Effective Theories of Dark Mesons @ LHC

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Outline

1) Motivation

2) Dark rhos -- kinetic mixing with SM

3) Dark pions -- resonant pair-production through dark rho

4) Dark pion decay -- “gaugephilic” versus “gaugephobic”

5) LHC signals, constraints, opportunities

6) Discussion

Imagine ...

Pions of QCD had exact SU(2) isospin symmetry:

1) $Q_u = -Q_d = \frac{1}{2}$ (electric charge commutes with t^3)

2) $m_u = m_d$ (up & down Yukawa couplings equal)

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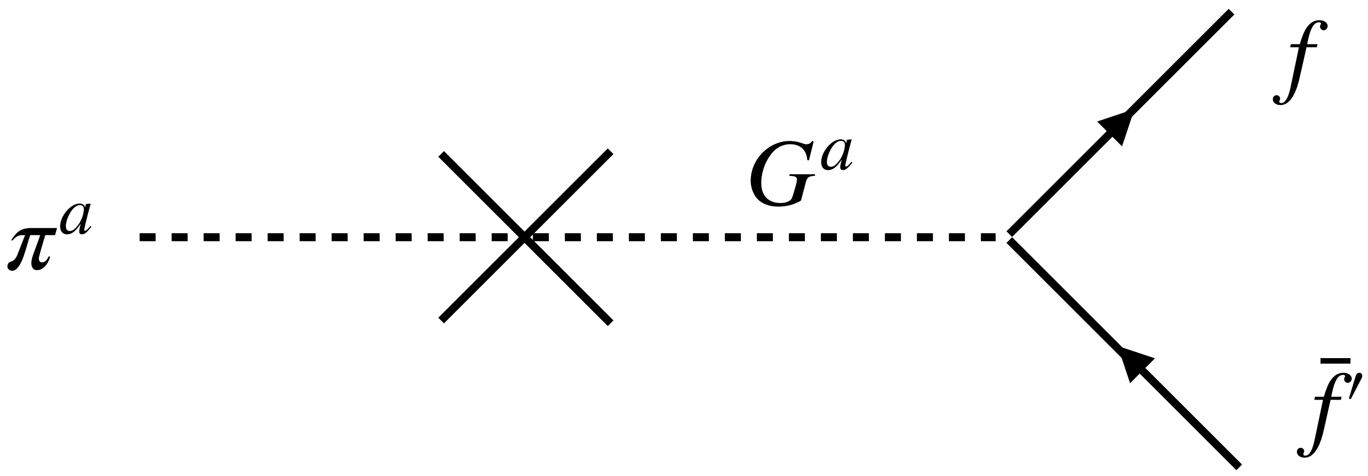
π^0 (still) decays -- through mixing with the Goldstone (just like $\pi^\pm$)

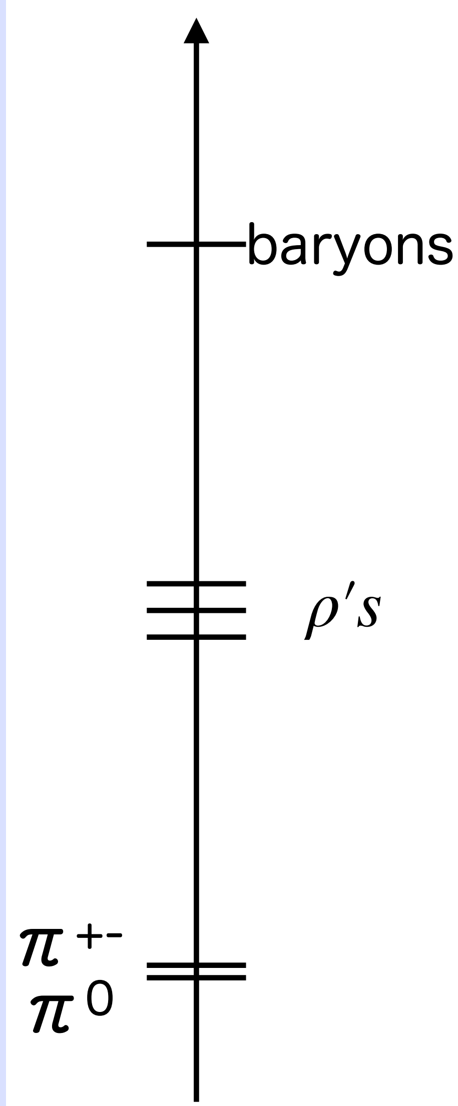


(highly suppressed by y_e since open mode is $\pi^0 \to e^+e^-$)

Weak decay $\pi^+ \to \pi^0 W^*$ possible, highly suppressed by phase space

“QCD” Mesons → “Dark” Mesons

“QCD” Mesons	“Dark” Mesons
$SU(3)_{color}$	$SU(N_{dark})$
Exact SU(2) isospin symmetry	Exact SU(2) custodial symmetry
chiral fermion masses (above EW scale)	vector-like and/or chiral fermion masses
fermions transform under EW + QCD	fermions transform under EW + “dark color”
2 flavors (u,d)	2 (and 4) flavor theories
pions in triplet	pions in triplet (or triplets + ...)
π^a/G^a mixing small (v^2/f^2 small)	effective π^a/G^a mixing small (v^2/M^2 small)



Plenty of Motivation ...

"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 (e.g., "Stealth Dark Matter")
  Dark mesons (e.g., Ectocolor DM; heavy chiral DM; etc.)
  SIDM/SIMP/etc.

- Theories that explain electroweak symmetry breaking, e.g.,
  Bosonic technicolor / strongly-coupled 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.

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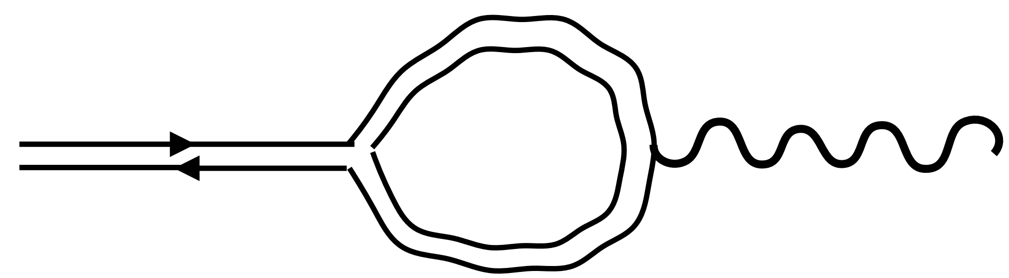
Dark ρ — B/W Kinetic Mixing

[Kilic, Okui, Sundrum 0906.0577]

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



Two types!

