises in Strongly-Coupled Dark Sectors

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CERN and University of Oregon

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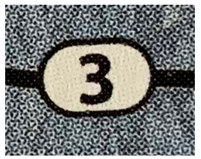
latuile.it & ChatGPT

Three Goals of my Talk:

Strongly coupled dark sectors provide well-motivated dark matter candidates with rich phenomenology.

Broad classes of dark baryon dark matter are weakly constrained by direct detection due to inherent symmetries of the dark sector.



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- dissappearing track searches
- new resonances (neutral, +, ++) arising from a newly identified anomaly

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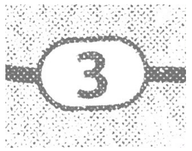

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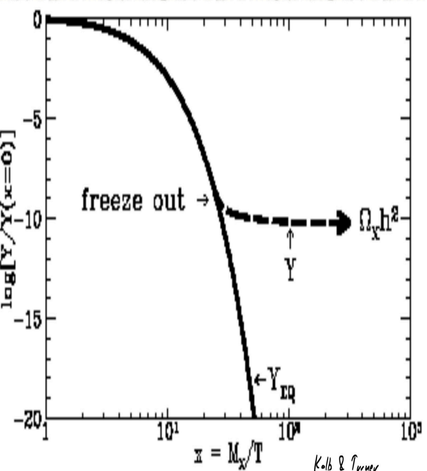
Matter *is* strongly-coupled (baryons!)

Dark matter stability (dark baryon number, meson parities)

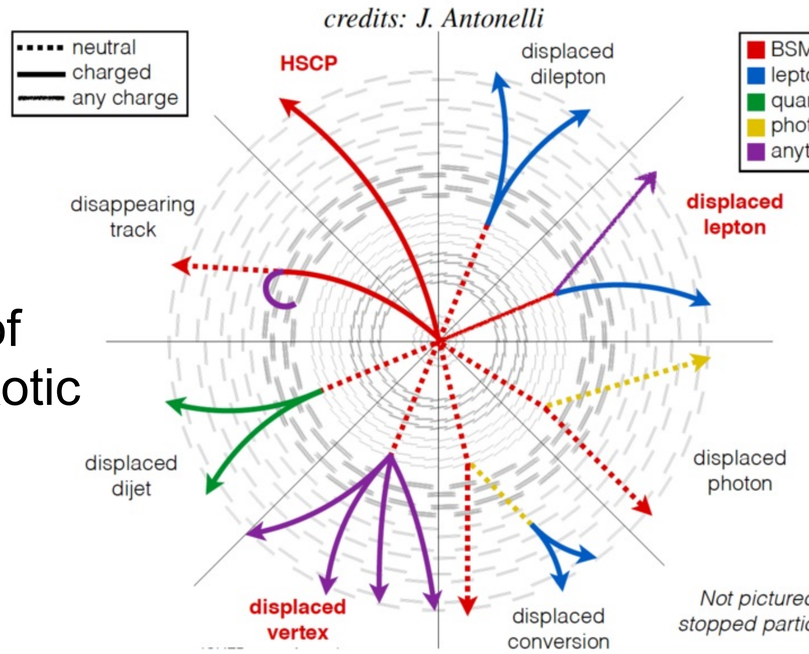
Me or ChatGPT?

Why Strongly-Coupled?

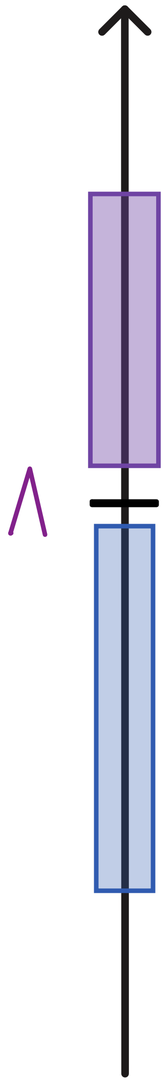


Abundance mechanisms with a wide range of DM mass scales (freeze-out; freeze-in; asymmetric; ...)

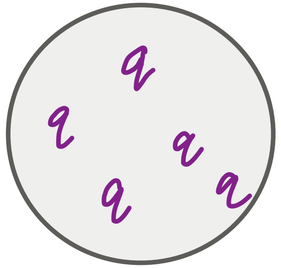
Rich spectrum of particles with exotic signals at LHC



Dark Sector States



Dark Baryons

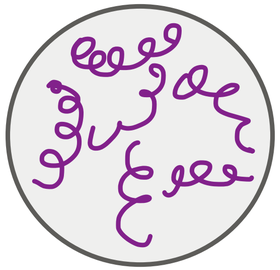


Reviews:
GK, Neil [1604.04627]
Del Nobile [2104.12785]
Cline [2108.10314]
Cirelli, Strumia, Zupan [2406.01705]
and recent work:
Asadi, GK, Mantel [2410.23631]
Asadi, Batz, GK [2410.14240]
Fleming, GK, Neil, Schaich, Vranas [2410.14540]

Dark Mesons (and Dark Pions)

Kilic, Okui, Sundrum [0906.0577]
Bai, Hill [1005.0008]
Buckley, Neil [1209.6054]
Hochberg et al [1402.5143, 1512.07917]
Antipin et al [1503.08749]
Ko, Tang [1609.02307]
GK, Martin, Ostdiek, Tong [1809.10183, 1809.10184]
Cheng, Li, Salvioni [2110.10691]
Asadi, Batz, Bernreuther, Costa, Homiller, GK [2507.13430]
Di Mauro, Gemmell, Batz, Curtin, Donato, Fornengo, Kribs [2602.15132]
...

