Searching for light dark particles at η,η' factories

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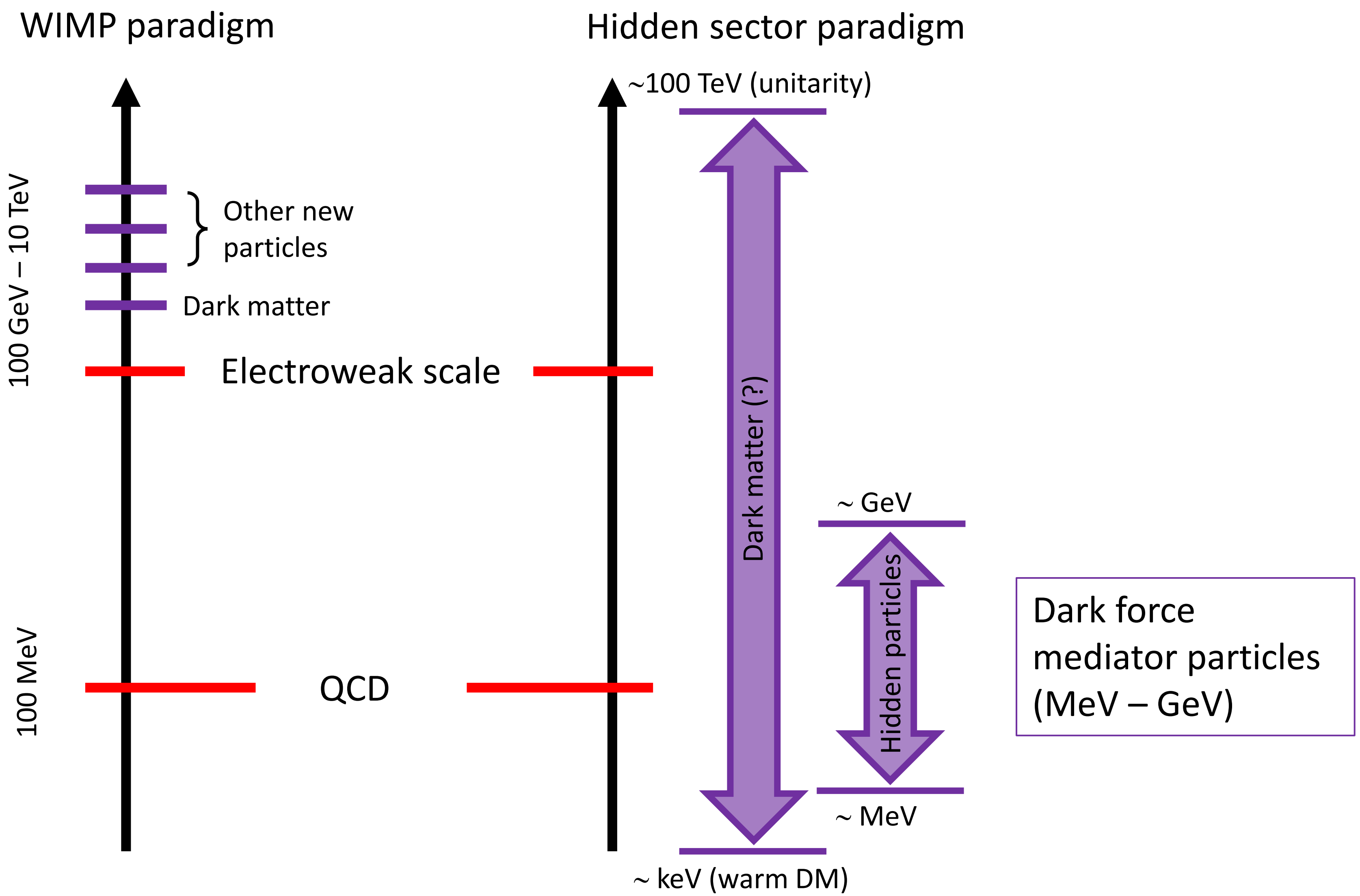
Light hidden particles

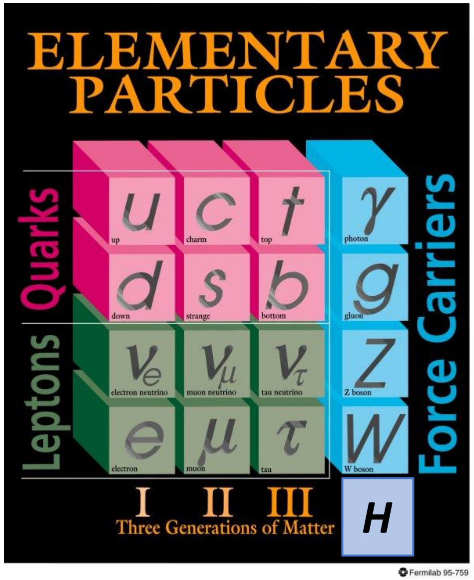


Motivations for hidden particles

Dark sector:

Matter + forces (like Standard Model)
Dark forces very weakly-coupling to SM particles

ϕ = mediator particle for dark force (light hidden particle)



Hidden mediator models:

- Dark scalars: $J^P = 0^+$
  Extended Higgs sector for dark matter

- Axions and axion-like particles (ALPs): $J^P = 0^-$
  Goldstone bosons from spontaneously broken global symmetries

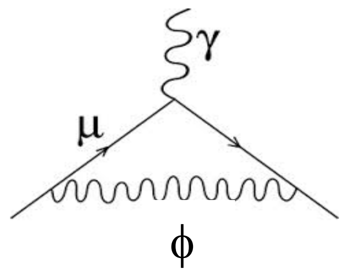
- Hidden photons or Z': $J^P = 1^-$
  Vector boson boson from U(1) gauge symmetry for dark matter
  Explains stability of dark matter (charge conservation)

We know all these particles exist for SM matter

Motivations for hidden particles

$(g\text{-}2)_\mu$ anomaly

Pospelov (2008)



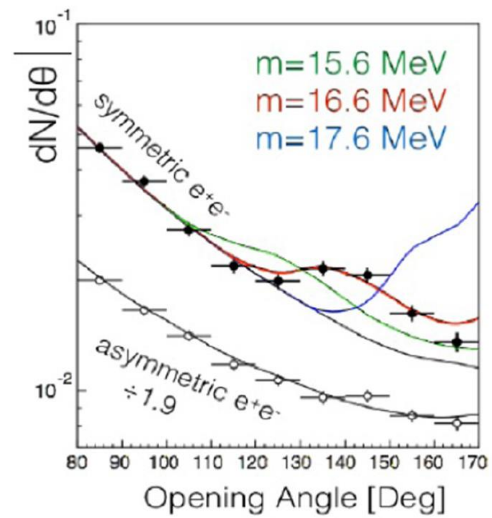
$m_\phi \sim$ MeV – GeV

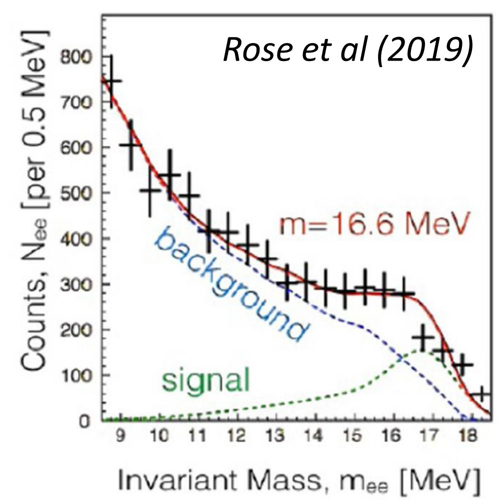
Atomki ^{8}Be/^{4}He/^{12}C anomalies

Krasznahorkay et al (2016/2019/2022)
Review: Alves et al (2023)

$^{8}Be^{*} \rightarrow {}^{8}Be\ \gamma$ (virtual) $\rightarrow {}^{8}Be\ e^{+}e^{-}$

$^{8}Be^{*} \rightarrow {}^{8}Be$ X (on-shell) $\rightarrow {}^{8}Be\ e^{+}e^{-}$



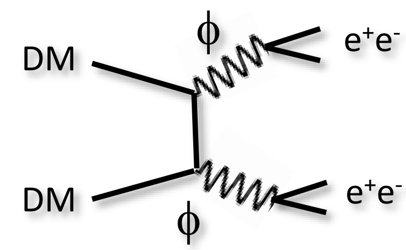


Hypothetical X boson with mass 17 MeV, coupled to quarks and electrons
Quantum numbers allowed: $J^P = 0^-, 1^-$, or 1^+

Motivations for hidden particles

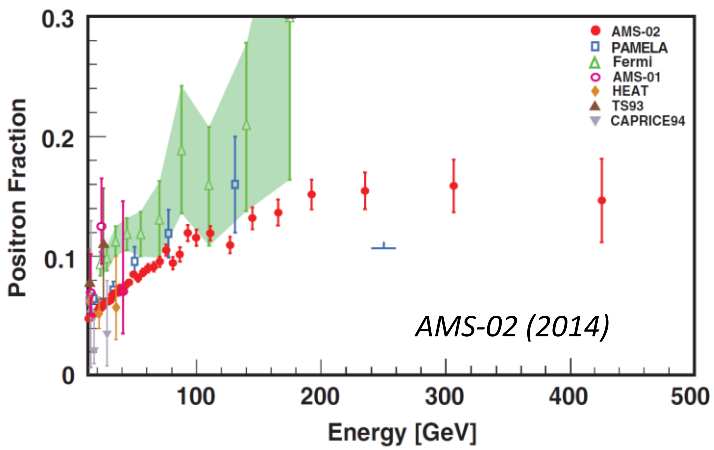
Anomalous signals from annihilating dark matter

$m_\phi \sim$ MeV – 200 MeV



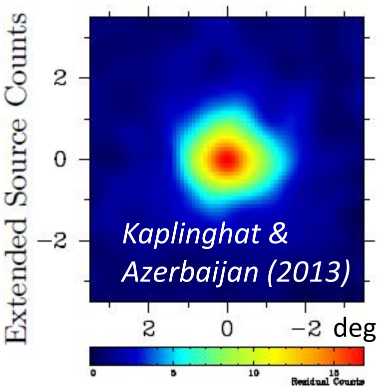
Positron excess

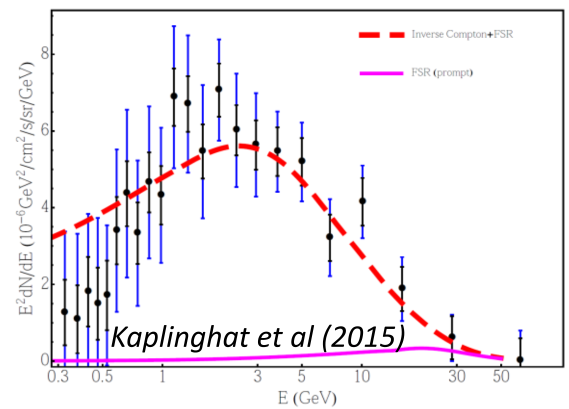
Rising positron fraction measured by cosmic ray detectors



Galactic center excess

Anomalous γ-ray signal from Fermi satellite



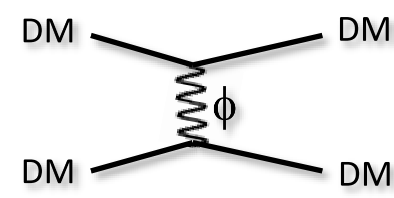


Other leading explanation: cosmic rays and γ-rays from pulsars

Motivations for hidden particles

Small-scale structure of DM halos

Discrepancy between theory (N-body simulations) and observations

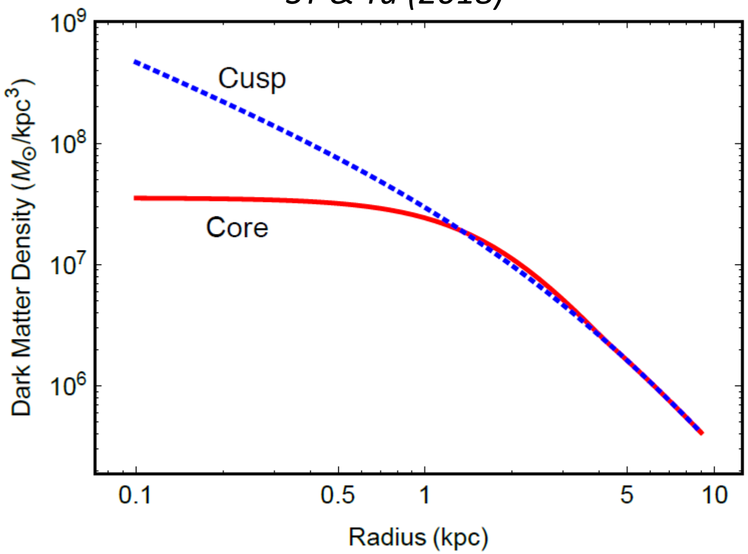


Self-interacting Dark Matter

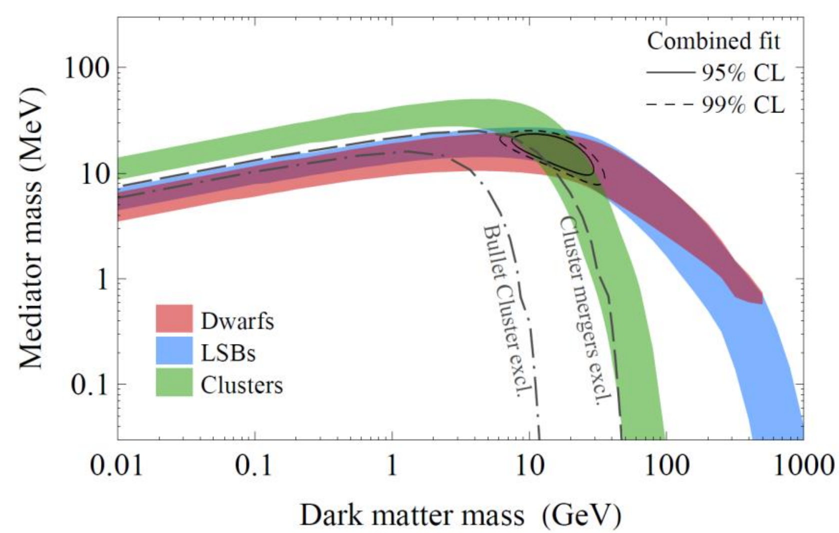
Elastic collisions due to extra dark force

