Darkcast: A Tool for Recasting Dark Photon Limits

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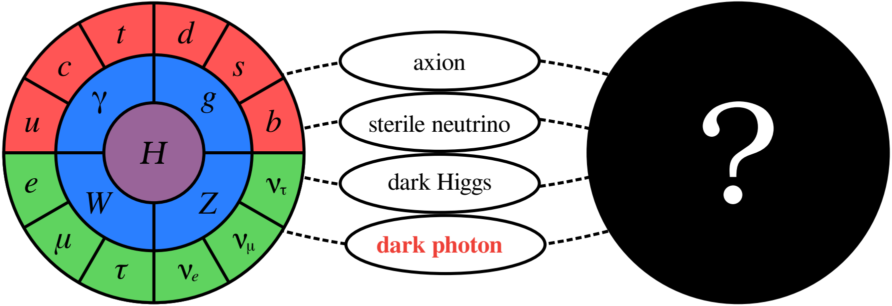
LHC Dark Matter Working Group

Dark Sector



$$g \equiv \frac{g'_e}{g_e}$$

Dark Photons

- minimal model, broken $U(1)$ gauge symmetry in dark sector
- allow mixing between dark and SM hypercharge fields

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{{m_{A'}}^2}{2}A'_{\mu}A'^{\mu} + g_e J^{\mu} A_{\mu} + g_e g J^{\mu} A'_{\mu}$$

1. mass of the dark photon, $m_{A'}$ and mixing g are free parameters
2. the dark photon couples like the photon, modified by g
3. if $m_{A'} < 2m_{\chi}$ then dark photon decays visibly

- what happens if 2 and 3 are relaxed?
- general models require m, g, 12 fermion couplings and an invisible width
- **dark photon limits can be recast to any general model**

Enter DARKCAST

- written by Yotam Soreq, Mike Williams, Wei Xue, and myself
- available at gitlab.com/philten/darkcast
- accompanying paper *Serendipity in dark photon searches*

The Plan

$$\sigma_A(m, g_A)\mathcal{B}_A(m)\varepsilon(\tau_A(m, g_A)) = \sigma_B(m, g_B)\mathcal{B}_B(m)\varepsilon(\tau_B(m, g_B))$$

- given a limit for at point (m, g_A) for model A, solve above to find limit point (m, g_B) for model B
- absolute cross-section can be tricky, ratios are easier

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} \frac{\varepsilon\big(\tau_A(m, g_A)\big)}{\varepsilon\big(\tau_B(m, g_B)\big)} \frac{\mathcal{B}_A(m)}{\mathcal{B}_B(m)} = 1$$

1. branching fraction ratio, $\frac{\mathcal{B}_A(m)}{\mathcal{B}_B(m)}$
2. cross-section ratio, $\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)}$
3. efficiency ratio, $\frac{\varepsilon\left(\tau_A(m, g_A)\right)}{\varepsilon\left(\tau_B(m, g_B)\right)}$

Branching Fractions

Widths

- width can be calculated perturbatively for fermions

$$\Gamma_{ff}(m, g) = \frac{g^2 c_f Q_f^2}{12\pi} m \left(1 + \frac{m_f^2}{m}\right) \sqrt{1 - 4\frac{m_f^2}{m}}$$

- c_f is 1 for charged leptons, 3 for quarks, and 1/2 for neutrinos
- Q_f is the model coupling for that fermion