Dark Glueballs

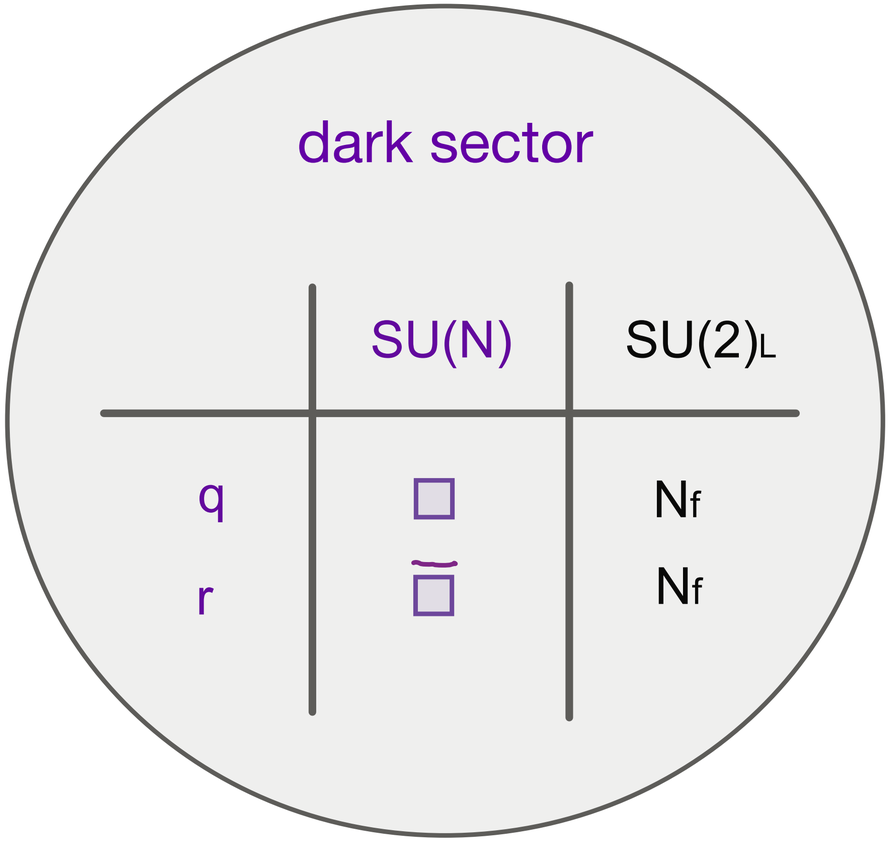


Juknevich, Melnikov, Strassler [0903.0883]
Juknevich [0911.5616]
Body, Feng, Kaplinghat, Tait [1402.3629]
Craig, Katz, Strassler, Sundrum [1501.05310]
Curtin, Verhaaren [1506.06141]
Forestell, Morrissey, Sigurdson [1605.08048; 1710.06447]
Acharya, Fairbairn, Hardy [1704.01804]
Curtin, Gemmell, Verhaaren [2202.12899]
Curtin, Gemmell [2211.05794]
Batz, Cohen, Curtin, Gemmell, GK [2310.13731]
Asadi, GK, Luty [2512.20696]
…

A strongly-coupled dark sector

New SU(N) confining gauge sector with vector-like fermions transforming under (part of) the SM gauge group.

For this talk



Confinement scale: $\Lambda \sim 100\ \text{GeV} - 10\ \text{TeV}$

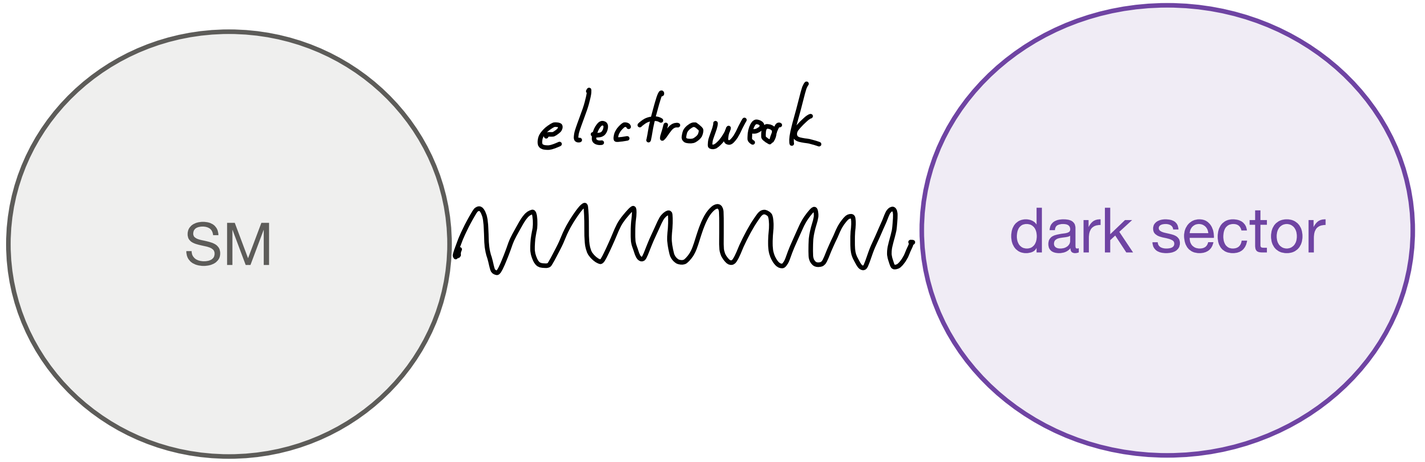
(> mf, enabling chiral Lagrangian for dark pions)

Anomaly-free; fermion mass: $m_f \left(q r + \text{h.c.} \right)$

$Q = \begin{pmatrix} q \\ r^\dagger \end{pmatrix} \longrightarrow m_f \bar{Q} Q$

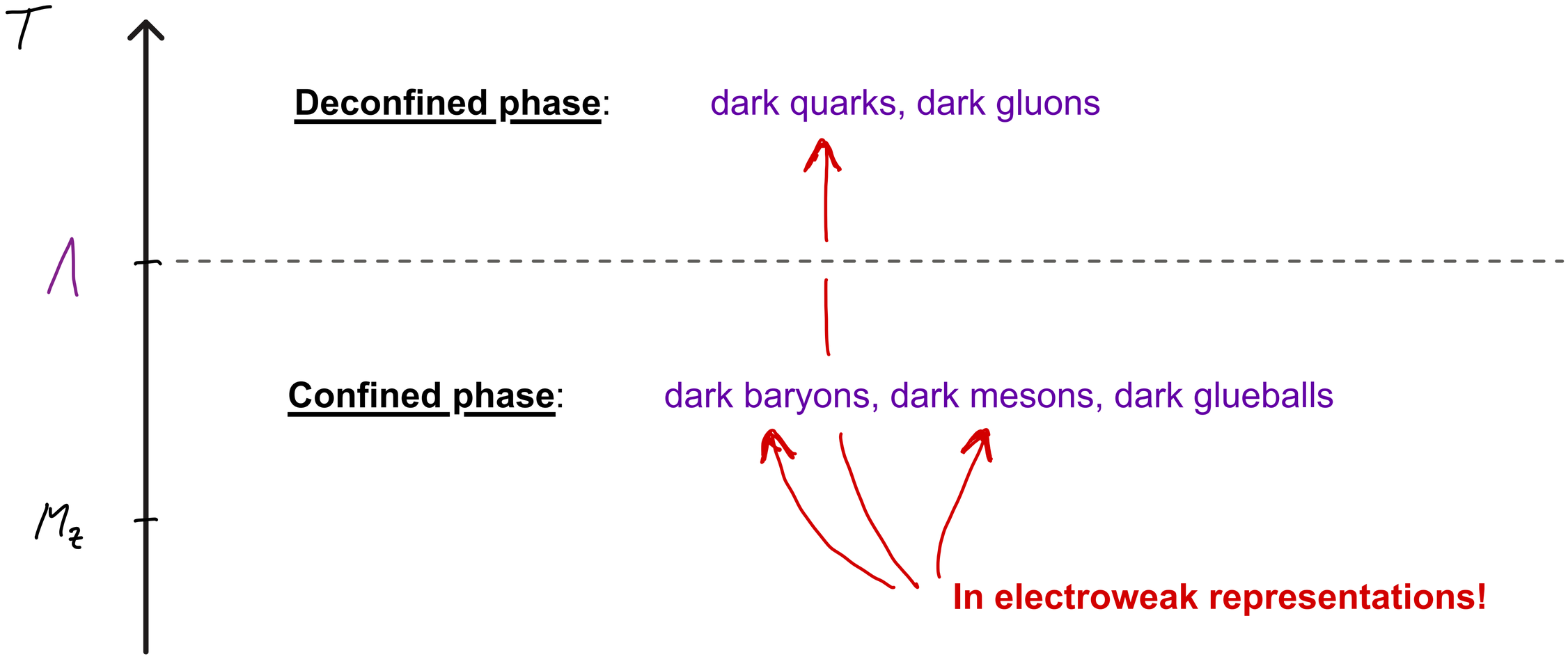
Equilibration at high temperatures

$T \gtrsim 1$



Provides a variety of possible dark matter abundance mechanisms ...
(not the subject of this talk)

