Vignettes from Strongly-Coupled Dark Sectors

Graham Kribs
University of Oregon

GK, Martin, Ostdiek, Tong 1809.10184 [JHEP]

Batz, Cohen, Curtin, Gemmell, GK 2310.13731 [JHEP]

Asadi, GK, Mantel [to appear]

18 June 2024

Crossroads from Theory to Phenomenology, CERN

Strongly-Coupled Dark Sectors

Benefits:

- Naturalness
- Rich phenomenology
- Automatic DM stability
  (e.g, dark baryon number)
- Wide variety of cosmological abundance mechanisms
  -> Freeze out
  -> Asymmetric
  -> Squeeze out
  •••
- Connections to EWSB
  -> Composite Higgs
  -> Neutral Naturalness

Challenges:

- Non-perturbative
  -> NDA estimates
  -> Large Nc
  -> Lattice simulations
- Many moving parts
  -> variety of potential constraints occurring simultaneously
- Dark sector may have nothing to do will outstanding problems of SM

Three Vignettes

- Dark glueballs

Batz, Cohen, Curtin, Gemmell, GK 2310.13731 [JHEP]

- Dark mesons

GK, Martin, Ostdiek, Tong 1809.10184 [JHEP]

- Dark baryons

Asadi, GK, Mantel [to appear]

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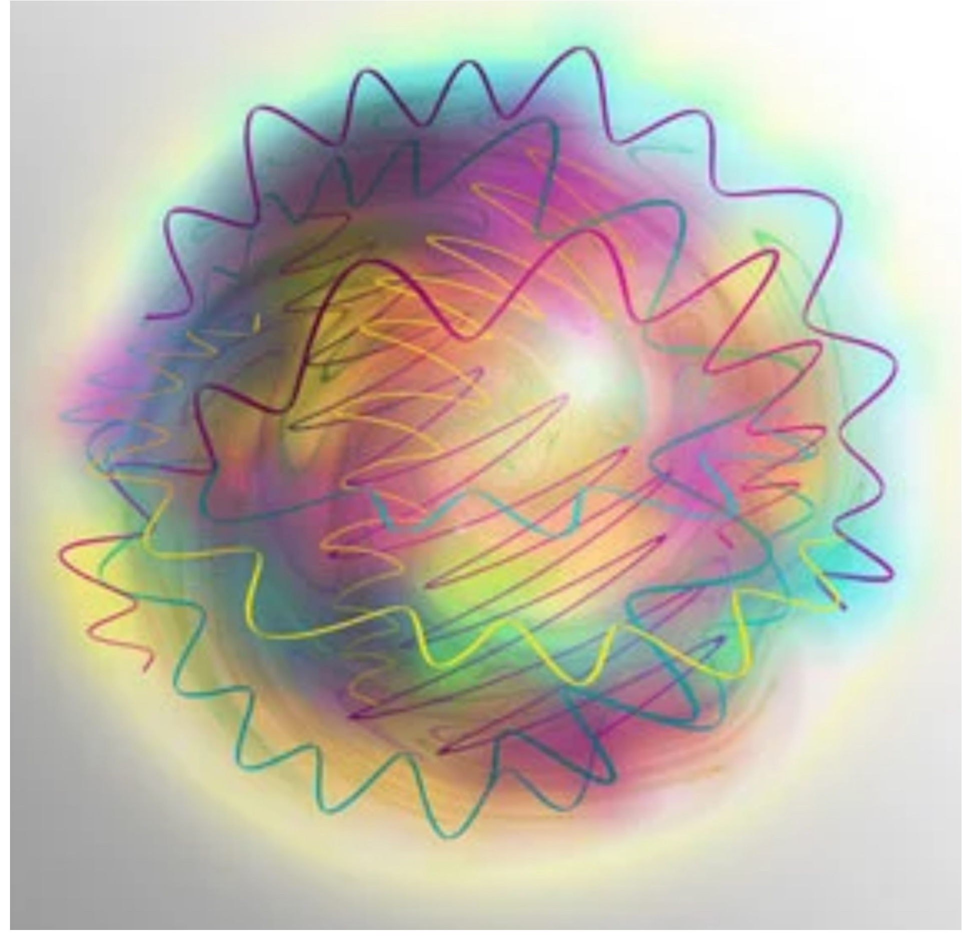
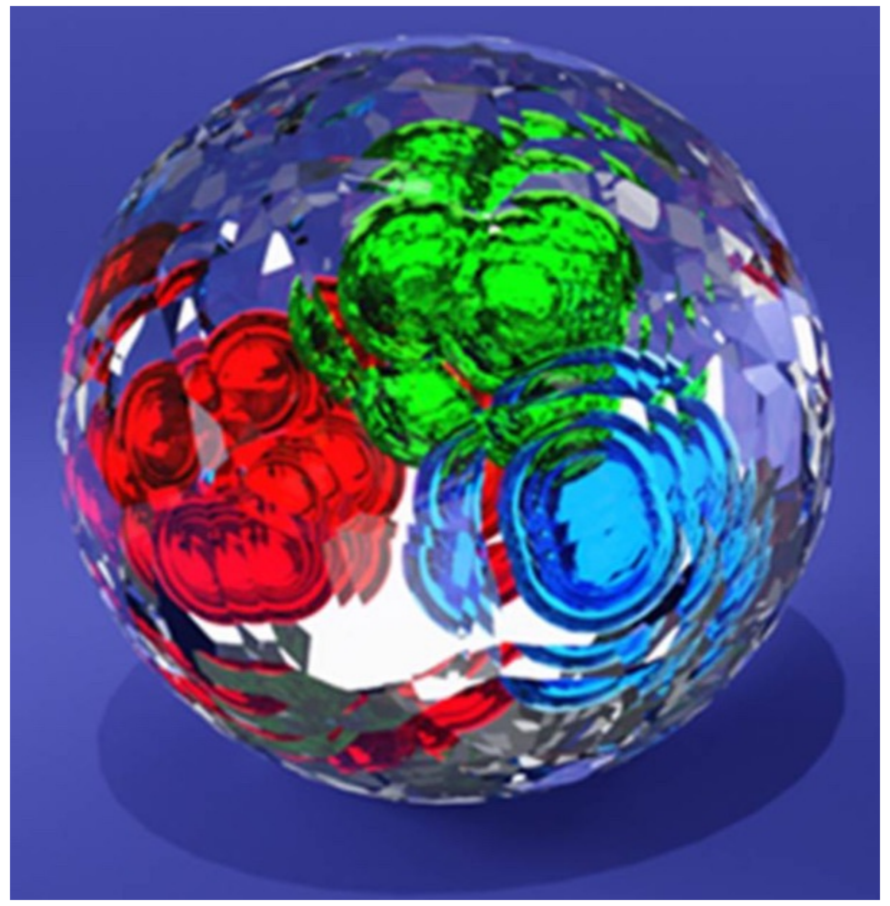
Dark Glueballs

• In an SU(N) confining theory with

$$m_f \gg \Lambda_{\rm dark}$$

==> Low energy theory is pure glue,
leading to dark glueball mesons:





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]
…

Dark Glueballs

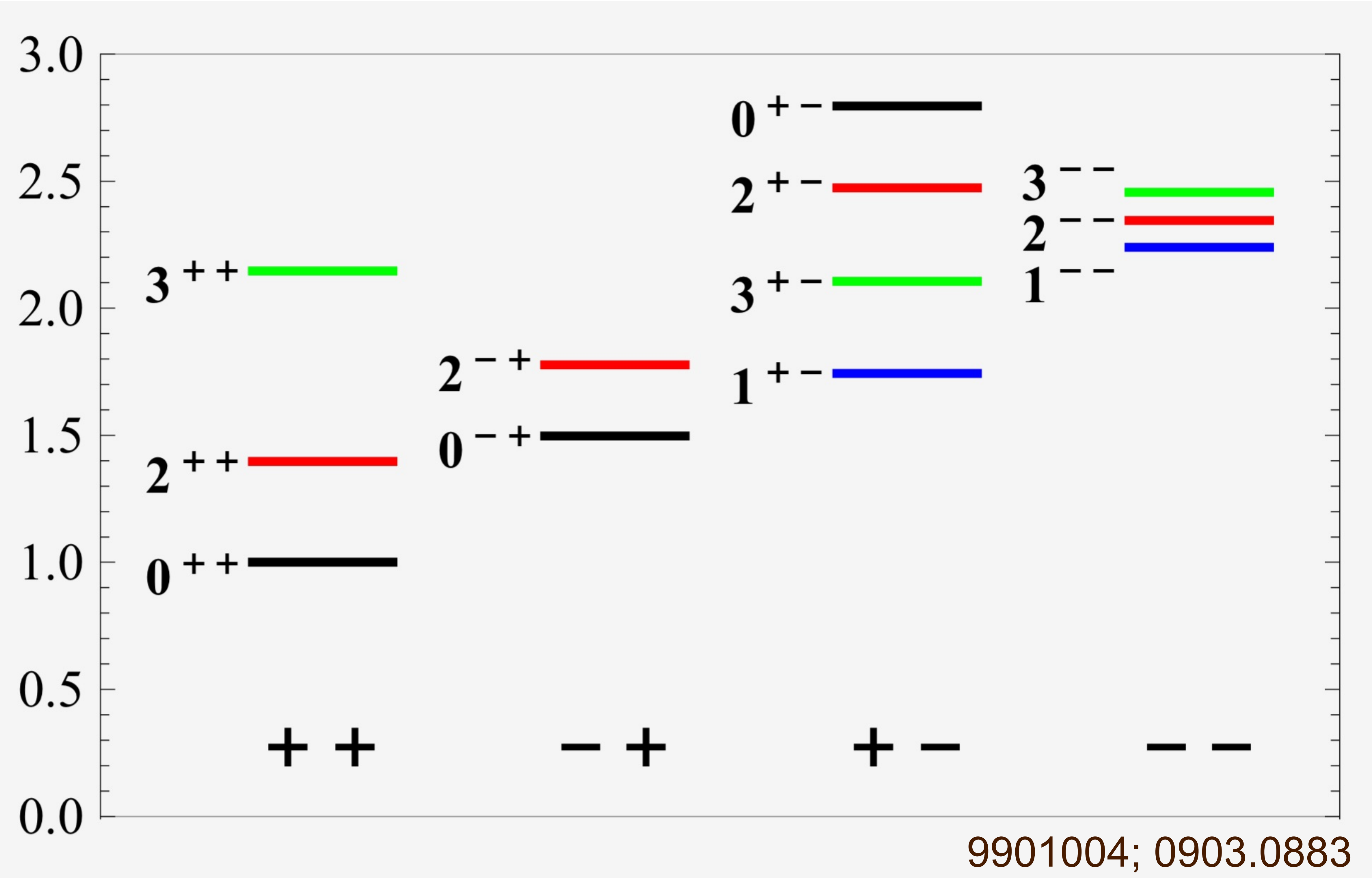
- Spectrum [for SU(3)] is known from lattice simluations

- Lightest state is 0++, followed by 2++, etc.

- Primary interest:

$$m_{0^{++}} < 2\, m_h \leftarrow \text{SM Higgs}$$

$$\frac{m_{J^{PC}}}{m_{0^{++}}}$$



J^{PC}

Dark Glueball Stability

After integrating out heavy dark quarks, generate higher dimensional interactions with SM:

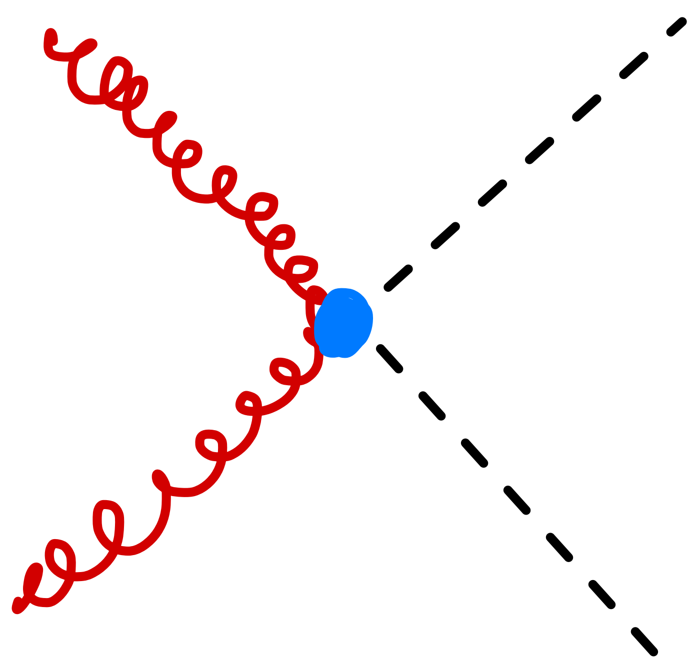
Dimension-6 Higgs portal

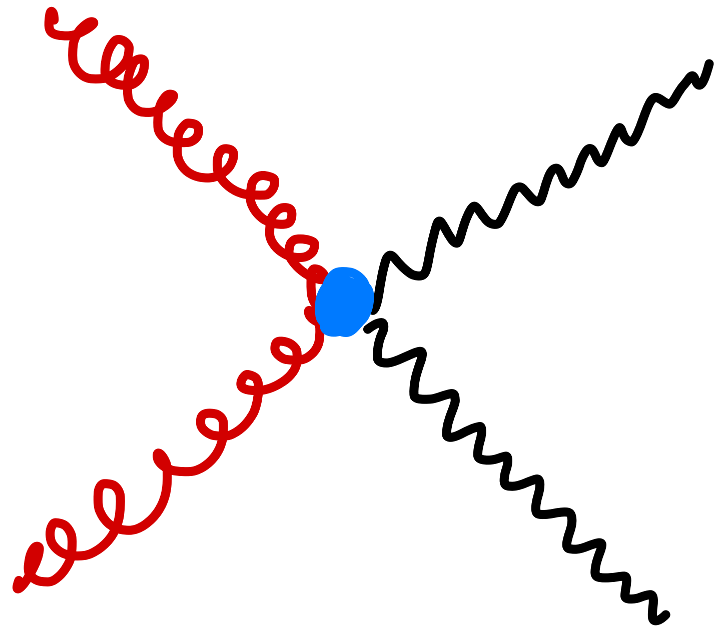
$$\frac{1}{\Lambda^2}\left(\mathrm{tr}\; G_{\mu\nu} G^{\mu\nu}\right) \cdot H^\dagger H$$

Dimension-8 Gauge portal

$$\frac{1}{\Lambda^2}\left(\mathrm{tr}\; G_{\mu\nu} G^{\mu\nu}\right)\left(\mathrm{tr}\; F^{SM}_{\mu\nu} F^{SM\,\mu\nu}\right)$$

e.g.



