# Project ALPs - Experiment

**Hang Zhou on behalf of BESIII group**

**Workshop of RU FOR5327**

**11.6.2025, Sankt Goar**

# Topics

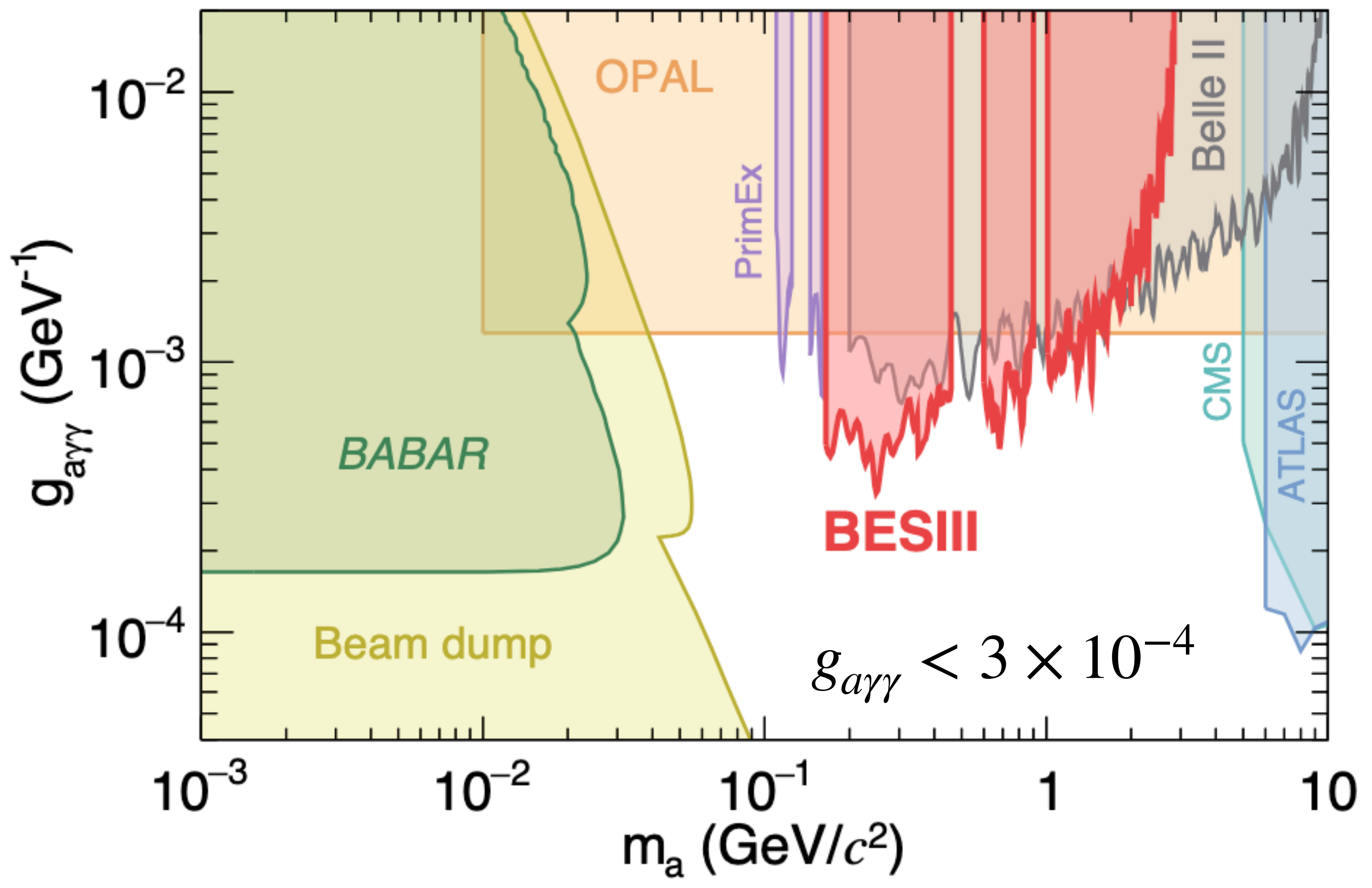
- **Axion-like particle (ALP) search at BESIII**
    - $e^+e^- \to \gamma\gamma\gamma$ (Thomas Lenz)
- **Dark photon search at BESIII**
    - $e^+e^- \to \gamma_{\mathrm{ISR}} l^+ l^- \ (l = e,\ \mu)$ (Maurice Anderson)
- **X17 search at BESIII**
    - $\psi(2S) \to \chi_{cJ} e^+e^-$ (Hang Zhou)
    - $J/\psi \to p\bar{p}e^+e^-$ (Saskia Plura)

# ALP search at BESIII

$$e^+e^- \to \gamma\gamma\gamma$$

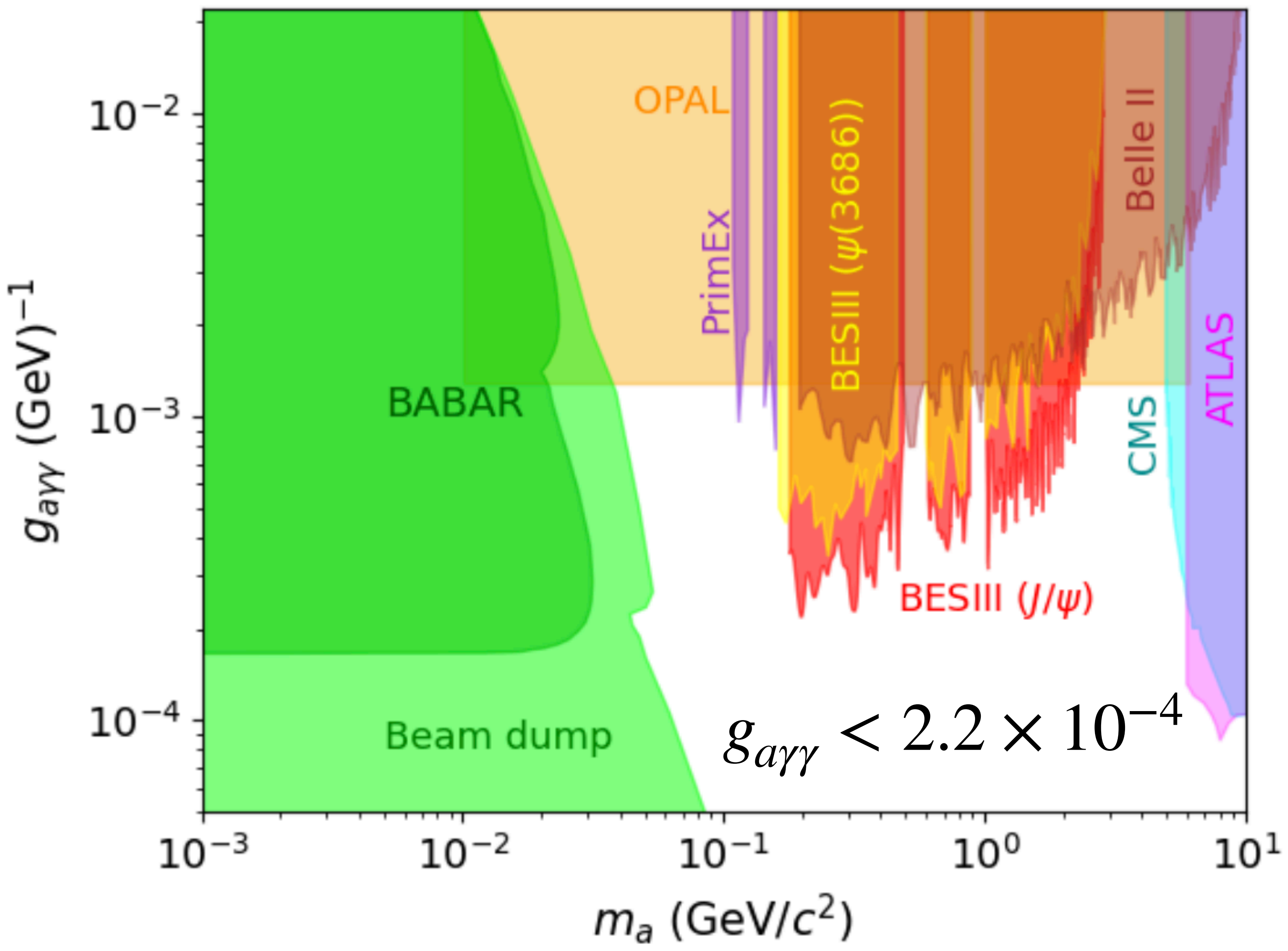
# Status

- Looking for an ALP couple only to photons $a \to \gamma\gamma$
- Time-like ALP strahlung process




$\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma\gamma\gamma$ with 2.7 Billion $\psi(2S)$

Phys.Lett.B 838, 137698 [BESIII] (2023)



