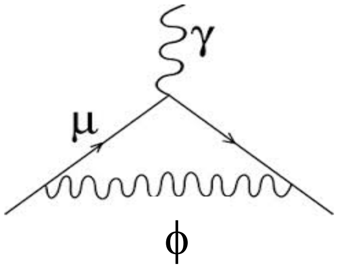
Dark sectors at η,η' factories

Sean Tulin

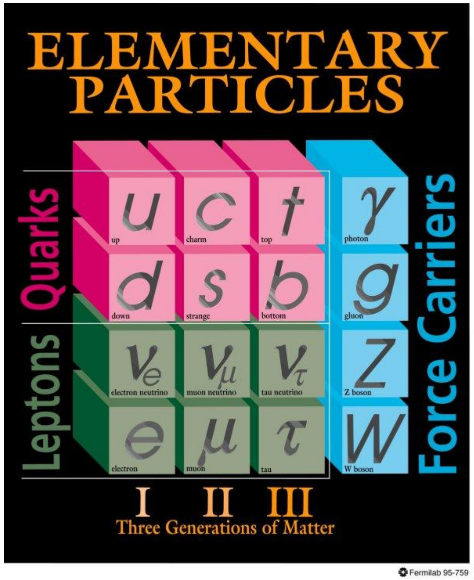
Motivations for sub-GeV new physics

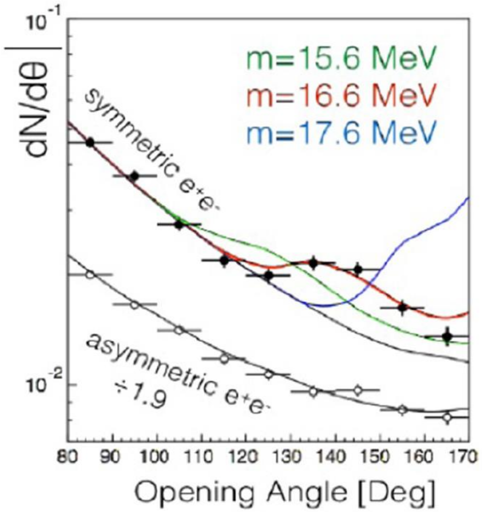
New gauge forces or scalar bosons beyond the minimal Standard Model

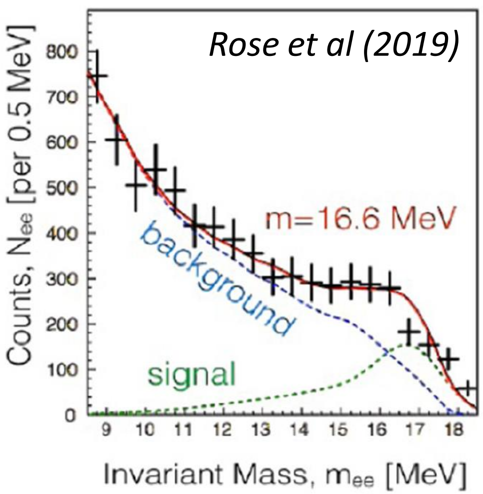


$(g\text{-}2)_\mu$ anomaly

Pospelov (2008)







$^8Be/^4He$ anomalies

Krasznahorkay et al (2016);
Feng et al (2016,2017)

Motivations for sub-GeV new physics

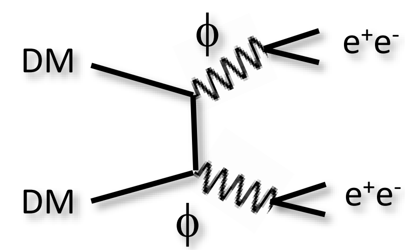
Dark matter physics:

- Dark sector: matter particles and forces, like the Standard Model
- Explains dark matter stability (dark charge conservation)

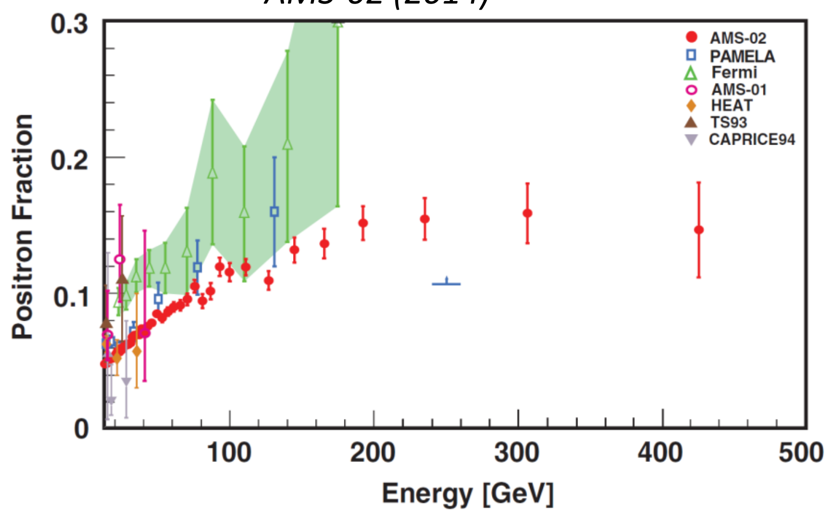
Motivations for sub-GeV new physics

Dark matter physics:

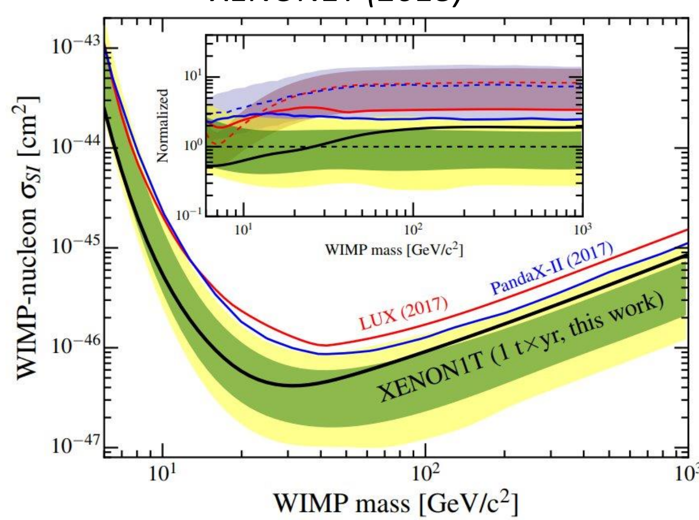
- Annihilating dark matter (indirect detection anomalies, light dark matter, relic density)



AMS-02 (2014)



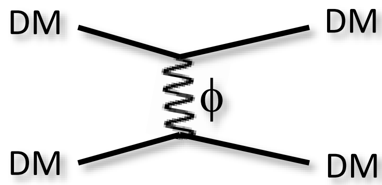
XENON1T (2018)



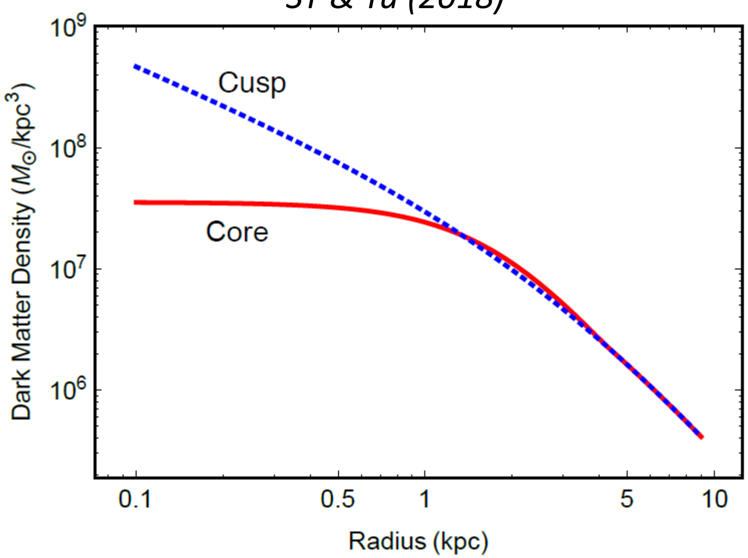
Motivations for sub-GeV new physics

Dark matter physics:

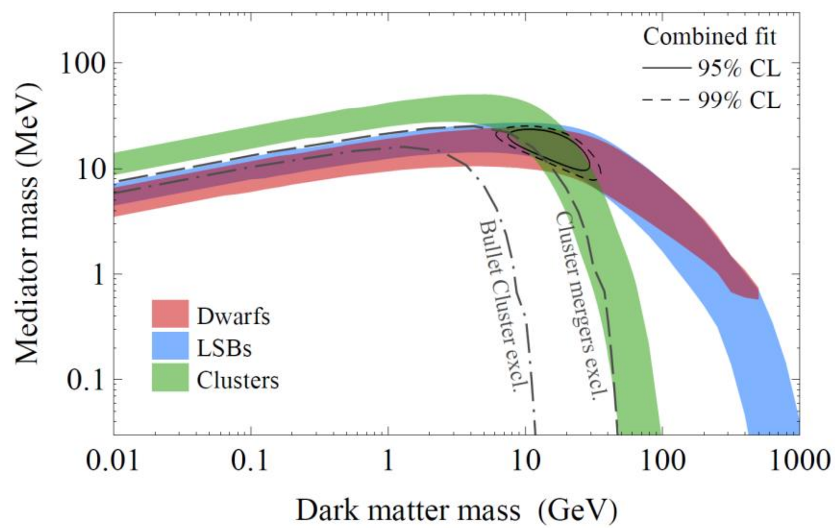
- Self-interacting dark matter



ST & Yu (2018)