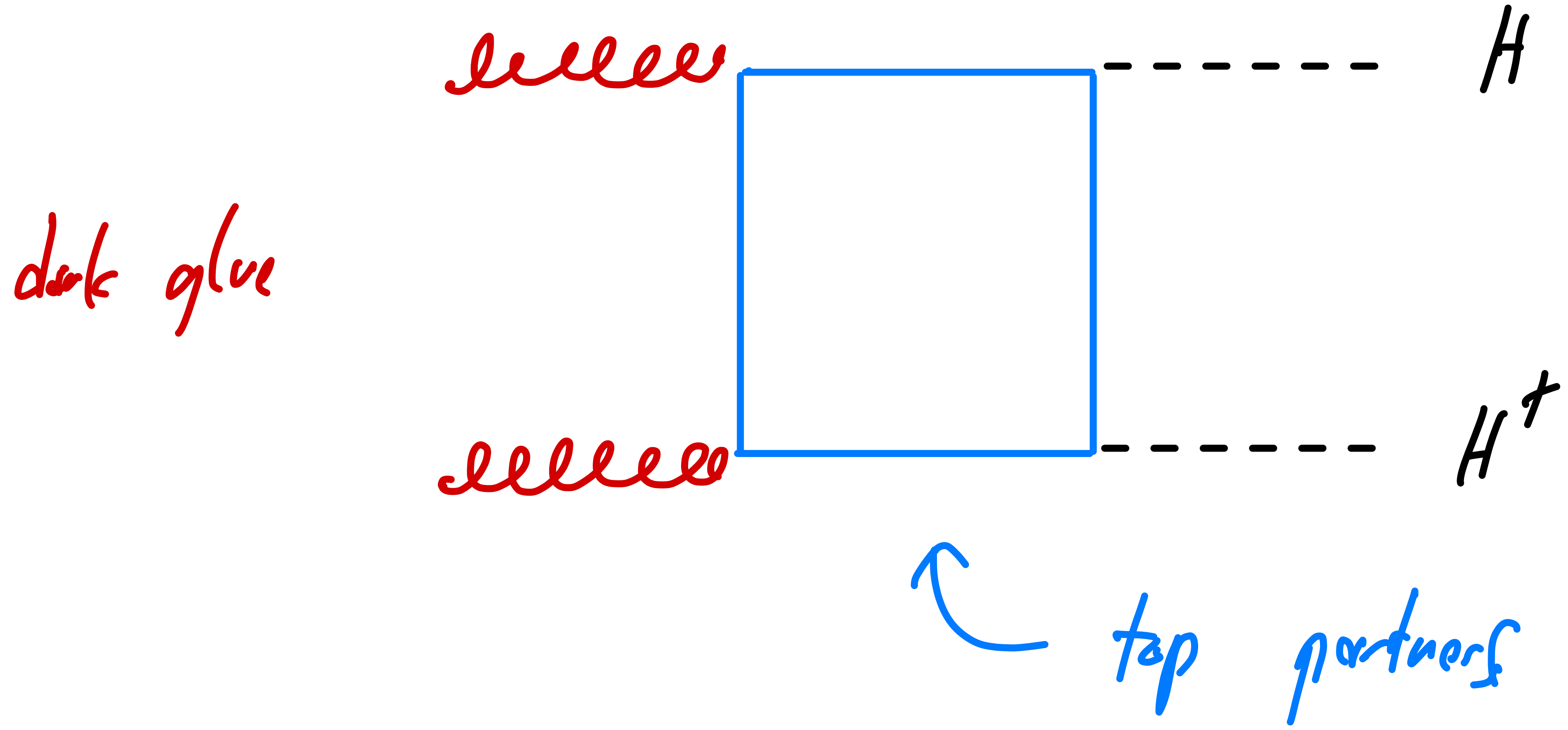


which operators are permitted depends on J^{PC} and states in the UV completion

Juknevich, Melnikov, Strassler [0903.0883]
Juknevich [0911.5616]

UV Completions

For example, in neutral naturalness theories, twin sector contains heavy quarks (top partners) with interaction with the dark Higgs that mixes with SM Higgs, leading to

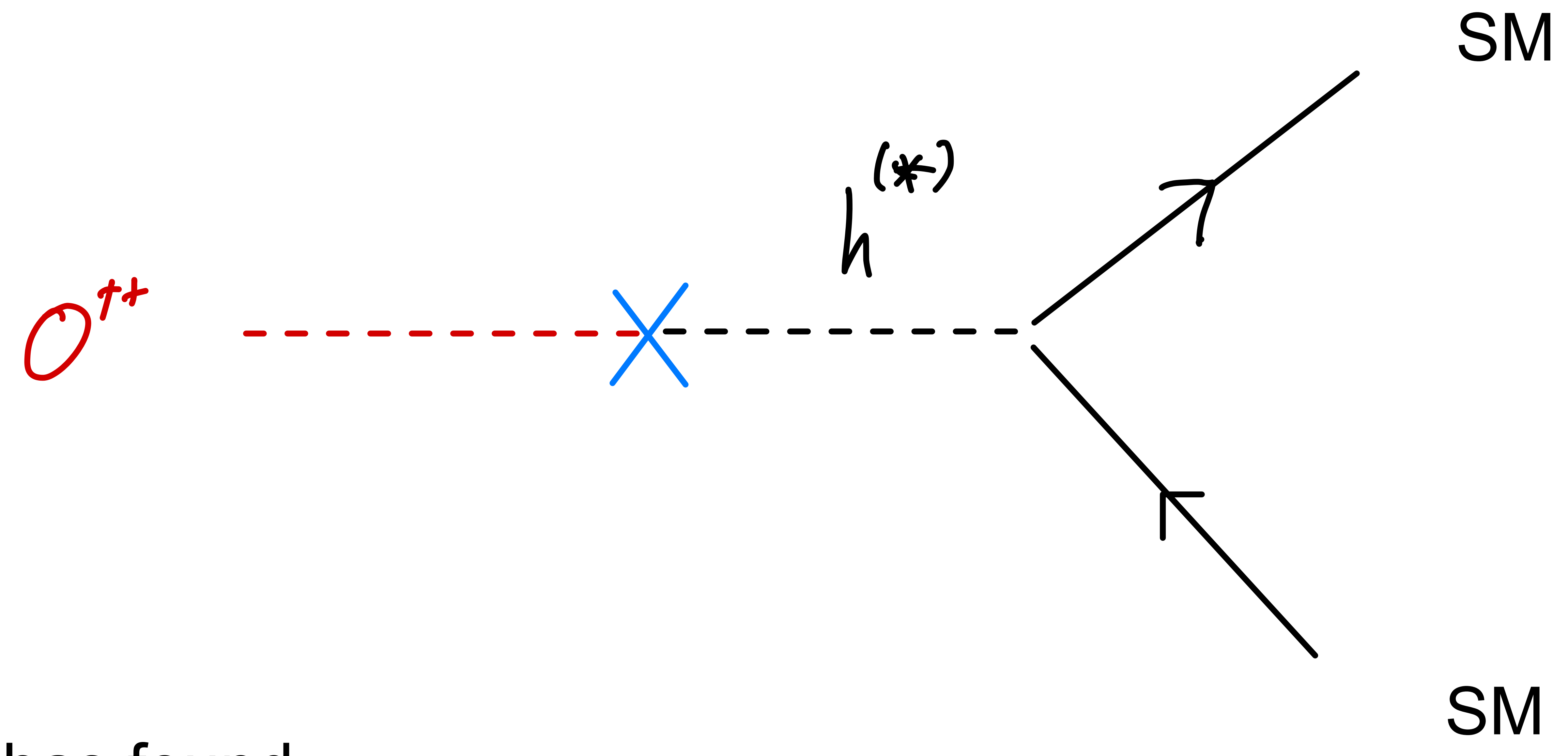


$$\sim \frac{\alpha_D}{4\pi} \cdot y_t^2 \cdot \frac{1}{m_{t'}^2} \cdot (\text{mixing})$$

Craig, Katz, Strassler, Sundrum [1501.05310]

EFT below Confinement Scale

0++ has tiny mixing with Higgs, leading to decays directly to SM



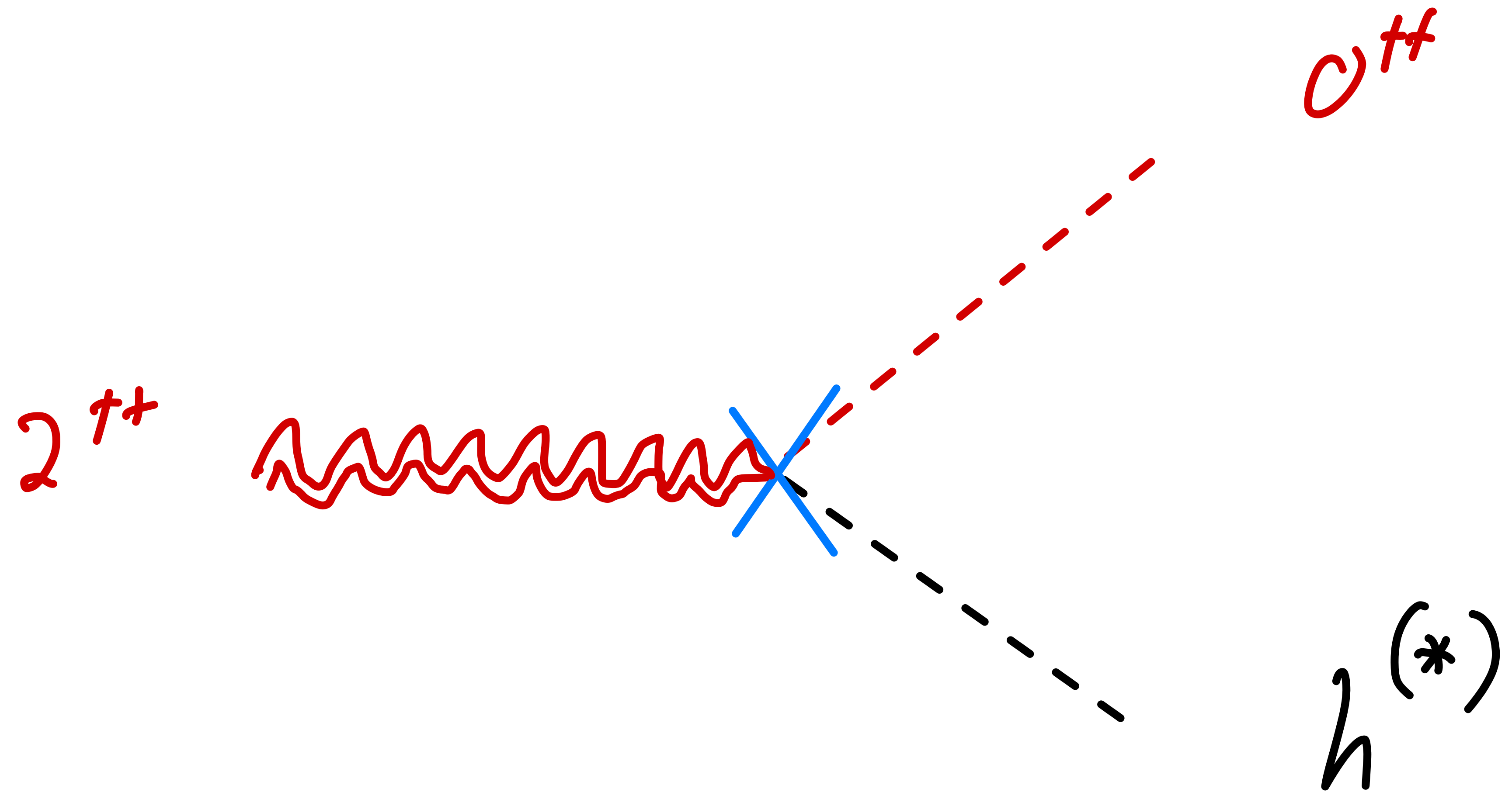
For SU(3), lattice has found

$$4\pi\alpha_D \underbrace{\langle 0|S|G_{\mu\nu}G^{\mu\nu}\rangle}_{F^S_{0^{++}}} \simeq (2.3)\, M_{0^{++}}^3$$

Chen et al [hep-lat/0510074]

Heavier Glueballs

2++, 0+-, … longer lifetimes since they decay via cascades to lighter glueballs with off-shell Higgs,