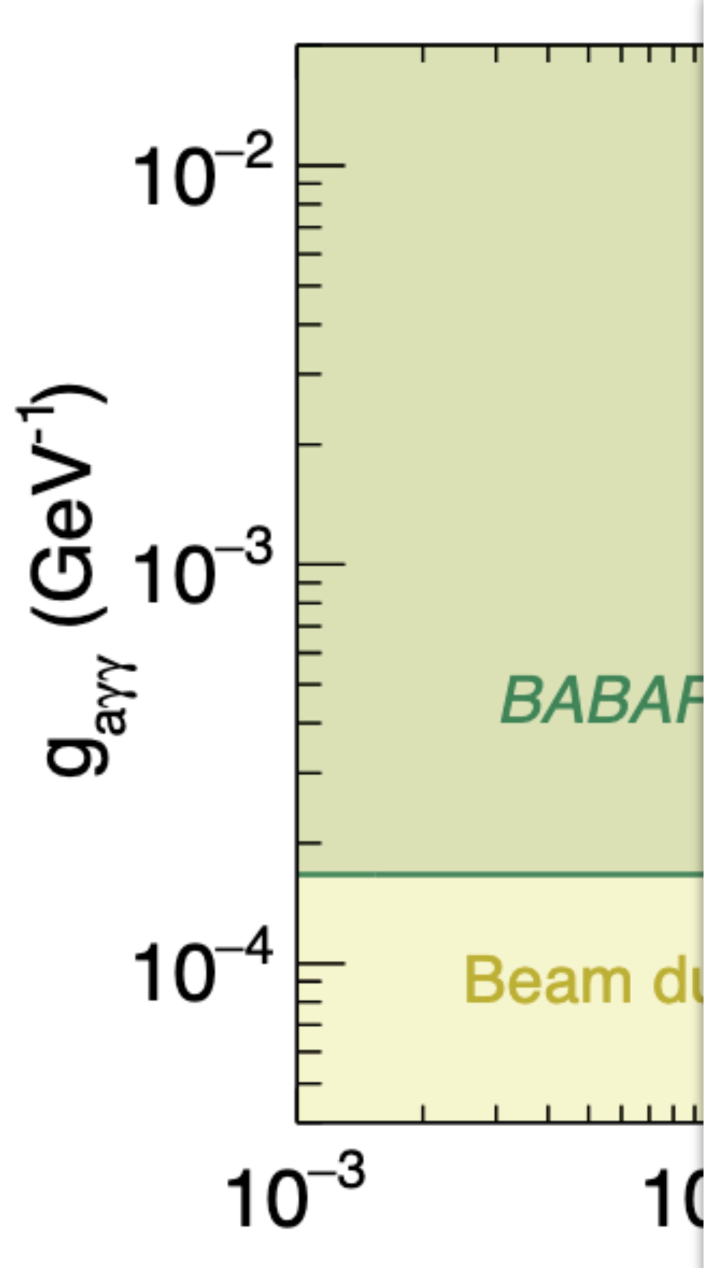

$J/\psi \to \gamma\gamma\gamma$ with 10 Billon $J/\psi$

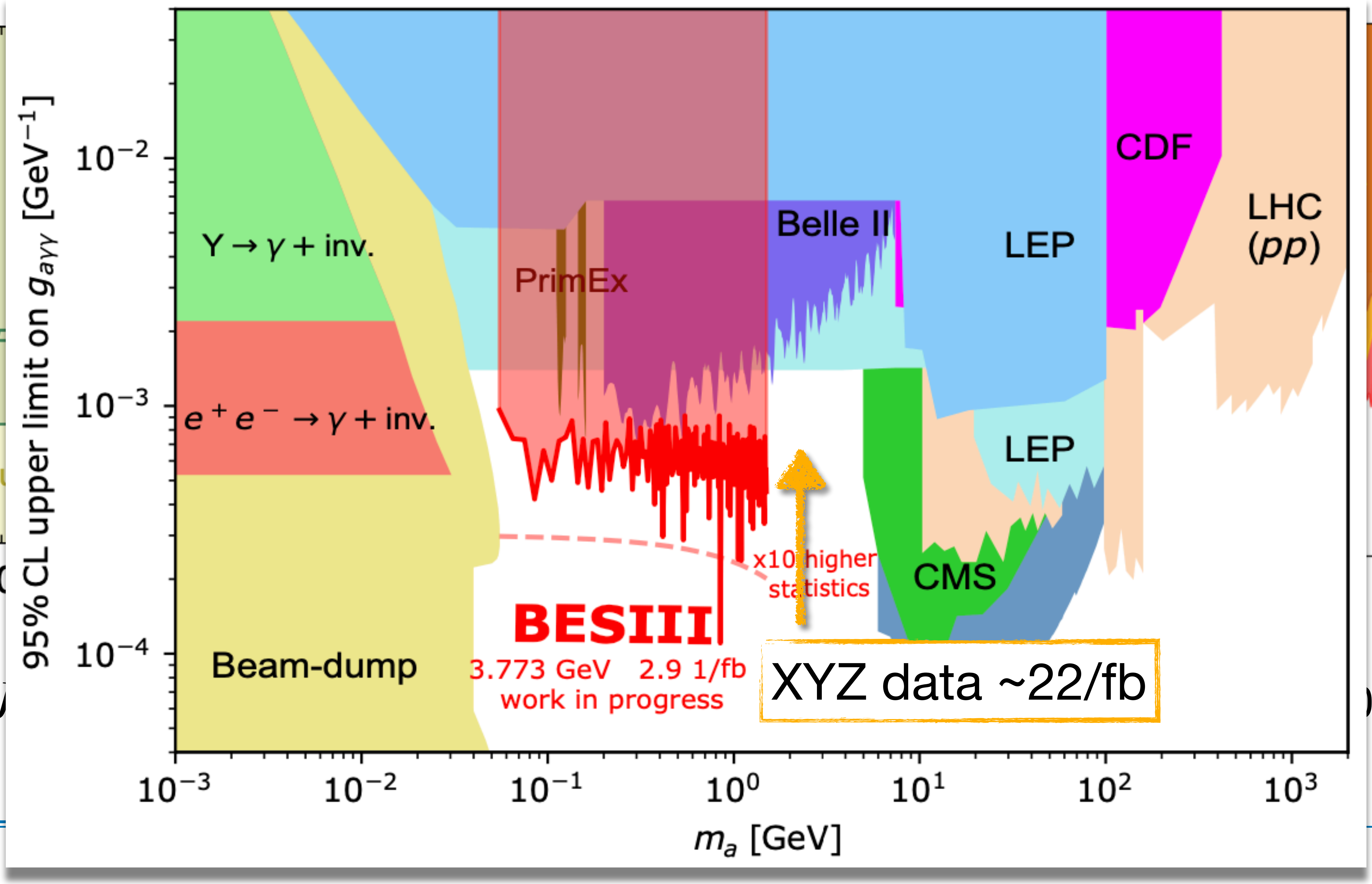
Phys.Rev.D 110, L031101 [BESIII] (2024)

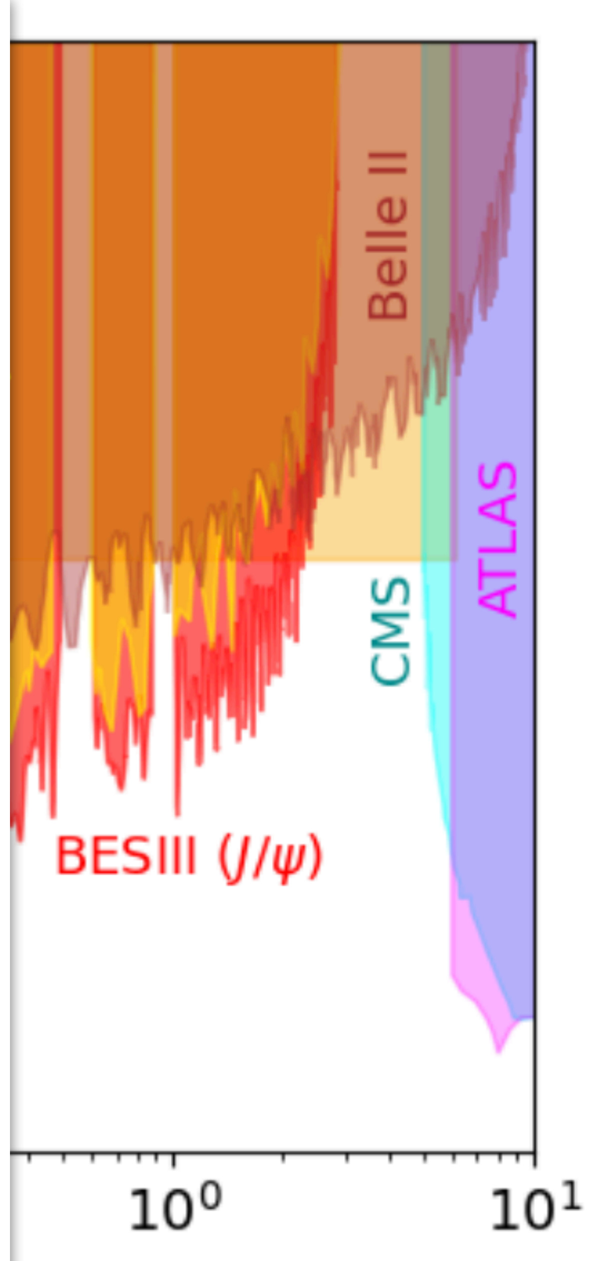
# Status

- Looking for an ALP couple only to photons $a \to \gamma\gamma$
- Time-like ALP strahlung process

Still under progress …




$\psi(2S) \to \pi^+\pi^- J$ … Billon $J/\psi$

Phys.L … [BESIII] (2024)

# Dark Photon Search at BESIII

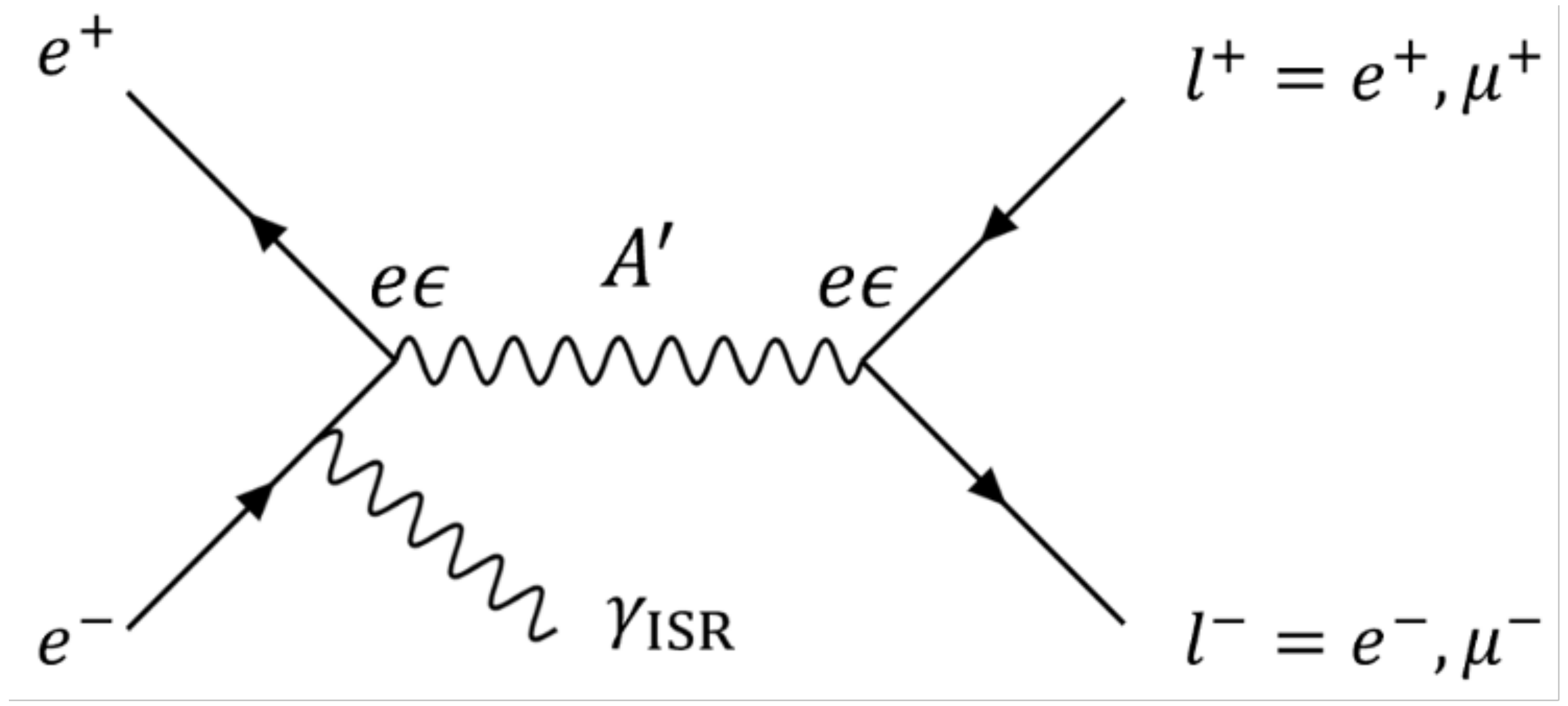
$$e^+e^- \rightarrow \gamma_{\mathrm{ISR}} l^+ l^-$$

# Introduction

- **Dark Photon** $A'$: force-mediating vector boson of Dark Sector
- **Kinetic mixing** between two U(1) gauge fields (dark photon and QED photon)

  [Phys. Lett.B 166 (1986), pp. 196–198]

  - Bridge between Dark Sector and SM
  - Direct coupling (decay) to SM particles (e.g. $e,\ \mu$)




- Search various invariant mass with initial state radiation (**ISR**) at **BESIII**

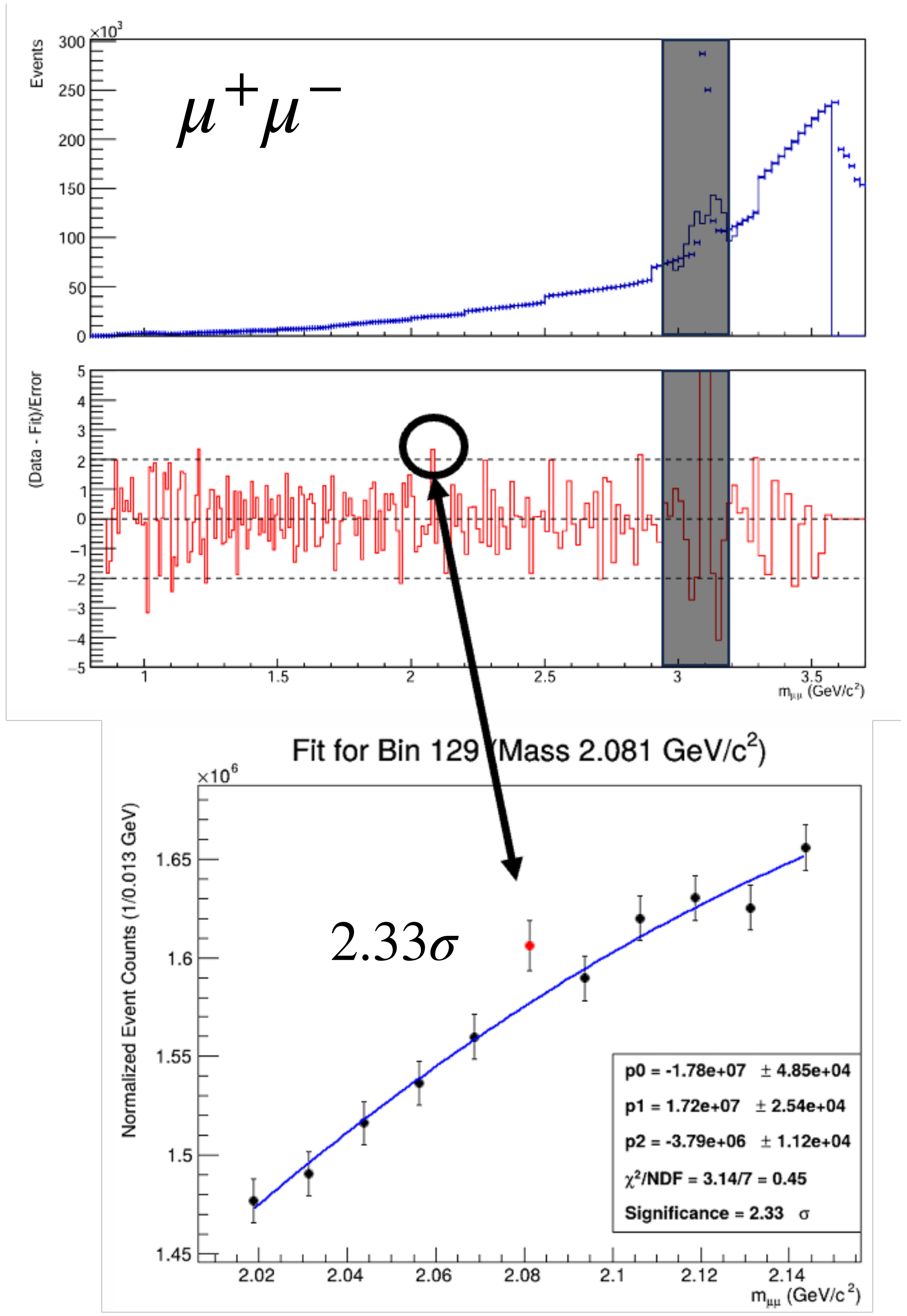
# Method

- Using $20\text{fb}^{-1}$ $\psi(3770)$ events, untag ISR photon to improve statistics

