New sensitivity of LHC measurements to composite dark matter model

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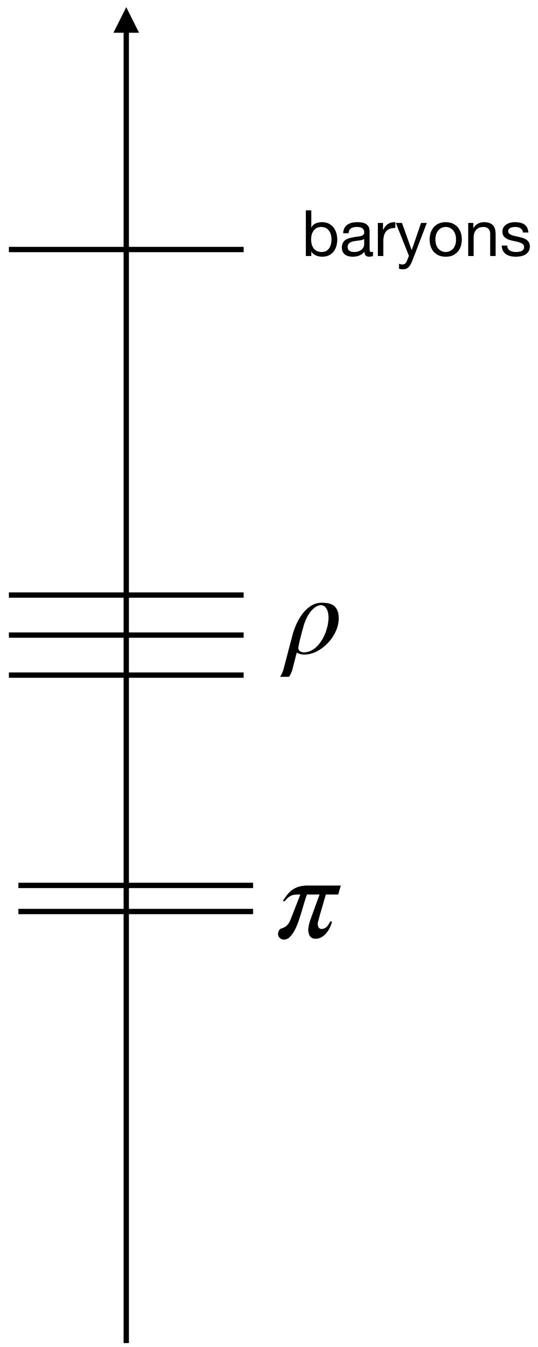
Composite dark matter scenarios

Appelquist et al arXiv:1402.6656

Spectrum



What if dark matter is a composite particle arising from non-Abelian dynamics?

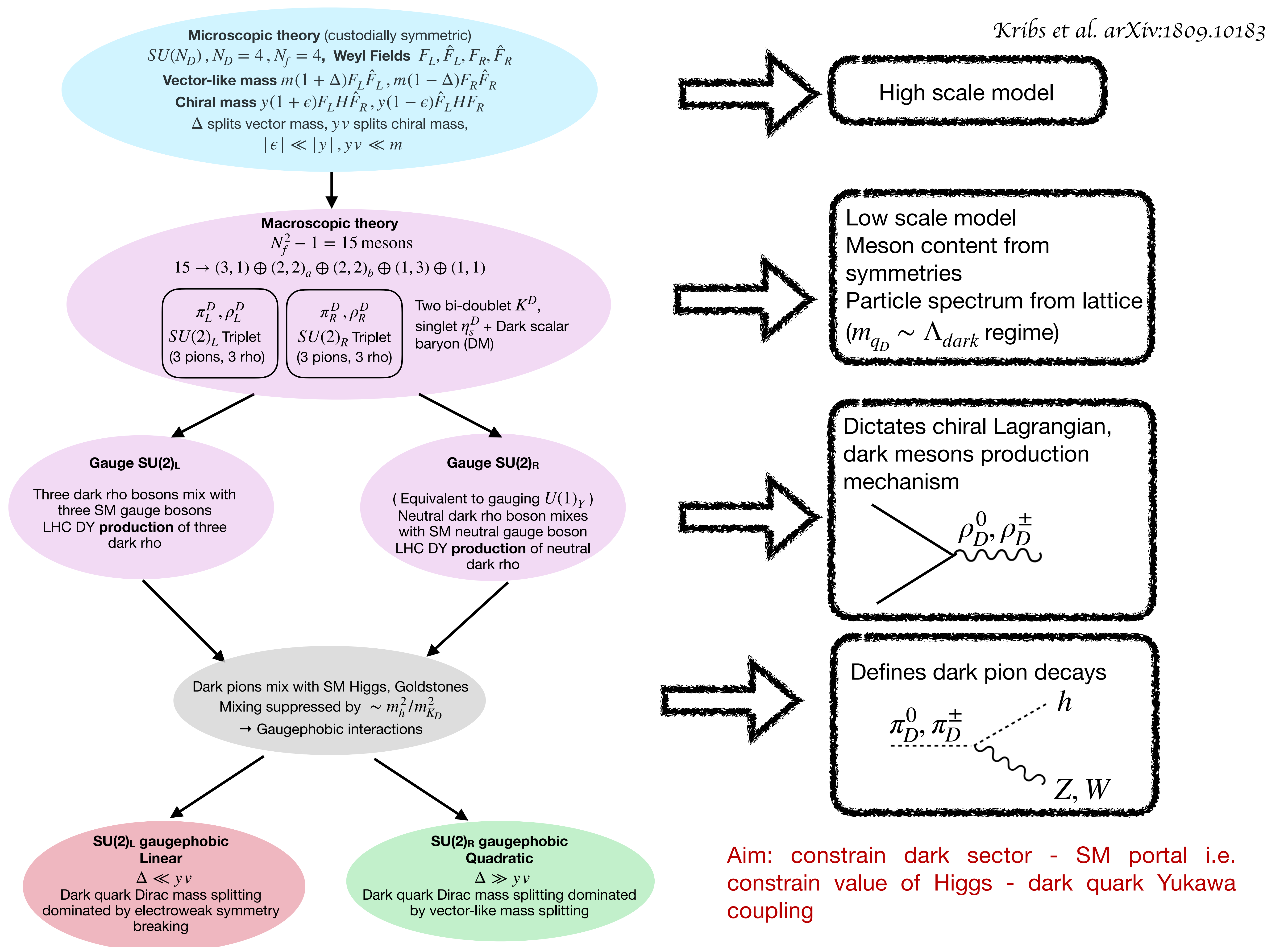
Theory under consideration: $SU(N_D)$ [$N_D = 4$, $N_f = 4$] gauge theory - confines at

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

Low energy theory: bound states of mesons and baryons, masses computed by lattice

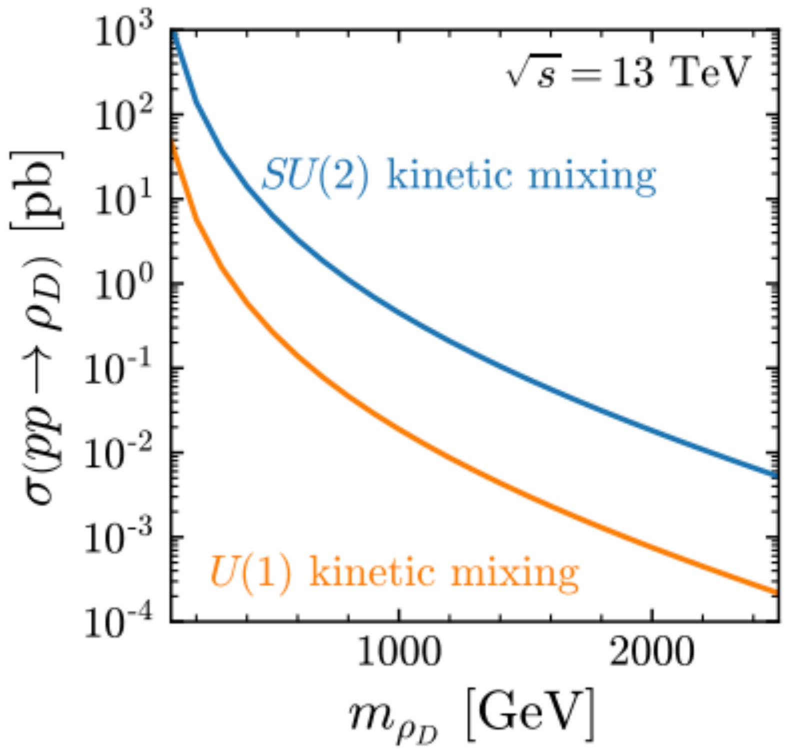
Dark fermions transform under electroweak part of the Standard Model

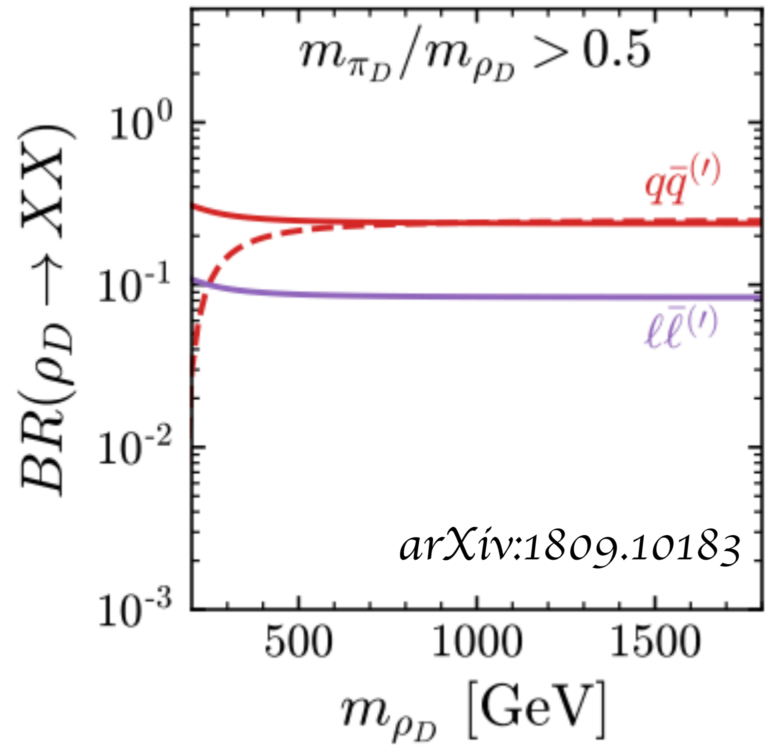
Important: Lattice does not predict absolute masses but bound state mass in terms of common mass scale of free choice