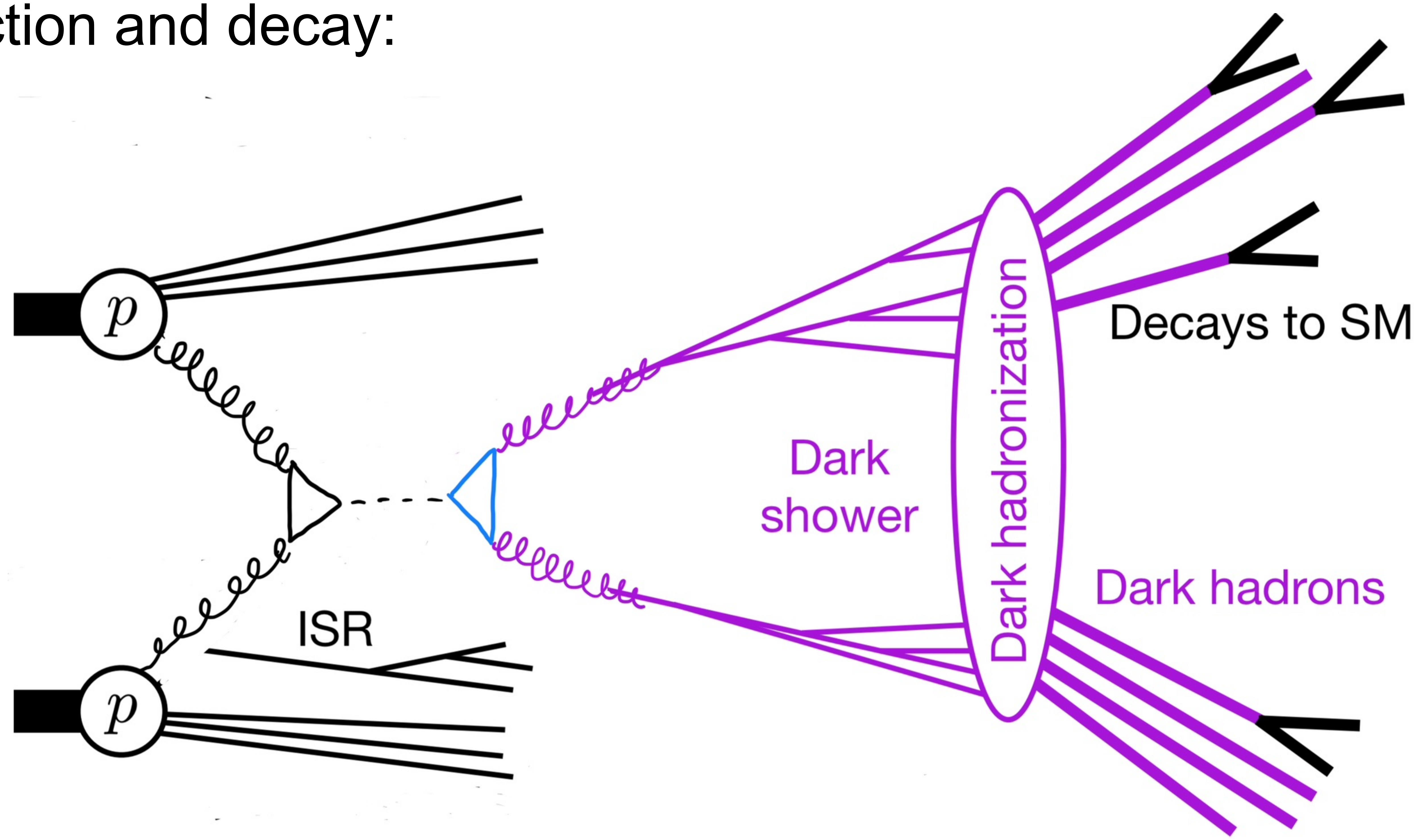
State	$D = 6$ operators	$D = 8$ operators
0^{++}	$bb,\ W^+W^-,\ ZZ,\ hh$	$gg,\ WW,\ ZZ,\ Z\gamma,\ \gamma\gamma$
2^{++}	$0^{\pm+}h(h^*)$	$gg,\ WW,\ ZZ,\ Z\gamma,\ \gamma\gamma$
0^{-+}	-	$gg,\ WW,\ ZZ,\ Z\gamma,\ \gamma\gamma$
3^{++}	$0^{-+}h,\ 2^{\pm+}h(h^*)$	$0^{-+}gg\ 2^{++}gg,\ 1^{+-}\gamma$
1^{+-}	-	$0^{\pm+}\gamma,\ 2^{-+}\gamma$
1^{--}	$1^{+-}h(h^*)$	$0^{\pm+}\gamma,\ 2^{\pm+}\gamma,\ ff$
$0^{+-},\ 2^{+-},\ 3^{+-}$ $2^{--},\ 3^{--}$	$J^{P-}h(h^*)$	$0^{\pm+}\gamma,\ 2^{\pm+}\gamma$

Juknevich [0911.5616]

0-+, 1+- decay only through dimension-8

Glueball phenomenology

LHC production and decay:

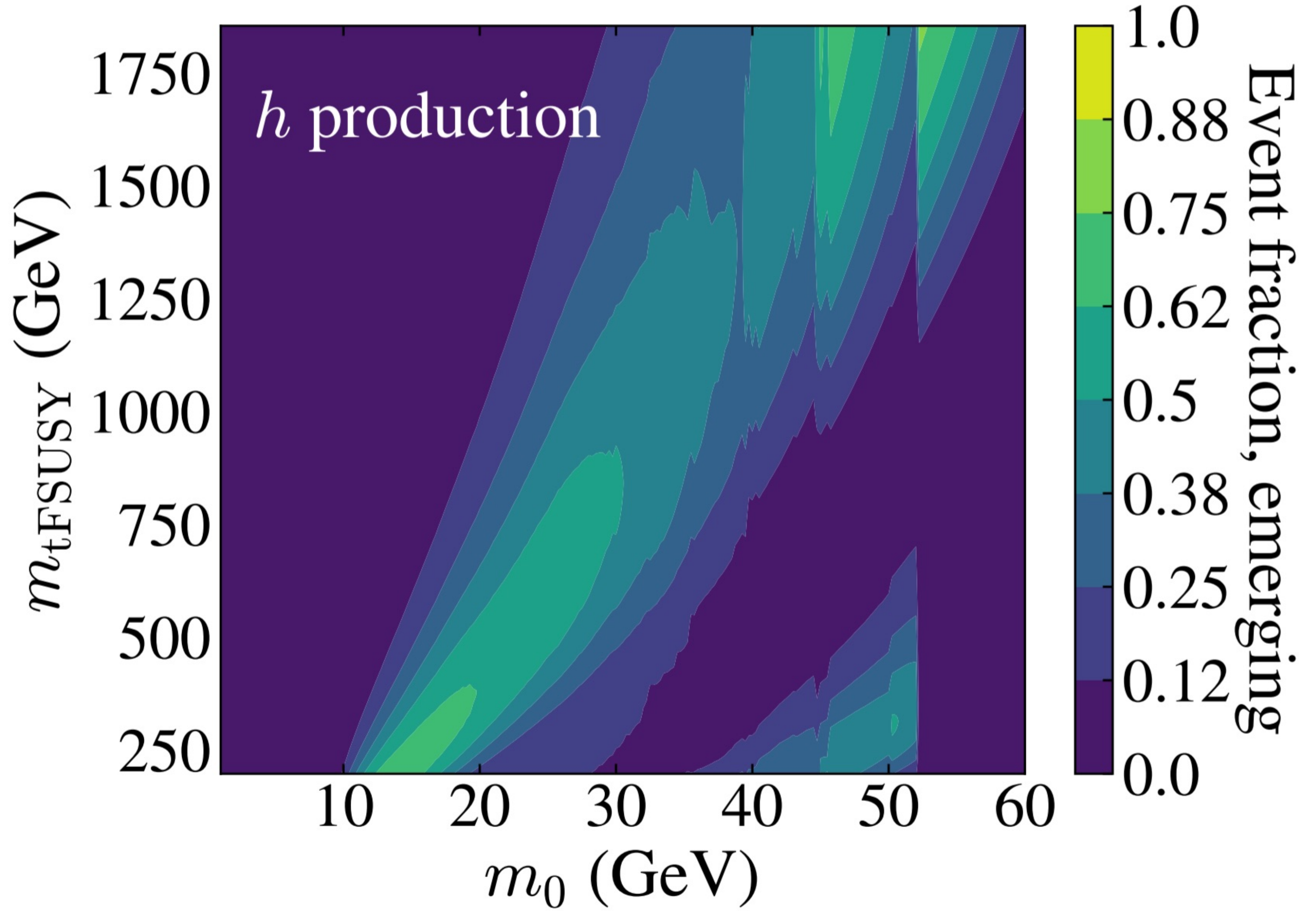


Adapted from Batz

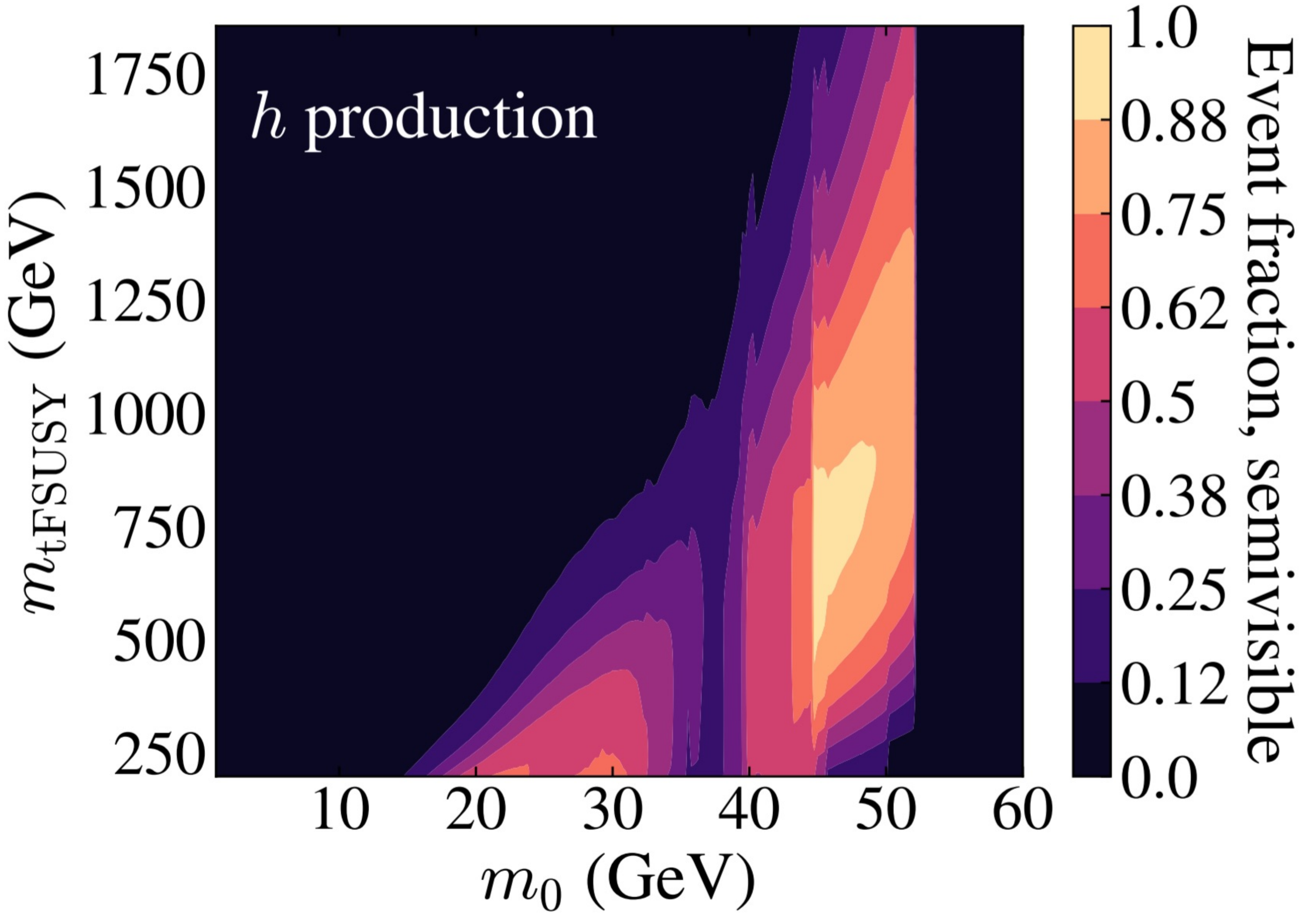
Our (Austin Batz) major contribution is a phenomenological model of dark hadronization with parametrized uncertainities that results in approximately thermal probability distribution of heavy glueball states.

Glueball phenomenology

Emerging jet signal region:
(at least one glueball
decays in tracker volume)



Semi-visible jet signal region:
(one prompt glueball decay
and one escapes detector)