Phases of this dark sector



Variety of cosmological implications...
(also not the subject of this talk)

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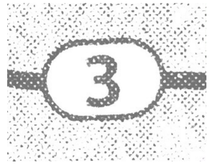

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Working Example: SU(3) with N_f=3 flavors of dark quarks

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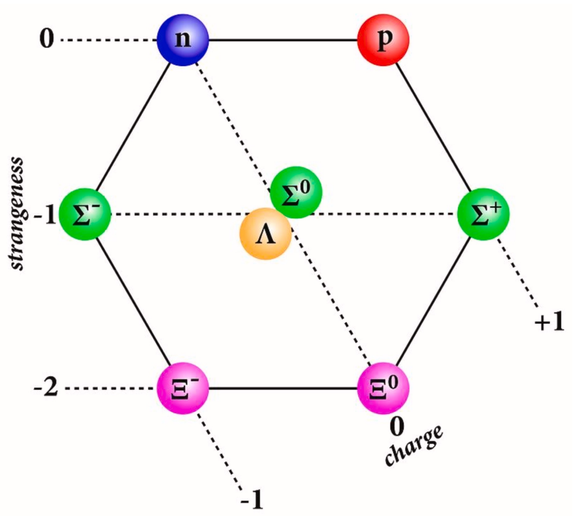
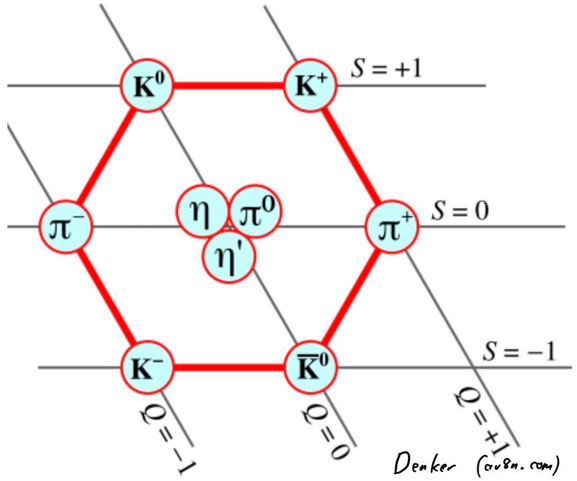
Dark Mesons

$$N_f \otimes N_f = 1 \oplus 3 \oplus 5 \oplus \cdots (2N_f - 1)$$

$$\eta' \,, \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix} \,, \begin{pmatrix} \eta^{++} \\ \eta^{+} \\ \eta^{0} \\ \eta^{-} \\ \eta^{--} \end{pmatrix}$$

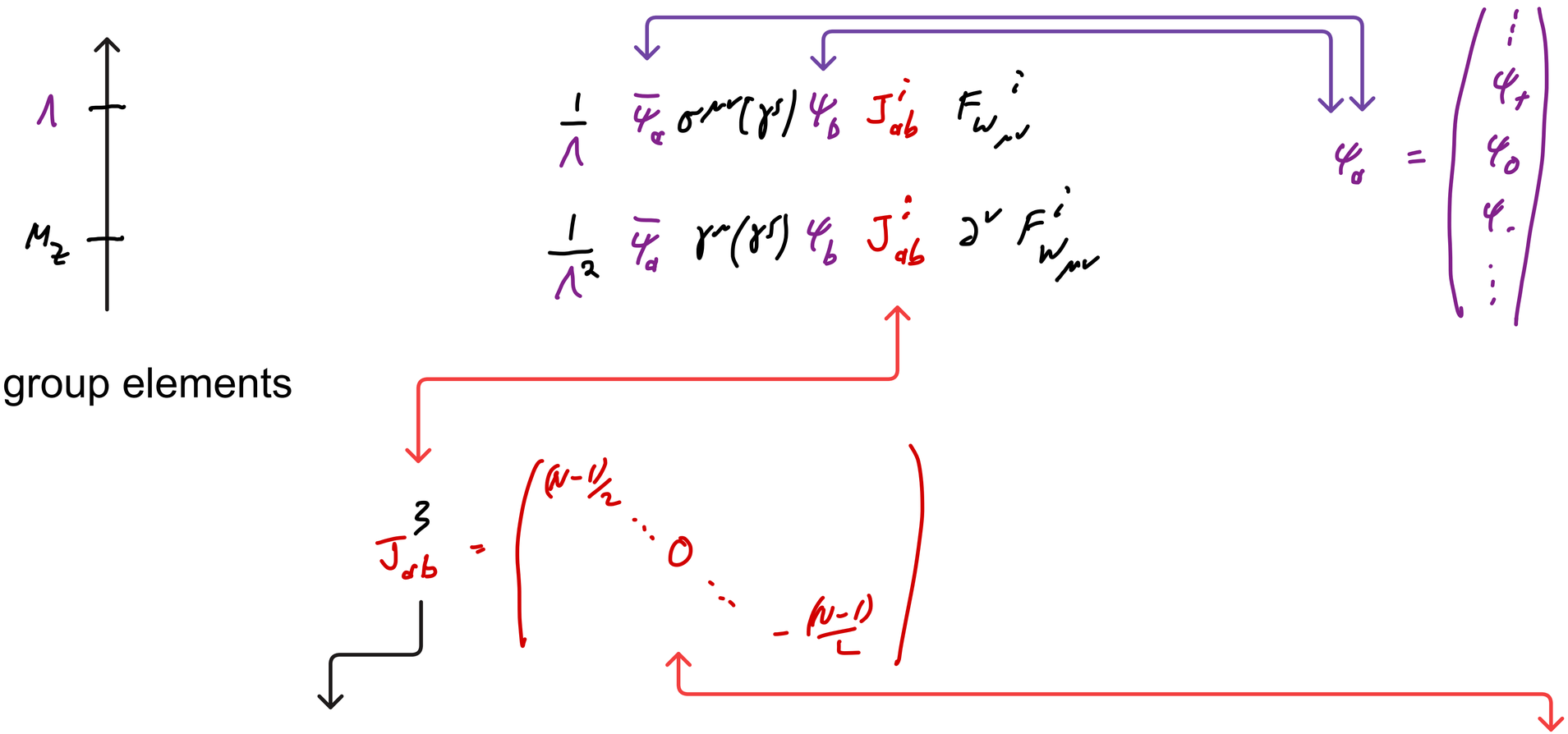
analogous to QCD





Surprise #1: Dark Baryon Moments are Suppressed

Below confinement scale, generate electroweak operators for **dark baryons**:



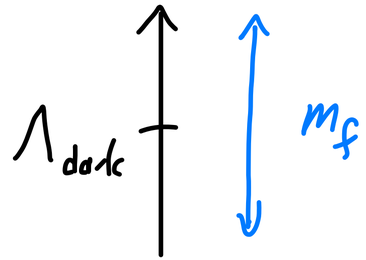
with group elements

The $\bar{\psi}_0 - \psi_0 - W^3$ interaction **absent**. Neutral dark baryon magnetic/electric dipole moments and charge radius / anapole **vanish**.

