New signatures of BSM physics hiding in QCD

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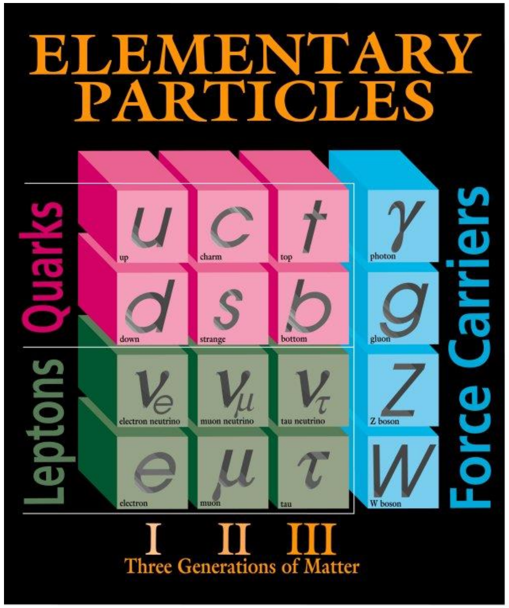
Searching for new forces

SM based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry. Are there any additional gauge symmetries? Look for new gauge bosons.



Fermilab 95-759

Motivations:

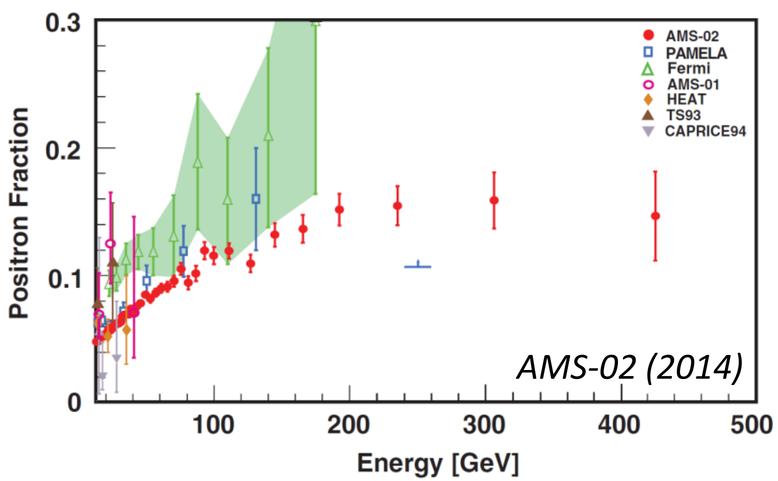
1. **Grand unified theories:** Generically have additional gauge bosons, but typically very heavy (10^{16} GeV).
2. **Dark matter:** Stability of dark matter related to new gauge symmetry?

   Can also give the right relic density.

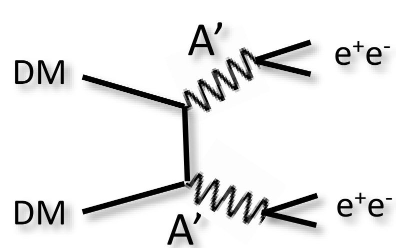
Motivations for new GeV-scale forces

Dark matter indirect detection anomalies
e.g. Pamela/AMS-02 positron excess

Pospelov & Ritz (2008); Arkani-Hamed et al (2008)

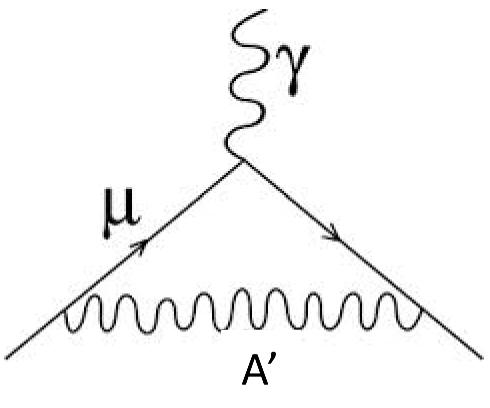


Dark matter annihilation



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

Pospelov (2008)



Dark matter and structure of galaxies

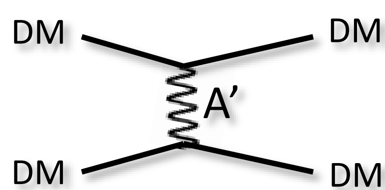
Kinematics of stars and gas in galaxies are tracers of dark matter mass distribution

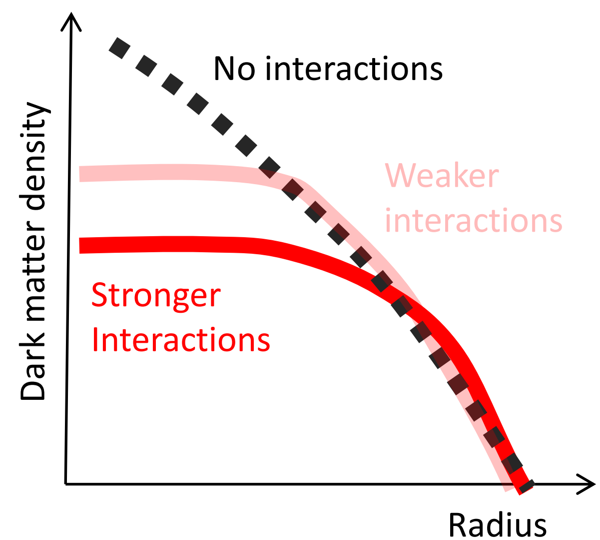
Galaxies and clusters are less dense than predicted from “vanilla” cold dark matter theory predictions

Moore (1994), Flores & Primack (1994)

Can be explained if dark matter interacts through a MeV—GeV scale dark photon

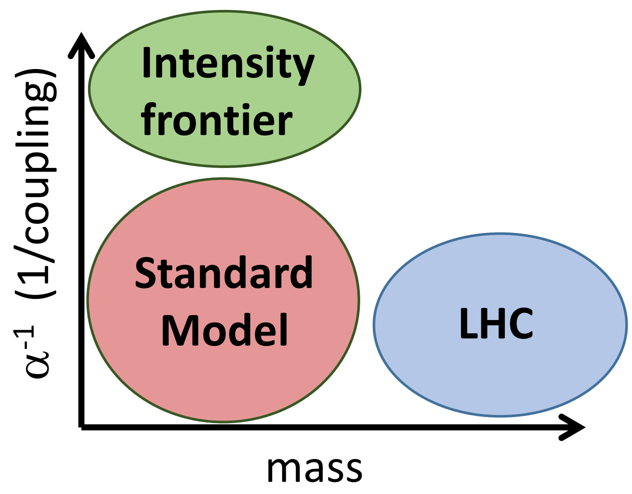
ST, Yu, Zurek (2013)





