

Analysis update of the X17 search in pp collisions

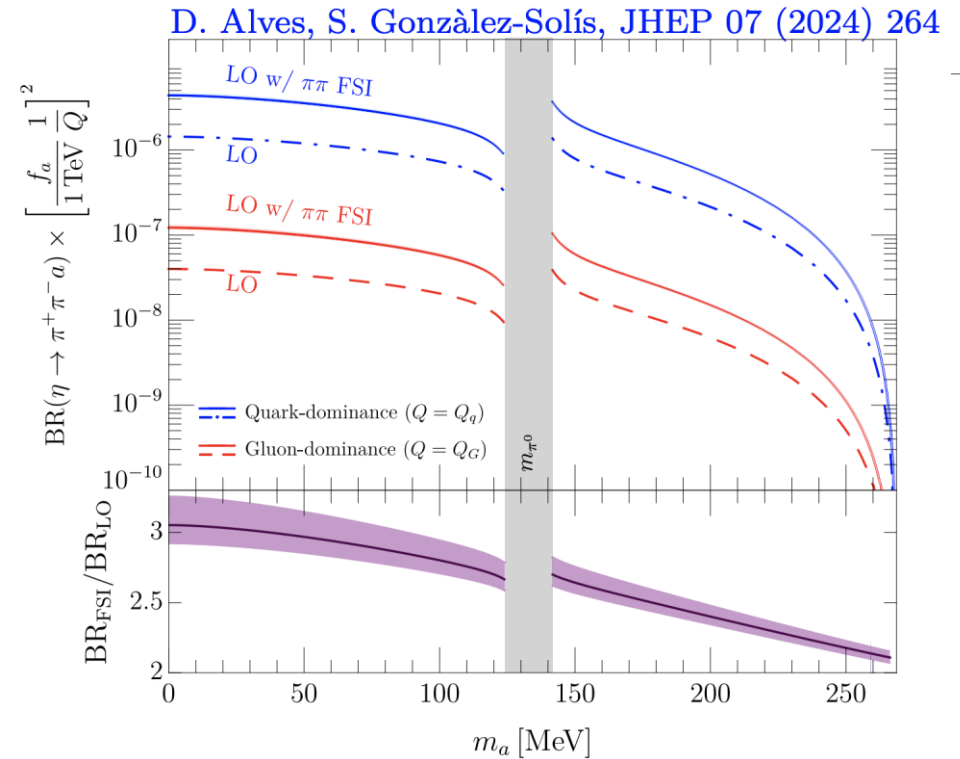


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ALP search in η decay

- Axion-Like Particle couples predominantly to the first generation of SM fermions
- Suppressed mixing-angle results in the isoscalar couplings of the axion
- Hadronic decay channels of η and η' could be coupled to ALP's:

$\eta(\eta') \rightarrow \pi^+\pi^- a (\rightarrow e^+ e^-)$
 "axio-hadronic decay"



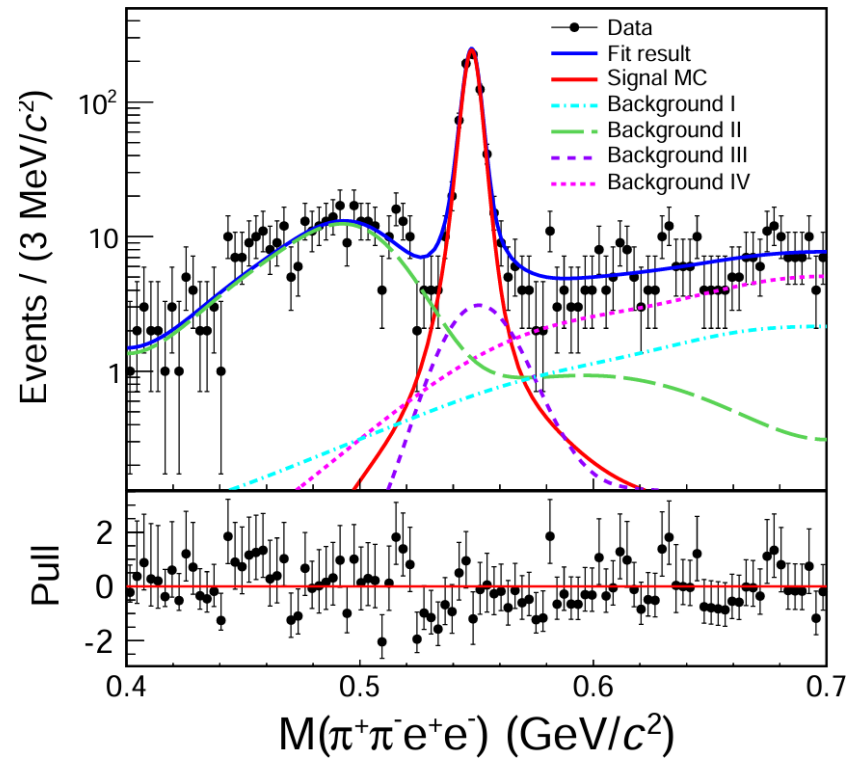
$$\Gamma \sim 4 \cdot 10^{-14} \text{ s}$$

$$BR = 3 \cdot 10^{-8} - 4 \cdot 10^{-6}$$

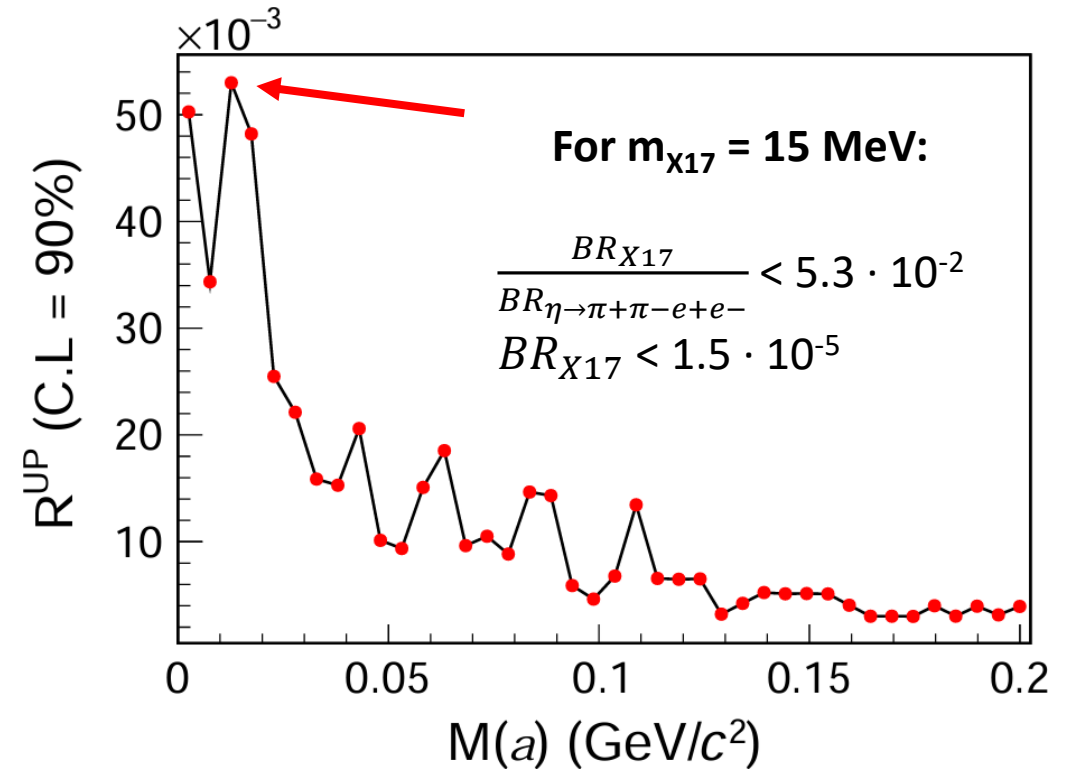
(for decay $\eta \rightarrow \pi^+\pi^- e^+ e^-$ (no X17) - $BR_{\text{PDG}} = 2.68 \cdot 10^{-4}$)

BESIII results

BESIII: $\eta \rightarrow \pi^+\pi^- e^+e^-$



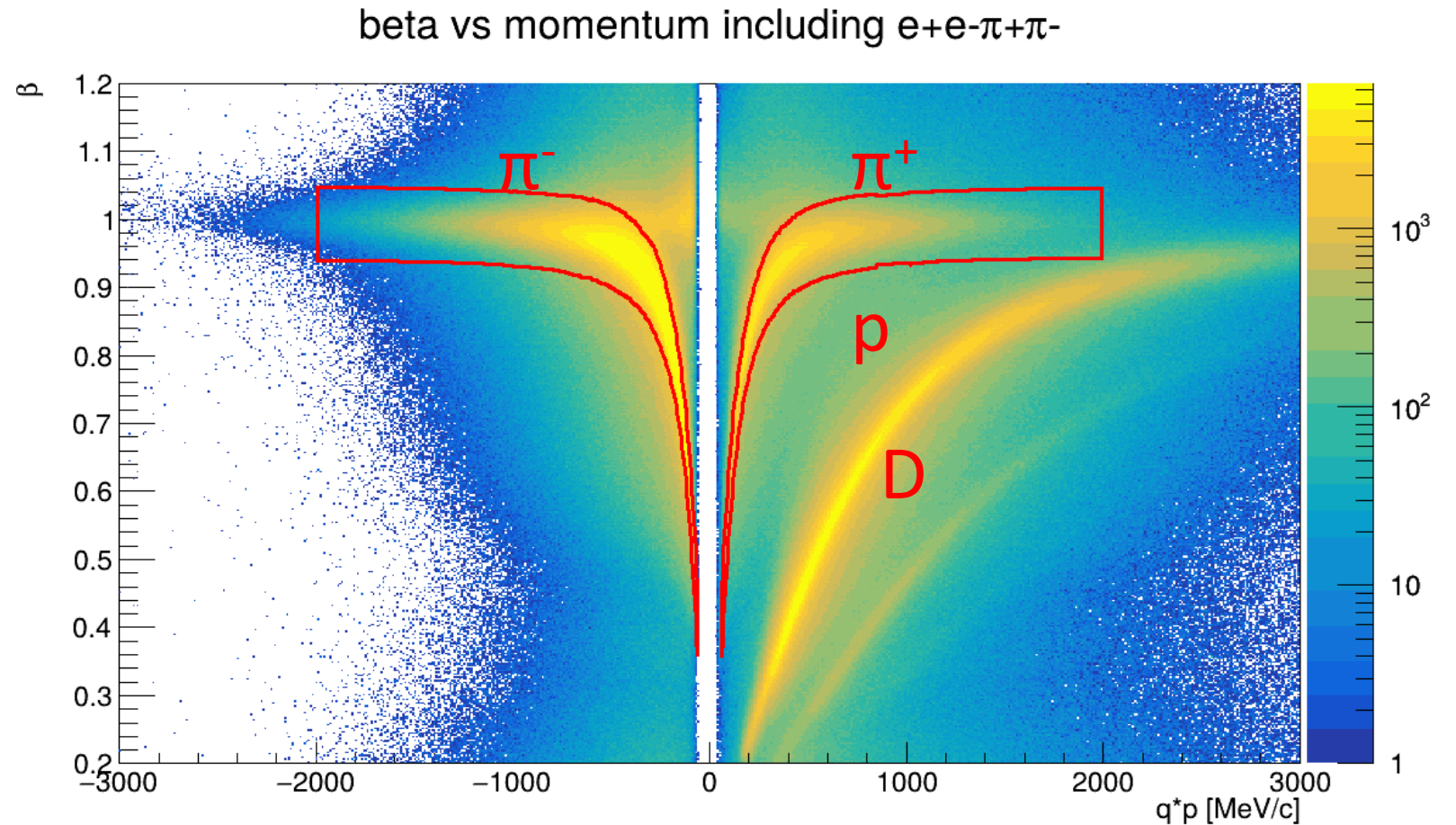
Upper limit for $\eta \rightarrow \pi^+\pi^- X_{17}$ branching ratio for different assumed X_{17} masses (2025)



