Effective Theories of Dark Mesons

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

Lattice for BSM @ Boulder 2018

Huh? Didn't you talk about this last year?

Yes . . .

While there are some elements of what I talked about then that reappear here, we have a qualitatively improved understanding, as you'll see.

In particular, some things I said then were wrong for rather subtle reasons — it took considerable effort to understand and appreciate the case that I had thought was relatively simple (stealth dark matter).

We now understand a wide class of theories — not only SDM, but also theories with and without custodial SU(2); vector-like theories with higher-dim operators; bosonic technicolor; composite Georgi-Machacek theories . . .

Dark Mesons

A new, strongly-coupled, confining gauge theory ("dark sector"*) exists with scales roughly near to the electroweak breaking scale.

The lightest states — "dark mesons" — can be constrained by existing searches, but as I'll argue, provide one interesting class of signals that — in broad swaths of parameter space — existing LHC searches (appear to be) not well-optimized.

*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.

Effective Theories of Dark Mesons

Kilic, Okui, Sundrum were way ahead of their time to recognize that the effective theory of (what I call “dark”) mesons provides a rich phenomenology to explore.

While what I ultimately want to study has some overlap with their original study (“vectorlike confinement”), there are several differences, and we’ll see, they lead to qualitatively different phenomenology at LHC.

Strongly-Coupled Theories

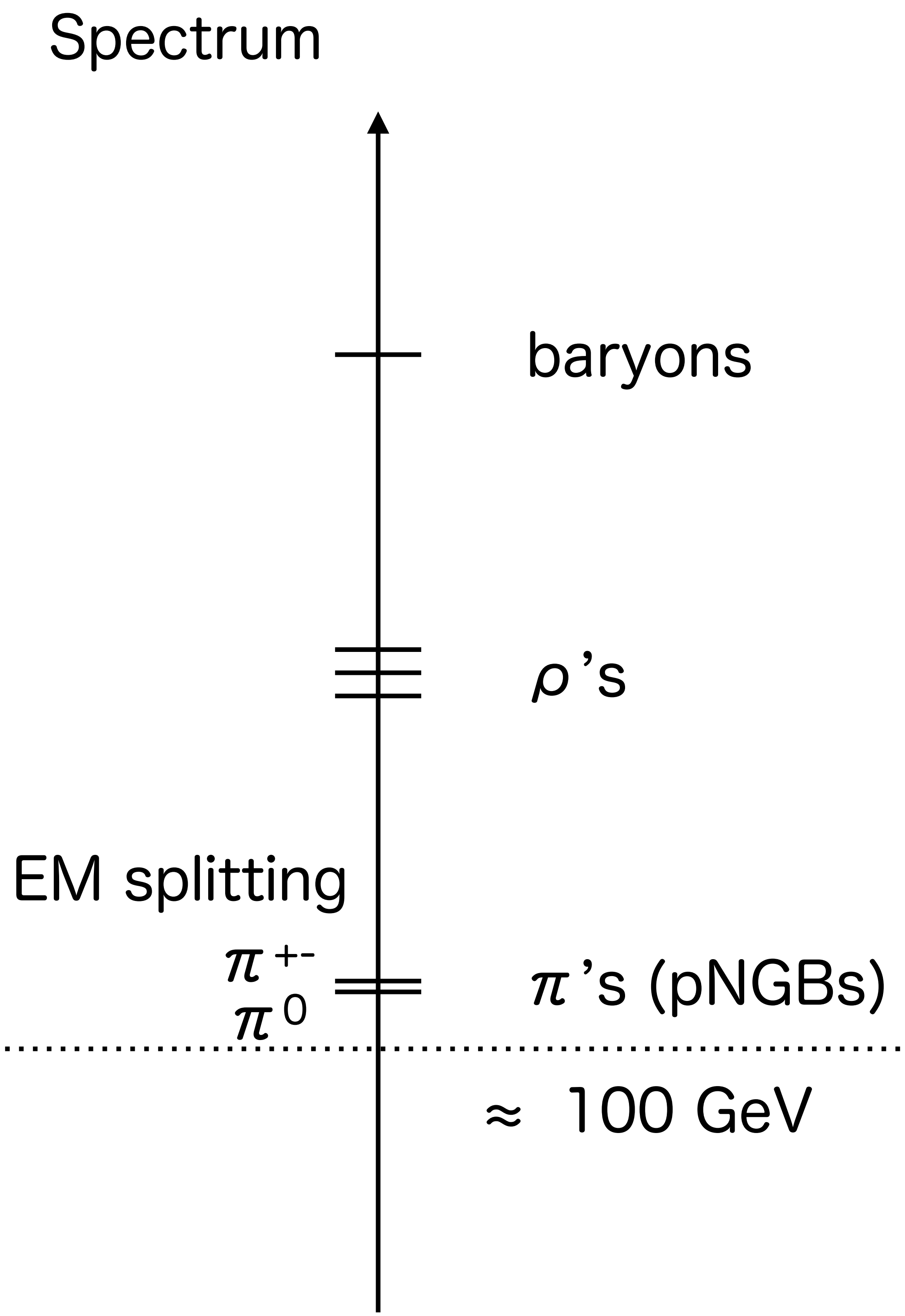
Are often a pain in the @#$% to deal with!

- many things known only approximately
- some things known from lattice
- some things not known at all

But in QCD, we have long used the chiral Lagrangian to obtain quantitative predictions for the pion interactions, and employed related effective theories involving the vector mesons.

Meson interactions also have well-known scalings at large N (large number of “dark colors”), that combined with NDA, give estimates of relevant couplings.

A Strongly-Coupled Theory



For now, imagine an SU(N)* gauge theory that confines at

$$\Lambda_{\rm dark} \sim 4\pi f$$

*(N > 2)

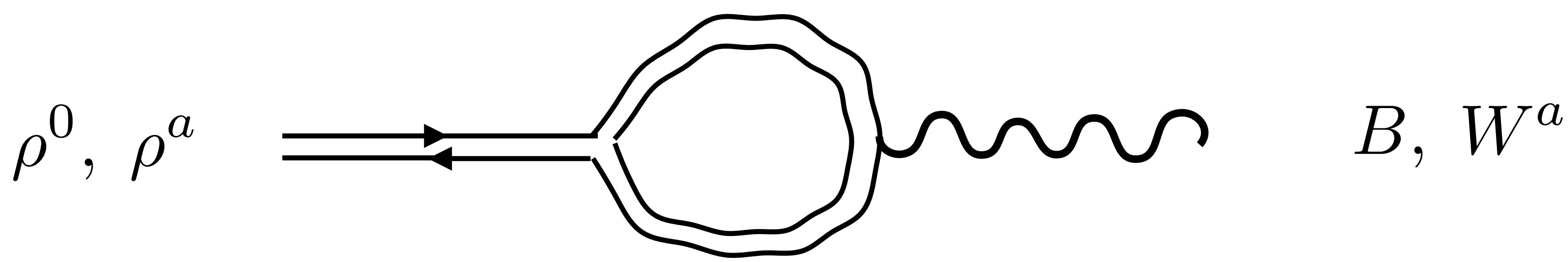
with several flavors of “dark fermions” that transform under the electroweak part of the Standard Model.

Emphasize: Mesons transform in electroweak multiplets.

The dark fermions have masses $M_f < 4\pi f$ whose origin, while critical to my discussion, I’ll discuss a bit later.

Vector Meson — SM Gauge Boson Mixing

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



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

Two types!