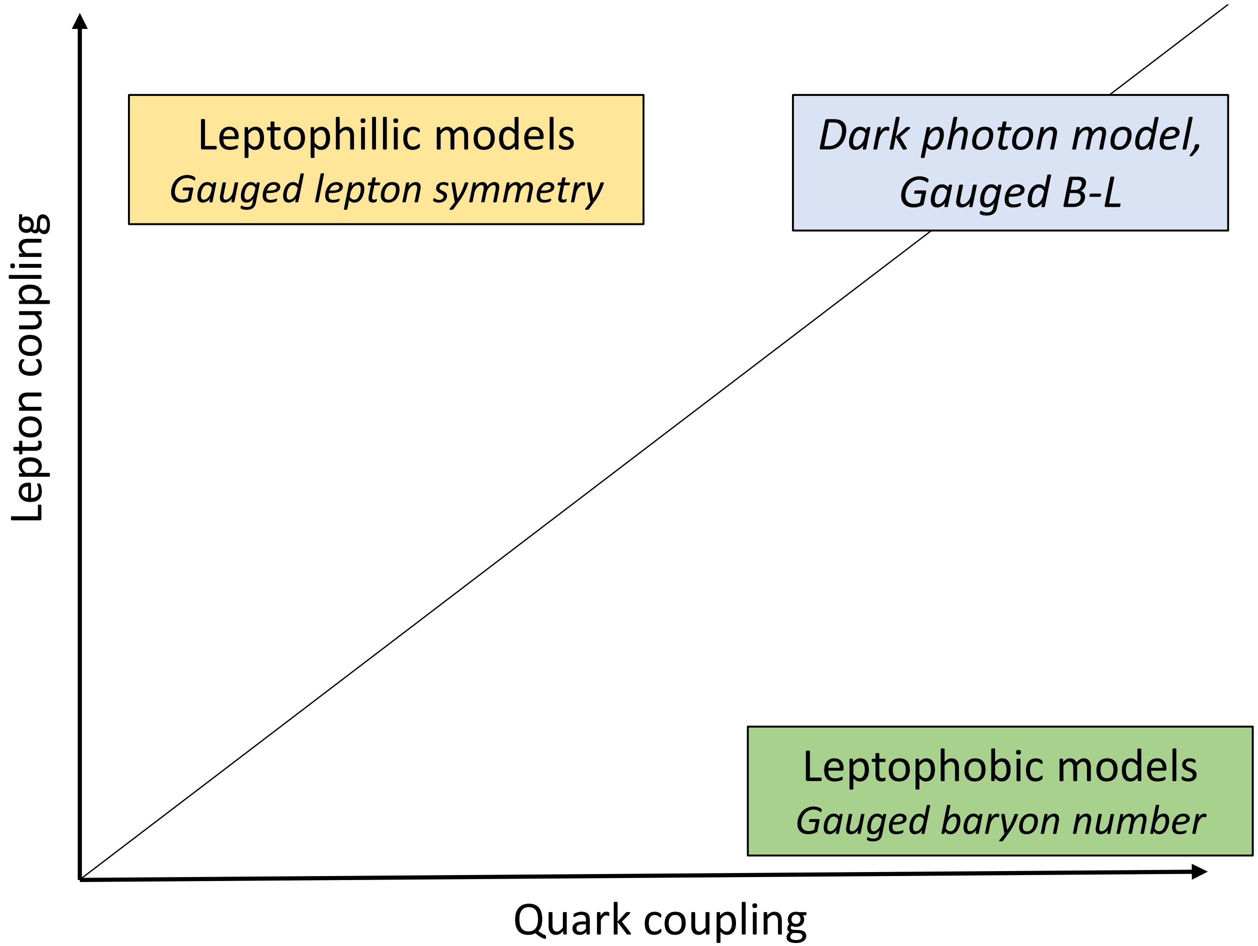
Motivations for new GeV-scale forces

Whether or not you take these anomalies seriously, intermediate energy experiments have a unique capability to explore new forces beyond the SM



