Search for the dark scalar S in $\eta(') \to S\pi^0$ at GlueX/JEF

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Introduction

Search for a MeV-GeV dark Higgs boson, S, that couples to quarks and gluons. Initially proposed by B. Batell et al. (arxiv:1812.05103) and refreshed by L. Gan et al. (arxiv:2007.00664)
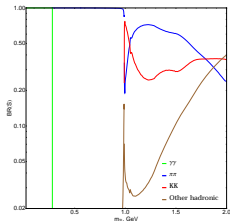
- B. Batell et al.:
  - For, $m_S < 2m_\pi$, $S \to \gamma\gamma$
  - For, $m_S \geq 2m_\pi$, $S \to$ hadrons and in particular $\pi\pi$

- L. Gan et al.:
  - For, $m_S < 2m_\pi$
    - ★ $S \to \gamma\gamma$
    - ★ If $m_S \geq 2m_e$, $S \to e^+e^-$
    - ★ If $m_S \geq 2m_\mu$, $S \to \mu^+\mu^-$
  - For, $m_S \geq 2m_\pi$, $S \to$ hadrons and in particular $\pi\pi$

- B. Batell et al.

- L. Gan et al.
- Different coupling for each decay mode
- Branching ratio (BR)
$$= \frac{\Gamma(\alpha_S^{\gamma\gamma})}{\Gamma(\alpha_S^{\gamma\gamma}) + \Gamma(\alpha_S^{e^+e^-}) + \Gamma(\alpha_S^{\mu^+\mu^-}) + \ldots}$$
- Γ partial decay width, $\Gamma \propto \alpha_S^2$
- Limit on $\alpha_S \times \mathrm{BR}$

Numbers of expected events and UL on observed events

Relation between number of expected events, $N_{th}{}^S$, and of UL on observed events, N_{obs}^{UL}

- $N_{th}{}^S = N_\eta \cdot \mathcal{B}(\eta \to S\pi^0)$
  - N_η: number of η; $N_\eta = \sigma \cdot \mathcal{L}$
    - ★ σ: cross-section
    - ★ $\mathcal{L}$: integrated luminosity
  - $\mathcal{B}$: branching ratio
- $N_{obs}^{UL} = N_{th}{}^S \cdot \epsilon$
  - ϵ: detection efficiency

Then,

- $\mathcal{B}(\eta \to S\pi^0) = \frac{N_{obs}^{UL}}{\epsilon \cdot N_\eta}$

So, for $S \to \gamma\gamma$

- $\mathcal{B}(\eta \to S\pi^0) = \frac{N_{obs}^{UL}}{\epsilon \cdot \mathcal{B}(S \to \gamma\gamma) \cdot N_\eta}$

- $\mathcal{B}(\eta \to S\pi^0) \simeq 0.056 \left(\frac{g_u}{7 \times 10^{-4}} \right)^2$ (B. Batell et al.)

- $\alpha_S = g_u^2/(4\pi)$

- $\alpha_s^{UL} = \frac{1}{4\pi} \frac{(7 \times 10^{-4})^2}{0.056} \frac{N_{obs}^{UL}}{\epsilon \cdot \mathcal{B}(S \to \gamma\gamma) \cdot N_\eta}$

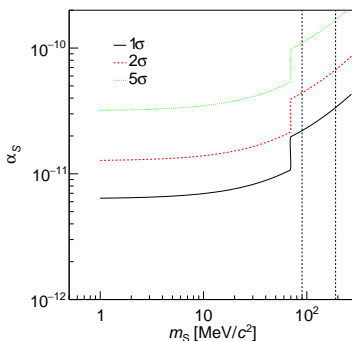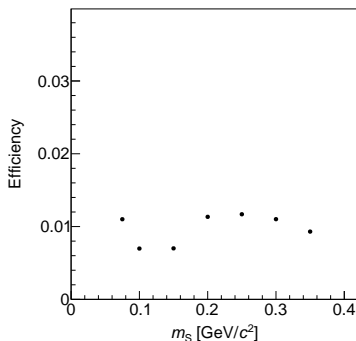# Sensitivity

Is defined as $N_{sig} = x\sqrt{N_{bkg}}$ where:

- N_{sig}, number of signal for a given m_S and window corresponding to $\Delta m_S = 2.5\sigma$ (σ is the signal resolution)
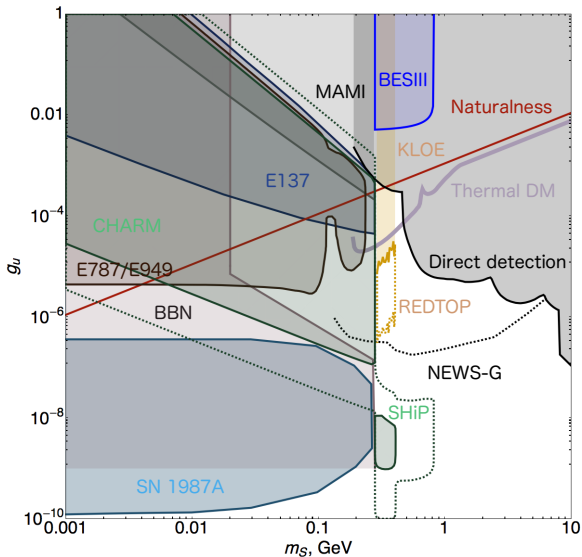- N_{bkg}, number of background for the same m_S and window
- x is the significance in "sigma" unit

Then by replacing N_{obs}^{UL} by N_{sig}

- $\alpha_s^{Sensitivity} = \frac{1}{4\pi} \frac{(7\times 10^{-4})^2}{0.056} \frac{x\sqrt{N_{bkg}}}{\epsilon \cdot \mathcal{B}(S\to\gamma\gamma)\cdot N_\eta}$
- $N_\eta = 5\times 10^7$ η

Comparison to existing bound and future experiments

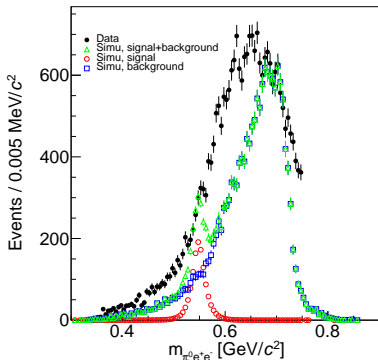For 100 days, $g_u \sim 7 \times 10^{-5}$

Selection critiria for $S \to e^- e^+$

- Kinematic fit: $\gamma p \to \eta p$ and $\eta \to \pi^0 e^- e^+$
  - η mass not used as constraint
  - π^0 mass not used as constraint

- Based on 11 variables (not yet optimized):
  - χ^2 (< 3)
  - Elasticity
  - Coplanarity between η and p
  - Mass conservation
  - Extra energy $(= 0)$
  - Unused tracks $(= 0)$
  - π^0 invariant mass
  - Cluster number below 4.5^o(?)
  - Vertex z and r
  - Proton momentum

Invariant mass distribution

After selection critiria applied

- No cut on cluster number below 4.5^o(?)
- Signal $= \eta \to \pi^0 e^- e^+$ (BR $< 10^{-5}$)
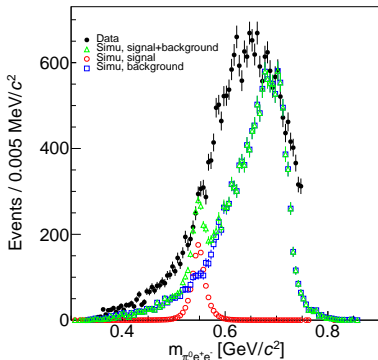- Background $= \omega \to \pi^0 e^- e^+$ (BR $= 7.7 \times 10^{-4}$)

- Fit to match distribution for mass above 700 MeV
- Missing contribution possibly due to $\omega \to \pi^0 \gamma$ (BR=0.0828) with γ conversion into $e^- e^+$ in target ($\sim 1\%$ probability)