Main selection criteria: $\pi^+ \pi^- e^+ e^-$

Following particles have to be selected: $\pi^+ \pi^- e^+ e^-$

- leptons selected by correlation windows in RICH and MDC
- pions selected by cuts on beta vs momentum distribution
- 3σ cut for gen4

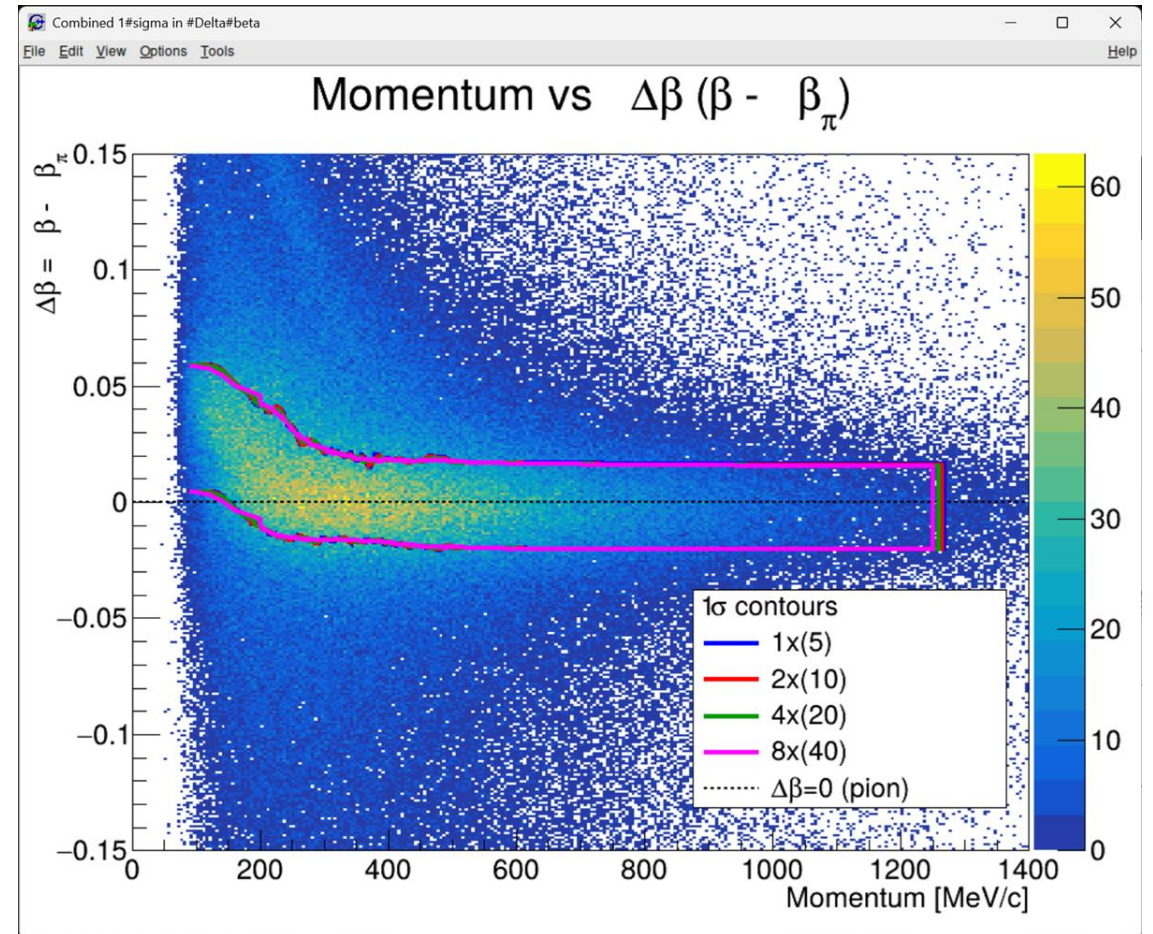


Procedure for identification of pions

- draw $\Delta\beta$ vs momentum distribution

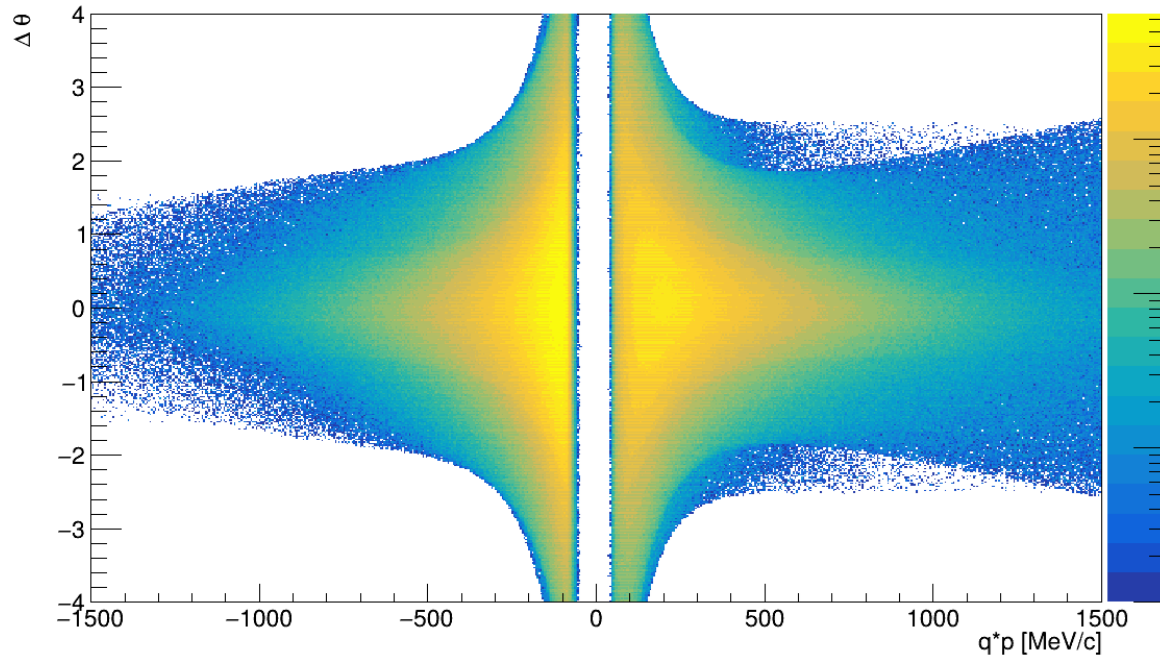
$$(\Delta\beta = \beta_{exp} - \beta_{theor}, \beta_{theor} = \frac{p}{\sqrt{p^2 + m_{\pi}^2}})$$

- divide it into slices covering different momentum range
- make projection to Y axis for each slice
- fit gaussian + polynomial + gaussian distribution
- get μ and σ values from fits

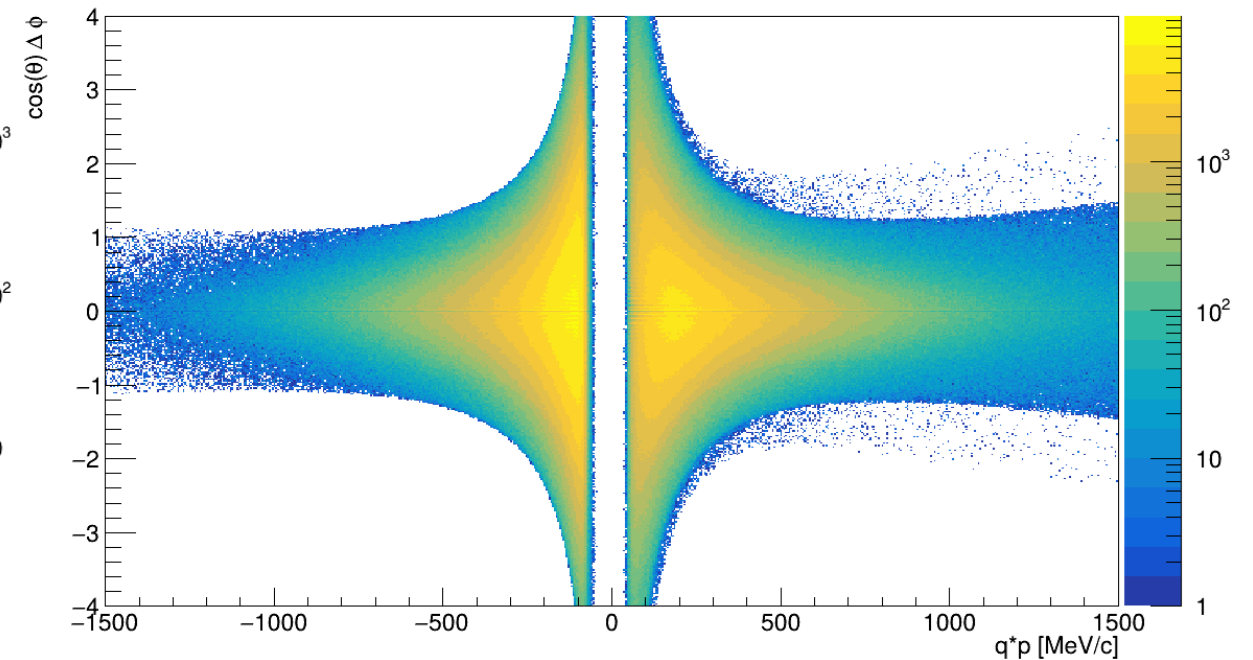


Lepton identification: Correlation windows $\Delta\theta$ vs $p \cdot q$, $\sin(\theta)\Delta\phi$ vs $p \cdot q$

