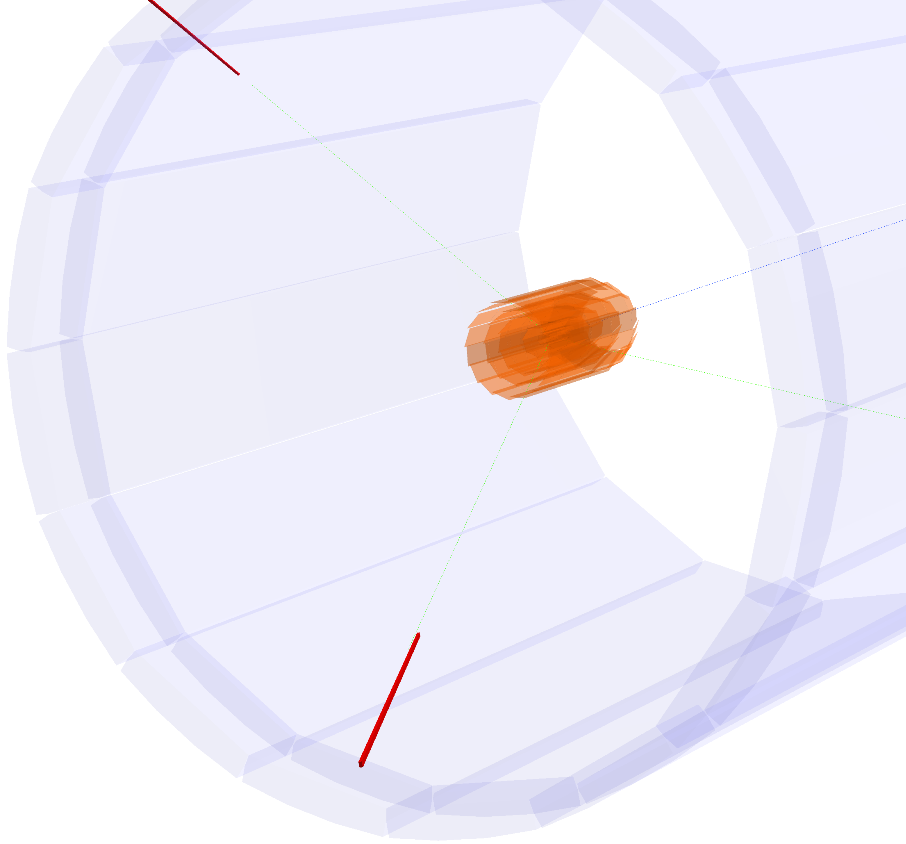


Search for Axion-Like Particles produced in e^+e^- collisions at the Belle II experiment.

10th January 2021

XXVII Cracow EPIPHANY Conference on Future of particle physics

Michael De Nuccio on behalf of the Belle II collaboration
(michael.de.nuccio@desy.de)

Belle II

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

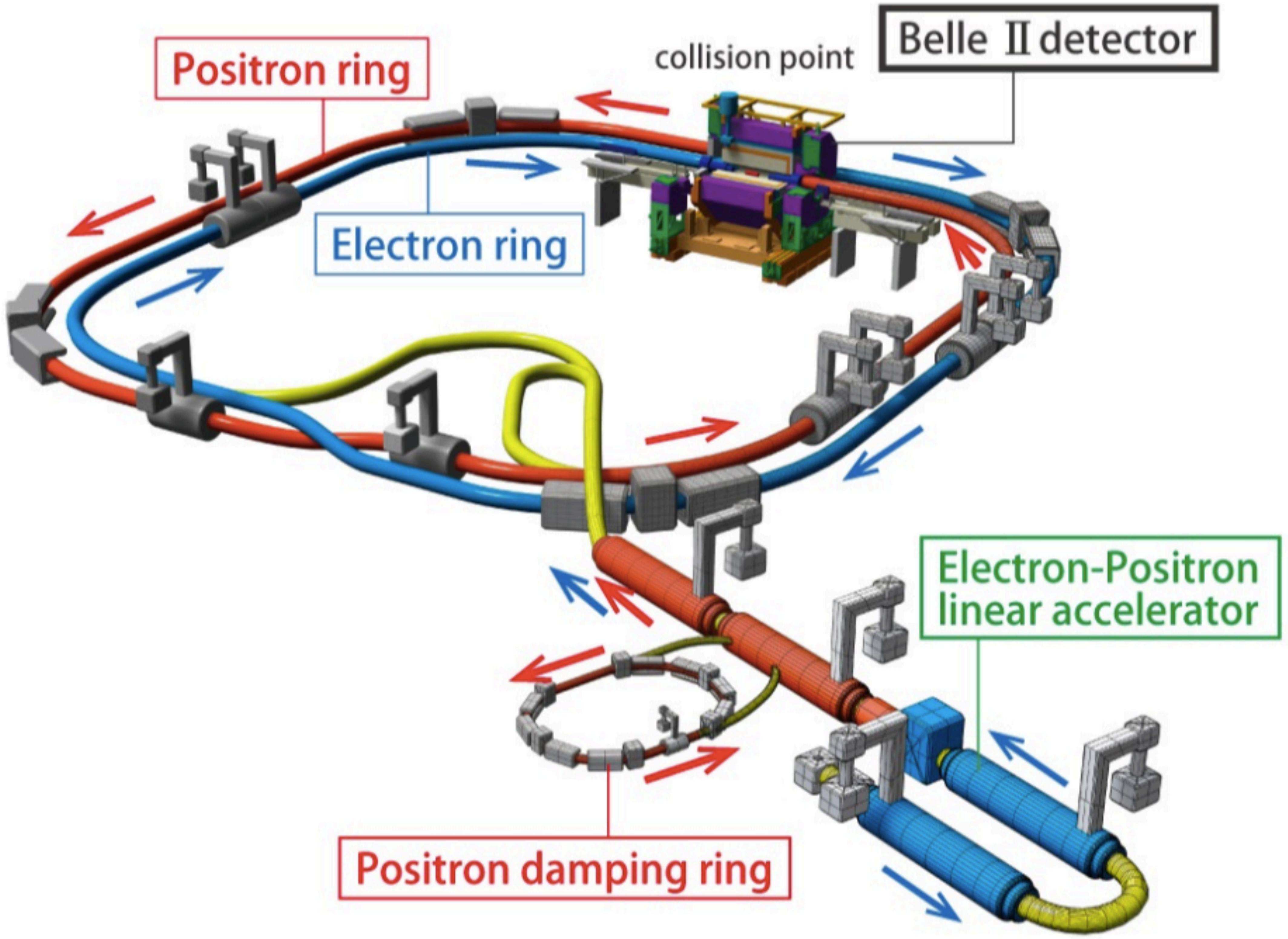
UHH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

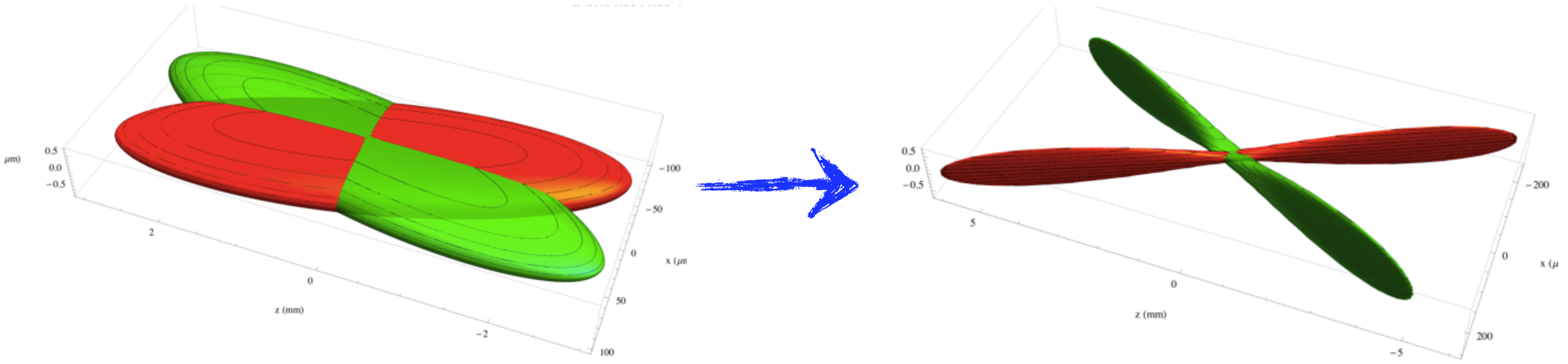
DESY.

SuperKEKB and Belle II.

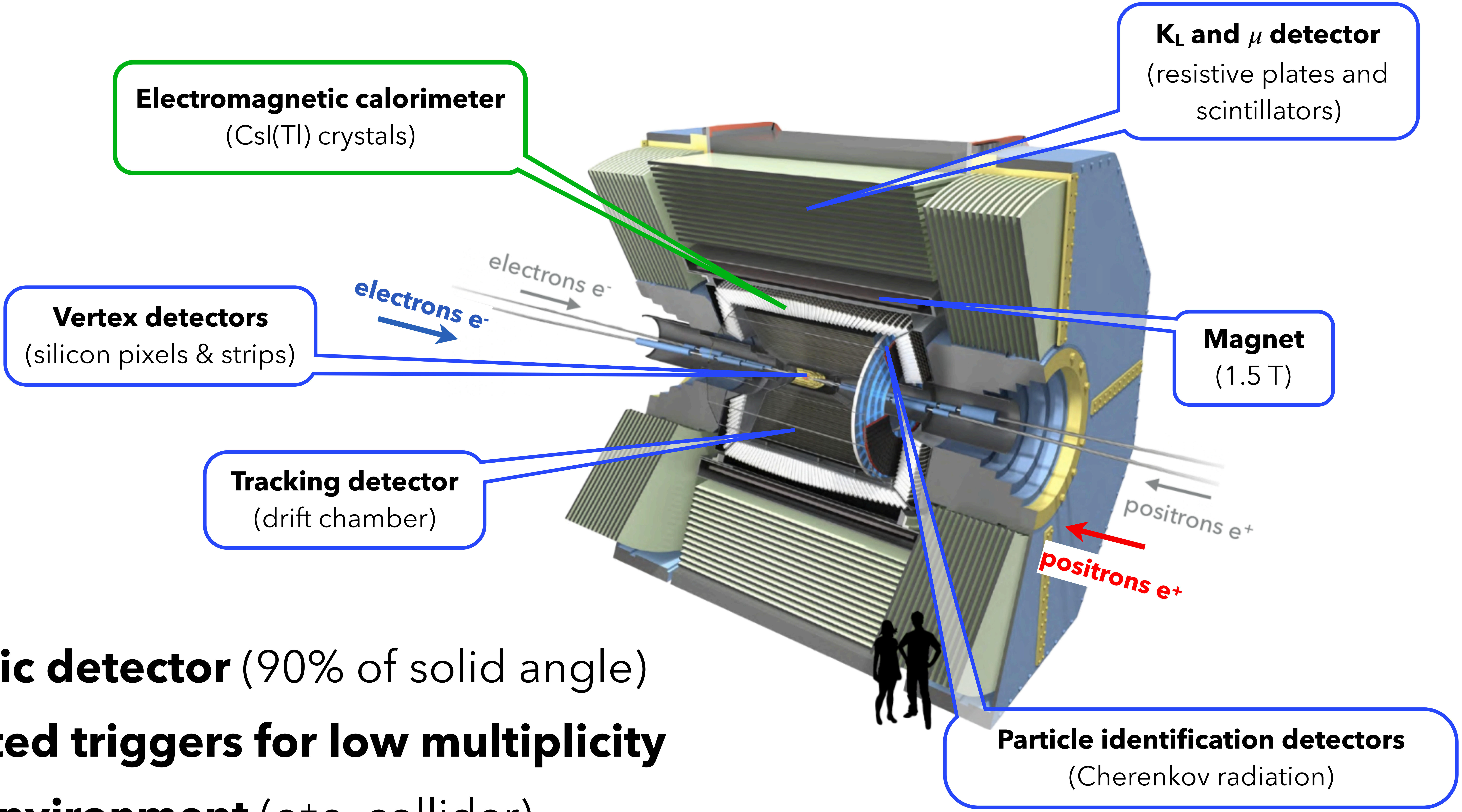
SuperKEKB

- **Asymmetric e^+e^- collider**
  @ $\Upsilon(4S)$ energy = 10.58 GeV
- Second-generation **B factory**
  (optimized to produce a lot of B mesons)
- **50 times** increase in luminosity
  with respect to predecessor KEKB: **~50 ab^{-1}**
  - Up to now: ~90 fb^{-1} = ~0.09 ab^{-1}
  - For this analysis: **445 pb^{-1}** = 0.000445 ab^{-1}
    (**early 2018 data only**)