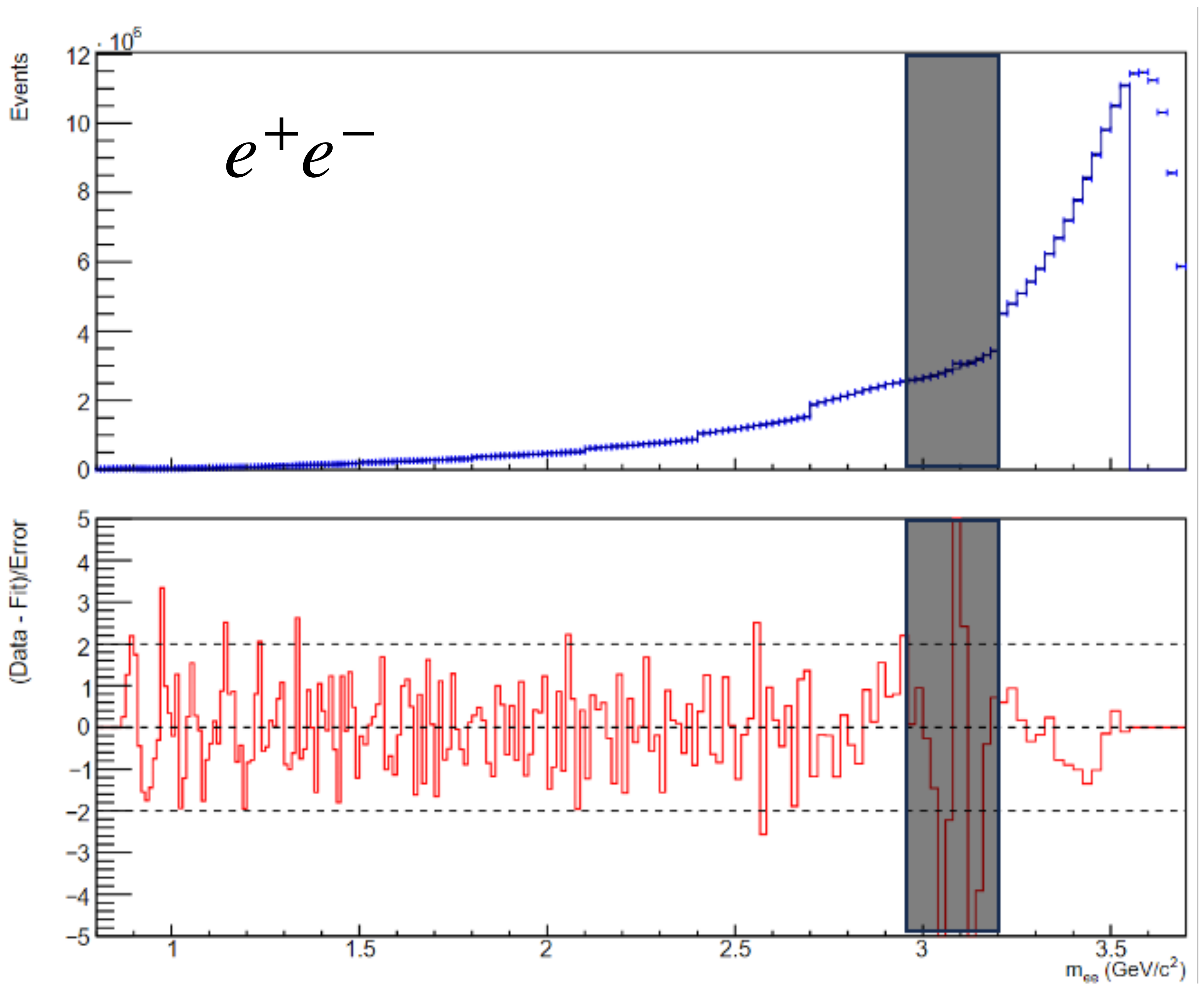
- Data-driven search for local derivation from QED background in $e^+e^-/\mu^+\mu^-$ **invariant mass** spectrum

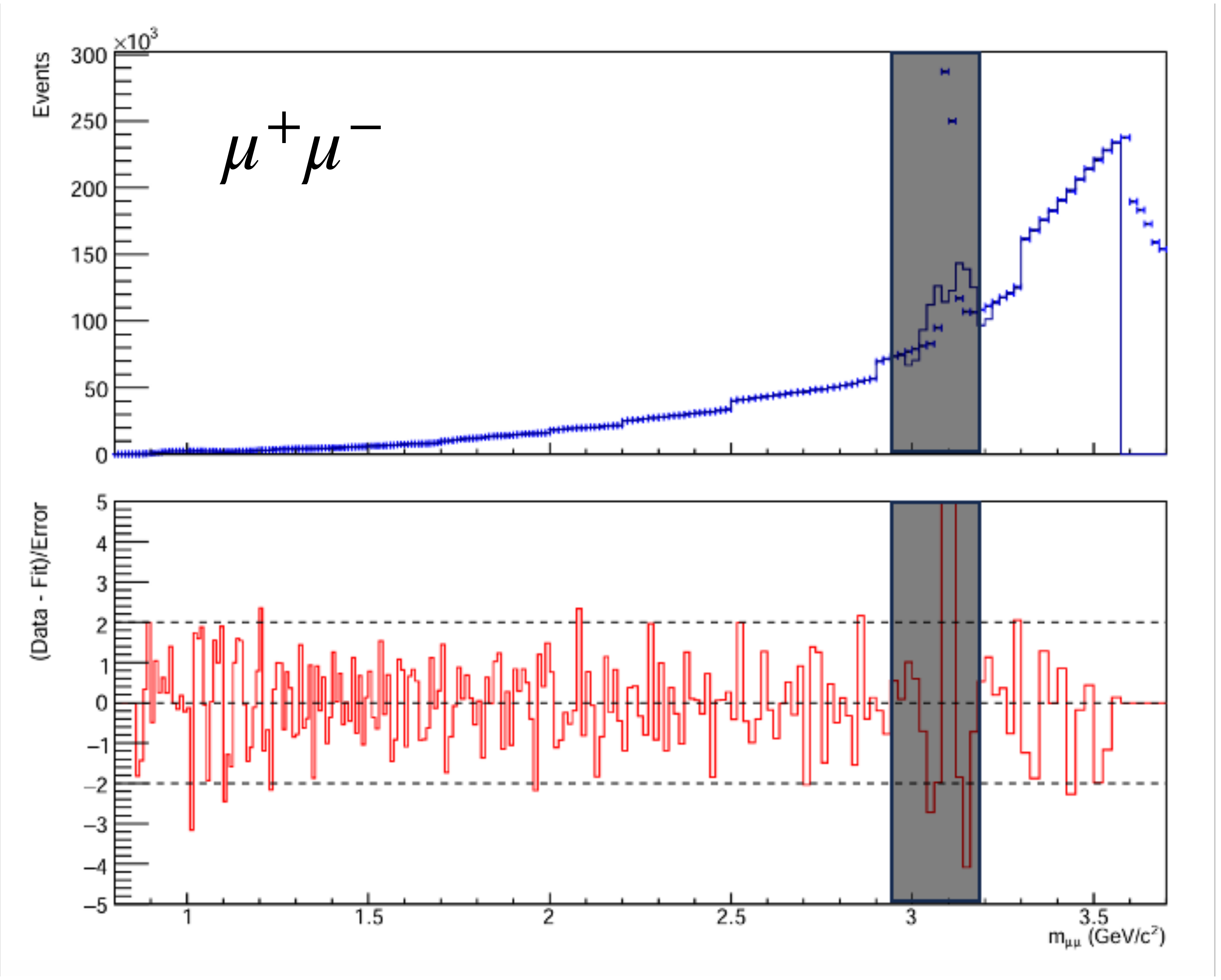
- Bump hunting: **sideband fit** (quadratic polynomial) of $\pm 5$ neighbouring bins in sliding mass window

- Modified frequentist $CL_s$ **method**: [*J. Phys. G 28 (2002), pp. 2693–2704*]
    - Is data more compatible with null (background-only) hypothesis or alternate (signal + background) hypothesis?
    - Set upper limit on signal $s$, where confidence level $CL = 1 - CL_s = 90\,\%$



# Method




Combine $e^+e^-$ and $\mu^+\mu^-$: $N = f \cdot N_{e^+e^-} + N_{\mu^+\mu^-}$

Correction factor $f = \dfrac{N_{\text{s-channel}}}{N_{\text{s-channel}} + N_{\text{t-channel}}}$ *[Phys. Lett. B 774 (2017), 252–257 (BESIII)]*

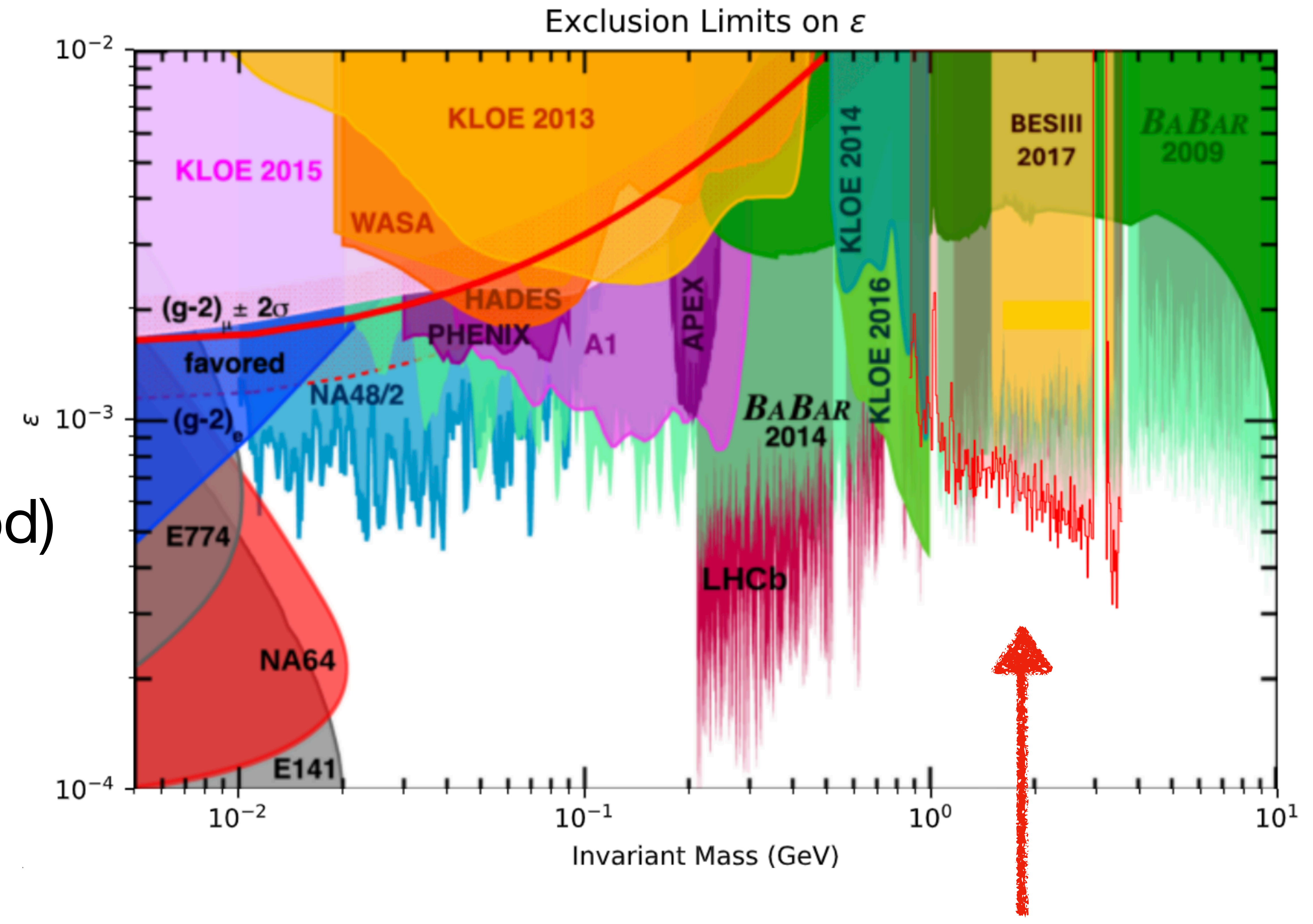
# Result

- Exclusion limit on kinetic mixing parameter *[Phys. Rev. D 80 (2009), 075018 J.D. Bjorken et al]*

$$\epsilon = \sqrt{\frac{2N_f\alpha}{3\pi} \cdot \frac{s_{\text{upper limit}}}{b} \cdot \frac{\Delta m}{m_{A'}}}$$

  - Number of possible decays: $N_f = 2 + R$
  - $\Delta m$: bin width based on mass resolution
  - $s_{\text{upper limit}}$: upper limit on signal ($CL_s$ method)
  - $b$: QED background (sideband fit)