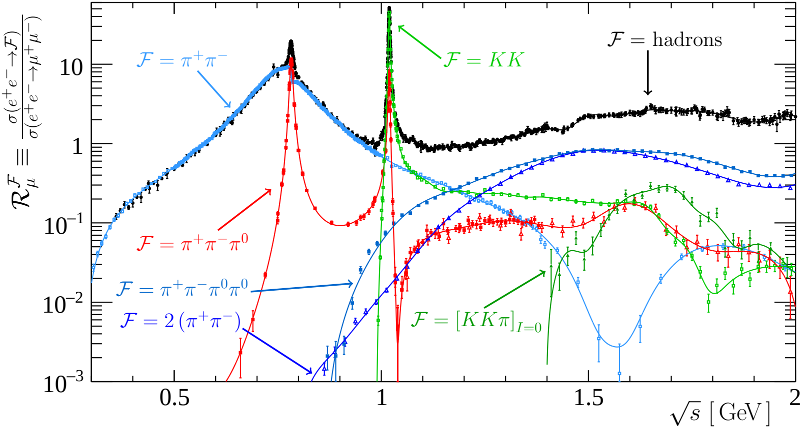
- but ... below 2 GeV this prediction is no longer reliable
- use data instead!

$$\Gamma_{\text{hadrons}}(m, g) = \Gamma_{\mu\mu}(m, g)\mathcal{R}(m)$$

- $\mathcal{R}(m)$ is $\sigma(ee \to \text{hadrons})/\sigma(ee \to \mu\mu)$

Beyond Leptons

- what about limits with exclusive hadronic final states?
- vector meson dominance (VMD) unreliable between 1 and 2 GeV
- use data $\ldots \mathcal{R}_{\mathcal{F}}(m)$ for exclusive hadronic final state $\mathcal{F}$



Hidden Symmetries

- what happens when we change the model?
- use hidden local symmetries framework for VMD
- vector mesons $V \in (\rho, \omega, \phi, K^*, \bar{K}^*)$ are gauge bosons of hidden $U(3)_V$ symmetry
- vertices take the form PV_iV_j with P from the pseudoscalar nonet $P \in (\pi, \eta, \eta', K, \bar{K})$

$$\mathrm{Tr}(T_{V_i}, T_{V_j}, T_P)$$

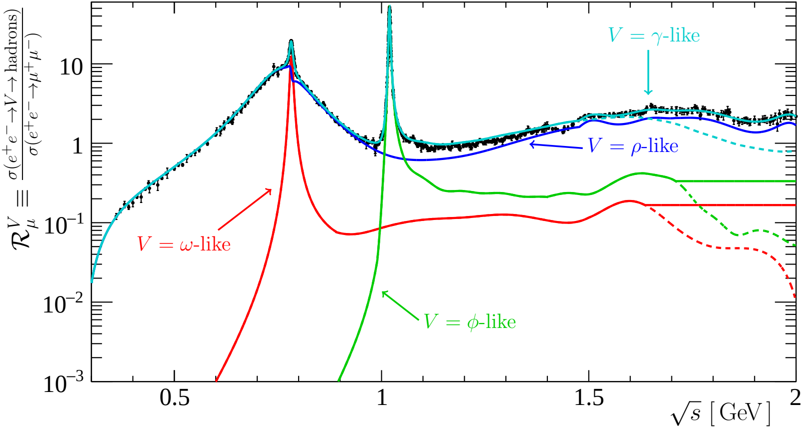
- T are the meson generators, *e.g.* $T_\omega = \frac{1}{2}(1, 1, 0)$
- external gauge fields mix through V

$$\mathrm{Tr}(T_V, Q)$$

- Q is the fermion coupling vector (Q_u, Q_d, Q_s)

