Searches for a Lepto-phobic "Dark Omega" with the GlueX Detector

Dave Mack (TJNAF)

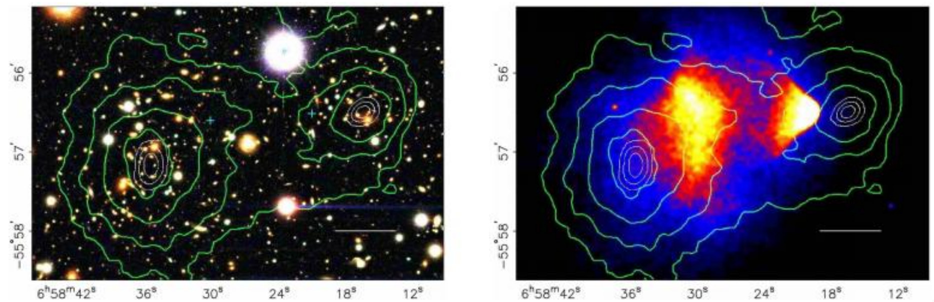
Hadron 2017
Salamanca, Spain
Sept 27, 2017

Physics Motivation

Galactic Observations Say Dark Matter Exists
But What the Heck Is It?

Based on strong astrophysical evidence, dark matter exists. It is beyond the SM.

Rotation curves of spiral galaxies.



Apparent segregation of dark matter and normal matter in the Bullet Cluster collision (inferred from lensing and X-rays, respectively).

Consistent extensions of the SM usually require a family of new particles for anomaly cancellation. The dark sector may be quite complex.

Experiments can

i. Search for stable dark matter

ii. Search for production of dark matter particles in accelerator experiments.

Motivation for a Lepto-phobic B Boson Search

Searches for a Visible Dark Vector Boson

lepto-phillic

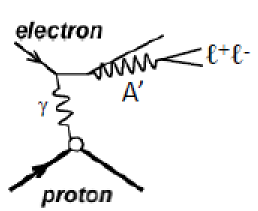
There has been much recent progress excluding phase space for a dark e/μ-loving photon A′.

Experiments search for $A' \rightarrow e^+e^-$ or $\mu^+\mu^-$.

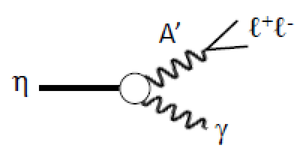
The phase space for a <u>visible</u>, electron loving particle which might be pulling muon(g-2) has been largely excluded in the last half decade.

Dark photon

Direct production:

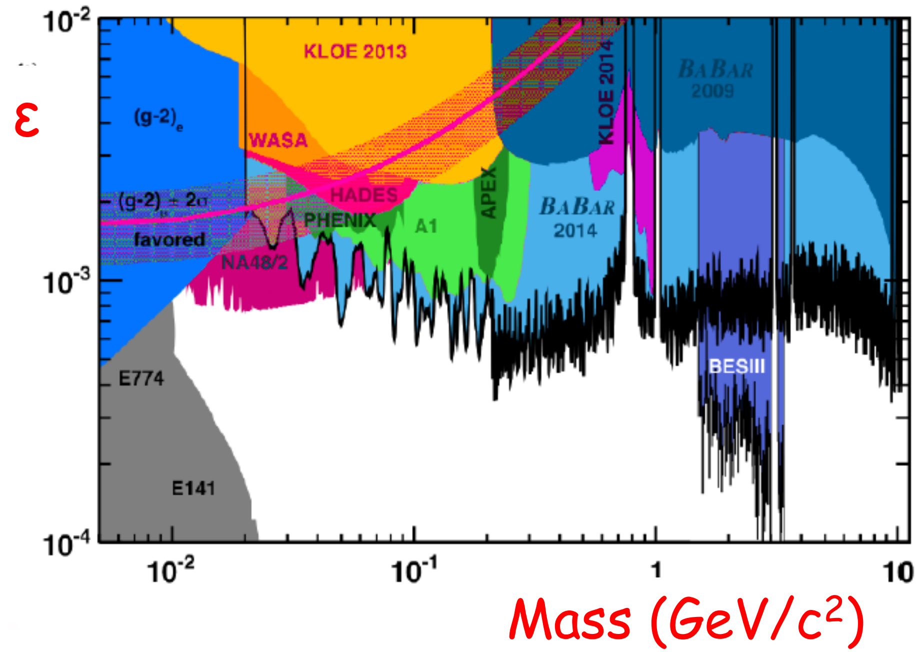


Meson decays:



$\sqrt{(\alpha'/\alpha_{EM})}$ vs Mass(A′)

Published or Preliminary Results



F. Curciarello, https://www.epj-conferences.org/articles/epjconf/pdf/2016/13/epjconf_fccp2016_01008.pdf

Searches for a Visible Dark Vector Boson

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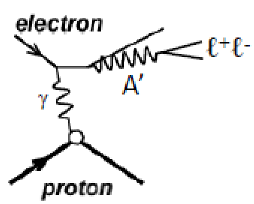

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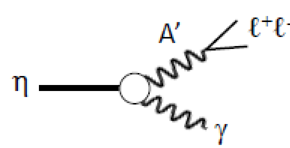
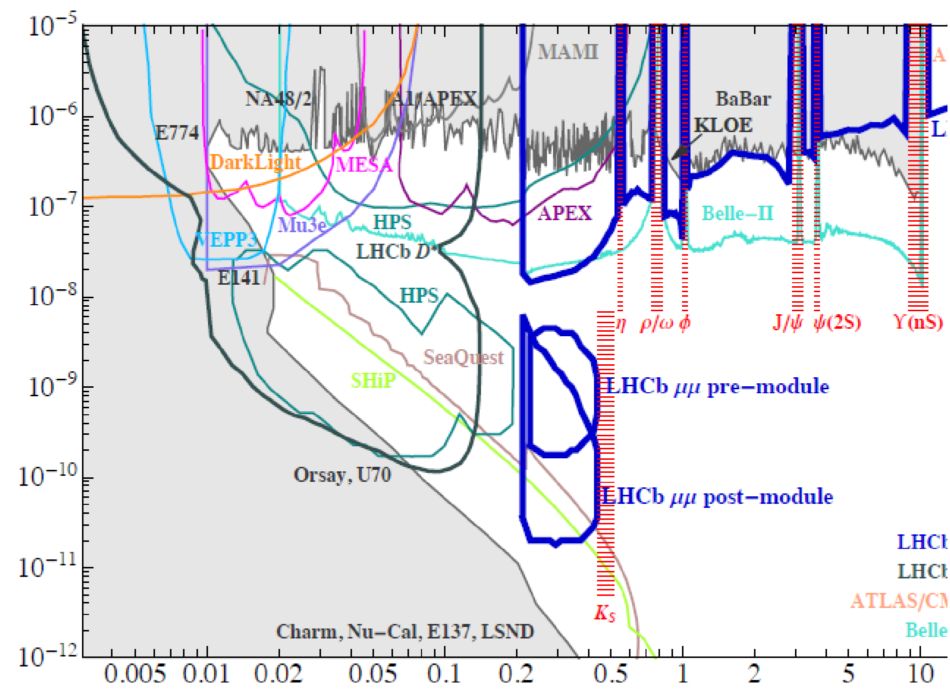


Sean Tulin MesonNet14 talk

α'/α_{EM} vs Mass(A′) Including Projected Sensitivities.

ε^2



Mass (GeV/c²)

P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue,
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.251803

Searches for a Visible Dark Vector Boson

lepto-phobic

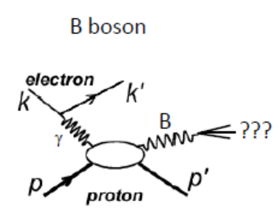
Due in part to high hadronic backgrounds, there has been less progress excluding phase space for a dark boson with suppressed couplings to electrons and muons.

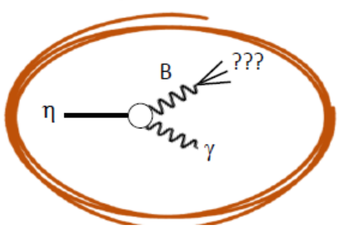
The formalism goes back to
A.E. Nelson, N. Tetradis, PLB221, 80 (1989)

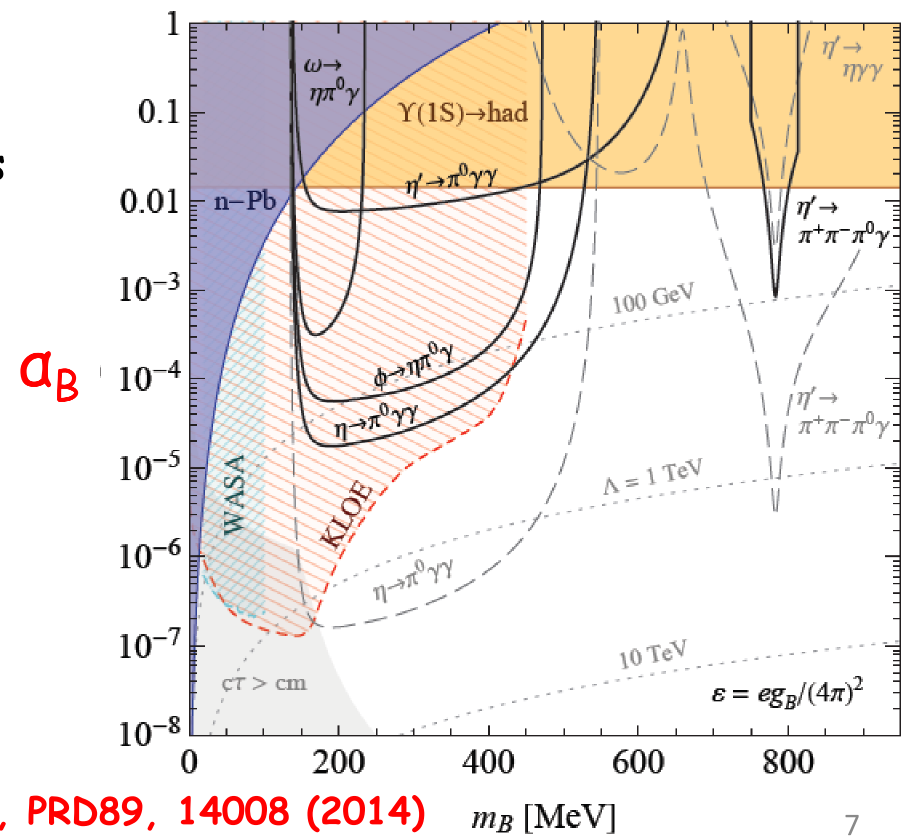
Recently Tulin considered a model with universal quark couplings, which preserves low energy symmetries of QCD.

$$\mathscr{L}_{\rm int} = (\tfrac{1}{3}g_B + \varepsilon Q_q e)\bar{q}\gamma^\mu q B_\mu - \varepsilon e \bar{\ell}\gamma^\mu \ell B_\mu$$
$$\alpha_B \equiv g_B^2/4\pi,$$

α_B vs Mass(B)
Including Projected Sensitivities.







Sean Tulin MesonNet14 talk

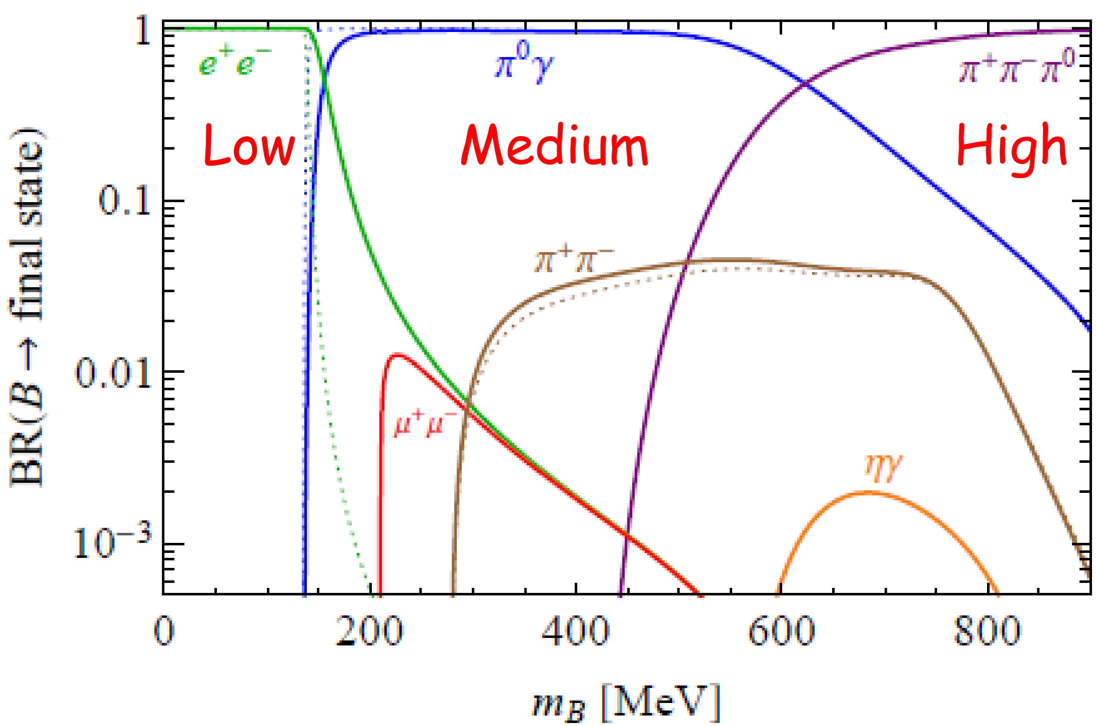
Sean Tulin, PRD89, 14008 (2014)

How Does the B/ω_D Decay?