Kaplinghat, ST & Yu (2016)



Outline: dark sectors at η,η′ factories

- Dark sector particles produced in meson decays

  New gauge bosons, scalars, pseudoscalars (ALPs)

  Precision tests of fundamental physics with η and η′ mesons
  Gan, Kubis, Passemar, ST (2020)

  Searching for new light hidden particles with η and η′ mesons
  ST, Gatto, Kubis [Snowmass 2021 LOI]

- Dark sector particles produced directly via photoproduction (B boson)

  New baryonic forces at electron-beam fixed target experiments
  Safa Ben Othman, Armita Jalooli, ST (in prep)

Larger η,η’ samples at future facilities

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	$\sim3x10^7$ (p+d), $\sim5x10^8$ (p+p)	-
KLOE-II	$3x10^8$	$5x10^5$
BESIII	$\sim10^7$	$\sim5x10^7$

Upcoming experiments

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

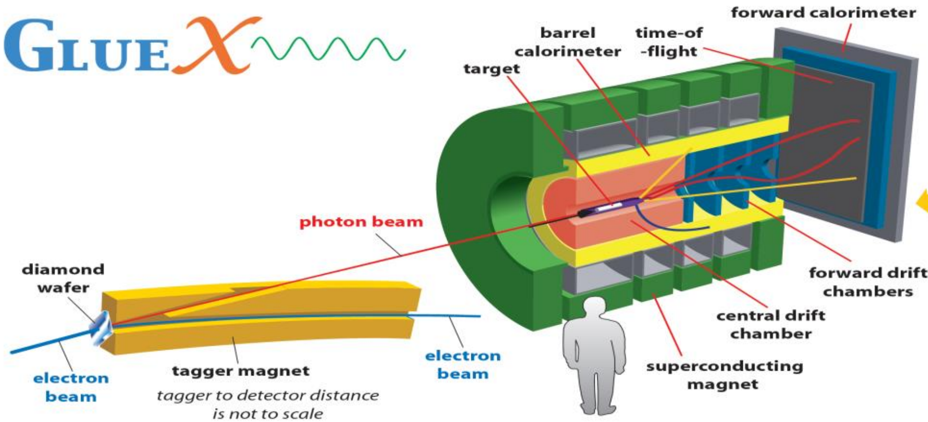
	η	η'	
Tagged mesons	$6.5x10^7$	$4.9x10^7$	per 100 days

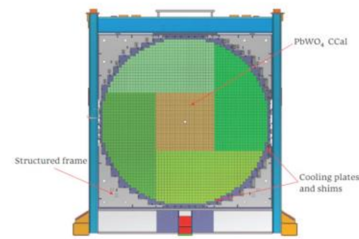
Rare Eta Decays with a TPC for Optical Photons (REDTOP) possibly at Fermilab (proposed)

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

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

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

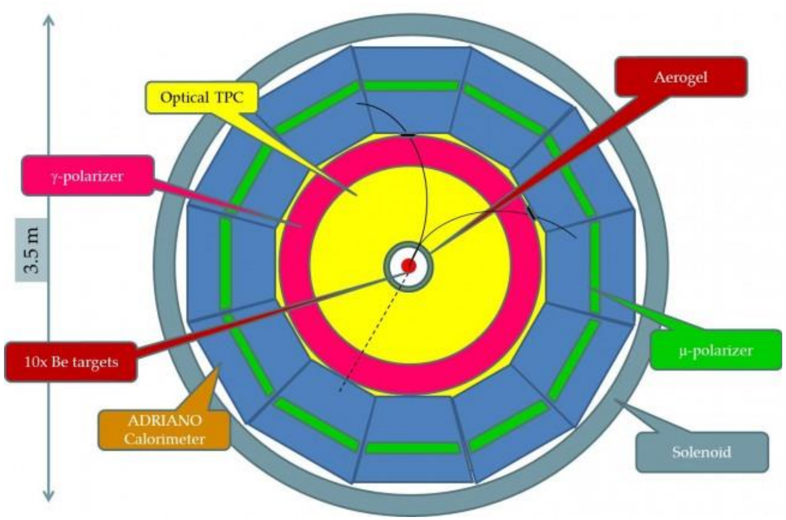


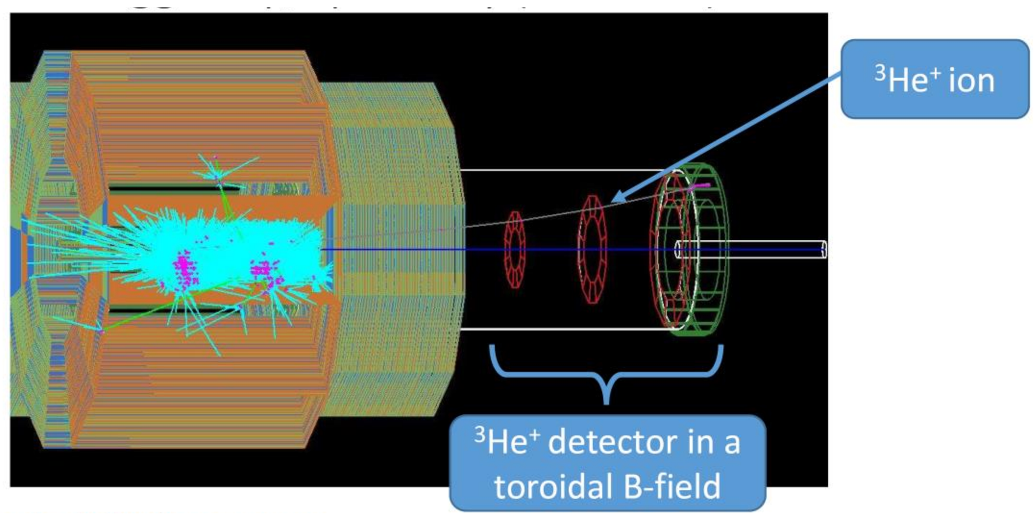


FCAL-II

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

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





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 [arxiv:2007.00664]

η, η' laboratory 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)

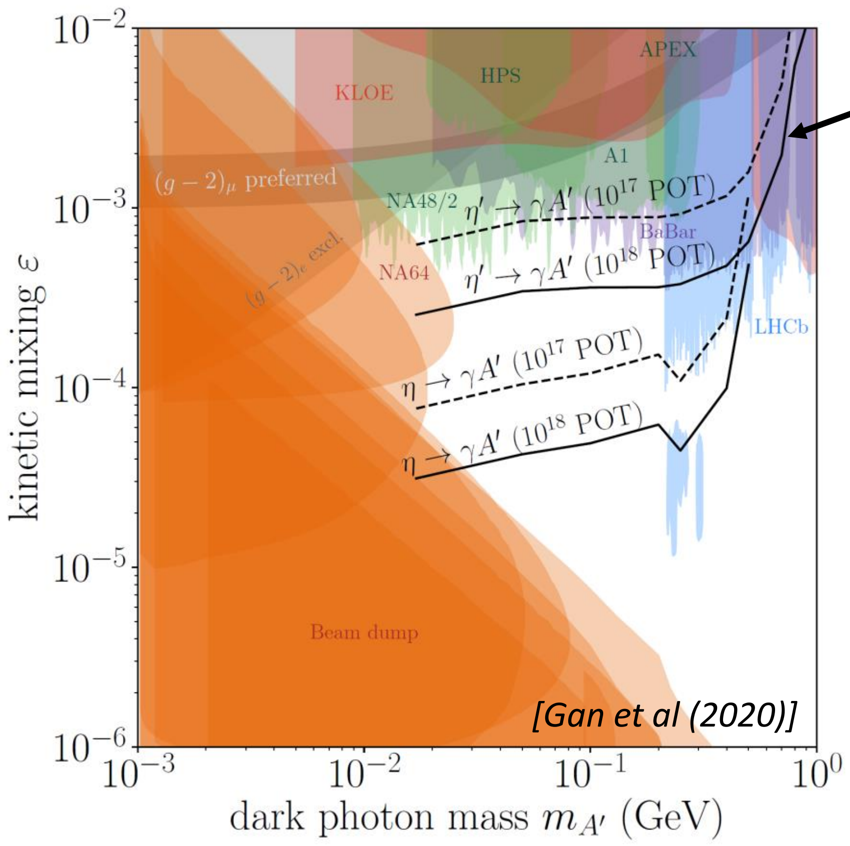
- Search strategies (visible final states):
  - Resonance searches (bump hunting)
  - Displaced vertices (long-lived decays)
  - Rare decays – new physics process mimics highly-suppressed SM channels

