Custodial Dark Pions

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

Dark Universe workshop, ICTP-SAIFR, Oct 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

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

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

`dark' bound states: dark mesons, baryons, etc.

playground for lots of BSM scenarios:

Here, I'll focus on $\Lambda_D \sim$ TeV scale,
assume fundamental H EW doublet exists

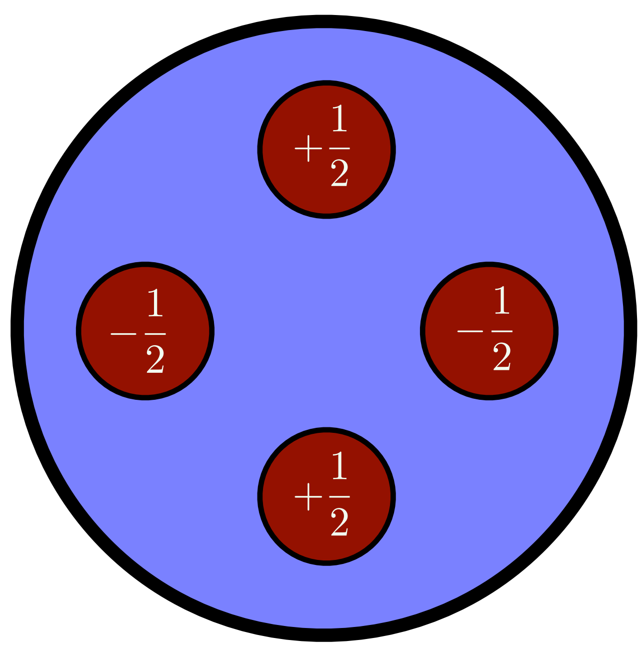
DM specific Motivations:

Composite DM: dark baryon is natural (usually heavy) DM candidate:

if constituents are EW-charged while keeping lightest dark baryon EW neutral, interactions with SM come from higher dimensional operators

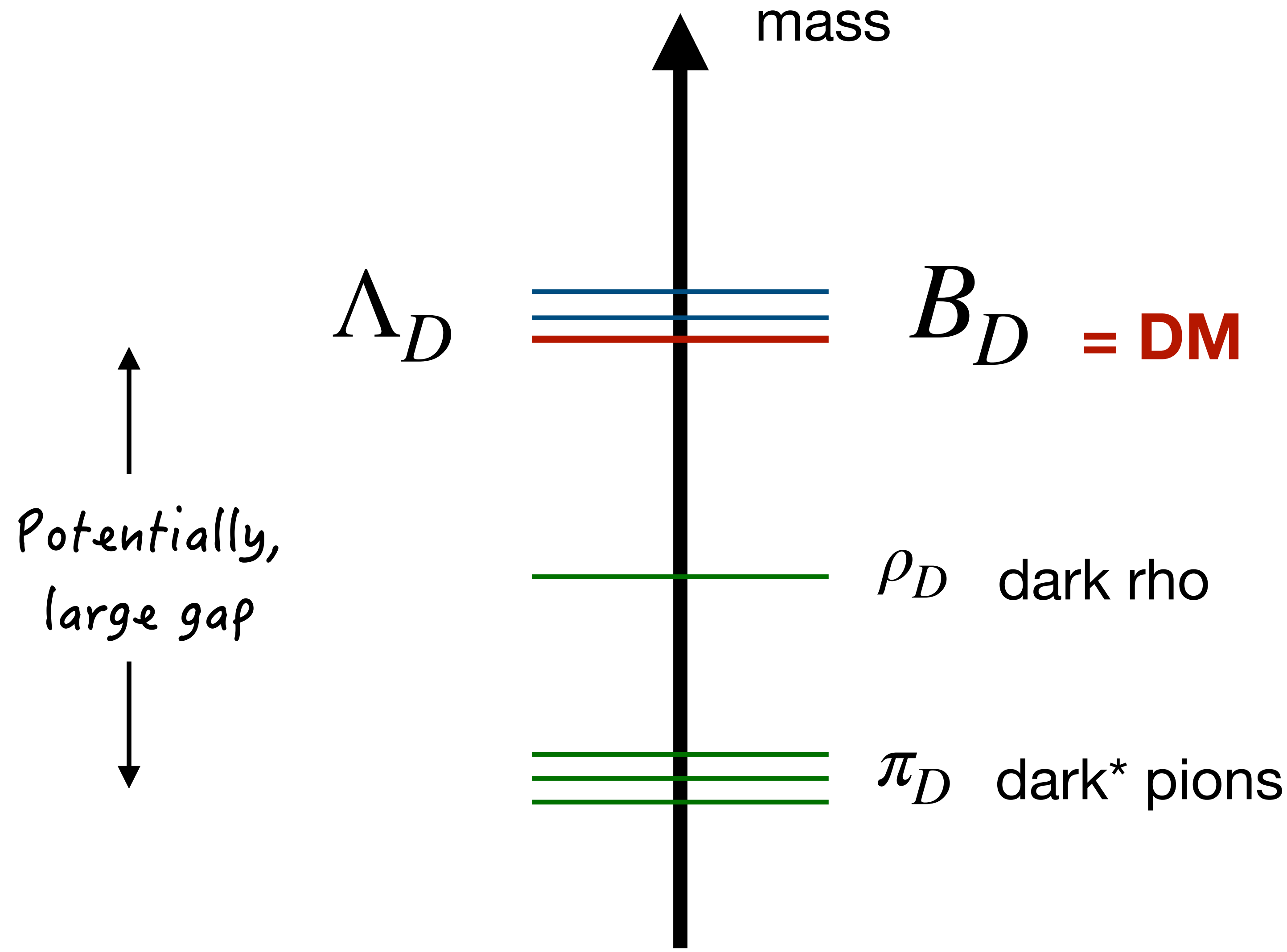
[Nussinov ’85, Chivukula ’90, Barr, Chivukula, Fahri ’90]

More recently [Antipin et al ’15, Huo et al ’16, Cline ’16, Mitridate ’17]



Dark spectra

Assume a spectrum ~ QCD



* SU(N_D) composite, NOT necessarily SM inert

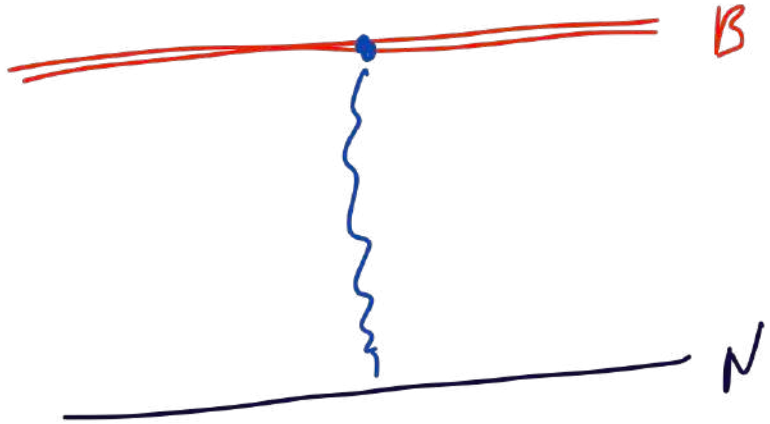
Abundance: either symmetric ($\bar{B}B \to n\, \pi_D$, etc.) or asymmetric

…wide range of scales possible

DM specific Motivations:

- Direct detection: if N_D is odd, DM = fermion, communicates via magnetic moment operator

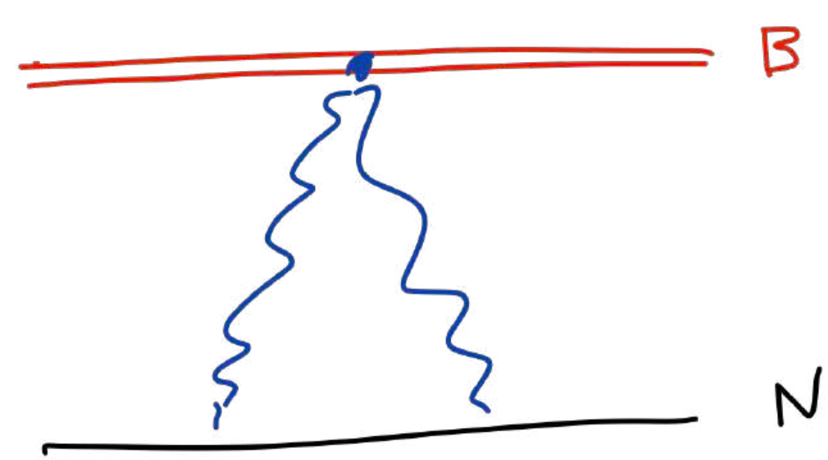
$$\frac{\bar{B}_D \sigma^{\mu\nu} B_D F^{\mu\nu}}{m_B}$$



Scaling up neutron: direct detection constrains demand $m_{DM} \gtrsim 20$ TeV

- Direct detection: if N_D is even, DM = boson, most important interactions come from polarizability

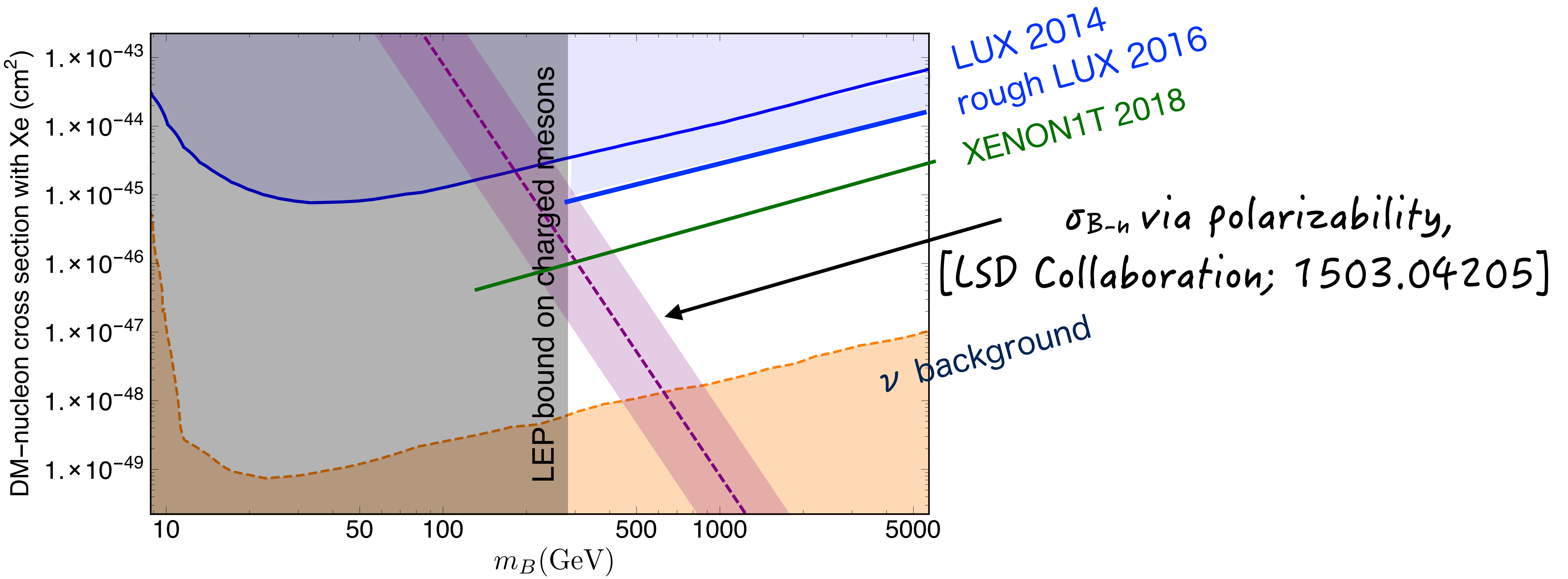
$$\frac{B_D^* B_D F^{\mu\nu} F_{\mu\nu}}{m_B^2}$$



DM specific Motivations:

Detecting "stealthy DM"

[1402.6656, 1503.04203, 1503.04205]



