Neutral η' Decays with the Crystal Ball

Physics:

- Photoprodution Cross Section
- $\Gamma(\eta' \to 2\gamma)/\Gamma(\eta \to 2\gamma)$
- $\eta' \to \eta\pi^0\pi^0 / \eta' \to 3\pi^0$
- C and CP violating decays

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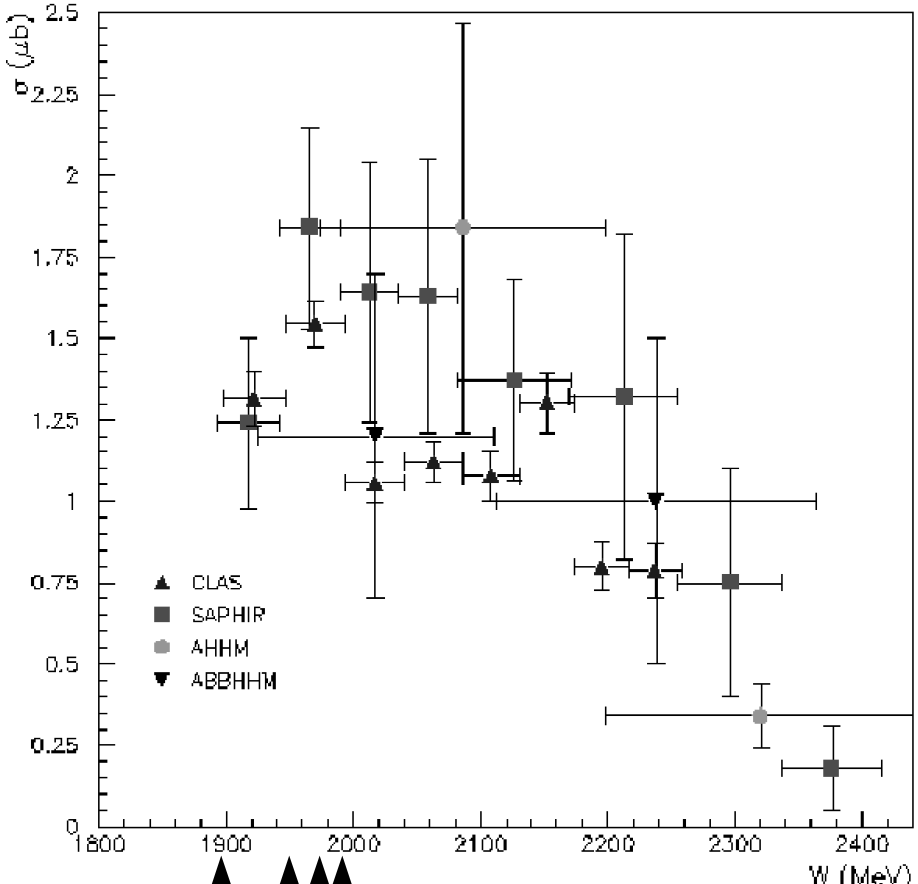
η' Photoproduction