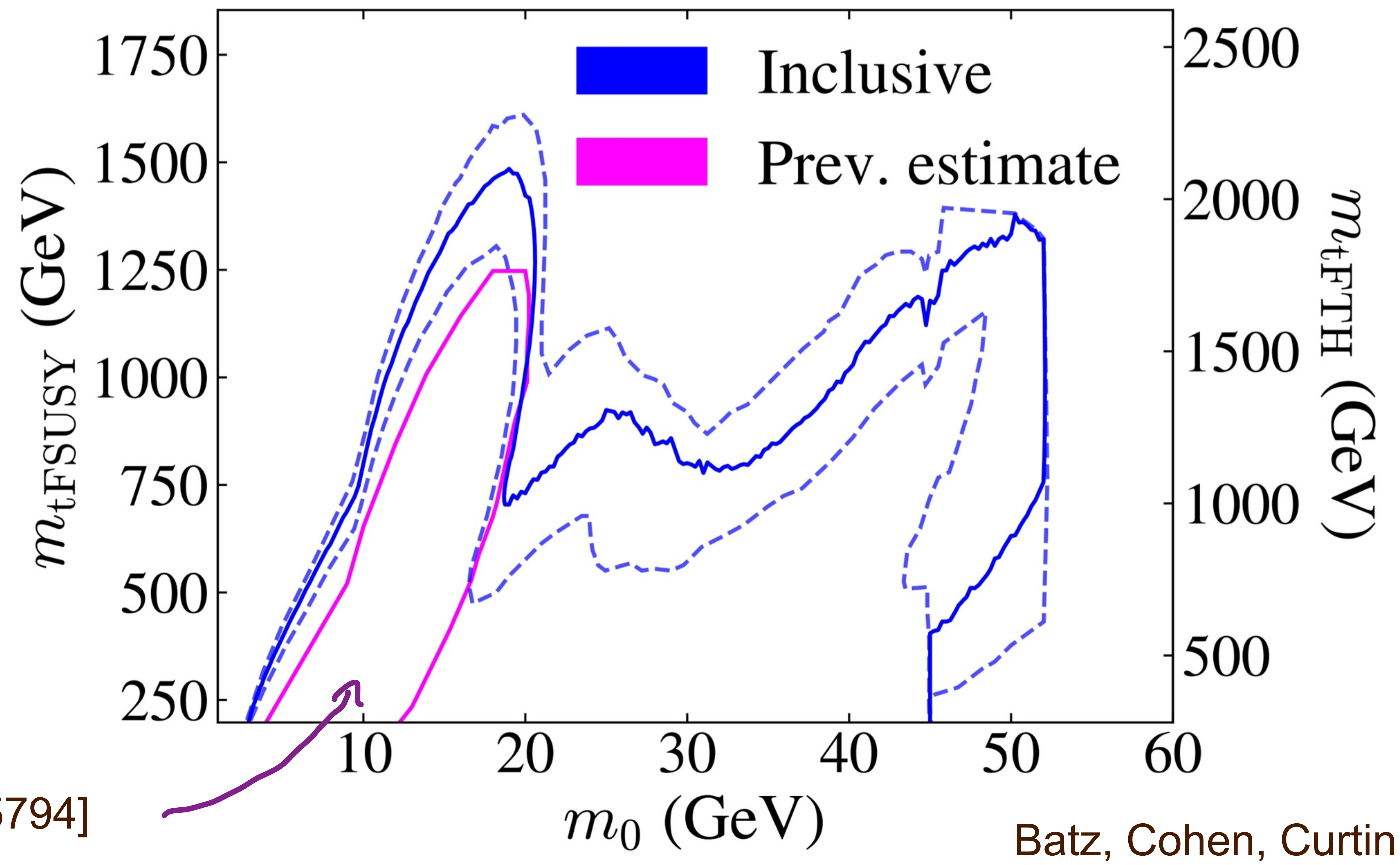


Stratifications occur crossing kinematic
boundaries for heavier glueballs

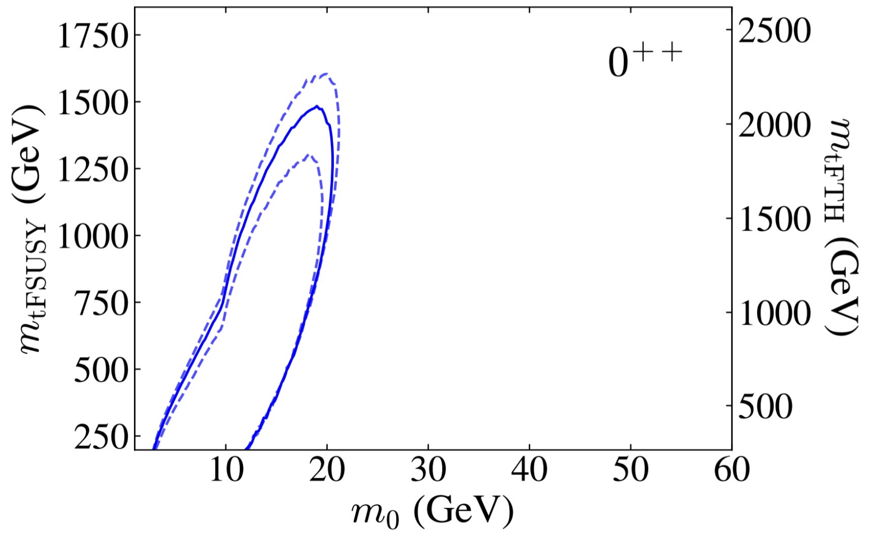
Batz, Cohen, Curtin, Gemmell, GK [2310.13731]

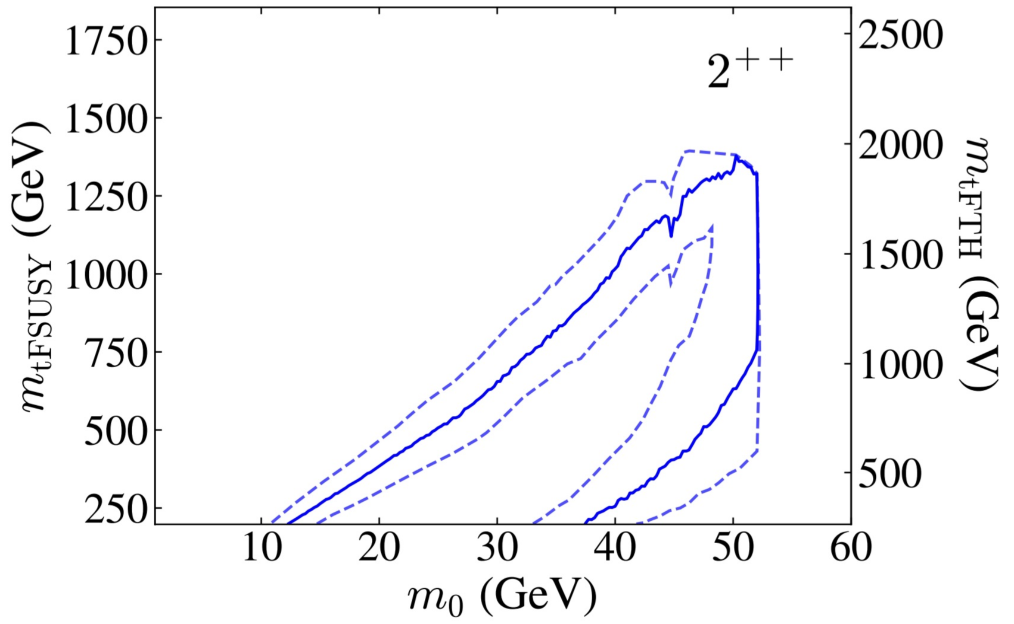
Glueball phenomenology

Sensitivity for MATHUSLA (3 ab-1; negligible background):



Curtin, Gemmell [2211.05794]





Batz, Cohen, Curtin, Gemmell, GK [2310.13731]

Including heavier glueballs significantly extends sensitivity.

Glueball Cosmology

Detailed Boltzmann evolution taking into account 2 <-> 2 and 3 <-> 2 reactions among glueball states, finds:

-> Essentially all heavier glueballs annihilate down to O++

-> C even states (2++, 0-+, 2-+) highly suppressed relative to 0++

-> Lightest C-odd state (0+-) relic abundance several orders of magnitude smaller than O++

Forestell, Morrissey, Sigurdson [1605.08048]

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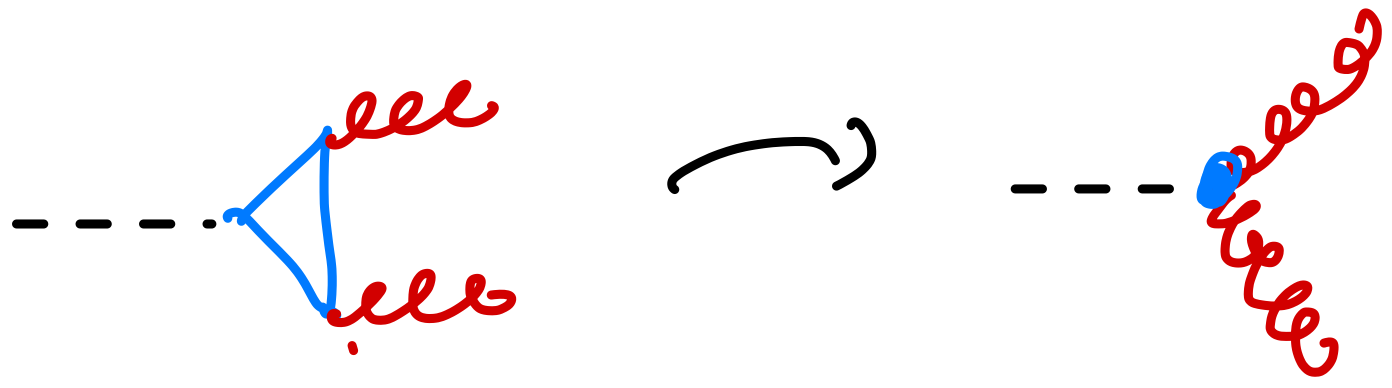
Dark Mesons

Many investigations

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]
…

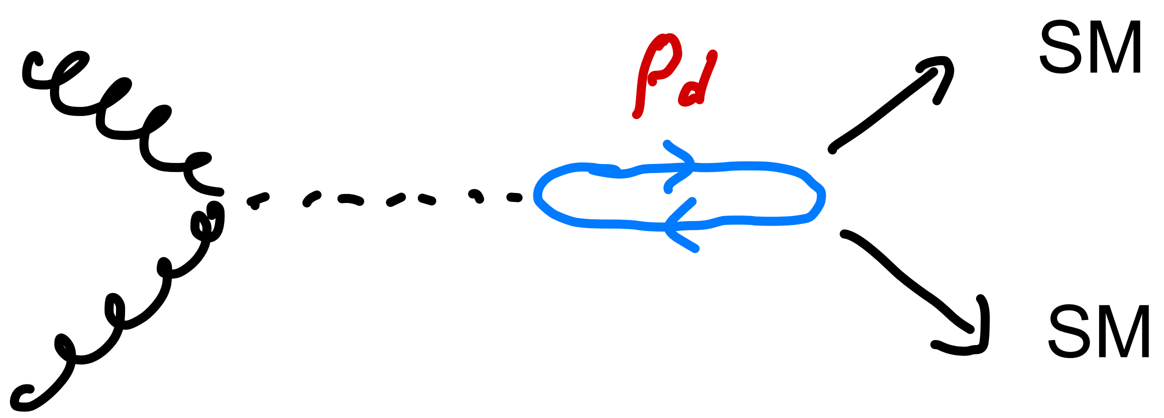
The higher dimensional operators that led to glueball decay relied on a sector of heavy dark quarks.

In our glueball study, assumption was that heavy quarks were too heavy to be produced directly.

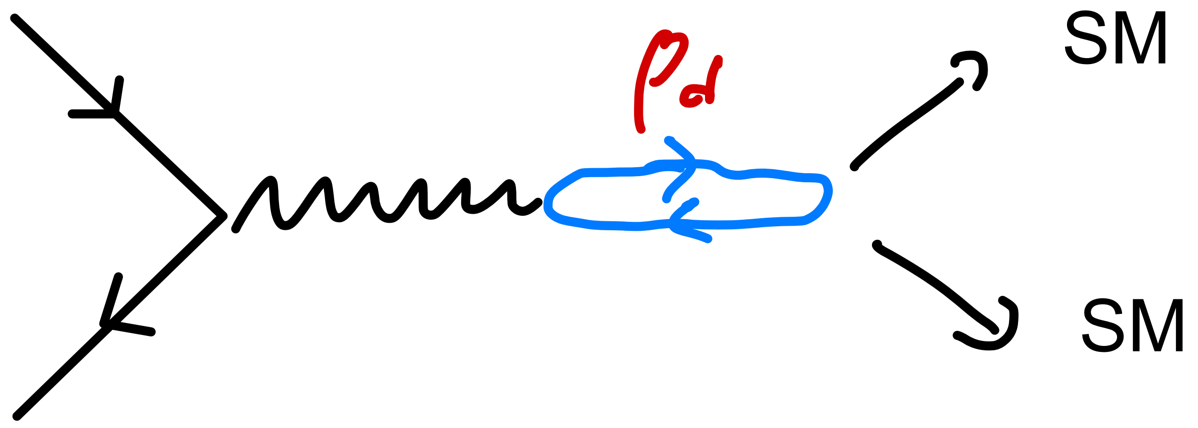
(i.e. )

Dark Quarkonium

Just as SM, produce a tower of heavy quarkonium states, can also imagine:



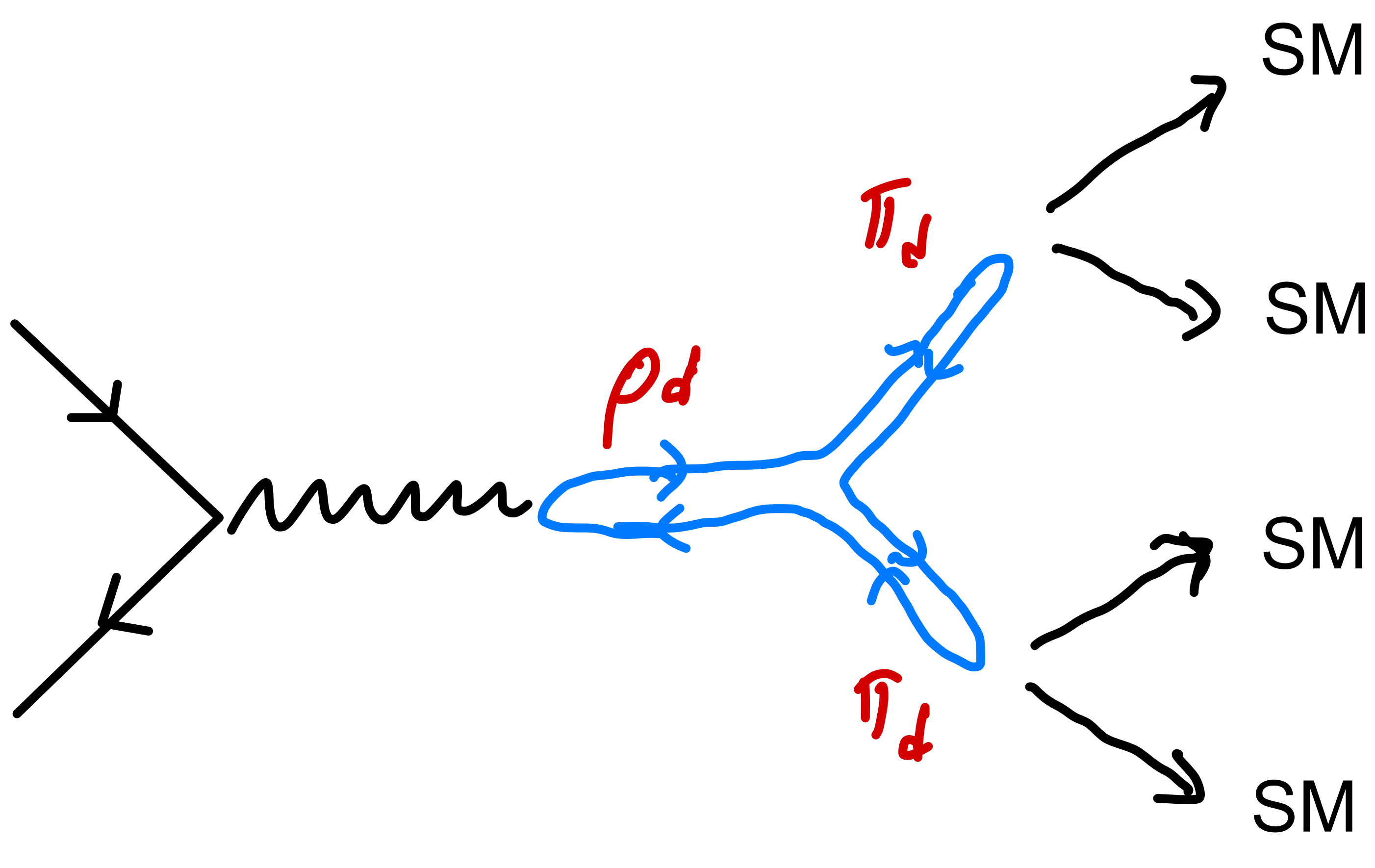
Higgs portal



vector boson portal (SM)

resonance searches

or



$\rho_d \rightarrow \pi_d\ \pi_d$

$\hookrightarrow$ SM SM

$\hookrightarrow$ SM SM

iff $m_{\rho_d} > 2 m_{\pi_d}$

(lighter quark regime)

higher multiplicity "diresonance" searches

Vectorlike EW Dark Fermions

- An example: Two (lighter) flavors of dark quarks transforming under SU(2)L:

	$SU(N)_{dark}$	$SU(2)_L$
q_1	N	2
q_2	$\bar{N}$	2

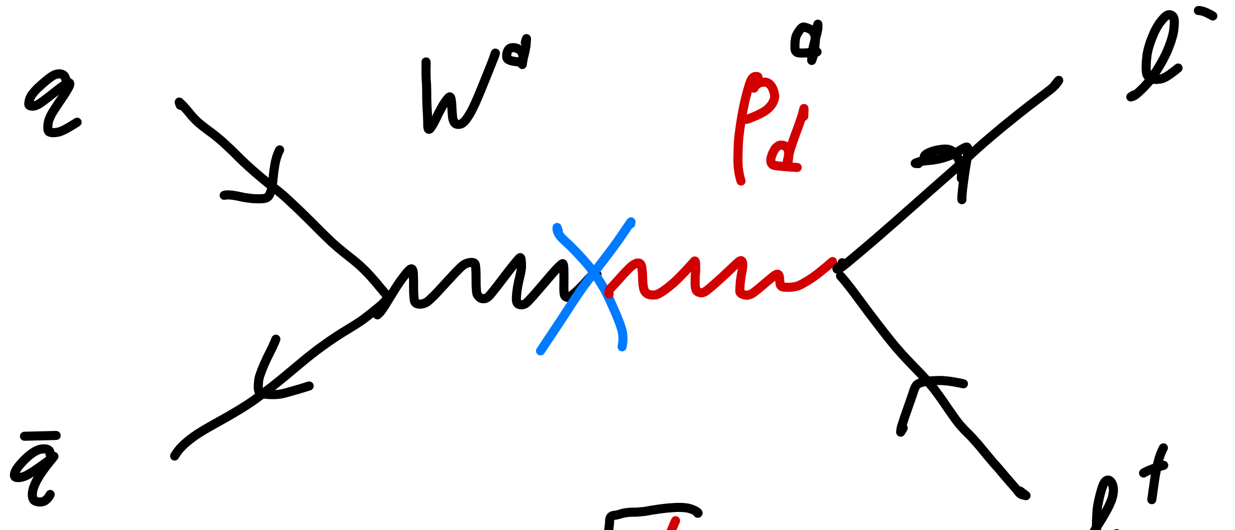
$(Y=0)$

Meson sector:

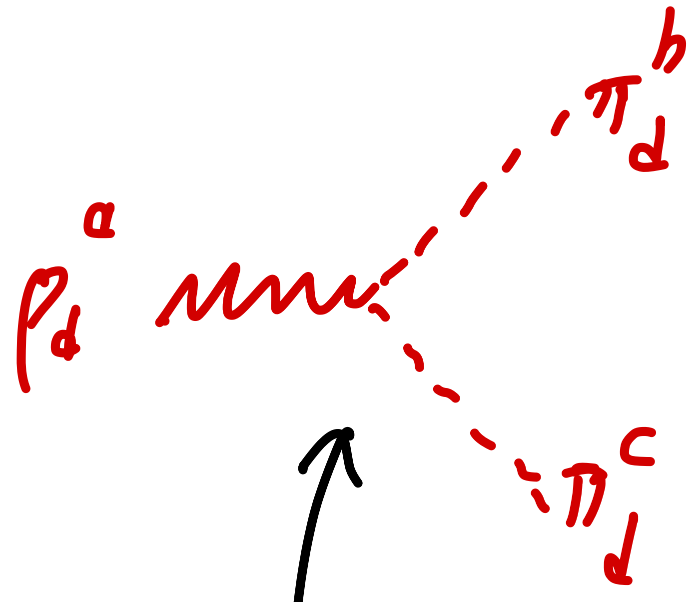
pion-like fields $\begin{pmatrix} \pi_d^+ \\ \pi_d^0 \\ \pi_d^- \end{pmatrix}$

vector-meson fields $\begin{pmatrix} \rho_d^+ \\ \rho_d^0 \\ \rho_d^- \end{pmatrix}$

Dark ρ resonances



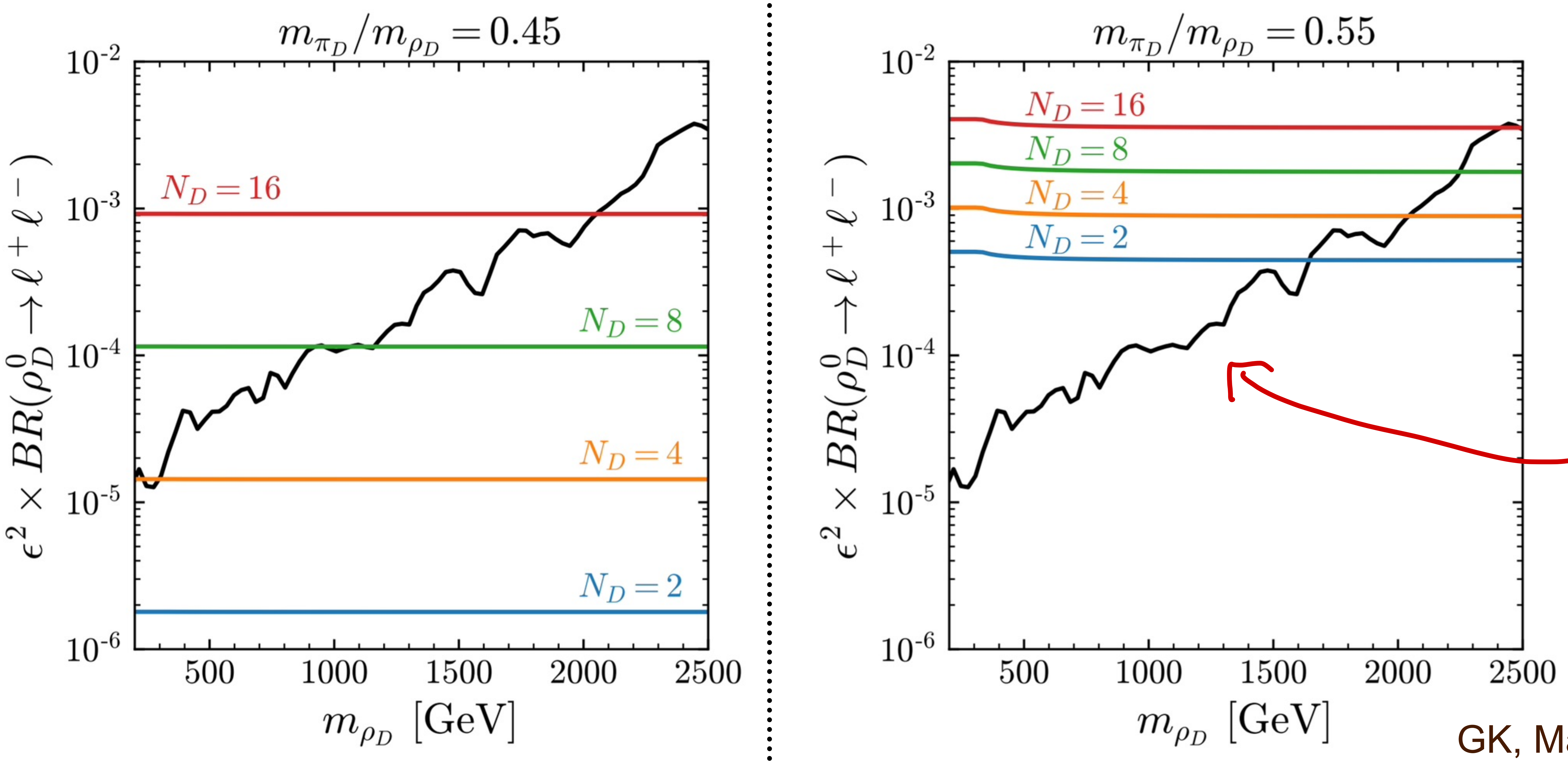
$$\varepsilon \sim \frac{\sqrt{N_c}}{4\pi} g$$

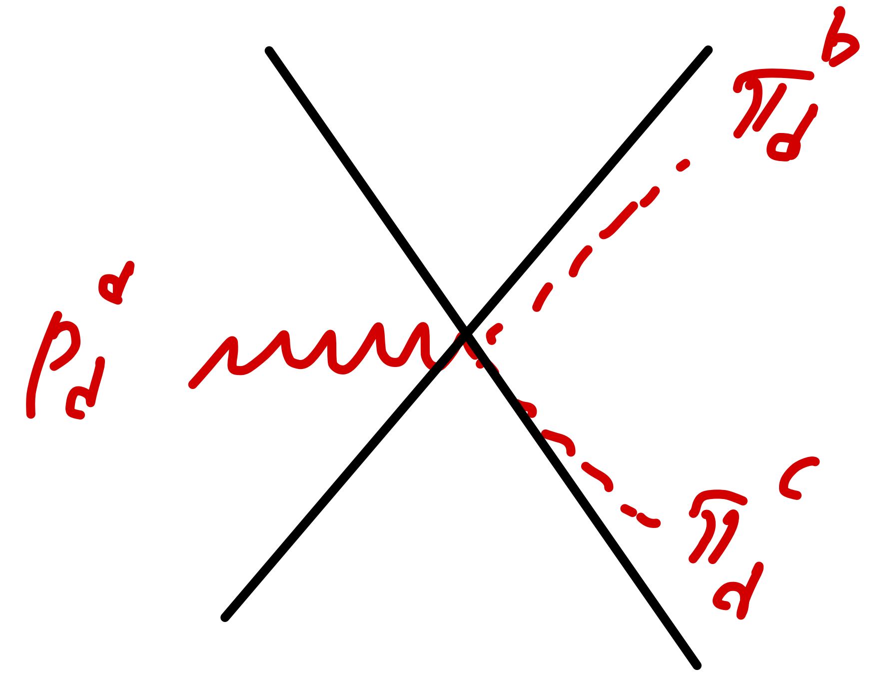


open

large N

$$g_{\rho\pi\pi} \sim \frac{4\pi}{\sqrt{N_D}}$$





kinematically forbidden

LHC dilepton bounds

GK, Martin, Ostdiek, Tong [1809.10184]

EFT for Dark Pions

If dark fermions have a small coupling to the Higgs field (e.g. mixing with heavier set of dark fermions through SM Higgs interactions) this leads to EFT of pions of the form

$$* \quad \Sigma^a \mathcal{O}_f^a \longrightarrow \frac{1}{v_\pi} \pi_d^a \mathcal{O}_f^a \qquad \mathcal{O}_f^a \rightarrow \begin{cases} m_q \, \bar{q} \gamma_5 q \\ \bar{q}' (m_{q'} P_L - m_q P_R) q \end{cases}$$

"gaugephobic"

and

$$\Sigma^a \overleftrightarrow{\partial}^\mu \mathcal{O}_\mu^a \longrightarrow \frac{1}{v_\pi} \pi_d^a \overleftrightarrow{\partial}^\mu \mathcal{O}_\mu^a \qquad \mathcal{O}_\mu^a \rightarrow v \, W_\mu^a h$$

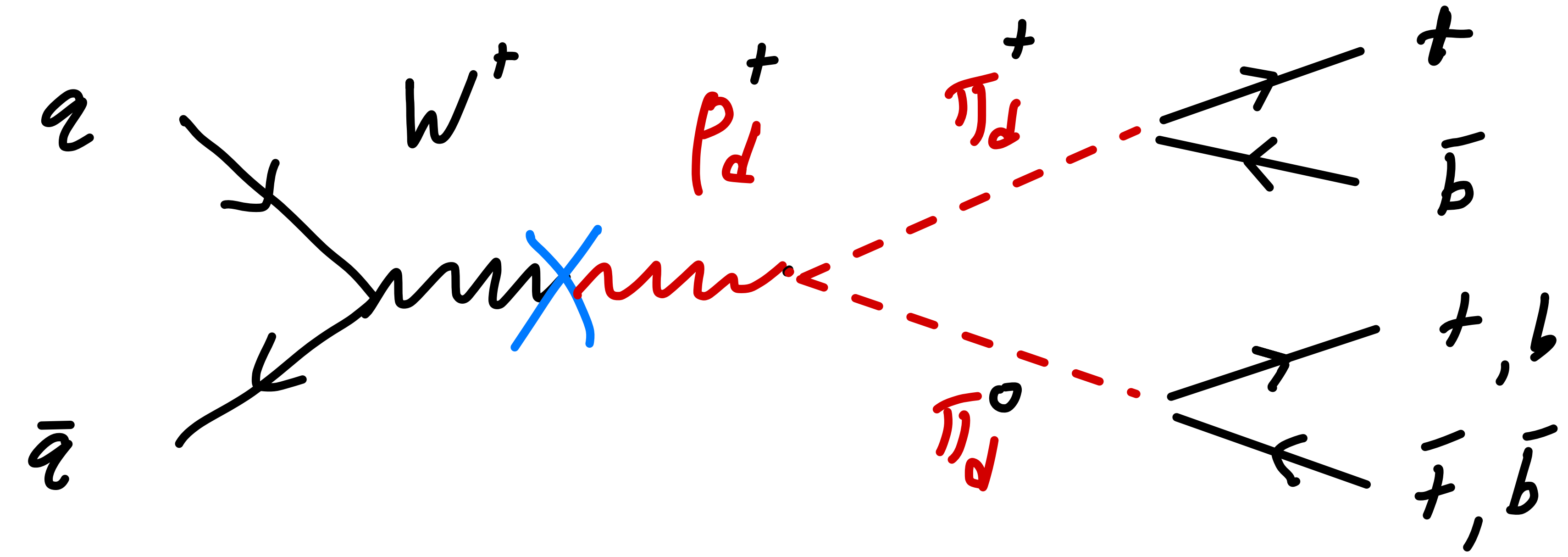
"gaugephilic"