We don't know in which direction beyond the Standard Model physics might be

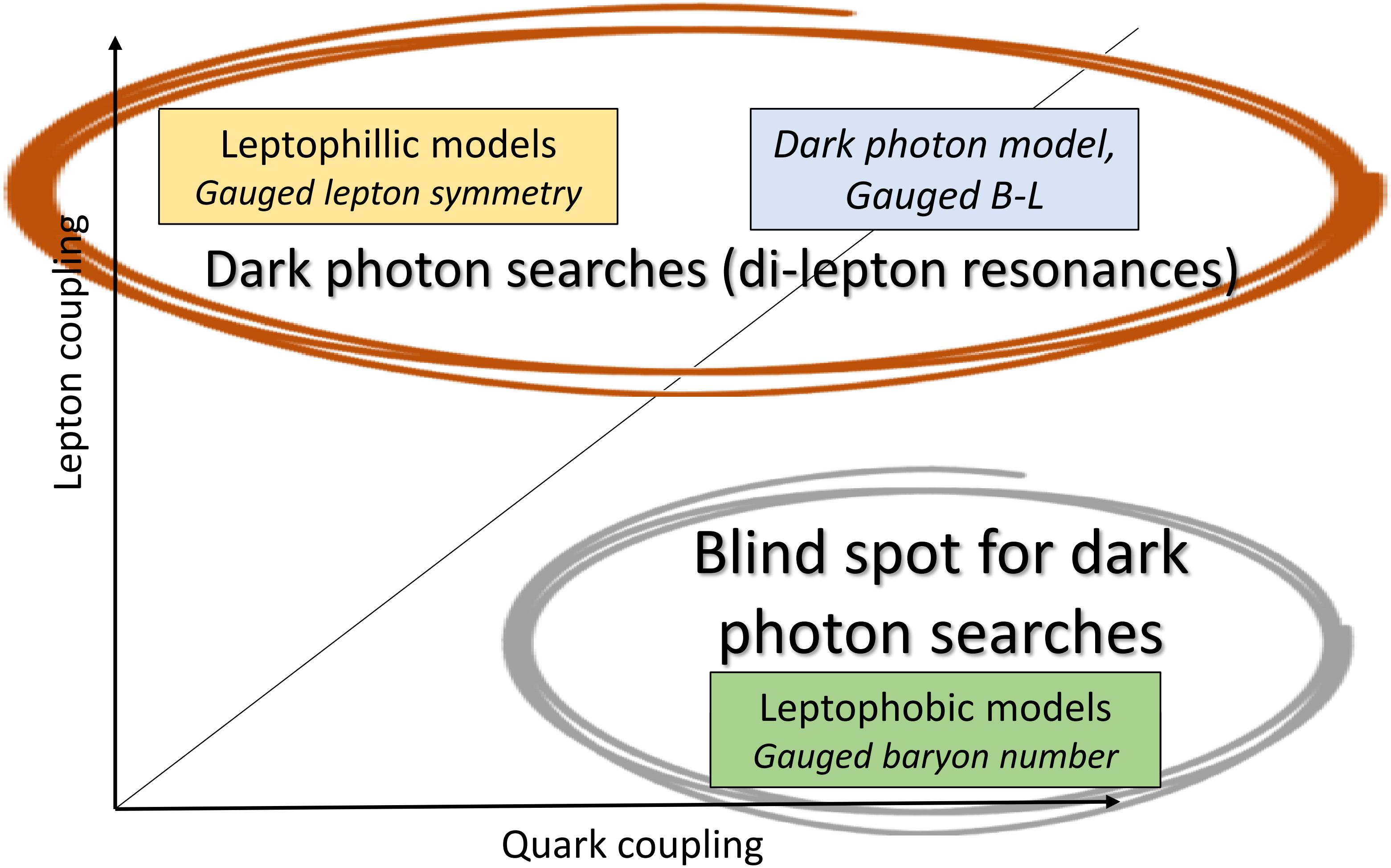
Dark photons and other new forces



Also a third axis: decays to invisible states (neutrinos, light dark matter)

Davoudiasl et al (2012), Batell et al (2009), deNiverville et al (2011,2012)

Dark photons and other new forces



Also a third axis: decays to invisible states (neutrinos, light dark matter)

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New force coupling to quarks

Most dark photon searches are for A' coupling to leptons (or light dark matter)

What if a new force couples mainly to quarks?

Not a new idea: *Radjoot (1989), Foot et al (1989), Nelson & Tetradis (1989), He & Rajpoot (1990), Carone & Murayama (1995), Bailey & Davidson (1995), Aranda & Carone (1998), Fileviez Perez & Wise (2010), Graesser et al (2011), Dobrescu & Frugiule (2014), Batell et al (2014), …*

Simplest model: Gauge boson *(B)* coupled to baryon number

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

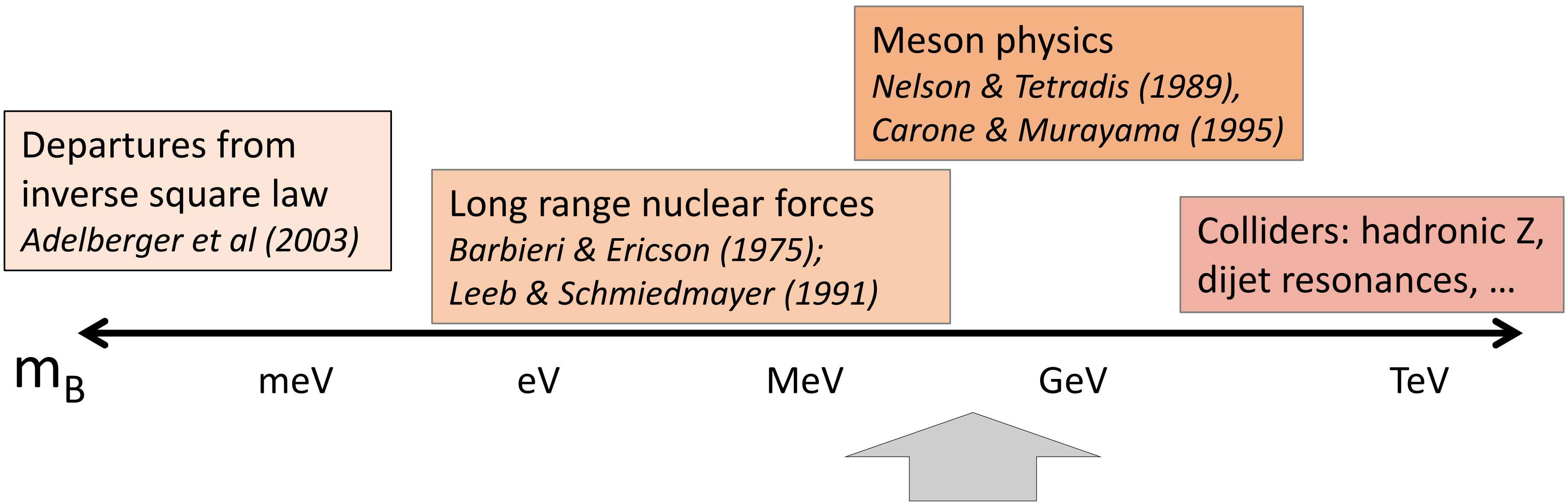
Flavor-universal charge g_B coupling to all quarks

Also known as: " leptophobic Z' " or " baryonic photon γ_B " or " Z'_B " or "*B* boson"

New force coupling to quarks

B = gauge boson coupled to baryon number

Discovery signals depend on the *B* mass



Is it possible to discover light weakly-coupled forces hiding in nonperturbative QCD regime?

Theoretical constraints from anomalies

- $U(1)_B$ gauge symmetry is anomalous

- Requires introducing new electroweak fermions at mass scale Λ to cancel the $(\text{electroweak})^2 \text{x} U(1)_B$ anomalies

- Cannot have Λ arbitrarily large. Typically* $m_B/\Lambda \gtrsim g_B/(4\pi)$

* but not always

- The absence of new fermions at colliders: Λ > 100 GeV

- Small gauge couplings: $g_B \lesssim 10^{-2} \times (m_B/100 \text{ MeV})$

$$\alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\,\text{MeV})^2$$

Detecting the B boson

- Can a weakly-coupling force ($g_B << 1$) be detected in the nonperturbative regime of QCD?

- B boson preserves the symmetries of QCD
  - Charge conjugation, parity, and isospin or $SU(3)_{flavor}$

- Previous lore: *Nelson & Tetradis (1989)*
  - Above $2m_\pi$, decay dominated by B $\rightarrow$ $\pi\pi$
  - B boson buried under huge $\rho \rightarrow \pi\pi$ background

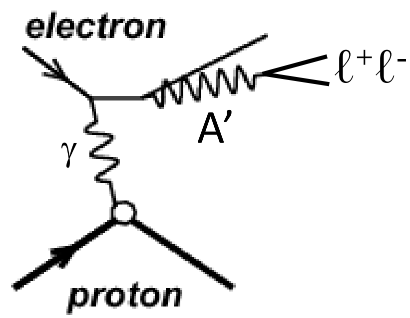
Baryonic force at the QCD scale

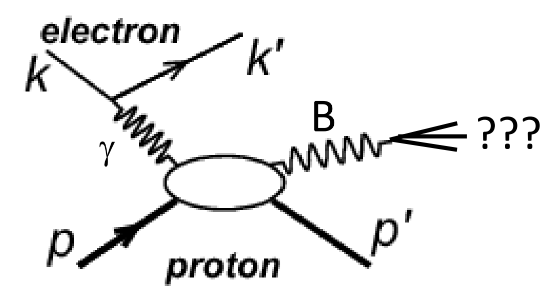
- How are the gauge bosons produced?
- What are the experimental signatures?

