Search for Axion-like Particles through Nuclear Primakoff Production in Hall D

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Axion-Like Particles (ALP)

- Proposed extension to Standard Model: new fundamental pseudoscalar particle
- Addition could explain:
  - Strong CP problem
  - Hierarchy Problem
  - Connection between SM and dark matter

Axion-Like Particles (ALP)

- Pseudoscalar boson: $S = 0$, $P = -1$
- Pseudo Nambu-Goldstone boson: $\Lambda \gg m_a$
  - Recent interest in GeV-scale ALP candidates

$$\mathscr{L}_{eff} = -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{c_\gamma}{4\pi\Lambda} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

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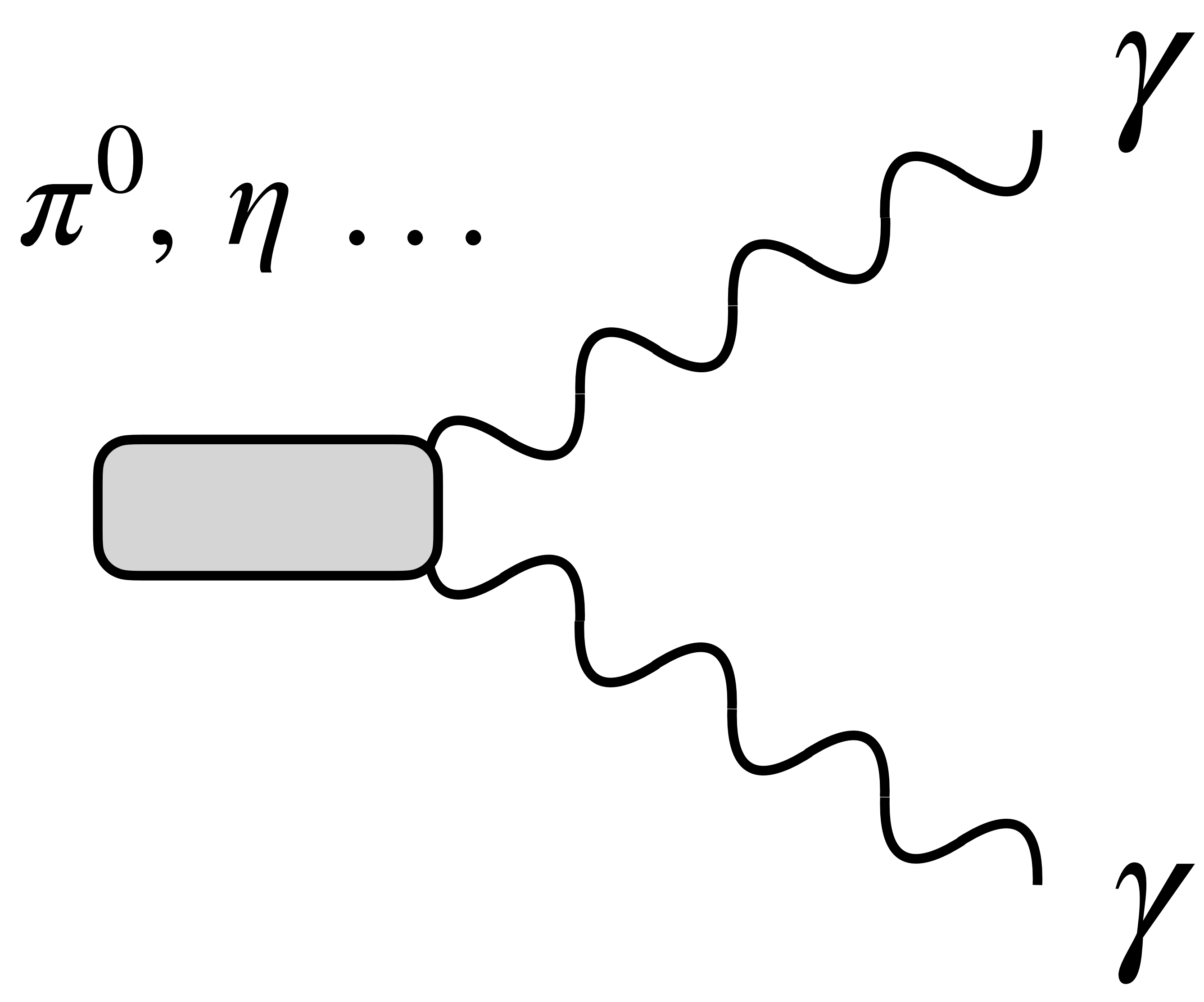
How do we measure pseudoscalars?

- Light mesons π^0, η, similarly couple to 2γ



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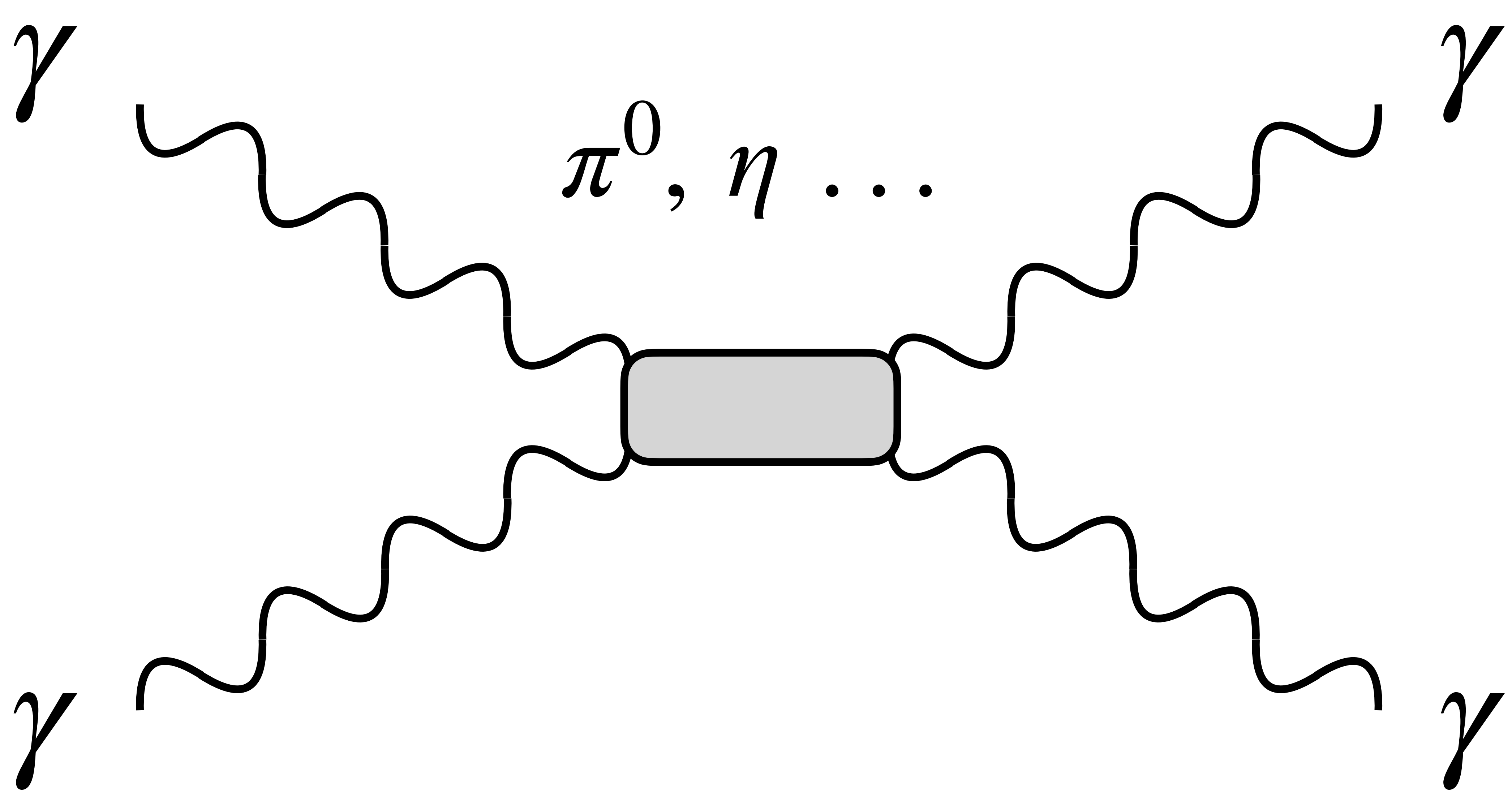

Nuclear Primakoff mechanism

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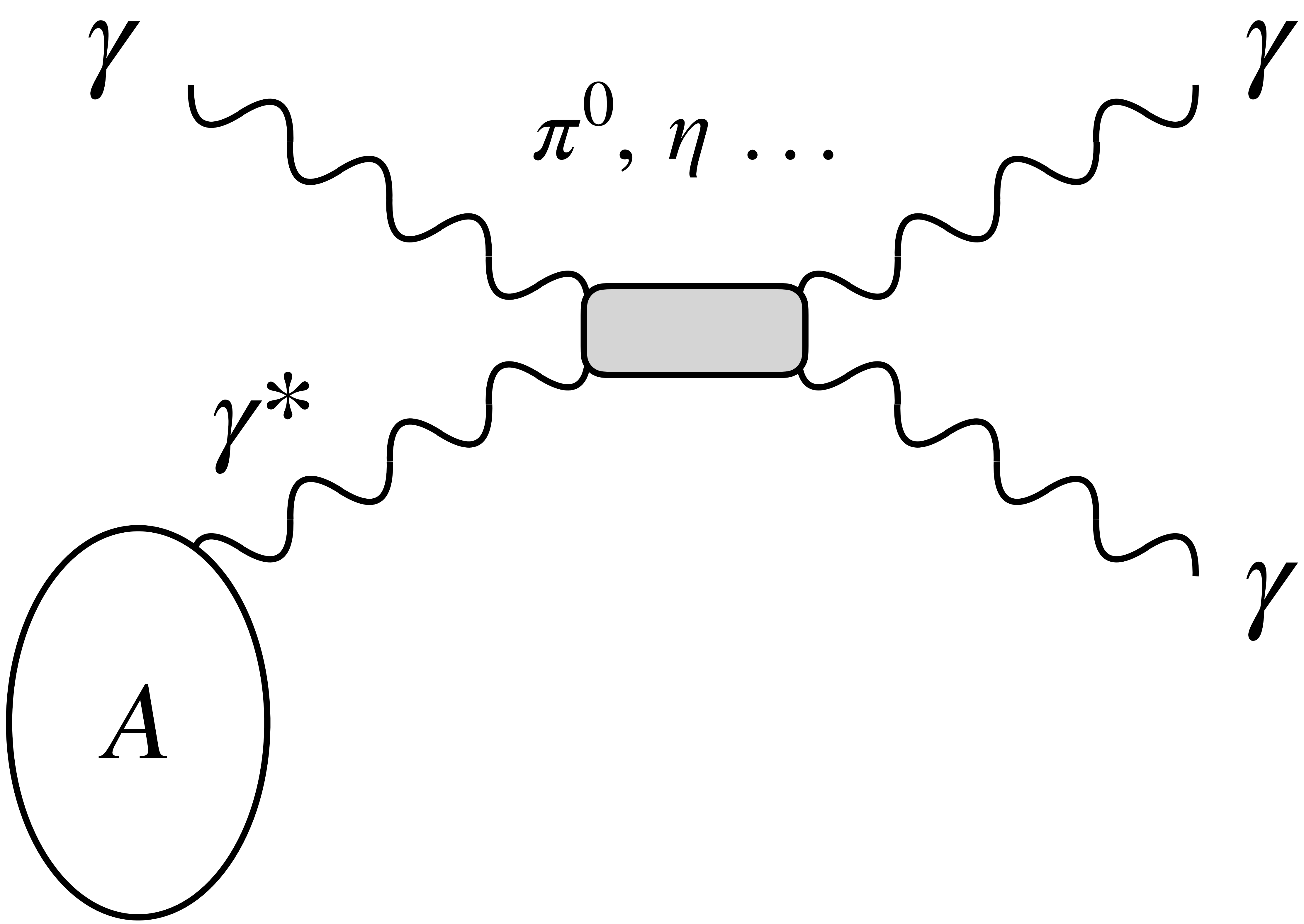
- Z^2 enhancement over proton target



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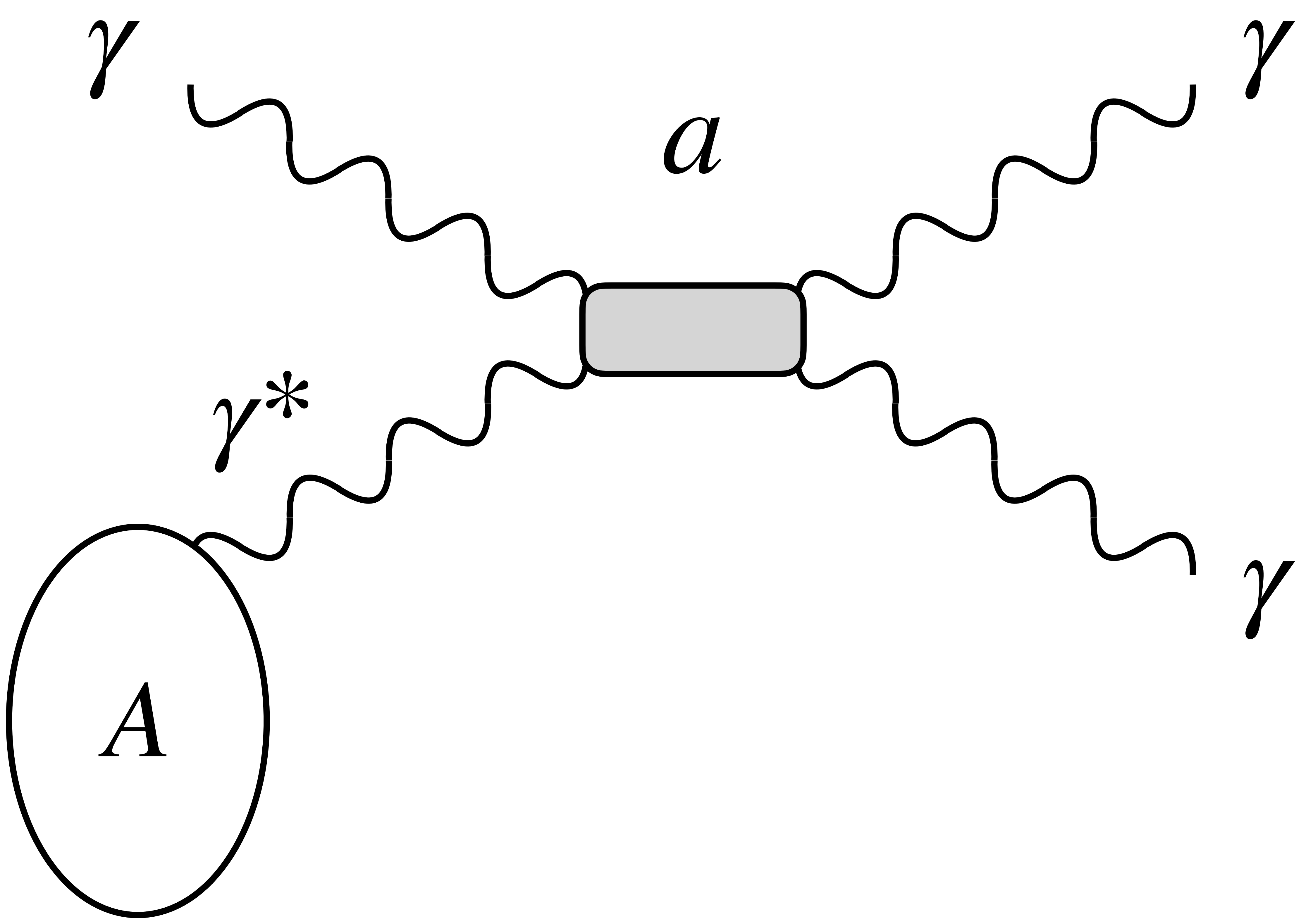
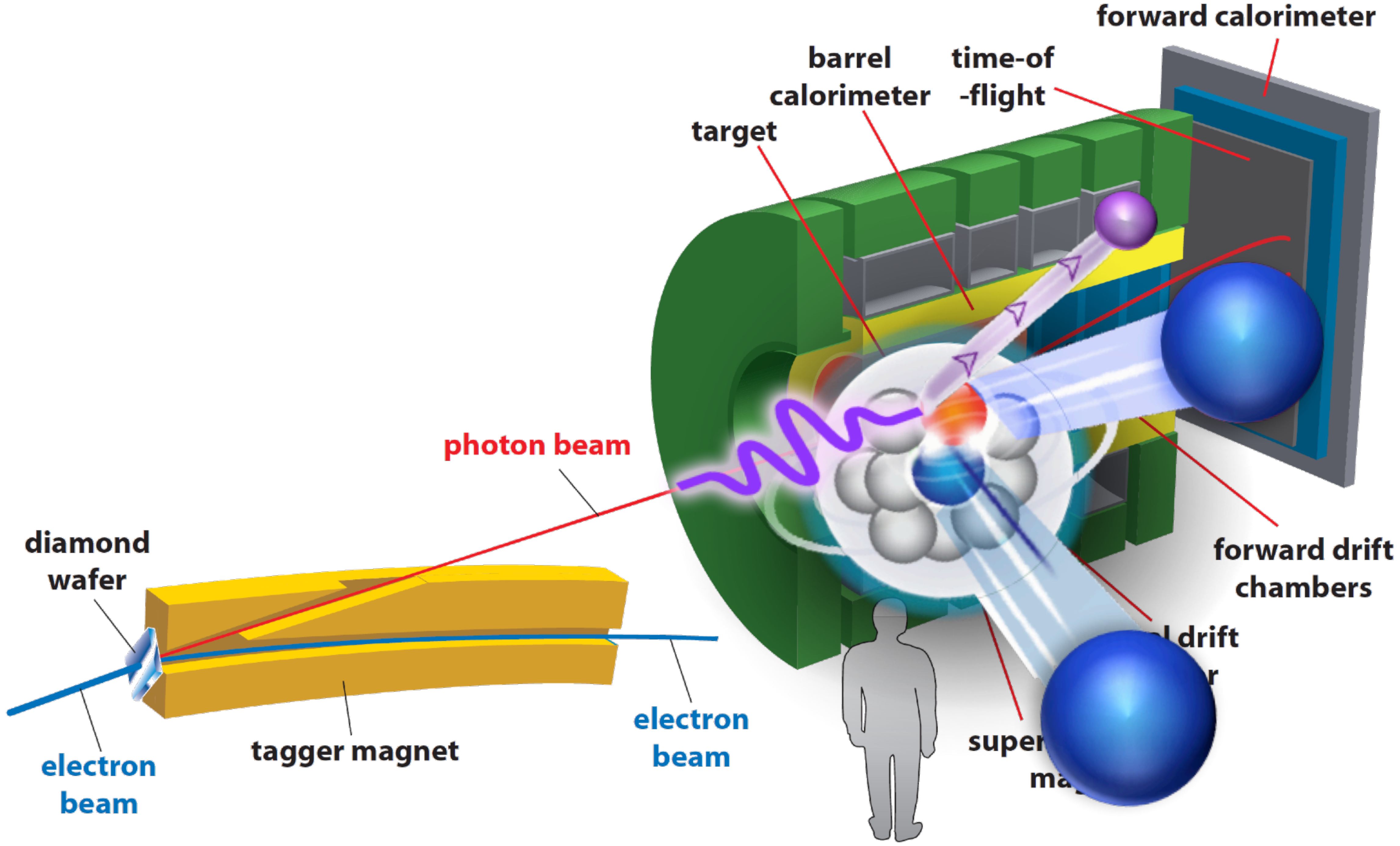
- **Possible mechanism for producing ALPs?**



Aloni et al. PRL (2019)

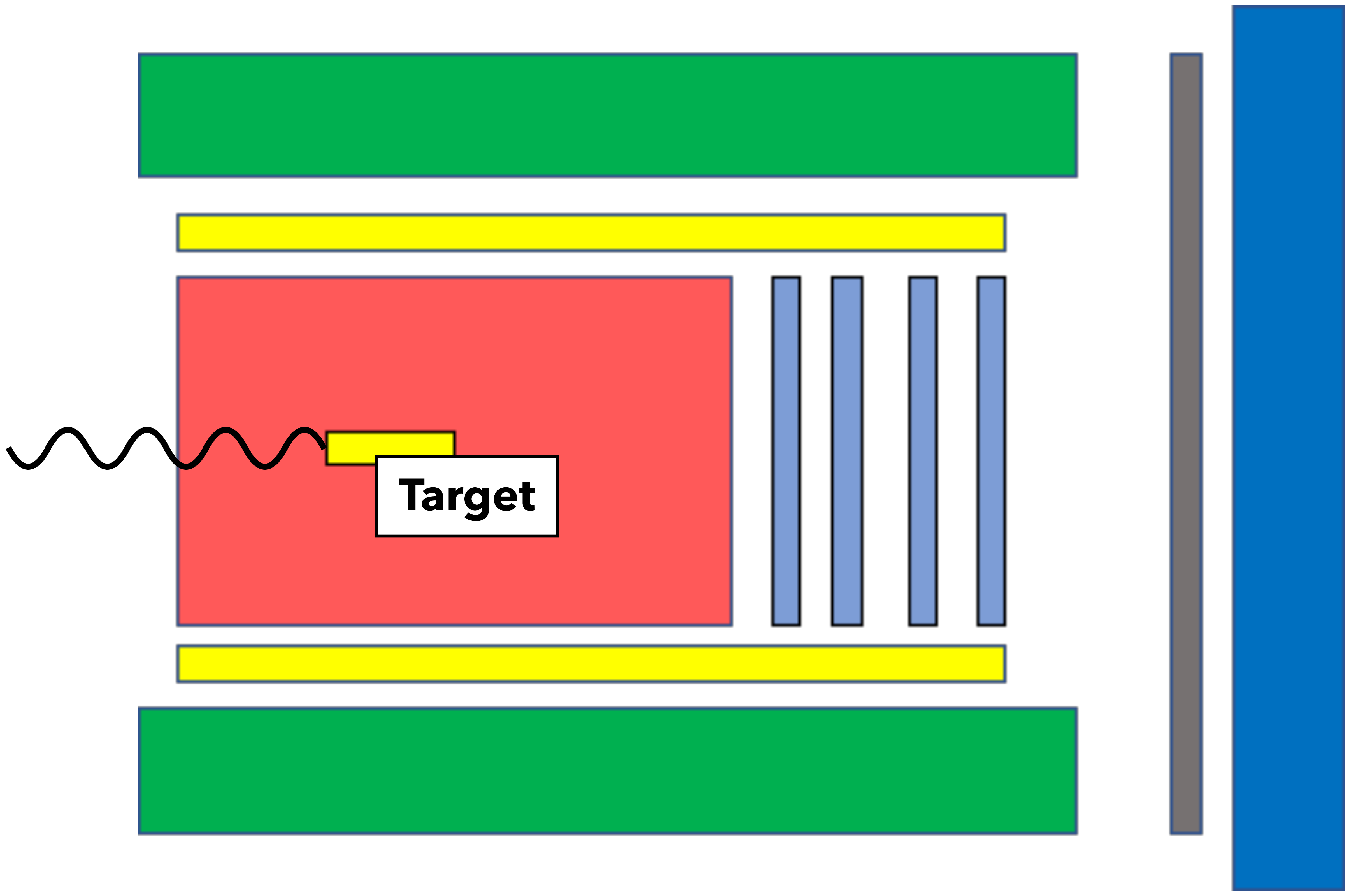
Hall D SRC-CT Experiment

- Dedicated high-energy photonuclear measurement
- ~40-day measurement of targets ^{2}H, ^{4}He, ^{12}C
- 10.8-GeV electron beam – tagged coherent bremsstrahlung
- Final-state particles detected in large-acceptance GlueX spectrometer
- **Searching for photon pairs from ^{12}C**



Photoproduction of photon pairs

Photon beam from tagger hall



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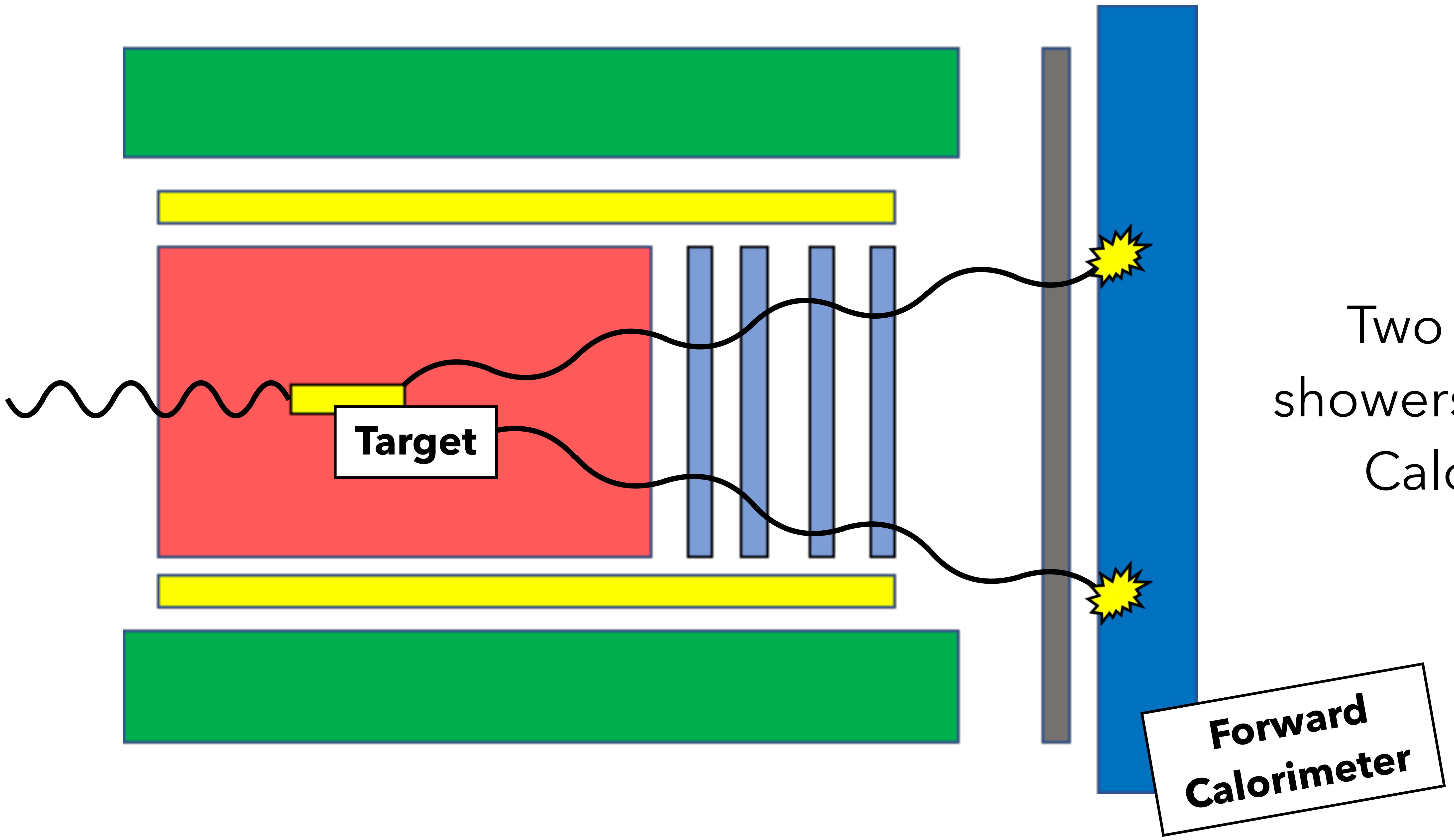

Two “neutral” showers in Forward Calorimeter

Photoproduction of photon pairs

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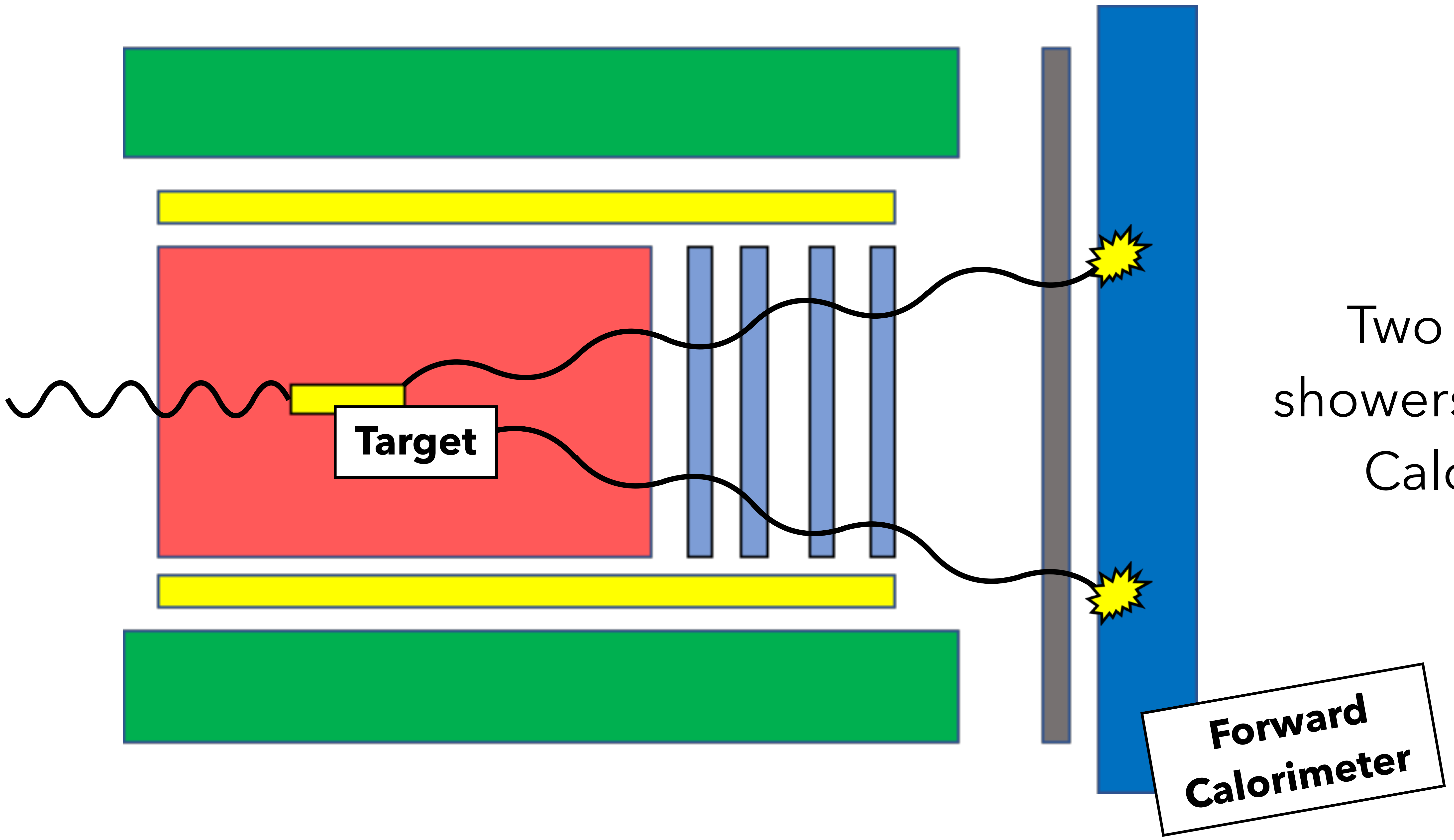


Two "neutral" showers in Forward Calorimeter

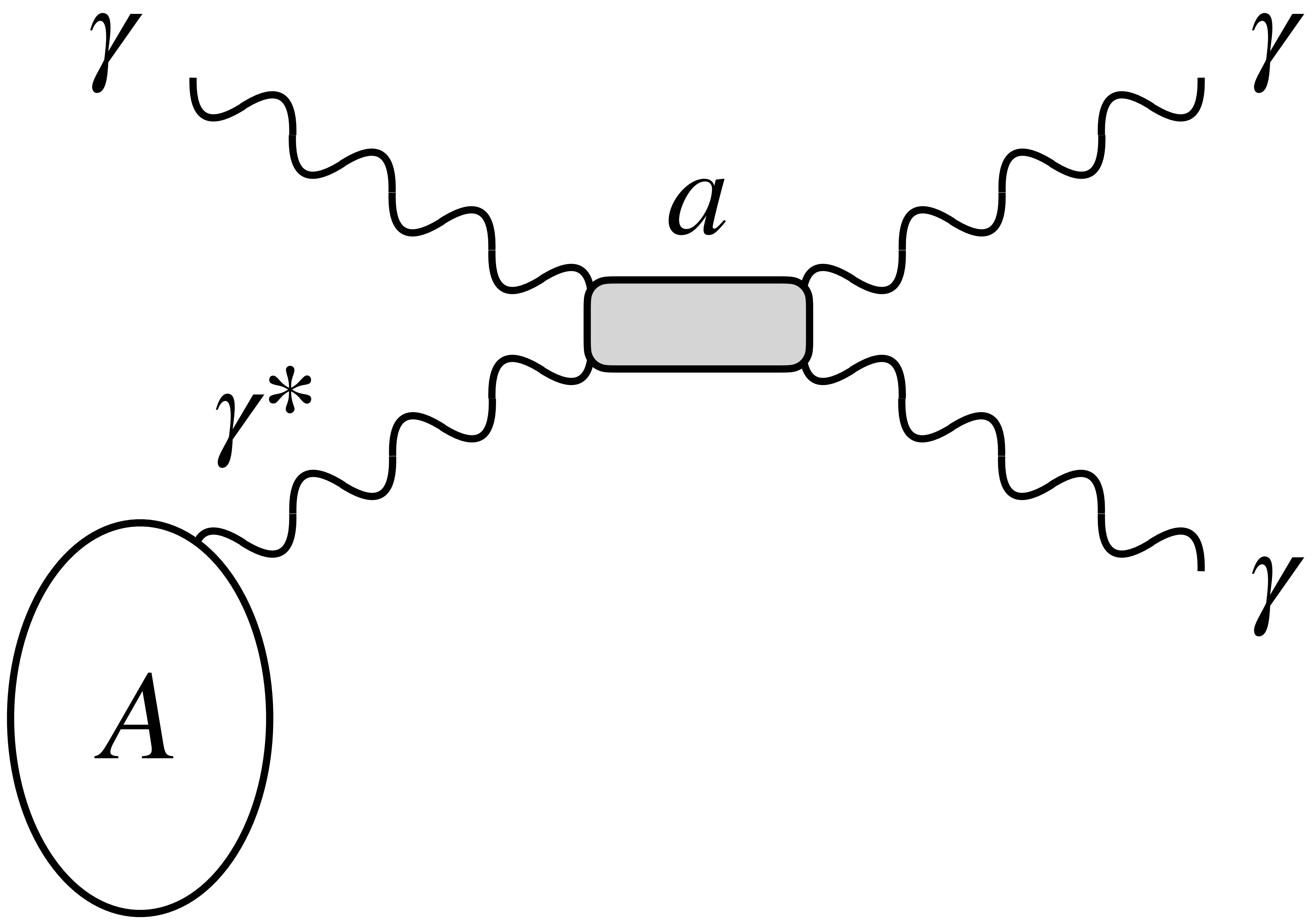
Simple event signature →
Reduction of background is key!