Tulin's model predicts an isoscalar vector boson called the B or "dark omega" (since it has the same quantum numbers as the ω or the φ).

This means the 2π decay of the B is suppressed by isospin conservation.

He worked out the mass-dependent decay modes in a Vector Meson Dominance model:



e^+e^- in Low range (probed in A' searches)

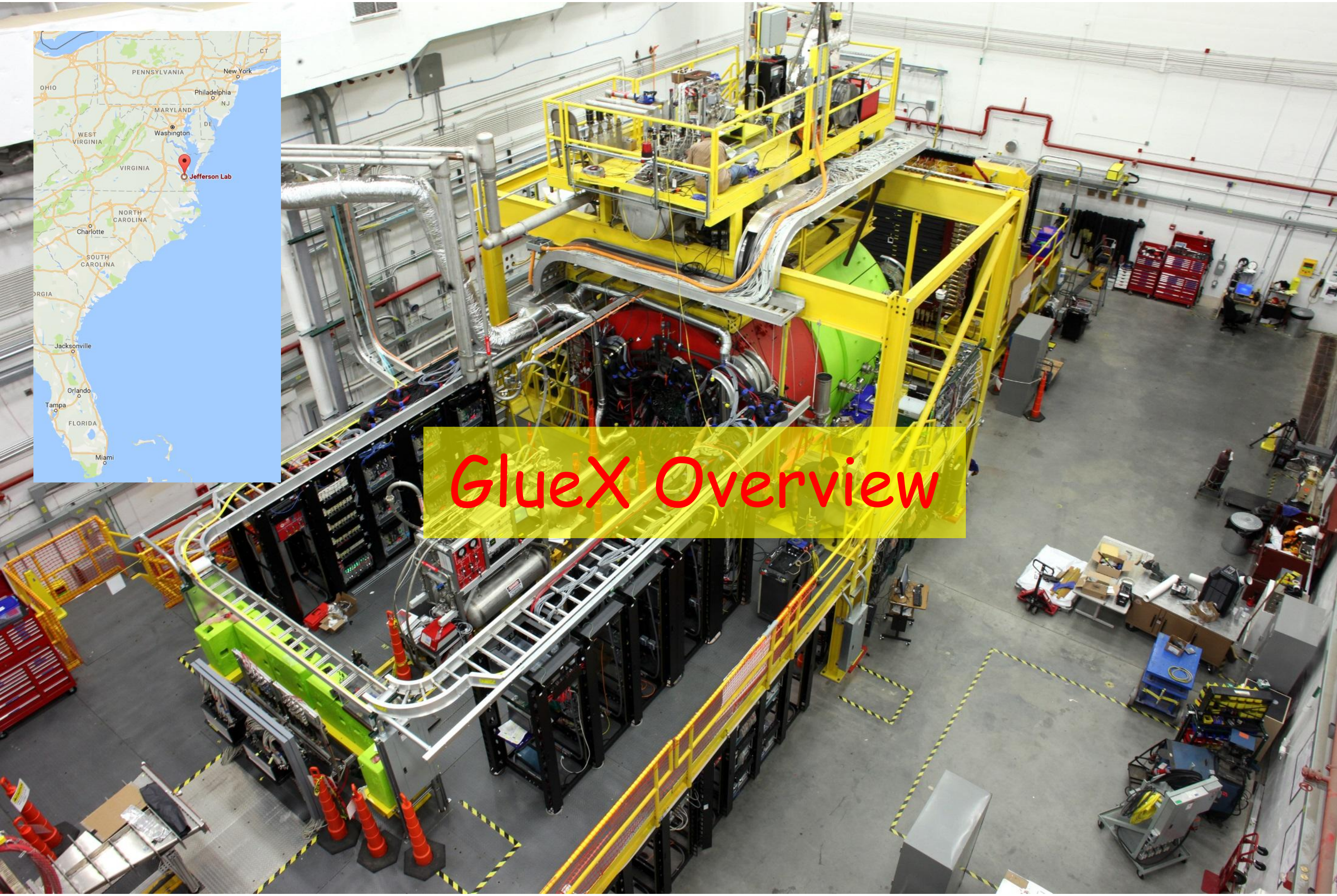
$\pi^0\gamma$ in Medium range

$\pi^+\pi^-\pi^0$ in High range

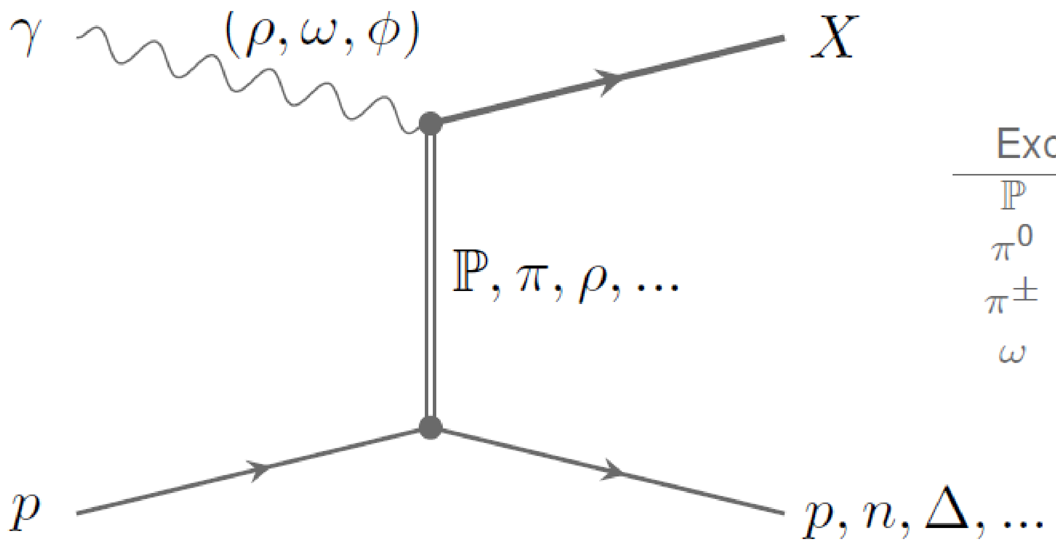
The GlueX detector is well suited for detecting the $\pi^0\gamma$ or $\pi^+\pi^-\pi^0$ final states with high acceptance.

Sean Tulin, Phys.Rev., D89, 14008 (2014)

GlueX Overview



GlueX Search for Exotic Mesons
(q-qbar-glue)

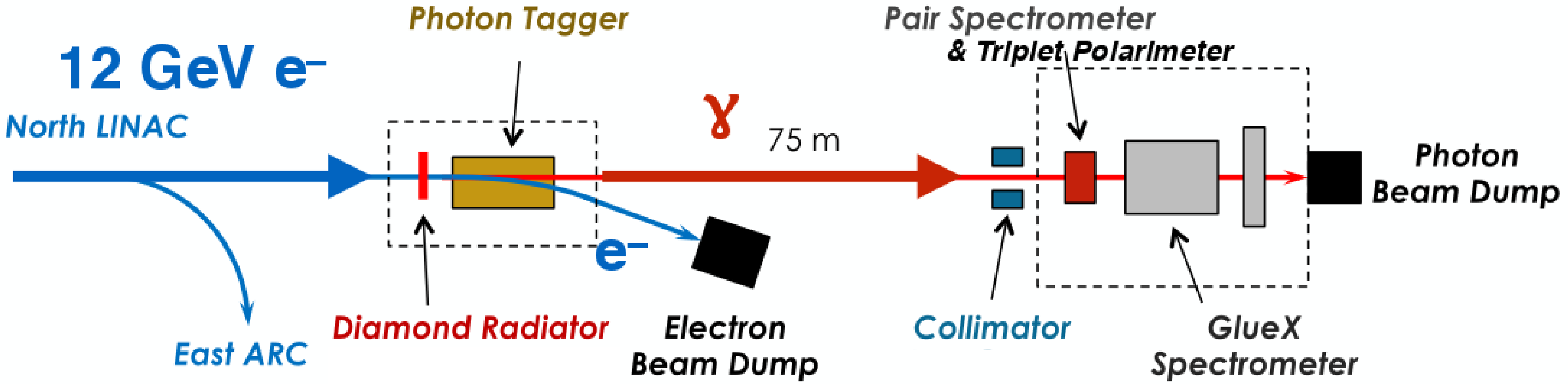


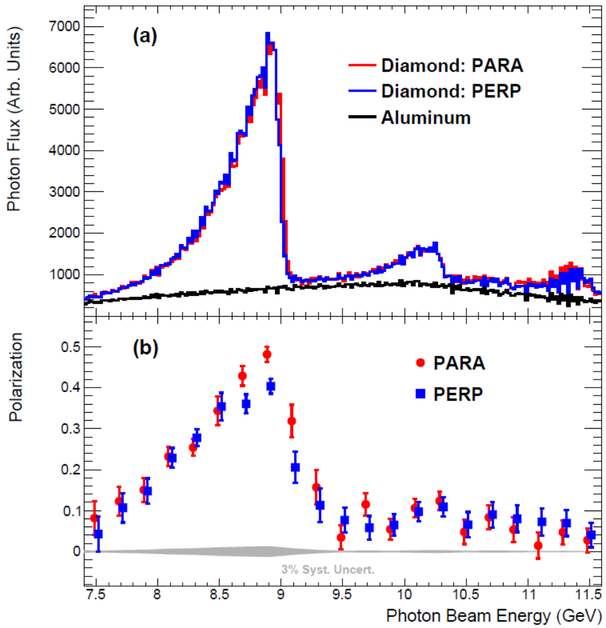
Exchange		Exotic Final States	
$\mathbb{P}$	0^{++}	b, h, h'	$2^{+-}, 0^{+-}$
π^0	0^{-+}	b_2, h_2, h_2'	2^{+-}
$\pi^\pm$	0^{-+}	$\pi_1^\pm$	1^{-+}
ω	1^{--}	π_1, η_1, η_1'	1^{-+}

Complementary Production Mechanism

- Photon coupling via vector meson dominance
- Wide variety of $I^G J^{PC}$ states accessible
- Photon polarization provides additional constraints

Photon Beamline





9 GeV Polarized Photon Beam

- Coherent Bremsstrahlung on thin diamond
- Energy tagged by scattered electrons
- Collimator to suppress incoherent part
- Linear polarization in peak $P_\gamma \approx 40\%$, measured by Triplet polarimeter: $\gamma e^- \rightarrow e^- e^+ e^-$
- Beam intensity: $1 - 5 \cdot 10^7\ \gamma/\text{s}$ in peak

GlueX Detector

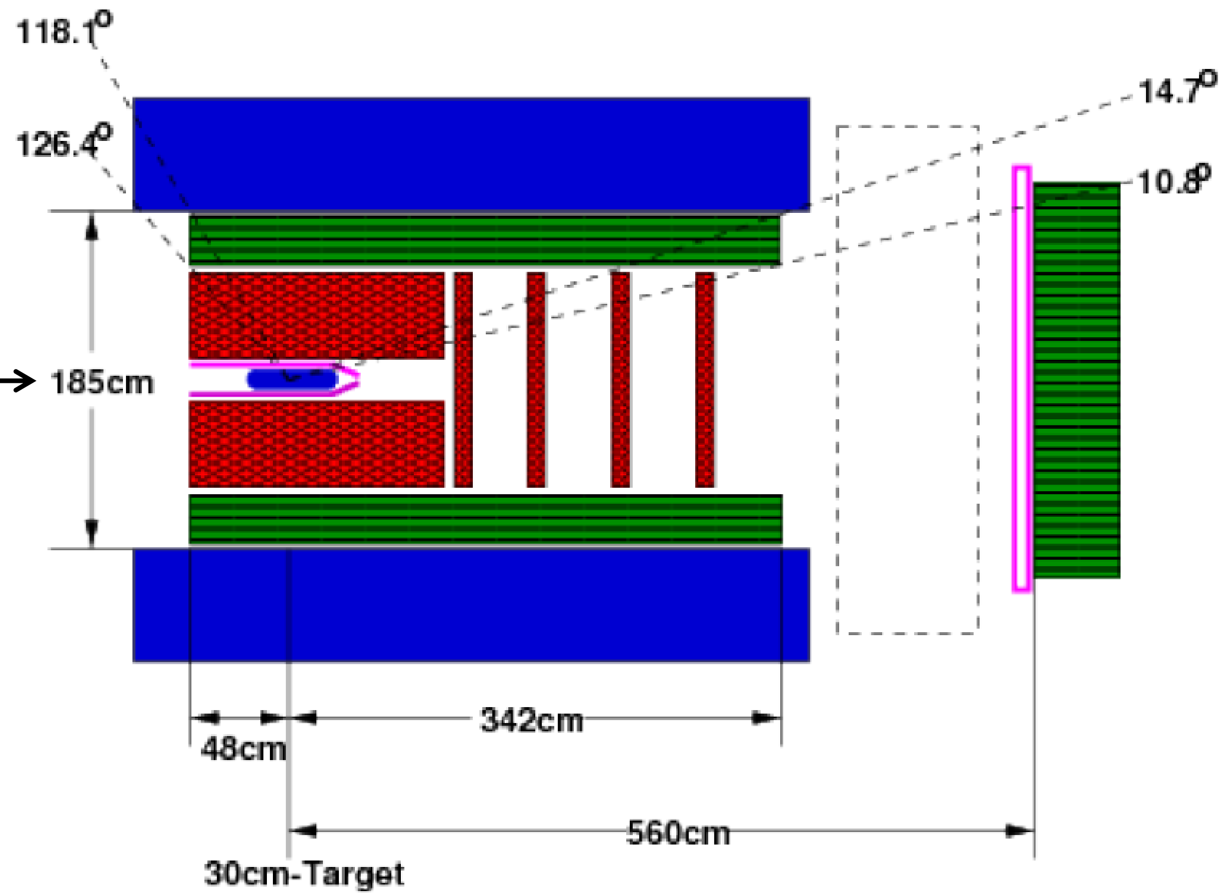
Solenoid, Target (blue)