Dark photon

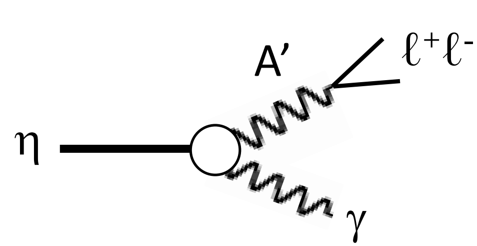
B boson

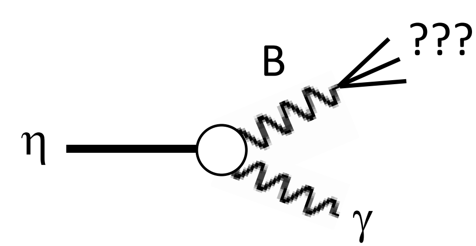
Direct production:





Meson decays:





Baryonic force at the QCD scale

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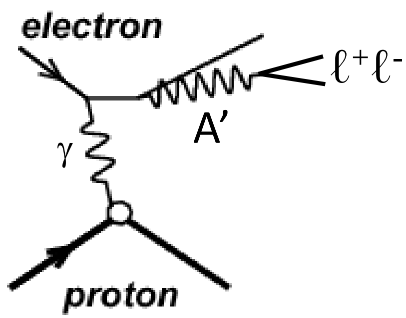
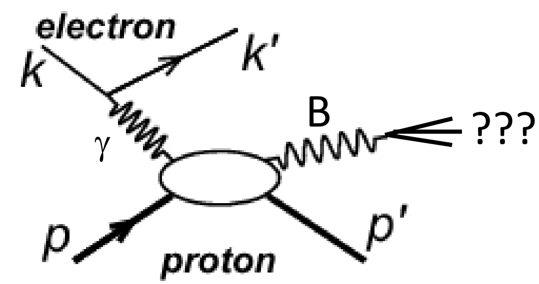
Dark photon

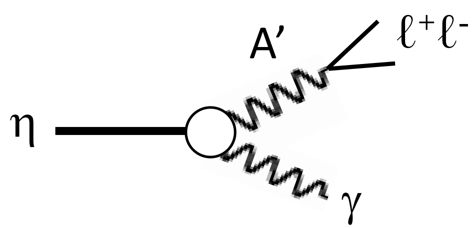
B boson

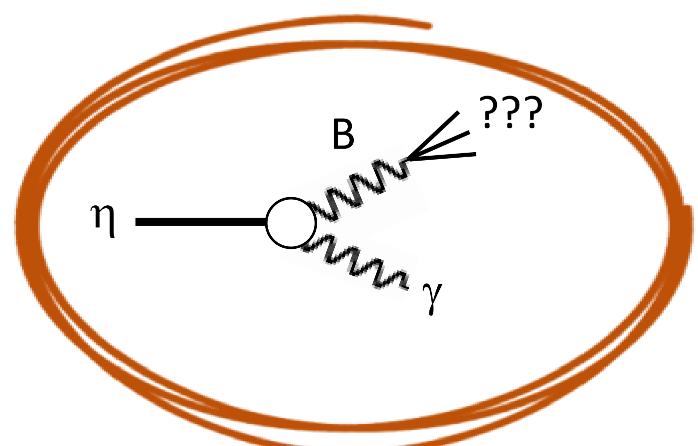
Direct production:





Meson decays:





B bosons signals in meson factories

- How are B bosons produced?

  Focus on light mesons: π^0, η, η', ω, ϕ

- How do B bosons decay?

B bosons production

- How are B bosons produced in meson decays?

$$\pi^0 \to B\gamma, \quad \eta \to B\gamma, \quad \eta' \to B\gamma, \quad \omega \to \eta B, \quad \phi \to \eta B$$

- Like Standard Model processes with γ replaced by B

$$\pi^0 \to \gamma\gamma, \quad \eta \to \gamma\gamma, \quad \eta' \to \gamma\gamma, \quad \omega \to \eta\gamma, \quad \phi \to \eta\gamma$$

- Calculating the decay rate: take η → Bγ as an example

$$\frac{\Gamma(\eta \to B\gamma)}{\Gamma(\eta \to \gamma\gamma)} = 2\frac{\alpha_B}{\alpha_{\rm em}}\left(1 - \frac{m_B^2}{m_\eta^2}\right)^3 \left|\frac{(\frac{1}{3}c_\theta - \frac{\sqrt{2}}{3}s_\theta)F_\omega(m_B^2) + (\frac{2}{3}c_\theta + \frac{\sqrt{2}}{3}s_\theta)F_\phi(m_B^2)}{c_\theta - 2\sqrt{2}s_\theta}\right|^2$$