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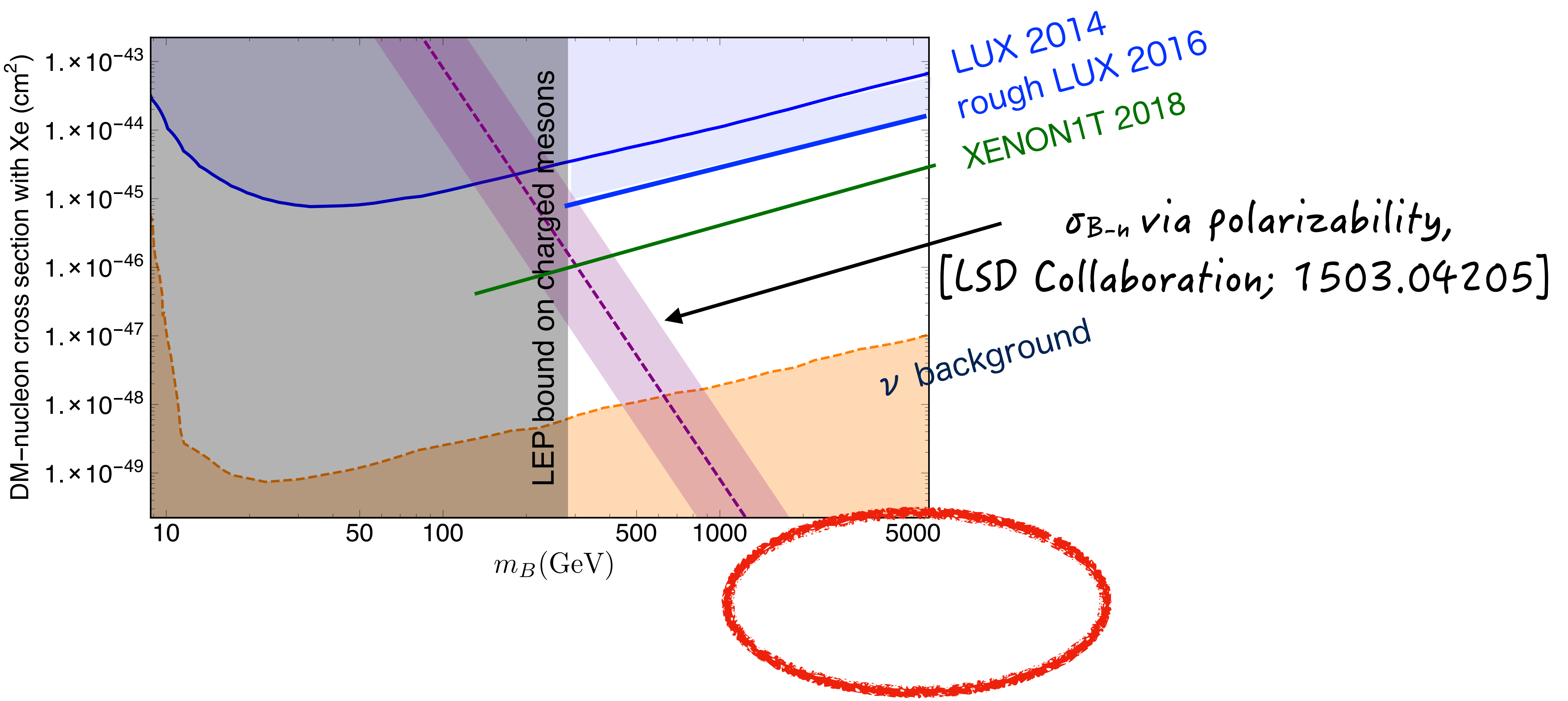
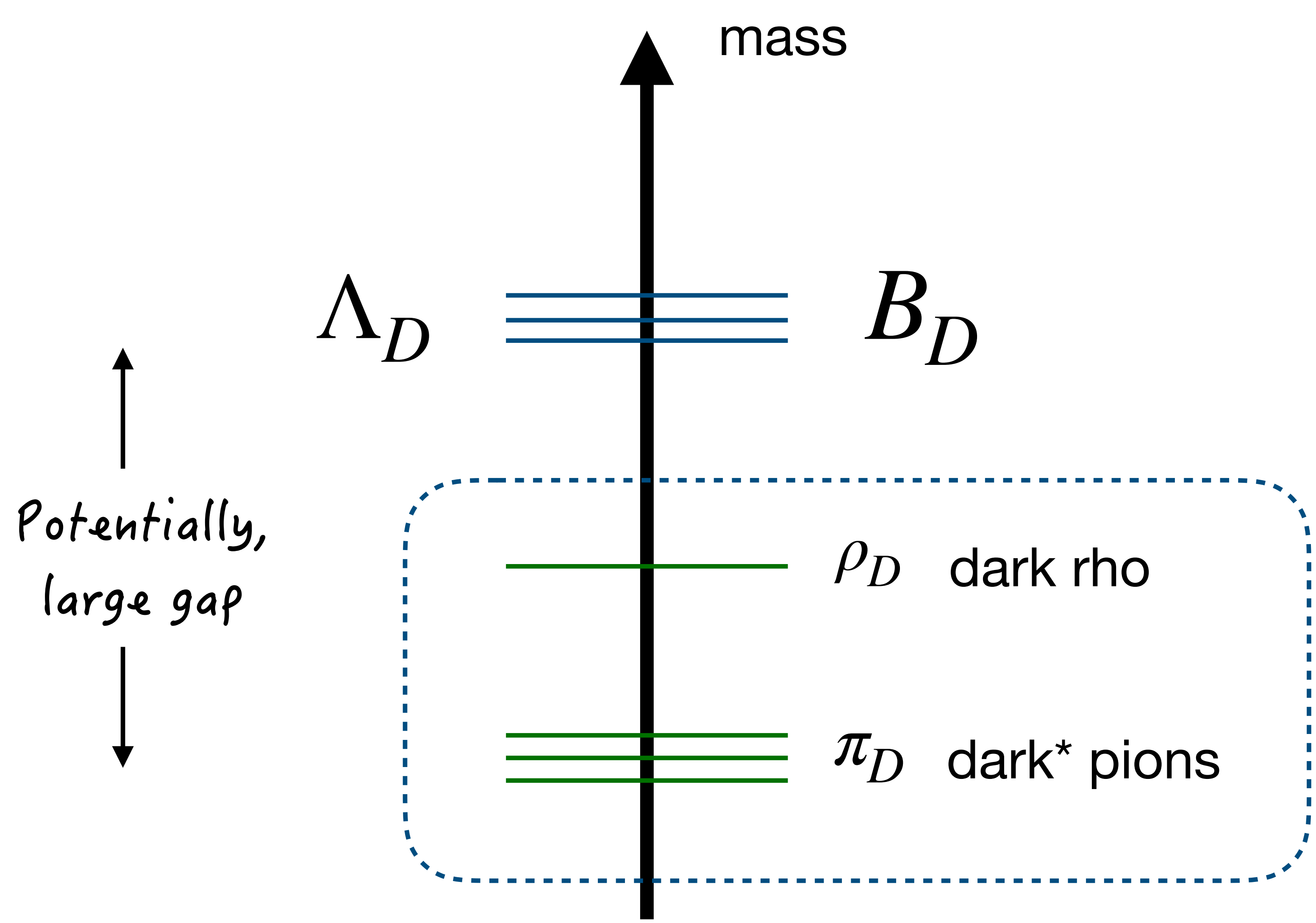


If DM sits out here, what do we do? Possible that the best chance is to detect stealthy dark sector at the LHC

Dark Mesons spectra

Assume a spectrum ~ QCD



* $SU(N_D)$ composite, NOT necessarily SM inert

LHC physics will be dominated by these lightest states, specifically on details of how these interact with /decay to SM: for LHC we care about dark mesons

EW-scale Dark Sector model space

Bosonic technicolor/
induced EWSB limit:
chiral EW charges

[Kagan, Samuel ‘90
Luty et al 1106.3346
…]

Dark sector with both vector like and chiral masses

vectorlike confinement limit
ψ_L, ψ_R have same EW charges

[Kilic et al 0906.0577]

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

$\langle H \rangle \neq 0$, becomes a chiral mass term connecting one state in ψ with χ

(leads to EW neutral lightest technibaryon for even N_D: [Chivukula '90])

Below Λ_D:

Map $\psi_{L,R}$, $\chi_{L,R}$ → π_D using NLSM $\Sigma = e^{i\pi_D/f}$

$$\sim L_{kin} + f^3\,\mathbf{Tr}\Big((M + y\Lambda(H))\Sigma + h.c\Big)$$

Different fermion components give π_D with different SM charges, masses i.e.

$(\bar{\psi}\gamma_5\psi)$ = $(3)_0$, mass^2 ~ f (M_ψ + y v)

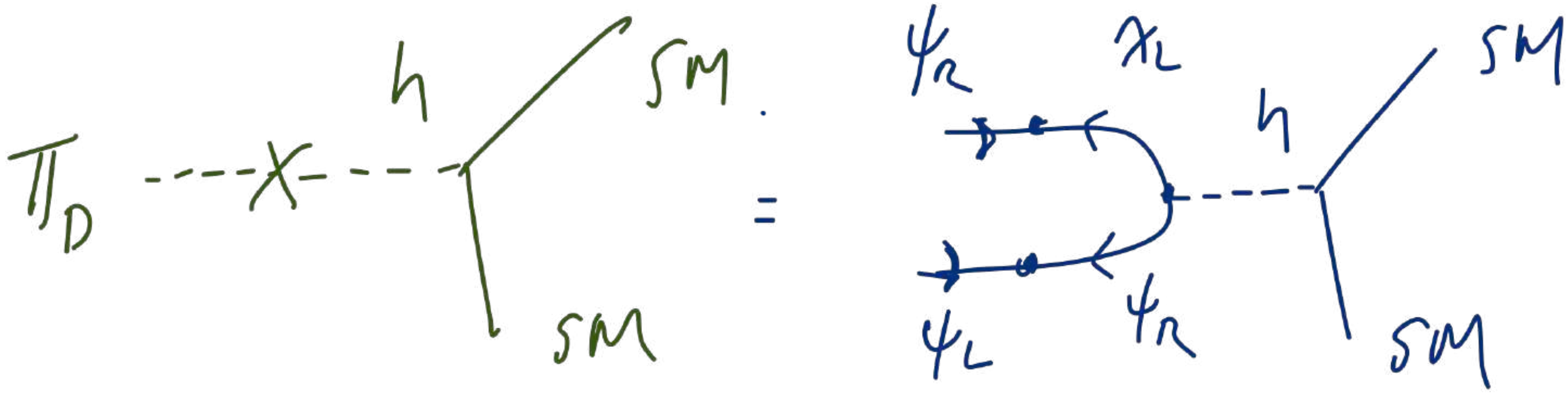
$(\bar{\chi}\gamma_5\chi)$ = $(1)_0$, mass^2 ~ (f M_χ + y v)

...

Play with ordering of M_ψ, M_χ, y v to adjust which multiplet is lightest. For each choice, expect vector composites ρ_D too

Why study this kind of theory?

1.) Avenue for dark pion decay: Pure vectorlike theory forbids this (accidental flavor symmetries), need to add in pion decay by hand. With chiral mix, decay comes automatically



(Want `dark' pion to be DM? Ask Yang)

Why study this kind of theory?

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

Small y means S $\sim \left(\frac{yv}{M_{\pi_D}}\right)^2$ not an issue

(also suppresses DM <-> SM interactions via Higgs)

Why study this kind of theory?

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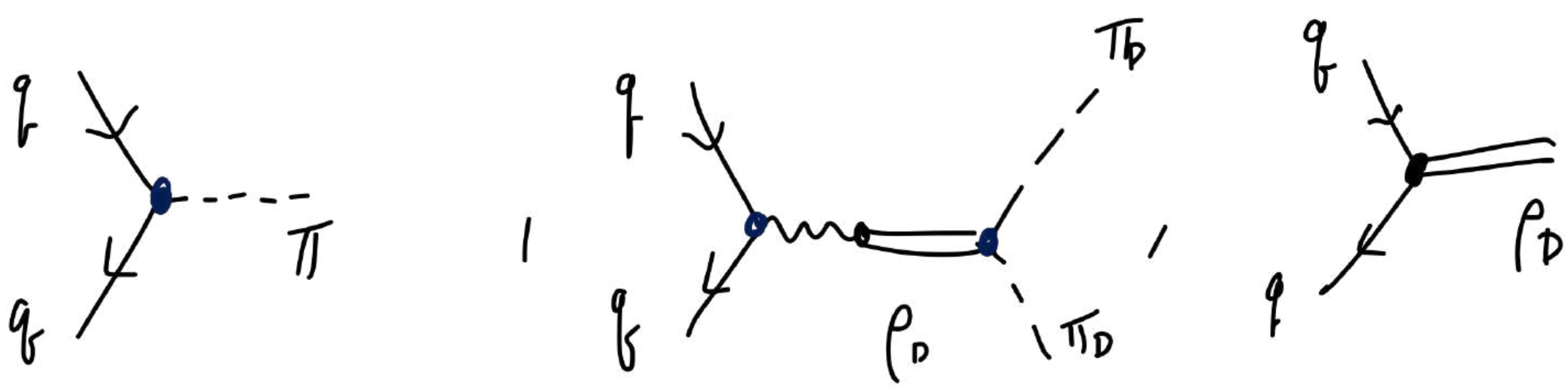
3.) Rich, relatively unique phenomenology.



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

Custodial Dark Mesons

If the theory contains EW doublets $\psi_{L,R}$, $\pi_D = \langle \psi_L \psi_R \rangle$ will be an EW triplet

$$\mathcal{L} \supset (H^\dagger \tau^A H)\, \pi_D^A$$ allowed, will generate a vev for π_D

causes issues with T parameter unless suppressed by high scale/small coefficient

Instead:

assign dark fermion charges under $SU(2)_L \times SU(2)_R$ = global, \`custodial' symmetry of Higgs potential, rather than $SU(2)_L \times U(1)_Y$

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

Custodial Dark Mesons

	$SU(N_D)$	$SU(2)_L$	$SU(2)_R$
ψ_L	$\square$	2	0
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χ_L	$\square$	0	2
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In addition to vector-like mass terms, two Yukawa permitted:

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

Custodial Dark Mesons

$$\begin{pmatrix} \psi^u_{L,R} \\ \psi^d_{L,R} \end{pmatrix} \qquad \begin{pmatrix} \chi^u_{L,R} \\ \chi^d_{L,R} \end{pmatrix}$$

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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

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

(all << Λ_D)

Two scenarios:

<u>'SU2L'</u>

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

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

EW triplets: (3,1)

<u>'SU2R'</u>

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

$$\tilde{\rho}_D^\mu \sim (\bar{\chi}\gamma^\mu\chi) \quad \text{lightest vector}$$

EW singlets: (1,3)

Custodial Dark Mesons

In either case:

$\pi_D = (3,1)$ or $\tilde{\pi}_D = (1,3)$ while $\mathbf{H}^2 = (1,1) + (3,3)$

forbids trilinear interaction with lightest dark pion

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allowed interactions include:

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

which lead to $\pi_D \to ff'$

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(more derivatives, e.g $\mathbf{H}\, D_\mu\, \mathbf{H}\, D^\mu\, \pi_D$: also forbidden)

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which lead to $\pi_D \to ff'$

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

Custodial Dark Mesons

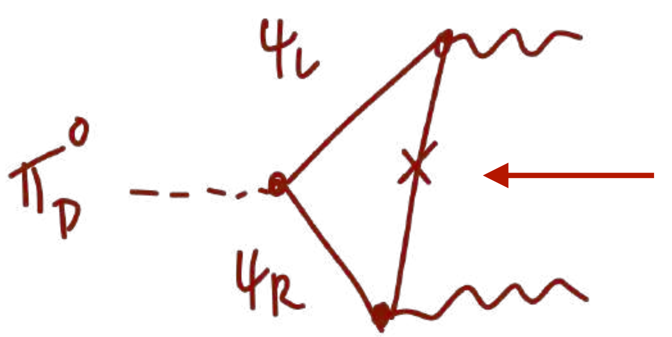
In addition to removing T parameter issue:

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

(some small amount from even higher dimensional terms ~ $(\mathbf{H}(D_\mu \mathbf{H}))^2 \pi_D^A$)

``gaugephobic''