$$\epsilon W^a_{\mu\nu} F^{a,\mu\nu}_\rho$$

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

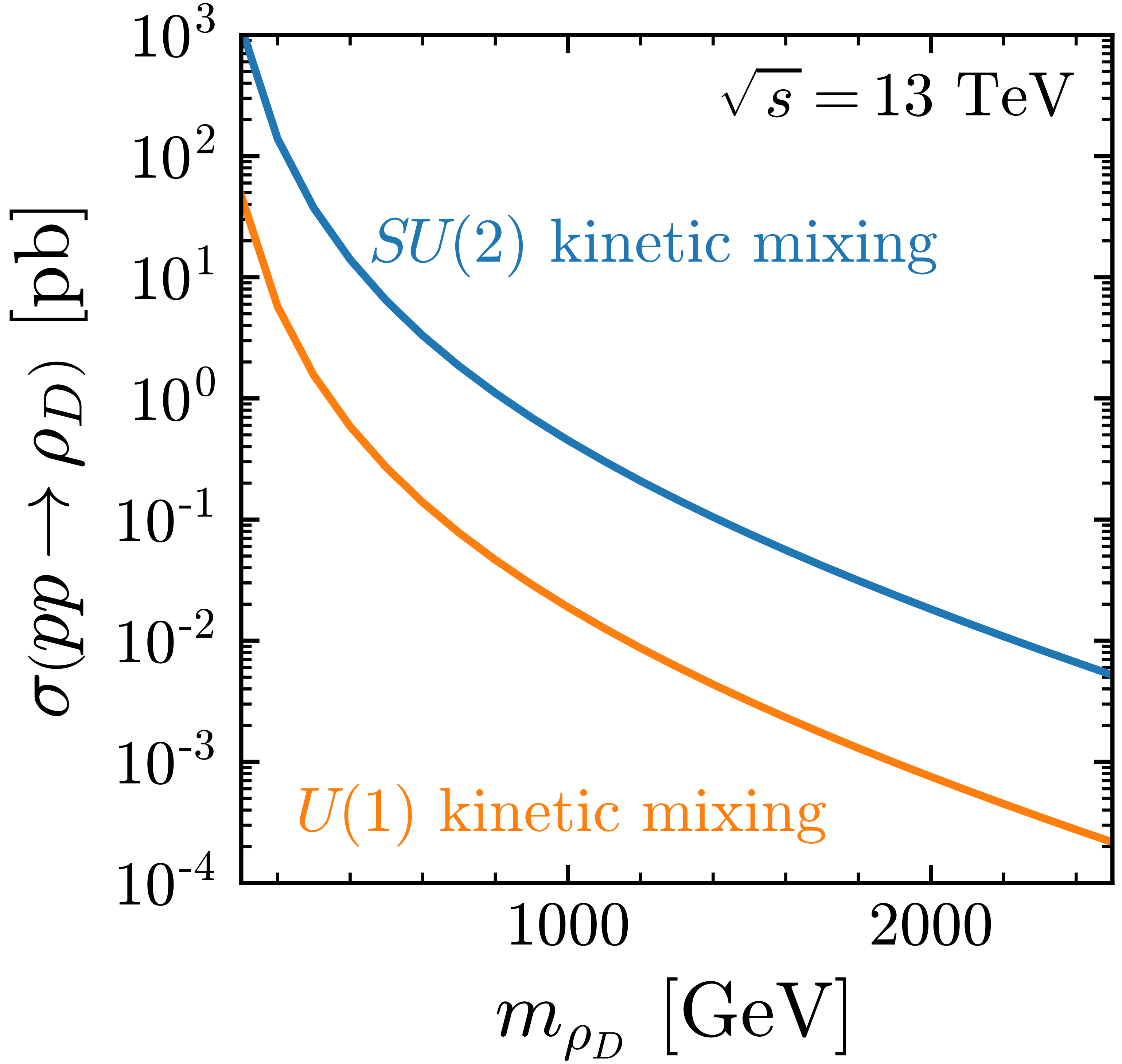
$$\epsilon' B_{\mu\nu} \delta^{3a} F^{a,\mu\nu}_\rho$$

U(1)-like (ρ^0 only)

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

This provides a portal into the dark sector!

Dark ρ_D production



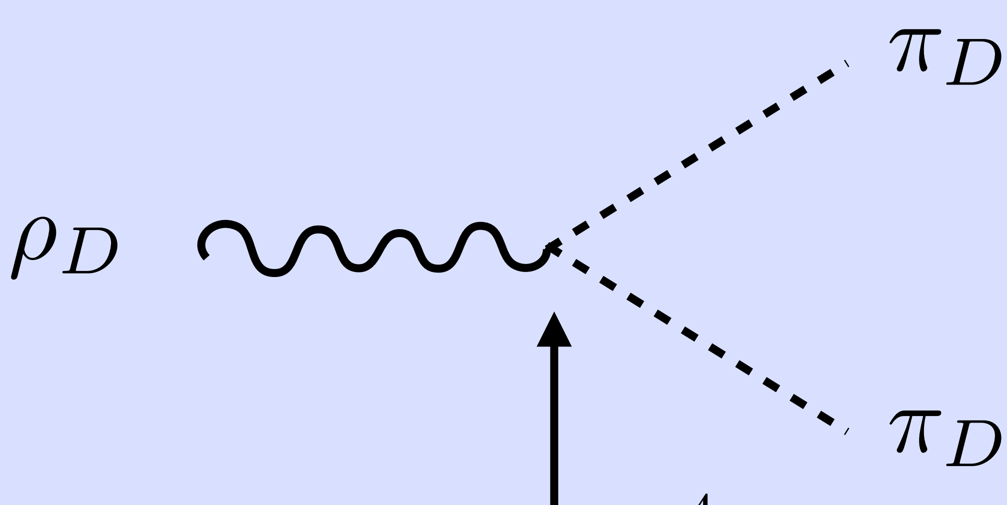
$N_{dark} = 4$

[GK, Martin, Ostdiek, Tong 1809.10184]

ρ_D Decay

Two Qualitatively Different Scenarios

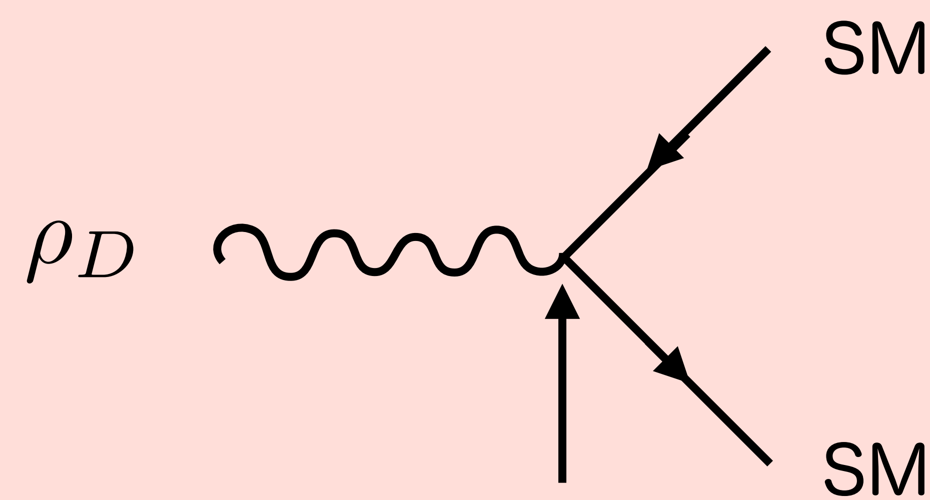
$$\frac{m_{\pi_D}}{m_{\rho_D}} < 0.5$$



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

Decays to dark pions dominate
(for N_{dark} not too large)