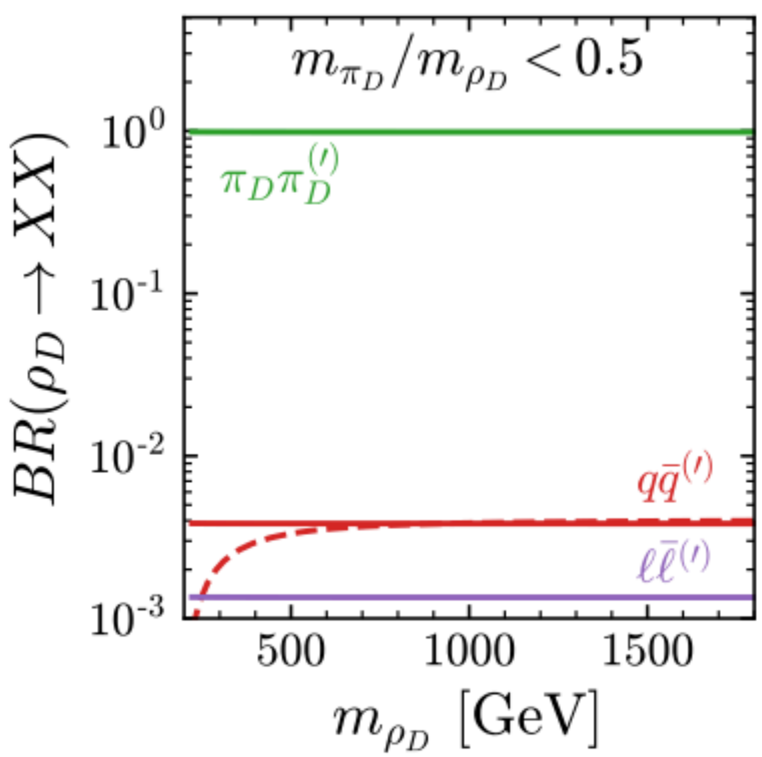


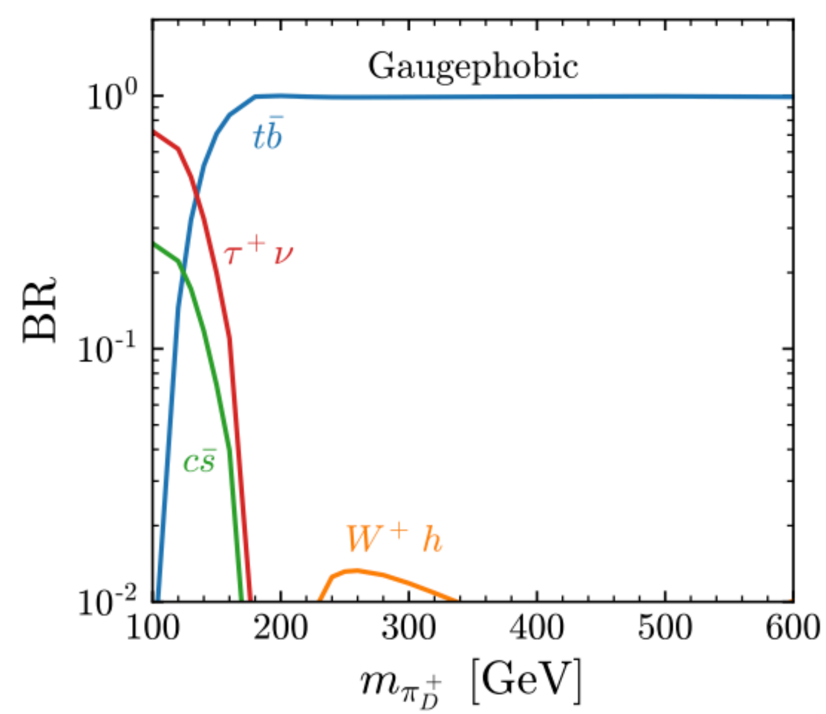
Kribs et al. arXiv:1809.10183
Microscopic theory (custodially symmetric)
$SU(N_D)$, $N_D = 4$, $N_f = 4$, Weyl Fields $F_L, \hat{F}_L, F_R, \hat{F}_R$
Vector-like mass $m(1+\Delta)F_L\hat{F}_L$, $m(1-\Delta)F_R\hat{F}_R$
Chiral mass $y(1+\epsilon)F_L H\hat{F}_R$, $y(1-\epsilon)\hat{F}_L H F_R$
Δ splits vector mass, yv splits chiral mass,
$|\epsilon| \ll |y|$, $yv \ll m$
High scale model
Macroscopic theory
$N_f^2 - 1 = 15$ mesons
$15 \to (3,1) \oplus (2,2)_a \oplus (2,2)_b \oplus (1,3) \oplus (1,1)$
π_L^D, ρ_L^D
$SU(2)_L$ Triplet
(3 pions, 3 rho)
π_R^D, ρ_R^D
$SU(2)_R$ Triplet
(3 pions, 3 rho)
Two bi-doublet K^D, singlet η_s^D + Dark scalar baryon (DM)
Low scale model
Meson content from symmetries
Particle spectrum from lattice
($m_{q_D} \sim \Lambda_{dark}$ regime)
Gauge SU(2)L
Three dark rho bosons mix with three SM gauge bosons
LHC DY production of three dark rho
Gauge SU(2)R
(Equivalent to gauging $U(1)_Y$)
Neutral dark rho boson mixes with SM neutral gauge boson
LHC DY production of neutral dark rho
Dictates chiral Lagrangian, dark mesons production mechanism
$\rho_D^0, \rho_D^\pm$
Dark pions mix with SM Higgs, Goldstones
Mixing suppressed by $\sim m_h^2/m_{K_D}^2$
→ Gaugephobic interactions
Defines dark pion decays
$\pi_D^0, \pi_D^\pm$
h
Z, W
SU(2)L gaugephobic
Linear
$\Delta \ll yv$
Dark quark Dirac mass splitting dominated by electroweak symmetry breaking
SU(2)R gaugephobic
Quadratic
$\Delta \gg yv$
Dark quark Dirac mass splitting dominated by vector-like mass splitting
Aim: constrain dark sector - SM portal i.e. constrain value of Higgs - dark quark Yukawa coupling

