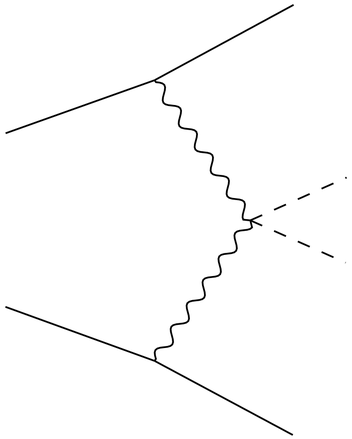
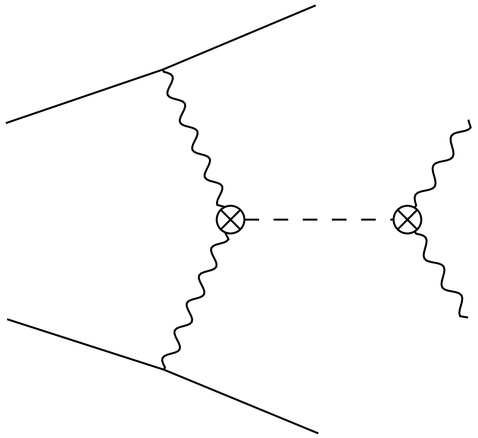
Dark Mesons Stopped in Their Tracks





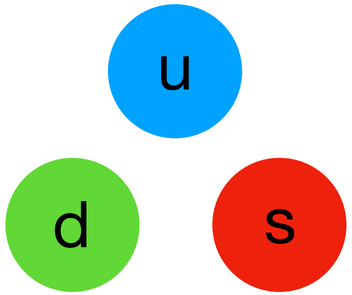
Austin Batz, University of Oregon

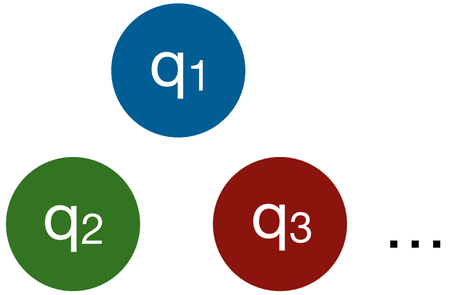
November 24, 2025

P Asadi, **AB**, E Bernreuther, M Costa, S Homiller, G Kribs, arXiv:2507.13430

Context: Confining Sectors

- Add some non-Abelian group with confinement in the IR
- Dark quarks and gluons bind into a rich spectrum of dark hadrons, several possible portals to SM
- Non-minimal solutions to DM, Hierarchy Problem, …





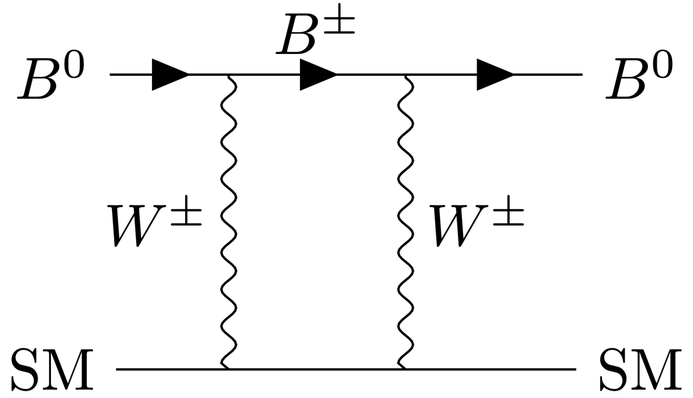
Context: Our UV Theory

$$\mathcal{L}_{\rm dark} = -\frac{1}{4} G^{\mu\nu\,a} G^a_{\mu\nu} + \overline{\mathbf{Q}} \left(i \not{D} - m_0 \right) \mathbf{Q}$$

- Vector-like dark quarks in the N_f-dimensional rep of $\mathrm{SU}(2)_L$
- Well-studied in the literature, often in DM context
- For us, no hypercharge
- $\mathrm{SU}(2)_L$ is a gauged subgroup of a flavor $\mathrm{SU}(N_f)$

Context: H-Parity and Noble DM

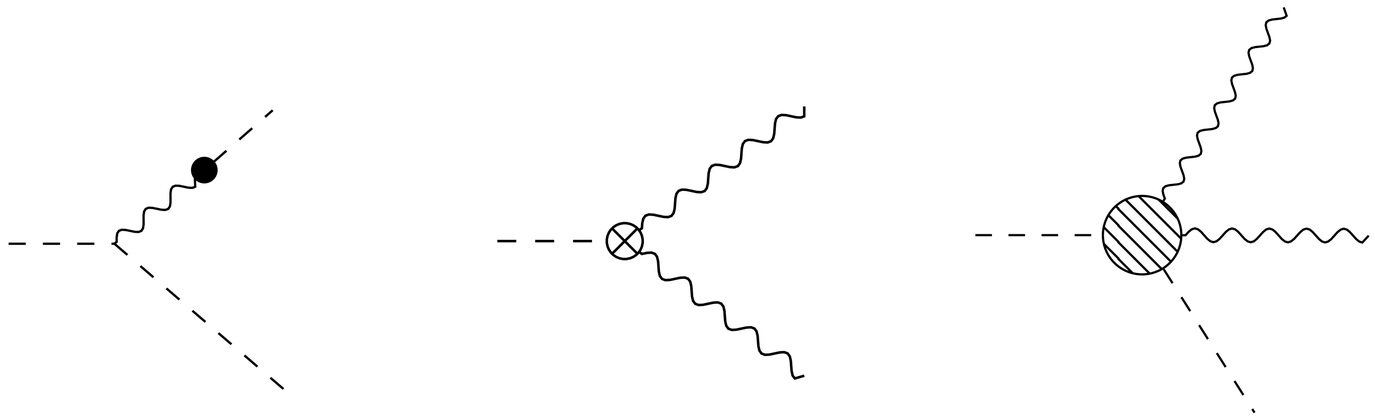
- If dark baryons are DM, a natural Z_2 protects them from direct detection via electromagnetic moments
  (H-parity: P Asadi, G Kribs, C Mantel, 2410.23631)
- Leading signals become EW loops