Tracking (red)

beam

Calorimetry (green)

Timing (magenta)



Running Periods

- Spring 2016: 12 GeV Engineering run
  - Electron Beam Energy: 12.05 GeV
  - Commissioning complete: Detector, Beamline, DAQ
  - Data taken for early physics results:
    $\sim$26 billion events, $\sim$7 billion with good quality
- Spring 2017: GlueX Phase-I, first part
  - Electron Beam Energy: 11.64 GeV
  - 58μm diamond radiator
  - DAQ trigger rate 30-50 kHz
  - Exceeded nominal luminosity
  - Accumulated $\sim$50 billion events (20%)

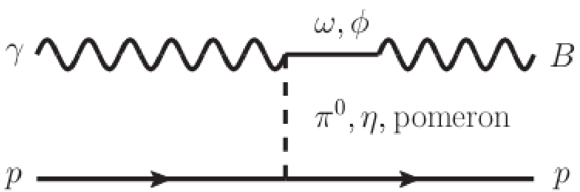
December 2017: Continue GlueX Phase-I

Constraints from Direct B Photo-production $\gamma+p \rightarrow B+p$

Direct B Production γ+p→B+p

Fanelli and Williams http://arxiv.org/abs/1605.07161

Off-shell ω, φ, and B mix. The amplitude to decay as a B is:



$$\mathcal{A}(\gamma p \to pB) \approx \left[\frac{2g_B}{3\sqrt{12\pi}}\right] \times \left(\frac{m_\omega^2 \mathcal{A}(\gamma p \to p\omega)^\mu}{D_\omega(m_B)} + \frac{m_\phi^2 \mathcal{A}(\gamma p \to p\phi)^\mu}{\sqrt{2} D_\phi(m_B)}\right) B_\mu^*.$$

The natural σ_+ and unnatural σ_- parity cross sections are:

$$\sigma_\pm(\gamma p \to pB) \approx \frac{4\alpha_B}{27}\Phi(m_B)\left[\frac{m_\omega^4 \sigma_\pm(\gamma p \to p\omega)}{\Phi(m_\omega)|D_\omega(m_B)|^2} + \frac{m_\phi^4 \sigma_\pm(\gamma p \to p\phi)}{2\Phi(m_\phi)|D_\phi(m_B)|^2} + \frac{\sqrt{2}\cos(\varphi_\pm) m_\omega^2 m_\phi^2 \sqrt{\sigma_\pm(\gamma p \to p\omega)\sigma_\pm(\gamma p \to p\phi)}}{|D_\omega(m_B)||D_\phi(m_B)|\sqrt{\Phi(m_\omega)\Phi(m_\phi)}}\right].$$

where the baryonic fine structure constant is $\alpha_B \equiv g_B^2/4\pi$,

The natural and unnatural parity cross sections have different functional forms, so we need the relative proportions at our beam energy for optimal exclusions. Ongoing GlueX analyses determine the relative importance of pomeron vs meson exchange:

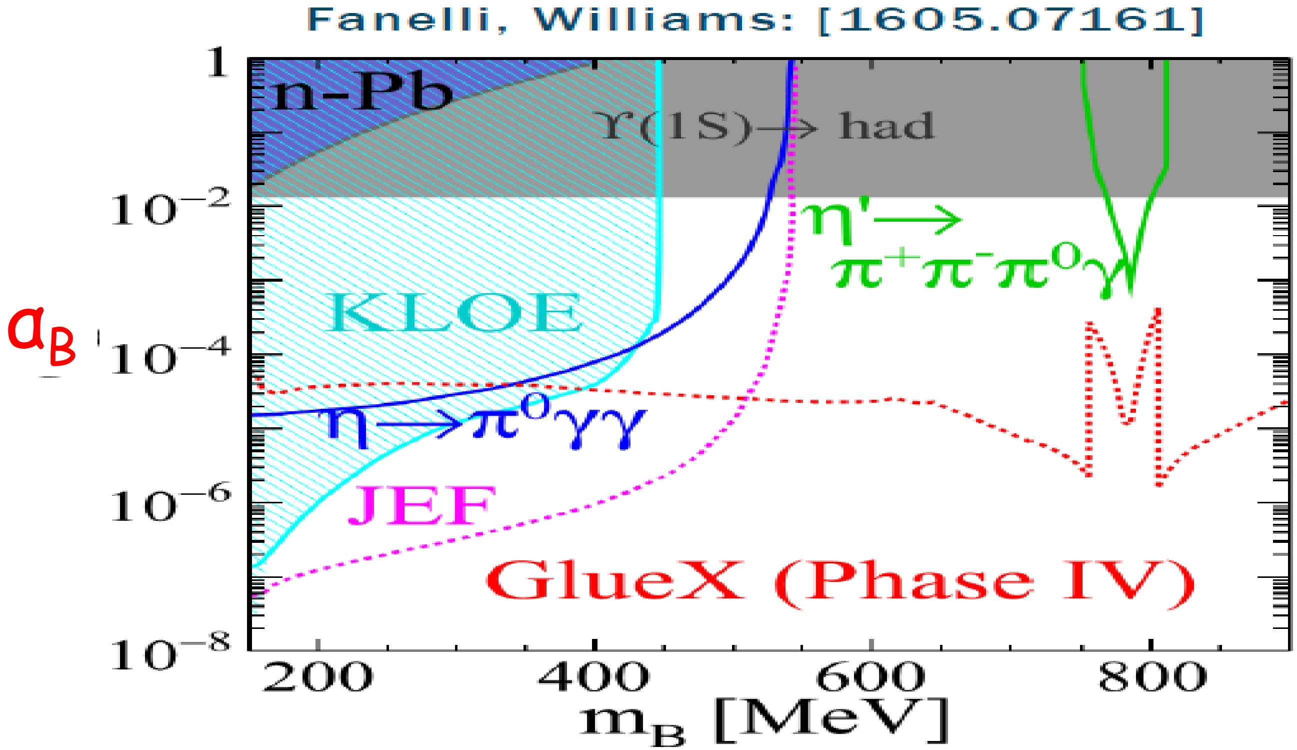
ω SDME's, M. Staib, PhD thesis, Sept 2017, Carnegie Mellon U. (publication in prep.)
φ SDME's, A. Barnes, PhD thesis, May 2017, U. of Connecticut

Direct Production Highlight

Constraints on α_B can be surprisingly weak: a coupling $\alpha_B \sim \alpha_{EM}$ has not yet been excluded in the 0.4-1 GeV/c^2 mass range.

Direct production is the most sensitive known technique to access the 0.4-1 GeV/c^2 mass range.

Each additional decade of exclusion requires a measurement with 100x greater Figure of Merit. This means we should be able to exclude the yellow phase space below with only a small fraction of the future GlueX total integrated luminosity.



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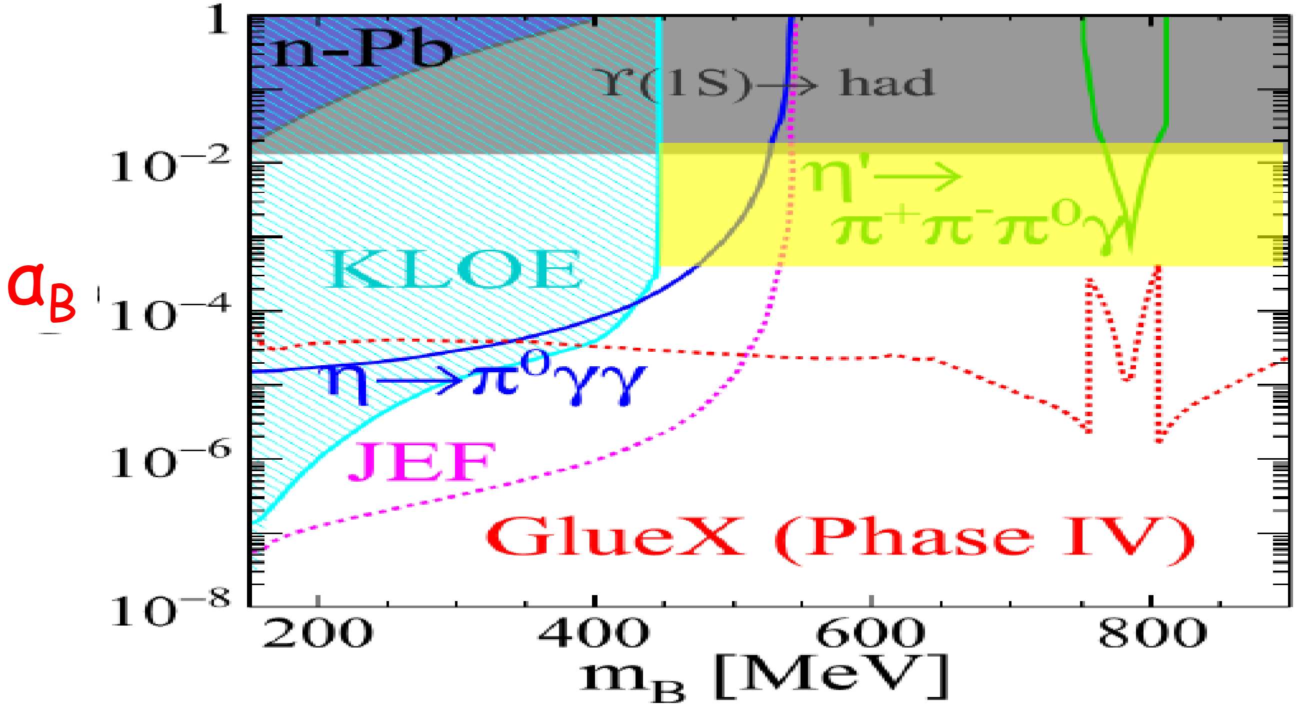
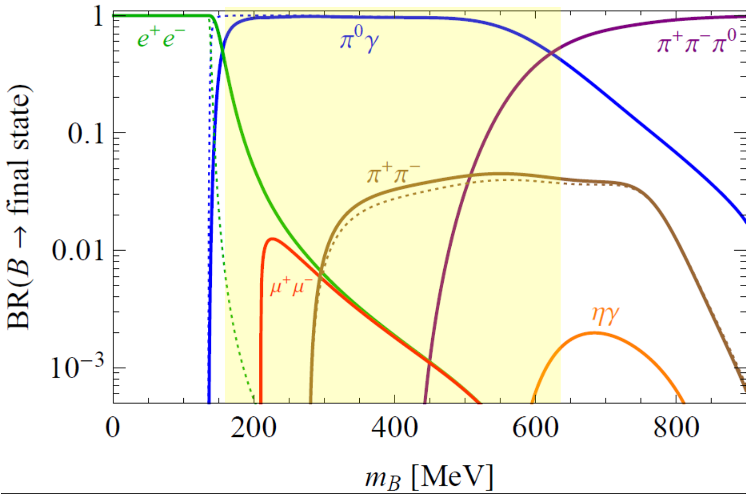
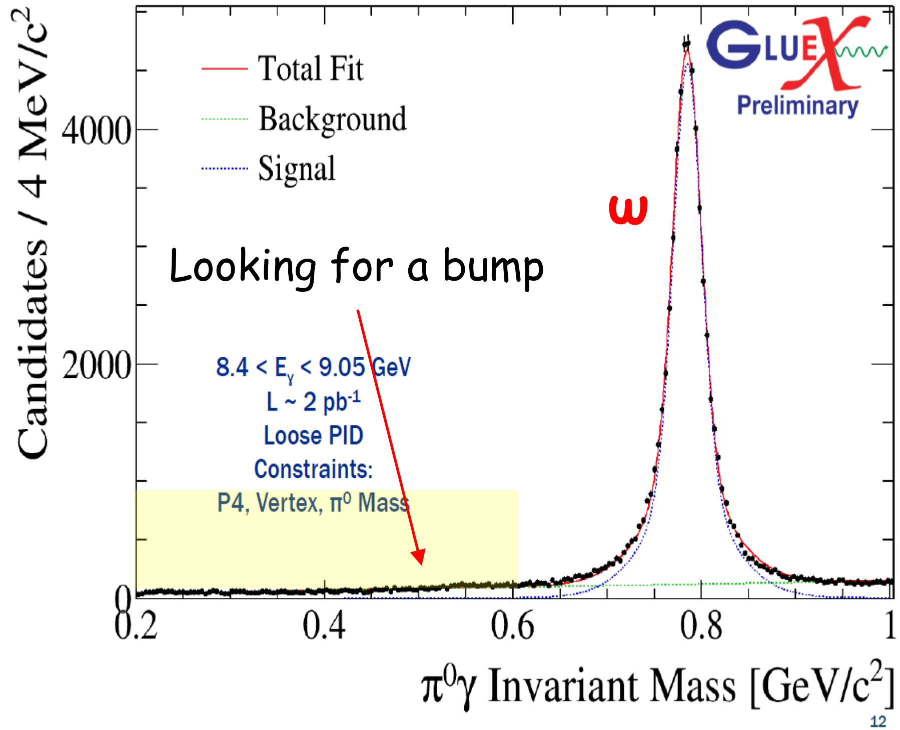
Fanelli, Williams: [1605.07161]



Direct B Production, Decaying to $\pi^0\gamma$

lower mass region M_B = 200-600 MeV/c^2

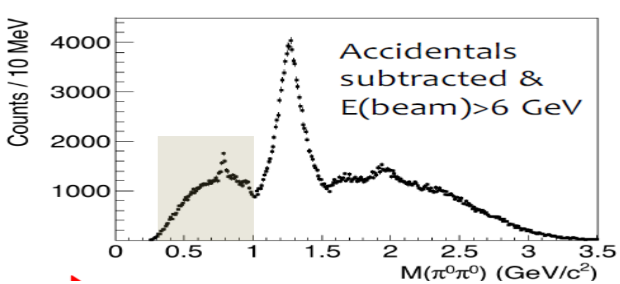




An exclusive measurement is made of

$$\gamma + p \to \pi^0\gamma + p$$

The small continuum background appears to be dominated by $2\pi^0$ (below) with a missing photon.