- Other possibilities: invisible or partially-invisible decays

Dark photon

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

$$\eta, \eta' \to \gamma A' \to \gamma \ell^+ \ell^-$$



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

[Gatto (2019)]

Worthwhile to also consider

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

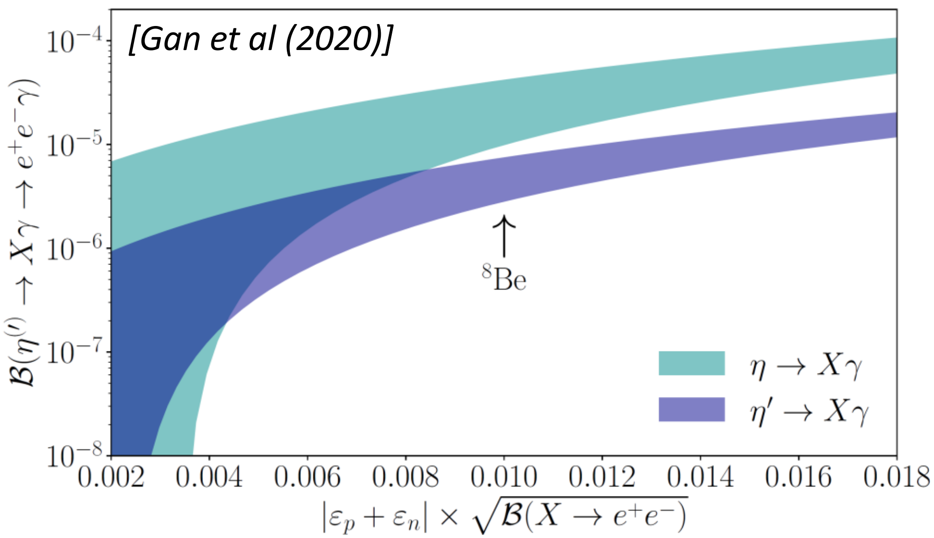
since $\mathcal{B}(\eta' \to \pi^+ \pi^- \gamma) \approx 10 \times \mathcal{B}(\eta' \to \gamma\gamma)$

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

[Feng et al (2016,2017)]

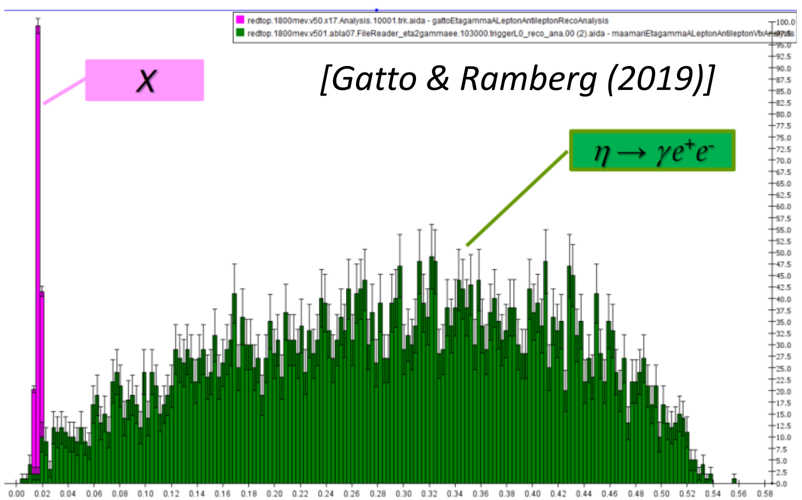
$$\eta, \eta' \to X\gamma \to e^+e^-\gamma$$

Theory prediction



Currently A2@MAMI limited to invariant mass m_{ee} > 30 MeV, but 17 MeV within reach of REDTOP

REDTOP Monte Carlo



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

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

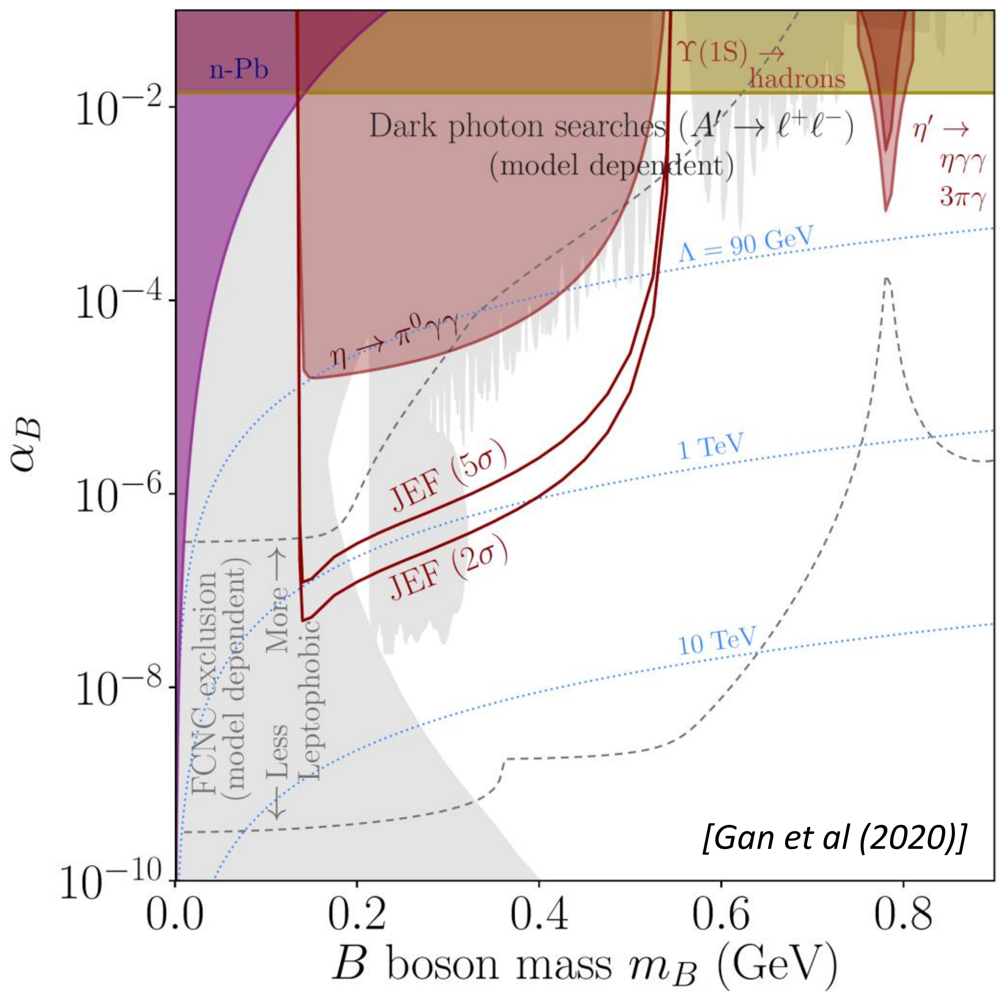
Model:

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

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

Mimics rare decay (0.025%) plus search for $\pi^0\gamma$ resonance

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



[Gan et al (2020)]

Light scalar boson (S)

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

Final states in SM arise via two-γ loop, very suppressed (single-γ process is C-violating)

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

$\gamma\gamma$ 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

Light scalar boson (S)

- Originally considered as possible signature for (light) SM Higgs boson

[Ellis et al (1976), Vainshtein et al (1980), Leutwyler & Shifman (1990)]

- Higgs-mixed scalar (Higgs portal model)

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

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

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

[Gan et al (2020)]

Scalar mixing angle $\theta_S < 10^{-3}$ in accessible mass range

Not competitive with other probes from FCNCs

[Beacham et al (2019)]

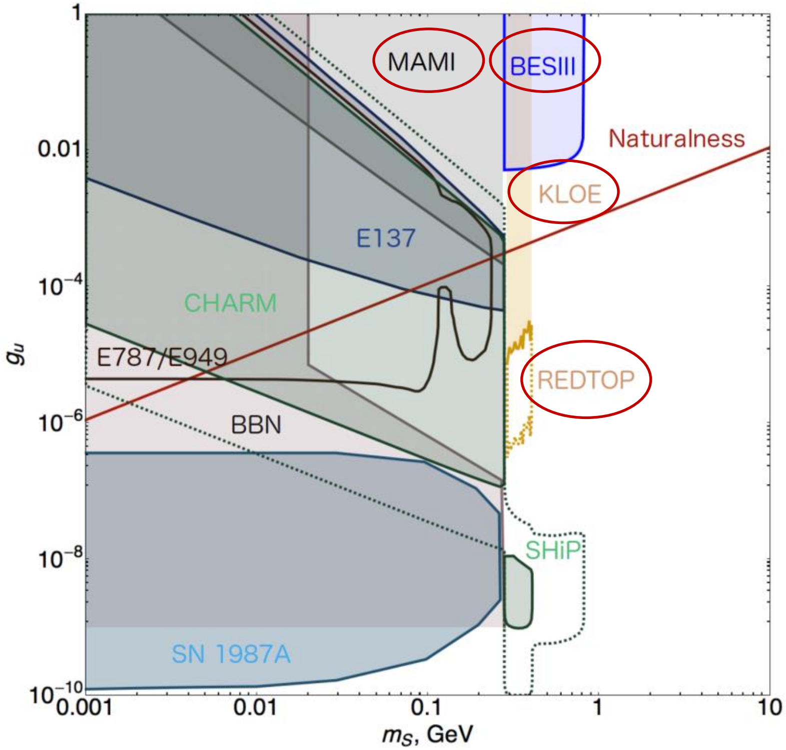
- General scalar model:

  η,η' sensitive to light-quark couplings, FCNCs sensitive to top coupling

Hadrophilic scalar boson

[Batell et al (2017,2018)]

Constraints from η,η' decays



Light scalar coupling to *u*-quarks only

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

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

More general couplings to *u,d*-quarks and e, μ, γ *[e.g., Liu, Cloet, Miller (2018)]*

Motivates searches for

$$\eta \to \pi^0 S \to \pi^0\gamma\gamma,\ \pi^0 e^+ e^-,\ \pi^0 \mu^+ \mu^-$$

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

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

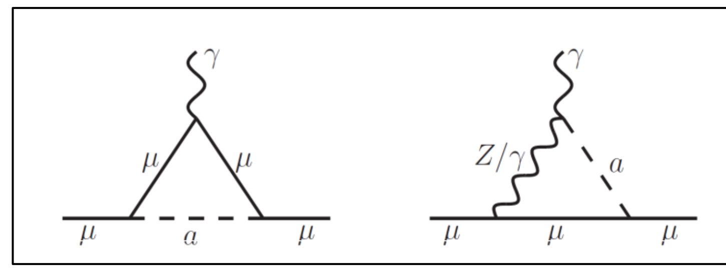
[Aloni et al (2019), Landini and Meggiolaro (2019)]

Model:

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

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

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



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

[Aloni et al (2019), Landini and Meggiolaro (2019)]

Model:

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

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')

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

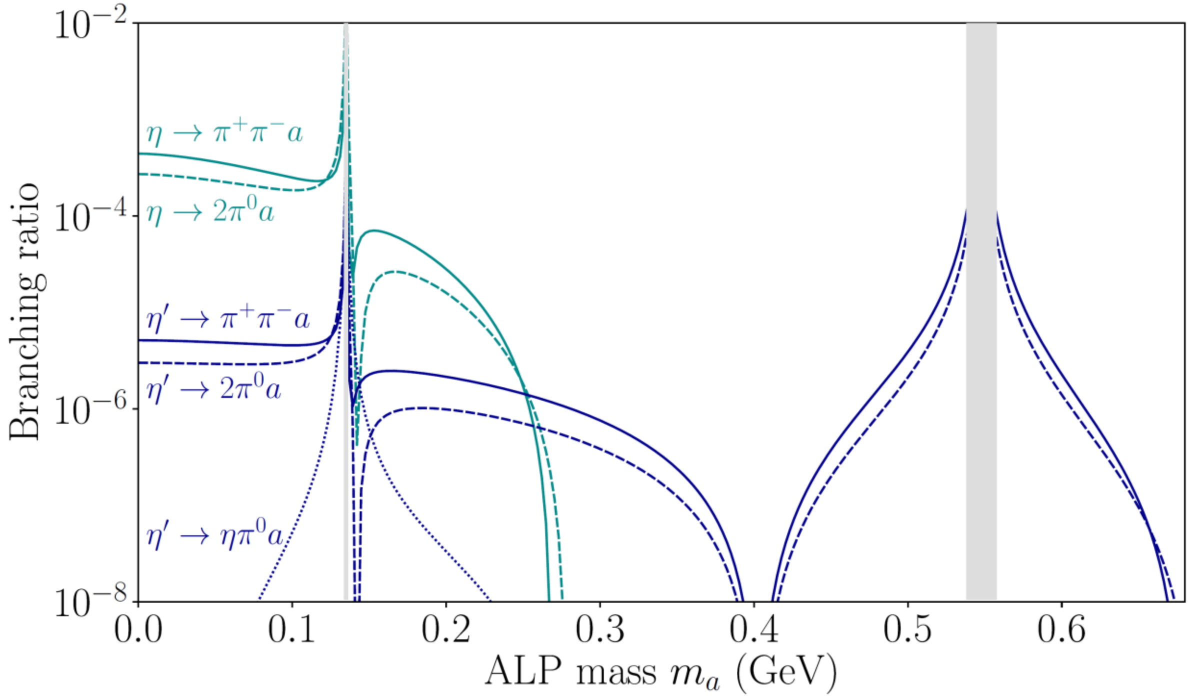
$$\eta' \to \eta\pi^0 a \to \eta\pi^0\gamma\gamma\,,\ \eta\pi^0 e^+ e^-\,,\ \eta\pi^0\mu^+\mu^-$$

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

η,η' branching ratios into ALPs

Fixed effective mass scale $\Lambda/|C_{GG}| = 32\pi^2 f_a \approx 3\,\mathrm{TeV}$

[Gan et al (2020)]



Calculated BR at leading order in χPT, but possible large corrections at NLO

Dark sector models

Models | Theory landscape | Predictions | Sensitivities

Dark sector models

Models	Theory landscape	Predictions	Sensitivities
Vector bosons	✓	✓	✓
Dark photon			
Leptophobic $U(1)_B$ boson			
Protophobic X(17) boson			

Dark sector models

Models	Theory landscape	Predictions	Sensitivities
Vector bosons			
Dark photon	✓	✓	✓
Leptophobic $U(1)_B$ boson	✓	✓	✓
Protophobic X(17) boson			
Scalar bosons			
u-quark coupling only	✓	✓	✓
	η' scalar form factors uncertain (η under good control)		
more general model	✗	✗	✗

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

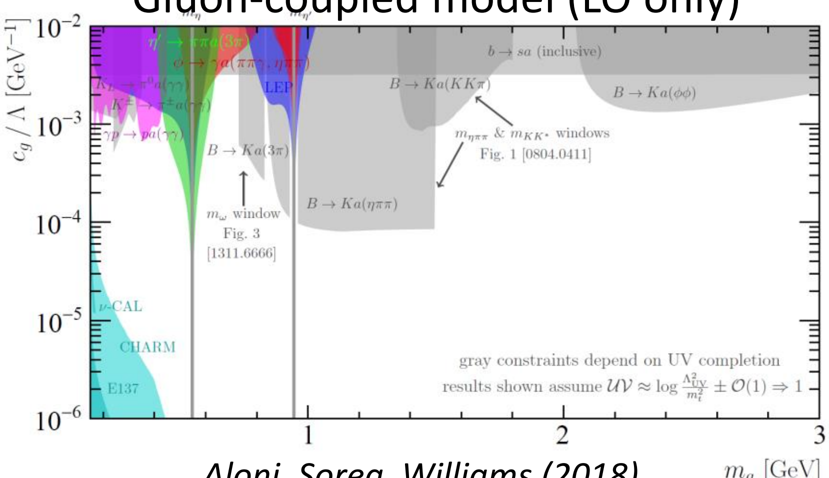
$$\eta \to \pi^0 S \to \pi^0 \gamma\gamma \quad \eta, \eta' \to \pi^0 S \to 3\pi, \quad \eta' \to \eta S \to \eta\pi\pi$$

Dark sector models

Models	Theory landscape	Predictions	Sensitivities

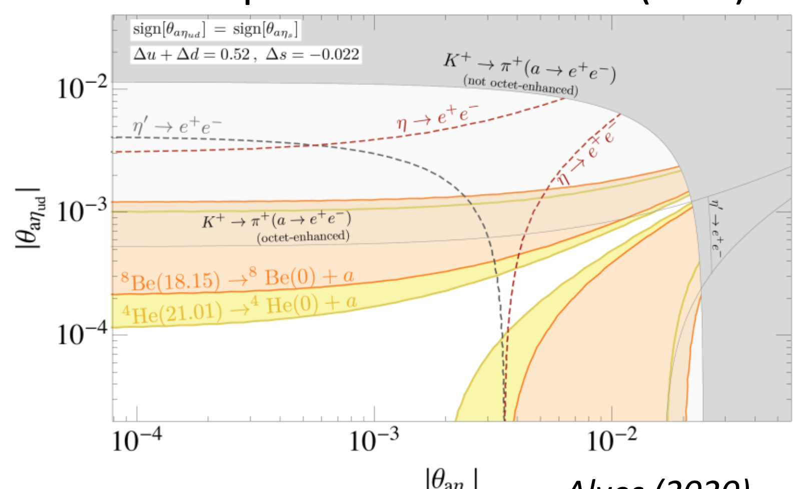
Axion-like particles η, η' constraints for simplified models only