- If lightest baryon is a singlet, even more suppressed!
  (Noble DM: P Asadi, **AB**, G Kribs, 2412.14240)

Outline

- Dark mesons spectrum
- The 5-plet anomaly
- Collider signals
- Conclusion



Dark Mesons

- Suppose dark quarks are lighter than confinement scale, trade microscopic parameters for f_π, m_π
- Chiral symmetry breaking leads to light(-ish) pNGBs
- Each meson species is in some $\mathrm{SU}(2)_L$ multiplet

$$\mathbf{N_f} \otimes \mathbf{N_f} = \mathbf{1} \oplus \underbrace{\mathbf{3} \oplus \mathbf{5} \oplus \cdots \oplus (\mathbf{2N_f - 1})}_{\text{pNGB reps}}$$

quark rep

$\hat{\eta}'$ with anomalous axial $\mathrm{U}(1)$

Z_2 Zoo: H, C, and G

- H-parity forbids neutral baryon EM moments

  $\mathbf{Q} \overset{\mathcal{H}}{\to} e^{i\pi J_y}\mathbf{Q}$ maps particles to other particles in the same EW multiplet

- G-parity (with SM analog) leads to meson selection rules

  $G = \mathcal{C}\mathcal{H}$ for dark sector matter, maps particles to anti-particles

  $G = \mathbb{1}$ for *all* SM fields

Dark Meson H, C, and G

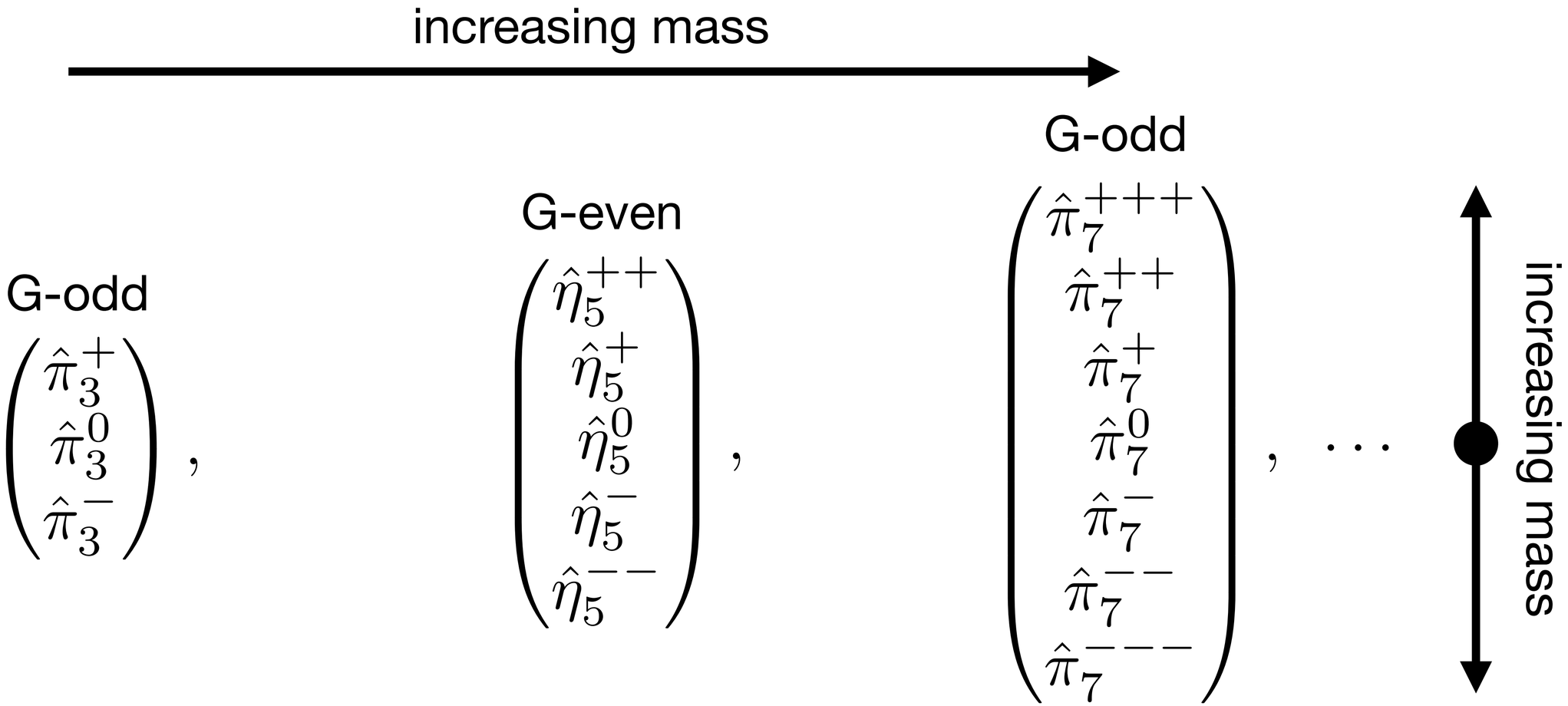
- All dark meson species are G eigenstates!