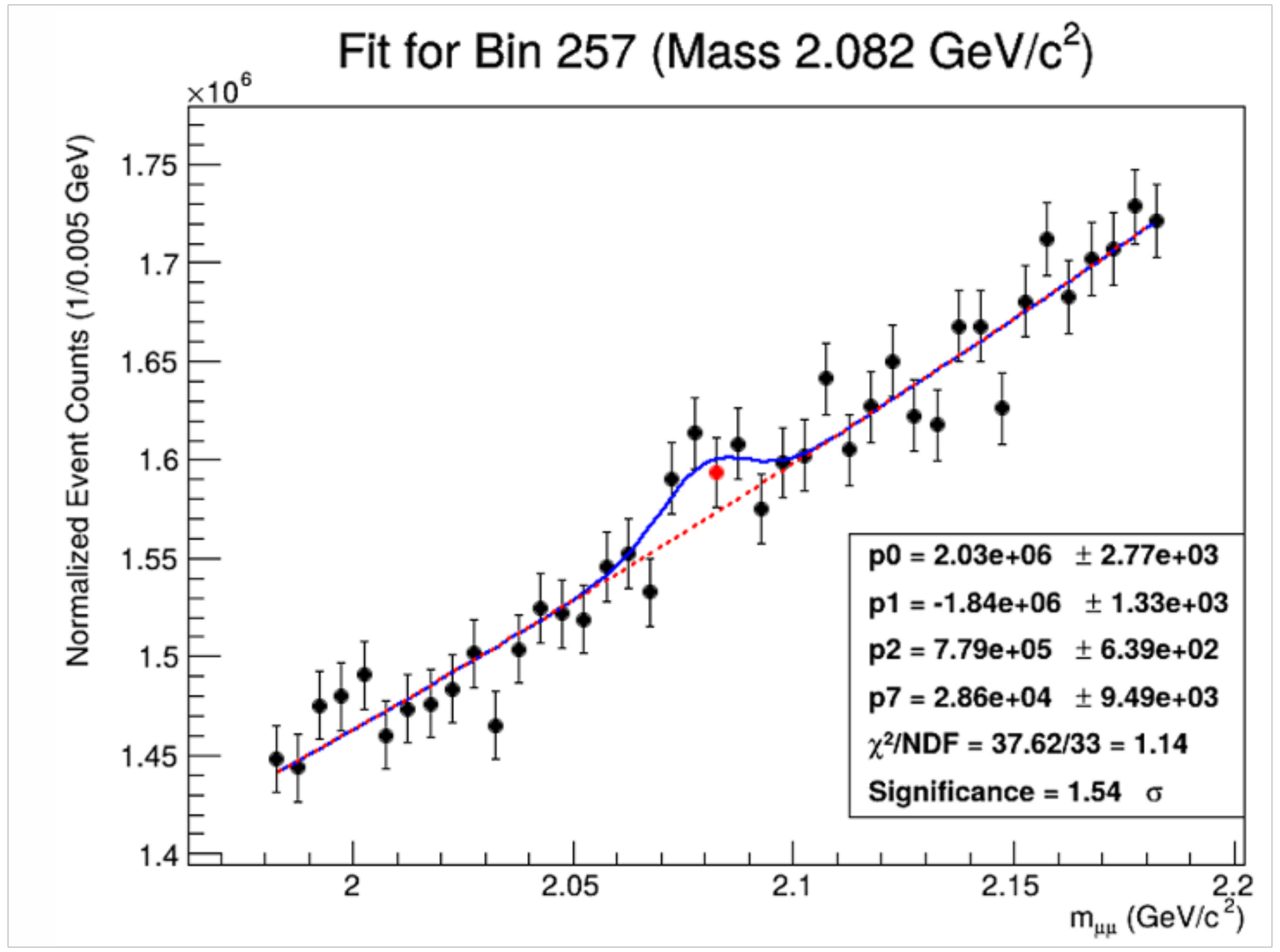
- Exceeds previous BESIII, BABAR, and LHCb limits for masses between ≈1.4 - 3.5 GeV




BESIII 2025 ($20\text{fb}^{-1}$)

# Outlook

- Correction factor in $e^+e^-$ channel can be further improved
- Test sideband fit method by inserting fake dark photon signal
  - Simulation with Babayaga@NLO [*Eur.Phys.J.C 71 (2011) p. 1680*]
- Cross check with direct signal fit instead of sideband fit
- Publication by Spring 2026

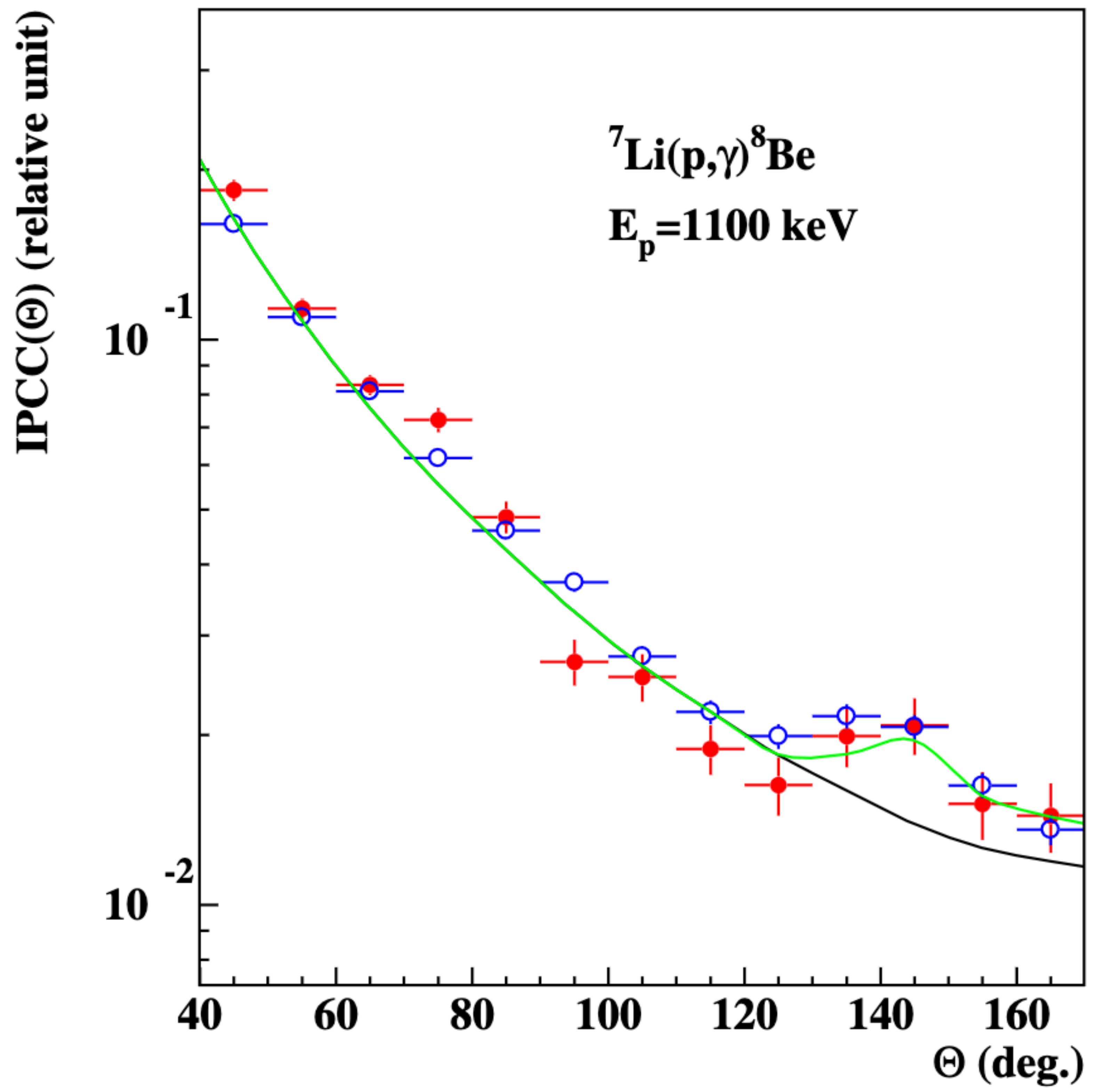


# X17 search at BESIII

$$\psi(2S) \to \chi_{cJ} e^+ e^-$$

# Introduction

- X17 was first observed by ATOMKI in $^{8}Be$, and is subsequently confirmed in $^{14}He$ and $^{12}C$ by ATOMKI




PhysRevLett. 116, 042501 (2016) A. J. Krasznahorka et al

# Introduction

- X17 was first observed by ATOMKI in $^{8}$Be, and is subsequently confirmed in $^{14}$He and $^{12}$C by ATOMKI
- So far no other single experiment observe X17
  - Allowed range:

2016 $\epsilon \in [2.0 \times 10^{-4},\ 1.4 \times 10^{-3}]$ (J.L. Feng *et al*)

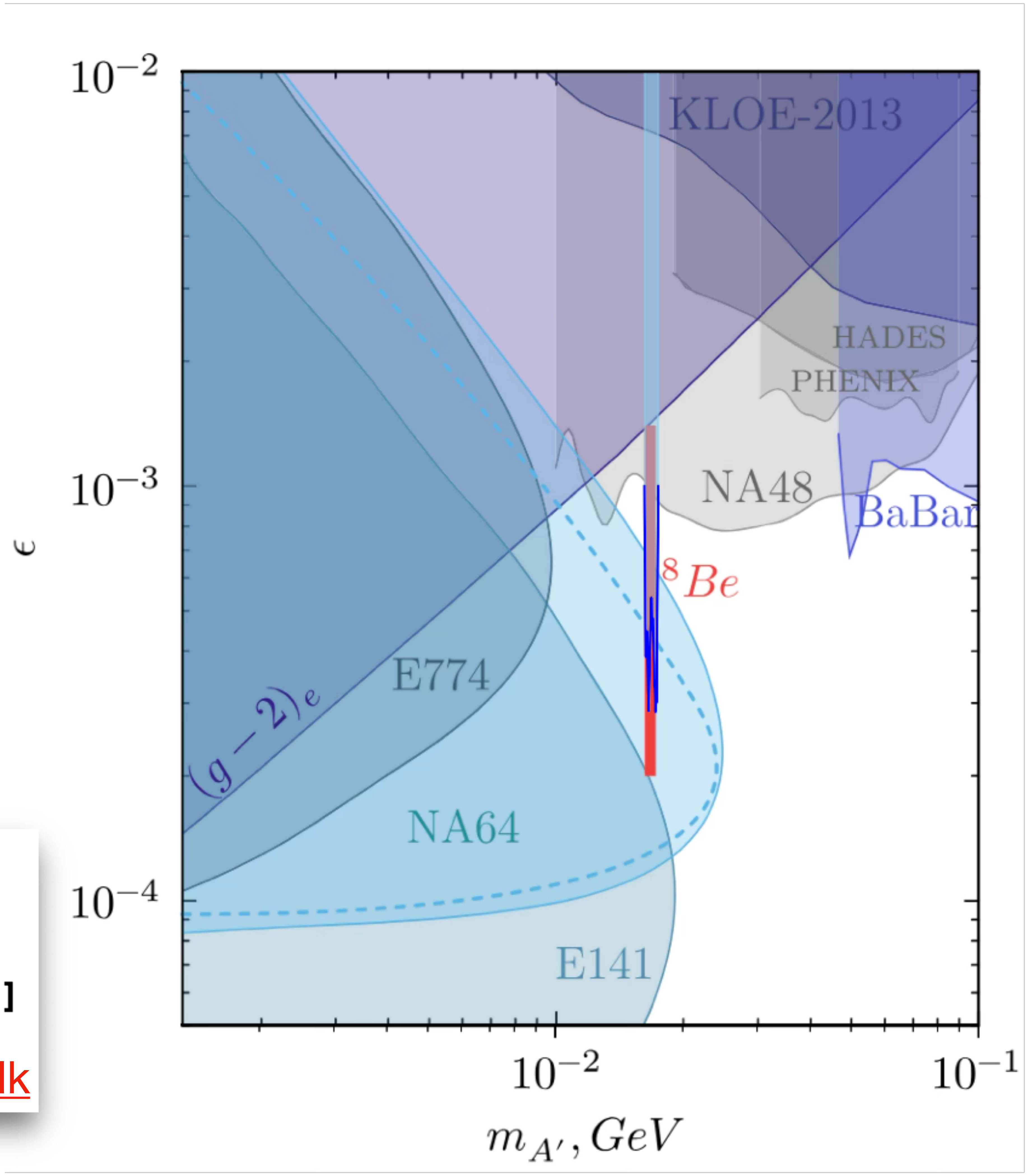
2020 $\epsilon \in [6.8 \times 10^{-4},\ 1.4 \times 10^{-3}]$ (NA64)

2025 $\epsilon < 5.6 \times 10^{-4}$ (PADME)

- BESIII can also contribute with the largest $\psi$ data

**Analyses of $J^P$ assignments** [JHEP 02 (2023) 154, JHEP04 (2024) 035]
- not a scalar if parity is conserved in the transition $^{8}$Be*(1$^+$) → $^{8}$Be(0$^+$) X
- not a pseudoscalar, as above, due to observation of $^{12}$C*(1$^-$) → $^{12}$C(0$^+$) X
- a protophobic vector, constrained by SINDRUM $\pi^+ \to e^+\nu\, e^+e^-$ [PRD 108 (2023) 055011]
- an axial vector, also severely constrained
- a spin-2 state, severely disfavored by SINDRUM limit

PADME's talk




PhysRevLett.117.071803 (2016) J.L. Feng et al

PhysRevD.101.071101 [NA64] (2020)

arXiv: 2505.24797 [PADME] (2025)

