Dark Mesons @ LHC

Graham Kribs
University of Oregon

papers in preparation with A. Martin, B. Ostdiek, T. Tong

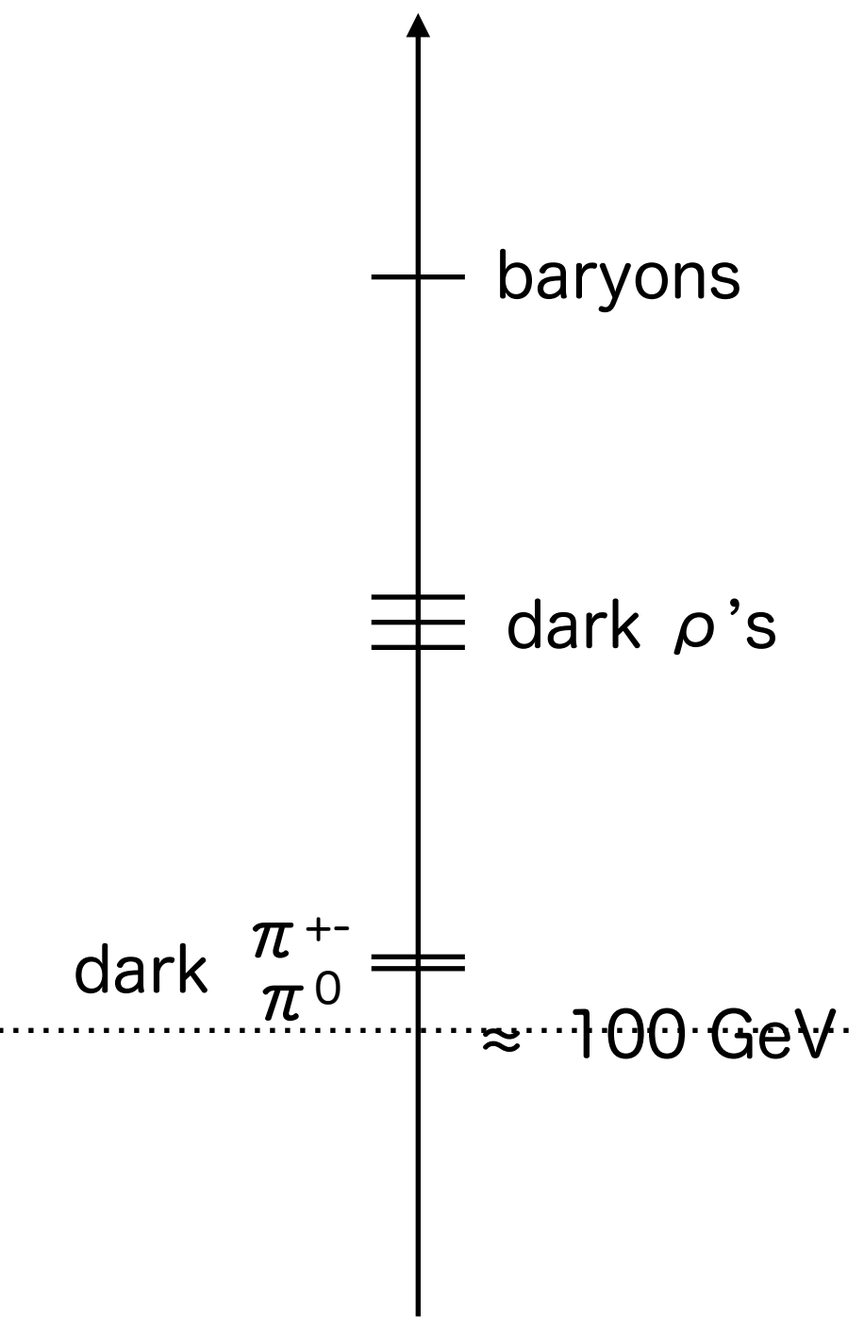
Fermilab HL/HE Workshop 2018

What's left for LHC to discover?

I'll argue that "dark mesons" are an intriguing case that:

a) are well-motivated from dark matter and EWSB models
b) have particles that are kinematically easily produced but existing LHC searches are not well-optimized
d) are qualitatively distinct from the standard paradigms of MET + X, supersymmetric searches, 2HDM, etc.

Dark Mesons



Suppose a new, strongly-coupled, confining gauge theory ("dark sector"*) exists near the weak scale.

Dark fermions exist — transform under EW group.

The lightest states — "dark mesons" — provide an interesting class of signals that — in broad swaths of parameter space — existing LHC searches are not well-optimized.

Opportunities for existing and future searches with high(er) luminosity.

*I'll use the nomenclature "dark" to distinguish from QCD, but the states are certainly not "dark" to LHC production/decay/sensitivity.

Motivation:
Strongly-coupled “Dark” Sectors near the Weak Scale

“Dark” sectors that contain a new, strongly-coupled, confining force near the weak scale are well-motivated from a wide variety of perspectives:

- Theories with strongly-coupled composite dark matter, e.g.,
  Dark baryons (“Stealth Dark Matter”)
  Dark mesons (Ectocolor DM; heavy chiral DM; etc.)
  SIMP mechanism (3->2 thermal freezeout via WZW)

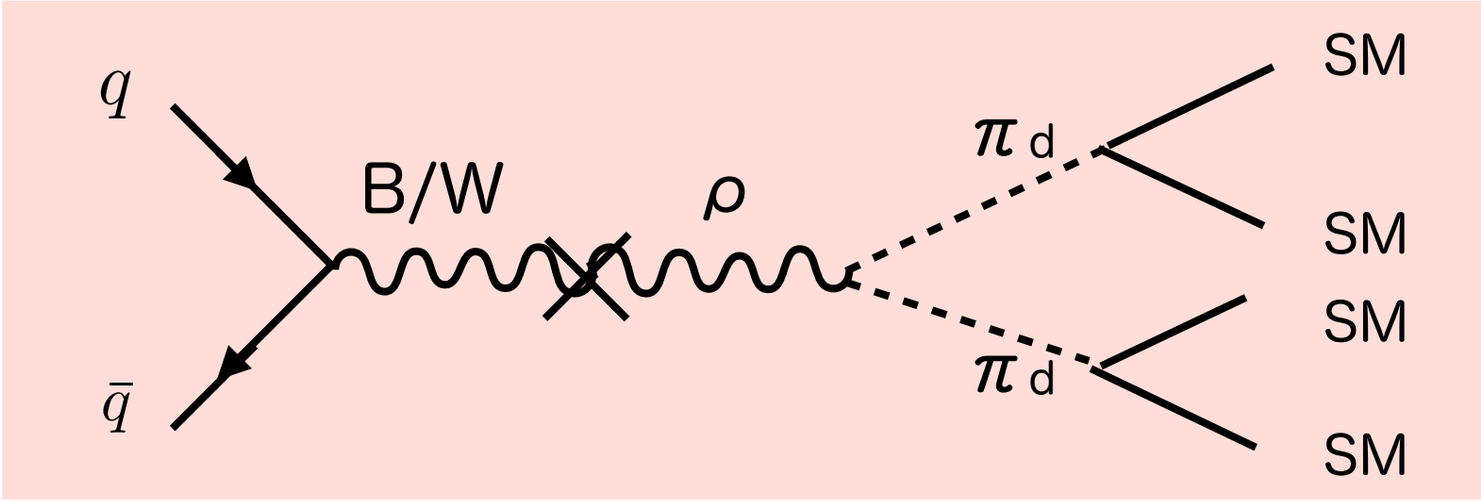
- Theories that explain electroweak symmetry breaking, e.g.,
  Bosonic technicolor / induced EWSB
  Composite Higgs theories
  Relaxion with new (non-QCD) dark sector

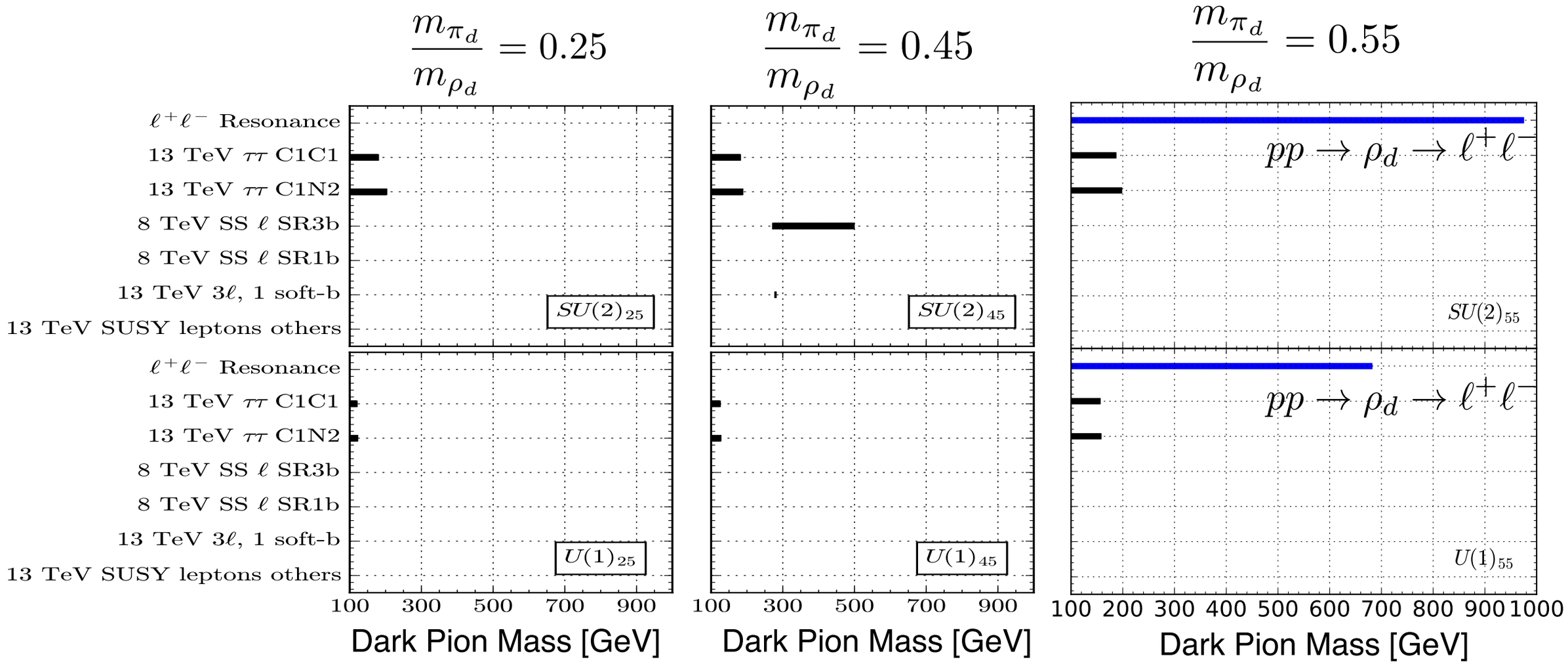
- Theories that provide interesting / novel LHC phenomena, e.g.,
  Hidden valleys
  Quirky theories and signals
  Vectorlike confinement

For this talk — focus is on LHC phenomena.