U(1)-like (ρ^0 only)

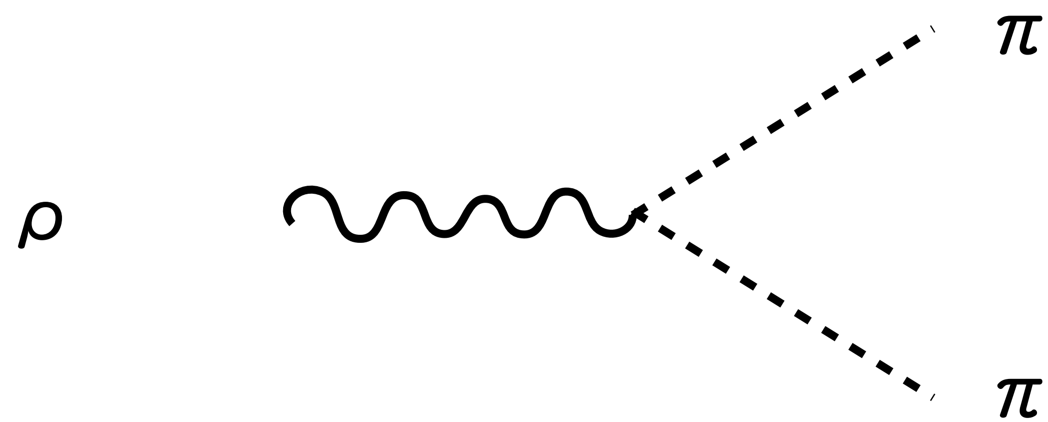
SU(2)-like $\rho^{\pm,0}$

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

This provides a portal into the dark sector!

Meson Self-Interactions

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

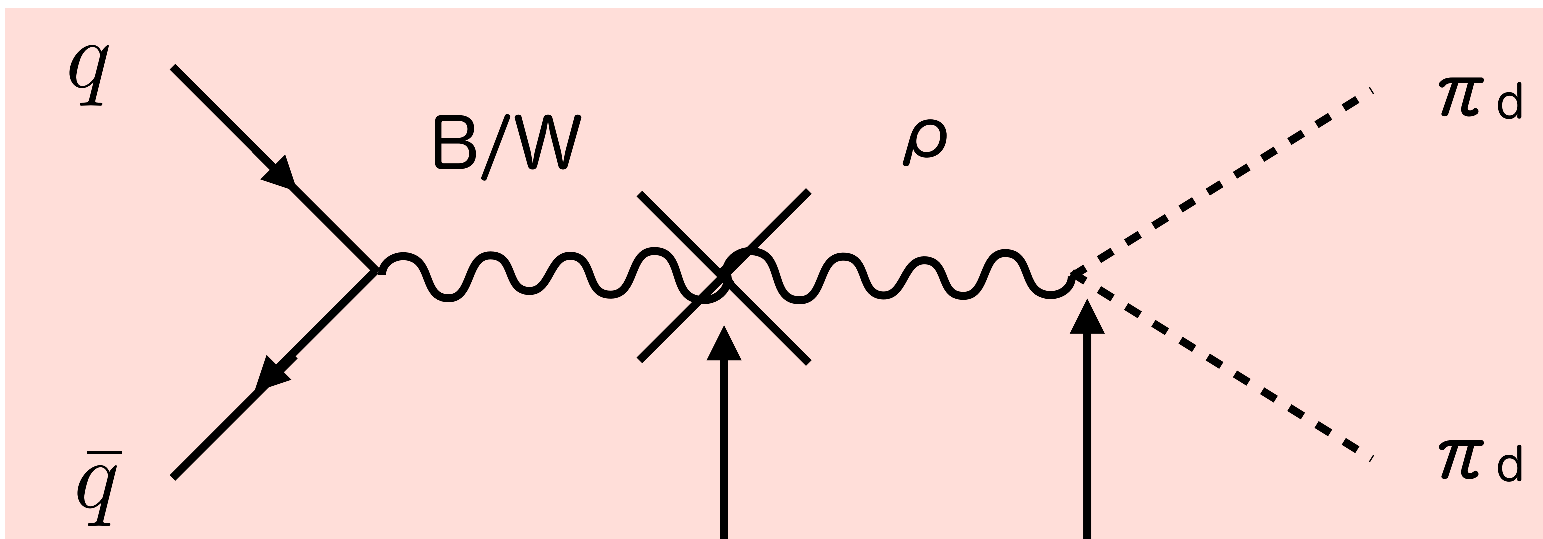


$$g_{\rho_d \pi_d \pi_d} f^{abc} (\rho_d^a)_\mu \pi_d^b D^\mu \pi_d^c$$

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

Dark Pion Pair-Production through ρ

Provides main source of dark pion production



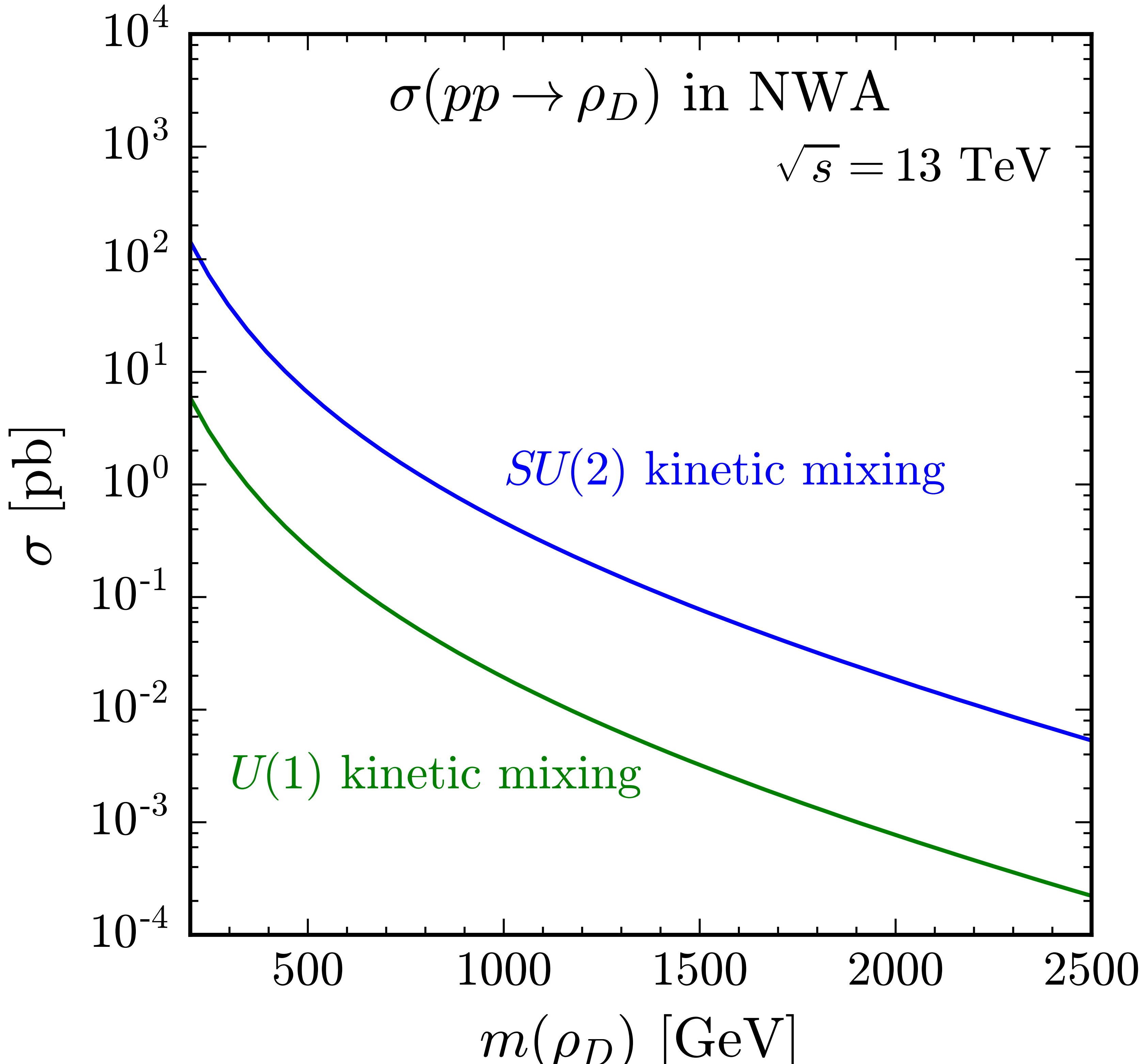
$$\epsilon \sim g^{(\prime)} \frac{\sqrt{N_{\rm dark}}}{4\pi}$$

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

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

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

Dark rho production



GK, Martin, Ostdiek, Tong (to appear)

How do dark pions decay?