- custodial limit also removes decay $\pi_D^0 \to \gamma\gamma$

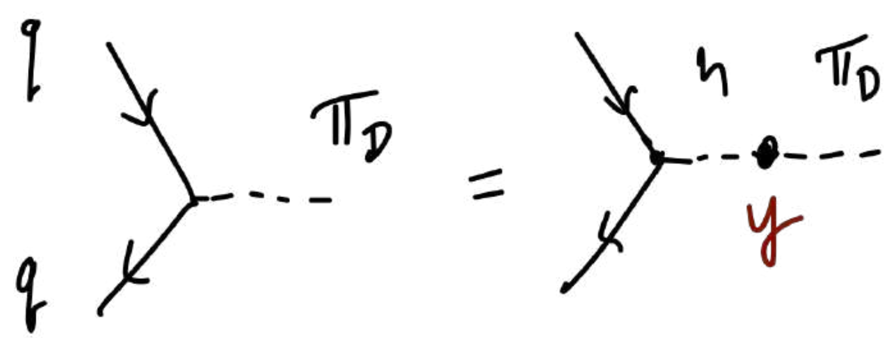


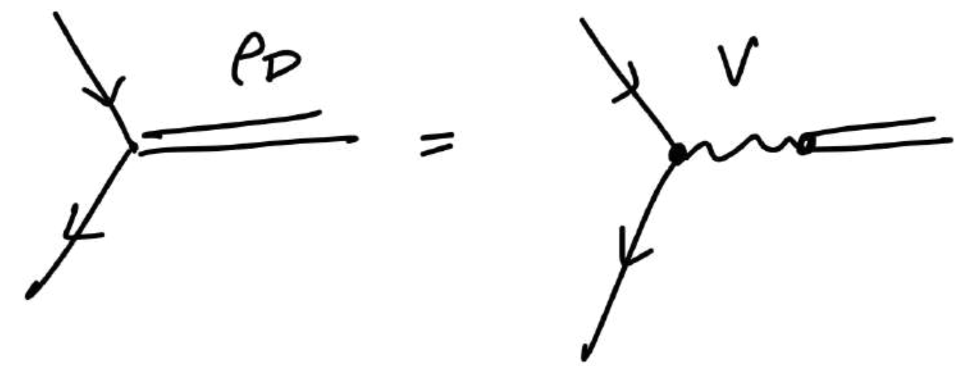
both components have same mass, |Q|

- 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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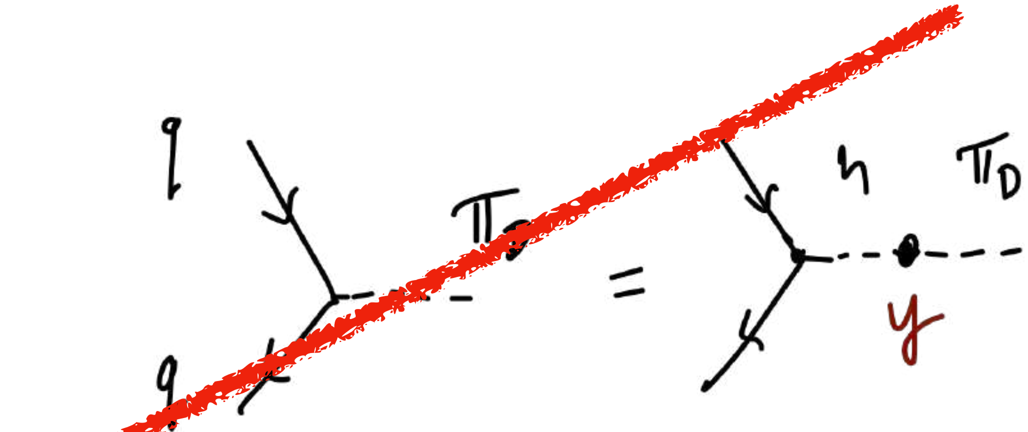

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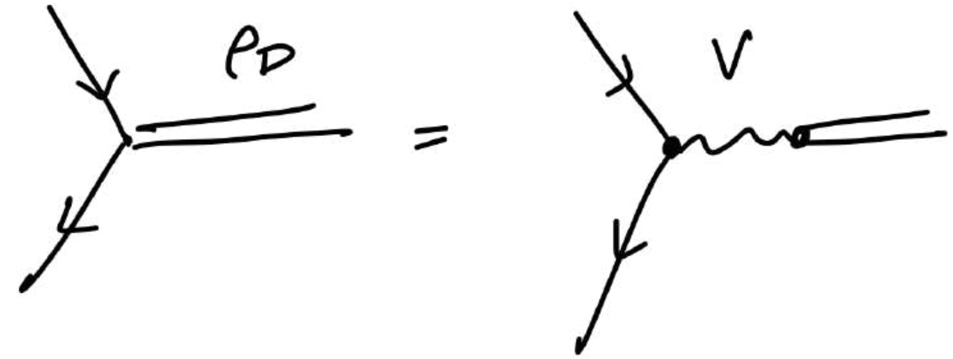

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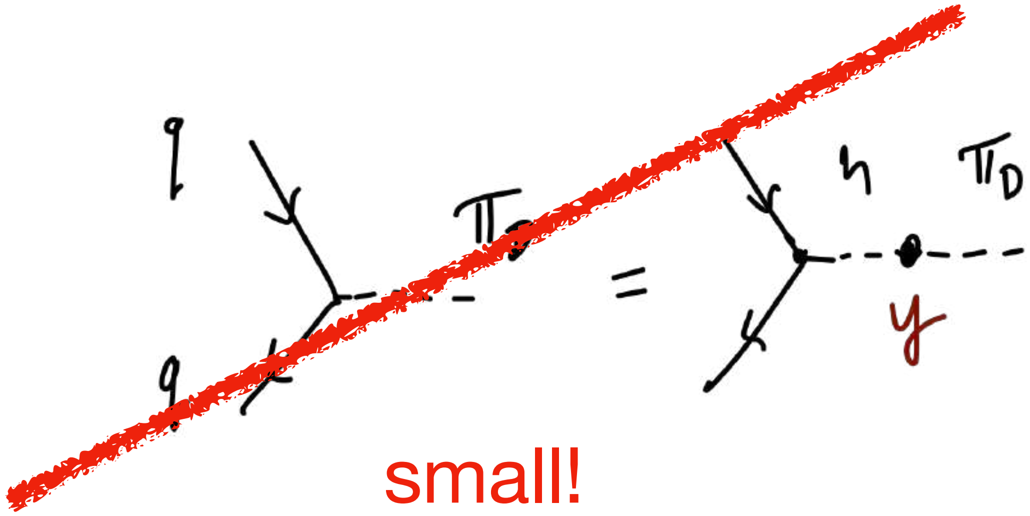
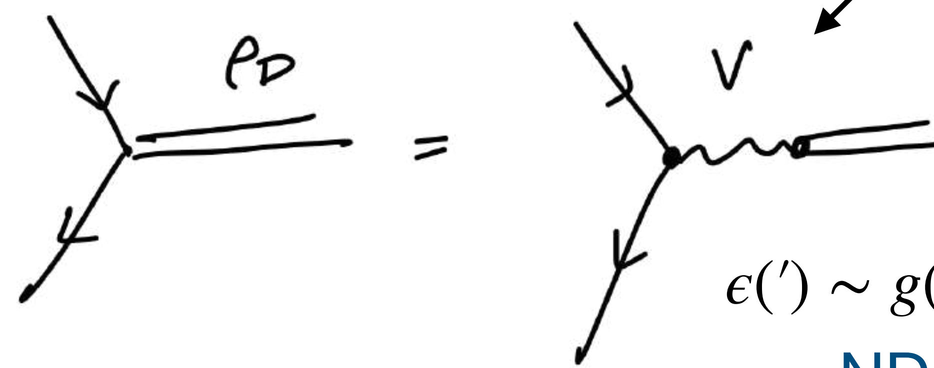


small!

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

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

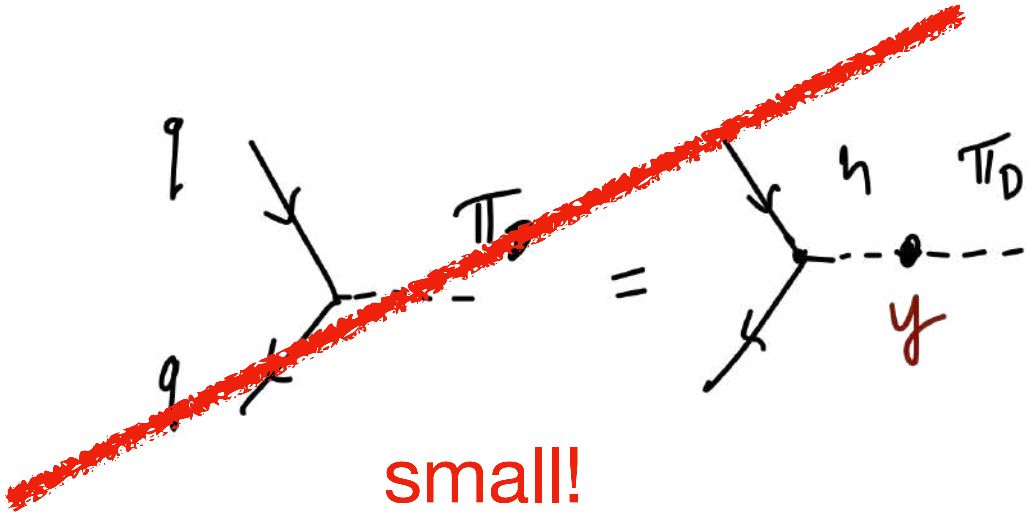


$$\epsilon(') \sim g(') \frac{\sqrt{N_D}}{4\pi}$$

NDA

analogous to ρ → γ VMD in QCD

Dark Mesons at the LHC: single production



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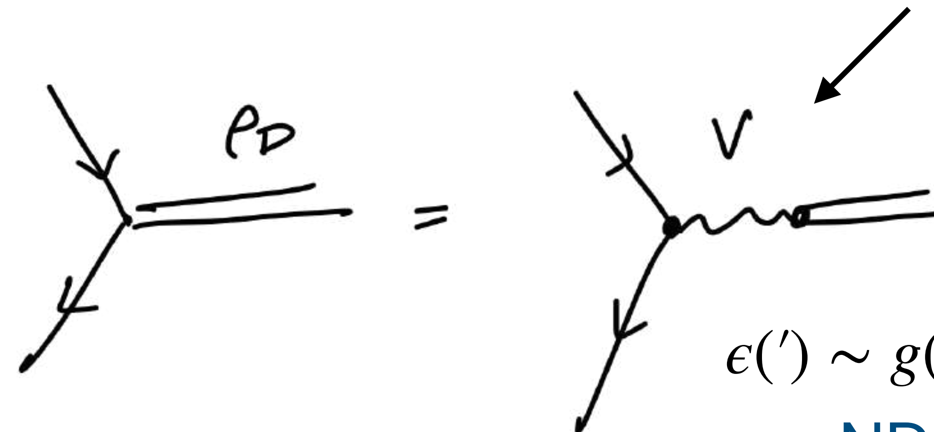

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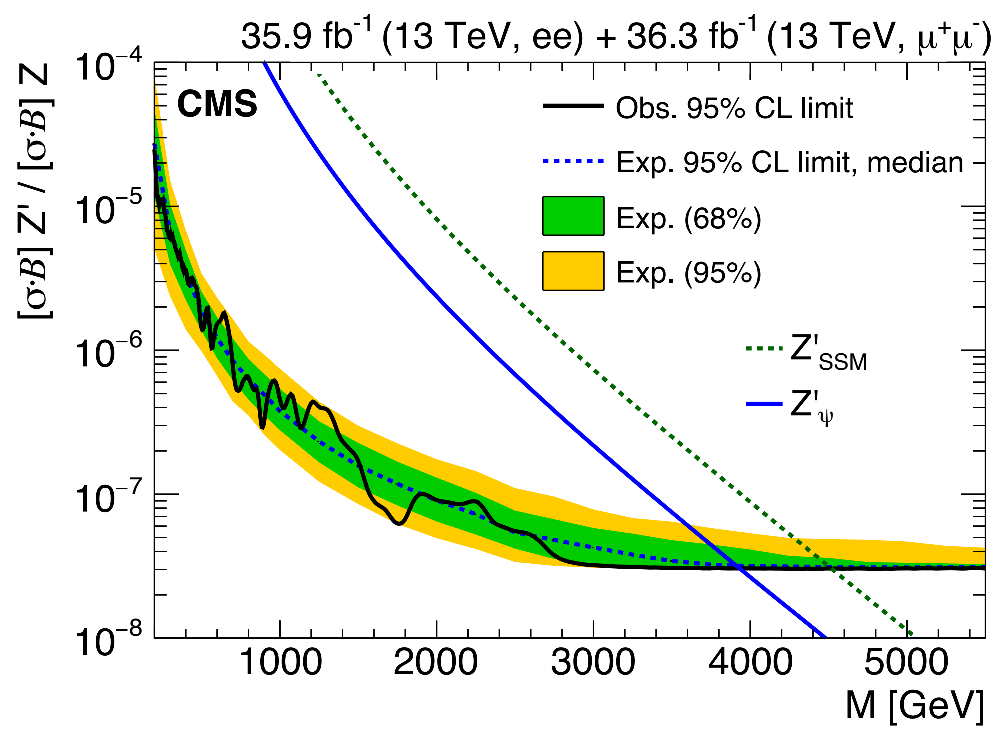
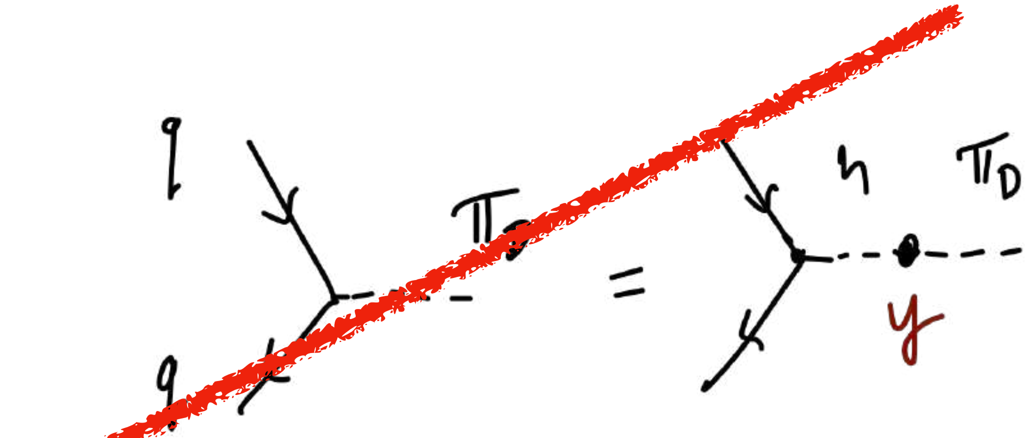
As ρ_D are similar to generic W'/Z', may expect strong bounds from $\rho_D \to \ell\ell$



Dark Mesons at the LHC: single production



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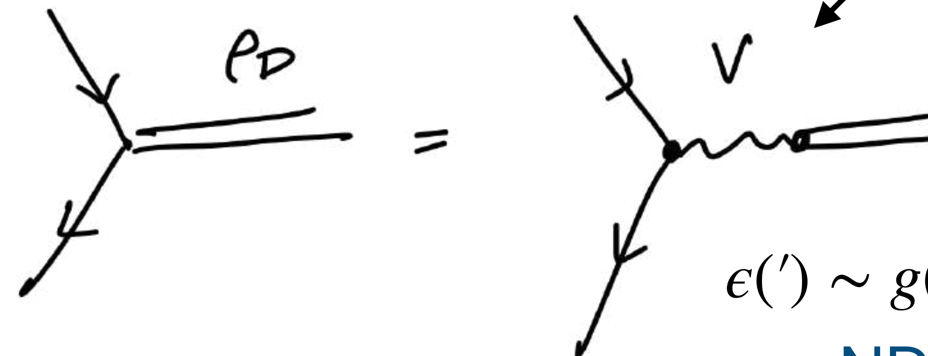