$\Delta\theta$ vs momentum

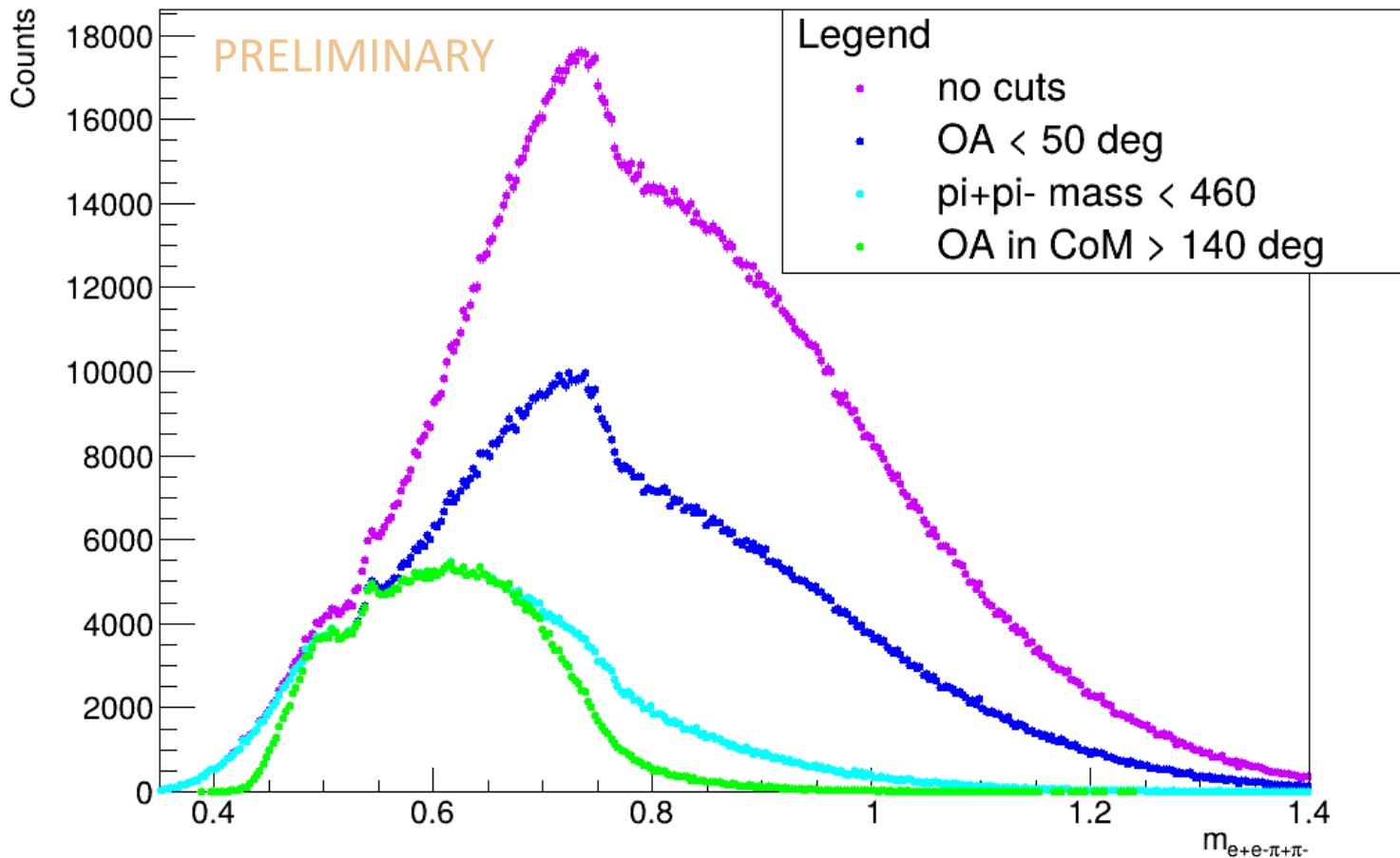


$\cos(\theta)\Delta\phi$ vs momentum



- correlation windows for $\Delta\theta$ vs $p \cdot q$ and $\sin(\theta)\Delta\phi$ vs $p \cdot q$ (where $\Delta\theta = \theta_{\text{RICH}} - \theta_{\text{MDC}}$, $\Delta\phi = \phi_{\text{RICH}} - \phi_{\text{MDC}}$)
- different windows for positive and negative particles, different windows for both systems

$\pi^+\pi^-e^+e^-$ invariant mass after consecutive cuts



Final set of cuts:

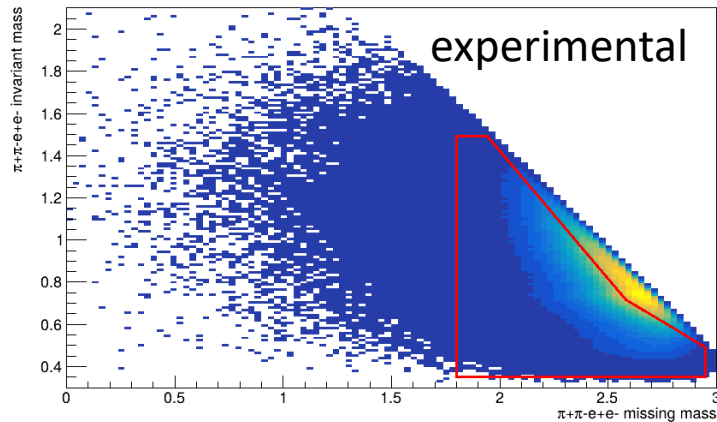
- vertexReco z > -500 mm
- $(\pi^+\pi^-)(e^+e^-)$ opening angle < 50°
- $\pi^+\pi^-$ invariant mass < 460 MeV
- $(\pi^+\pi^-)(e^+e^-)$ opening angle in C.o.M. > 140°

Two potential cuts tested, but rejected:

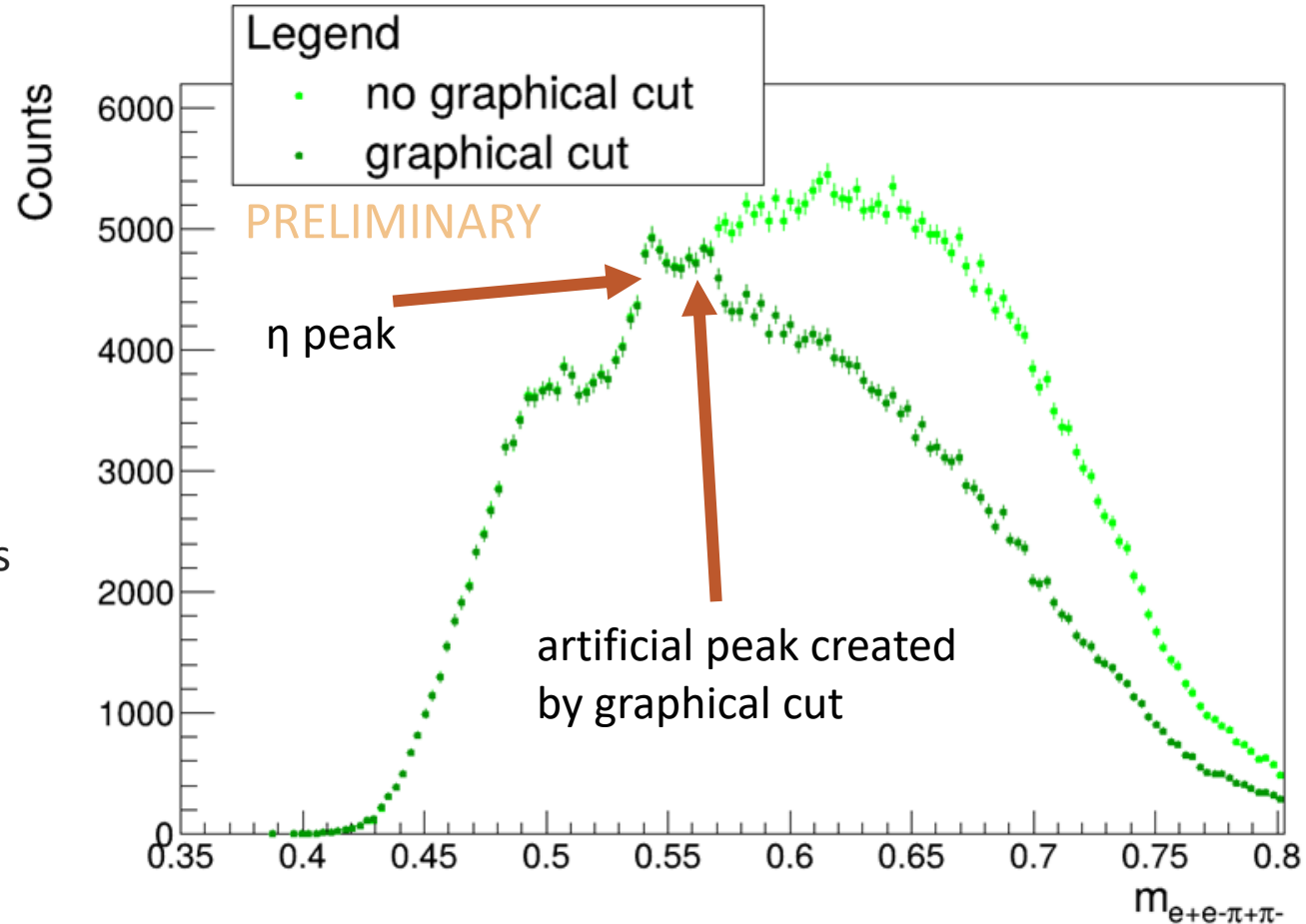
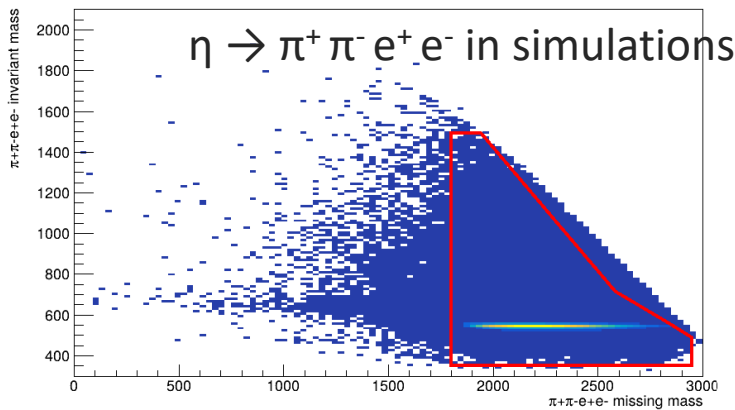
- $\pi^+\pi^-e^+e^-$ missing mass vs invariant mass (graphical cut)
- e^+e^- opening angle < 6°

Graphical cut

$\pi^+\pi^-e^+e^-$ missing mass vs invariant mass



$\pi^+\pi^-e^+e^-$ missing mass vs invariant mass



Graphical cut finally rejected:

- produces artificial peak
- mainly works for high $\pi^+\pi^-e^+e^-$ invariant masses, above studied region

SMASH simulations

/lustre/hades/dstsim/feb22/p4500p/gen4/smash/
smash_standard/root/

SMASH → Geant → DST

10^{10} events simulated in SMASH (10^5 files, each
with 10^5 events)

present η decay channels:

- $\eta \rightarrow \pi^+ \pi^- \pi^0 (e^+ e^- \gamma)$
- $\eta \rightarrow \pi^+ \pi^- \pi^0 (\gamma \gamma)$
- $\eta \rightarrow \pi^+ \pi^- \gamma (e^+ e^-)$

/lustre/hades/dstsim/feb22/p4500p/gen4/smash/
smash_eta/root/

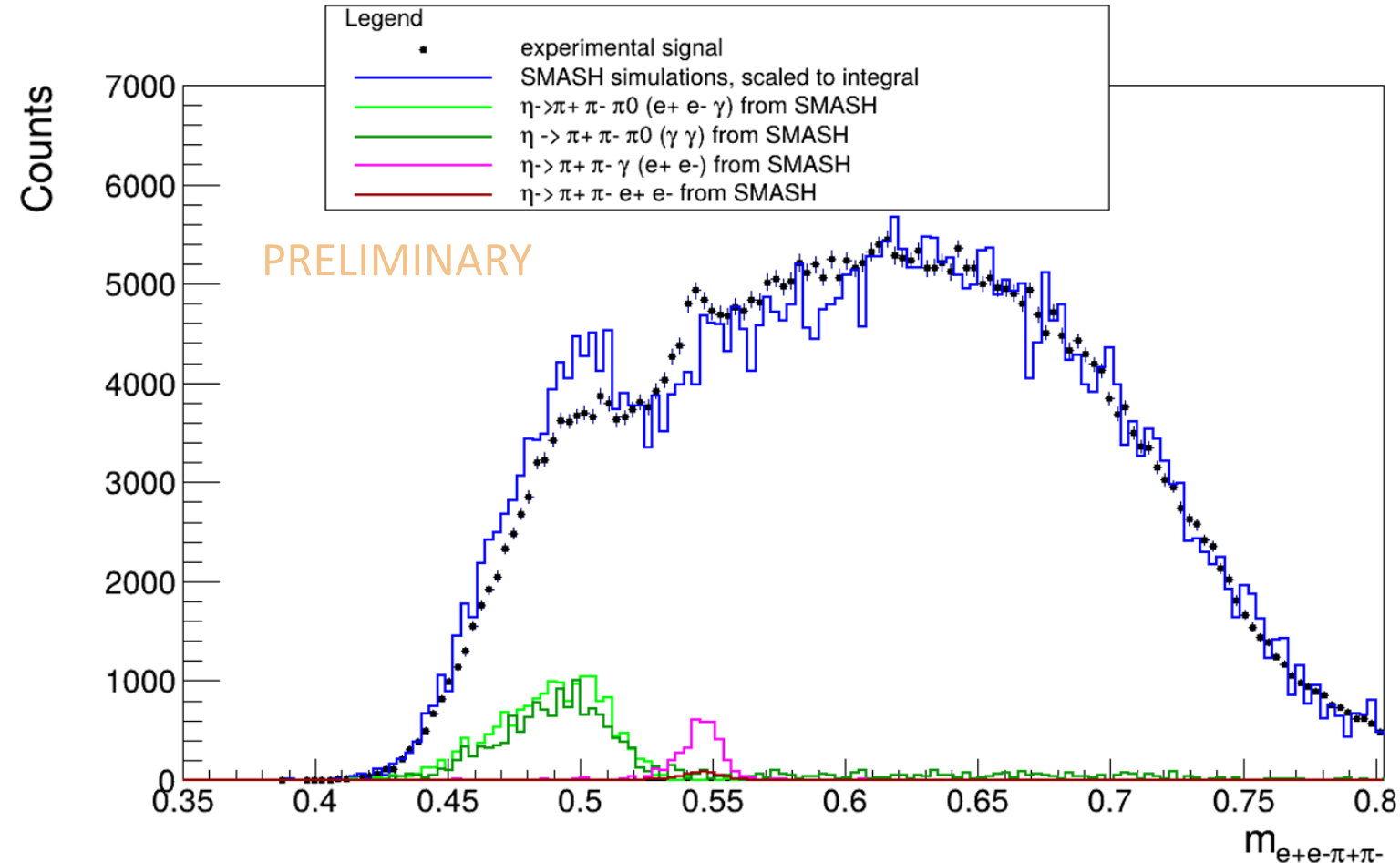
SMASH → Geant → DST

10^{10} events simulated in SMASH (10^5 files, each
with 10^5 events)

added η decay channels:

- $\eta \rightarrow \pi^+ \pi^- e^+ e^-$
- $\eta \rightarrow \pi^+ \pi^- X17 (e^+ e^-)$

$\pi^+\pi^-e^+e^-$ invariant mass

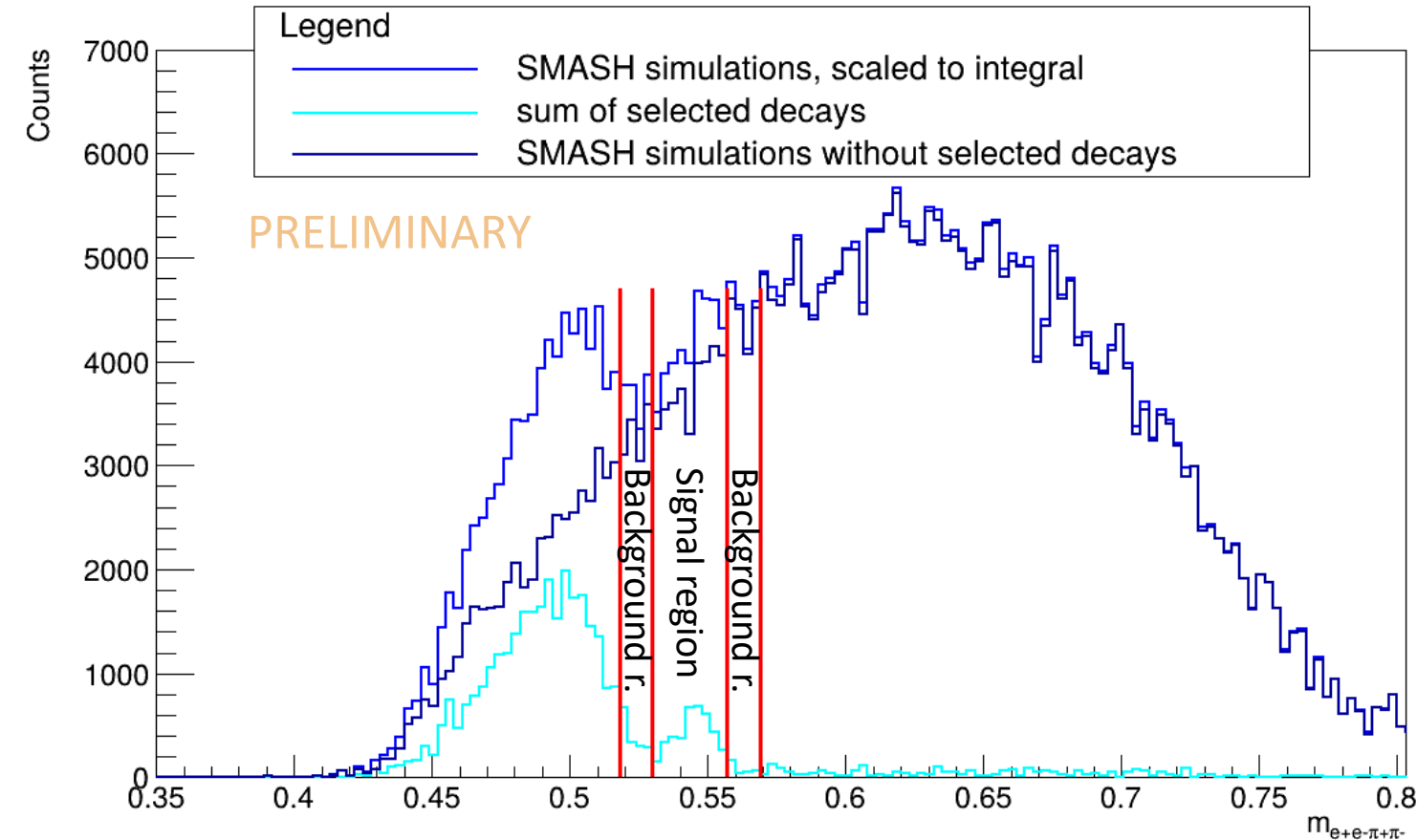


➤ three η decay channels can be extracted from standard SMASH simulations by setting conditions on HGeantKine ID of particles, they parents and grandparents

➤ example: $\eta \rightarrow \pi^+ \pi^- \pi^0 (e^+ e^- \gamma)$ decay:

	ID	Parent ID	Gparent ID
π^+	8	17	---
π^-	9	17	---
e^+	2	7	17
e^-	3	7	17

Simulations without selected decays



➤ extracted three η decay channels were added:

$$\eta \rightarrow \pi^+ \pi^- \pi^0 (e^+ e^- \gamma)$$

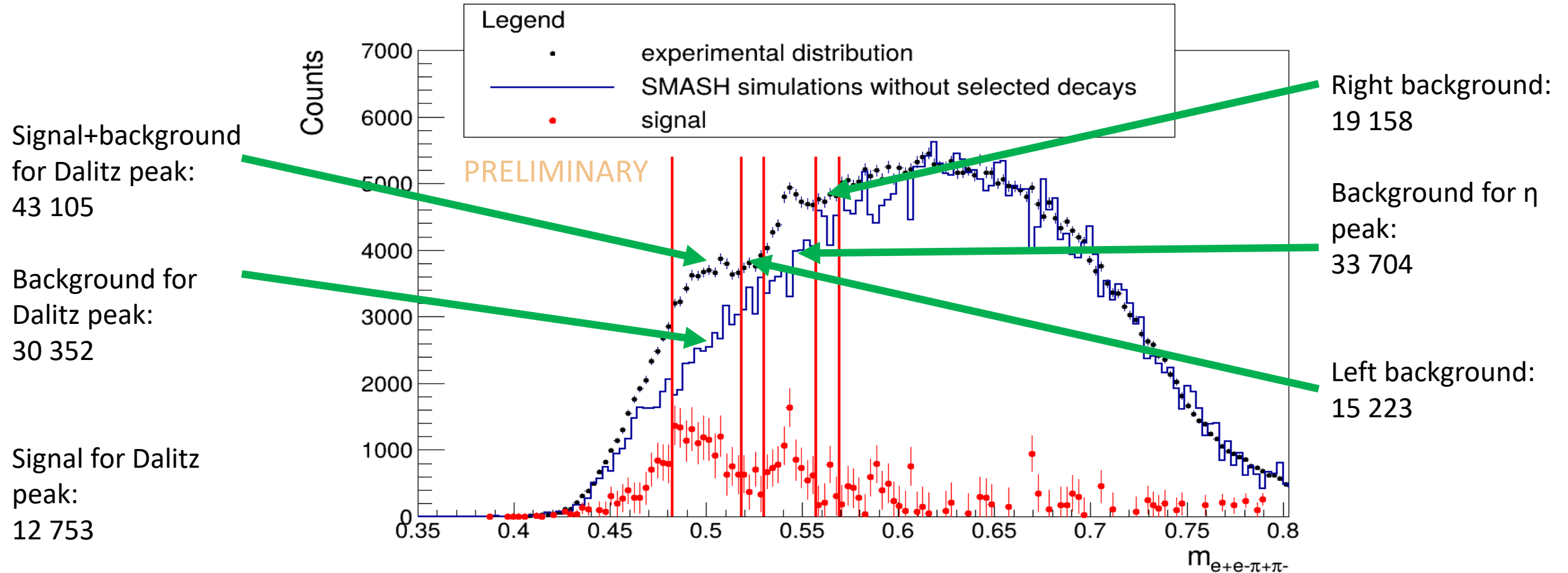
$$\eta \rightarrow \pi^+ \pi^- \pi^0 (\gamma \gamma)$$

$$\eta \rightarrow \pi^+ \pi^- \gamma (e^+ e^-)$$

➤ then the sum was subtracted from SMASH results

➤ final distribution is SMASH simulation without η decay channels

Sideband analysis



Different method to calculate events: fit

Fitted function:

$$A \cdot (x - x_0)^a \cdot \exp(-B \cdot (x - x_0)^b)$$

Background for Dalitz peak:

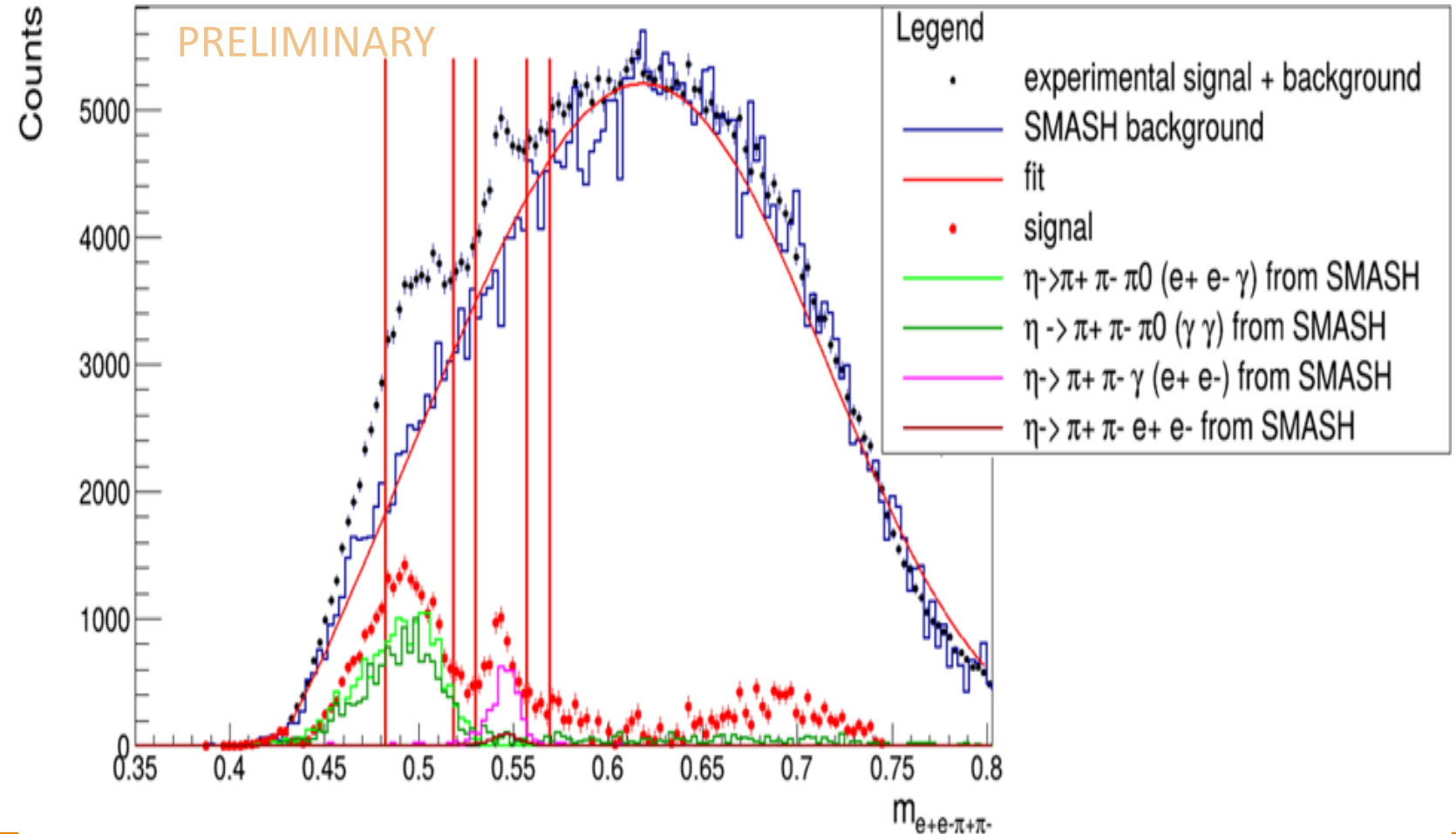
30 352 \rightarrow 29 620

Signal for Dalitz peak:

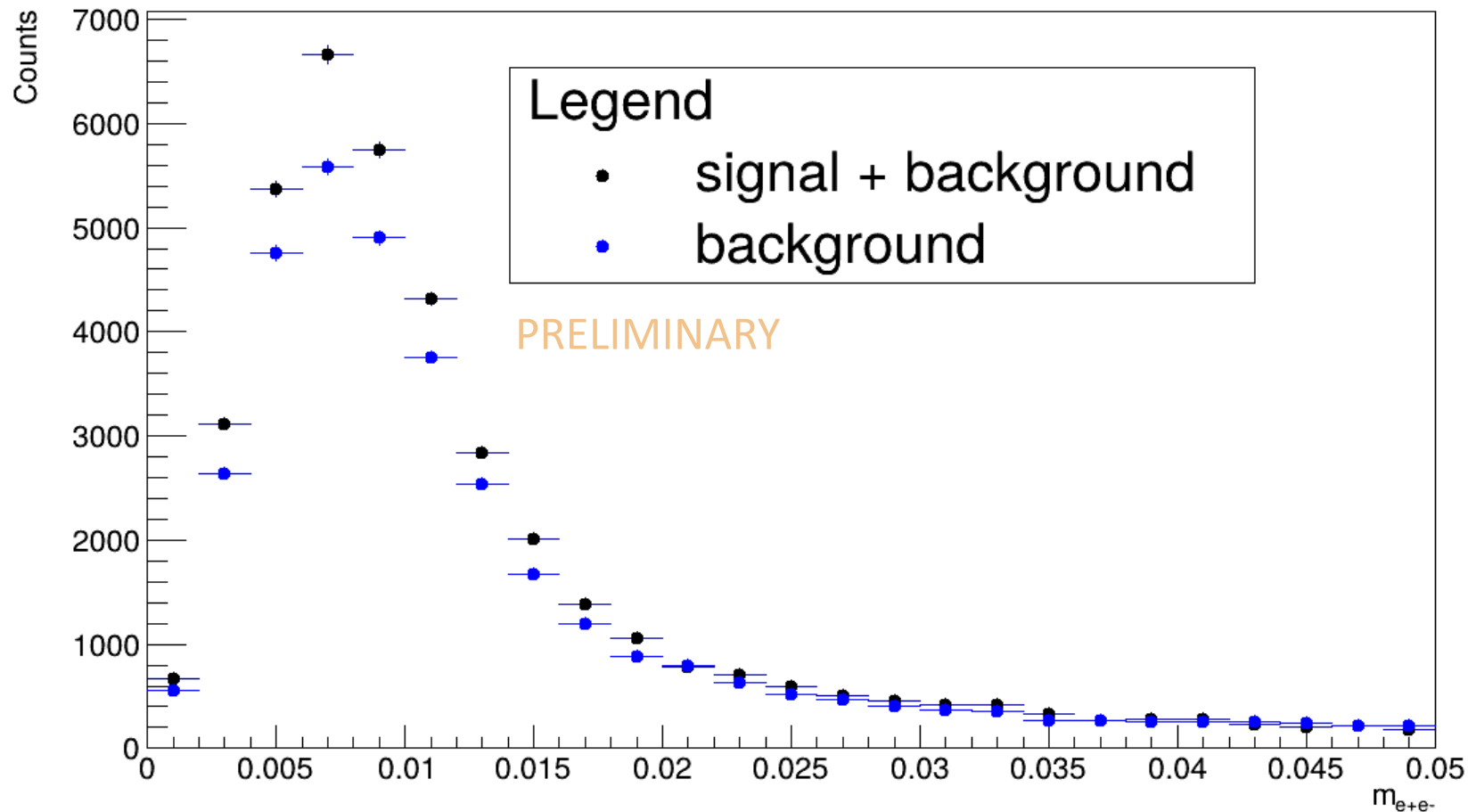
12 753 \rightarrow 13 564

Background for η peak:

33 704 \rightarrow 35 248



Sideband analysis: e^+e^- invariant mass



From $\pi\pi e e$ distribution:
right background: 19 158
background for Dalitz peak:
33 704
left background: 15 223