Invariant mass distribution

After selection critiria applied

- One or more cluster below 4.5^o
- Signal $= \eta \to \pi^0 e^- e^+$ (BR $< 10^{-5}$)
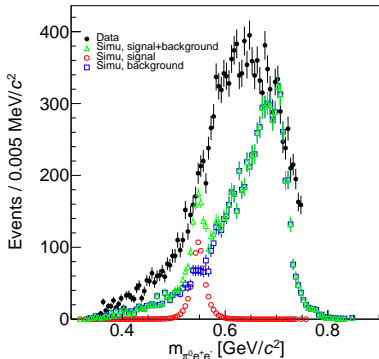- Background $= \omega \to \pi^0 e^- e^+$ (BR $= 7.7 \times 10^{-4}$)

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Invariant mass distribution

After selection critiria applied

- Two or more cluster below 4.5^{o}
- Signal $= \eta \to \pi^0 e^- e^+$ (BR $< 10^{-5}$)
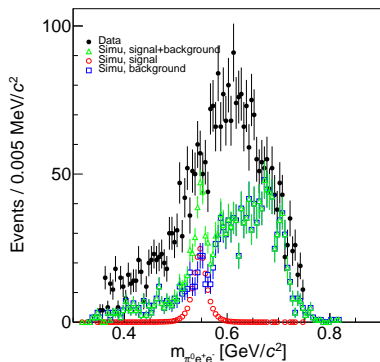- Background $= \omega \to \pi^0 e^- e^+$ (BR $= 7.7 \times 10^{-4}$)

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Invariant mass distribution

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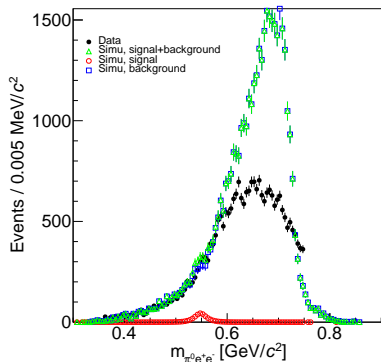
Remark on ω simulation

- There is no card available for $\omega \to \pi^0 e^- e^+$ in gen_amp
- I used genEtaRegge and evtgen with Belle (II) decay file
- Not sure if it is correct

```
#
Decay omega
0.892000000 pi-      pi+       pi0                    OMEGA_DALITZ; #[Reconstructed PDG2011]
0.082800000 pi0      gamma                            VSP_PWAVE; #[Reconstructed PDG2011]
0.015300000 pi-      pi+                              VSS; #[Reconstructed PDG2011]
0.000460000 eta      gamma                            VSP_PWAVE; #[Reconstructed PDG2011]
0.000770000 pi0      e+        e-                     PHOTOS PHSP; #[Reconstructed PDG2011]
0.000130000 pi0      mu+       mu-                    PHOTOS PHSP; #[Reconstructed PDG2011]
0.00150    pi+  pi- gamma                  PHSP;
0.000066000 pi0      pi0       gamma                  PHSP; #[Reconstructed PDG2011]
0.00050    pi+ pi- pi+ pi-                 PHSP;
0.000072800 e+        e-                             PHSP;  #[New mode added] #[Reconstructed PDG2011]
0.000090000 mu+      mu-                             PHSP;  #[New mode added] #[Reconstructed PDG2011]
Enddecay
#
```

Invariant mass distribution

After selection critiria applied

- No cut on cluster number below $4.5^{o}(?)$
- Signal $= \eta \to \pi^0 e^- e^+$ (BR $< 10^{-5}$)
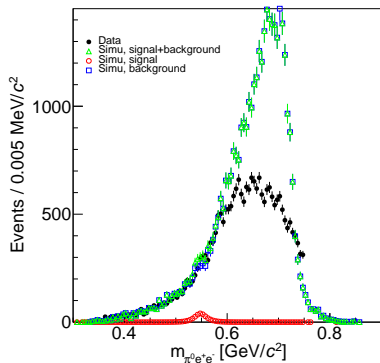- Background $= \omega \to \pi^0 e^- e^+$ (BR $= 7.7 \times 10^{-4}$)

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Invariant mass distribution

After selection critiria applied

- One or more cluster below 4.5^{o}
- Signal $= \eta \rightarrow \pi^0 e^- e^+$ (BR $< 10^{-5}$)
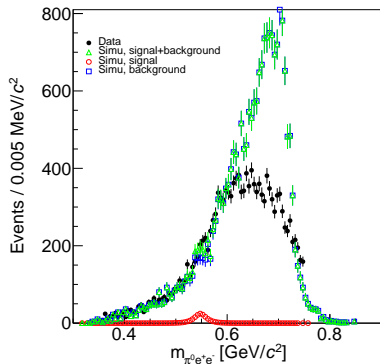- Background $= \omega \rightarrow \pi^0 e^- e^+$ (BR $= 7.7 \times 10^{-4}$)