Punchline — Recasted Constraints:

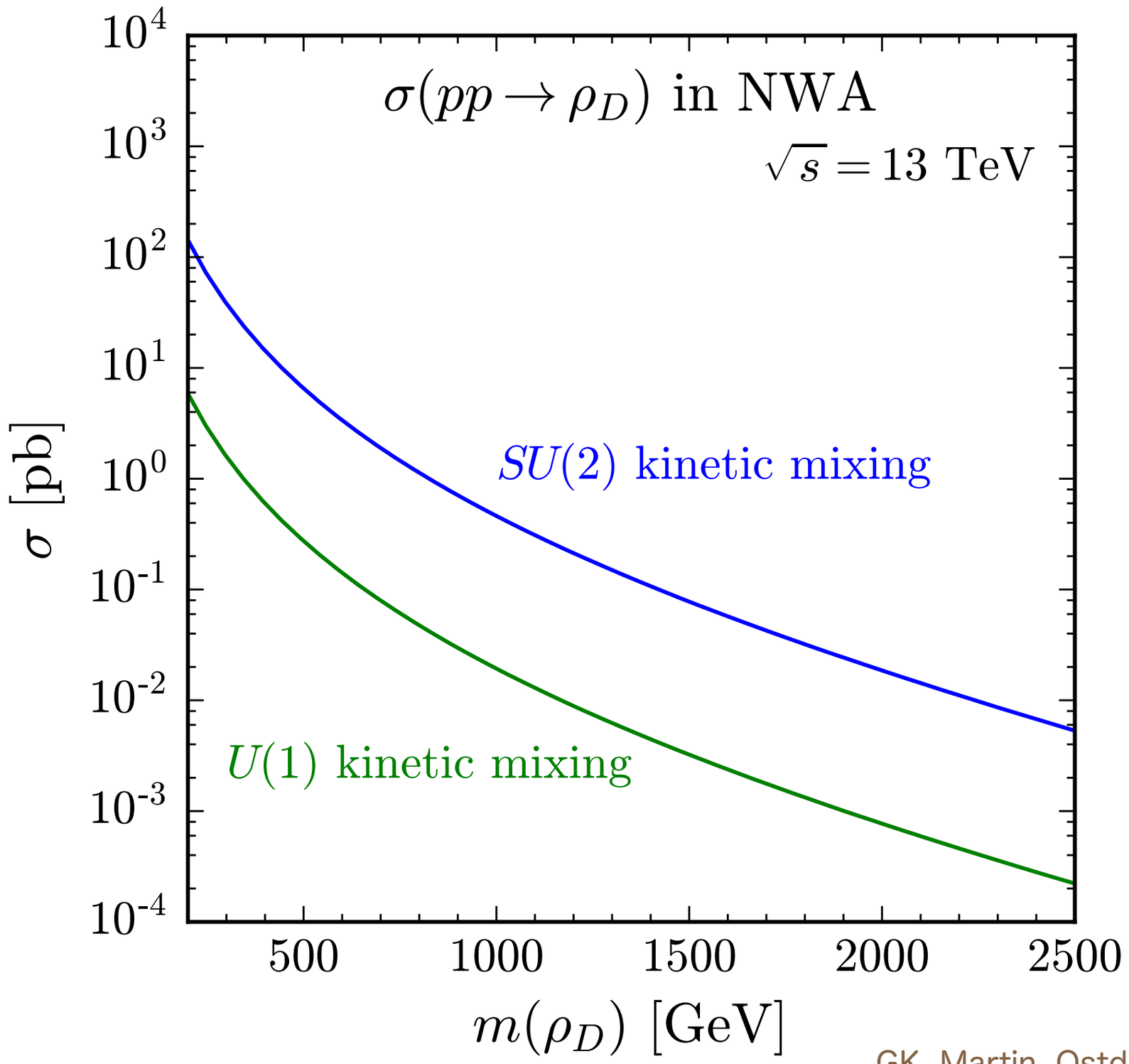
One interesting possibility is dark pions pair-produced through a “dark rho” resonance:





GK, Martin, Ostdiek, Tong (to appear)

Dark rho production

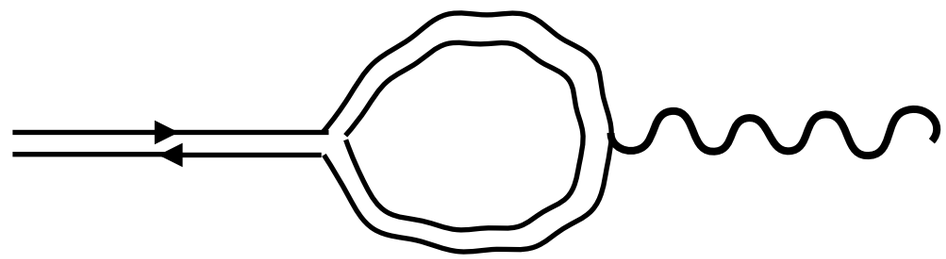


GK, Martin, Ostdiek, Tong (to appear)

Vector Meson — SM Gauge Boson Mixing

One of the critical observations is ρ <—> gauge boson kinetic mixing

$\rho^0,\ \rho^a$



$B,\ W^a$

$$\epsilon_B B_{\mu\nu} F^{\mu\nu}_{\rho_d} + \epsilon_W W_{\mu\nu} F^{\mu\nu}_{\rho'_d}$$

Two types!

U(1)-like (ρ^0 only)

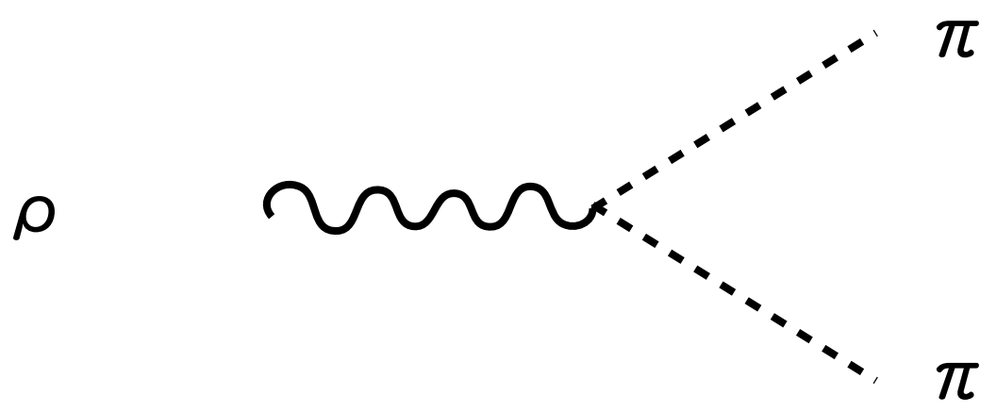
SU(2)-like $\rho^{\pm,0}$

$$\epsilon \sim g^{(\prime)} \frac{\sqrt{N_{\rm dark}}}{4\pi}$$

This provides a portal into the dark sector!