$m_\phi \sim$ MeV – GeV

ST & Yu (2018)



Kaplinghat, ST & Yu (2016)



Other leading explanations: supernova feedback, systematic uncertainties

Putting aside the anomalies…

Worldwide experimental program searching for light hidden particles

Mainly focused on:

- Lepton couplings (ϕ decaying to e^+e^- or $\mu^+\mu^-$ resonances)
- Invisible couplings (ϕ decaying to DM particles)
- Heavy-flavor couplings (ϕ emitted in FCNC decay)

What about light hidden particles coupling to light quarks and gluons?

Can there be new dark physics hidden in low-energy QCD?

η,η' mesons are laboratories for testing these models

η, η' laboratories for dark sectors

- On-shell decays to new light particles in the MeV—GeV range
  - Vector bosons (hidden photons), scalar bosons, axion-like particles (ALPs)

- Leading decays of η are already suppressed $\sim \mathcal{O}\left(\alpha_{\rm em}^2\right)$ or $\mathcal{O}\left((m_u - m_d)^2\right)$
- Larger mass reach for η' but worse sensitivity (total width larger by ~100)

- Decays to light hidden particles are 2- or 3-body decays that mimic 3-, 4-, or 5-body final states (often very rare)

- Search strategies (visible final states):
  - Resonance searches (bump hunting)
  - Displaced vertices (long-lived decays)
  - Rare decays – new physics process mimics highly-suppressed SM channels

- Other possibilities: invisible or partially-invisible decays

Larger η,η' samples at future facilities

Slide adapted from L. Gan

Previous Experiments:

Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	$2x10^7$	-
CB MAMI-C	$6x10^7$	10^6
WASA-COSY	$\sim 3x10^7$ (p+d), $\sim 5x10^8$ (p+p)	-
KLOE-II	$3x10^8$	$5x10^5$
BESIII	$\sim 10^7$	$\sim 5x10^7$

Upcoming experiments

Jefferson Eta Factory (JEF) at JLab Hall D (approved)

	η	η'	
Tagged mesons	$6.5x10^7$	$4.9x10^7$	per 100 days

Rare Eta Decays with a TPC for Optical Photons (REDTOP) possibly at Fermilab (proposed)

Phase I (untagged mode)	$2x10^{13}$	10^{11}	per year
Phase II+ (tagged mode)	$1x10^{13}$	10^{11}	

Rich physics program at η,η' factories

Standard Model highlights
- Theory input for light-by-light scattering for $(g\text{-}2)_\mu$
- Extraction of light quark masses
- QCD scalar dynamics

Fundamental symmetry tests
- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

Dark sectors (MeV—GeV)
- Vector bosons (dark photon, B boson, X boson)
- Scalars
- Pseudoscalars (ALPs)

(Plus other channels that have not been searched for to date)

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[52]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Gan, Kubis, Passemar, ST (2020)

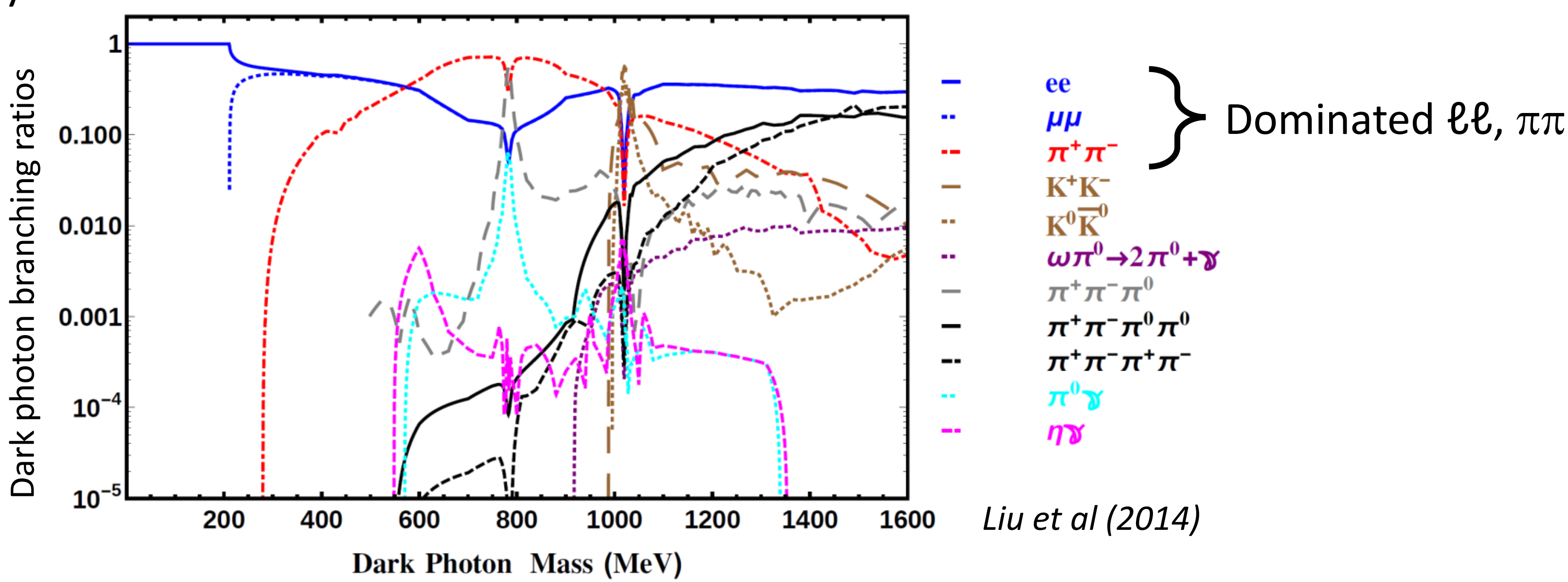
Dark photon

[Fayet (2007), Reece & Wang (2009), …]

Hidden vector boson coupled to electric charge (ε << 1) $\mathcal{L}_{\rm int} = -e\varepsilon\, j^{\mu}_{\rm em} A'_{\mu}$

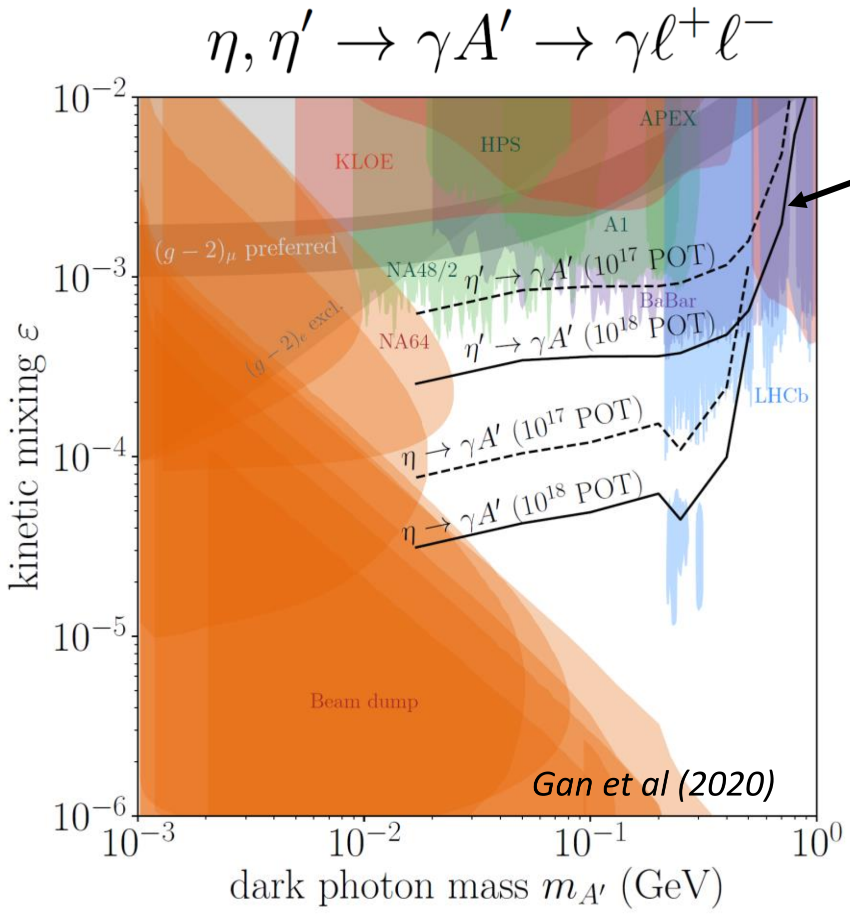
Production: $\eta, \eta' \to \gamma A'$ (Analogous to SM decay $\eta, \eta' \to \gamma\gamma$)

Decay:



Liu et al (2014)

Dark photon



REDTOP sensitivities projected for FNAL/BNL (10^{18}) or CERN (10^{17}) POT

Gatto (2019)

Many other experiments targeting same dark photon parameter space

Worthwhile to also consider

$$\eta' \to \pi^+\pi^- A' \to \pi^+\pi^- \ell^+\ell^-$$

since $\mathcal{B}(\eta' \to \pi^+\pi^-\gamma) \approx 10 \times \mathcal{B}(\eta' \to \gamma\gamma)$

Protophobic X(17) vector boson
to explain Atomki ^{8}Be/^{4}He/^{12}C anomalies

Feng et al (2016,2017)

$$\underbrace{{}^8\text{Be}^* \rightarrow {}^8\text{Be}\, X}_{\text{Production: quark coupling (u,d)}} \underbrace{\rightarrow {}^8\text{Be}\, e^+ e^-}_{\text{X decay: lepton coupling (e)}}$$

Protophobic X(17) vector boson to explain Atomki ^{8}Be/^{4}He/^{12}C anomalies

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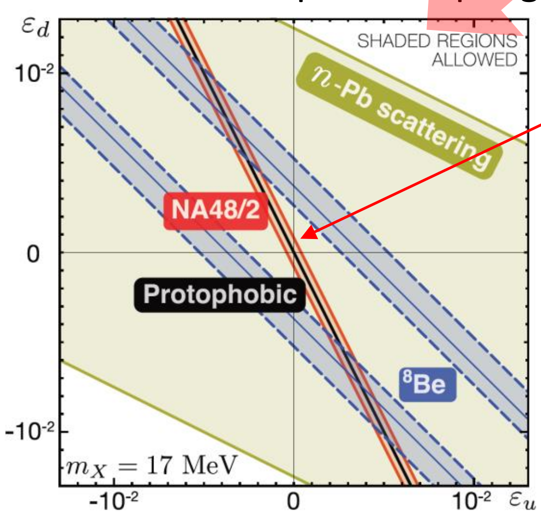
$$^8\mathrm{Be}^* \rightarrow {}^8\mathrm{Be}\, X \rightarrow {}^8\mathrm{Be}\, e^+ e^-$$

Production: quark coupling (u,d)

X decay: lepton coupling (e)

Constraints on quark couplings



Feng et al (2016)

Stringent limits from $\pi^0 \rightarrow \gamma\, e^+e^-$ decay (NA48/2)
"Proton coupling" $|2\varepsilon_u + \varepsilon_d|$ to π^0 must be small

Opportunity for η,η' mesons

X boson cannot be η,η'-phobic *Gan et al (2020)*

η coupling $\approx 2\varepsilon_u - \varepsilon_d + 0.9\, \varepsilon_s$
η' coupling $\approx 2\varepsilon_u - \varepsilon_d - 1.4\, \varepsilon_s$