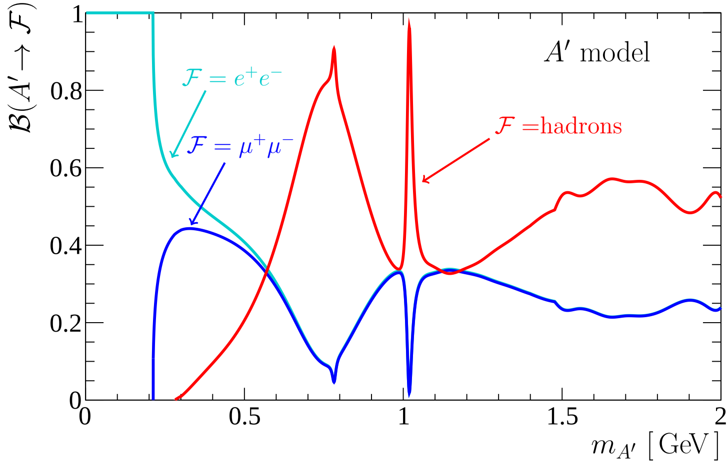
Vector Decomposition

$$\Gamma_{\mathcal{F}}(m) = \frac{g^2}{12\pi} m \sum_{V_i - V_j} c_{V_i} c_{V_j} \mathrm{Tr}(T_{V_i}, Q) \mathrm{Tr}(T_{V_j}, Q) \mathcal{R}_{\mathcal{F}}^{V}(m)$$



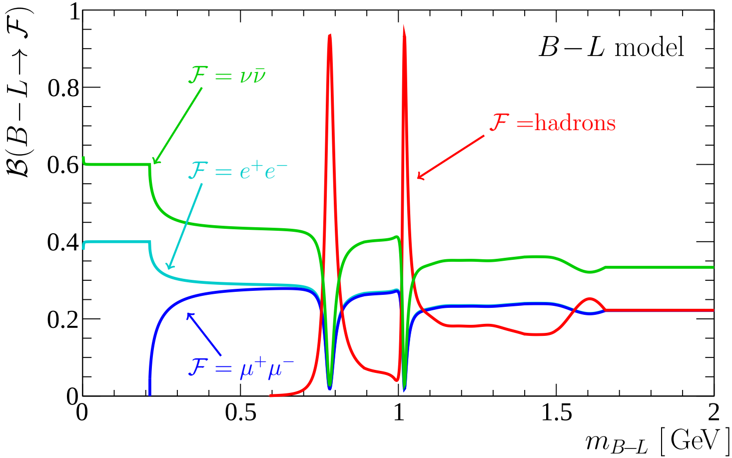
Dark Photon

$$Q = g_e \left(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3} \right)$$

