Custodial Dark Pions

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based on 1809.10184, 1809.10183 with G. Kribs, B. Ostdiek and T. Tong

Lattice meets BSM, Syracuse, May 2 2019

Motivations

composite Dark sector = sector with matter charged under a new \`dark' confining force SU(N_D)

new matter is inert under SM color, but may carry SM EW quantum #s

$$\psi_L = (\Box, 0, ???), \quad \psi_R = (\Box, 0, ???)$$

SU(N_D) **SU(3)$_c$** **EW**

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playground for lots of BSM scenarios:

Here, I'll focus on Λ_D ~ EW scale,
assume fundamental H EW doublet exists

Motivations: EW-scale Dark Sector model space

Bosonic technicolor/
induced EWSB limit:
chiral EW charges

[Kagan, Samuel '90

Luty et al 1106.3346

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Dark sector with both vector like and chiral masses

vectorlike confinement limit
ψ_L, ψ_R have same EW charges

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Example:

	$SU(N_D)$	$SU(2)_L$	$U(1)_Y$
ψ_L	$\square$	2	0
ψ_R	$\square$	2	0
χ_L	$\square$	0	$\frac{1}{2}$
χ_R	$\square$	0	$\frac{1}{2}$
...	...		

Vectorlike masses allowed $M_\psi(\psi_L^\dagger \psi_R + h.c.), \quad M_\chi(\chi_L^\dagger \chi_R + h.c.)$

Yukawa terms: $y(\psi_L^\dagger H^* \chi_R + h.c.)$ etc. permitted as well

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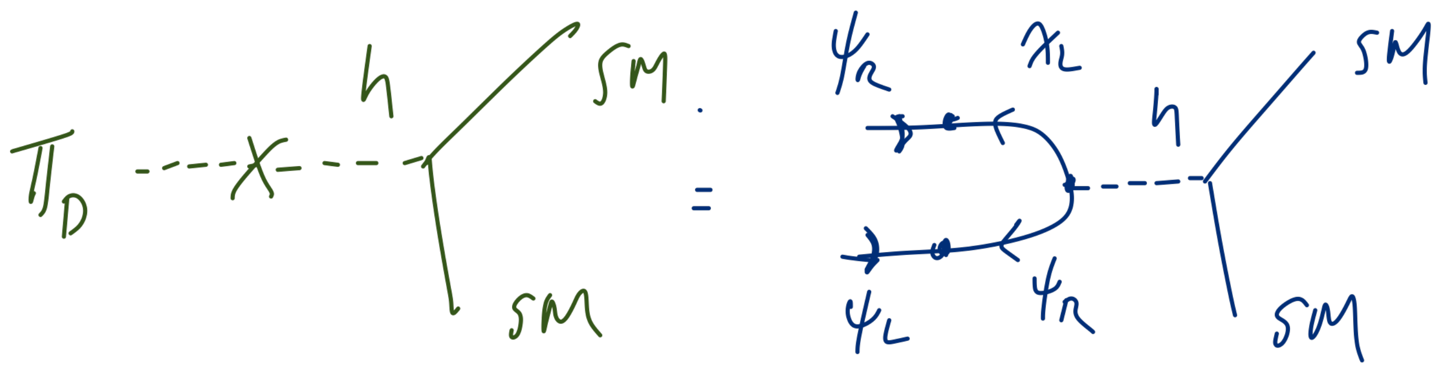
Below Λ_D: $\sim Tr((M + yH)\Sigma + h.c)$ $\quad \Sigma = e^{i\pi_D/f}$

Why study this kind of theory?

1.) Avenue for dark pion decay: important in composite DM scenarios — dark baryon (typically) is DM

But dynamics leading to dark baryons also makes dark pions. Need these to be able to decay. Pure vectorlike theory forbids this (accidental flavor symmetries), need to add in pion decay by hand. With chiral mix, decay comes automatically



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2.) Vector like masses: can take y→ small without making π_D dangerously light

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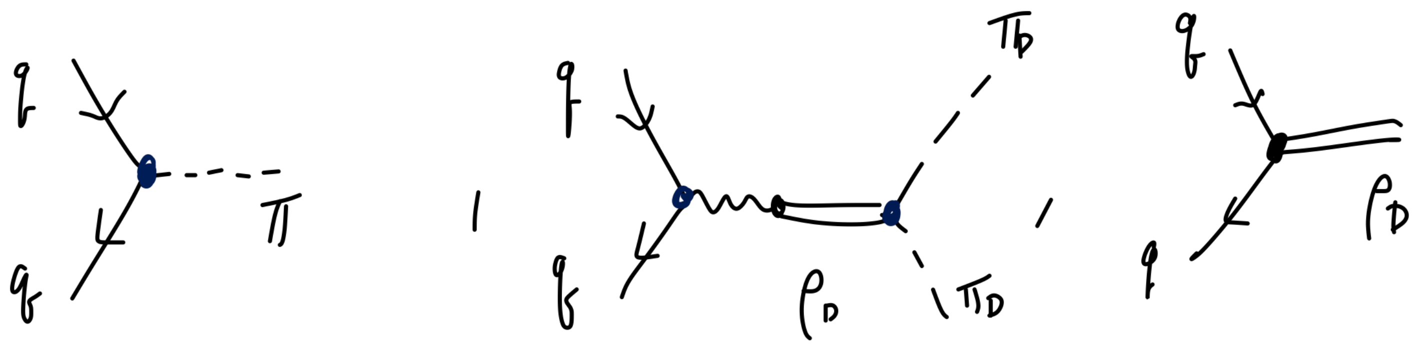
3.) Rich, relatively unique phenomenology.



Exposes holes/biases in current searches: surprisingly light dark mesons are still allowed by existing searches

Custodial Dark Mesons

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under $SU(2)_L \times SU(2)_R$: H promoted to bi-doublet **H** ~ (2,2)

$$\mathcal{H}_{i_L i_R} = \frac{1}{\sqrt{2}} \begin{pmatrix} (v+h-iG^0)/\sqrt{2} & G^+ \\ -G^- & (v+h+iG^0)/\sqrt{2} \end{pmatrix}$$

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SM matter: $Q_L \sim (2,1)$ $\begin{pmatrix} u_R \\ d_R \end{pmatrix} = Q_R \sim (1,2)$

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In addition to vector-like mass terms, two Yukawa permitted:

$$y\,(\psi_L^\dagger \mathbf{H} \chi_R + h.c.) \qquad y'\,(\psi_R^\dagger \mathbf{H} \chi_R + h.c.)$$

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Effectively 4 ‘flavors’ under SU(N_D):

2 `up type’, 2 `down’ type: custodial symmetry means mass matrices identical

Custodial Dark Mesons: Important parameters

$$M_{\psi}, M_{\chi}, y, y'$$

$$yv, y'v \ll M_{\psi,\chi}$$

(all << Λ_D)

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<u>'SU2L'</u>

$$M_\psi \ll M_\chi : \quad \pi_D^a \sim (\bar{\psi}\gamma_5\tau^a\psi) \quad \text{lightest}$$

$$\rho_D^{a\mu} \sim (\bar{\psi}\gamma^\mu\tau^a\psi) \quad \text{lightest vector}$$

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EW triplets: (3,1)

<u>'SU2R'</u>

$$M_\chi \ll M_\psi : \quad \tilde{\pi}_D \sim (\bar{\chi}\gamma_5\chi) \quad \text{lightest}$$

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EW singlets: (1,3)

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allowed interactions include:

$$y_{SM}\,(Q_L \tau^A\, \mathbf{H}\, Q_R)\, \pi^A \qquad y_{SM}\,(Q_L \mathbf{H}\, \tau^A\, Q_R)\, \tilde{\pi}^A$$

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which lead to $\pi_D \rightarrow ff'$

Keep Δy_{SM}, g' but no new sources of custodial symmetry breaking from strong sector = 'minimal custodial violation'

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- omitting $(H^\dagger \tau^A H)\, \pi_D^A$ removes $\pi_D \to h + W/Z$ decay

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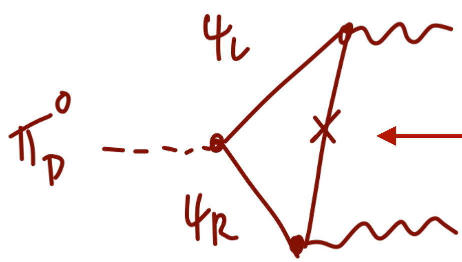

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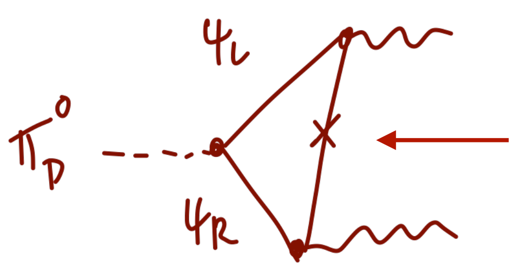

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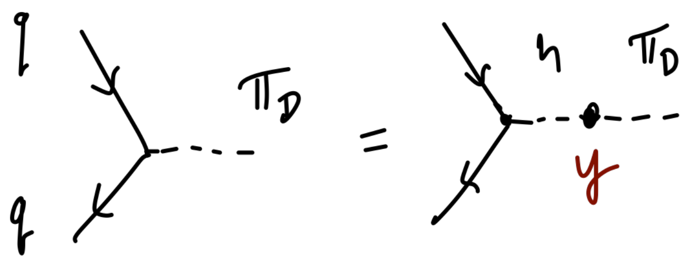
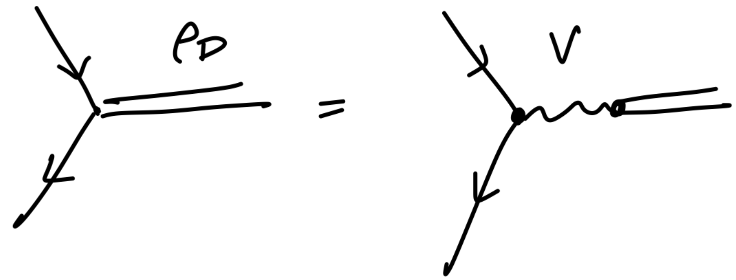
- stealthier DM (removes charge radius interaction for dark baryons)

