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

Igal Jaeglé

Thomas Jefferson National Accelerator Facility

for the GlueX Collaboration

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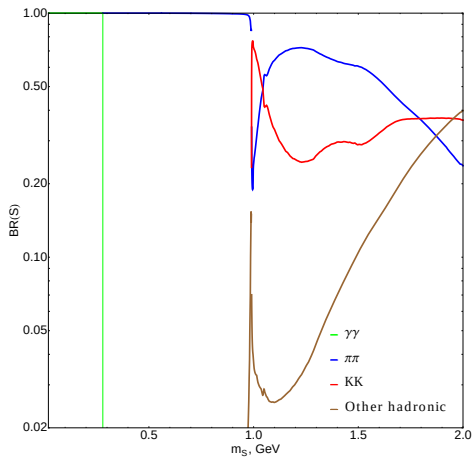
Introduction

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, $\mathrm{N_{th}}^{S}$, and of UL on observed events, $\mathrm{N_{obs}^{UL}}$

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

Then,

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

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

- $\mathcal{B}(\eta \to S\pi^0) = \frac{\mathrm{N_{obs}^{UL}}}{\epsilon \cdot \mathcal{B}(S \to \gamma\gamma) \cdot \mathrm{N}_\eta}$
- $\mathcal{B}(\eta \to S\pi^0) \simeq 0.056 \left(\frac{g_u}{7\times10^{-4}}\right)^2$ (B. Batell et al.)
- $\alpha_S = g_u^2/(4\pi)$
- $\alpha_s^{\mathrm{UL}} = \frac{1}{4\pi} \frac{(7\times10^{-4})^2}{0.056} \frac{\mathrm{N_{obs}^{UL}}}{\epsilon \cdot \mathcal{B}(S \to \gamma\gamma) \cdot \mathrm{N}_\eta}$

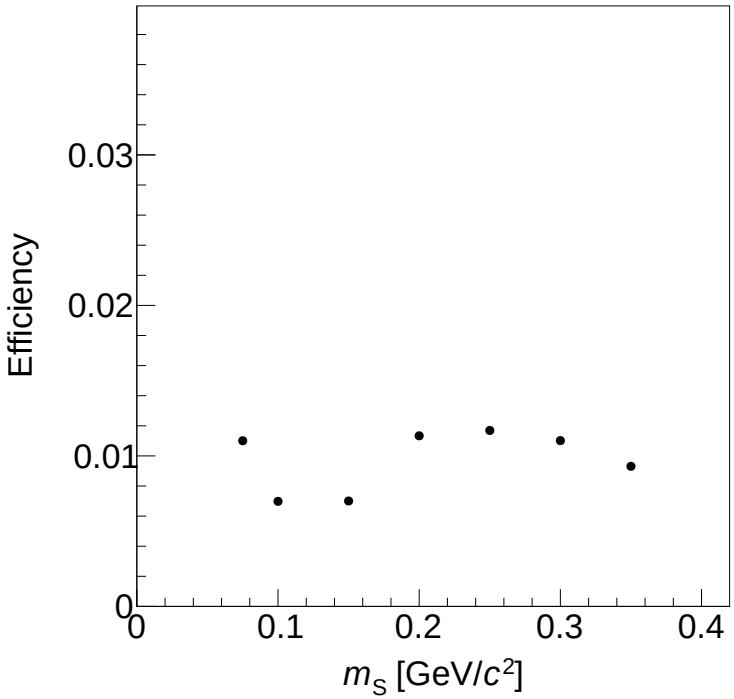
Sensitivity

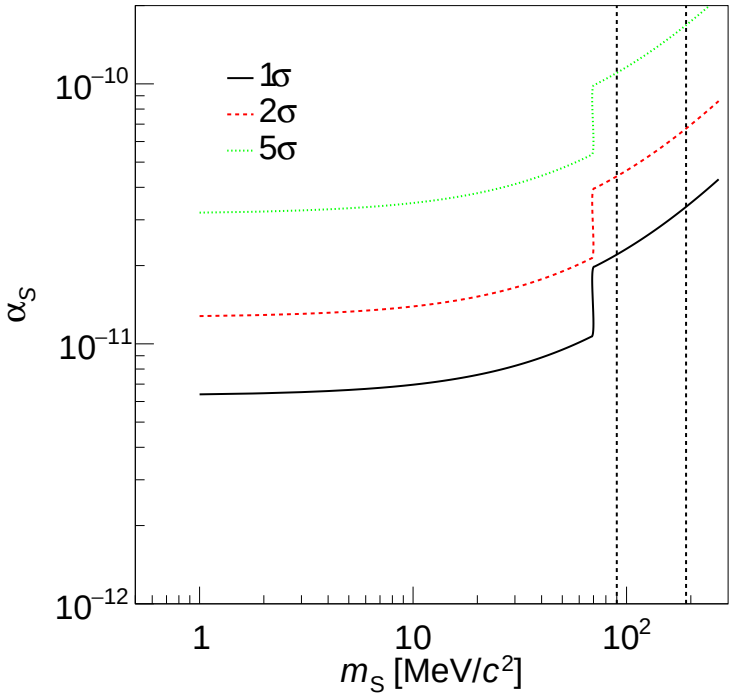
Is defined as $\mathrm{N_{sig}} = x\sqrt{\mathrm{N_{bkg}}}$ where:

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

Then by replacing $\mathrm{N_{obs}^{UL}}$ by $\mathrm{N_{sig}}$

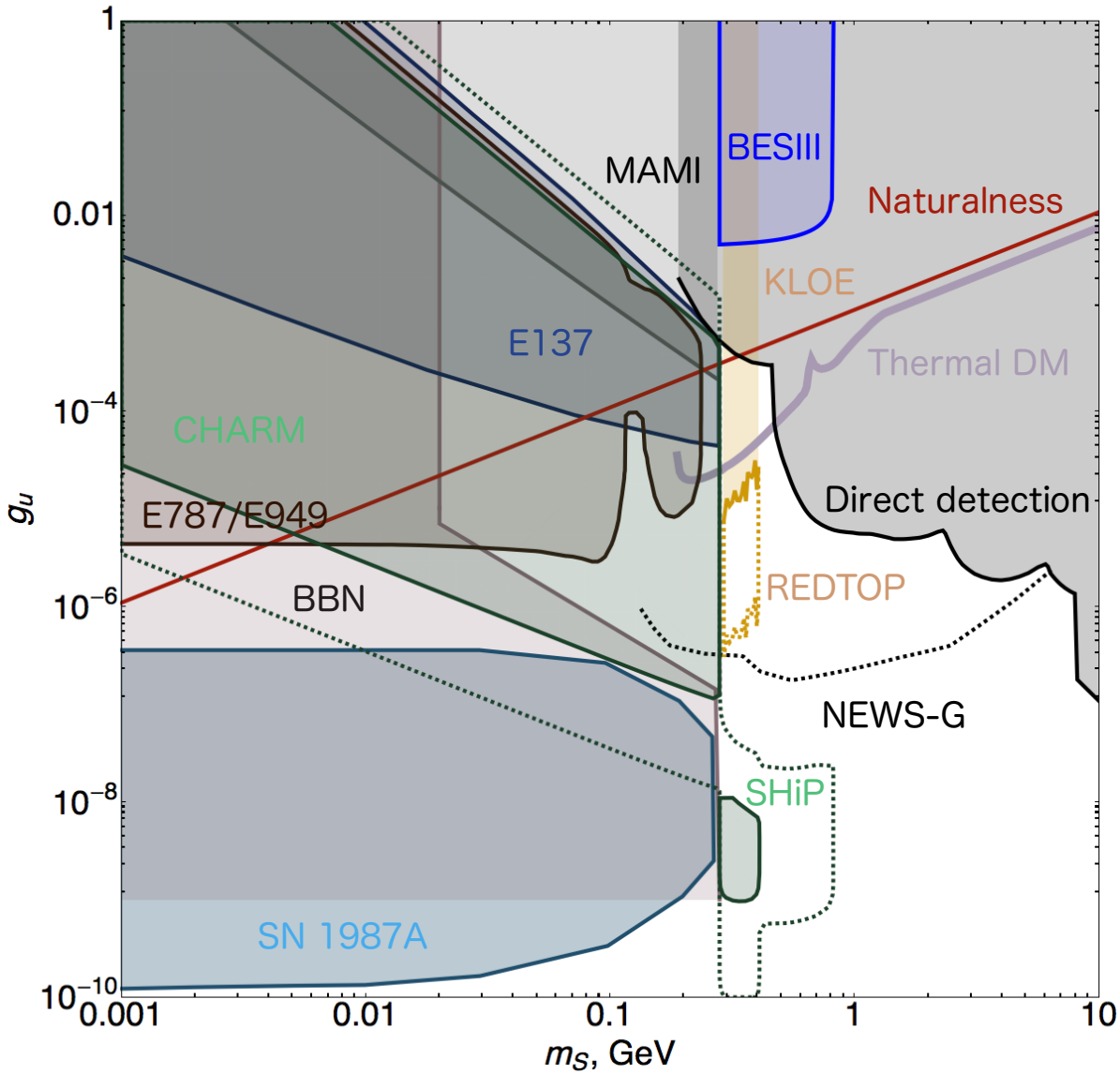
- $\alpha_s^{\mathrm{Sensitivity}} = \frac{1}{4\pi}\frac{\left(7\times10^{-4}\right)^2}{0.056}\frac{x\sqrt{\mathrm{N_{bkg}}}}{\epsilon\cdot\mathcal{B}(S\to\gamma\gamma)\cdot\mathrm{N}_\eta}$
- $\mathrm{N}_\eta = 5 \times 10^7\ \eta$