Modeling an ALP signal

- Cross section model given by Aloni:

$$\frac{d\sigma_{\gamma A\to aA}}{dt} = \alpha Z^2 F_A^2(t)\Gamma_{a\to\gamma\gamma}\mathscr{H}(m_A, m_a, s, t)$$

- ALP photoproduction events generated at given mass and coupling



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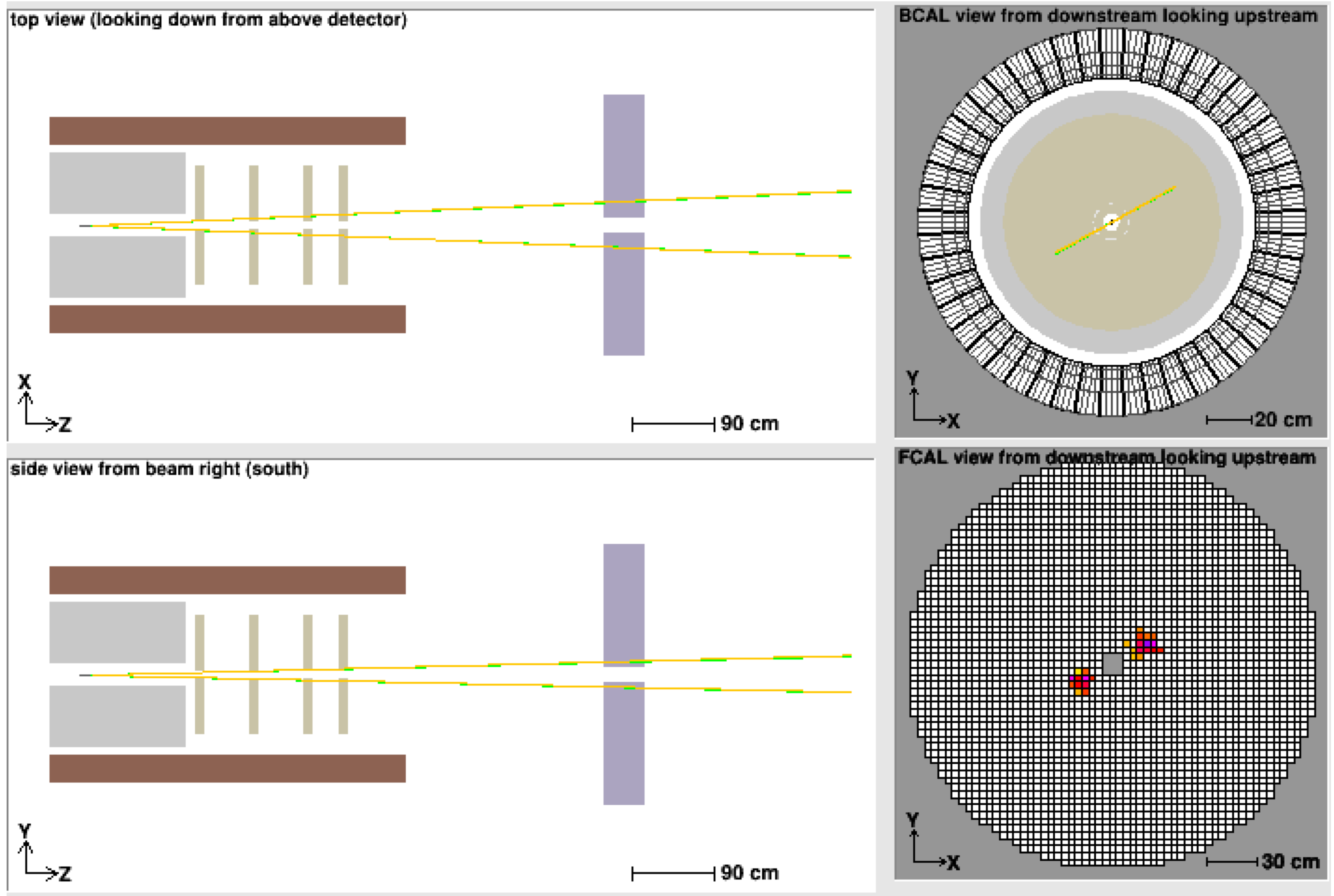
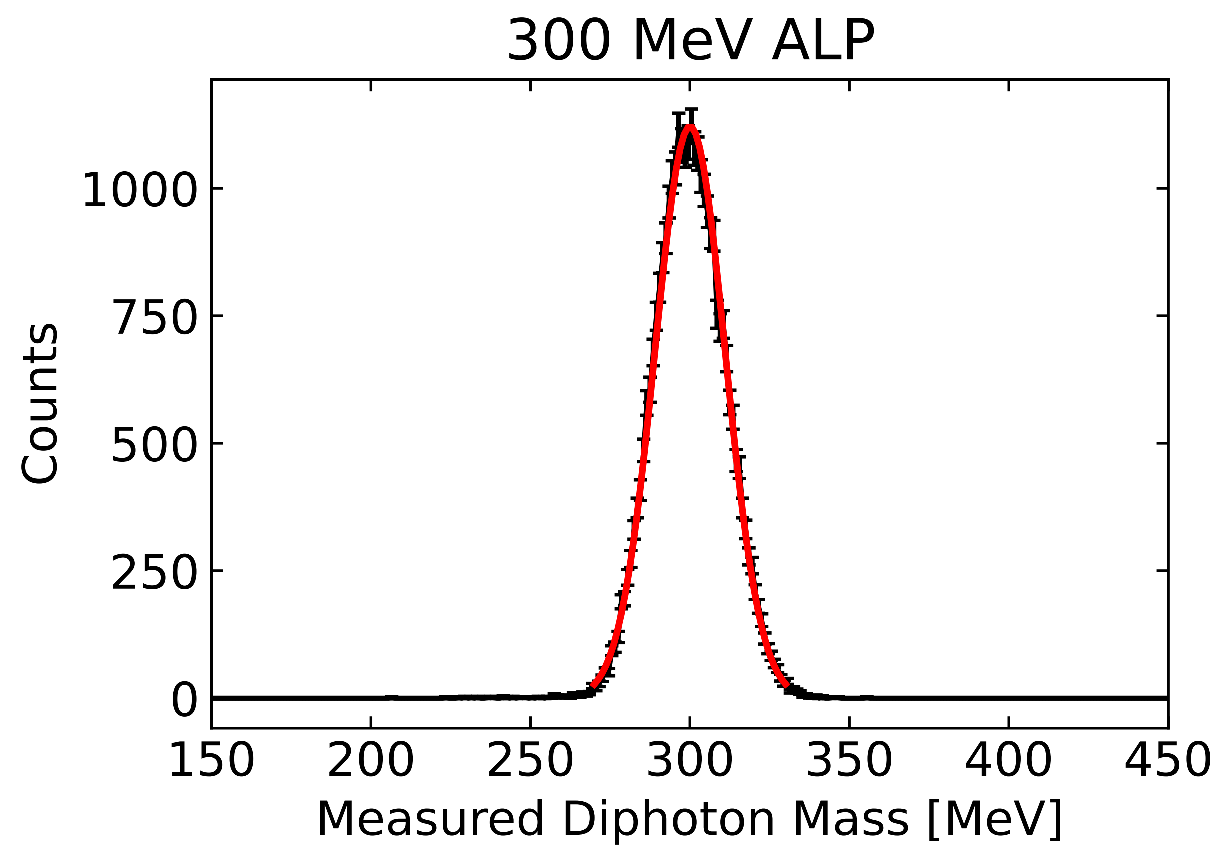
- GEANT model of GlueX detector response to signal

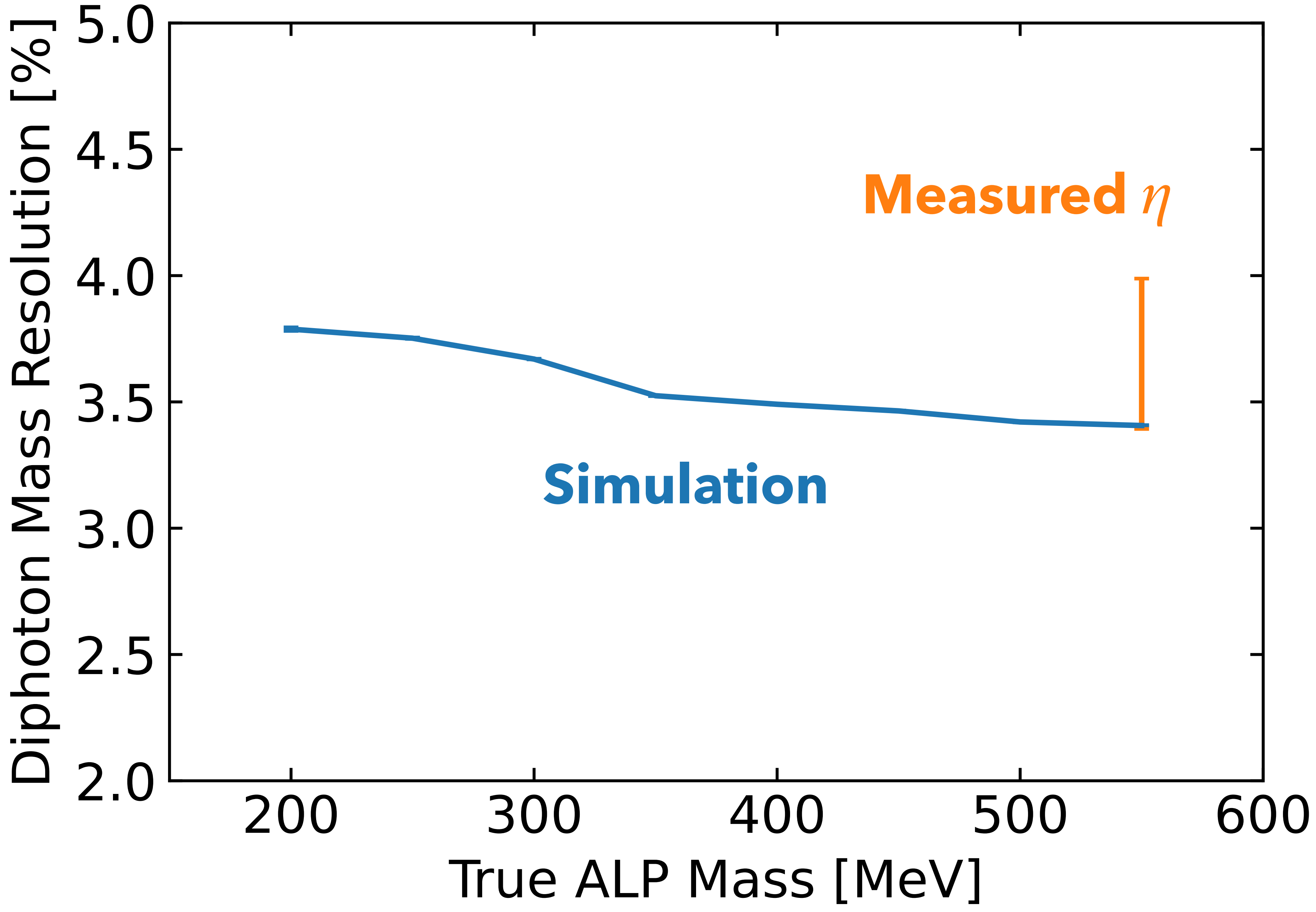
- "Random-trigger" events from data give impact of coincidence events on event selection

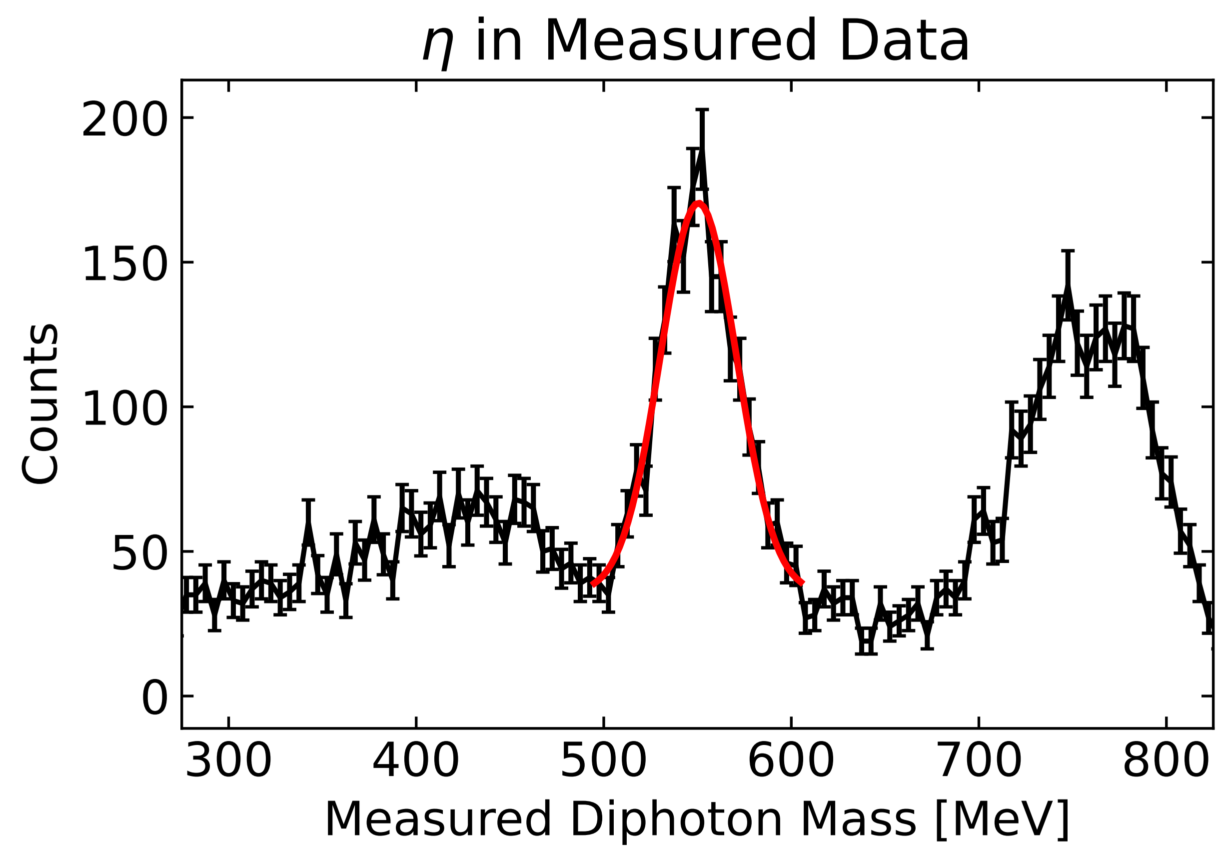
$m_a = 300$ MeV



Simulation gives ALP mass resolution



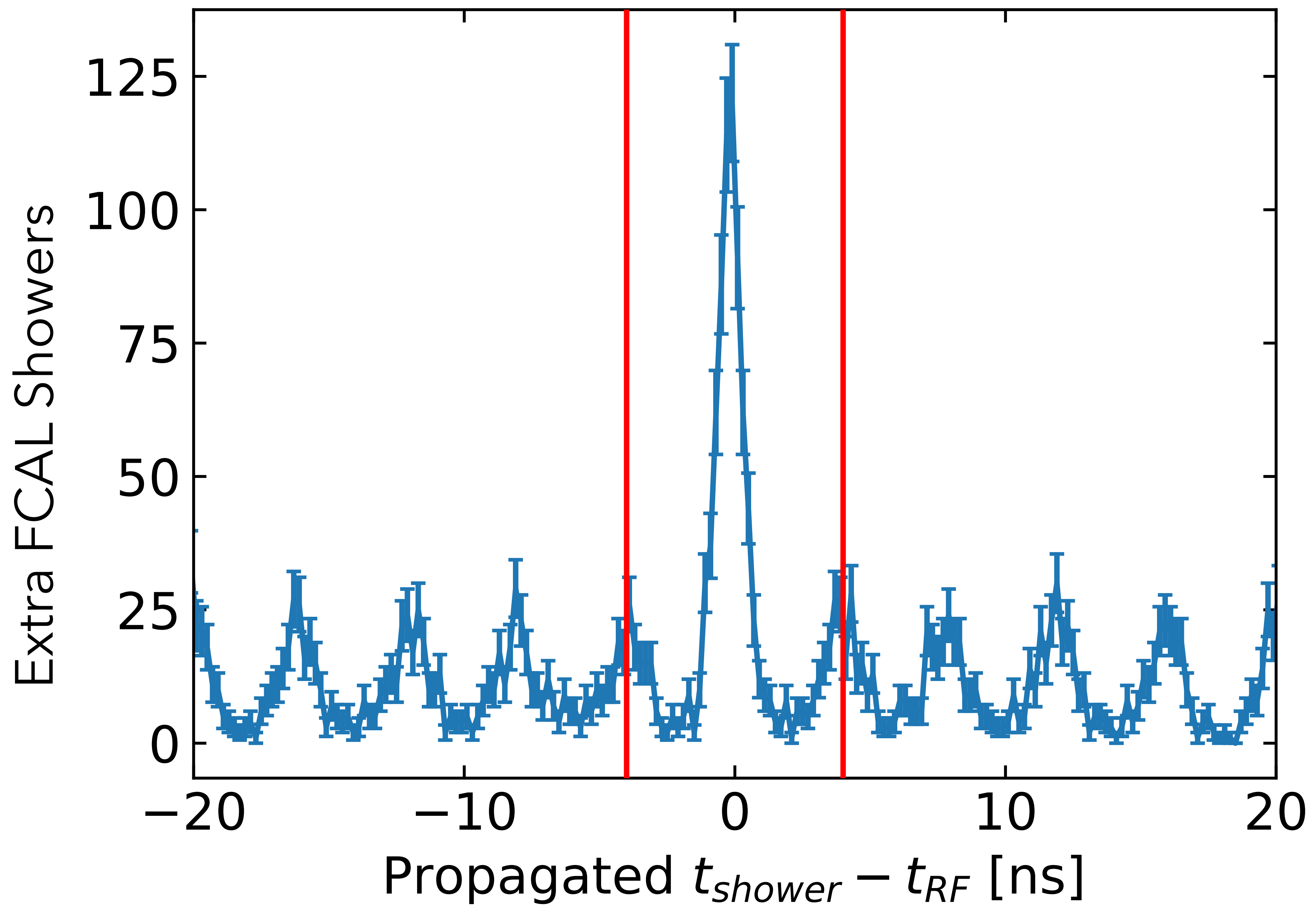




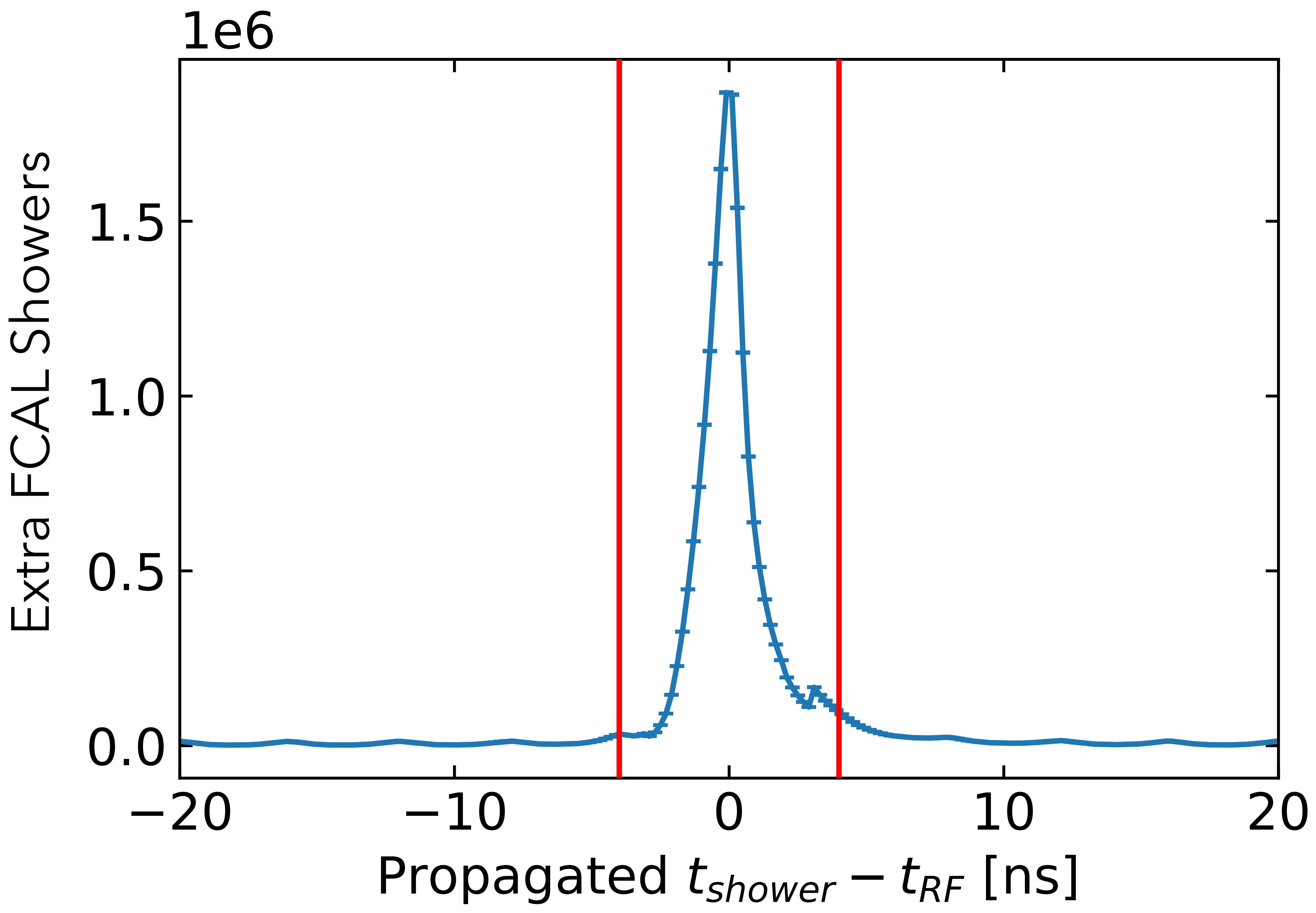
Simulation validated against measured η meson

Comparison with simulation to optimize selection
Example: How many extra showers can we allow?

ALP Simulation: Few additional on-time showers compared with accidental rate



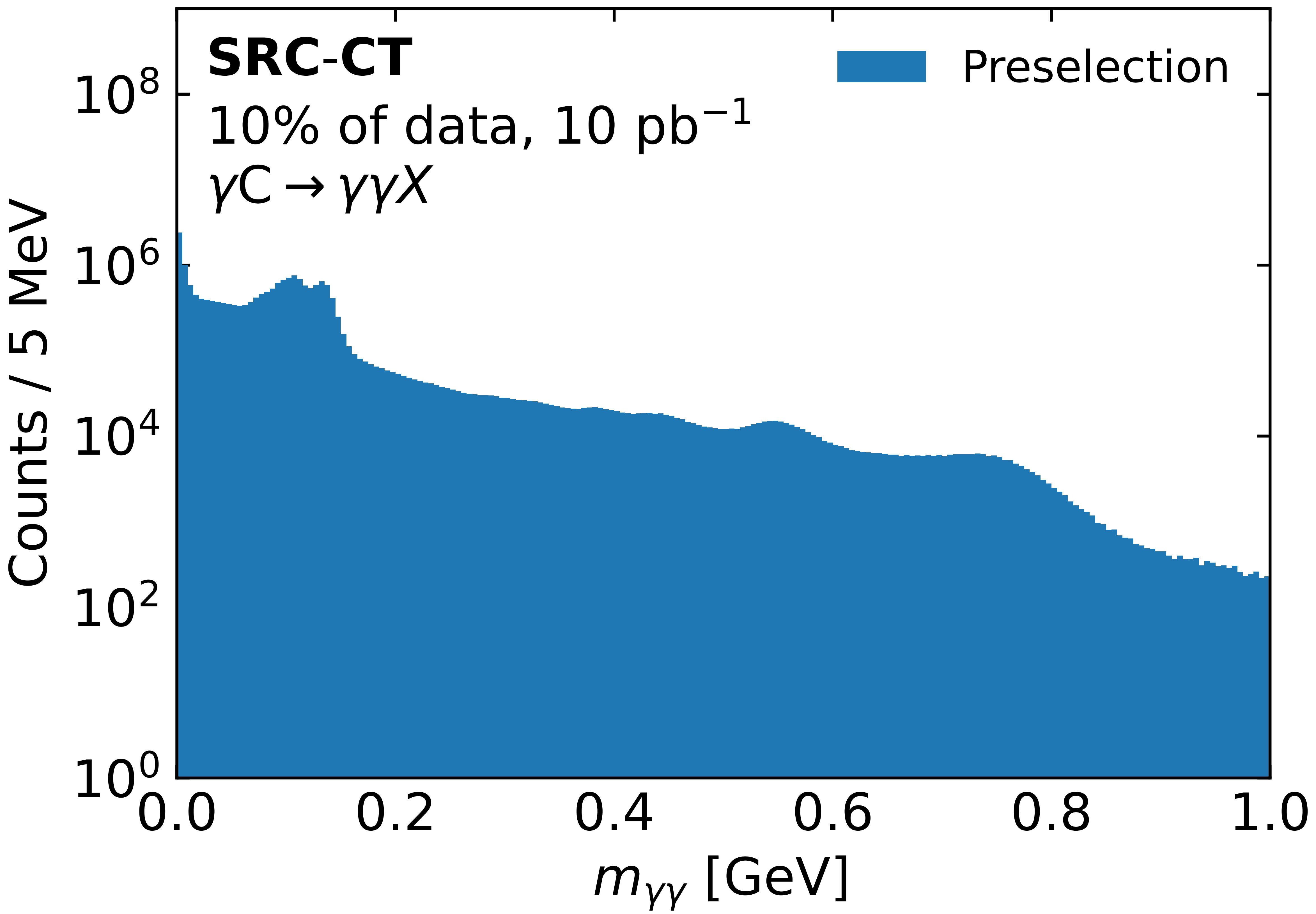
2-photon Data: Large excess of extra showers within short time of the event



Selection criteria: Veto events with extra FCAL showers within 4 ns

Event Selection Criteria

- Good photon selection:
  - $|t_{\text{shower}} - t_{\text{RF}}| < 3$ ns
  - $E_{\text{shower}} > 100$ MeV
  - $R_{\text{shower}} < 105.5$ cm