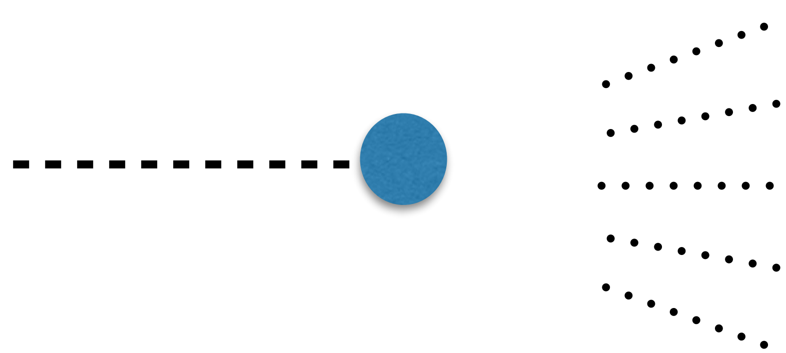
Several possibilities that depend on the underlying theory:

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).

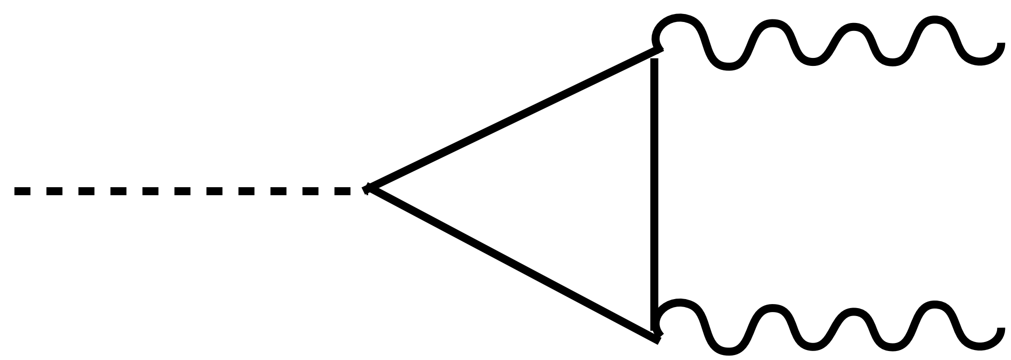
The phenomenological solution lies outside of the dark sector,
i.e., requiring higher dimensional interactions to break the
species symmetries



and is not particularly predictive.

How do dark pions decay?

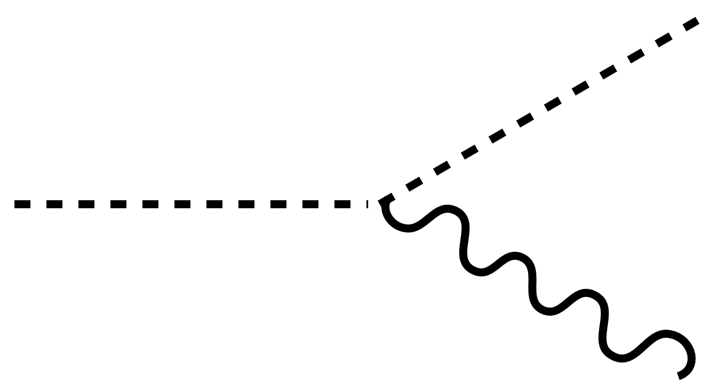
Case 1: π^0 decay through the chiral anomaly



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: π^+ -> $\pi^0 W^*$ 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)

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

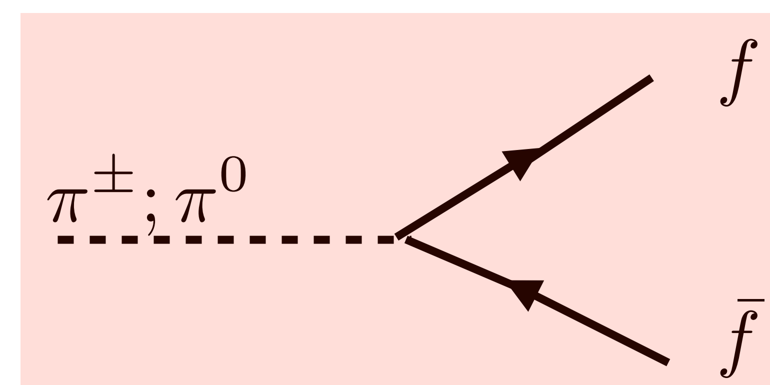
Also requires π's in EW representations; everyplace there was a would-be Higgs Goldstone interaction, there is now an interaction with the π:

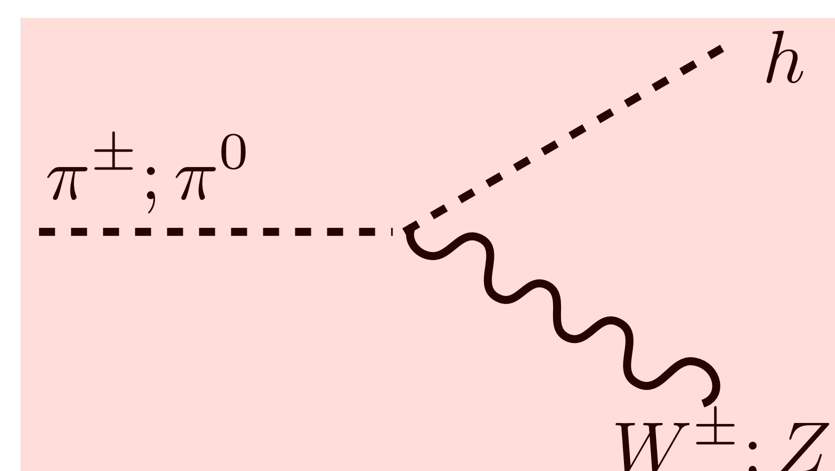
$$y_u\, Q H u^c + y_d\, Q H^\dagger d^c$$

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

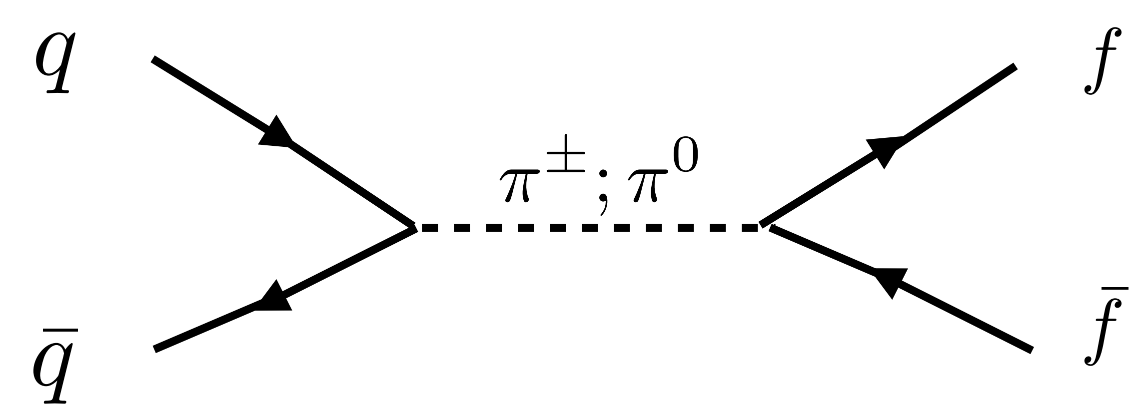
$$(D_\mu H)^\dagger D^\mu H$$

- → $c_\pi\, \partial_\mu \pi^0 Z^\mu h$
- → $c_\pi\, \partial_\mu \pi^+ W^{-\mu} h$