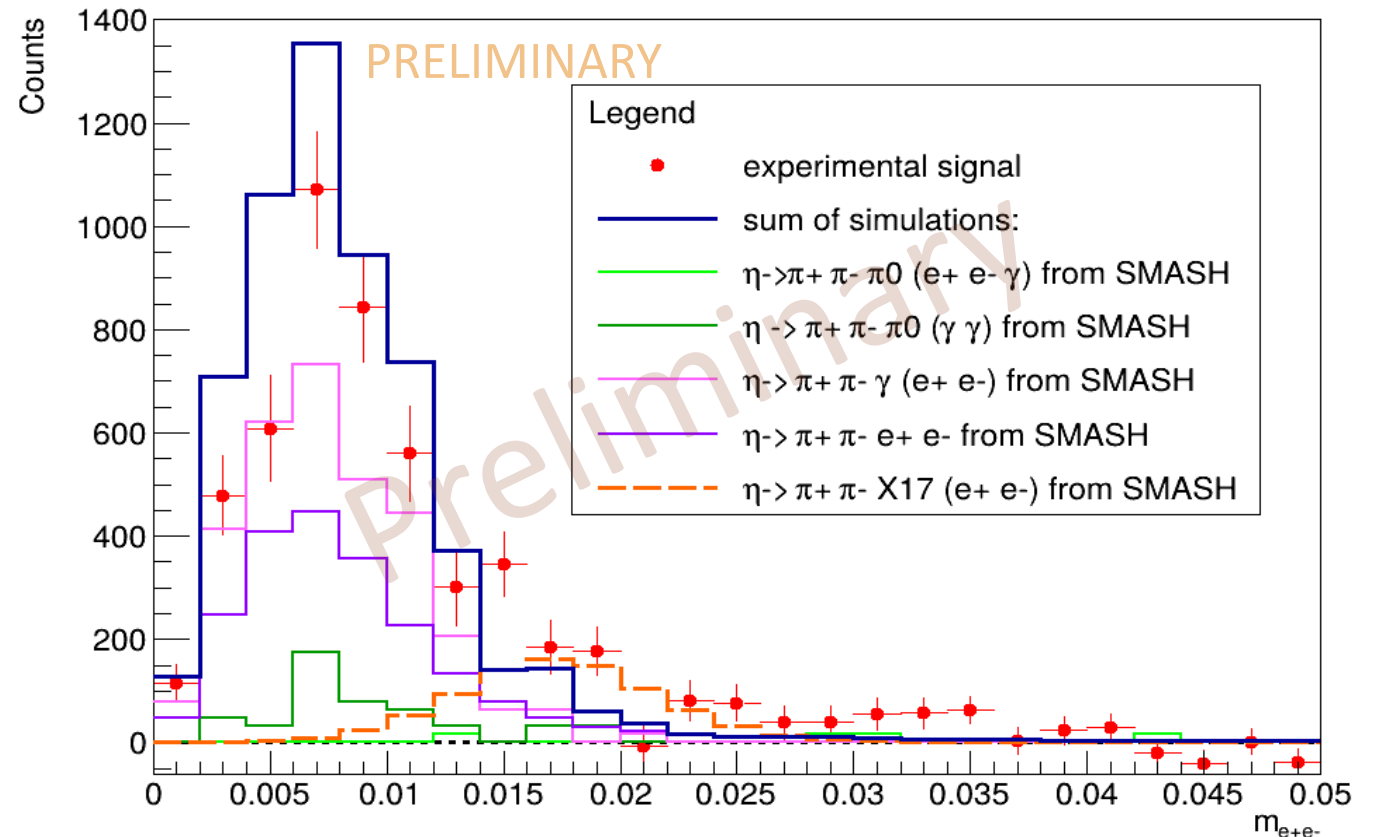
For e^+e^- distribution:
background scaled by
35248

19158 + 15223

Extraction of number of expected X17 events

- Final distribution of e^+e^- invariant mass after background subtraction
- No clear peak indicating ALP existence is visible

$$N_{\text{signal}} = N_{\text{signal with background}} - N_{\text{background}}$$



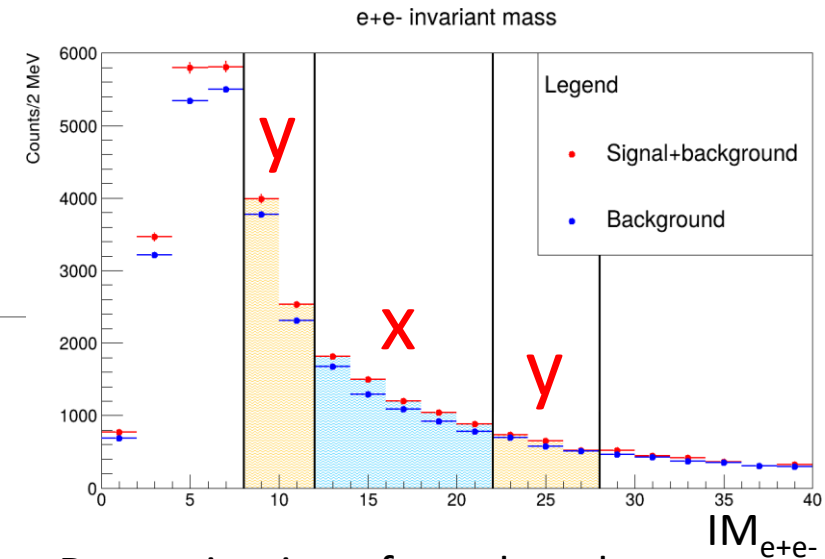
Upper limit extraction

Method developed by Wolfgang A. Rolke (Nuclear Instruments and Methods in Physics Research Section A, Volume 551, Issue 2-3, p. 493-503.)

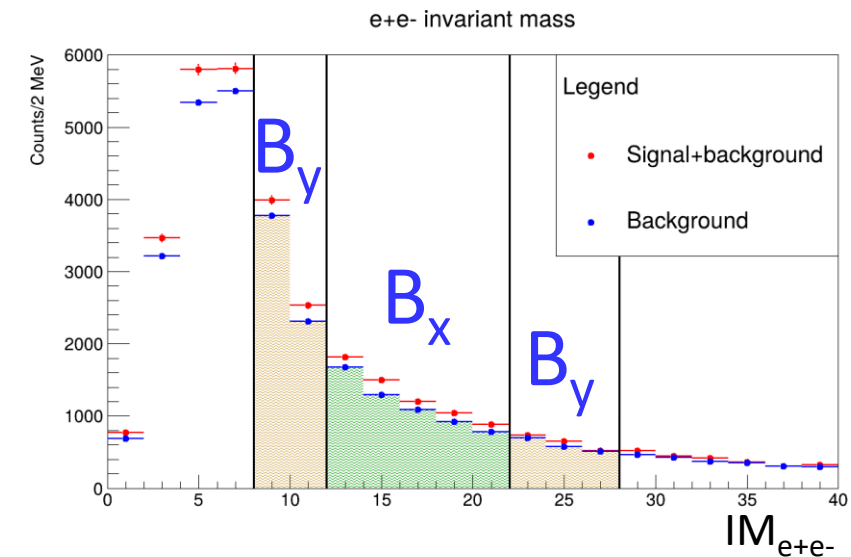
Parameters for Poisson background and known efficiency:

- x – events in the signal region ($IM_{\pi+\pi-e+e-}$ around η peak)
- y – events in the background region ($IM_{\pi+\pi-e+e-}$ in background region)
- B_x – number of side band background events in the signal region ($IM_{\pi+\pi-e+e-}$ around η peak)
- B_y – number of side band background events in the background region ($IM_{\pi+\pi-e+e-}$ in background region)
- $\tau = \left(\frac{B_y}{B_x}\right)$

Assumed confidence level: 0.9

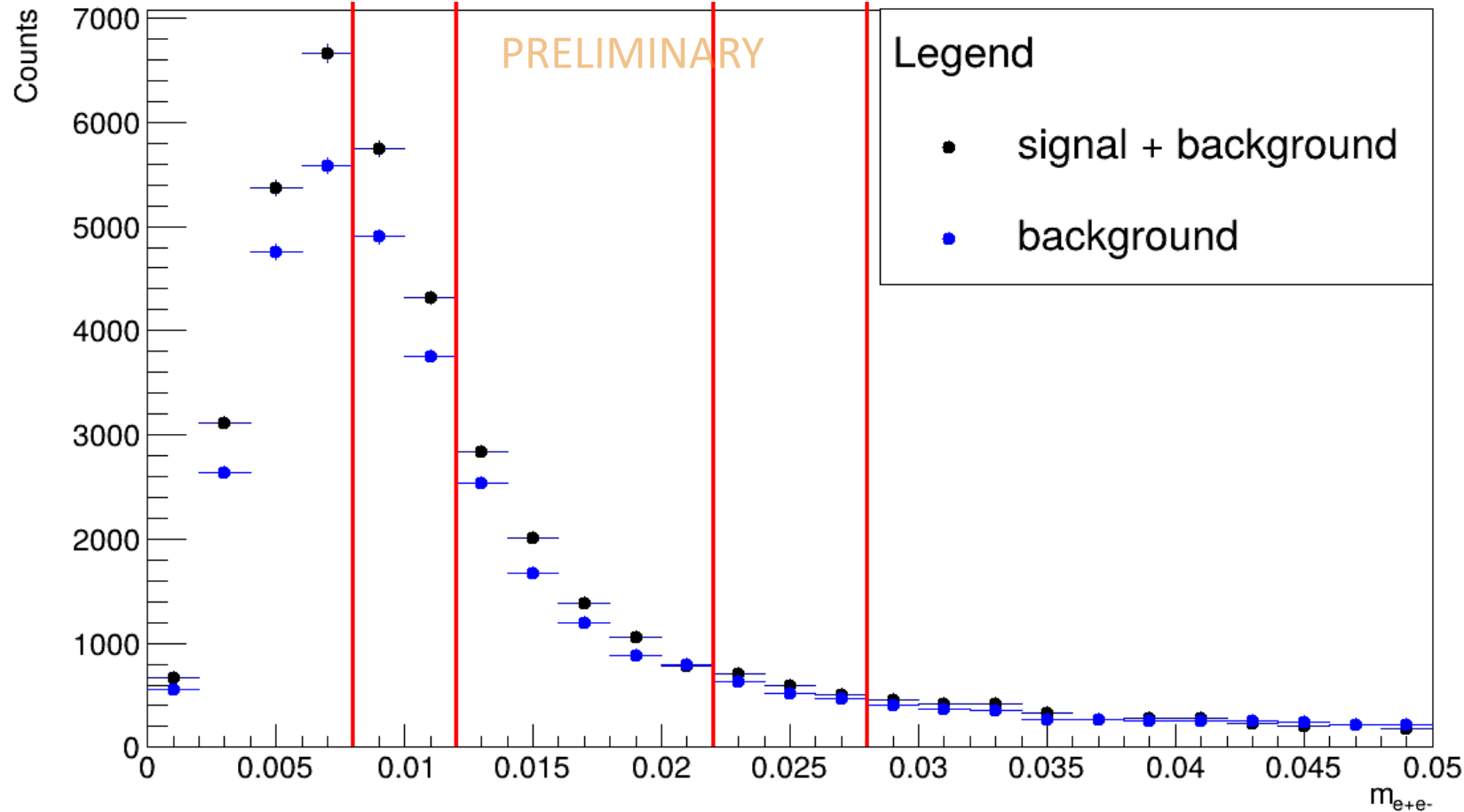


Determination of x and y values.



Determination of B_x and B_y values.