[LSD 1503.04203]

Dark Mesons at the LHC: single production





analogous to ρ → γ VMD in QCD

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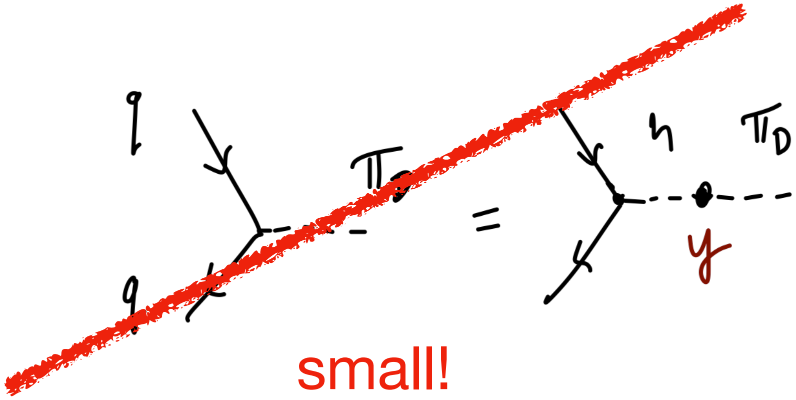

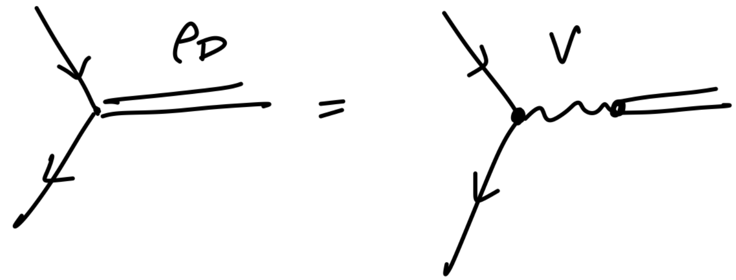

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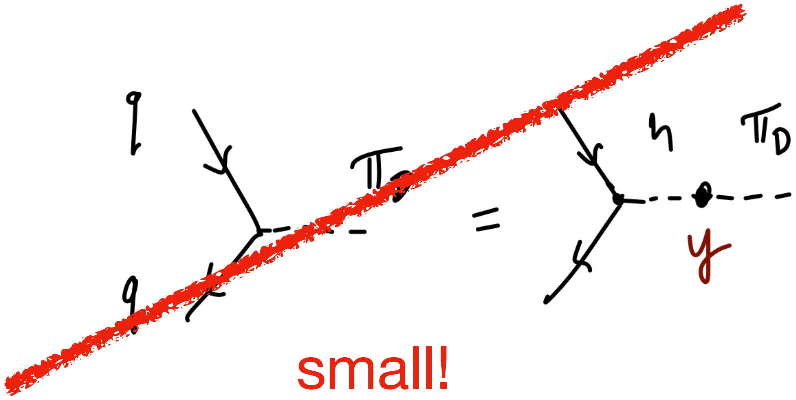

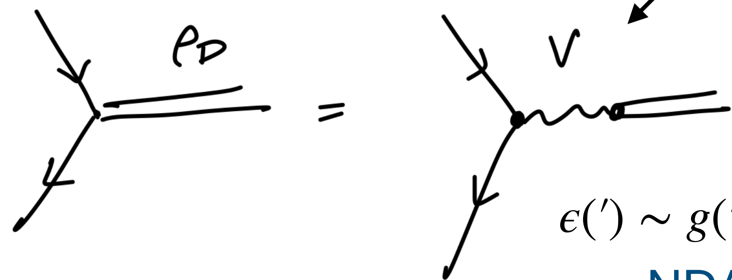

$\epsilon\, \rho^{a}_{D,\mu\nu}\, W^{a,\mu\nu}$

$\epsilon'\rho_{D,\mu\nu}\, B^{\mu\nu}$

$$\epsilon(') \sim g(')\,\frac{\sqrt{N_D}}{4\pi}$$

NDA

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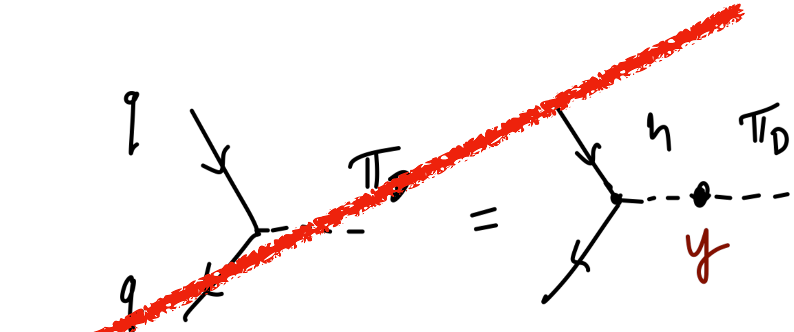

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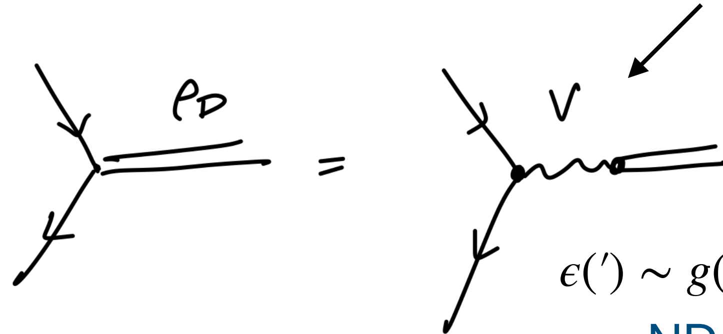

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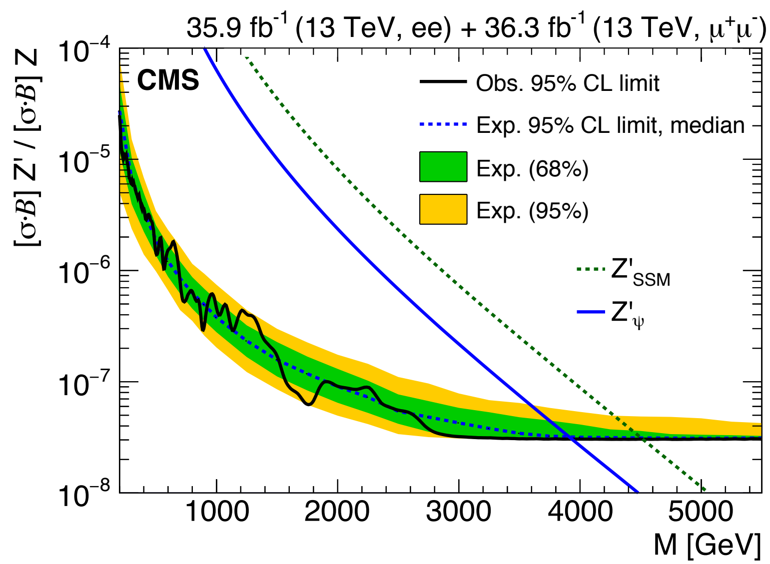

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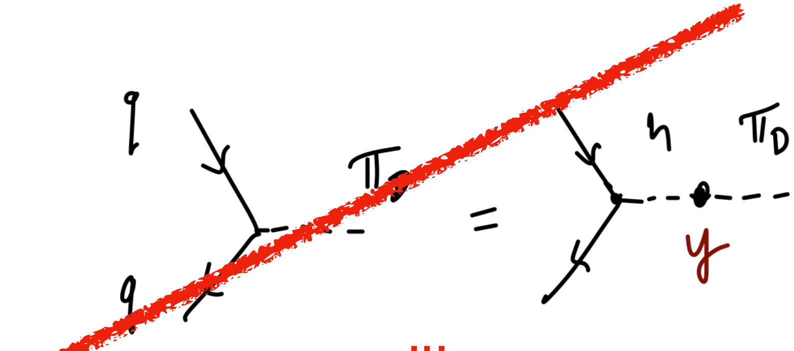

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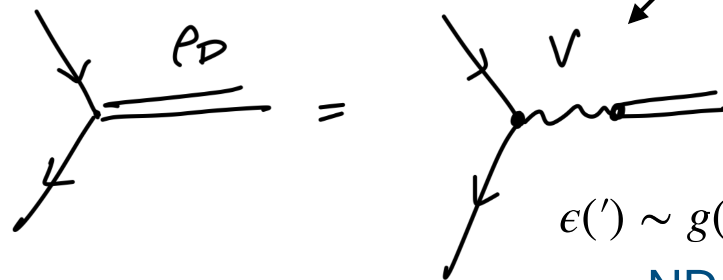

$$\epsilon(') \sim g(')\, \frac{\sqrt{N_D}}{4\pi}$$

NDA

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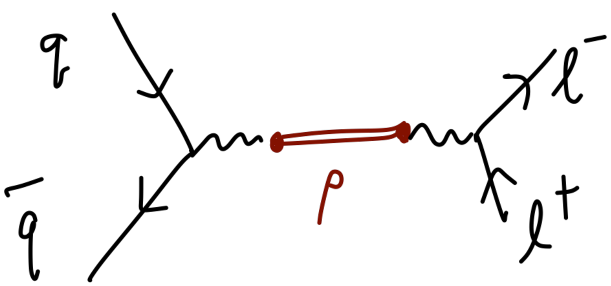
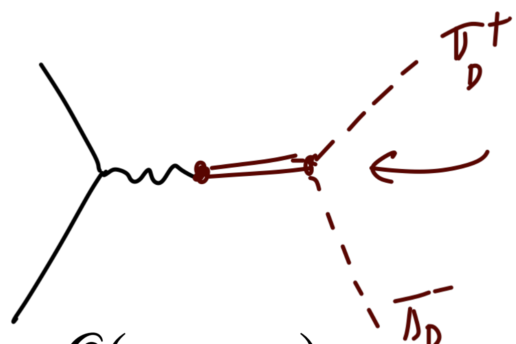
As ρ_D are similar to generic W'/Z', may expect strong bounds from $\rho_D \to \ell\ell$

However, if $\rho_D \to \pi_D\, \pi_D$ is kinematically opens, totally dominates



$\mathcal{O}(g^2\epsilon^2)$

vs.