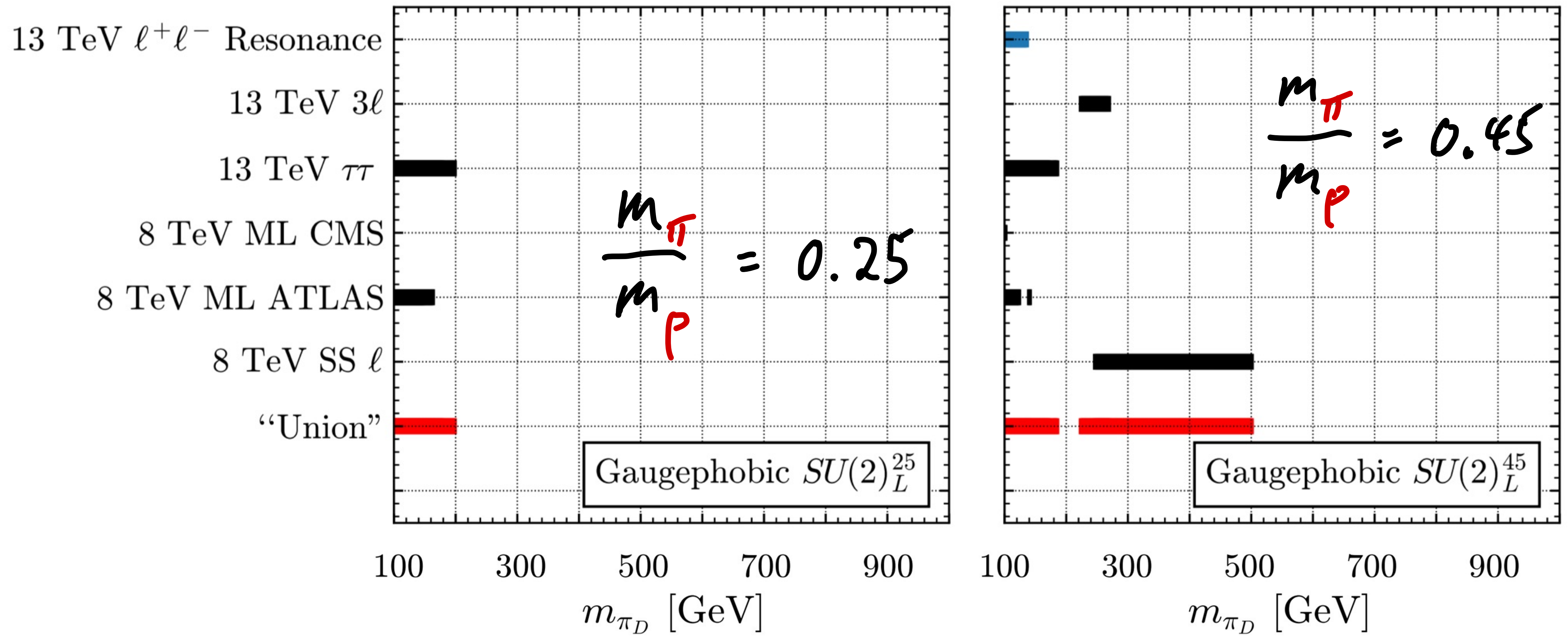
similar to how SM Goldstones interact (e.g. Landau gauge)

* Not derivatively coupled since Higgs interactions within dark sector explicitly violate chiral symmetries.

Our LHC Constraints from Recasting (2018)

e.g.





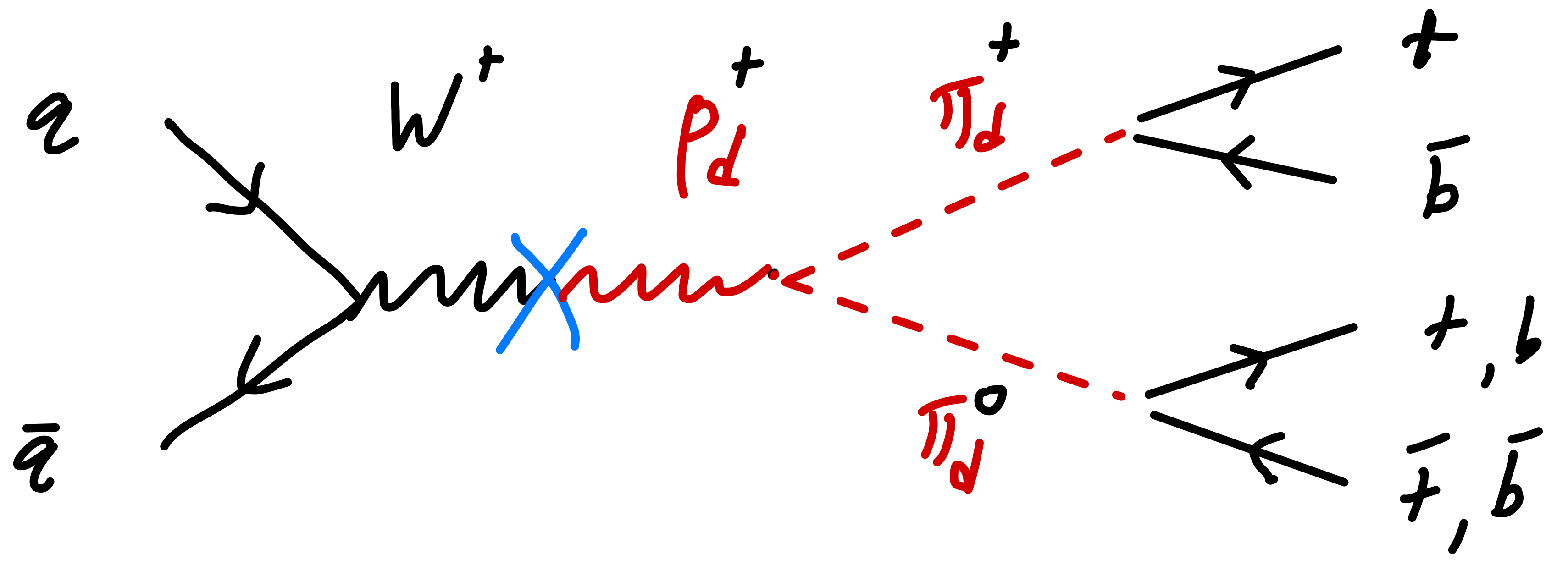
Dark pions $m_{\pi_d} \gtrsim 200$ GeV

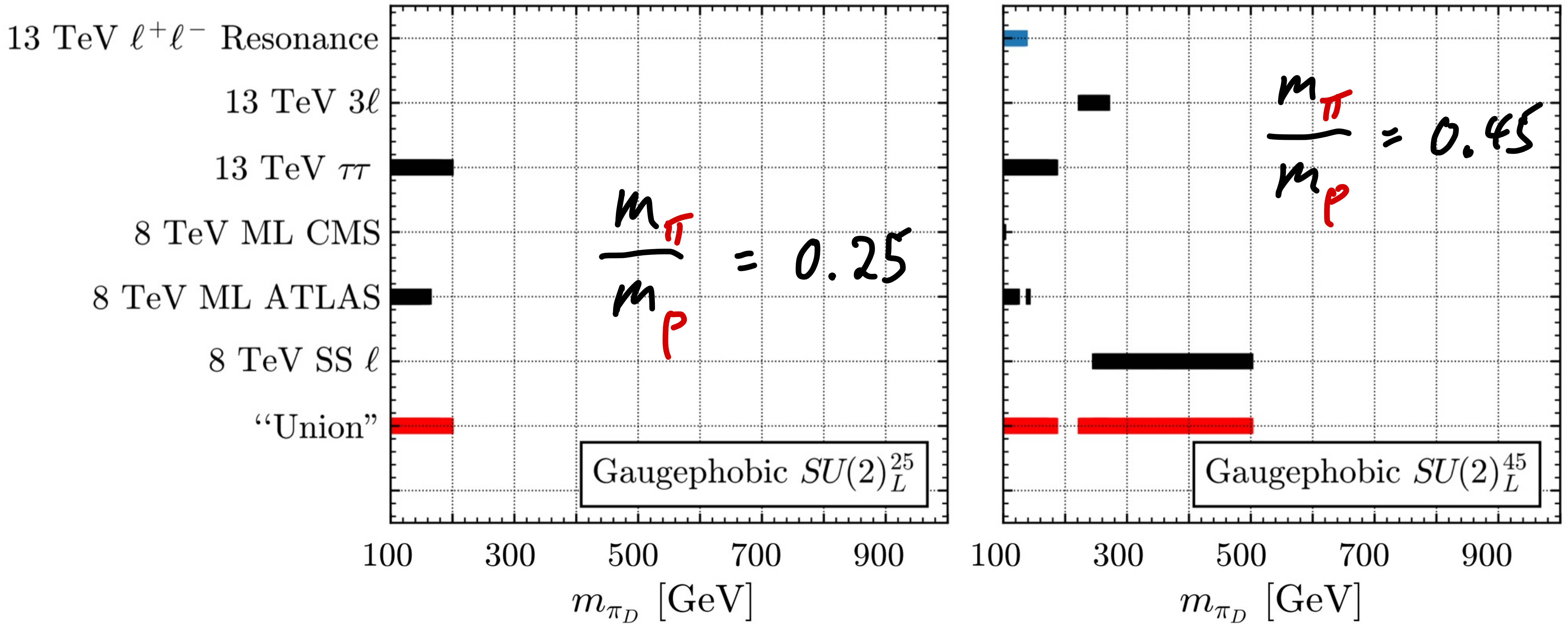
$m_{\rho_d} \gtrsim 800$ GeV

allowed.

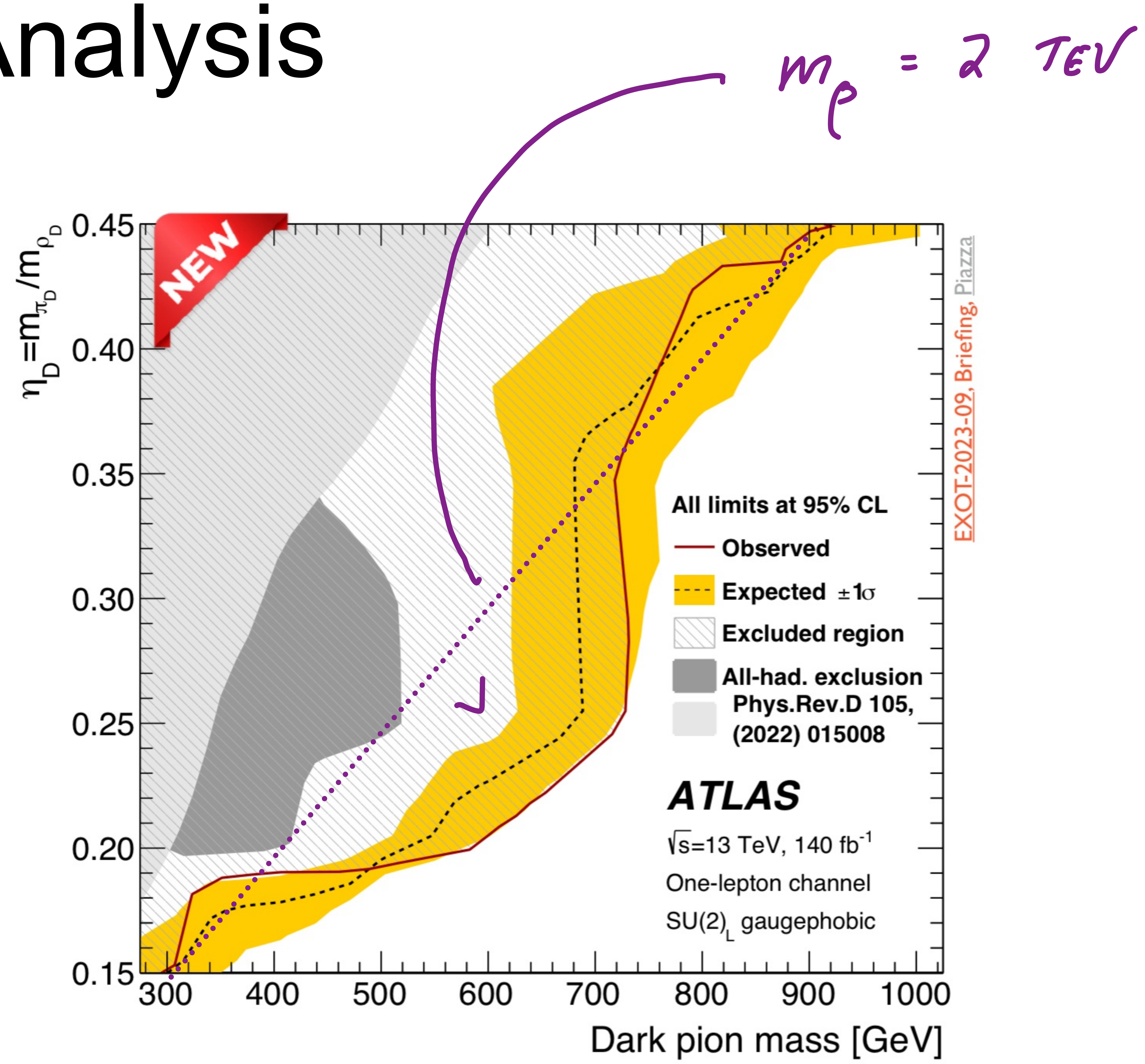
ATLAS Dedicated Analysis

e.g.





~~Dark pions $m_{\pi_d} \gtrsim 200$ GeV~~
~~$m_{\rho_d} \gtrsim 800$ GeV allowed.~~



Analysis with large participation from Oregon ATLAS group!

Presented: Heather Gray @ LHCP June 2024.

Can Dark Pions be Stable? G-parity

If there are no Higgs interactions among dark sector fermions, Bai-Hill recognized that a broad class of theories contains a dark anolog of G-parity, familiar from the SM:

$$G \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix} \longrightarrow \begin{pmatrix} -\pi^+ \\ -\pi^0 \\ -\pi^- \end{pmatrix}$$

We'll encounter something similar (but distinct for dark baryons), so let me elaborate on the model.

Bai, Hill [1005.0008]

Thanks to Hitoshi Murayama for pointing out typo in signs for $\pi^\pm$!