Protophobic X(17) vector boson to explain Atomki ^{8}Be/^{4}He/^{12}C anomalies

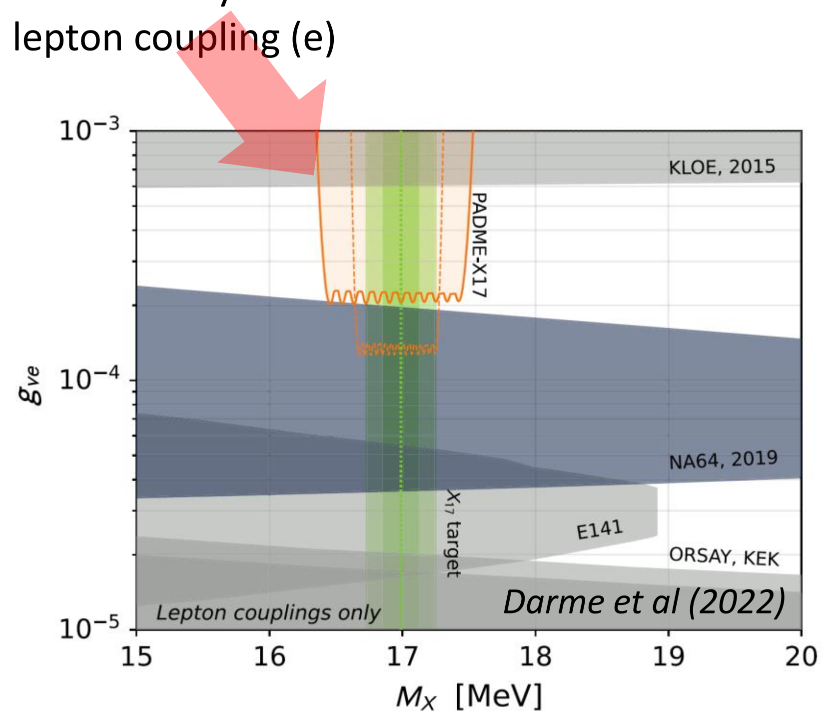
Feng et al (2016,2017)

$$^8\mathrm{Be}^* \rightarrow {}^8\mathrm{Be}\, X \rightarrow {}^8\mathrm{Be}\, e^+ e^-$$

Production: quark coupling (u,d)

X decay: lepton coupling (e)

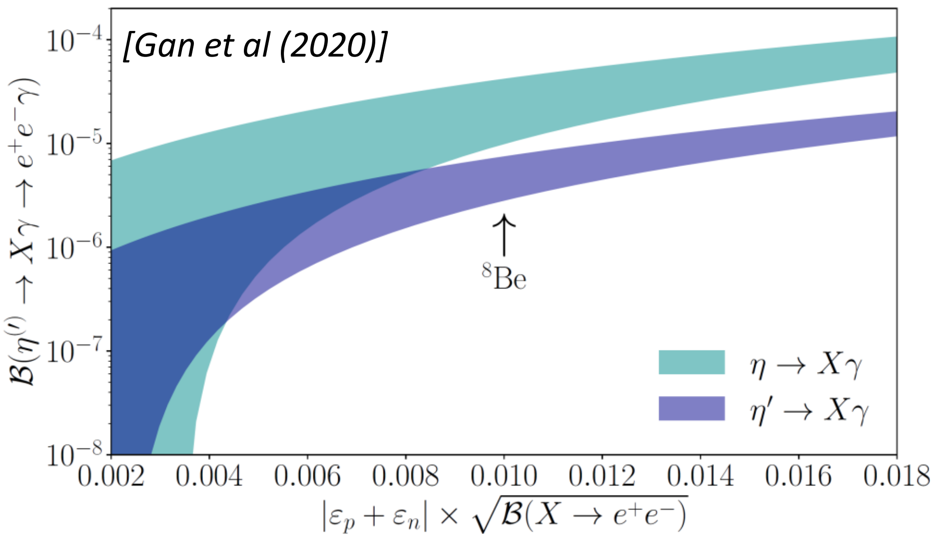
Dark photon searches at e⁻ beam experiments constrain electron coupling



Protophobic X(17) vector boson to explain Atomki $^{8}Be/^{4}He/^{12}C$ anomalies

$$\eta, \eta' \rightarrow X\gamma \rightarrow e^+e^-\gamma$$

Theory prediction



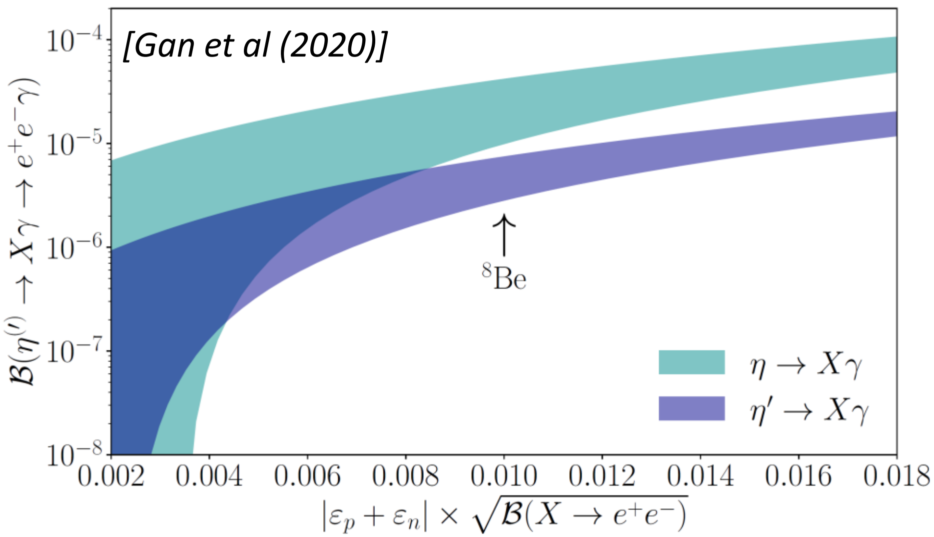
$BR(\eta \rightarrow X\gamma \rightarrow e^+e^-\gamma) \approx 2 \times 10^{-5}$

$BR(\eta' \rightarrow X\gamma \rightarrow e^+e^-\gamma) \approx 5 \times 10^{-6}$

Protophobic X(17) vector boson to explain Atomki ^{8}Be/^{4}He/^{12}C anomalies

$$\eta, \eta' \rightarrow X\gamma \rightarrow e^{+}e^{-}\gamma$$

Theory prediction



BR(η → X γ → e⁺e⁻ γ) ≈ 2 x 10^{-5}

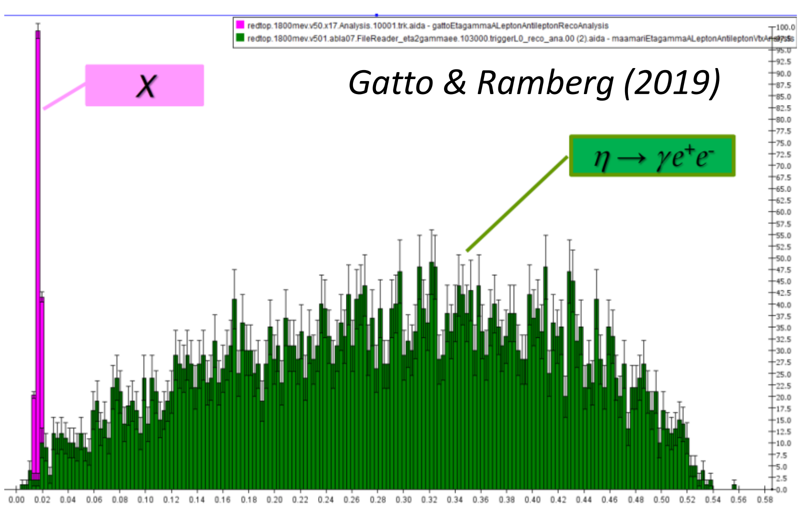
BR(η' → X γ → e⁺e⁻ γ) ≈ 5 x 10^{-6}

Experiment

Challenge: invariant mass m_{ee} = 17 MeV

A2@MAMI: m_{ee} > 30 MeV

REDTOP Monte Carlo



Other X(17) candidates to explain Atomki ^{8}Be/^{4}He/^{12}C anomalies

1. Protophobic vector boson *Feng et al (2016,2017)*

2. Piophobic axion *Alves (2021); Alves et al (2022)*

Decay channel	Expected rate
$\mathrm{Br}(\eta \to \pi\,\pi\,a)$	$\mathcal{O}(10^{-3} - 10^{-4})$
$\mathrm{Br}(\eta' \to \pi\,\pi\,a)$	$\mathcal{O}(10^{-3} - 10^{-4})$

} Disfavored by recent measurement in ^{12}C *Krasznahorkay et al (2022)*

3. Axial vector or mixed parity vector boson *Delle Rose et al (2019)*

Predictions for η,η' decays not worked out (as far as I know)

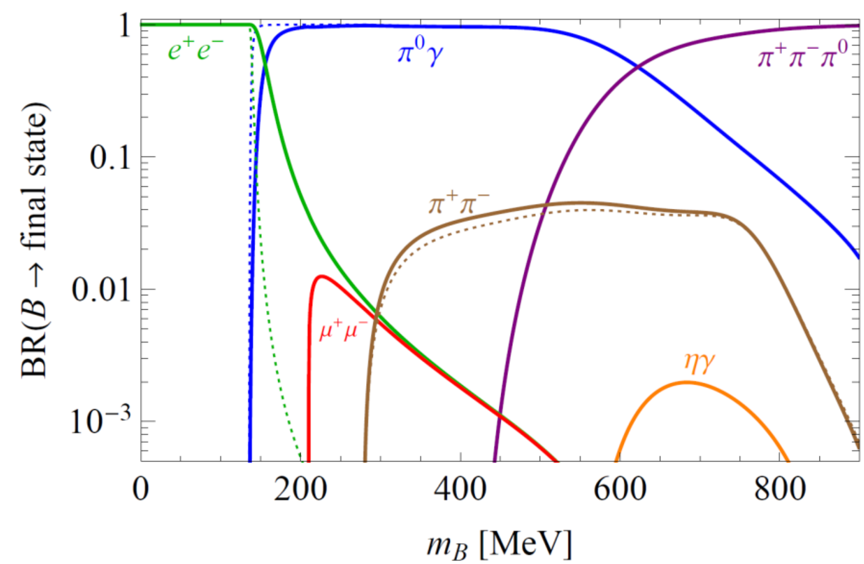
Leptophobic B boson from gauged $U(1)_B$

Lee & Yang (1955), Pais (1973), Nelson & Tetradis (1989), …

Model: $\mathscr{L} = \frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu$

Flavor-universal coupling to quarks
Suppressed couplings to leptons
Mass m_B, coupling $\alpha_B = g_B^2/4\pi$

Similar decays as ω meson



Decay → Production ↓	$B \to e^+e^-$ $m_B \sim 1 - 140$ MeV	$B \to \pi^0\gamma$ $140 - 620$ MeV	$B \to \pi^+\pi^-\pi^0$ $620 - 1000$ MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	–	–	–
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	–	–
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	–	–
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	–	

TABLE I: Summary of rare light meson decays induced by B gauge boson.