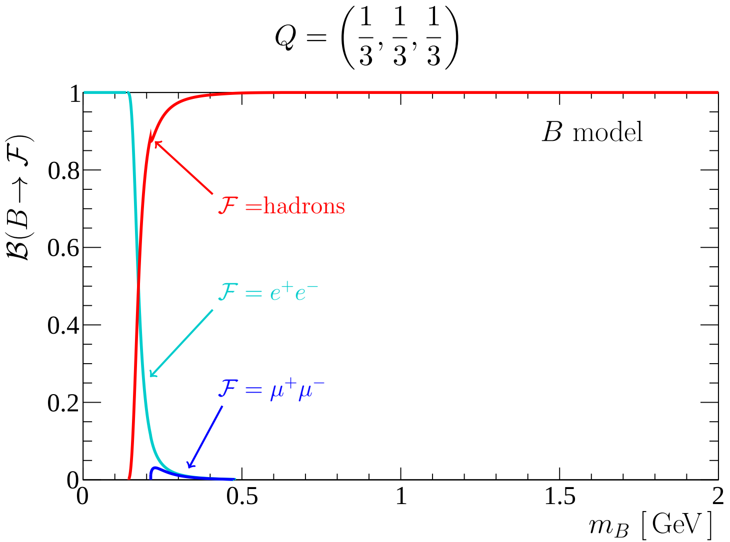


$B - L$ Boson

$$Q = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$$

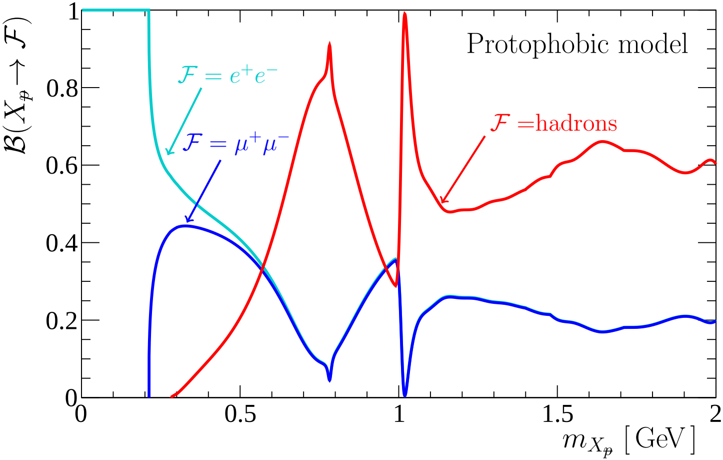


B Boson


$Q = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$
B model
$\mathcal{F}$ =hadrons
$\mathcal{F} = e^+e^-$
$\mathcal{F} = \mu^+\mu^-$
$\mathcal{B}(B \to \mathcal{F})$
m_B [GeV]
0
0.2
0.4
0.6
0.8
1
0.5
1.5
2

Protophobic Boson

$$Q = \left(\frac{1}{3}, \frac{2}{3}, \frac{2}{3}\right)$$



Decay Summary

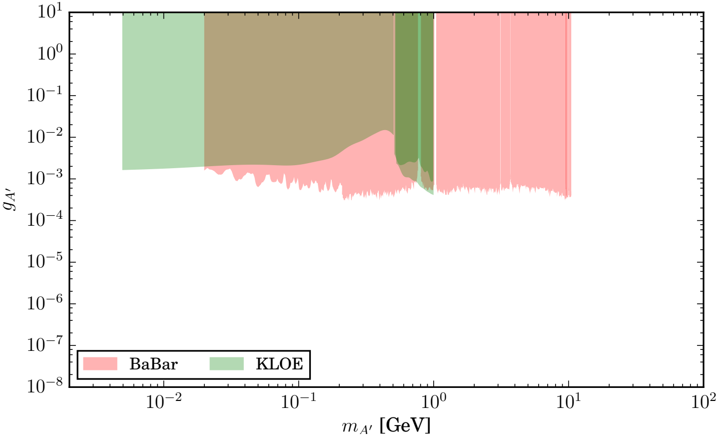
- example `bfrac.py` demonstrates all the available channels

- $f\bar{f}$ for $f \in (e, \mu, \tau, \nu_e, \nu_\mu \nu_\tau, d, u, s, c, b, t)$
- $\pi^+\pi^-$
- $\pi^+\pi^-\pi^+\pi^-$
- $\pi^-\pi^-\pi^0\pi^0$
- $\pi^+\pi^-\pi^0$
- KK
- $KK\pi$
- remaining hadronic states (grouped together) to recover $\mathcal{R}$
- invisible

Cross-section Ratios

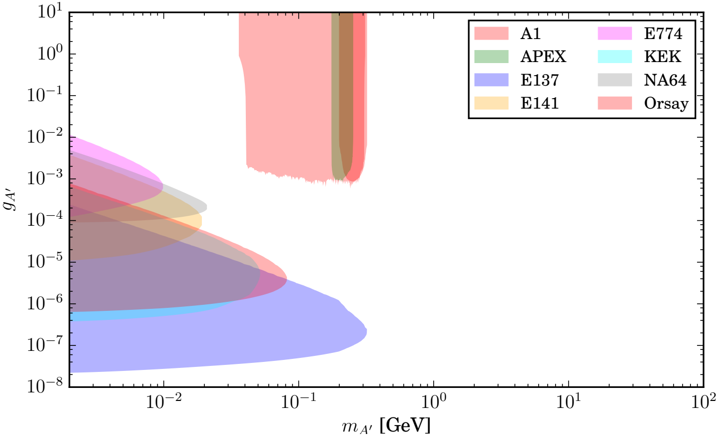
Electron Annihilation

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2 {Q^e_A}^2}{{g_B}^2 {Q^e_B}^2}$$