Trolke method



Signal+background
distribution:
left region 10 061
central region 8 079
right region 1 819

Background distribution:
left region 8 658
central region 7 076
right region 1 622

TRolke upper limit: **94**

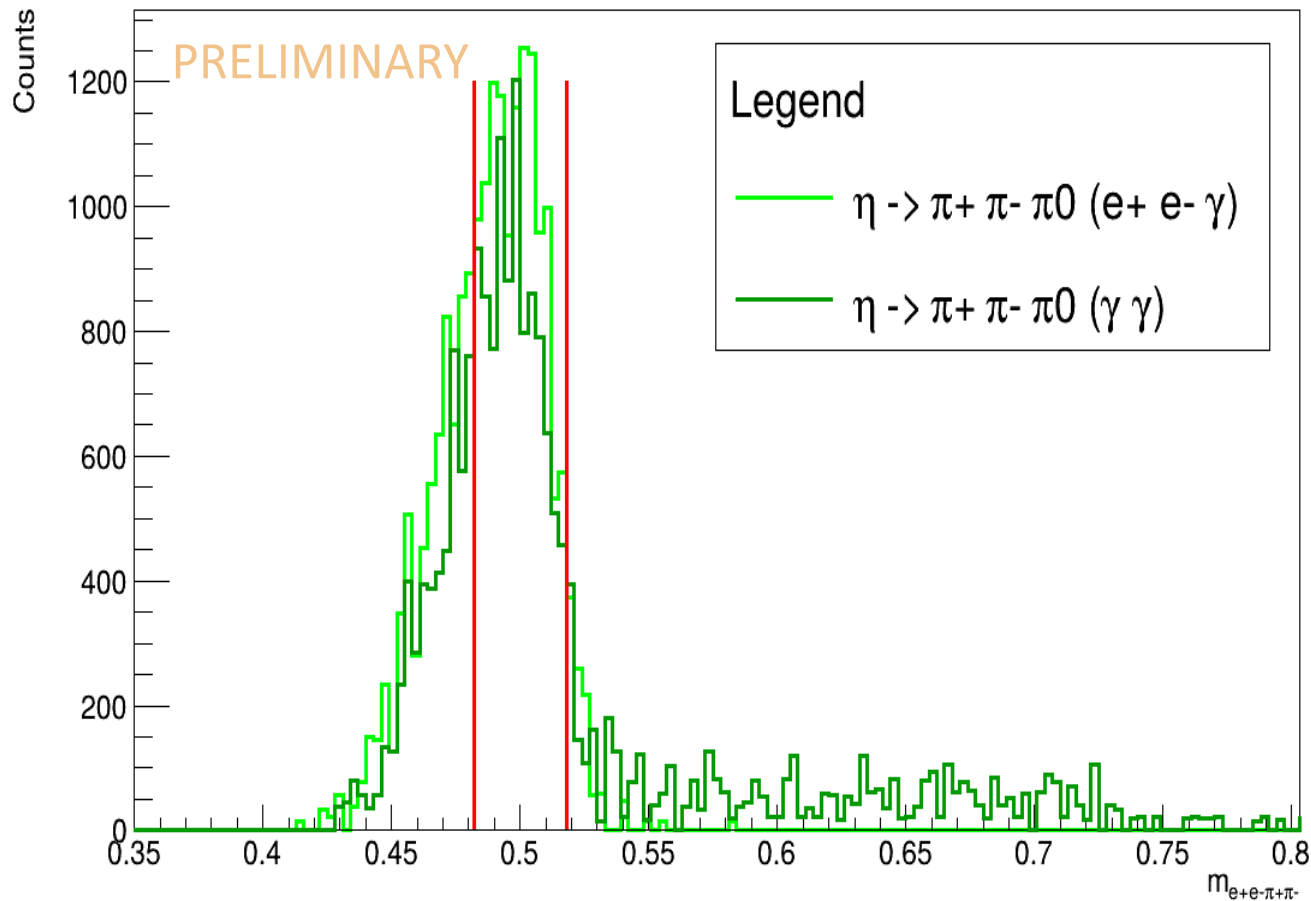
Scaling of branching ratio

- to calculate upper limit of branching ratio for $\eta \rightarrow \pi^+ \pi^- X_{17}$ decay we need some reference
- such reference can be Dalitz decay $\eta \rightarrow \pi^+ \pi^- \pi^0$, where number of observed events is equal number of events in the left peak

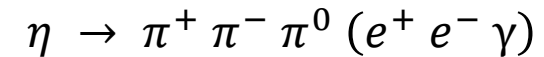
$$BR_{X_{17}} = BR_{Dalitz} \frac{\epsilon_{Dalitz}}{\epsilon_{X_{17}}} \cdot \frac{N_{X_{17}}}{N_{Dalitz}}$$

- BR – branching ratio = $23.02 \cdot 10^{-2}$
- ϵ – efficiency · acceptance
- N – number of events

Finding ε factors: Dalitz decays

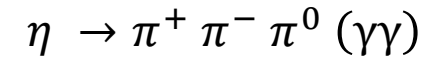


Scaling to luminosity required



12 073 events observed

9 447 332 events in simulations in 4π



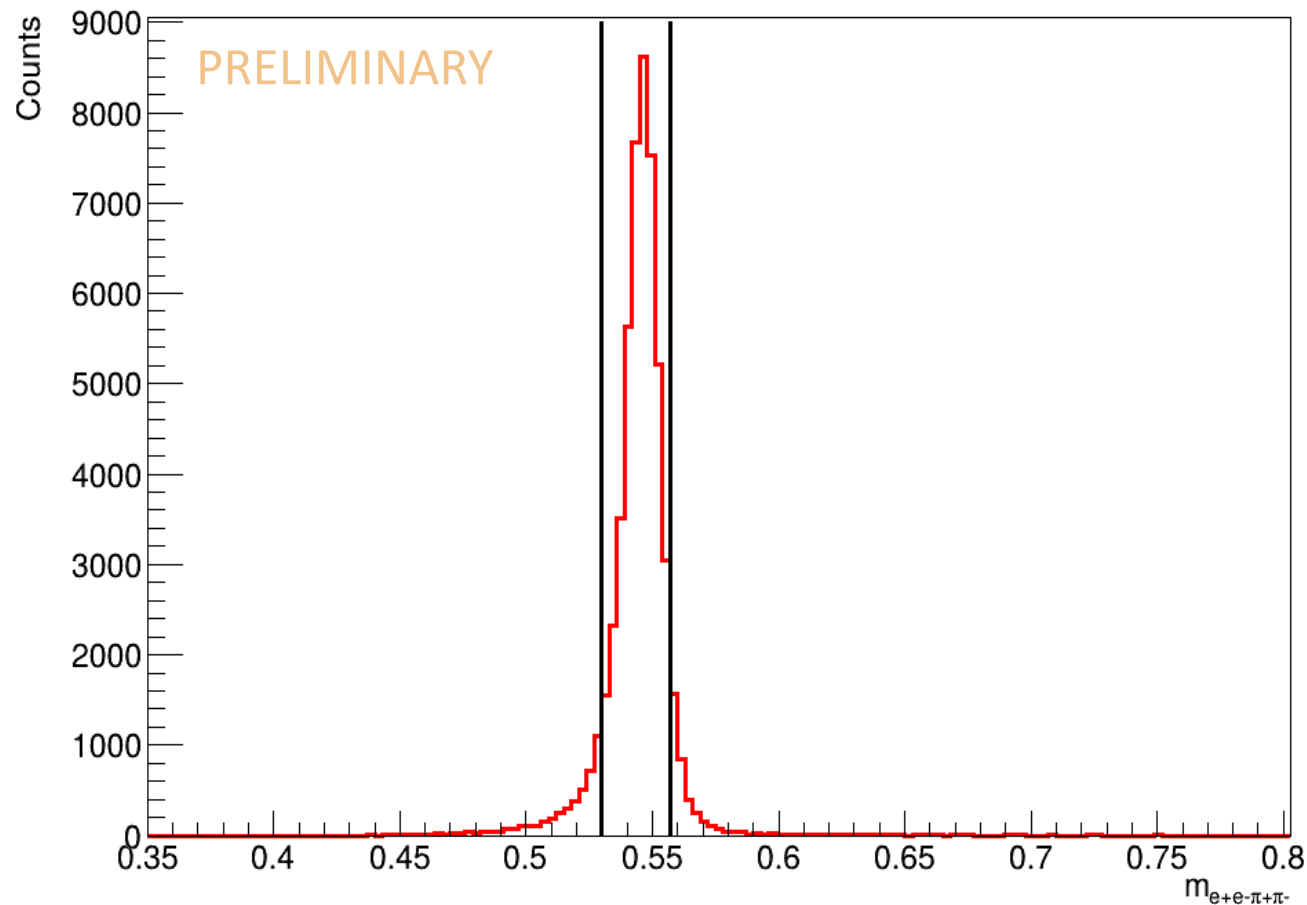
9 811 events observed

790 350 214 events in simulations in 4π

$$\varepsilon = \frac{12073 + 9811}{9447332 + 790350214}$$

$\varepsilon = 0.00003097$

Finding ϵ factors: decay with X17



11 777 273 events in analysed simulations

58 253 events observed after all cuts

$$\epsilon = 0.004946$$

Extraction of number of expected X17 events

- Final distribution of e^+e^- invariant mass after background subtraction
- Prediction of upper limit for X17 events according to **W. Rolke et al., Nucl. Phys. A, 551, 493-503 (2005)**

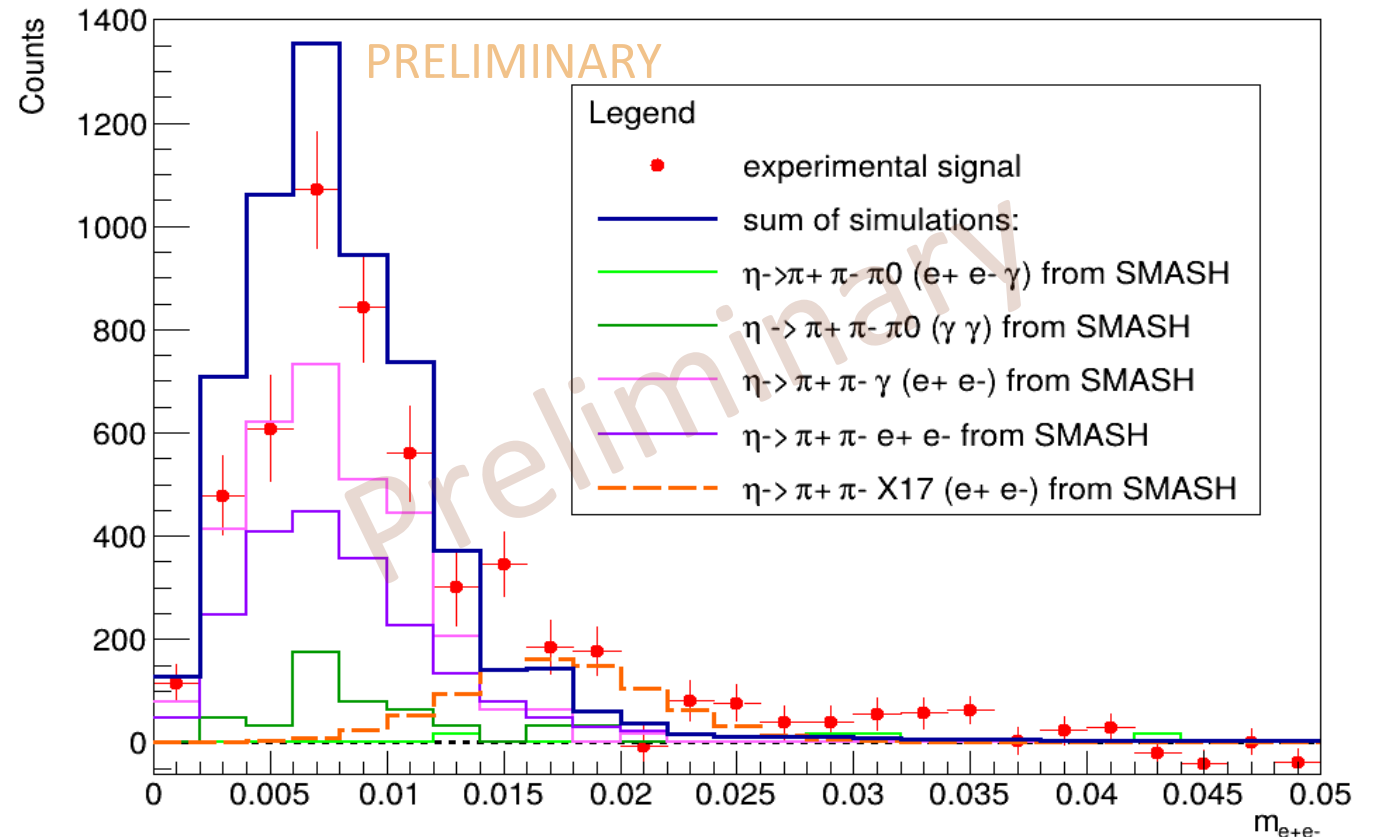
$$N_{X17} < 94 \text{ (CL=90\%)}$$

$$N_{\text{Dalitz}} = 13\,564$$

$$\text{BR}_{\text{Dalitz}} = 23.02 \cdot 10^{-2}$$

$$\text{BR}_{\eta \rightarrow \pi^+\pi^-X17} < 8.9 \cdot 10^{-6}$$

$$N_{\text{signal}} = N_{\text{signal with background}} - N_{\text{background}}$$