LHC phenomenology



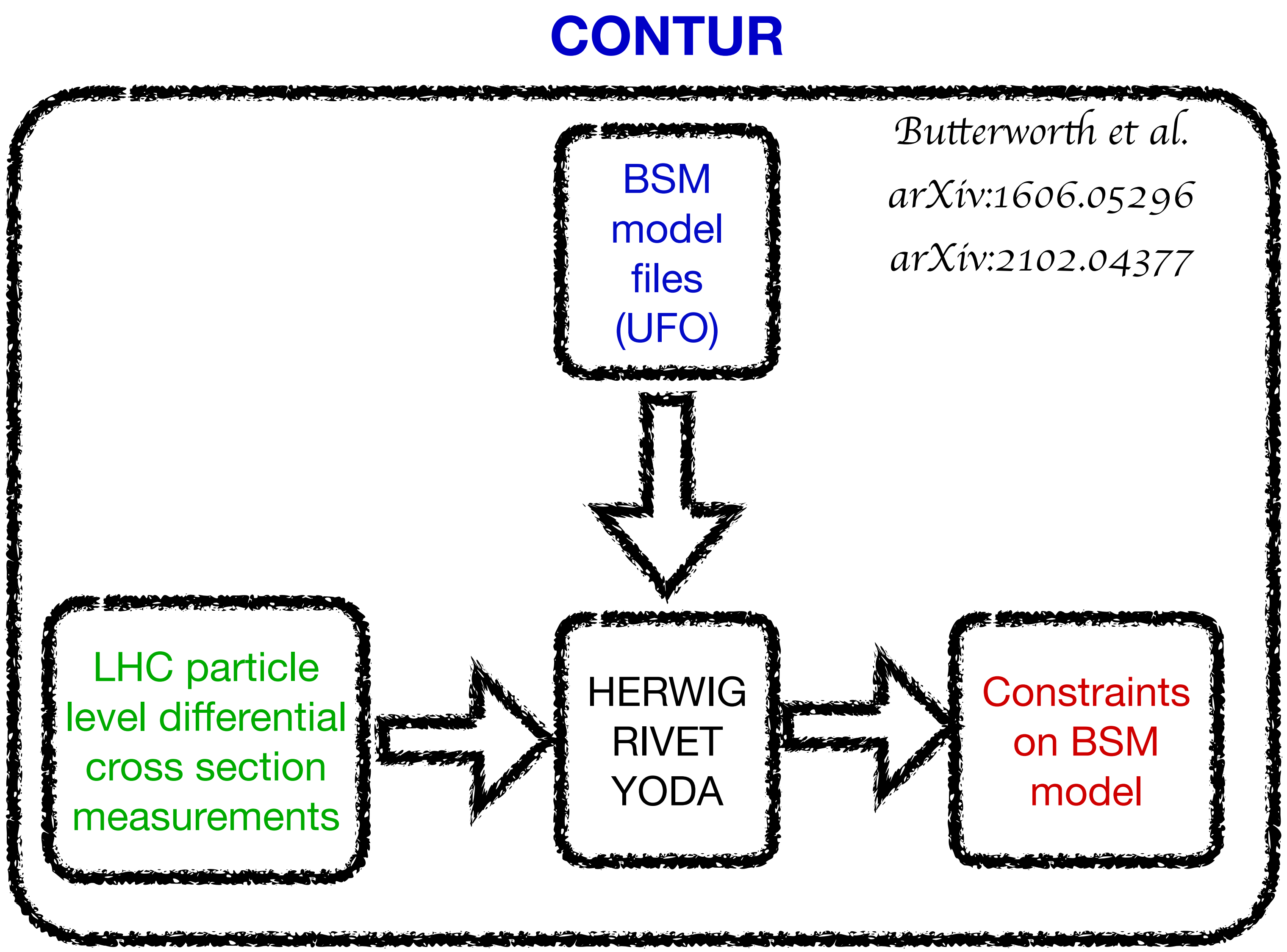


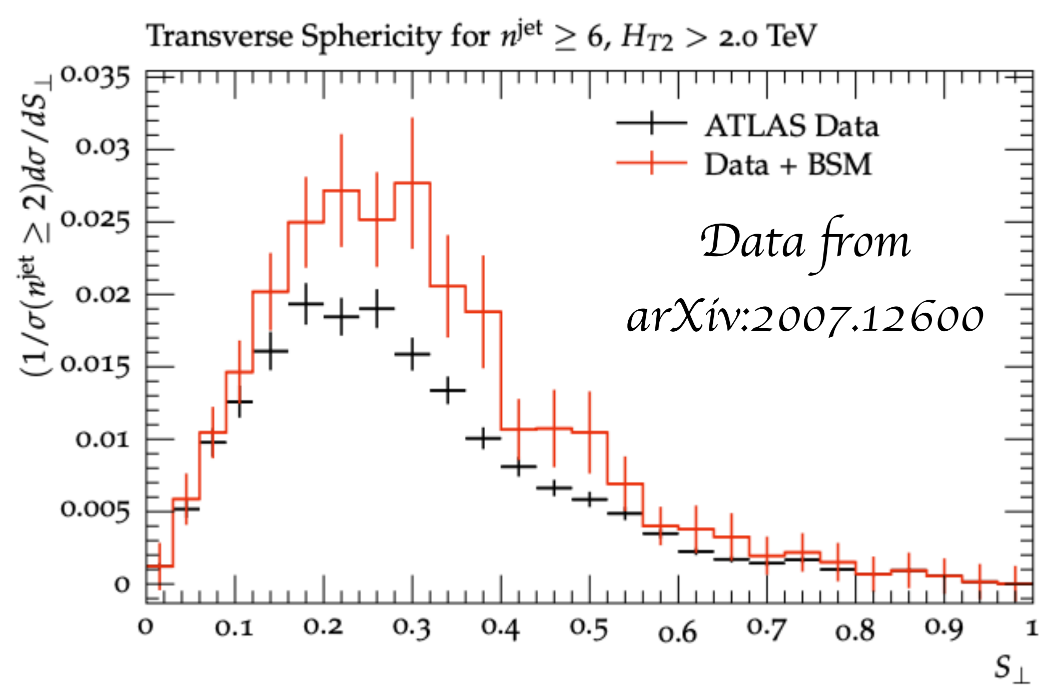




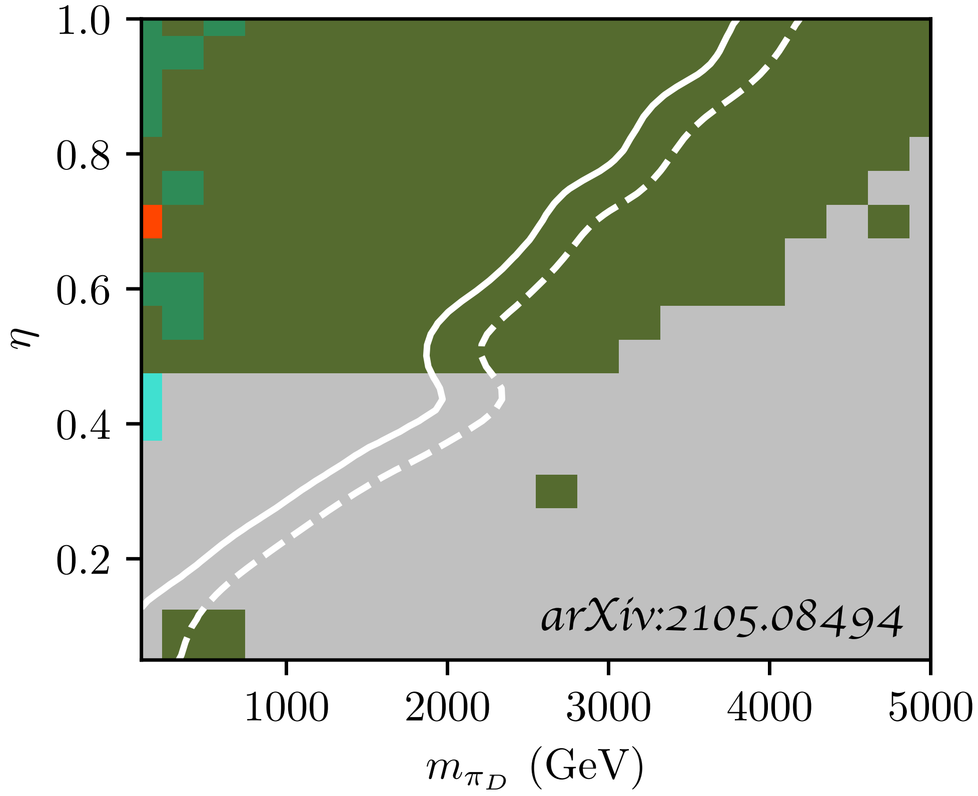
- Dark rho production cross-section depends on which of the triplets is gauged
- If dark rho does not decay to dark pions, dark rho decays to leptons will provide Z' like resonance signature
- If dark rho can decay to dark pion, it will almost always do so
- Dark pion decays feature a variety of final states specially featuring third generation SM fermions

Use Standard Model differential cross-section measurements to exclude presence of signal in phase spaces already compatible with the SM calculations

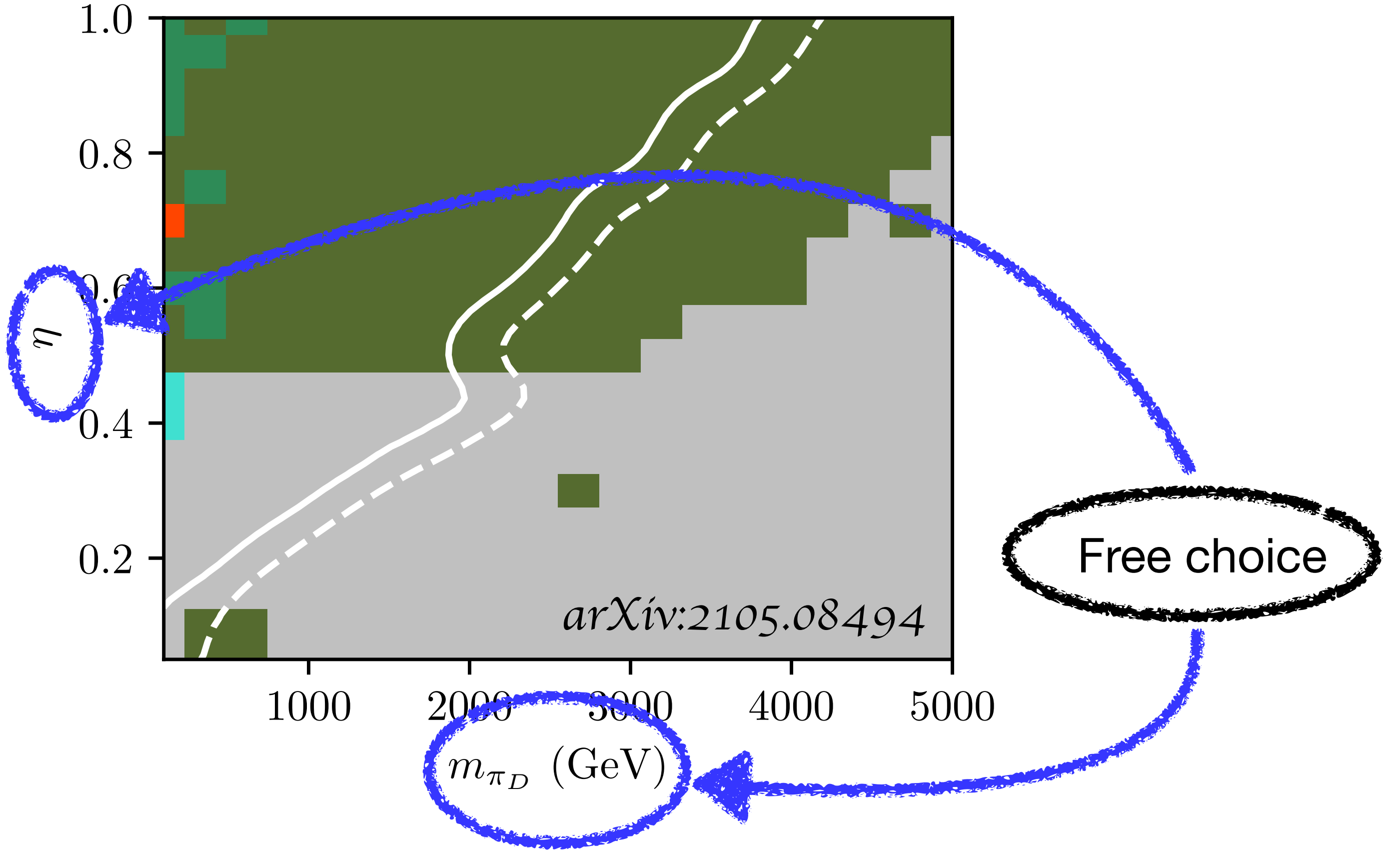




LHC limits from CONTUR



LHC limits from CONTUR



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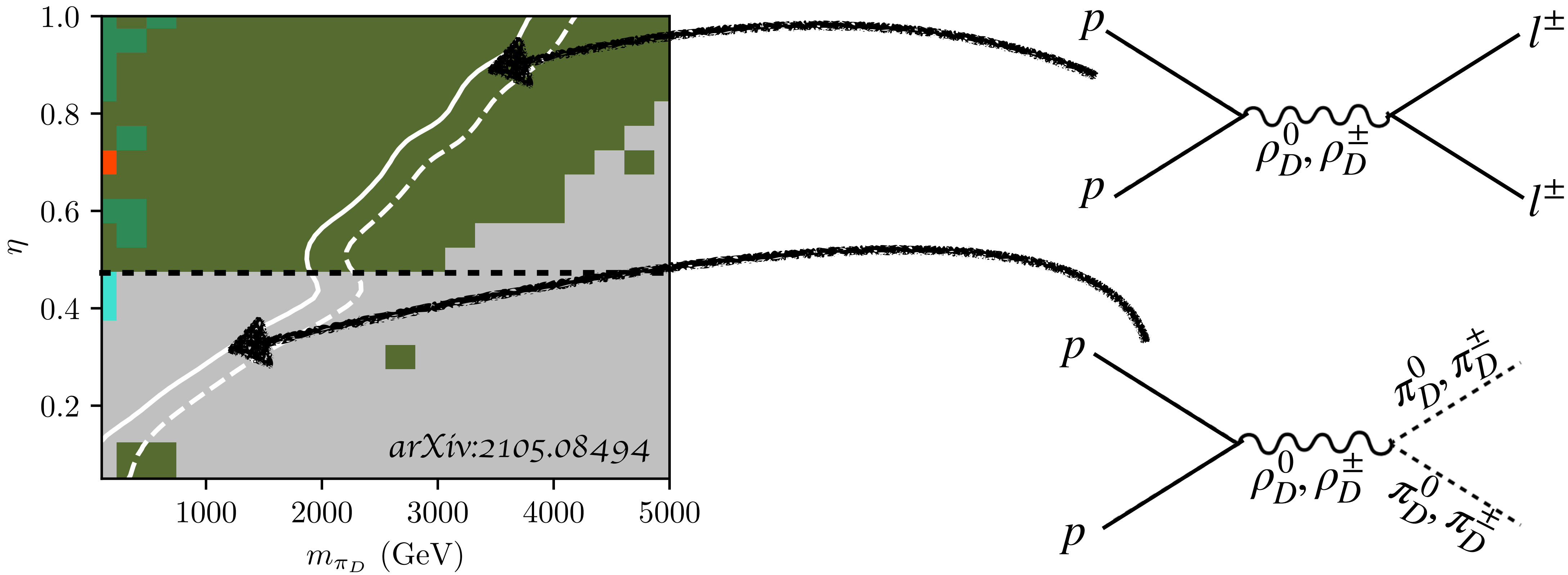