Asadi, Mantel, GK 2410.23631 [PRD]

Dark Parities

Holds independent of Nc, Nf and scale:



G-parity

Bai, Hill 1005.0008

Rotate 2-component fermion fields by:

$$q_a \to S_{ab}\, q_b$$
$$r_a \to r_b\, S^{\dagger}_{ba}$$

$$S = \exp\left[i\pi J^2\right]$$

Global rotation by SU(2)L generator

combine with charge conjugation of dark quarks:

$$r \to C\bar{r} = q$$
$$q \to C\bar{q} = r$$

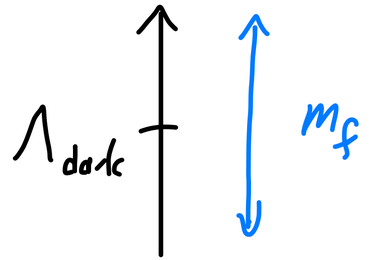
Dark mesons transform under G:

3-plet, 7-plet, ... G-odd $\quad (\pi \to -\pi)$

1-plet, 5-plet, ... G-even $\quad (\eta' \to +\eta')$

Surprise #1.5: New Dark Parities

Holds independent of Nc, Nf and scale:



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H-parity

Asadi, Mantel, GK 2410.23631

Global rotation by SU(2)L generator

combine with charge conjugation of EW gauge fields:

$$W^a_\mu \to (W^a_\mu)^c = \begin{cases} +W^2_\mu \\ -W^{1,3}_\mu \end{cases}$$
$$B_\mu \to (B_\mu)^c = -B_\mu$$

Lagrangian also invariant.

H-parity transformations of dark baryons

$$S\begin{pmatrix}\Sigma_1\\ \Sigma_0\\ \Sigma_{-1}\end{pmatrix}=\begin{pmatrix}+\Sigma_1\\ -\Sigma_0\\ +\Sigma_{-1}\end{pmatrix} \qquad S\begin{pmatrix}\Lambda_{++}\\ \Lambda_{+}\\ \Lambda_{0}\\ \Lambda_{-}\\ \Lambda_{--}\end{pmatrix}=\begin{pmatrix}+\Lambda_{++}\\ -\Lambda_{+}\\ +\Lambda_{0}\\ -\Lambda_{-}\\ +\Lambda_{--}\end{pmatrix}$$

e.g. $\bar{\Sigma}_0\,\sigma^{\mu\nu}\,\Sigma_0\,F_{\mu\nu}$

$\rightarrow (-\bar{\Sigma}_0)\,\sigma^{\mu\nu}(-\Sigma_0)(-F_{\mu\nu})$ odd under H-parity

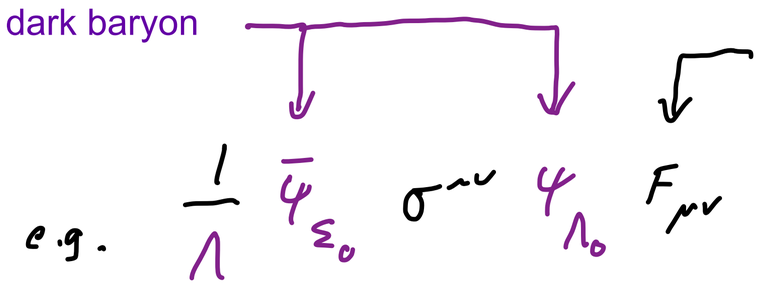
$\rightarrow$ **forbidden by H-parity!**

Z-exchange, dim-5, dim-6 EM moments
vanish -- independent of scale of Λ **relative to** M_Z

dimension (in NR EFT)	EM moments
4	
5	~~$\bar{\psi}_{B_0}\sigma^{\mu\nu}\psi_{B_0}F_{\mu\nu}$~~ ~~$\bar{\psi}_{B_0}\sigma^{\mu\nu}\gamma_5\psi_{B_0}F_{\mu\nu}$~~
6	~~$\bar{\psi}_{B_0}\partial^\mu\psi_{B_0}\partial^\nu F_{\mu\nu}$~~ | ~~$\psi^\dagger_{B_0}\partial^\mu\psi_{B_0}\partial^\nu F_{\mu\nu}$~~ ~~$\bar{\psi}_{B_0}\gamma_5\partial^\mu\psi_{B_0}\partial^\nu F_{\mu\nu}$~~

H-parity even interactions of dark baryons with SM

Allowed Interaction



← EM transition moments (between baryons with different H-parities)

$\frac{1}{\Lambda^3}\ \bar{\psi}\psi\ F_{\mu\nu}F^{\mu\nu}$ ← polarizability (dim-7)

$\frac{1}{\Lambda^3}\ \bar{\psi}\psi \times \begin{cases} Q\cdot H u^c \\ Q \not{D} Q \\ \vdots \end{cases}$ ← EW loops (dim-7)

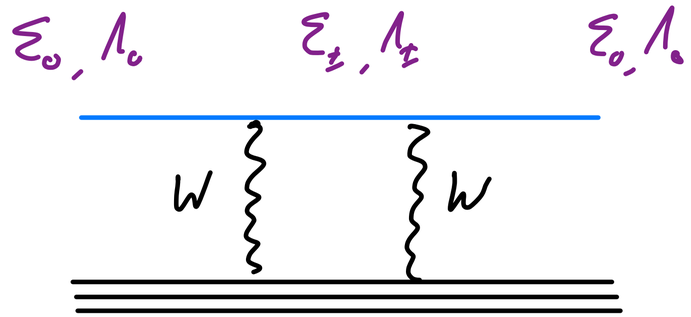
Importance

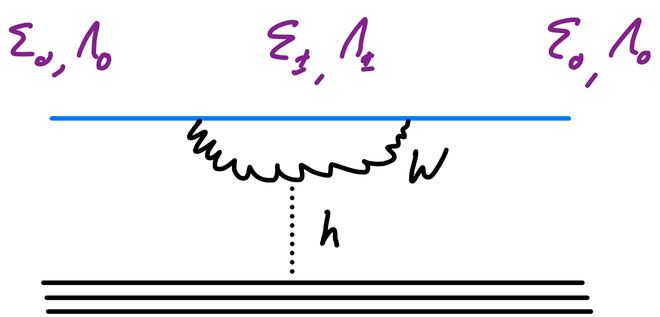
Dark transition moments (inelastic DM)

Leading interaction for EW singlets

Leading interaction for EW multiplets

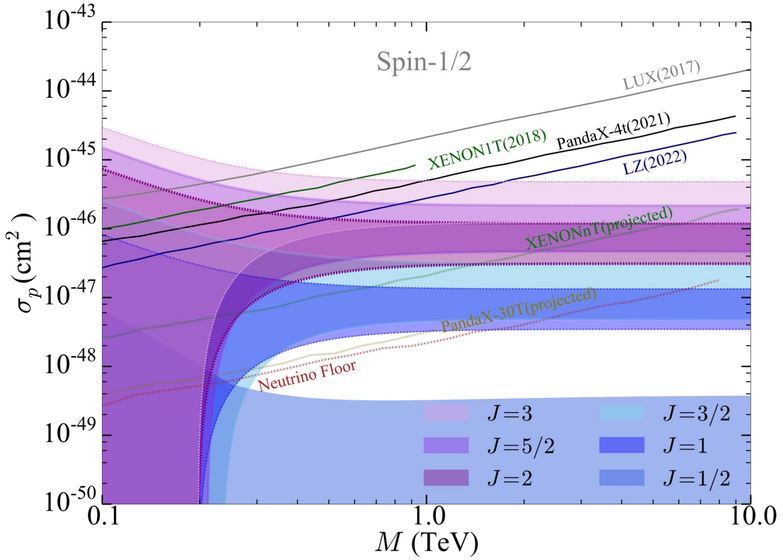
Direct Detection through electroweak loops





EFT* with M(Σ_0, Λ_0) >> Mw:

*(Majorana)



← 5-plet

← duplet

Chen, Ding, Hill [2309.02715]

Excellent opportunity for ongoing direct detection searches through nuclear recoil!