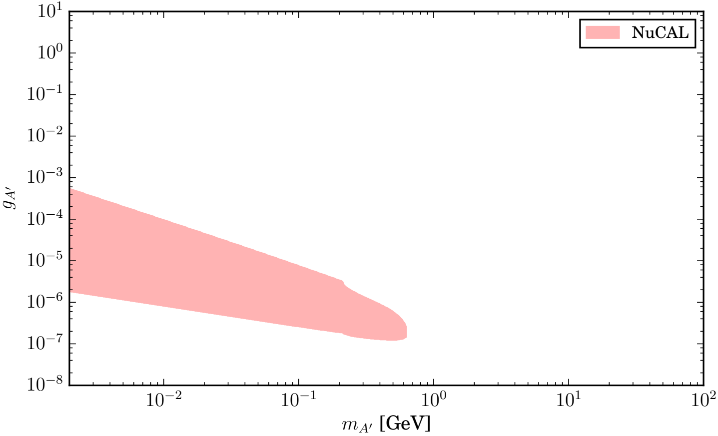
Electron Bremsstrahlung

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2 {Q^e_A}^2}{{g_B}^2 {Q^e_B}^2}$$



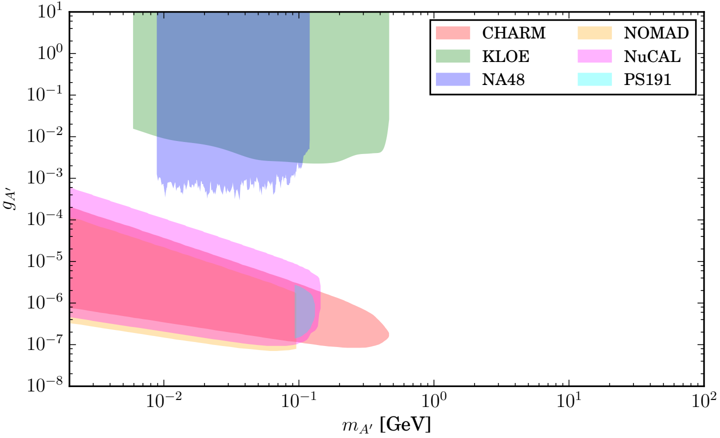
Proton Bremsstrahlung

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2(2Q_A^u + Q_A^d)^2}{{g_B}^2(2Q_A^u + Q_A^d)^2}$$



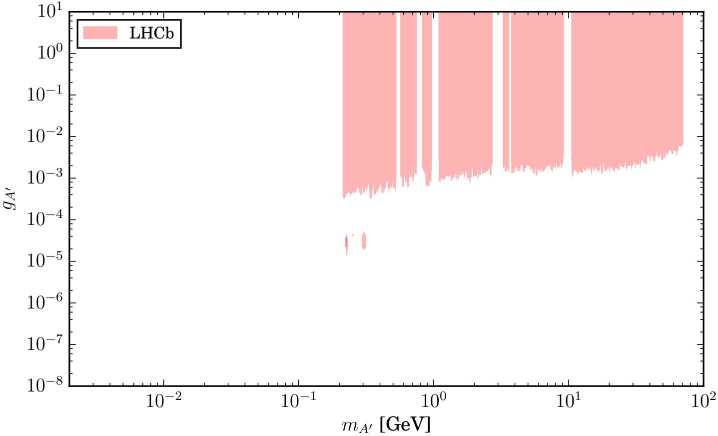
Hadrons ($X \to YA$)

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \frac{{g_A}^2 \sum_V \mathrm{Tr}(T_X, T_Y, T_V)\mathrm{Tr}(T_V, Q_A)\mathrm{BW}_V(m)}{{g_B}^2 \sum_V \mathrm{Tr}(T_X, T_Y, T_V)\mathrm{Tr}(T_V, Q_B)\mathrm{BW}_V(m)}$$