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

$\mathcal{O}(g\epsilon g_{\rho\pi\pi})$

Dark Mesons at the LHC: single production

$$\frac{\Gamma(\rho_D \to \ell\ell)}{\Gamma(\rho_D \to \pi_D \pi_D)} \sim \frac{g^4 N_D^2}{(16\pi^2)^2} \ll 1$$

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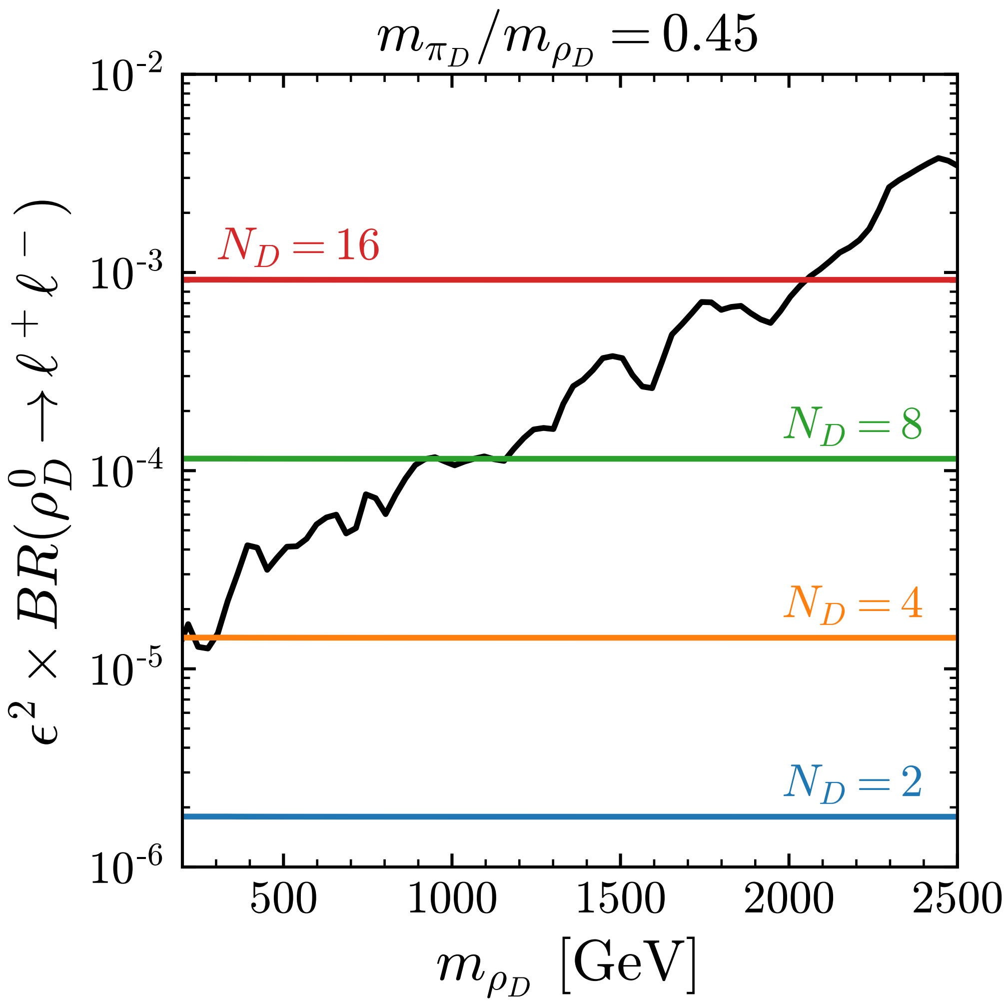

For small N_D, bound is significantly less than $Z' \to \ell\ell$ expectation, even for $m_\pi/m_\rho = 0.45$

For lower m_π/m_ρ, bound disappears completely

Focus on $N_D = 4$, consider $m_\pi/m_\rho = 0.45, 0.25$

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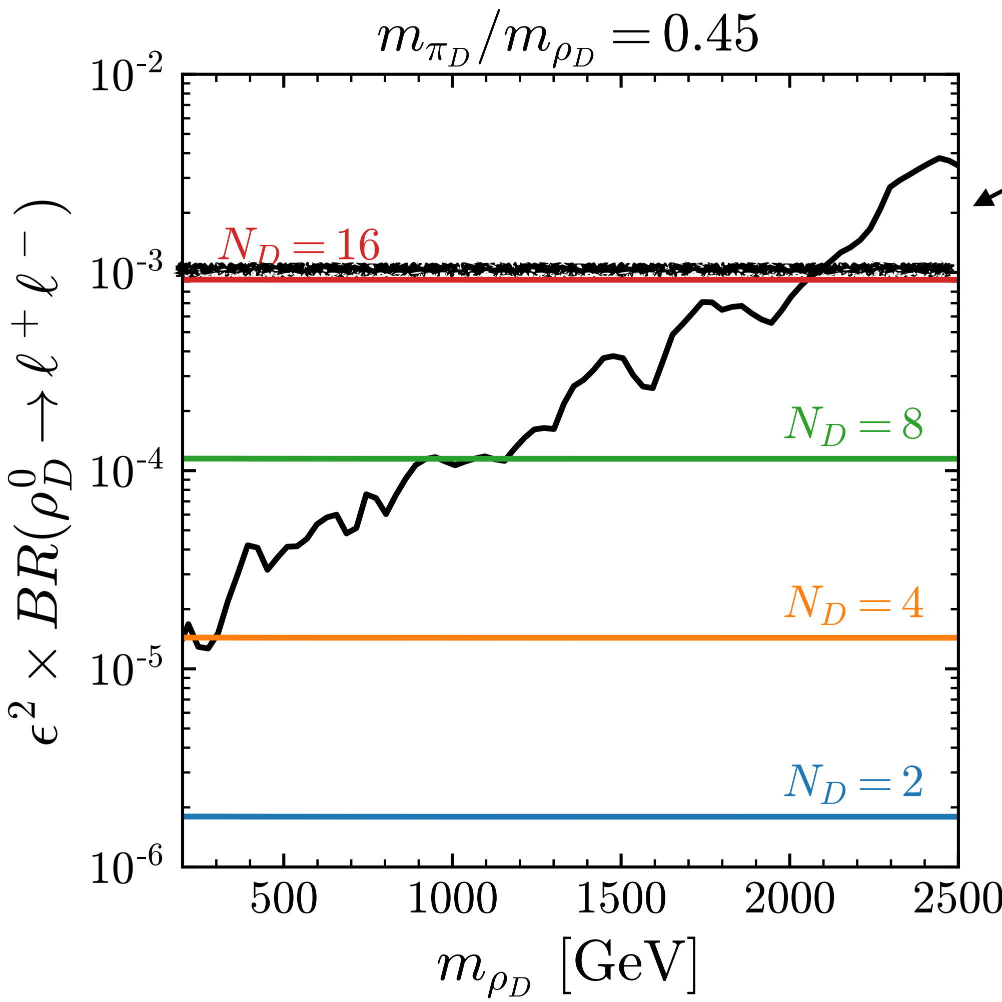

$N_D = 4$, $m_{\pi D}/m_{\rho D} = 0.55$

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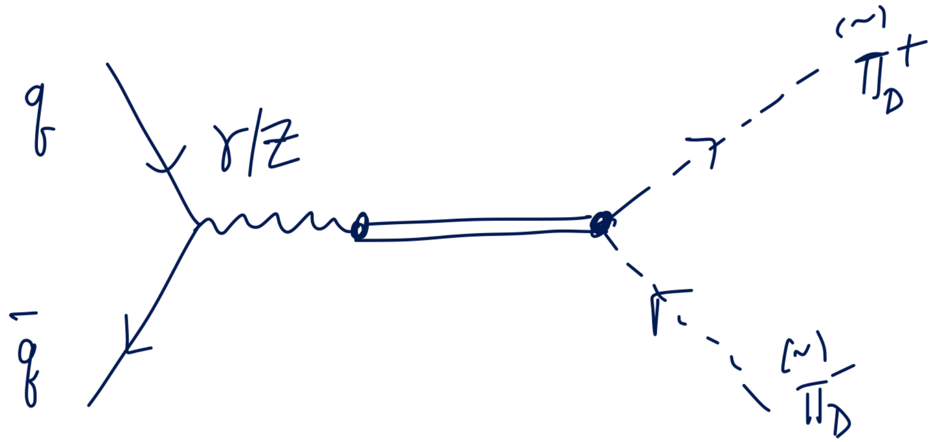
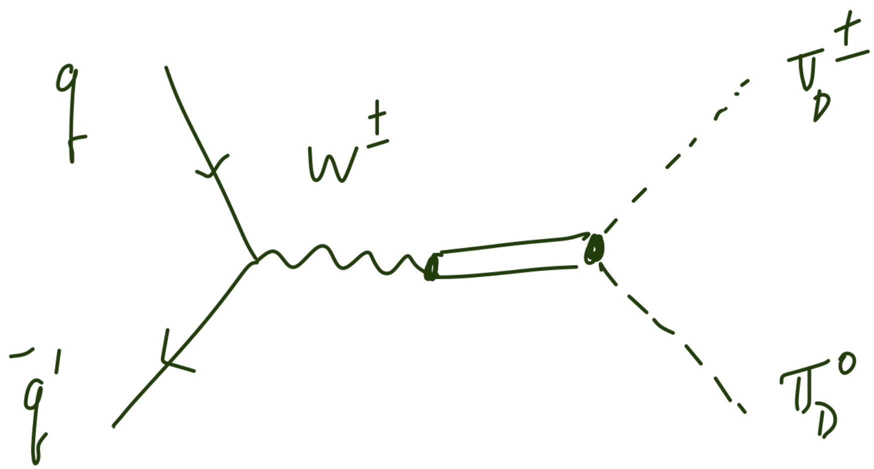
Dark Mesons at the LHC: pair production