Meson Self-Interactions

Combined with the well-known ρ-π-π interaction

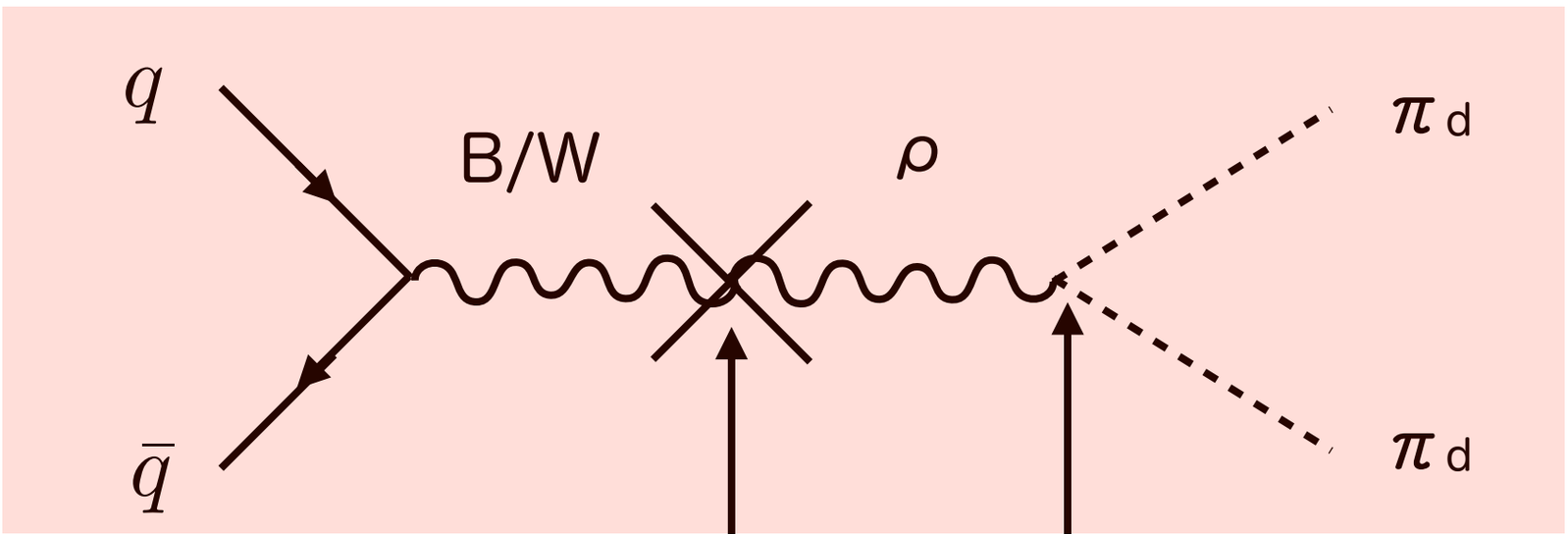


$$g_{\rho_d \pi_d \pi_d} f^{abc} (\rho_d^a)_\mu \pi_d^b D^\mu \pi_d^c$$

$$g_{\rho_d \pi_d \pi_d} \sim \frac{4\pi}{\sqrt{N_{\rm dark}}}$$

Dark Pion Pair-Production through ρ

Provides main source of dark pion production



$$\epsilon \sim g^{(\prime)} \frac{\sqrt{N_{\rm dark}}}{4\pi}$$

$$g_{\rho_d \pi_d \pi_d} \sim \frac{4\pi}{\sqrt{N_{\rm dark}}}$$

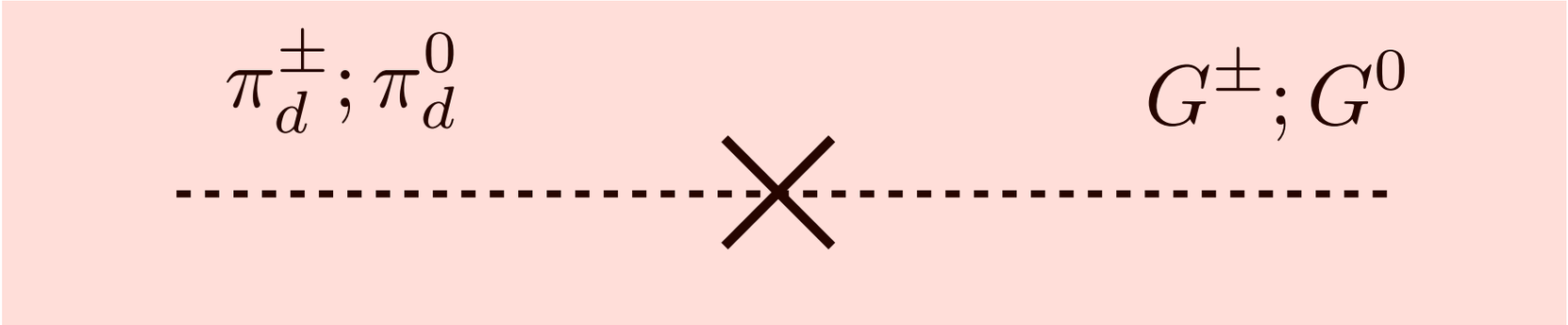
Cross section scales as electroweak production with a (substantial!) ρ-resonance enhancement.

Throughout the talk I'll assume $m_\rho > 2m_\pi$

How do dark pions decay?

Several possibilities — I don't have time to go into all of them.
(See backup slides for details.)

Suffice to say, the most interesting possibility from the perspective of current and future LHC running is:

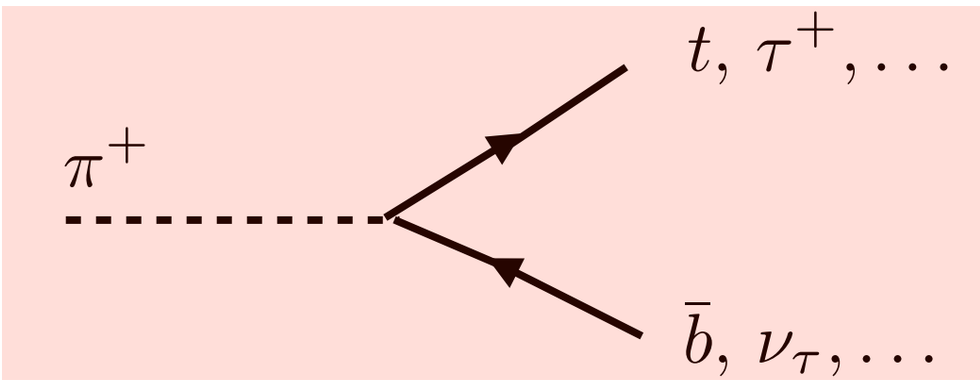


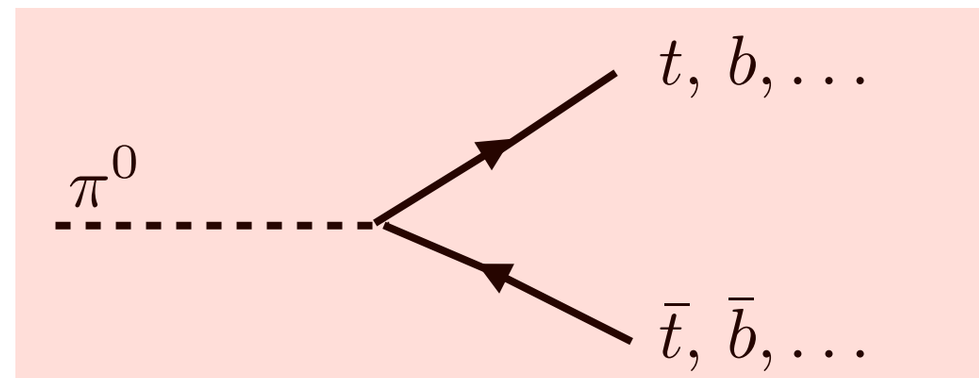
Small mixing between (lightest) dark pions and Higgs goldstone bosons.

Dark pion decay to $f\bar{f}^{(\prime)}$

The $G^{\pm,0} \longleftrightarrow \pi^{\pm,0}$ mixing* causes dark π decay into fermions proportional to Yukawa couplings:

(*in vector-like models, need suitable dark fermion representations that permit higher-dim operators with H)



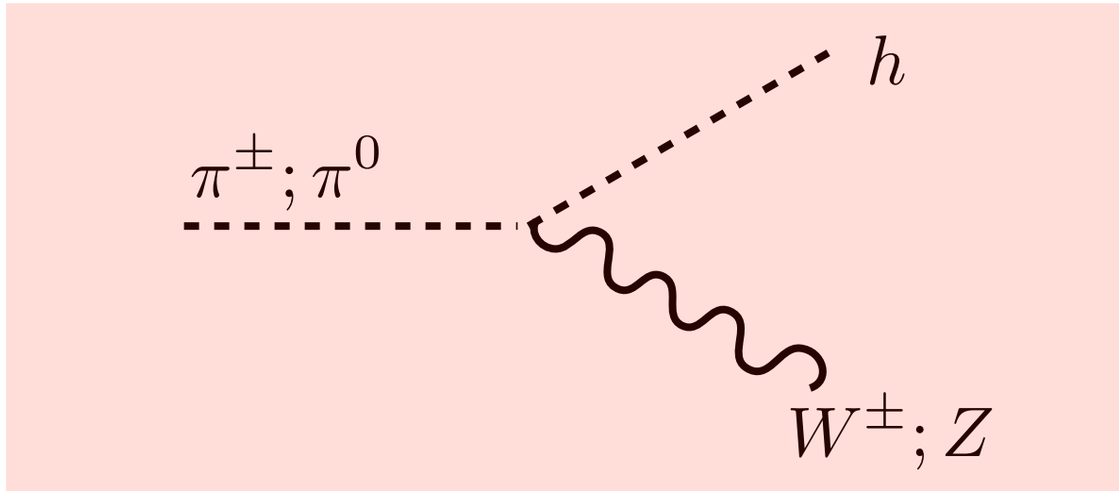


$$\lambda_{\pi-\mathrm{GB}-h} \sim y_f\, c_\pi$$

Just like as if QCD pions were scaled up in mass.

Dark pion decay to $W^{\pm}h,\ Zh$

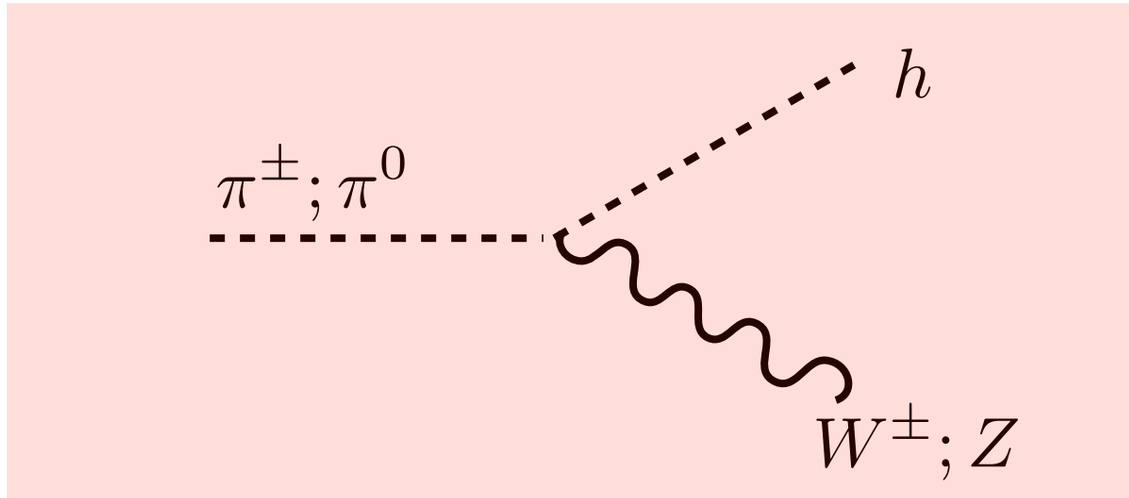
For decays to $W^{\pm}h,\ Zh$:



Intriguingly, there are, however, two distinct classes of theories:

Gaugephilic	Gaugephobic
$\lambda_{\pi-\mathrm{GB}-h} \sim g\, c_{\pi}$	$\lambda_{\pi-\mathrm{GB}-h} \sim g\, c_{\pi} \times \frac{m_h^2}{m_K^2}$ suppressed!
	↓ heavier state mixes with h boson

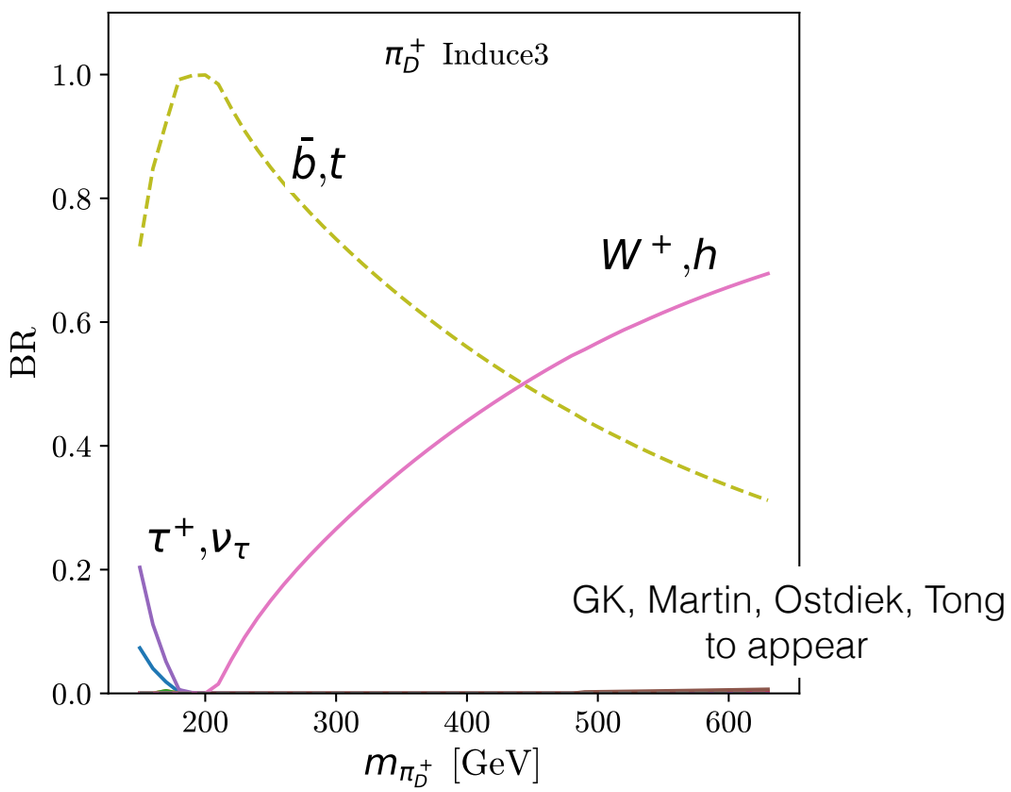
We've seen this before

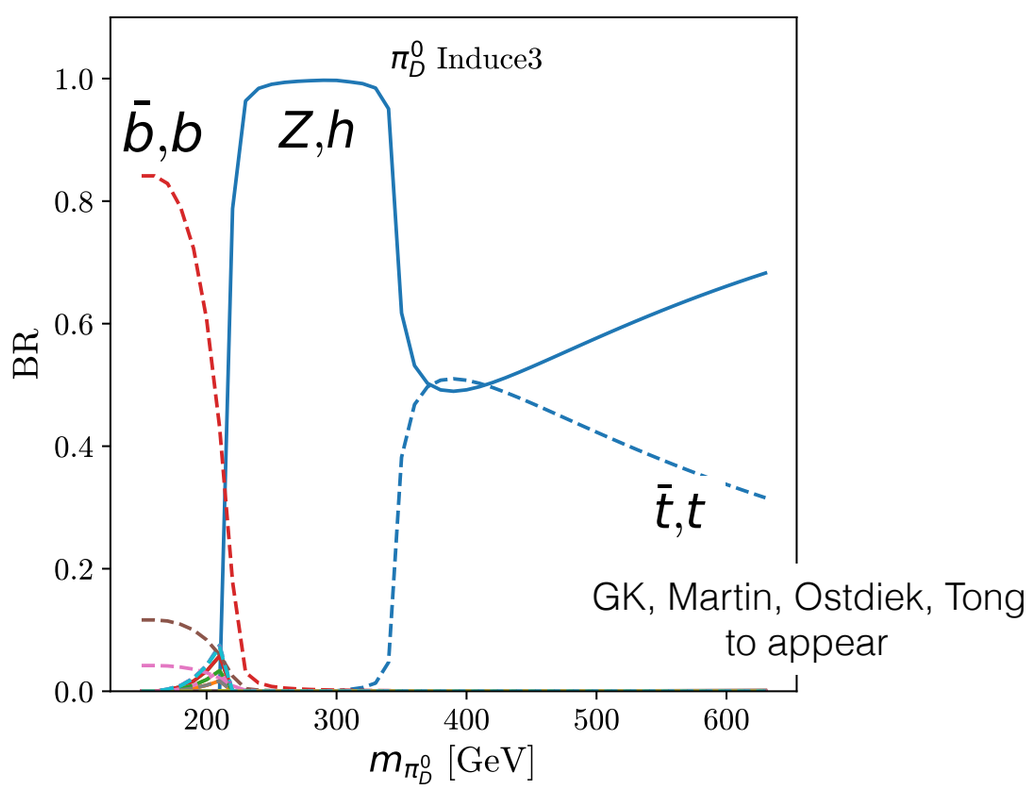


Gaugephilic	Gaugephobic
Georgi-Machacek model (replace $\pi^{\pm,0} \to H_3^{\pm,0}$ triplet) $\lambda_{\pi-\mathrm{GB}-h} \sim g\, s_H$ ↓ mixing angle (c_π)	2HDM Type II (replace $\pi^{\pm,0} \to H^{\pm}, A^0$) $\lambda_{\pi-\mathrm{GB}-h} \sim g \cos(\beta - \alpha) \sim g \frac{m_h^2}{m_H^2}$