The sensitivity depends in part on the resolution and the reconstruction efficiency:

- A check on the resolution model for a hypothetical B peak is provided by the SM $\omega \to \pi^0\gamma$ peak.
- The reconstruction efficiency is checked by comparing to the known ratio for $\omega \to \pi^0\gamma / \omega \to \pi^+\pi^-\pi^0$

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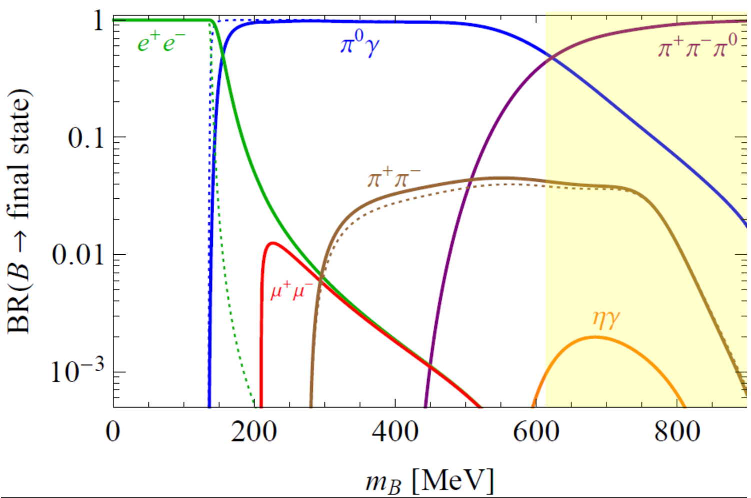
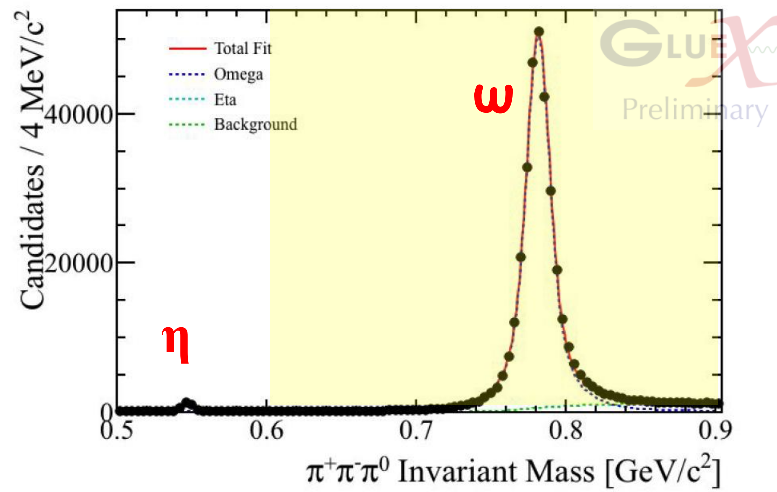
Direct B Production, Decaying to $\pi^+\pi^-\pi^0$

higher mass region M_B = 600-900 MeV/c^2

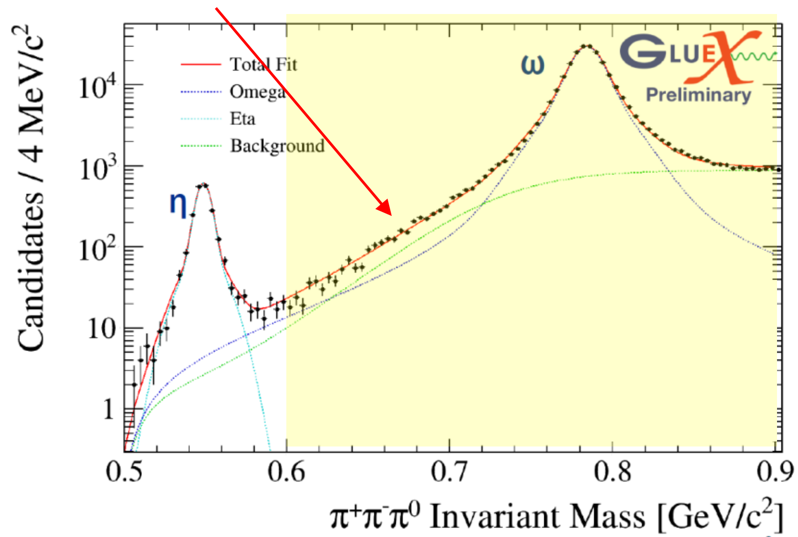




An exclusive measurement is made of

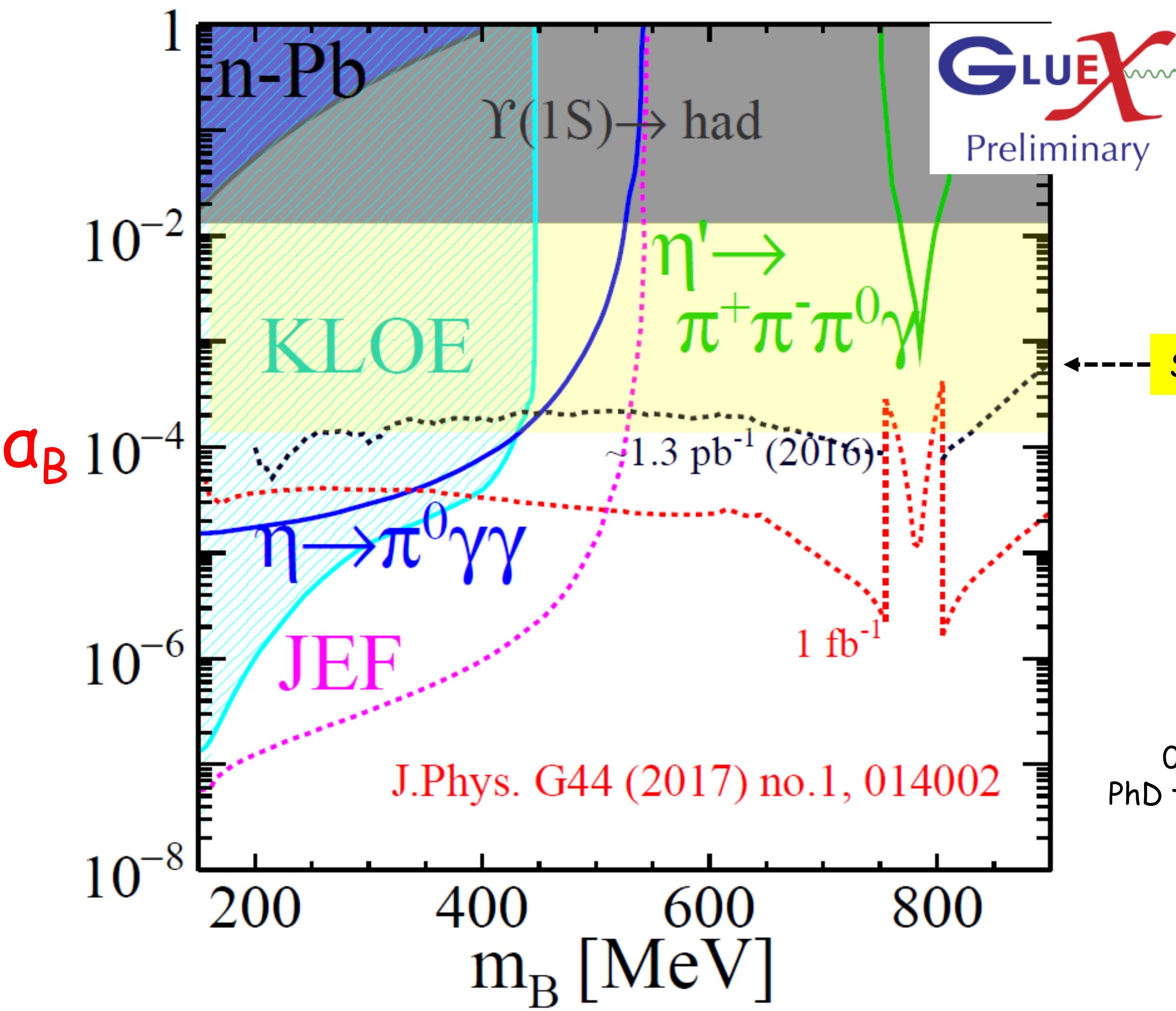
$\gamma + p \rightarrow \pi^+\pi^-\pi^0 + p$

Looking for a bump



- A check on the resolution model for a hypothetical B peak is provided by the two SM $\eta,\omega \rightarrow \pi^+\pi^-\pi^0$ peaks.
- The reconstruction efficiency is checked by comparing to the known ratio for $\omega \rightarrow \pi^0\gamma / \omega \rightarrow \pi^+\pi^-\pi^0$.

Expected Constraints on Lepto-phobic Dark Coupling and Mass Using Direct B Production



Spring 2016 Preliminary

B Boson constraints for 0.2-0.9 GeV/c^2 will be the PhD thesis of John Hardin (MIT).

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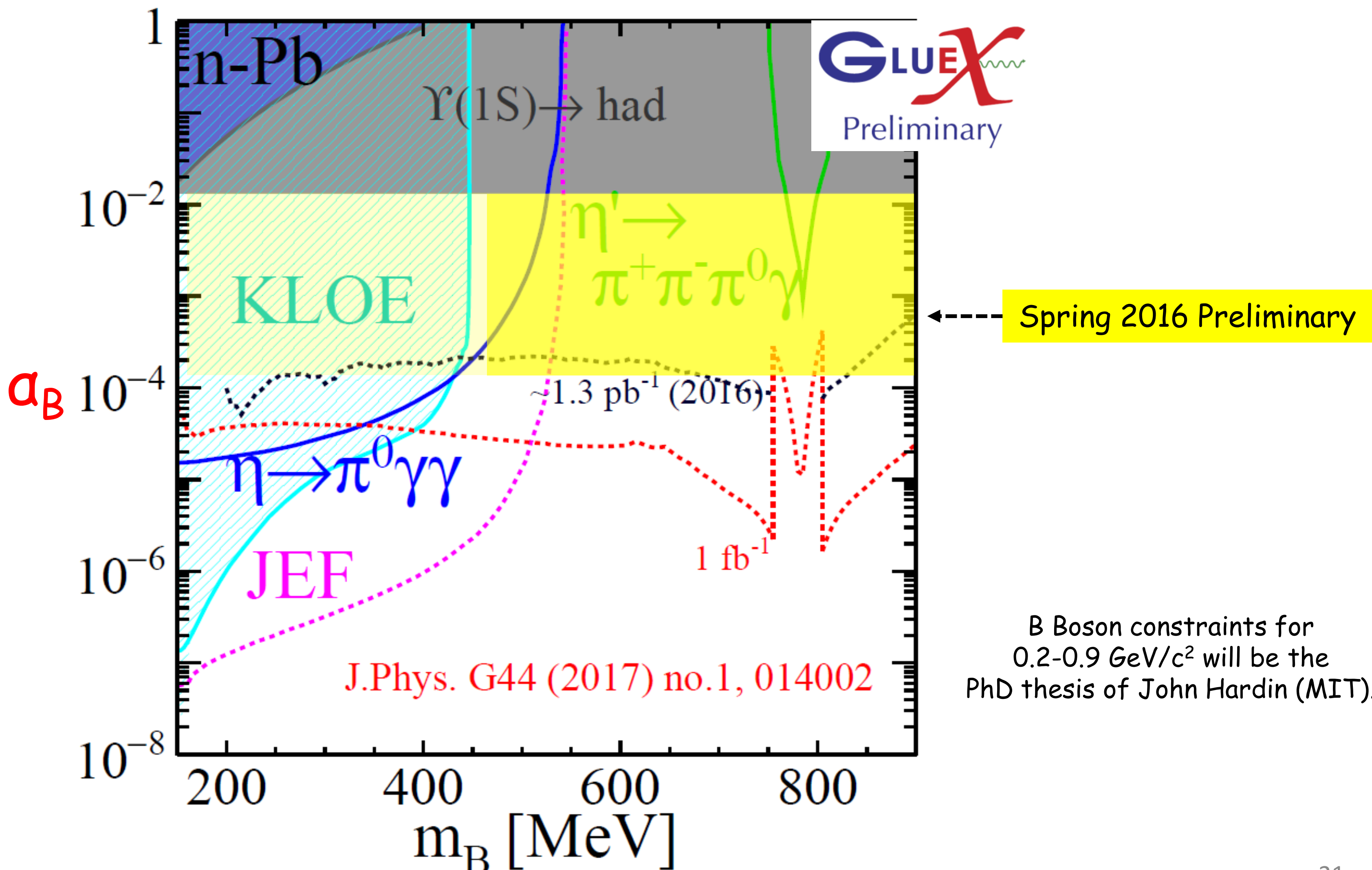