Leptophobic B boson from gauged $U(1)_B$

Lee & Yang (1955), Pais (1973), Nelson & Tetradis (1989), …

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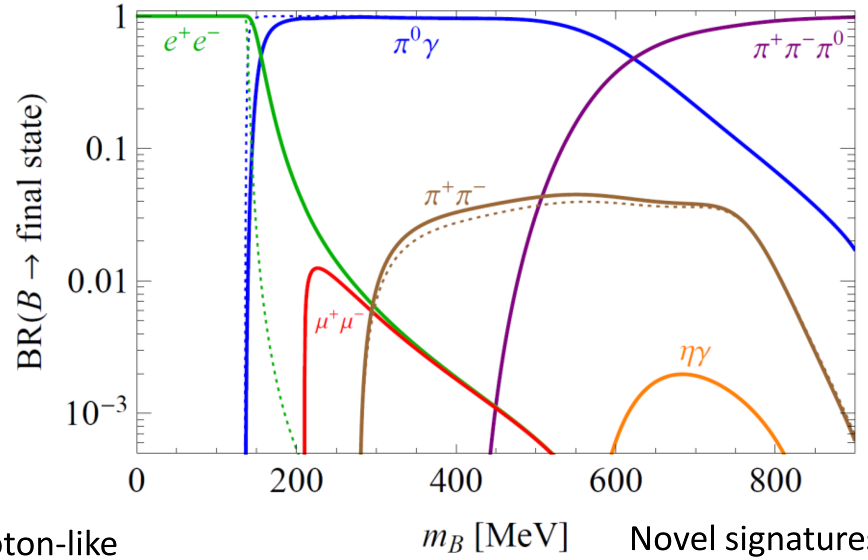

Dark-photon-like | Novel signatures

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$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	–	–
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
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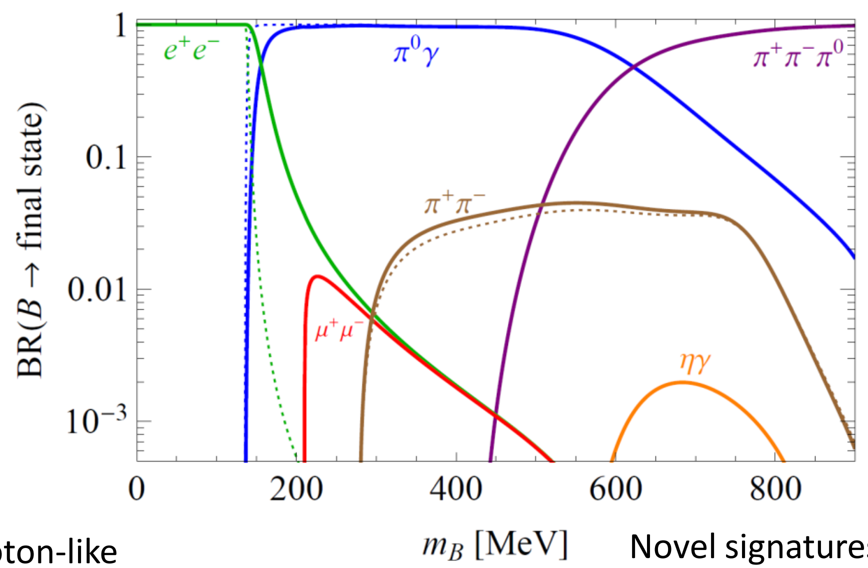

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$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	–	–
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	–	–
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Leptophobic B boson from gauged $U(1)_B$

Additional model complications:

- Coupling to leptons generated radiatively via heavy quark loops

$$\mathcal{L}_{\text{int}} = \left(\tfrac{1}{3} g_B + \varepsilon e Q_q\right) \bar{q}\gamma^\mu q B_\mu - \varepsilon e \bar{\ell}\gamma^\mu \ell B_\mu$$

Dark photon constraints still relevant across range of full mass range

- Anomaly cancellation requires new electrically-charged fermions

  Constraints from direct searches (can be at or above electroweak scale)

  Enhanced contributions to FCNCs *Dror et al (2017)*

Leptophobic B boson from gauged $U(1)_B$

Search channels:

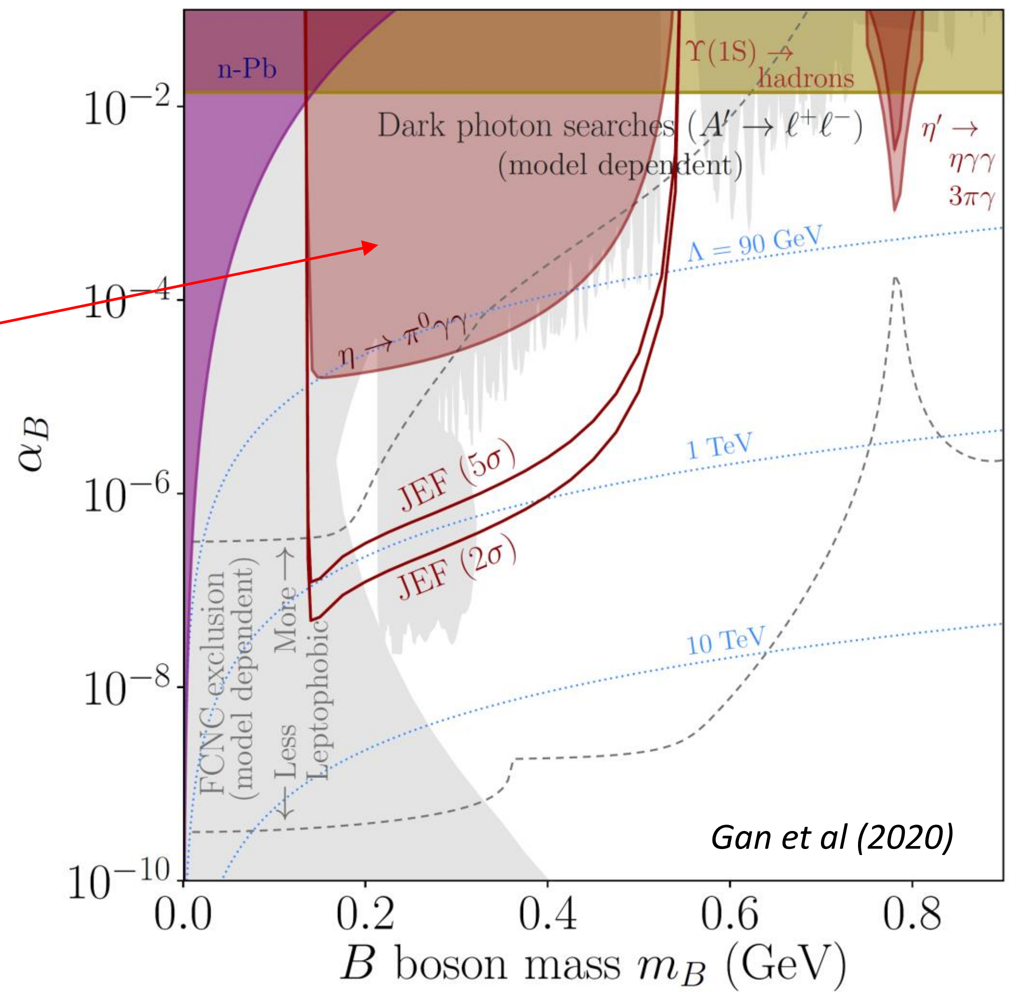
$$\eta \to B\gamma \to \pi^0\gamma\gamma$$

Mimics rare decay (0.025%)
Plus $\pi^0\gamma$ resonance

Quoted limit assuming zero SM contribution

See talk by Sergi Gonzalez-Solis

$$\eta' \to B\gamma \to \pi^0\gamma\gamma\,,\, \eta\gamma\gamma$$
$$\pi^+\pi^-\pi^0\gamma$$



Leptophobic B boson from gauged $U(1)_B$

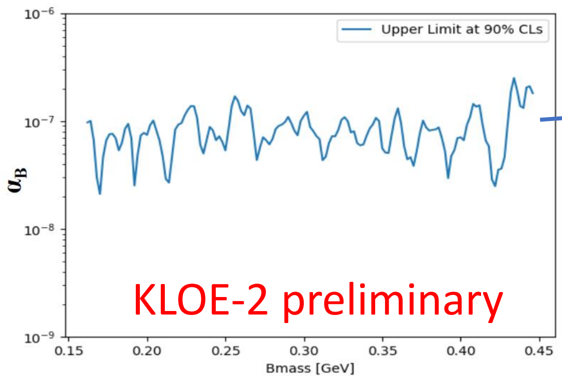
Search channels:

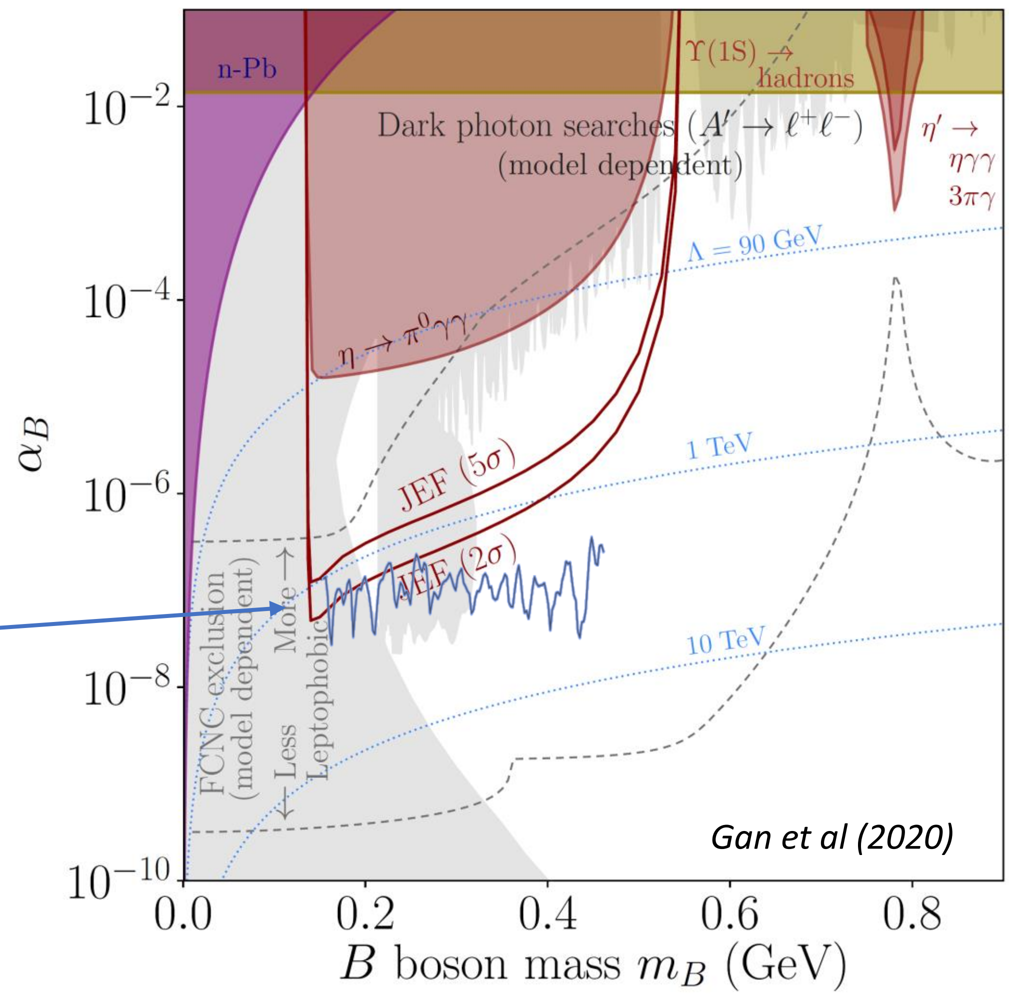
$$\phi \to \eta B \to \eta \pi^0 \gamma$$

Mimics rare decay (0.007%)
Plus $\pi^0\gamma$ resonance

Studied at KLOE-2

See talk by Simona Giovannella





Light scalar boson (S)

$$\mathcal{L}_{\mathrm{int}} = -\sum_{q=u,d,s,c,b,t} \kappa_q \frac{m_q}{v} \bar{q} q S + \kappa_G \frac{\alpha_s}{12\pi v} S G^a_{\mu\nu} G^{a\mu\nu}$$

Scalar boson coupled to quarks and gluons

Light scalar boson (S)

$$\mathcal{L}_{\rm int} = -\sum_{q=u,d,s,c,b,t} \kappa_q \frac{m_q}{v}\bar{q}qS + \kappa_G \frac{\alpha_s}{12\pi v} S\, G^a_{\mu\nu}G^{a\mu\nu}$$

Scalar boson coupled to quarks and gluons

Usual assumption: Coupling $\propto$ mass
Higgs mixing model: flavor-universal $\kappa_q = \sin\theta_S$

Predictions for η, η' decays: *Ellis et al (1976), Vainshtein et al (1980), Leutwyler & Shifman (1990); Bezrukov & Gorbunov (2009); Gan et al (2020)*

$$\mathcal{B}(\eta \to \pi^0 S) \approx 1.8\times 10^{-6}\sin^2\theta_S \times \lambda^{1/2}\left(1, \frac{M^2_{\pi^0}}{M^2_\eta}, \frac{m^2_S}{M^2_\eta}\right)$$

$$\mathcal{B}(\eta' \to \pi^0 S) \approx 5.4\times 10^{-8}\sin^2\theta_S \times \lambda^{1/2}\left(1, \frac{M^2_{\pi^0}}{M^2_{\eta'}}, \frac{m^2_S}{M^2_{\eta'}}\right)$$

$$\mathcal{B}(\eta' \to \eta S) \approx 4.7\times 10^{-5}\sin^2\theta_S \times \lambda^{1/2}\left(1, \frac{M^2_{\eta}}{M^2_{\eta'}}, \frac{m^2_S}{M^2_{\eta'}}\right)$$

Light scalar boson (S)

$$\mathcal{L}_{\text{int}} = -\sum_{q=u,d,s,c,b,t} \kappa_q \frac{m_q}{v} \bar{q} q S + \kappa_G \frac{\alpha_s}{12\pi v} S G^a_{\mu\nu} G^{a\mu\nu}$$

Scalar boson coupled to quarks and gluons

Usual assumption: Coupling $\propto$ mass
Higgs mixing model: flavor-universal $\kappa_q = \sin\theta_S$