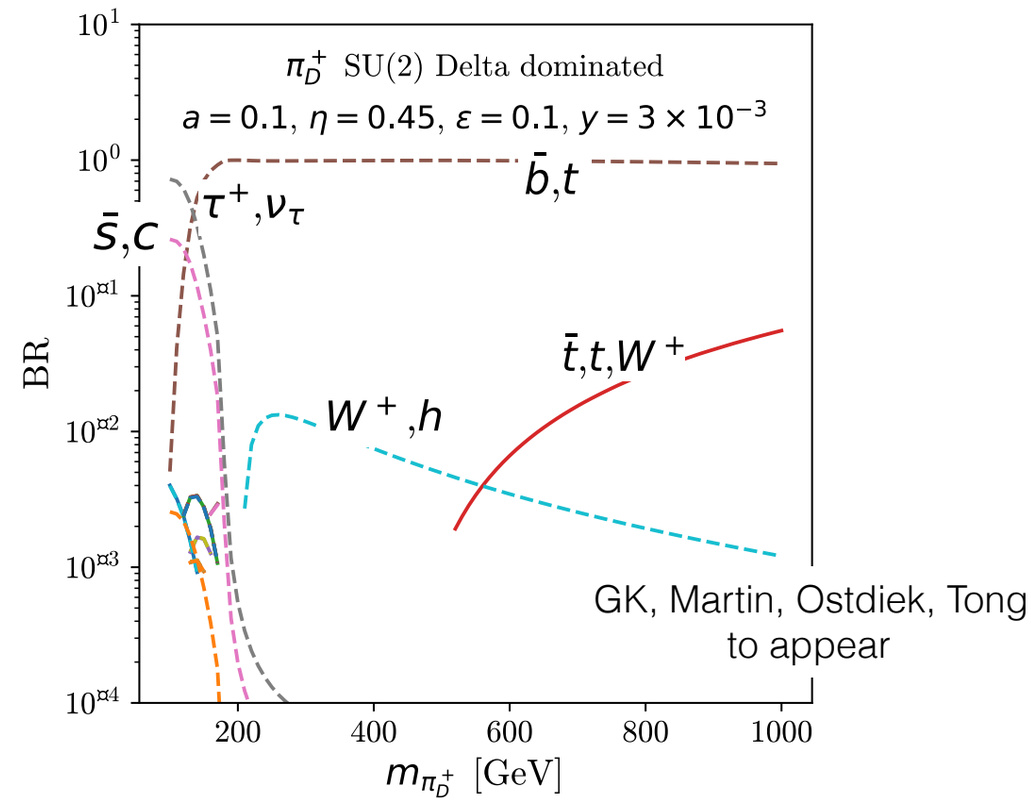
It makes a difference

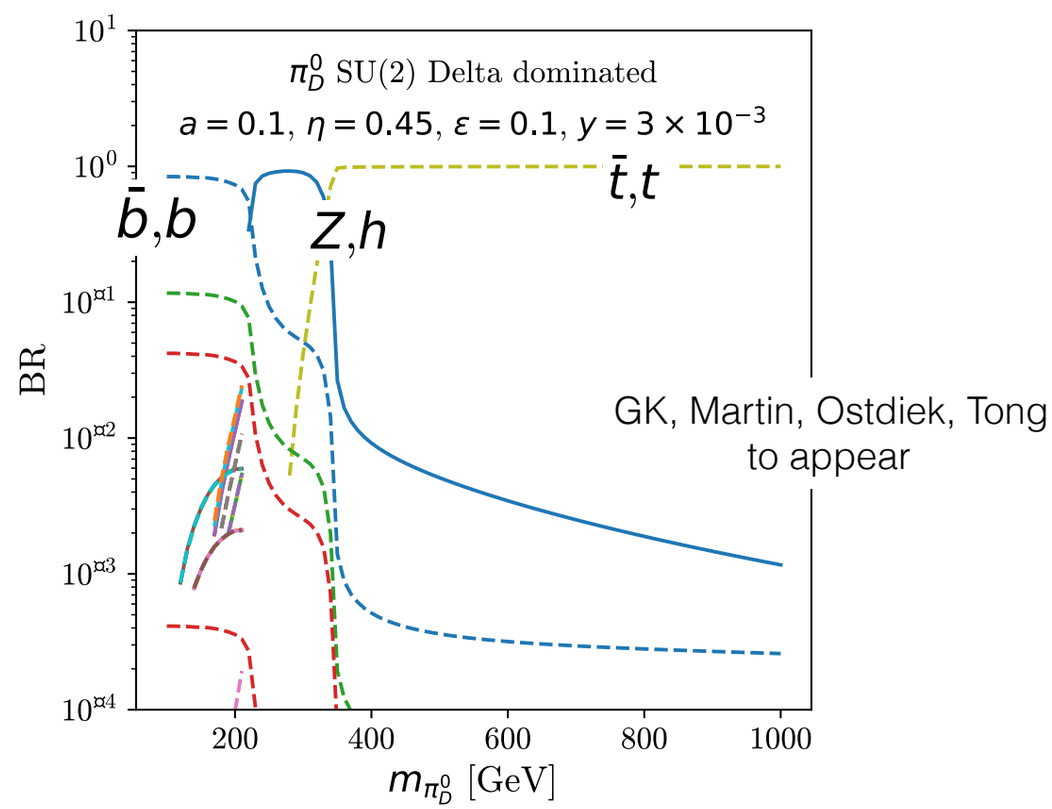
Gaugephilic





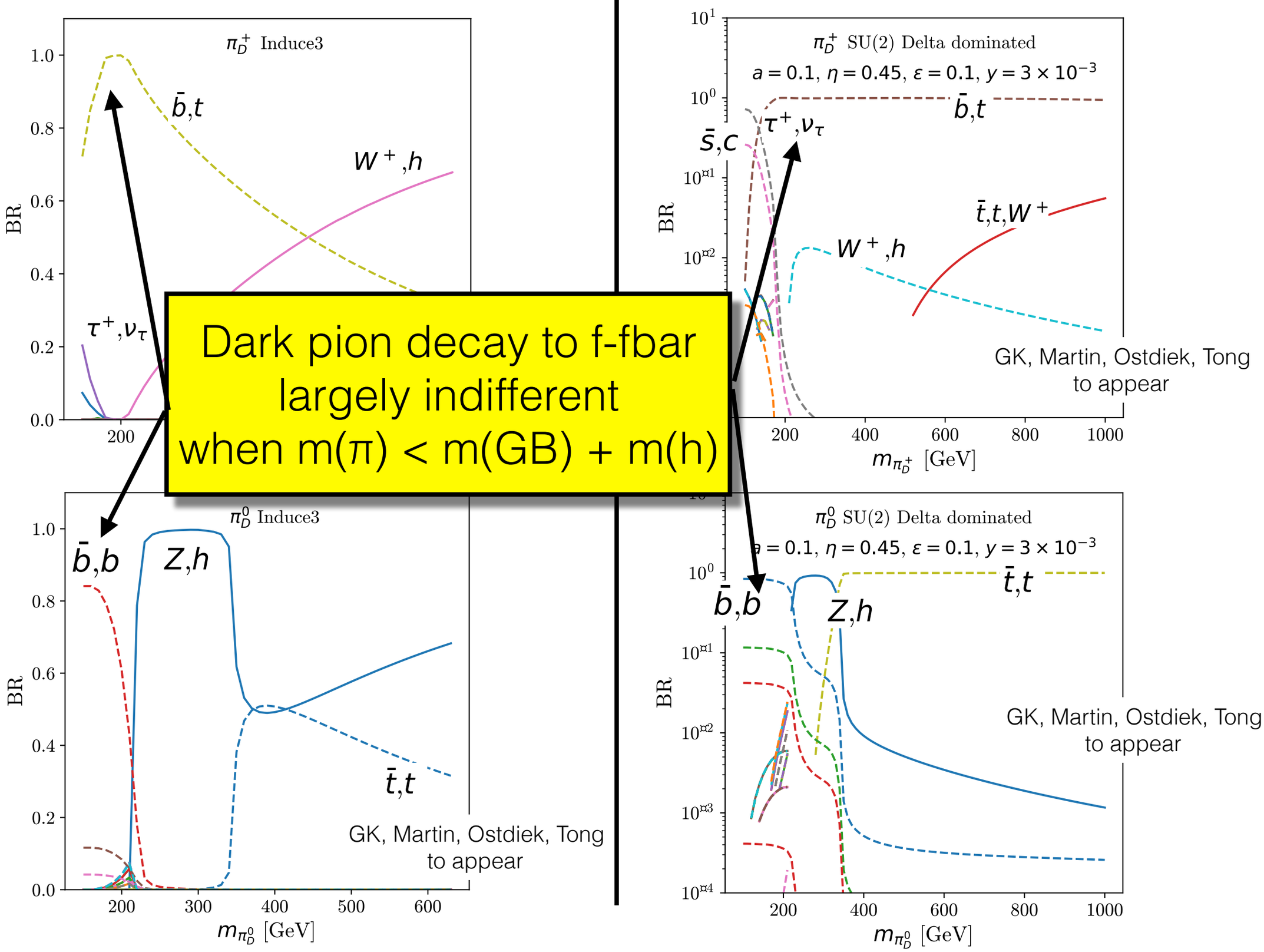
Gaugephobic





It makes a difference

Gaugephilic | Gaugephobic



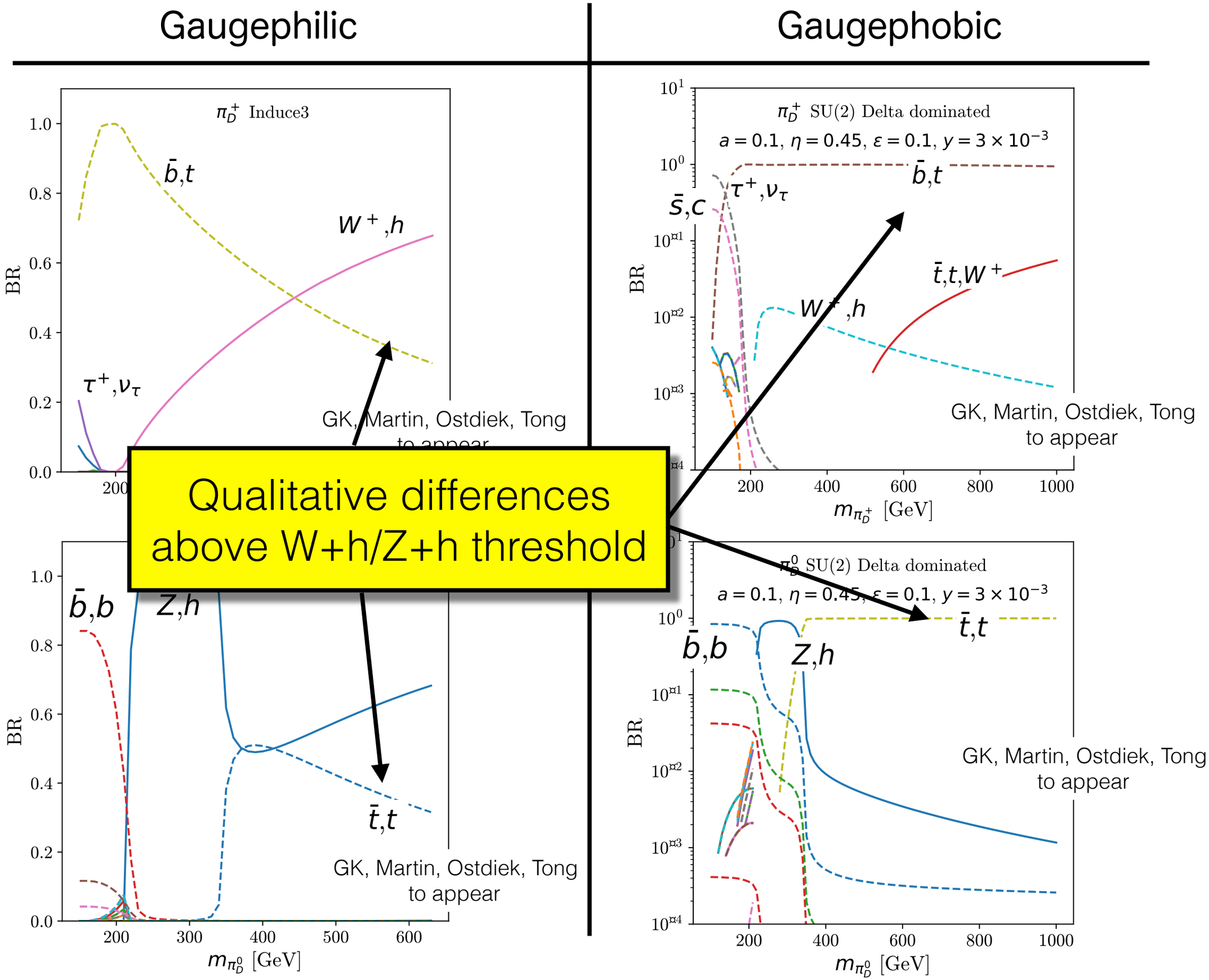
Dark pion decay to f-fbar largely indifferent when m(π) < m(GB) + m(h)