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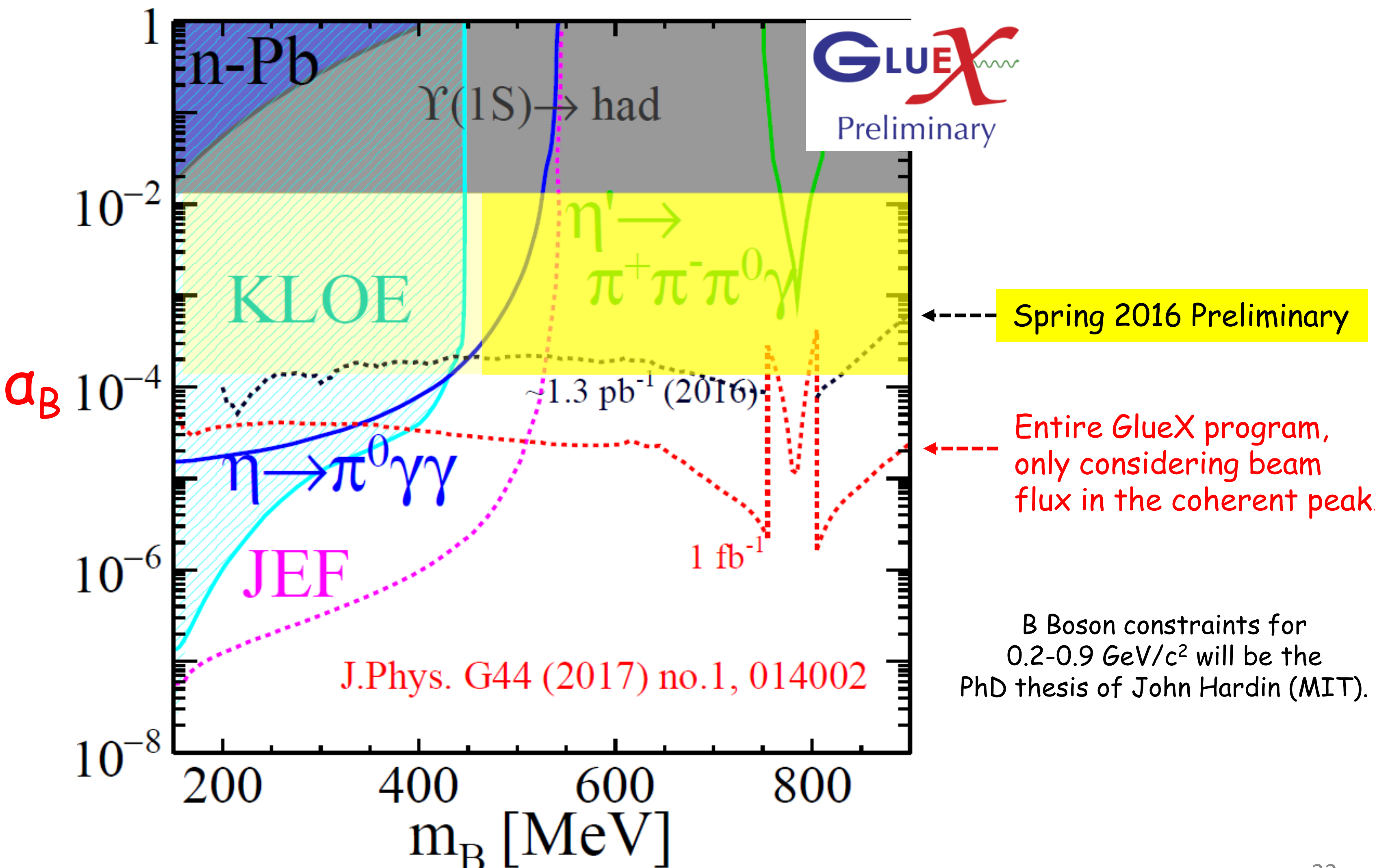

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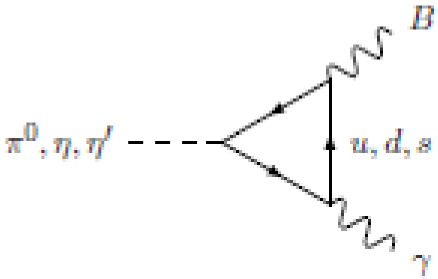
Constraints from Meson Decays

New weakly-coupled Forces in Low-energy QCD

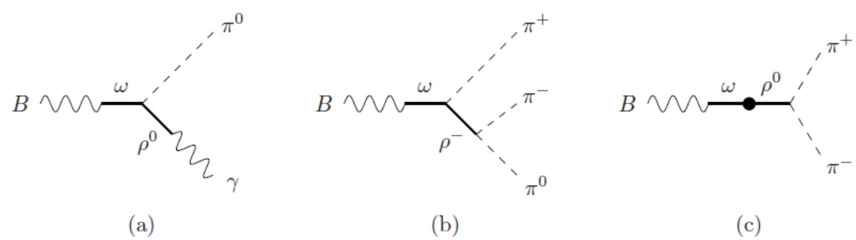
S. Tulin http://arxiv.org/abs/1404.4370

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



$$\frac{\Gamma(P\to B\gamma)}{\Gamma(P\to\gamma\gamma)} \approx \frac{\alpha_B}{\alpha_{\rm em}}\left(1-\frac{m_B^2}{m_P^2}\right)^3 \times \begin{cases} 2 & P=\pi^0 \\ \frac{1}{2} & P=\eta \\ \frac{2}{49} & P=\eta' \end{cases} .$$

Accurate constraints on α_B requires getting the hadronic physics right.
Eg, the VMD has interference between the ω and φ contributions.
There are no significant interpretational ambiguities below 0.95 GeV/c2.



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

One of the most interesting decay branches is

$$\Gamma(B\to\pi^0\gamma) = \frac{\alpha_B \alpha_{\rm em} m_B^3}{96\pi^3 f_\pi^2}\left(1 - m_\pi^2/m_B^2\right)^3 |F_\omega(m_B^2)|^2$$

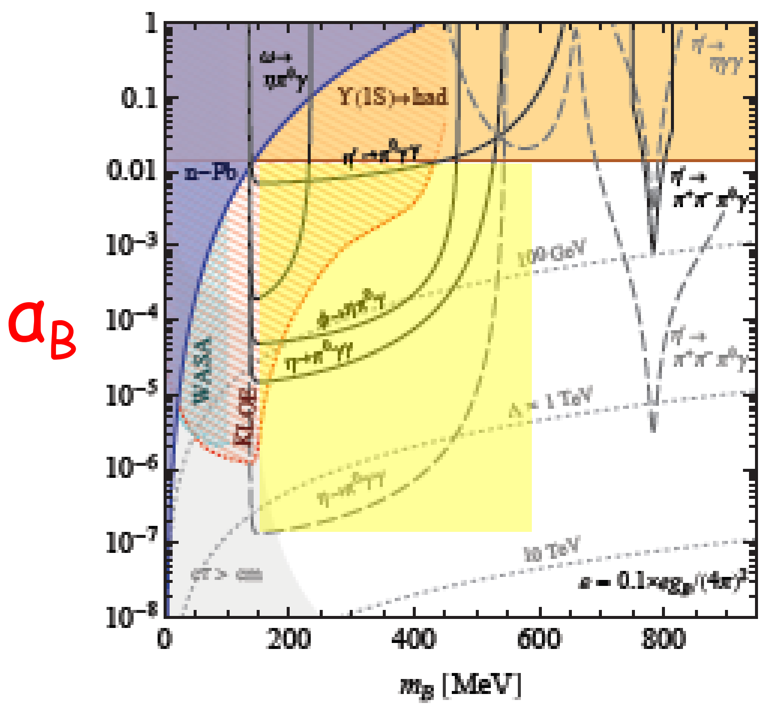
Considering both production and decay, the B signal is proportional to α_B^2 hence g_B^4.

Medium Mass Range

4γ options from $\eta^{(\prime)} \rightarrow \gamma + B$

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.



Lots of options, and each one needs study. We chose the 4γ channels because of GlueX collaboration interest in the rare, doubly radiative decays $\eta^{(\prime)} \rightarrow \pi^0\, 2\gamma$, as well as photoproduction of the scalar $a_0(980) \rightarrow \eta\pi^0$.

$\eta^{(\prime)} \rightarrow \gamma + B \rightarrow \pi^0\, 2\gamma$

In GlueX, our channel will be

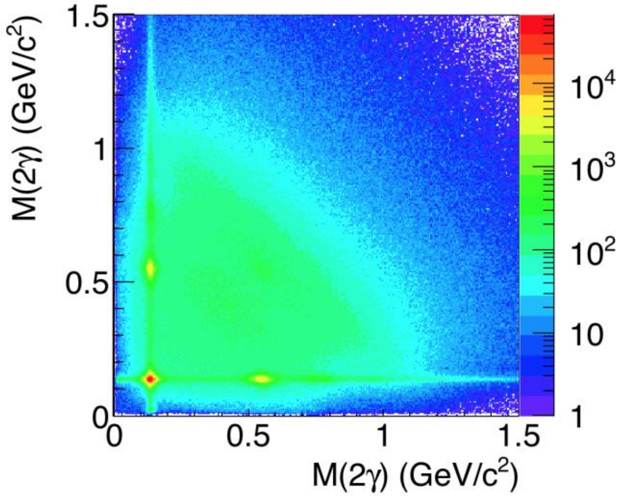
$\gamma + p \rightarrow\ p + \pi^0\, 2\gamma$

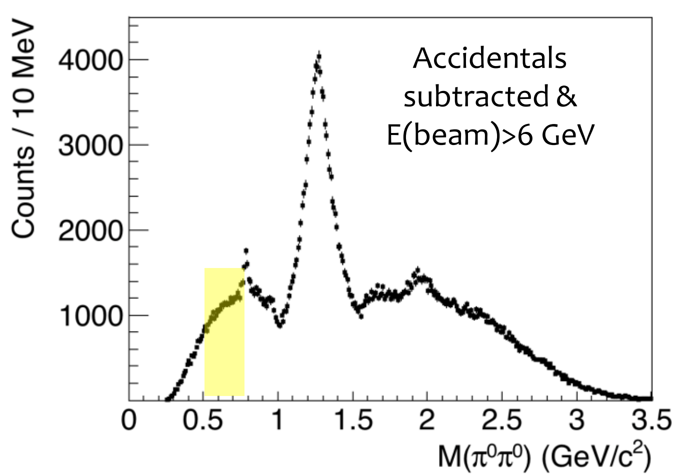
Background Studies Using Spring 2016 Data

4γ Event Filtering to $\pi^0 2\gamma$

plots by Shuang Han (Wuhan U.)

"4γ" is mostly $2\pi^0$ and $\pi^0\eta$.