Predictions for η, η' decays: *Ellis et al (1976), Vainshtein et al (1980), Leutwyler & Shifman (1990); Bezrukov & Gorbunov (2009); Gan et al (2020)*

$$\mathcal{B}(\eta \to \pi^0 S) \approx 1.8 \times 10^{-6} \sin^2\theta_S \times \lambda^{1/2}\left(1, \frac{M^2_{\pi^0}}{M^2_\eta}, \frac{m^2_S}{M^2_\eta}\right)$$

$$\mathcal{B}(\eta' \to \pi^0 S) \approx 5.4 \times 10^{-8} \sin^2\theta_S \times \lambda^{1/2}\left(1, \frac{M^2_{\pi^0}}{M^2_{\eta'}}, \frac{m^2_S}{M^2_{\eta'}}\right)$$

$$\mathcal{B}(\eta' \to \eta S) \approx 4.7 \times 10^{-5} \sin^2\theta_S \times \lambda^{1/2}\left(1, \frac{M^2_{\eta}}{M^2_{\eta'}}, \frac{m^2_S}{M^2_{\eta'}}\right)$$

FCNC constraints
(B → KS, K → πS)

$$\sin^2\theta_S \lesssim 10^{-6}$$

Beacham et al (2019)

Light scalar boson (S)

$$\mathcal{L}_{\text{int}} = -\sum_{q=u,d,s,c,b,t} \kappa_q \frac{m_q}{v} \bar{q} q S + \kappa_G \frac{\alpha_s}{12\pi v} S G^a_{\mu\nu} G^{a\mu\nu}$$

General model: independent couplings to quarks

FCNCs

η, η′ decays

Constrains heavy flavor (top) couplings

Constrains light quark couplings

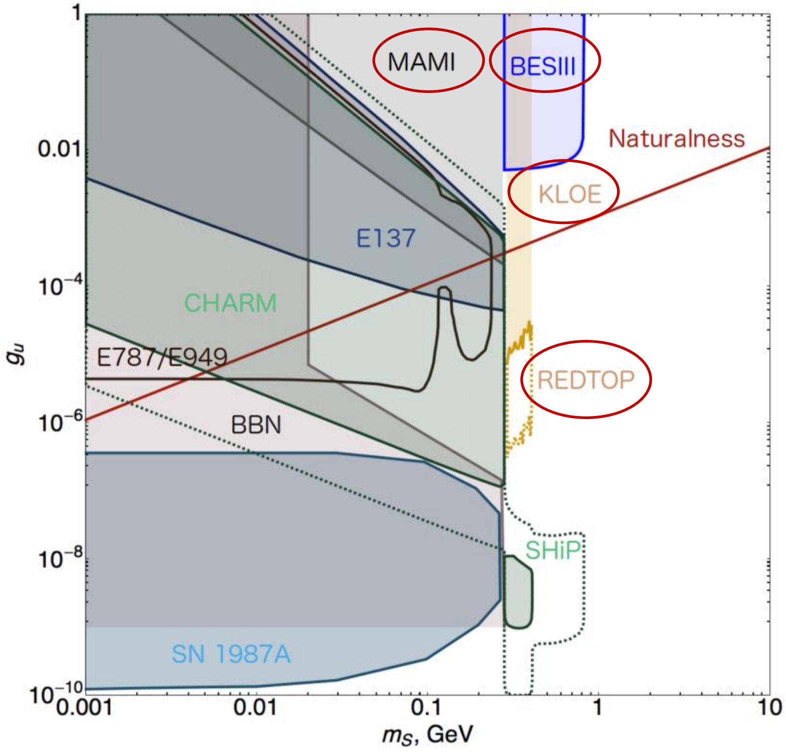
η, η′ decays complementary to other tests

Sensitive to “flipped” scalar model
with larger couplings to light quarks

Hadrophilic scalar boson

Batell et al (2017,2018)

Constraints from η,η' decays



Light scalar coupling to *u*-quarks only

$$\eta \to \pi^0 S \to \pi^0 \gamma\gamma$$

$$\eta, \eta' \to \pi^0 S \to 3\pi$$

General scalar boson

General couplings to *u*,*d*-quarks and e, μ, γ *Liu, Cloet, Miller (2018); Gan et al (2020)*

$$\eta, \eta' \to \pi^0 S \to \pi^0 \ell^+ \ell^- , \quad \eta' \to \eta S \to \eta \ell^+ \ell^-$$

Mimics very rare SM decays (γγ–loop, since single-γ process is C-violating)
Dilepton resonance

$$\eta \to \pi^0 S \to \pi^0 \gamma\gamma$$

γγ resonance in rare decay

$$\eta, \eta' \to \pi^0 S \to 3\pi, \quad \eta' \to \eta S \to \eta\pi\pi$$

Bump-hunting in Dalitz distributions

General scalar boson

More work required from theorists (pheno + χPT specialists)

Scalar transition form factors for η' decays not well known

$$\langle \pi^0(p) | \tfrac{1}{2}(\bar{u}u - \bar{d}d) | \eta^{(\prime)}(k) \rangle = B_0 \Gamma^{u-d}_{\pi\eta^{(\prime)}}(t)$$

$$\langle \pi^0(p) | \tfrac{1}{2}(\bar{u}u + \bar{d}d) | \eta^{(\prime)}(k) \rangle = B_0 \Gamma^{u+d}_{\pi\eta^{(\prime)}}(t)$$

$$\langle \pi^0(p) | \bar{s}s | \eta^{(\prime)}(k) \rangle = B_0 \Gamma^{s}_{\pi\eta^{(\prime)}}(t)$$

Mapping out phenomenologically allowed parameter space

Axion-like particles (ALPs) and η,η' decays

Aloni et al (2019), Landini and Meggiolaro (2019), see talk by Sergi Gonzalez-Solis

Model:

$$\mathcal{L}_{\rm ALP} = \mathcal{L}_{\rm QCD} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \underbrace{\frac{1}{2}m_0^2 a^2 - \frac{\alpha_s}{8\pi f_a} a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu}} - \frac{\alpha_{\rm em} c_\gamma}{8\pi f_a} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{\partial^\mu a}{2 f_a}\bar{q} c_q \gamma_\mu \gamma_5 q - \frac{\partial^\mu a}{2 f_a}\bar{\ell} c_\ell \gamma_\mu \gamma_5 \ell$$

ALP mass:

$$m_a^2 = m_0^2 + \frac{M_\pi^2 F_\pi^2}{2 f_a^2}\left(\frac{m_u m_d}{(m_u + m_d)^2}\right)$$

Not necessarily the QCD axion

Free parameters:
Mass m_a
Decay constant f_a
Quark, lepton, photon couplings

Axion-like particles (ALPs) and η,η' decays

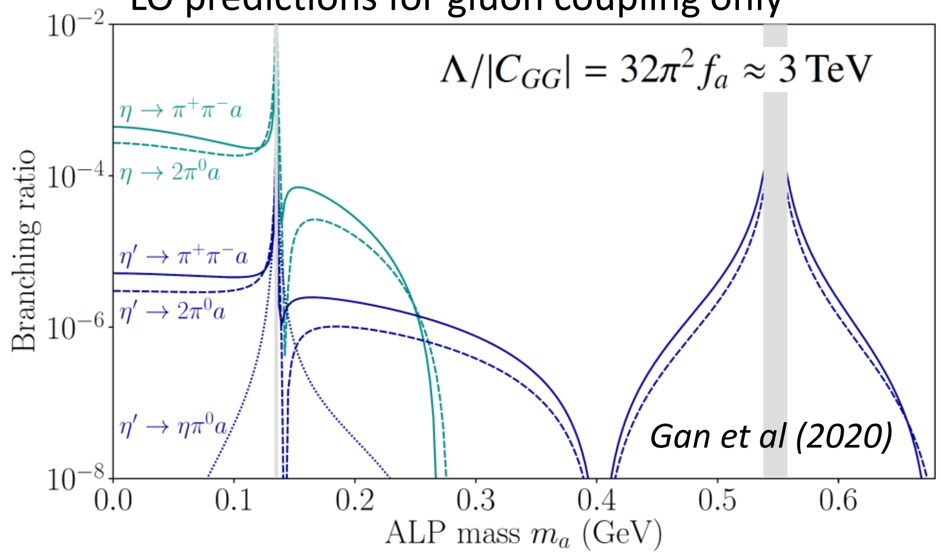
Model:

$$\mathcal{L}_{\rm ALP} = \mathcal{L}_{\rm QCD} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_0^2 a^2 - \frac{\alpha_s}{8\pi f_a} a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{\alpha_{\rm em} c_\gamma}{8\pi f_a} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{\partial^\mu a}{2 f_a}\bar{q} c_q \gamma_\mu\gamma_5 q - \frac{\partial^\mu a}{2 f_a}\bar{\ell} c_\ell \gamma_\mu \gamma_5 \ell$$

ALP quark and gluon couplings → production in η, η' decays

$$\eta \to \pi\pi a$$
$$\eta' \to \pi\pi a$$
$$\eta' \to \eta\pi^0 a$$

LO predictions for gluon coupling only



Compare to talk by Sergi Gonzalez-Solis

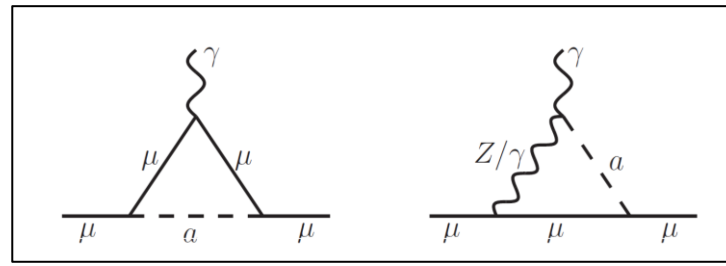
Axion-like particles (ALPs) and η,η' decays

Model:

$$\mathcal{L}_{\rm ALP} = \mathcal{L}_{\rm QCD} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_0^2 a^2 - \frac{\alpha_s}{8\pi f_a} a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \underbrace{\frac{\alpha_{\rm em} c_\gamma}{8\pi f_a} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}} - \frac{\partial^\mu a}{2 f_a}\bar{q} c_q \gamma_\mu \gamma_5 q - \underbrace{\frac{\partial^\mu a}{2 f_a}\bar{\ell} c_\ell \gamma_\mu \gamma_5 \ell}$$

Lepton/photon couplings:
motivated by $(g\text{-}2)_\mu$

Marciano et al (2016), Bauer et al (2017)



Axion-like particles (ALPs) and η,η' decays

Signatures: many complicated 4- and 5-body final states

$$\eta \to \pi\pi a \to \pi\pi\gamma\gamma\,,\ \pi\pi e^{+}e^{-}\,,\ \pi\pi\mu^{+}\mu^{-}$$ (and same for η')

$$\eta' \to \pi\pi a \to \pi\pi\,\pi^{+}\pi^{-}\gamma\,,\ 5\pi$$

$$\eta' \to \eta\pi^{0}a \to \eta\pi^{0}\gamma\gamma\,,\ \eta\pi^{0}e^{+}e^{-}\,,\ \eta\pi^{0}\mu^{+}\mu^{-}$$

Most of these had no motivation to be studied. Can they be searched for?

Direct photoproduction of new gauge bosons

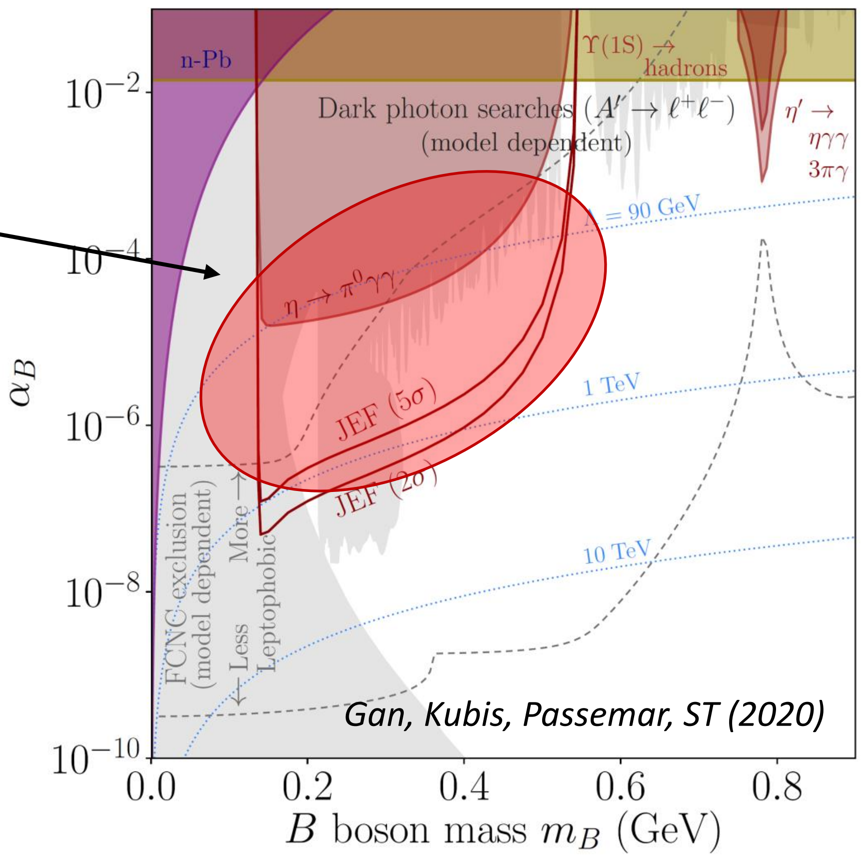
Safa Ben Othman, Armita Jalooli, ST (in prep); see also Fanelli and Williams (2016)