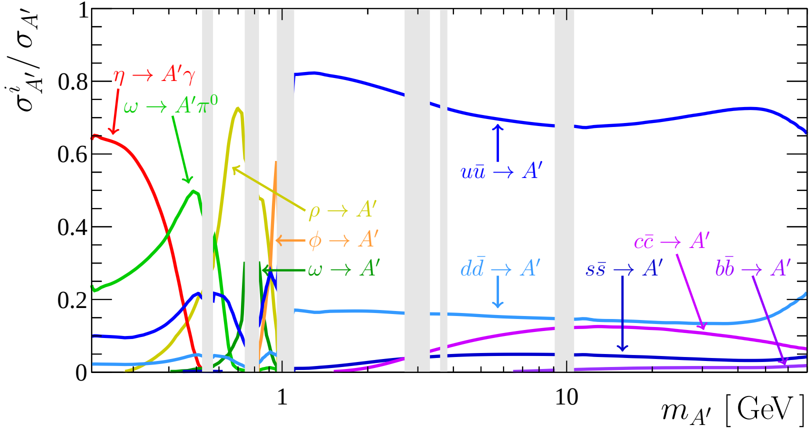
LHC

$$\frac{\sigma_A(m, g_A)}{\sigma_B(m, g_B)} = \sum_i f_i(m) \frac{\sigma_A^i(m, g_A)}{\sigma_B^i(m, g_B)}$$



LHC Production Fractions

- templates taken from Monte Carlo and fit against LHCb result



Cross-section Ratio Summary

- example `contribute.py` demonstrates how production mechanisms can be specified
- `help(Production)` gives more documentation

- proton bremsstrahlung, $pA \to pAX$
- fermion bremsstrahlung, $fA \to fAX$ for $f \in (e, \mu, \tau, \nu_e, \nu_\mu \nu_\tau, d, u, s, c, b, t)$
- Drell-Yan, $f\bar{f} \to X$ for $f \in (e, \mu, \tau, \nu_e, \nu_\mu \nu_\tau, d, u, s, c, b, t)$
- vector meson mixing, $V \to X$ for $V \in (\rho^0, \omega, \phi)$
- meson decays of the form $M_i \to M_j X$ for $M \in (\gamma, \rho, \pi^0, \omega, \phi, \eta, \eta')$

Efficiencies

Efficiencies

- define proper time fiducial region with t_0 and t_1

$$\varepsilon(\tau) = e^{-t0/\tau} - e^{-t1/\tau}$$

- for prompt limits, $t_0 = 0$ and t_1 depends on the boost

$$t_1 = \frac{L_{\text{max}}}{\gamma}$$

- for displaced beam-dump limits, relate t_0 and t_1

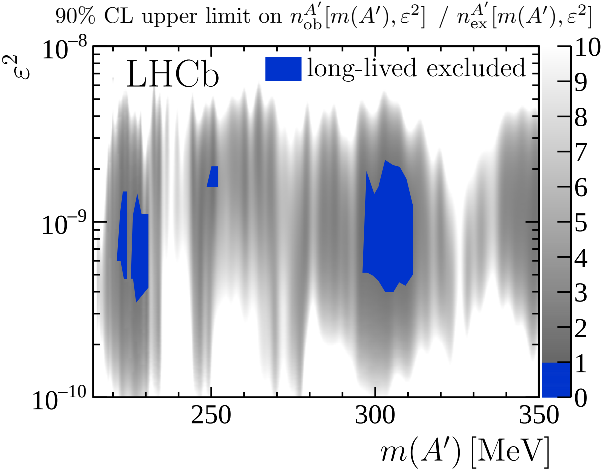
$$t_1 = t_0 + \frac{L_{\text{detector}}}{L_{\text{shield}}}$$

- both the upper and lower limit provide a solution, so equate and solve

$$\sigma(m, g_{\text{max}})\mathcal{B}(m)\varepsilon(\tau(m, g_{\text{max}}) = \sigma(m, g_{\text{min}})\mathcal{B}(m)\varepsilon(\tau(m, g_{\text{min}})$$