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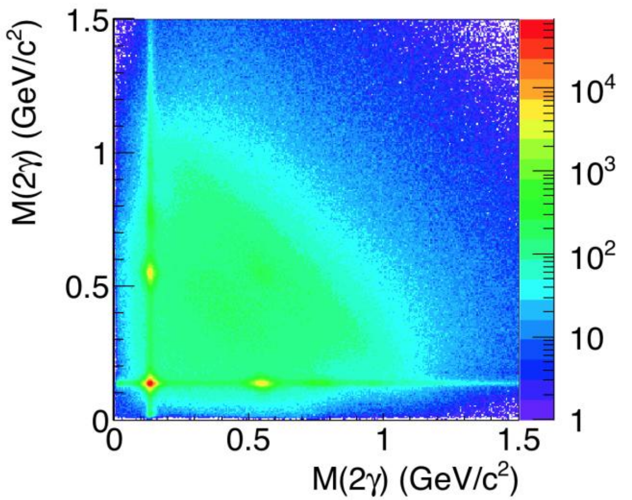
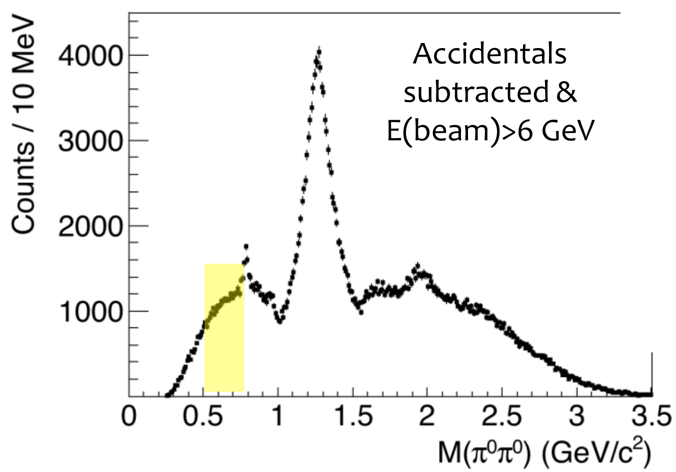
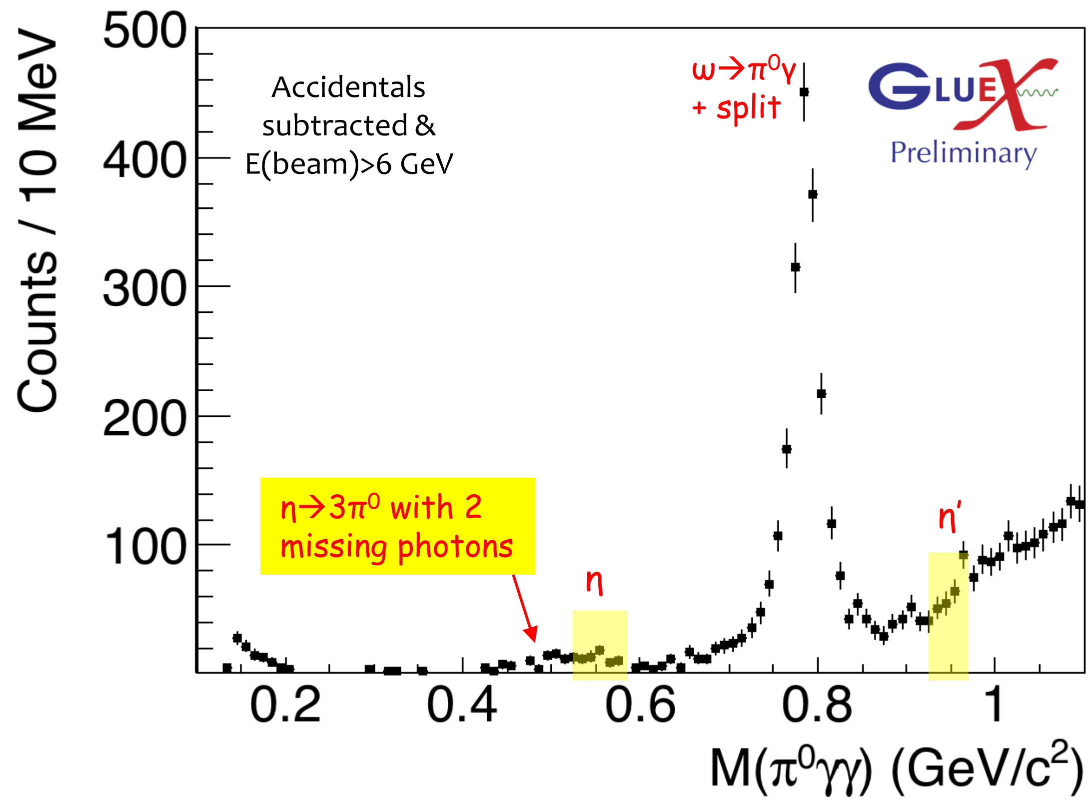




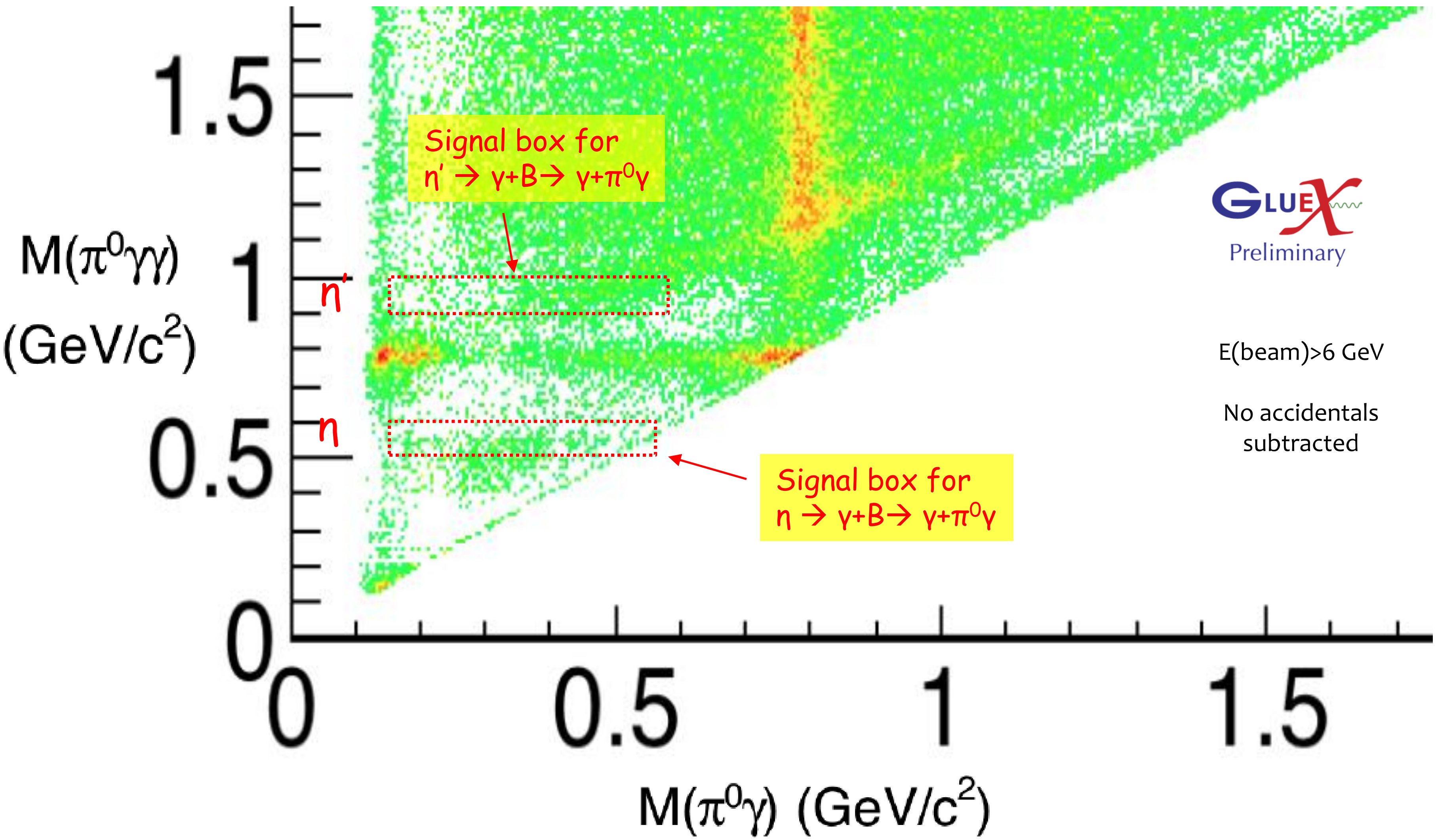
M("$\pi^0 2\gamma$") after removing $2\pi^0$ and $\pi^0\,\eta$, keeping candidates with CL > 0.01 .



No credible peak from the SM rare decays yet.
Expected signal is ~ as large as fluctuations in bkg.
Need Spring 2017 statistics.

Background Studies Using Spring 2016 Data

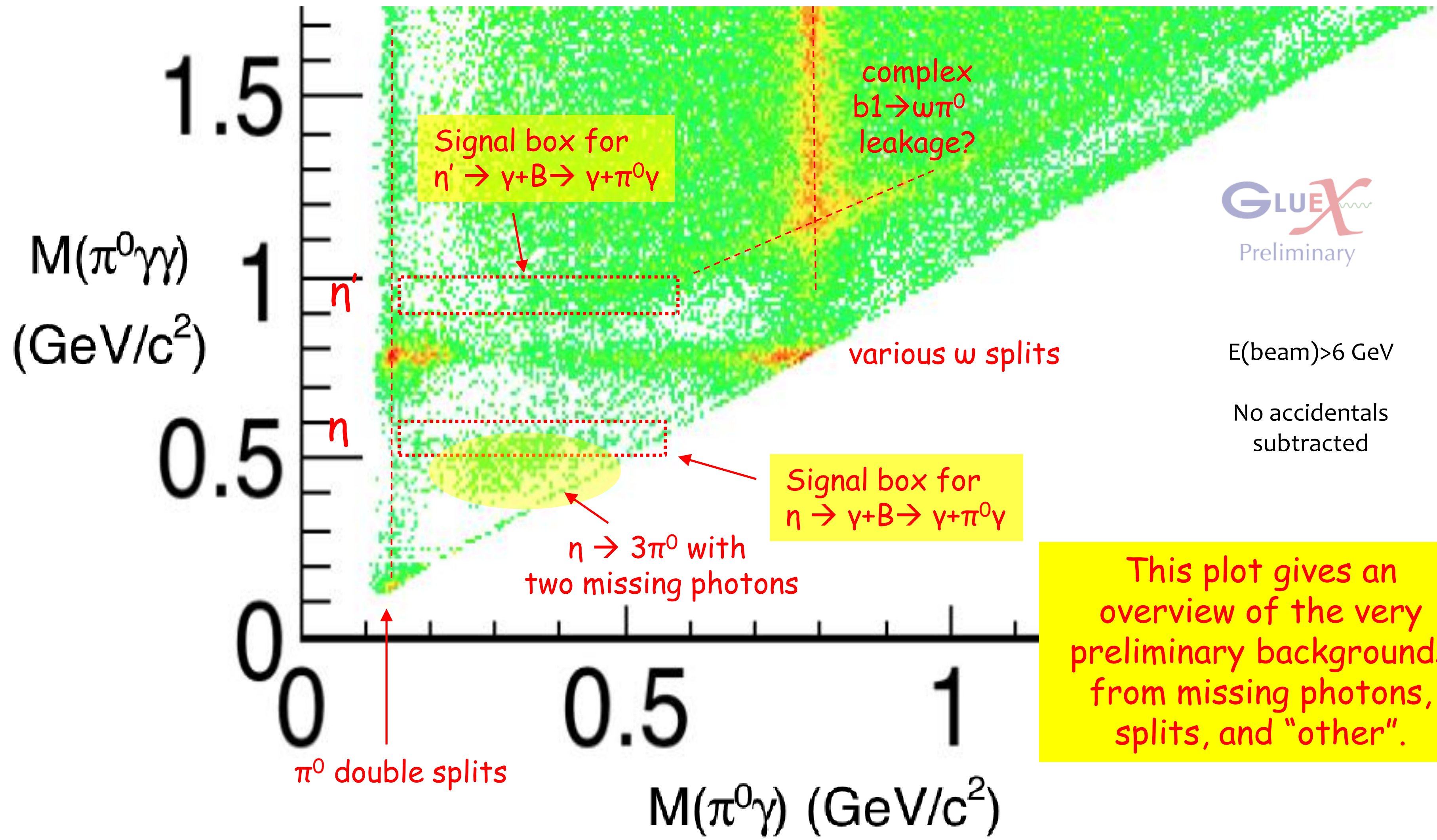
How We Will Search for $\eta^{(\prime)} \rightarrow \gamma + B$



E(beam)>6 GeV

No accidentals subtracted

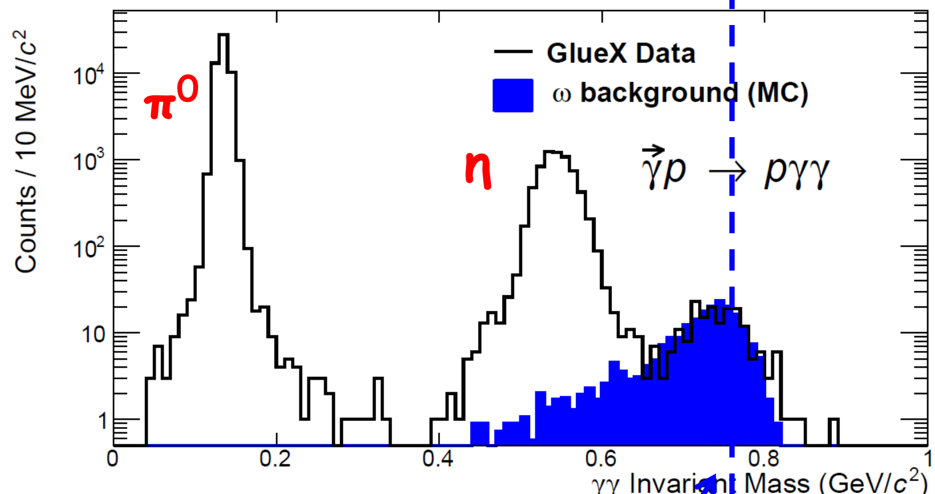
Background Studies Using Spring 2016 Data
How We Will Search for $\eta^{(\prime)} \rightarrow \gamma + B$



This plot gives an overview of the very preliminary backgrounds from missing photons, splits, and "other".