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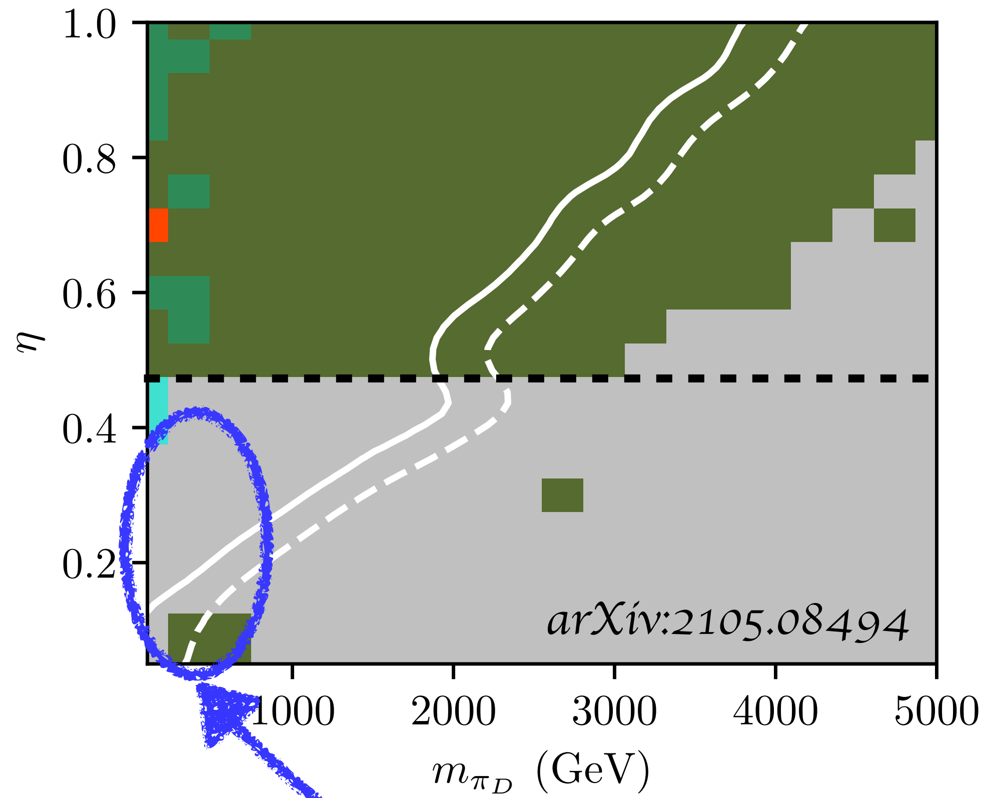
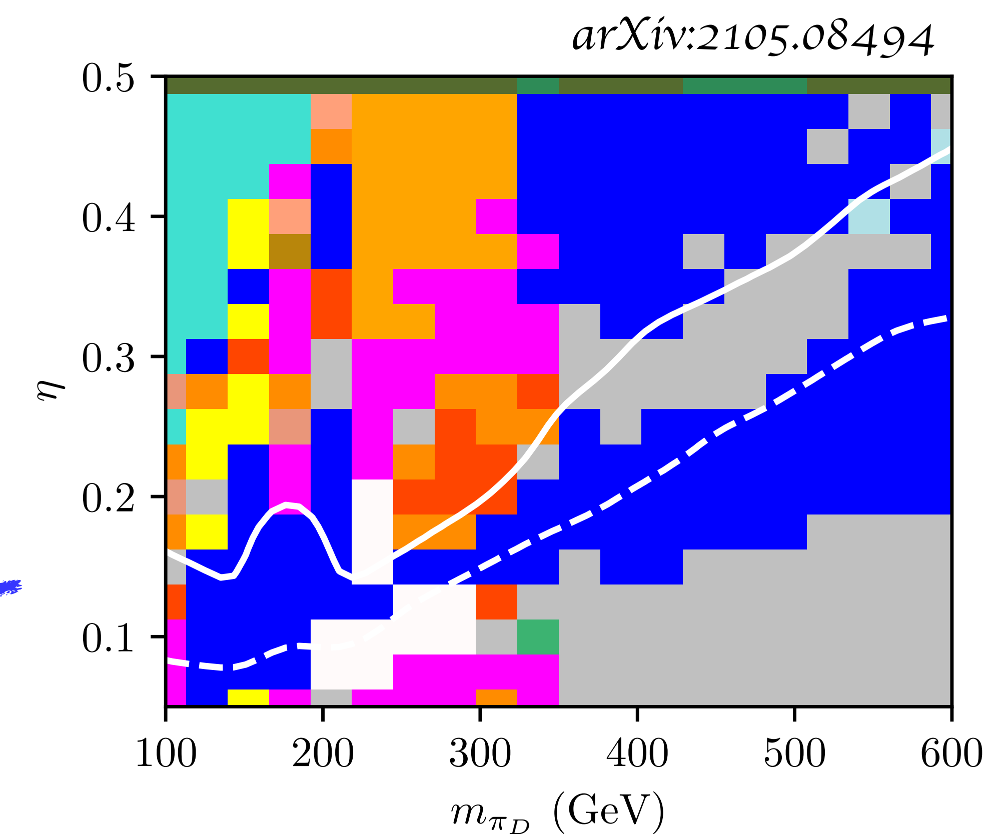
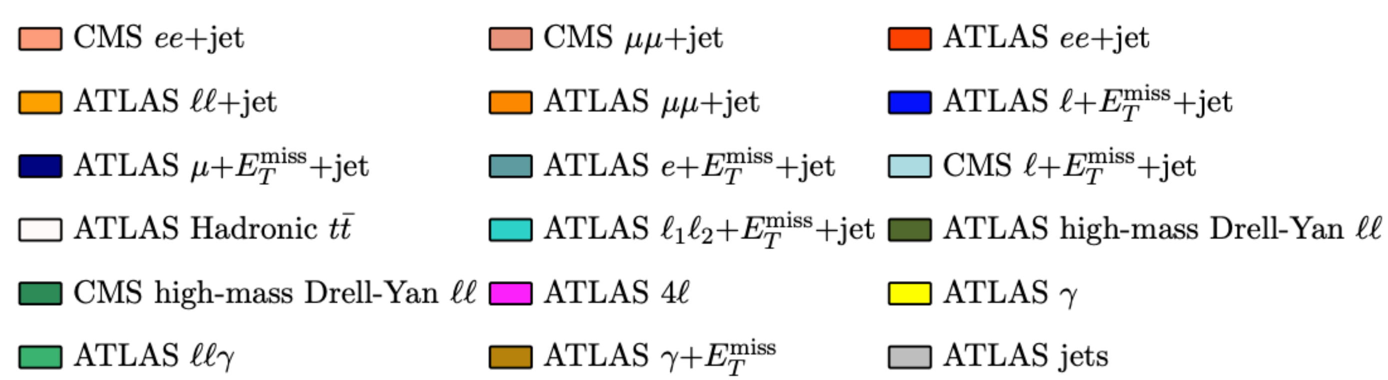


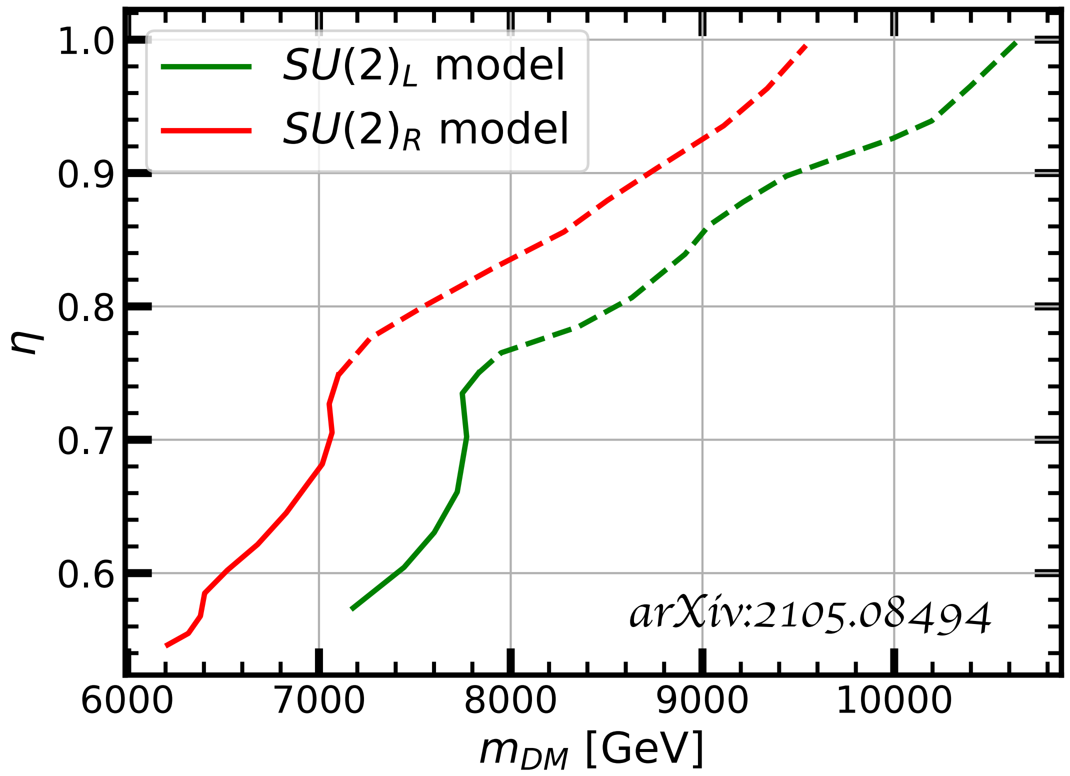


1. Turn off resonance searches
2. Turn off multi-jet analyses which suffers from QCD uncertainties
3. Sensitivity to a variety of other SM differential measurements



Dark matter

See also arXiv:1503.04203

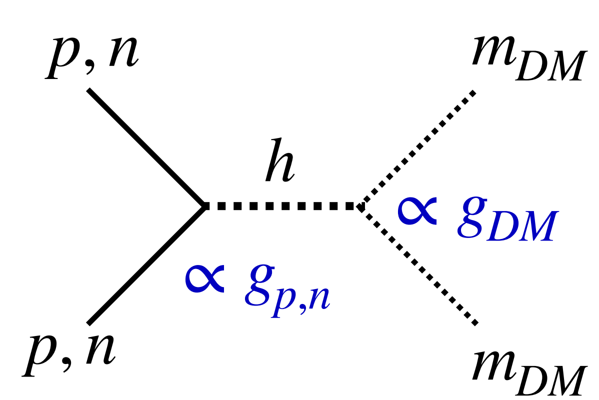


$$m_{\mathrm{DM}}(\eta) = \frac{amS0(\eta)}{amps(\eta)} \times m_{\pi_D}(\eta)$$

- m_{π_D} - excluded dark pion mass from LHC
- $amS0(\eta), amps(\eta)$ predicted by lattice
- LHC exclusions together with the lattice results push the dark matter mass limits to multi-TeV mass range