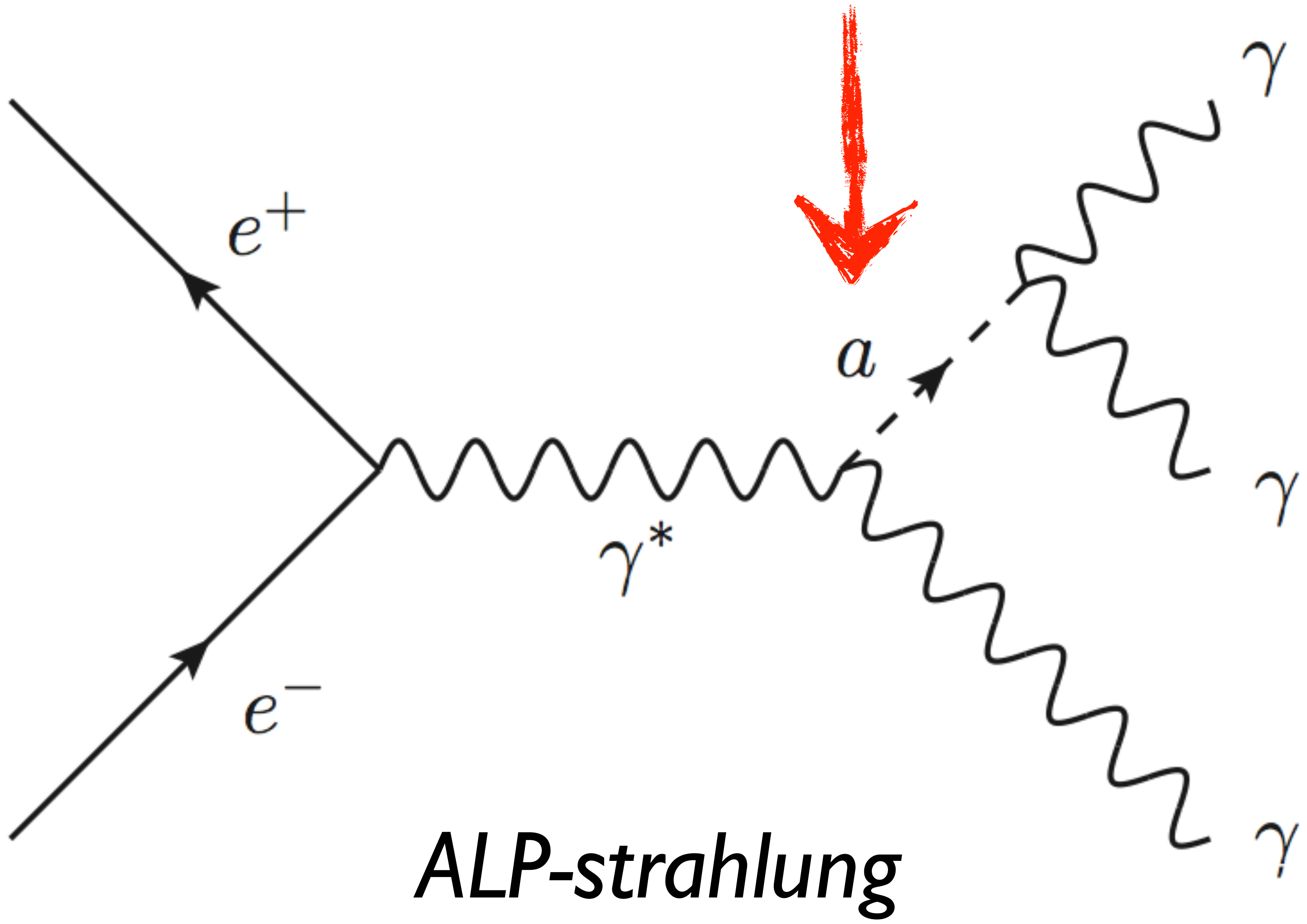
Belle II

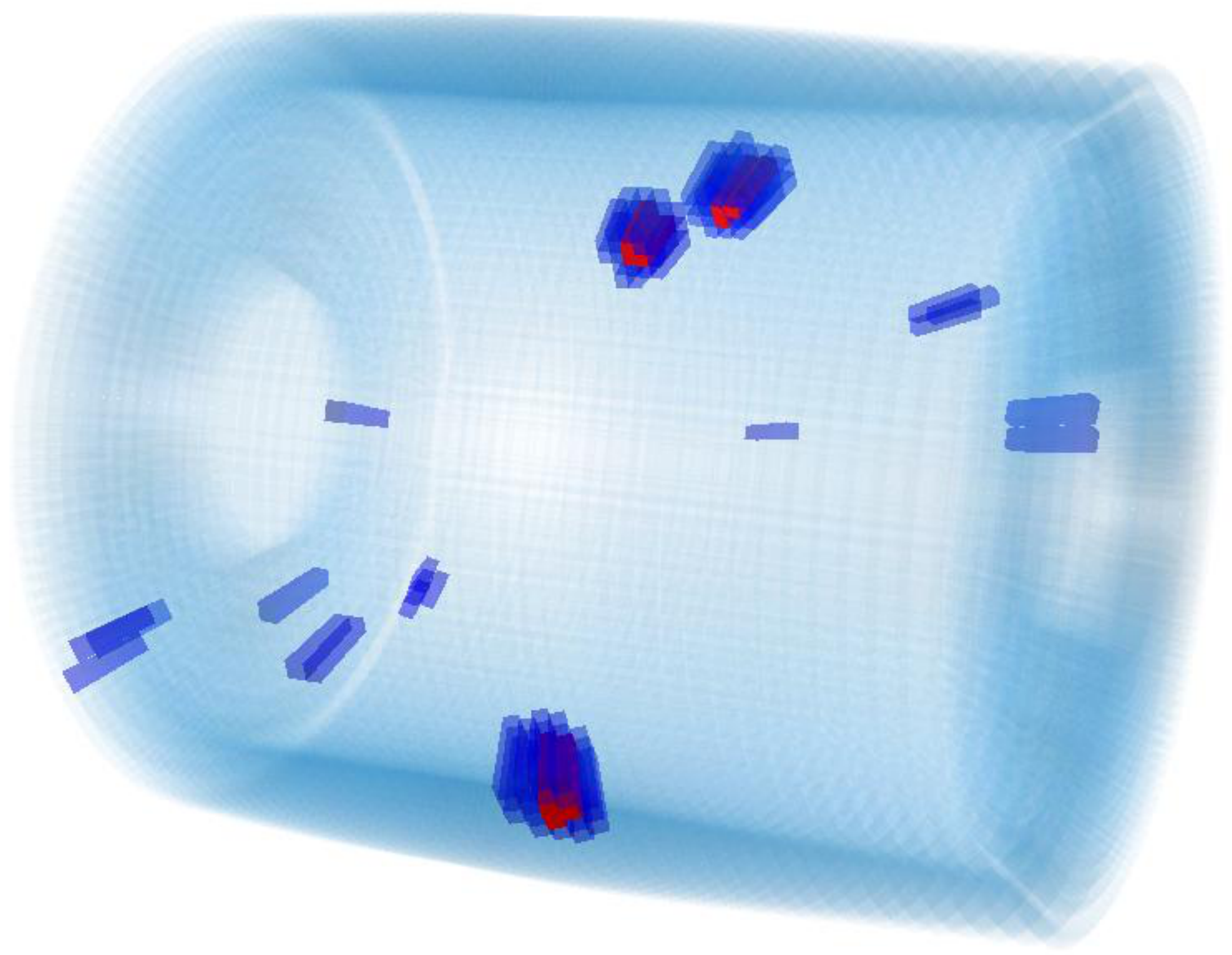


- **Hermetic detector** (90% of solid angle)
- **Dedicated triggers for low multiplicity**
- **Clean environment** (e^+e^- collider)

Axion-Like Particles.

Physical process



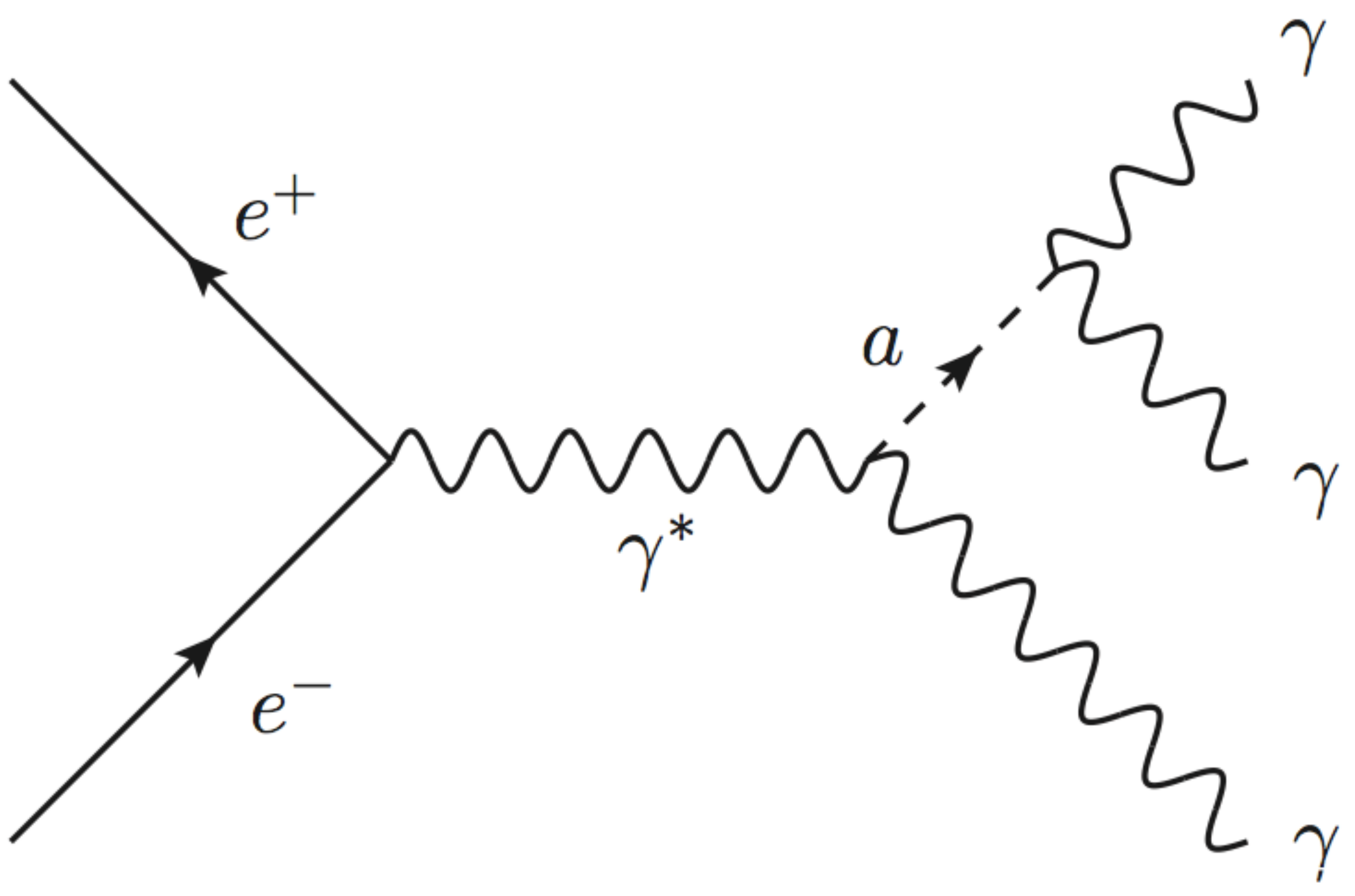


Belle II simulation, signal only

- Axions:
  proposal to solve strong CP problem
- Axion-like particles (***a***, **ALP**s):
  ~axions, but no mass-coupling constraint
  Massive, neutral, pseudoscalar
- Possible portals to **Dark Sector**