Dark pions pair produced via Drell-Yan augmented by mixing with composite vector mesons:



Neutral current: present in either scenario



Charged current: only present in SU(2)L setup

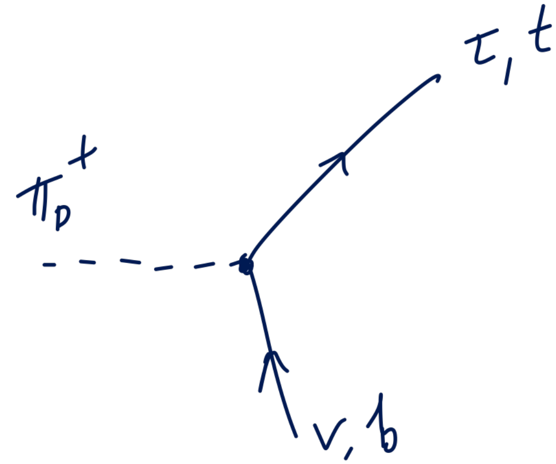
$$\sigma(pp \to \pi_D \pi_D \to SM\,SM) \simeq \sigma(pp \to \rho_D)\, BR(\pi_D \to SM)^2$$

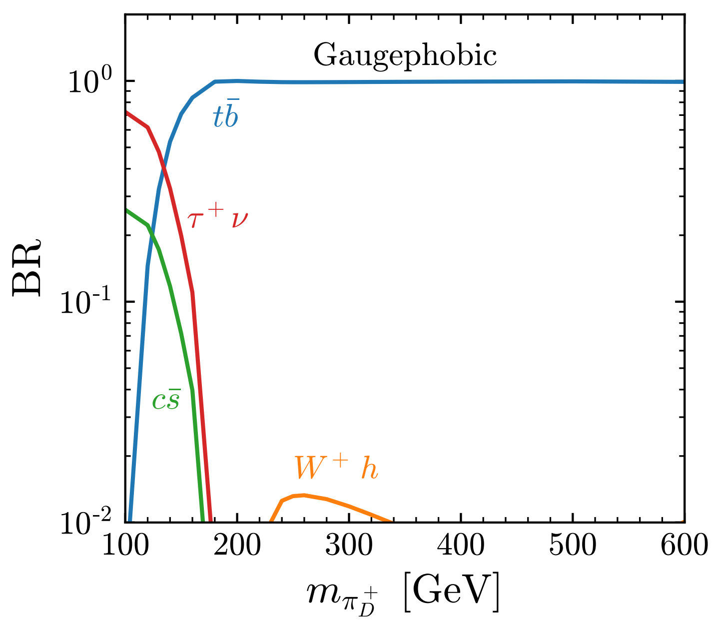
size of π_D → SM coupling drops out

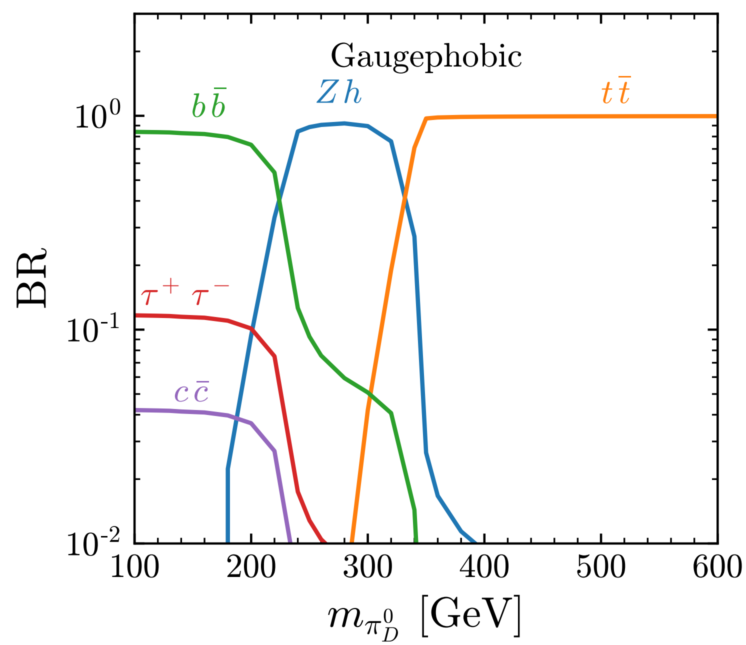
Dark Mesons at the LHC: pair production

π_D decay: 3rd gen fermions.

no BSM sources of MET







Combination of pair production with ~ weak cross-section & decays to 3rd generation stuff without extra MET = difficult territory for the LHC

Dark Mesons at the LHC: pair production

$$pp \to \pi_D^+ \pi_D^- \to \tau^+ \tau^- \nu_\tau \bar{\nu}_\tau$$

$$pp \to \pi_D^\pm \pi_D^0 \to \tau^\pm \nu_\tau \bar{b} b$$

...

\`light π_D' channels

$$pp \to \pi_D^+ \pi_D^- \to t\bar{t}b\bar{b},\ t\bar{b}\tau^- \nu_\tau$$

$$pp \to \pi_D^\pm \pi_D^0 \to t\bar{b}Zh,\ t\bar{b}\bar{b}b$$

...

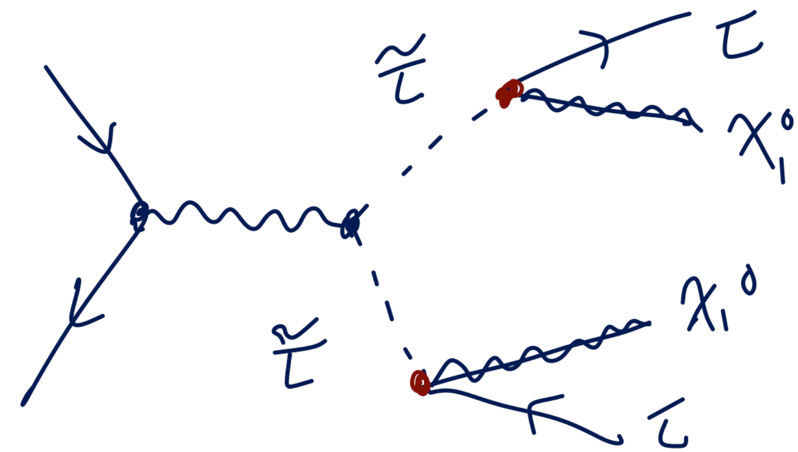
\`heavy π_D' channels

Systematically checked all (well, as many as we could find) searches that would capture the relevant final states

Current LHC searches with these final states:

- often involve extra MET

e.g.



ATLAS-CONF-2016-093

Requires MET > 150 GeV

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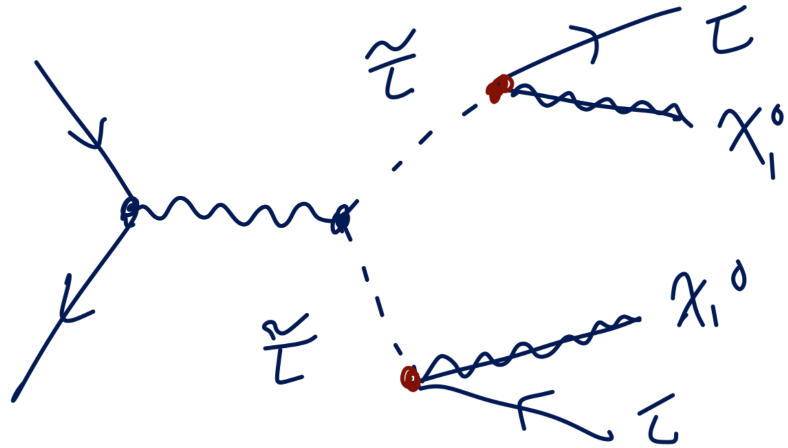

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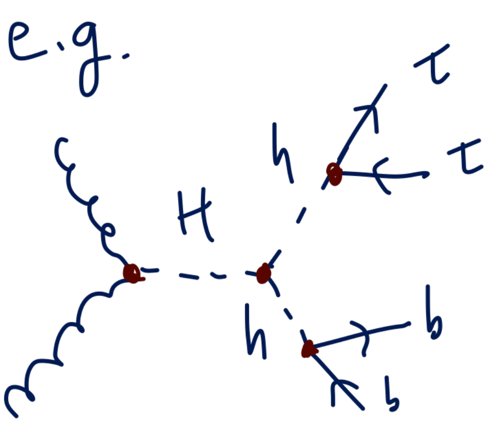
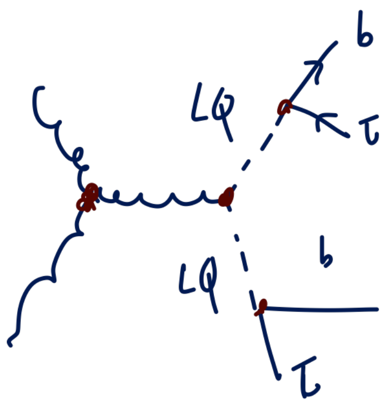
- or assume the wrong resonance structure

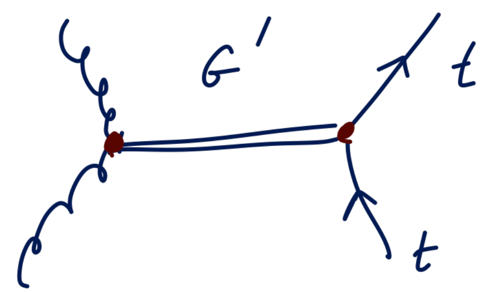
e.g.