Ratio of gauge couplings

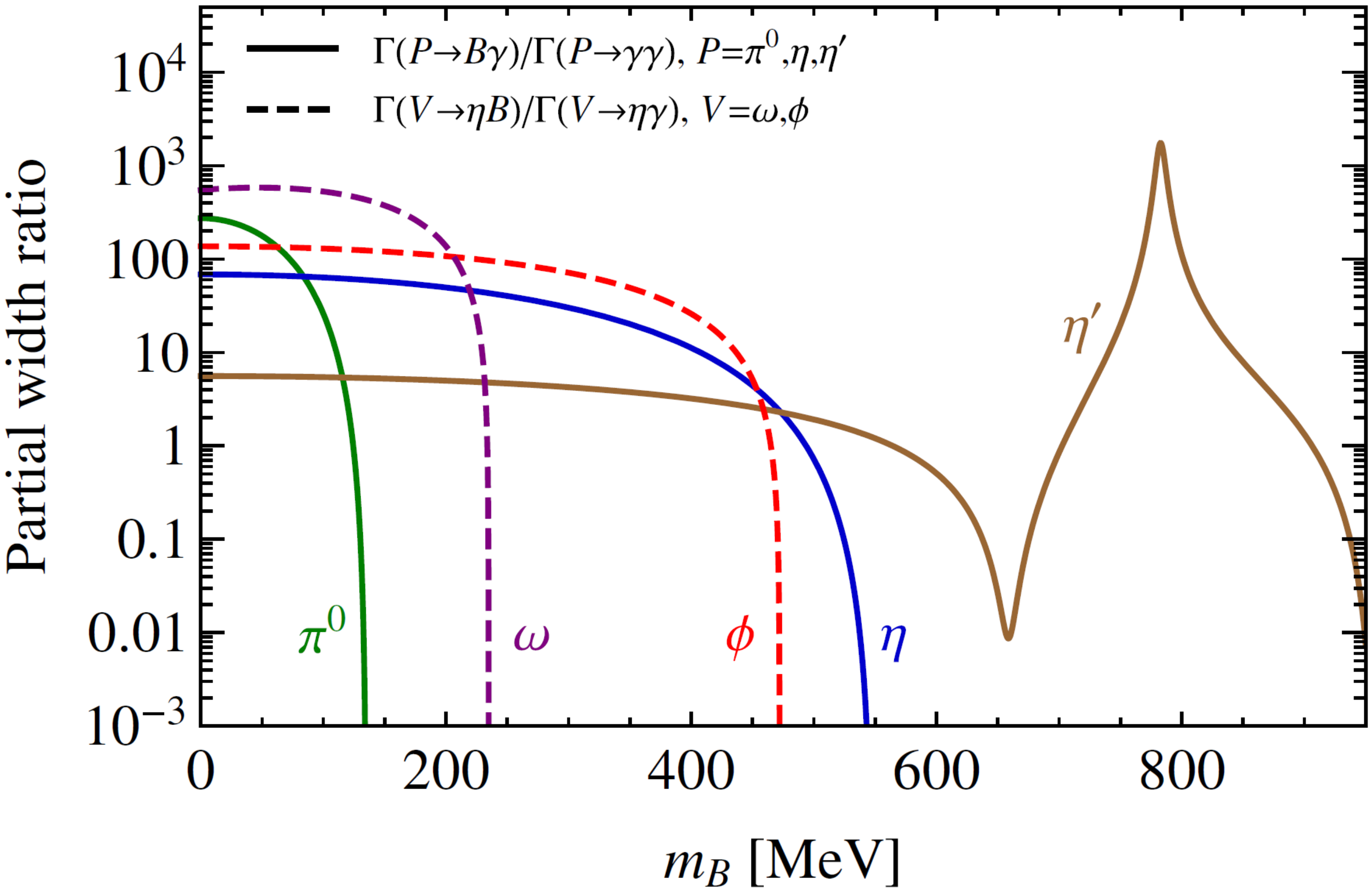
Phase space

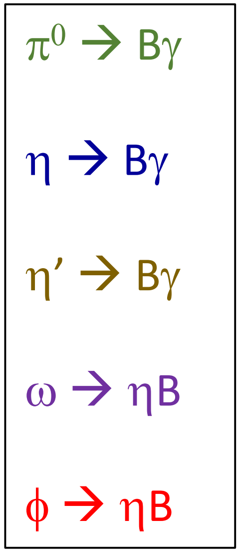
~O(1)

Combinatorical factors and form factors (vector meson dominance)
θ = η-η' mixing angle

B bosons production

B production rate in meson decays relative to SM process (normalized to $\alpha_B = 1$)





B boson decay

How does B decay? Worry: B → $\pi\pi$ is hopeless.

Recall the original Lagrangian: $\mathscr{L} = \frac{g_B}{3}\bar{q}\gamma^\mu q B_\mu$

The quantum numbers for B:

- *J* = 1
- *P* = *C* = –
- *I* = 0
- G = –

B boson decay

B has same quantum numbers as the **ω** meson

Particle Data Book

$\omega(782)$

$$I^G(J^{PC}) = 0^-(1^{--})$$

$\omega(782)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\pi^0$	(89.2 ± 0.7) %	
Γ_2	$\pi^0\gamma$	(8.28 ± 0.28) %	S=2.1
Γ_3	$\pi^+\pi^-$	$(1.53^{+0.11}_{-0.13})$ %	S=1.2
Γ_9	e^+e^-	$(7.28 \pm 0.14) \times 10^{-5}$	S=1.3
Γ_{15}	$\mu^+\mu^-$	$(9.0 \pm 3.1) \times 10^{-5}$	
Γ_{16}	3γ	$< 1.9 \times 10^{-4}$	CL=95%

$\omega \to \pi\pi$ forbidden by G-parity
(Isospin-violating ρ–ω mixing)

B boson decay

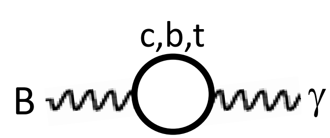
Expect B decays to be qualitatively similar to ω decays

- B $\rightarrow$ $\pi\pi$ is forbidden by G-parity

- $m_B \sim m_\pi$ – 1 GeV:
  Dominated by B $\rightarrow$ $\pi^0\gamma$ or $\pi^+\pi^-\pi^0$ (when allowed)
  New signatures that are not being covered in dark photon searches

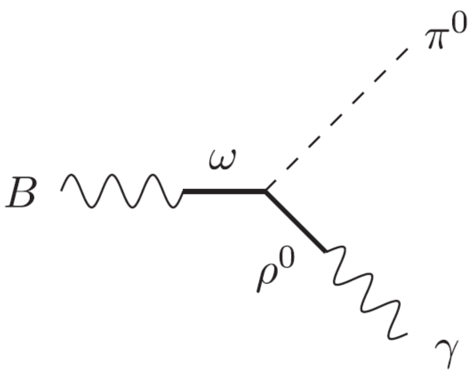
- $m_B < m_\pi$:
  Dominated by B $\rightarrow$ e^+e^-
  Covered by dark photon searches

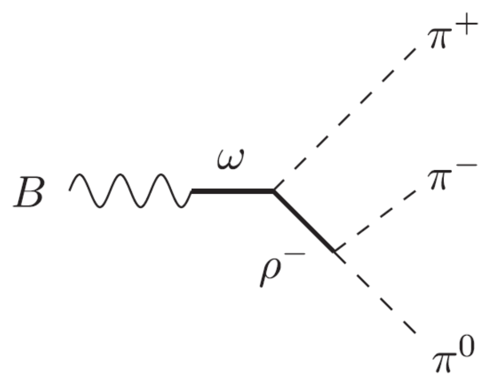
Leptonic couplings to B arise because B mixes with γ through heavy quark loops
B is *mostly* leptophobic with a subleading (and model-dependent) lepton coupling