The "Missing Photon" Problem in Rare Decays of Eta→4γ

Simple example for M(2γ):



M(2γ)

$\omega \rightarrow \pi^0\gamma$ with a missing photon

The eta has a big decay branch to $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$. Photons can become "missing" due to

- going down the beam-pipe, thus becoming truly lost,

or only apparently becoming lost due to

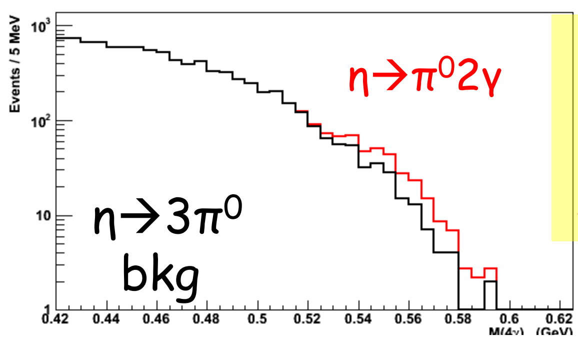
- falling below energy threshold, or

- the merging of photon showers in the EM calorimeter.

Proposed JEF Upgrade of FCAL
(installing a high resolution, lead tungstate insert into FCAL)

Lead tungstate has better energy resolution, and there is less chance of shower merging because the blocks and their Moliere radii are smaller.

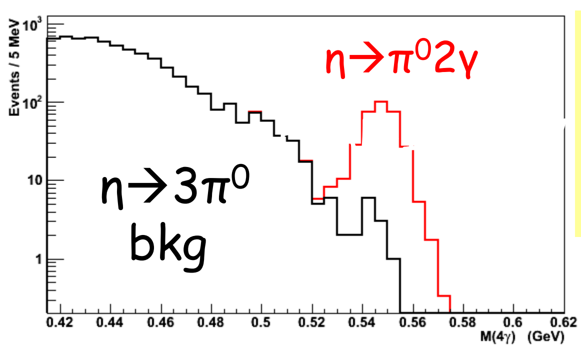
- η decay would provide stringent constraints in the 140-550 MeV range.
- Indirectly sensitive to TeV-scale physics: a positive signal would imply a new fermion with a mass up to a few TeV .



FCAL

(Pb Glass)

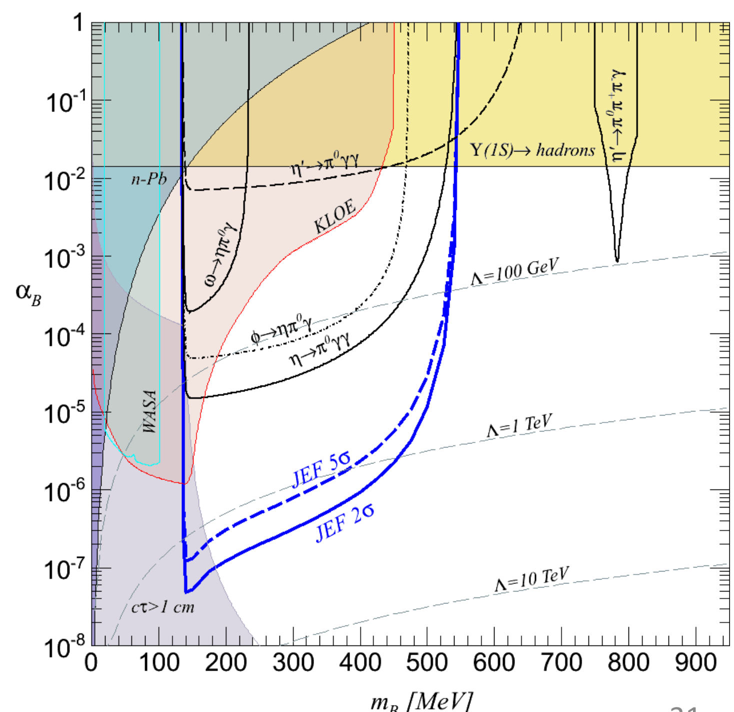
S/Bkg = 0.1



FCAL-II

(PWO insert)

S/Bkg = 10



Summary

I have overviewed lepto-phobic, dark B/ω_D boson searches in GlueX.

- The earliest results will come from a direct B/ω_D photo-production search in the formalism of Fanelli and Williams http://arxiv.org/abs/1605.07161 . Significant new constraints will soon be placed on the challenging mass range 0.5-0.9 GeV/c^2.

This is the PhD thesis of John Hardin (MIT).

Two recent GlueX PhD analyses of SDMEs will reduce interpretational uncertainties.

- We are also exploring B/ω_D production from meson decays uses Sean Tulin's formalism in http://arxiv.org/abs/1404.4370 .

We have focused on $\eta \rightarrow \gamma + B$ due to the SM control peak from the rare radiative decay, $\eta \rightarrow \pi^0 2\gamma$.

Background studies were made using Spring 2016 data by Shuang Han and Nian Qin (Wuhan U.).

We'll need to include Spring 2017 data to see the rare decay peak above background fluctuations before we can begin a preliminary search.

Upgrading the forward calorimeter would potentially allow a MUCH more sensitive exclusion for the mass range 0.15-0.5 GeV/c^2. (JEF program) The sensitivity would arguably be TeV-scale.

Acknowledgements

The Organizers and staff, for this conference and the opportunity to visit Salamanca.

For discussions, stolen slides, and all their original work:

Cris Fannelli, Mike Williams, John Hardin (MIT)

Zhenyu “Jane” Zhang, Shuang Han, Nian Qin (Wuhan U.)

Sean Tulin

Liping Gan and the JEF collaboration (Simon Taylor, Somov, etc)

… and the GlueX practice talk crew.

Extras

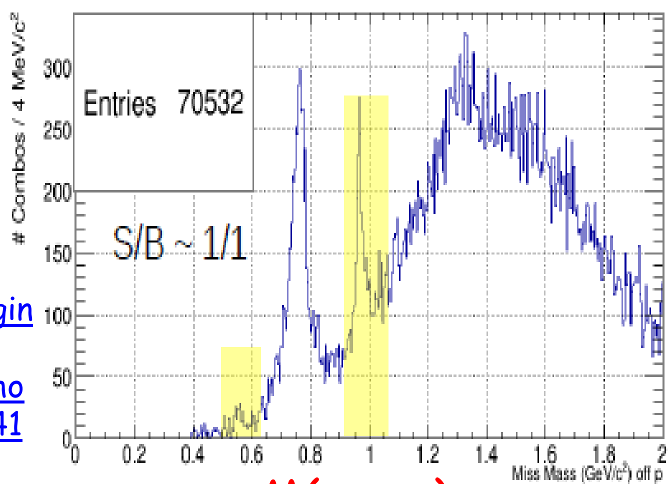
Another Dark Side: B'/ρ_D

The $B/\omega_D \rightarrow \pi^+\pi^-$ channel is generally suppressed relative to other potential branches because it's isospin violating. However, the $\pi^+\pi^-$ channel can be used to search for B'/ρ_D as outlined by Gardner et al. in http://arxiv.org/abs/1509.00050 .

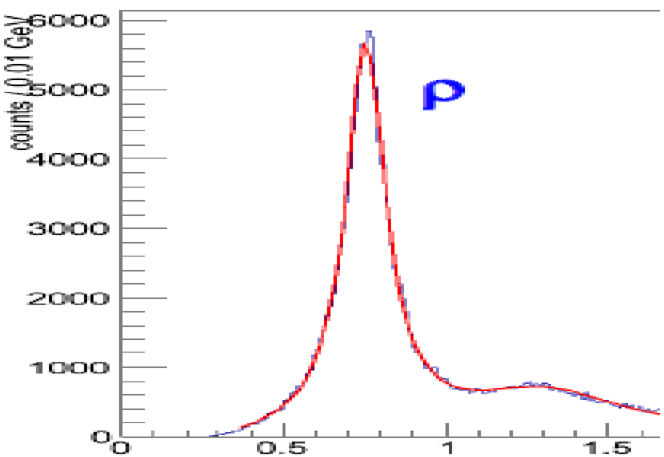
Searching in the Dalitz plots of $\eta^{(')} \rightarrow \gamma(\pi^+\pi^-)$ will suppress SM background.

Mass Range	Meson Decay	Direct Production
0.3 – 0.75+? GeV/c^2 ($\rho_D \rightarrow \pi^+\pi^-$)	$\gamma + p \rightarrow p + \underline{\eta'} \rightarrow p + \gamma(\pi^+\pi^-)$ (same channel as radiative decay being explored by Mahmoud Kamel, m_B ~ 0.3-0.75 GeV/c^2) $\gamma + p \rightarrow p + \underline{\eta} \rightarrow p + \gamma(\pi^+\pi^-)$ (m_B ~ 0.3-0.5 GeV/c^2)	$\gamma + p \rightarrow p + B \rightarrow p + \pi^+\pi^-$ (For the B/ω_D case, see red curves of Fig 3 of the MIT preprint.)

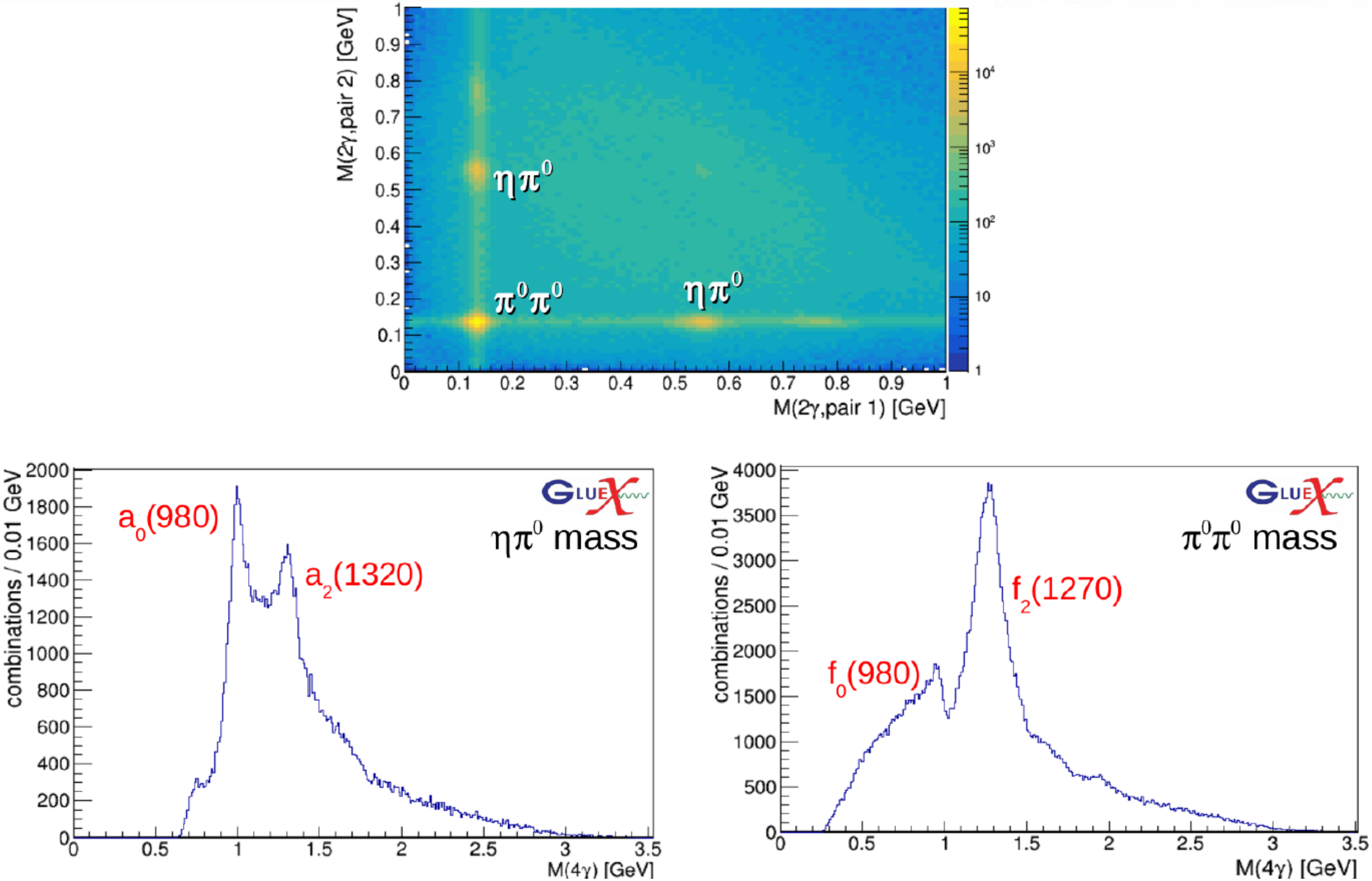
Mahmoud Kamel
http://argus.phys.uregina.ca/cgi-bin/private/DocDB/ShowDocument?docid=3041