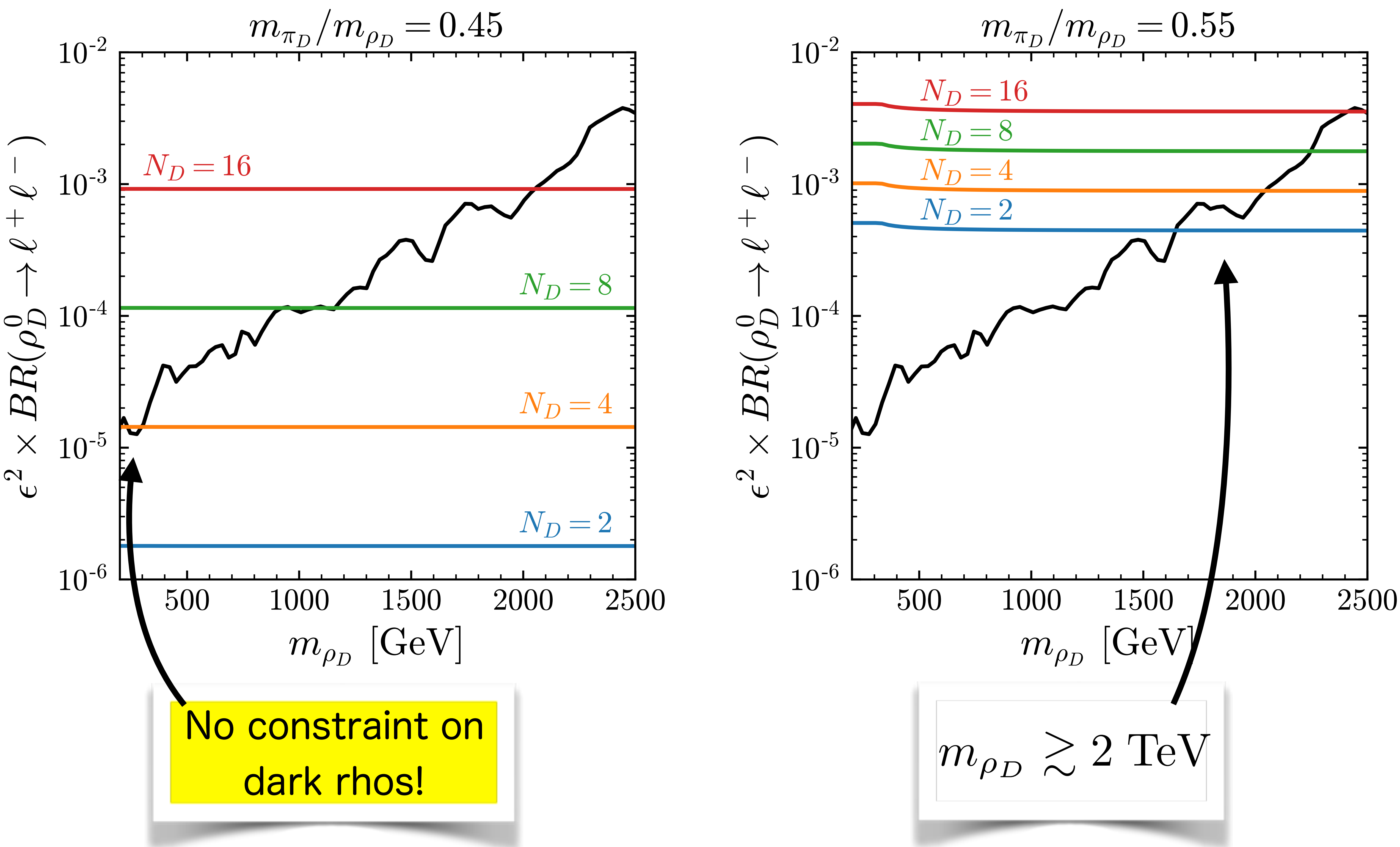
$$\frac{m_{\pi_D}}{m_{\rho_D}} > 0.5$$



$$\sim \left(g^{(\prime)}\right)^2 \frac{\sqrt{N_{\text{dark}}}}{4\pi}$$

Decays to SM dominate
(especially $\rho_D^0 \to \ell^+ \ell^-$)

Dilepton Resonances: Two Different Outcomes



[GK, Martin, Ostdiek, Tong 1809.10184]

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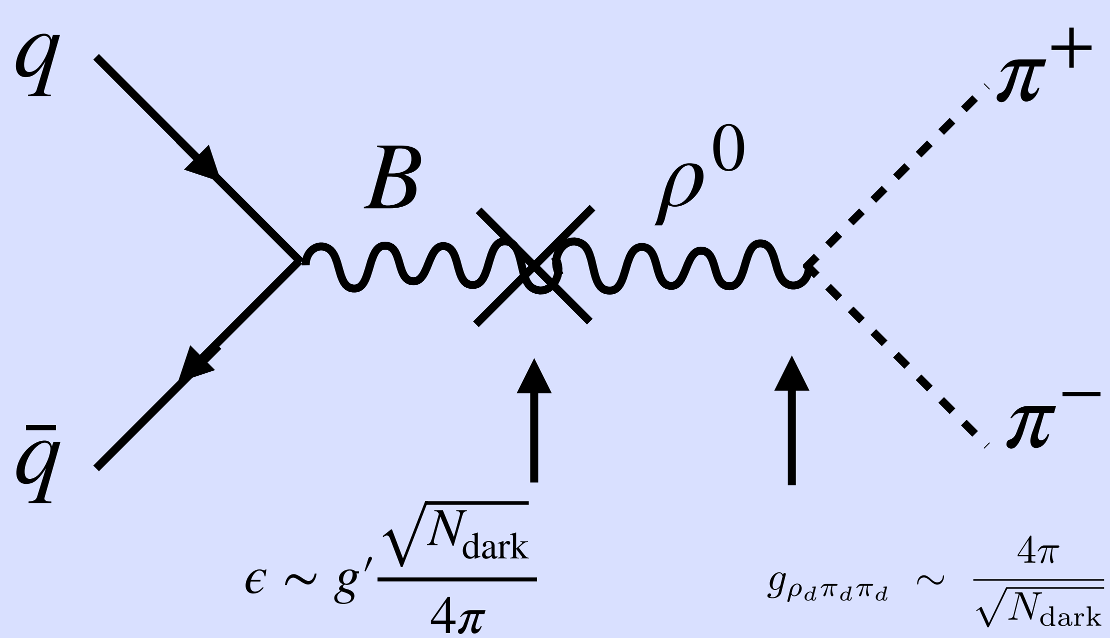
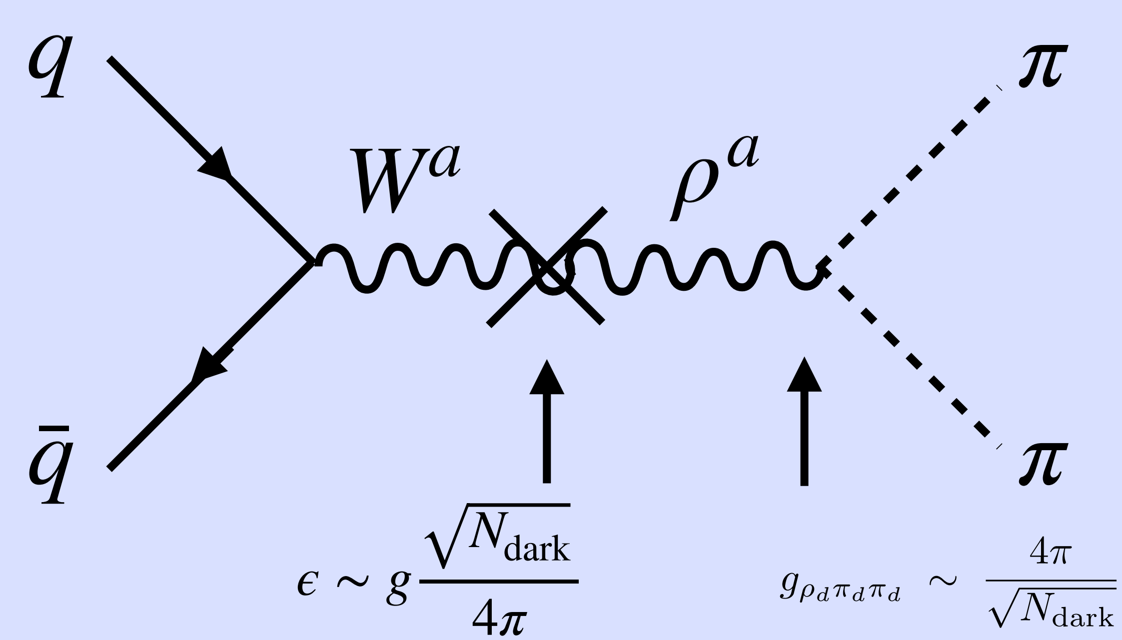
Dark Pion Pair-Production through ρ

Provides main source of dark pion production

U(1) mixing



SU(2) mixing



Cross section proportional to electroweak (coupling)^2 with a (substantial!) ρ-resonance enhancement.

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How do dark pions decay?

Seek lowest dimension operator(s) preserving custodial SU(2).

