Study of the process $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta$ with CMD-3

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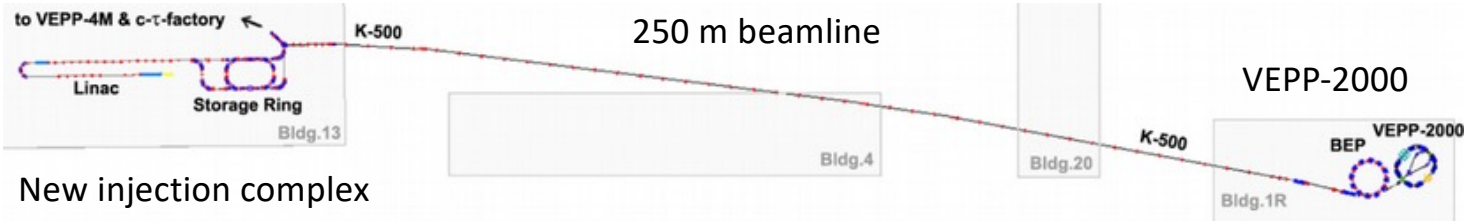
Budker INP, Novosibirsk

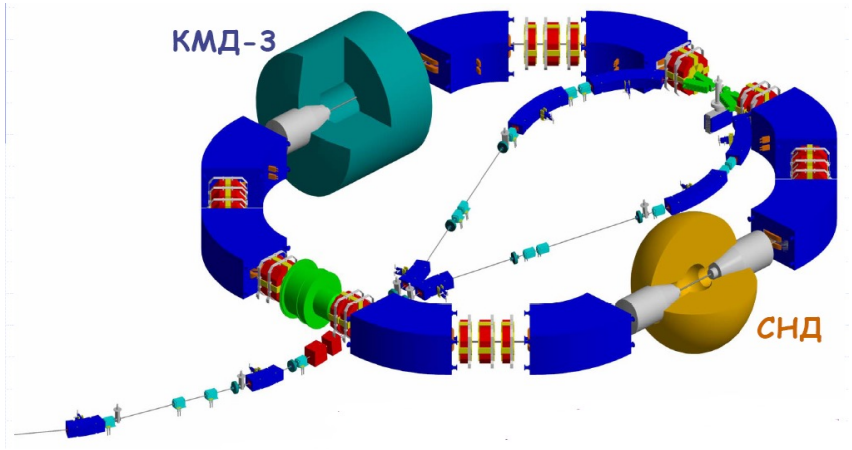
Lomonosiv25, August 2025

VEPP-2000 (after upgrade 2013-2016)



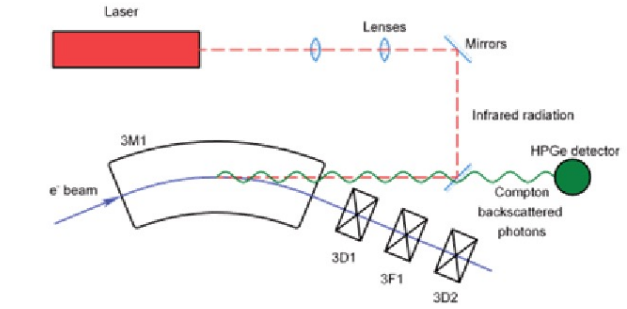
VEPP-2000 parameters:

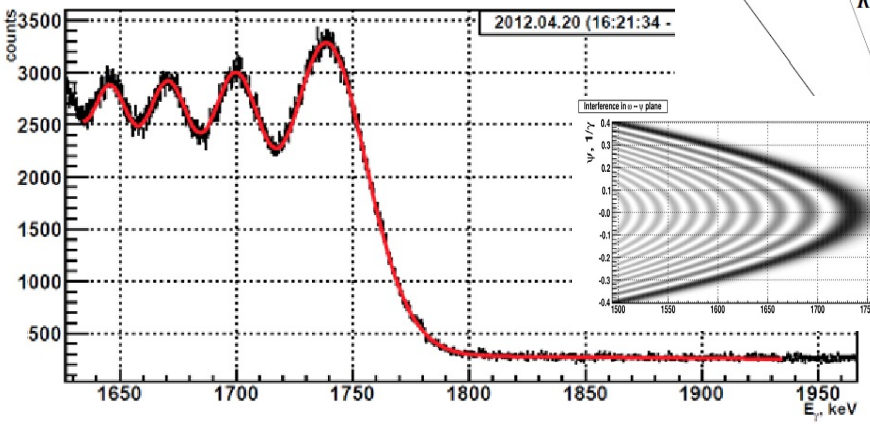
- c.m. energy 0.3-2.0 GeV
- circumference – 24.4 m
- round beam optics
- Luminosity at 2 GeV:
  1.0×10^{32} cm^{-2} sec^{-1} (project)
  0.8×10^{32} cm^{-2} sec^{-1} (achieved)