GK, Martin, Ostdiek, Tong to appear

GK, Martin, Ostdiek, Tong to appear

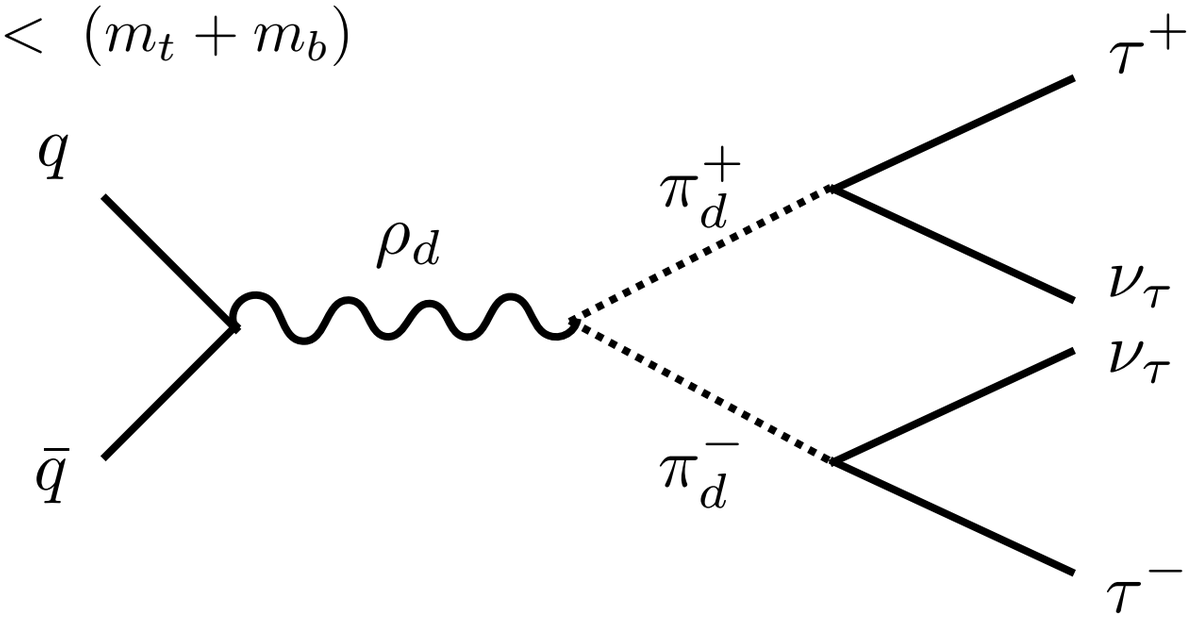
GK, Martin, Ostdiek, Tong to appear

It makes a difference

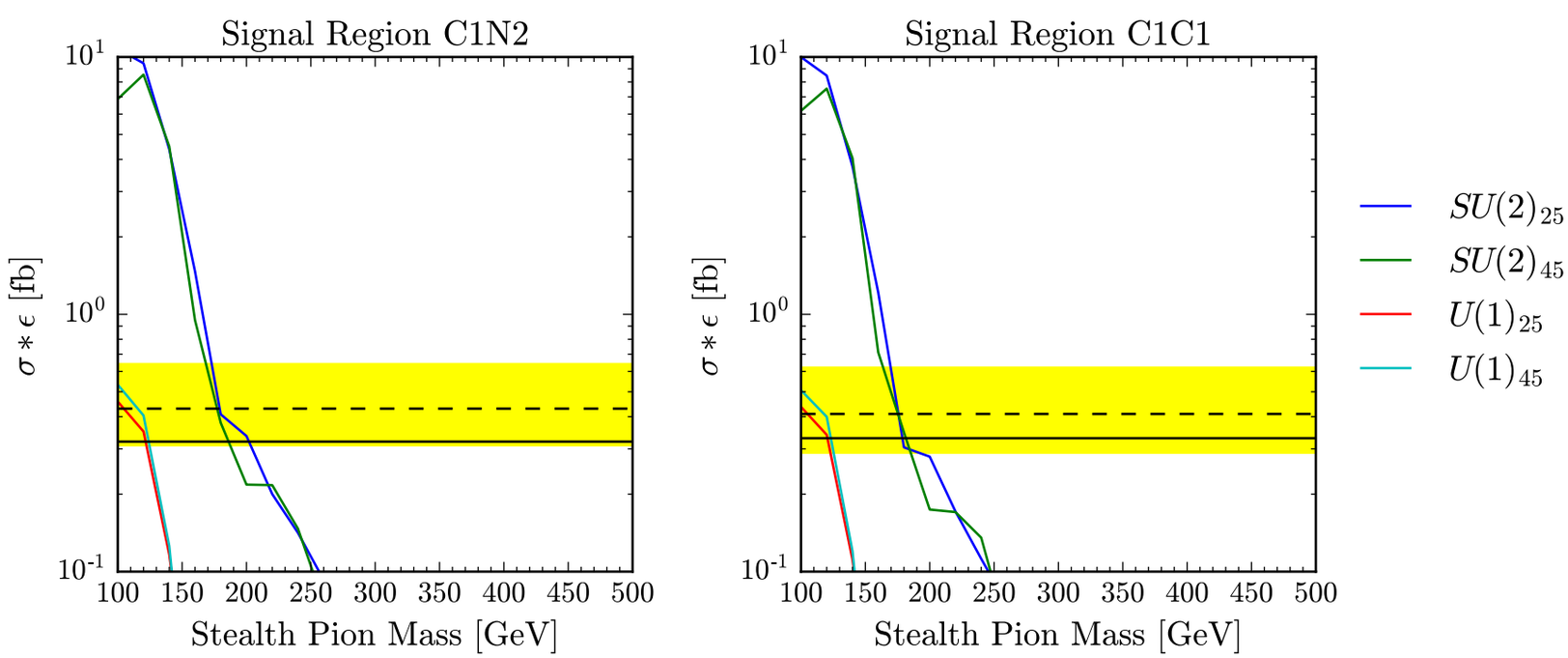


LHC Sensitivity I

When $m_{\pi_d} < (m_t + m_b)$



One can recast new physics searches involving final state tau's, e.g. EW gauginos @ ATLAS:



Suggests charged dark pions less than about 130-200 GeV are ruled out.

GK, Martin, Ostdiek, Tong (to appear)

LHC Sensitivity II: Beyond Taus

Multilepton searches are generically sensitive to:

$$q\bar{q} \to \rho \to \pi^+\pi^- \to W^+h\,W^-h$$

$$q\bar{q} \to \rho \to \pi^\pm\pi^0 \to W^\pm h\,Zh$$

$$q\bar{q} \to \rho \to \pi^\pm\pi^0 \to t\bar{b}\,Zh$$

$$q\bar{q} \to \rho \to \pi^\pm\pi^0 \to t\bar{b}\,\tau^+\tau^-$$

however, there is no large MET (nor large M_{eff}) making recasted supersymmetric searches for gaugino production not optimal.

For gaugephobic models the hadronic modes are more challenging

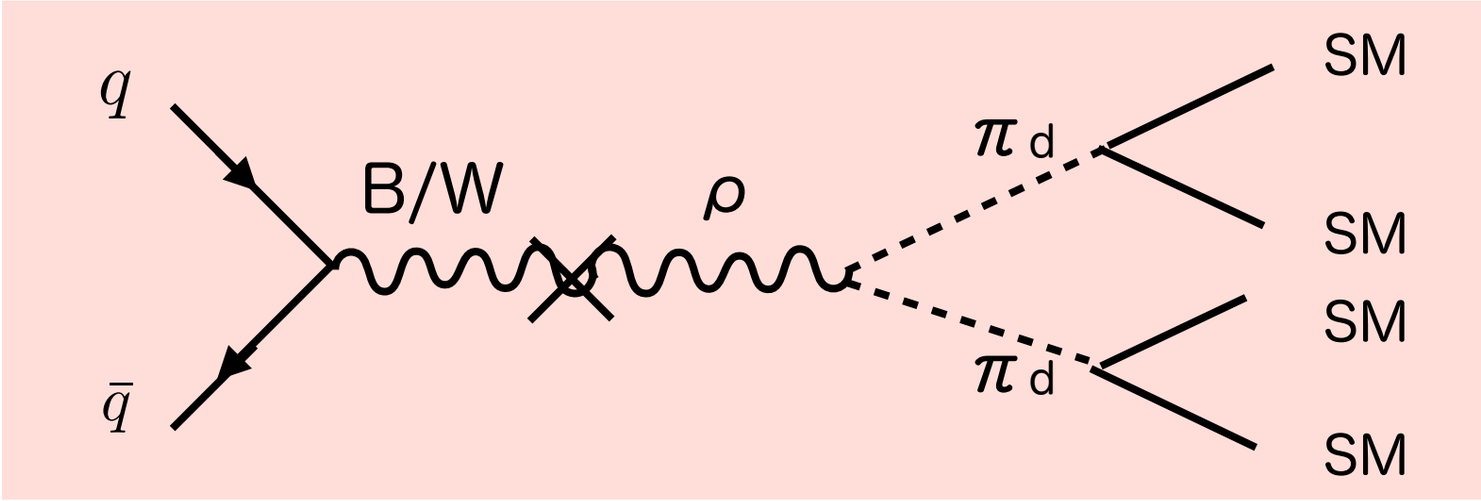
$$q\bar{q} \to \rho \to \pi^\pm\pi^0 \to t\bar{b}\,b\bar{b}$$