If the SM preserved custodial symmetry, two terms @ dim-4:

Effective coupling to fermions

$$\left(\frac{1}{v_\pi}\right) (\mathcal{Y} v)\ \pi^a\, (Q_L t^a Q_R)$$

Triplet interaction with fermions

Effective coupling to gauge bosons

$$\left(\frac{\xi}{v_\pi}\right) g v\, W^a_\mu \left(h \overleftrightarrow{\partial}^\mu \pi^a\right)$$

Triplet interaction with gauge bosons

How do dark pions decay?

Seek lowest dimension operator(s) preserving custodial SU(2).
With SM custodial symmetry violation:

Effective coupling to fermions

$$\left(\frac{1}{v_\pi}\right)\sqrt{2}\Big[\pi_D^+\bar{\psi}_u(m_d P_R - m_u P_L)\psi_d + \pi_D^-\bar{\psi}_d(m_d P_L - m_u P_R)\psi_u + \frac{i}{\sqrt{2}}\pi_D^0(m_u\,\bar{\psi}_u\gamma_5\psi_u - m_d\,\bar{\psi}_d\gamma_5\psi_d)\Big]$$

$(\pi_D^+, \pi_D^0, \pi_D^-)$ interaction with fermions

Effective coupling to gauge bosons

$$\left(\frac{\xi}{v_\pi}\right) m_W \left[(W_\mu^-\, h \overleftrightarrow{\partial}^\mu \pi_D^+) + (W_\mu^+\, h \overleftrightarrow{\partial}^\mu \pi_D^-) + \frac{1}{\cos\theta_W}(Z_\mu\, h \overleftrightarrow{\partial}^\mu \pi_D^0)\right]$$

$(\pi_D^+, \pi_D^0, \pi_D^-)$ interaction with gauge bosons

Effective Lagrangian for Custodially Symmetric Dark Pion Decay

Ultraviolet Origin of Effective Theory

Bosonic technicolor / strongly-coupled induced EWSB

$$+4\pi f^3 y\,\mathrm{Tr}\,(\mathcal{H}\Sigma^\dagger + h.c.)$$

Stealth Dark Matter

$$+4\pi c_D f^3\,\mathrm{Tr}\left(L\mathcal{M}R^\dagger\Sigma^\dagger + h.c.\right)$$

$$G^{\pm,0} \longleftrightarrow \pi^{\pm,0}$$

mixing

Vector-like theories

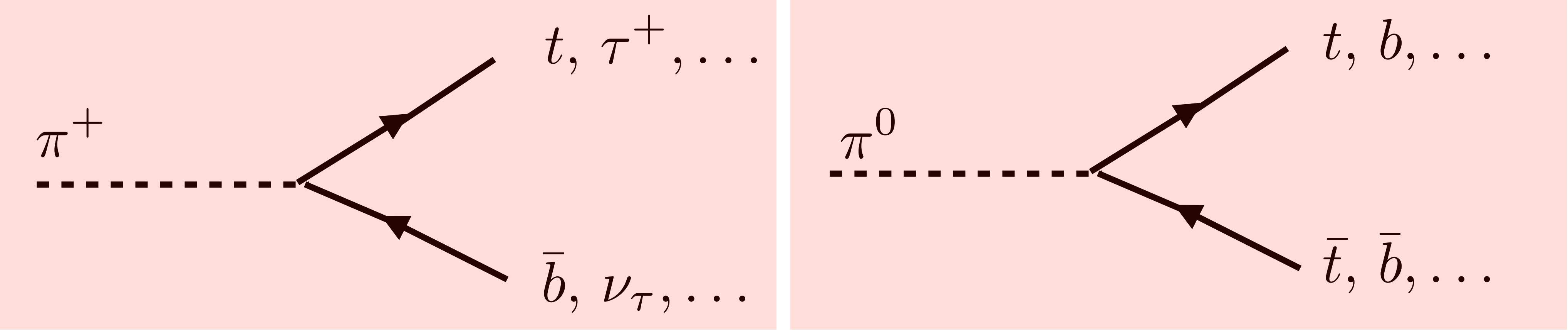
$$c_{7f}\frac{4\pi f^3}{\Lambda^3}\,(\mathrm{Tr}\Sigma_L t_L^a)\,Q_L t_L^a \mathcal{H} Y_{ud}\hat{Q}_R$$

$$c_{9C}\frac{4\pi f^3}{\Lambda^5}\epsilon_{abc}\delta_{de}\mathrm{Tr}\left[\Sigma_L t_L^a\right]\mathrm{Tr}\left[(D_\mu\mathcal{H})^\dagger t_L^b (D^\mu\mathcal{H}) t_R^d \mathcal{H}^\dagger t_L^c \mathcal{H} t_R^e\right]$$

Direct interactions through higher-D operators

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

$(\pi_D^+, \pi_D^0, \pi_D^-)$ decay to fermions proportional to Yukawa couplings

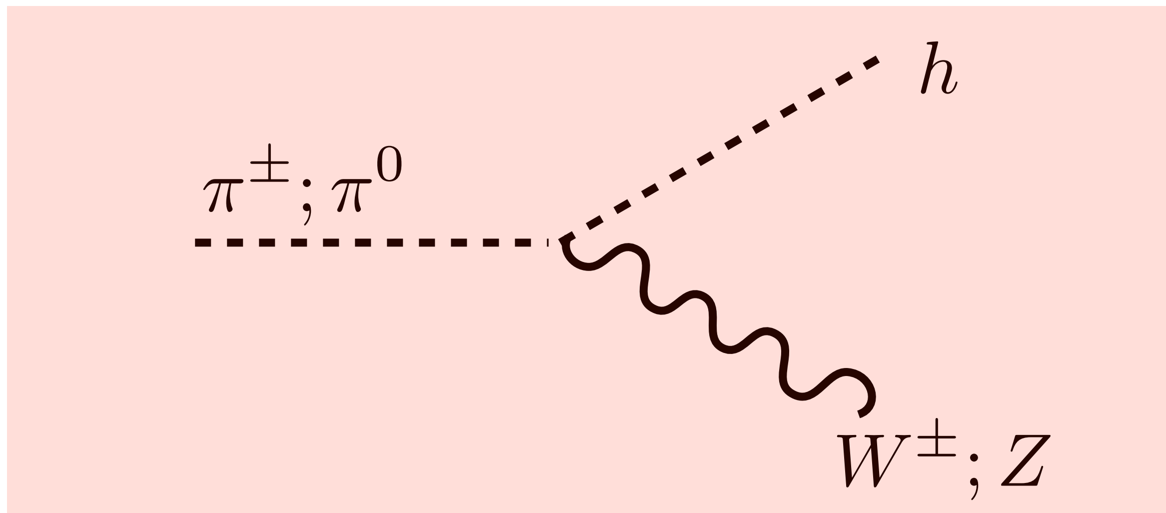


$$\lambda \sim \frac{m_f}{v_\pi}$$

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

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

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



$$\lambda \sim \frac{\xi\, M_{W,Z}}{v_{\pi}}$$

There are TWO distinct classes of theories:

Gaugephilic

$$\xi \sim 1$$

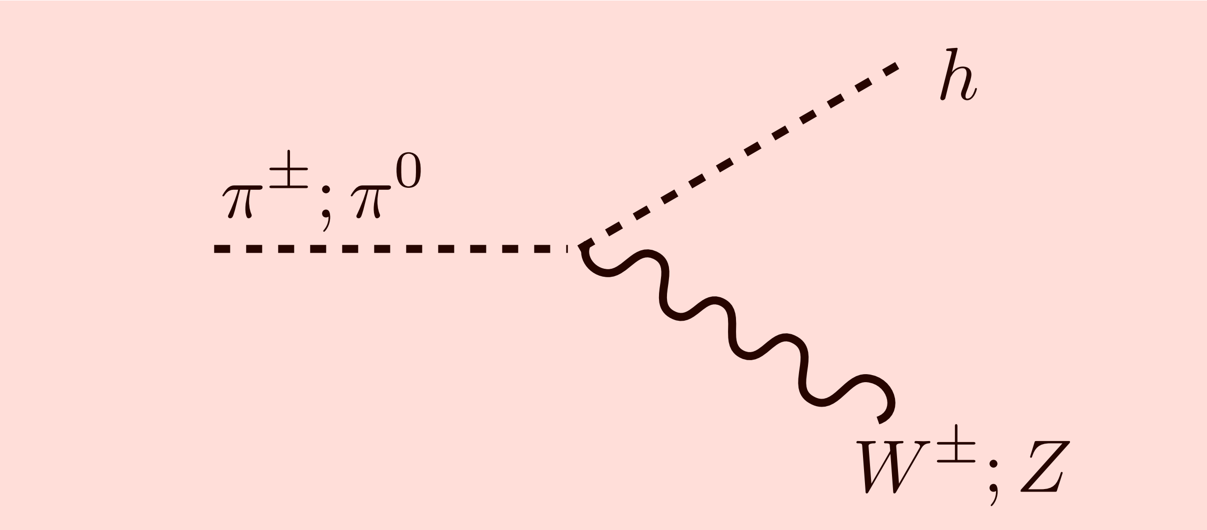
Gaugephobic

$$\xi \sim \frac{m_h^2}{m_{K_D}^2 - m_h^2}$$

suppressed!

↓ heavier state mixes with Higgs boson

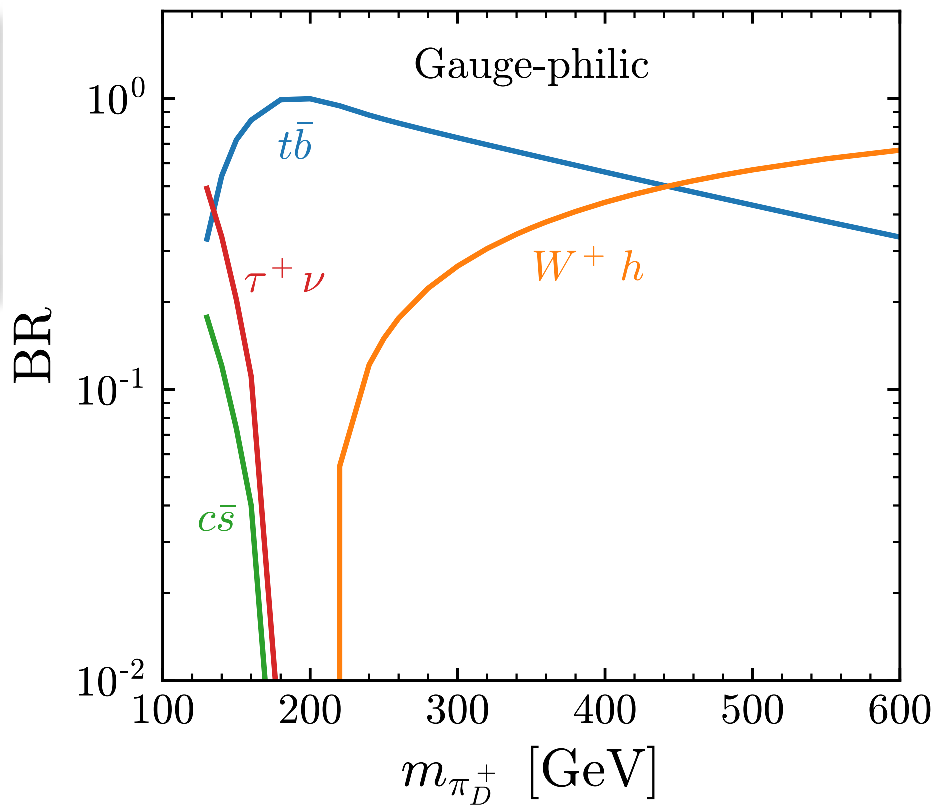
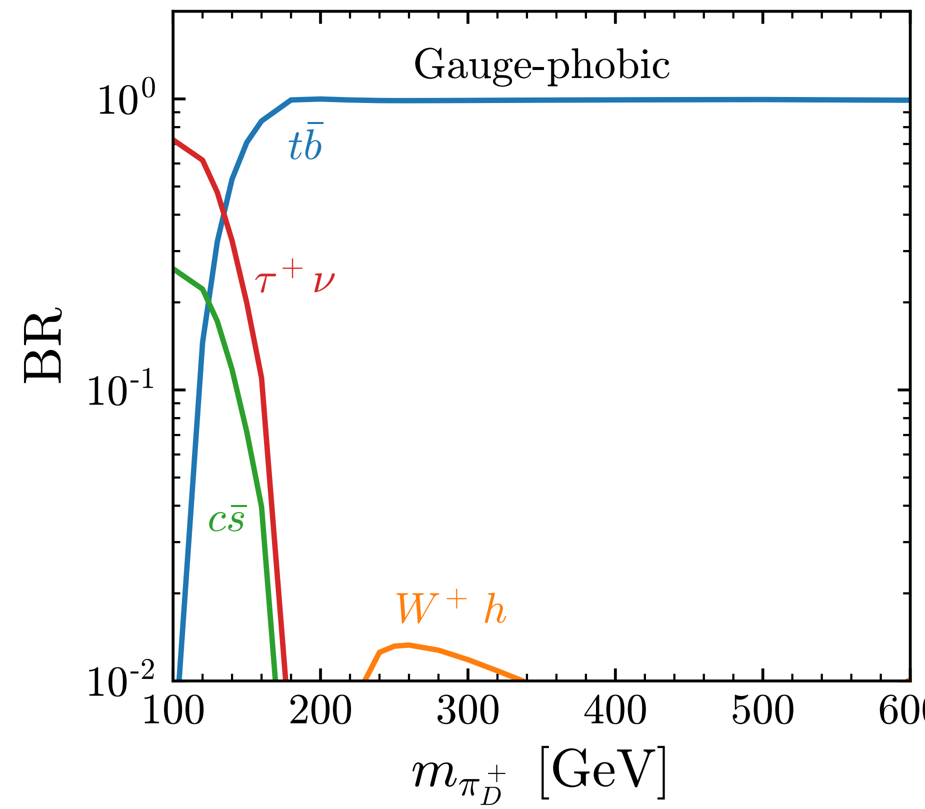
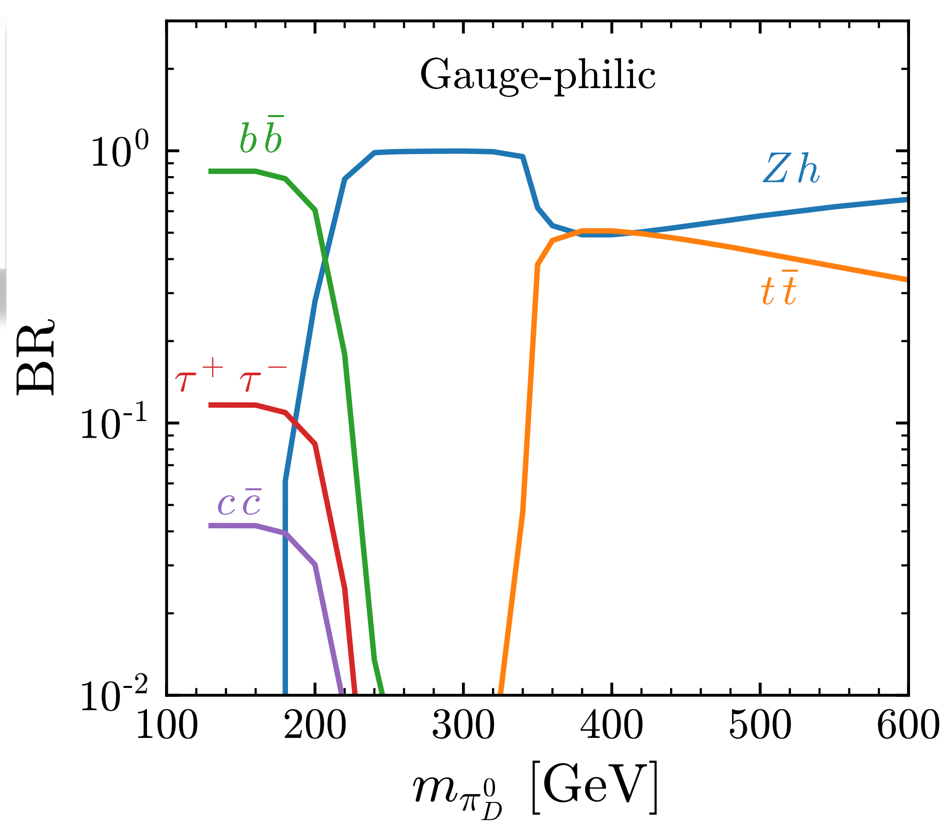
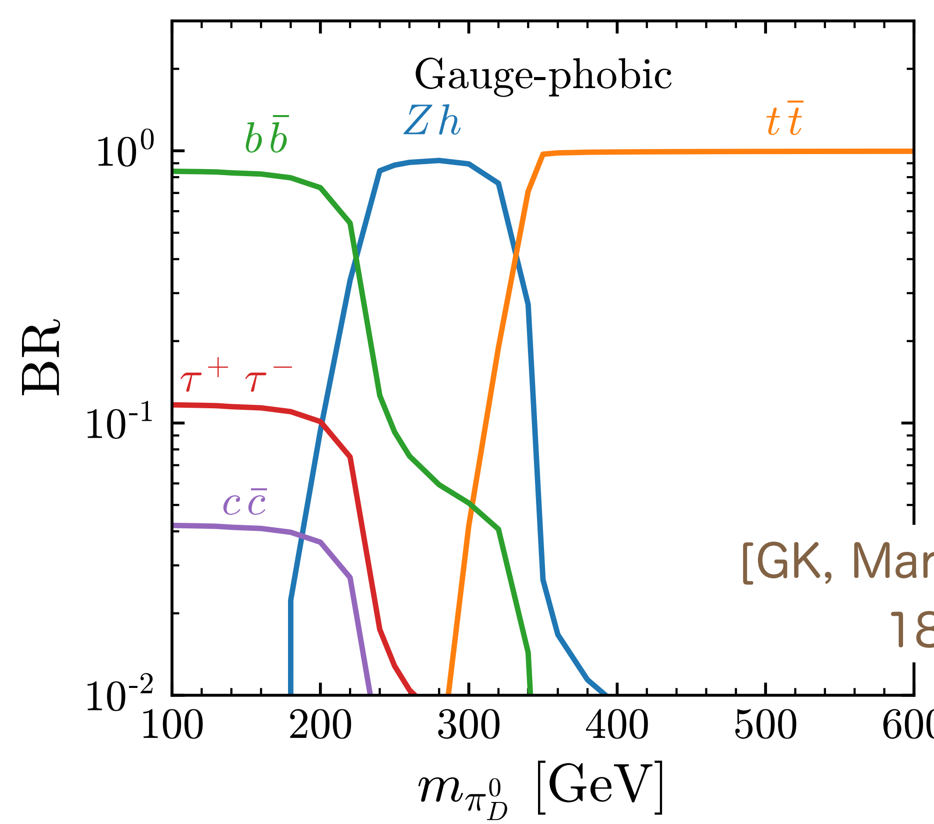
We've seen this before