# Introduction

- X17 was first observed by ATOMKI in $^8$Be, and is subsequently confirmed in $^{14}$He and $^{12}$C by ATOMKI
- So far no other single experiment observe X17
  - Allowed range:

2016 $\epsilon \in [2.0\times10^{-4},\ 1.4\times10^{-3}]$ (J.L. Feng *et al*)

2020 $\epsilon \in [6.8\times10^{-4},\ 1.4\times10^{-3}]$ (NA64)

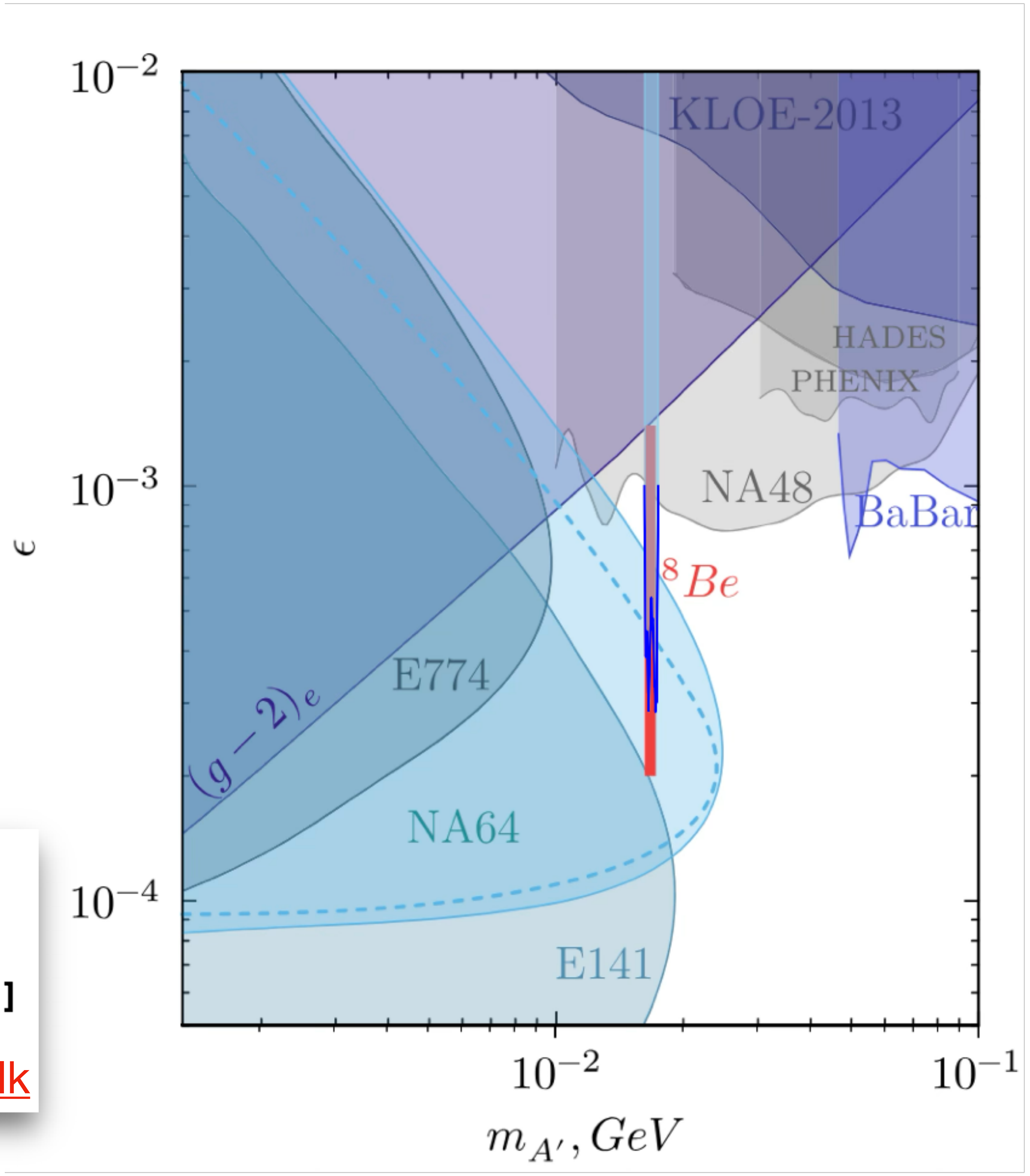
2025 $\epsilon < 5.6\times10^{-4}$ (PADME)

- BESIII can also contribute with the largest $\psi$ data

**Analyses of J$^P$ assignments** [JHEP 02 (2023) 154, JHEP04 (2024) 035]
- not a scalar if parity is conserved in the transition $^8$Be*(1$^+$) → $^8$Be(0$^+$) X
- not a pseudoscalar, as above, due to observation of $^{12}$C*(1$^-$) → $^{12}$C(0$^+$) X
- a protophobic vector, constrained by SINDRUM $\pi^+ \to e^+\nu\, e^+e^-$ [PRD 108 (2023) 055011]
- an axial vector, also severely constrained
- a spin-2 state, severely disfavored by SINDRUM limit

PADME's talk

- X17 is not required by $(g-2)_\mu$, but still need confirmation



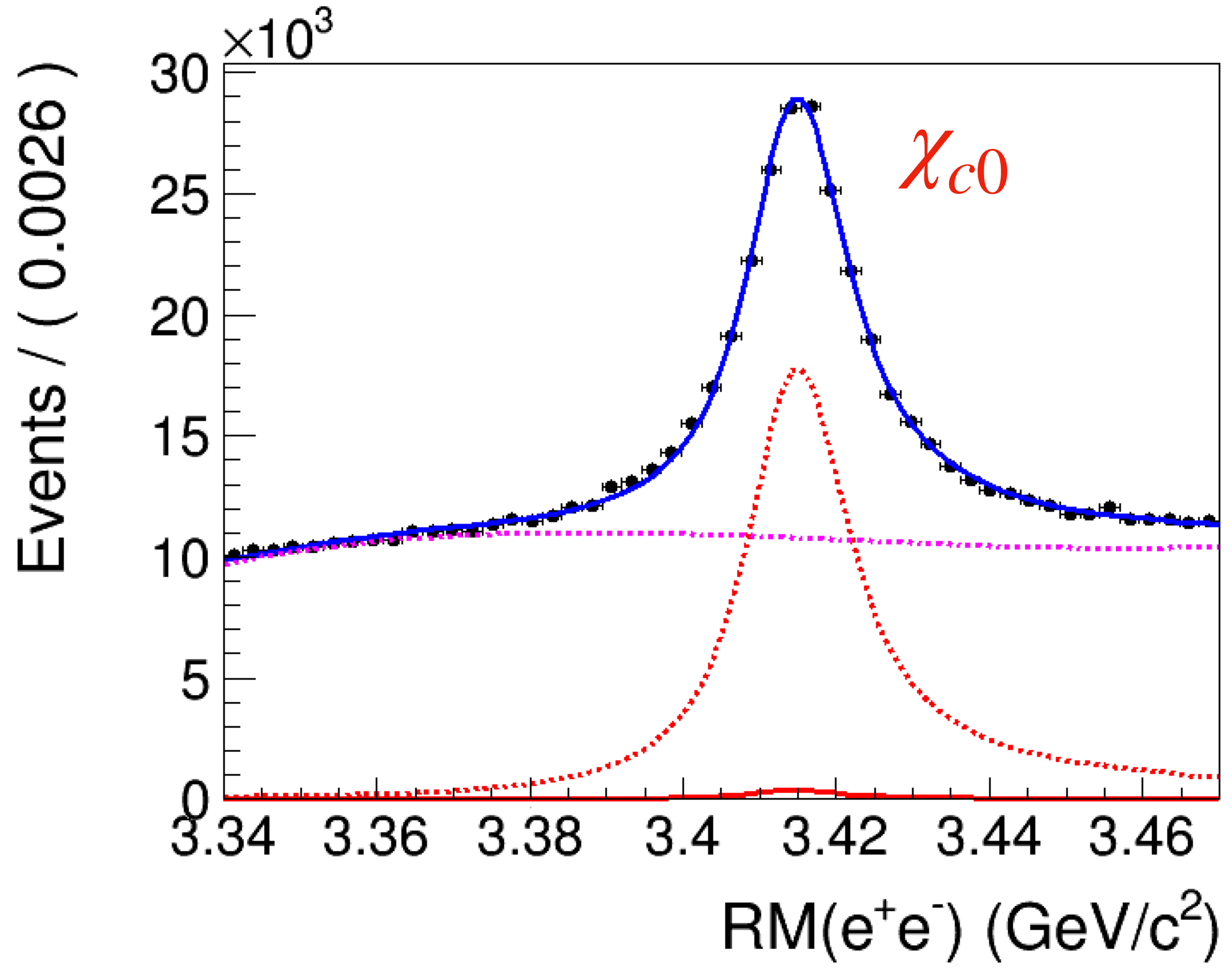

PhysRevLett.117.071803 (2016) J.L. Feng et al

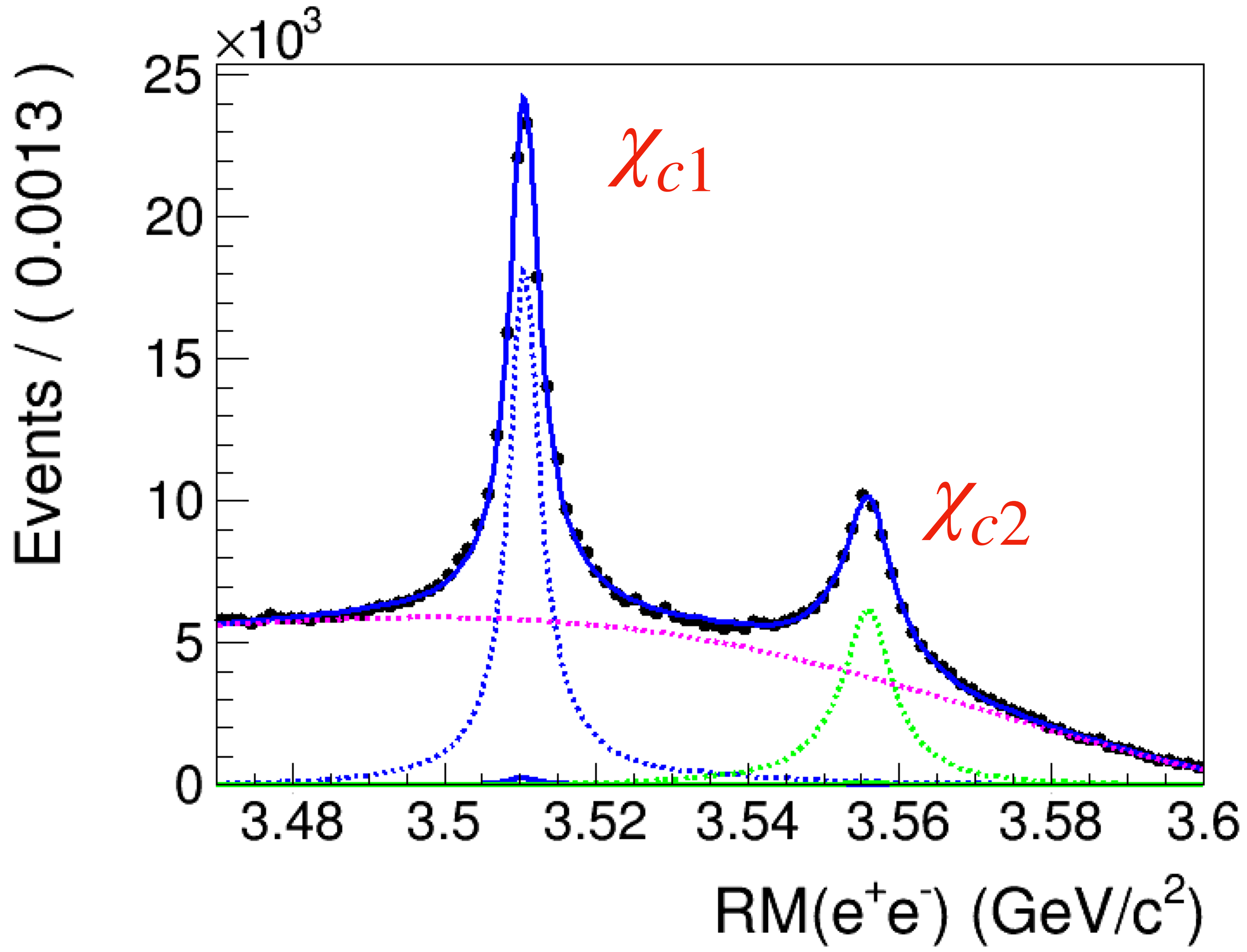
PhysRevD.101.071101 [NA64] (2020)

arXiv: 2505.24797 [PADME] (2025)

# Method

- Using 2.7 Billion $\psi(2S)$ events at BESIII
- reconstruct only $e^+e^-$ to improve statistic, especially for $\chi_{c0}$
- Access $\chi_{cJ}$ signals via recoil mass of $e^+e^-$: $RM(e^+e^-)$
- Similar process, with only charmonium involved