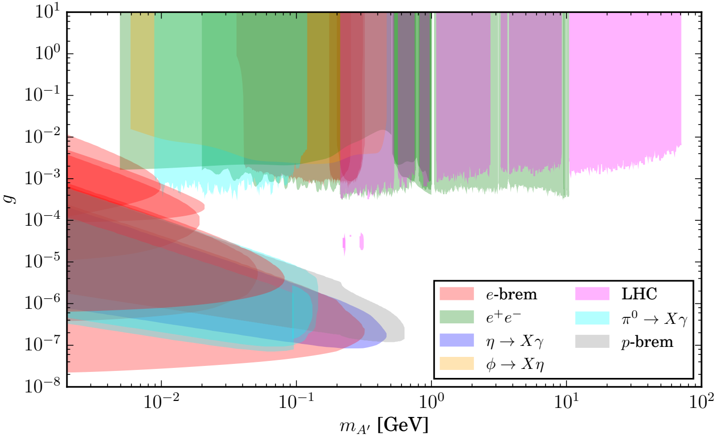
Even Better . . .

- provide limits on expected over observed as function of g and m, *ala* LHCb

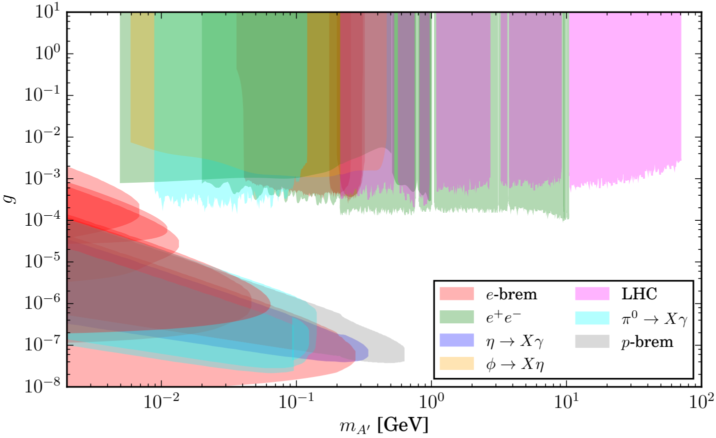


Conclusions

Dark Photon


10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
g
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
$m_{A'}$ [GeV]
e-brem
e^+e^-
$\eta \to X\gamma$
$\phi \to X\eta$
LHC
$\pi^0 \to X\gamma$
p-brem

$B - L$ Boson


10^{1}
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g
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10^{0}
10^{1}
10^{2}
$m_{A'}$ [GeV]
e-brem
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$\eta \to X\gamma$
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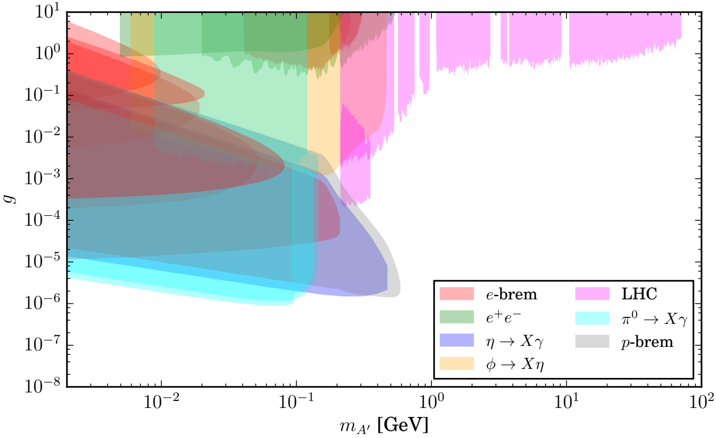
B Boson