$$\lambda \sim \frac{\xi\, M_{W,Z}}{v_\pi}$$

Gaugephilic	Gaugephobic
Georgi-Machacek model	2HDM
(replace $\pi^{\pm,0} \to H_3^{\pm,0}$ triplet)	(replace $\pi^{\pm,0} \to H^{\pm},\ A^0$)
$\xi \sim s_H \sim \mathcal{O}(1)$	$\xi \sim \cos(\beta-\alpha) \sim \frac{m_h^2}{m_H^2 - m_h^2}$
↓ mixing angle	Suppressed! ↓ heavier state mixes with Higgs boson

It makes a difference!

	Gaugephilic	Gaugephobic
$\pi_D{}^{\pm}$		
π_D^0		

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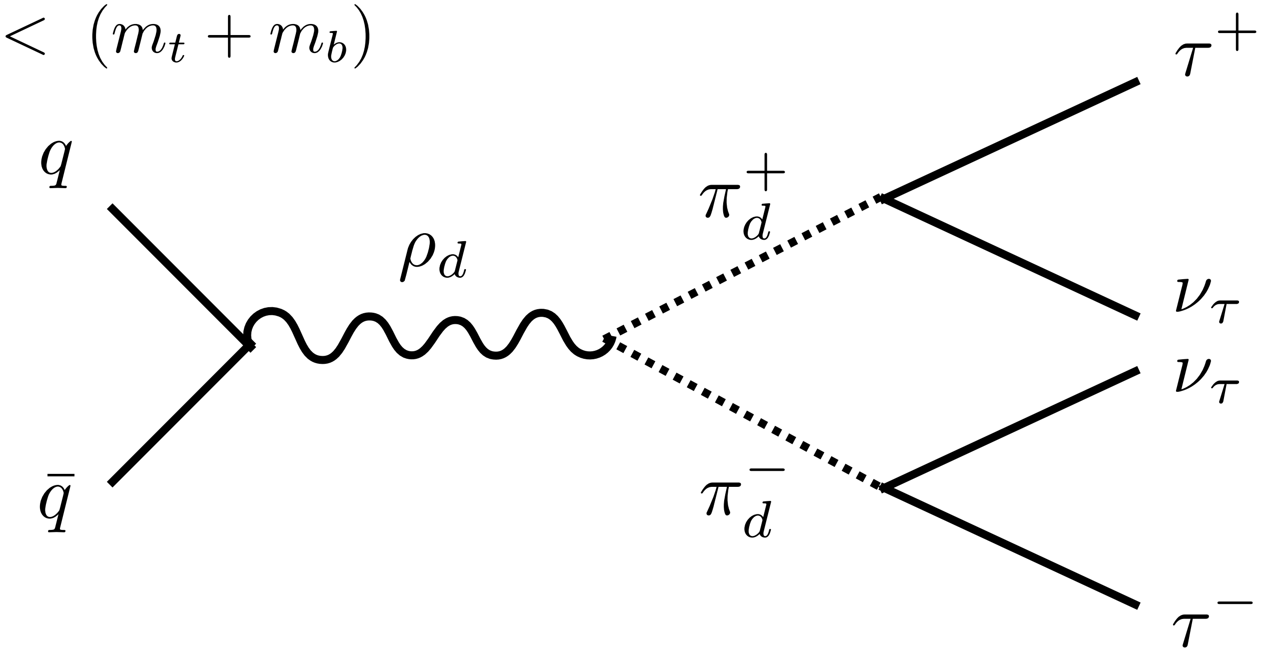
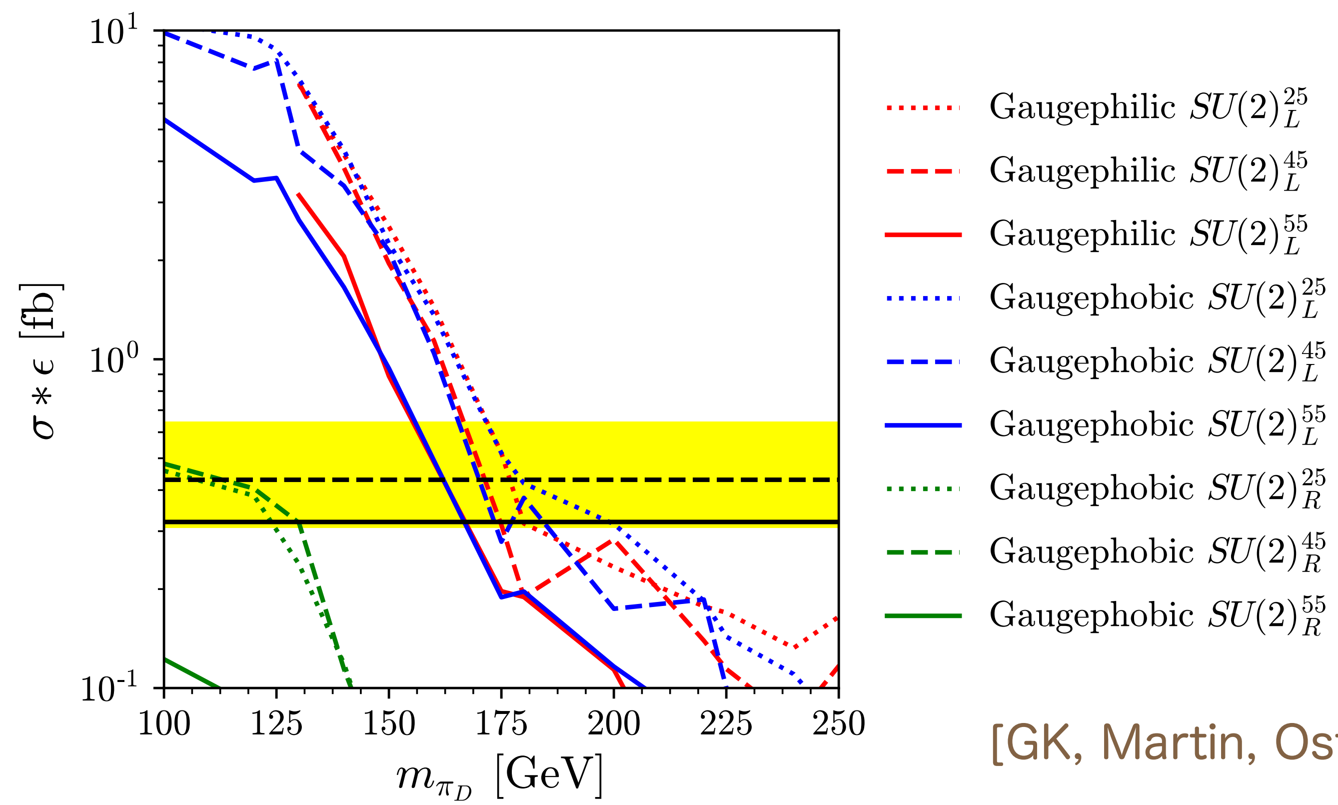
LHC Sensitivity I