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, JHEP 1712 (2017) 094

Physical process



Signal: $e^+e^- \rightarrow \gamma a$, $a \rightarrow \gamma\gamma$

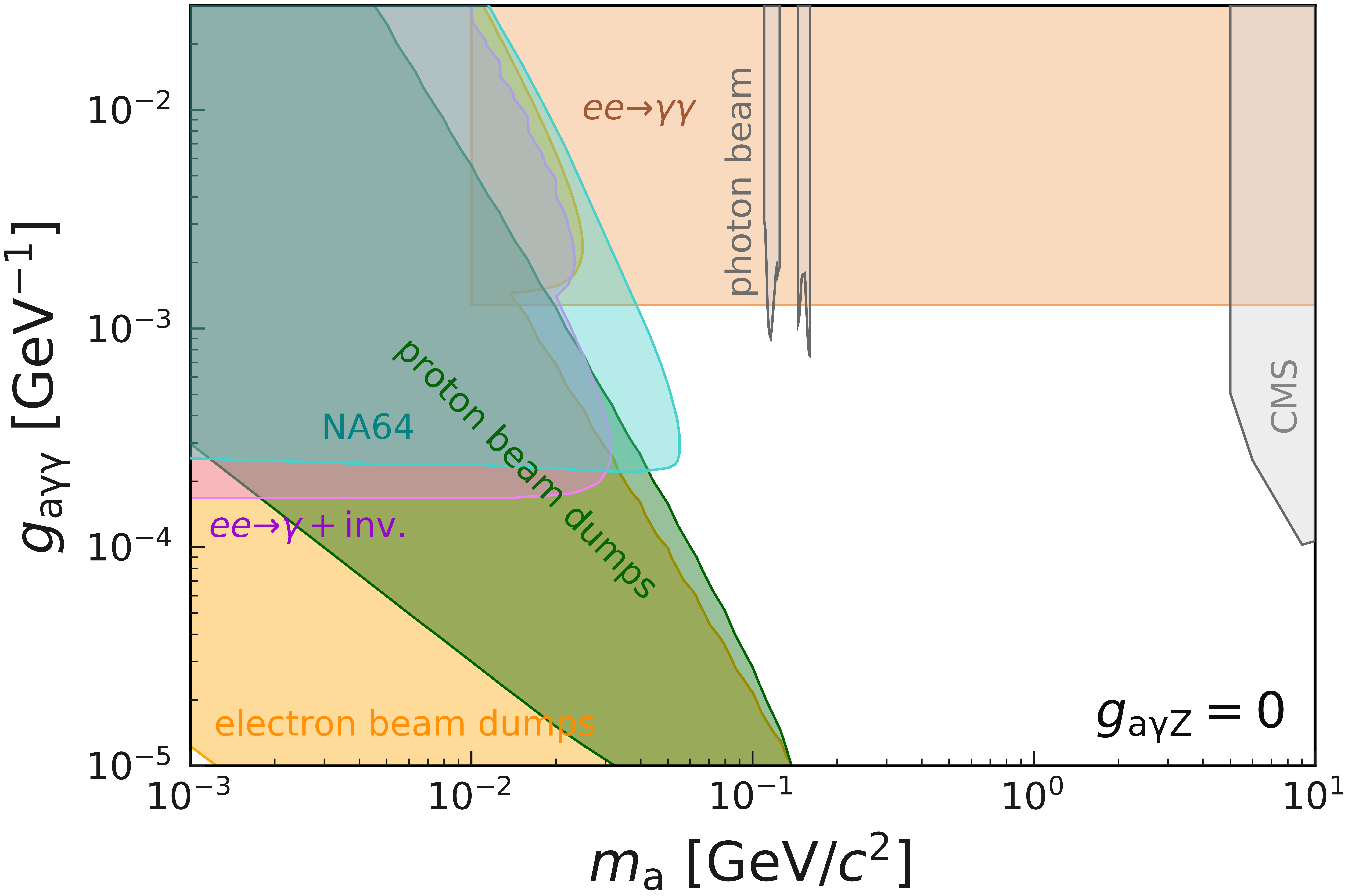
- 3-γ final state
- No tracks
- No missing energy

Main **backgrounds**:

- $e^+e^- \rightarrow \gamma\gamma(\gamma)$
- $e^+e^- \rightarrow e^+e^-(\gamma)$
  (if we don't reconstruct the tracks)
- $e^+e^- \rightarrow \pi^0/\eta/\eta' \gamma$
  negligible peaking backgrounds

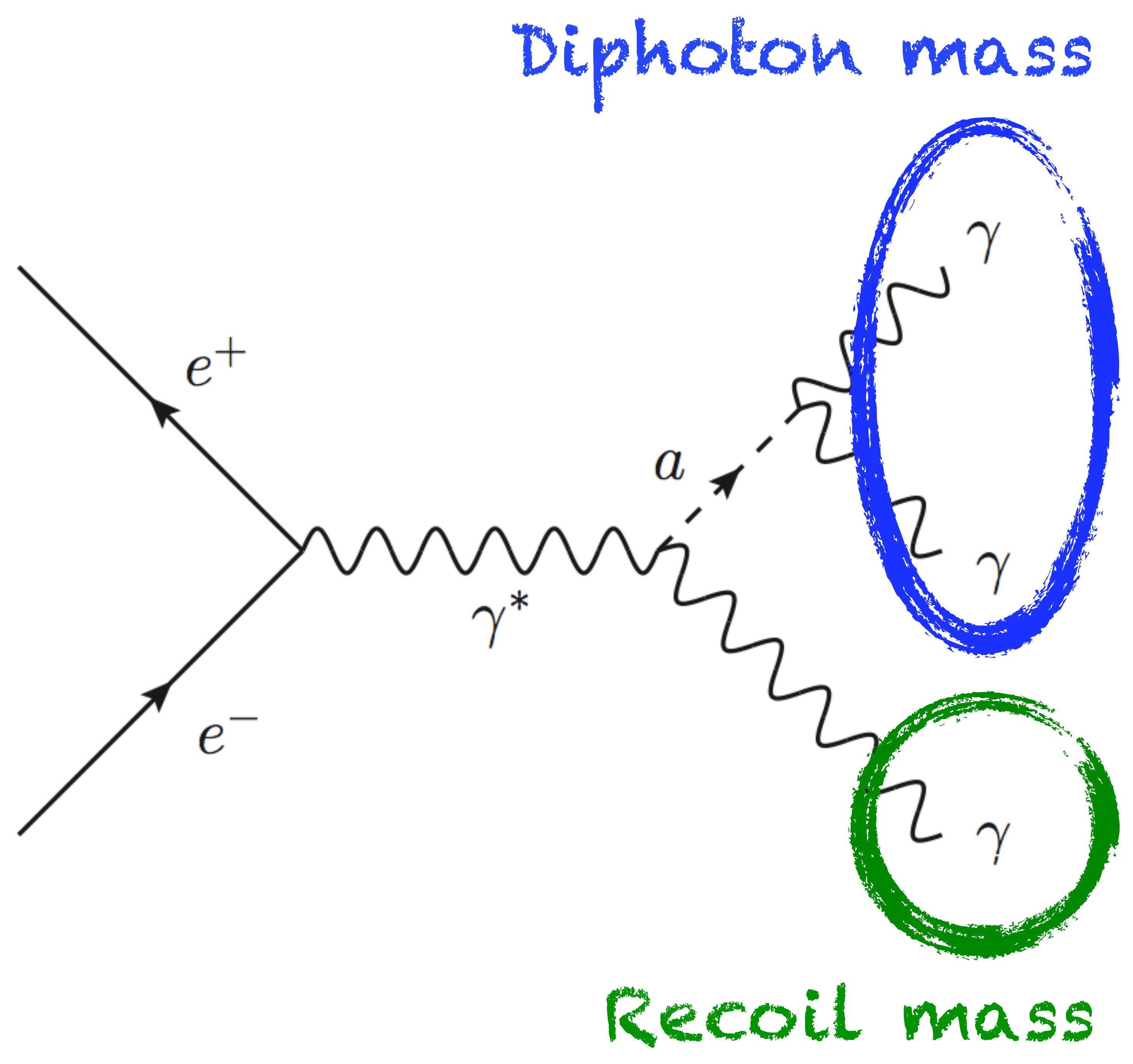
- **Peak hunt** throughout the kinematically-allowed mass spectrum
  - Scan mass range $\mathbf{m_a} \in$ **[0.2, 9.7] GeV/c²**
- **1D fit** of signal peak over smooth background