Energy measurement

Starting from 2012, beam energy and energy spread are monitored continuously using Compton backscattering system with about 30 keV uncertainty

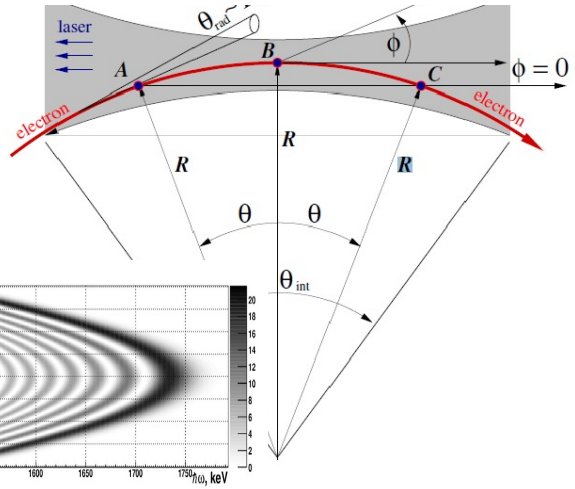




Two sources of photons are used: **ytterbium** and **CO lasers**.

CO (5 nm) at the energy above **500 MeV**,

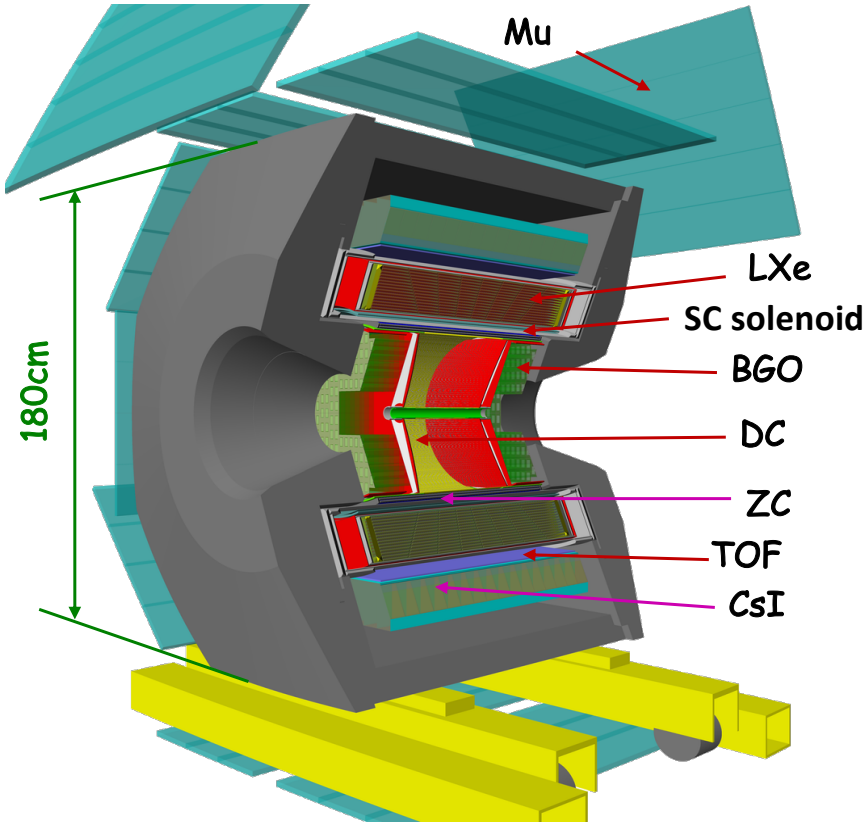
Nd:YAG (1 nm) at the energy below **500 MeV**.