$$G = \mathcal{C}\mathcal{H}$$

$$\begin{aligned}
\mathcal{H}|J,\, Q\rangle &= \quad (-1)^{J-Q}|J,\, -Q\rangle\,, \\
\mathcal{C}|J,\, Q\rangle &= (-1)^{Q+s+\ell}|J,\, -Q\rangle\,, \\
G|J,\, Q\rangle &= (-1)^{J+s+\ell}|J,\, Q\rangle
\end{aligned}$$

rep charge

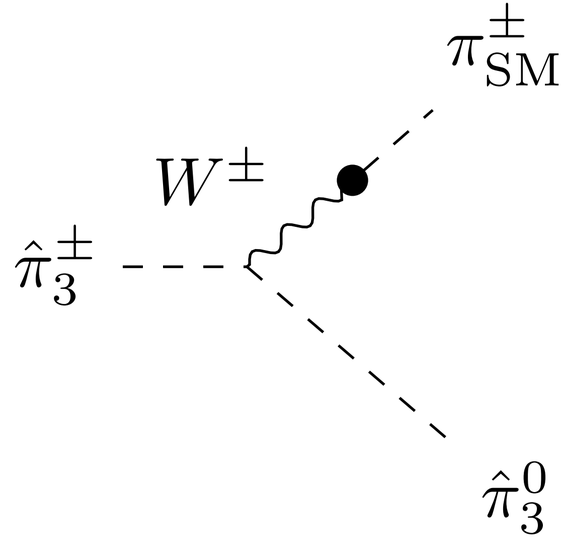
Tower of pNGBs



3-plet Cascade Decays

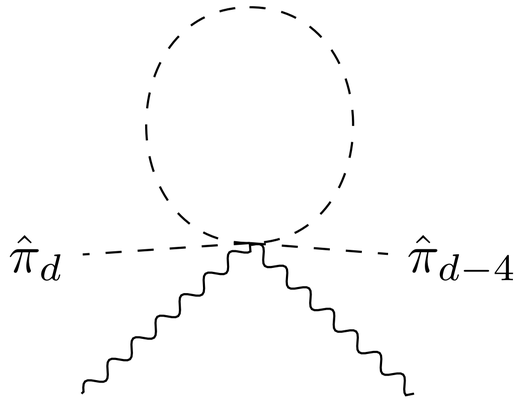
- Charged 3-plet cascades by emitting off-shell W
  - permitted for all multiplets, but required for 3-plet
  - small phase space → long lifetime (few cm)
- Decays of the neutral 3-plet violate G
  - can't be done with renormalizable operators, but dim-5 can do it:

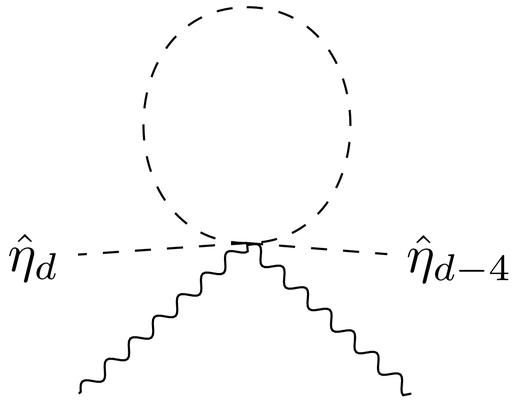
$$B_{\mu\nu}\overline{\mathbf{Q}}\,\sigma^{\mu\nu}\,\mathbf{Q}, \quad H^\dagger\tau^a H\,\overline{\mathbf{Q}}\,J^a\,\mathbf{Q}$$



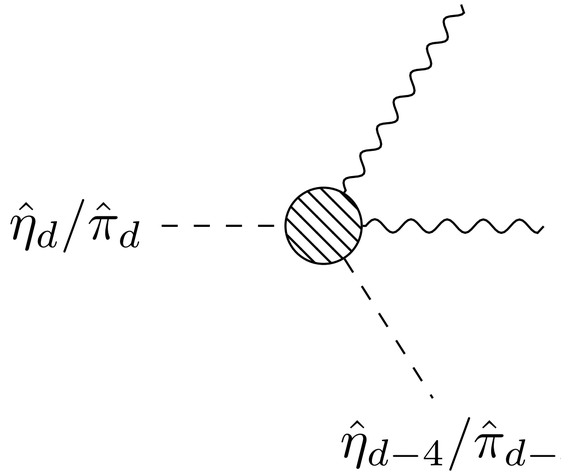
Higher Rep Hopping Decays

- Dim-6 operators in chiral Lagrangian lead to loops





- Higher multiplets hop to lower ones with the same G-parity



Anomalies with EW

- An anomaly couples pNGBs to EW bosons
  - analogous to SM pion anomaly with QED

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

gauged flavor generators

pNGB

broken flavor generators

- The 5-plet is the *only* pNGB for which this is non-zero
  - due to gauge invariance and symmetries of the trace