Vector-like Dark Fermion Sector

fermions:

	$SU(N)_{dark}$	$SU(2)_L$
q_1	N	N_f
q_2	$\bar{N}$	N_f

with vector-like dark fermion mass : $m_f\left(q_1 q_2 + h.c.\right)$

Bai-Hill recognized theory has a global parity:

$$G \equiv S \otimes C$$

charge conjugation

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

J^2: $SU(2)_L$ generator

SU(2) is Special

All reps are real -> there is a unitary transformation that relates the original and conjugate reps:

$$S^\dagger J^a S = -J^{a*} = (J^a)^T \qquad \text{with} \qquad S = \exp\left[i\pi J^2\right]$$

Bai-Hill recognized that if you rotate with S and charge conjugate the dark quarks:

$$q_1 \xrightarrow{S} S\, q_1 \xrightarrow{c.c.} S\, q_2 \qquad\qquad \underbrace{q_1^\dagger \bar{\sigma}^\mu D_\mu}_{J^a} q_1 \longrightarrow \underbrace{q_2^\dagger \bar{\sigma}^\mu D_\mu}_{[J^a]^T} q_2$$

$$q_2 \xrightarrow{S} S^\dagger q_2 \xrightarrow{c.c.} S^\dagger q_1 \qquad\qquad \underbrace{q_2^\dagger \bar{\sigma}^\mu D_\mu}_{[J^a]^T} q_2 \longrightarrow \underbrace{q_1^\dagger \bar{\sigma}^\mu D_\mu}_{J^a} q_1$$

<u>Lagrangian is invariant.</u>

Dark Pion Stability

This symmetry persists in the confining IR description, where pions transform as multiplets of SU(2)L.

For example, if q_1, q_2 are in Nf = 2 reps (doublets), then dark pions transform as

$$\begin{pmatrix} \pi_d^+ \\ \pi_d^0 \\ \pi_d^- \end{pmatrix} \quad \text{triplet under SU(2)L}$$

that transforms under G-parity as

$$G \begin{pmatrix} \pi_d^+ \\ \pi_d^0 \\ \pi_d^- \end{pmatrix} \longrightarrow \begin{pmatrix} -\pi_d^+ \\ -\pi_d^0 \\ -\pi_d^- \end{pmatrix} \longleftarrow$$

Only <u>even</u> powers of π_d^0 are allowed by G-parity.

π_d^0 becomes possible dark matter candidate.

(Up to UV violations at dimension-5)

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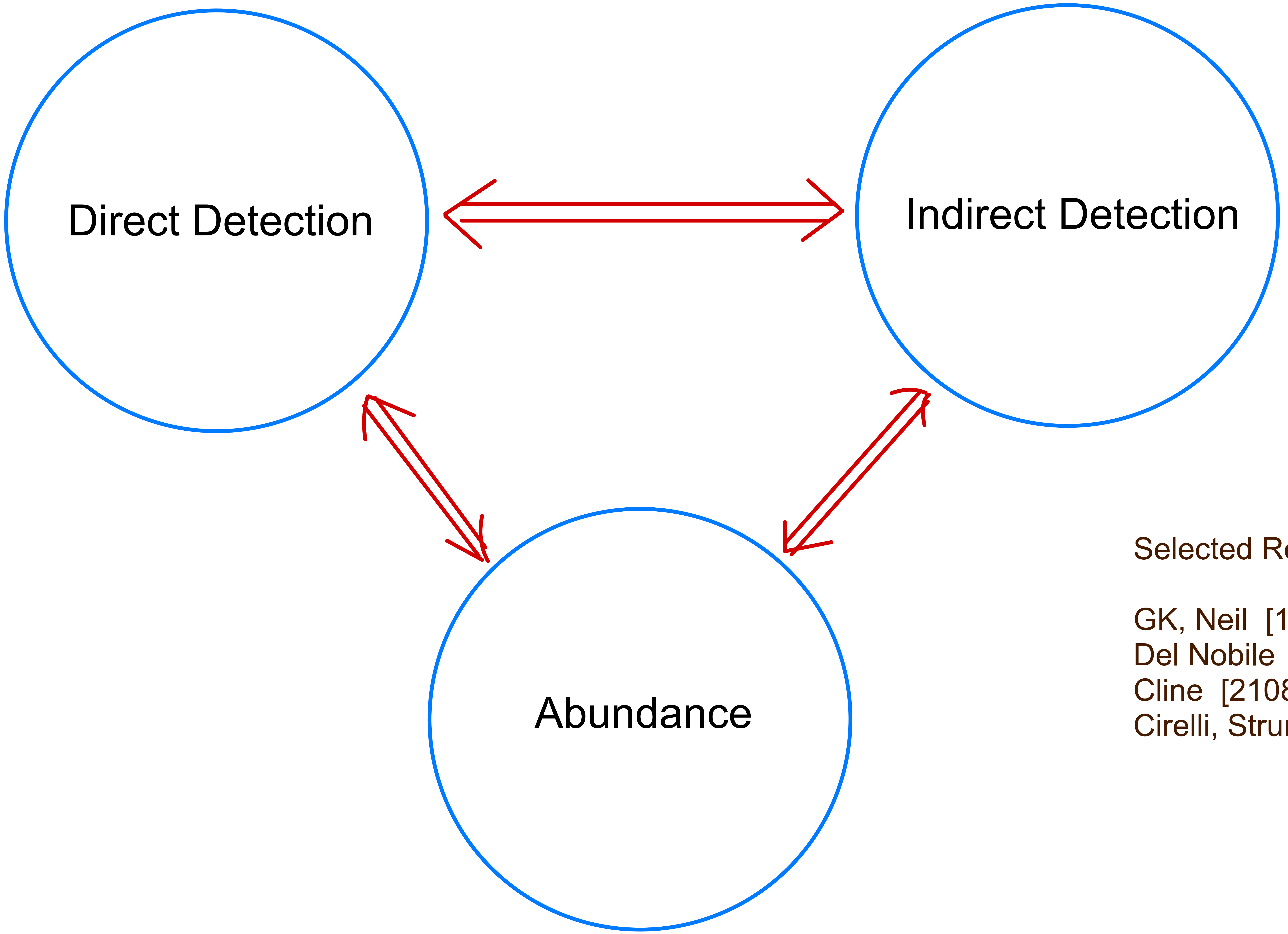
Asadi, GK, Mantel [to appear]

Dark Baryons as Dark Matter



Selected Reviews:

GK, Neil [1604.04627]
Del Nobile [2104.12785]
Cline [2108.10314]
Cirelli, Strumia, Zupan [2406.01705]

EFT of Dark Baryons for Direct Detection

Variety of UV theories, e.g.

Gudnason, Kouvaris, Sannino [hep-ph/0608055]
GK, Roy, Terning, Zurek [0909.2034]
Appelquist, … GK, et al [1402.6656; 1503.04203; 1503.04205]
Detmold, McCullough, Pochinsky [1406.2276; 1406.4116]
Antipin, Redi, Strumia, Vigiani [1503.08749]
Mitridate, Redi, Smirnoff, Strumia [1707.05380]
Contino, Podo, Revello [2008.10607]
…

Common ingredient is an electrically neutral dark baryon "B0" that serves as (dominant) component of dark matter.*

*Not considering dark nuclei …

EFT is constructed from effective interactions of B0, with low energy theory in terms of expansion of nonrelativistic field. However, for ease of presentation, write operators with relativistic notation and field normalization:

e.g. ψ_{B_0} spin-$\frac{1}{2}$ neutral baryon (odd N_c)

ϕ_{B_0} spin-0 neutral baryon (even N_c)

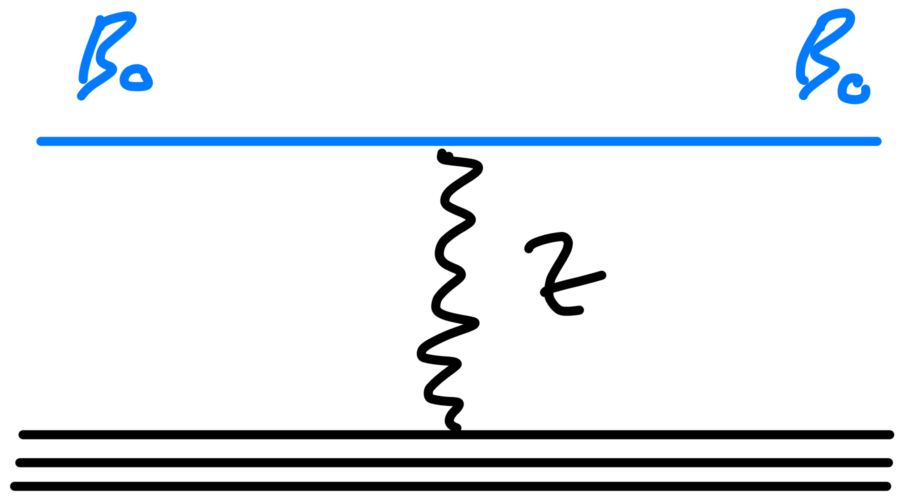
Direct Detection

dimension (in NR EFT)	EM moments	Electroweak Operators	Higgs Operators
4		$\bar{\psi}_{B_0} \gamma^\mu \psi_{B_0} Z_\mu$	
5	$\bar{\psi}_{B_0} \sigma^{\mu\nu} \psi_{B_0} F_{\mu\nu}$ * $\bar{\psi}_{B_0} \sigma^{\mu\nu} \gamma_5 \psi_{B_0} F_{\mu\nu}$		$\bar{\psi}_{B_0} \psi_{B_0} H^\dagger H$ | $\phi^\dagger_{B_0} \phi_{B_0} H^\dagger H$
6	$\bar{\psi}_{B_0} \partial^\mu \psi_{B_0} \partial^\nu F_{\mu\nu}$ | $\phi^\dagger_{B_0} \partial^\mu \phi_{B_0} \partial^\nu F_{\mu\nu}$ * $\bar{\psi}_{B_0} \gamma_5 \partial^\mu \psi_{B_0} \partial^\nu F_{\mu\nu}$		
7	$\bar{\psi}_{B_0} \psi_{B_0} F_{\mu\nu} F^{\mu\nu}$ | $\phi^\dagger_{B_0} \phi_{B_0} F_{\mu\nu} F^{\mu\nu}$	$\left.\begin{matrix} \bar{\psi}_{B_0} \psi_{B_0} \\ \phi^\dagger_{B_0} \phi_{B_0} \end{matrix}\right\} \times \left\{\begin{matrix} Q \cdot H u^c \\ Q \not{\partial} Q \\ \vdots \end{matrix}\right.$	

* CP violating

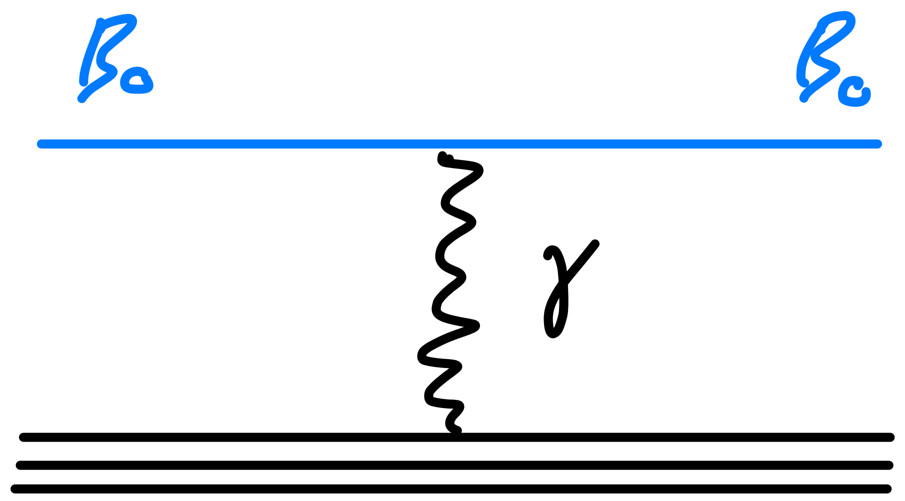
(Naive) Expectations

Dimension-4 (Z-exchange) highly constrained:



$c_Z \lesssim 10^{-4}$

Dimension-5 magnetic dipole moment:



Careful matching to nucleon EFT — most relevant interactions:

$$\begin{cases} \mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N \\ \mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp) \end{cases}$$

Fitzpatrick et al [1203.3542]

Constraint from LZ: $m_{B_0} \gtrsim 100$ TeV assuming $\mu_{B_0} \sim \mu_{\text{neutron}}$

Eby, Fox, GK [2312.08478]

Dark Baryons in Electroweak Multiplets

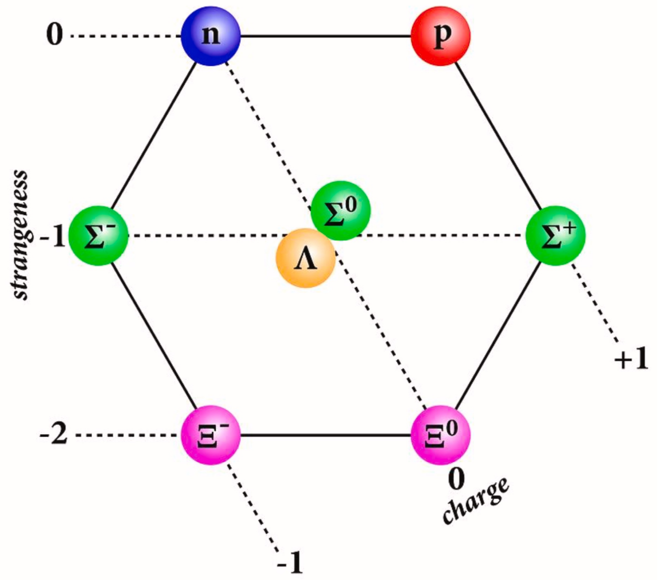
Theory considered previously:

fermions:

	$SU(N)_{dark}$	$SU(2)_L$
f_1	N	N_f
f_2	$\bar{N}$	N_f

Contains baryons in SU(2)L reps:

$$\text{e.g.} \begin{cases} N_c = 3 \\ N_f = 3 \end{cases} : \begin{pmatrix} \Sigma^+ \\ \Sigma_0 \\ \Sigma^- \end{pmatrix}, \begin{pmatrix} B^{++} \\ B^+ \\ \Lambda_0 \\ B^- \\ B^{--} \end{pmatrix}$$



In $m_f \gg \Lambda_{\text{dark}}$ limit, Nc=Nf=3, use quark model to calculate magnetic dipole moments

$$\begin{pmatrix} \mu_{\Sigma_0} & \mu_{\Sigma_0 \Lambda_0} \\ \mu_{\Lambda_0 \Sigma_0} & \mu_{\Lambda_0} \end{pmatrix} = \begin{pmatrix} 0 & \text{finite} \\ \text{finite} & 0 \end{pmatrix}$$

(the zeros were also observed in Antipin, Redi, Strumia, Vigiani [1503.08749])

“Guardian” parity

Hidden parity for dark baryons in real reps of SU(2)L:

$$q_1 \longrightarrow S\, q_2 \qquad\qquad S = \exp\left[i \pi J^2 \right]$$

$$q_2 \longrightarrow S^{\dagger} q_1$$

combined with charge conjugation on SM gauge fields:

$$W_\mu^a \longrightarrow (W_\mu^a)^c = \begin{cases} + W_\mu^2 \\ - W_\mu^{1,3} \end{cases} \qquad \left[\text{and} \quad B_\mu^a \to (B_\mu^a)^c \right]$$

resulting dark quark interactions involve:

$$S^{\dagger} J^a S\, W_\mu^a \longrightarrow$$ Invariant!