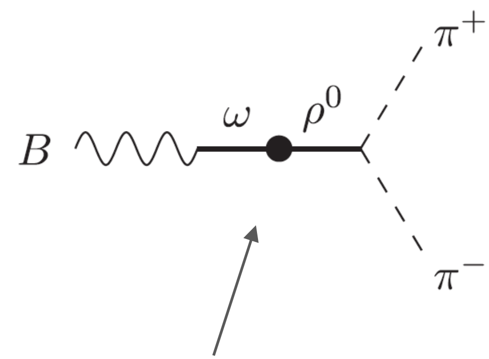
B boson decay

Hadronic decay rates calculated using vector meson dominance



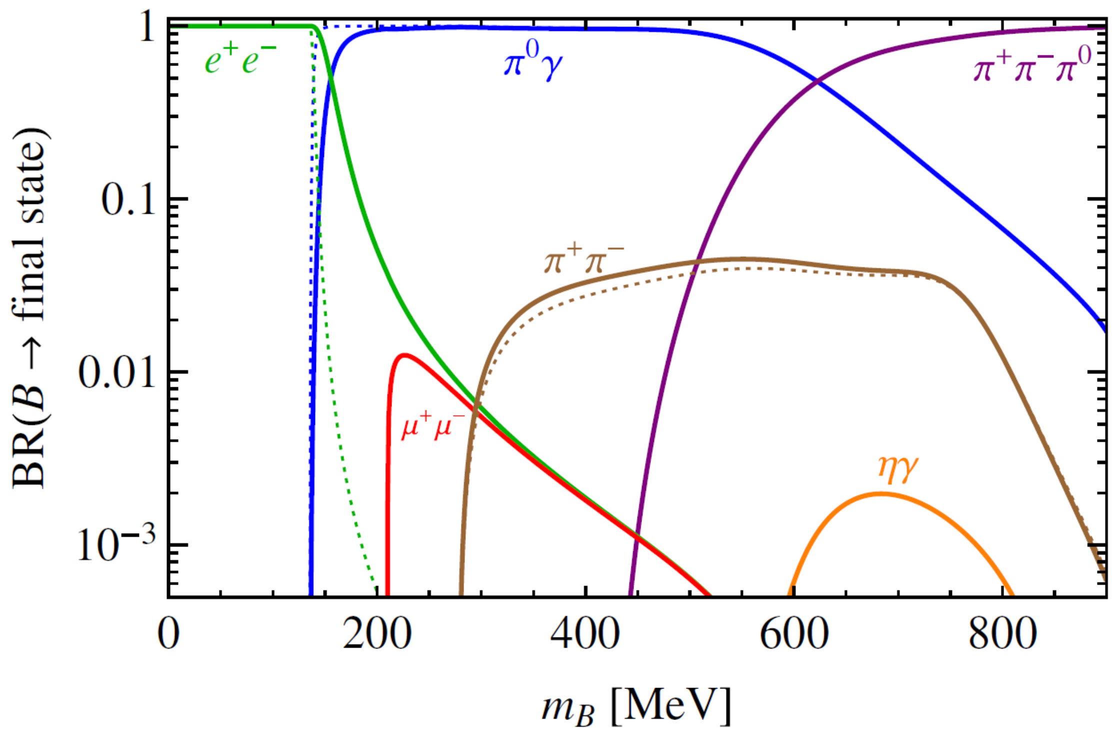


+ permutations



Isospin-violating mixing
Not well-known away from ω pole

B boson branching ratios



Solid vs dashed shows model dependence of leptonic couplings due to B-γ mixing

Solid: $\varepsilon = eg_B/16\pi^2$ Dotted: $\varepsilon = 0.1\ eg_B/16\pi^2$

B boson signal channels

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

Covered by dark photon searches
Limits are more model dependent

New signals not being covered in dark photon searches

A new type of signature for meson factories:

$\pi^0\gamma$ resonances in rare decays

B boson signal channels

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

Covered by dark photon searches
Limits are more model dependent

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A new type of signature for meson factories:

$\pi^0\gamma$ resonances in rare decays

$\eta \rightarrow \pi^0\gamma\gamma$

Particle Data Book

η $\quad I^G(J^{PC}) = 0^+(0^{-+})$

η DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Neutral modes		
Γ_1	neutral modes	(72.12 ± 0.34) %	S=1.2
Γ_2	2γ	(39.41 ± 0.20) %	S=1.1
Γ_3	$3\pi^0$	(32.68 ± 0.23) %	S=1.1
Γ_4	$\pi^0 2\gamma$	$(2.7\ \pm0.5\ )\times10^{-4}$	S=1.1

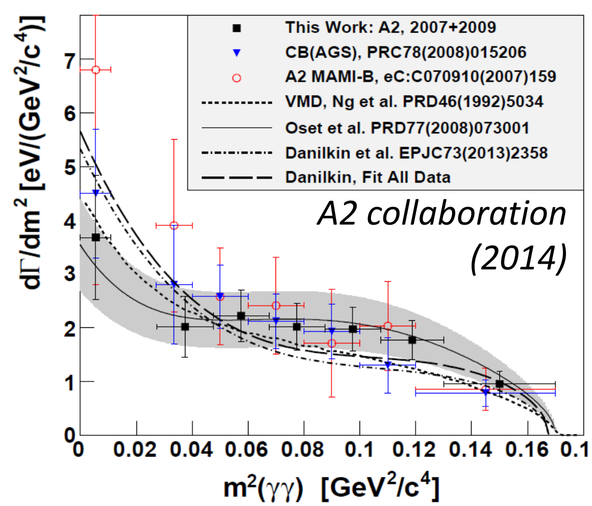
First measurement claimed at CERN, 1966.

Early history for this channel fraught with controversy (both experiment and theory).

Achasov et al (2001)

Active target of study as a probe of ChPT at $O(p^6)$ and QCD model predictions (using $m_{\gamma\gamma}$ invariant mass spectrum)

Past and on-going: GAMS, SND at VEPP-2M, Crystal Ball at AGS/MAMI, KLOE (prelim), WASA (prelim), …
Future: Jefferson Eta Factory, KLOE 2, …



$\eta \rightarrow \pi^0\gamma\gamma$

B boson signature: $\eta \rightarrow B\gamma \rightarrow \pi^0\gamma\gamma$ mimics the rare SM decay $\eta \rightarrow \pi^0\gamma\gamma$

Nelson & Tetradis (1989)

Total rate constraint:

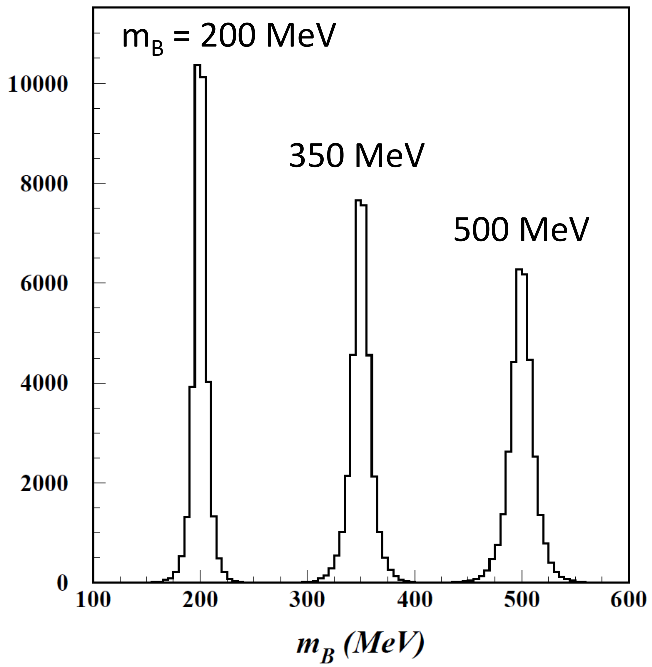
$$\frac{\Gamma(\eta \to B\gamma)}{\Gamma(\eta \to \gamma\gamma)} = 2\frac{\alpha_B}{\alpha_{\rm em}}\left(1 - \frac{m_B^2}{m_\eta^2}\right)^3 \times O(1) \quad < \quad \frac{\Gamma(\eta \to \pi^0\gamma\gamma)}{\Gamma(\eta \to \gamma\gamma)} \sim 10^{-3}$$