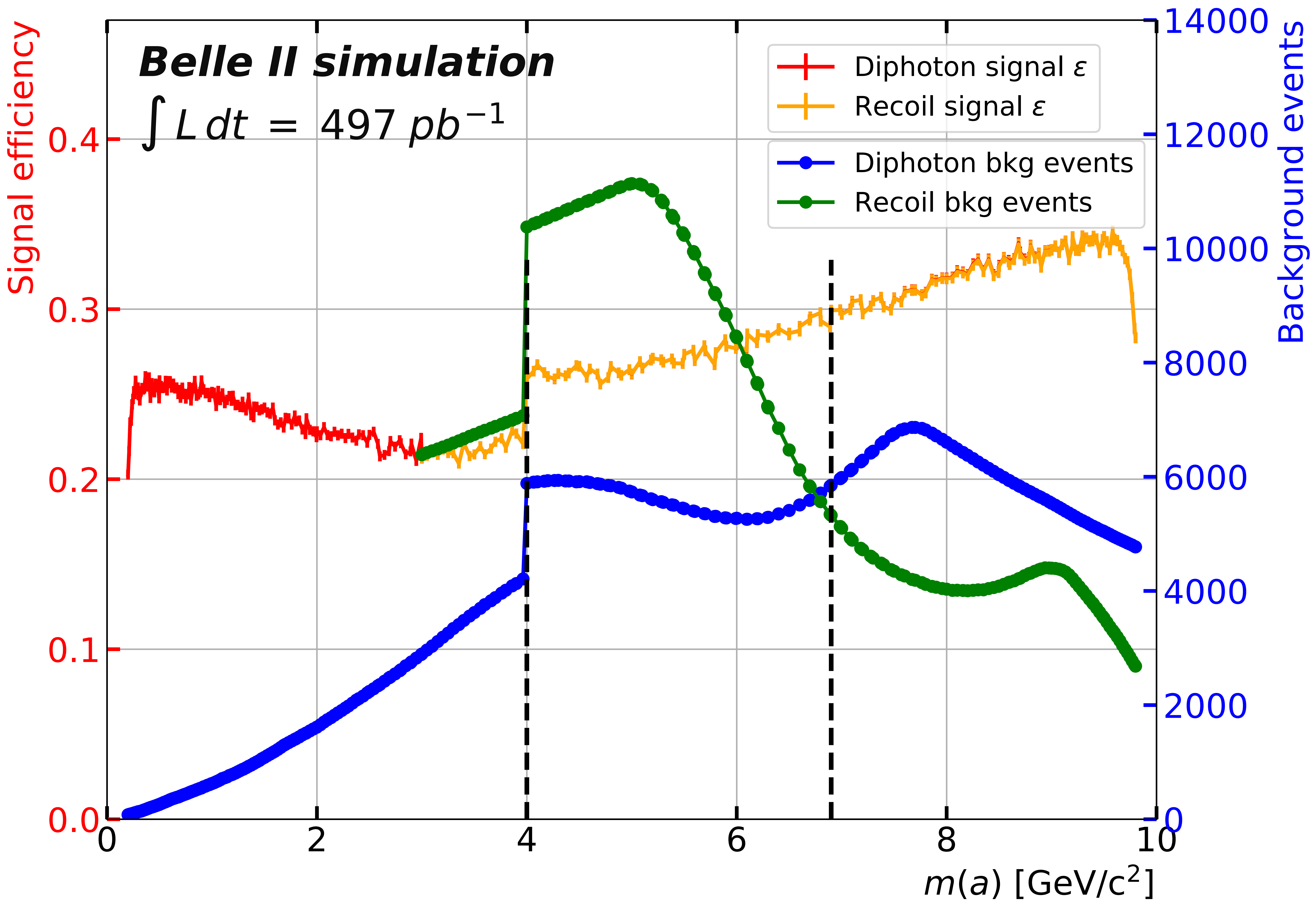
Previous status of searches



Selection performances

- Background rate
- Signal efficiency

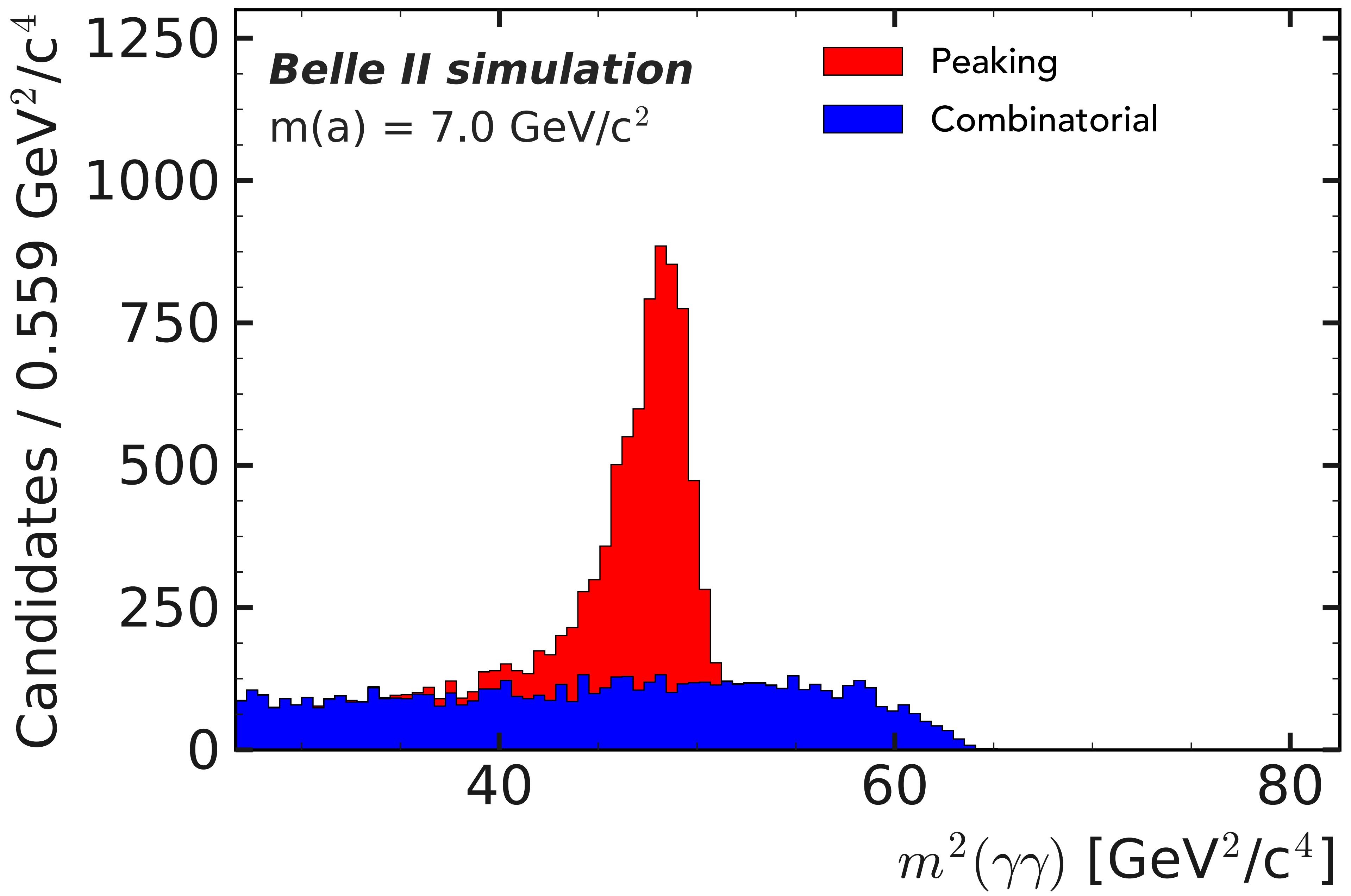




Signal & background modeling

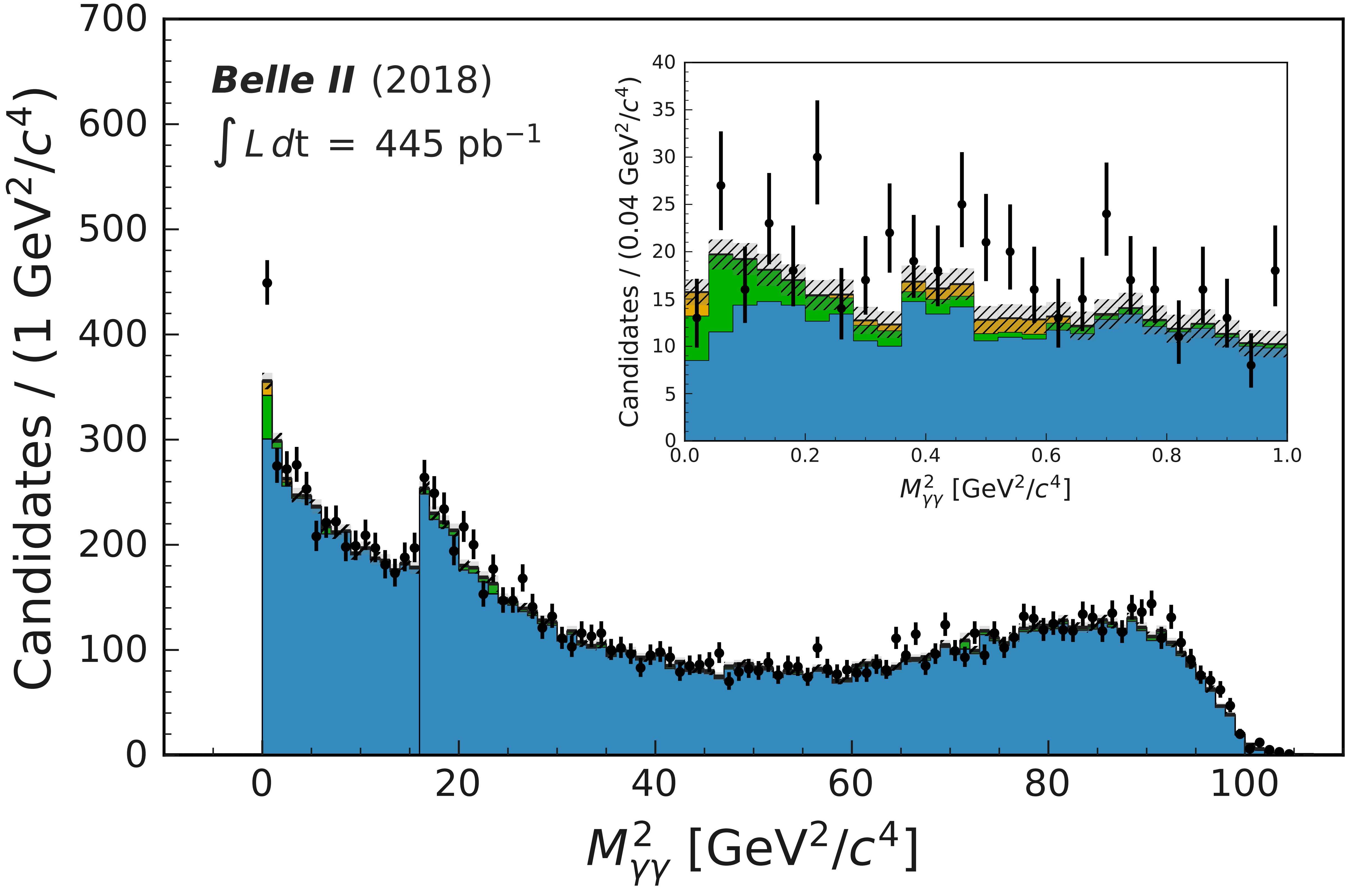
(3 $\gamma \Longrightarrow$ 3 candidates per event)

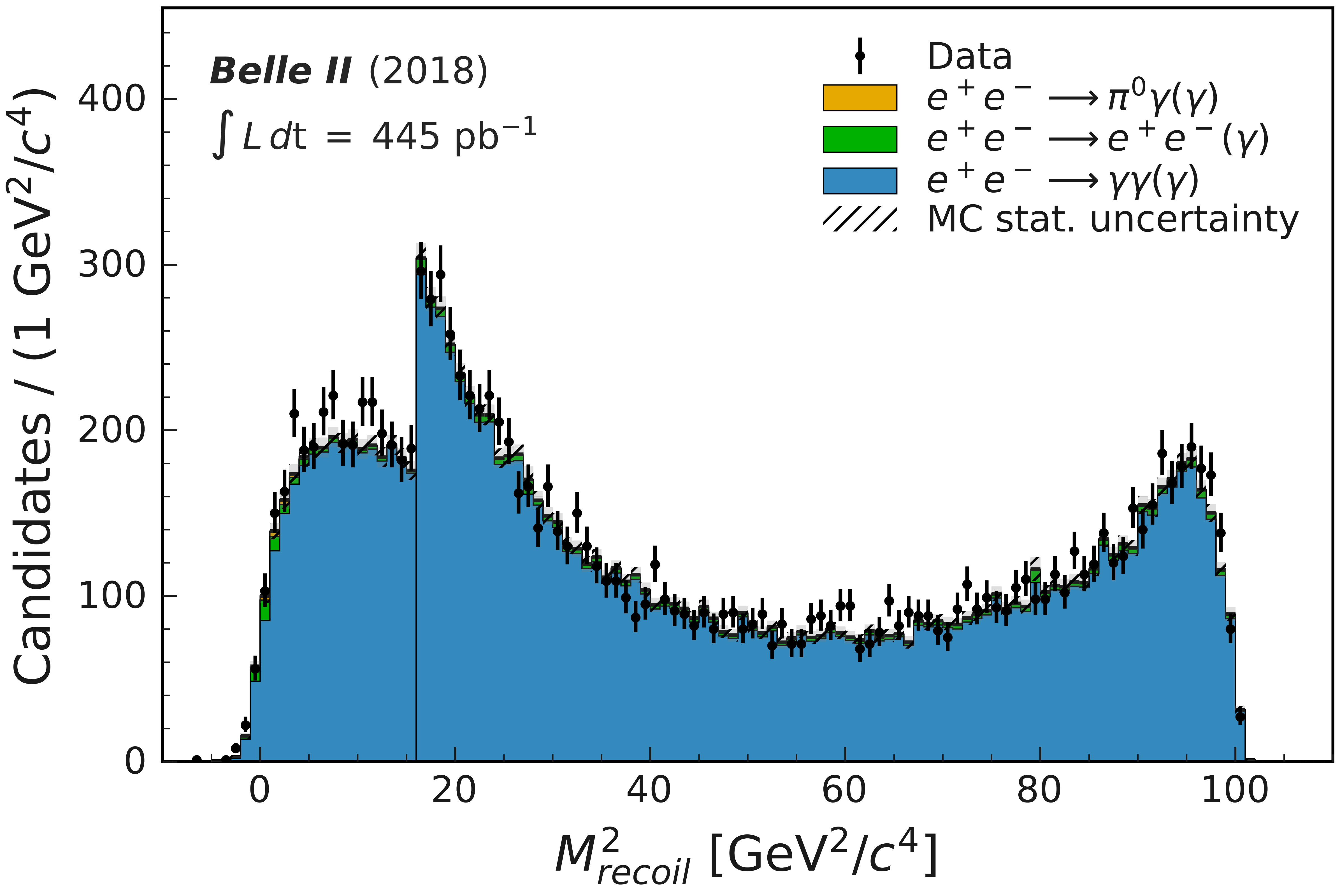
- **Signal**:
  - **Peaking** component: modeled with a **Crystal Ball** (CB):
    fit each MC sample
    interpolate parameters
    fixed for the final fit
  - **Combinatorial** component:
    modeled with a **Kernel Density Estimator** (KDE)
    fixed for the final fit