Holds independent of Nc, Nf and scale

Λ_{dark} m_f

“Guardian” parity violating operators

Critically, Guardian-parity persists in the confined description, i.e., dark baryons Nc=Nf=3:

$$\mathcal{G}\begin{pmatrix}\Sigma^+\\ \Sigma_0\\ \Sigma^-\end{pmatrix} = \begin{pmatrix}+\,\Sigma^-\\ -\,\Sigma_0\\ +\,\Sigma^+\end{pmatrix} \qquad \mathcal{G}\begin{pmatrix}B^{++}\\ B^{+}\\ \Lambda_0\\ B^{-}\\ B^{--}\end{pmatrix} = \begin{pmatrix}+\,B^{--}\\ -\,B^{-}\\ +\,\Lambda_0\\ -\,B^{+}\\ +\,B^{++}\end{pmatrix}$$

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

$\to (-\bar\Sigma_0)\,\sigma^{\mu\nu}\,(-\Sigma_0)(-F_{\mu\nu})$

$\to$ odd under Guardian-parity

Forbidding all dim-4 Z-exchange, and dim-5, dim-6 EM moments: $\longrightarrow$

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

"Guardian" parity preserving operators

Allowed interactions:

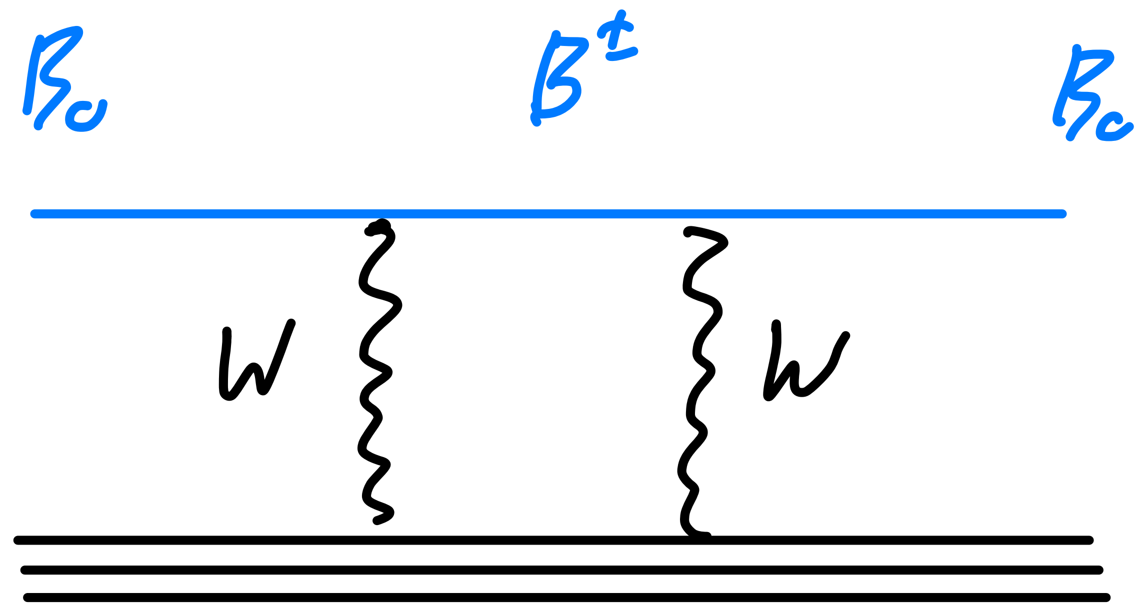
$\bar{\psi}_{B_0} \psi_{B_0} H^\dagger H$ $\longleftarrow$ generated only if dim-5: $q_i^\dagger q_i H^\dagger H$ present in UV

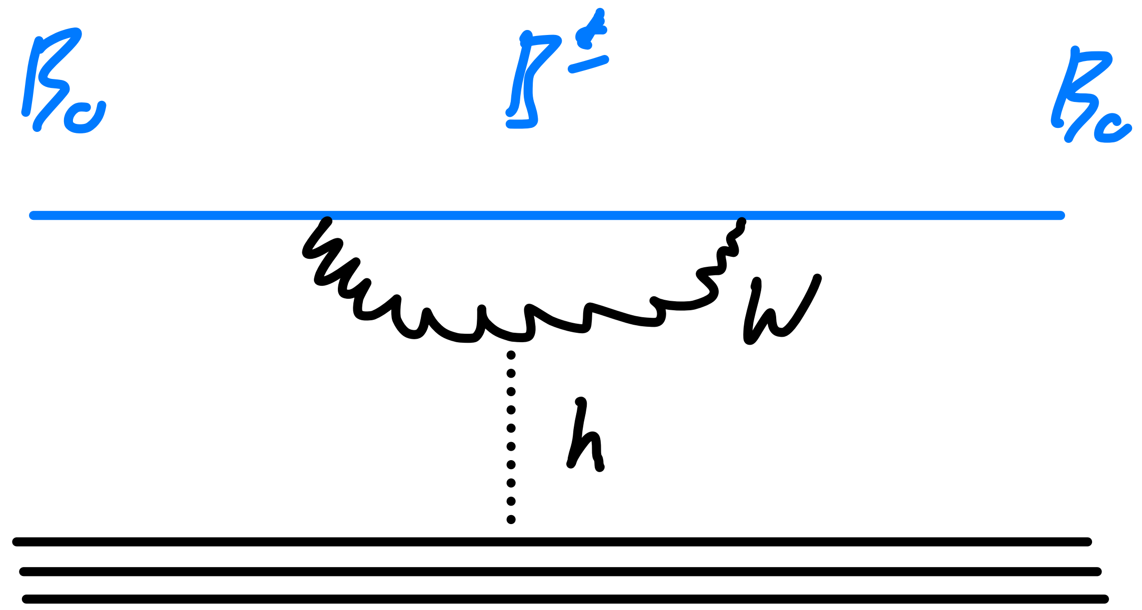
$\bar{\psi}_{B_0} \psi_{B_0} F_{\mu\nu} F^{\mu\nu}$ $\longleftarrow$ polarizability (dim-7)

$\bar{\psi}_{B_0} \psi_{B_0} \times \begin{cases} Q \cdot H u^c \\ Q \not{D} Q \\ \vdots \end{cases}$ $\longleftarrow$ EW loops (dim-7)

e.g. $\bar{\psi}_{\Sigma_0} \sigma^{\mu\nu} \psi_{\Lambda_0} F_{\mu\nu}$ $\longleftarrow$ EM transition moments
(between baryons with different Guardian-parities)

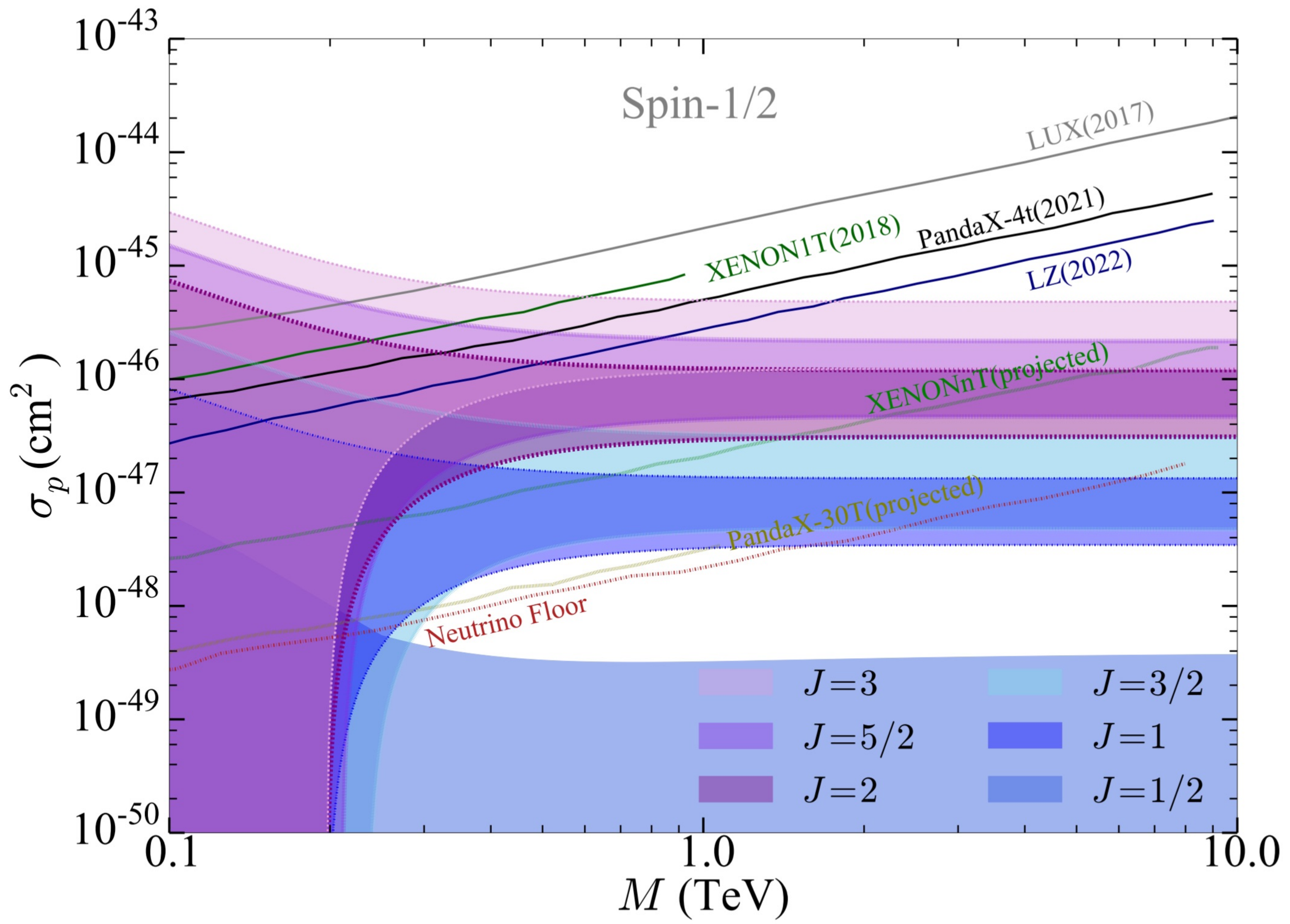
Electroweak Loops





EFT* with M(B_0) >> Mw:

*(Majorana)



5-plet

triplet

Chen, Ding, Hill [2309.02715]

Summary

Strongly-coupled dark sectors have a rich theory space that is (still!) yielding surprises, such as Guardian-parity for dark baryons.

23 Dark glueballs have diverse lifetimes, motivating long-lived search strategies at LHC and (potential) dedicated facilities to long-lived particles.

18 Dark mesons (that decay through Higgs interactions) evaded LHC searches until now. What else could be hidden in high(er) lumi data?

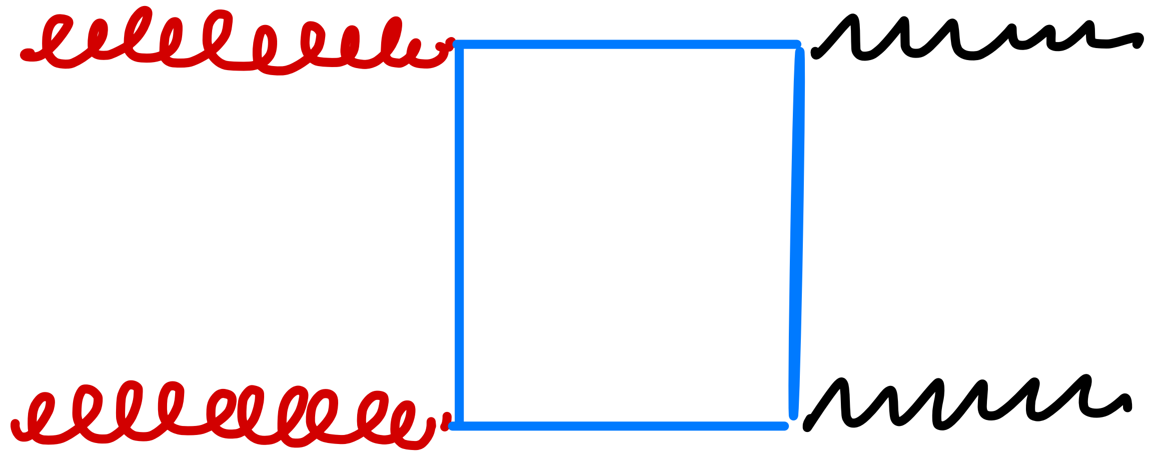
24 Dark baryons as (one of) the most elegant explanation(s) for dark matter, are only being tested now — strengthening the case for continued pursuit of scattering off nuclei, e.g., electroweak loop contribution near neutrino floor

Thank you!

Decays only through dimension-8

The going rate for dimension-8:

glueball



$$\Gamma \sim \frac{\alpha_{dark}^2 \, \alpha_{SM}^2}{1000\pi} \cdot \frac{m_{J^{PC}}^3 F_{J^{PC}}^2}{M^8}$$

approximating $m_{J^{PC}}^7 F_{J^{PC}}^2 \sim m_{J^{PC}}^9$, lifetime is

$$\tau \sim (0.1\ \mathrm{s}) \cdot \left(\frac{m_{J^{PC}}}{20\ \mathrm{GeV}}\right) \cdot \left(\frac{M / m_{J^{PC}}}{100}\right)^8$$

becomes dangerously long lived (constraints from BBN) if $\dfrac{M}{m_{J^{PC}}} \gtrsim 100$.