Comparison to existing bound and future experiments

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



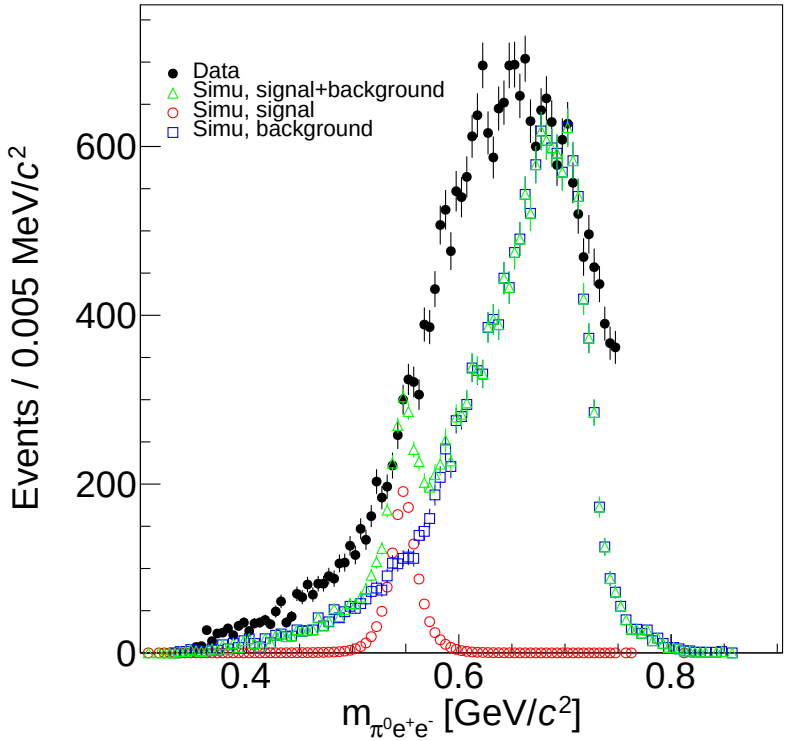
Selection critiria for $S \rightarrow e^- e^+$

- Kinematic fit: $\gamma p \rightarrow \eta p$ and $\eta \rightarrow \pi^0 e^- e^+$
  - 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
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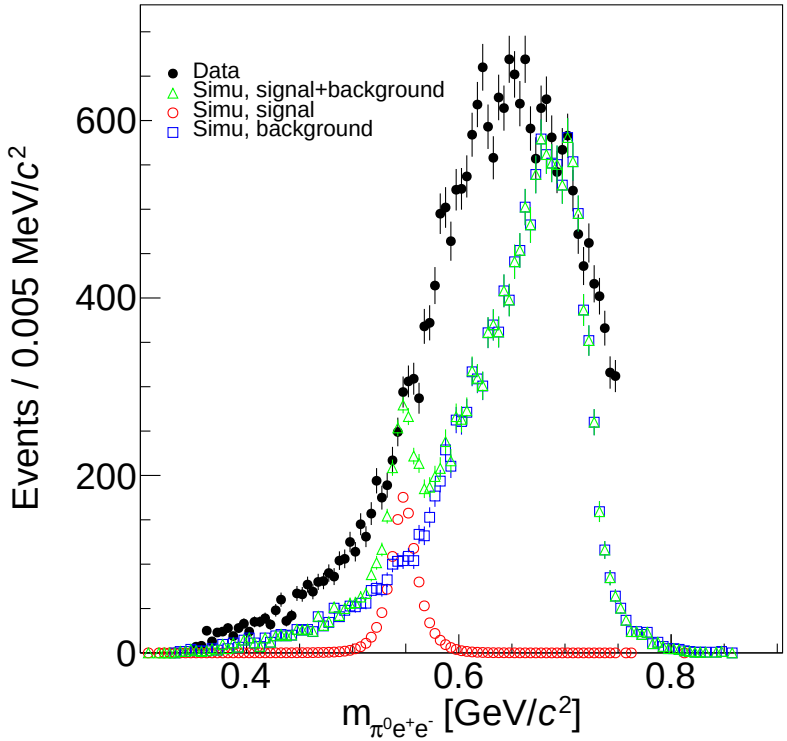

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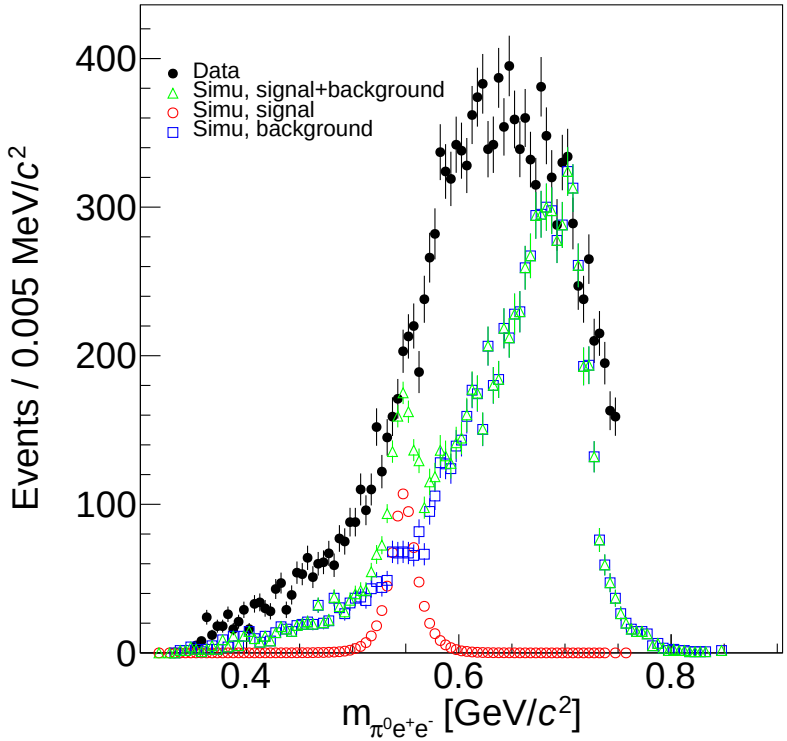

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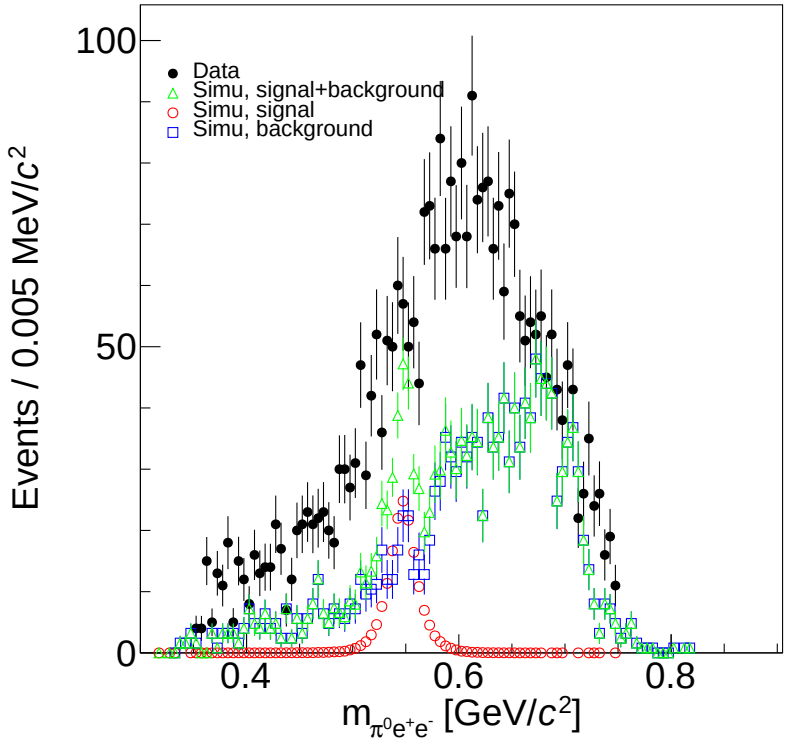

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Remark on ω simulation

- 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

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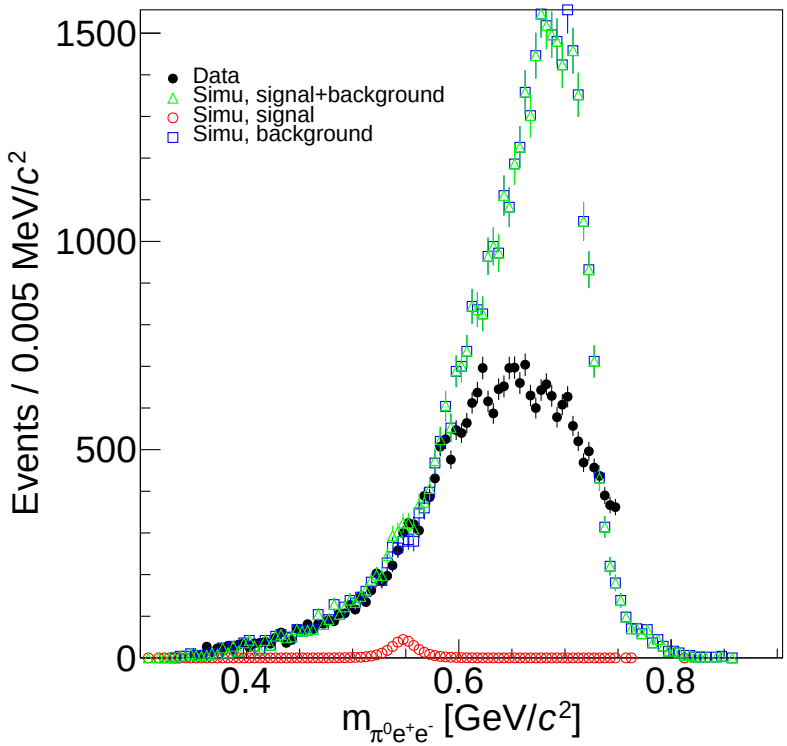

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After selection critiria applied

- One or more cluster below 4.5^o
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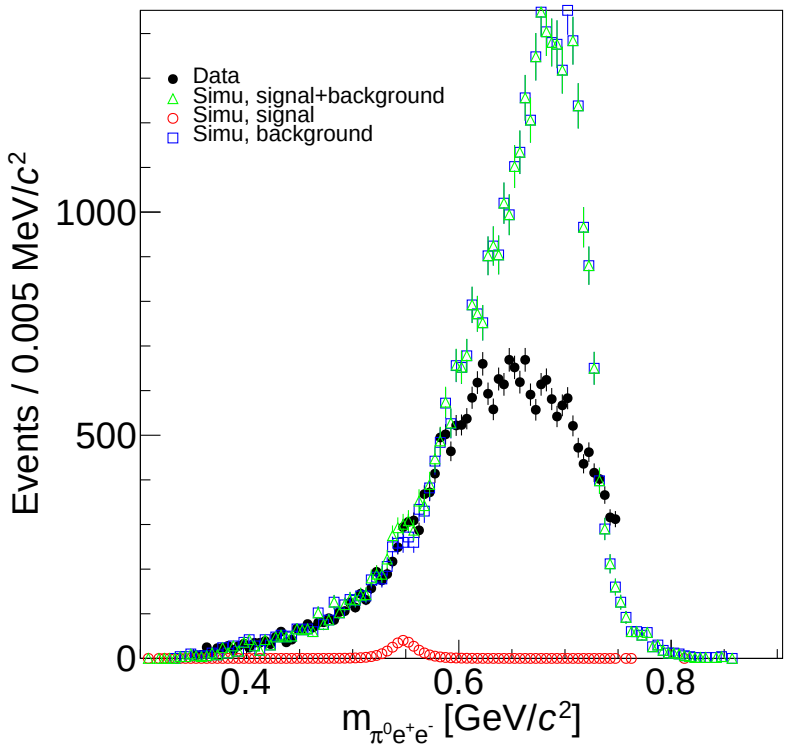