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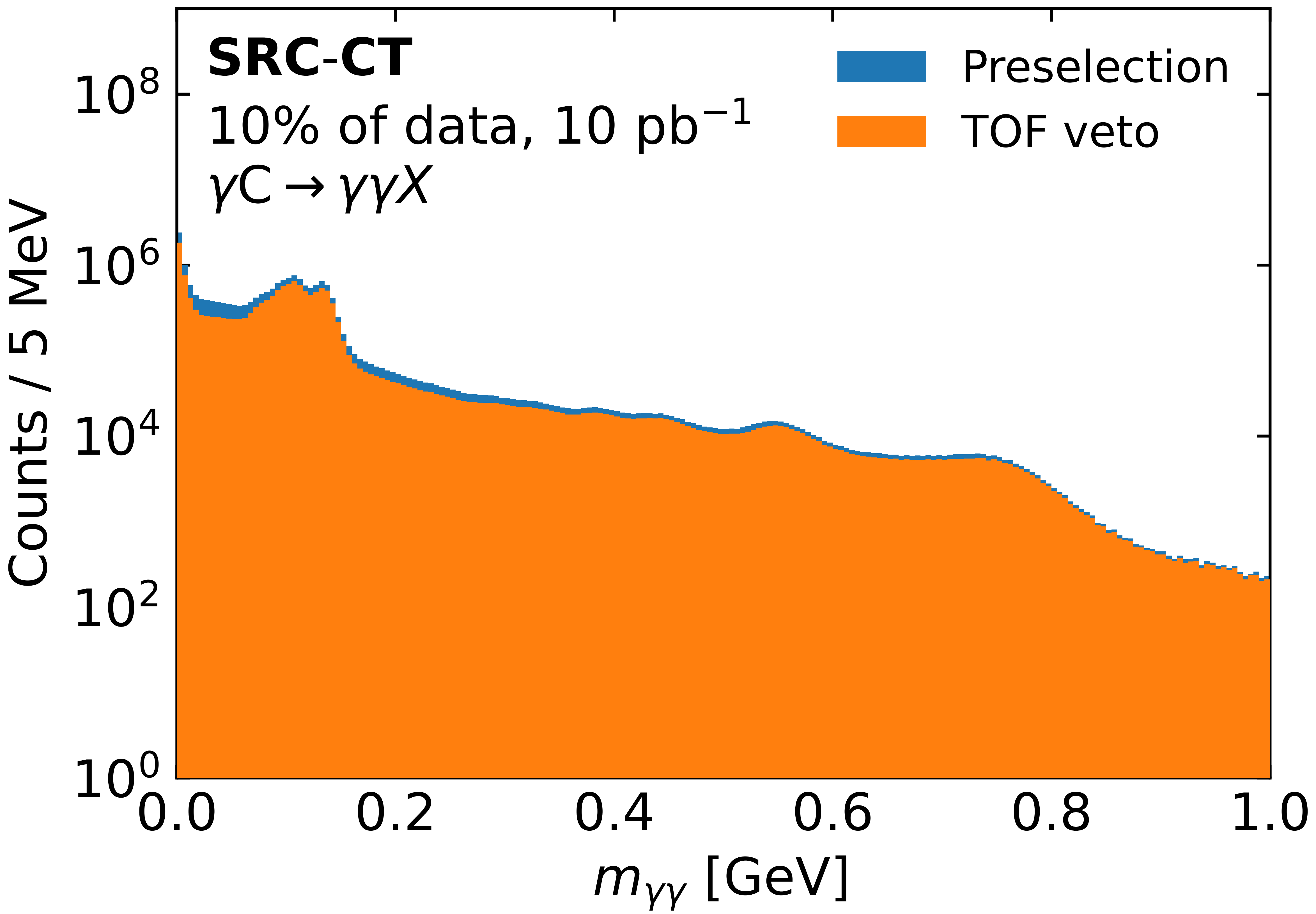

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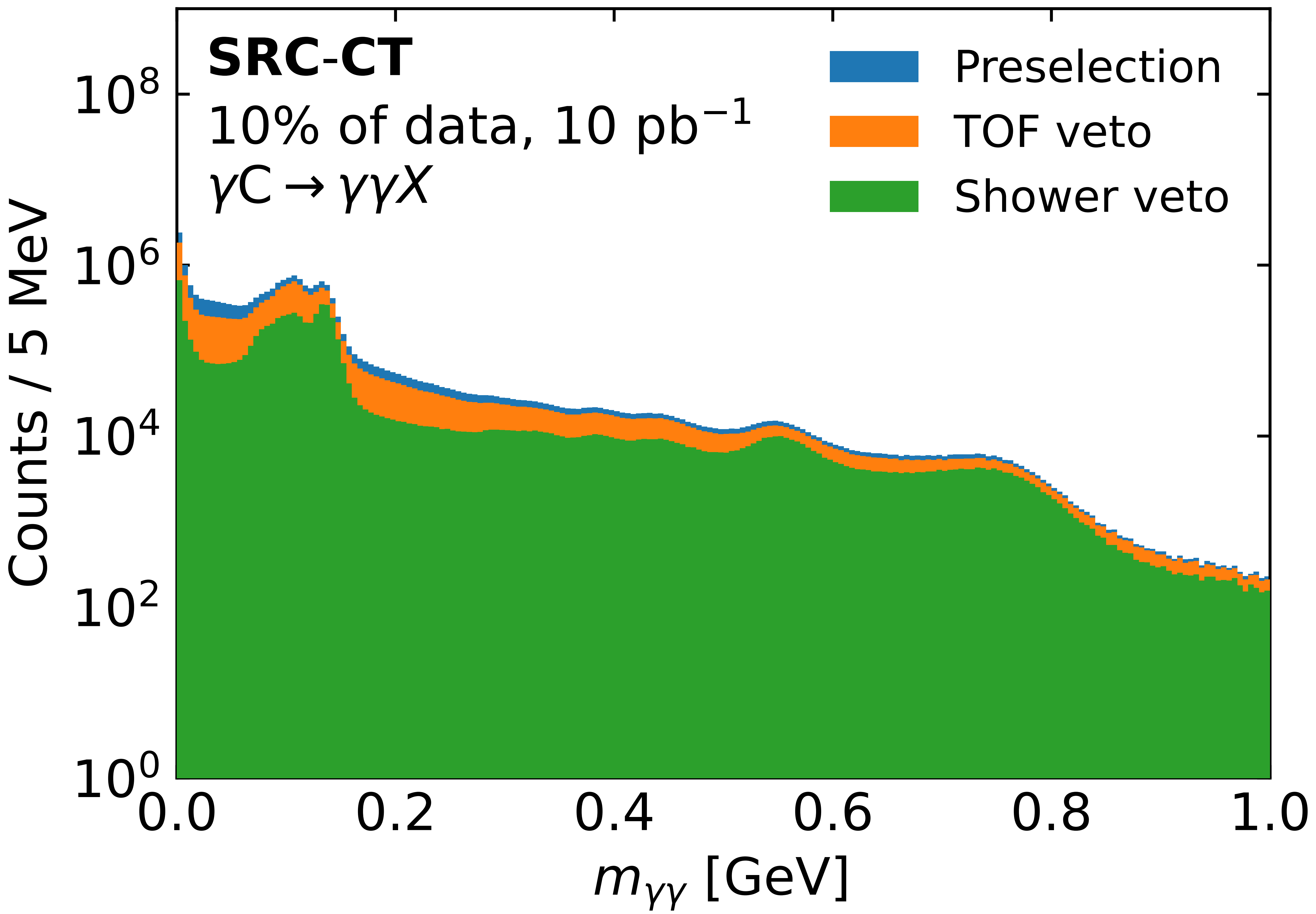

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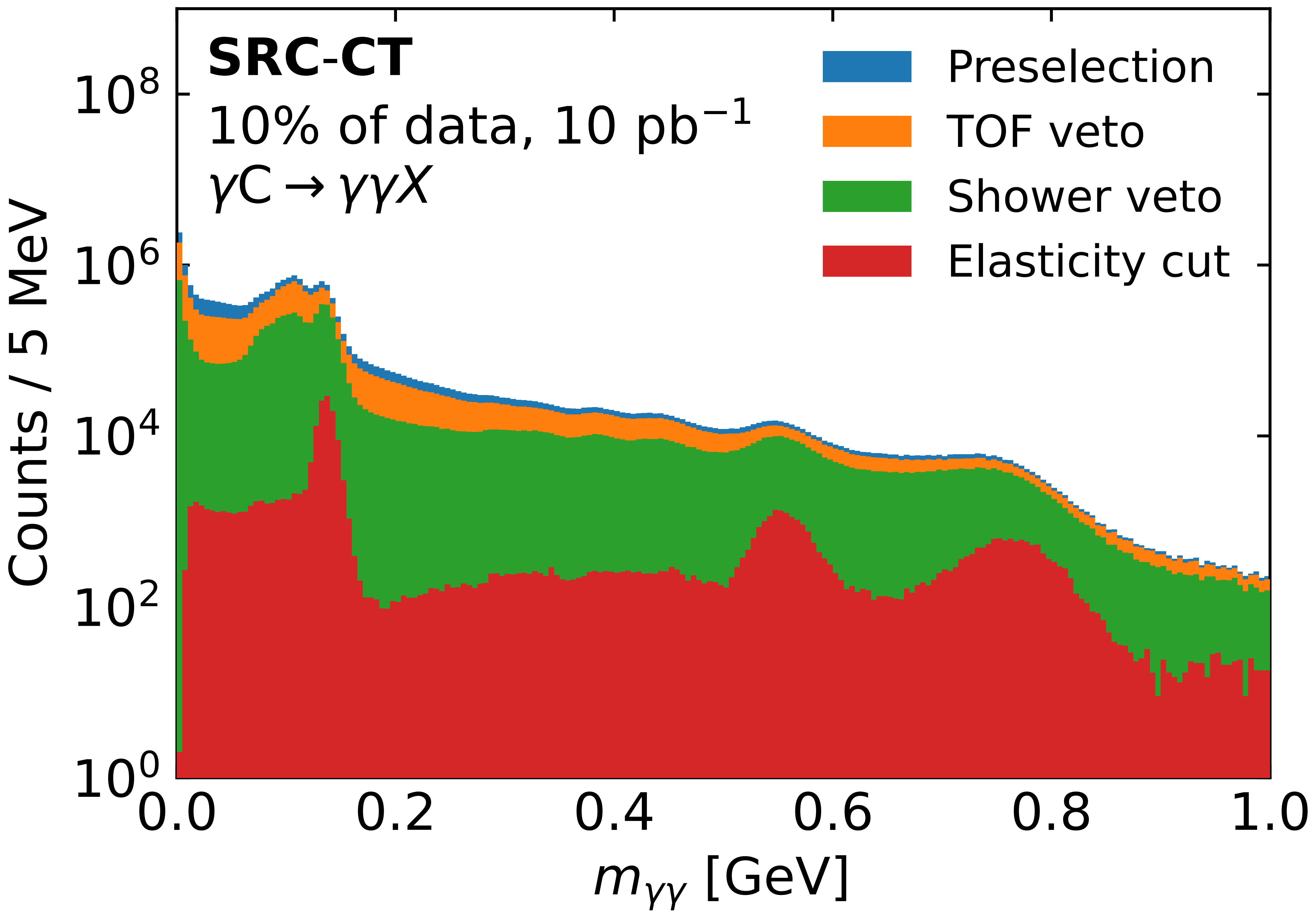

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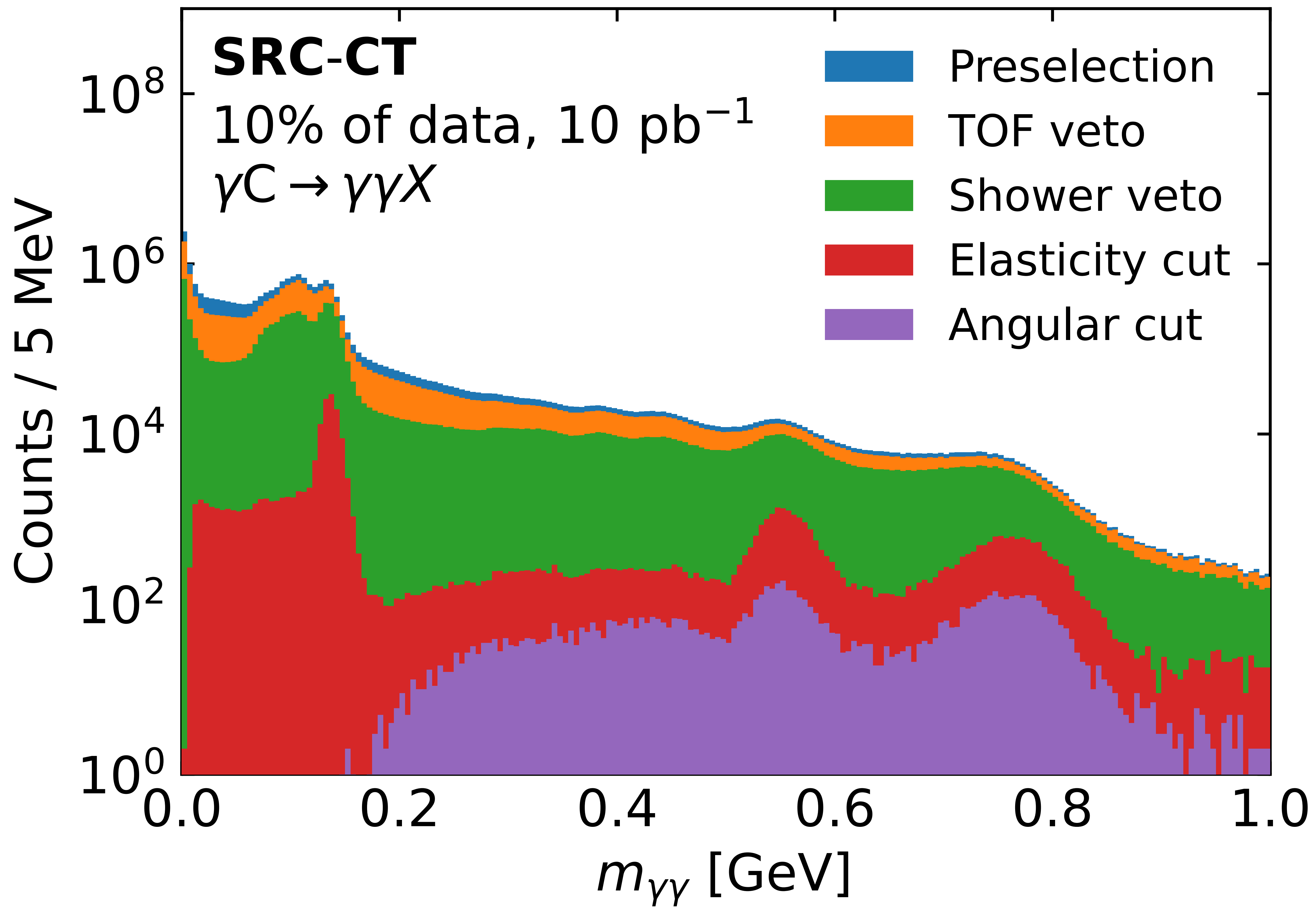
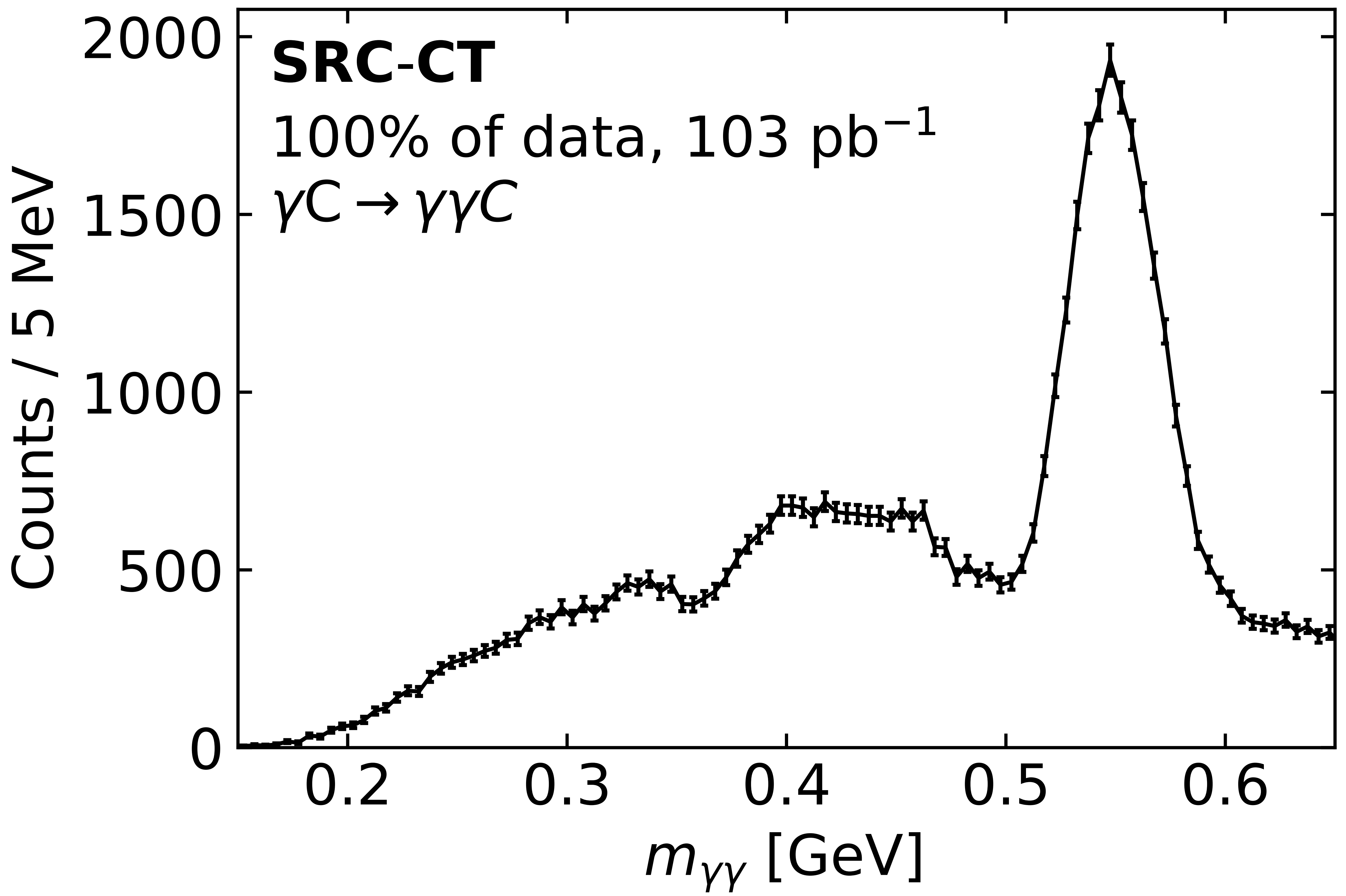


2-photon invariant mass spectrum

- Performing "bump hunt" over diphoton invariant mass, search for new resonance



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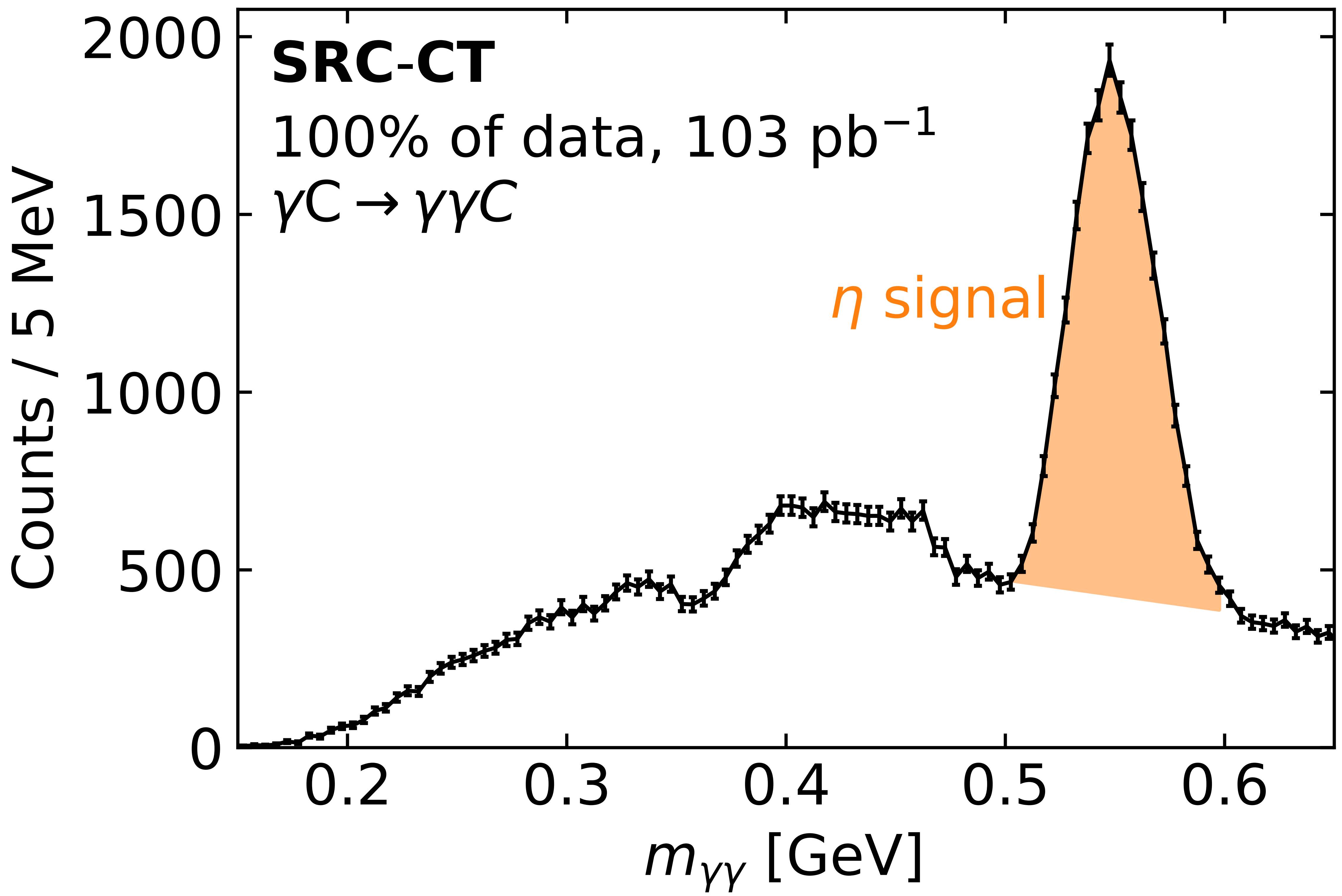

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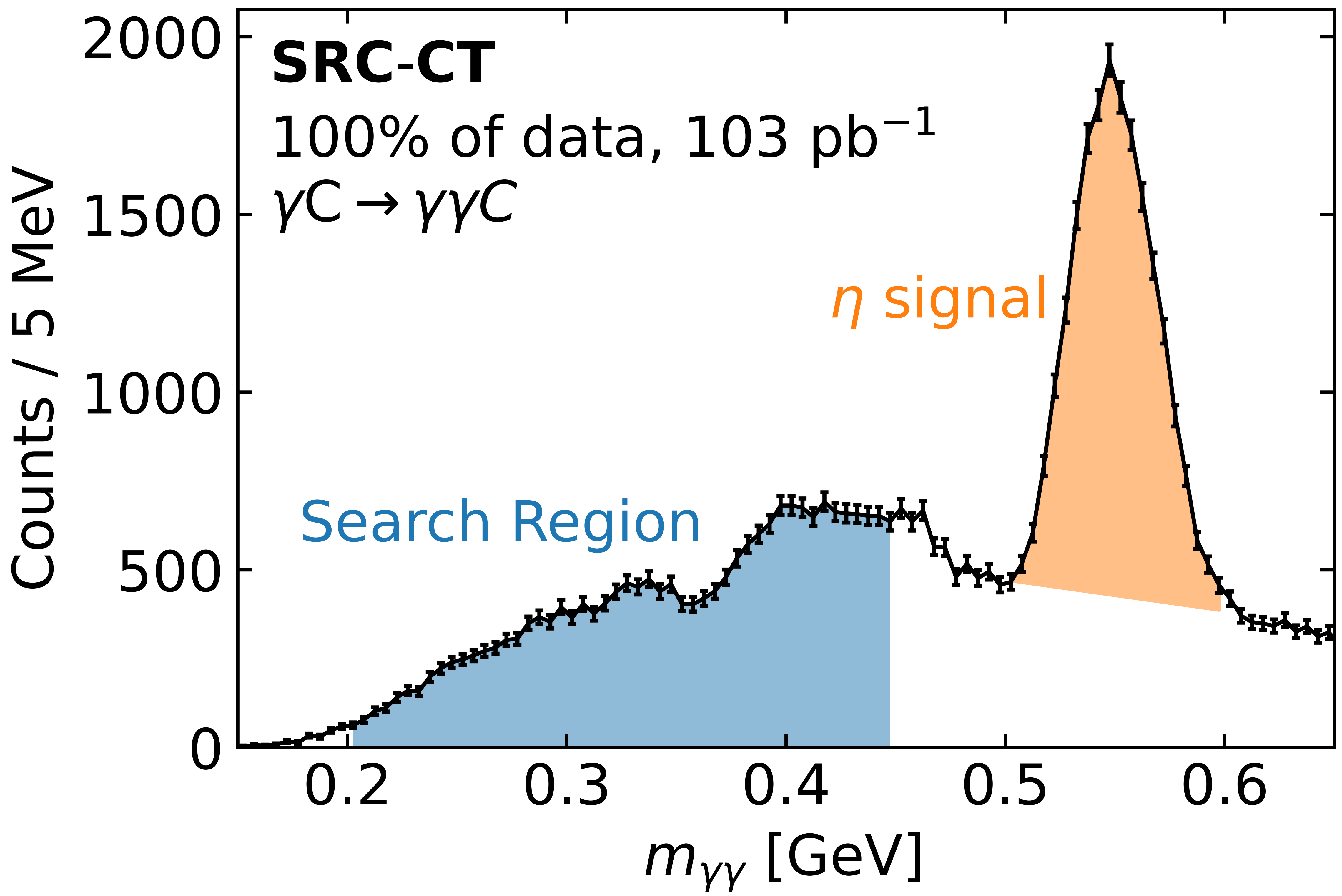

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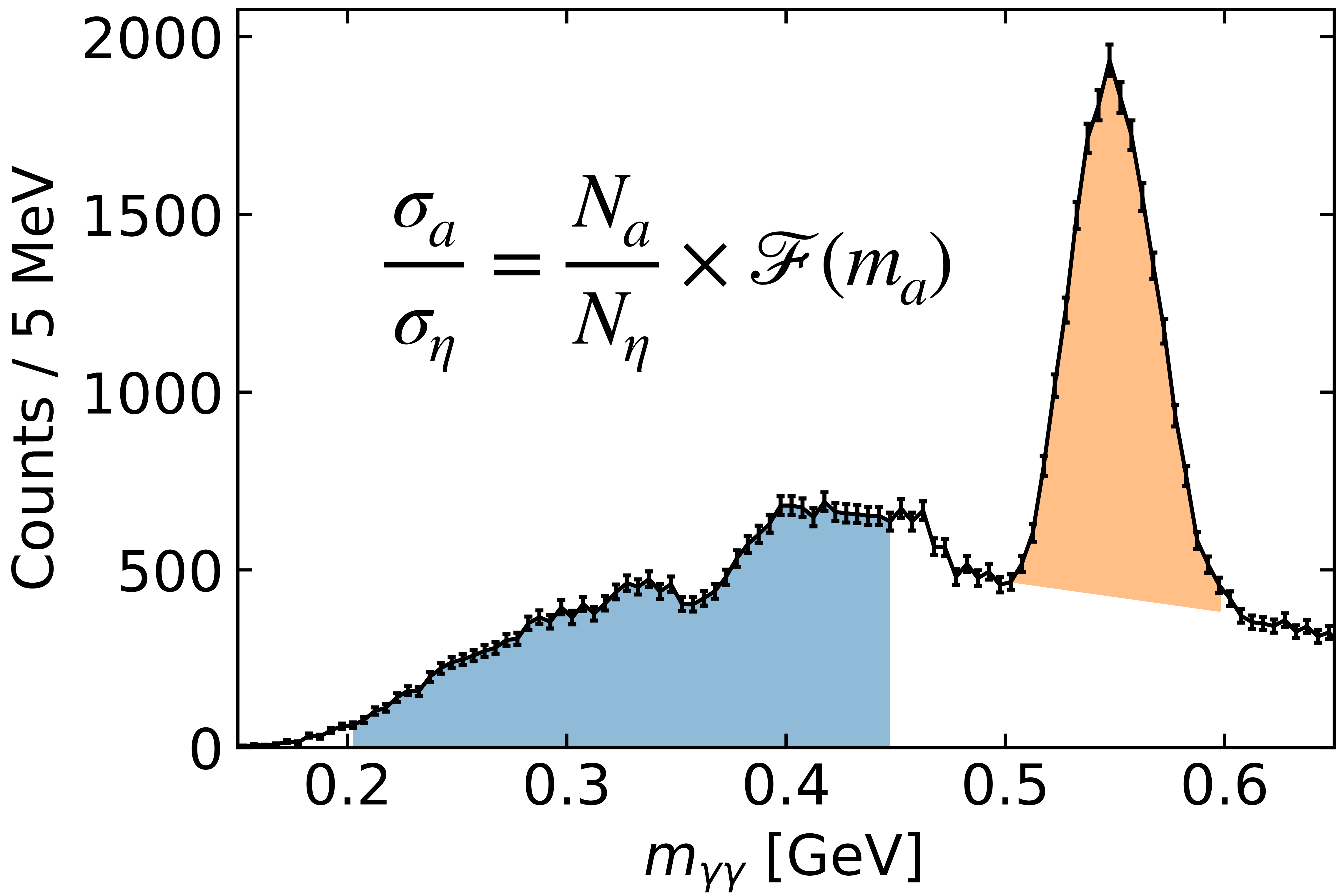
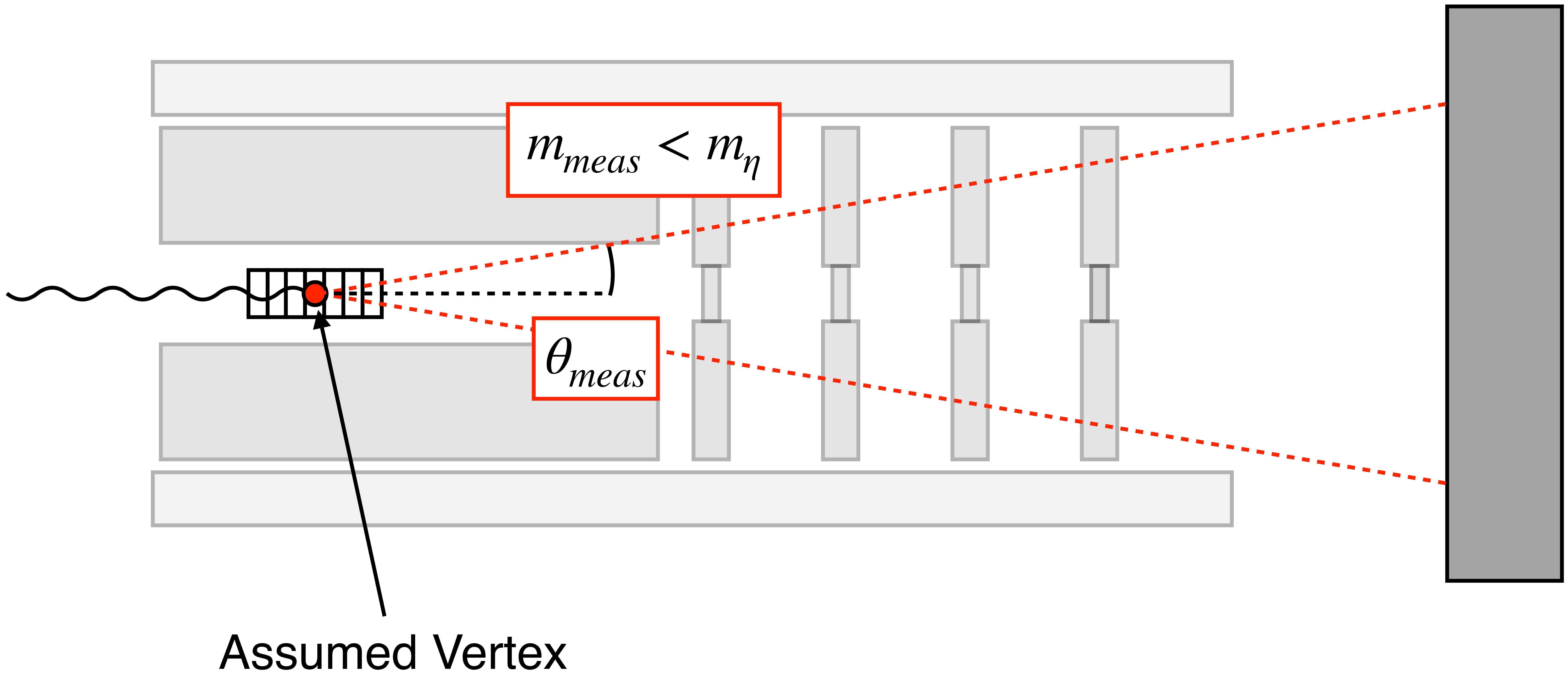
- Effective search region $200 < m_a < 450$ MeV/c^2
- Known η resonance serves as normalization/reference channel