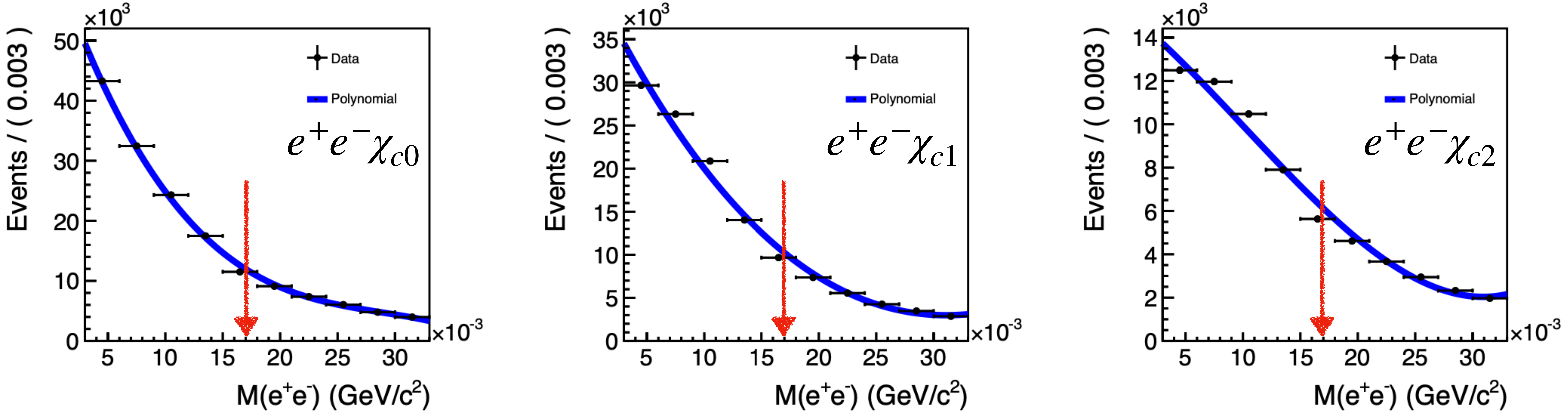


# Result

- Invariant mass of $M(e^+e^-)$: bin-by-bin fit to $RM(e^+e^-)$
- Mixing strength $\epsilon$: constrained by 3 channels

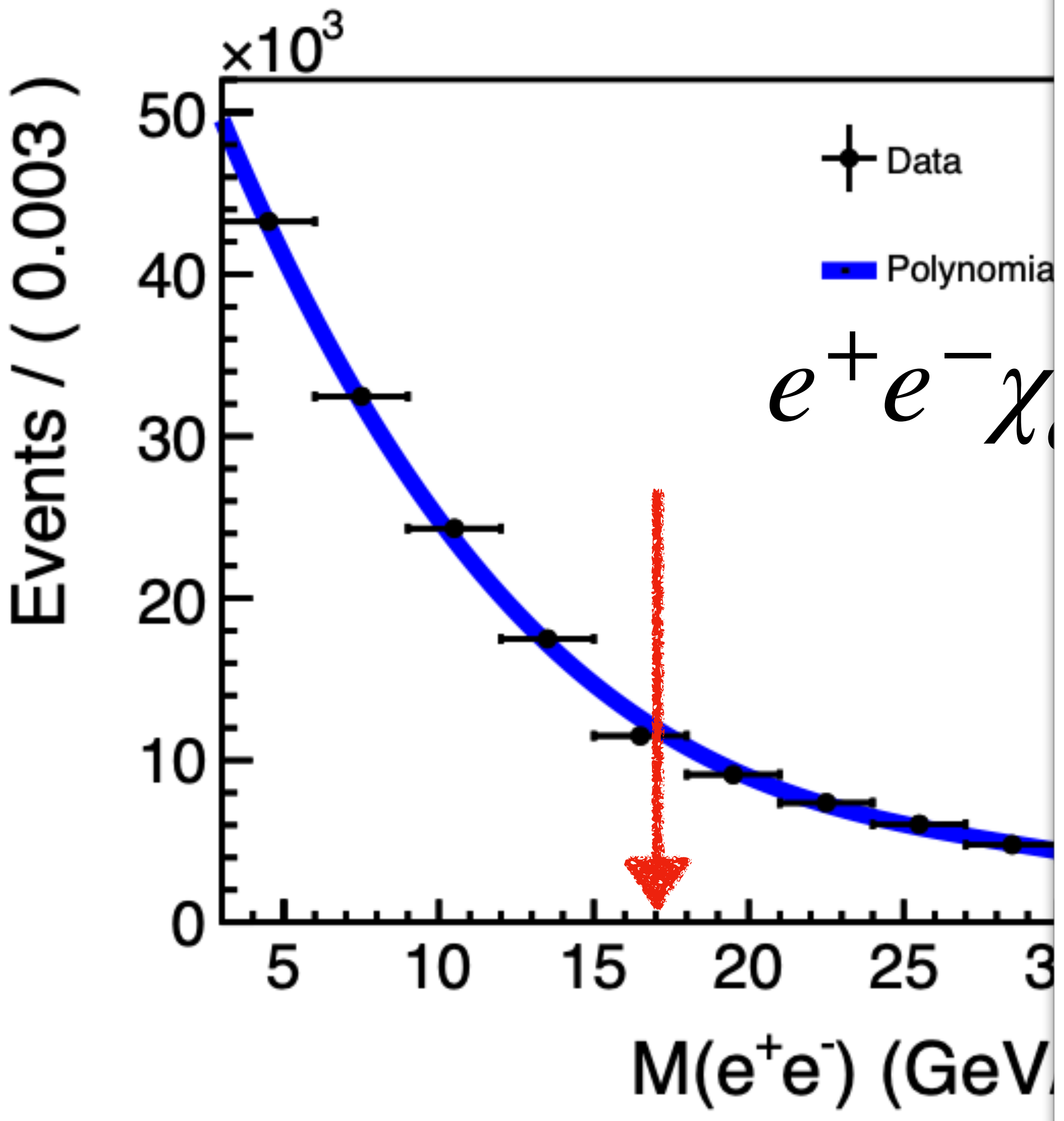
$$\frac{\mathscr{B}\left(\psi(2S)\to\chi_{cJ}X17\right)}{\mathscr{B}\left(\psi(2S)\to\chi_{cJ}\gamma\right)} = \epsilon^2 |F(q^2)|^2 \frac{\lambda^3\left(m^2_{\psi(2S)},\, m^2_{\chi_c J},\, m^2_{X17}\right)}{\lambda^3\left(m^2_{\psi(2S)},\, m^2_{\chi_c J},\, 0\right)}$$

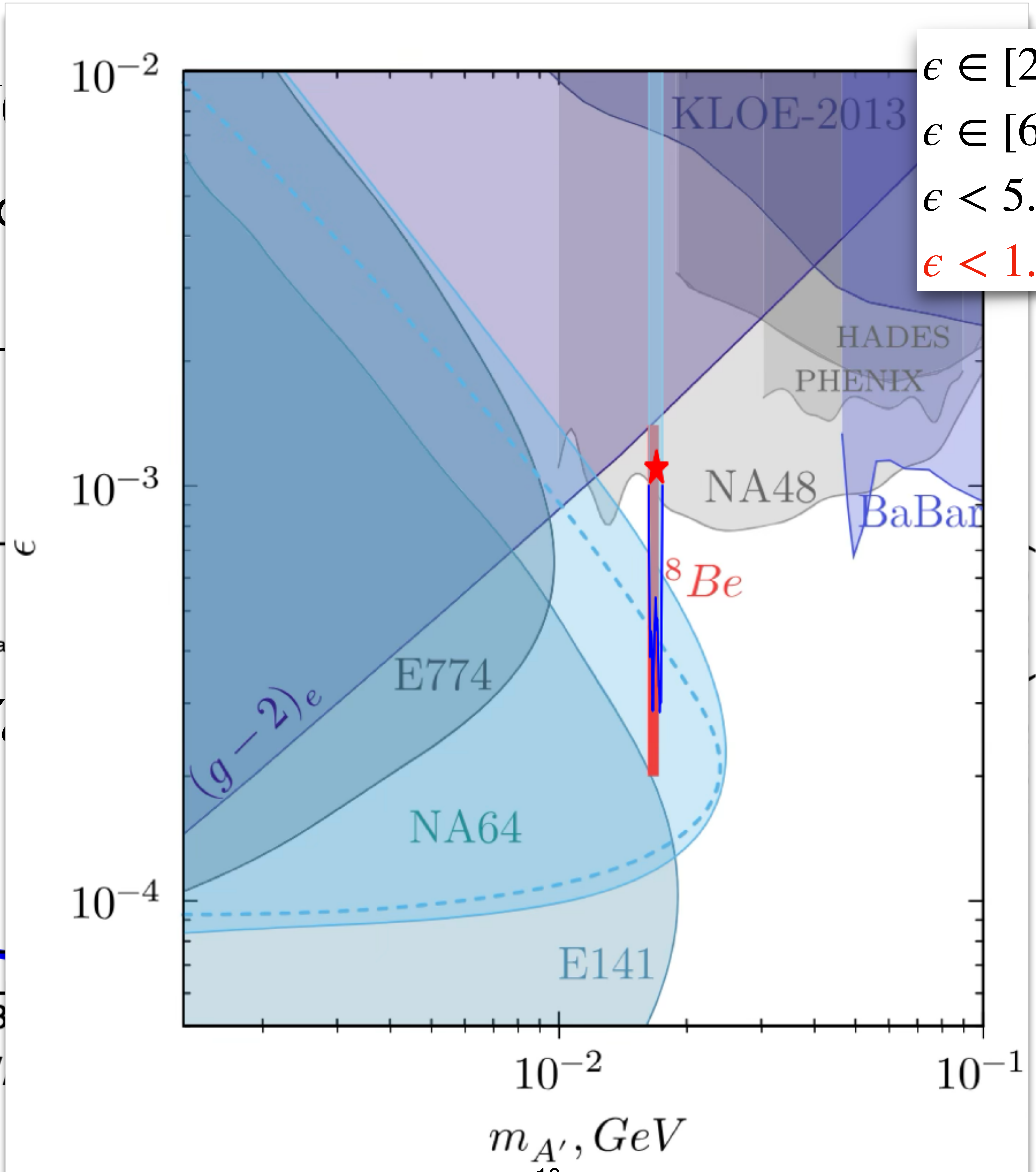


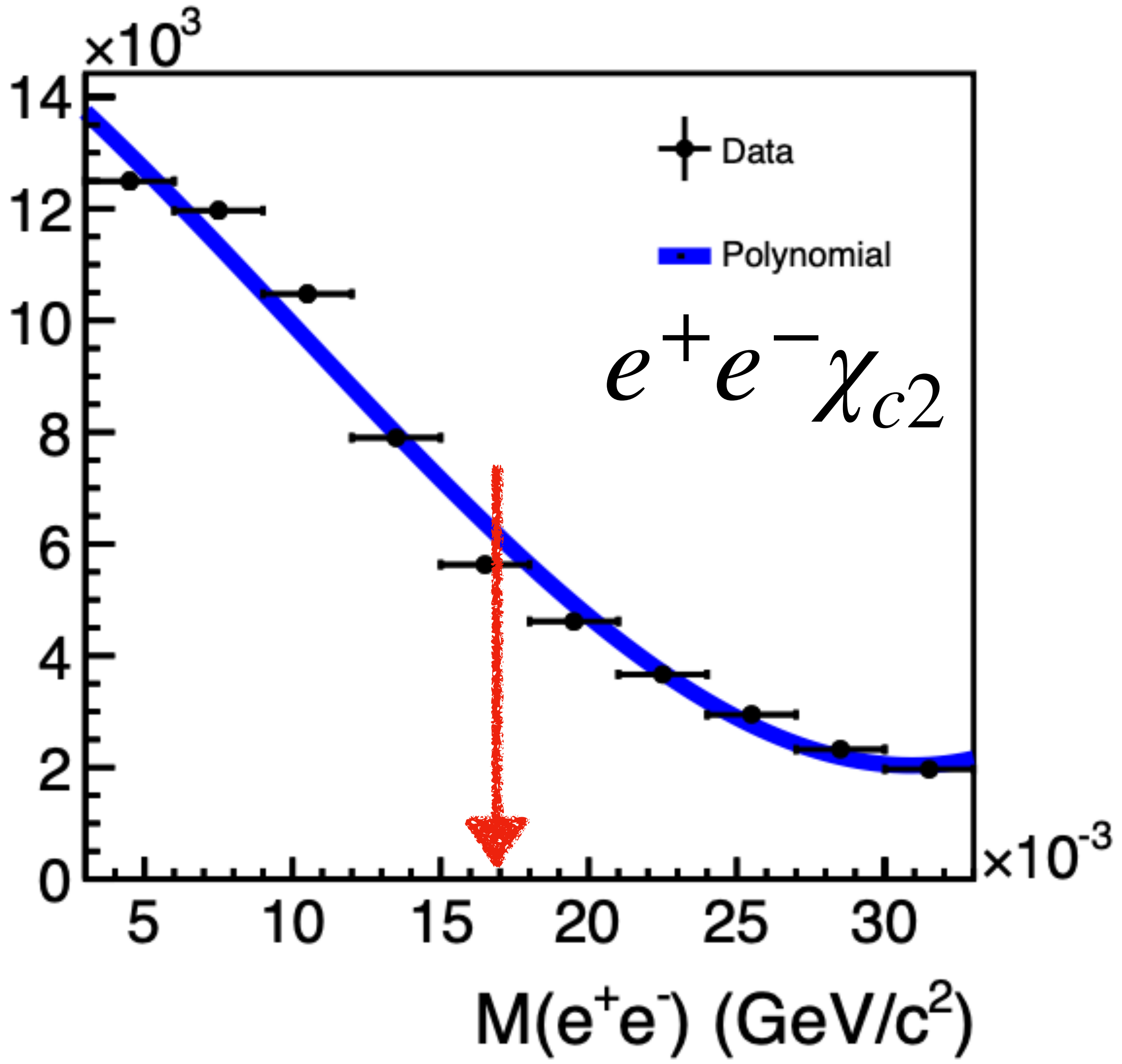
# Result

- Invariant mass of $M$(
- Mixing strength $\epsilon$: co

$$\frac{\mathscr{B}\left(\psi(2S)\rightarrow\chi_{cJ}X17\right)}{\mathscr{B}\left(\psi(2S)\rightarrow\chi_{cJ}\gamma\right)}$$