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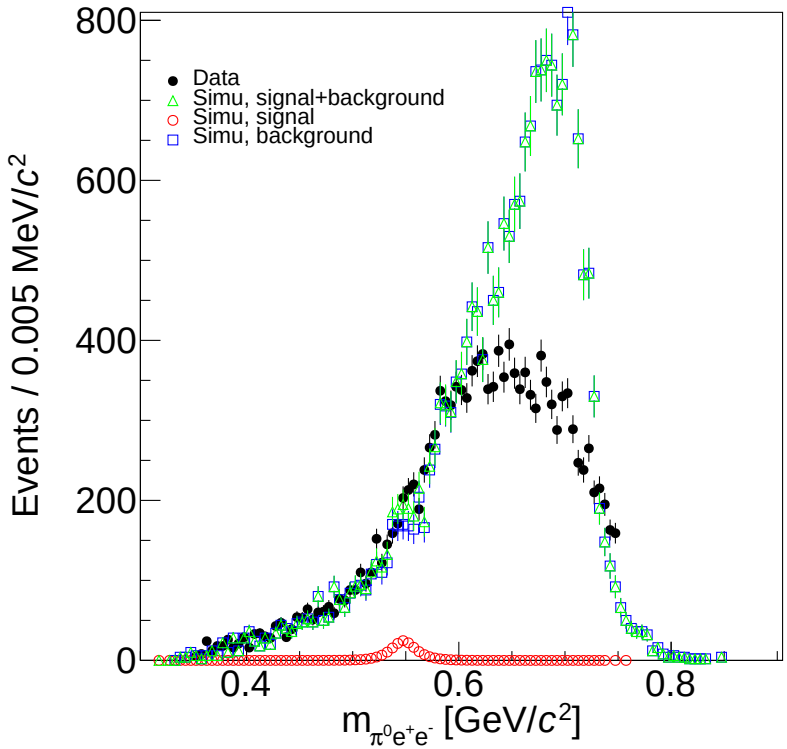

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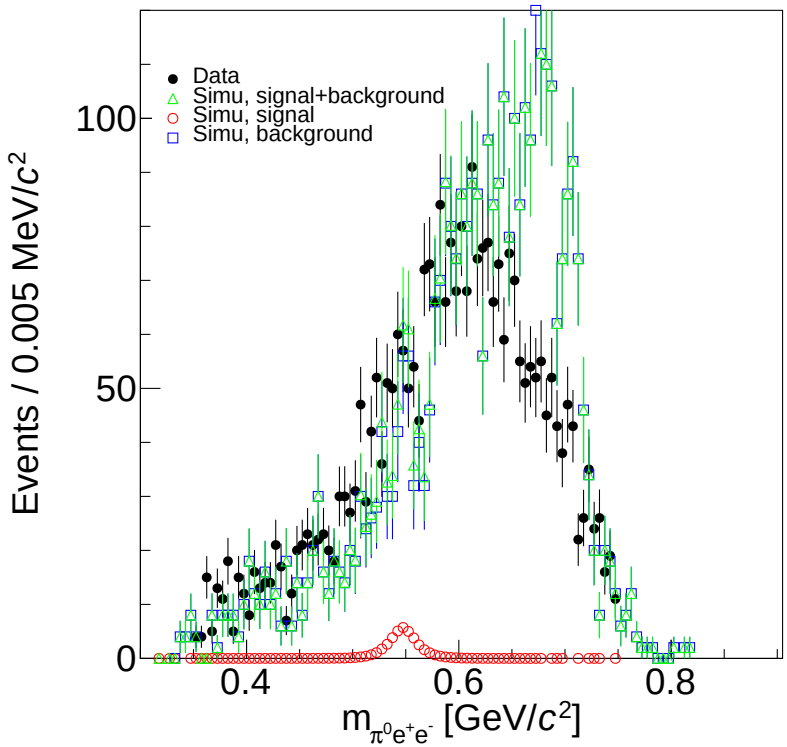
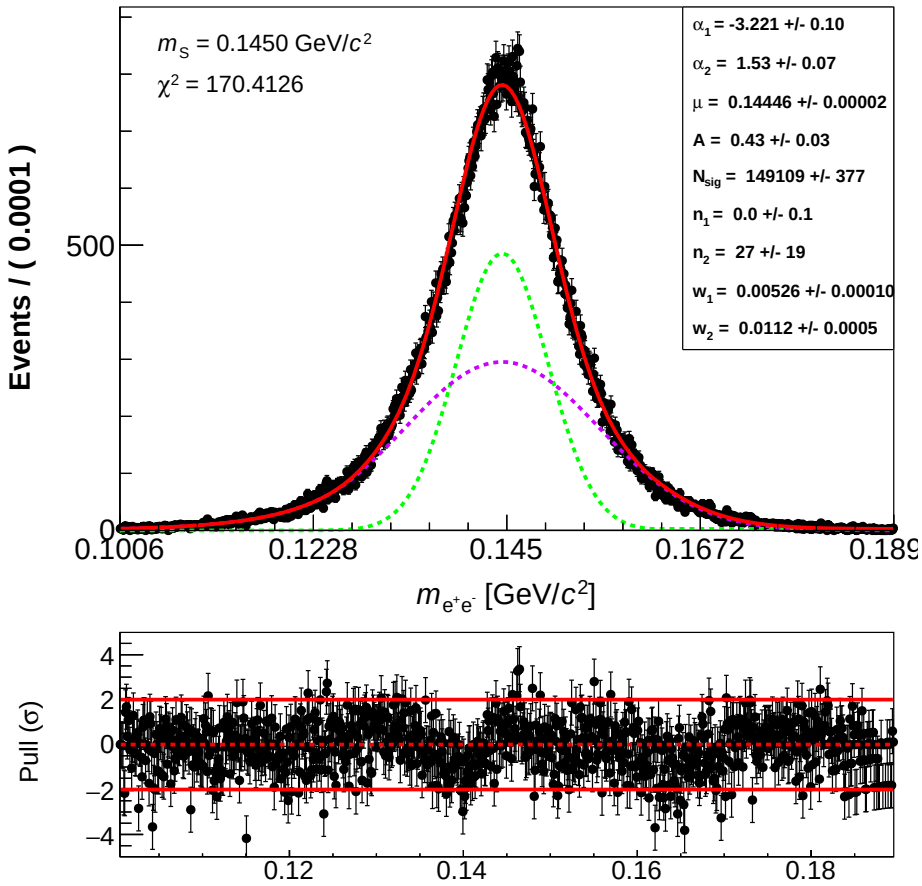


- Fit to match distribution for mass below 700 MeV

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

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

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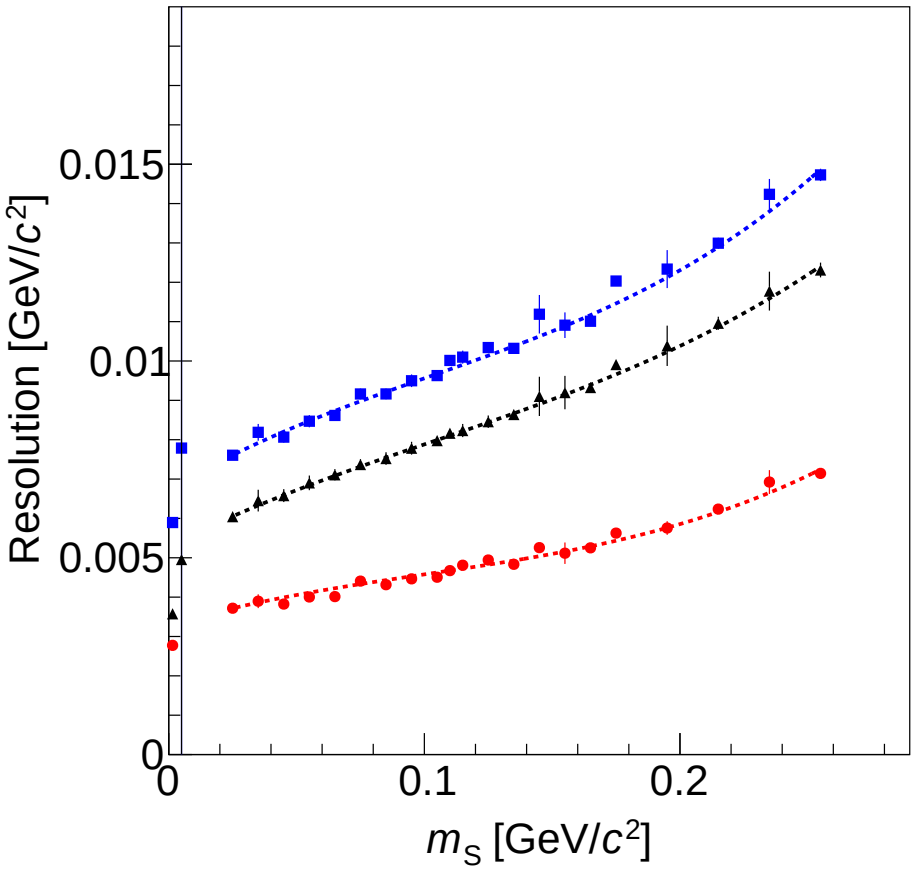
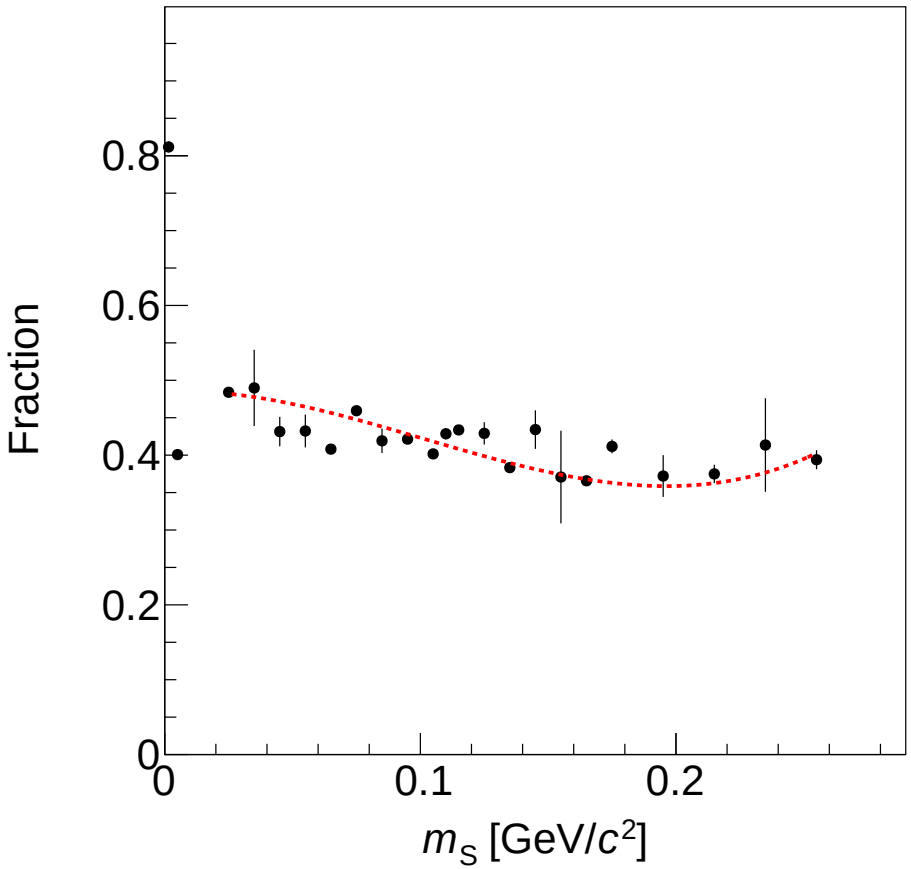