η' Cross Section



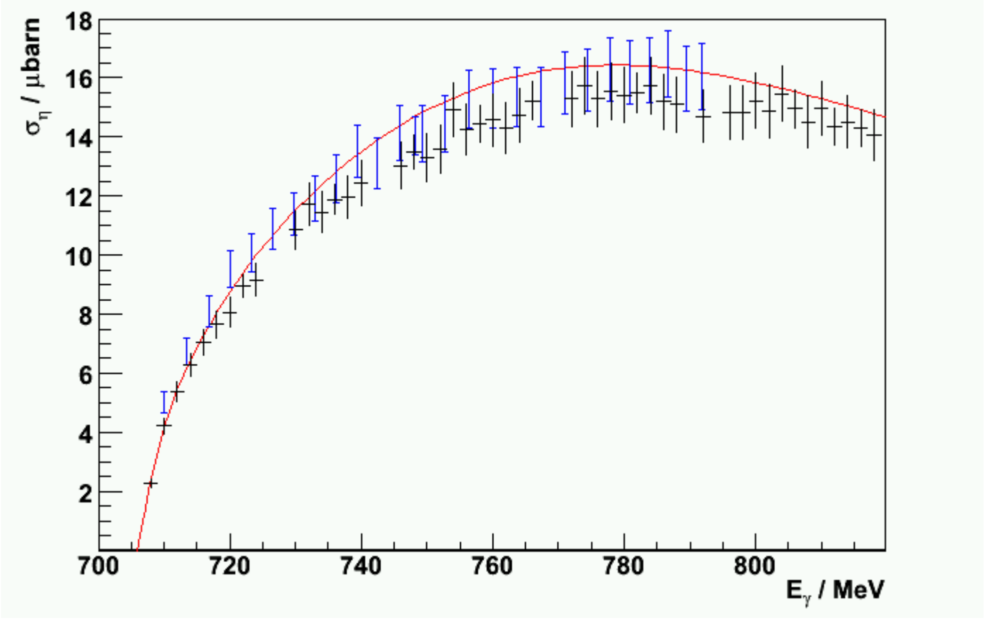
E_γ=1650 MeV

E_γ=1600 MeV

E_γ=1558 MeV

E_γ=1447 MeV (threshold)

η Cross Section



- First goal: determine η' photoproduction cross section with high precision as for η
- Get normalisations under control
- Examie not well known threshold region

η/η'

- Dominant decays:

$\eta' \to \eta\pi^+\pi^-$	BR=44.6 %	
$\eta' \to \rho^0\gamma$	BR=29.4 %	(including nonresonant $\pi^+\pi^-\gamma$)
$\eta' \to \eta\pi^0\pi^0$	BR=20.7 %	
$\eta' \to \omega\gamma$	BR=3.0 %	
$\eta' \to 2\gamma$	BR=2.1 %	$\eta' \to 3\pi^0$ BR=0.156%

- η and η' are perfectly suited to study symmetries and symmetry violations in QCD
- $\eta' \to \eta\pi\pi$ and $\eta' \to \pi\pi\pi$ sensitive to $\pi\eta$ and $\pi\pi$ scattering lengths (FSI)
- $\eta/\eta' \to \pi\pi\pi$ is sensitive to isospin symmetry breaking due to light quark mass difference m_u-m_d
- Anomalous decays $\eta/\eta' \to 2\gamma$ probe chiral anomalies of QCD
- PDG lists 7 C or CP violating decays of the η' meson, 9 for the η
- η and η' closely related to each other, they have the same quantum numbers:

$$\boxed{I^G(J^{PC})=0^+(0^{-+})}$$

$\Gamma(\eta' \to 2\gamma)/\Gamma(\eta \to 2\gamma)$

- From chiral symmetry breaking 8 pseudescalar Goldstone-bosons are expected:

  $(\pi^+, \pi^-, \pi^0, K^+, K^-, K^0, \bar{K}^0, \eta_8)$ SU(3)-octet

- Have the same quantum numbers as respective $q\bar{q}$ pairs:

  $(u\bar{d}, d\bar{u}, (u\bar{u}-d\bar{d}), u\bar{s}, s\bar{u}, d\bar{s}, s\bar{d}, (u\bar{u}+d\bar{d}-2s\bar{s}))$

- 9th state possible, lightest candidate η'(958):

  $\eta_0 \sim (u\bar{u}+d\bar{d}+s\bar{s})$ SU(3)-singlet

- Neither η nor η' are pure singlet or octet states (θ=-(20±2)°):

  $$\eta = \eta_0 \sin\theta - \eta_8 \cos\theta$$

  $$\eta = \eta_0 \cos\theta + \eta_8 \sin\theta$$

- Also scheme with two mixing angles possible and additional gluonic content

- For extraction of mixing angle both decay widths have to be known with high precision

  η: $\Gamma(\eta \to \text{all}) = (1.30 \pm 0.07)$ keV $\Gamma(\eta \to 2\gamma) = (39.31 \pm 0.20)\%$

  η': $\Gamma(\eta' \to \text{all}) = (0.30 \pm 0.09)$ keV $\Gamma(\eta' \to 2\gamma) = (2.10 \pm 0.12)\%$

- Theoretically mixing not fully understood. Connection to QCD is missing (N_C, m_q)

Determination of $(m_d-m_u)/m_s$

- Gross, Treiman, Wilczek, Phys. Rev. D **19**, 2188 (1979):

$$\frac{\Gamma(\eta'\to 3\pi^0)}{\Gamma(\eta'\to\eta\pi^0\pi^0)}=\Phi\cdot\left(\frac{m_d-m_u}{m_s-\hat{m}}\right)^2 \qquad \hat{m}=\frac{1}{2}(m_u+m_d)$$

- Two assumptions:
  a) Decay $\eta'\to 3\pi^0$ proceeds entirely via $\eta'\to\eta\pi^0\pi^0$ followed by π^0-η mixing
  b) Amplitudes for both decays are constant over phase space

- Borasoy, Meißner, Nißler, Phys. Lett. B 643, 41 (2006):
  „Our results clearly indicate that the two underlying assumptions ... are not justified."