CMS: 1707.02909



CMS 1408.0806



ATLAS 1505.07018

Most successful

- low mass: $m_{\pi D} \lesssim 300$ GeV

'multi-lepton' searches:

catchall for 3+ leptons, one of which may be τ
Binned by MET, # jets, # b jets (100+ channels!)

Searches done by both ATLAS/CMS at 8 TeV, no 13 TeV versions(!)

- for high mass: $m_{\pi D} \gtrsim 300$ GeV

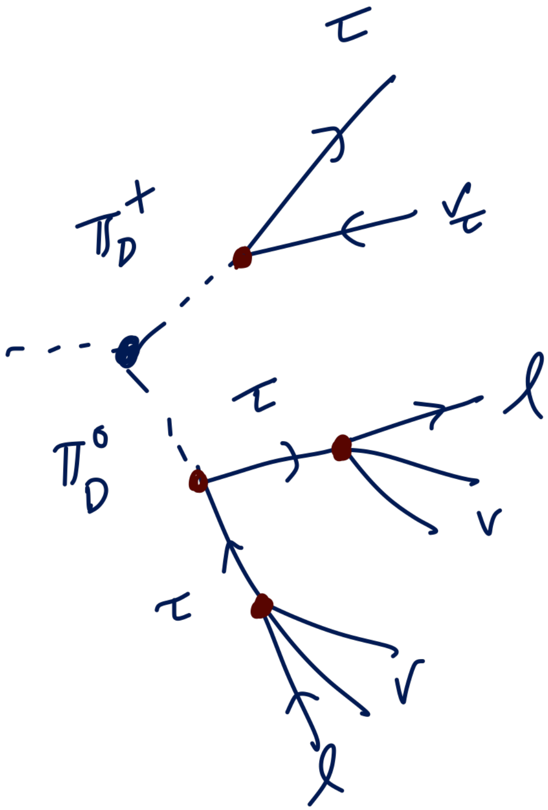
Same sign leptons:

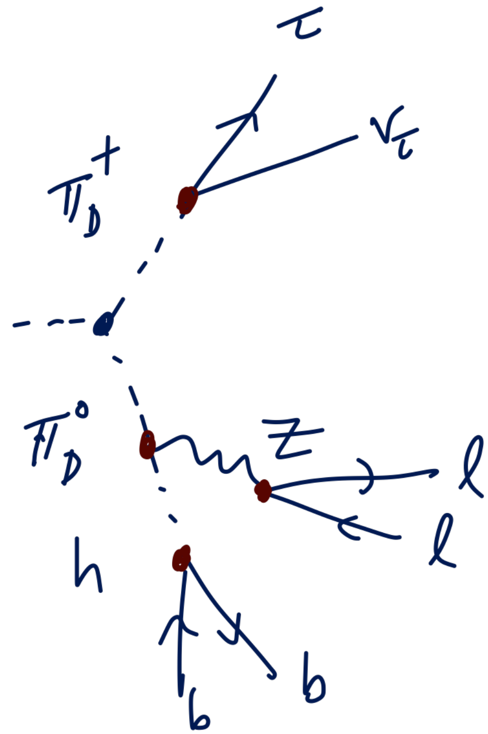
Large MET requirement, further binned by #jets and #b

Analyses at both 8 & 13 TeV, but 8 TeV more sensitive!
13 TeV version imposes: $pT_{\ell 1} + pT_{\ell 2} + MET > 600$ GeV
as its aimed at SUSY — totally kills our signal

Why do these searches work?

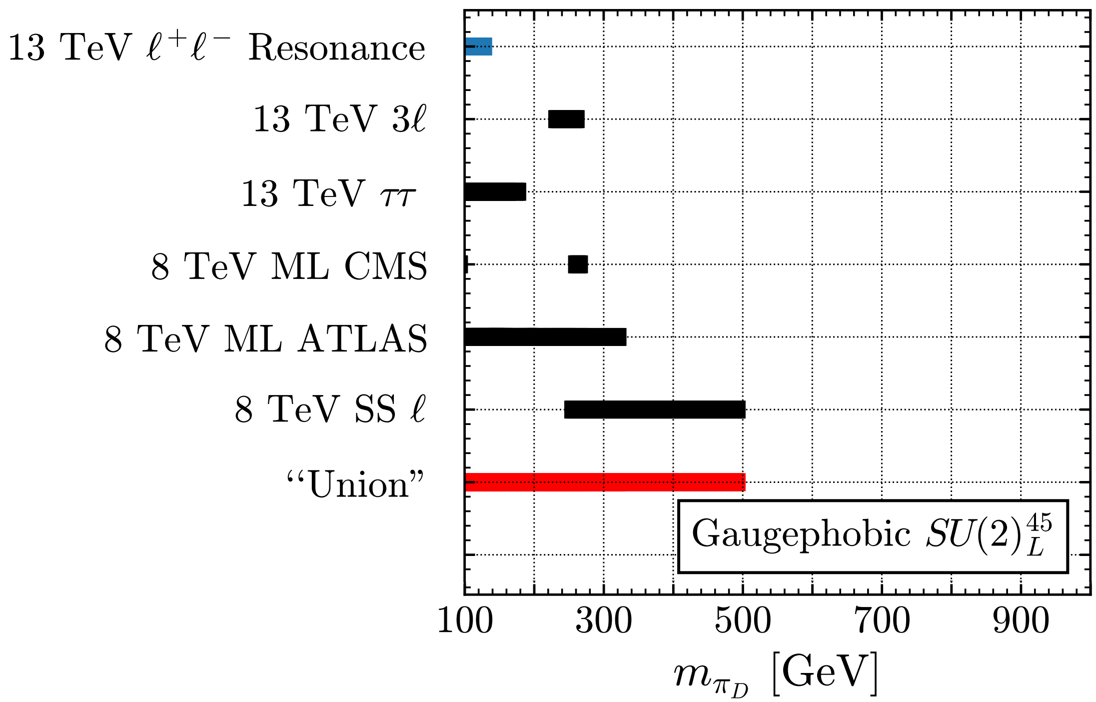
Routes to multiple leptons from $\pi^+_D\,\pi^0_D$