Gluon-coupled model (LO only)



Aloni, Soreq, Williams (2018)

Piophobic axion model (NLO)



Alves (2020)

Go beyond simplified models and LO predictions

Direct photoproduction of new gauge bosons

Safa Ben Othman, Armita Jalooli, ST (in prep)

See also: *Fanelli and Williams (2016)*

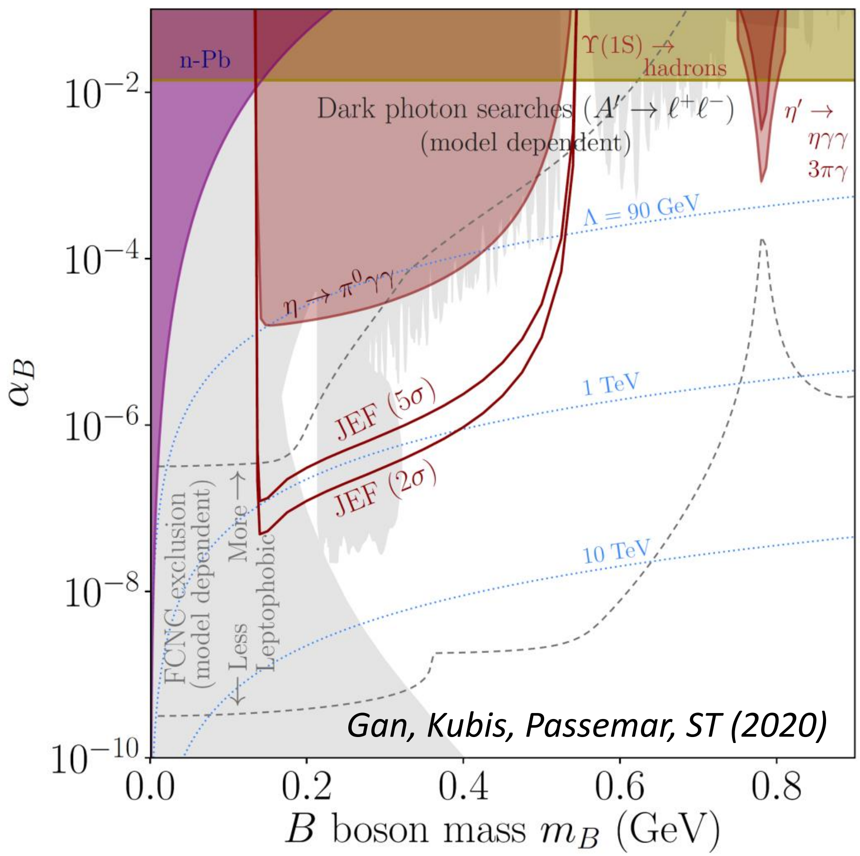
B boson model: $U(1)_B$ gauge boson

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

Motivation: Benchmark model for new force coupled to quarks with suppressed lepton signatures