$M(\gamma\pi^+\pi^-)$



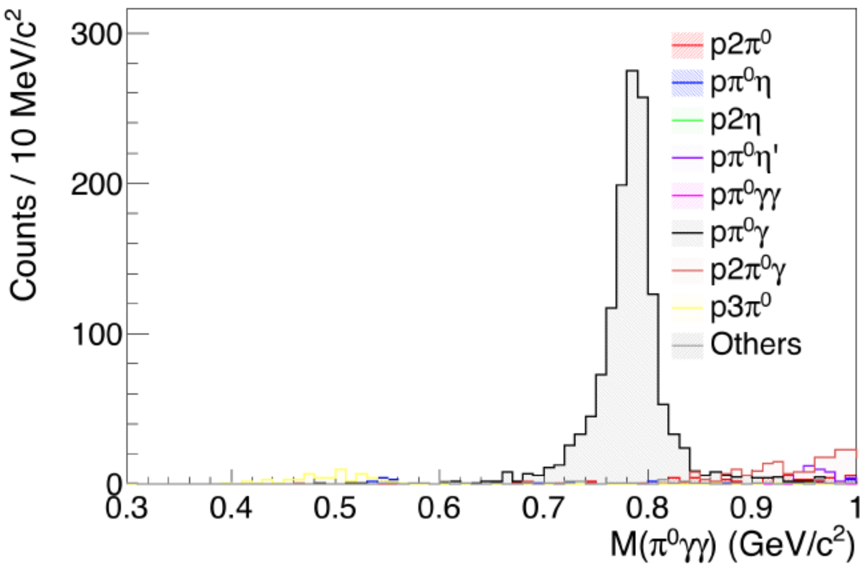
$M(\pi^+\pi^-)$

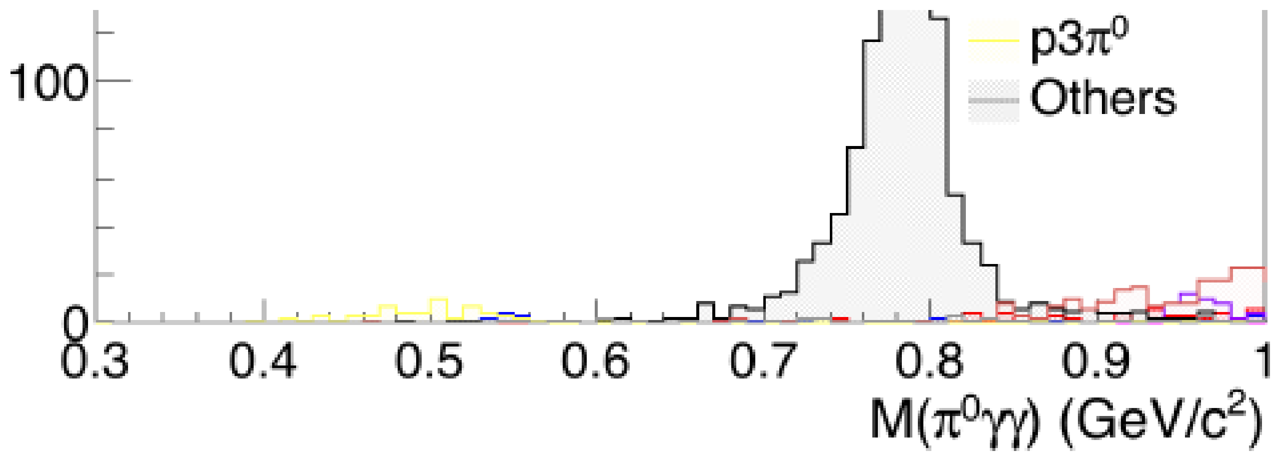


M(2γ,pair 2) [GeV]
M(2γ,pair 1) [GeV]
ηπ0
π0π0
ηπ0
combinations / 0.01 GeV
a0(980)
a2(1320)
ηπ0 mass
M(4γ) [GeV]
combinations / 0.01 GeV
f0(980)
f2(1270)
π0π0 mass
M(4γ) [GeV]

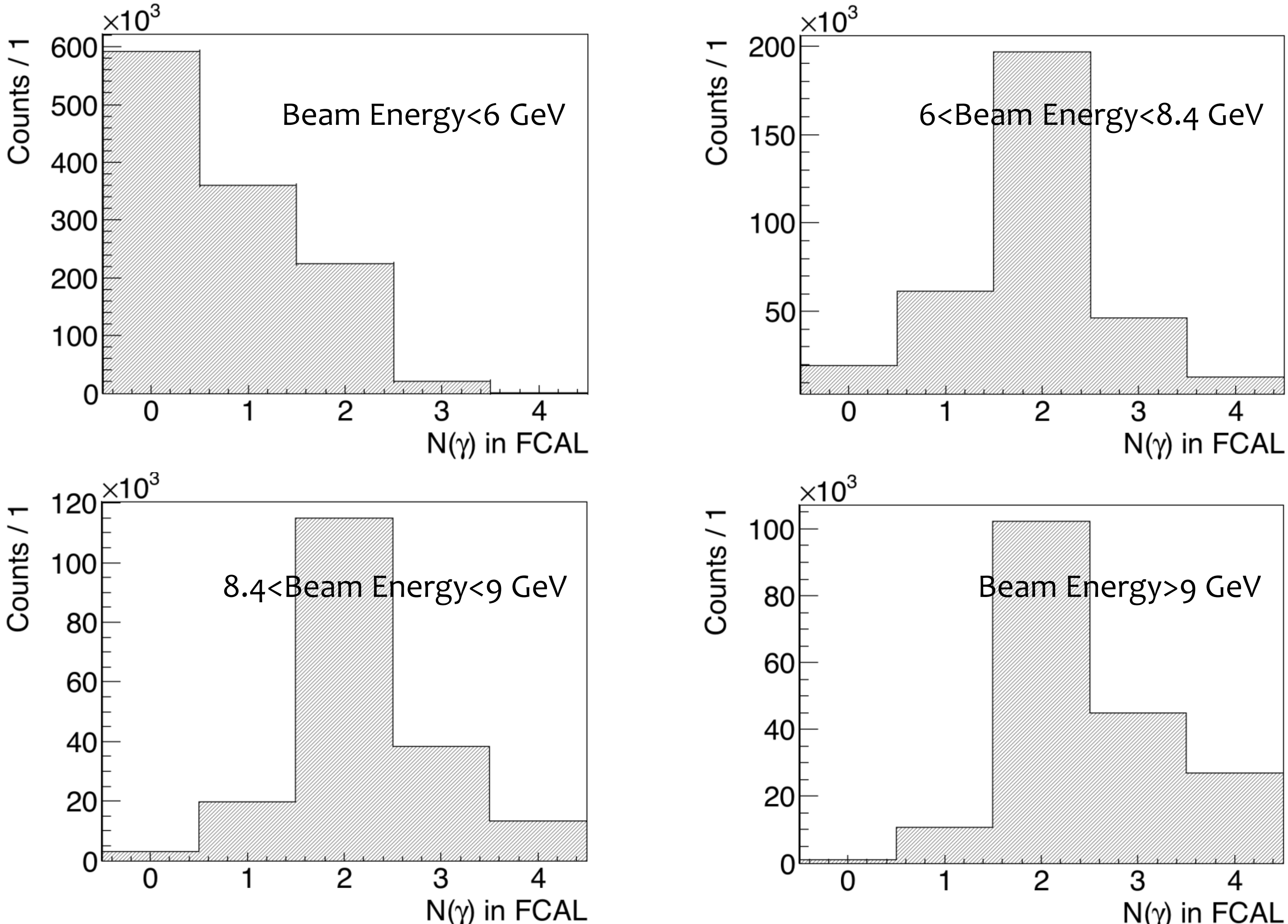
MC Bkg Study

BE>6 GeV





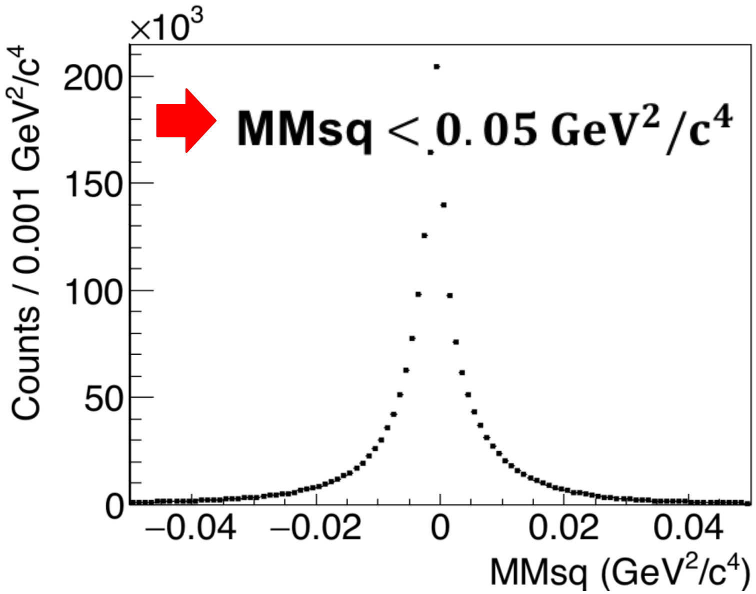
Number of Photons in FCAL

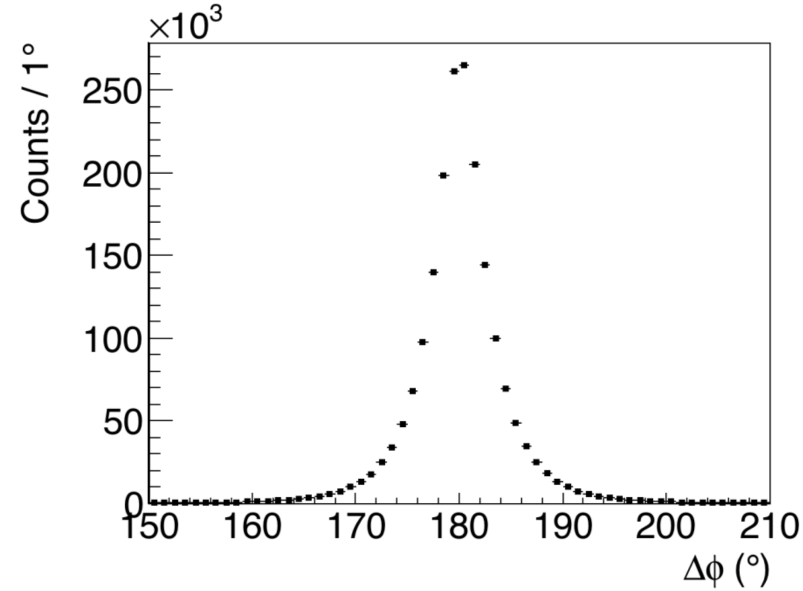


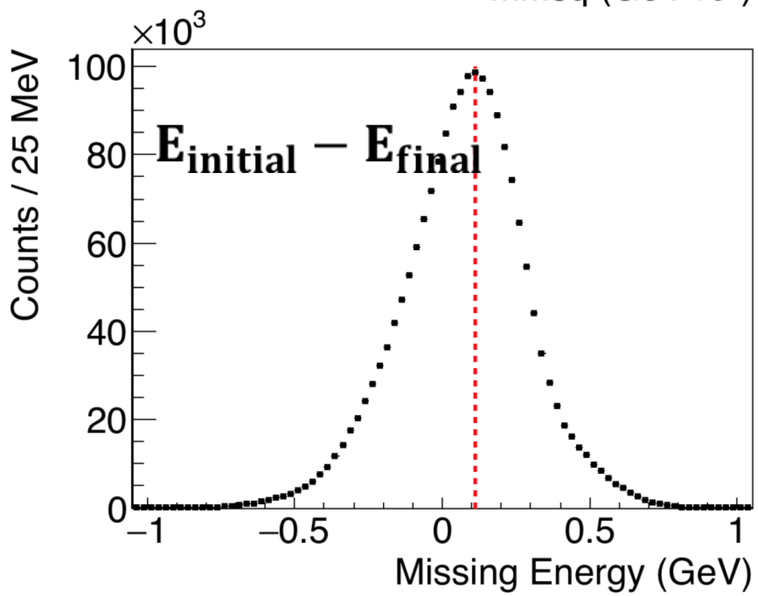
For all events

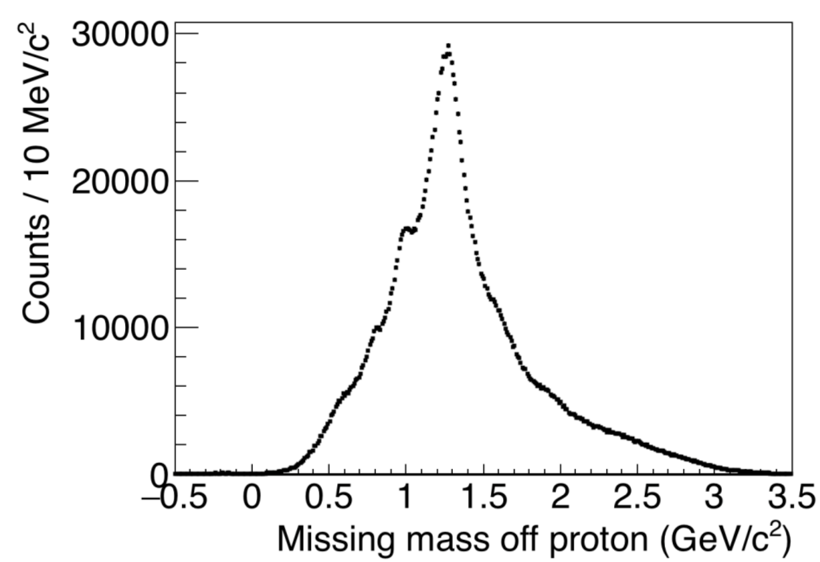
Most of the photons are in BCal when Beam Energy<6 GeV.

Event Selection Check









<ins>**For all events**</ins>

The measured energy of initial state is systematically larger than the energy of final state by about 100 MeV.