(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.,

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

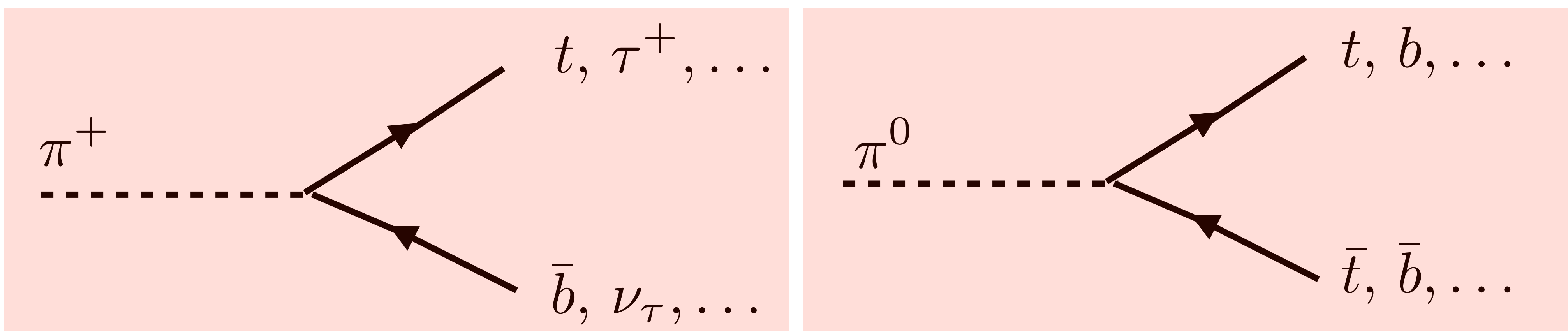
Varieties of dark fermion masses

	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)	

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

All varieties can lead to $G^{\pm,0} \longleftrightarrow \pi^{\pm,0}$ mixing*, and result in π decay to fermions proportional to Yukawa couplings

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

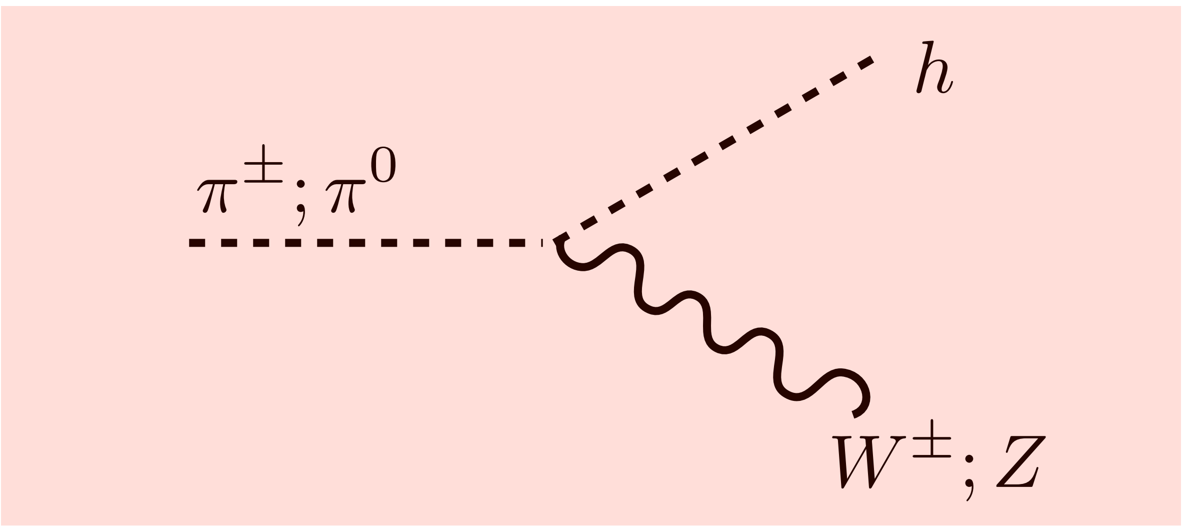


$$\lambda_{\pi-\mathrm{GB}-h} \sim y_f\, c_\pi$$

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

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

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

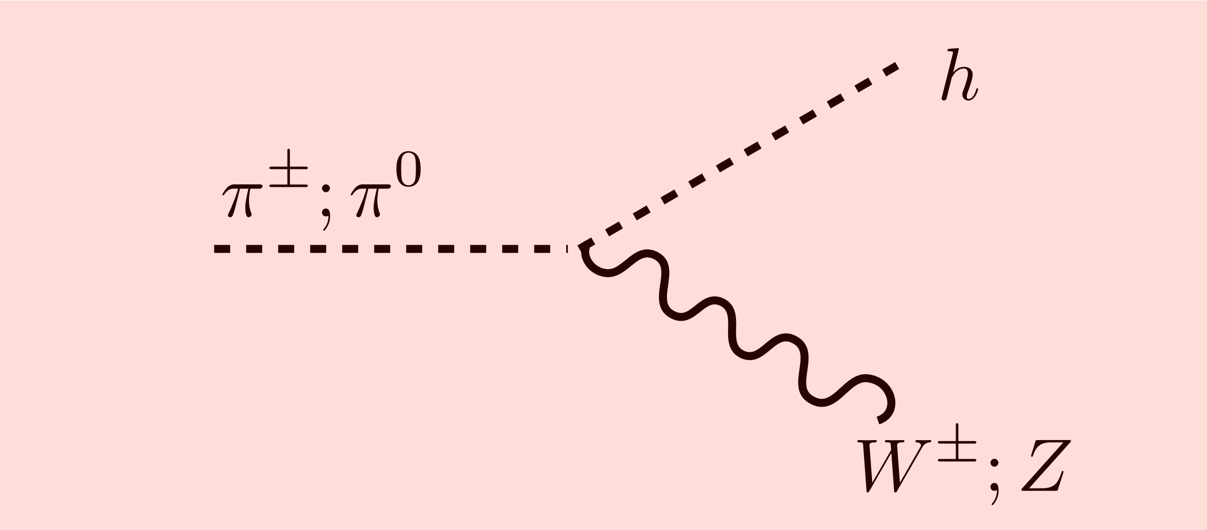


Intriguingly, there are, however, two distinct classes of theories:

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!