- Fit to match distribution for mass below 700 MeV

Invariant mass distribution

After selection critiria applied

- Two or more cluster below 4.5^o
- Signal $= \eta \rightarrow \pi^0 e^- e^+$ (BR $< 10^{-5}$)
- Background $= \omega \rightarrow \pi^0 e^- e^+$ (BR $= 7.7 \times 10^{-4}$)

- Fit to match distribution for mass below 700 MeV

Invariant mass distribution

After selection critiria applied

- Three or more cluster below 4.5°
- Signal = $\eta \to \pi^0 e^- e^+$ (BR < 10^{-5})
- Background = $\omega \to \pi^0 e^- e^+$ (BR = 7.7×10^{-4})
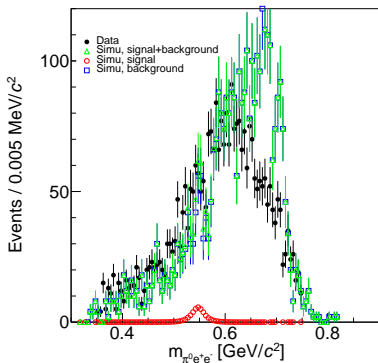
- Fit to match distribution for mass below 700 MeV
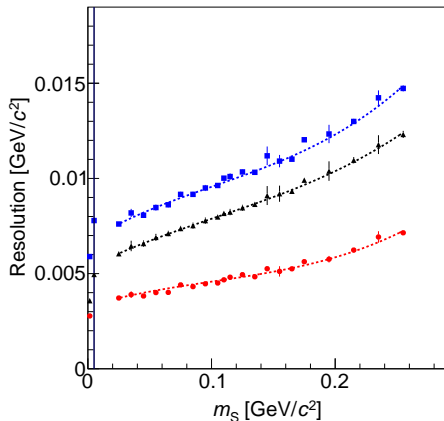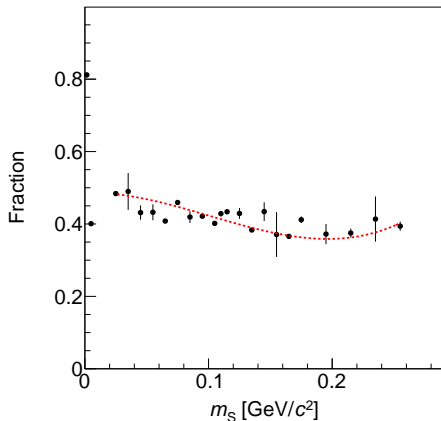
Simulation of $S \to e^- e^+$

23 masses simulated between di-electron threshold and di-pion threshold
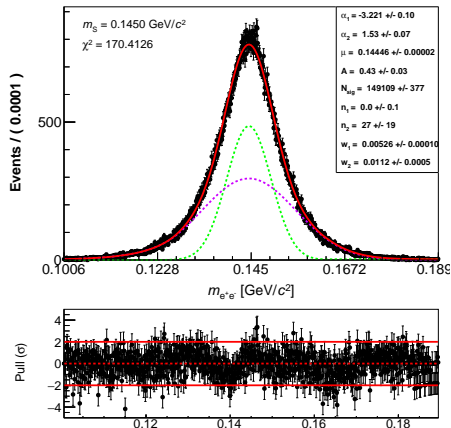
- Signal PDF corresponds to 2 Crystal Balls with common mean
- Used Jared's script to parametrize each fit parameter as function of the mass
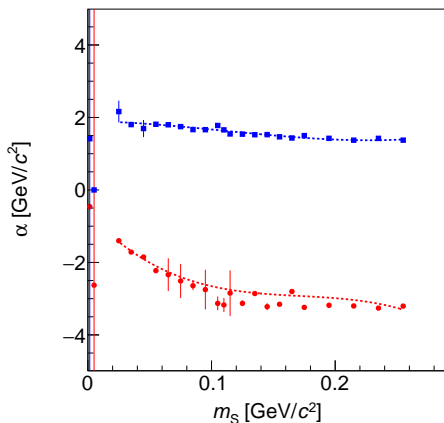
Simulation of $S \to e^- e^+$