$\epsilon\, \rho^{a}_{D,\mu\nu}\, W^{a,\mu\nu}$

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

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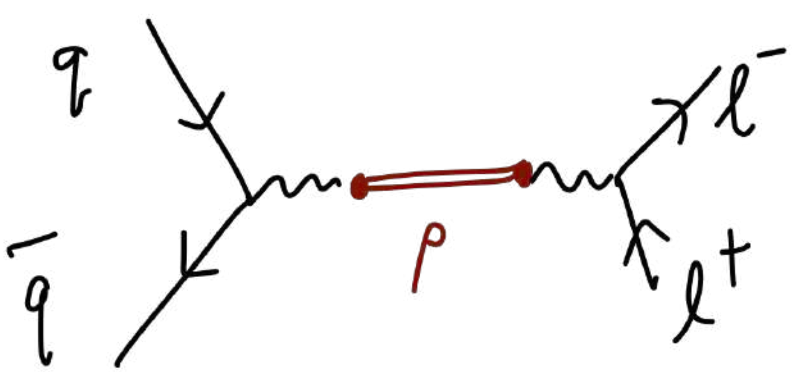
analogous to ρ → γ VMD in QCD

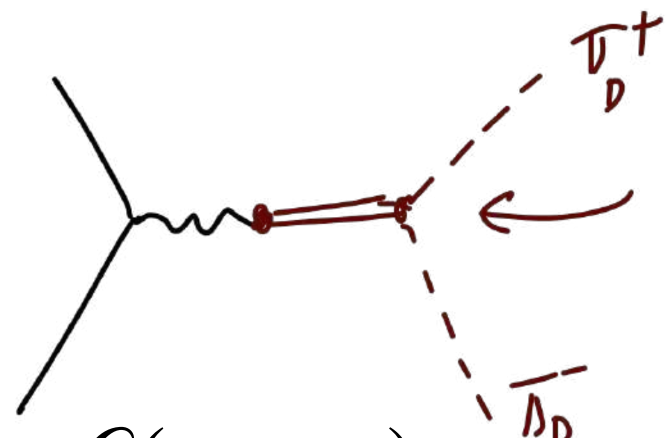
As ρ_D are similar to generic W'/Z', may expect strong bounds from $\rho_D \to \ell\ell$

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



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

vs.

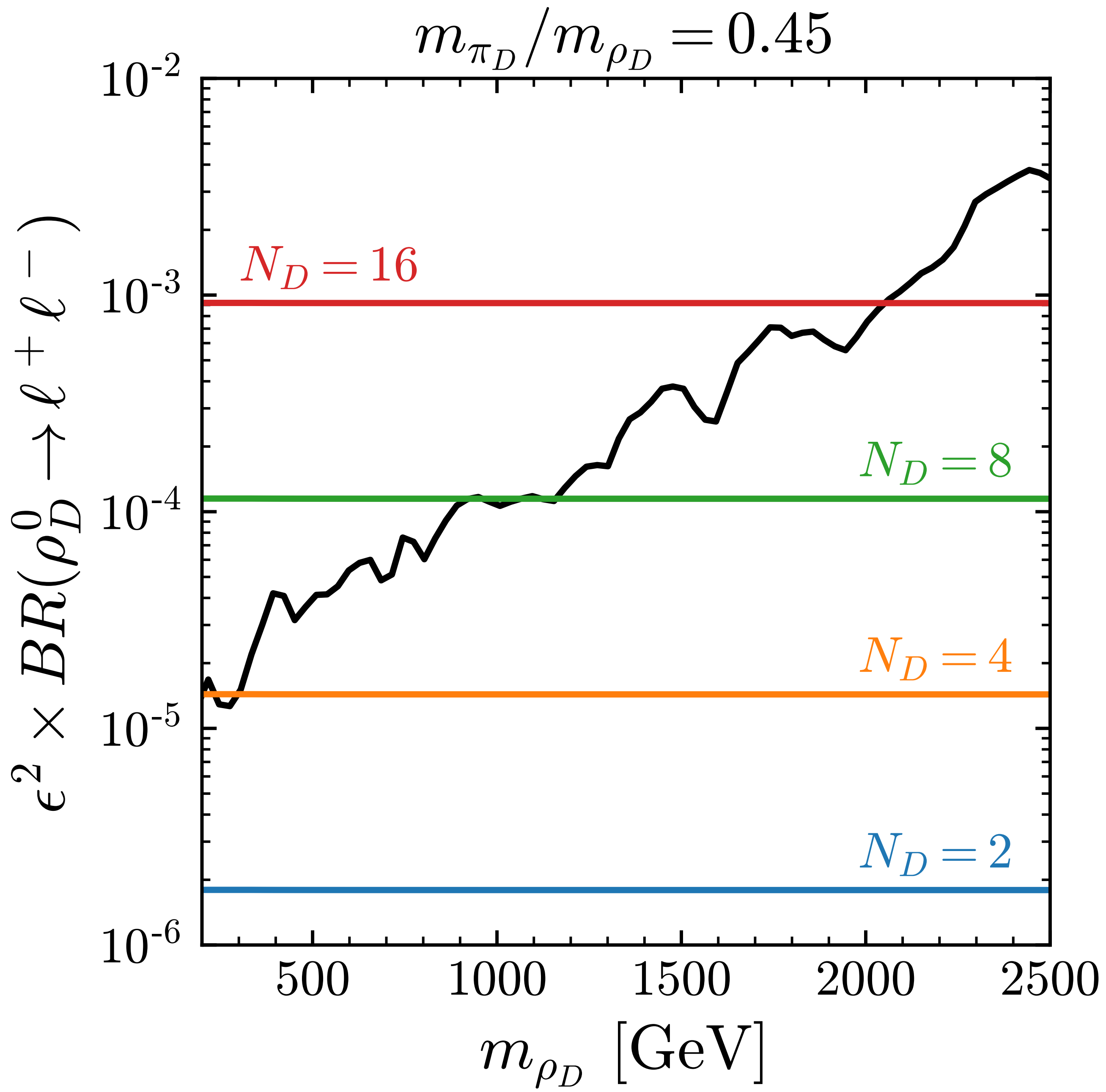


$g_{\rho\pi\pi} \sim \dfrac{4\pi}{\sqrt{N_D}}$

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

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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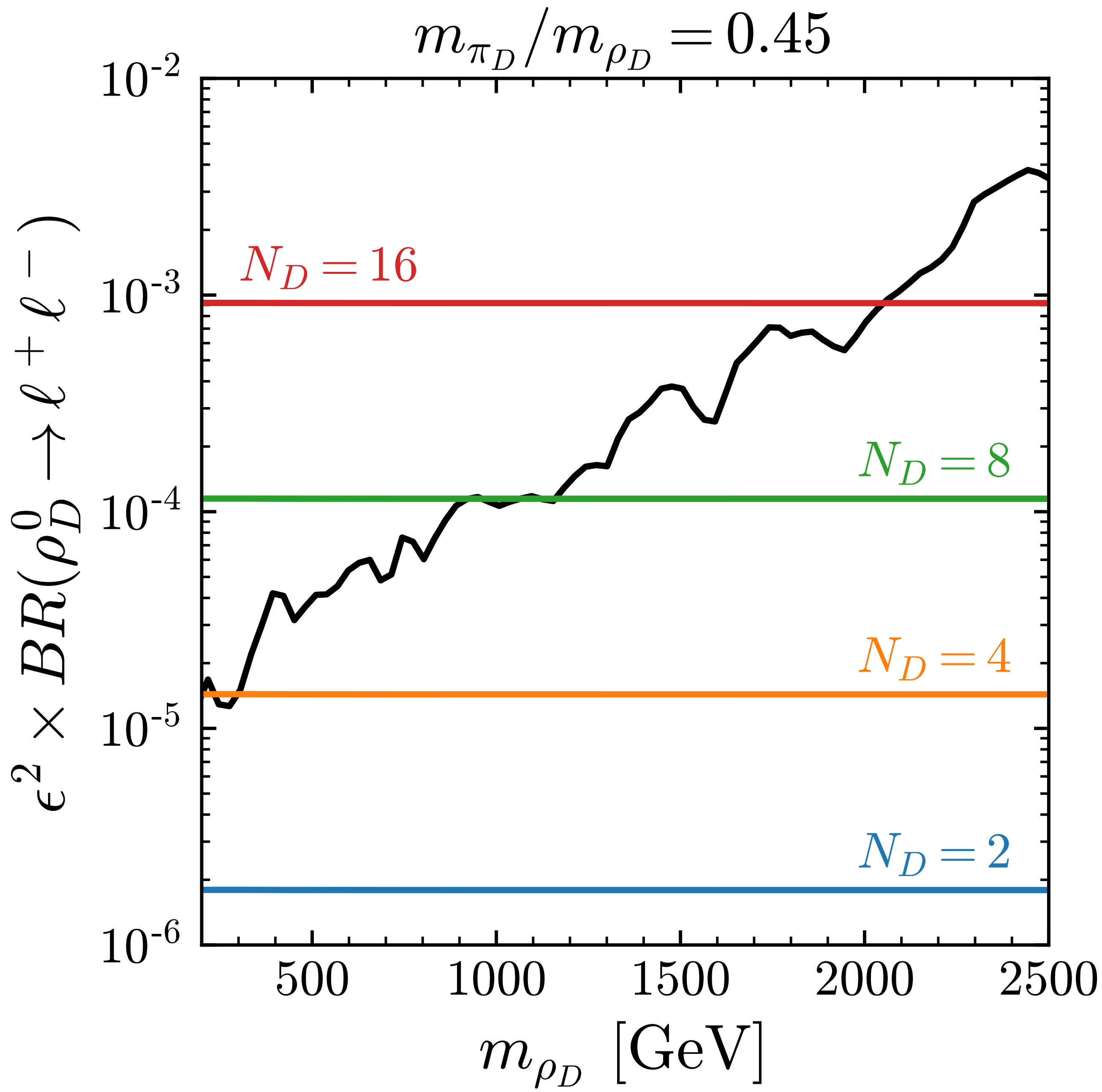

For small N_D, bound is significantly less than Z' → ℓℓ expectation, even for $m_\pi/m_\rho = 0.45$

For lower m_π/m_ρ, bound disappears completely

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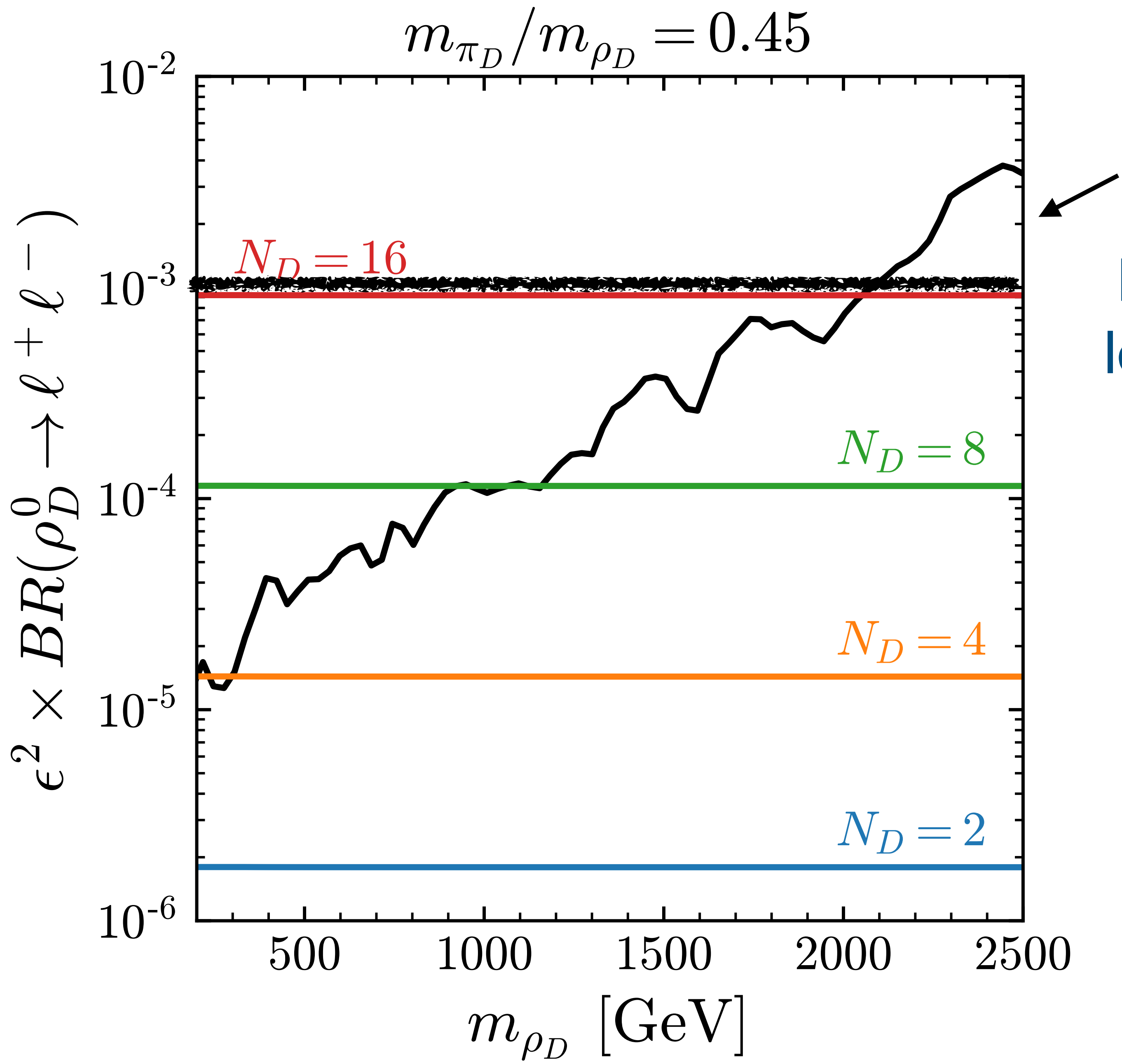