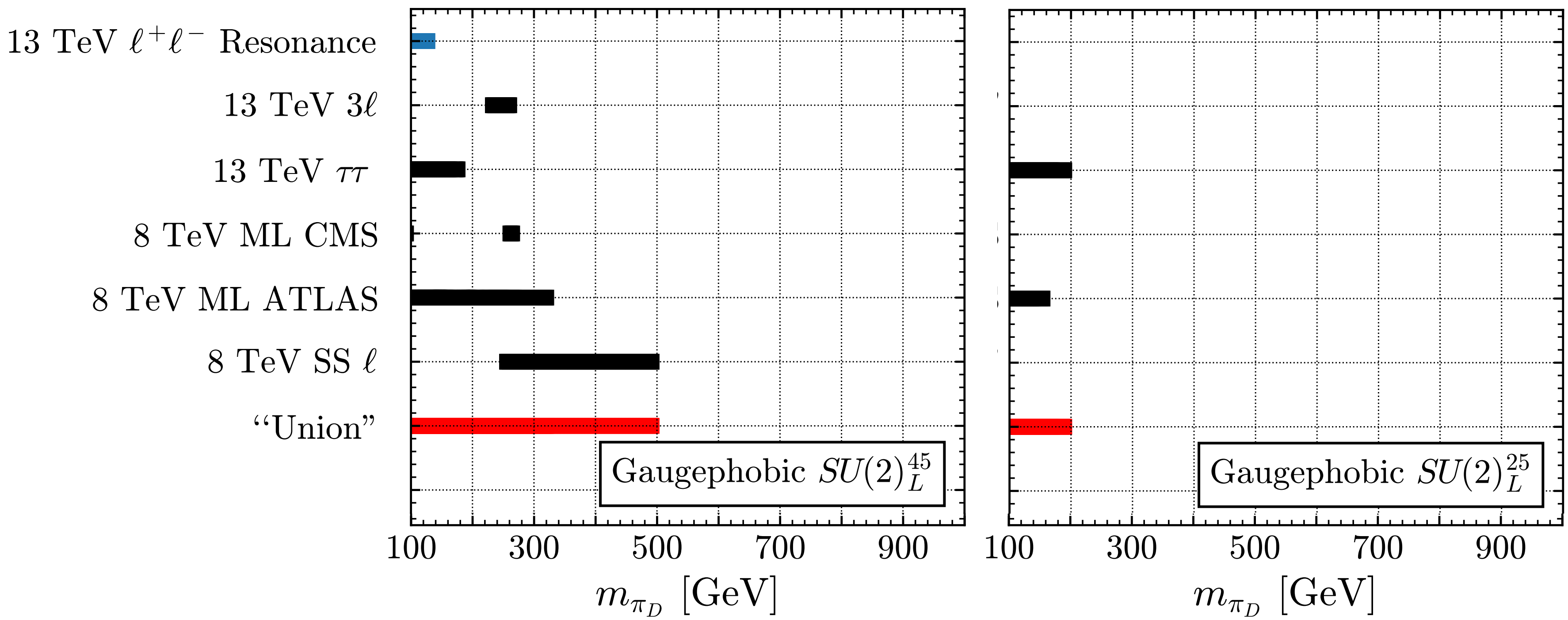


No such possibility with $\pi^+_D\,\pi^-_D$

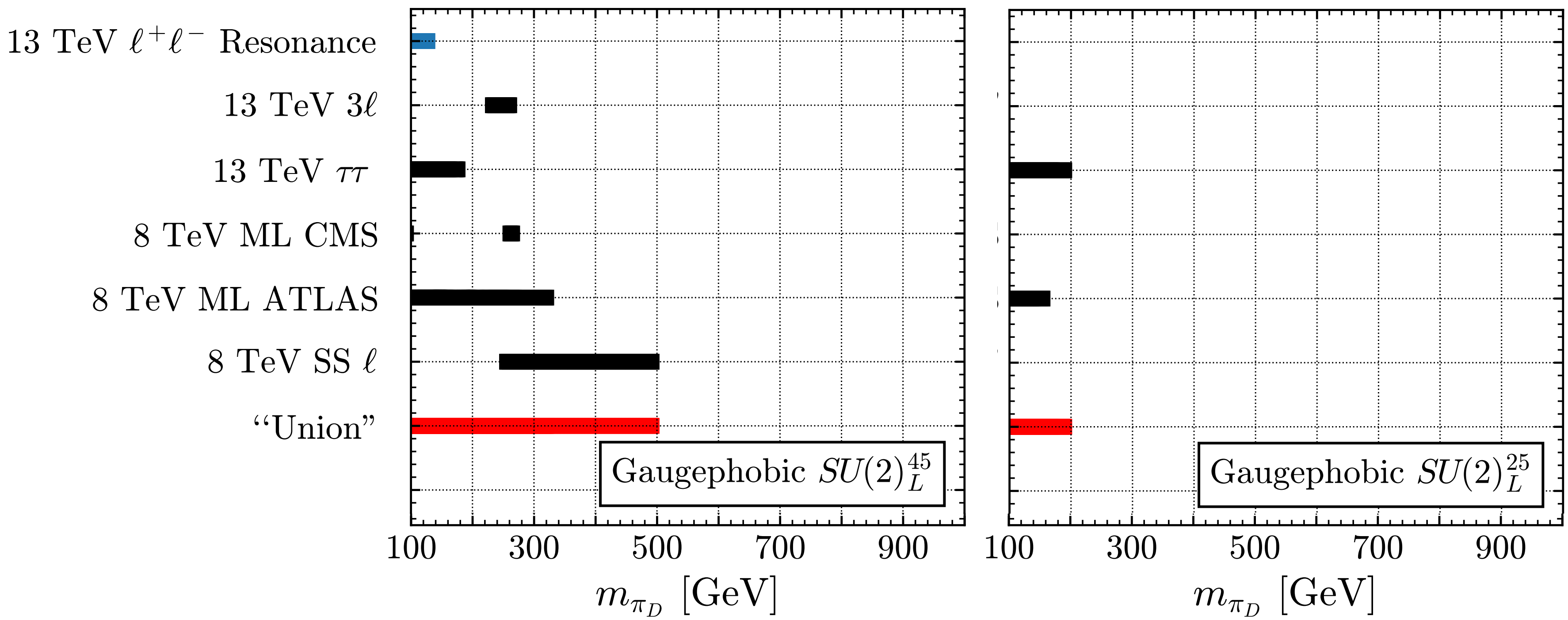
Combination



Combination



Combination

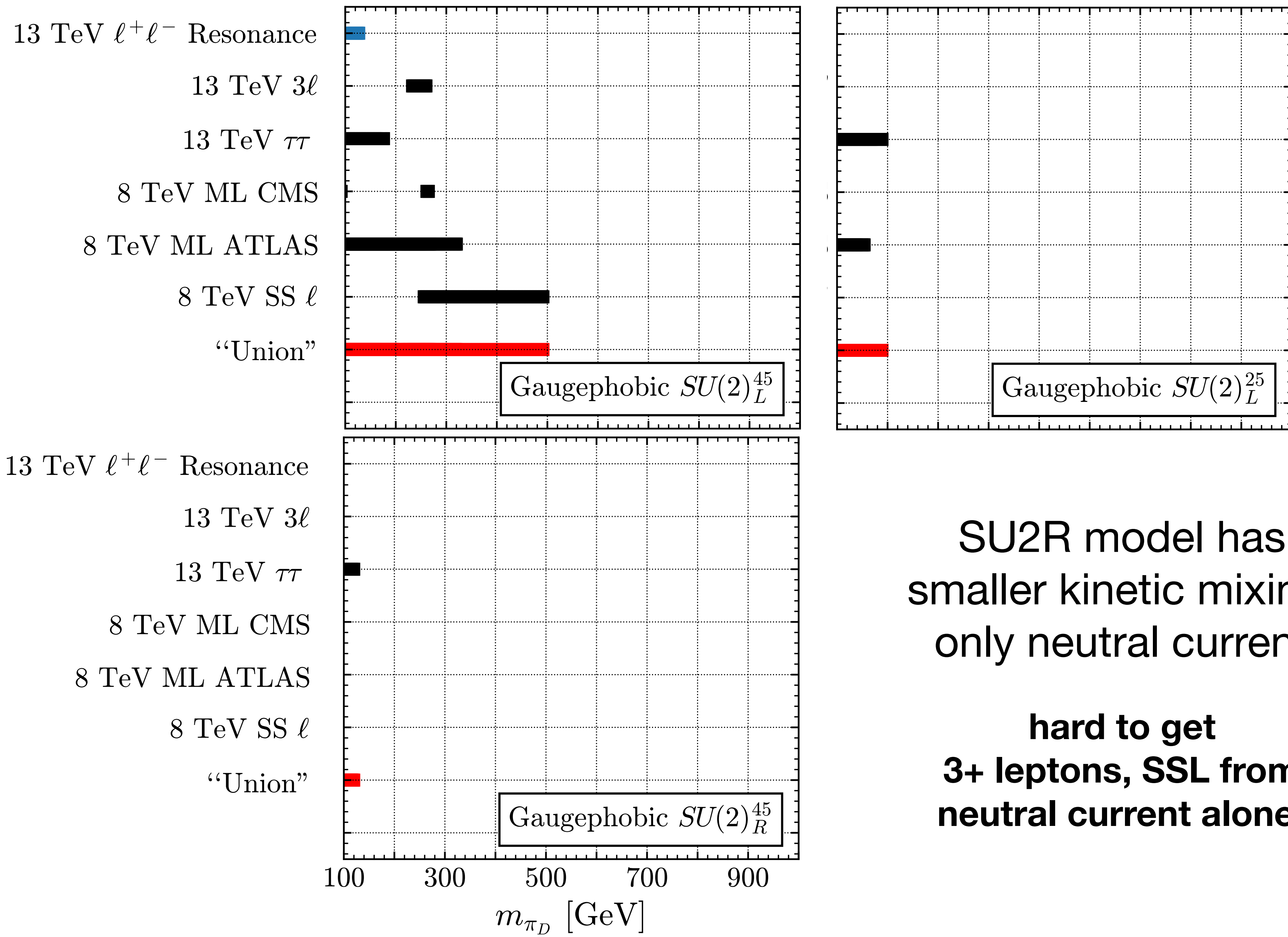


Decreasing $m_{\pi D}/m_{\rho D}$, fixed $m_{\pi D}$ means heavier ρ_D, smaller resonant piece of cross section

$$\frac{m_{\pi_D}}{m_{\rho_D}} = 0.45 : \quad m_{\pi_D} \gtrsim 500\,\textbf{GeV}$$

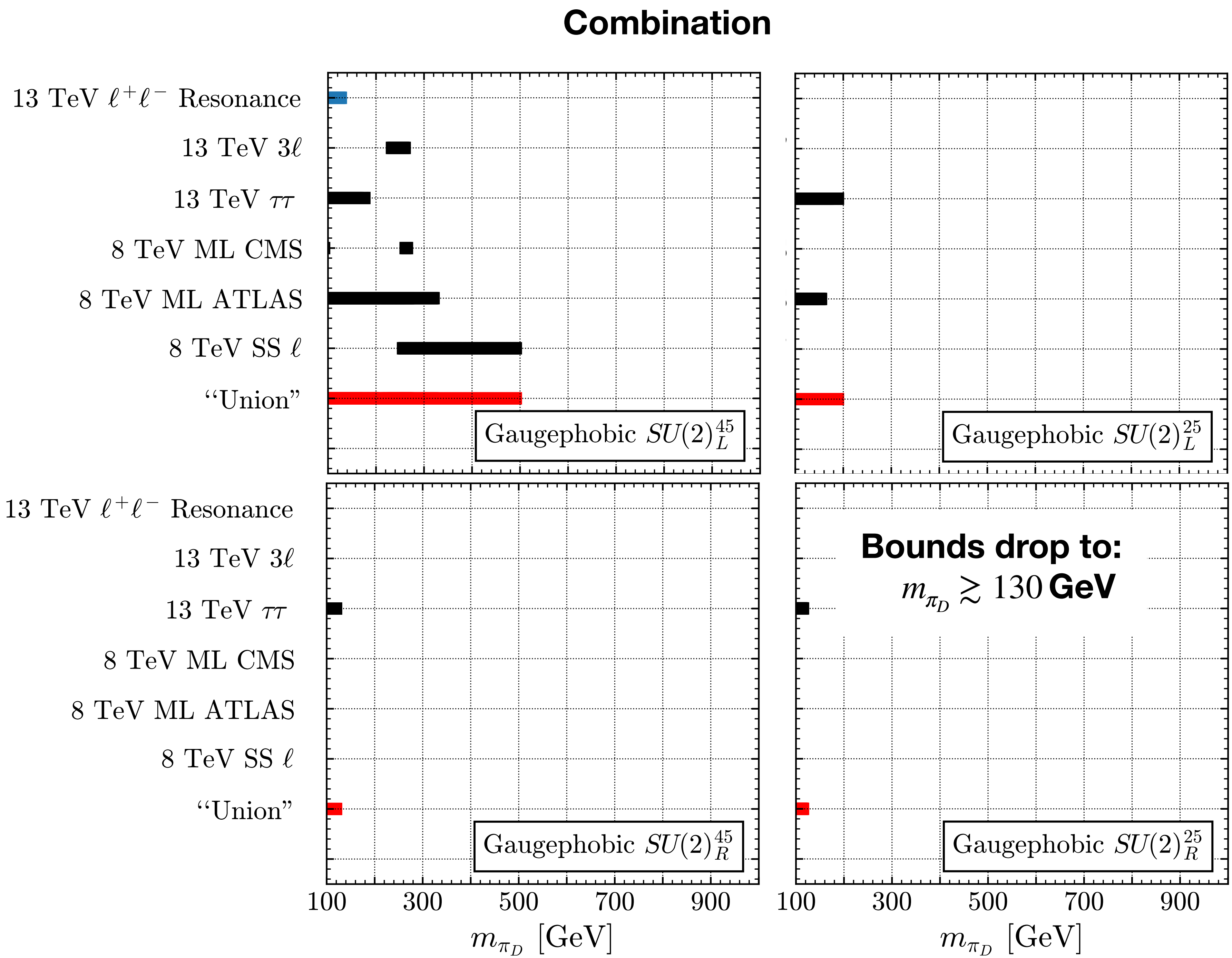
$$\frac{m_{\pi_D}}{m_{\rho_D}} = 0.25 : \quad m_{\pi_D} \gtrsim 200\,\textbf{GeV}$$

Combination



SU2R model has smaller kinetic mixing, only neutral current

hard to get 3+ leptons, SSL from neutral current alone!