E = 993.662 ± 0.016 MeV

M.N. Achasov et al. arXiv:1211.0103v1 [physics.acc-ph] 1 Nov 2012

CMD-3 detector



Tracking:

× Drift Chamber in 1.3 T magnetic field

$\sigma_{R\varphi}$ ~ 100 μm, σ_Z ~ 2.5mm

$\sigma_p/P \sim \sqrt{0.6^2+(4.4*p[GeV])^2}$,%

Magnet:

0.25 X_0 1.3 T SC solenoid in common cryostat with LXe calorimeter

Calorimetry:

× Combined EM calorimeter (LXe,CsI, BGO)

13.4 X_0 in barrel part

$\sigma_E/E \sim 0.034/\sqrt{E\ [GeV]} \oplus 0.020$ - barrel

$\sigma_E/E \sim 0.024/\sqrt{E\ [GeV]} \oplus 0.023$ -endcap

× LXe calorimeter with 7 ionization layers with strip readout

~2mm measurement of conversion point, tracking capability,

shower profile (from 7 layers + CsI)

PID:

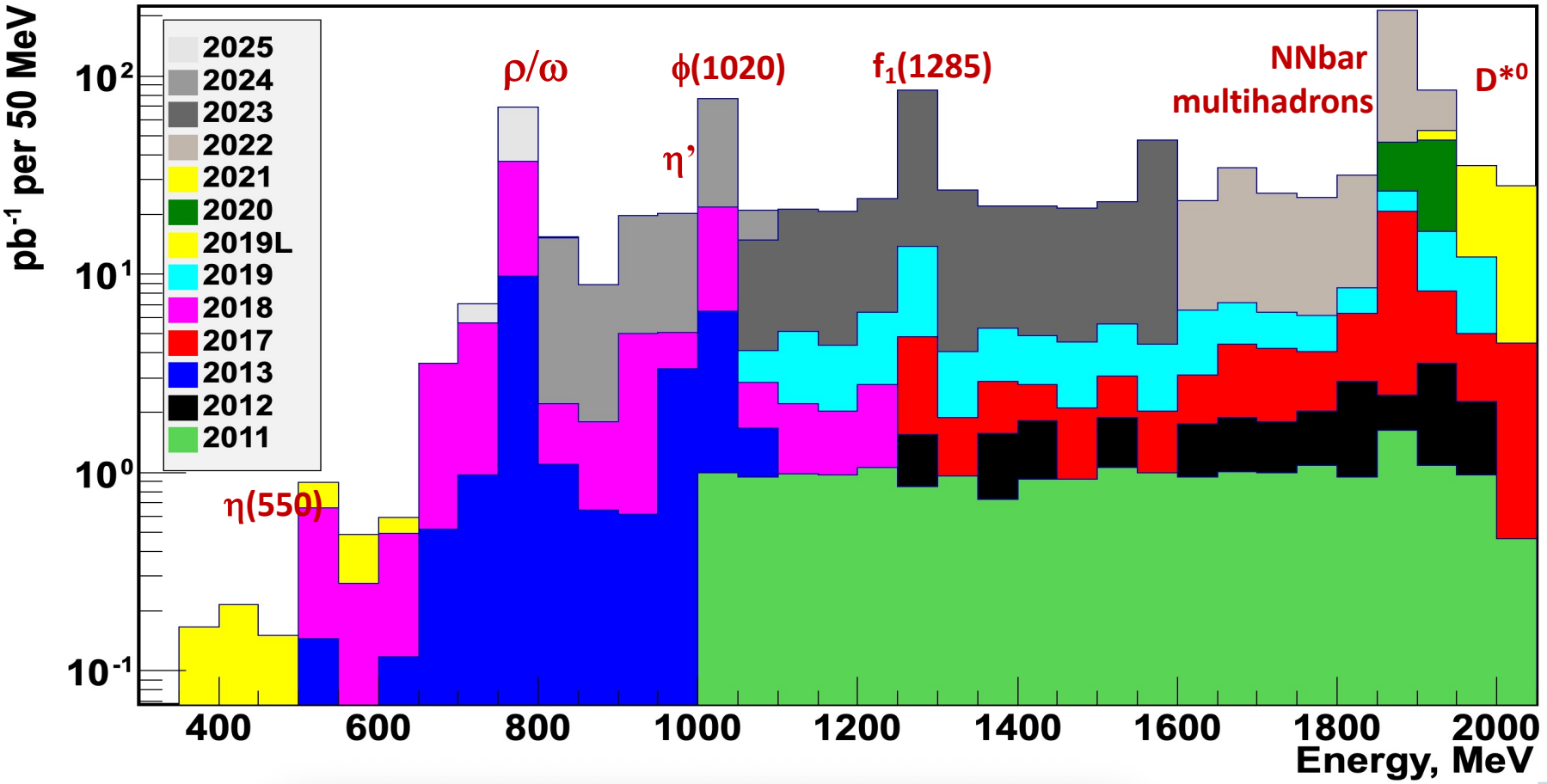
× TOF system (σ_T < 1nsec)