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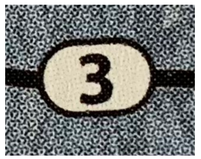

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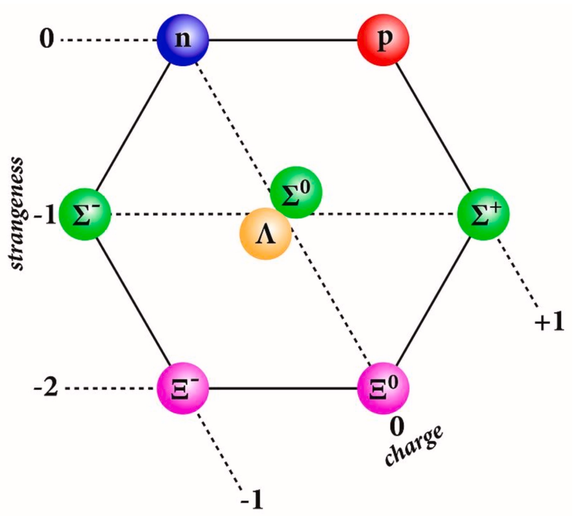
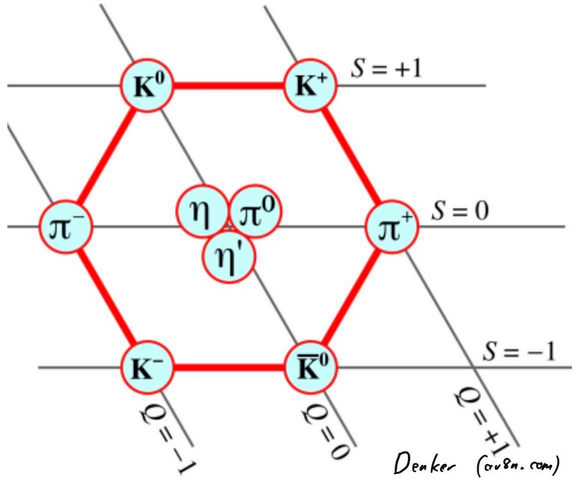
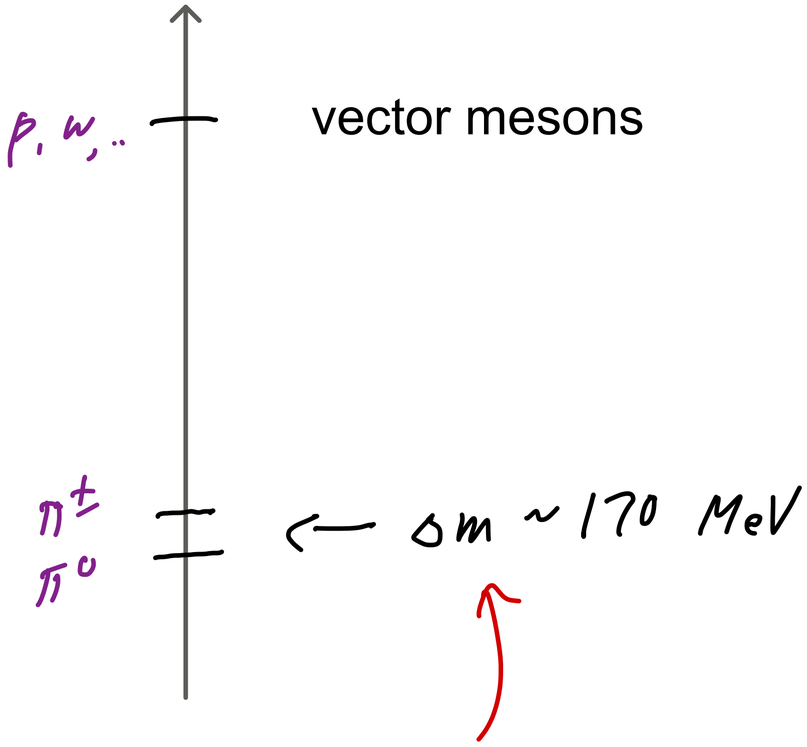
analogous to QCD