Combination
13 TeV $\ell^+\ell^-$ Resonance
13 TeV 3ℓ
13 TeV $\tau\tau$
8 TeV ML CMS
8 TeV ML ATLAS
8 TeV SS ℓ
"Union"
Gaugephobic $SU(2)^{45}_L$
Gaugephobic $SU(2)^{25}_L$
Gaugephobic $SU(2)^{45}_R$
Gaugephobic $SU(2)^{25}_R$
Bounds drop to:
$m_{\pi_D} \gtrsim 130$ GeV
100
300
500
700
900
m_{π_D} [GeV]

Further directions

There are other interesting custodial charge assignments:

$$\xi_{L,R} = (\square, 2, 2)$$

Composites: $\hat{\pi}_D \sim (3,3)$ of custodial symmetry

Now: $Tr(\mathbf{H}\,\hat{\pi}_D\,\mathbf{H})$ allowed without T-parameter issue

``gaugephilic”

$\hat{\pi}_D \to W/Z + h$ unsuppressed, becomes dominant decay,
changes LHC bounds somewhat (see backup)

Composite Georgi-Machacek model

Conclusions

Weak scale strong dynamics involving SU(2) × U(1) charged constituents is alive and well !

- mixed vector/chiral setup avoids issues in pure vector or chiral
- several scenarios to consider: **custodial setup especially nice**

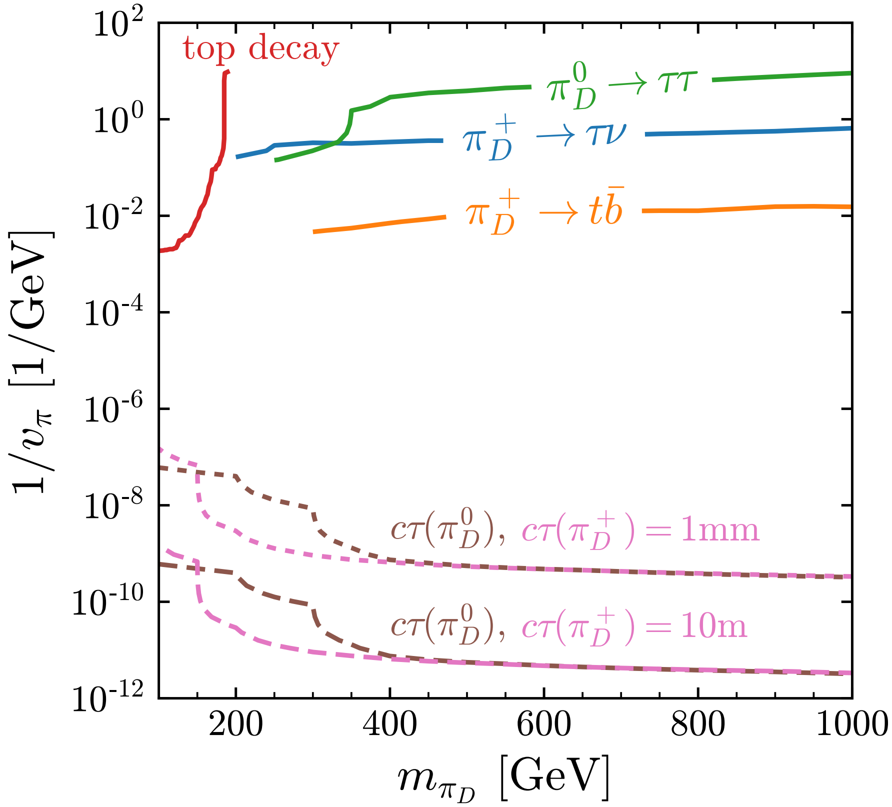
Provided $m_{\rho D} > 2m_{\pi D}$ and N_D small, essentially no LHC limit from $\rho_D \to \ell\ell$

- pair produced π_D sneak through **most** searches as ~small production rates (non-colored) & their decays involve primarily 3rd gen stuff. Hurt by no BSM MET & searches focusing on multi-TeV scale (leads to 8 TeV bounds better than 13)

- limits are especially weak ($m_{\pi D} \gtrsim$ 130 GeV) in scenarios where lightest composites are SU2 singlets (SU(2)R setup)

EXTRA

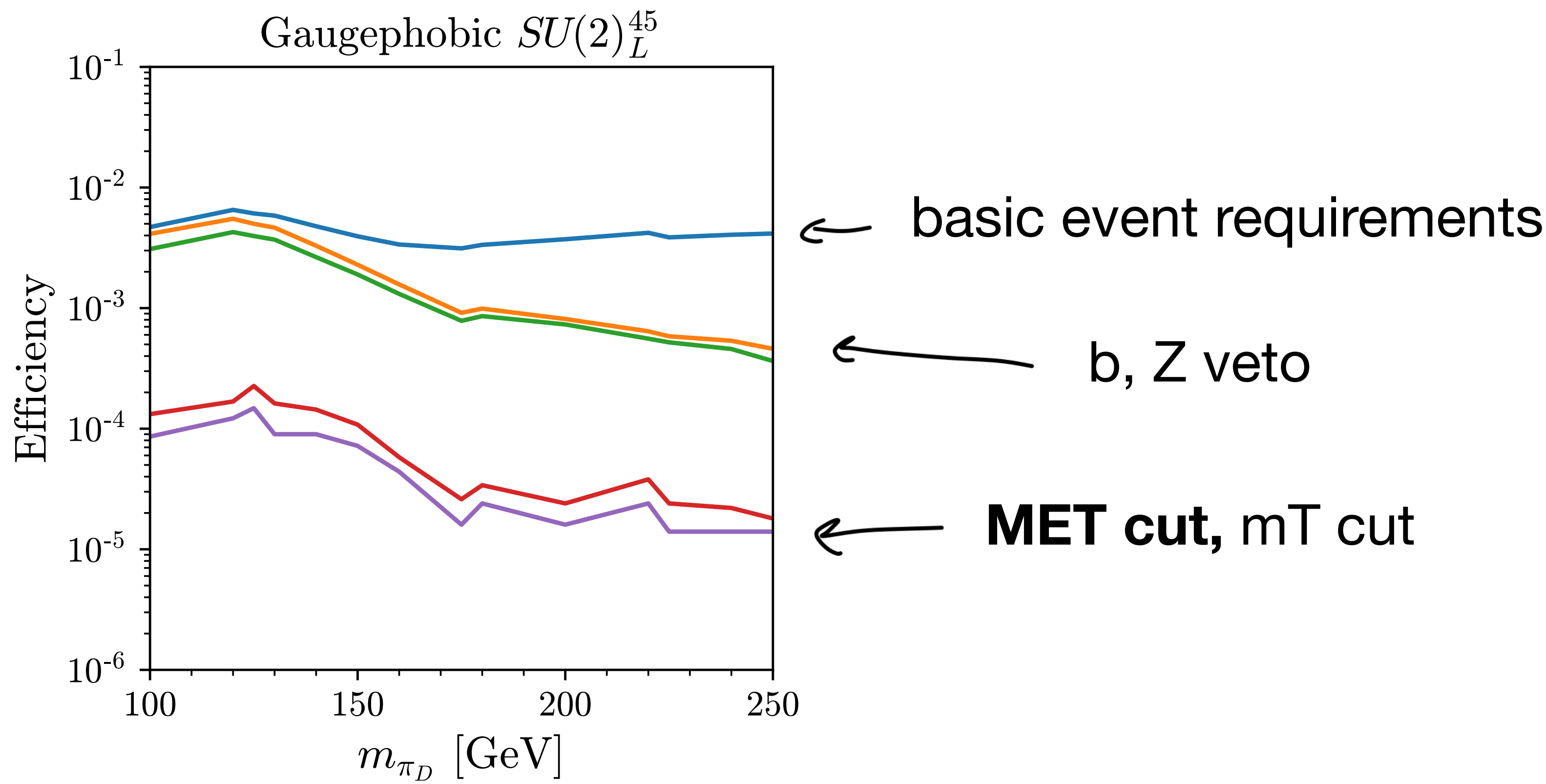
Single production/top decay limits on π_D



Unlike pair production, limits depend on overall π_D-SM coupling strength rather than BR