m_K^2 → heavier state mixes with h boson

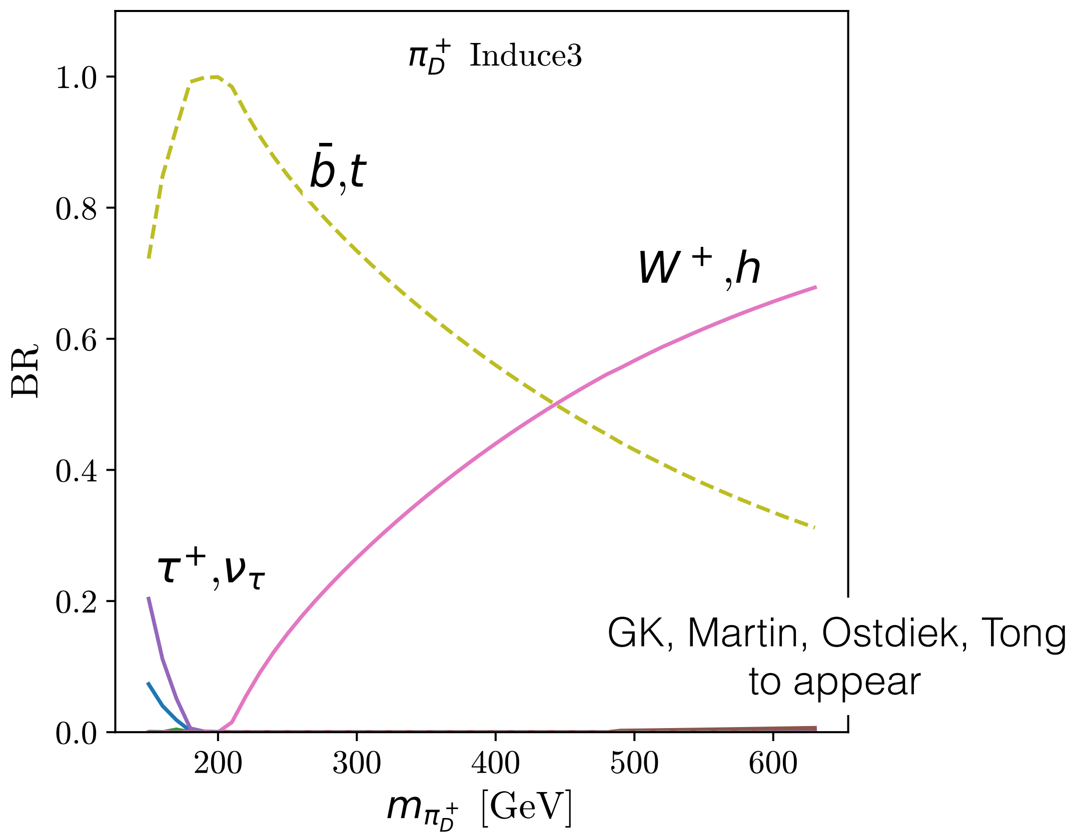
We've seen this before

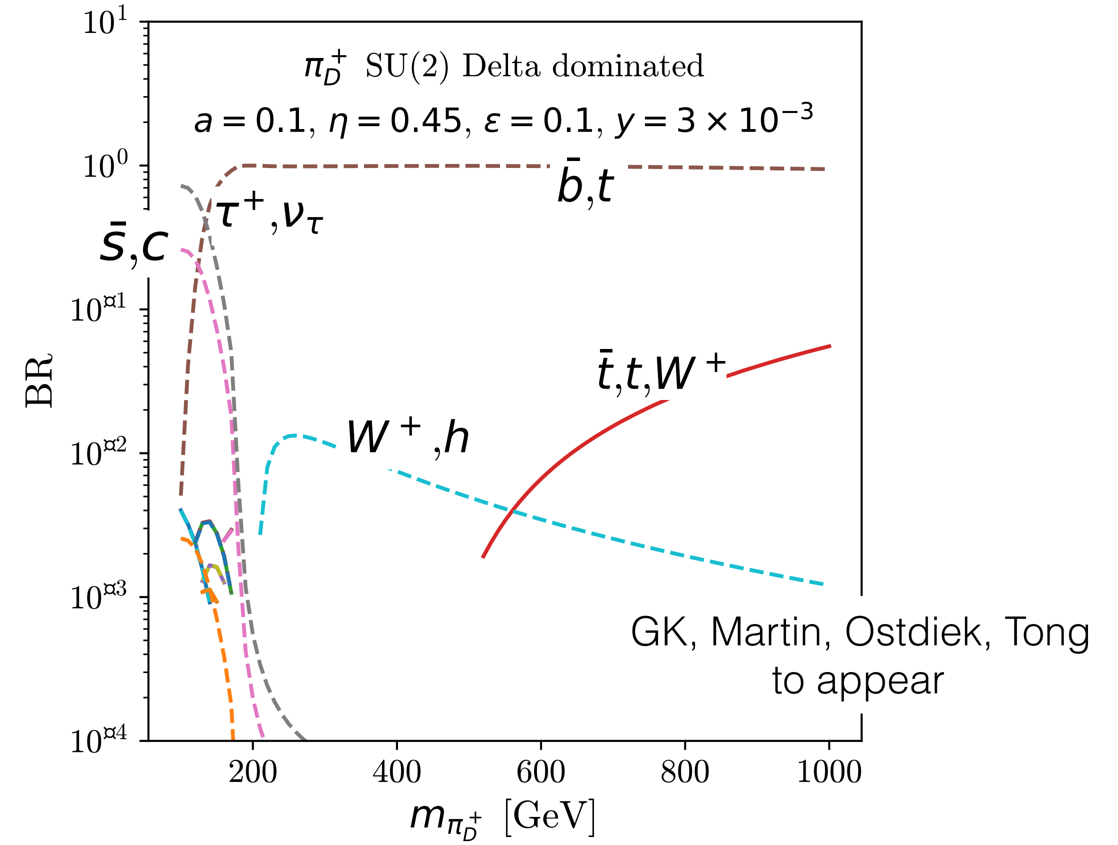


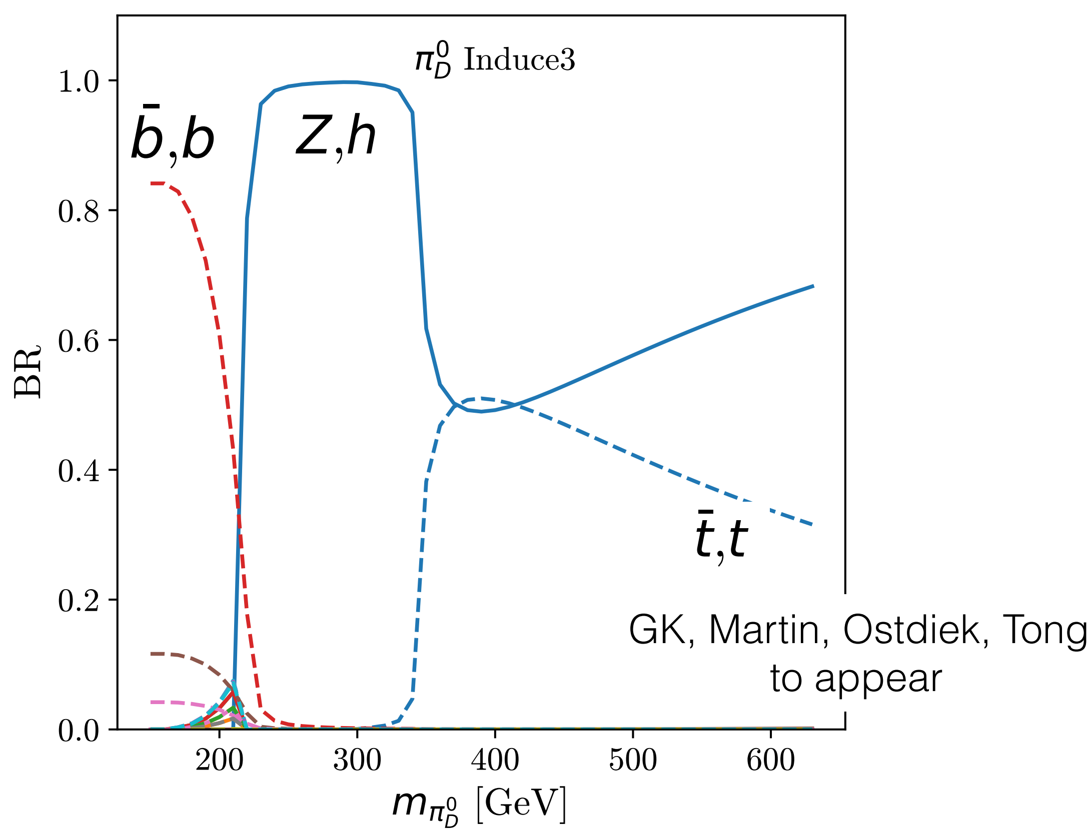
Gaugephilic	Gaugephobic
Georgi-Machacek model (replace $\pi^{\pm,0} \to H_3^{\pm,0}$ triplet)	2HDM Type II (replace $\pi^{\pm,0} \to H^{\pm},\ A^0$)
$\lambda_{\pi-\mathrm{GB}-h} \sim g\, s_H$ ↓ mixing angle (c_π)	$\lambda_{\pi-\mathrm{GB}-h} \sim g \cos(\beta-\alpha) \sim g \frac{m_h^2}{m_H^2}$