$\epsilon\in[2.0\times10^{-4},\ 1.4\times10^{-3}]$ (J.L. Feng *et al*)

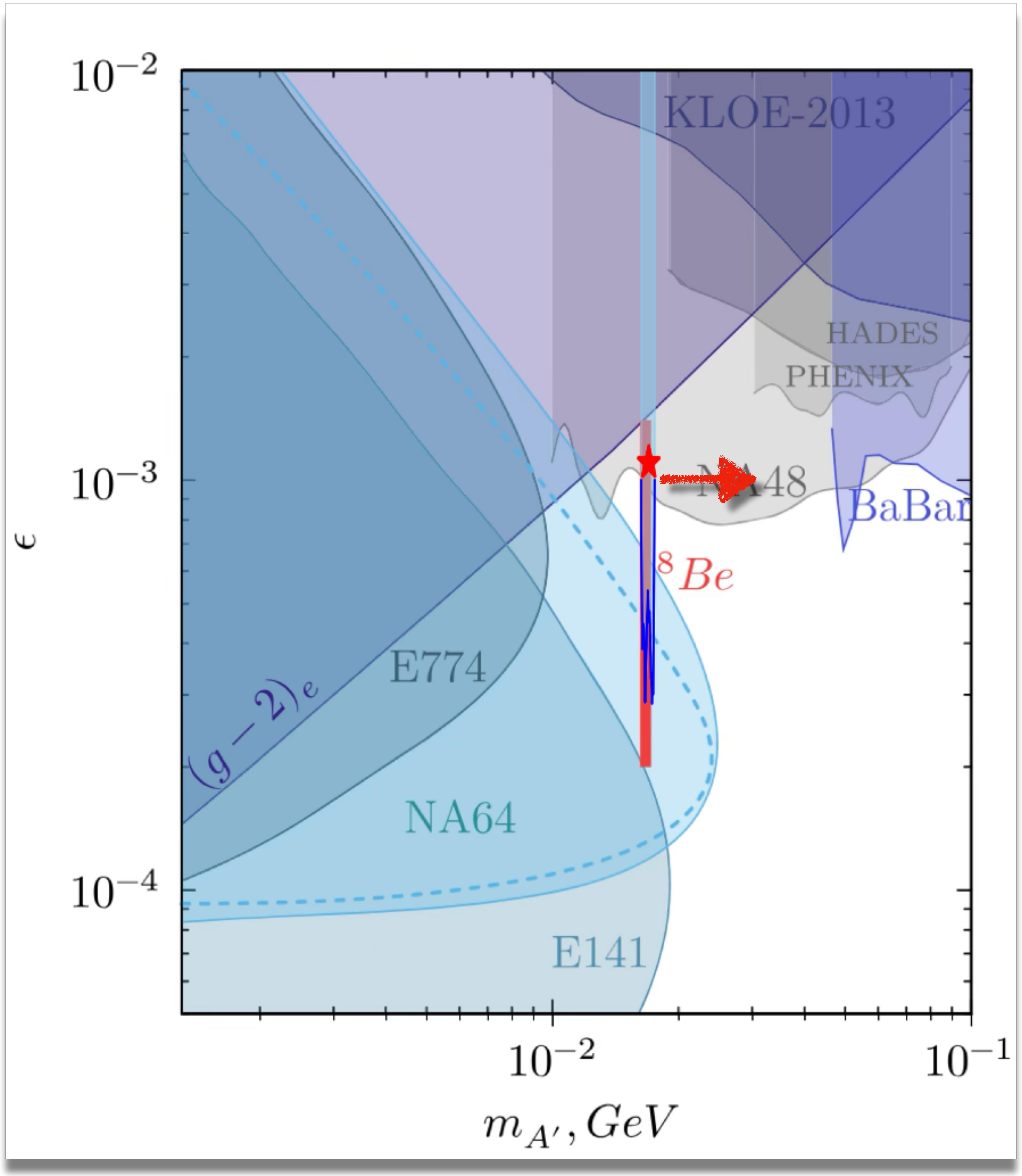
$\epsilon\in[6.8\times10^{-4},\ 1.4\times10^{-3}]$ (NA64)

$\epsilon<5.6\times10^{-4}$ (PADME)

$\epsilon<1.1\times10^{-3}$ (This work)

# Outlook

- Consider the systematic uncertainty on $\epsilon$
- Extend searching range to ~ 30 MeV
- The new version of memo is almost ready
- Expect to submit to journal by the end of 2025

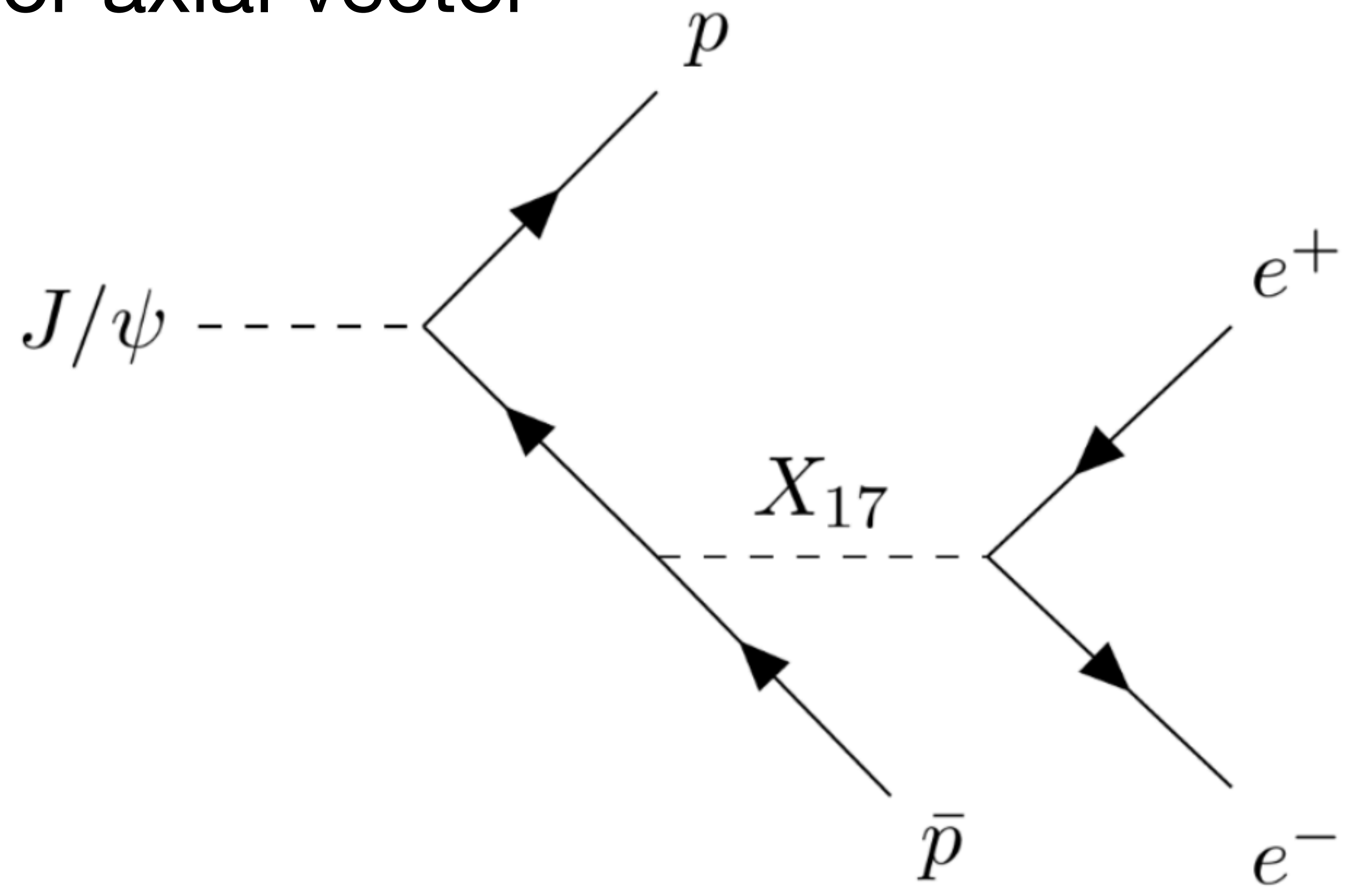


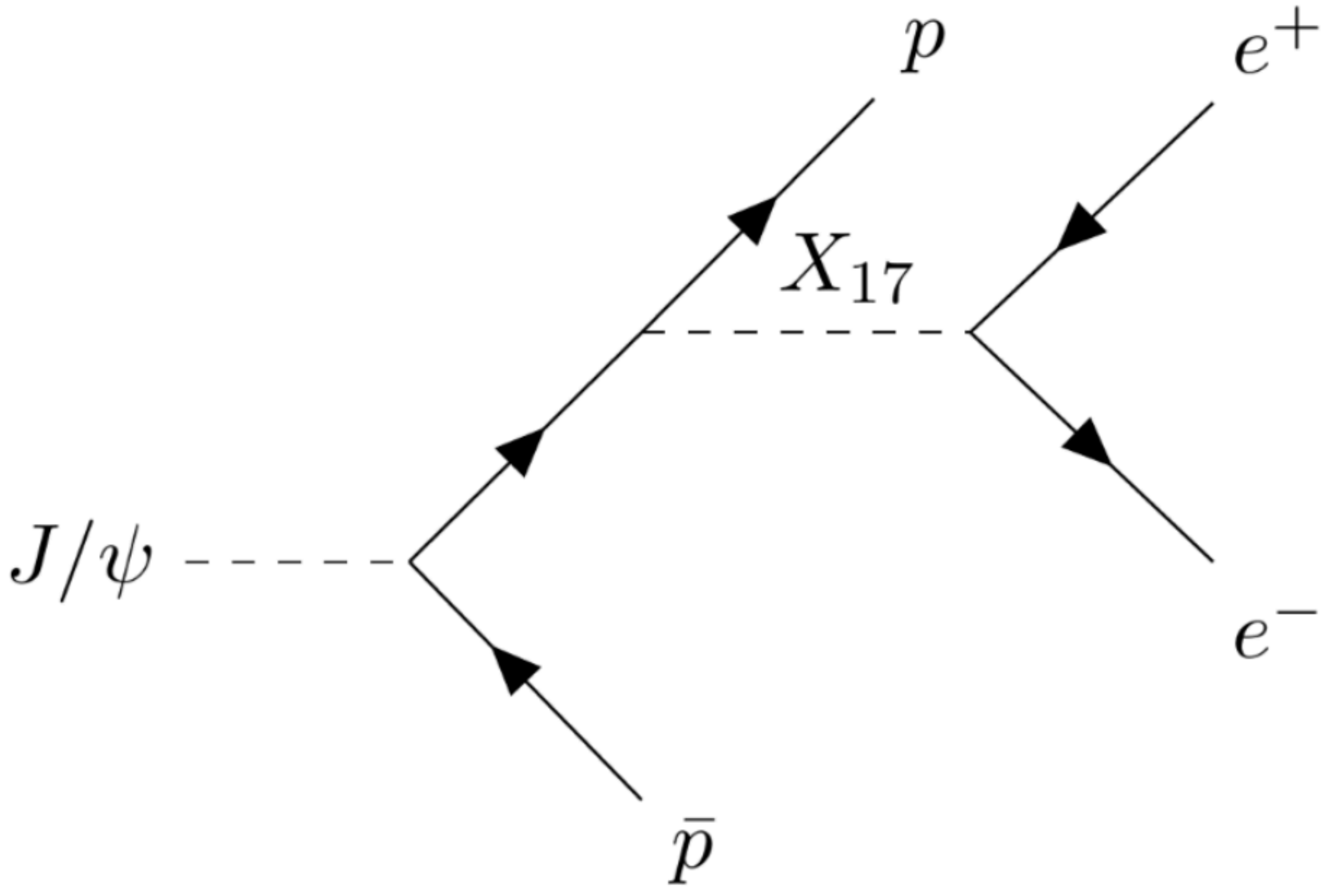
# X17 search at BESIII

$$J/\psi \to p\bar{p}e^+e^-$$

# Method

- Utilise 10 Billion $J/\psi$ events at BESIII
- Consider full process: $J/\psi \to p\bar{p}e^+e^-$
- Large number of nucleons needed for X17 production
  - $\mathscr{B}(J/\psi \to p\bar{p}) = (2.120 \pm 0.029) \times 10^{-3}$
- Self-developed MCX17 by **Saskia Plura**
  - Couplings by M. Vanderhaeghen, J. Backens
  - X17 as a pseudo scalar or axial vector