- **Background**:
  - Modeled with a **polynomial**
  - Choice of **polynomial order** and **fit range**:
    reduced χ^2 and smoothness criteria
  - Polynomial parameters are **floating** for the final fit

Data/MC comparison





Great agreement already in 2018 (data taking for calibration & tuning purposes)

10.1103/PhysRevLett.125.161806

Upper Limit (UL) extraction

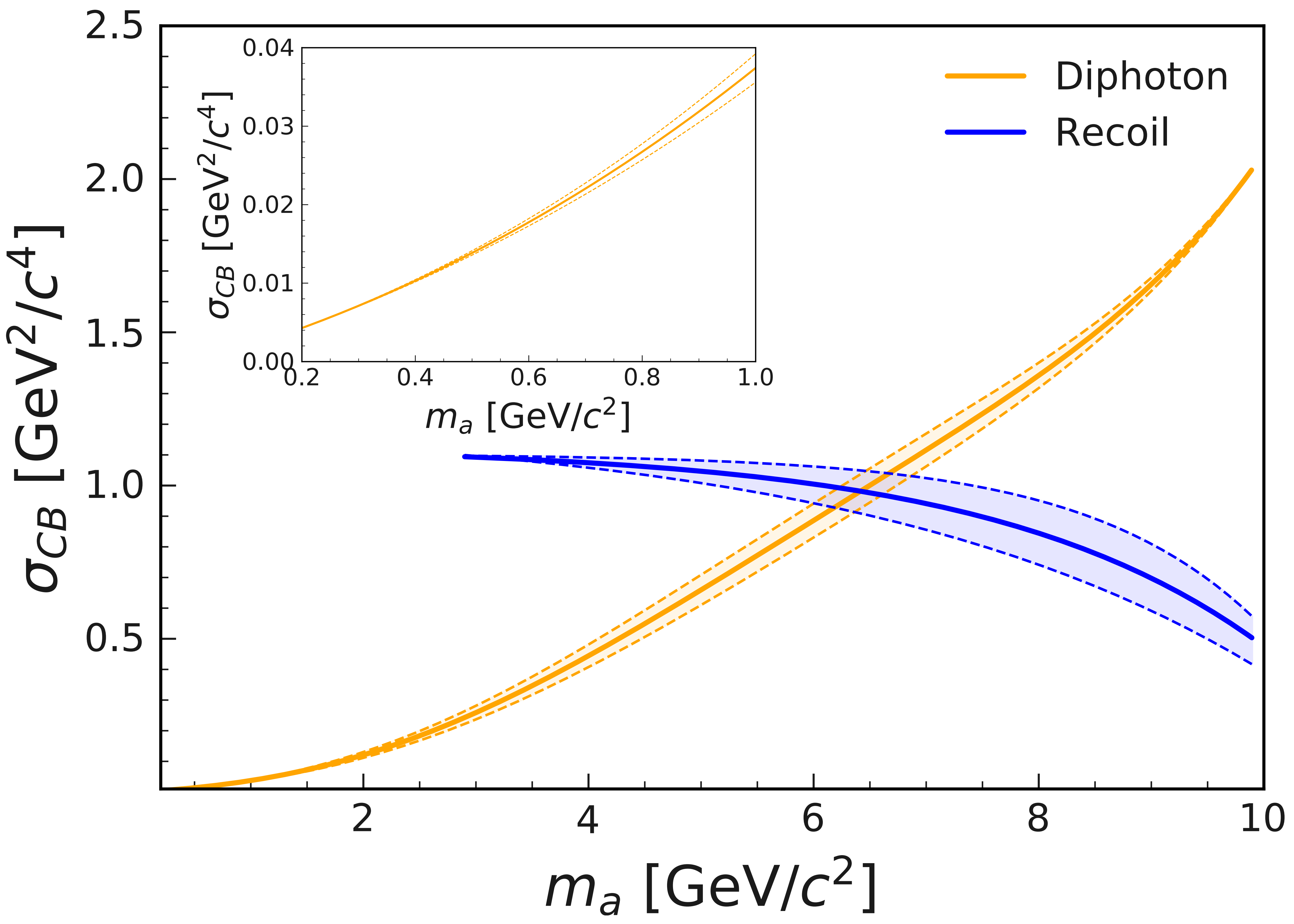
- Binned NLL approach, CLs method
- Allow only positive signal yields, i.e. cross section $\sigma_{a\gamma\gamma} \geq 0$
- ALP mass scan in **steps of 0.5 σ_{CB}** to search for signal peaks
- If **no global significance > 3** is found (with systematics): we **set limits**
  - No *local* significance > 3 has been found

Systematic uncertainties

Systematic uncertainties are **small wrt statistical** uncertainties.

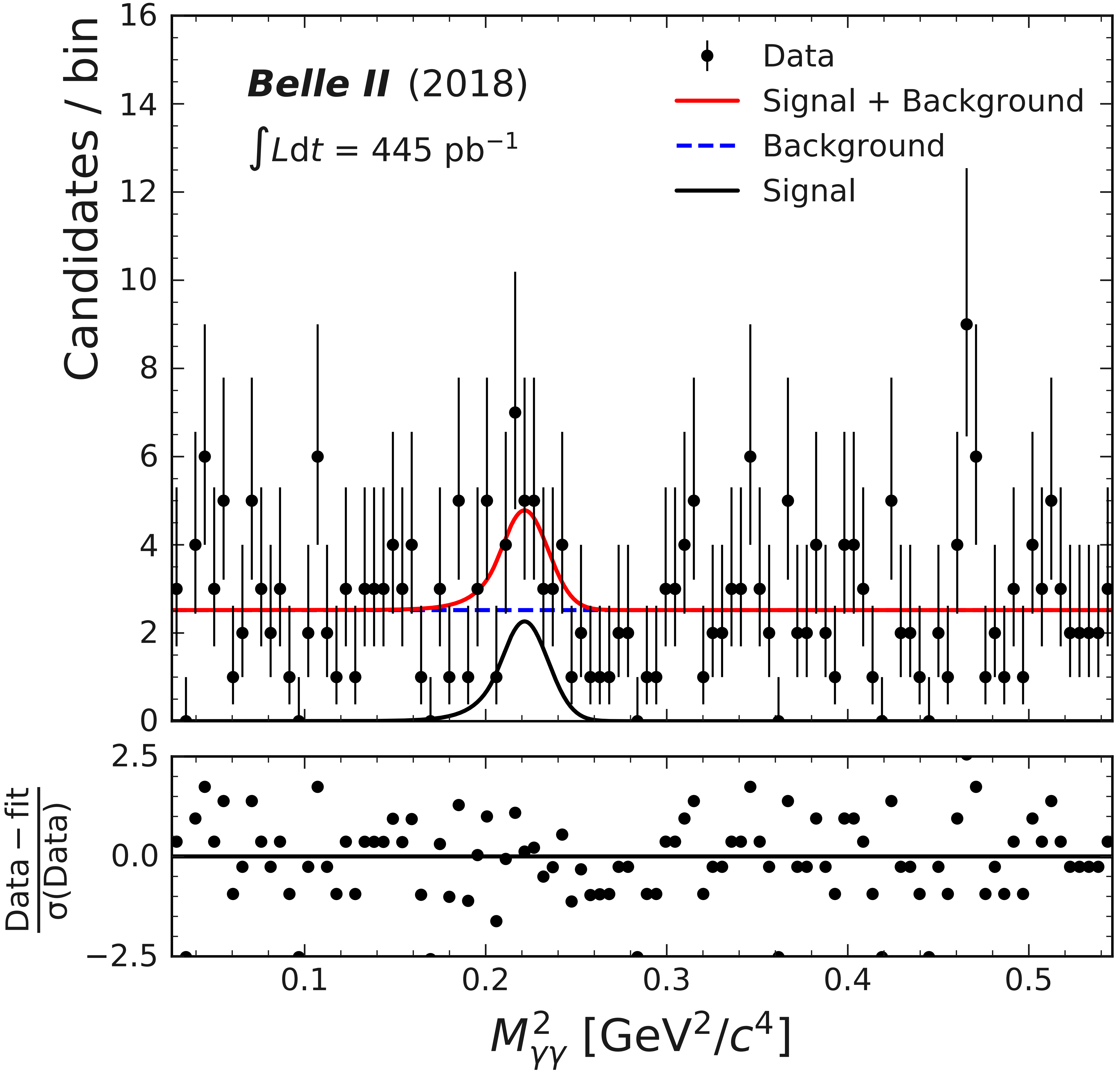
Systematics are from:

- **Choice of background polynomial order & fit range** (least irrelevant):
  - Modify order and range and re-perform UL extraction, take the weakest limit (highest UL $\Longleftrightarrow$ lowest significance)
- **Signal efficiency**
- **Signal resolution**
  from photon resolution studies