- Large coupling of the $\eta'\to 3\pi$ process to ρ(770) resonance

- Borasoy, Meißner, Nißler, Phys. Lett. B 643, 41 (2006):
  „More precise data on η and η' decays needed in order to eventually clarify this issue."

Slope Parameters

- Energy release small (~141 MeV) in $\eta' \to \eta\pi^0\pi^0$

$$|M|^2 = |1+\alpha y|^2 + c x + d x^2$$

x, y = Dalitz plot variables

- Dalitz plot variations due to $\eta\pi$ and $\pi\pi$ scattering described by α (linear parametrisation):

GAMS-2000	α=-0.058±0.013	5400 Events
CLEO	α=-0.021±0.025	6700 Events
VES	α=-0.072±0.012±0.006	7000 Events

- Im(α) so far consistent with 0
- C-violating decay parameter c=0.015±0.011±0.014 (VES with 20k events)
- d assumed to be 0

- $\eta' \to 3\pi^0$ has only one parameter as in $\eta \to 3\pi^0$:

$$|M|^2 = (1 + 2\beta z)$$

$z = x^2 + y^2$

- Only value so far from GAMS-2000: α=-0.1±0.3 with 40 events

$\pi\pi$ and $\pi\eta$ Scattering Lengths

- $\eta'\to\eta\pi^+\pi^-$ contributes to $\eta'\to\eta\pi^0\pi^0$ via $\pi^+\pi^-\to\pi^0\pi^0$, also for $\eta'\to 3\pi^0$

- Cusp arises at $\pi^+\pi^-$ threshold in $\pi^0\pi^0$ invariant mass spectrum

- Cabibbo and Isidori as well as Bissegger *et al.* have developed framework to extract a_0-a_2 from $K\to 3\pi$ and $\eta\to 3\pi$ $\pi^0\pi^0$ invariant mass spectrum, but cusp effect in η decay only at 1% level

- Rough estimate from Kubis (HISKP) for cusp strength:

  $K^+\to 3\pi$: 2

  $K_L\to 3\pi$: 1/3

  $\eta\to 3\pi$: 1/3

  $\eta'\to\eta 2\pi$: 1.3 – 1.5

- As cusps were measured with high statistics in Kaon decays this it is not to be seen as a highlight to see it in η' sector

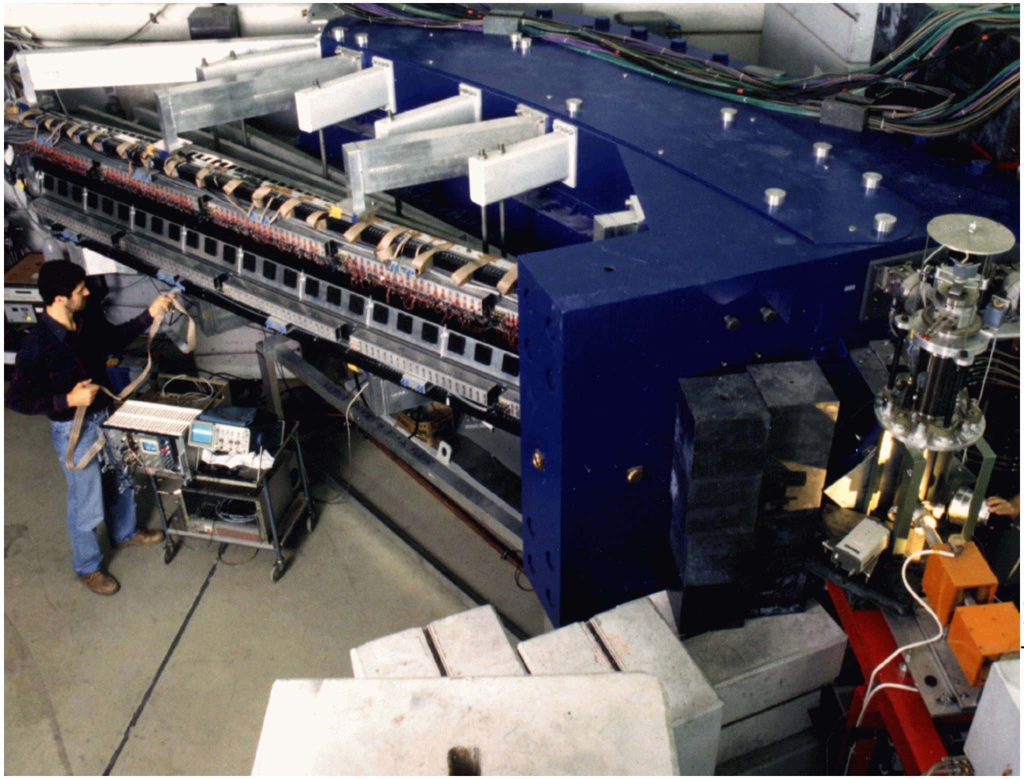
- Schneider, Kubis, Meißner (soon on arXiv) state an 8% cusp effect in $\eta'\to\eta\pi^0\pi^0$ → extraction of $\pi\eta$ scattering length is possible, which can not easily be measured in other experiments