Plenty of room to avoid these bounds while still having prompt π_D decays

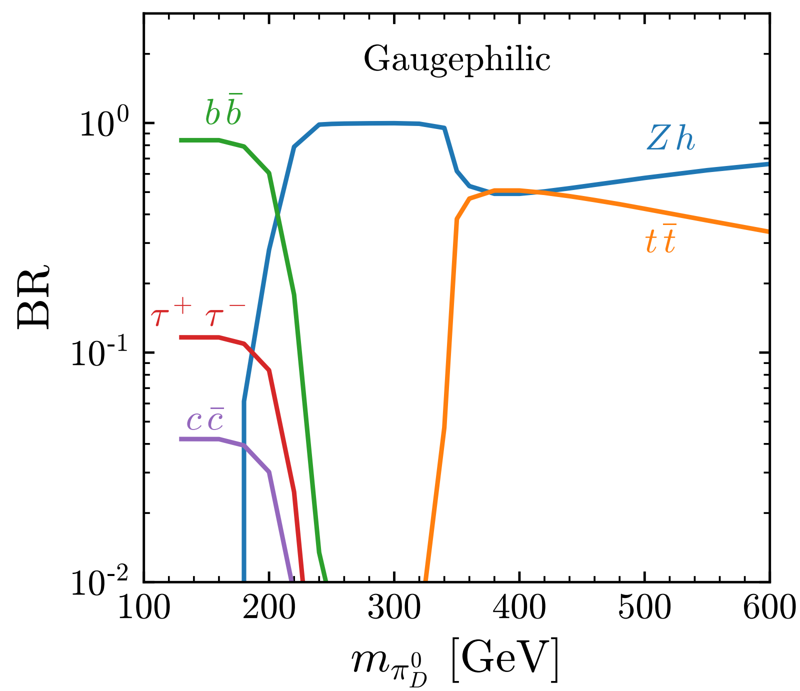
Dark pion efficiency in pp → $\tau^+\tau^-$ + MET search

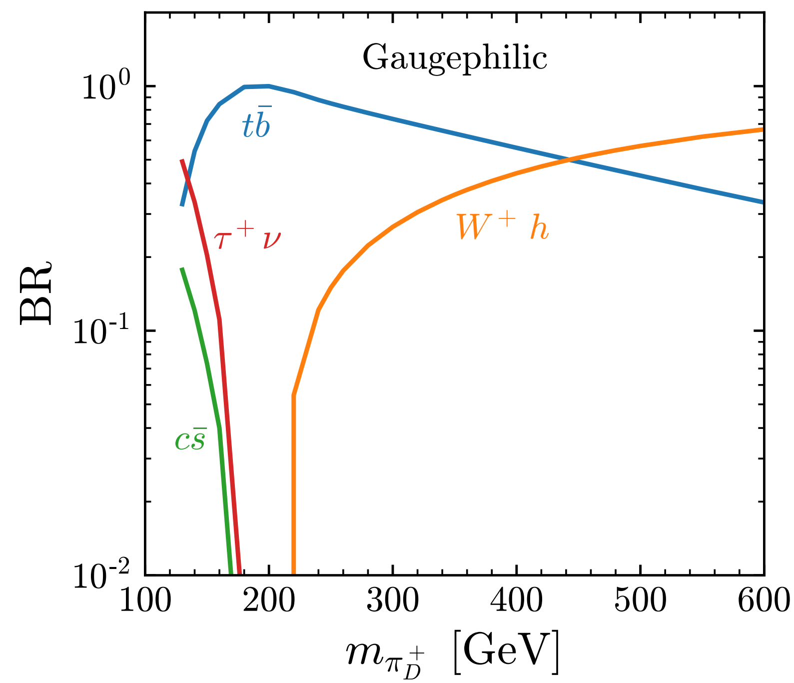


Branching fractions for the "gaugephilic" model, $\hat{\pi}_D \in (3,3)$

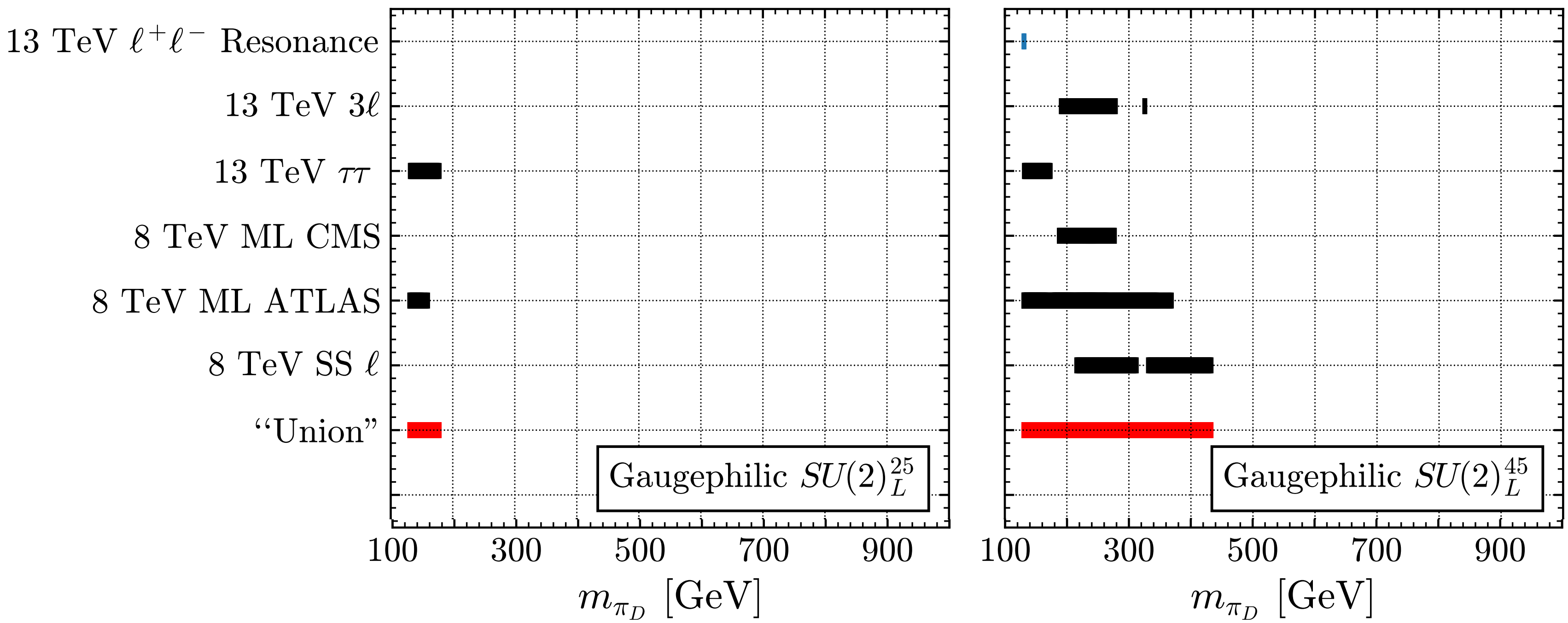
(3,3) → 1 + 3 + 5 once EWSB occurs (& custodial symmetry broken)

focus on BR and limits of triplet





LHC limits for the "gaugephilic" model, $\hat{\pi}_D \in (3,3)$

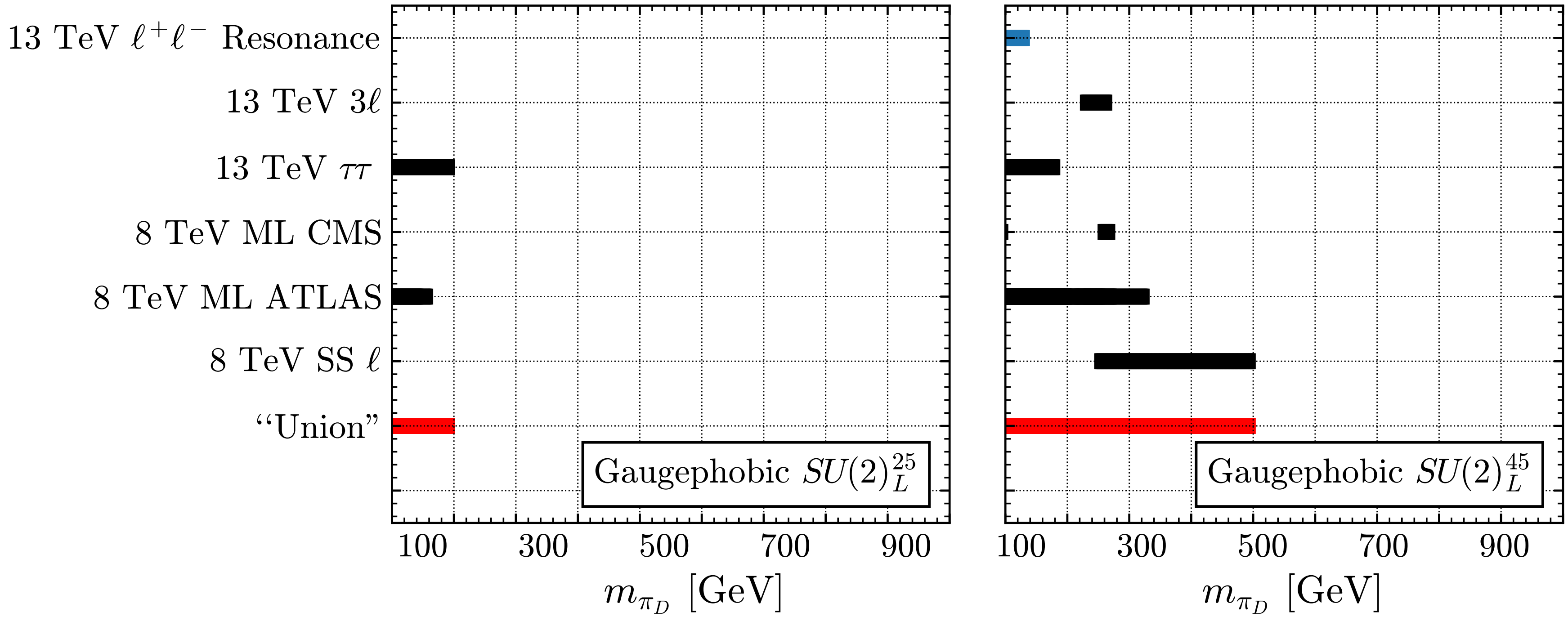


Limits are actually slightly weaker*

Can be traced to lower b-jet multiplicity in gauge-philic case from smaller BR($\pi_D \to t\, b, t\bar{t}$)

* (these limits are only from a triplet with unsuppressed $\pi \to h\, W/Z$, not complete GM model which will contain other states)

LHC limits for the "gaugephilic" model, $\hat{\pi}_D \in (3,3)$



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