- Signal PDF corresponds to 2 Crystal Balls (CBs) with common mean
- Used Jared's script to parametrize each fit parameter as function of the mass
- Red: CB 1 width
- Blue: CB 2 width
- Black: weighted width

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

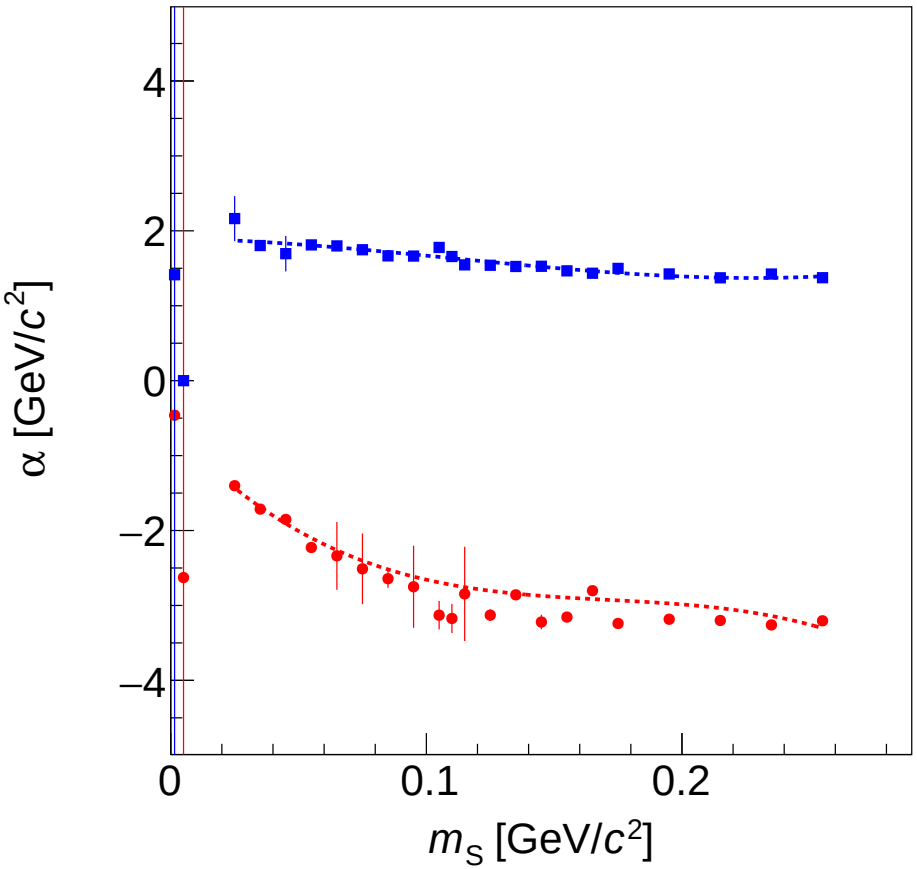
23 masses simulated between di-electron threshold and di-pion threshold



- 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 $S \rightarrow e^- e^+$

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



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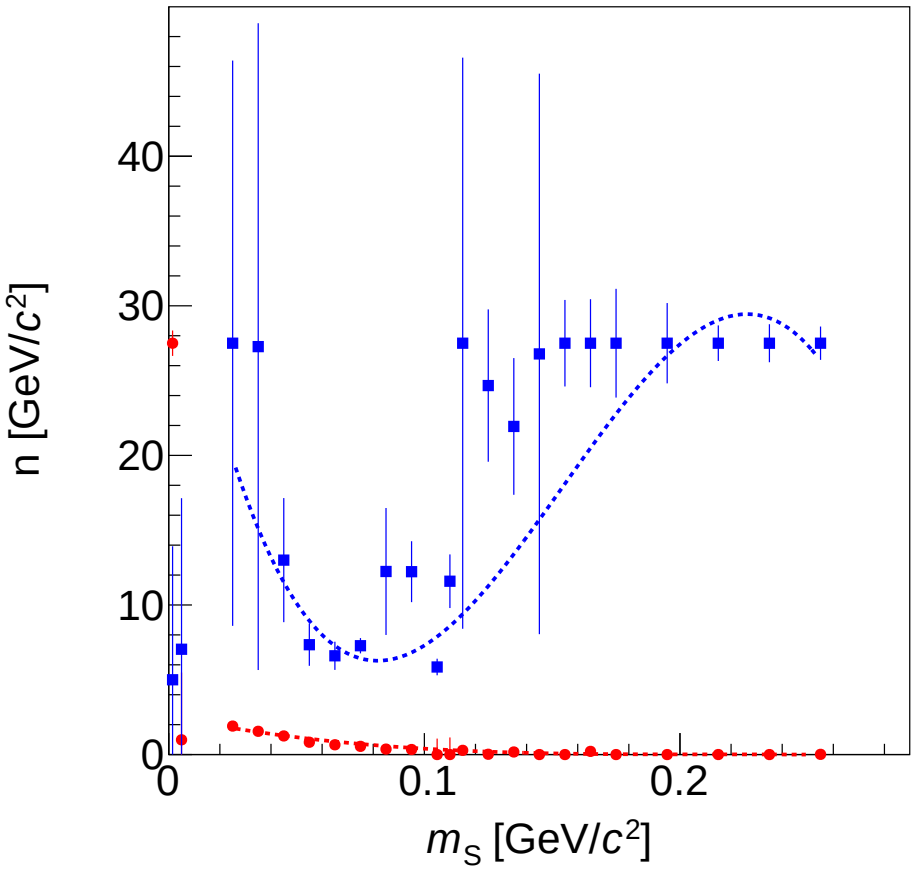