Off-target backgrounds dominate search region



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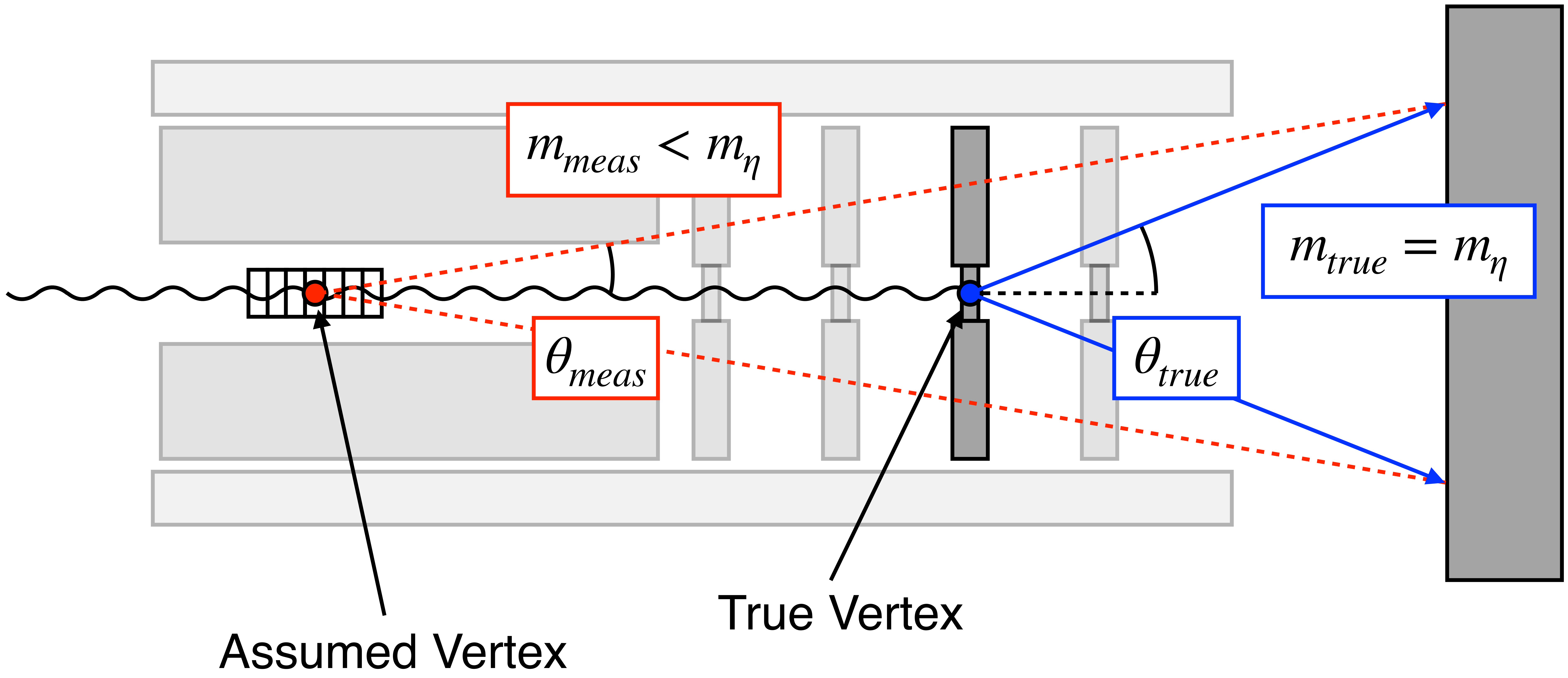
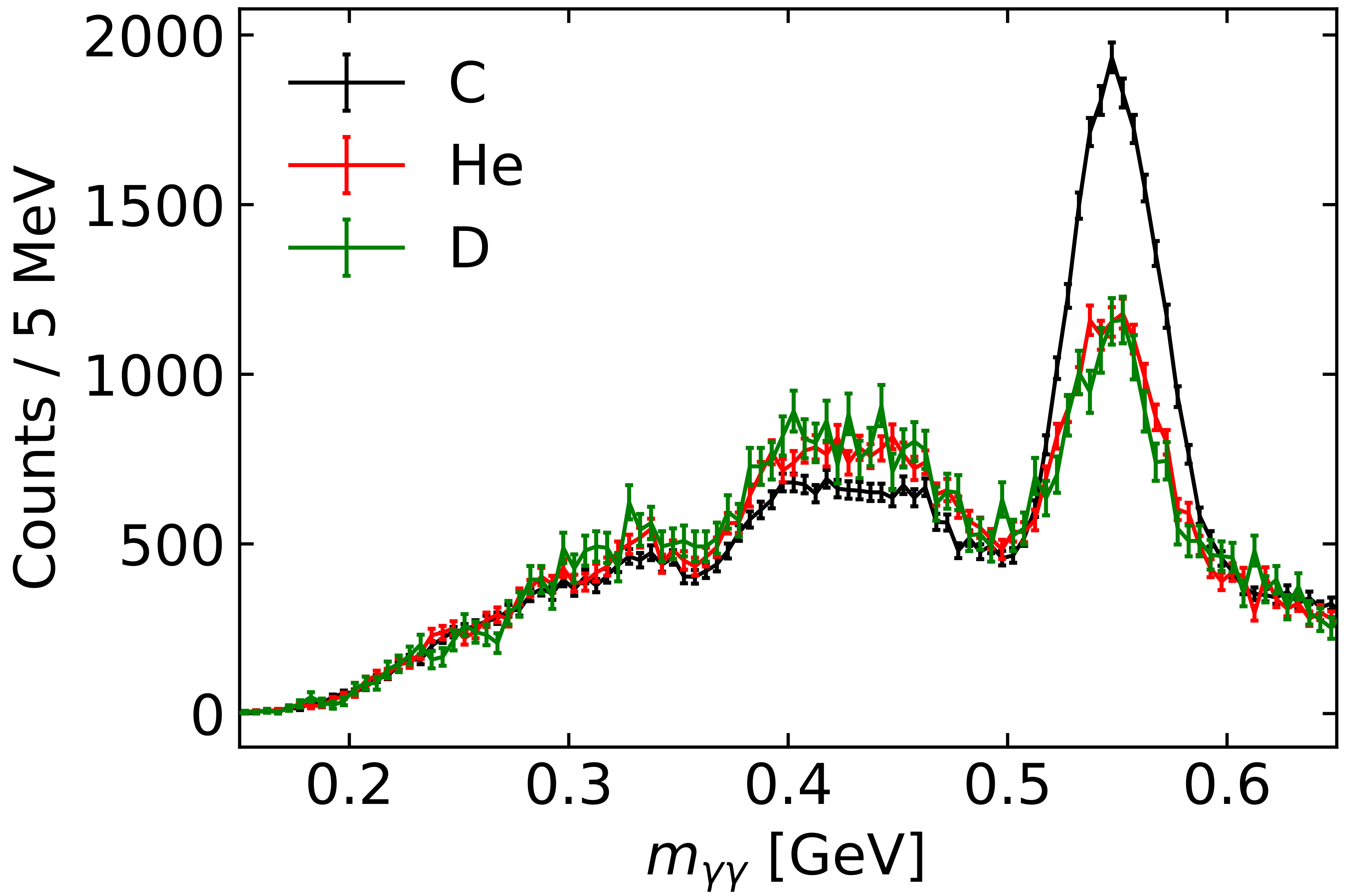
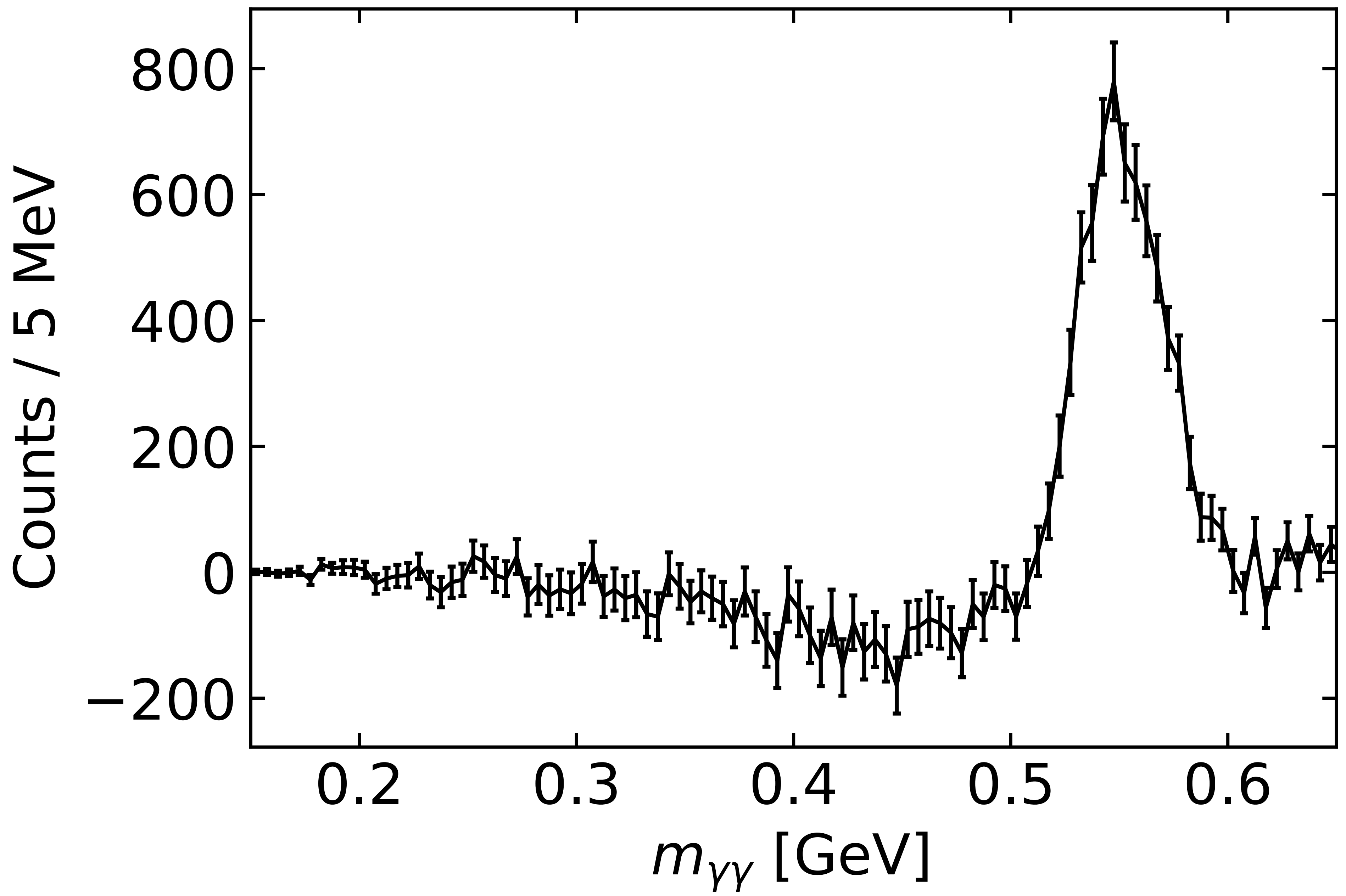


Comparing targets gives measure of beamline backgrounds





Subtract small-Z from large-Z to account for beamline effects

$$\sigma_{Primakoff} \sim Z^2$$

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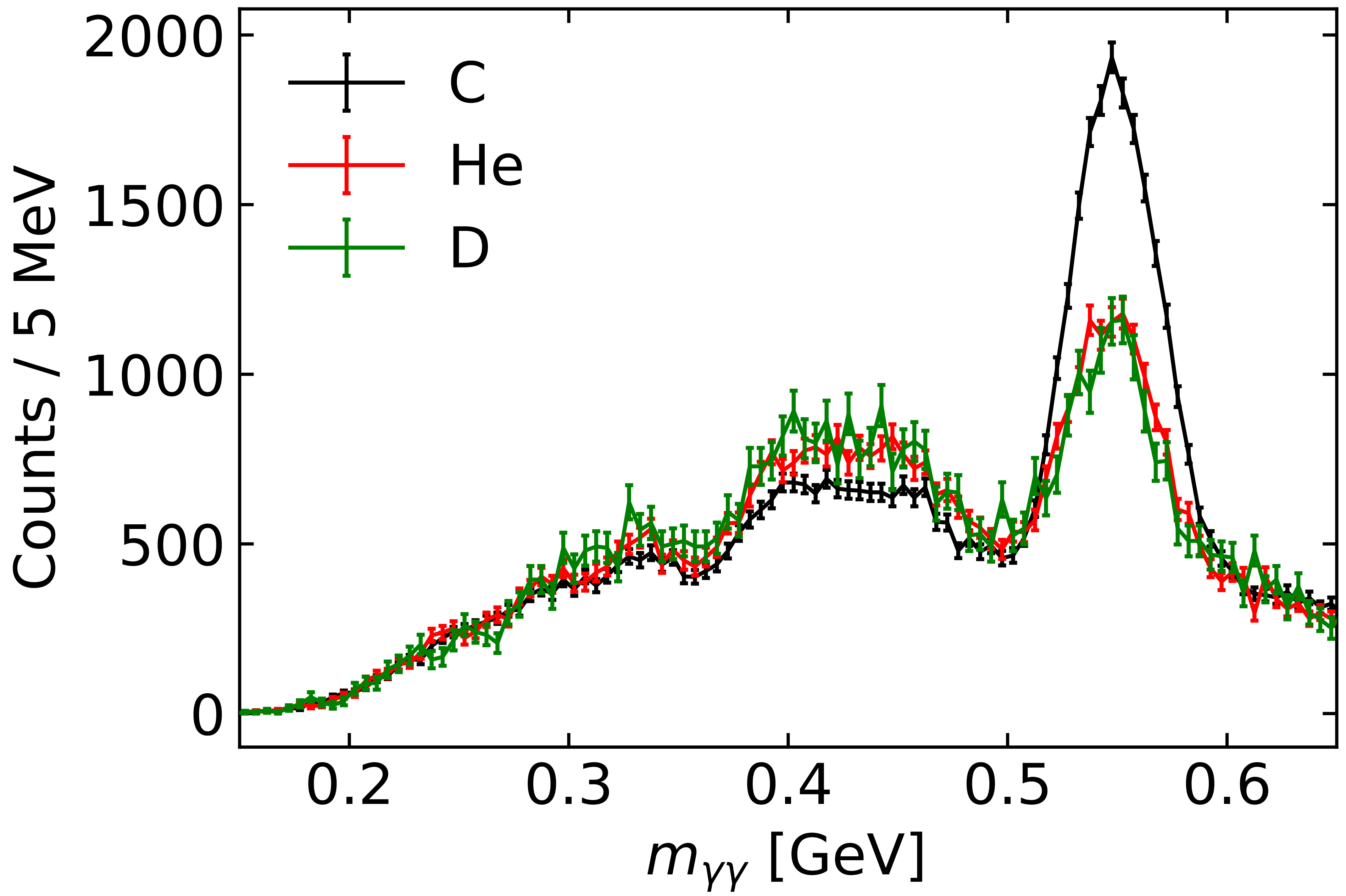

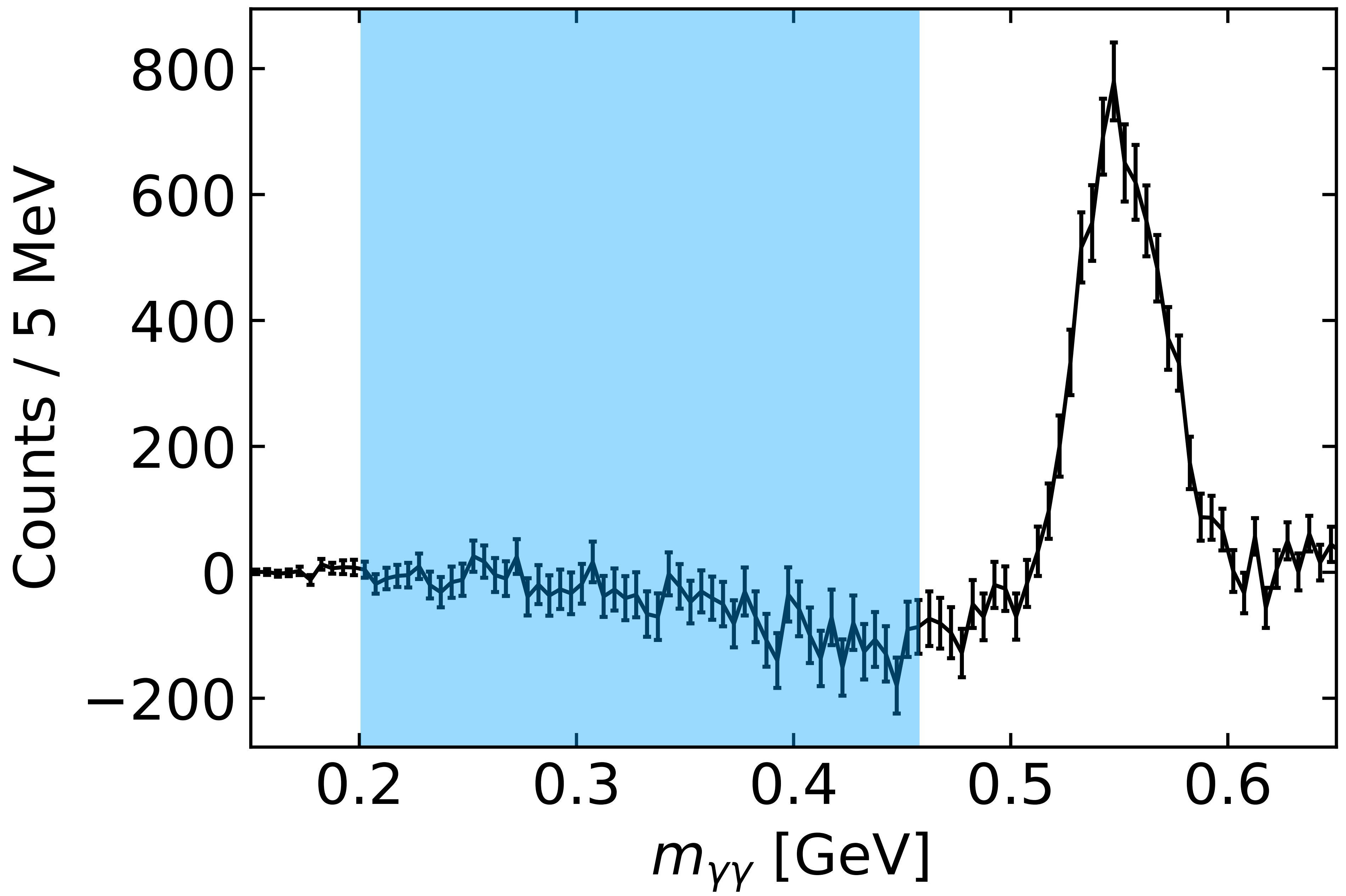

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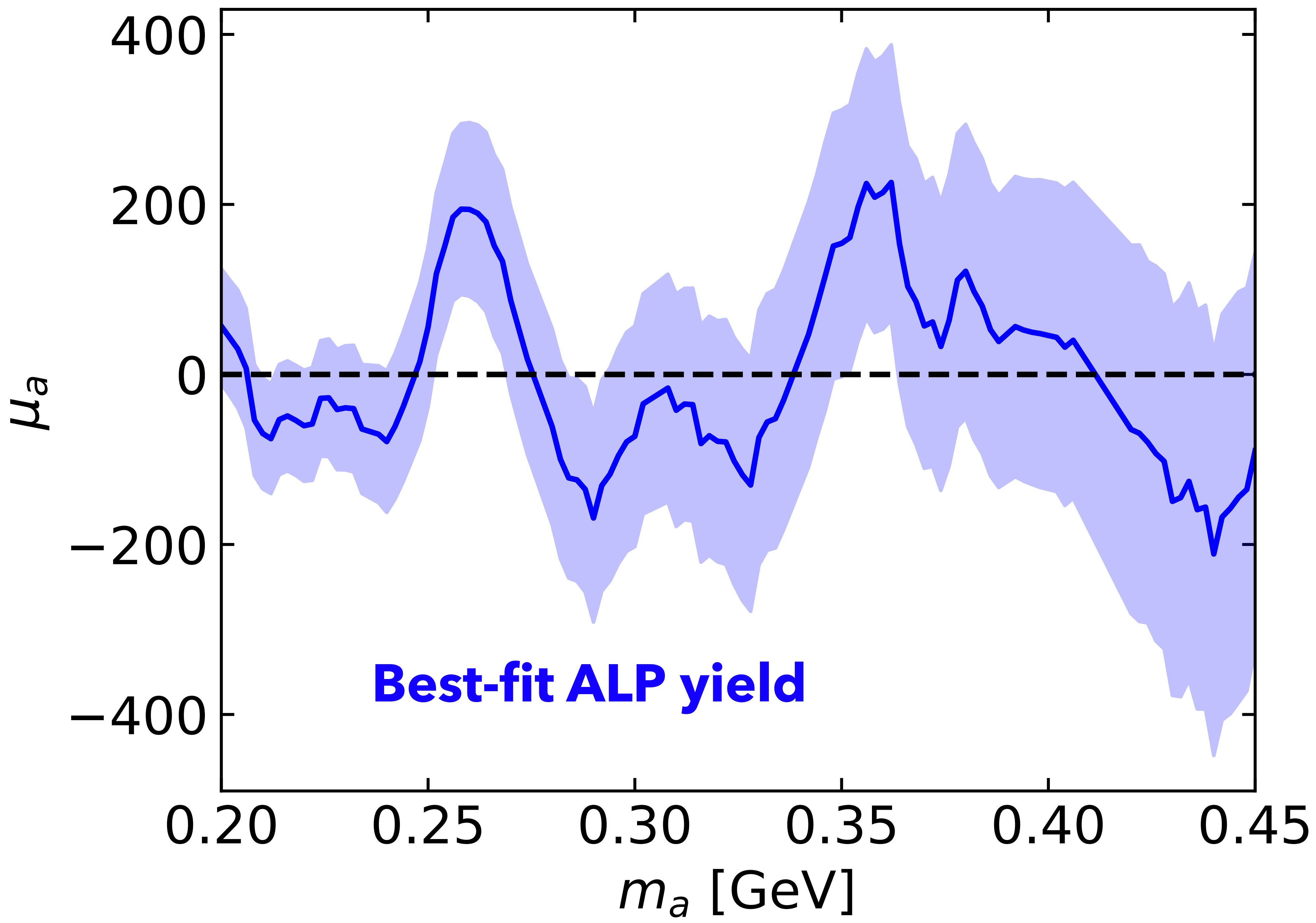
Search for bumps over polynomial background

Likelihood ratio test:

$$\lambda(\mu) = L(\mu)/L_{null}$$

First test: “Test of Discovery”



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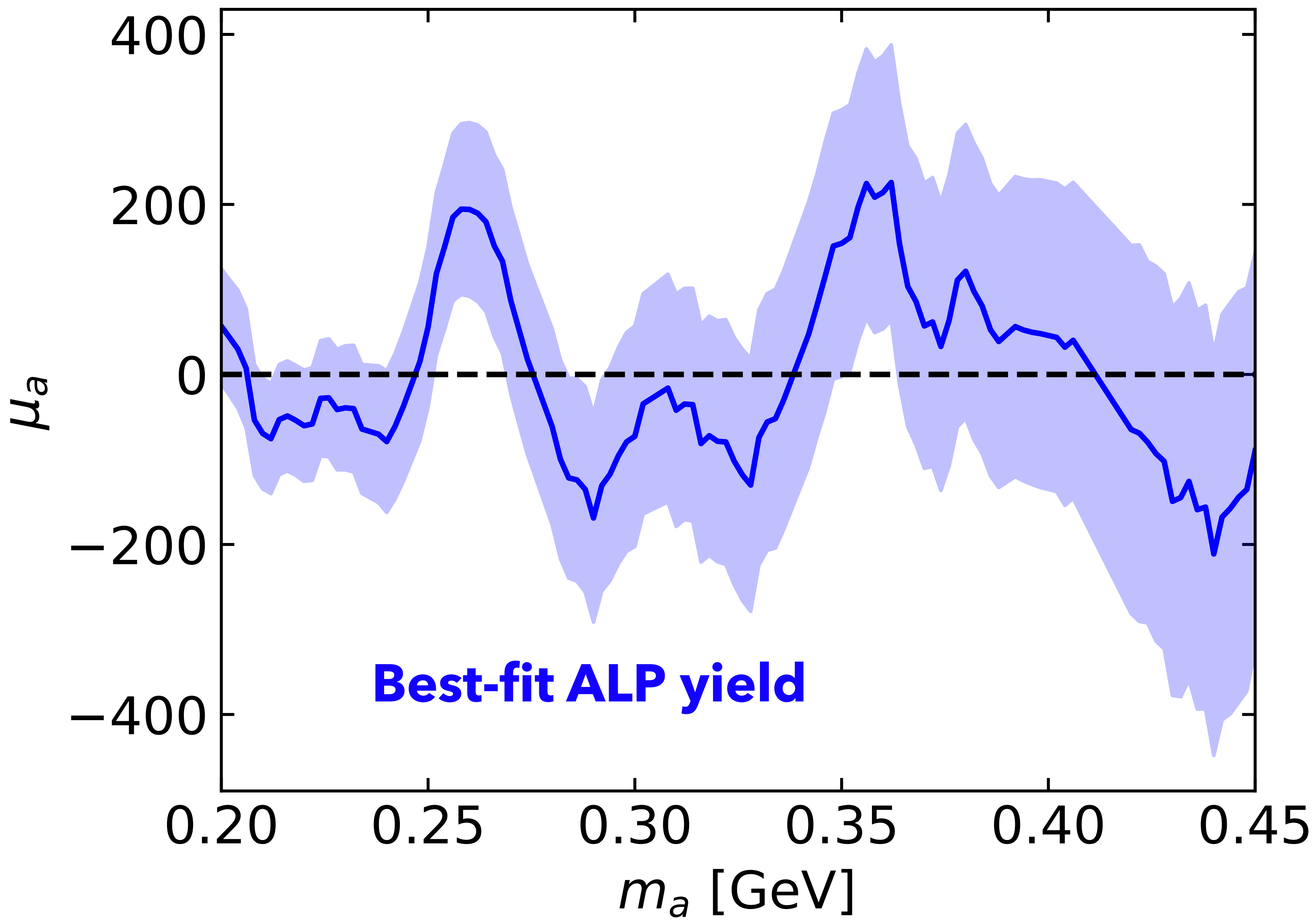

How well do the data reject the null hypothesis $\mu_a = 0$?

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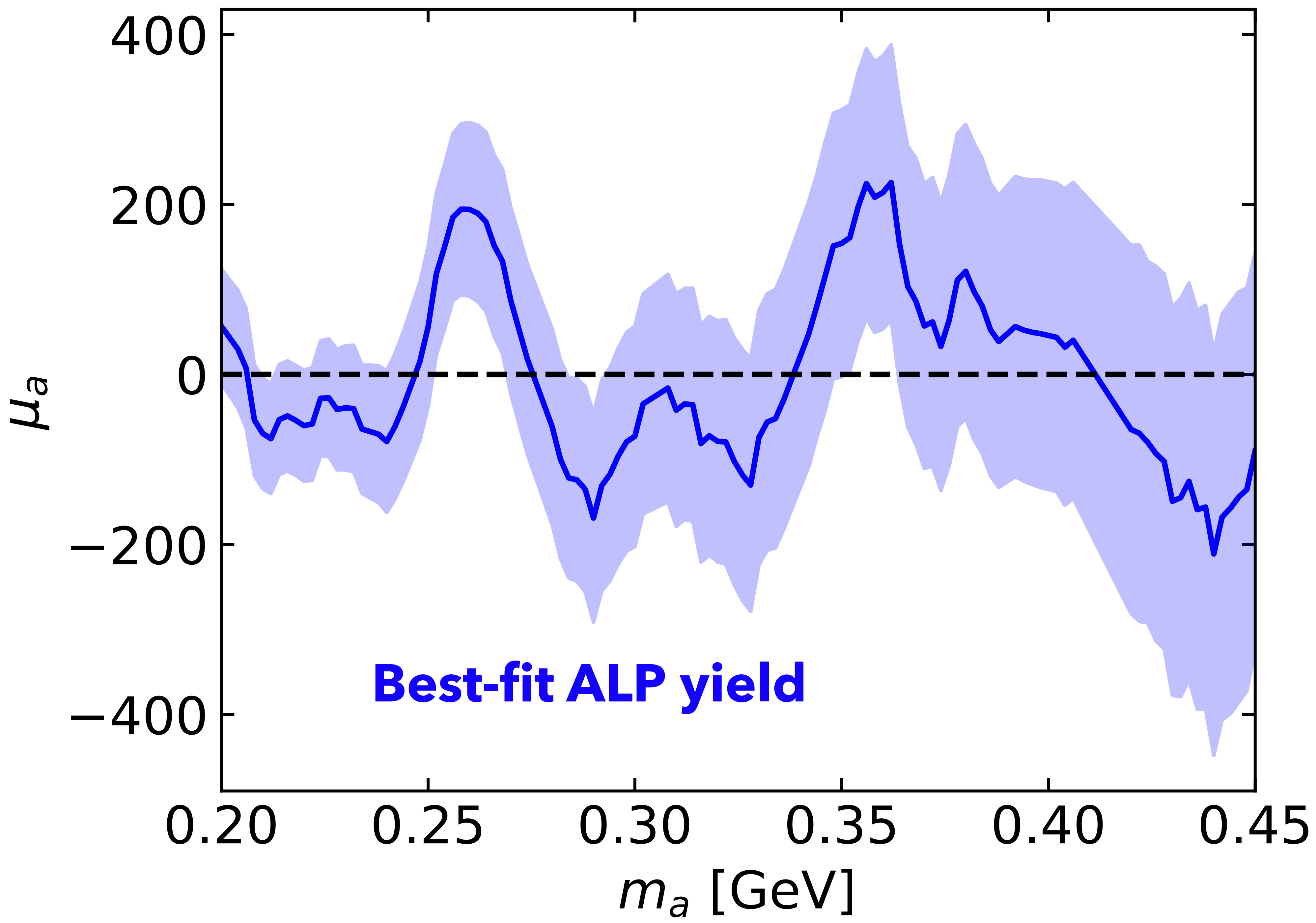