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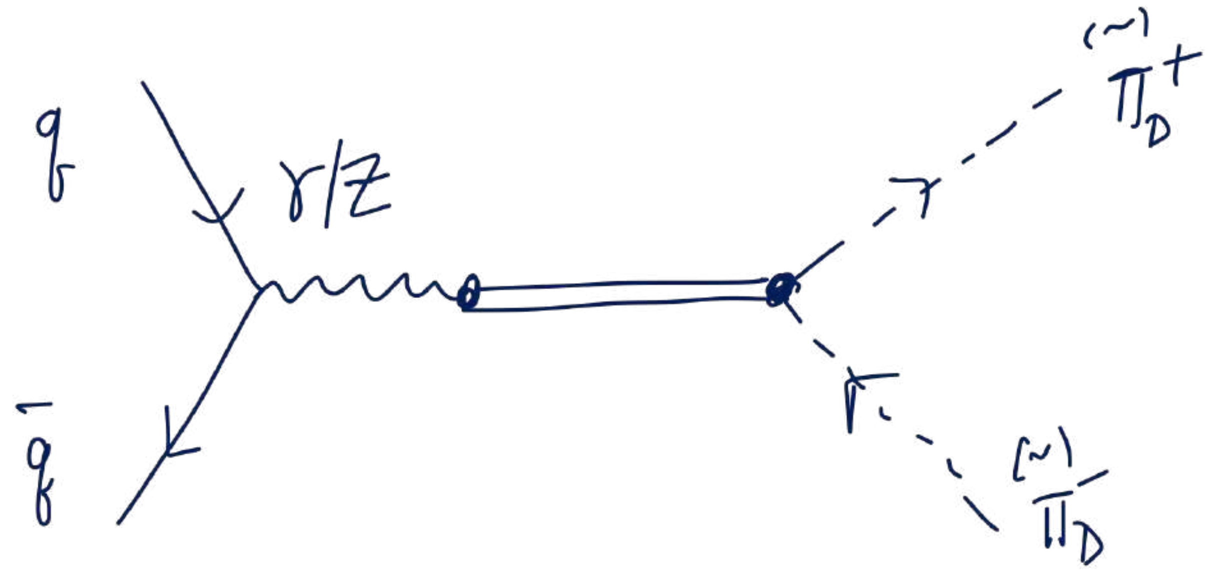
For lower m_π/m_ρ, bound disappears completely

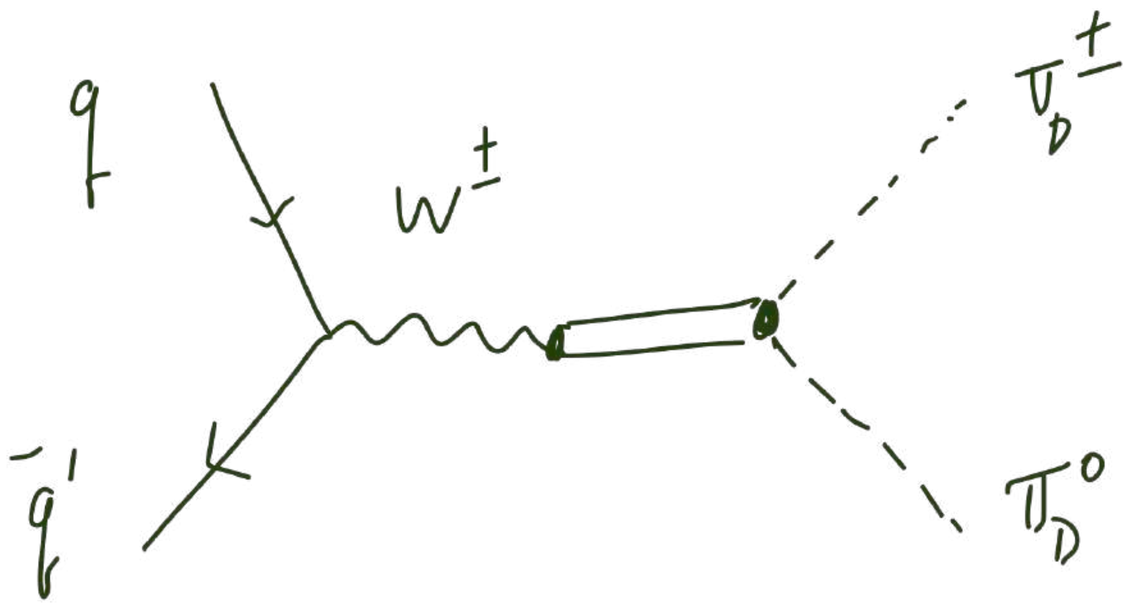
Focus on $N_D = 4$, consider $m_\pi/m_\rho = 0.45, 0.25$

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

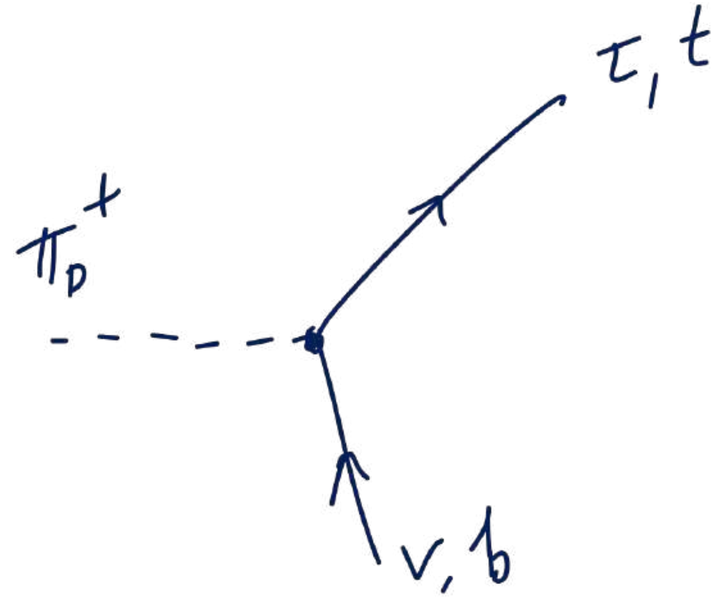
$$\sigma(pp \to \pi_D \pi_D \to SM\, SM) \simeq \sigma(pp \to \rho_D)\, BR(\pi_D \to SM)^2$$

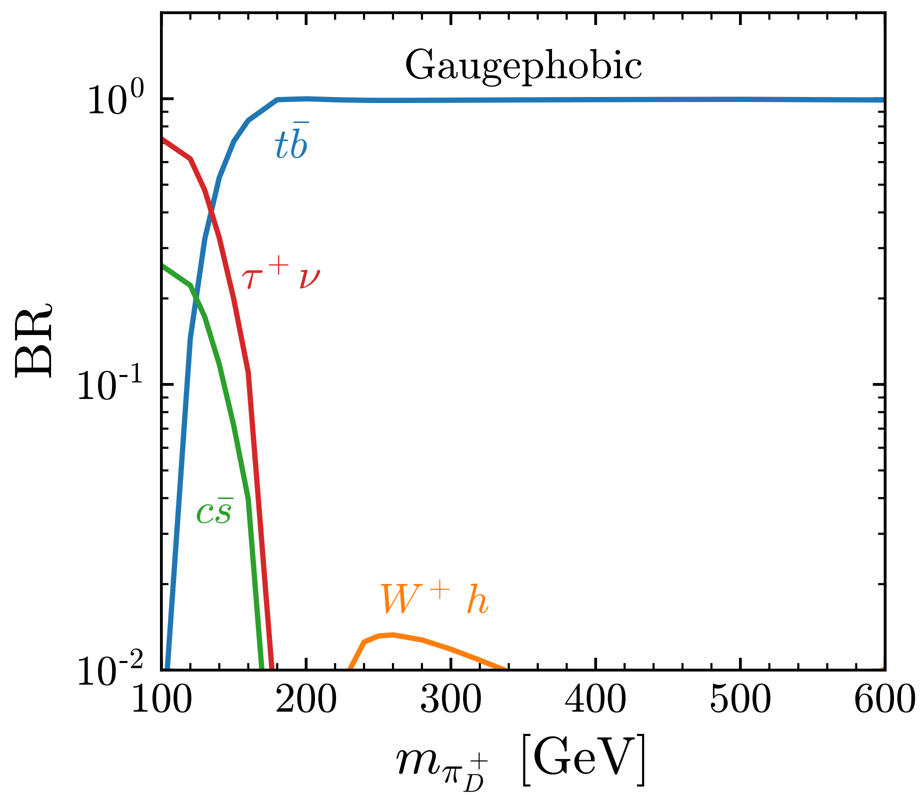
size of $\pi_D \to$ SM coupling drops out. Parameters: m_π, m_π/m_ρ, $N_D = 4$

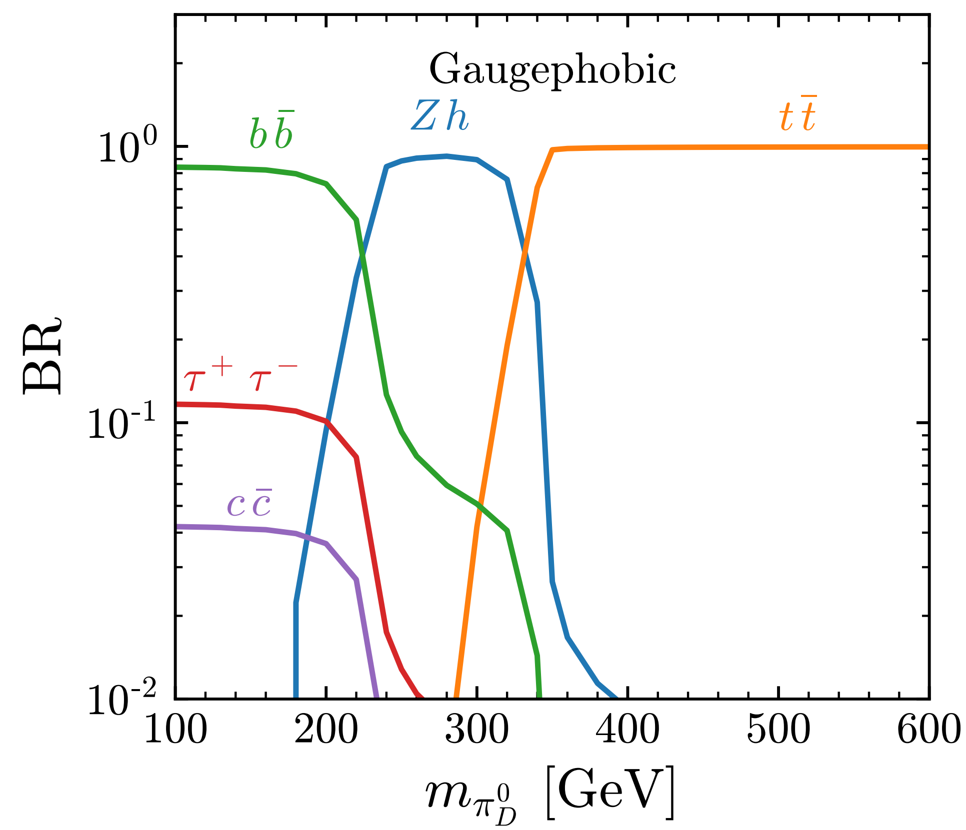
Dark Mesons at the LHC: pair production

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

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

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

...

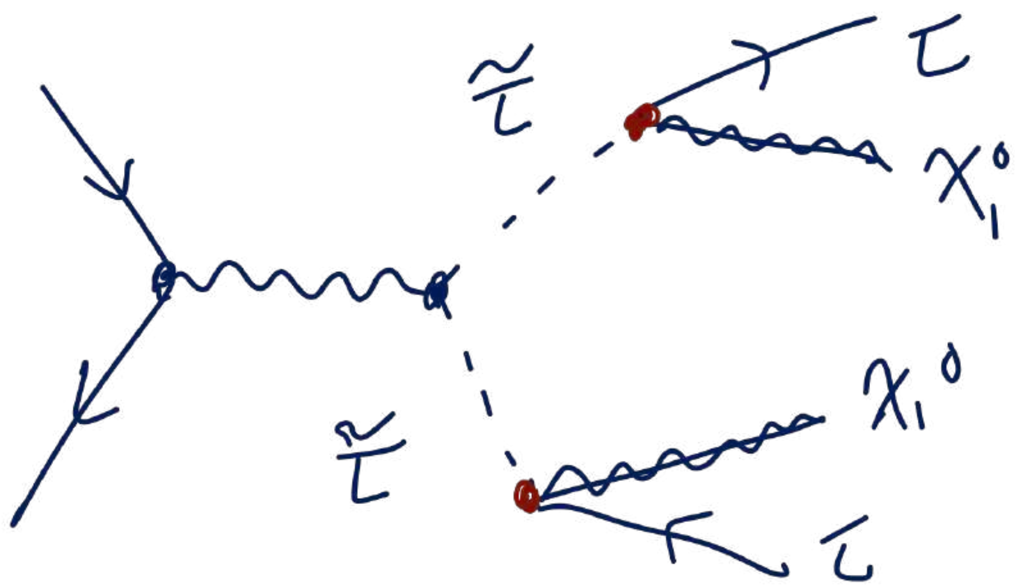
`heavy π_D' channels

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

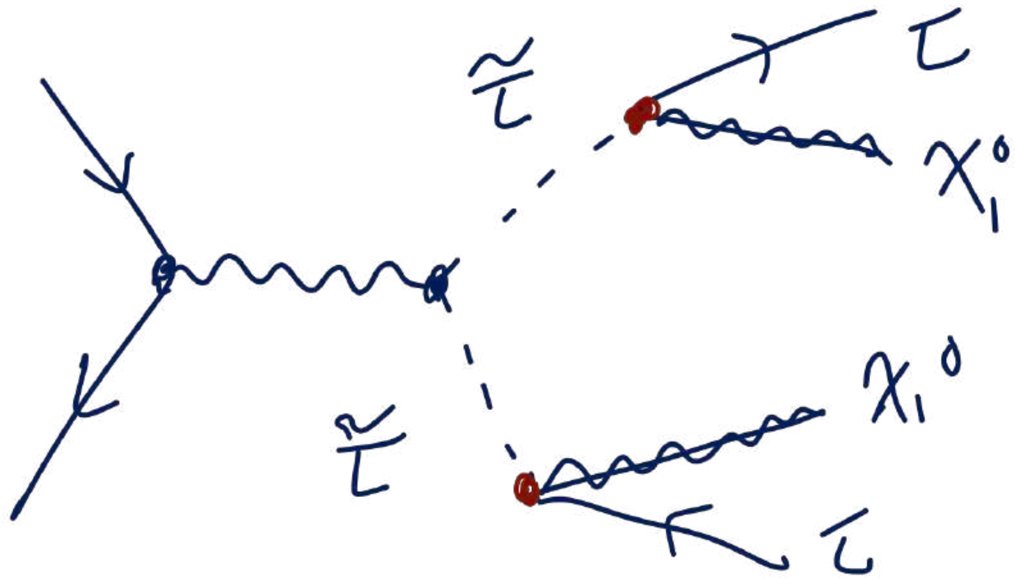
Requires MET > 150 GeV

inefficient
for π_D

Current LHC searches with these final states:

- often involve extra MET

e.g.