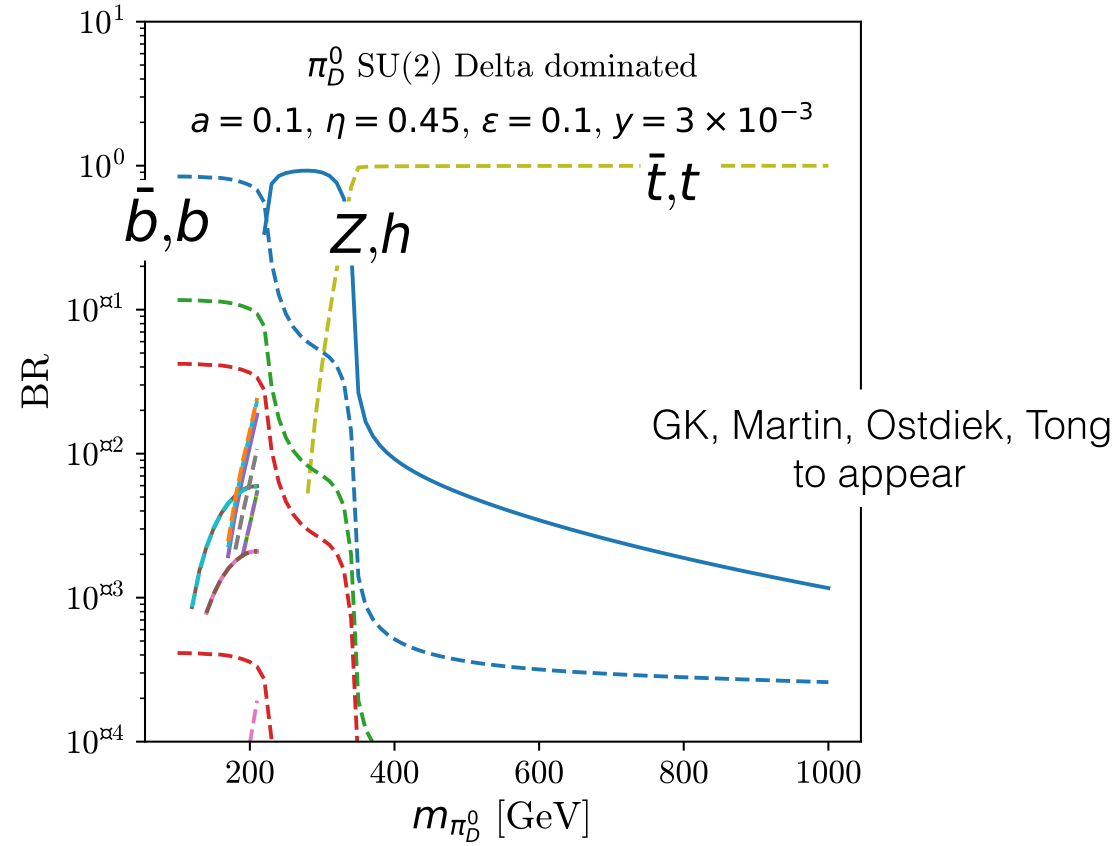
It makes a difference

Gaugephilic	Gaugephobic

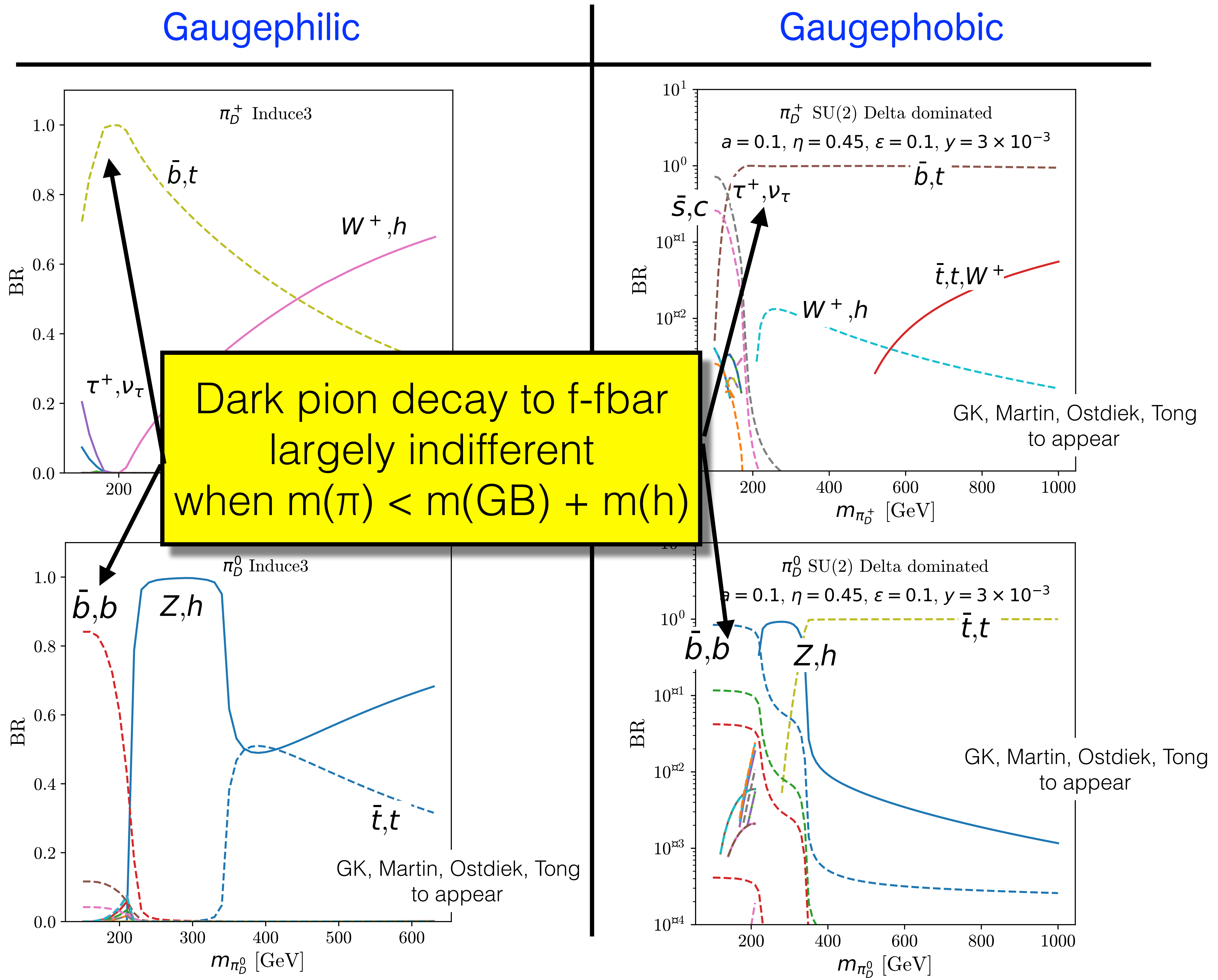






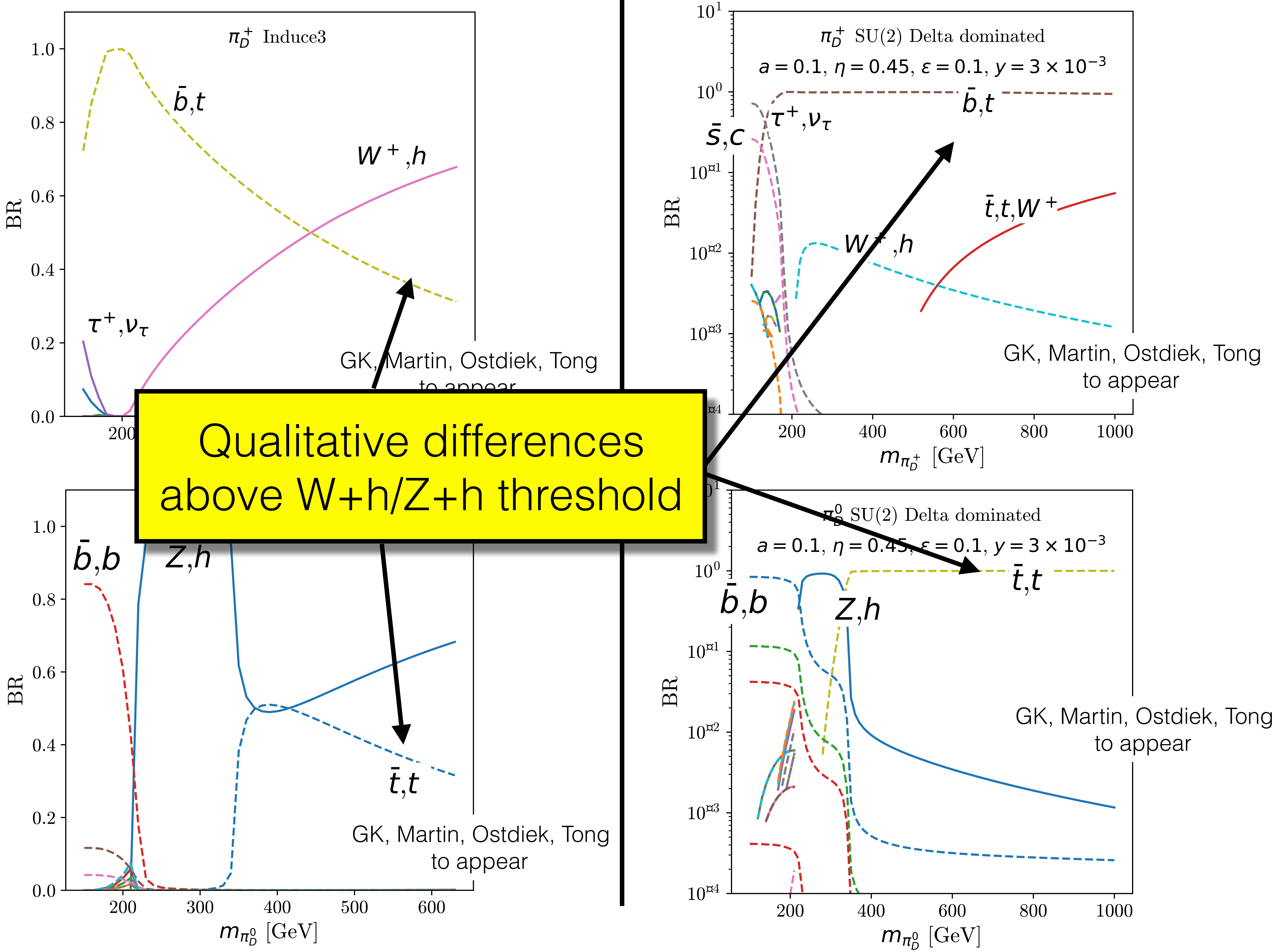


It makes a difference



It makes a difference

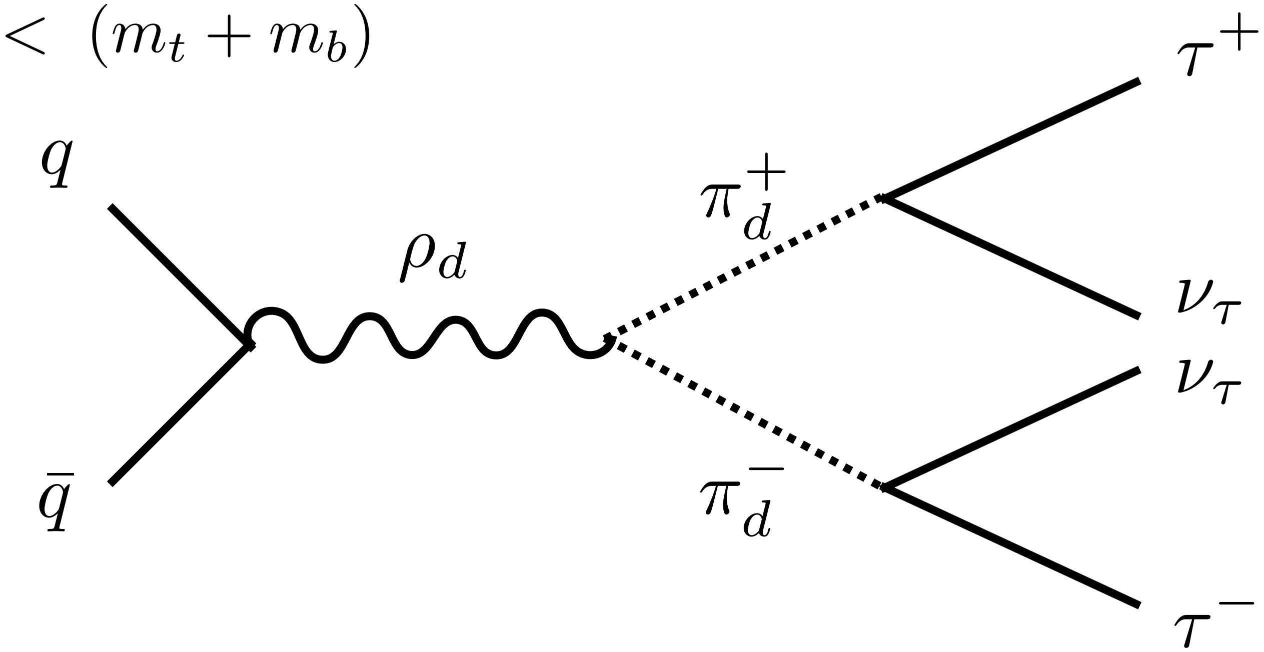