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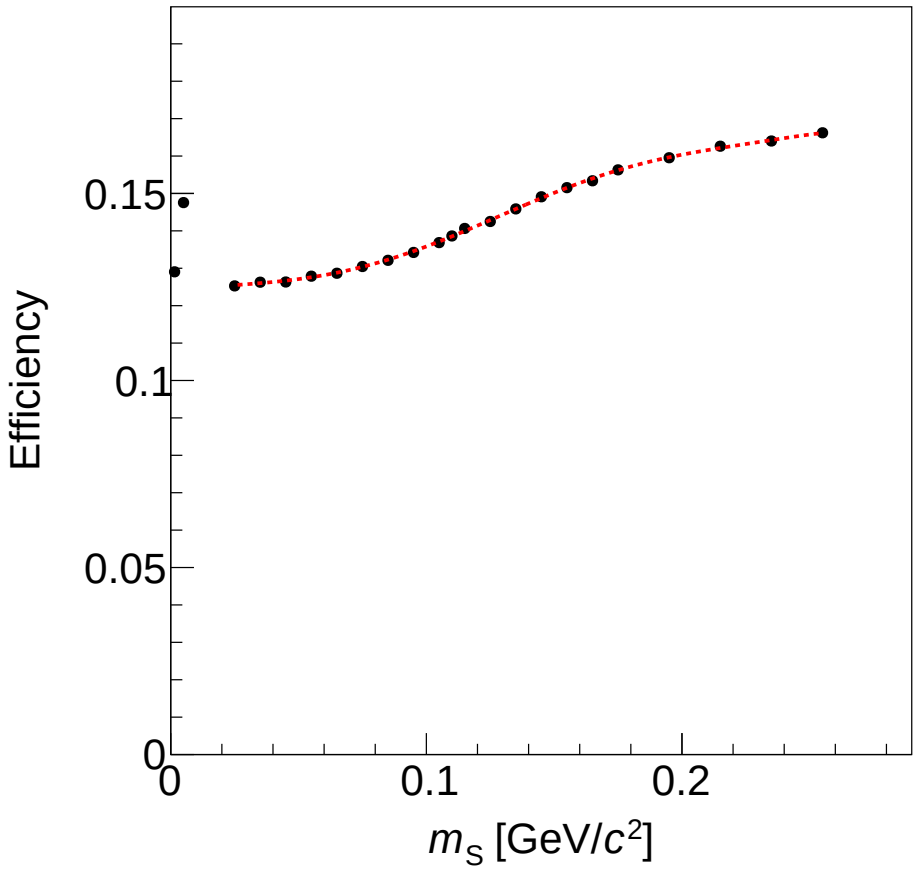
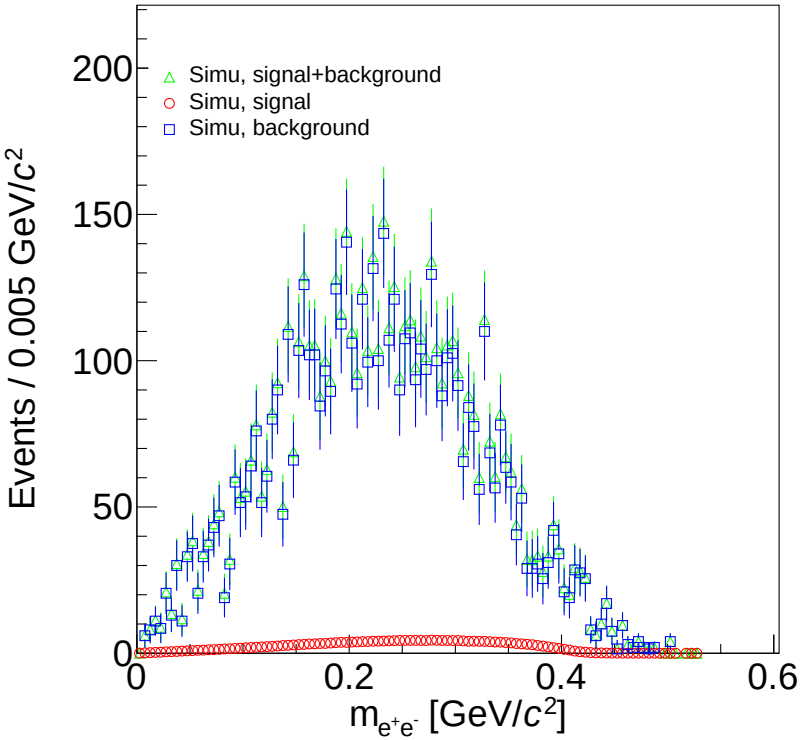
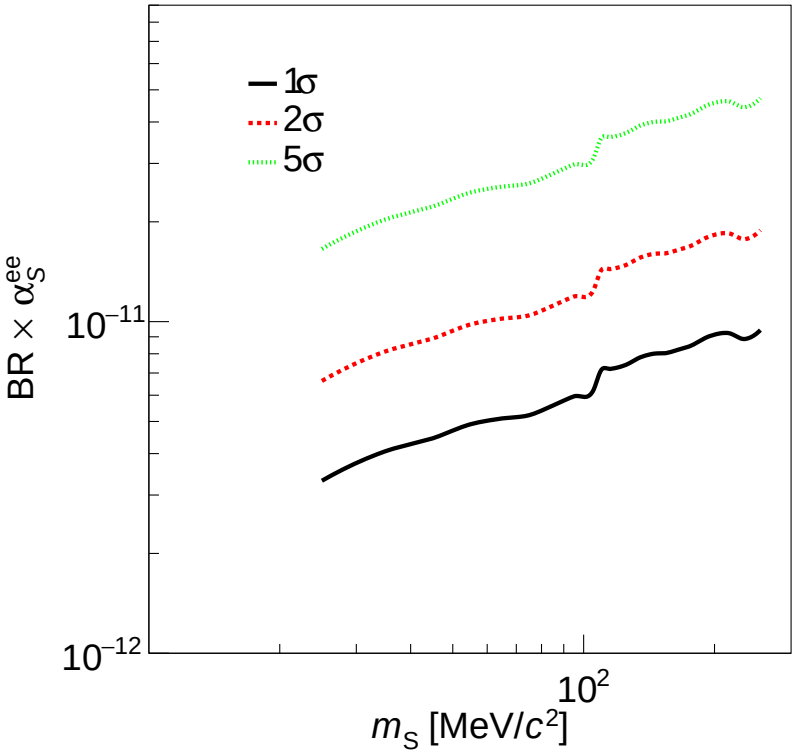


- Signal PDF corresponds to 2 Crystal Balls (CBs) with common mean
- Used Jared's script to parametrize each fit parameter as function of the mass
- Calculated detection efficiency

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
- $\sqrt{\mathrm{N_{bkg}} \times \frac{\mathcal{L}_{\mathrm{JEF}}}{\mathcal{L}_{\mathrm{Spring2017}}}}$ for a given m_S and window corresponding to $\Delta m_S = 2.5\sigma$ (σ is the signal resolution)



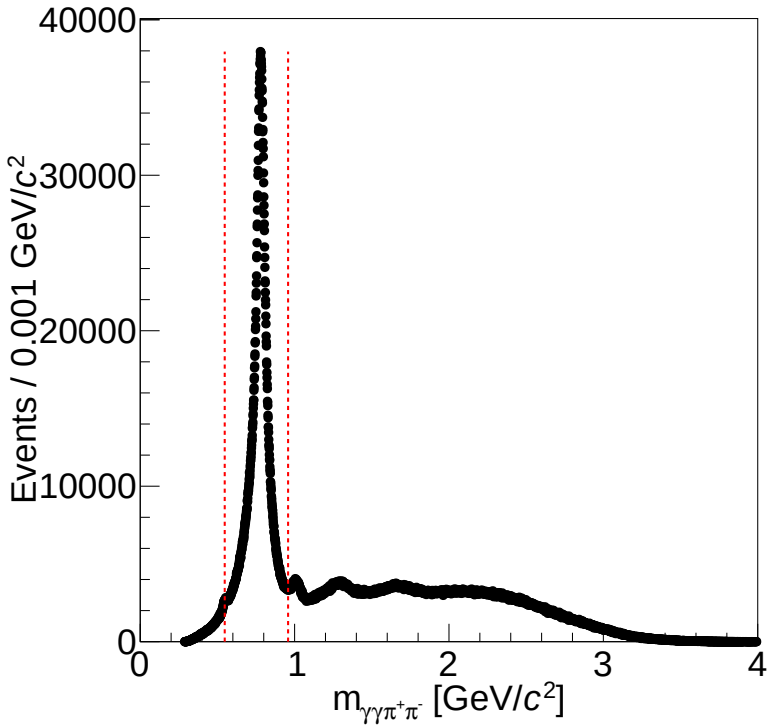


$S \to \pi^+\pi^-$

Three modes:

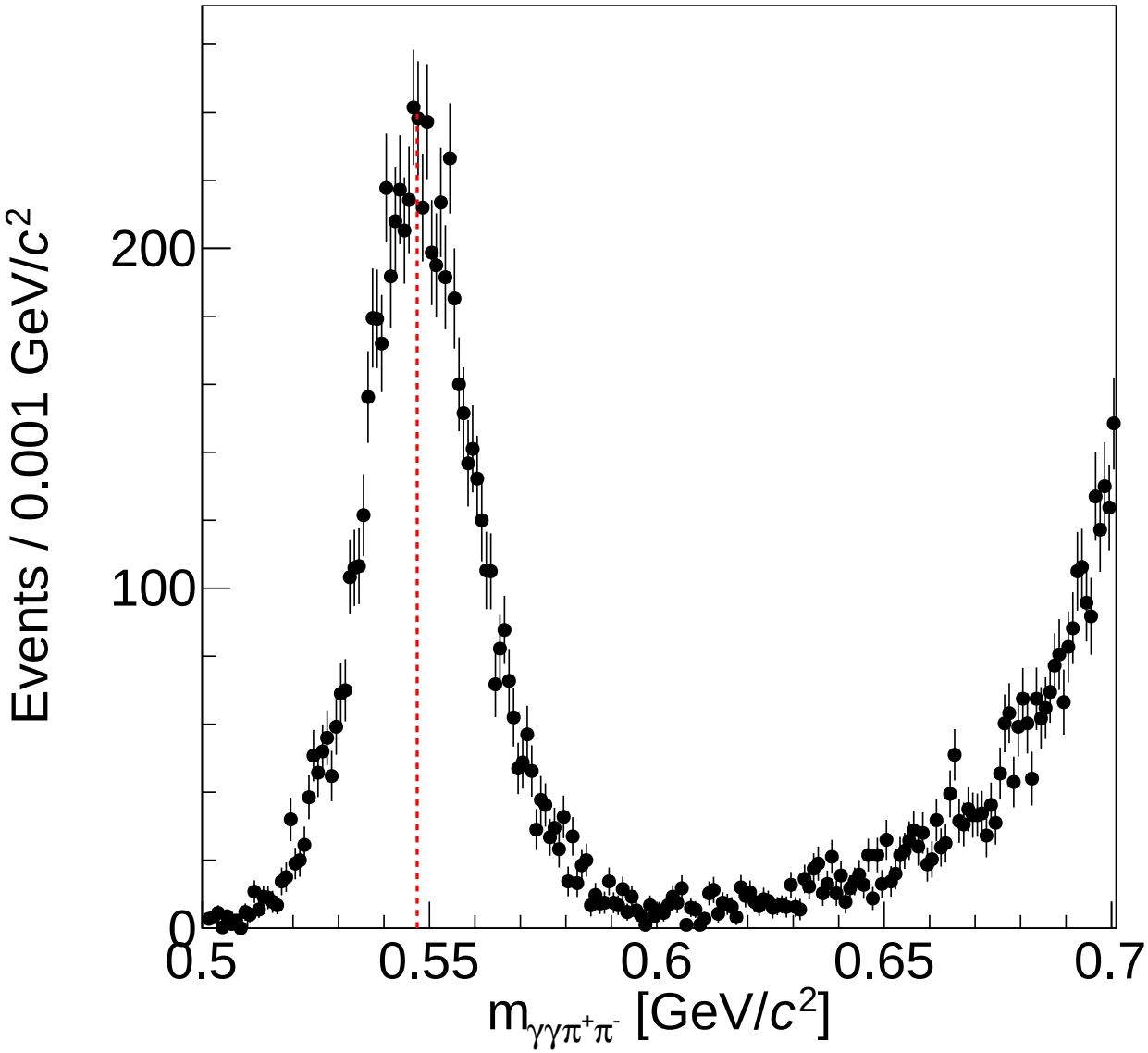
- $\eta \to \pi^0 S$
  $=> m_{\pi\pi} \leq m_S \leq m_\eta - m_\pi$
- $\eta' \to \pi^0 S$
  $=> m_{\pi\pi} \leq m_S \leq m'_\eta - m_\pi$
- $\eta' \to \eta S$
  $=> m_{\pi\pi} \leq m_S \leq m'_\eta - m_\eta$