Requires $\alpha_B < 10^{-5} \ll \alpha_{em}$

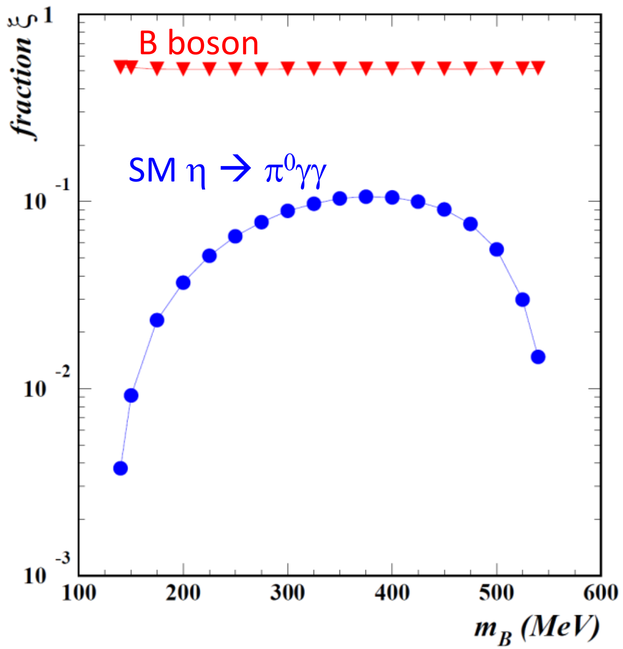
$\eta \rightarrow \pi^0\gamma\gamma$

Kinematics: Boost sensitivity by searching for $\pi^0\gamma$ resonance in $\eta \rightarrow \pi^0\gamma\gamma$

Preliminary Monte Carlo study by JEF collaboration



Reconstruction of m_B from $m(\pi^0\gamma)$



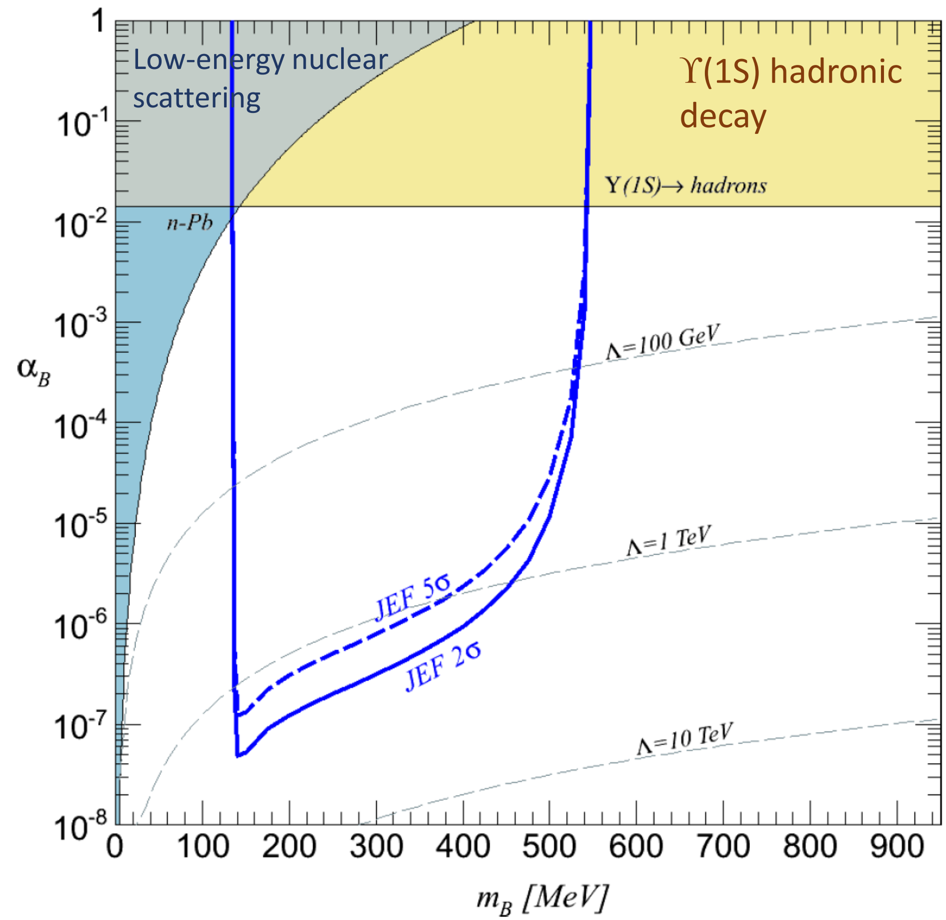
Acceptance fraction for a cut around m_B

$\eta \rightarrow \pi^0\gamma\gamma$

Kinematics: Boost sensitivity by searching for $\pi^0\gamma$ resonance in $\eta \rightarrow \pi^0\gamma\gamma$

Preliminary Monte Carlo study by JEF collaboration

η decays sensitive to forces hidden in QCD up to 10^5 times weaker than electromagnetism



$\phi \rightarrow \eta\pi^0\gamma$

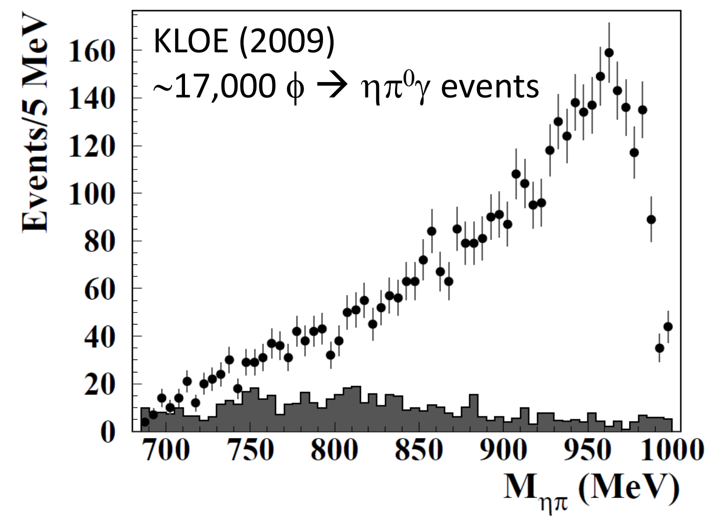
$\phi(1020)$ $I^G(J^{PC}) = 0^-(1^{--})$