B boson parameter space

Decay production (η, ϕ decay)

$$\eta \to B\gamma \to \pi^0\gamma\gamma$$

$$\phi \to \eta B \to \eta\pi^0\gamma$$



Direct photoproduction of new gauge bosons

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B boson parameter space

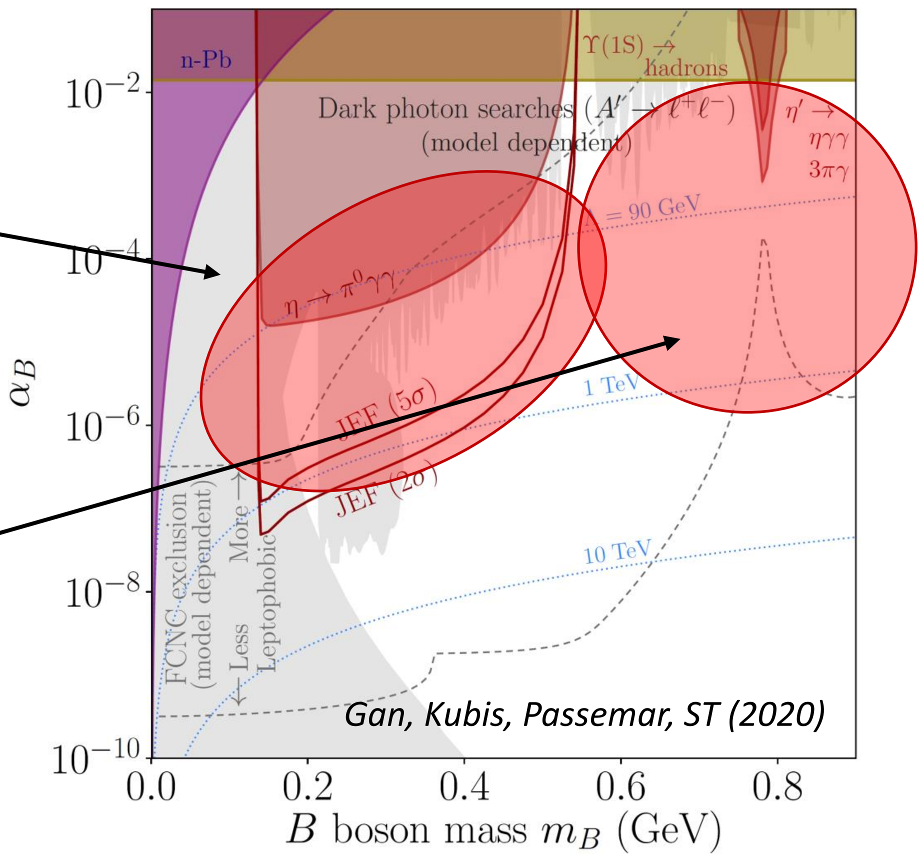
Decay production (η, ϕ decay)

$$\eta \to B\gamma \to \pi^0\gamma\gamma$$

$$\phi \to \eta B \to \eta\pi^0\gamma$$

Direct production

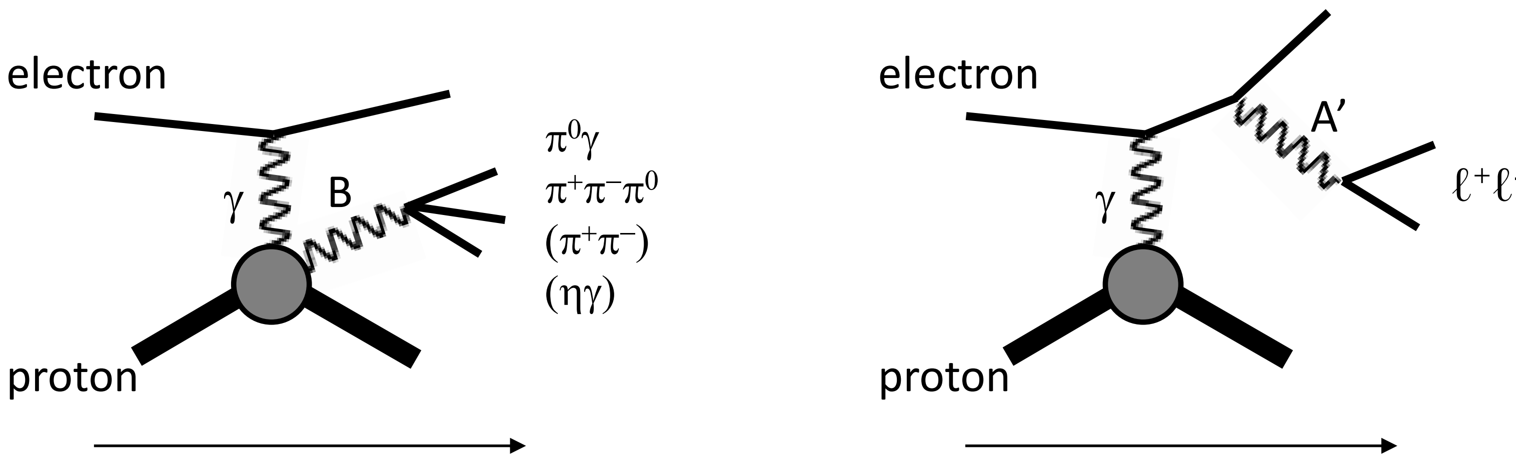
$$\gamma p \to Bp \to \pi^0\gamma\, p\,,\ \pi^+\pi^-\pi^0\, p$$



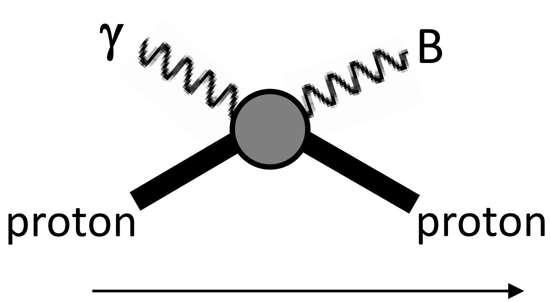
Direct production of new gauge forces

Leptophobic B boson production

Dark photon production



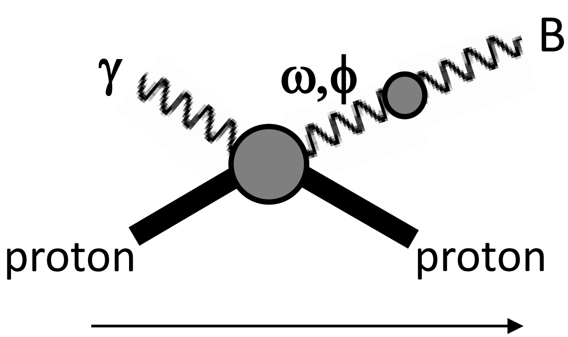
B boson production



Sub-GeV B boson: dominated by diffractive scattering (Q < GeV)

Cannot be calculated in perturbative QCD and must be modeled

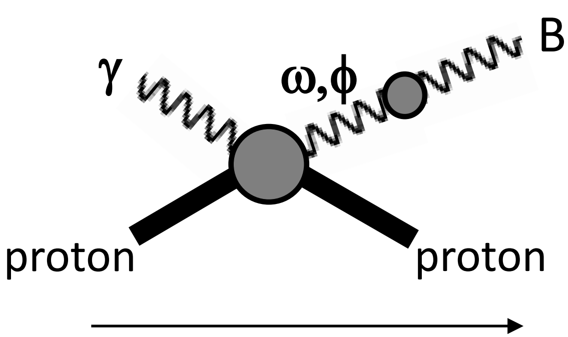
B boson production



Assumption I:
Vector meson dominance (VMD)

External gauge fields couple by mixing with QCD vector mesons (isoscalar only)

B boson production



Assumption I:
Vector meson dominance (VMD)

External gauge fields couple by mixing with QCD vector mesons (isoscalar only)

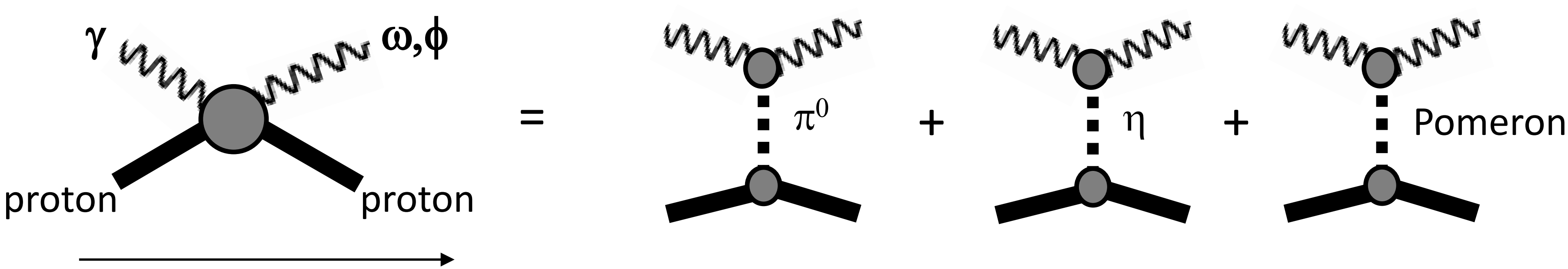
$$V(k,\lambda) \Longrightarrow\!\!\!\times\!\!\sim\!\!\sim B(k,\lambda) = \frac{\sqrt{2} f_V m_V}{k^2 - m_V^2 + i m_V \Gamma_V} \mathrm{Tr}\left[\boldsymbol{T}_V \left(\tfrac{1}{3} g_B \boldsymbol{I} + \varepsilon e \boldsymbol{Q} \right) \right]$$

(Function of meson mass, width, decay constant) x (group theoretic factor) x (BSM couplings)

$$\mathcal{M}(\gamma p \to Bp) = -\mathcal{M}(\gamma p \to \omega p) \left(\frac{\sqrt{2} g_B f_\omega F_\omega(m_B^2)}{3 m_\omega} \right) - \mathcal{M}(\gamma p \to \phi p) \left(\frac{g_B f_\phi F_\phi(m_B^2)}{3 m_\phi} \right)$$

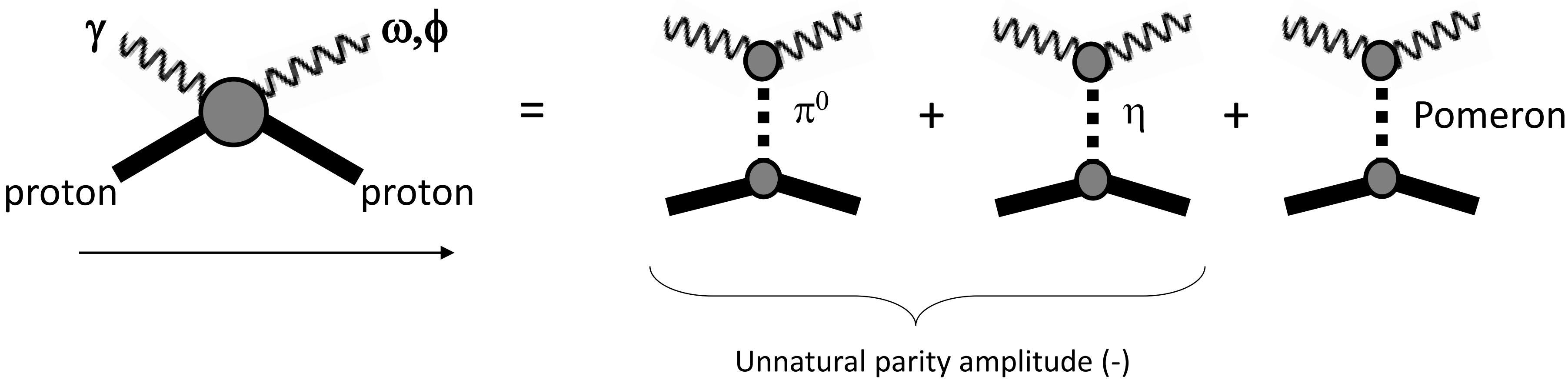
B boson production

Assumption II: t-channel exchange model for SM matrix elements



B boson production

Assumption II: t-channel exchange model for SM matrix elements

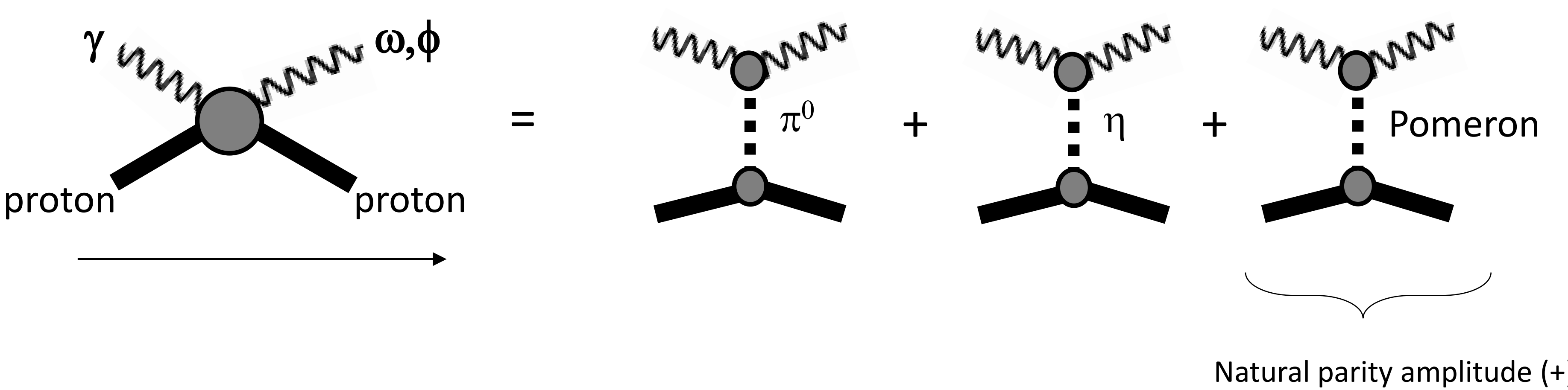


Each coupling dressed with a form factor $F(t,\Lambda,m)=\frac{\Lambda^2-m^2}{\Lambda^2-t}$ *Friman & Soyeur (1996)*