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



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



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Charged dark pions less than about 130-180 GeV are ruled out.

LHC Sensitivity II: Beyond Taus

Model-independent multilepton searches are generically sensitive to:

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

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

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

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

Model-dependent multilepton searches (SUSY gauginos), however, are much less optimal due to large MET (or large M_{eff}) requirements.

For gaugephobic models the hadronic modes can be challenging

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

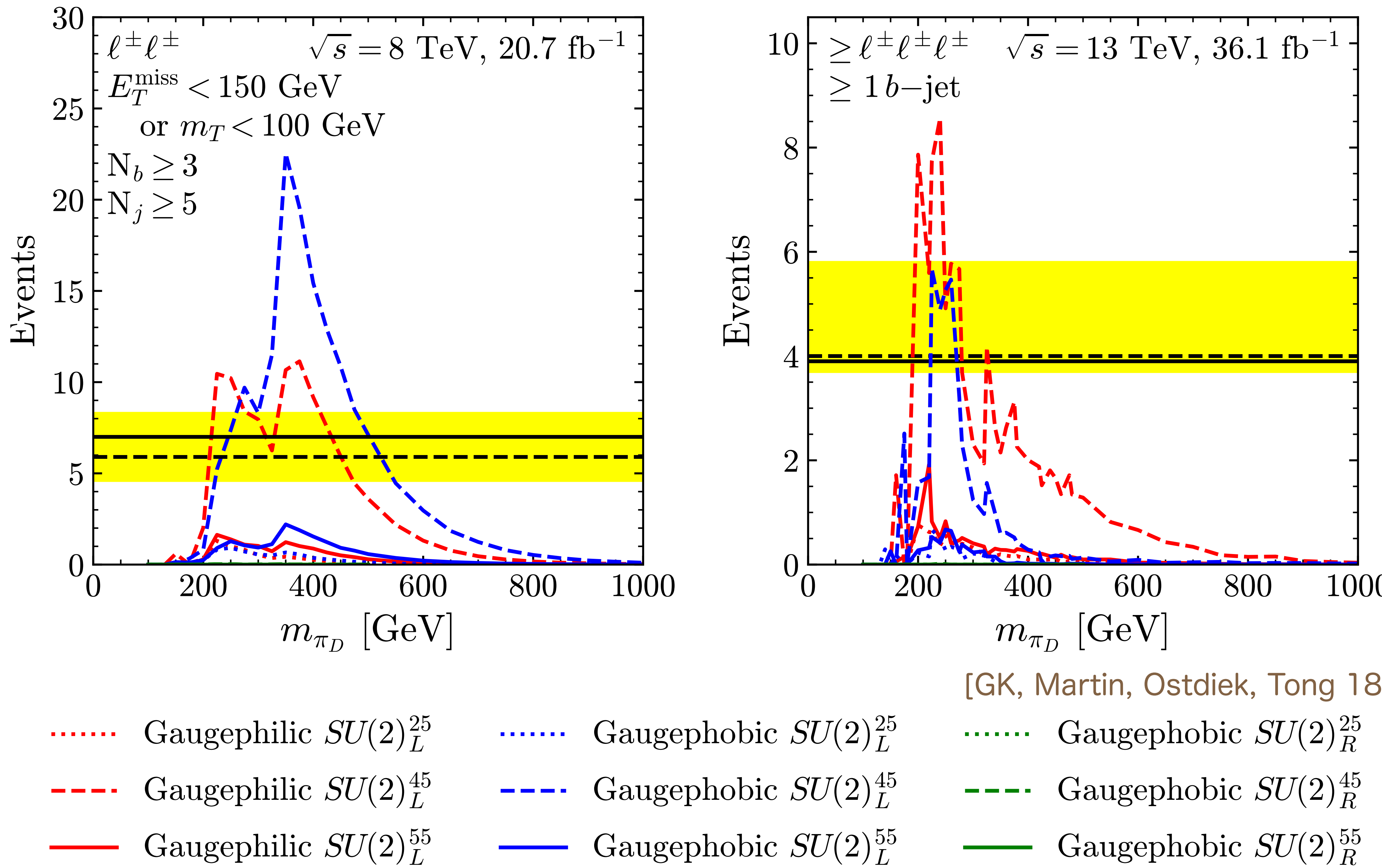
$$q\bar{q} \to \rho \to \pi^+\pi^- \to t\bar{b}\,\bar{t}b$$

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

Multilepton Constraints

8 TeV Constraints

13 TeV Constraints



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8 TeV Constraints Stronger Than 13 TeV!