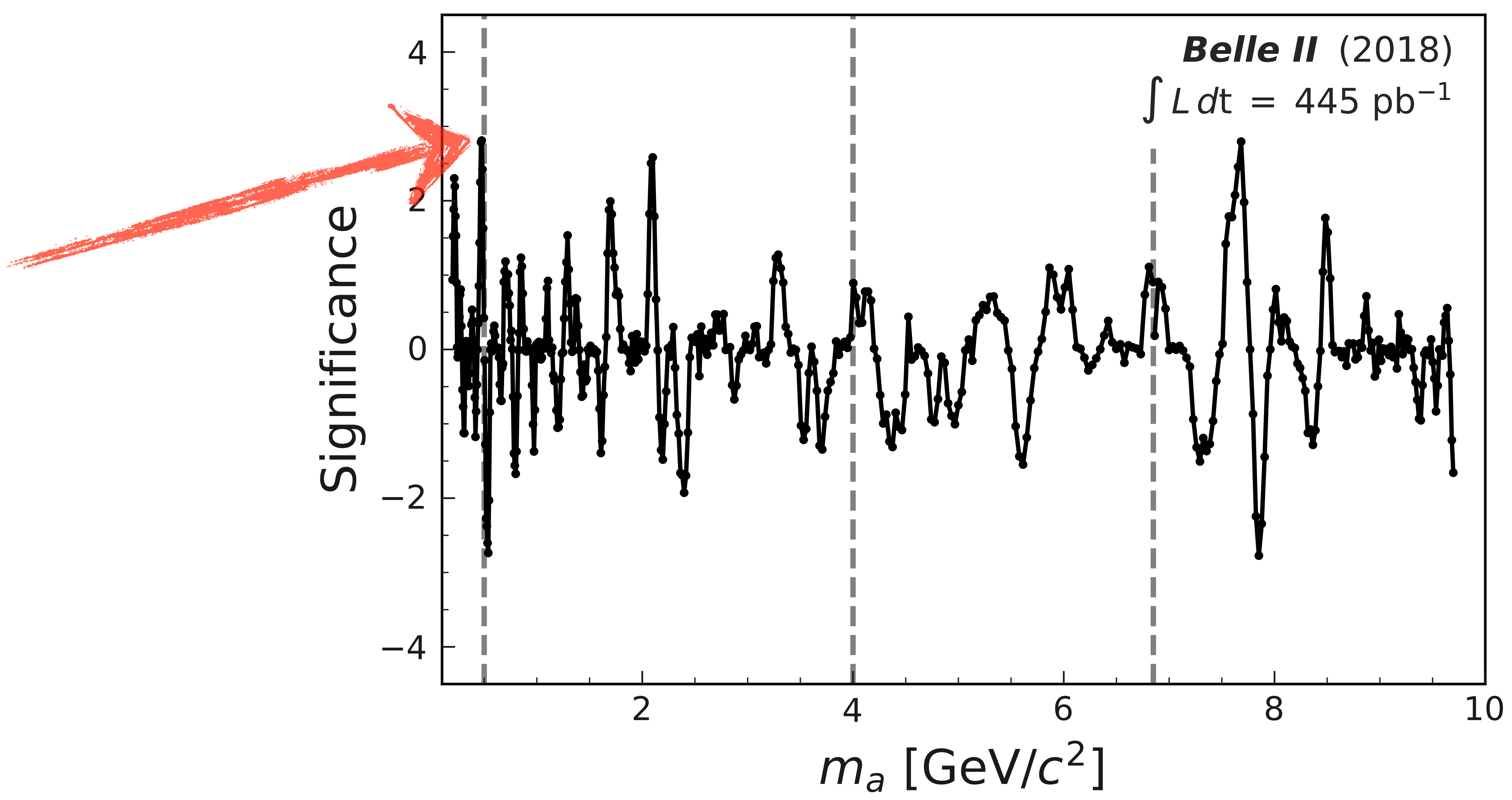
10.1103/PhysRevLett.125.161806

Results



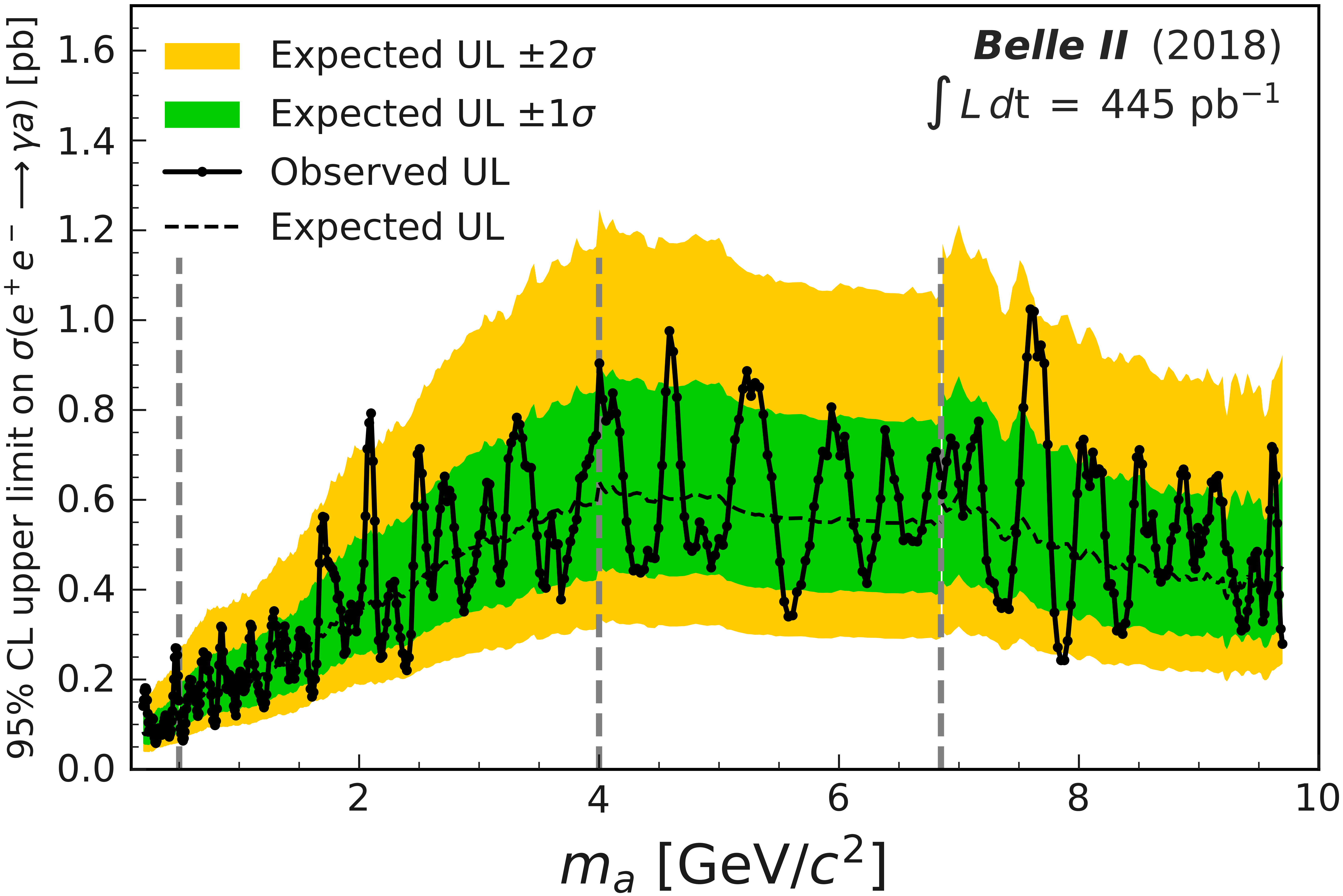
Max local significance:

2.8 σ @ m_a = 0.477 GeV/c²



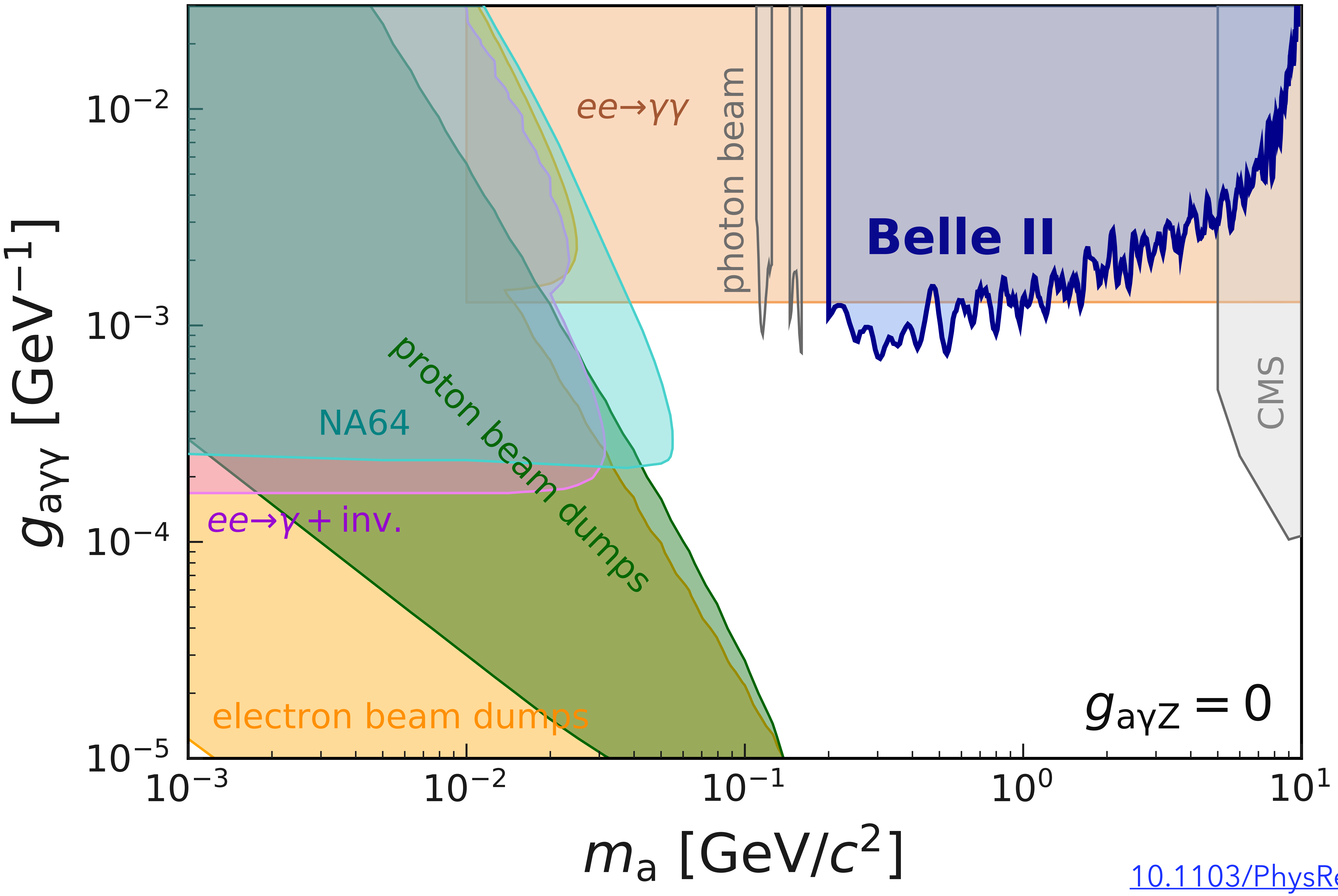
10.1103/PhysRevLett.125.161806

Results



10.1103/PhysRevLett.125.161806

Results



10.1103/PhysRevLett.125.161806

Summary.

Summary

- **Search** for the direct production of a light pseudoscalar **ALP** *a* decaying into two photons
    - $e^+e^- \to \gamma a,\ a \to \gamma\gamma$
    - $m_a \in [0.2, 9.7]$ GeV/c^2
- **No evidence for ALPs**
- Set 95% CL UL on $g_{a\gamma\gamma}$
    - These are the **strongest limits** to date **for $m_a \in$ [0.2, 1] GeV/c^2**
    - Prospects: ~20 stronger limits with full Belle II data set
- Results published in **PRL**: [10.1103/PhysRevLett.125.161806](https://doi.org/10.1103/PhysRevLett.125.161806)

Backup.

Selection variables

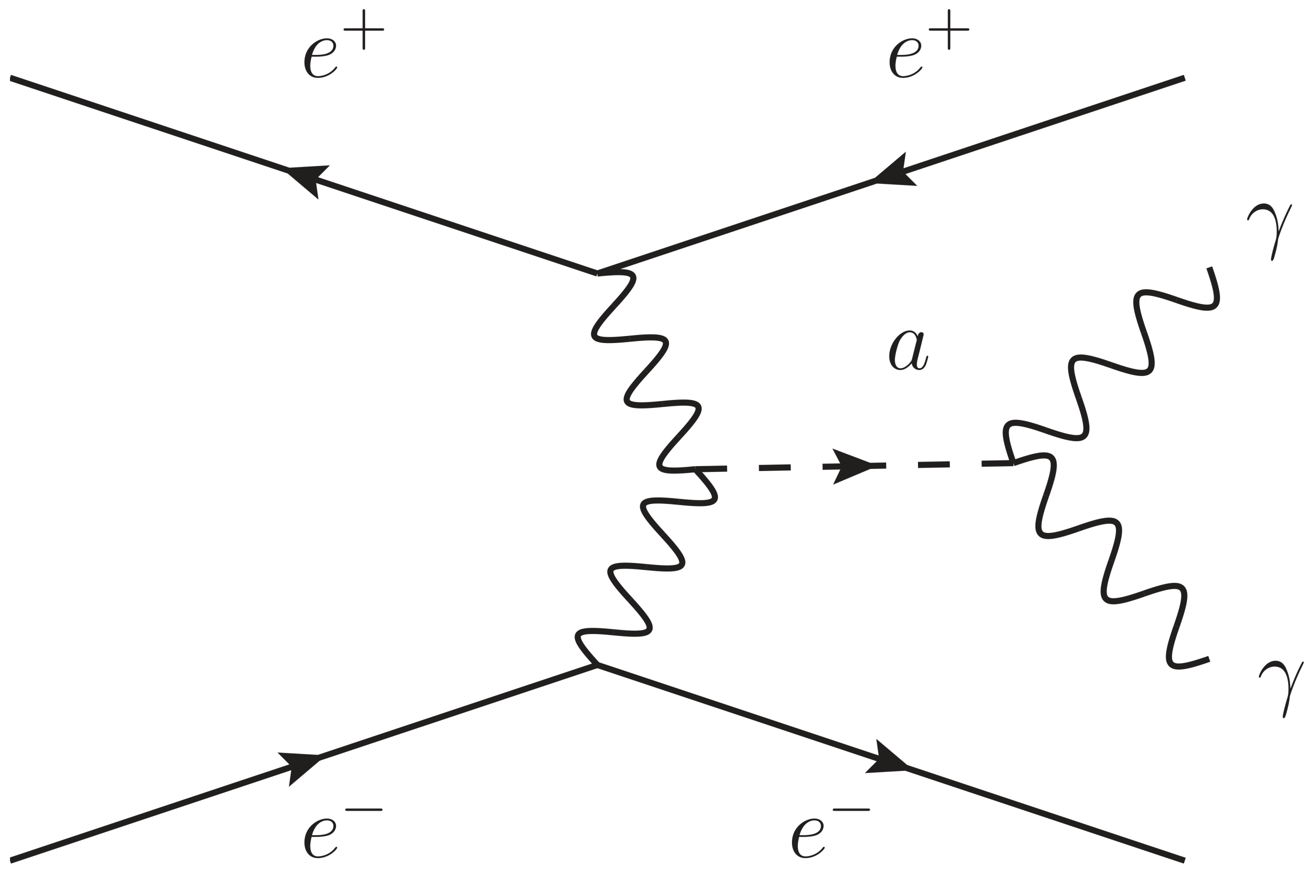
- PFM studies
- Sanity requirements
- Studies on other datasets
- Studies on sidebands