Number of parameters: 6 couplings + 6 momentum scales $\Lambda \sim m_\rho$

B boson production

Assumption II: t-channel exchange model for SM matrix elements



Calculated from Vp→Vp scattering + VMD for coupling initial γ *Ewerz et al (2013)*

Include additional t-dependent form factor $F_{pV}(t) = \exp(b_V t)$ *Laget & Mendez-Galain (1995)*

$$\frac{d\sigma_+(\gamma p \to \omega p)}{dt} = \frac{2\alpha_{\rm em} f_\omega^2 s^2}{m_\omega^2 (s - m_p^2)^2} \beta_{\mathbb{P}NN}^2 \beta_{\mathbb{P}\omega\omega}^2 |F_{p\omega}(t)|^2 \left(\frac{s}{s_0}\right)^{2\alpha_{\mathbb{P}}(t)-2}$$

Model parameters

fixed parameter	input value	source	fitted parameter	prior
$g_{\pi\gamma\omega}$	1.81 ± 0.03	$\omega \to \pi^0\gamma$	$g_{\pi NN}$	13 ± 1
$g_{\eta\gamma\omega}$	0.35 ± 0.02	$\omega \to \eta\gamma$	$g_{\eta NN}$	4 ± 1
$g_{\pi\gamma\phi}$	0.137 ± 0.003	$\phi \to \pi^0\gamma$	$\Lambda_{\pi^0 NN}$	0.8 ± 0.2 GeV
$g_{\eta\gamma\phi}$	0.704 ± 0.007	$\phi \to \eta\gamma$	$\Lambda_{\eta NN}$	0.8 ± 0.2 GeV
f_ω	198 ± 2 MeV	$\omega \to e^+e^-$	$\Lambda_{\pi^0\gamma\omega}$	0.8 ± 0.2 GeV
f_ϕ	228 ± 1 MeV	$\phi \to e^+e^-$	$\Lambda_{\eta\gamma\omega}$	0.8 ± 0.2 GeV
$\beta_{\mathbb{P}NN}$	1.87 GeV^{-1}	pp, $p\bar{p}$ data	$\Lambda_{\pi^0\gamma\phi}$	0.8 ± 0.2 GeV
$\alpha_{\mathbb{P}}(0)$	1.08	pp, $p\bar{p}$ data	$\Lambda_{\eta\gamma\phi}$	0.8 ± 0.2 GeV
$\alpha'_{\mathbb{P}}(0) = s_0^{-1}$	0.25 GeV^{-2}	pp, $p\bar{p}$ data	$\beta_{\mathbb{P}\omega\omega}$	none
			$\beta_{\mathbb{P}\phi\phi}$	none
			b_ω	none
			b_ϕ	none

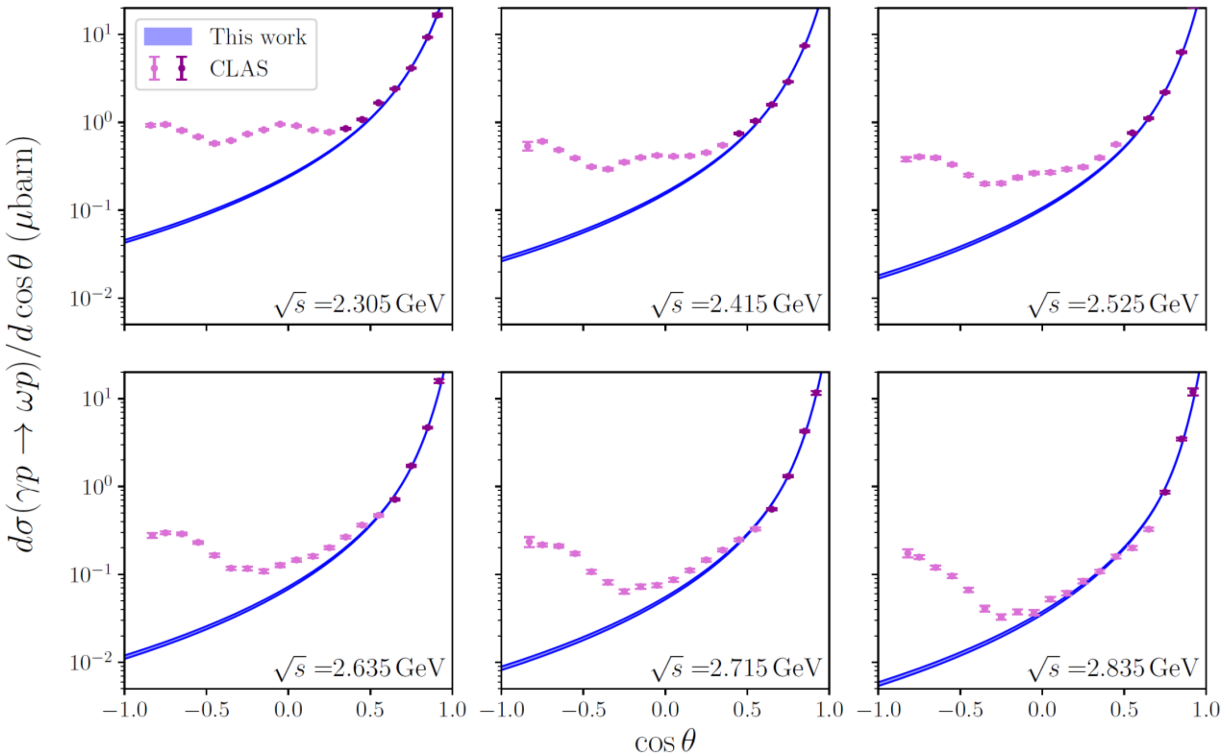
Model parameters

Determine model parameters using experimental data for differential cross sections for vector meson photoproduction

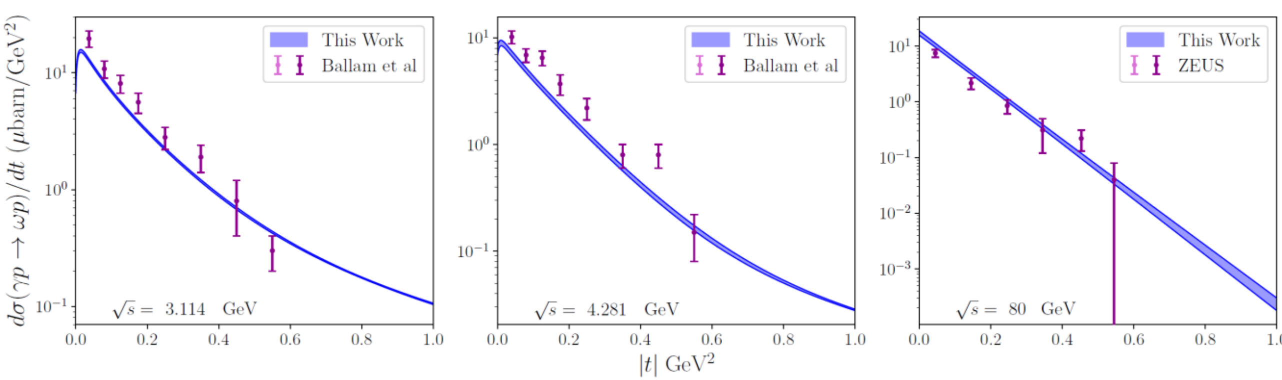
Data sets:	Energy:
• Mainly CLAS *(Williams et al 2009; Dey et al 2014)*	up to $\sqrt{s} \approx 2.8$ GeV
• Older data: SLAC *(Ballam et al 1973)*, NINA *(Barber et al 1984)*	up to $\sqrt{s} \approx 4.2$ GeV
• High energy: ZEUS *(Derrick et al 1996)*	$\sqrt{s} \approx 80$ GeV

Perform MCMC

Restricted to data points with $|t| < 1\ \mathrm{GeV}^2$ and $\sqrt{s} > 2.3$ GeV