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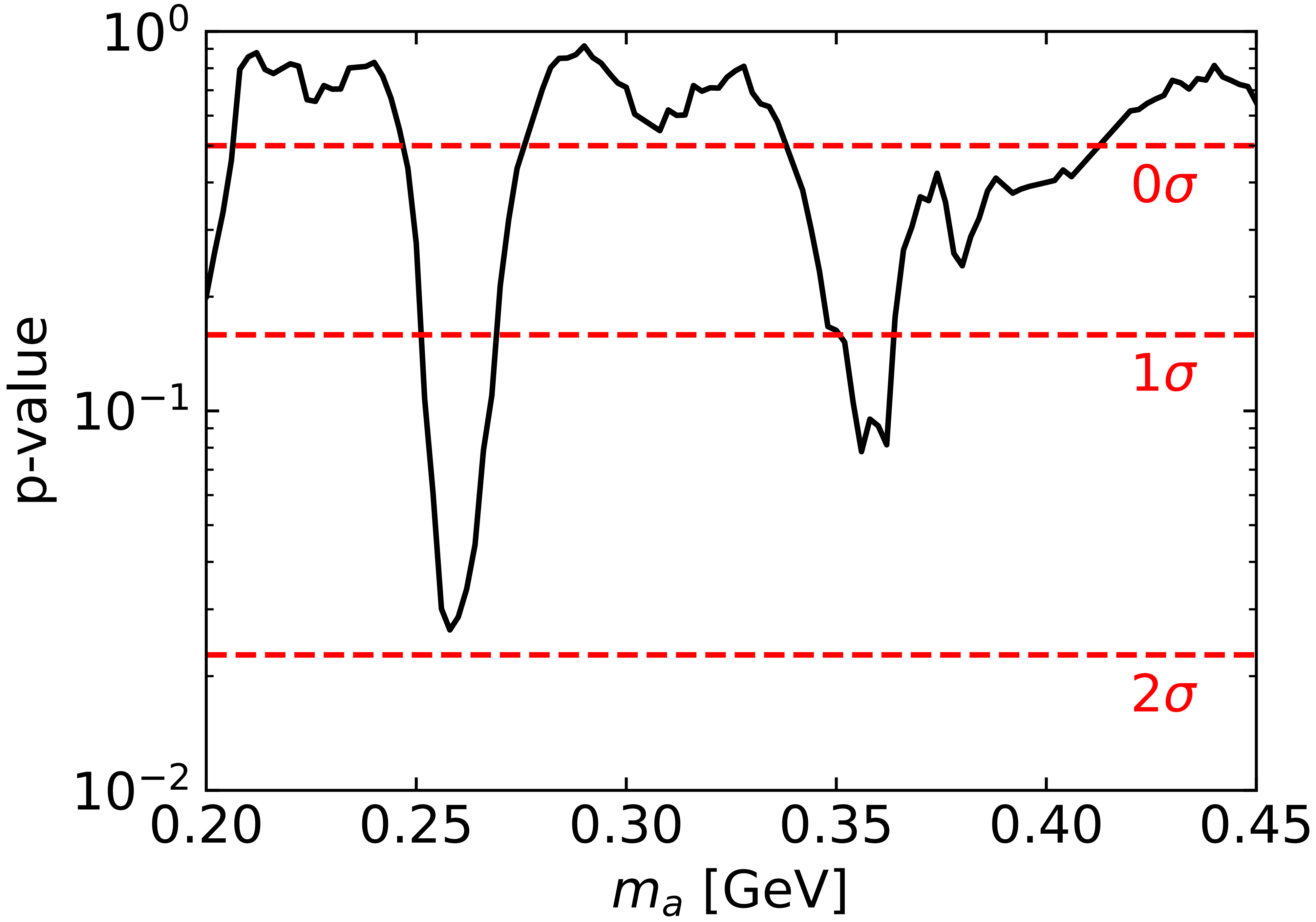
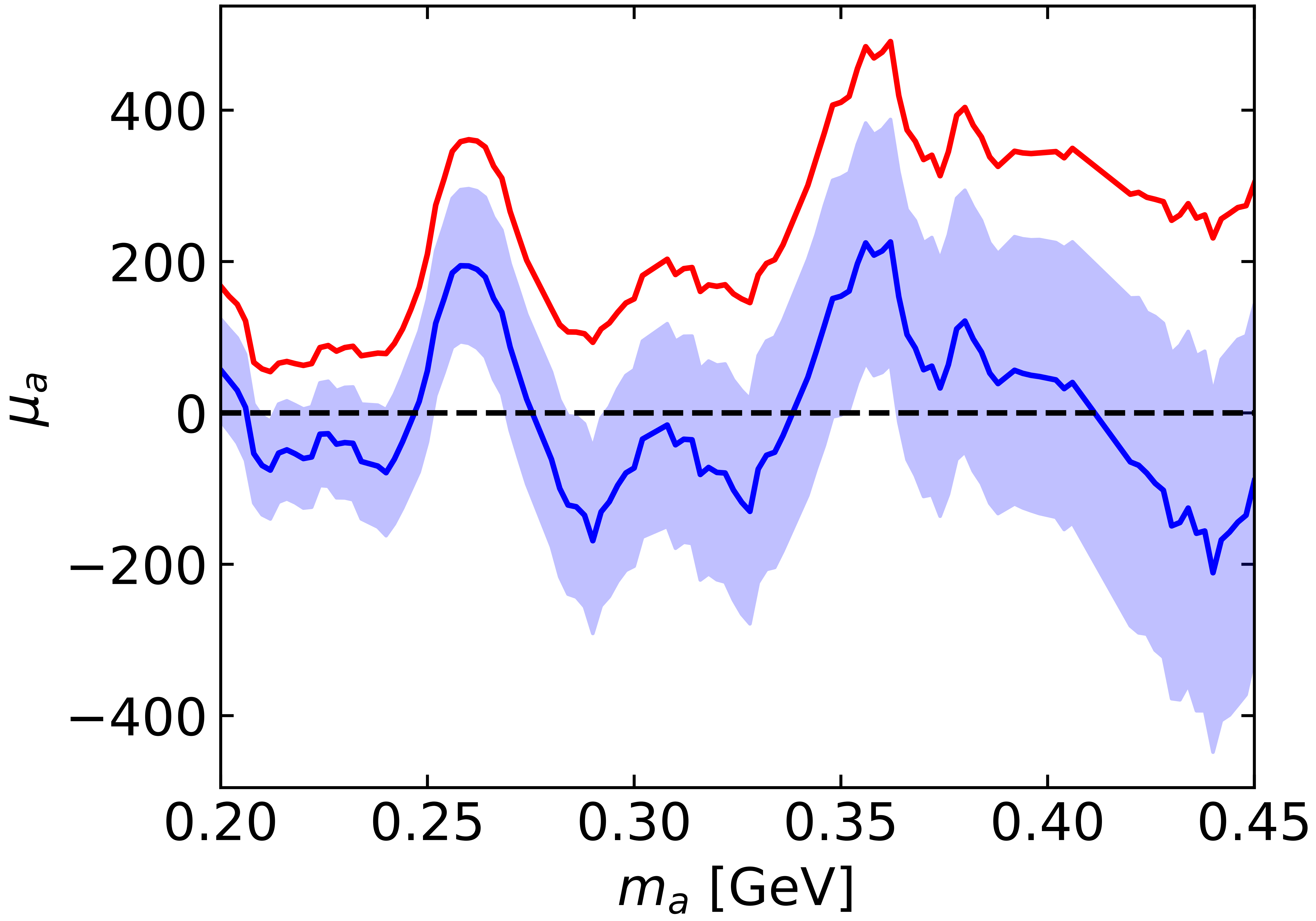


No statistically significant excess observed

Second test: "Test of Exclusion"



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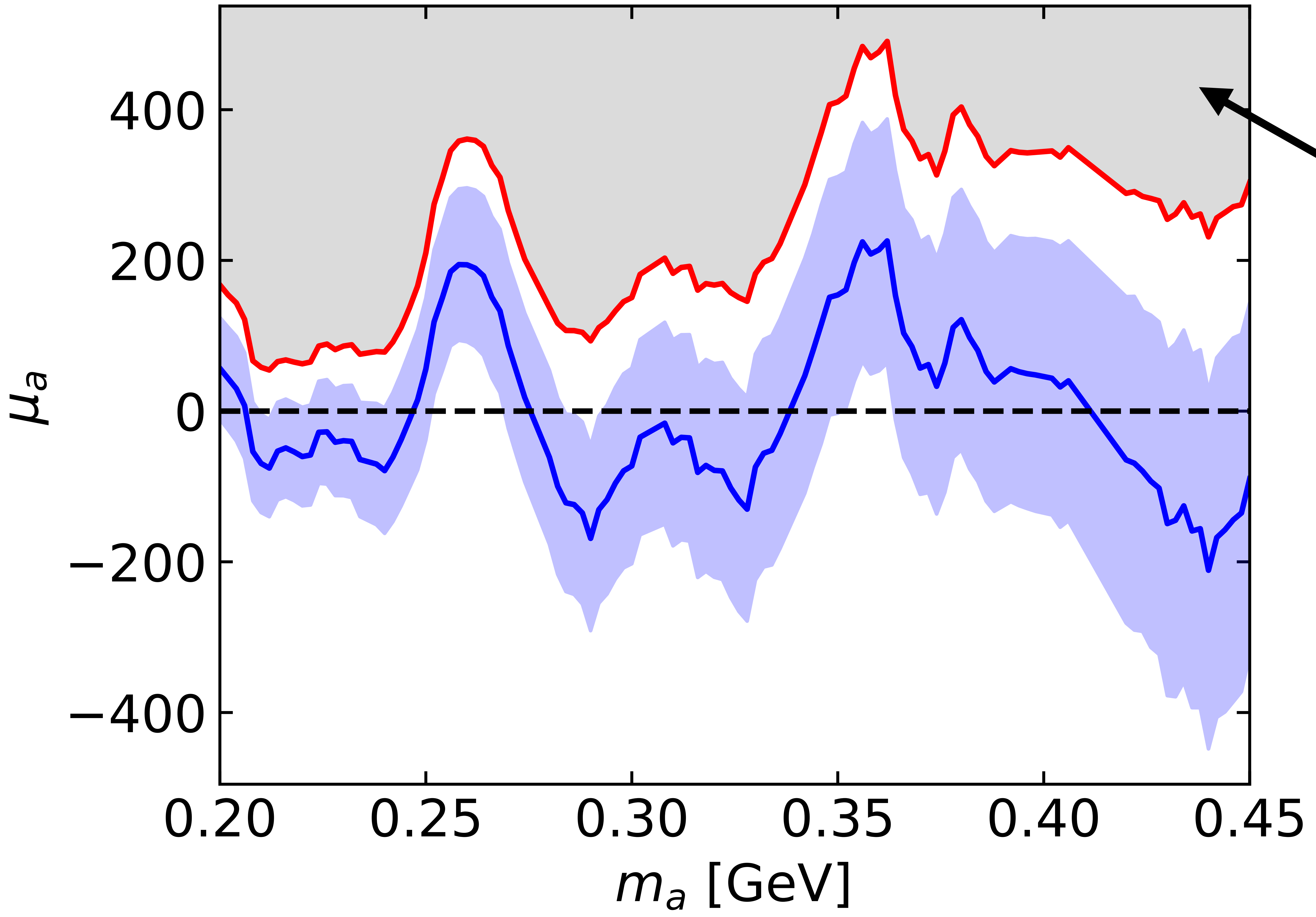
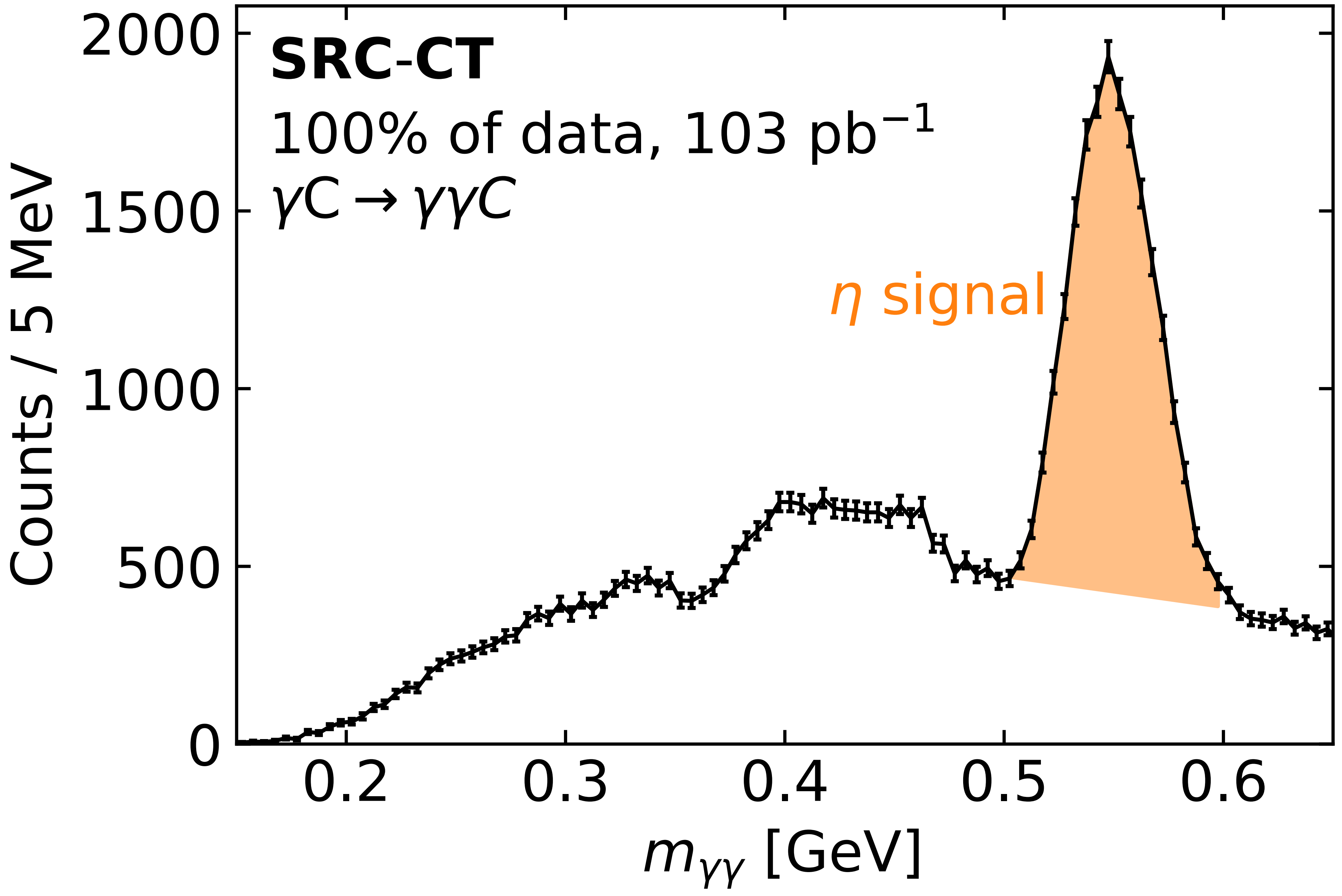
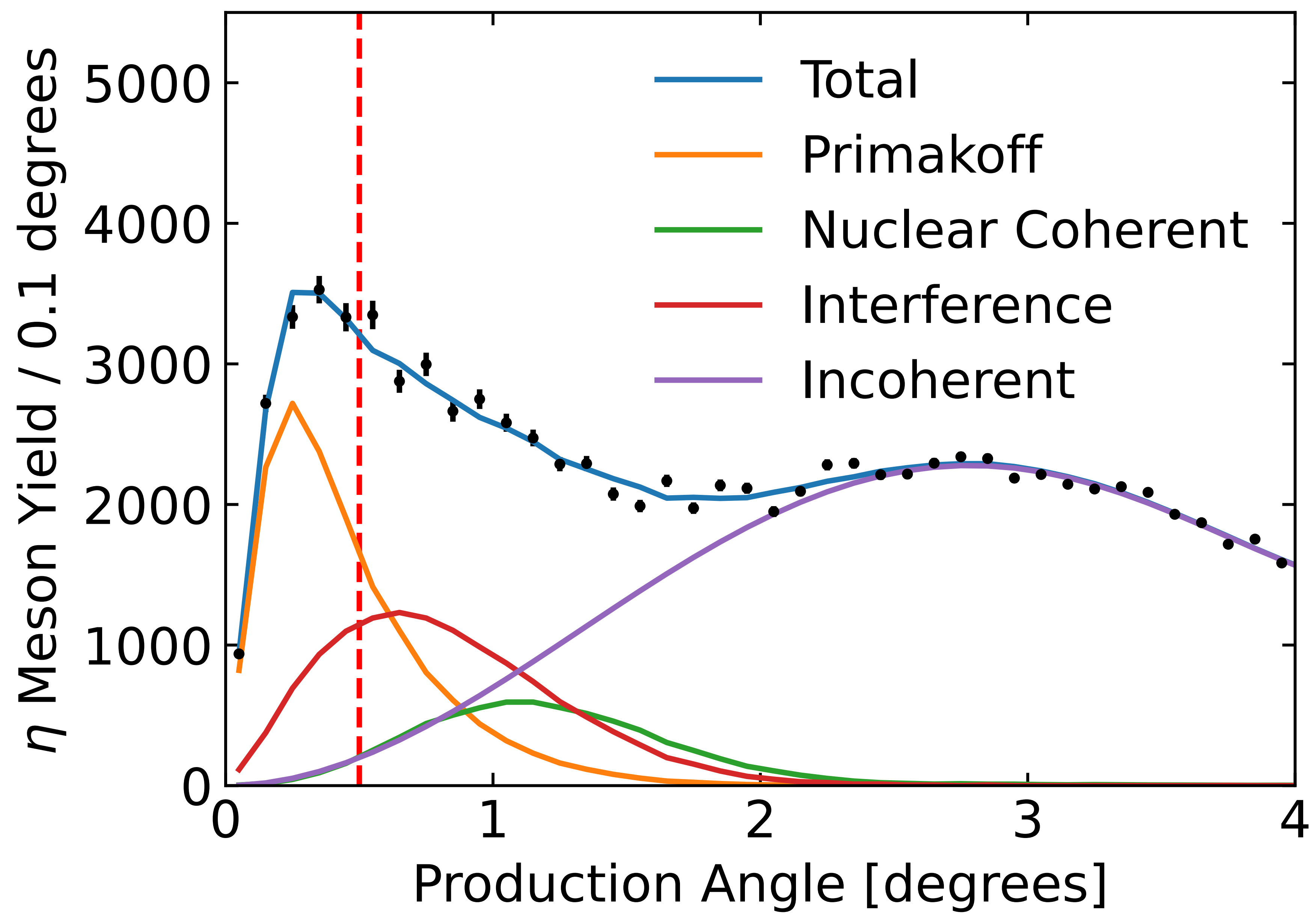


Excluded at 95% CL

Normalize ALP yield to measured Primakoff η





Angular distribution used to determine Primakoff contribution to η production

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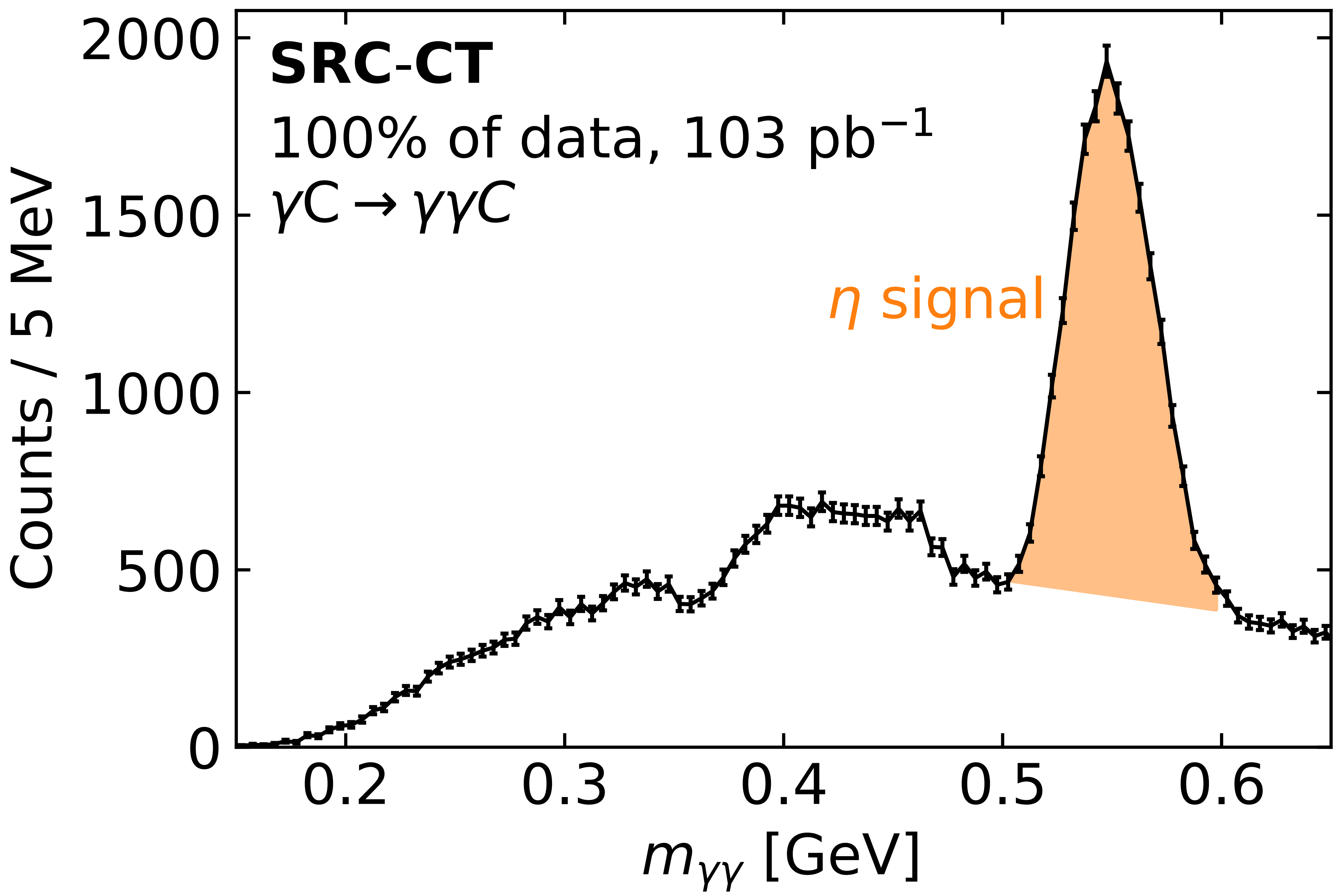
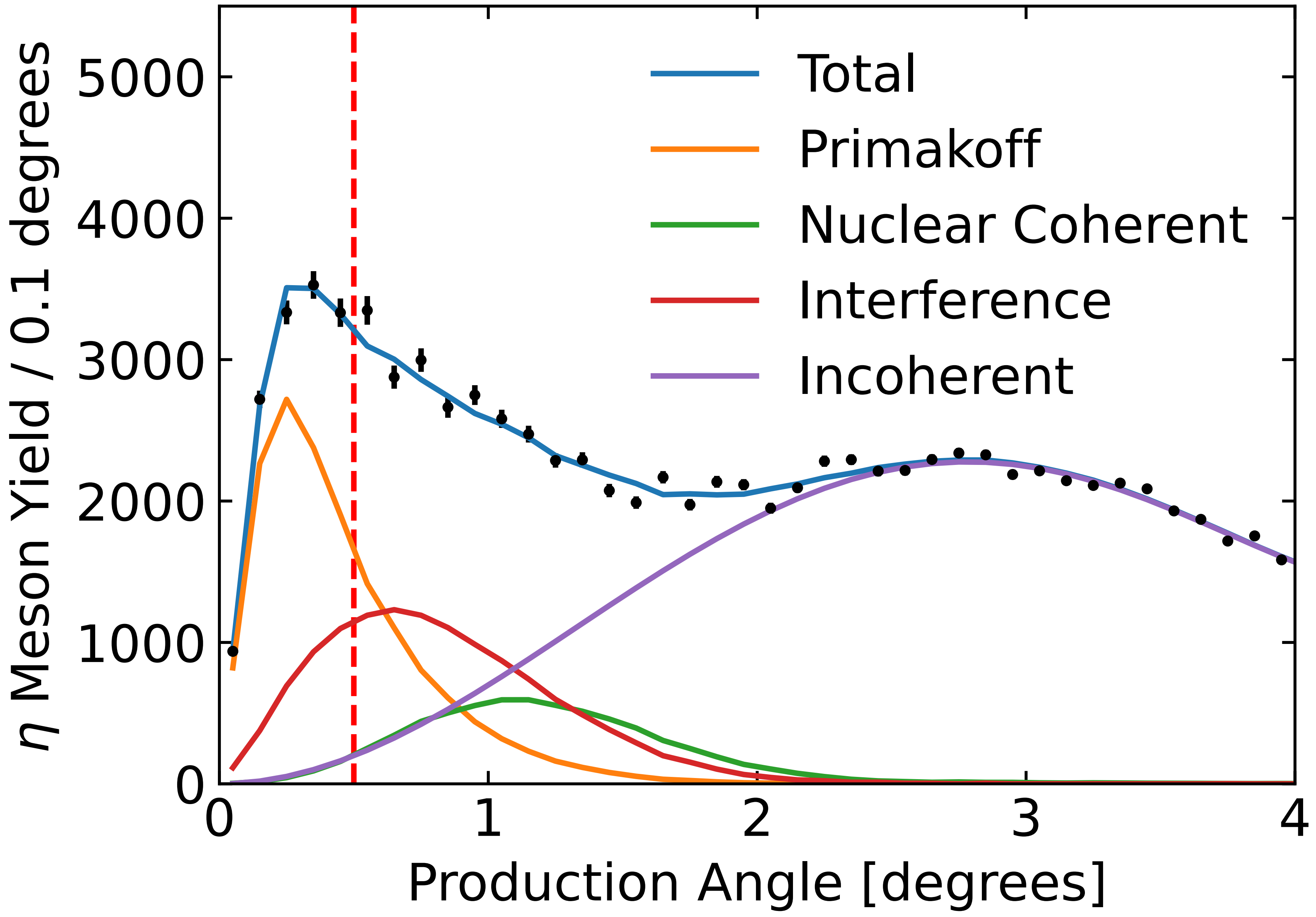
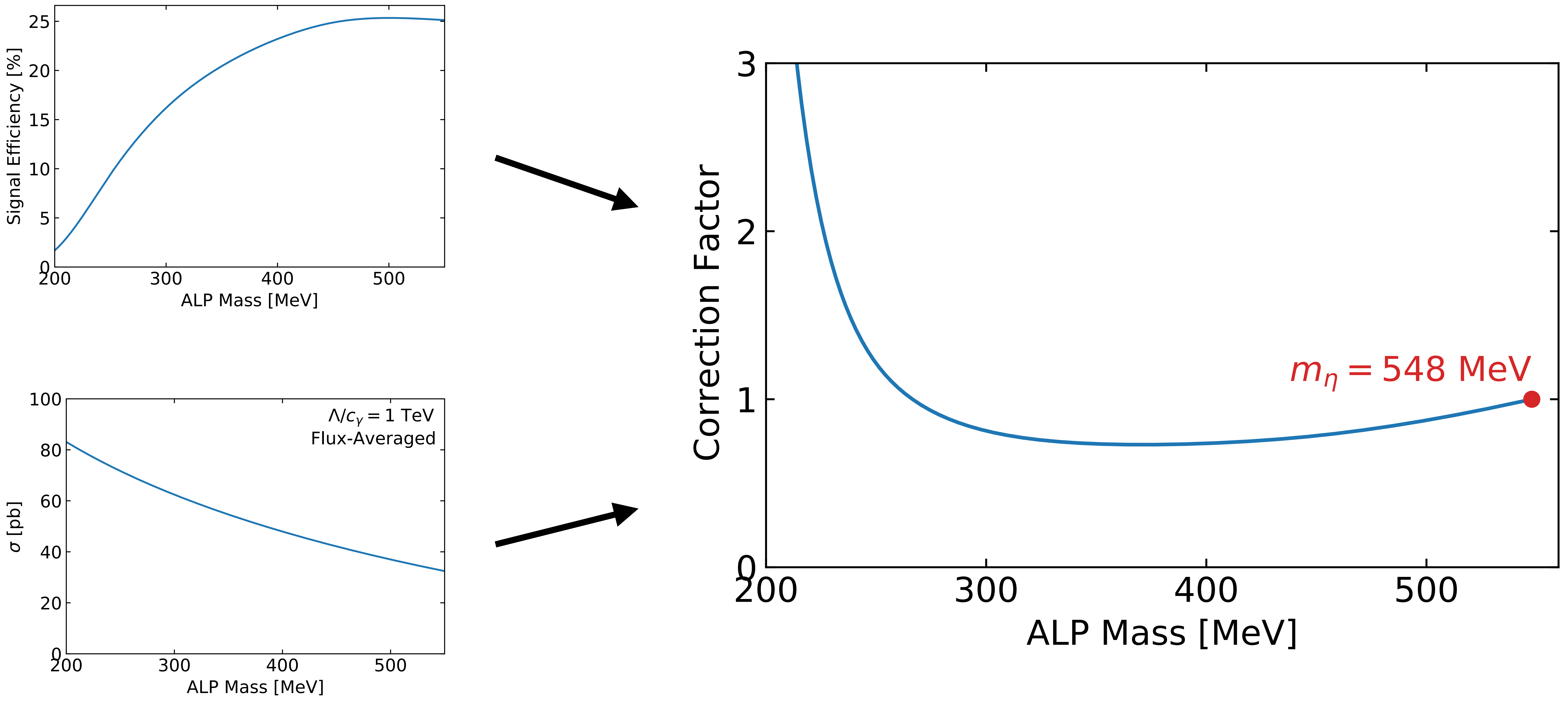




Angular distribution used to determine Primakoff contribution to η production

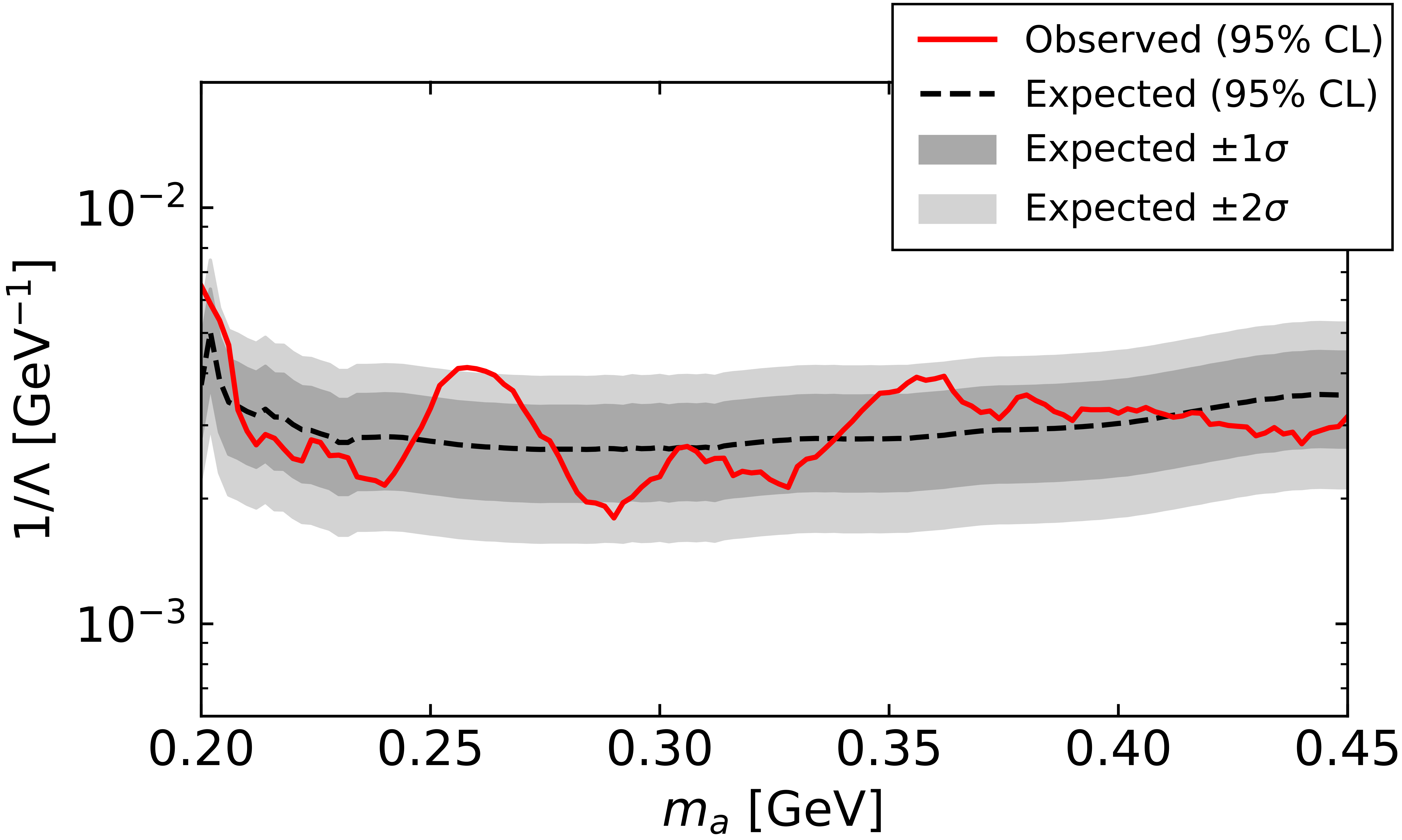
(More detailed study of Primakoff production ongoing in PrimEx and SRC-CT data)