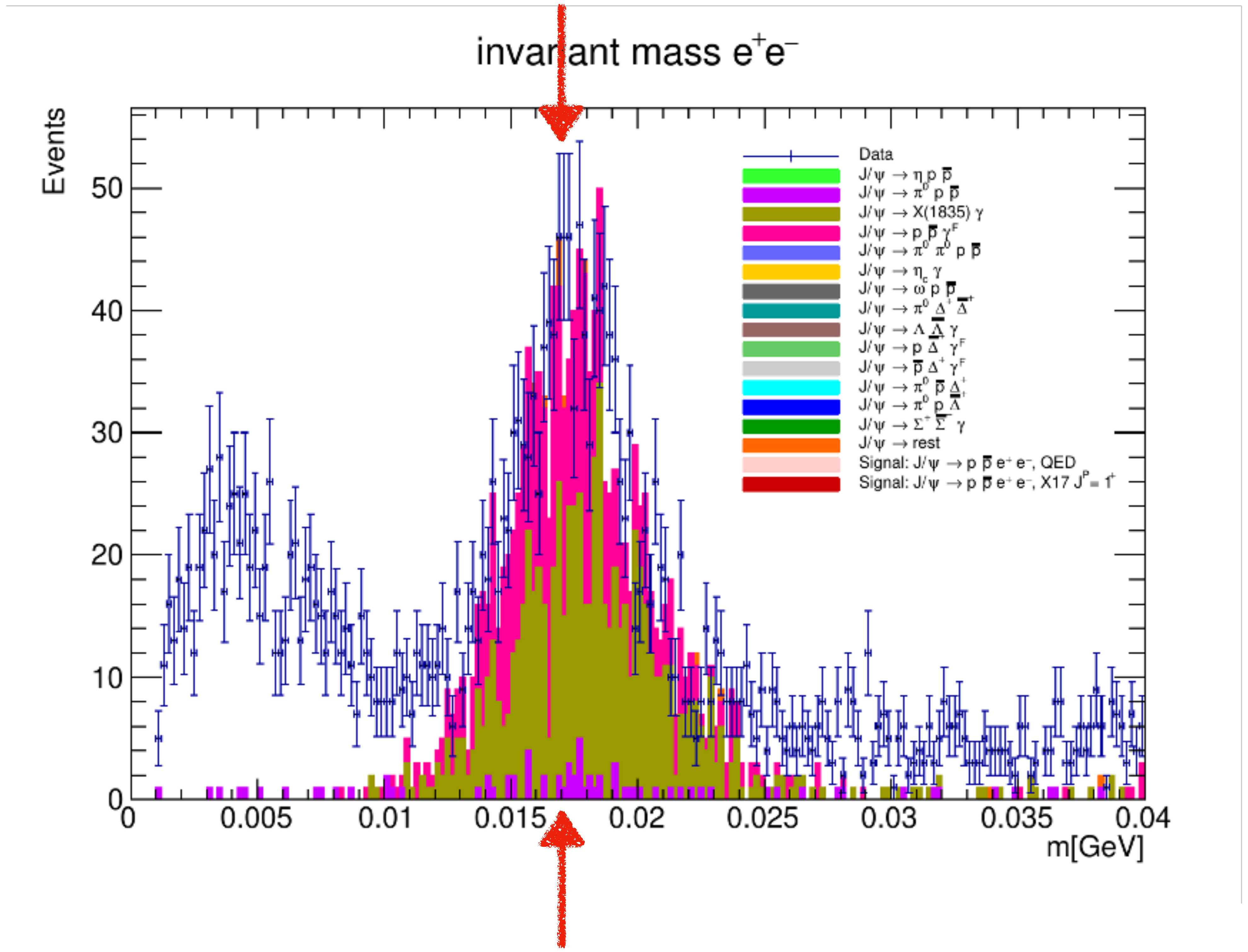


# Result

- Only **1** expected X17 event per 10 Billion $J/\psi$ decays
- QED process is 3 orders of magnitude larger (~3100/10 Billion $J/\psi$ decays)
    - Calculated assuming constant form factor
- Example analysis strategy for X17 search on future larger data sets (e.g. STCF)

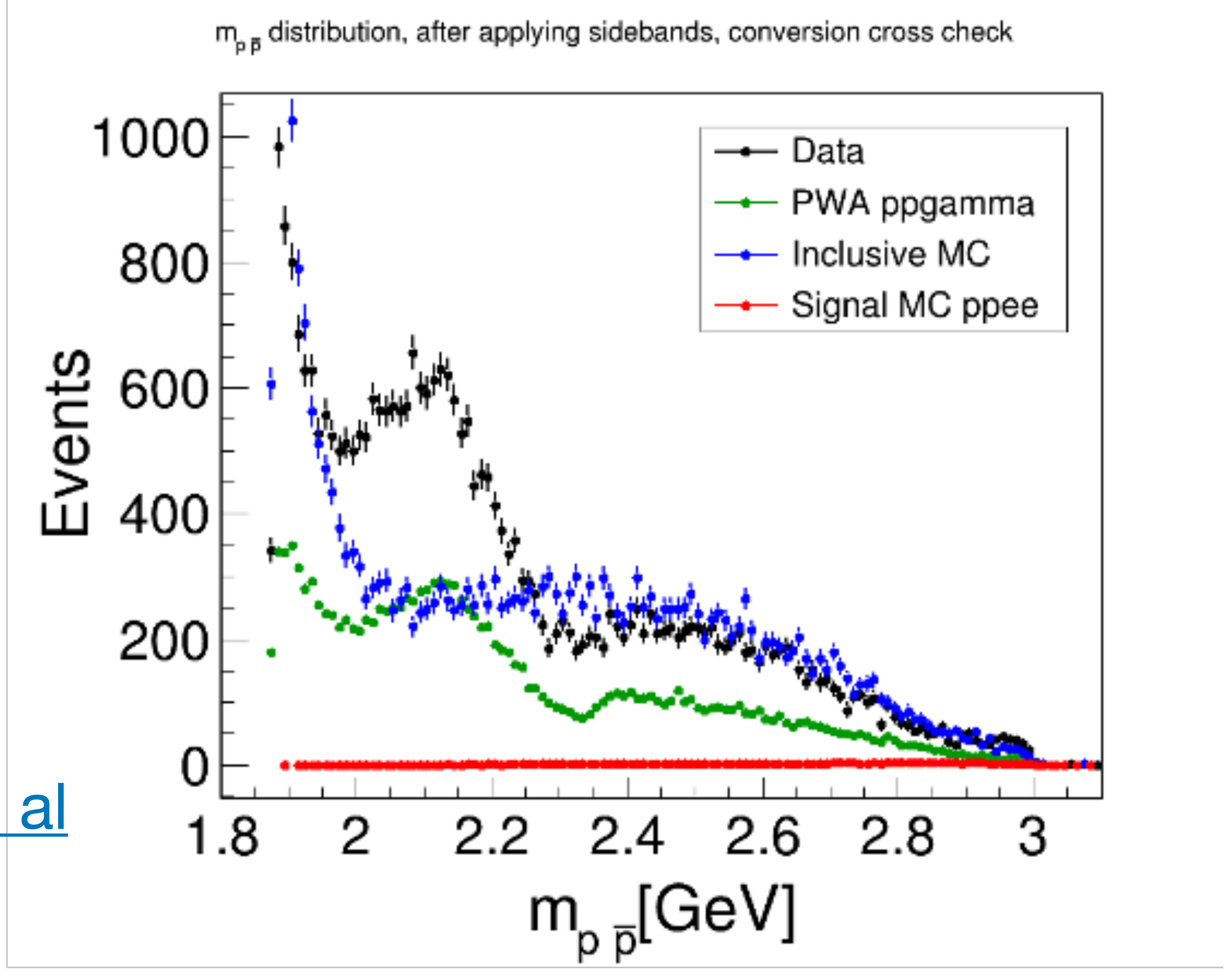
| Mode | Decay width (GeV) |
|---|---|
| **QED** | $(2.8899 \pm 0.0146) \cdot 10^{-11}$ |
| **X17 pseudo scalar** | $(1.0747 \pm 0.0004) \cdot 10^{-14}$ |
| **X17 axial vector** | $(7.9281 \pm 0.0075) \cdot 10^{-15}$ |



# Outlook

- SM process could provide insights into the time-like proton form factor in the unphysical region, analysis is ongoing (to be completed by Spring 2026)
    - Low transverse momentum of $e^+e^-$
    - efficiency drops around $\eta_c$ peak in $m_{p\bar{p}}$

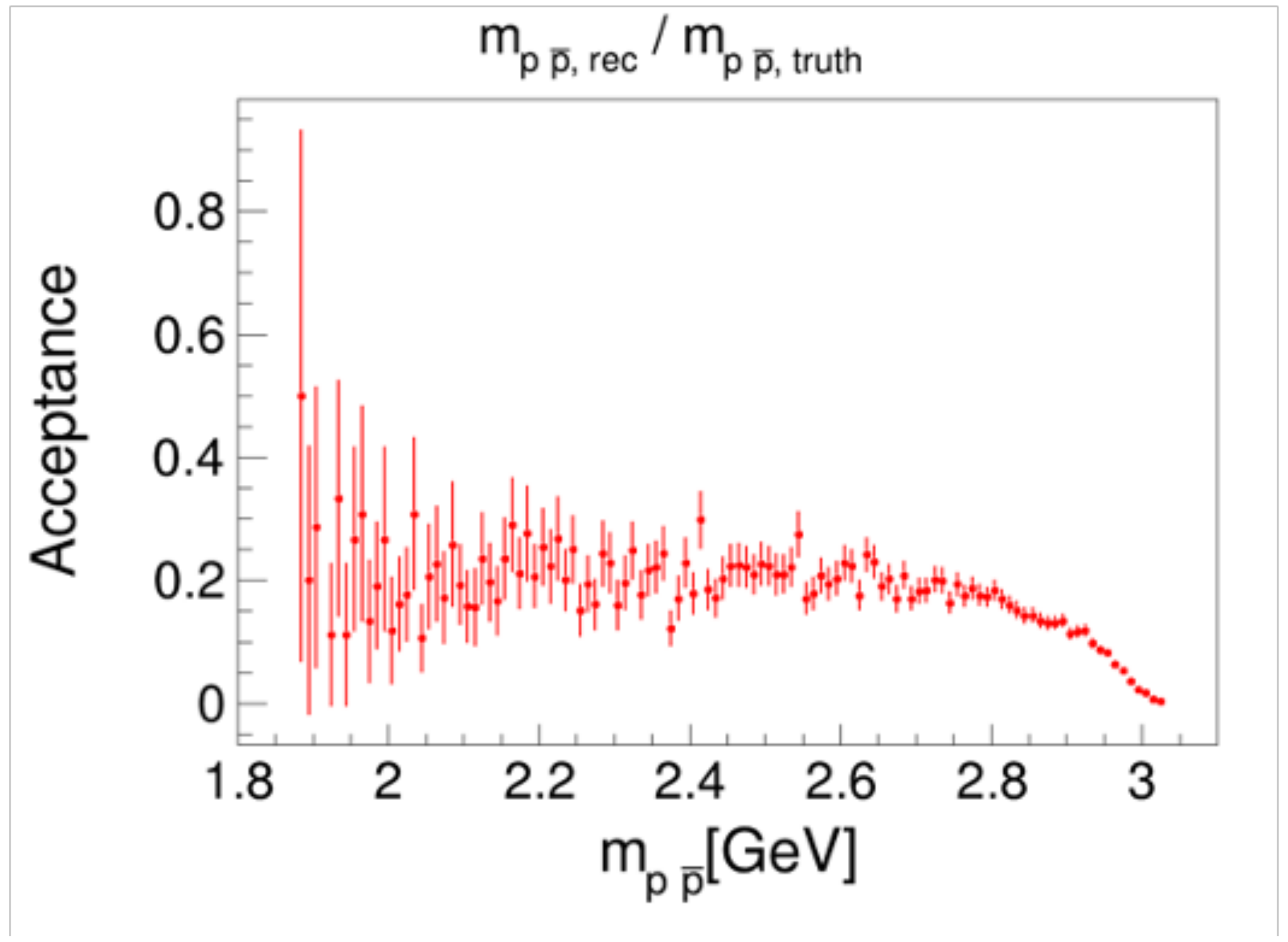
Phys.Lett.B 856, 138887l (2024) Y.H. Lin et al




- Study of transition form factor of $X(1835)$ is possible

- $J/\psi \to \eta_c e^+e^-$ process can be used to search for X17 with larger statistics (e.g. STCF)

JHEP 04, 091 (2021) K. Ban et al



# Summary

- **ALP:** higher sensitivity can be reached with all BESIII data
- **Dark photon:** achieve better sensitivity between 1.4-3.5 GeV
- **X17:** constraint from charmonium transition
- Everything is in progress …