The 5-plet Anomaly

$$\mathcal{L}_{\text{anomaly}} = c\,\frac{g_W^2}{16\pi^2}\,\frac{N_c}{f_\pi}\varepsilon^{\mu\nu\alpha\beta}\Bigg[\sqrt{\frac{3}{2}}\,\hat{\eta}_5^{++}\,(W^1_{\alpha\beta}+iW^2_{\alpha\beta})(W^1_{\mu\nu}+iW^2_{\mu\nu})$$
$$-\sqrt{6}\,\hat{\eta}_5^{+}\,W^3_{\mu\nu}(W^1_{\alpha\beta}+iW^2_{\alpha\beta})$$
$$+\hat{\eta}_5^{0}\,(2W^3_{\mu\nu}W^3_{\alpha\beta}-W^1_{\mu\nu}W^1_{\alpha\beta}-W^2_{\mu\nu}W^2_{\alpha\beta})$$
$$+\sqrt{6}\,\hat{\eta}_5^{-}\,W^3_{\mu\nu}(W^1_{\alpha\beta}-iW^2_{\alpha\beta})$$
$$+\sqrt{\frac{3}{2}}\,\hat{\eta}_5^{--}\,(W^1_{\alpha\beta}-iW^2_{\alpha\beta})(W^1_{\mu\nu}-iW^2_{\mu\nu})\Bigg]$$

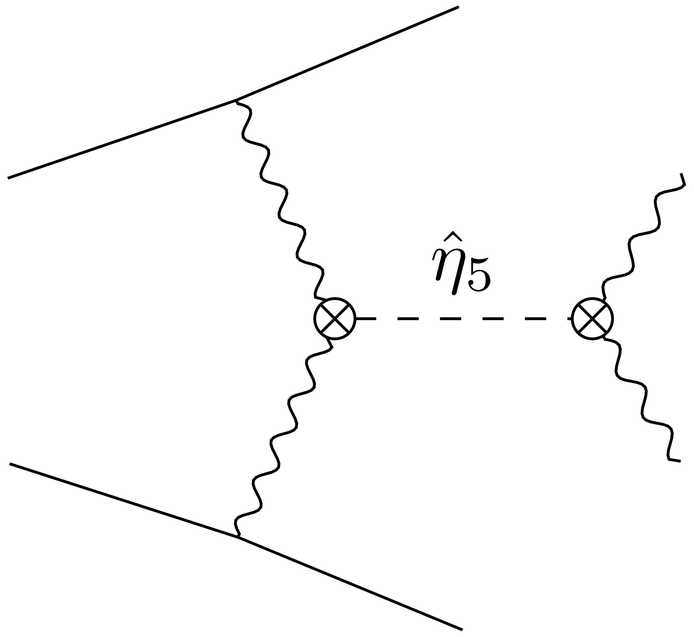
$c = \dfrac{1}{12\sqrt{10}}\sqrt{\dfrac{(N_f+2)!}{(N_f-3)!}}$ is a cute calculation, scales like $N_f^{5/2}$

Processes in the IR provide insight into UV parameters!

Anomaly-induced Processes

- Not just decay, also resonant production via vector boson fusion!

- Clear pheno implications at the LHC



Review of pNGBs

Species	$\mathrm{SU}(2)_L$ Rep.	$N_{f,\mathrm{min}}$	G-parity	Dominant decay
$\hat{\pi}_3$	$\mathbf{3}$	2	-1	cascade ($\hat{\pi}_3^{\pm}$), G-violation ($\hat{\pi}_3^0$)
$\hat{\eta}_5$	$\mathbf{5}$	3	$+1$	anomaly
$\hat{\pi}_7,\ \hat{\pi}_{11},\ \hat{\pi}_{15},\ldots$	$\mathbf{7}, \mathbf{11}, \mathbf{15}, \ldots$	$4, 6, 8, \ldots$	-1	hopping
$\hat{\eta}_9,\ \hat{\eta}_{13},\ \hat{\eta}_{17},\ldots$	$\mathbf{9}, \mathbf{13}, \mathbf{17}, \ldots$	$5, 7, 9, \ldots$	$+1$	

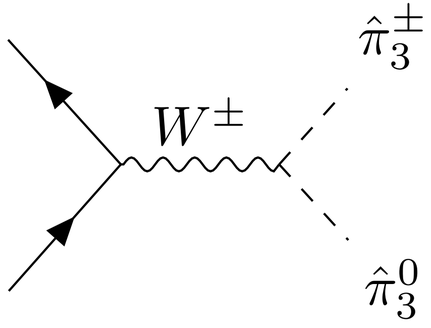
Dark Mesons at the LHC

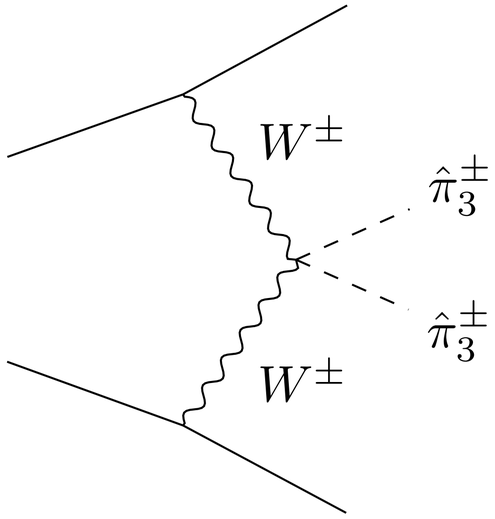
- 3-plet and 5-plet each have striking signatures
- Existing searches place strong bounds