Cuts are listed in the order they are applied

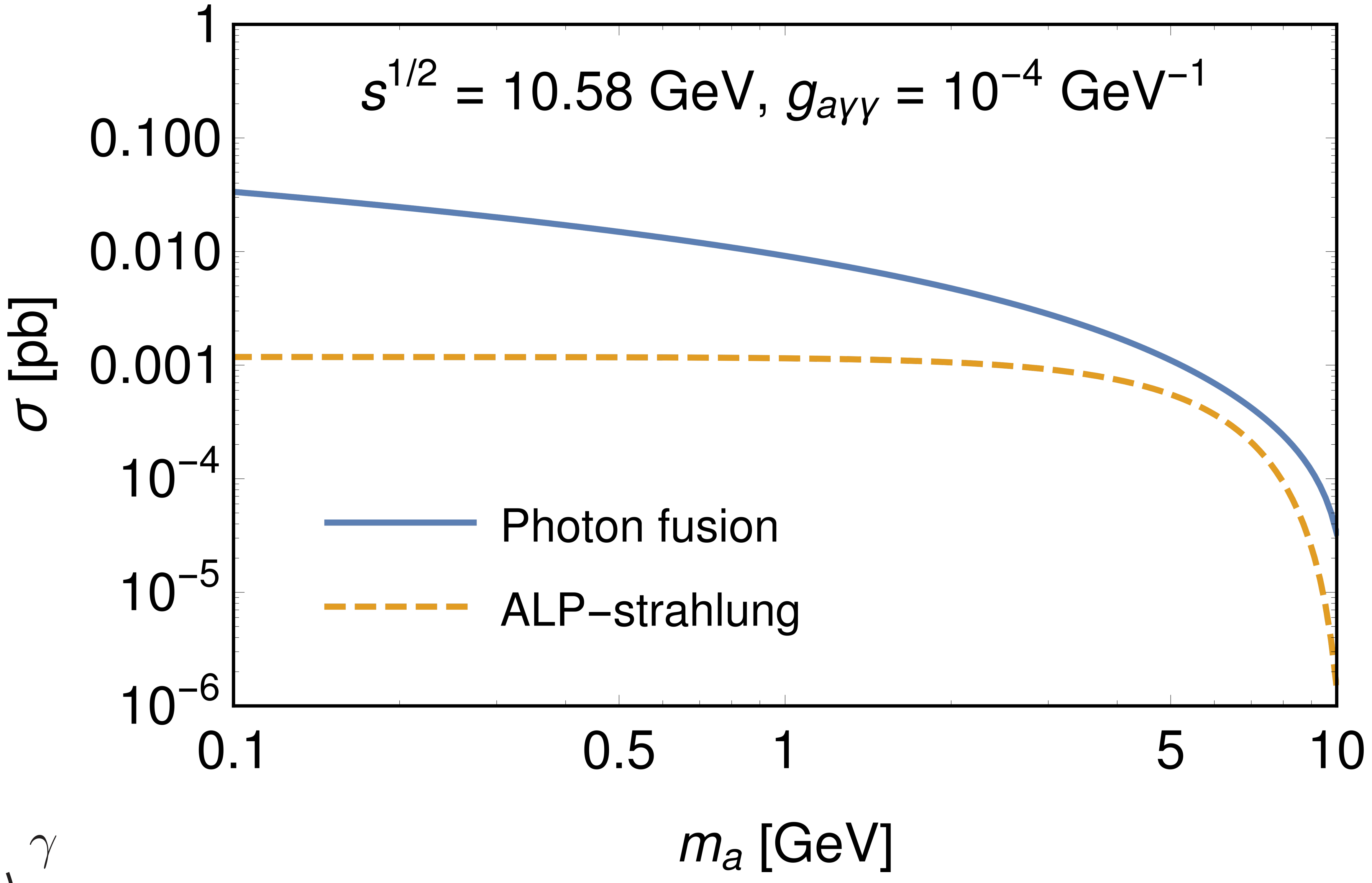
- $E_\gamma \geq 650$ MeV if $m_a \geq 4.0$ GeV/c^2
  $E_\gamma \geq 1000$ MeV if $m_a < 4.0$ GeV/c^2
- $37.3° \leq \theta_\gamma \leq 123.7°$ (barrel acceptance)
- clusterNHits > 1.5
- 3 most energetic γ
- $0.88\sqrt{s} \leq m_{\gamma\gamma\gamma} \leq 1.03\sqrt{s}$
  (9.31 GeV/$c^2 \leq m_{\gamma\gamma\gamma} \leq 10.90$ GeV/c^2)
- TimeVar* < 10
- 0 good tracks
- $\Delta\theta \geq 0.014$ rad OR $\Delta\varphi \geq 0.4$ rad
- clusterZernikeMVA of most isolated photon > 0.6

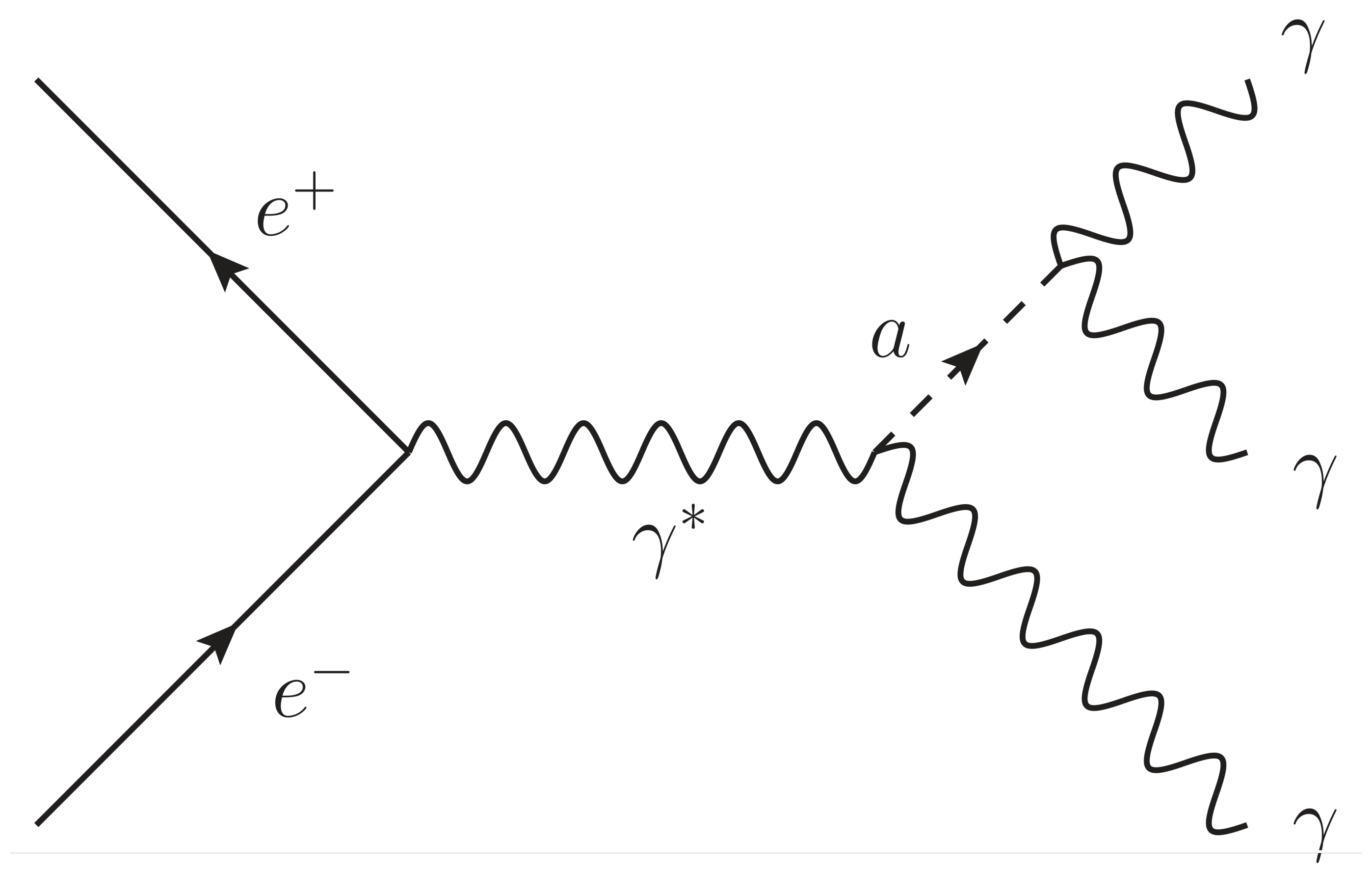
*) TimeVar = $|(t - \sum(t/\Delta t^2)/\sum(1/\Delta t^2))/\Delta t|$

ALPs - theory



Photon-fusion





ALP-strahlung

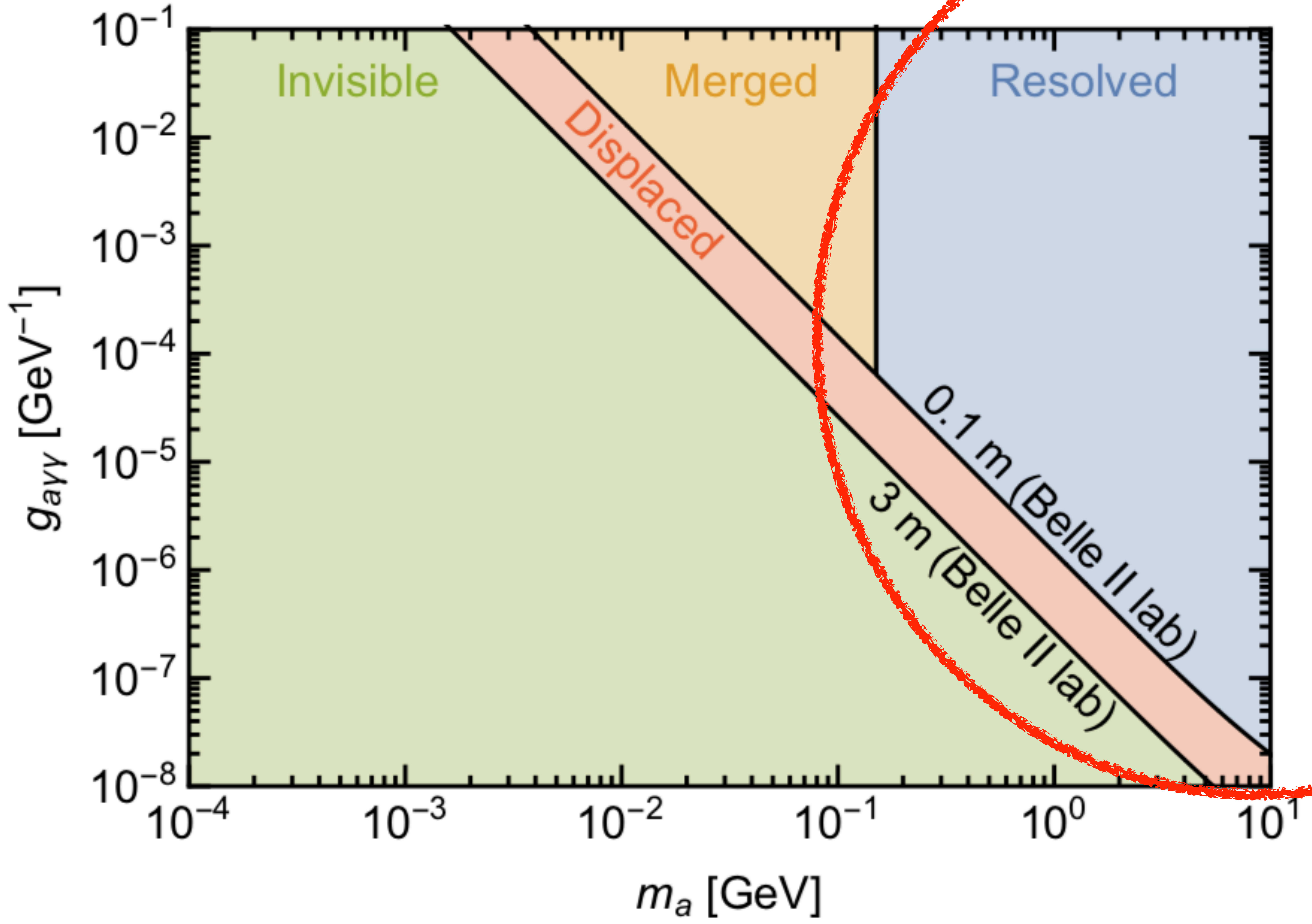
Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, [JHEP 1712 (2017) 094]