23 masses simulated between di-electron threshold and di-pion threshold

- Signal PDF corresponds to 2 Crystal Balls (CBs) with common mean
- Used Jared's script to parametrize each fit parameter as function of the mass
- Red: CB 1 width
- Blue: CB 2 width
- Black: weighted width

Simulation of $S \to e^- e^+$

23 masses simulated between di-electron threshold and di-pion threshold

- Signal PDF corresponds to 2 Crystal Balls (CBs) with common mean
- Used Jared's script to parametrize each fit parameter as function of the mass
- CB 1 proportion
- CB 2 proportion = 1 - fraction
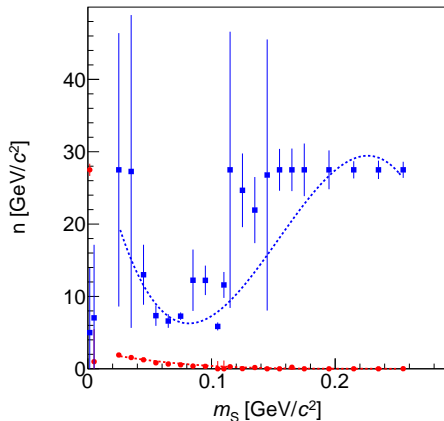
Simulation of $S \to e^- e^+$

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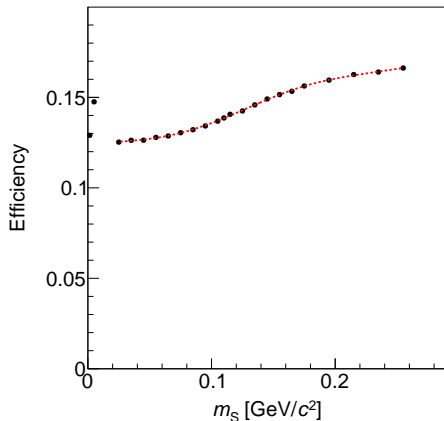# Simulation of $S \rightarrow e^- e^+$

23 masses simulated between di-electron threshold and di-pion threshold

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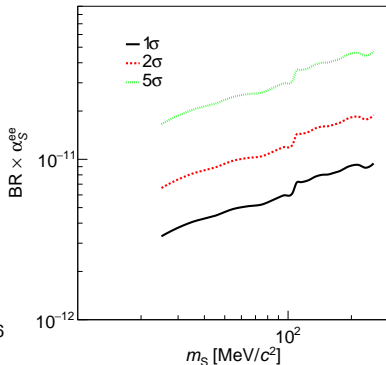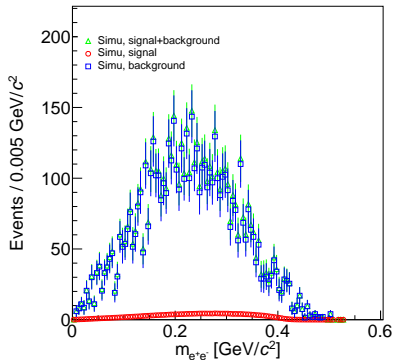# Simulation of $S \to e^- e^+$

23 masses simulated between di-electron threshold and di-pion threshold

- Signal PDF corresponds to 2 Crystal Balls (CBs) with common mean
- Used Jared's script to parametrize each fit parameter as function of the mass
- Calculated detection efficiency

Expected sensitivity

- Take solution (2) with fit to match distribution for mass below 700 MeV
- Di-electron invariant mass after cut on $m_{\pi^0 e^+ e^-}$ between 480 and 600 MeV
- $\sqrt{N_{\mathrm{bkg}} \times \frac{\mathcal{L}_{\mathrm{JEF}}}{\mathcal{L}_{\mathrm{Spring2017}}}}$ for a given m_S and window corresponding to $\Delta m_S = 2.5\sigma$ (σ is the signal resolution)

Conclusion

To be continued