	Mode	Fraction (Γ_i/Γ)
Γ_6	$\eta\gamma$	(1.309 ± 0.024) %
Γ_{22}	$\pi^0\eta\gamma$	$(7.27 \pm 0.30) \times 10^{-5}$

Active target of study for understanding QCD scalar resonances

$\phi \rightarrow a_0(980)^*\gamma \rightarrow \eta\pi^0\gamma$

Achasov & Ivanchenko (1989)



$\phi \rightarrow \eta\pi^0\gamma$

B boson signature: $\phi \rightarrow \eta B \rightarrow \eta\pi^0\gamma$ mimics the rare SM decay $\phi \rightarrow \eta\pi^0\gamma$

Total rate constraint:

$$\frac{\Gamma(\phi \to \eta B)}{\Gamma(\phi \to \eta\gamma)} = \frac{\alpha_B}{\alpha_{\rm em}} \frac{\lambda(m_\phi, m_\eta, m_B)^{3/2}}{\lambda(m_\phi, m_\eta, 0)^{3/2}} |F_\phi(m_B^2)|^2 < \frac{\Gamma(\phi \to \eta\pi^0\gamma)}{\Gamma(\phi \to \eta\gamma)} \sim 1/200$$

Requires $\alpha_B < 5\text{x}10^{-5} \ll \alpha_{em}$

Significant improvements could be made by searching for a $\pi^0\gamma$ resonance in the $\phi \rightarrow \eta\pi^0\gamma$ events

Constraints on B boson

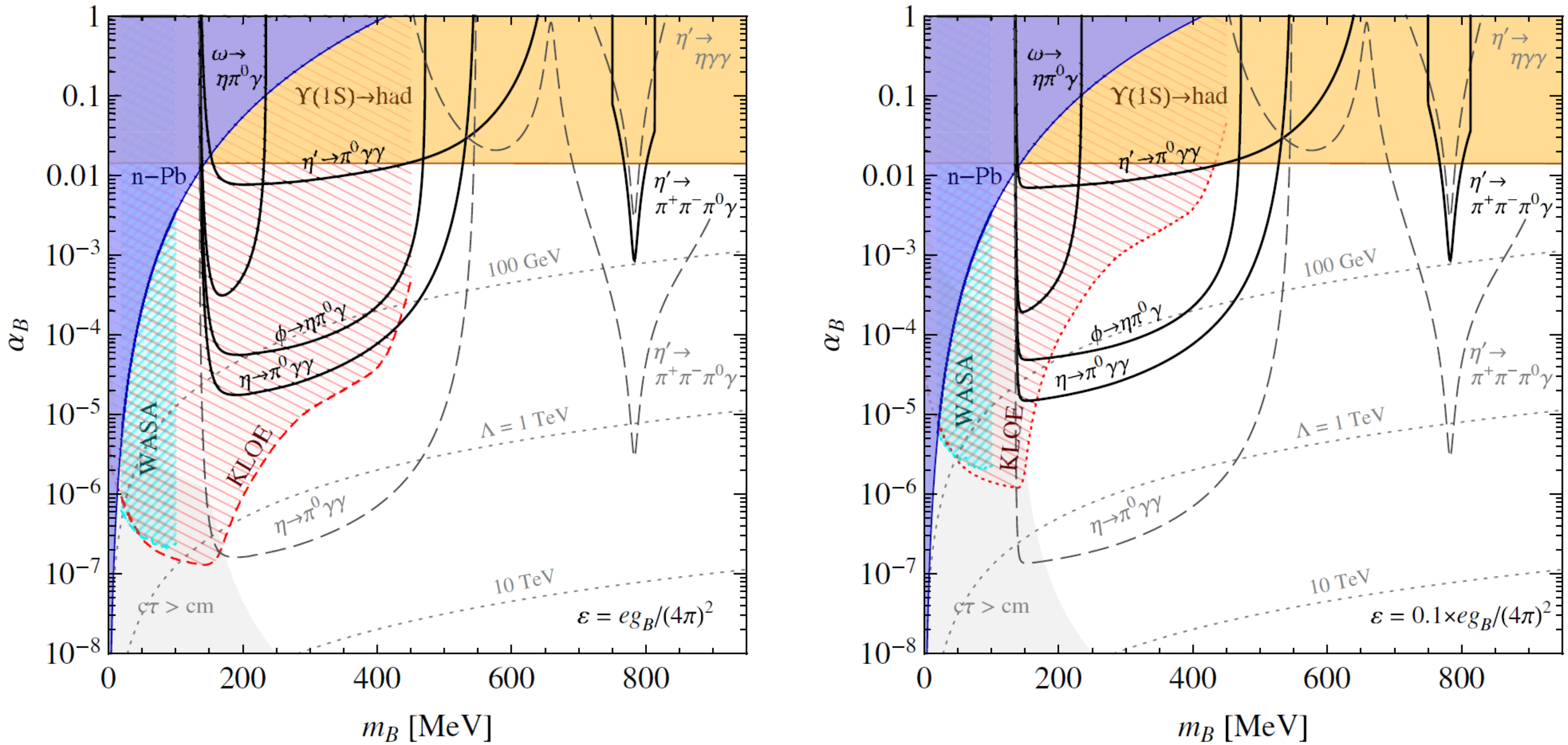


FIG. 2 (color online). Limits on baryonic gauge boson coupling α_B and mass m_B, for different values of kinetic mixing parameter ε. Thick black contours are current exclusion limits from radiative light meson decays based on their total rate (assuming the QCD contribution is zero). Dashed gray contours illustrate the reach of possible future constraints at the level of $\mathrm{BR}(\eta \to B\gamma \to \pi^0\gamma\gamma) < 3 \times 10^{-6}$ [50], $\mathrm{BR}(\eta' \to B\gamma \to \pi^+\pi^-\pi^0\gamma) < 10^{-4}$, and $\mathrm{BR}(\eta' \to B\gamma \to \eta\gamma\gamma) < 10^{-4}$. Shaded regions are exclusion limits from low-energy n-Pb scattering and hadronic $\Upsilon(1S)$ decay. Hatched regions are excluded by A' searches from KLOE [58] and WASA [57]. A' limits applied to B are model dependent, constraining possible leptonic B couplings. Limits shown here are for $\varepsilon = eg_B/(4\pi)^2$ (left plot) and $0.1 \times eg_B/(4\pi)^2$ (right plot). Gray shaded regions show where B has a macroscopic decay length $c\tau > 1$ cm. Dotted contours denote the upper bound on the mass scale Λ for new electroweak fermions needed for anomaly cancellation, assuming $\Lambda \lesssim 4\pi m_B/g_B$.

Conclusions

- New forces beyond the Standard Model:
  - Motivated by dark matter
  - Would be a game-changing particle physics discovery

- GeV-scale leptophobic forces are a blind spot to dark photon searches, but can be searched for in existing/future light meson factories

- Smoking gun signature: a $\pi^0\gamma$ resonance in rare meson decays.