Limitations of 13 TeV Search Regions

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

JHEP 09 (2017) 084

CERN-EP-2017-108
5th October 2017

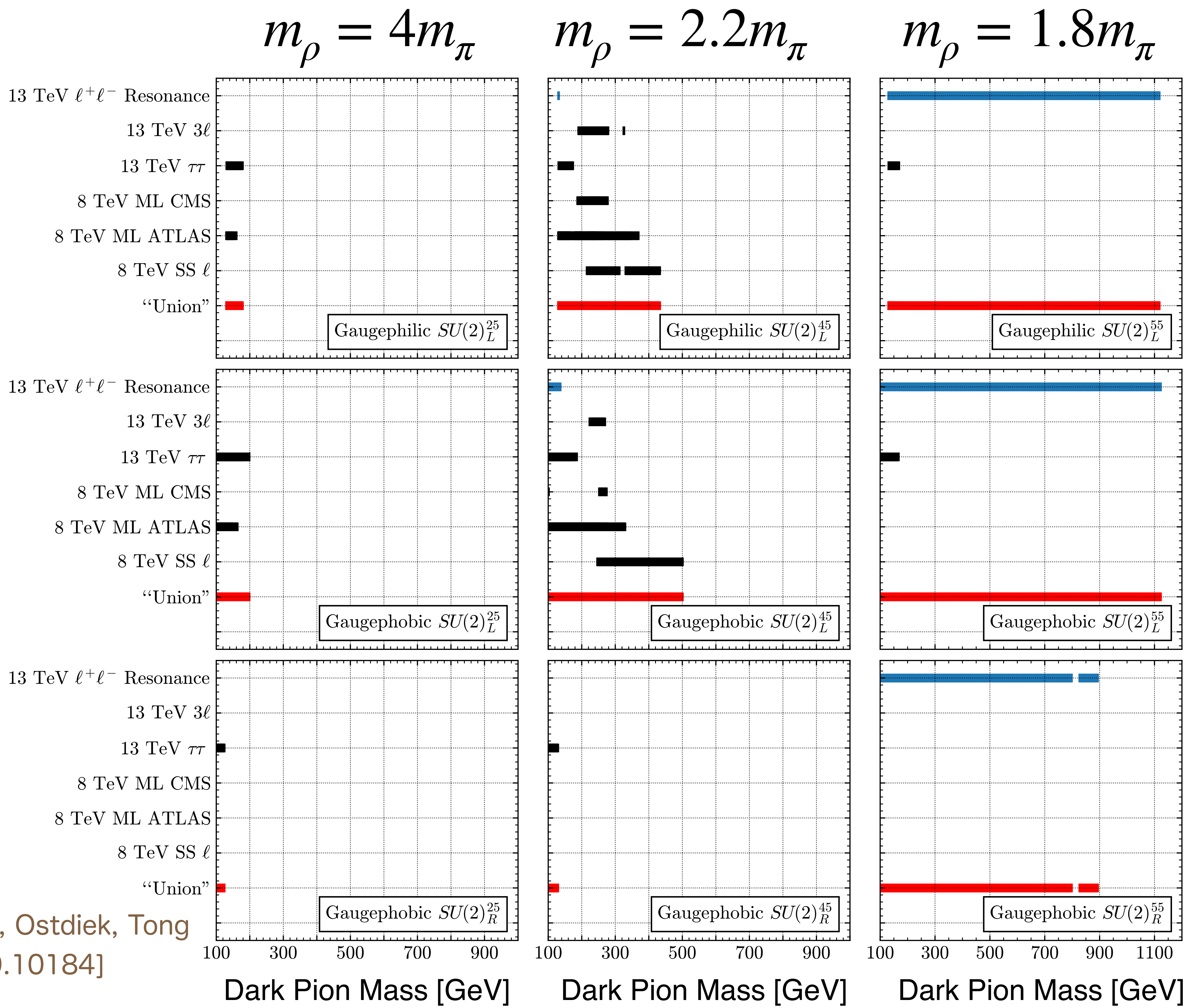
Search for supersymmetry in final states with two same-sign or three leptons and jets using 36 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collision data with the ATLAS detector

The ATLAS Collaboration

Signal region	$N^{\text{signal}}_{\text{leptons}}$	$N_{b\text{-jets}}$	N_{jets}	p_T^{jet} [GeV]	E_T^{miss} [GeV]	m_{eff} [GeV]	$E_T^{\text{miss}}/m_{\text{eff}}$	Other
Rpc2L2bS	$\geq$ 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	$20,10 < p_T^{\ell_1}, p_T^{\ell_2} < 100$ GeV
Rpc2Lsoft2b	$\geq$ 2SS	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	$20,10 < p_T^{\ell_1}, p_T^{\ell_2} < 100$ 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 E_T^{miss} and m_{eff}

Current Bounds from LHC



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We examined MANY other searches...

Search	$\sqrt{s}$ [TeV]	Comments
ATLAS search for a CP-odd Higgs boson decaying to Zh [142]	8	Veto events with more than 2 b-tagged jets kills efficiency
ATLAS search for $t\bar{t}$ resonances [143]	8	Must have exactly one lepton. We have too many jets, confuses search
CMS Pair produced leptoquark [144]	8	Looking for $b\bar{b}\tau^+\tau^-$. Has minor sensitivity to overall rates, would do better with shape analysis but not enough data is provided to recast this.
ATLAS search for SUSY in final states with multiple b-jets [145]	13	Looking for heavy states, so demands large $E_T^{\rm miss}$ and m_{eff}
CMS search for Vh [146]	13	Looking for single production. Needs very boosted hard object.
CMS Di-Higgs $\to$ $\tau\tau\, b\bar{b}$ [147]	13	Neutral pions decay through mixing with the Higgs. Measurement uses BDTs and is not recastable.
CMS Low mass vector resonances $\to q\bar{q}$ [148]	13	Looks for a bump on the falling soft-drop jet mass spectrum. Not enough information to recast the designed decorrelated tagger. Only sensitive to $\sigma \gtrsim 10^3$ pb.
CMS Vector-like T $\to$ $t\,h$ [149]	13	Looking for $t\,h$ resonance, only very heavy and needs QCD production.

Discussion

A new strongly coupled sector, near the weak scale, that preserves custodial SU(2), 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.

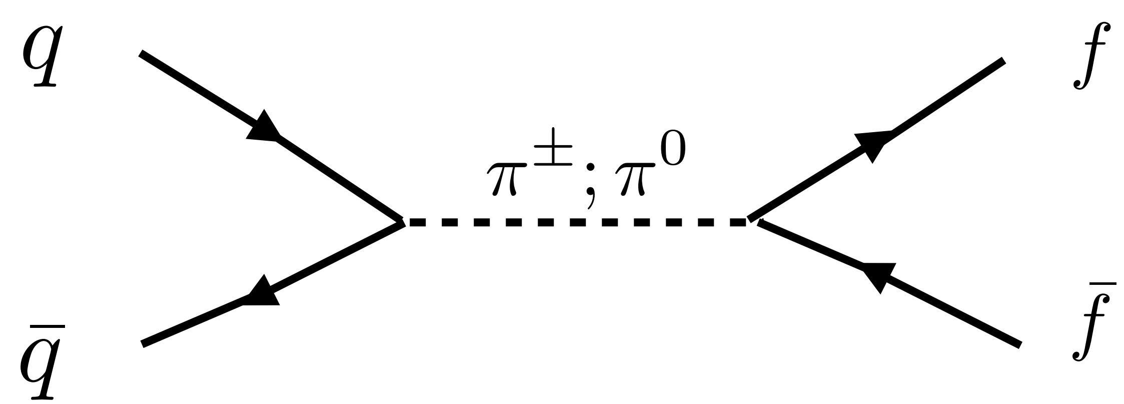
Some signals are already searched for (and set constraints). Many search strategies are, however, not well-optimized for signals with small MET and comparably small M_{eff}.

Best constraints limit $\sigma(pp \to \rho \to \pi\pi) \lesssim 0.5 - \text{few pb}$

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

Aside — single production of dark pions:



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

Chang et al., have explored constraints (pretty tough).
[Chang, Galloway, Luty, Salvioni, Tsai 1411.6023]

In dark sectors that are approximately vector-like (safe from S parameter; Higgs coupling constraints), single production modes are suppressed.

Bounds on $\frac{1}{v_\pi}$ from single π_D productoin