particle ID mainly for p, n

× Muon range system

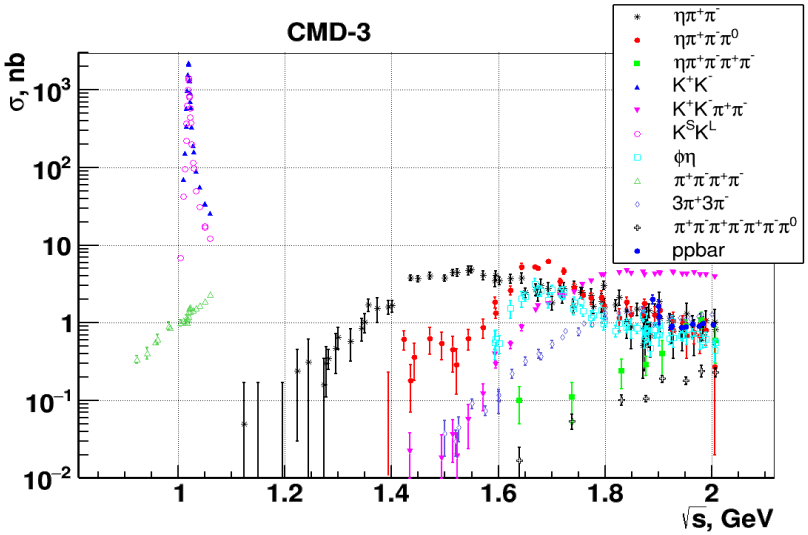
CMD-3 Collaboration at VEPP2000 collider

Integrated luminosity collected > 1000 1/pb



More than 10 papers are published. More than 20 exclusive e+e- -> hadrons cross sections are under study.

Data analysis



Our strategy is: the exclusive measurement of each final state with detailed study of the production dynamics – each channel has few intermediate states!

Publication speed depends on limited manpower and complicated structures and interferences of intermediate states – no solid theory for this energy region.

Signature	Final states (preliminary, published)
2 charged	$\pi^+\pi^-$, K^+K^-, K_SK_L, $p\bar{p}$
2 charged + γ's	$\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-2\pi^0$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\eta$, $\pi^+\pi^-2\pi^0\eta$, $K^+K^-\pi^0$, $K^+K^-2\pi^0$, $K^+K^-\eta$, $K_SK_L\pi^0$, $K_SK_L\eta$
4 charged	$2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K_SK^\pm\pi^\mp$
4 charged + γ's	$2(\pi^+\pi^-)\pi^0$, $2\pi^+2\pi^-2\pi^0$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\omega$, $2\pi^+2\pi^-\eta$, $K^+K^-\omega$, $K_SK^\pm\pi^\mp\pi^0$
6 charged	$3(\pi^+\pi^-)$, $K_SK_S\pi^+\pi^-$
6 charged + γ's	$3(\pi^+\pi^-)\pi^0$
Neutral	$\pi^0\gamma$, $2\pi^0\gamma$, $3\pi^0\gamma$, $\eta\gamma$, $\pi^0\eta\gamma$, $2\pi^0\eta\gamma$
Other	$n\bar{n}$, $\pi^0e^+e^-$, ηe^+e^-
Rare decays	η', $D^*(2007)^0$

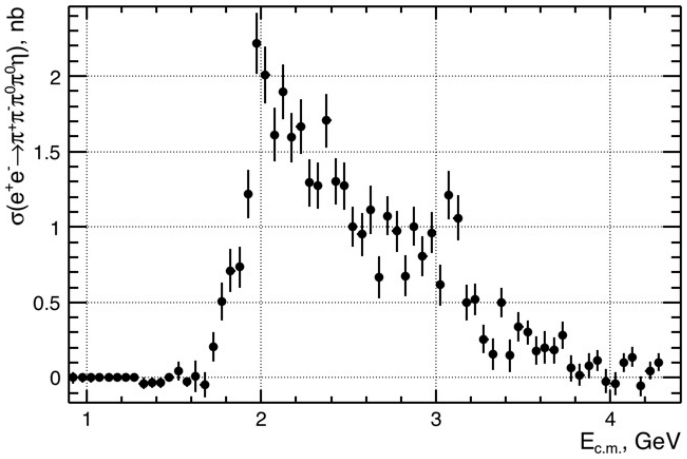
e+e- -> $\pi^+\pi^-$ has been published!