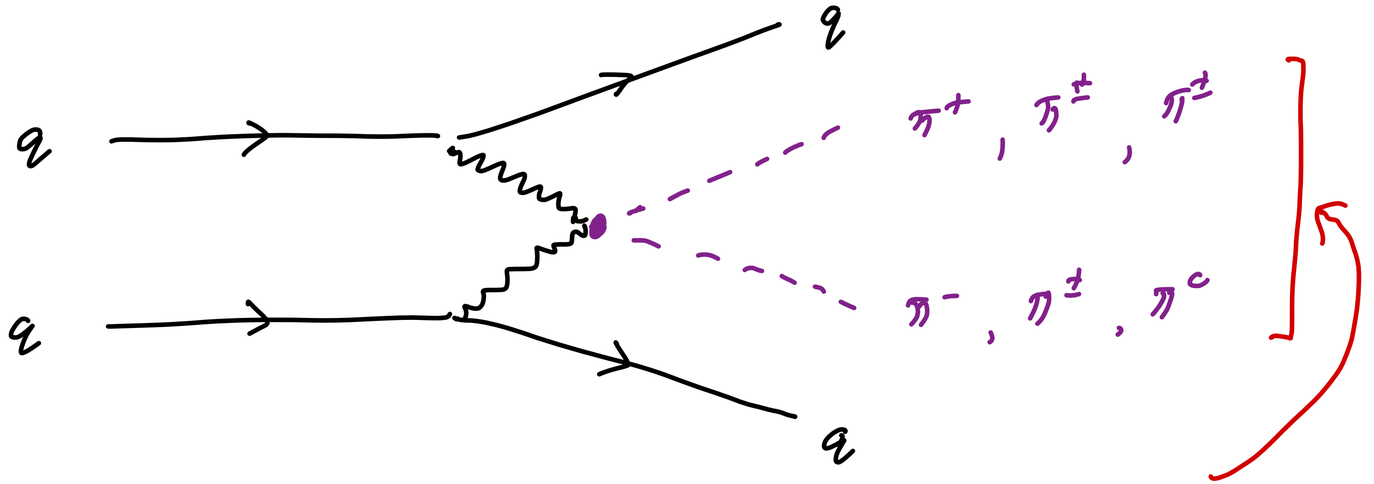


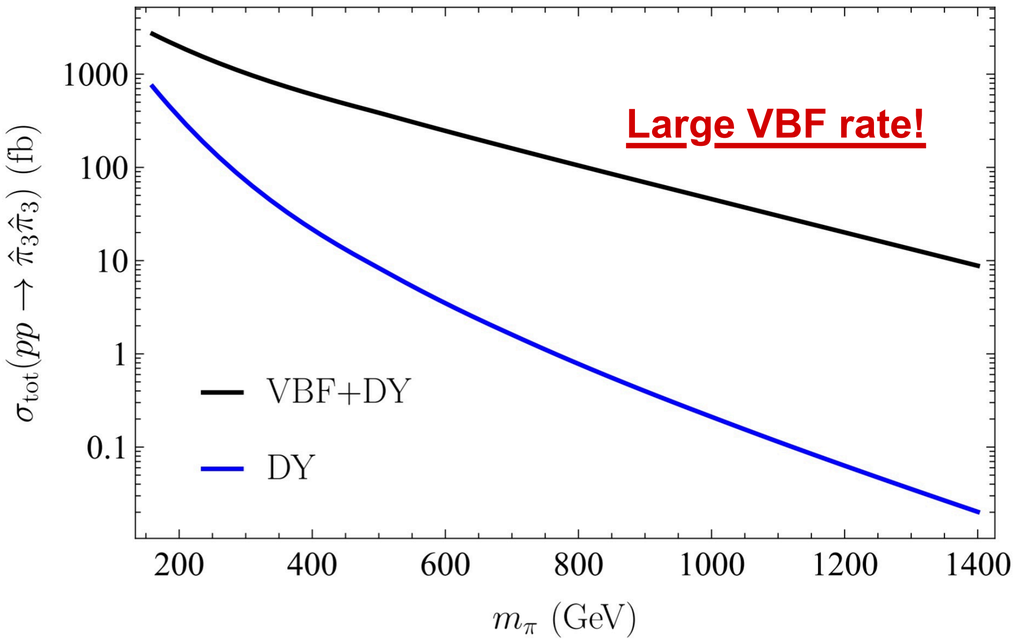


Dark Triplet



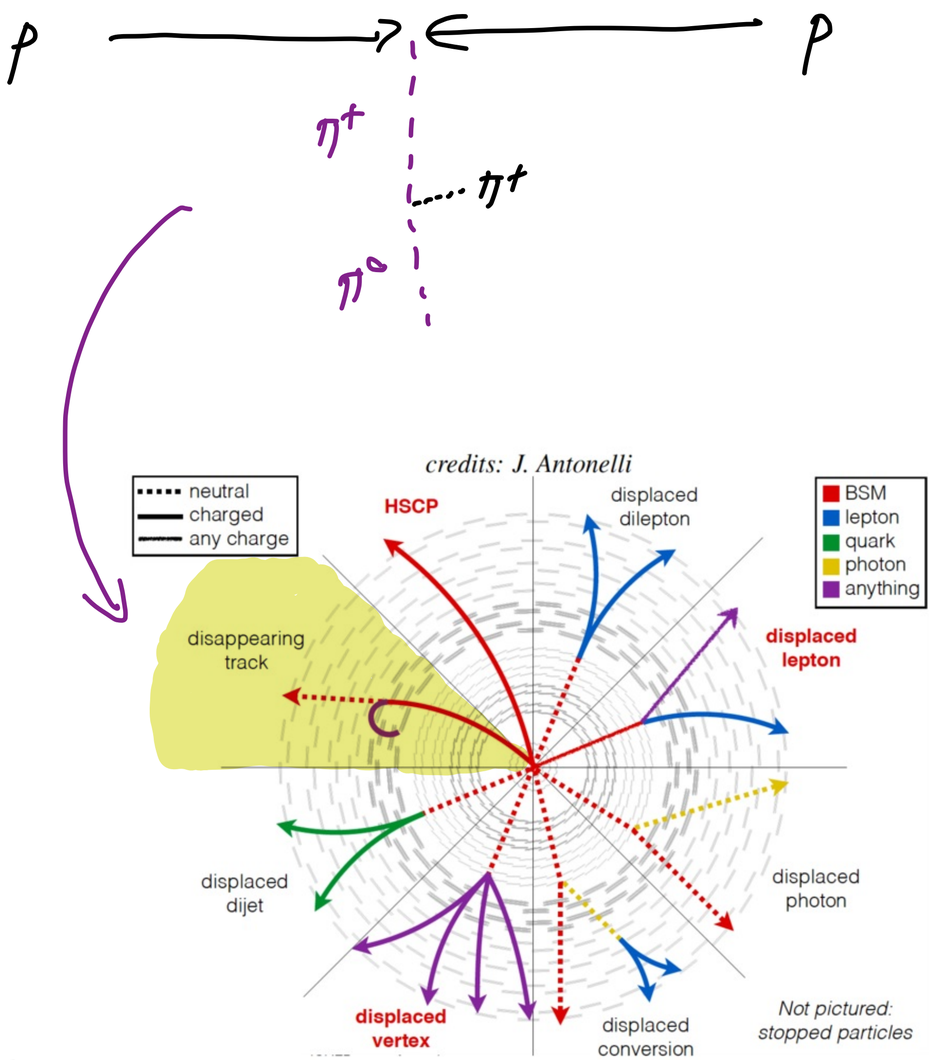
Dominant production at LHC is vector-boson fusion:

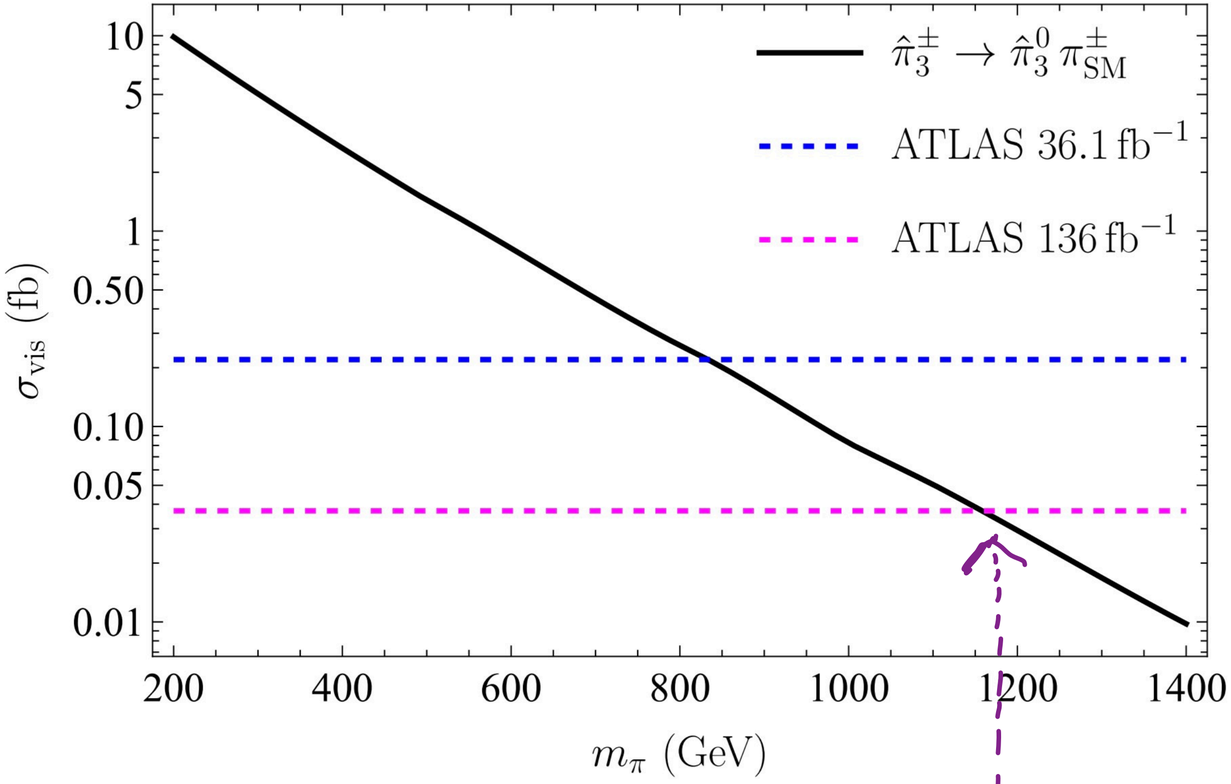




Asadi, Batz, Bernreuther, Costa, Homiller, GK
2507.13430

Surprise #2: Large Rate for Disappearing Track Signal



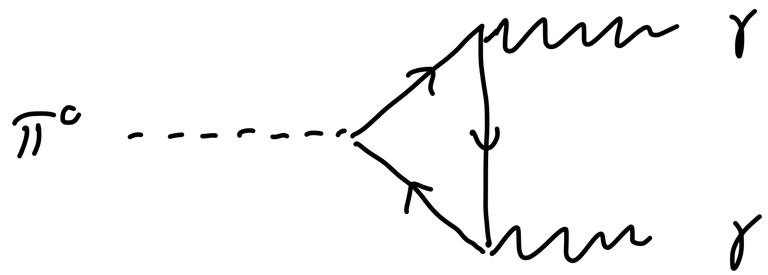


$m_{\pi^\pm} \gtrsim 1.2$ TeV

Asadi, Batz, Bernreuther, Costa, Homiller, GK 2507.13430

Surprise #3: Dark 5-plet and a new Global Anomaly

Just like the π^0 has a global-gauge-gauge anomaly in SM:



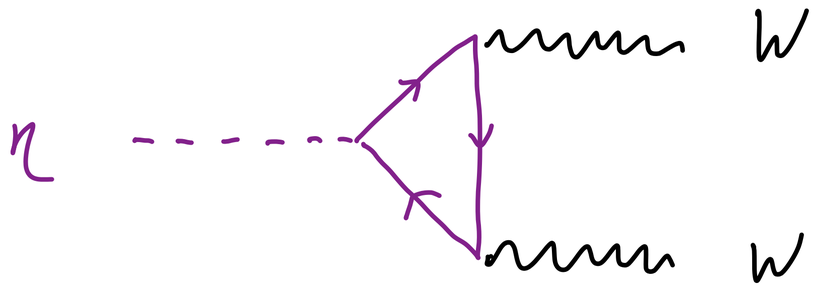
$$\mathcal{L}^{\rm QED}_{\rm anomaly} \propto \pi^0_{\rm SM} F\widetilde{F}\,{\rm Tr}\left[T^0\,Q^2\right]$$

$$Q = \begin{pmatrix} 2/3 & & \\ & -1/3 & \\ & & -1/3 \end{pmatrix}$$

$$T^0 = \frac{1}{2}\begin{pmatrix} 1 & & \\ & -1 & \\ & & 0 \end{pmatrix}$$

The **5-plet** η is the unique* dark pion that has a global-gauge-gauge anomaly:

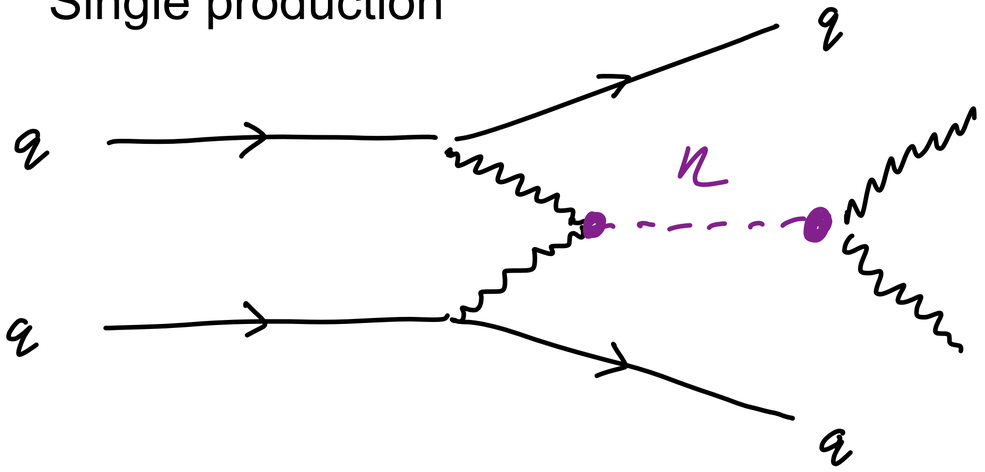
*η' also has anomaly, but is heavy (not a pion)