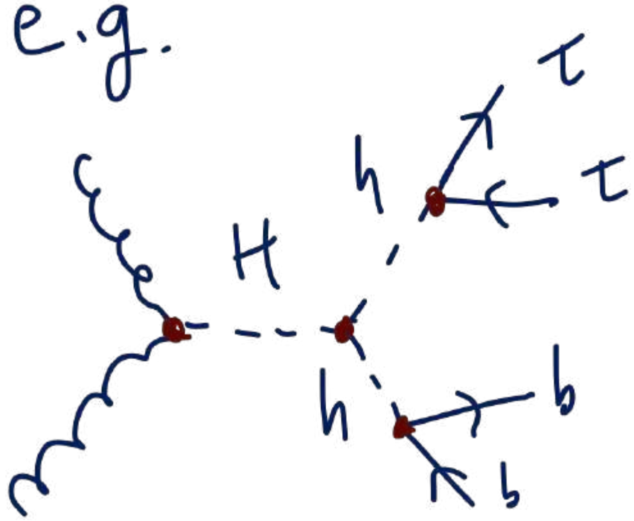
ATLAS-CONF-2016-093

Requires MET > 150 GeV

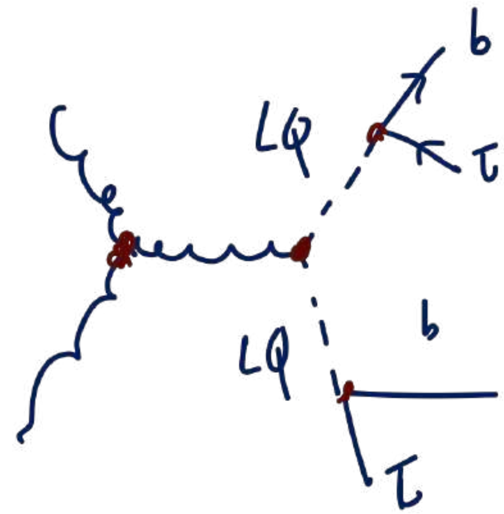
inefficient for π_D

- or assume the wrong resonance structure

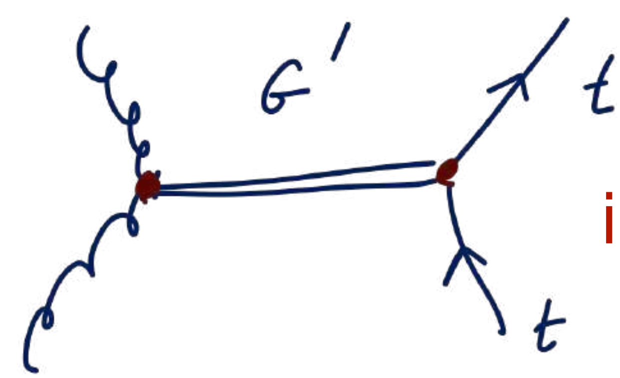
e.g.



CMS: 1707.02909



CMS 1408.0806



ATLAS 1505.07018

inefficient for π_D

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 (yet!)

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

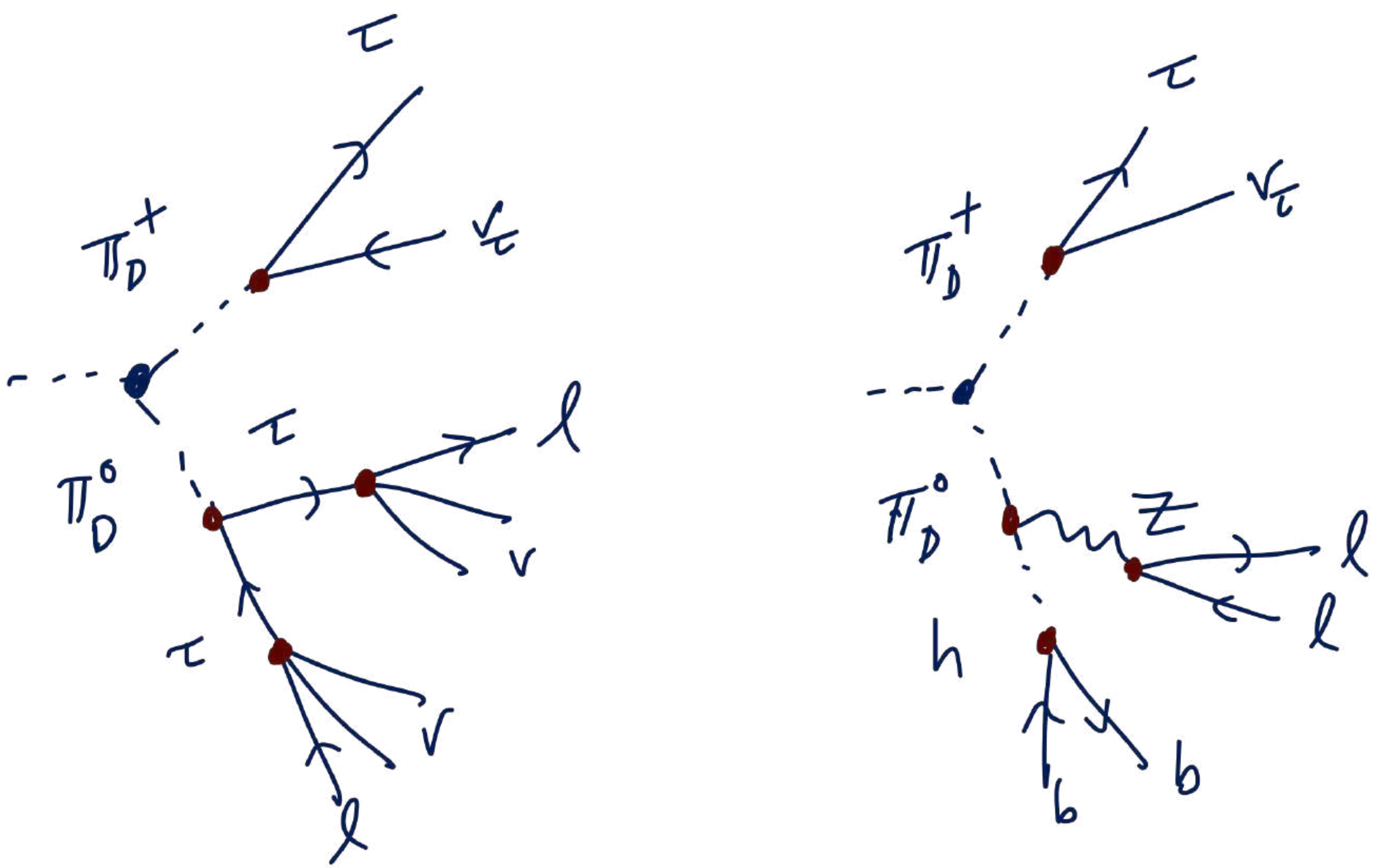
Same sign leptons:

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

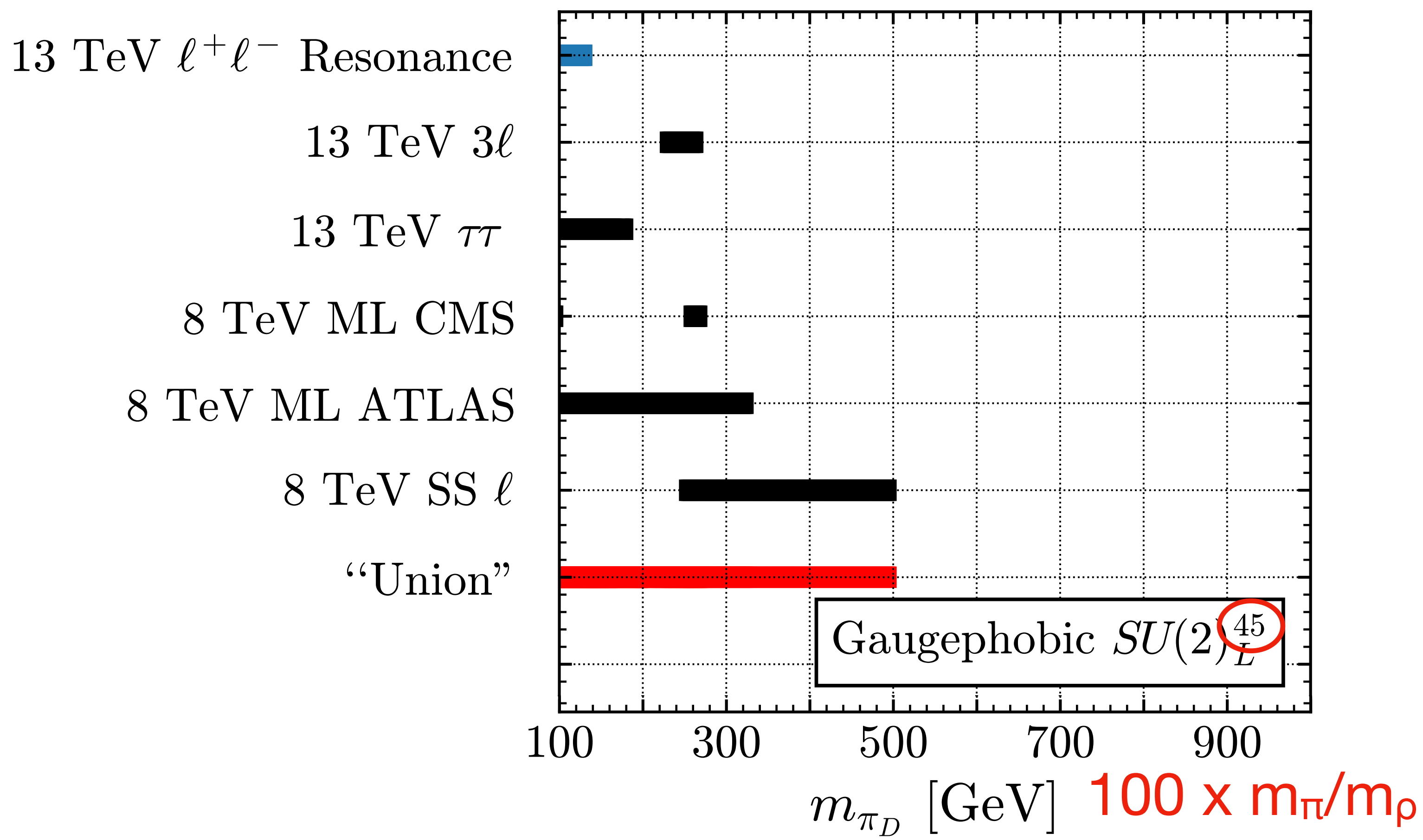
Why do these searches work?