Yield corrected for mass-dependent efficiency and cross-section effects

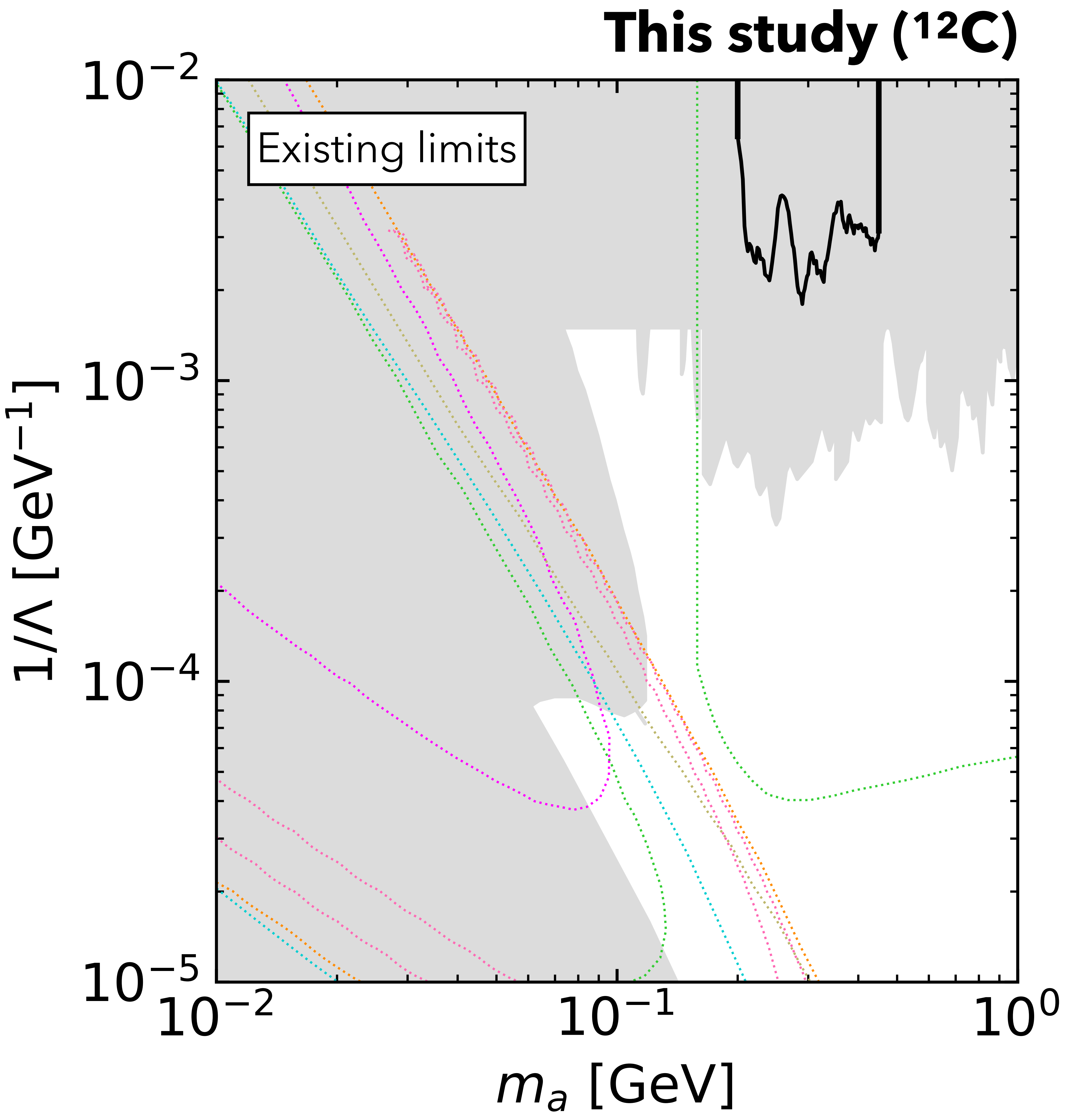


Limits on ALP yield convert to limit on coupling

$$\frac{1}{\Lambda^2} \sim \frac{N_a}{N_\eta}\Gamma_{\eta\to\gamma\gamma}$$



How do we compare with world limits?



- Limits are reasonable but surpassed by world data
  - Short experiment, split between several light nuclei

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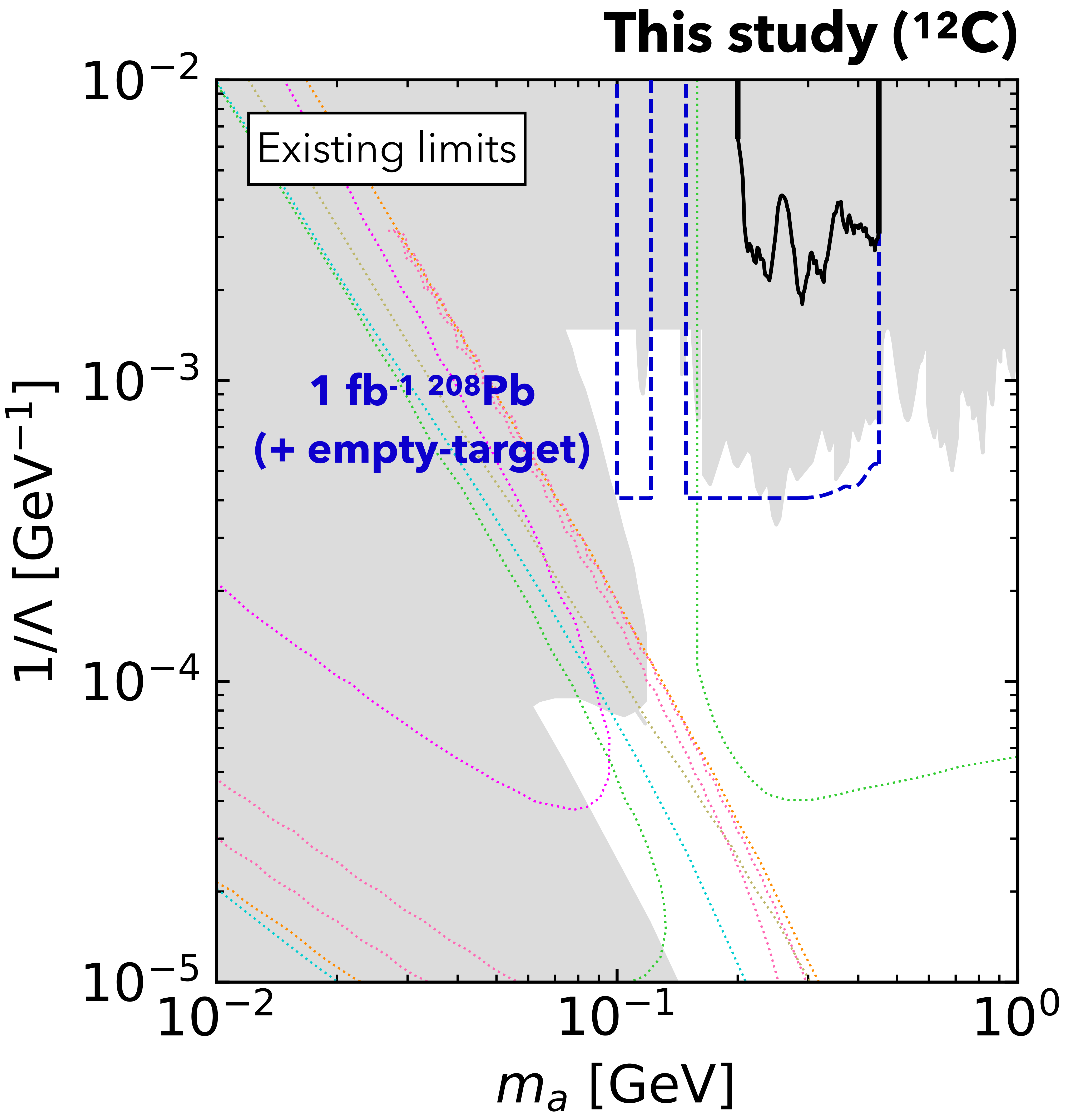
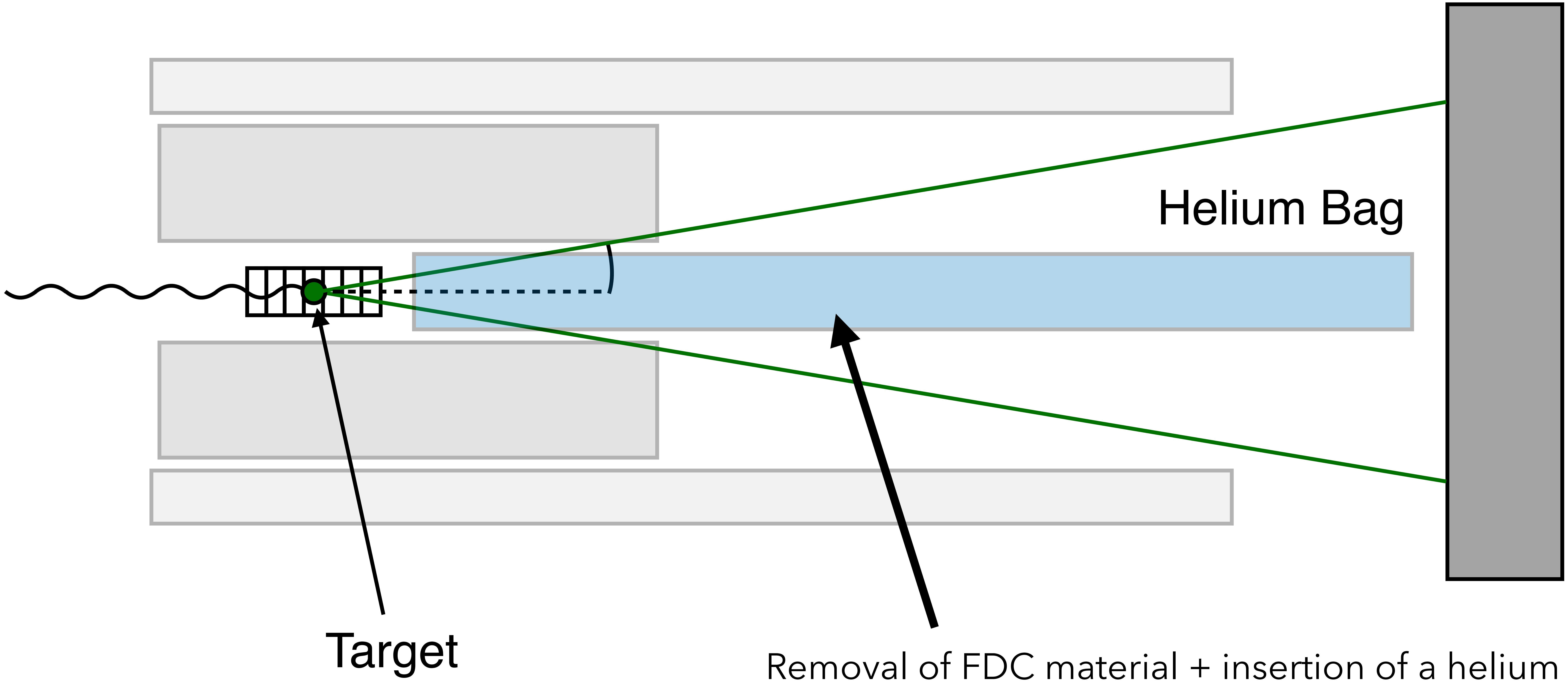


- Limits are reasonable but surpassed by world data
    - Short experiment, split between several light nuclei
- What about a dedicated run with large Z?

Limiting factor is beamline background; Removing material reduces backgrounds



Removal of FDC material + insertion of a helium balloon reduces beamline material by $40\times$

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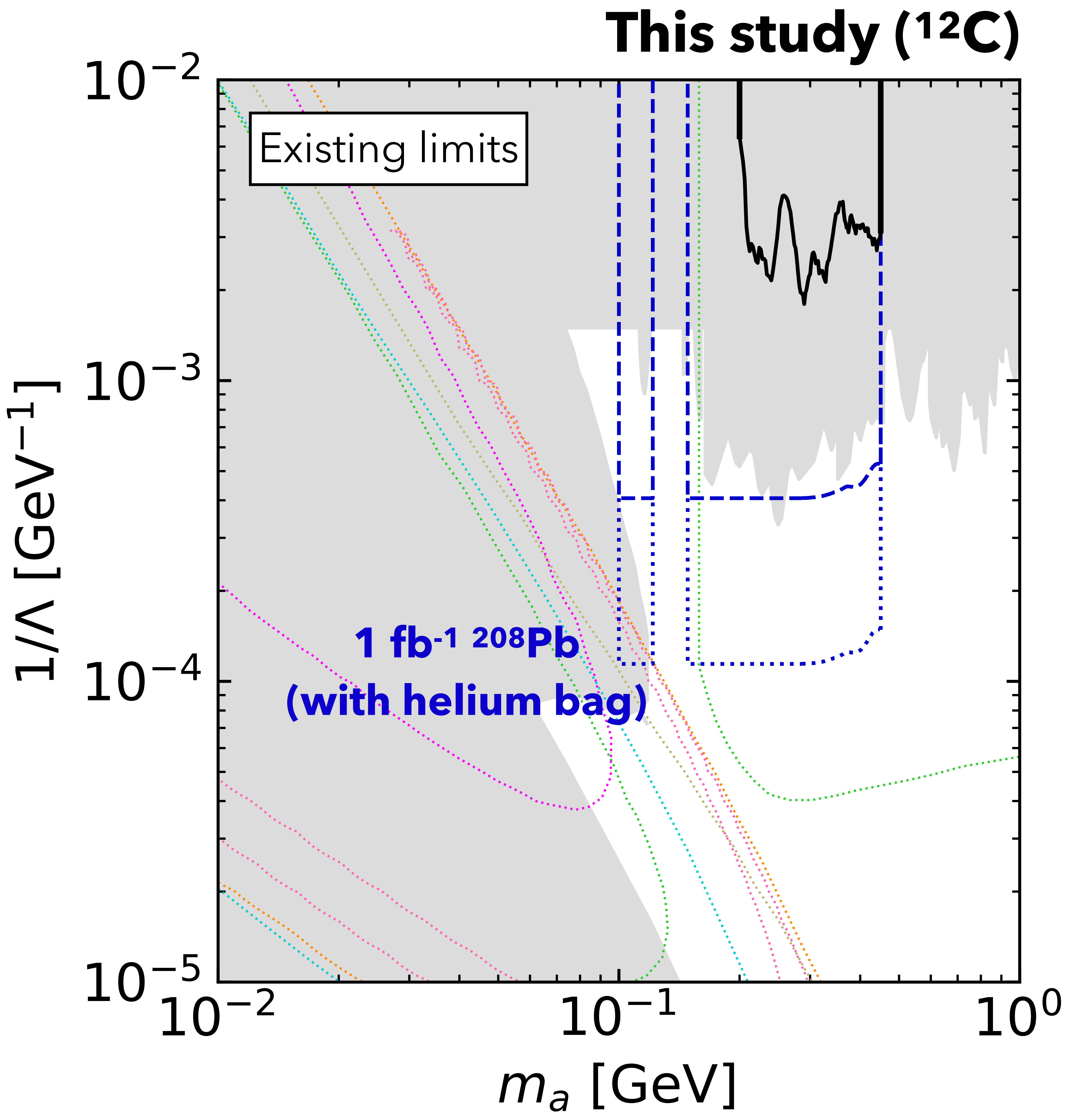
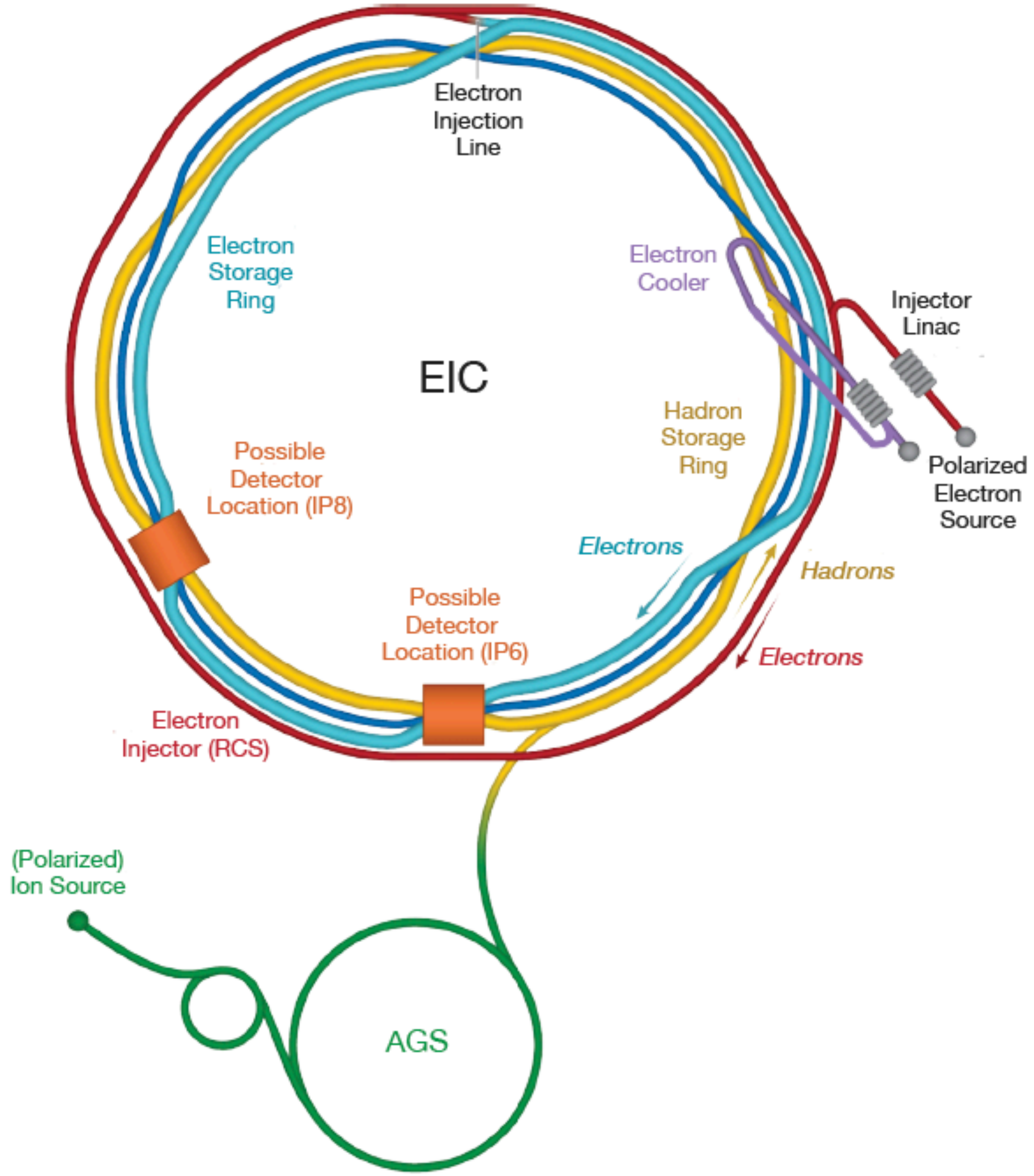
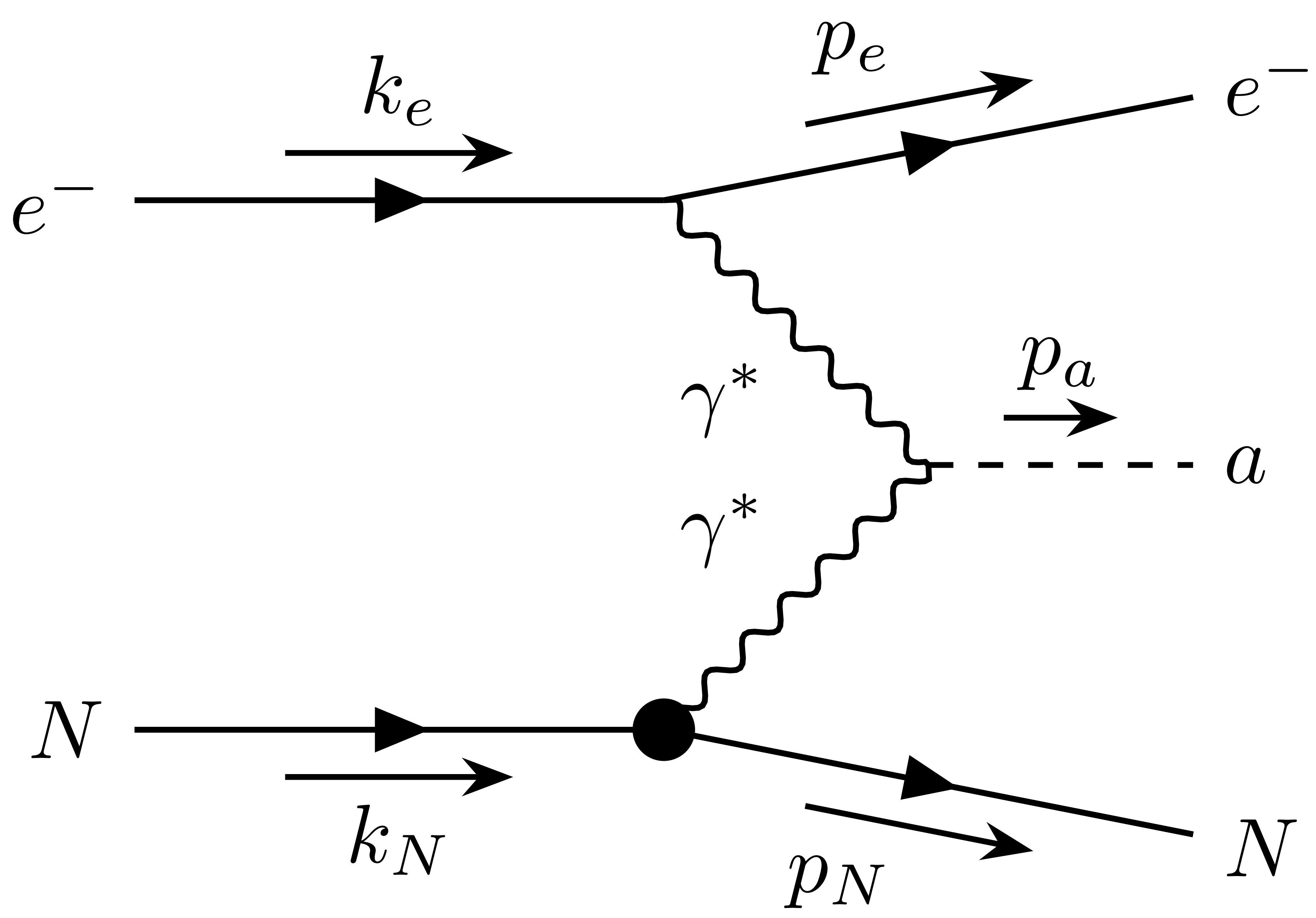


- Limits are reasonable but surpassed by world data
  - Short experiment, split between several light nuclei
- What about a dedicated run with large Z?
- Modified experimental setup could significantly improve precision

ALP Searches at the EIC





EIC reaches large effective photon energies

R. Balkin et al, JHEP (2024)

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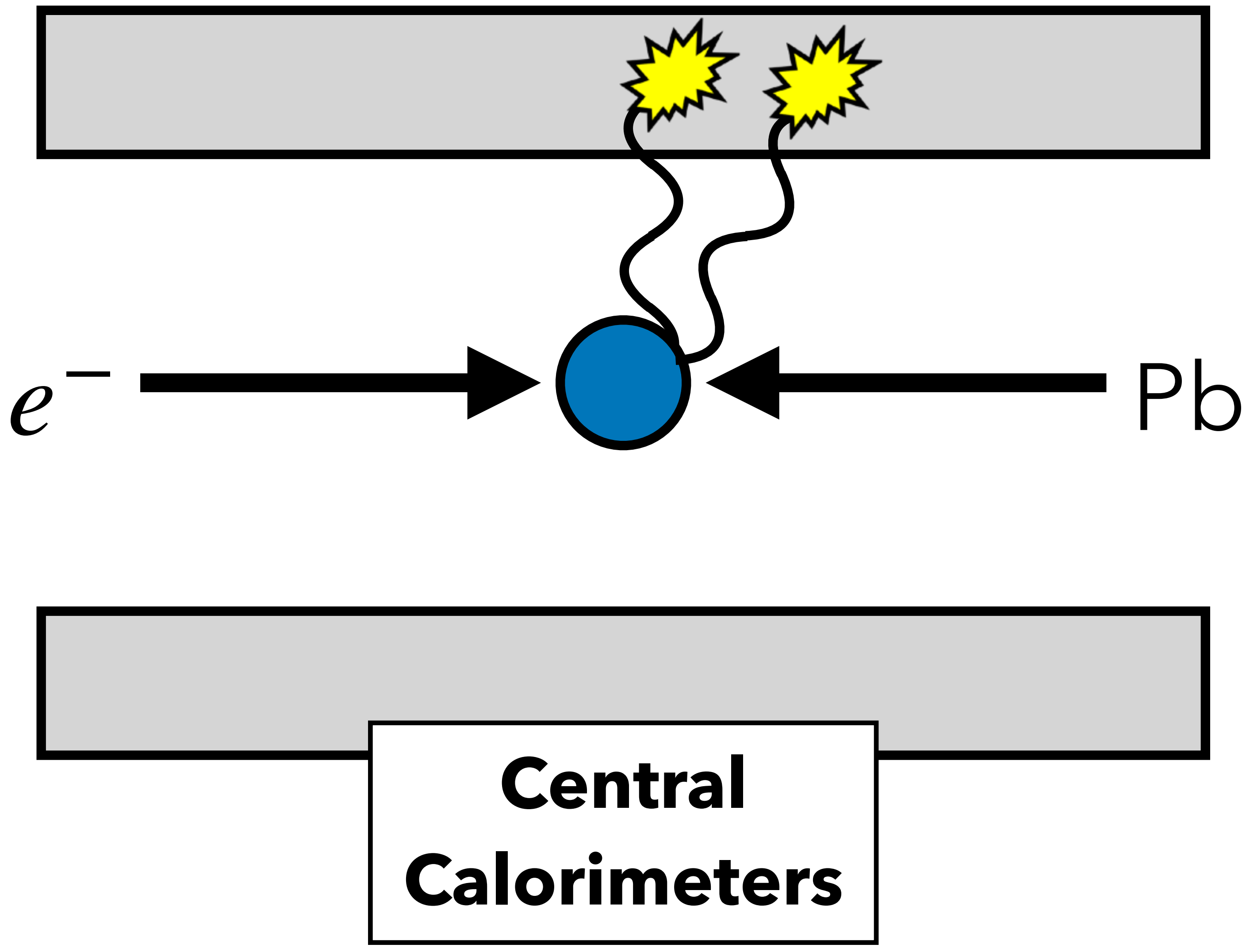