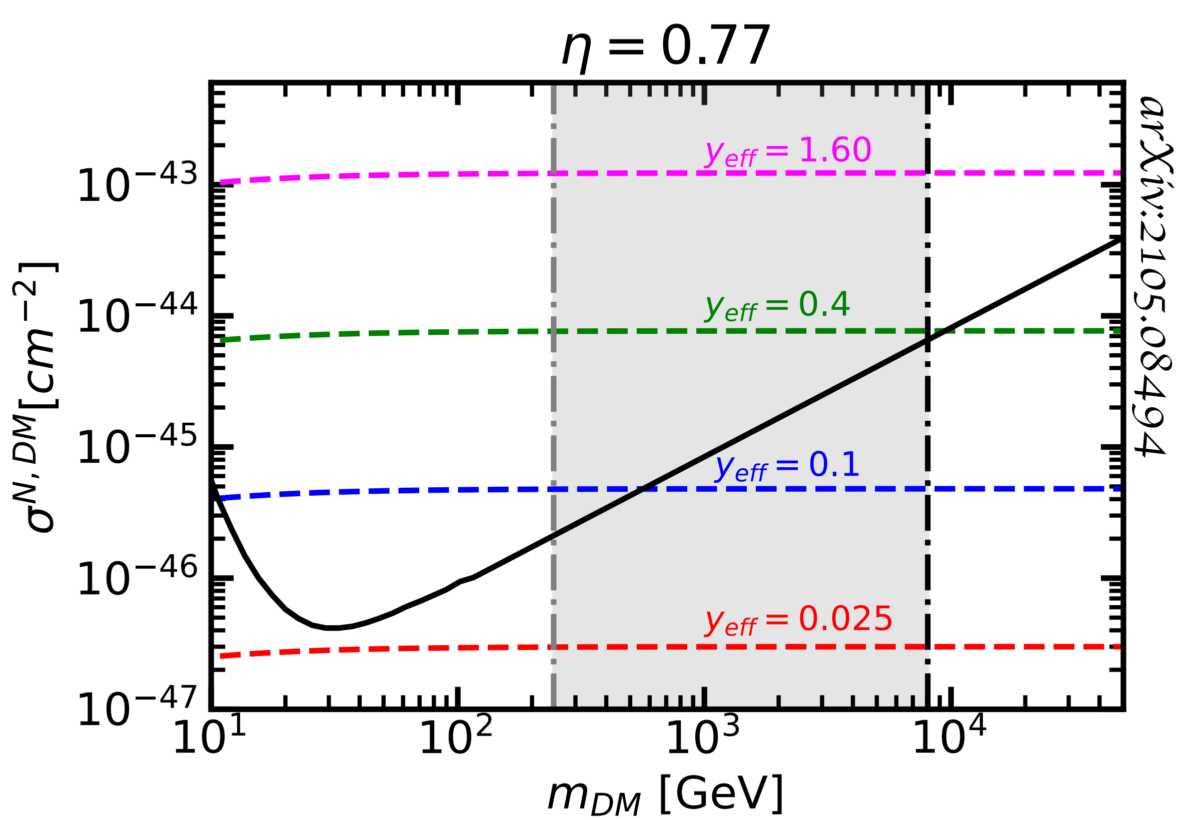
$$\mathcal{M}_{p,n} = \frac{g_{p,n}\, g_{DM}}{m_h^2}$$

$$g_{\mathrm{DM}} \simeq y_{\mathrm{eff}} \times f_f^{\mathrm{DM}}$$



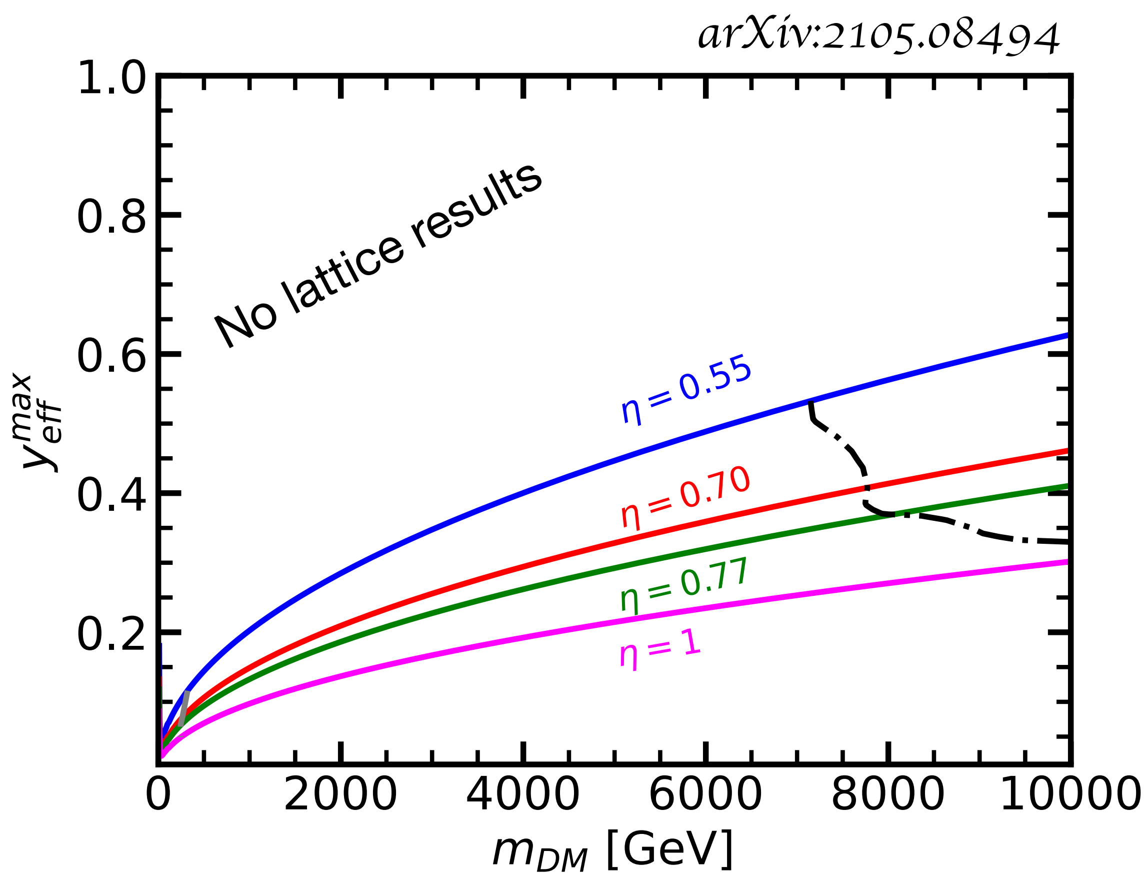
Direct detection limits push dark quark coupling to the Higgs to lower values

How strongly can such model couple with the Higgs?



Combined limits

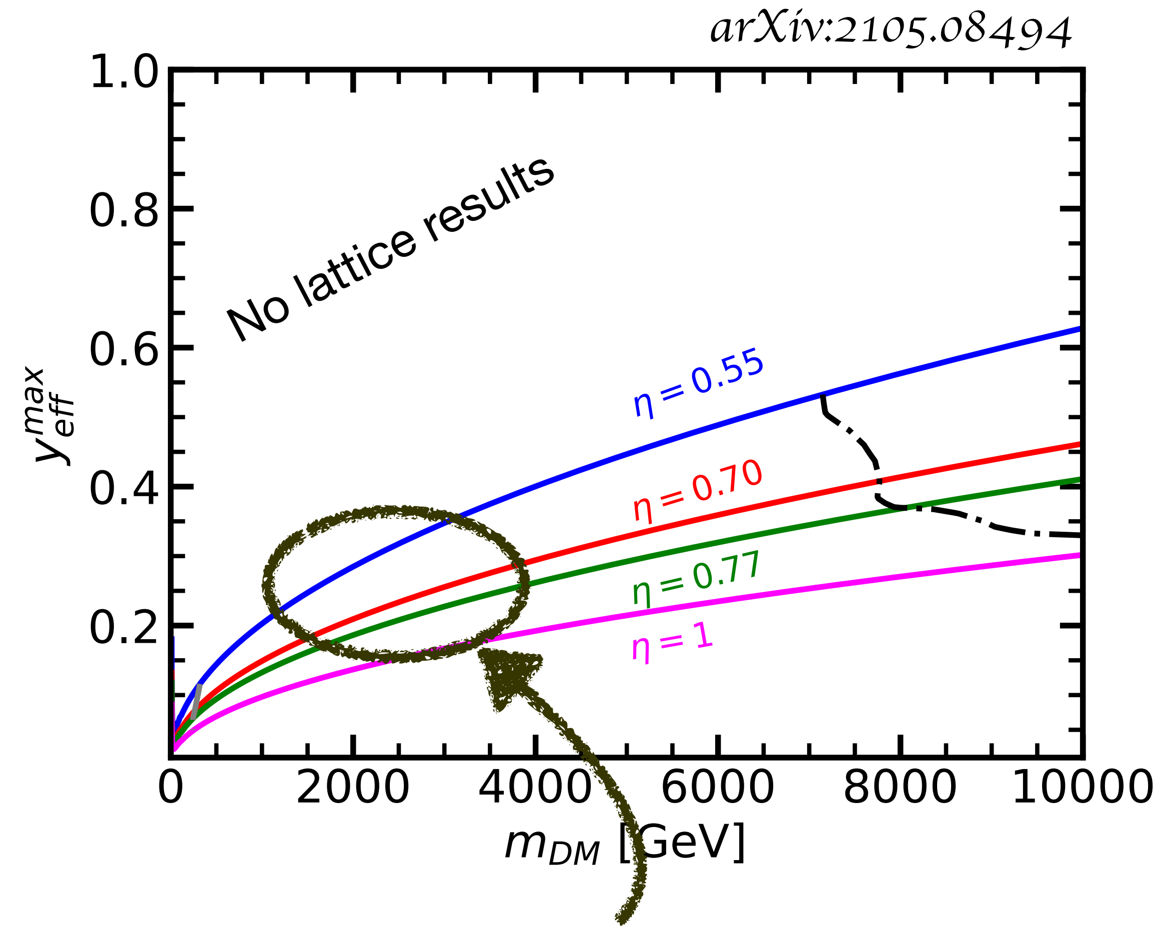
Combination of direct detection limits, LHC measurements and DY searches



Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Combined limits

Combination of direct detection limits, LHC measurements and DY searches

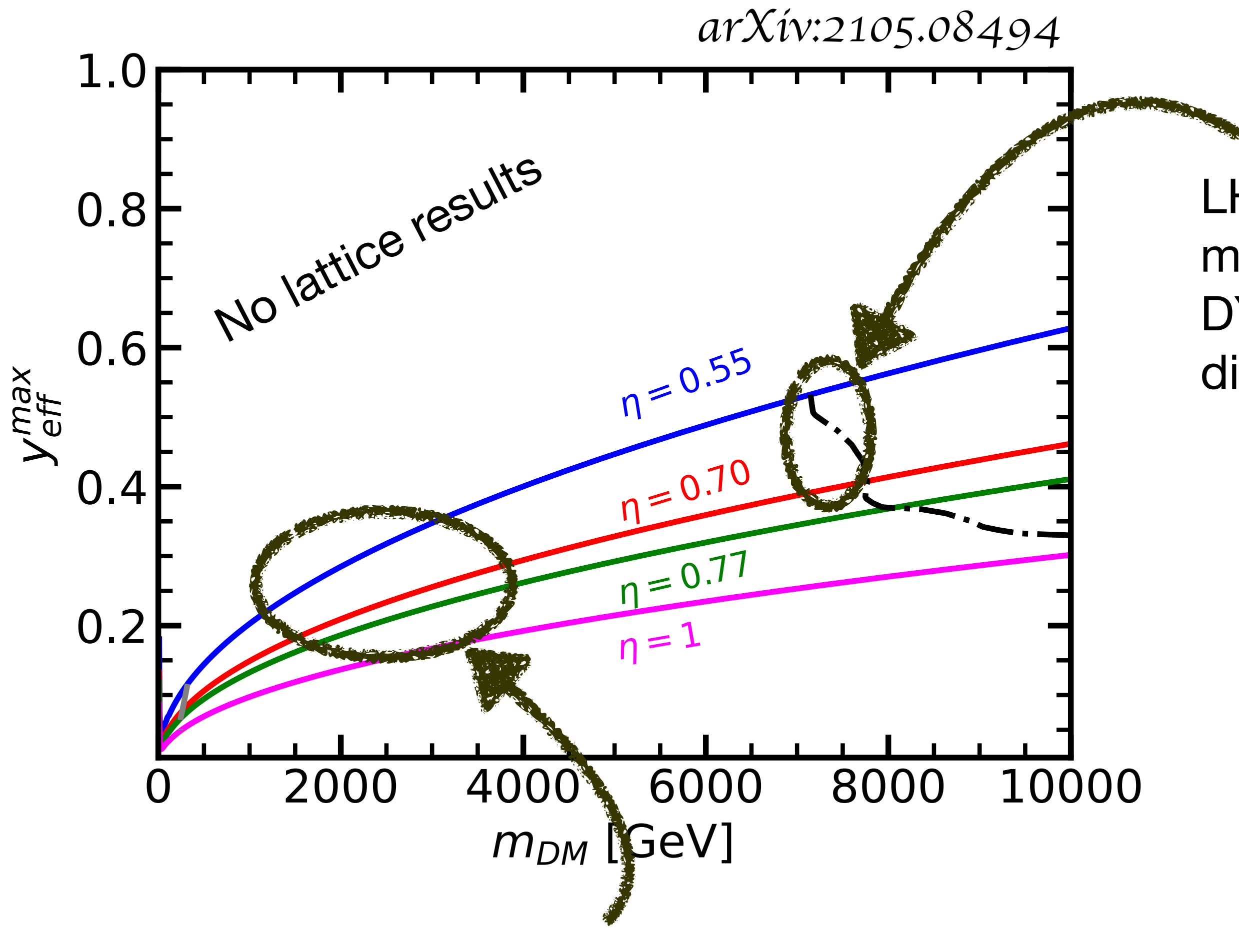


Direct detection only

Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Combined limits

Combination of direct detection limits, LHC measurements and DY searches



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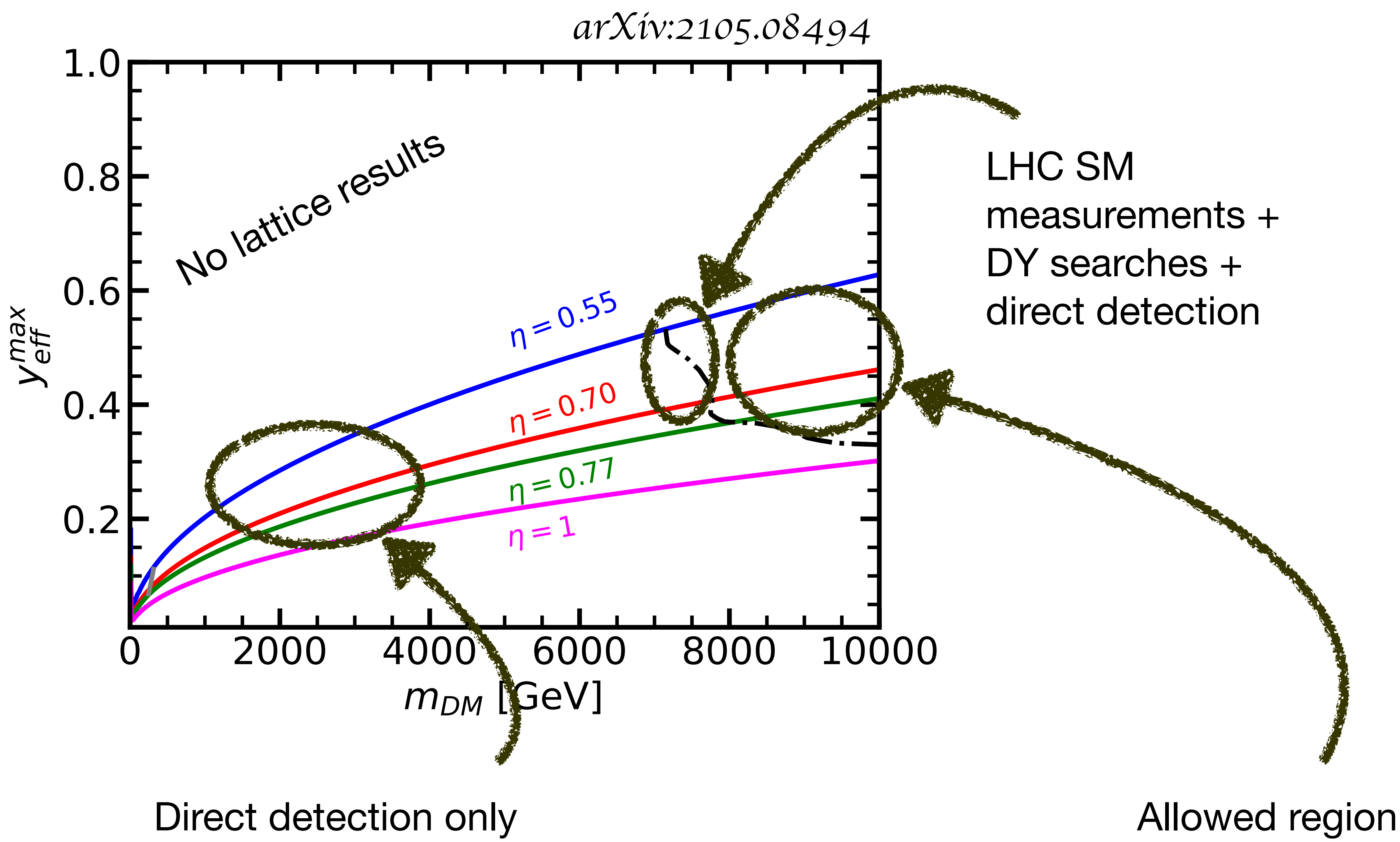


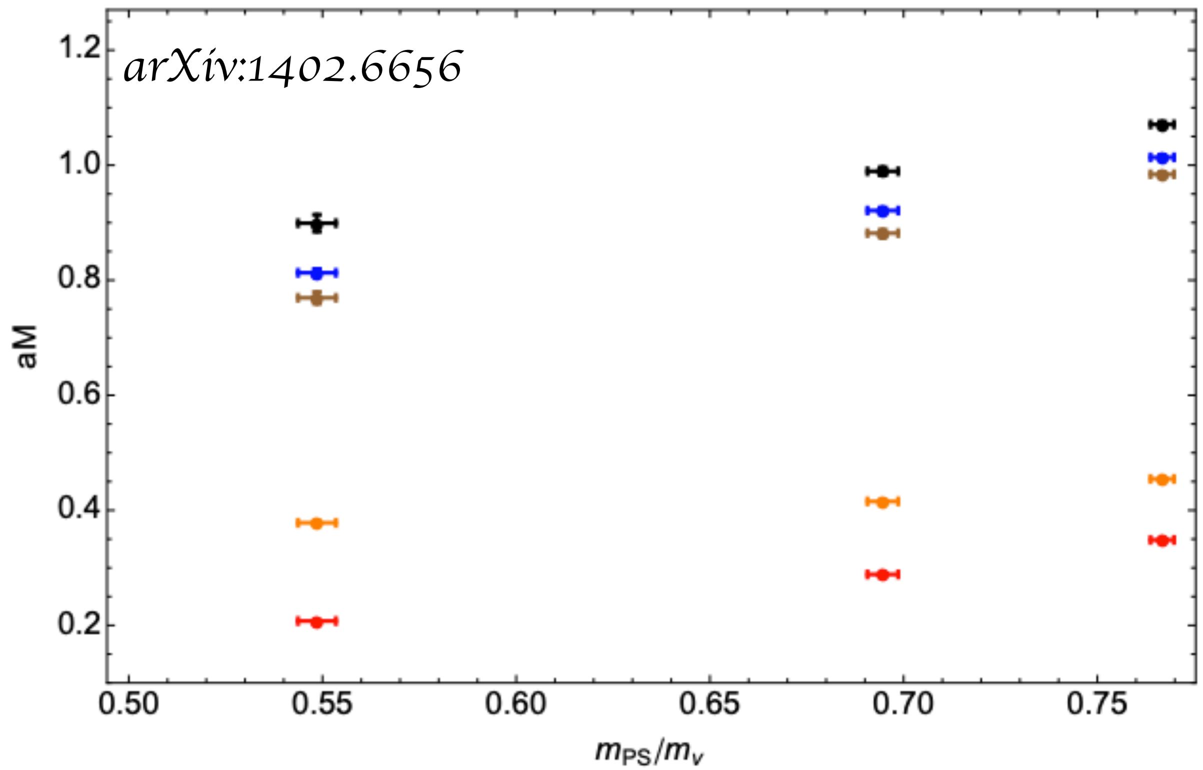
Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Conclusions

1. Explored specific dark sector theory where vector like dark quarks under SU(N) gauge group are also charged under the SM and get chiral masses. The model features dark mesons and a dark scalar baryon as a dark matter candidate.
2. We use lattice results to fix relative masses of bound state spectra.
3. Due to chiral couplings, the dark quarks and hence dark matter couples with Higgs and produced signals at direct detection experiments.
4. The dark rho mesons get produced at the LHC via DY processes and can decay to pions if phase space allowed. The pion decays are further dominated by third generation SM fermions.
5. We used the SM differential measurements to constrain such theories and in particular showed that a combination of measurements and searches pushes the rho and pion masses to multi-TeV region.
6. Using lattice results, we translated the pion mass limit to dark matter (dark baryon) mass limit and shows that it is pushed to multi-TeV range as well.
7. In combination with the direct detection limits these studies provided an updated limits on dark quark coupling to the Higgs and on the masses of the bound state spectrum.

Backup

Details of lattice



η	$amps$	amv	$amS0$	f_f^{DM}
0.77	0.3477	0.4549	0.9828	0.153
0.70	0.2886	0.4170	0.8831	0.262
0.55	0.2066	0.3783	0.7687	0.338

1. Lattice calculations done for mass degenerate quarks
2. In the limit when $m_{q_D} \sim \Lambda_{dark}$
3. Calculations done for specific pion to rho meson mass ratio, lowest mass ratio considered is 0.55, largest is 0.77
4. Interpolation in the pion to rho mass ratios to obtain values at other pion to rho masses

Details of lattice: direct detection

arXiv:1402.6656

The dark matter nucleus cross-section

$$\sigma_0(B,a) = \sigma(B,N)\frac{\mu(m_B,m_a)^2}{\mu(m_B,m_N)^2 A^2}$$

Expressing the amplitude

$$\mathcal{M}_a = \frac{y_f y_q}{2m_h^2}\sum_f \langle B|\bar{f}f|B\rangle \sum_q \langle a|\bar{q}q|a\rangle$$

The Higgs SM quark scattering

$$\langle a|m_q\bar{q}q|a\rangle \equiv m_a f_q^{(a)}$$

$$\langle a|m_q\bar{q}q|a\rangle = \frac{2}{27}m_a\left(1 - \sum_{q=u,d,s} f_q^{(a)}\right)$$