Loose selection critiria based on the same variables as other decay modes



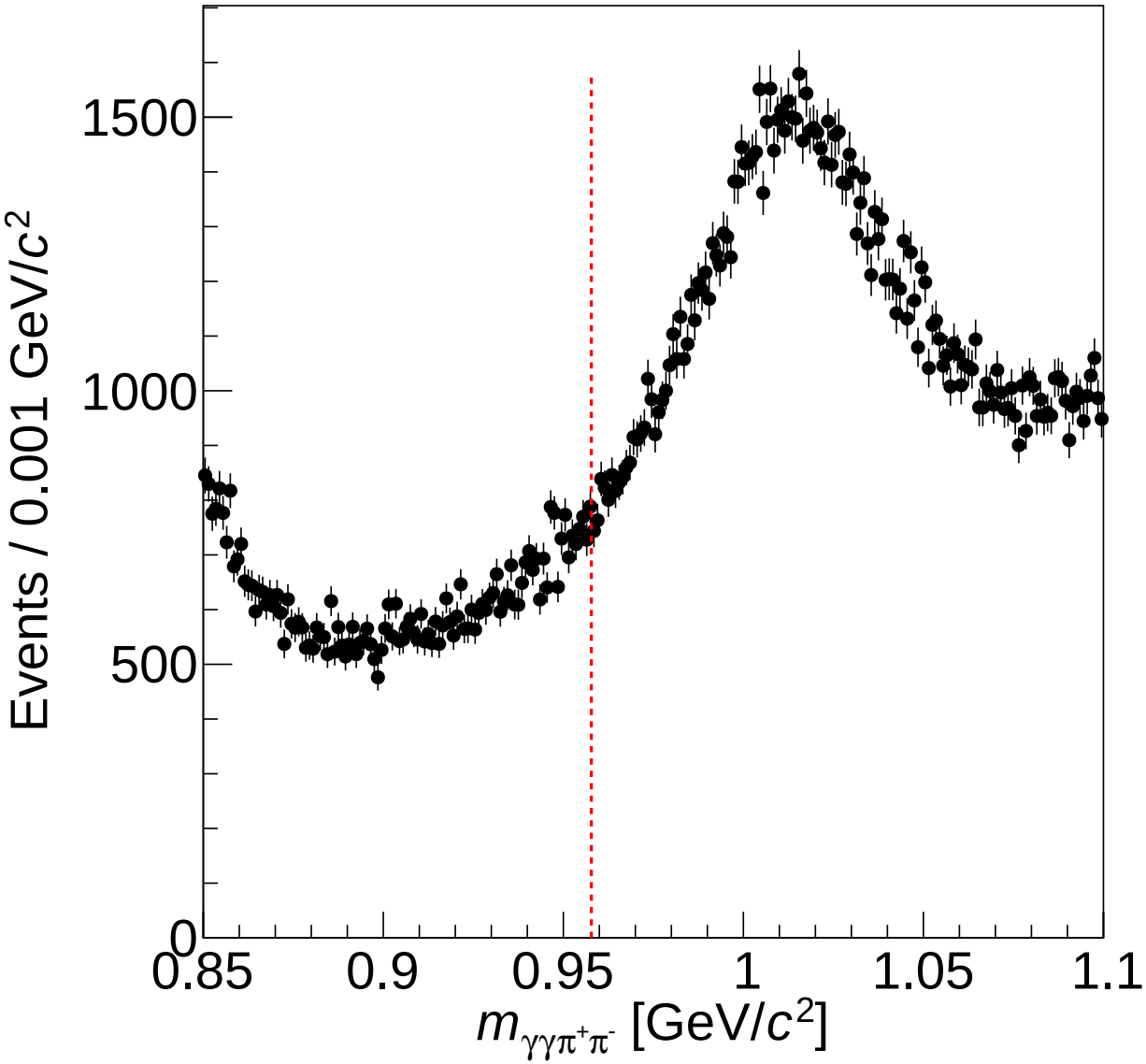
$\gamma p \to \eta p$, $\eta \to S\pi^0$, and $S \to \pi^+\pi^-$

Cuts in diphoton invariant mass around the π^0 mass



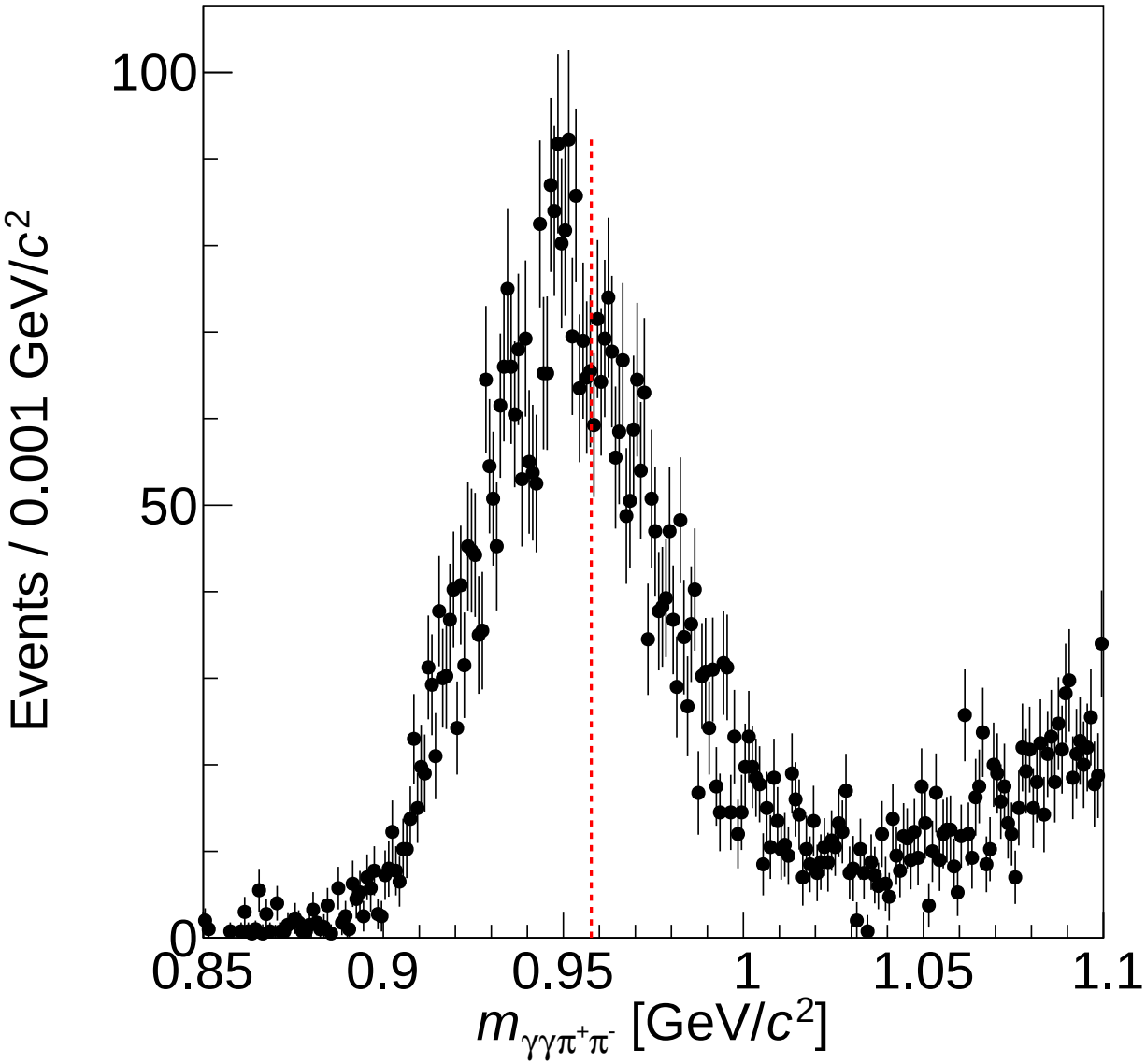
$\gamma p \to \eta' p$, $\eta' \to S\pi^0$, and $S \to \pi^+\pi^-$

Cuts in diphoton invariant mass around the π^0 mass

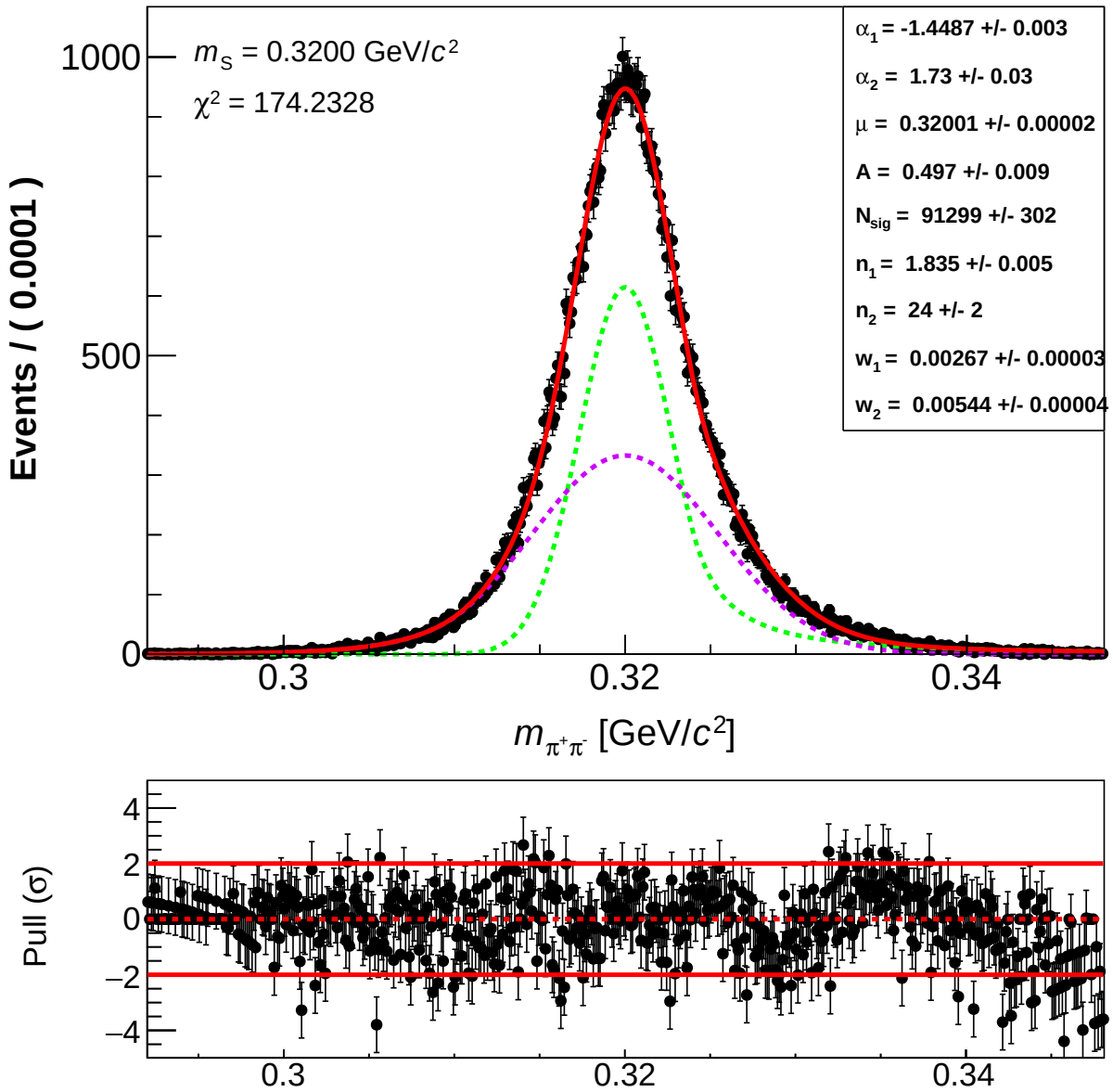


$\gamma p \to \eta' p$, $\eta' \to S\eta$, and $S \to \pi^+\pi^-$

Cuts in diphoton invariant mass around the η mass



$\gamma p \to \eta p$, $\eta \to S\pi^0$, and $S \to \pi^+\pi^-$, PDF and efficiency