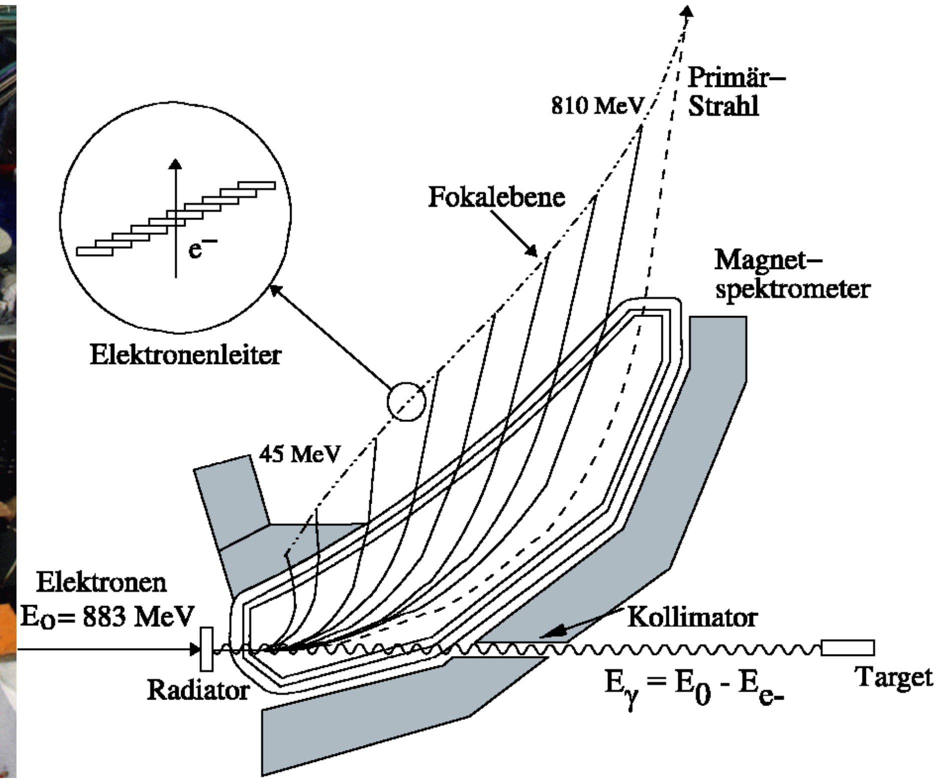
C and CP Violating Decays

- In QED and QCD C and CP sysmmetry should be conserved
- η' well suited to investigate symmetry breaking
- Only weak upper limits for C and CP violating η' decays exist
- C violating:
  - $\eta' \to \eta e^+ e^-$ BR$<2.4\cdot 10^{-3}$
  - $\eta' \to \pi^0 e^+ e^-$ BR$<1.4\cdot 10^{-3}$
  - $\eta' \to 3\gamma$ BR$<1.0\cdot 10^{-4}$
- CP violating:
  - $\eta' \to 4\pi^0$ BR$<5.0\cdot 10^{-4}$
- CPT violating:
  - $\eta' \to \pi^0 \mu^+ \mu^-$ BR$<6.0\cdot 10^{-5}$
  - $\eta' \to \eta \mu^+ \mu^-$ BR$<1.5\cdot 10^{-5}$