Motivation for the multi-hadron states study

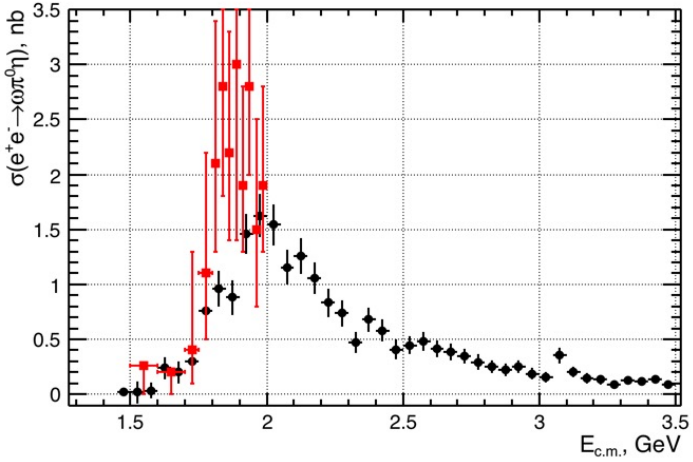
- Channels $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0$ and $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta$ are new for CMD-3 and are very rich for the intermediate states – see BaBar analysis.
- For $\pi^+\pi^-\pi^0\pi^0\pi^0$ the $\omega\pi^0\pi^0$, $\omega f_0(980)$, $\phi f_0(980)$, $\rho\eta$, $\rho^+\rho^-\pi^0$.... are seen
- For $\pi^+\pi^-\pi^0\pi^0\eta$ the $\omega a_0(980)$, $\phi a_0(980)$, $\rho^+\rho^-\eta$..... are seen
- A search for the $f_1(1285) \to a_0\pi^0 \to \eta\pi^0\pi^0$ reaction needs this development – a C-odd resonance at E=641 МэВ – We have collected about 50 pb^{-1}!
- The HPV in small from these reactions, but if there are many un-seen states with un-known intermediate channels – significant contribution to the muon (g-2) can be. Intermediate states study is very important!