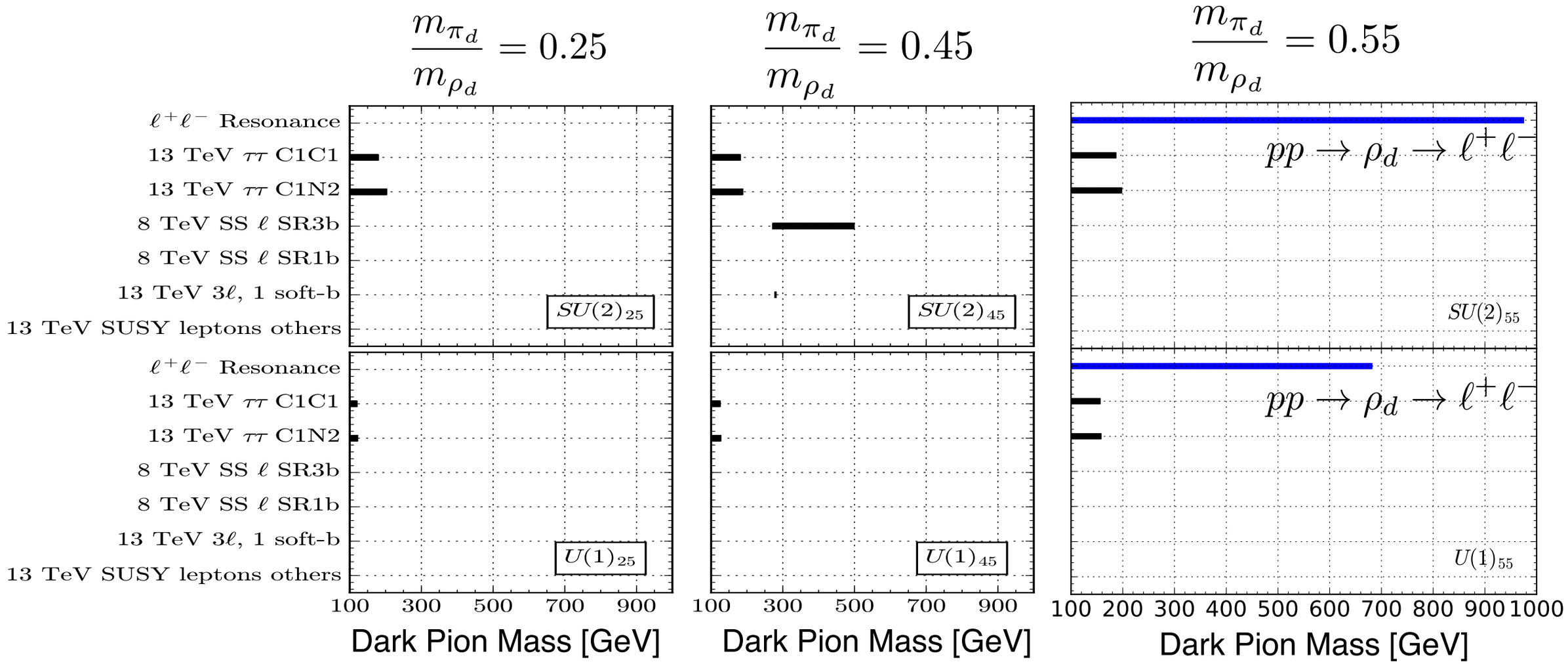
$$q\bar{q} \to \rho \to \pi^+\pi^- \to t\bar{b}\,\bar{t}b$$

$$q\bar{q} \to \rho \to \pi^\pm\pi^0 \to t\bar{b}\,t\bar{t}$$

Punchline — Recasted Constraints:

One interesting possibility is dark pions pair-produced through a “dark rho” resonance:





GK, Martin, Ostdiek, Tong (to appear)

One Example of Recasting Difficulties

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

JHEP 09 (2017) 084

CERN-EP-2017-108
5th October 2017

Search for supersymmetry in final states with two same-sign or three leptons and jets using 36 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collision data with the ATLAS detector

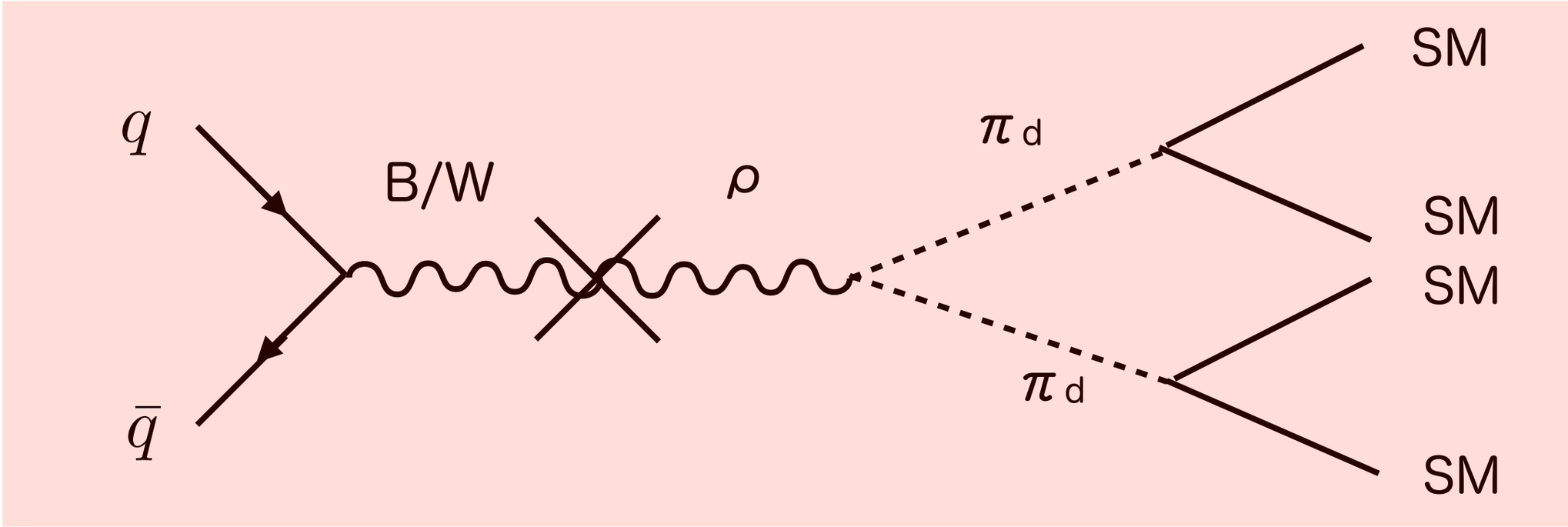
The ATLAS Collaboration

Signal region	$N_{\text{leptons}}^{\text{signal}}$	$N_{b\text{-jets}}$	N_{jets}	$p_{\text{T}}^{\text{jet}}$ [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	m_{eff} [GeV]	$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}$	Other
Rpc2L2bS	$\geq$ 2SS	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	–
Rpc2L2bH	$\geq$ 2SS	≥ 2	≥ 6	> 25	–	> 1800	> 0.15	–
Rpc2Lsoft1b	$\geq$ 2SS	≥ 1	≥ 6	> 25	> 100	–	> 0.3	$20,10 < p_{\text{T}}^{\ell_1}, p_{\text{T}}^{\ell_2} < 100$ GeV
Rpc2Lsoft2b	$\geq$ 2SS	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	$20,10 < p_{\text{T}}^{\ell_1}, p_{\text{T}}^{\ell_2} < 100$ GeV
Rpc2L0bS	$\geq$ 2SS	$= 0$	≥ 6	> 25	> 150	–	> 0.25	–
Rpc2L0bH	$\geq$ 2SS	$= 0$	≥ 6	> 40	> 250	> 900	–	–
Rpc3L0bS	≥ 3	$= 0$	≥ 4	> 40	> 200	> 600	–	–
Rpc3L0bH	≥ 3	$= 0$	≥ 4	> 40	> 200	> 1600	–	–
Rpc3L1bS	≥ 3	≥ 1	≥ 4	> 40	> 200	> 600	–	–
Rpc3L1bH	≥ 3	≥ 1	≥ 4	> 40	> 200	> 1600	–	–
Rpc2L1bS	$\geq$ 2SS	≥ 1	≥ 6	> 25	> 150	> 600	> 0.25	–
Rpc2L1bH	$\geq$ 2SS	≥ 1	≥ 6	> 25	> 250	–	> 0.2	–
Rpc3LSS1b	$\geq \ell^{\pm}\ell^{\pm}\ell^{\pm}$	≥ 1	–	–	–	–	–	veto $81 < m_{e^{\pm}e^{\pm}} < 101$ GeV
Rpv2L1bH	$\geq$ 2SS	≥ 1	≥ 6	> 50	–	> 2200	–	–
Rpv2L0b	$=$ 2SS	$= 0$	≥ 6	> 40	–	> 1800	–	veto $81 < m_{e^{\pm}e^{\pm}} < 101$ GeV
Rpv2L2bH	$\geq$ 2SS	≥ 2	≥ 6	> 40	–	> 2000	–	veto $81 < m_{e^{\pm}e^{\pm}} < 101$ GeV
Rpv2L2bS	$\geq \ell^{-}\ell^{-}$	≥ 2	≥ 3	> 50	–	> 1200	–	–
Rpv2L1bS	$\geq \ell^{-}\ell^{-}$	≥ 1	≥ 4	> 50	–	> 1200	–	–
Rpv2L1bM	$\geq \ell^{-}\ell^{-}$	≥ 1	≥ 4	> 50	–	> 1800	–	–

Only one signal region has no requirements on ETmiss and Meff

Simplified “Dark Meson”-like Models

The entire class of theories is covered by generic 1->2->4 production/ decay final state.



Obviously prioritizing the heaviest SM final states (3rd generation, W, Z, h) is theoretically motivated.

Landscape of Effective Theories of Mesons

Generally, we find that when dark mesons are in

doublet representations —> gaugephobic
triplet representation —> gaugephilic

Examples:

2 flavor chiral theory SU(2) x SU(2) —> gaugephilic ("bosonic technicolor")
(dark pions in $\mathbf{2} \times \mathbf{2} = \mathbf{1} + \mathbf{3}$)

2 flavor vectorlike theory SU(2) x SU(2) —> gaugephilic ("crappy triplet model")
plus dim-5 chiral interaction ($\mathbf{2} \times \mathbf{2} = \mathbf{1} + \mathbf{3}$)

4 flavor hybrid theory SU(4) x SU(4) —> gaugephobic ("stealth dark matter")
($\mathbf{4} \times \mathbf{4} = \mathbf{1} + \mathbf{3} + \mathbf{3} + \mathbf{2}_c + \mathbf{2}_c$)

4 flavor SU(4)/SO(4) —> gaugephilic ("GM model")
($(\mathbf{3}, \mathbf{3}) = \mathbf{1} + \mathbf{3} + \mathbf{5}$)

...

Discussion

A new strongly coupled sector near the weak scale is possible, motivated, and yields interesting signals @ LHC.

Dark pions, in the context of this talk, are really just a set of scalar multiplets in various electroweak representations. Unlike 2HDM et al., searches, pair-production is dominant.

Some signals are already searched for (and set constraints). Many search strategies are, however, not well-optimized for signals with small MET and comparably small M_{eff}.

Simplified models of 1—>2—>4 production/decay, prioritizing 3rd generation, W, Z, h final states, is a ideal target for searches going into high luminosity running of LHC.