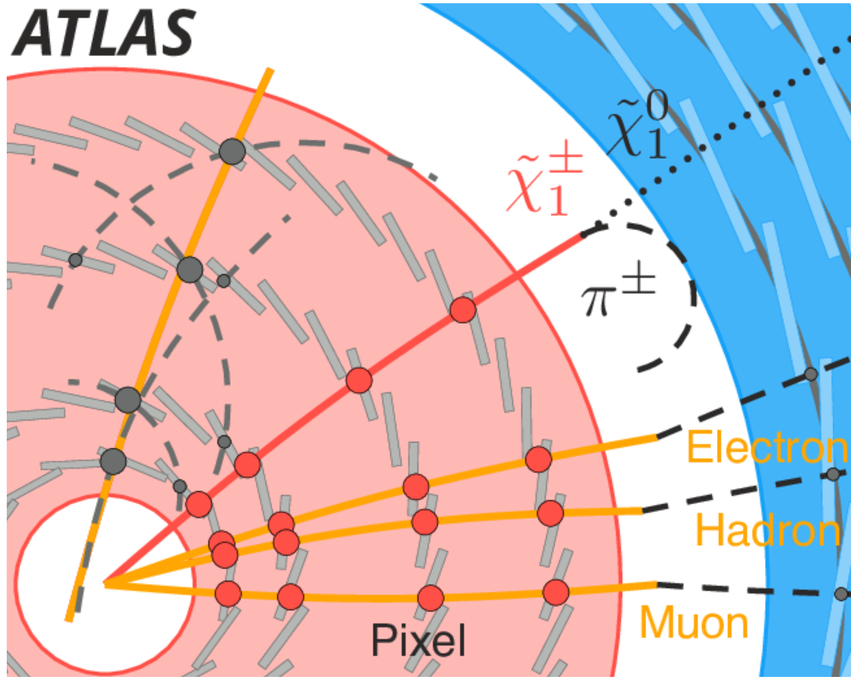
Species	Production	Lifetime	Signal
$\hat{\pi}_3^{\pm}$	pairs via DY and VBF	$\mathcal{O}(0.1)$ ns	disappearing tracks
$\hat{\pi}_3^0$		collider-stable	
$\hat{\eta}_5^0$, $\hat{\eta}_5^{\pm}$, $\hat{\eta}_5^{\pm\pm}$	resonances via the anomaly	prompt	diboson decays

3-plet: Disappearing Tracks

- Production via VBF/DY
- Displaced decay analogous to chargino
- Targets of powerful LLP searches