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

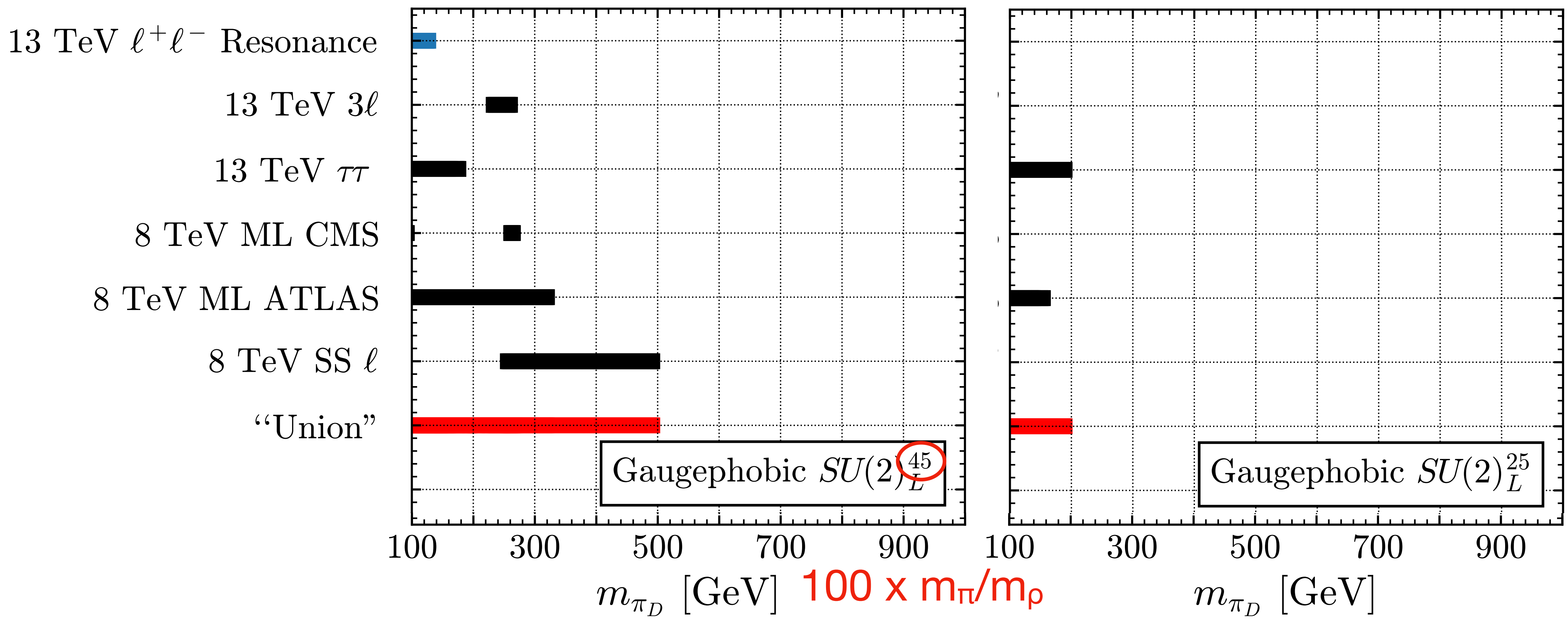


No such possibility with $\pi^+_D\,\pi^-_D$

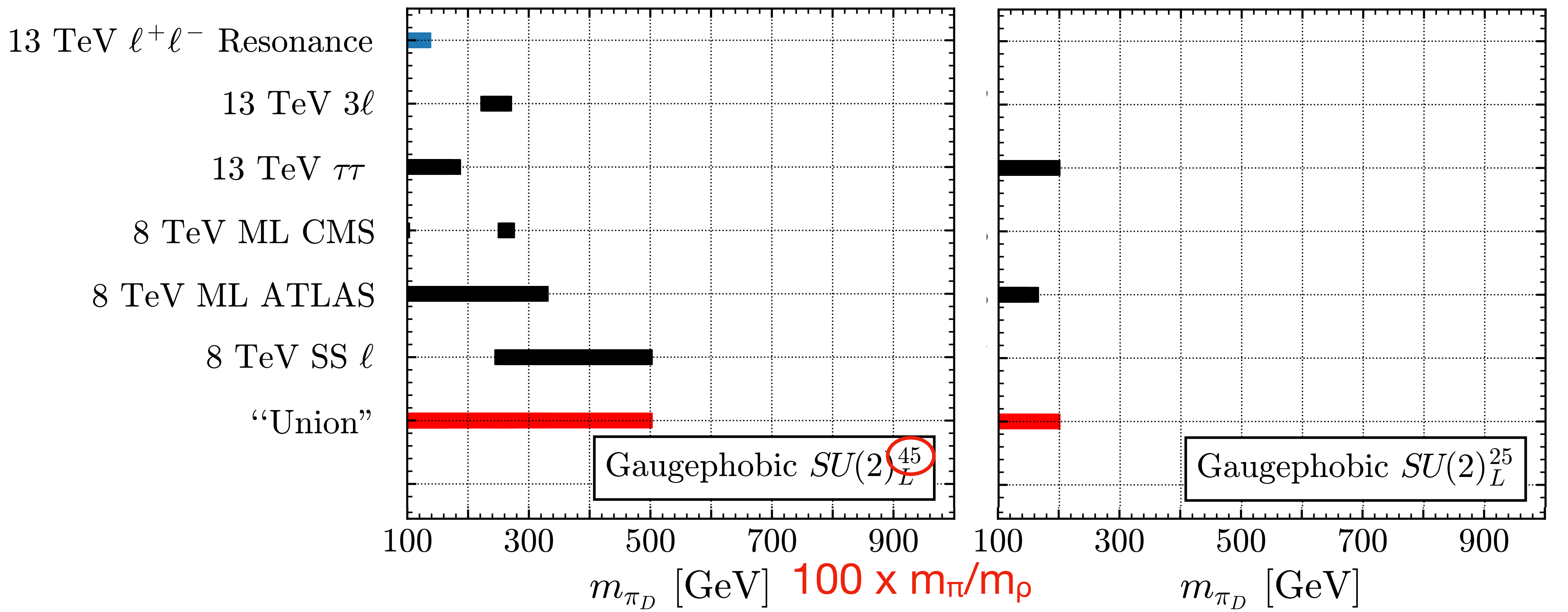
Combination



Combination



Combination

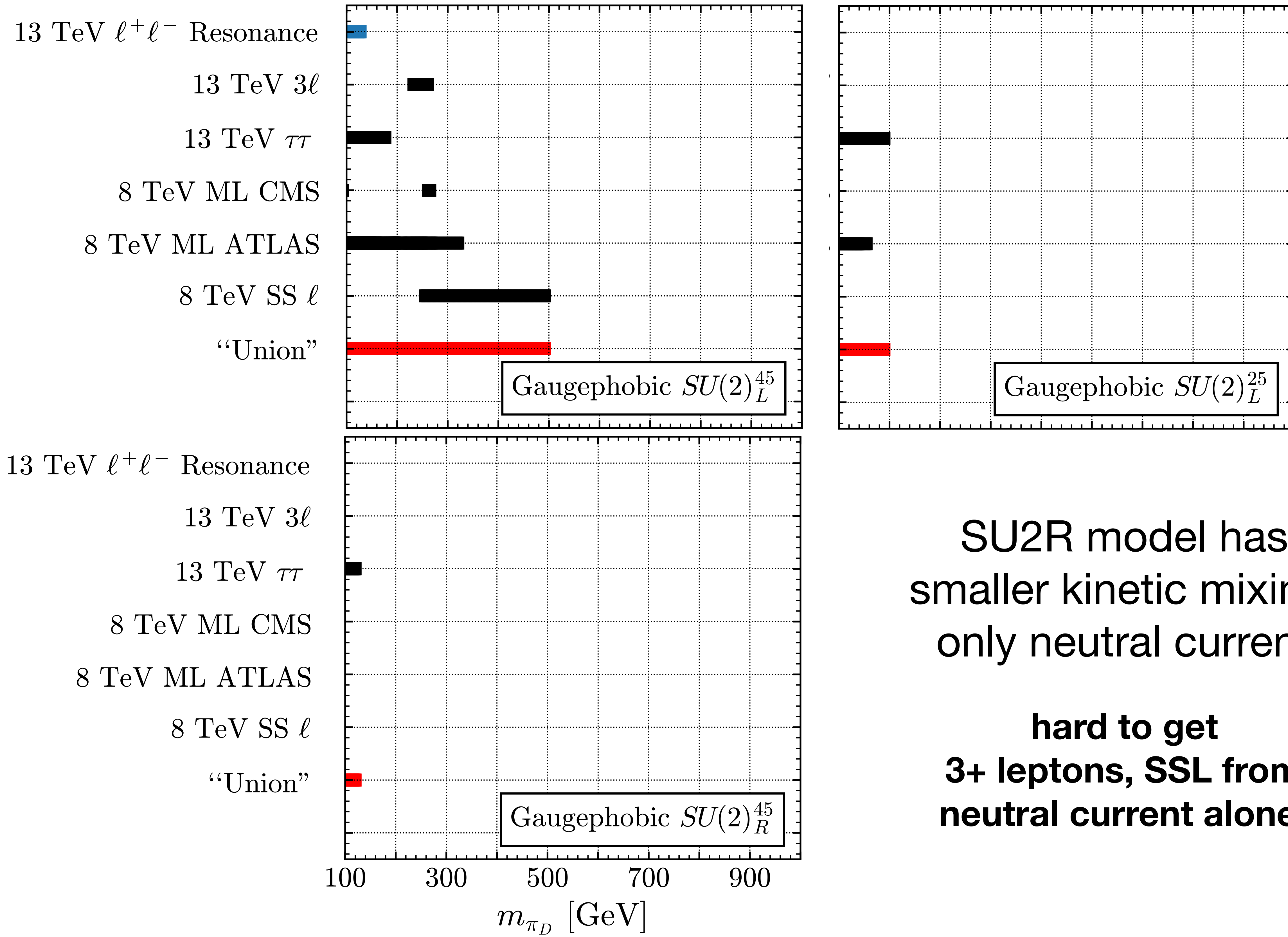


Decreasing $m_{\pi D}/m_{\rho D}$, fixed $m_{\pi D}$ means heavier ρ_D, smaller resonant piece of cross section

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

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

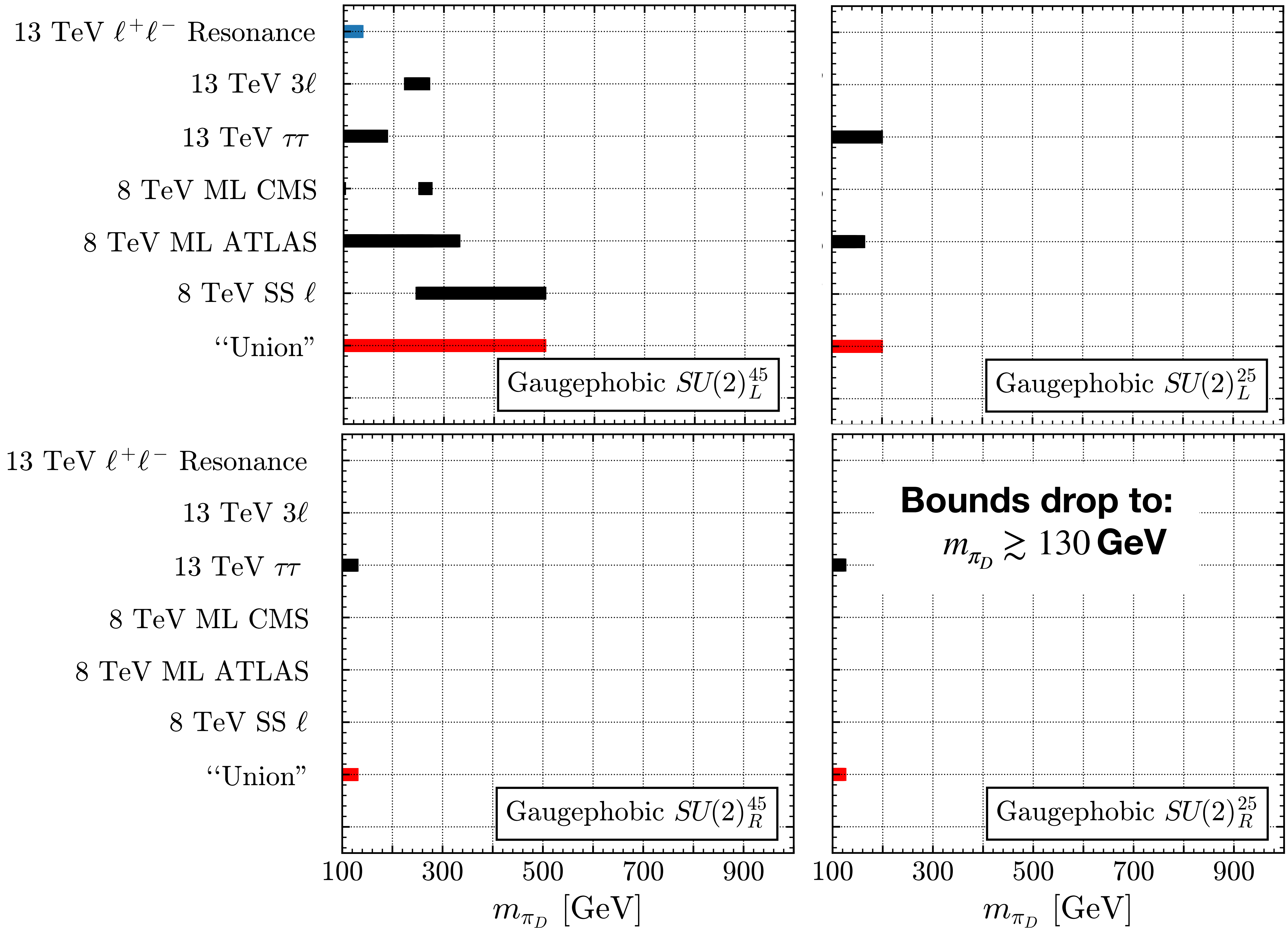
Combination



SU2R model has smaller kinetic mixing, only neutral current

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

Combination



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 ! Motivated by 'stealthy DM' but more general statement

- 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)

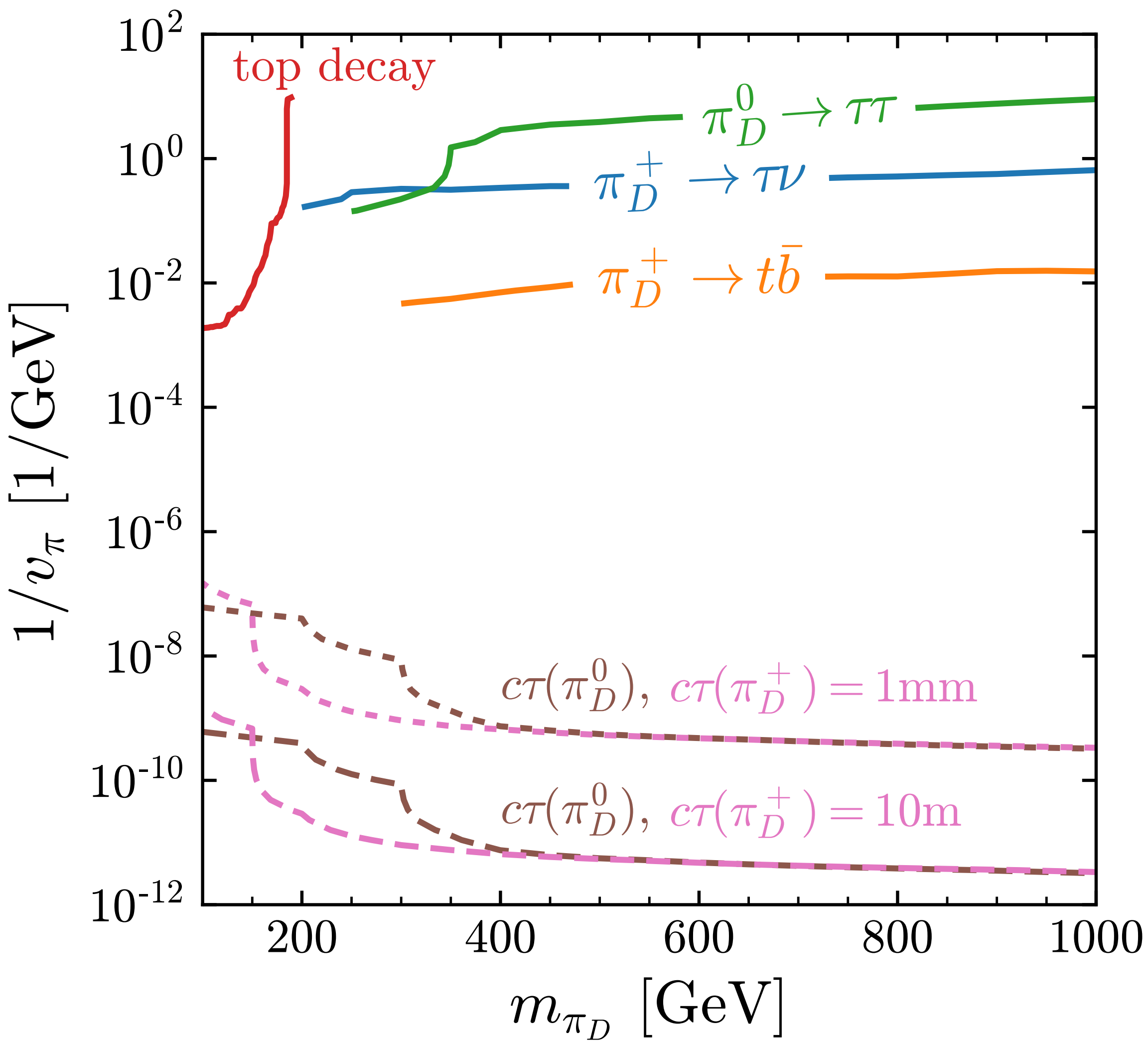
- limits are especially weak ($m_{\pi D} \gtrsim 130$ GeV) in scenarios where lightest composites are SU2 singlets (SU(2)R setup)

Finally: be very careful opening Uber doors!

Thank you!