BaBar and SND study

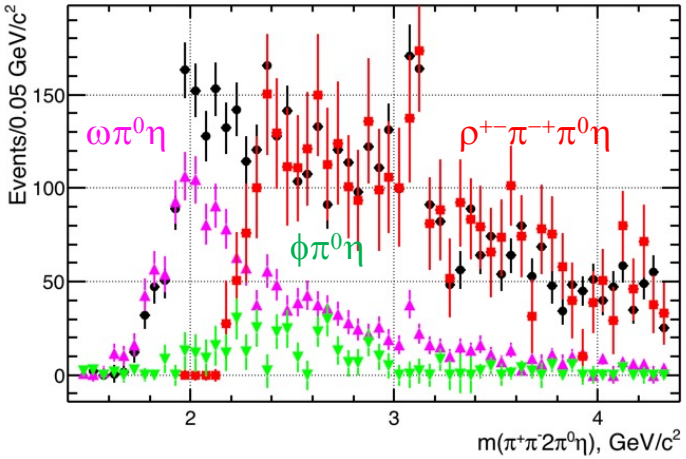
e+e- -> $\pi^+\pi^-\pi^0\pi^0\eta$



The $\omega\pi^0\eta$ channel BaBar-SND

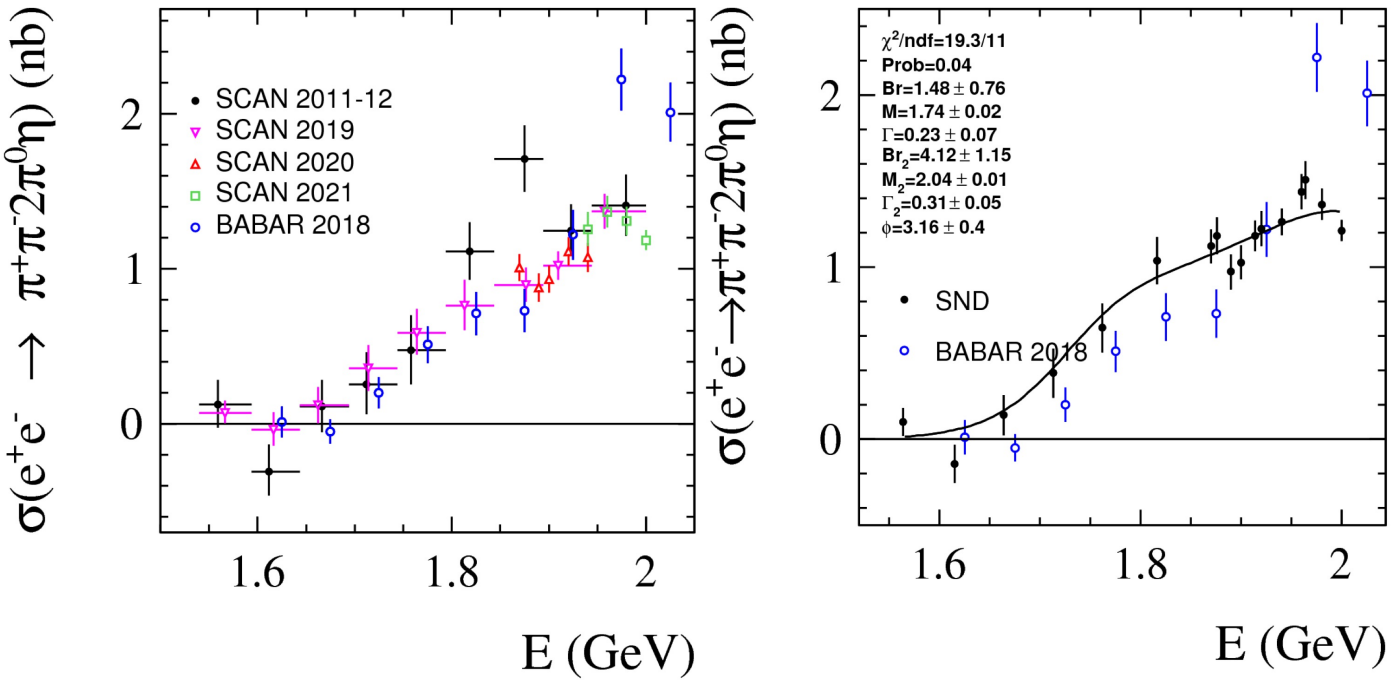


Intermediate states contribution



SND - preliminary

Talk by A.Botov ar RAN session, Dubna 2024



Our analysis

Data used:

- Scan 2020 – from 1.870 to 1.935 GeV – 5 points with 10 pb^{-1}/point — 46.870 pb^{-1}
- Scan 2021 – from 1.935 to 2007 GeV – 4 points with 10pb^{-1}/point (24 pb^{-1} at 2007) — 48.400 pb^{-1}
- Scan 2021-2022 at NN threshold and below to 1.600 Gev: — 282.844 pb^{-1}
  - 18 point at the threshold with ~1 MeV step – 10 pb^{-1}/point (x5 to 2017 scan)
  - 13 points below threshold with 10 MeV step – 5-10 pb^{-1}/point
- Scan 2023 – from 1.600 down to 1.400 GeV – with ~10pb^{-1}/point — 176.860 pb^{-1}
  (used for a cross check)

Simulation:

Reactions e+e- -> $\omega\pi^0\pi^0$, $\omega\pi^0\eta$, $\omega a_0(980)$ $\pi^+\pi^-\eta$ (η–>$3\pi^0$ – channel for a cross check)

Event selection – our “standard” set for tracks and photons:

- Two “good” beam-originated tracks passed half of DC radius with a dE/dX corresponding to $\pi^+\pi^-$
- Four and more photons with 25 МэВ threshold (60 МэВ for small angles in BGO) – $\pi^+\pi^-\pi^0\pi^0(\eta)$
- Six and more photons for the signal