Search for Axion Like Particles using η meson decays in the HADES experiment

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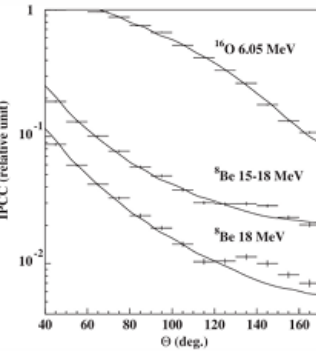
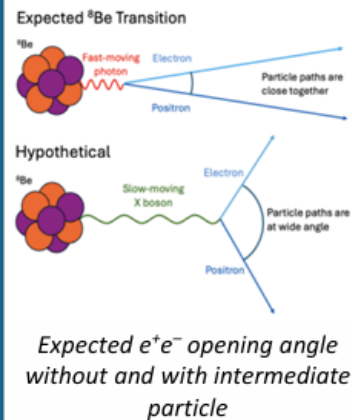


Introduction

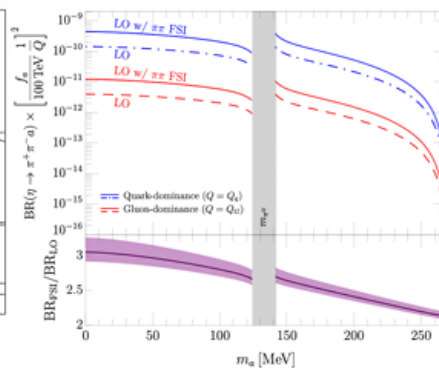
- η is a meson with mass $547.862 \pm 0.017 \text{ MeV}/c^2$ and mean lifetime $(5.0 \pm 0.3) \cdot 10^{-19} \text{ s}$ [1].
- η is pseudoscalar particle ($J^P = 1^-$). According to axion theory, axions couple with pseudoscalar particles.
- If X17 particle exists, it should appear in $\eta \rightarrow \pi^+\pi^-X17(e^+e^-)$ decay.
- $\eta \rightarrow \pi^+\pi^-e^+e^-$ can be used for testing CP symmetry violation.

Axion-like-Particle (ALP)

- X17 is a candidate for ALP particle [2], firstly postulated after experiment ATOMKI in Hungary. There was observed a difference between theoretical results and experimental predictions for opening angle between e^+ and e^- in nuclear transitions. Simulations have shown that a new particle can explain this difference and its mass should be $\sim 17 \text{ MeV}/c^2$.
- Postulated Axiohadronic decay of eta $\eta \rightarrow \pi^+\pi^-X17$ was theoretically studied by D. Alves and S. G. Solis. According to their work, Braching Ratio for this decay should be in range from 10^{-10} to 10^{-6} [3].



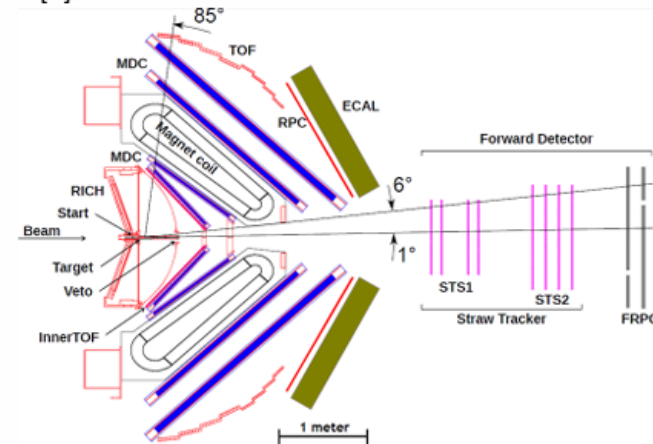
predictions of BR for $\eta \rightarrow \pi^+\pi^-X17$ decay [3]



e^+e^- opening angle distribution for ATOMKI experiment results [2]

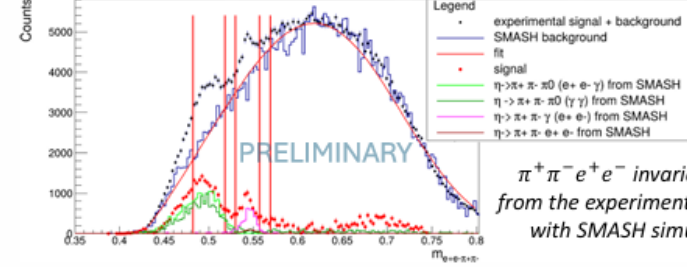
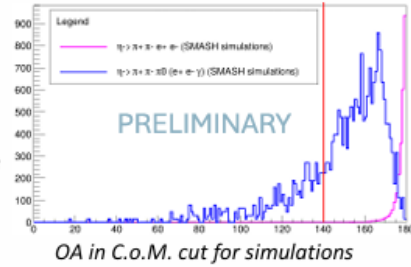
HADES detector

- HADES is experiment located in in Helmholtz GSI Institute in Darmstadt, Germany.
- Results from proton protons collisions at energy 4.5 GeV are studied.
- The most recent proton proton experimental run was conducted in February 2022 and took 28 days [4].



Selection criteria

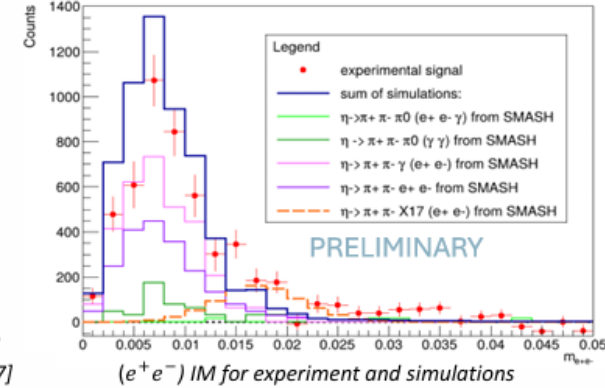
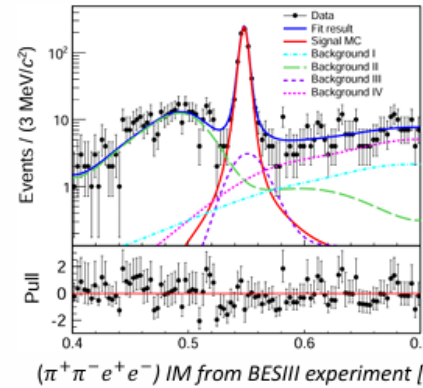
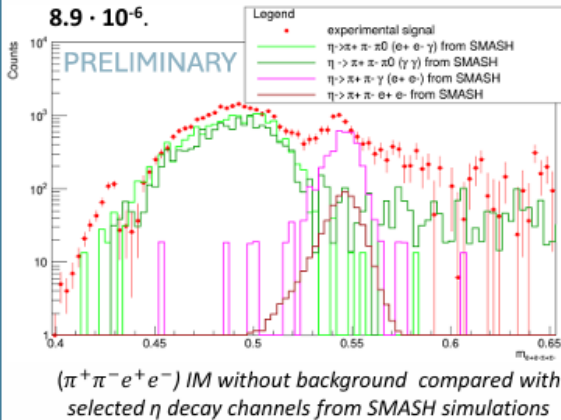
- 1) $(\pi^+\pi^-)(e^+e^-)$ opening angle in LAB frame $< 50^\circ$
- 2) $(\pi^+\pi^-)$ invariant mass < 460 MeV/c²
- 3) $(\pi^+\pi^-)(e^+e^-)$ opening angle in C.o.M. frame $> 140^\circ$



$\pi^+\pi^-e^+e^-$ invariant mass from the experiment compared with SMASH simulations

η peak analysis

- Distribution of $(\pi^+\pi^-e^+e^-)$ invariant mass (IM) includes visible peak in η mass region and one peak on the left side. Peak on the left was caused by Dalitz decays ($\eta \rightarrow \pi^+\pi^-\pi^0$).
- A set of simulations have been prepared using Monte Carlo event generator PLUTO and Geant3 [5].
- Sideband analysis was performed to obtain (e^+e^-) invariant mass distribution for events in η peak. This distribution was compared with simulations.
- No visible signal indicating ALP existence has been observed in e^+e^- invariant mass distribution. A special method developed by Wolfgang T. Rolke was performed to find upper limit for number of events with X17 particles [6].
- Preliminary calculated upper limit at CL=90% is 94 events, which corresponds to upper limit for branching ratio of $\eta \rightarrow \pi^+\pi^-X17$ decay equal $8.9 \cdot 10^{-6}$.



References:

- [1] Website: pdg.lbl.gov (Particle Data Group)
- [2] A. J. Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016).
- [3] D. S. M. Alves et al., J. High Energy Phys. 2024, 264 (2024)
- [4] G. Agakichiev et al. (HADES), Eur. Phys. J. A 41, 243 (2009).
- [5] I. Frohlich et al., PoS ACAT2007, 076 (2007).
- [6] W. T. Rolke et al., doi.org/10.1016/j.nima.2005.05.068
- [7] M. Albikin et al. (BESIII), JHEP 07, 135 (2024)

Acknowledgements:

We acknowledge support by: National Science Centre (NCN) under the grant agreement no. SONATA-BIS-13 2023/50/E/ST2/00673, Jagiellonian University under the grant Research Support Module edition 2023/2024 agreement no.WSPR.WFAIS.1.10.2023.41, and Jagiellonian University under the grant Research Support Module edition 2025 agreement no.WSPR.WFAIS.1.3.2025.29