Gaugephilic | Gaugephobic



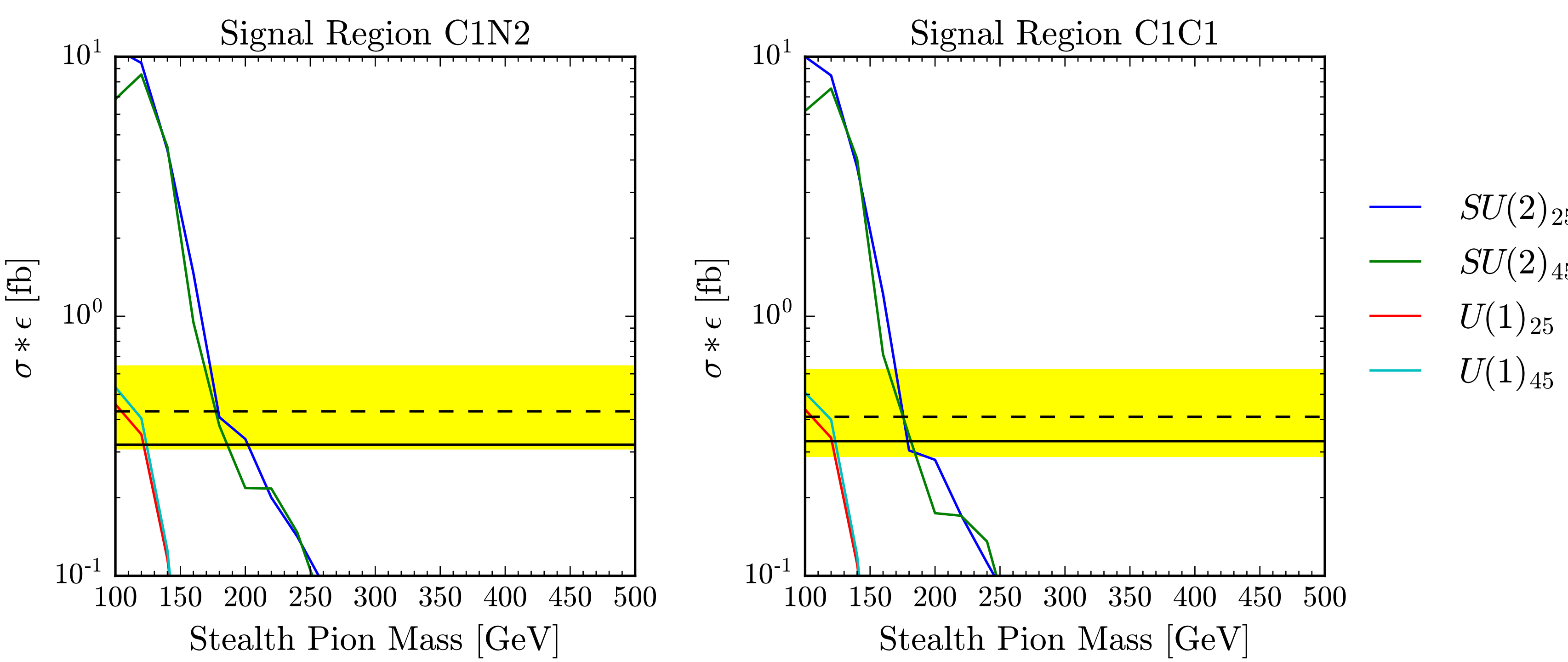
Qualitative differences above W+h/Z+h threshold

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 $M_{\rm eff}$) making recasted supersymmetric searches for gaugino production not optimal.