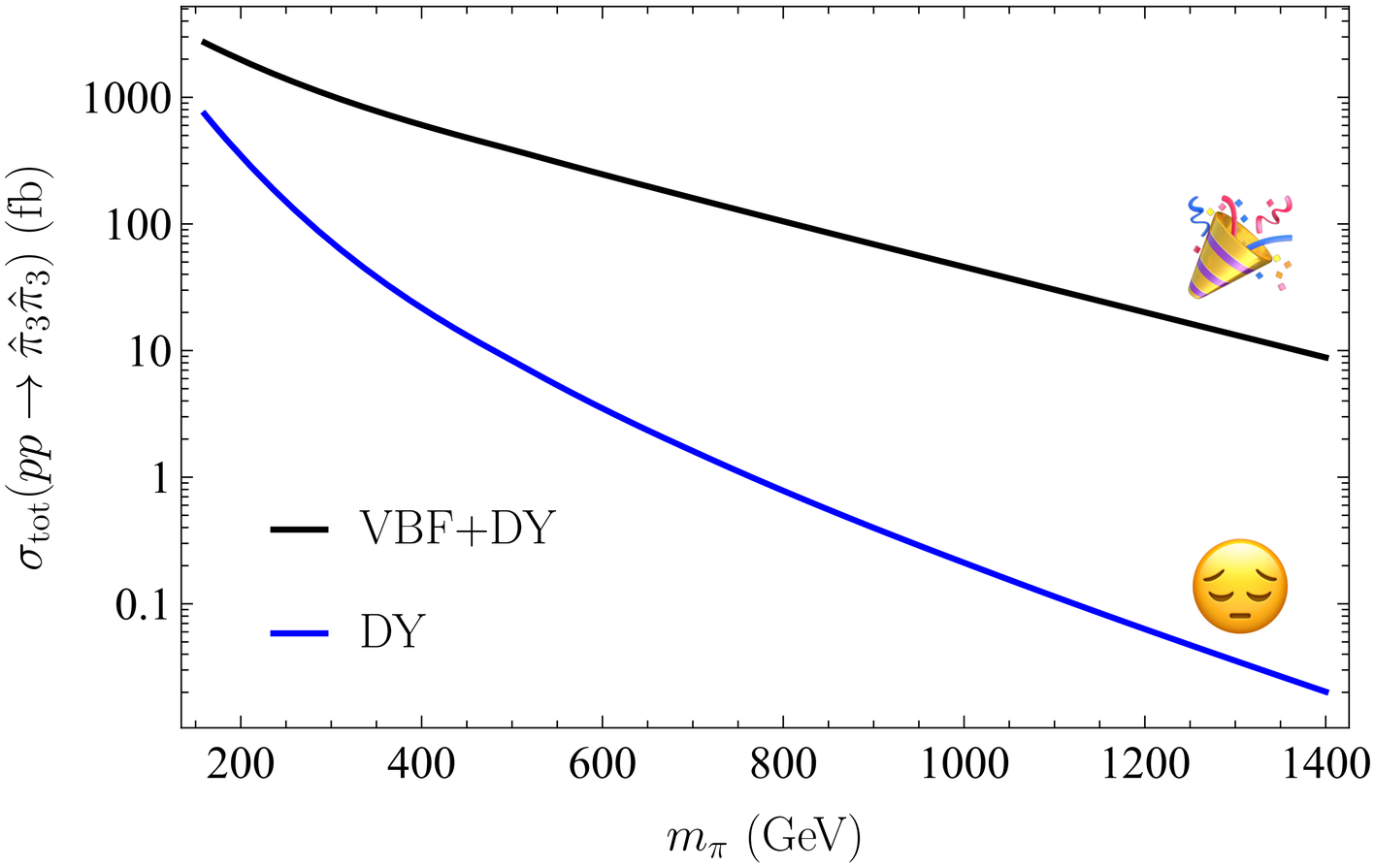




arXiv:2201.02472

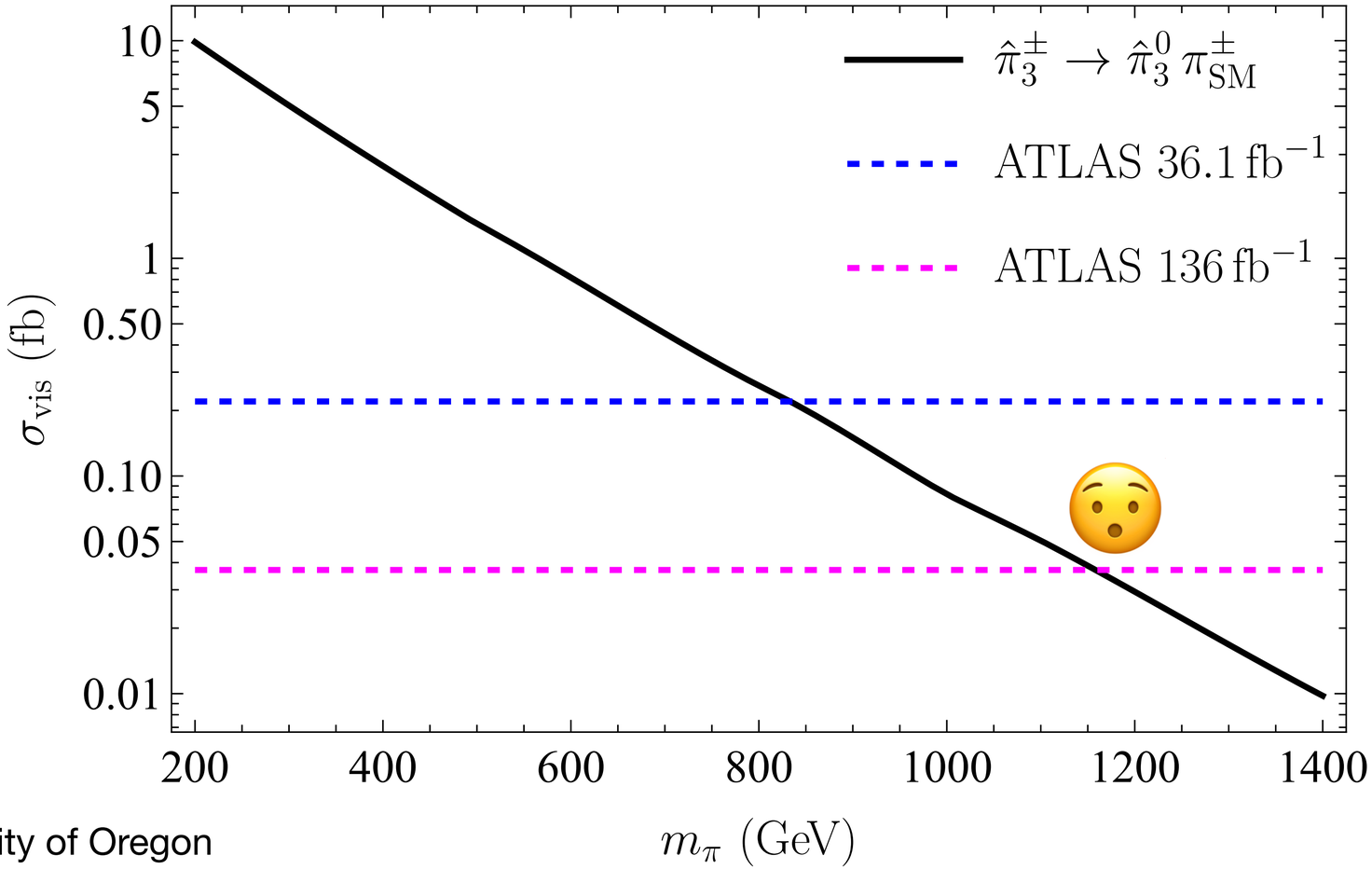
VBF >> DY

- DY cross section plummets as a function of mass



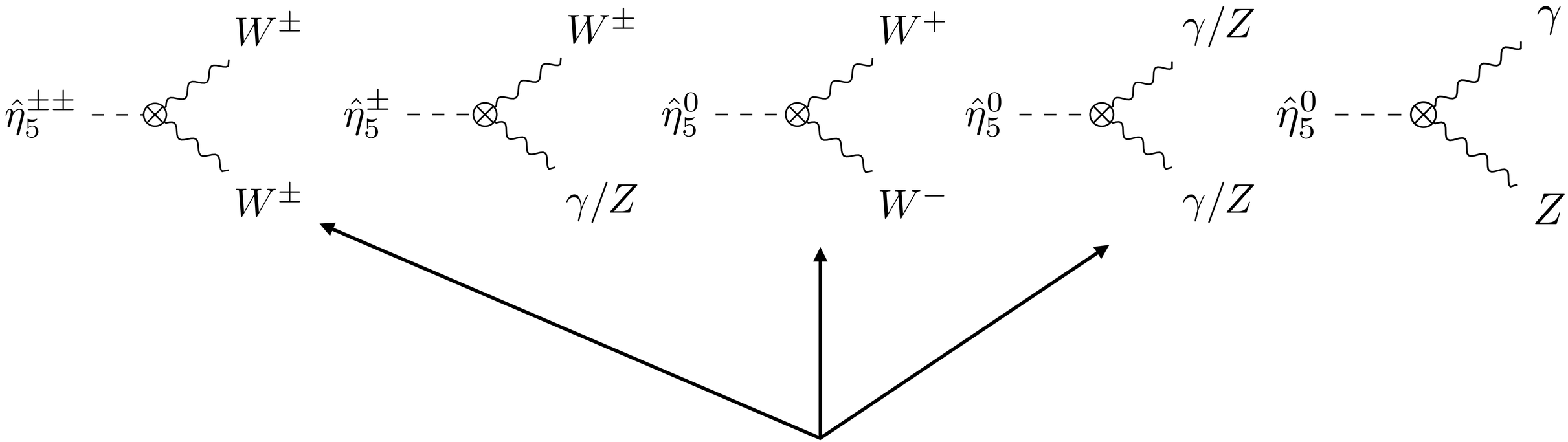
$m_\pi \gtrsim 1.2\,\mathrm{TeV}$!