Direct photoproduction of new gauge bosons

B boson parameter space

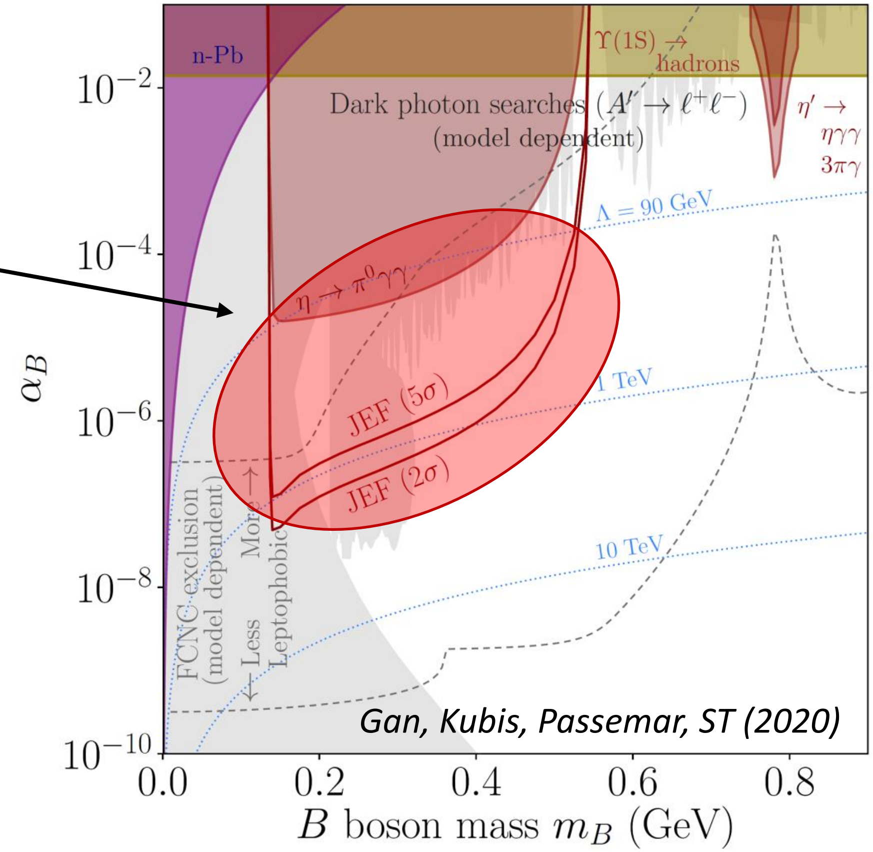


Direct photoproduction of new gauge bosons

B boson parameter space

Region accessible in η decay

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

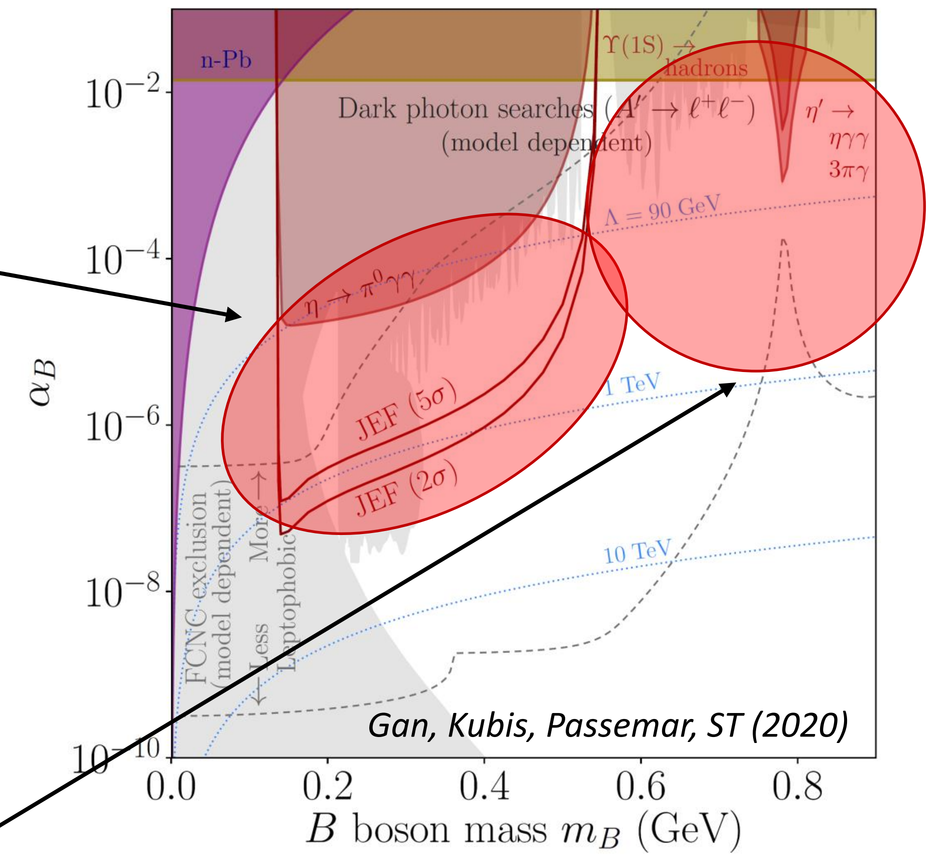


Direct photoproduction of new gauge bosons

B boson parameter space

Region accessible in η decay

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

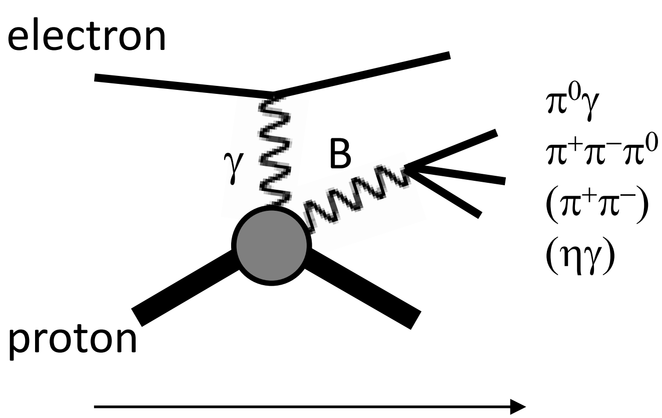


Direct production

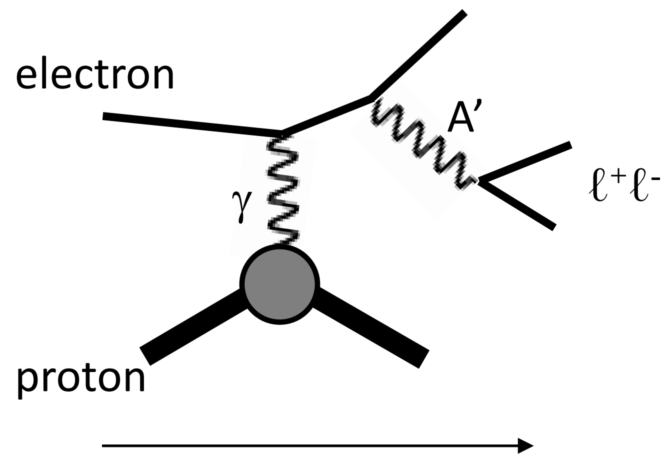
$$\gamma p \to Bp \to \pi^0\gamma\, p\,,\ \pi^+\pi^-\pi^0\, p$$

Direct production of new gauge forces

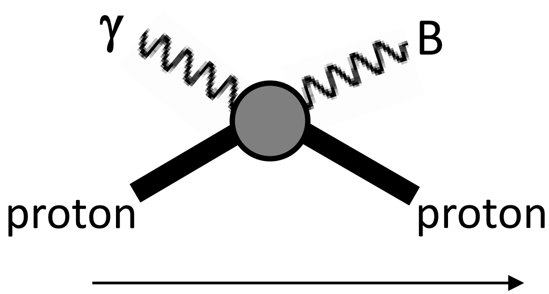
Leptophobic B boson production



Dark photon production



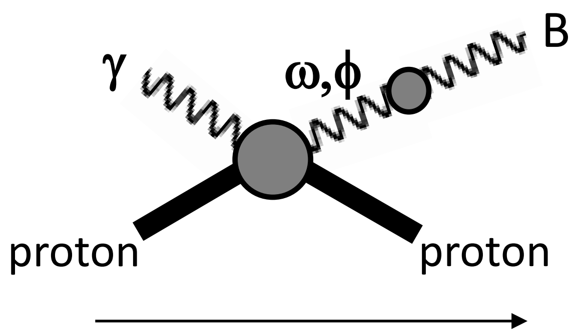
B boson production



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

Cannot be calculated in perturbative QCD and must be modeled

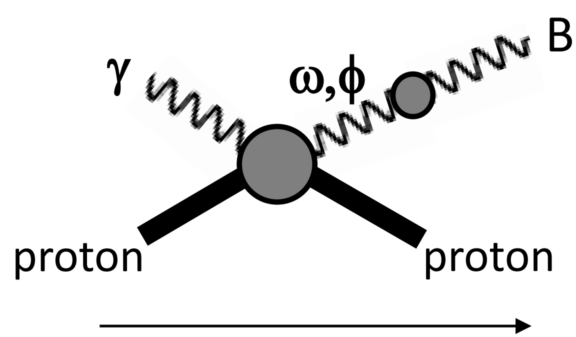
B boson production



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)

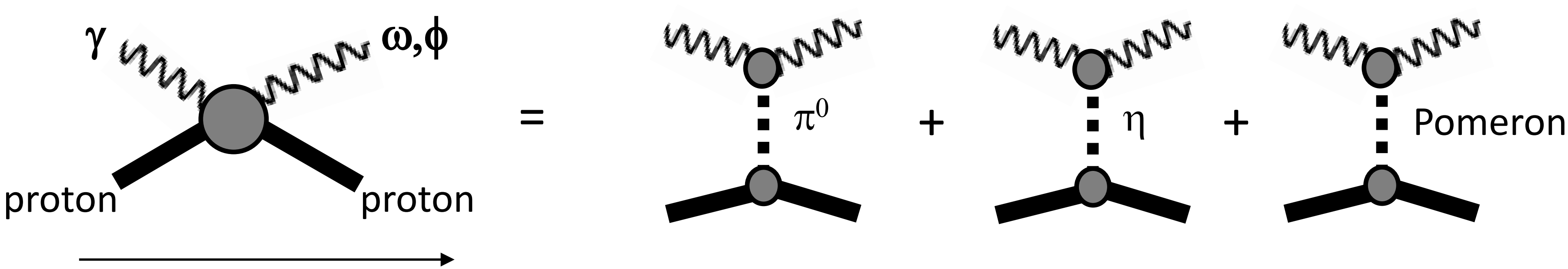
$$V(k,\lambda) \Longrightarrow\!\!\!\times\!\!\sim\!\!\sim B(k,\lambda) = \frac{\sqrt{2} f_V m_V}{k^2 - m_V^2 + i m_V \Gamma_V} \mathrm{Tr}\left[\boldsymbol{T}_V \left(\tfrac{1}{3} g_B \boldsymbol{I} + \varepsilon e \boldsymbol{Q}\right)\right]$$

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

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

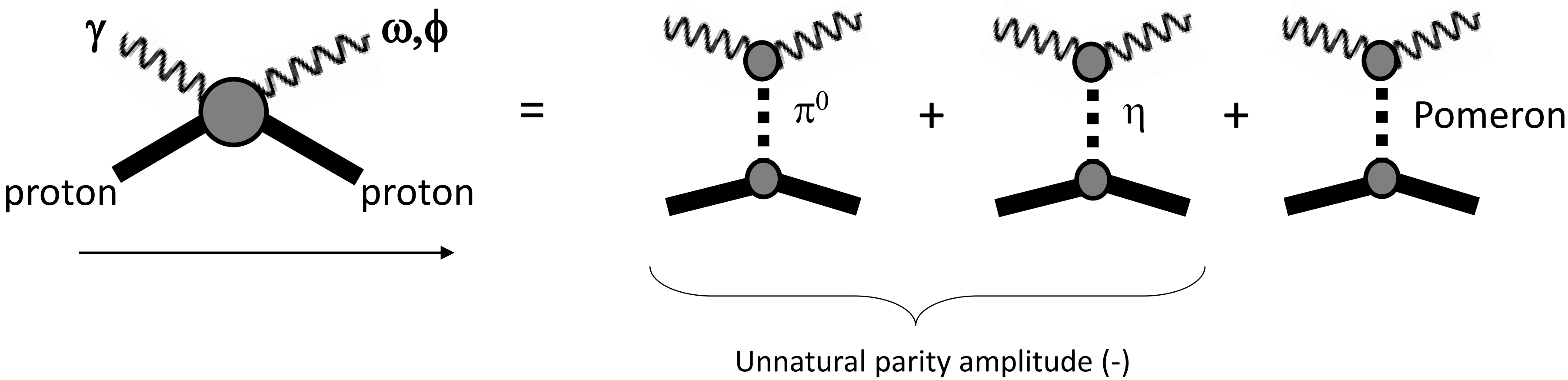
B boson production

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



B boson production

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

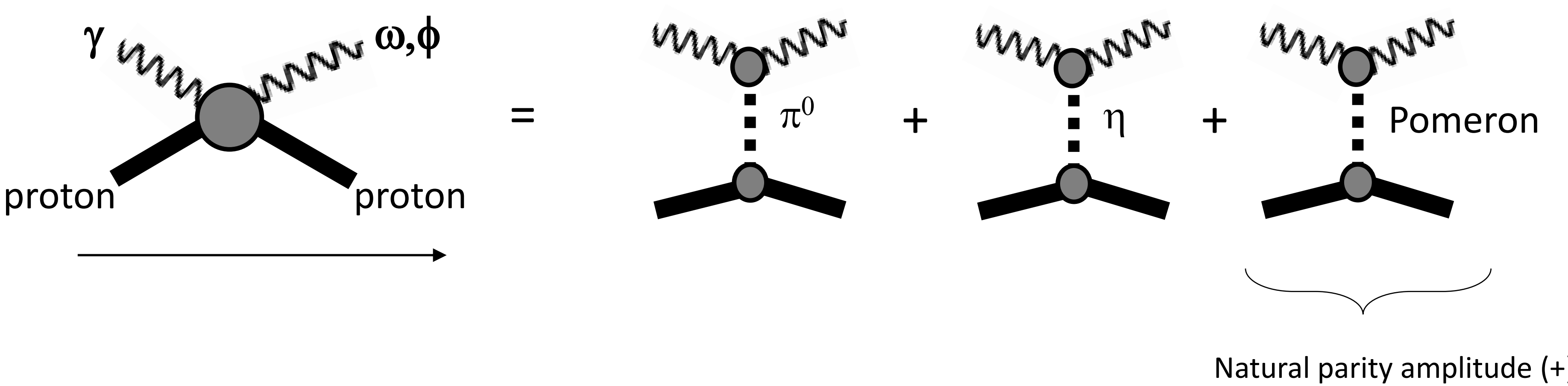


Each coupling dressed with a form factor $F(t,\Lambda,m) = \frac{\Lambda^2 - m^2}{\Lambda^2 - t}$ *Friman & Soyeur (1996)*