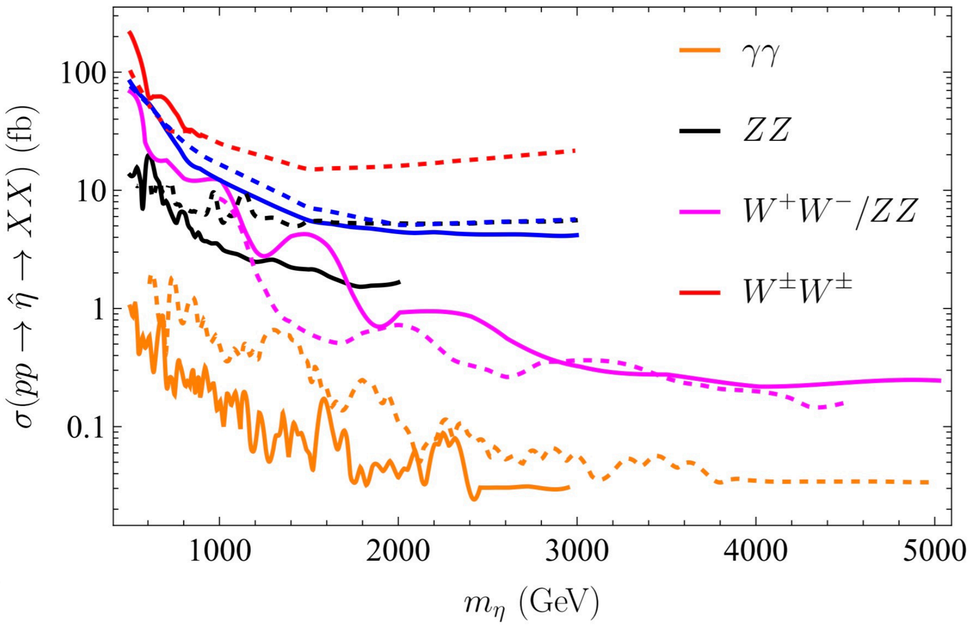


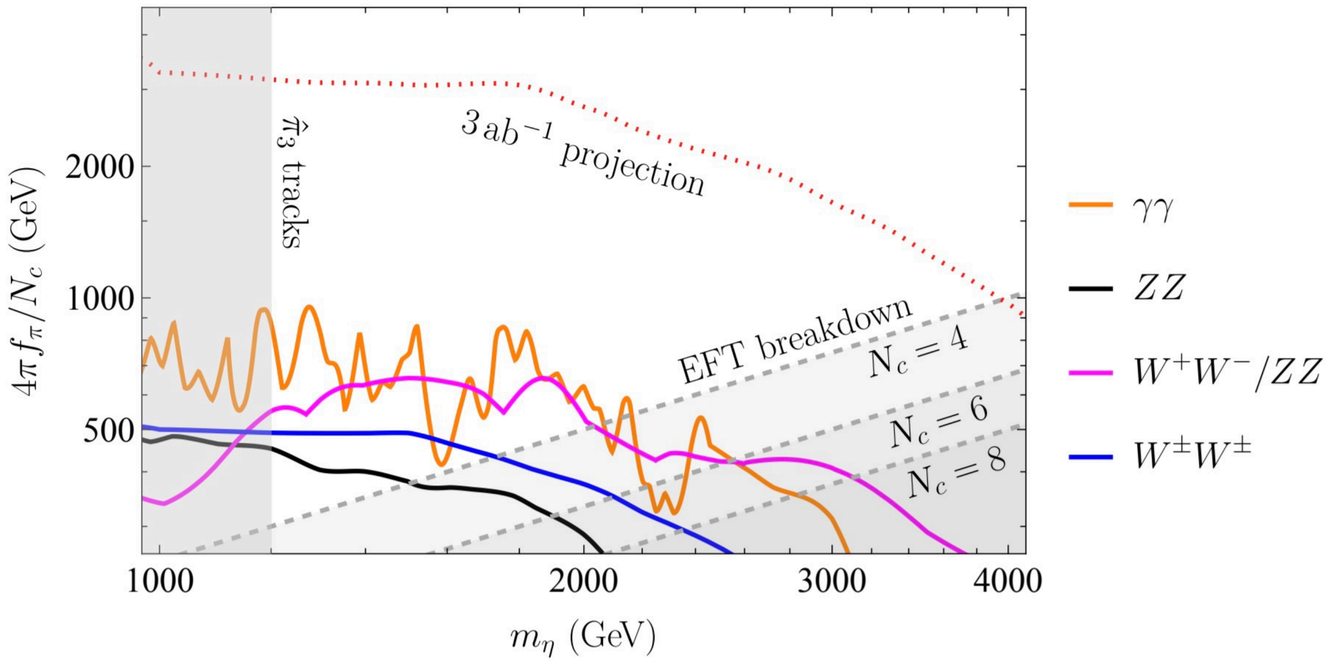
$$\mathcal{L}_{\rm anomaly} = \frac{g_W^2}{16\pi^2}\frac{N_c}{f_\pi}\hat{\phi}^a\varepsilon^{\mu\nu\alpha\beta}W^i_{\mu\nu}W^j_{\alpha\beta}{\rm Tr}\left[T^a J^i J^j\right]$$

Dark 5-plet Scalar Resonances

Single production





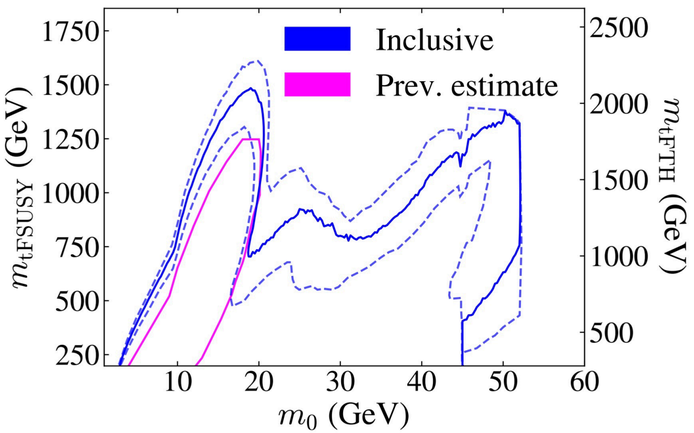


High lumi @ LHC has great discovery potential!

Asadi, Batz, Bernreuther, Costa, Homiller, GK 2507.13430

More Dark Meson Surprises...

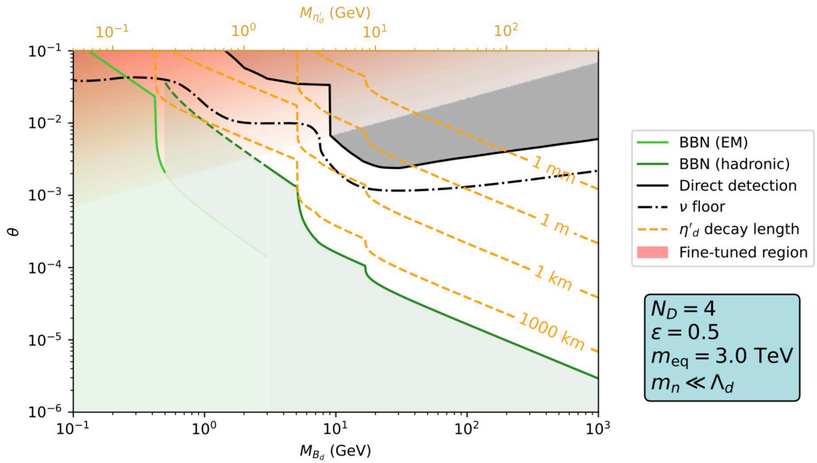
Glueballs



Long-lived glueballs lead to displaced signals (MATHUSLA)

Batz, Cohen, Curtin, Gemmell, GK 2310.13731

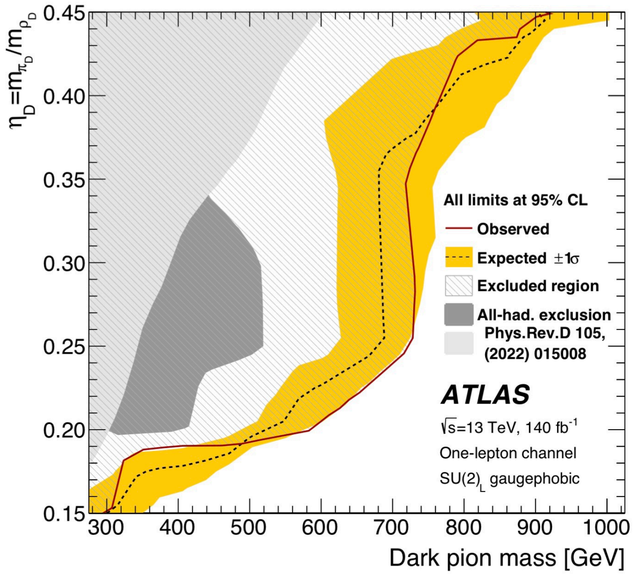
1-flavor theories



Long-lived eta' in theories with light composite DM

Fleming, GK, Neil, Schaich, Vranas 2412.14540

2+ flavor theories



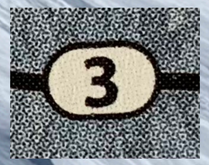
Prompt signals at ATLAS in theories where mesons can decay through Higgs interactions

ATLAS results 2405.20061; based on GK, Martin, Ostdiek, Tong 1809.10184

Summary

H-parity allows dark baryons to be viable DM candidates as low as a few hundred GeV despite being made of EW charged constituents.

LHC constraints on triplet dark pions > 1.2 TeV from dissappearing track searches (huge rate from VBF & large multiplicity).



5-plet dark pions have global-[SU(2)]^2 anomaly providing new TeV scale resonances (neutral, +, ++) as a promising target for high-lumi LHC.

Thank you!