EXTRA

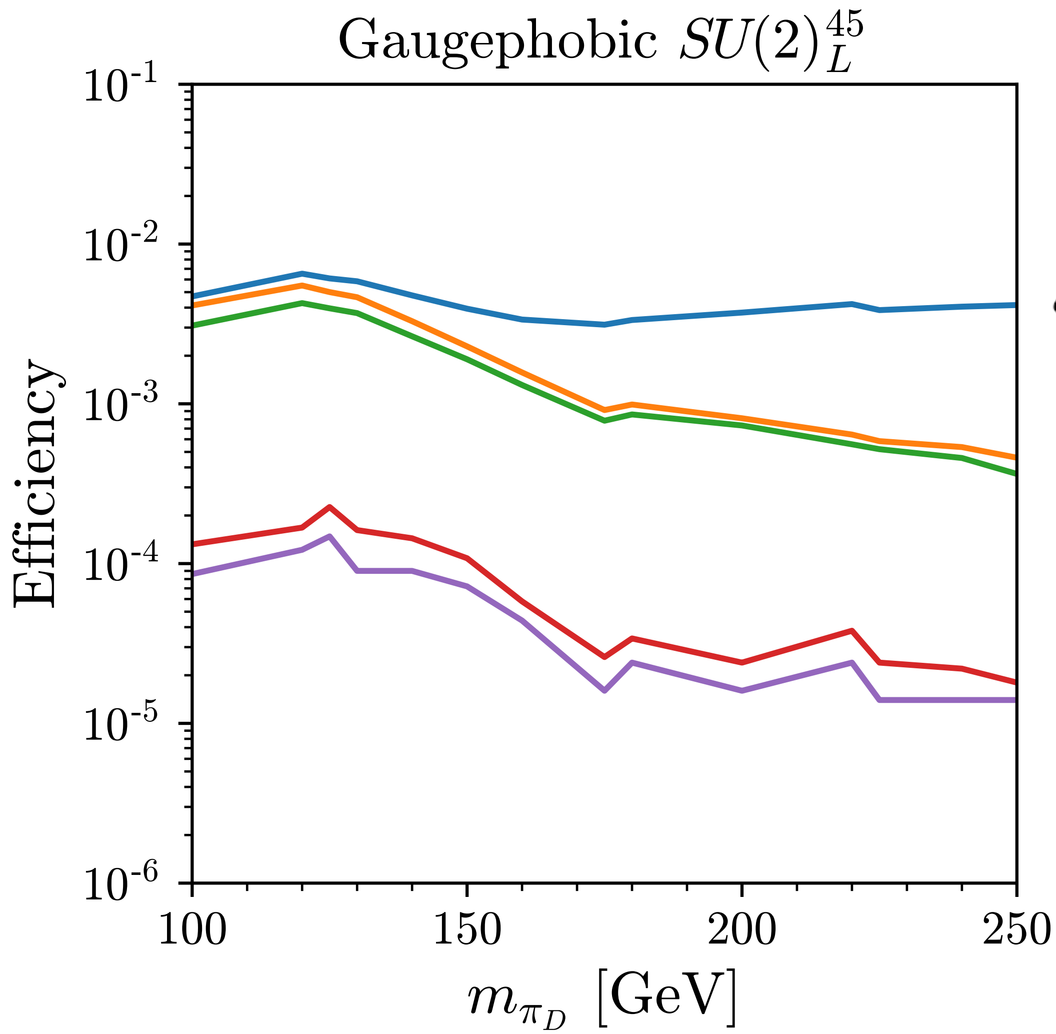
Single production/top decay limits on π_D



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



basic event requirements

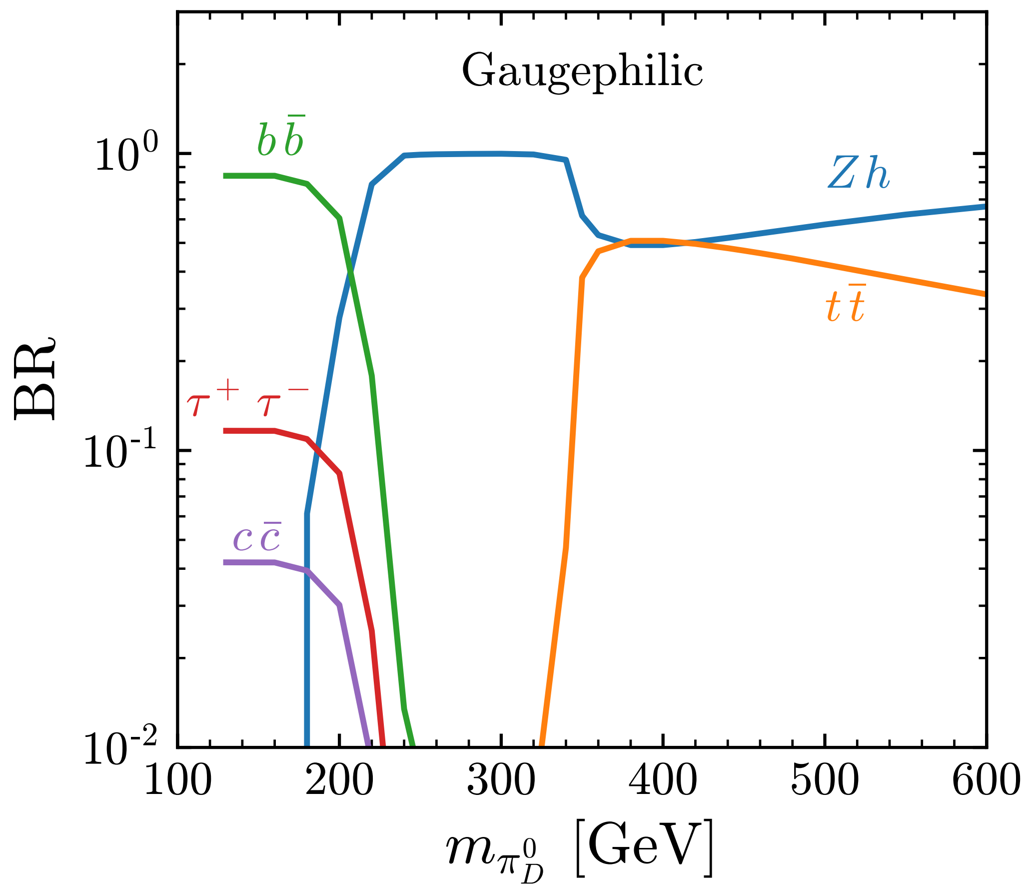
b, Z veto

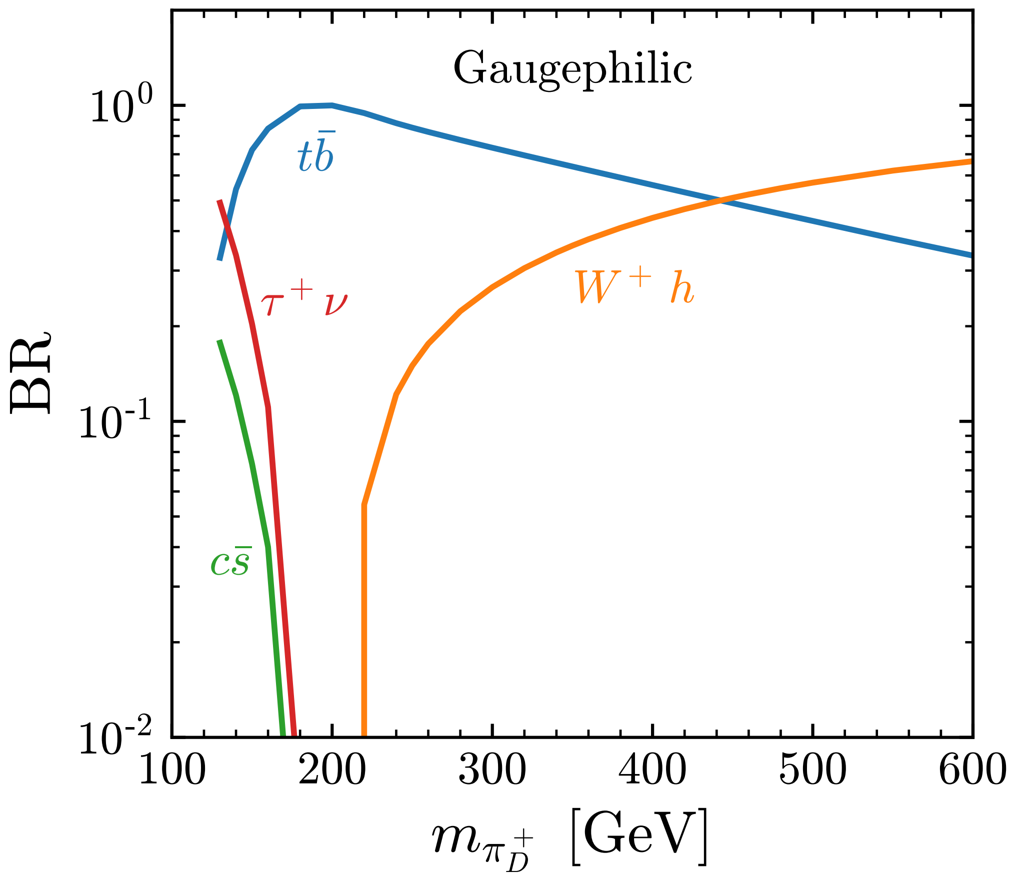
MET cut, mT cut

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

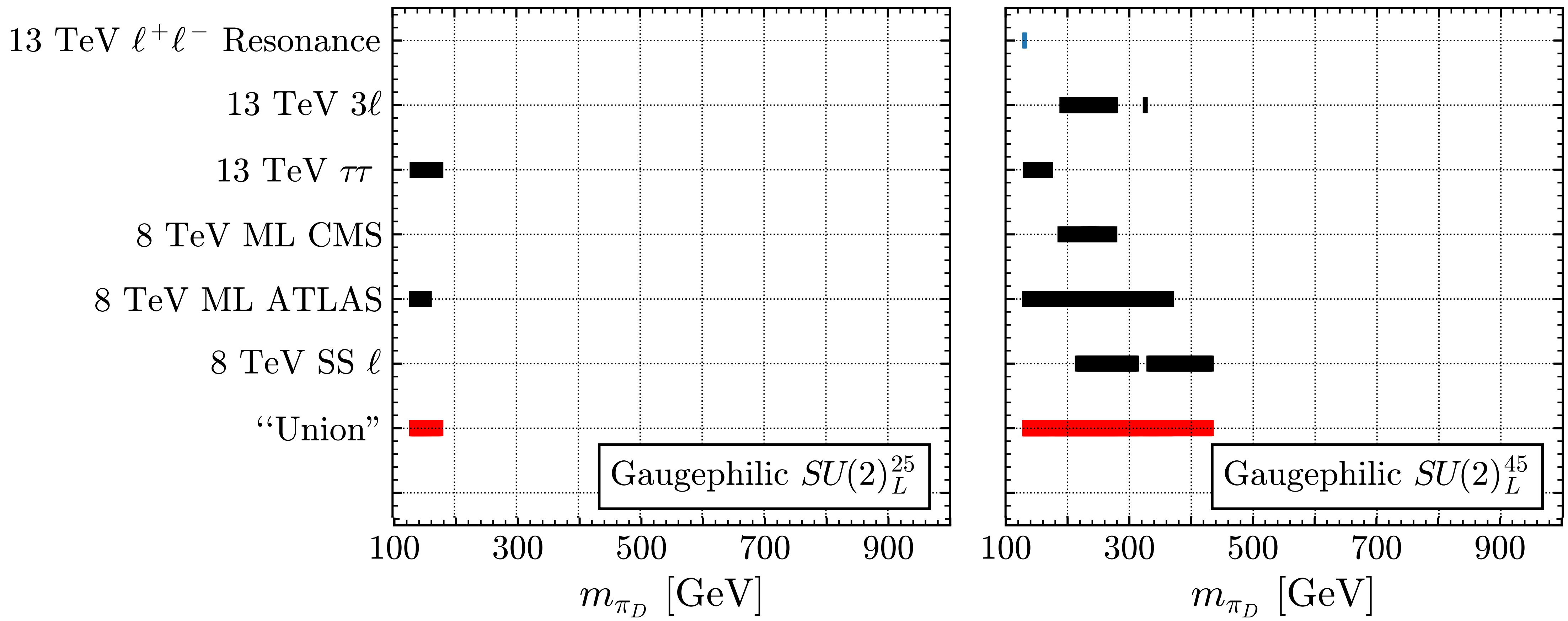
(3,3) → 1 + 3 + 5 once EWSB occurs (& custodial symmetry broken)

focus on BR and limits of triplet





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

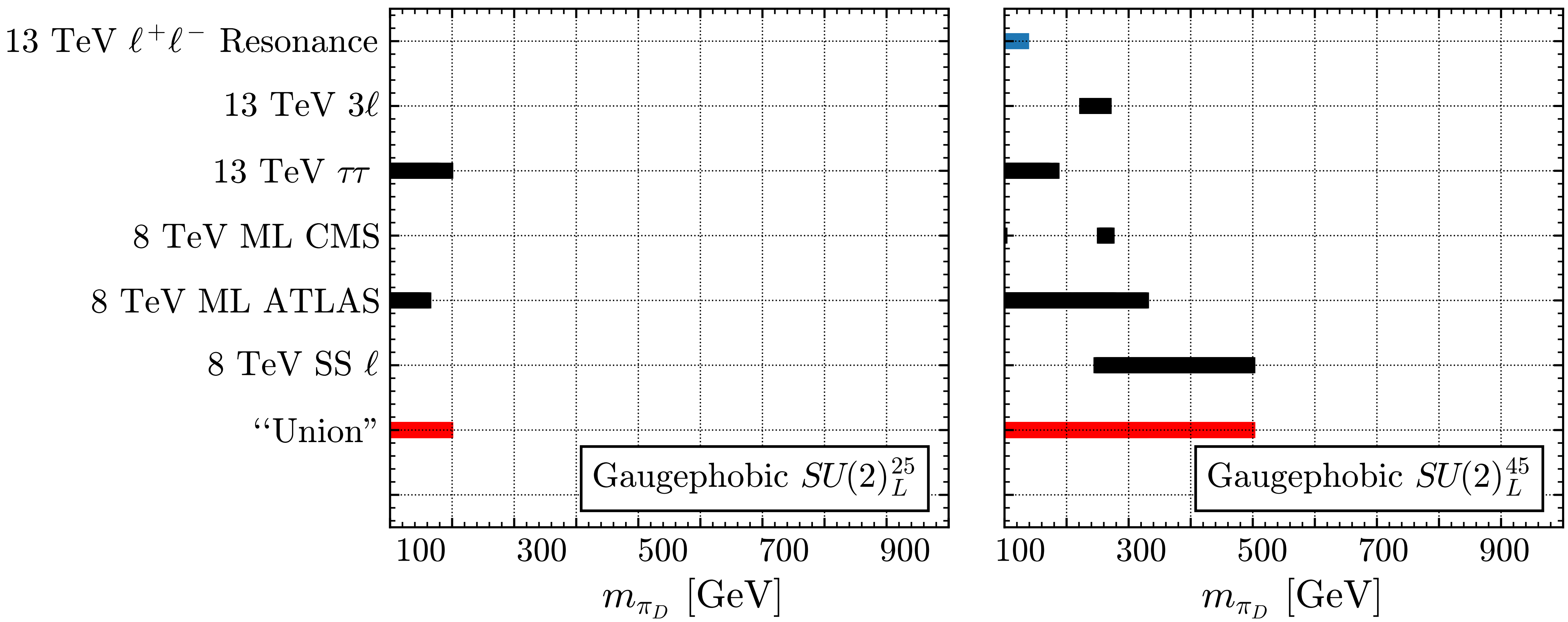


Limits are actually slightly weaker*

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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