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)*

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

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

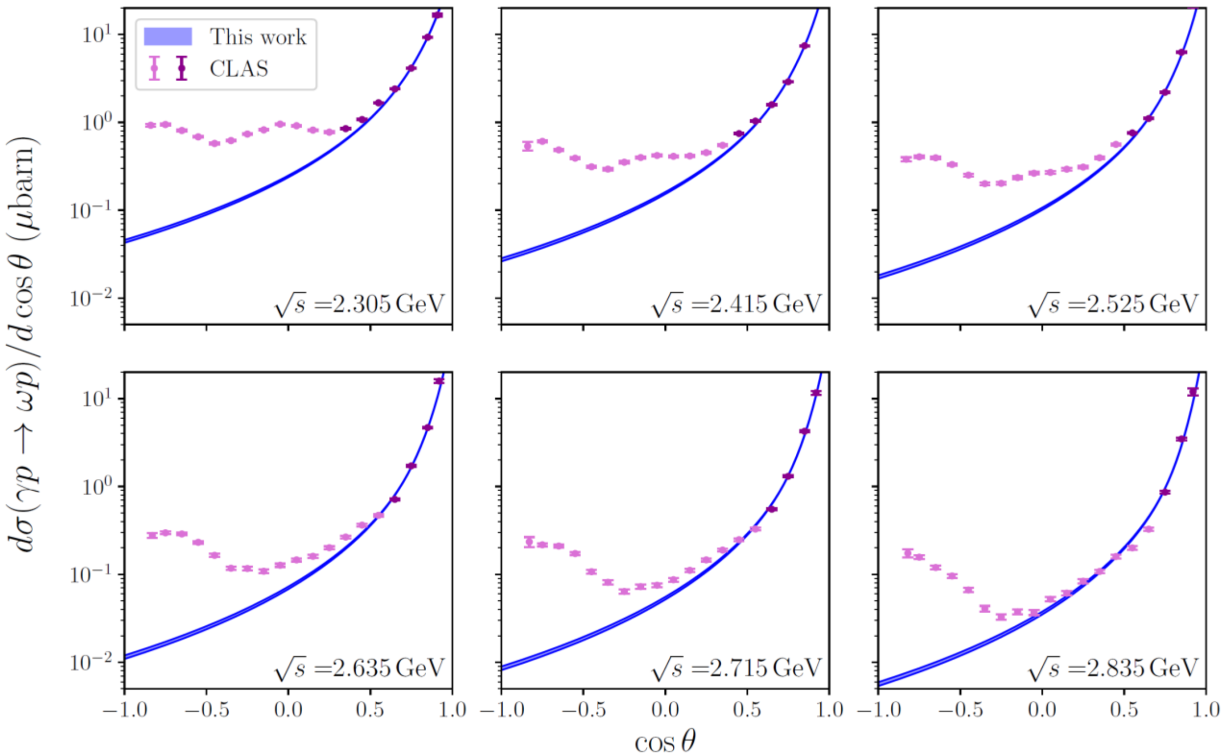
Data sets:

- 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

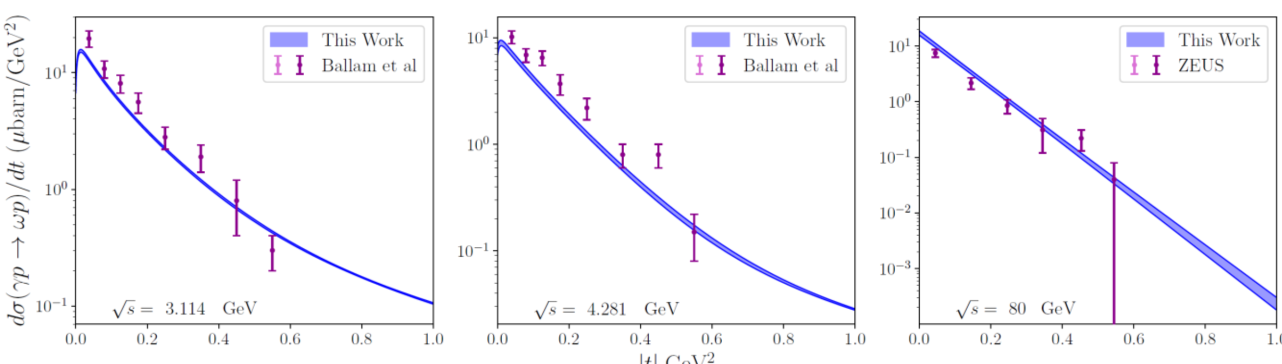
Energy:

Perform MCMC

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

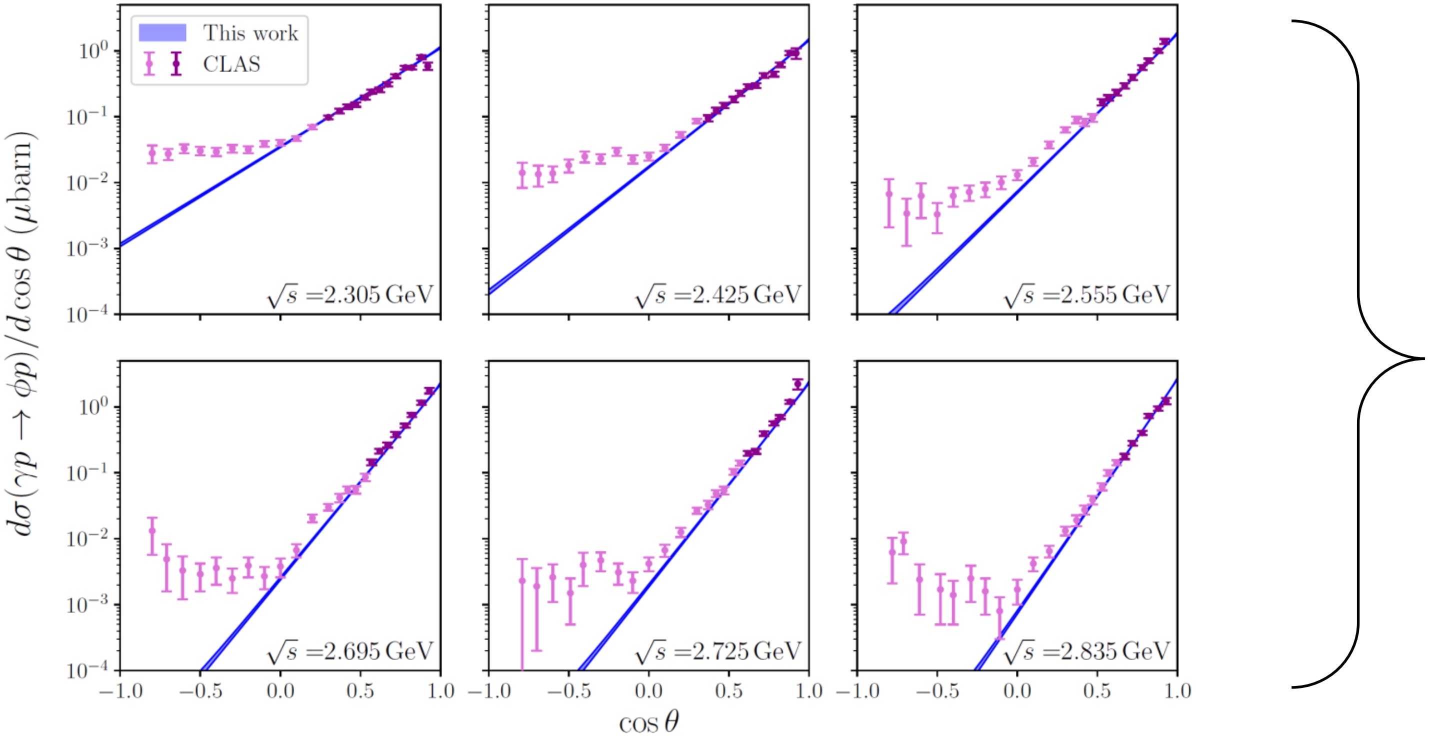


CLAS

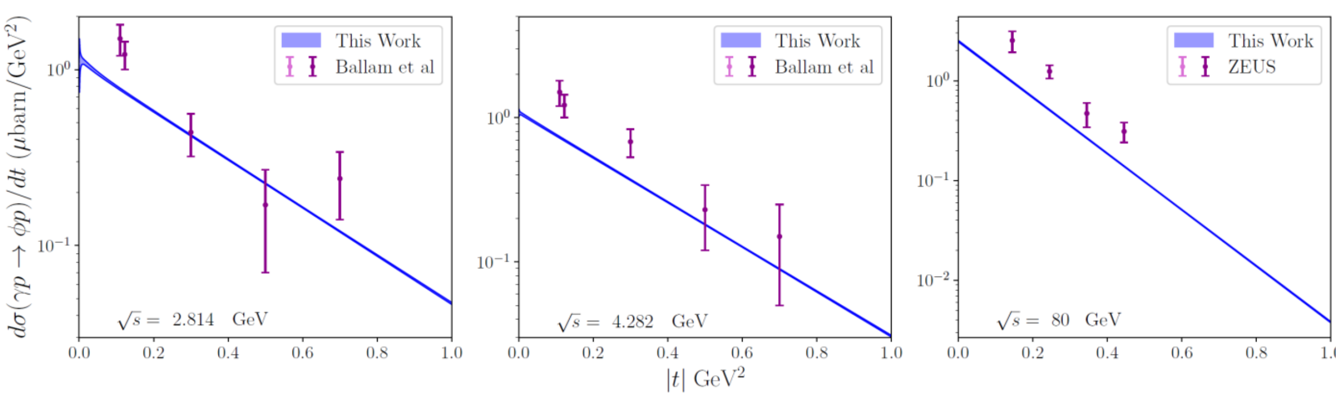


Other datasets

Preliminary



CLAS



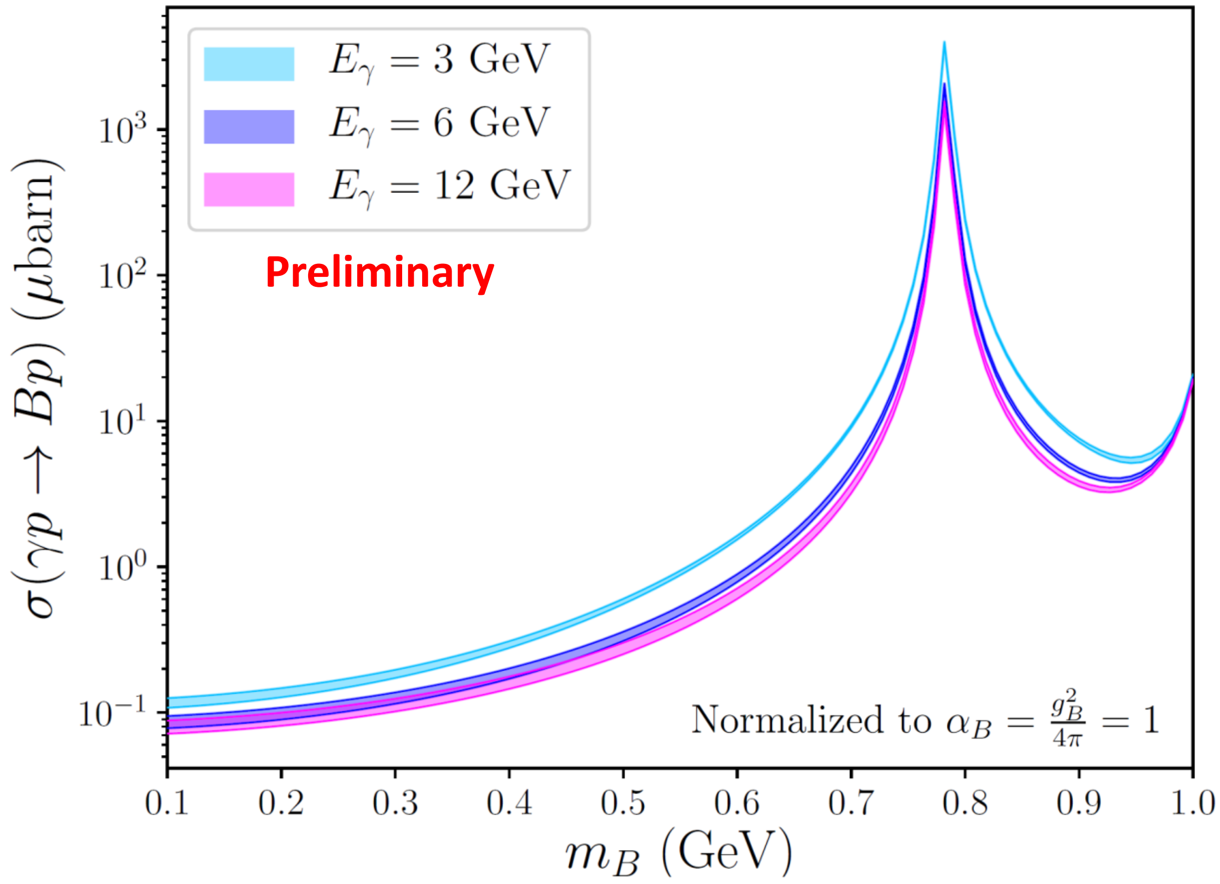
Other datasets

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



Straightforward to calculate differential cross section as well

B boson photoproduction

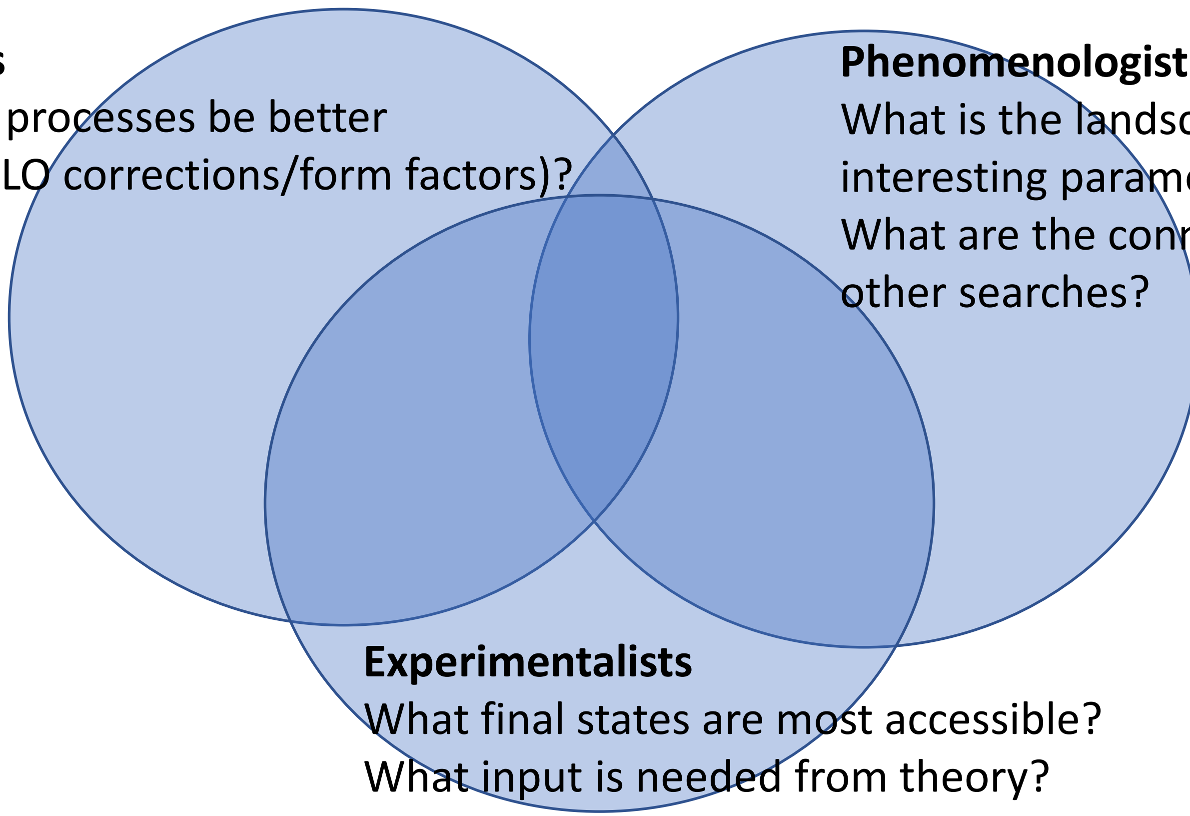
- B boson model predictions are in good shape

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

- Questions remain:
  - What are the expected backgrounds?
  - What do experimentalists need to interface model predictions with their simulations?
  - …

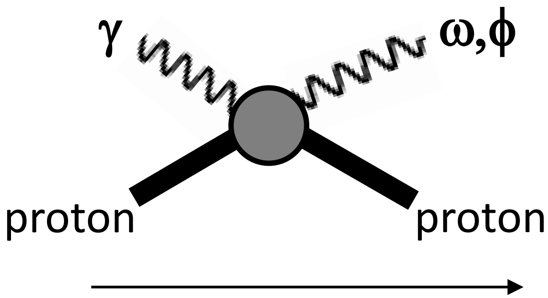
Summary

- η,η' factories offer complementary probes of dark sectors and synergy with Standard Model η,η' decay studies
- Dark sector models well known but much remains



Backup slides

B boson production



Need vector meson photoproduction matrix elements (SM process)

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

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

(Φ = phase space factors)