- Re-used re-interpretation framework for an earlier search (2008.08581)



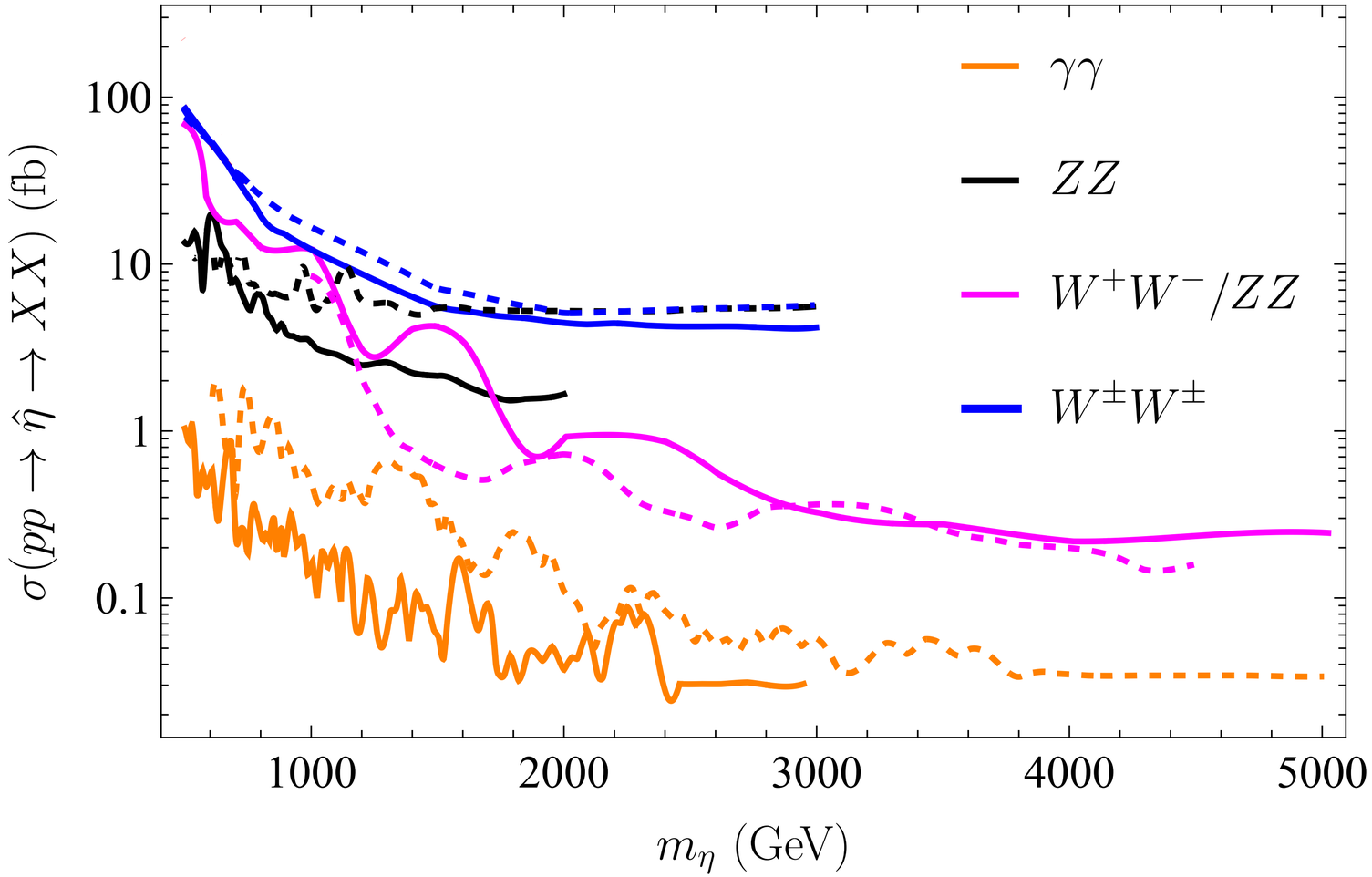
5-plet: Resonances

- Several combinations of final states with different relative rates, some with clean signals