  Not possible with current rates

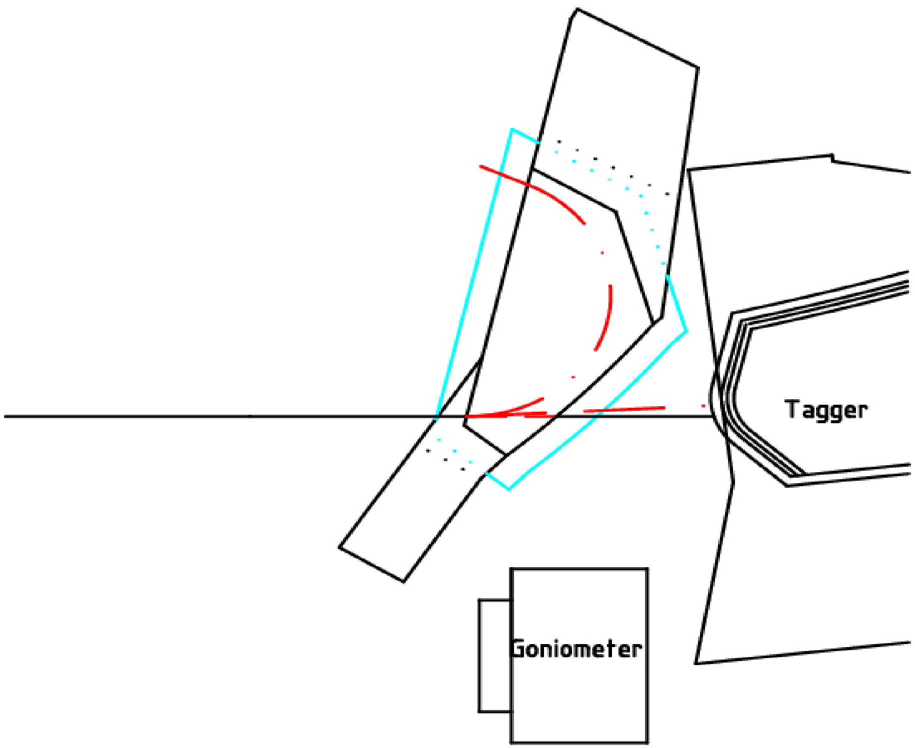
Glasgow-Mainz-Tagger



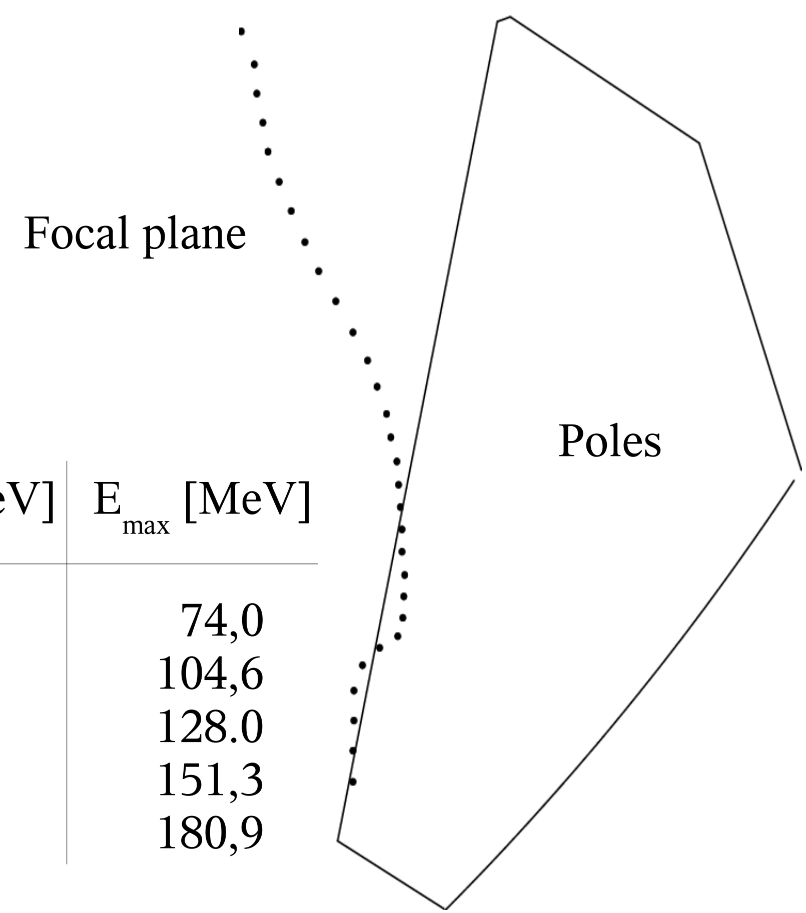


- Photon beam produced by Bremsstrahlung at radiator: $e^- + A \rightarrow e^- + A + \gamma$
- 353 overlapping scintillators → 352 channels
- Electrons momentum analysed in magnetic spectrometer
- Energy tagging through $E_\gamma = E_0 - E_{e-}$
- $\Delta E_\gamma \approx 2$MeV at 883 MeV electron energy, $\Delta E_\gamma \approx 4$MeV at 1558 MeV electron energy
- Tagging range: 5 to 92% of the electron beam energy

End-Point Tagger



- Suitable magnet from MAMI-A
- Plan: use 1.5 T field → 150 MeV range
- Use cards and PMTs from Lund tagger
- 64 channels → ΔE=2.3 MeV
- Possibly include end-point tagger in trigger



	$E_\gamma[MeV]$	$E_e[MeV]$
$K\pi\Sigma$	1299.9	208.1
$\omega\pi$	1366.3	141.7
last tagger channel	1445	113
η'	1446.6	61.4
$K\Lambda(1405)$	1454.0	54
f_0	1491.8	16.2
a_0	1501.4	6.6

B [T]	E_{min} [MeV]	E_{max} [MeV]
0,7	2,9	74,0
1,0	4,0	104,6
1,2	4,8	128.0
1,5	5,3	151,3
1,8	6,0	180,9

Event Rate Estimate

- Incoming electron beam energy: E_0 = 1558 MeV
- Photon energy range tagged: E_γ = 1450 – 1550 MeV → ΔE_γ = 100 MeV
- Photon flux: $N_\gamma = 10^5\ s^{-1}\ MeV^{-1}$
- Number of protons in a 10 cm lH_2 target: $N_t = 4.3\cdot10^{23}\ cm^{-2}$