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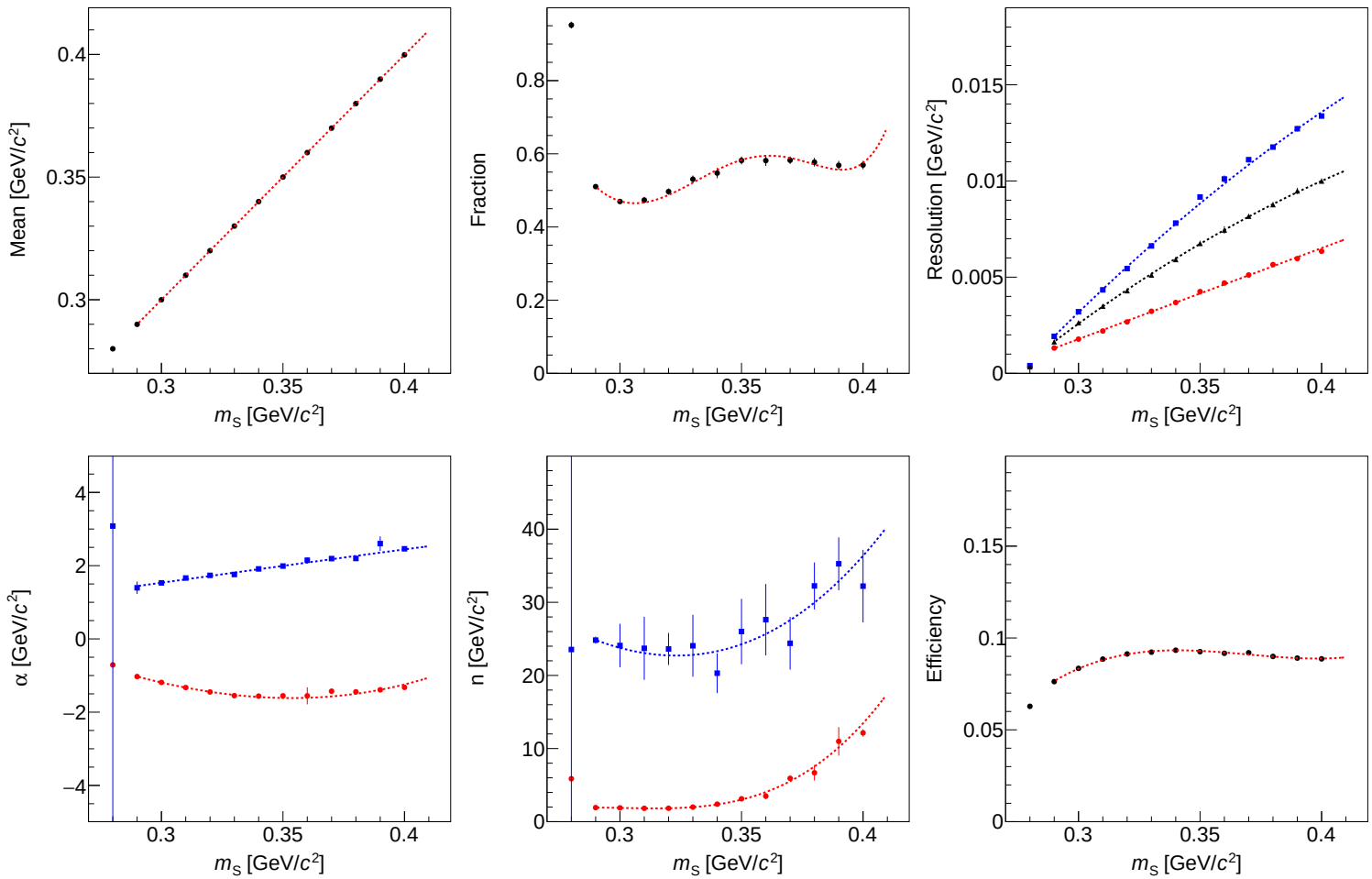
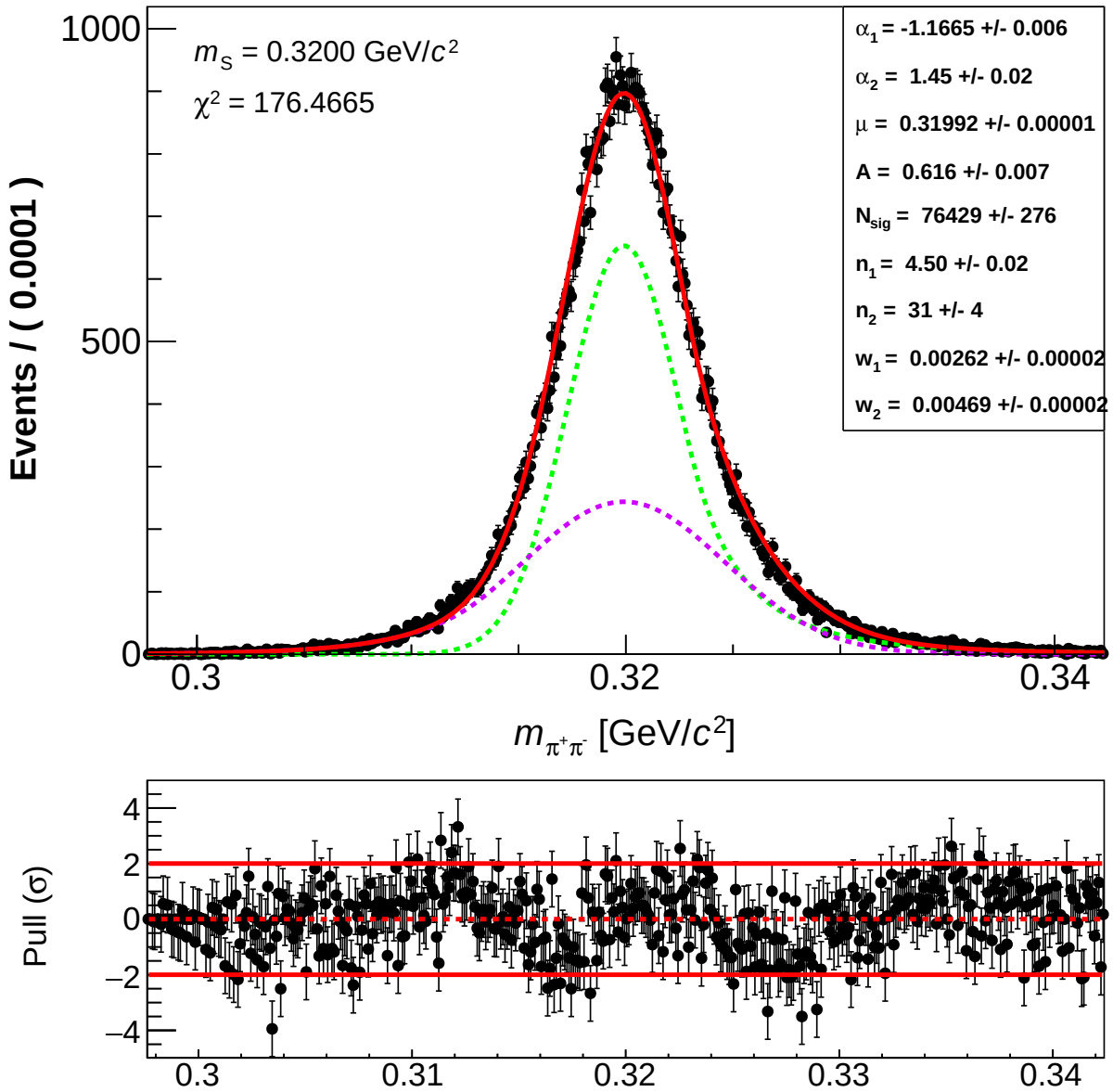


$\gamma p \to \eta' p$, $\eta' \to S\pi^0$, and $S \to \pi^+\pi^-$, PDF and efficiency