Existing Limits

- Diboson resonances are targets of many searches

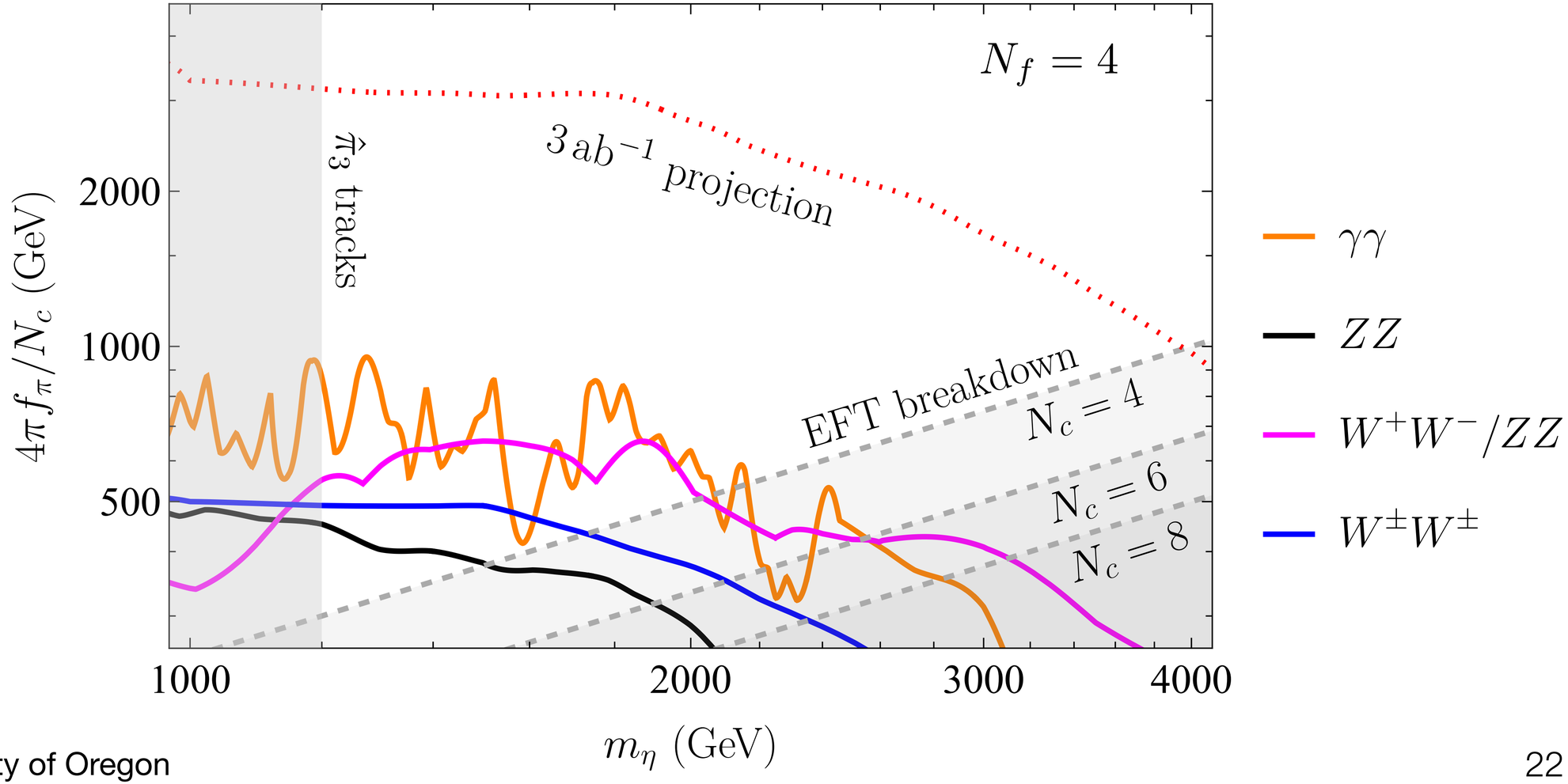


Solid: ATLAS
Dashed: CMS

5-plet Parameter Space

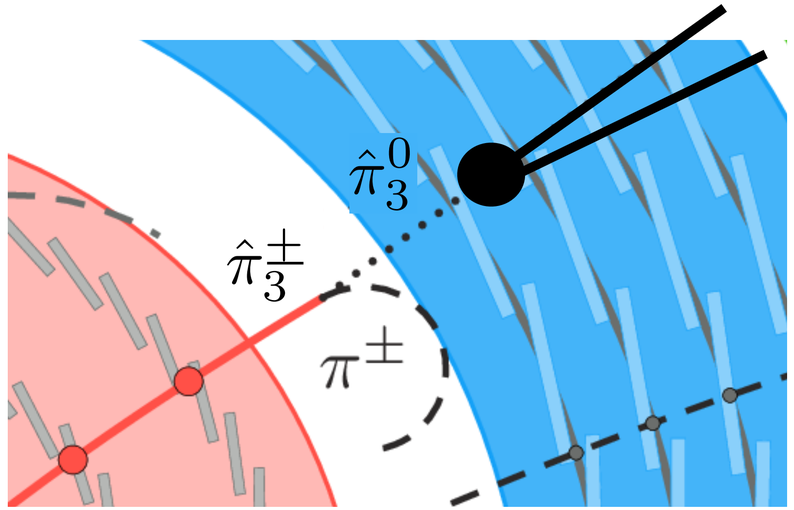
- Opportunity for significant HL-LHC improvement

Branching ratios cause bounds from each final state to be similar



Potential Future Directions

- G-violating decays within the detector
  - Could probe a UV scale that suppresses dim-5 operators



- Vector mesons mixing with EW bosons
  - Relevant when decay constant is small enough

Conclusion

- Confining dark sector with EW charge
- Rich spectrum of dark mesons in various reps
- 3-plet is long-lived, 5-plet decays via anomaly
- LLP searches constrain 3-plet above ~1.2 TeV
- 5-plet resonances more strongly probed by HL-LHC
- Other possible signals from heavier dark mesons / G violation