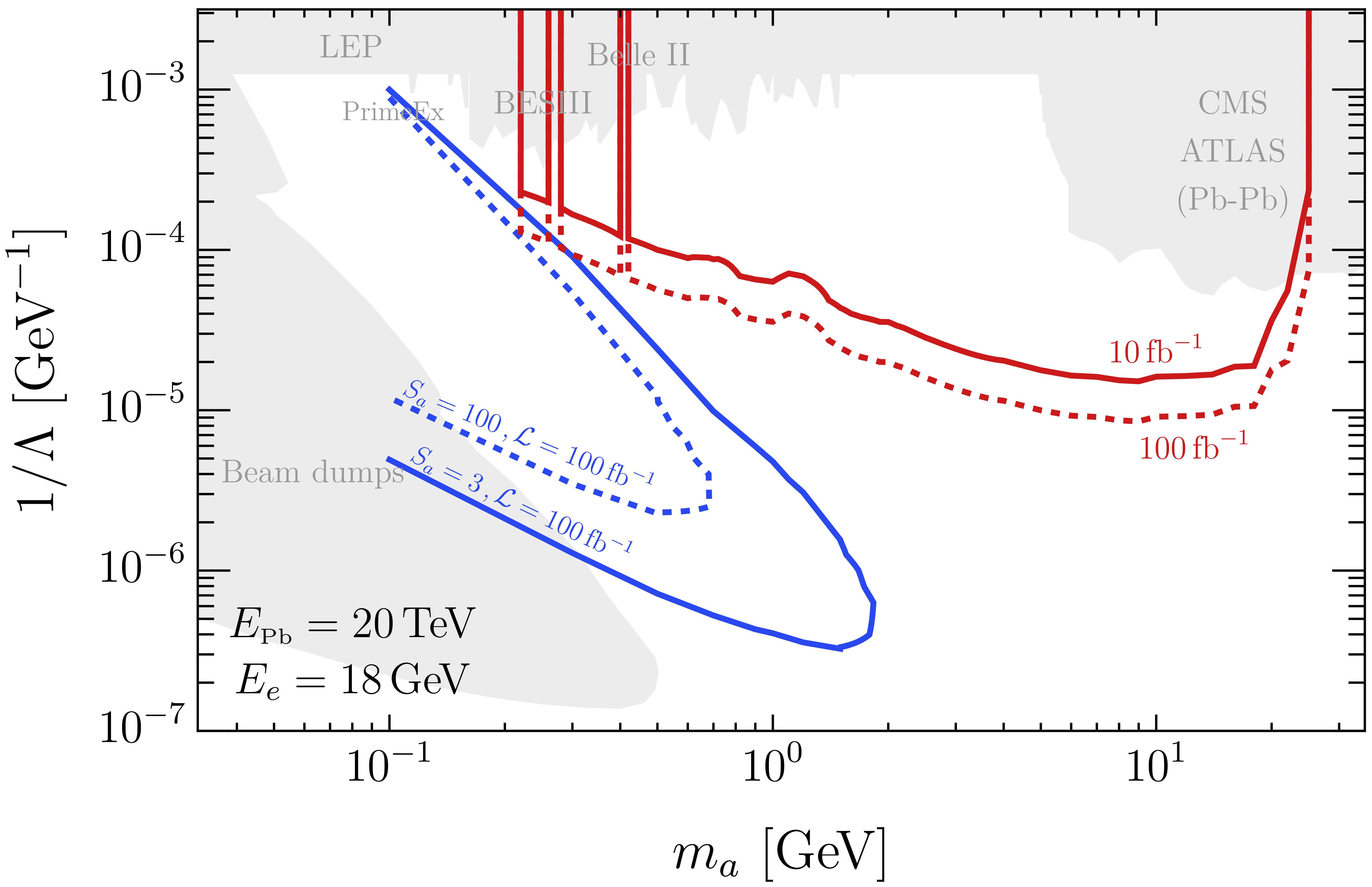

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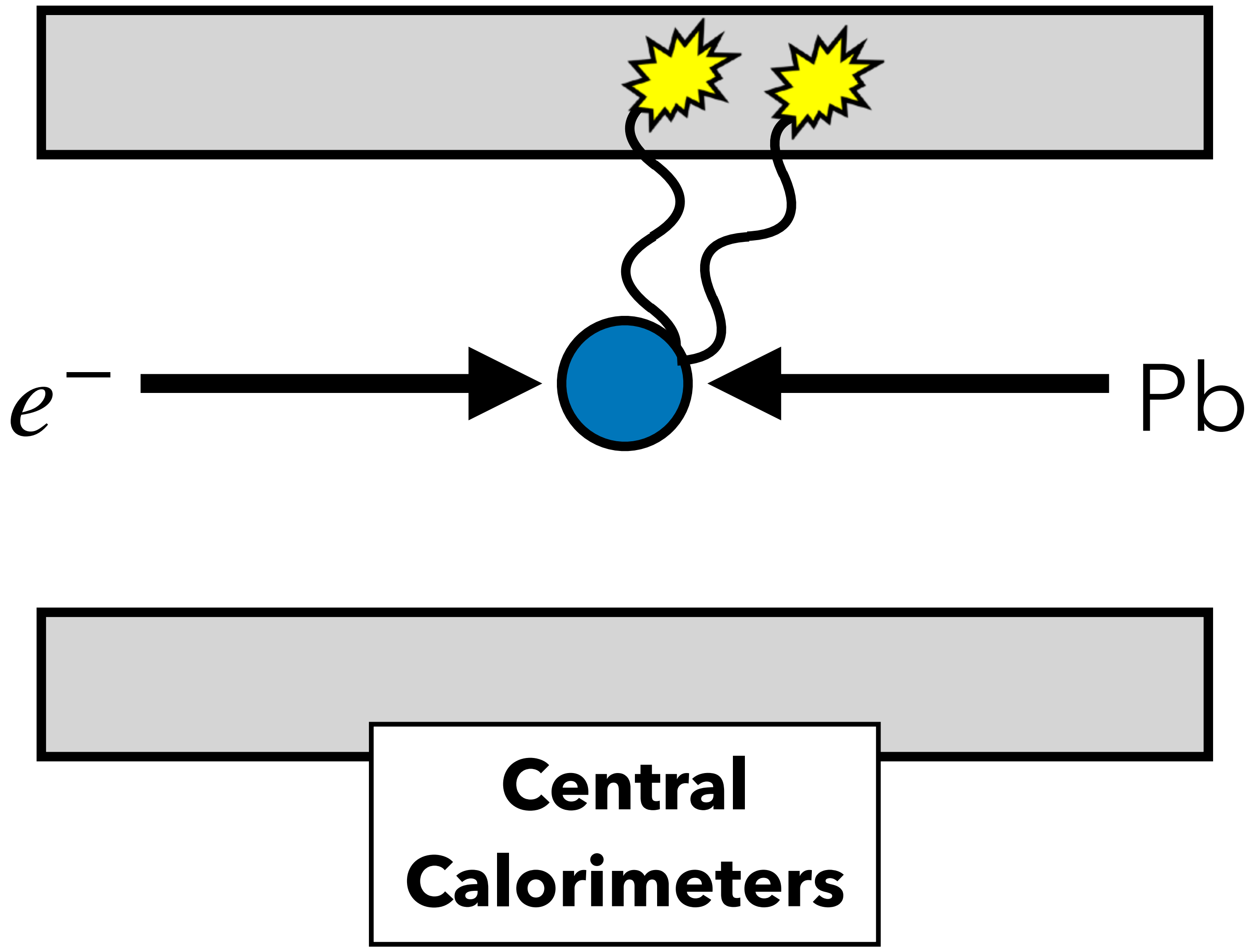
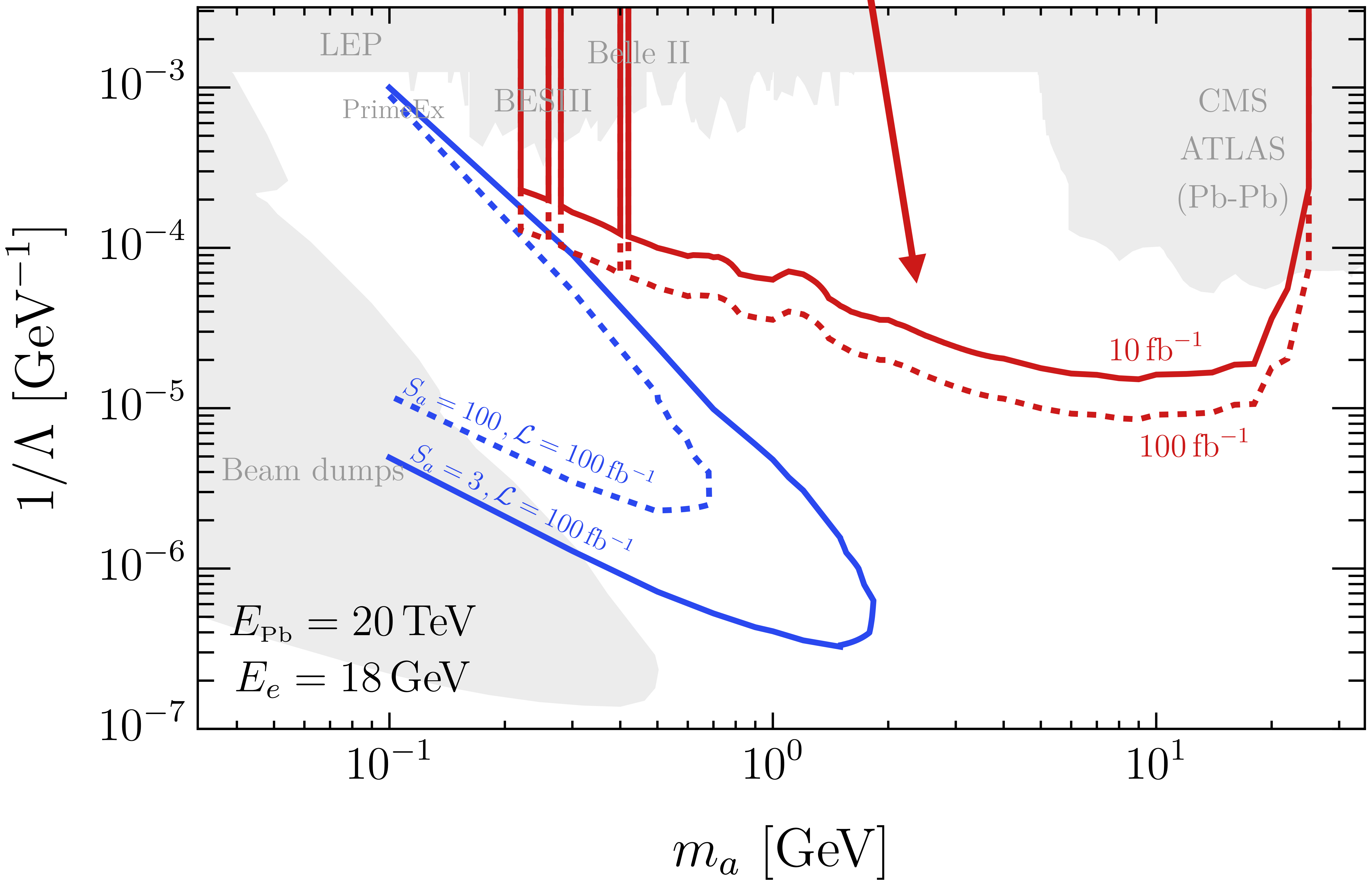


"Prompt" ALP production at interaction point



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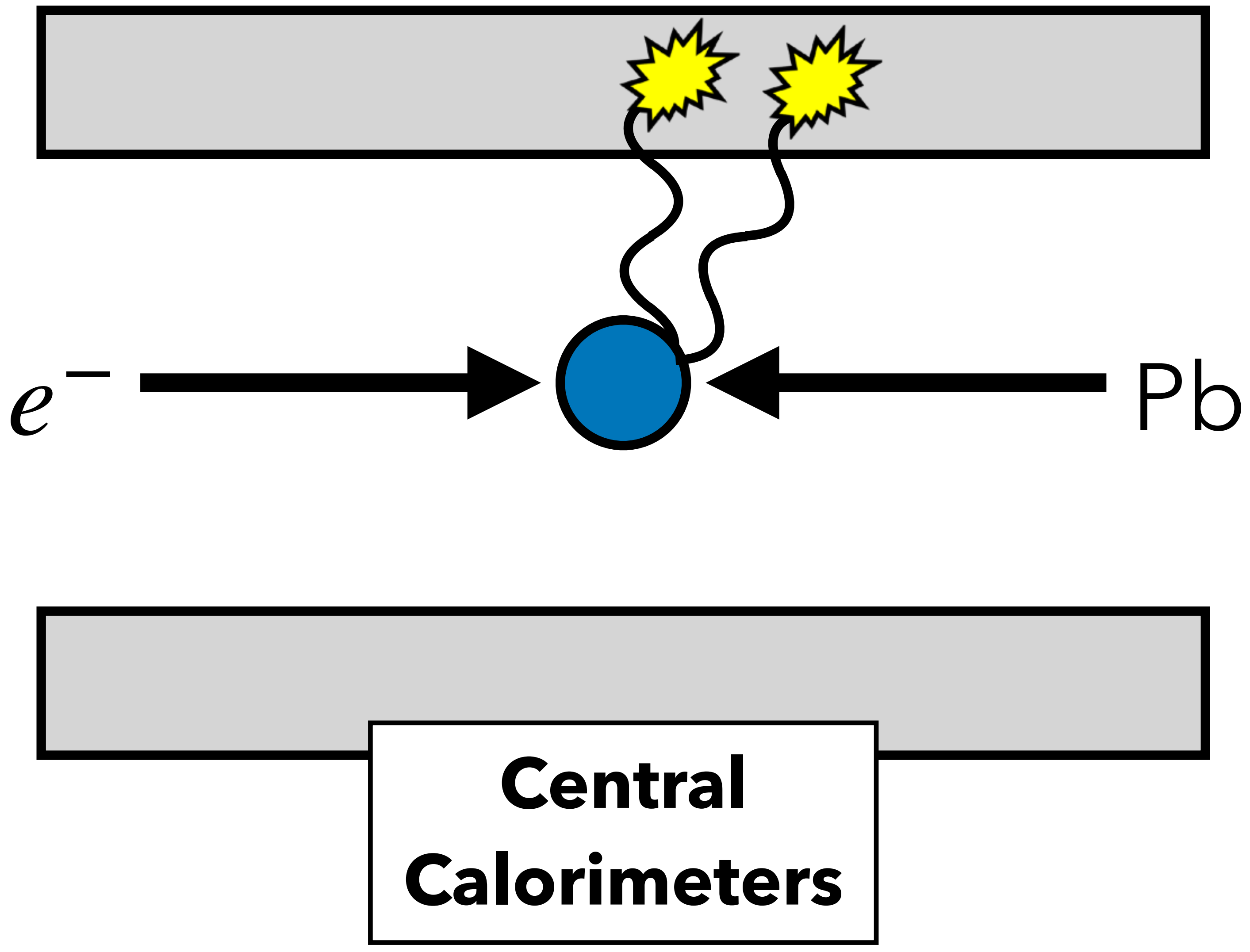
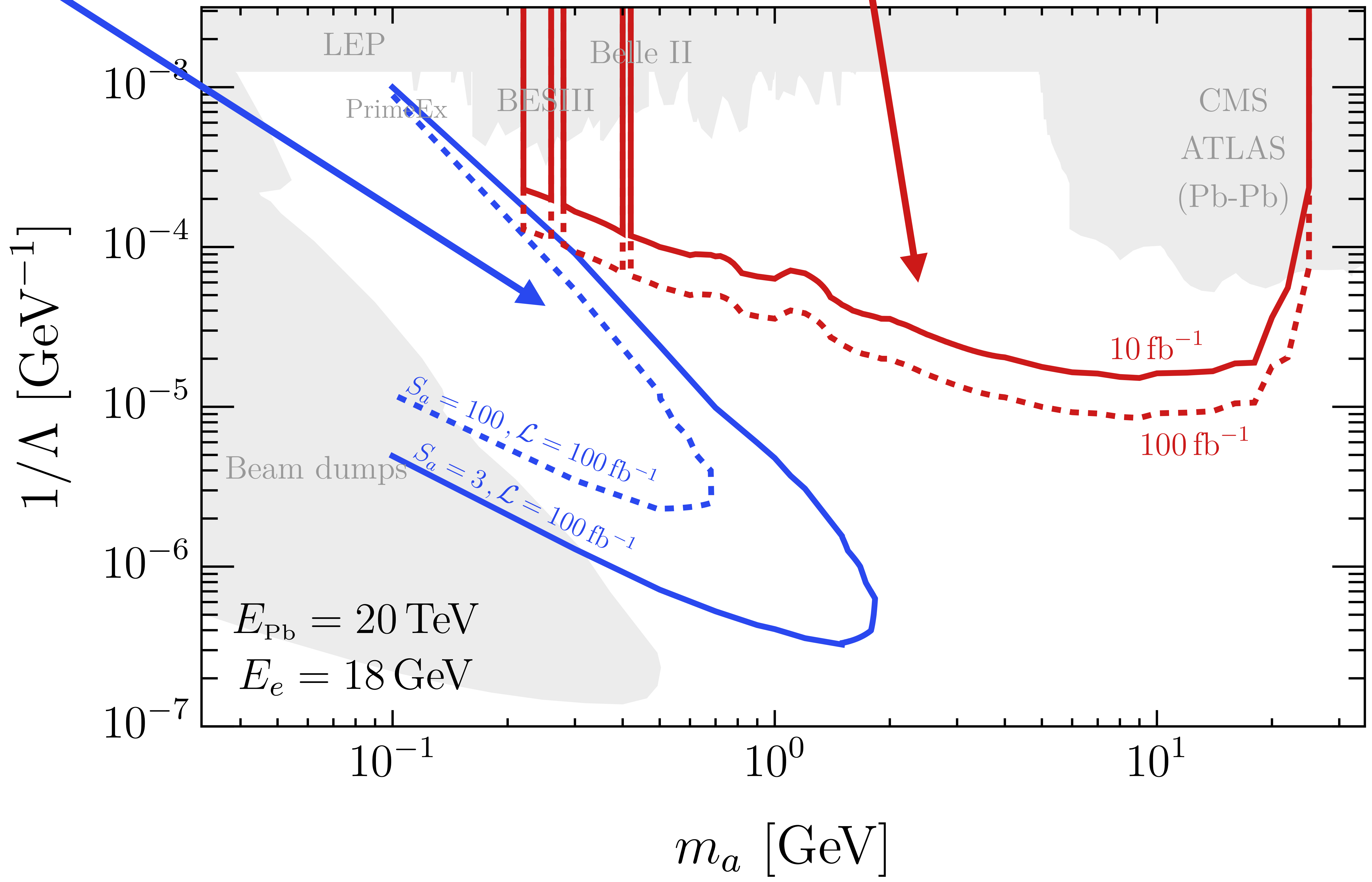
ALP Searches at the EIC

Long-lived ALP, displaced vertex

"Prompt" ALP production at interaction point

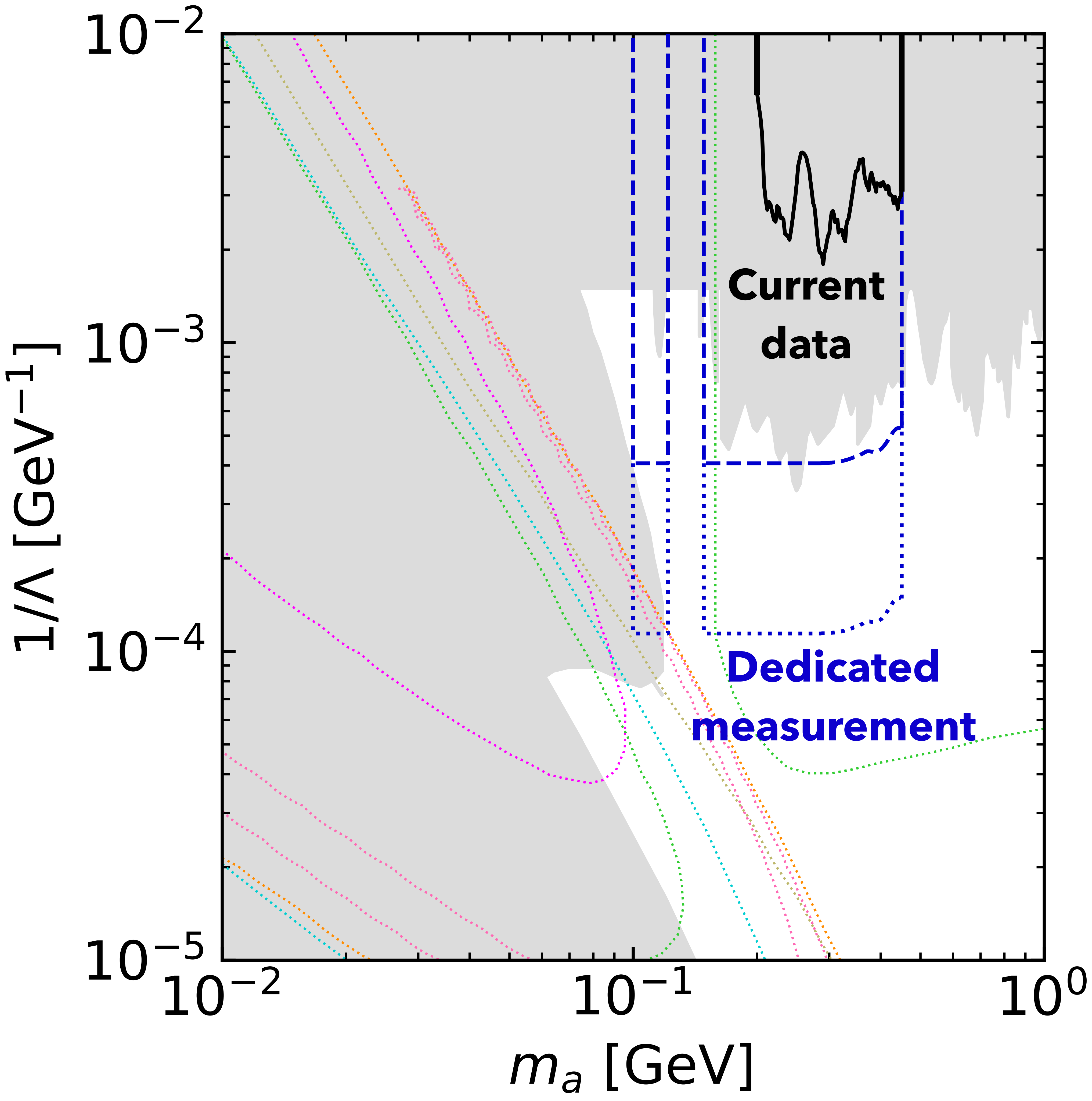




R. Balkin et al, JHEP (2024)

Conclusions

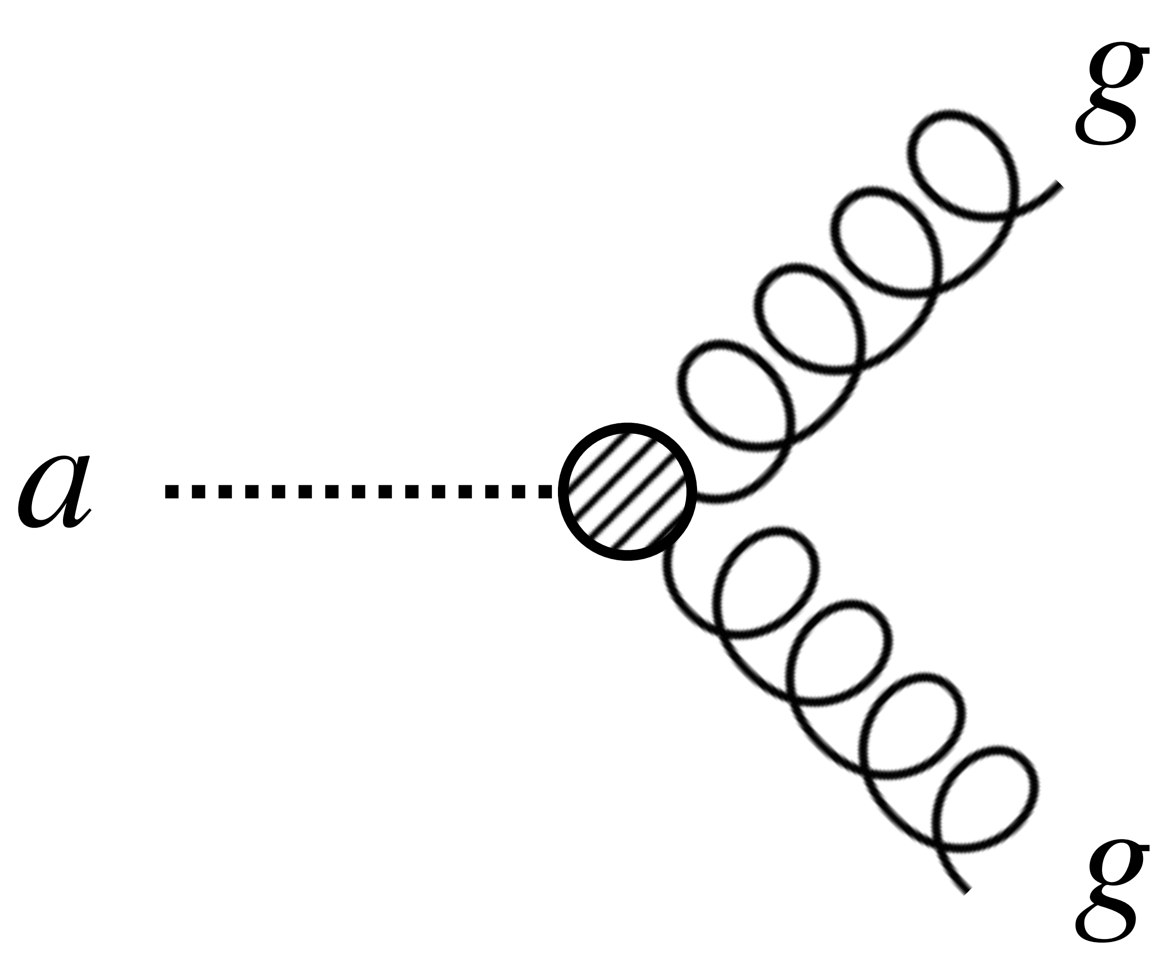
- New measurement studying Primakoff photoproduction, recently accepted to Phys. Lett. B
- Study demonstrates feasibility of search method, identifies experimental challenges
- Dedicated experiment on heavy nuclei could provide world-leading limits on QCD-scale ALPs

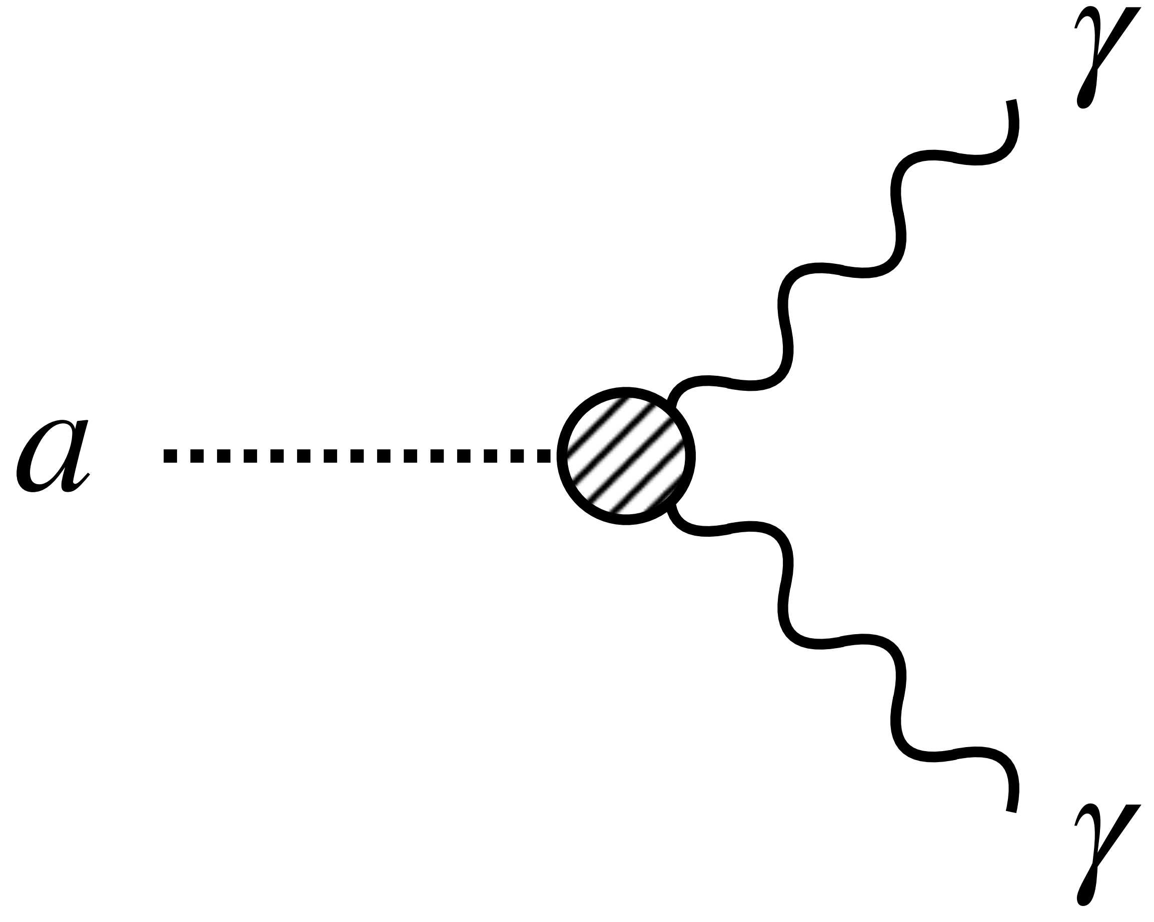


arXiv: 2308.06339

Backup

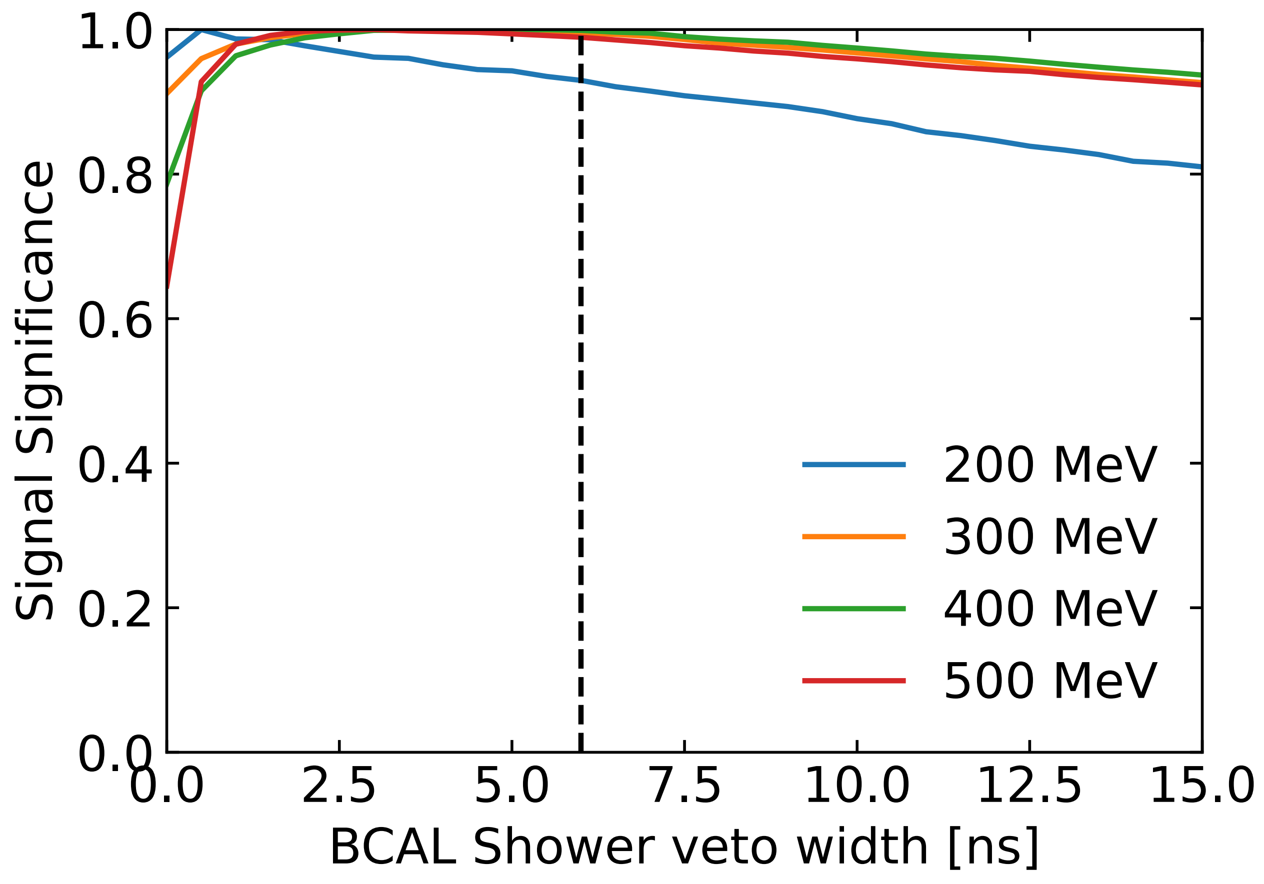
Axion-Like Particles (ALP)