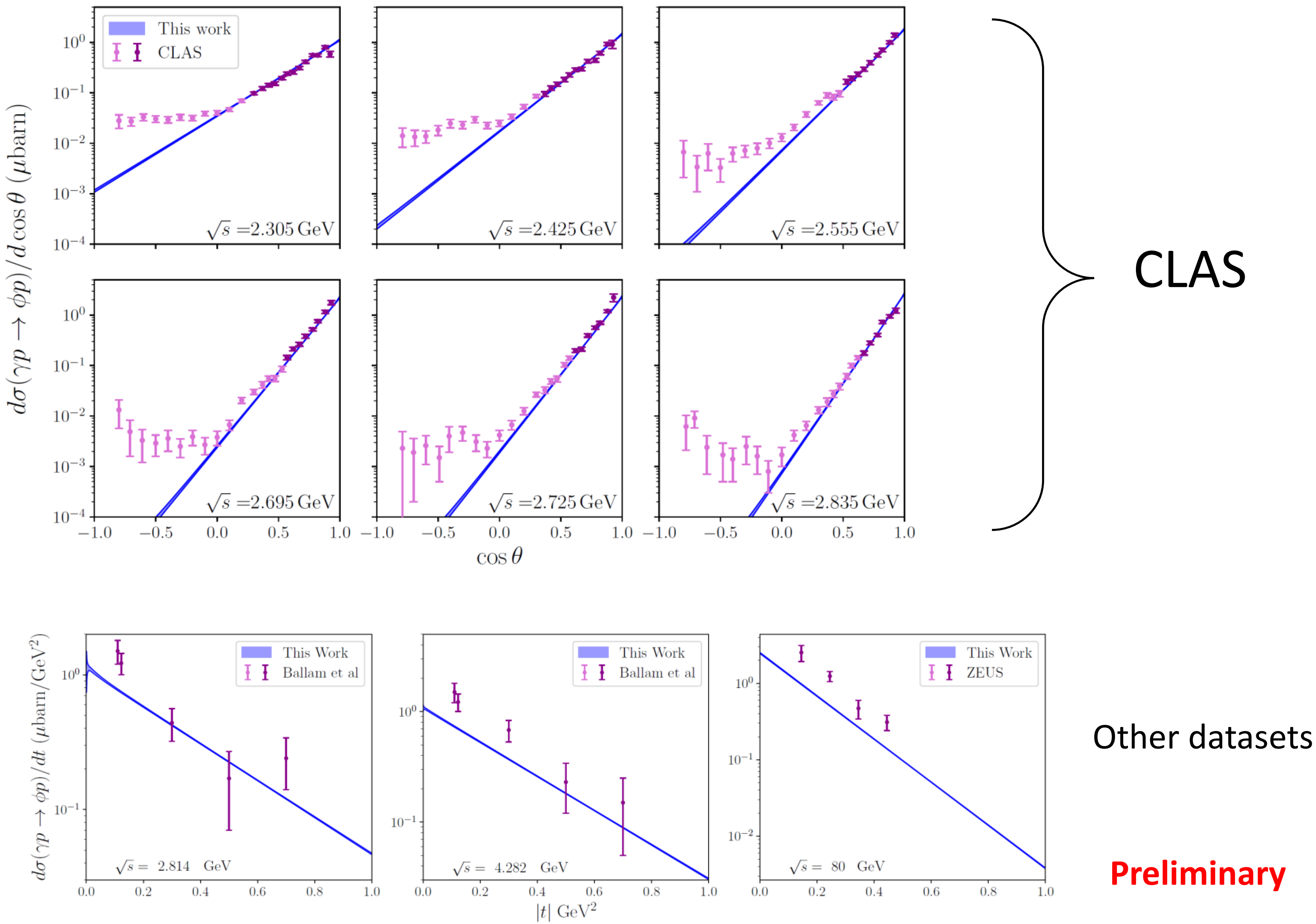


CLAS



Other datasets

Preliminary

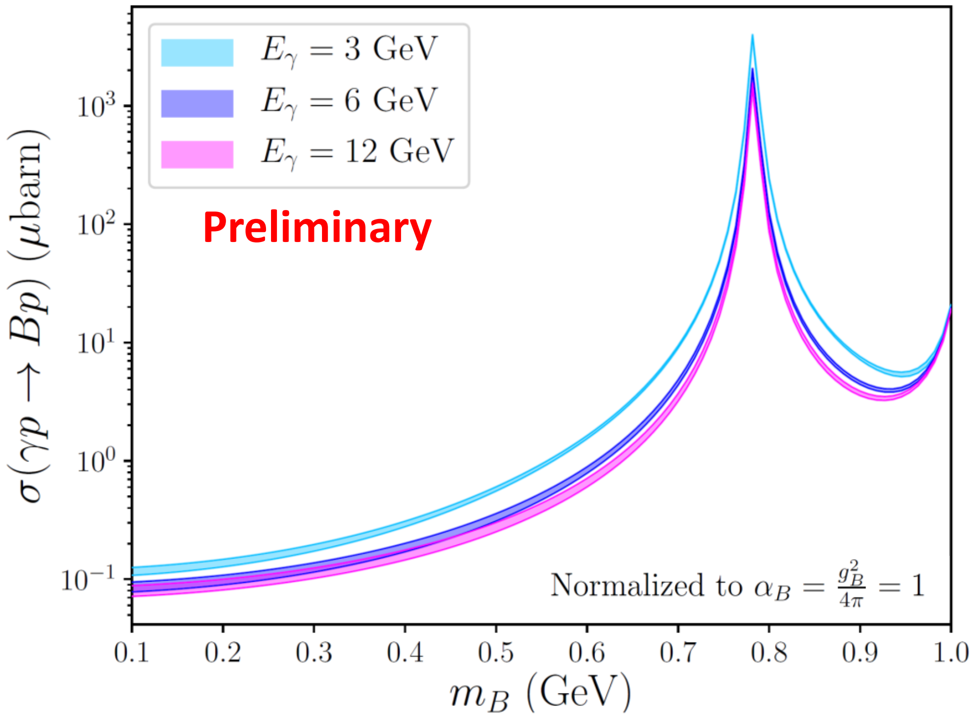


This work
CLAS
$d\sigma(\gamma p \to \phi p)/d\cos\theta$ (μbarn)
$\sqrt{s}$ =2.305 GeV
$\sqrt{s}$ =2.425 GeV
$\sqrt{s}$ =2.555 GeV
$\sqrt{s}$ =2.695 GeV
$\sqrt{s}$ =2.725 GeV
$\sqrt{s}$ =2.835 GeV
$\cos\theta$
CLAS
This Work
Ballam et al
ZEUS
$d\sigma(\gamma p \to \phi p)/dt$ (μbarn/GeV^2)
$\sqrt{s}$ = 2.814 GeV
$\sqrt{s}$ = 4.282 GeV
$\sqrt{s}$ = 80 GeV
$|t|$ GeV^2
Other datasets
Preliminary

Model parameters

fixed parameter	input value	source	fitted parameter	prior	best-fit value
$g_{\pi\gamma\omega}$	1.81 ± 0.03	$\omega \to \pi^0\gamma$	$g_{\pi NN}$	13 ± 1	13.0 ± 0.4
$g_{\eta\gamma\omega}$	0.35 ± 0.02	$\omega \to \eta\gamma$	$g_{\eta NN}$	4 ± 1	4 ± 1
$g_{\pi\gamma\phi}$	0.137 ± 0.003	$\phi \to \pi^0\gamma$	$\Lambda_{\pi^0 NN}$	0.8 ± 0.2 GeV	0.8 ± 0.1
$g_{\eta\gamma\phi}$	0.704 ± 0.007	$\phi \to \eta\gamma$	$\Lambda_{\eta NN}$	0.8 ± 0.2 GeV	0.7 ± 0.3
f_ω	198 ± 2 MeV	$\omega \to e^+e^-$	$\Lambda_{\pi^0\gamma\omega}$	0.8 ± 0.2 GeV	0.8 ± 0.1
f_ϕ	228 ± 1 MeV	$\phi \to e^+e^-$	$\Lambda_{\eta\gamma\omega}$	0.8 ± 0.2 GeV	0.8 ± 0.2
$\beta_{\mathbb{P}NN}$	1.87 GeV^{-1}	$pp, p\bar{p}$ data	$\Lambda_{\pi^0\gamma\phi}$	0.8 ± 0.2 GeV	0.5 ± 0.2
$\alpha_{\mathbb{P}}(0)$	1.08	$pp, p\bar{p}$ data	$\Lambda_{\eta\gamma\phi}$	0.8 ± 0.2 GeV	0.6 ± 0.3
$\alpha'_{\mathbb{P}}(0) = s_0^{-1}$	0.25 GeV^{-2}	$pp, p\bar{p}$ data	$\beta_{\mathbb{P}\omega\omega}$	none	2.0 ± 0.1
			$\beta_{\mathbb{P}\phi\phi}$	none	0.620 ± 0.005
			b_ω	none	3.8 ± 0.1
			b_ϕ	none	1.40 ± 0.01

B boson production cross section



Conclusions

Light hidden particles are well-motivated extensions of Standard Model (possibly connected to dark matter)

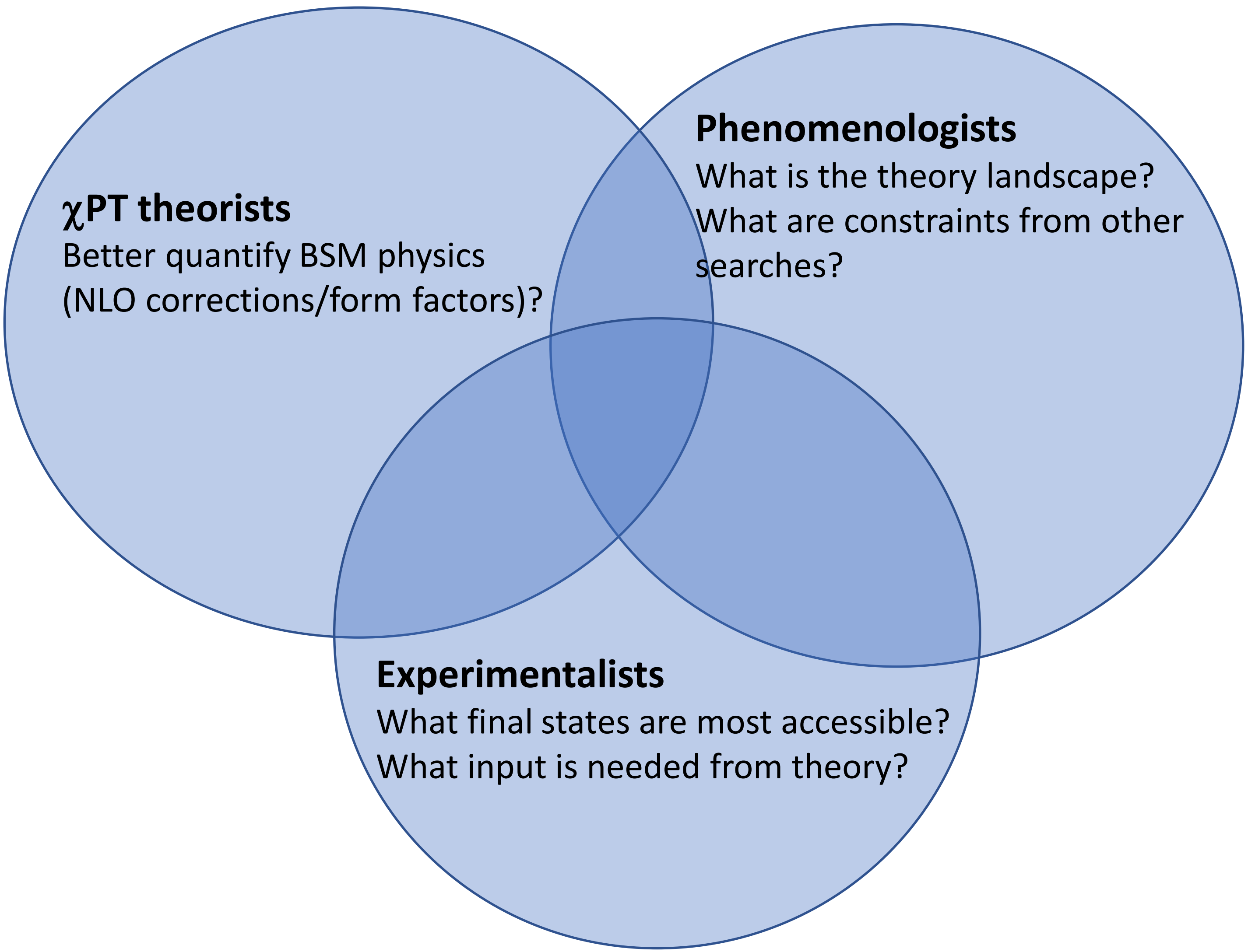
Worldwide effort is mostly focused on leptonic, invisible/long-lived, or heavy flavor signatures

η,η' mesons are an interesting place to look for hidden particles because probe couplings to light quarks/gluons

BSM searches in parallel with Standard Model η,η' decay studies

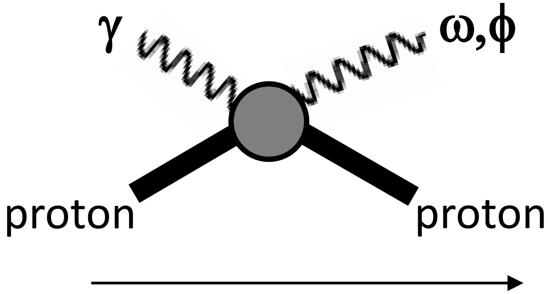
Conclusions

Progress on this front requires collaboration!



Backup slides

B boson production



Need vector meson photoproduction matrix elements (SM process)

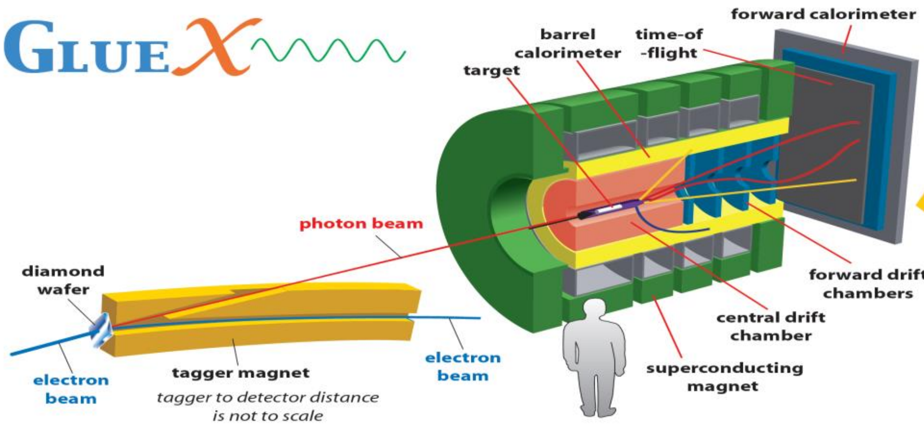
Previous approach: Fanelli & Williams (2016) $\mathcal{M}(\gamma p \to Vp) \sim \sqrt{\sigma(\gamma p \to Vp)}$

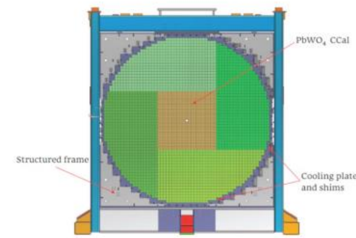
$$\sigma_\pm(\gamma p \to Bp) = \frac{4\alpha_B \Phi(m_B)}{27} \left(\frac{|F_\omega(m_B^2)|^2 \sigma_\pm(\gamma p \to \omega p)}{\Phi(m_\omega)} + \frac{|F_\phi(m_B^2)|^2 \sigma_\pm(\gamma p \to \phi p)}{2\Phi(m_\phi)} + \frac{\cos\varphi_\pm |F_\omega(m_B^2)||F_\phi(m_B^2)| \sqrt{2\sigma_\pm(\gamma p \to \omega p)\sigma_\pm(\gamma p \to \phi p)}}{\sqrt{\Phi(m_\omega)\Phi(m_\phi)}} \right)$$

(Φ = phase space factors)

Jefferson Eta Factory (JEF) experiment   γ beam (10 GeV) on H target

GlueX + upgraded forward calorimeter at Jefferson Lab (Hall D)





FCAL-II

Rare Eta Decays with a TPC for Optical Photons (REDTOP)

proton beam (1-3 GeV) on nuclear target (Be/D)