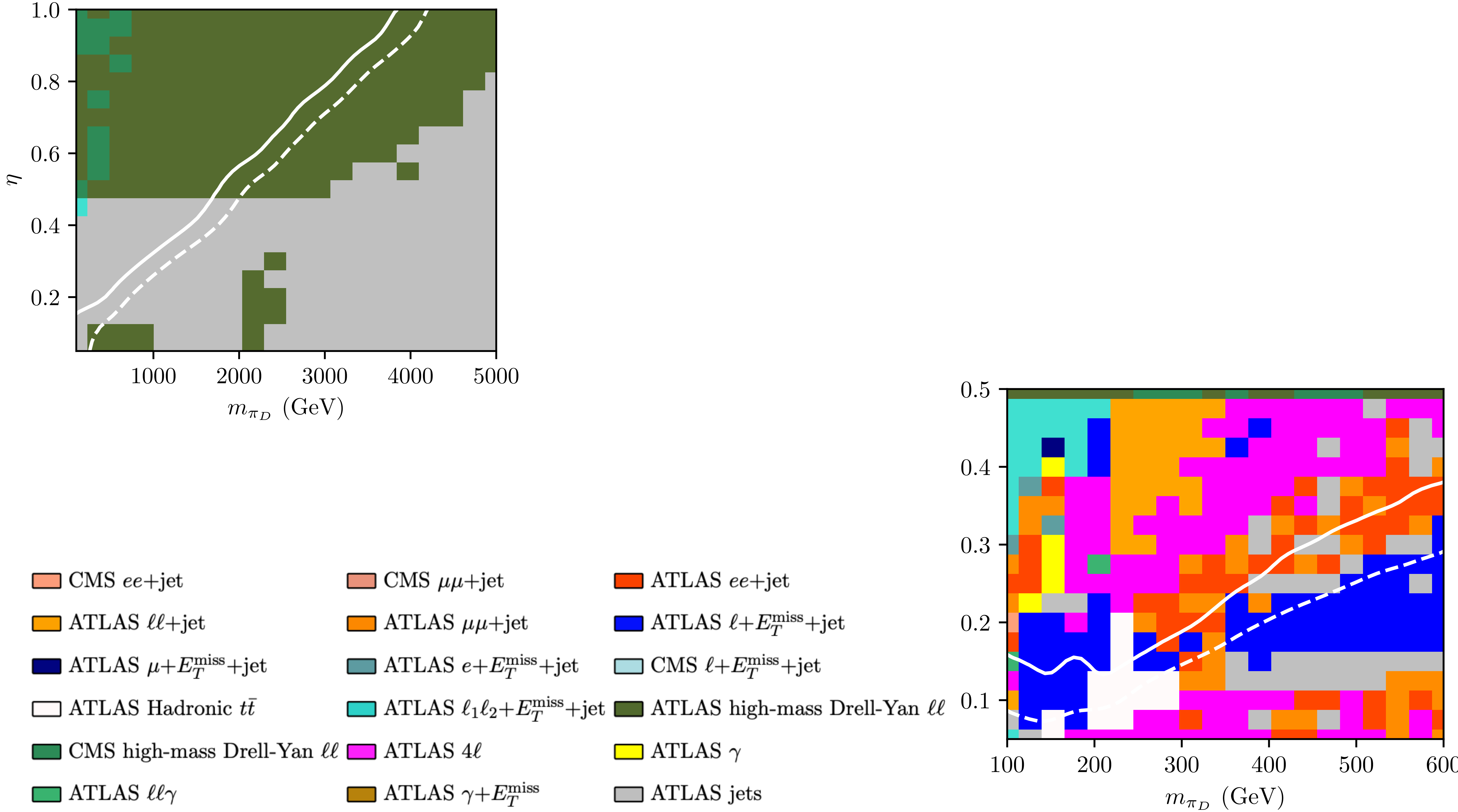
The Higgs dark quark scattering

$$\langle B|m_f\bar{f}f|B\rangle \equiv m_B f_f^{(B)}$$

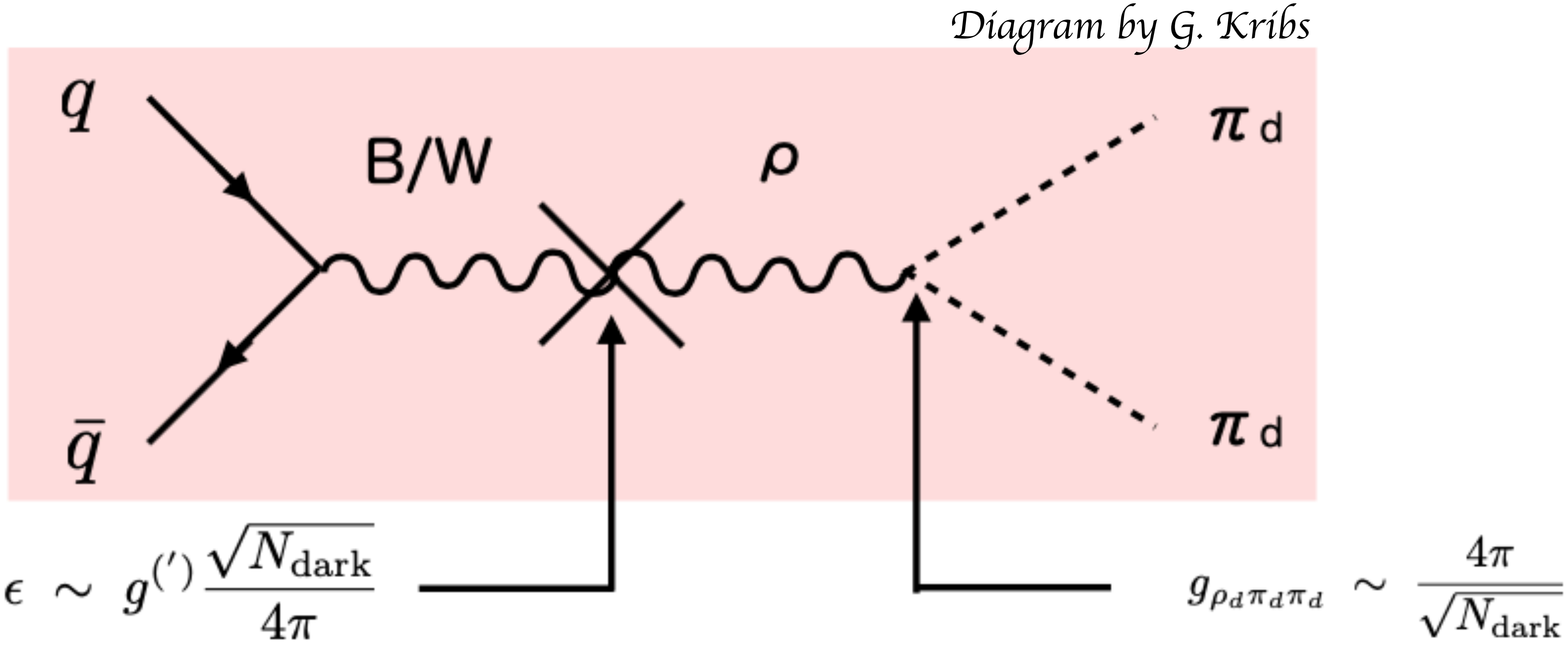
The quantities $f_q^{(a)}$ and $f_f^{(B)}$ (called f_f^{DM} in slides) computed on lattice