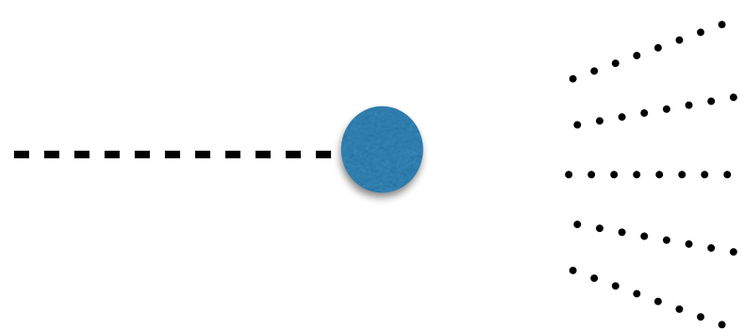
Backup

How do dark pions decay?

Case 0: They don't — due to accidental flavor "species" symmetries.

This is a generic problem with vectorlike confinement
(dark fermions that acquire purely vector-like masses).

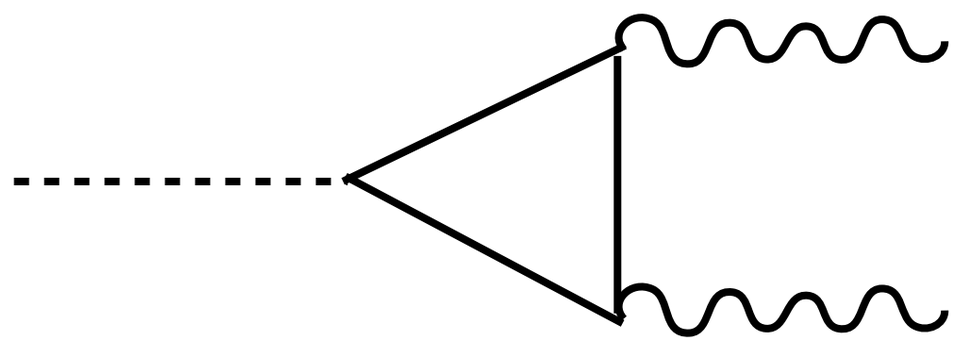
The phenomenological solution lies outside of the dark sector,
i.e., requiring higher dimensional interactions to break the
species symmetries



and is not particularly predictive.

How do dark pions decay?

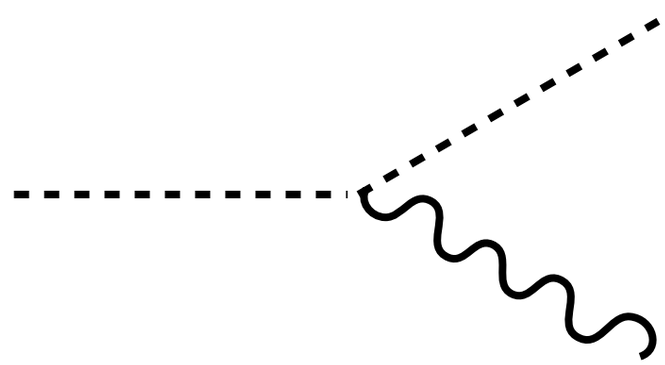
Case 1: π^0 decay through the chiral anomaly



Requires gauge interactions to explicitly violate axial global symmetries. Popularized by model-builders following the infamous diphoton craze.

How do dark pions decay?

Case 2: $\pi^+ \to \pi^0 W^*$ weak decay



Requires π's in EW representations. Given the dark pion mass splittings are usually small, this mode is typically far off-shell, and often sub-dominant (e.g., π^+ of QCD).

How do dark pions decay?

Case 3: π^{+0-} mixes with G^{+0-} (Goldstones from Higgs doublet)

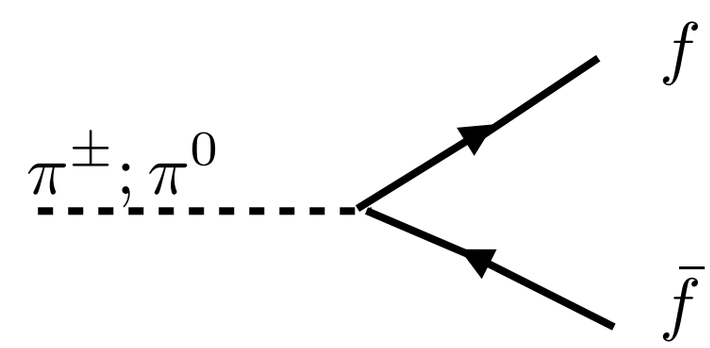
$$\begin{pmatrix} \pi_{\rm phys} \\ G_{\rm phys} \end{pmatrix} = \begin{pmatrix} \approx 1 & c_\pi \\ -c_\pi & \approx 1 \end{pmatrix} \begin{pmatrix} \pi \\ G \end{pmatrix}$$

Also requires π's in EW representations; everyplace there was a would-be Higgs Goldstone interaction, there is now an interaction with the π:

$$y_u\, QHu^c + y_d\, QH^\dagger d^c$$

$$\to c_\pi \pi^0 \left(y_t t\bar{t} + y_b b\bar{b} + y_\tau \tau^+\tau - + \ldots\right)$$

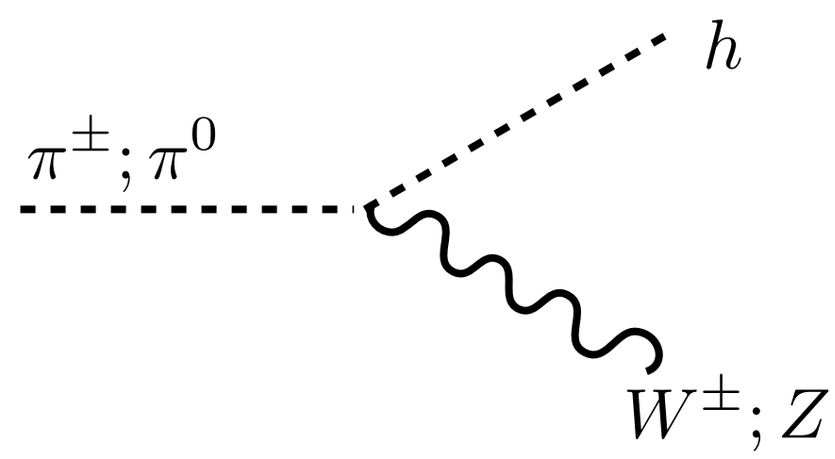
$$\to c_\pi \pi^+ \left(y_t t\bar{b} + y_\tau \tau^+ \nu_\tau + \ldots\right)$$



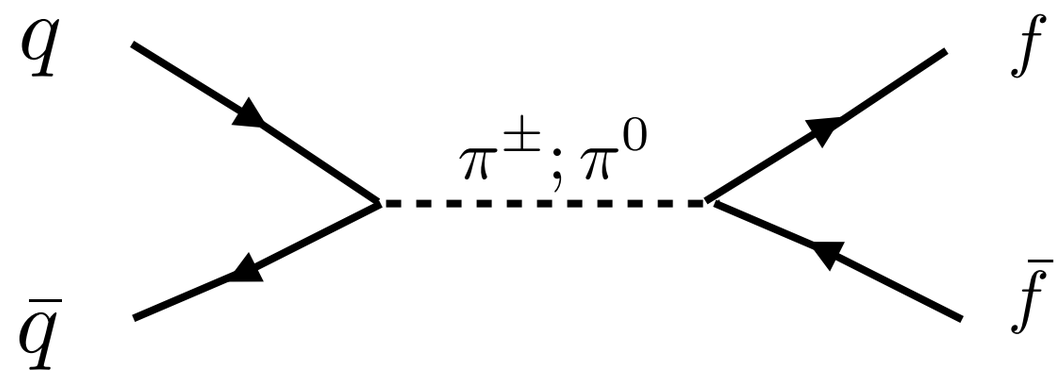
$$(D_\mu H)^\dagger D^\mu H$$

$$\to c_\pi\, \partial_\mu \pi^0 Z^\mu h$$

$$\to c_\pi\, \partial_\mu \pi^+ W^{-\mu} h$$



(Aside — single dark pion production:



Very familiar from standard 2HDM ($\pi^{\pm,0} \rightarrow H^{\pm}, A^{0}$),
this can occur when Goldstone / dark pion mixing is large,
e.g., in bosonic technicolor / induced EWSB.

Chang et al., have explored constraints (pretty tough).

In dark sectors that are approximately vector-like,
single production modes are highly suppressed.)

From a purely theoretical perspective

All of the decay possibilities that deserve study, and several could be occurring simultaneously in one model.

From a purely experimental perspective

Case 0
(decay through
higher dim operators)

SUCKS.

(not predictive*)

*caveats. . .

Case 1
(decay through
anomaly)

AWESOME.

(but so easy we know the answer —
no diphoton resonances . . . after all)

Case 2
(weak decay with small splittings)

SORTOF SUCKS.

(tough slog; substantial effort for,
e.g., nearly degenerate Higgsinos)

Case 3
(mixes with Goldstones)

PROMISING.

(not obviously ruled out,
nor obviously super-difficult)

Theories with $G^{\pm,0} \longleftrightarrow \pi^{\pm,0}$ mixing

Require Higgs interactions with the dark fermions — i.e., chiral masses. such as Yukawa couplings

$$y\, F H F' + \ldots$$

and/or higher dimensional operators, e.g.,

$$\frac{F_1^i \epsilon_{ij} H^j F_2 \cdot H^\dagger}{\Lambda} + h.c.$$

Three varieties of dark fermion masses

	Vector-like	Pure Chiral	Hybrid
$MFF' + h.c.$	yes	no	yes
$y\,FHF' + h.c.$	no	yes	yes
model examples	• SM below EWSB $SU(3)_c \times U(1)_{\rm em}$ • vector-like confinement	• SM above EWSB $SU(3)_c \times SU(2)_L \times U(1)_{\rm em}$ • bosonic technicolor	• stealth dark matter
drawbacks	· some pions stable (species symmetries)	· may break EW symmetry (S parameter constraints)	