- η' photoproduction cross section (average): σ(γp→η'p) = 1 μb

$$N_{\eta'} = \Delta E_\gamma \cdot N_\gamma \cdot N_t \cdot \sigma(\gamma p \rightarrow \eta' p) \cdot 3600\, s \approx 1.5 \cdot 10^4 / h$$

- Detection efficiency of $\eta' \rightarrow \eta\pi^0\pi^0$ ~ 30%, livetime ~ 80% and BR($\eta' \rightarrow \eta\pi^0\pi^0$)=20%
  → 700 good $\eta' \rightarrow \eta\pi^0\pi^0$ events per hour
- Current highest statistics ~7000 events. To increase by one order of magnitude at least 100 hours of beam time.

Summary

- Although, or maybe because, the η' meson is not a Goldstone boson and to heavy to be treated in χPT in the standard way, it is interesting and important to measure η' decays
- Proposed channels: $\eta' \to 2\gamma$ in combination with $\eta \to 2\gamma$, $\eta' \to \eta\pi^0\pi^0$, $\eta' \to 3\pi^0$
- Physic goals: η-η' mixing, slope parameters from Dalitz plots, cusps, $\pi\pi$ and $\pi\eta$ scattering lengths
- (Improve upper limits for branching ratios of C and CP violating η' decays like $\eta' \to \eta e^+e^-$, $\eta' \to \pi^0 e^+ e^-$, $\eta' \to 3\gamma$, $\eta' \to 4\pi^0$) if possible!!
- New equipment as $PbWO_4$ crystals in TAPS and end-point tagger and increased e^- energy could improve event rate.
- Proposed η' production rate: $1.5 \cdot 10^4$/h, main neutral decay $\eta' \to \eta\pi^0\pi^0$ 700/h