10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
g
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
$m_{A'}$ [GeV]
e-brem
e^+e^-
$\eta \to X\gamma$
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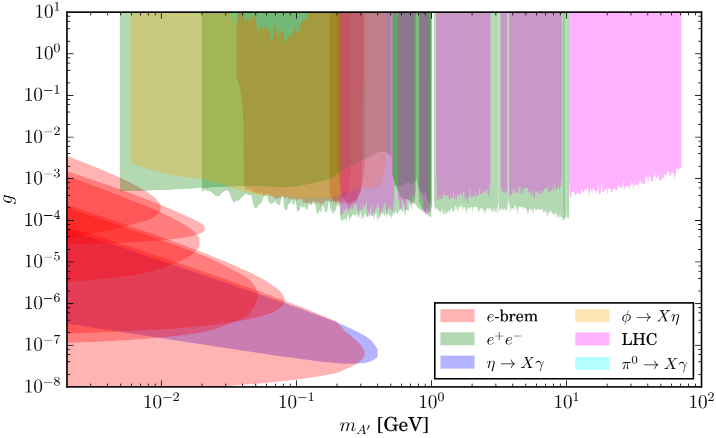
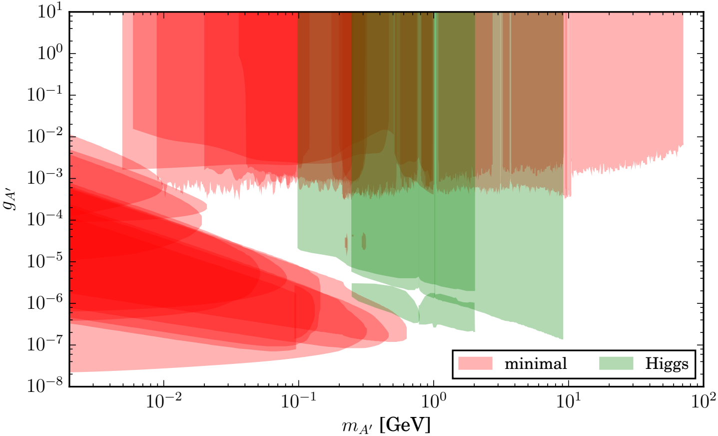
Protophobic Boson



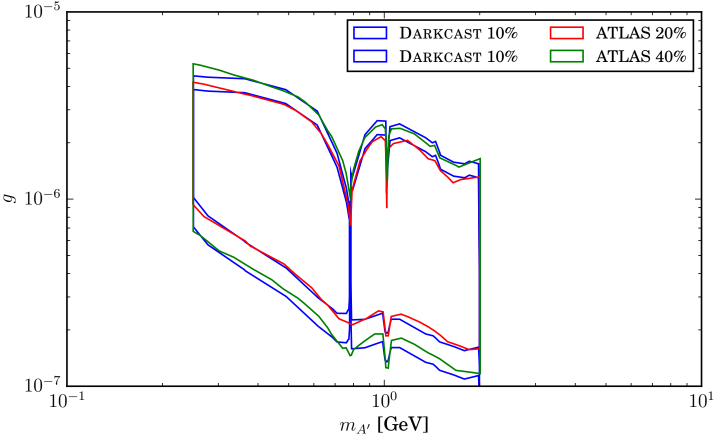
ATLAS and CMS

- both ATLAS and CMS have dark photon results, but from non-minimal $H \to A'A'$ models
- if recast to the minimal model, they are suppressed by $g^2 \mathcal{B}_{H\to\gamma\gamma}$



Recast?

- bounds available, not recastable
- functionality added to Darkcast, not yet public
- efficiency approximations need some work



Outlook

- **if you need to calculate widths, branching fractions, or recast, Darkcast is your tool**!
  - exclusive hadronic final states are provided
  - most relevant production mechanisms are implemented
  - a large library of documented dark photon bounds is available
  - a library of citations for relevant literature is maintained
- inclusion of future experimental reach on the way, but not as recastable limits
- decoupling production and decay prototyped, not yet public
- requests and suggestions are very welcome!