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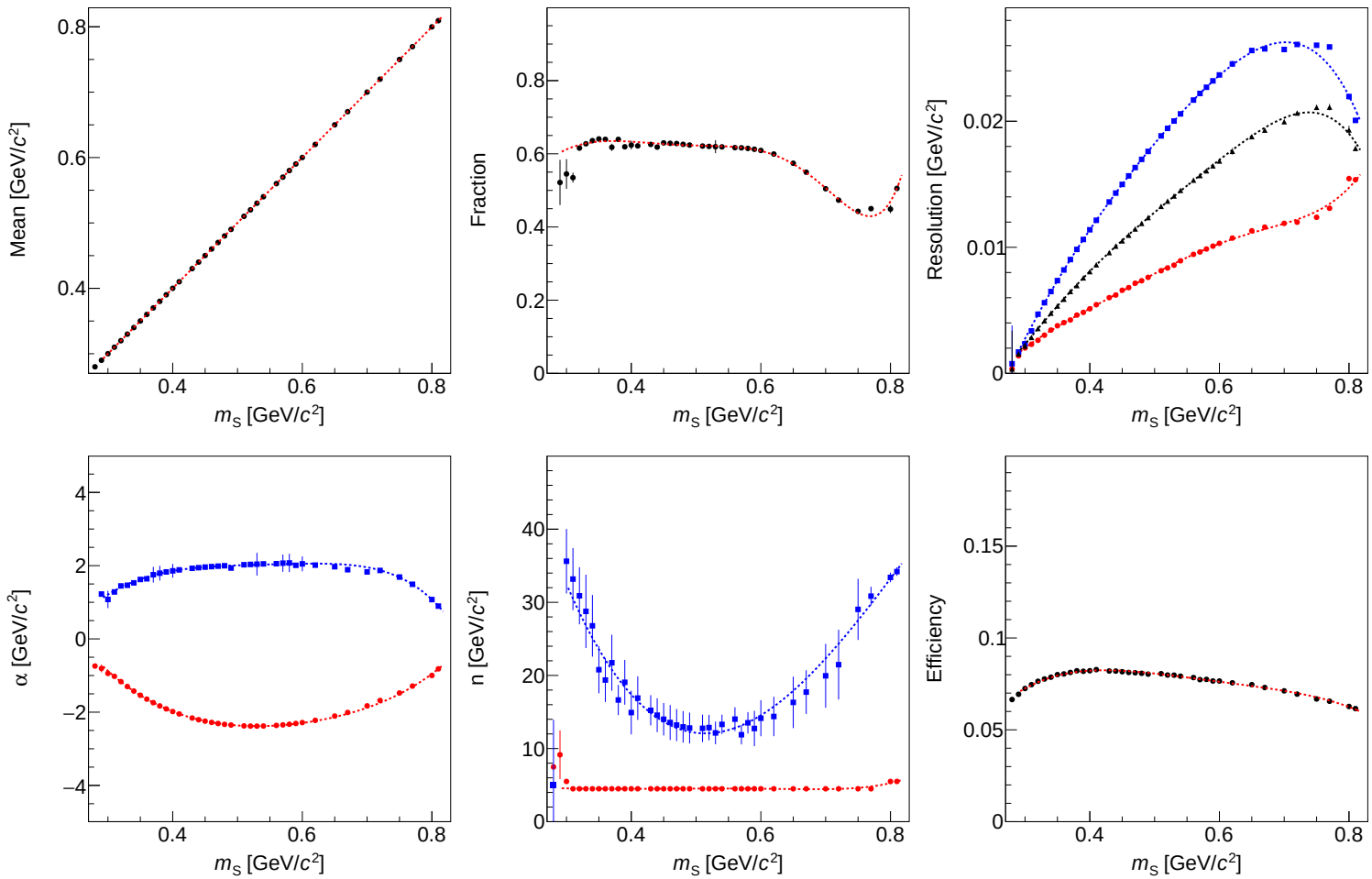

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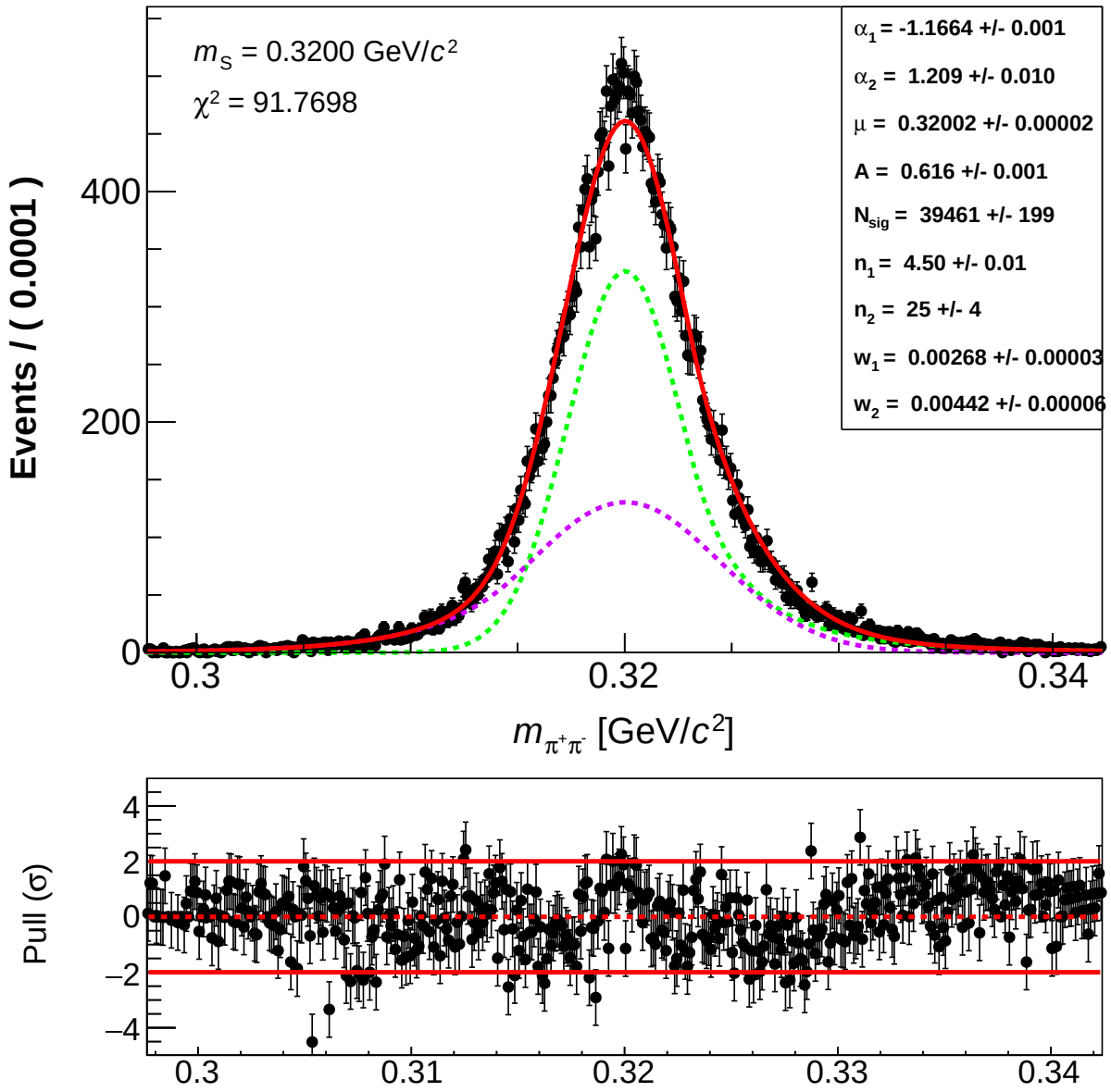

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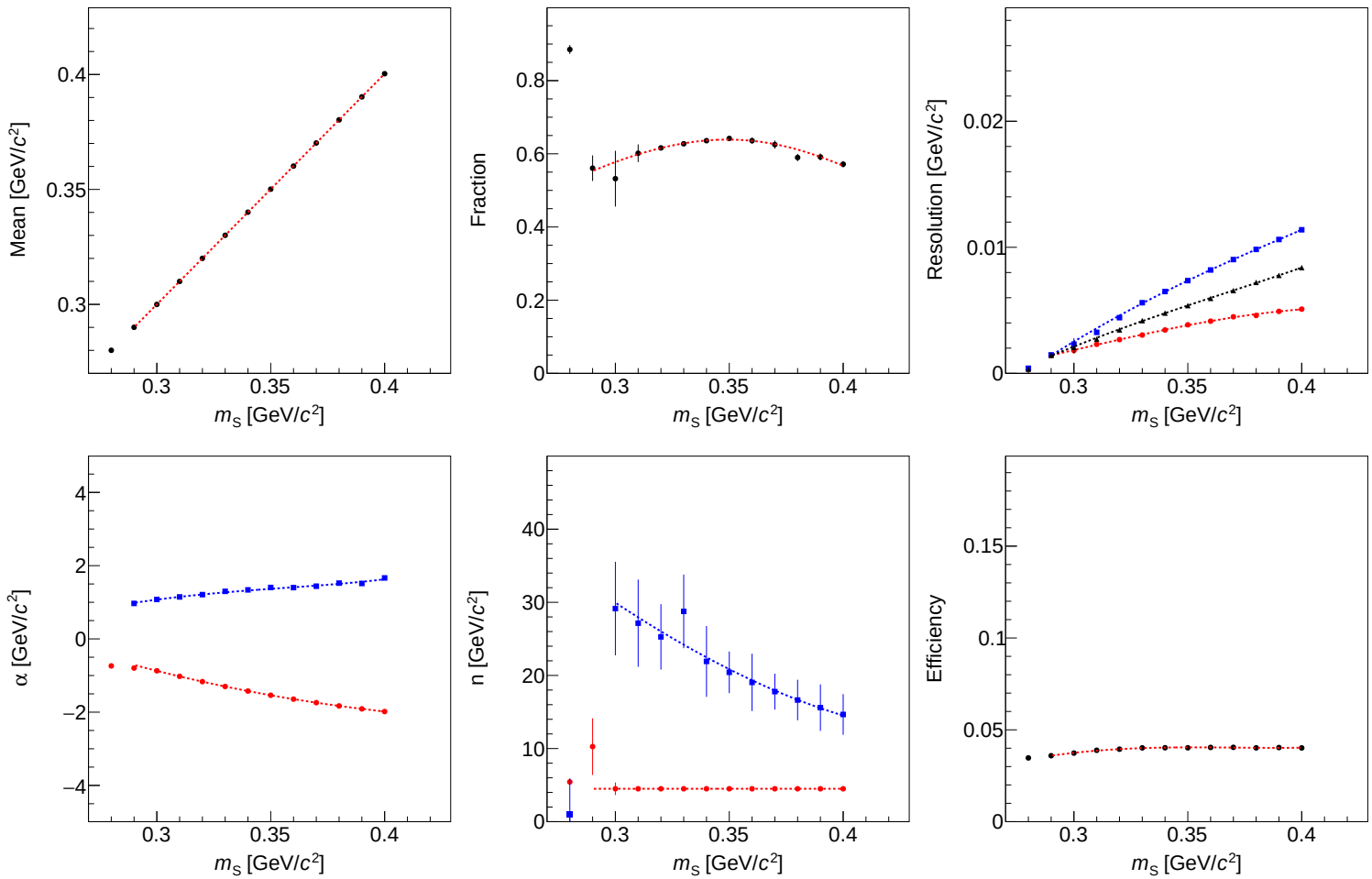

Conclusion

To be continued