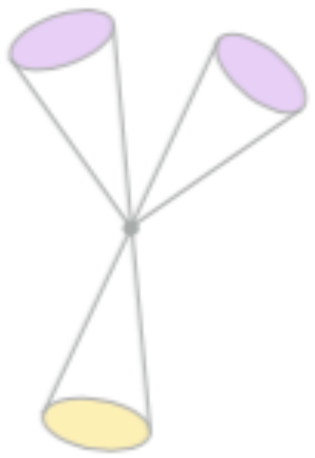
ALPs - analysis

Two of the photons overlap or **merge**

Current focus

ALP decays outside of the detector or decays into **invisible** particles: single photon final state





Three **resolved**, high energetic photons

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, [JHEP 1712 (2017) 094]

Selection variables

Selection optimization via **maximization** of **Punzi Figure of Merit** (PFM)

- PFM as function of 1 variable
  - Other variables fixed
- Vary cut on that variable
- For multiple ALP masses
- Repeat for all variables

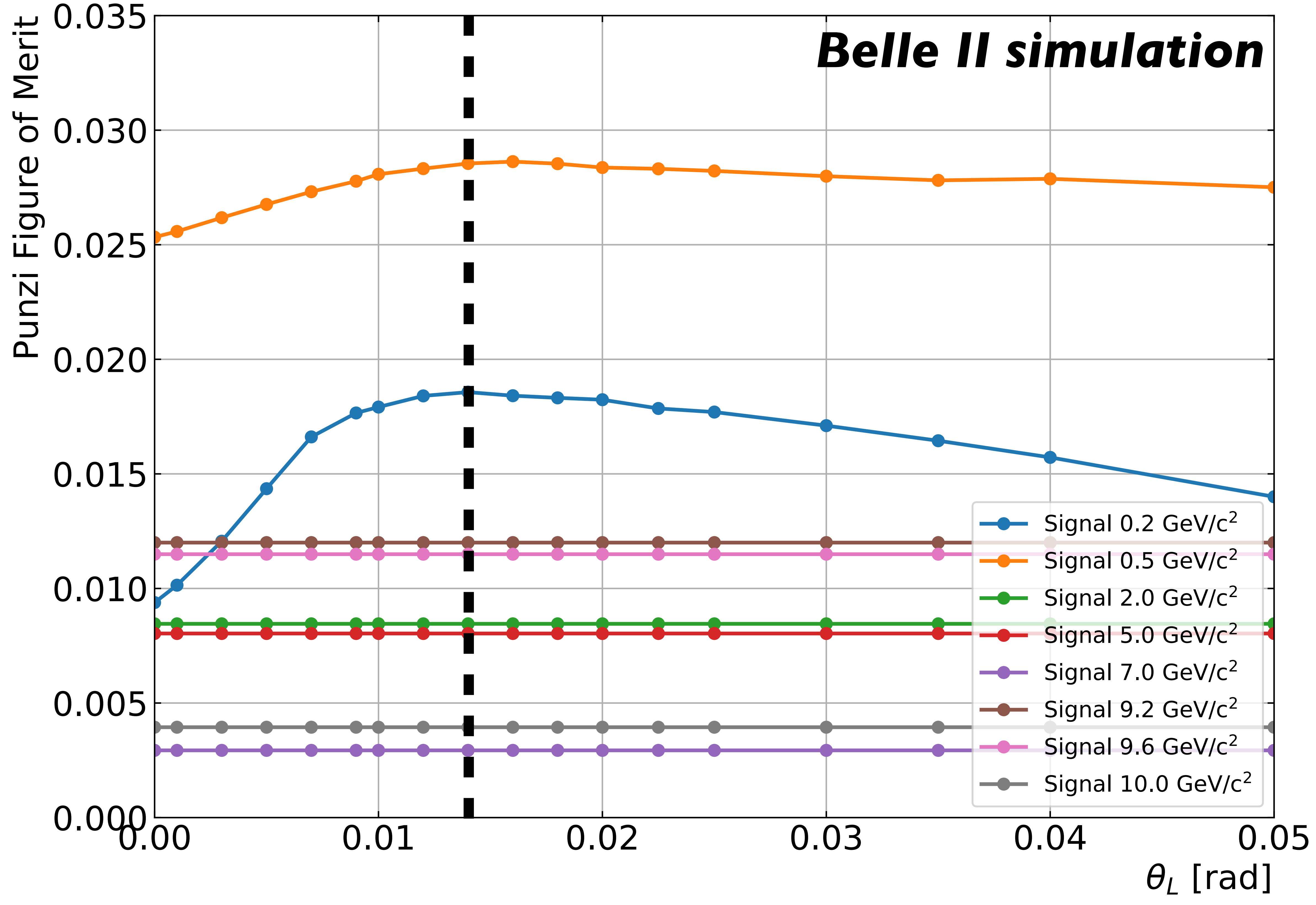
$$PFM = \frac{\epsilon_S}{\frac{a}{2} + \sqrt{B}}$$

Signal efficiency

bkg candidates passing the cuts

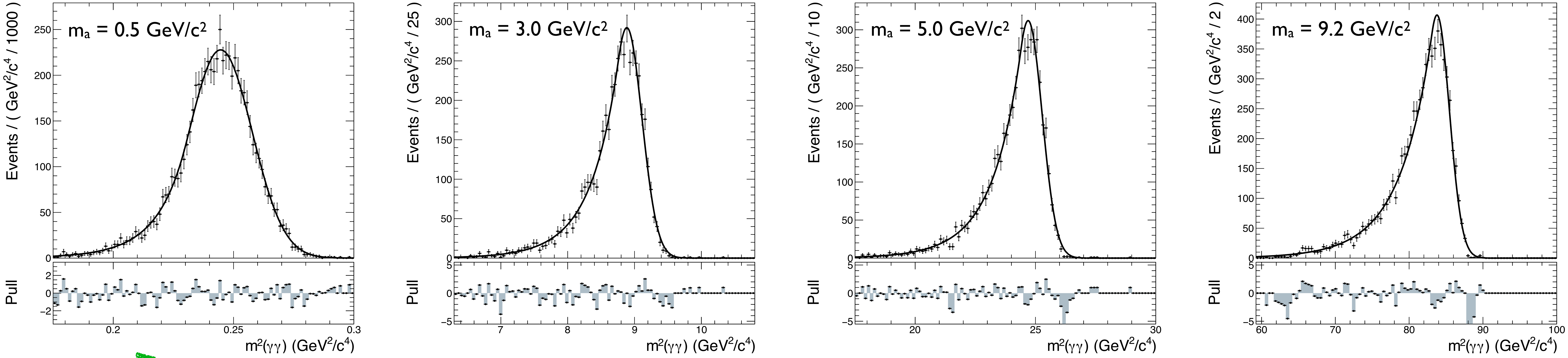
Number of sigmas corresponding to one-sided Gaussian tests at a given significance (a=5)

One **example** of PFM scan:



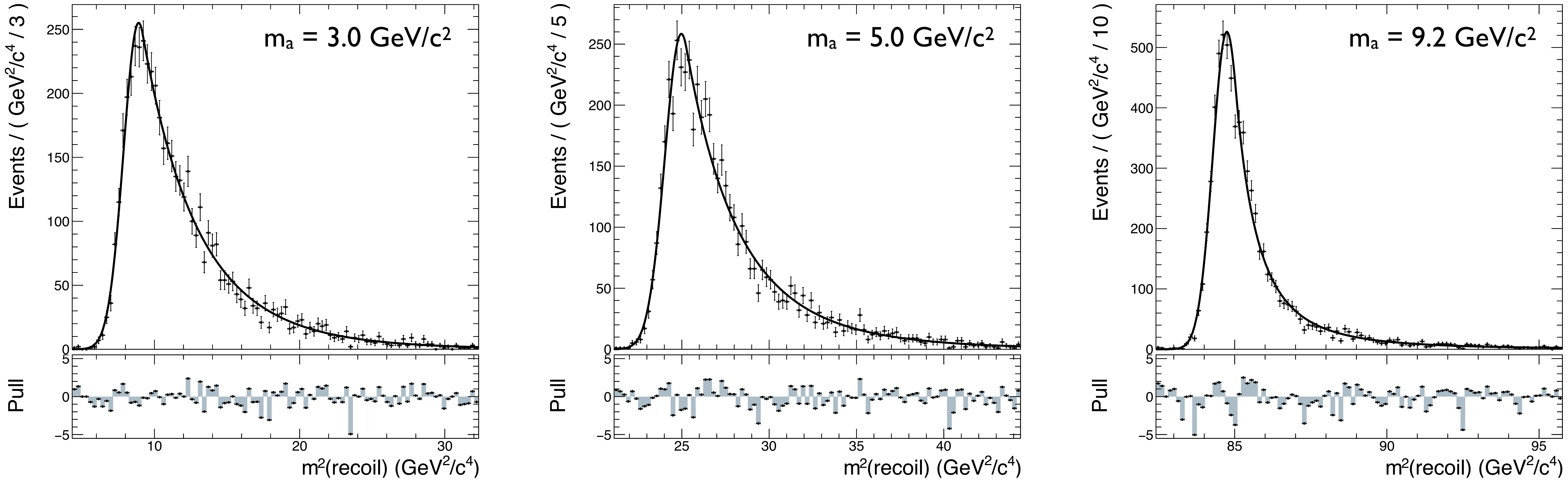
(https://arxiv.org/pdf/physics/0308063.pdf)

Signal peaking



Squared **diphoton** mass

Squared **recoil** mass



Background modeling

Choice of polynomial order & fit range with reduced χ^2 and smoothness criteria

- $m_a \in [0.2, 0.5]$ GeV/c^2 $\Longrightarrow$ 2nd order, fit range $[m_a^2 - 20 \cdot \sigma_{CB}, m_a^2 + 30 \cdot \sigma_{CB}]$
- $m_a \in [0.5, 6.85^*]$ GeV/c^2 $\Longrightarrow$ 4th order, fit range $[m_a^2 - 20 \cdot \sigma_{CB}, m_a^2 + 30 \cdot \sigma_{CB}]$
- $m_a \in [6.85^*, 9.7]$ GeV/c^2 $\Longrightarrow$ 5th order, fit range $[m_a^2 - 25 \cdot \sigma_{CB}, m_a^2 + 25 \cdot \sigma_{CB}]$