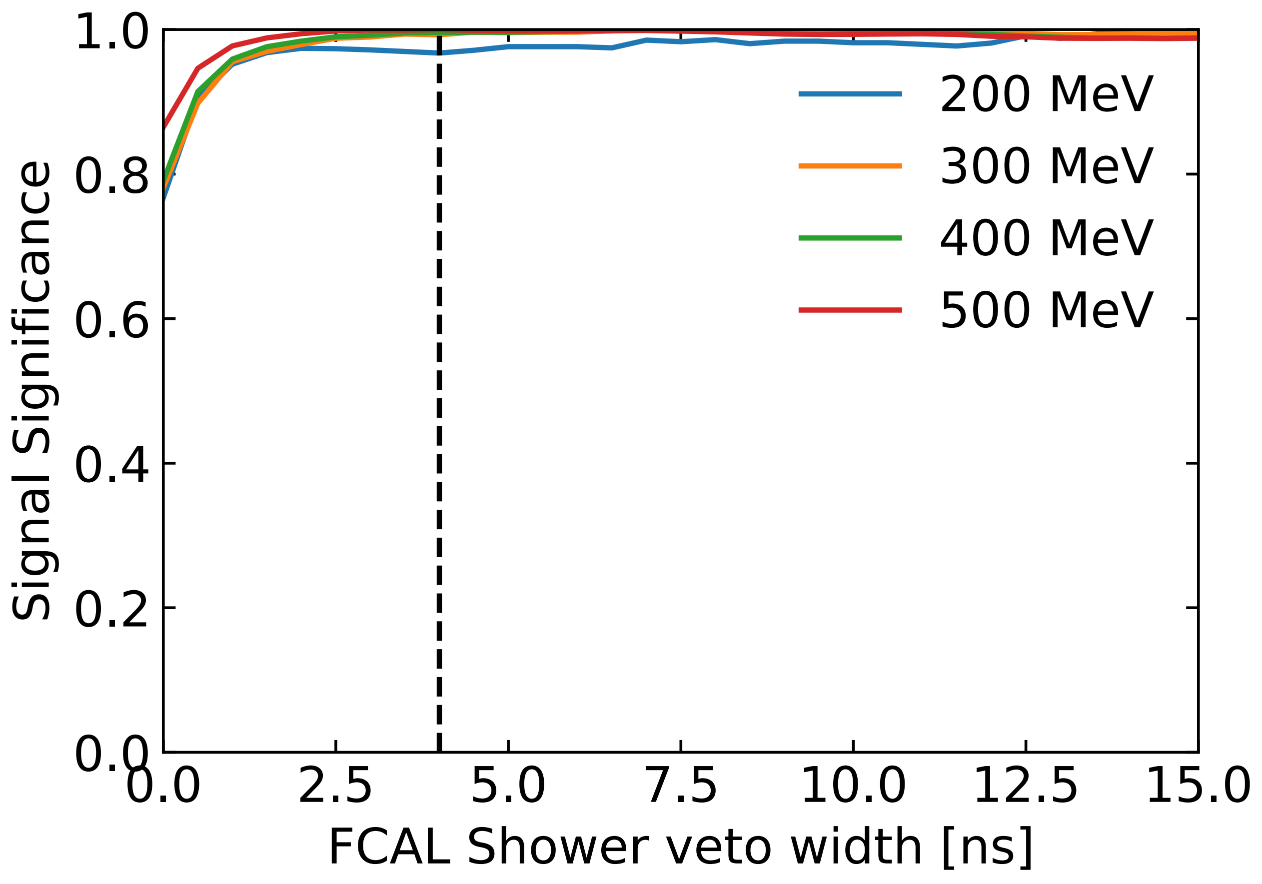


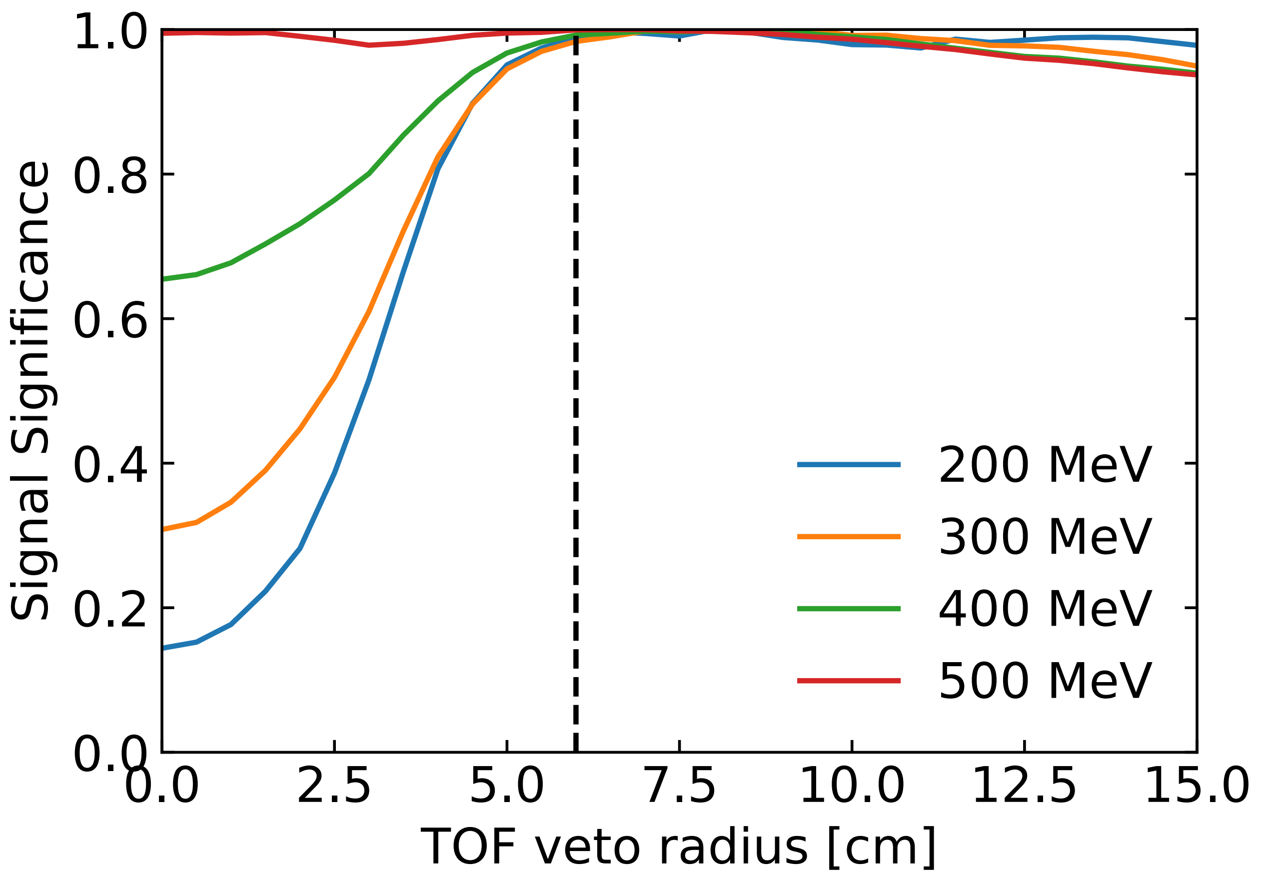


$$\mathcal{L}_{eff} = -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{c_\gamma}{4\pi\Lambda} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

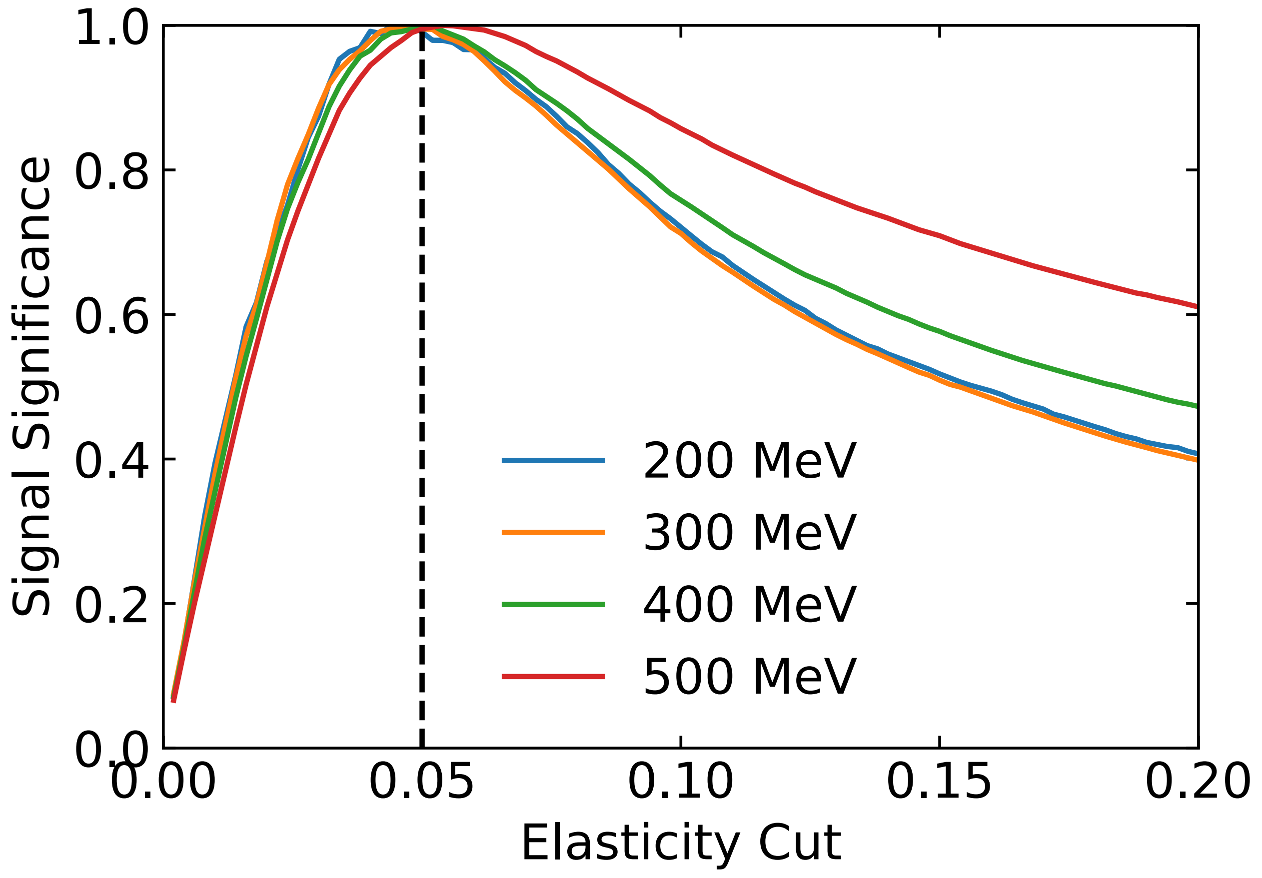
Cut Optimization

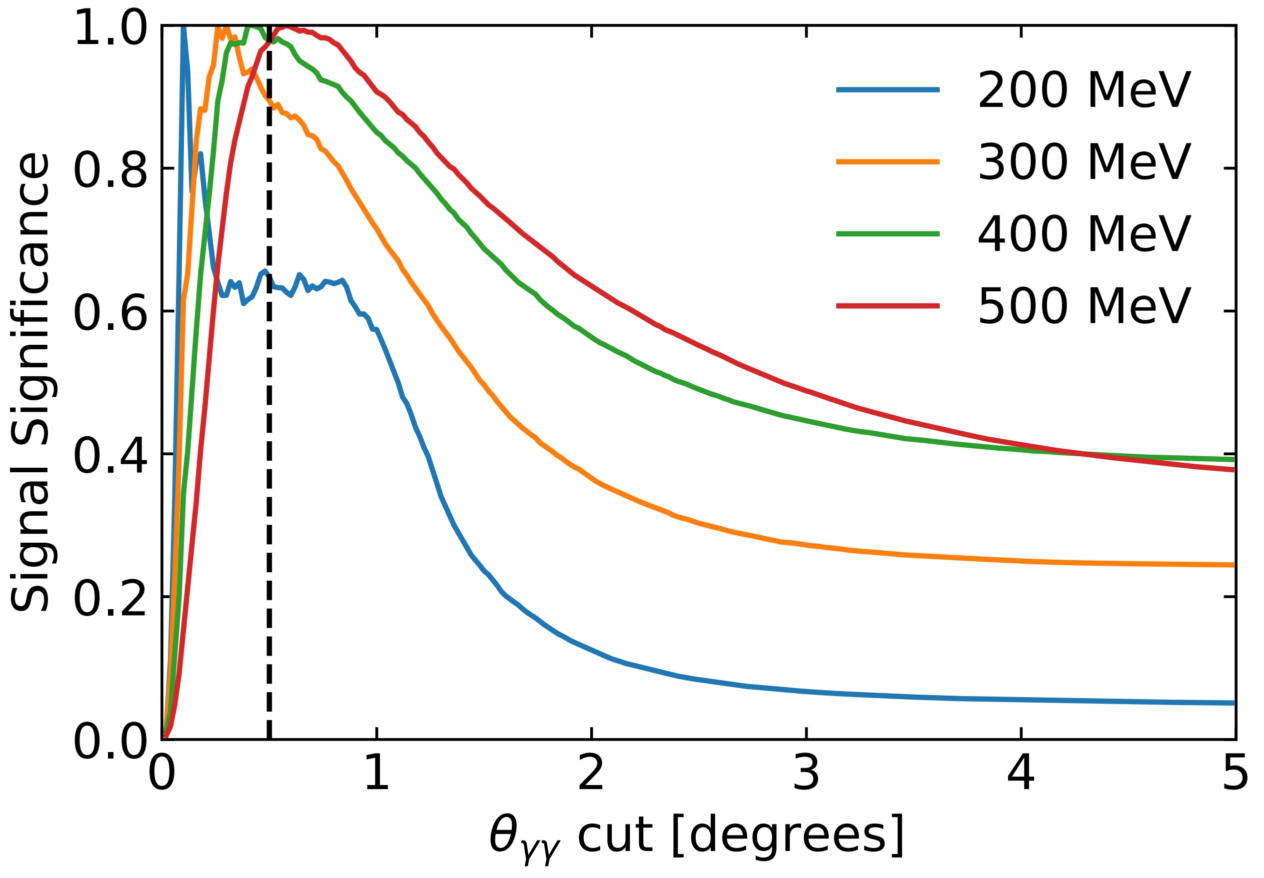






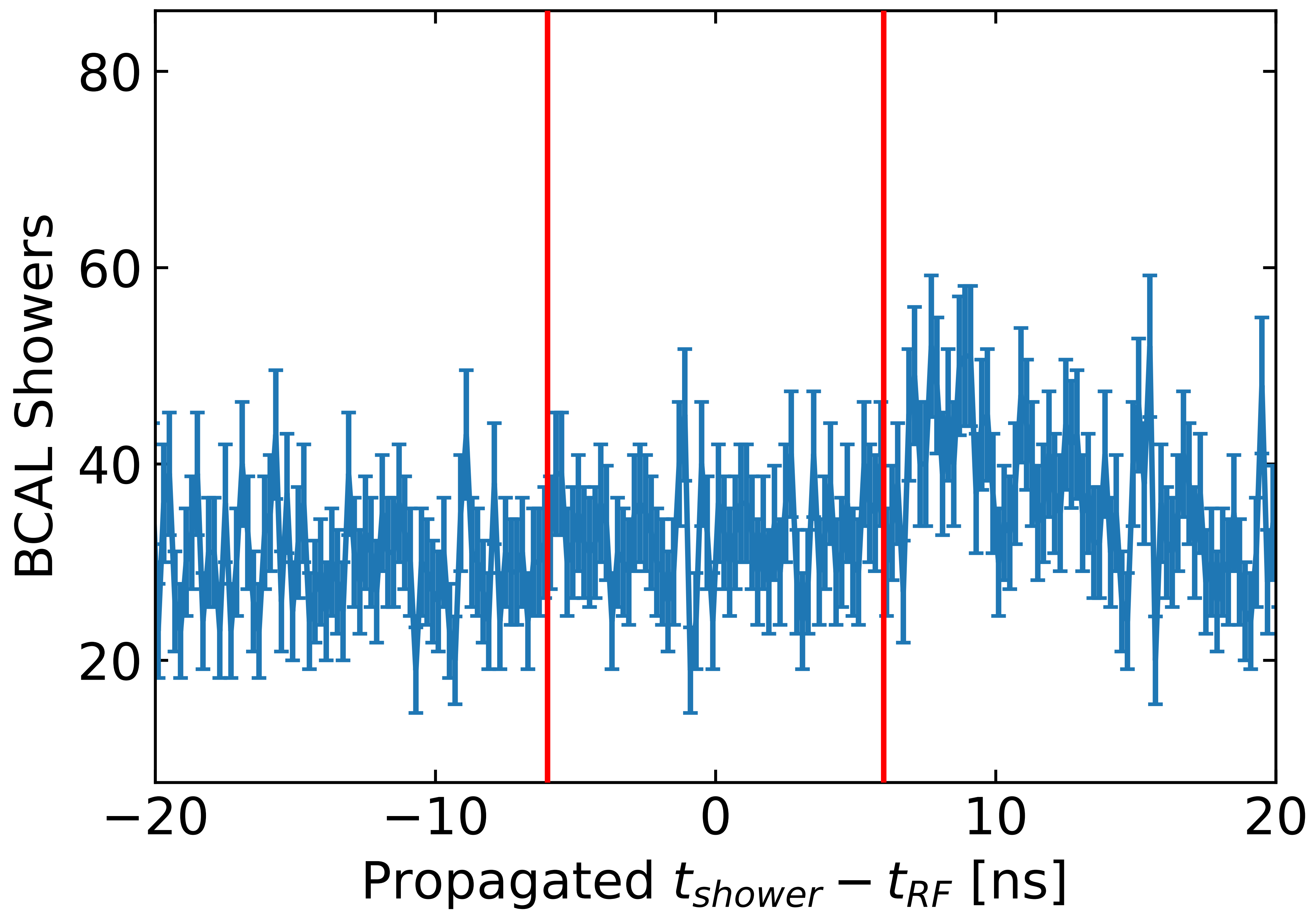
$$\text{Signal Significance} = \frac{N_{sim}^2}{N_{data}}$$



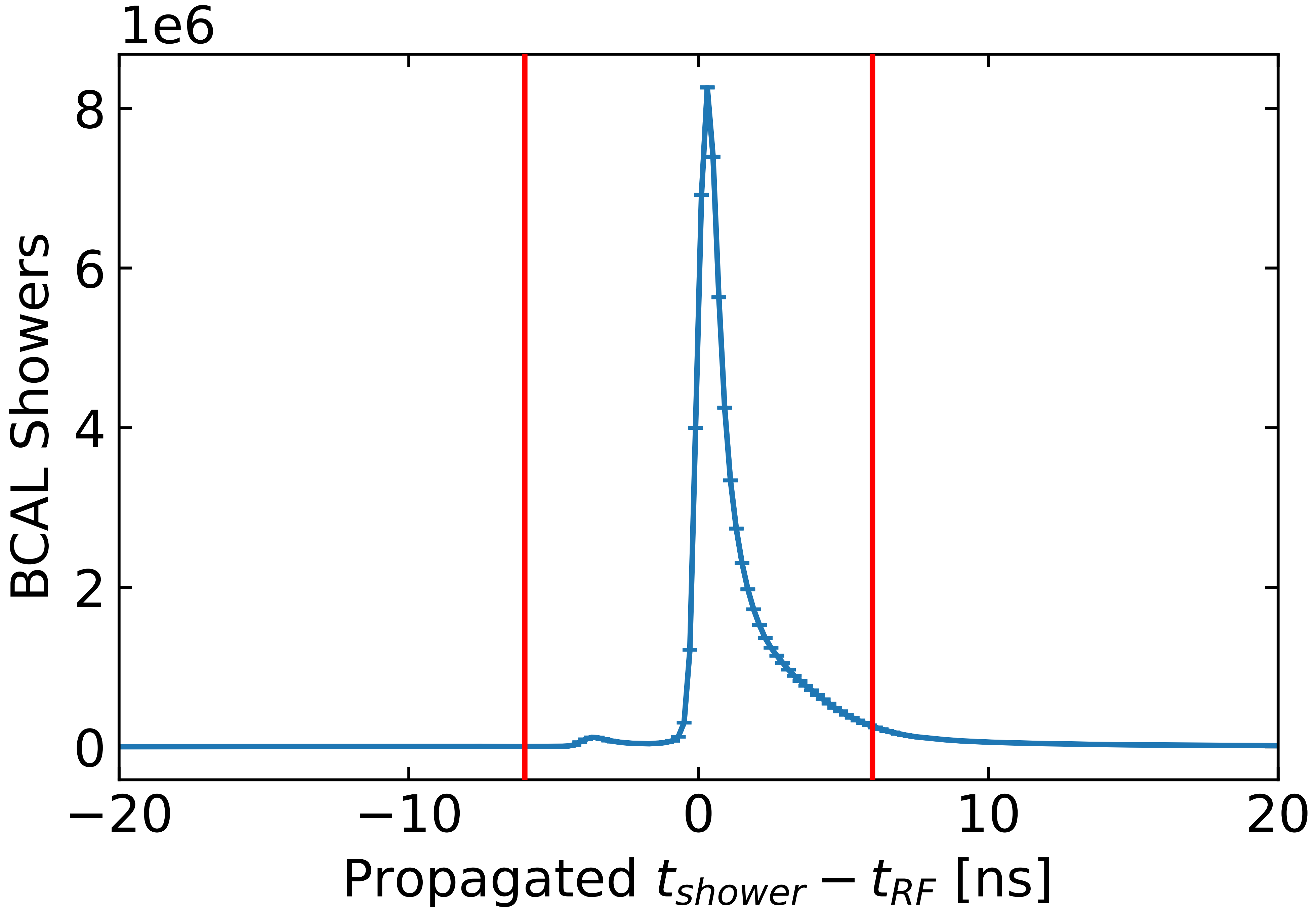


Extra BCAL Showers

ALP Simulation

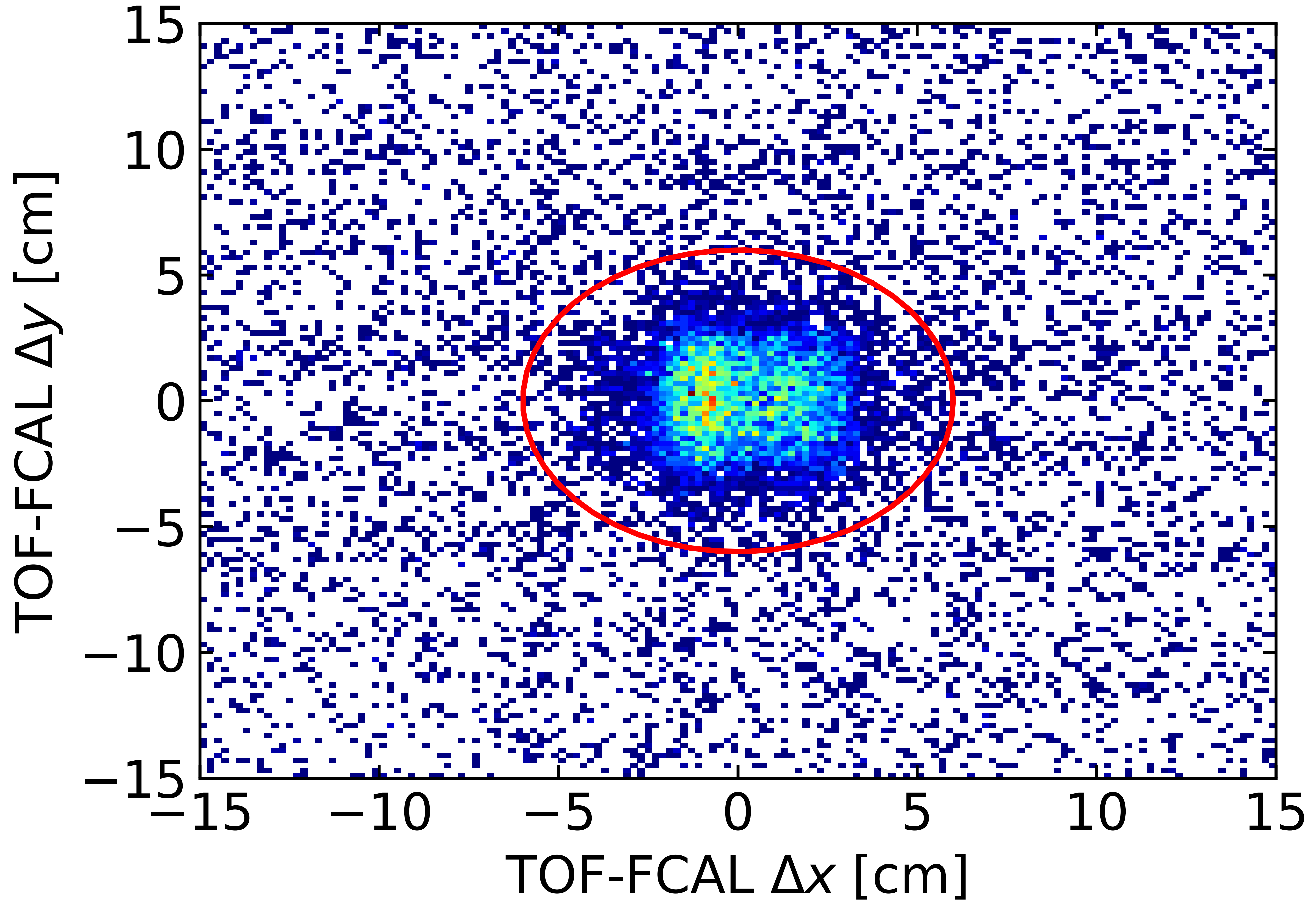


2-photon Data

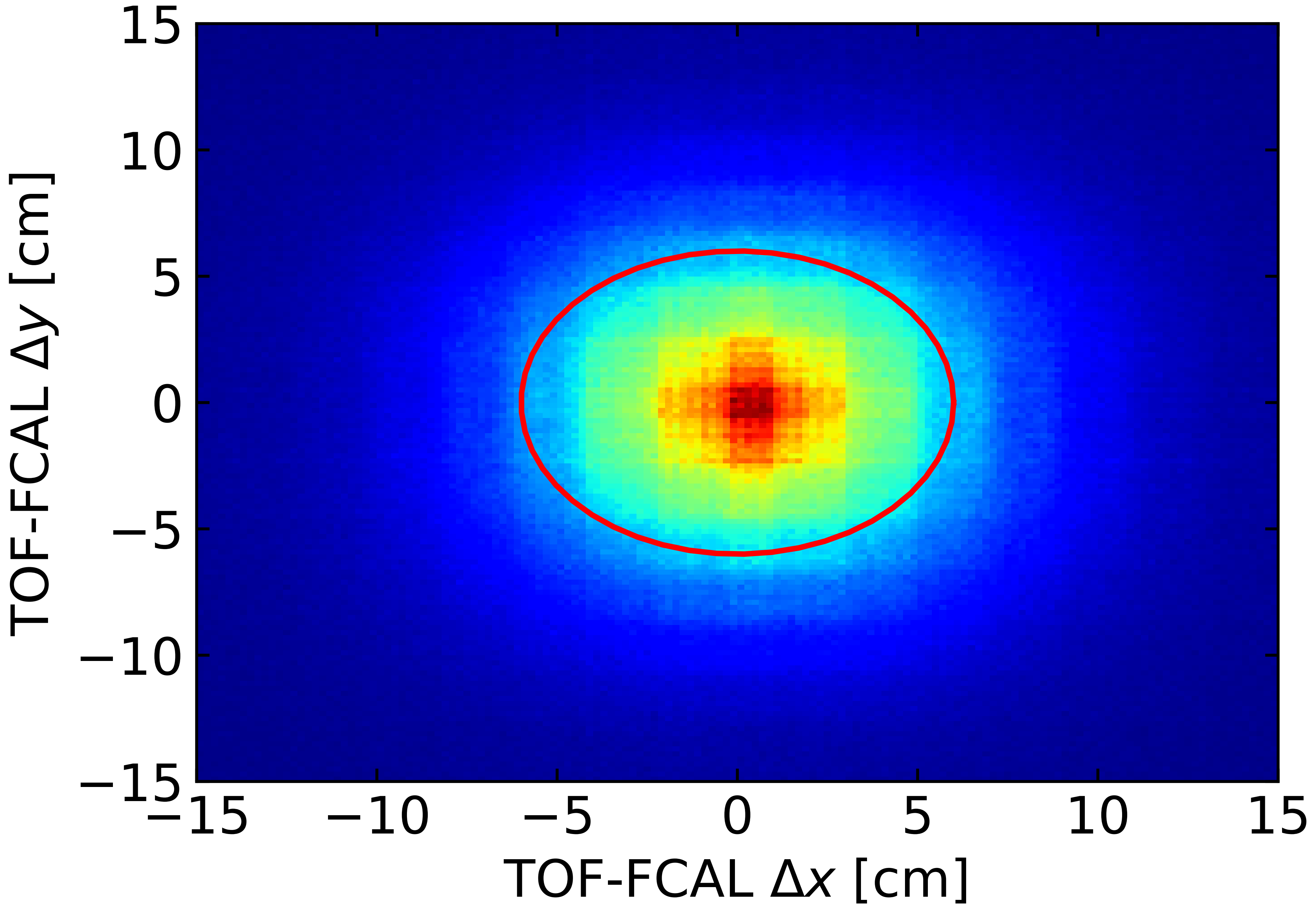


TOF Hits

ALP Simulation

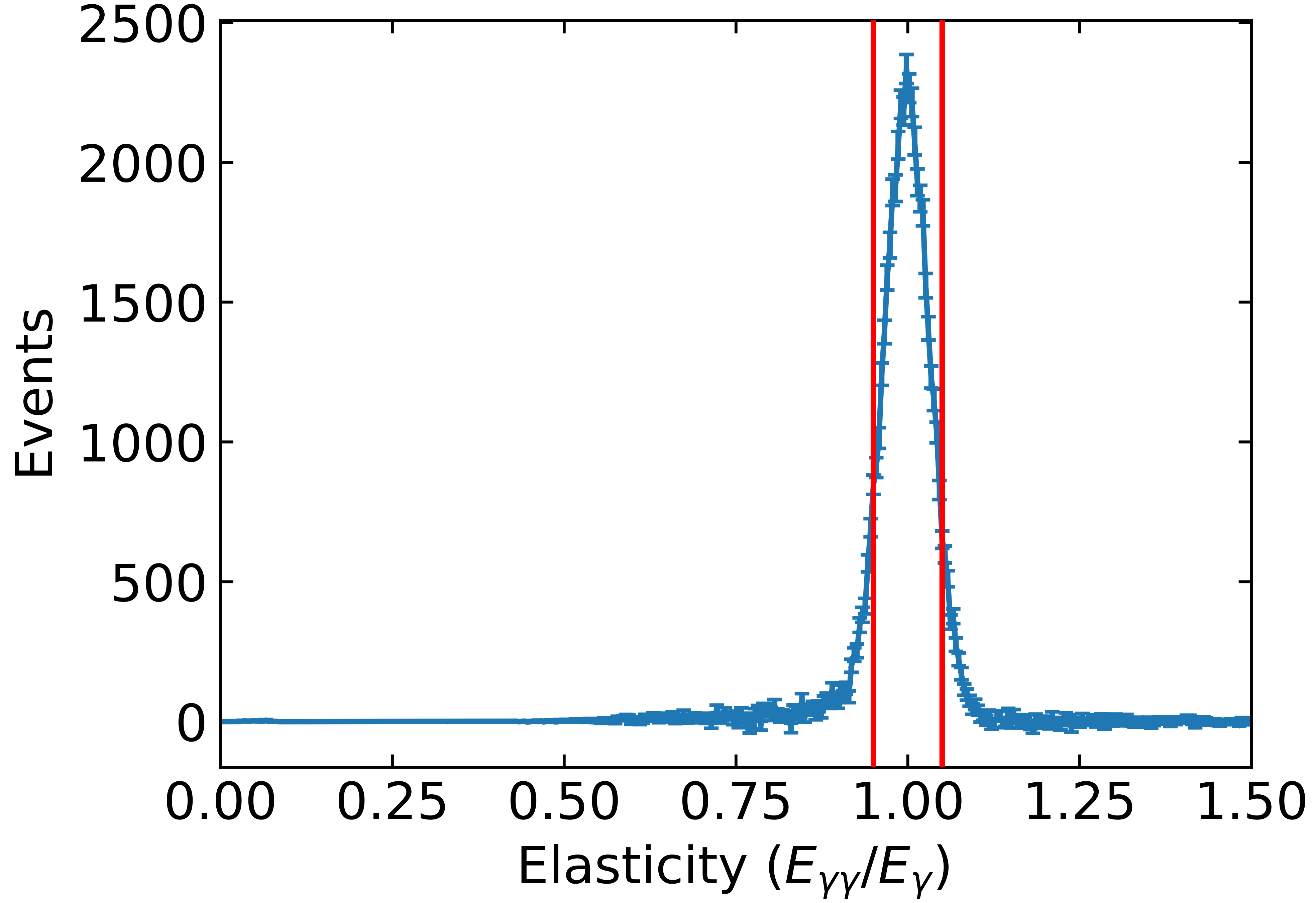


2-photon Data



Diphoton Elasticity

ALP Simulation



2-photon Data