For gaugephobic models the hadronic modes are more challenging

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

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

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

One Example of Recasting

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

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	$N^{\text{signal}}_{\text{leptons}}$	$N_{b\text{-jets}}$	N_{jets}	p_T^{jet} [GeV]	E_T^{miss} [GeV]	m_{eff} [GeV]	$E_T^{\text{miss}}/m_{\text{eff}}$	Other
Rpc2L2bS	≥ 2SS	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	–
Rpc2L2bH	≥ 2SS	≥ 2	≥ 6	> 25	–	> 1800	> 0.15	–
Rpc2Lsoft1b	≥ 2SS	≥ 1	≥ 6	> 25	> 100	–	> 0.3	$20,10 < p_T^{\ell_1}, p_T^{\ell_2} < 100$ GeV
Rpc2Lsoft2b	≥ 2SS	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	$20,10 < p_T^{\ell_1}, p_T^{\ell_2} < 100$ GeV
Rpc2L0bS	≥ 2SS	= 0	≥ 6	> 25	> 150	–	> 0.25	–
Rpc2L0bH	≥ 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	≥ 2SS	≥ 1	≥ 6	> 25	> 150	> 600	> 0.25	–
Rpc2L1bH	≥ 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	≥ 2SS	≥ 1	≥ 6	> 50	–	> 2200	–	–
Rpv2L0b	= 2SS	= 0	≥ 6	> 40	–	> 1800	–	veto $81 < m_{e^\pm e^\pm} < 101$ GeV
Rpv2L2bH	≥ 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	–	–

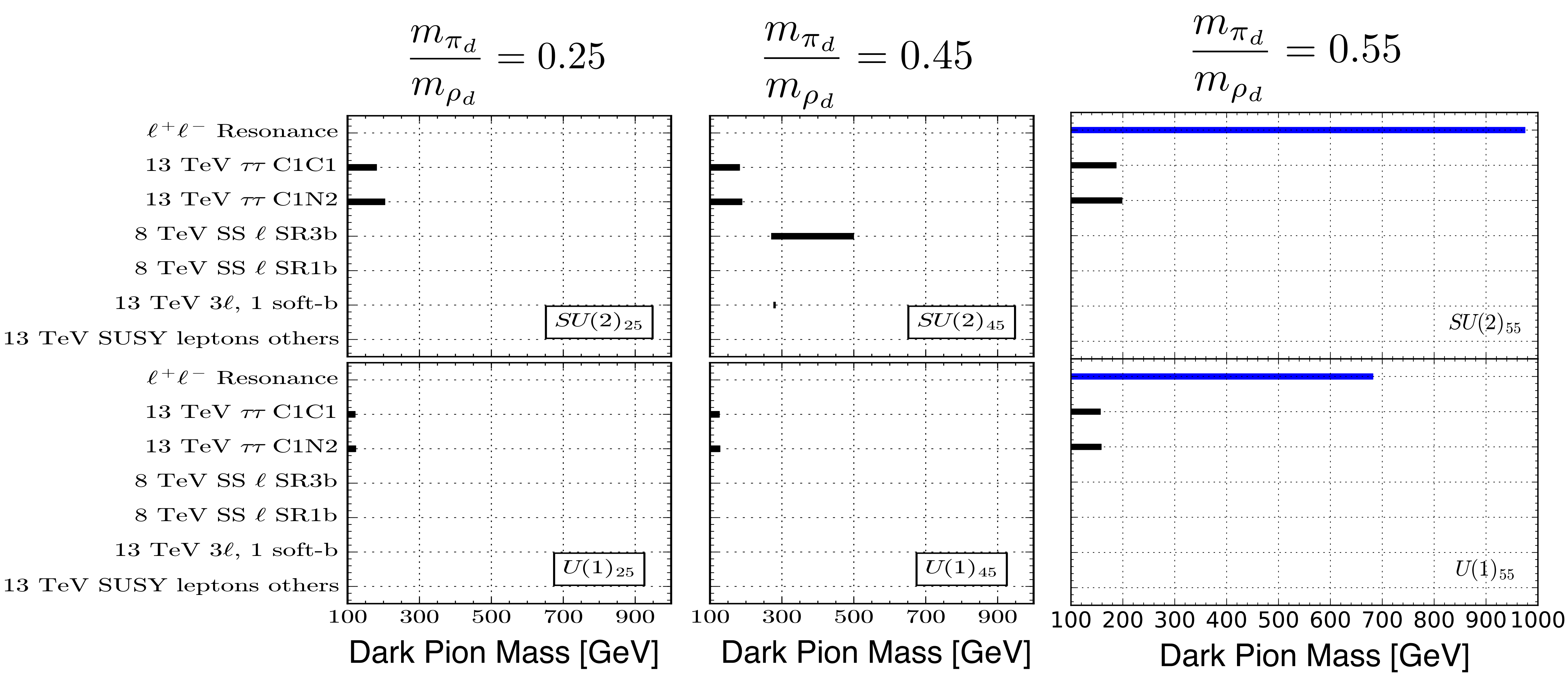
Only one signal region has no requirements on ETmiss and Meff

Preliminary Constraints

Thus far, we have found:

Strong constraints on $pp \to \rho_d \to \ell^+\ell^-$ when $\frac{m_{\pi_d}}{m_{\rho_d}} > 0.5$

Weak constraints on $pp \to \rho_d \to \pi_d\pi_d$



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Landscape of Effective Theories of Mesons

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 ($\mathbf{2} \times \mathbf{2} = \mathbf{1} + \mathbf{3}$)
that breaks custodial SU(2)

2 flavor vectorlike theory SU(2) x SU(2) —> gaugephilic ("vectorlike confinement")
plus dim-7 chiral interaction ($\mathbf{2} \times \mathbf{2} = \mathbf{1} + \mathbf{3}$) + higher dim-interaction
that preserves custodial SU(2)

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.

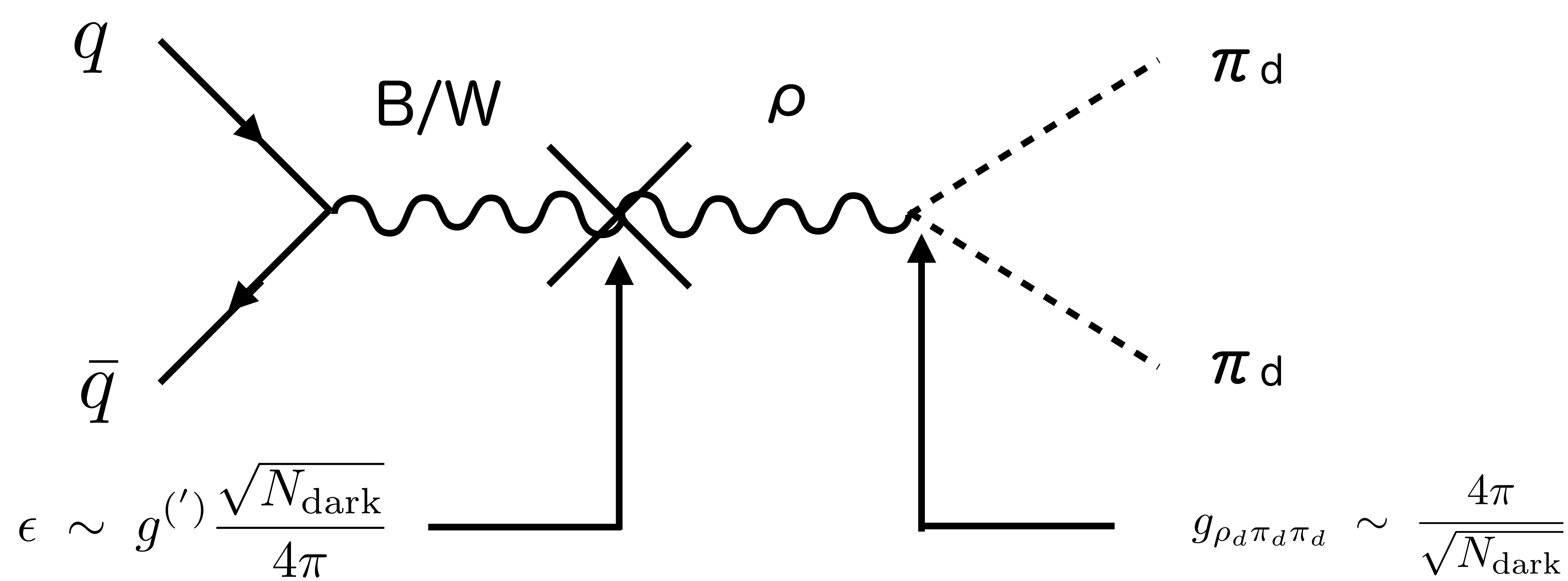
Some signals are already searched for (and set constraints). Many search strategies are, however, not well-optimized for signals with small MET and comparably small M_{eff}.

Theory space is interesting — gaugephilic/gaugephobic distinction reveals properties of underlying theory. Many "just a bunch of EW scalar" theories can be UV completed into pNGBs of a strongly-coupled theory.

Extra

Large N

Dark pion pair-production is roughly invariant



Dark ρ production back to dileptons scales with N