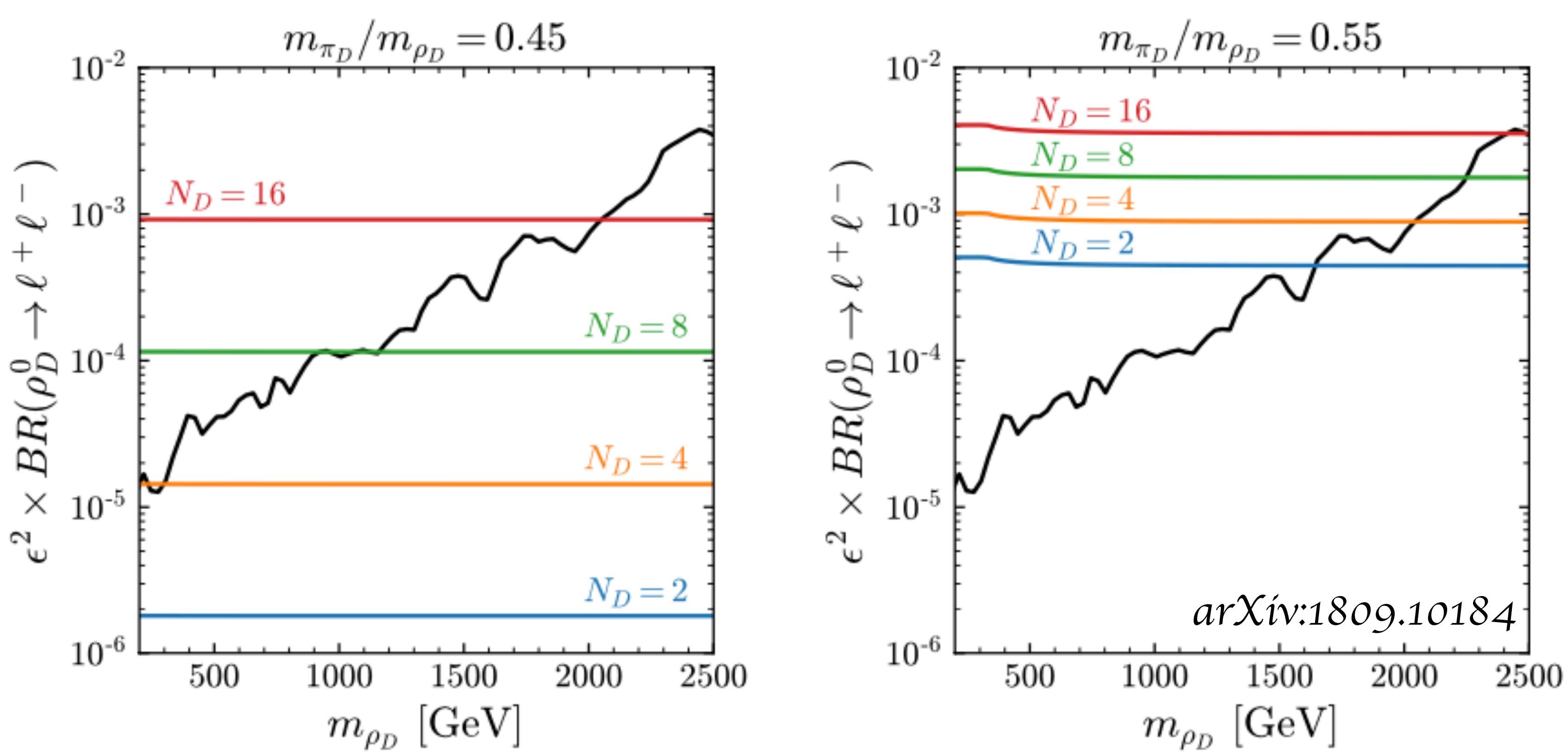
Results of $SU(2)_R$ scenarios

Qualitatively similar results



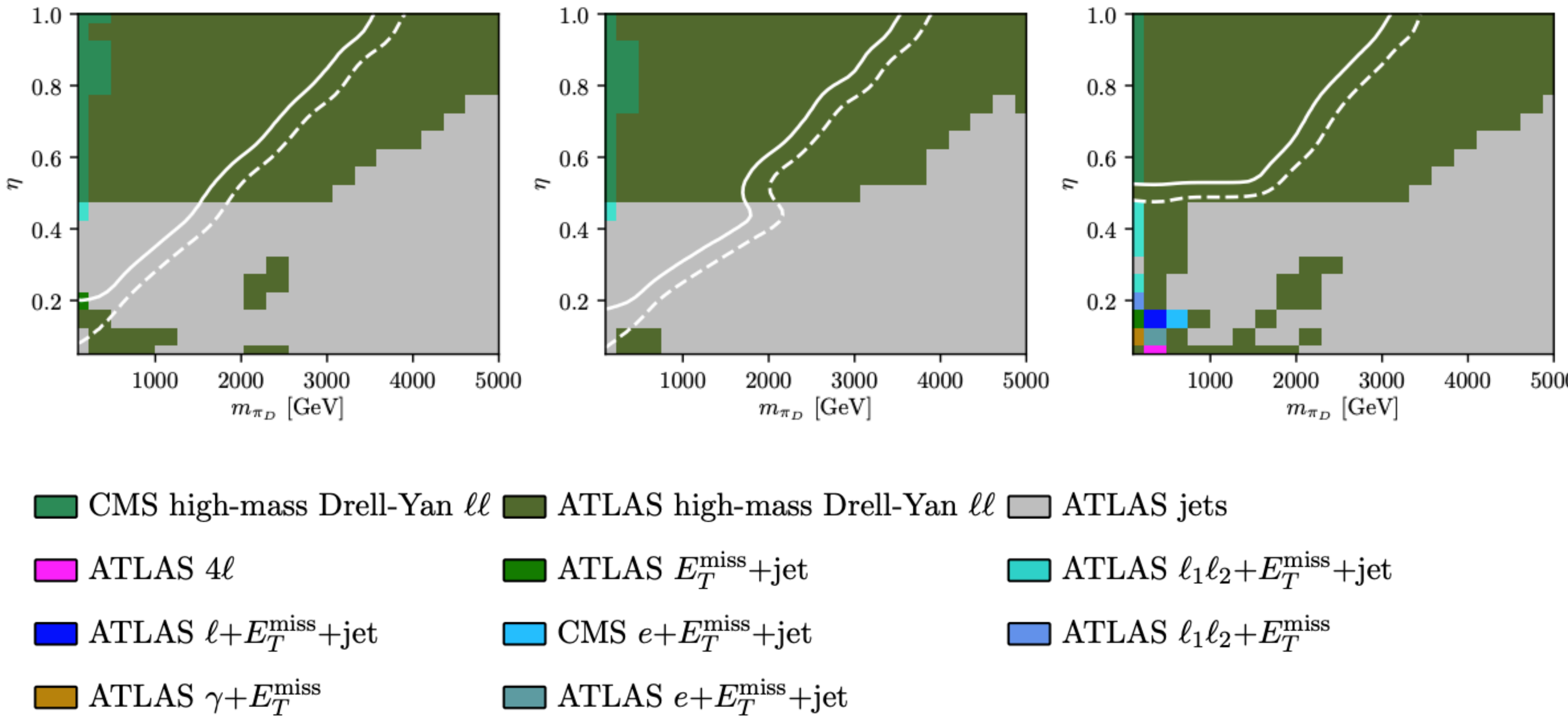
Results for N_D = 2





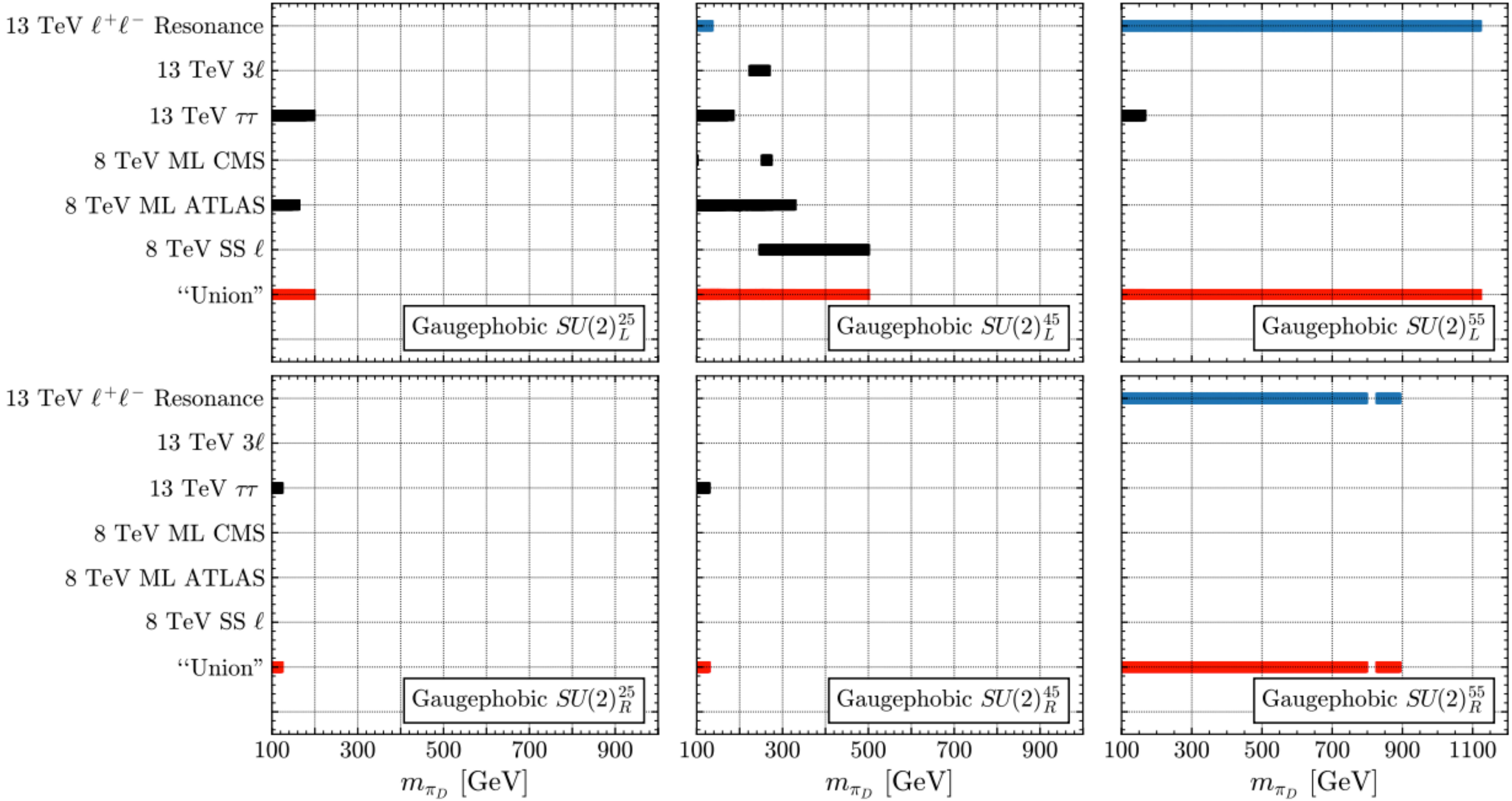
Results for $N_D = 2$

LHC reach reduces



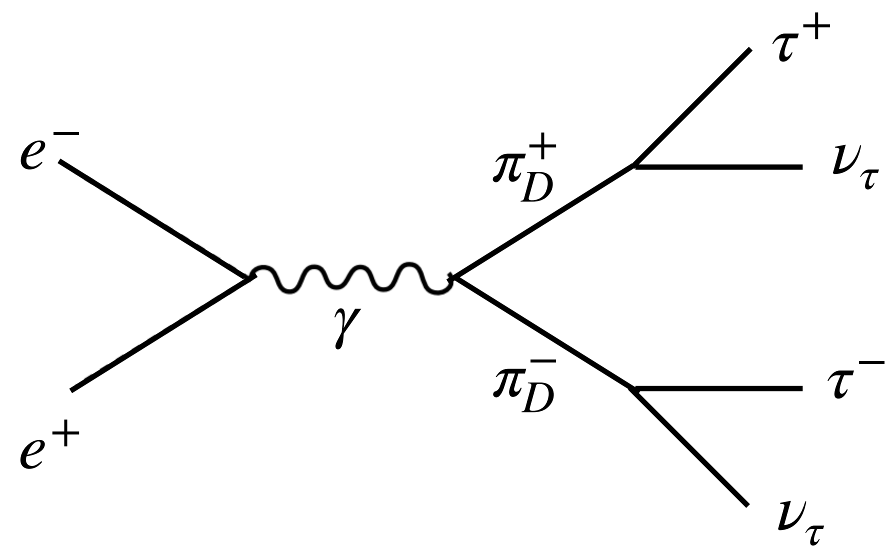
Previous constraints

arXiv:1809.10184



LEP constraints

arXiv:1809.10184



Reuse stau searches $m_{\pi_D} > 86.6\,\mathrm{GeV}$

Pushes DM mass to > 100's of GeV

Lagrangian

arXiv:1809.10184

$$\mathcal{L} = \mathcal{L}_{\text{strong}} + \mathcal{L}_{\text{kinetic mixing}} + \mathcal{L}_{\text{decay}}$$

$$\begin{aligned}\mathcal{L}_{\text{strong}} = & -\frac{1}{4}{\rho_D}^a_{\mu\nu}{\rho_D}^{a\mu\nu} - \frac{m^2_{\rho_D}}{2}{\rho_D}^a_\mu {\rho_D}^{a\mu} \\ & + \frac{1}{2}\left(D_\mu {\pi_D}^a\right)^\dagger \left(D^\mu {\pi_D}^a\right) - \frac{1}{2}m^2_{\pi_D}{\pi_D}^a{\pi_D}^a \\ & - g_{\rho_D\pi_D\pi_D} f^{abc}{\rho_D}^a_\mu {\pi_D}^b D^\mu {\pi_D}^c,\end{aligned}$$

$$\epsilon \approx \frac{\sqrt{N_D}}{4\pi}g, \quad SU(2)_L \text{ model}$$

$$\epsilon' \approx \frac{\sqrt{N_D}}{4\pi}g' \quad SU(2)_R \text{ model}$$

$$\mathcal{L}_{\text{kinetic mixing}} = -\frac{\epsilon}{2}{\rho_D}^a_{\mu\nu}F^{a\mu\nu} = \begin{cases} -\frac{\epsilon}{2}{\rho_D}^a_{\mu\nu}W^{a\mu\nu} & SU(2)_L \text{ model} \\ -\frac{\epsilon'}{2}{\rho_D}^0_{\mu\nu}B^{\mu\nu} & SU(2)_R \text{ model}\end{cases}$$

$$\begin{aligned}\mathcal{L}_{decay} = & \frac{\sqrt{2}}{v_\pi}\Big[{\pi_D}^+\bar{\psi}_u(m_dP_R - m_uP_L)\psi_d + {\pi_D}^-\bar{\psi}_d(m_dP_L - m_uP_R)\psi_u \\ & + \frac{i}{\sqrt{2}}{\pi_D}^0(m_u\,\bar{\psi}_u\gamma_5\psi_u - m_d\,\bar{\psi}_d\gamma_5\psi_d)\Big] \\ & - \xi\frac{m_W}{v_\pi}\left[(W^-_\mu\, h\overleftrightarrow{\partial}^\mu{\pi_D}^+) + (W^+_\mu\, h\overleftrightarrow{\partial}^\mu{\pi_D}^-) + \frac{1}{\cos\theta_W}(Z_\mu\, h\overleftrightarrow{\partial}^\mu{\pi_D}^0)\right]\end{aligned}$$