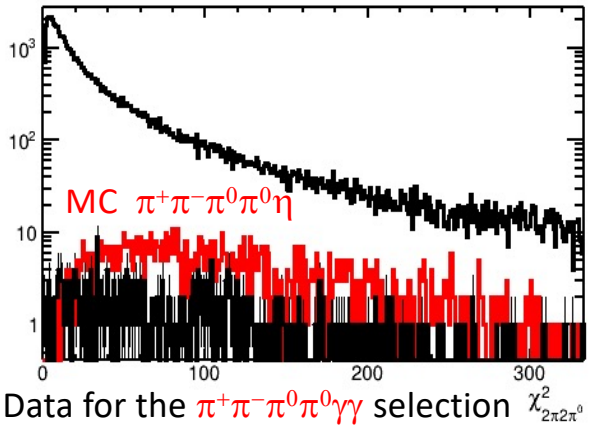
Kinematic fit

We perform fit in two hypotheses –

First: 2 charged pions and >=4 photons - one photon pair with π^0 mass and another photon pair without any constrain - 5C fit - a backgroun (huge!) from $\pi^+\pi^-\pi^0\pi^0$ - the obtained Chi2 is used to suppress it.

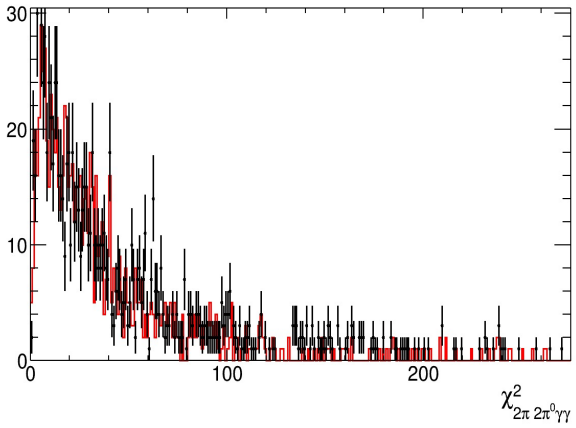
Second: 2 charged pions and 6 and more photons. Two best pairs (in the +-60 МэВ window around mass π^0) are under π^0 mass constrains массой, and remaining pair has no constrain – 6C fit. All possible combinations (15 for each 6 photons) are tested to look for the best Chi2.

Data hypothesis $\pi^+\pi^-\pi^0\gamma\gamma$

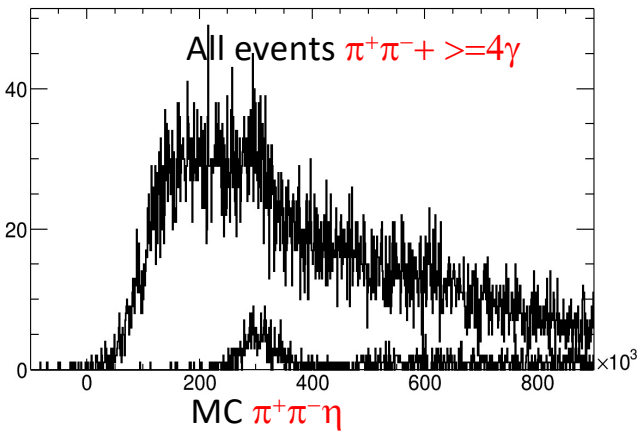


Data for the $\pi^+\pi^-\pi^0\pi^0\gamma\gamma$ selection

Data and MC hypotheis $\pi^+\pi^-\pi^0\pi^0\gamma\gamma$



Missing mass for $\pi^+\pi^-$

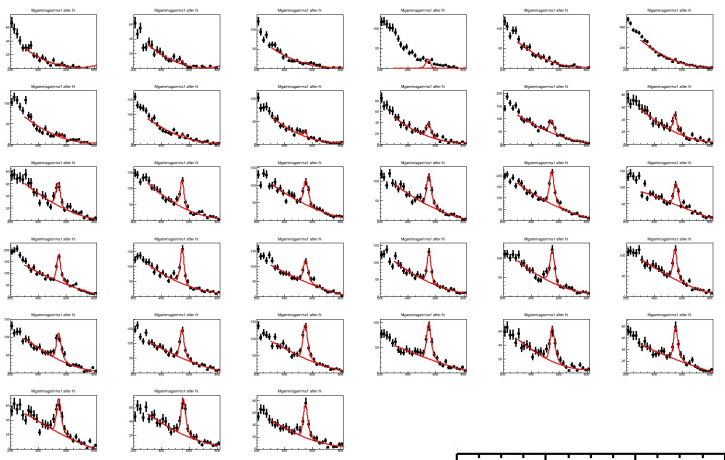


Energy-momentum conservation and photon angles in the π^0 rest system are used for the selections.

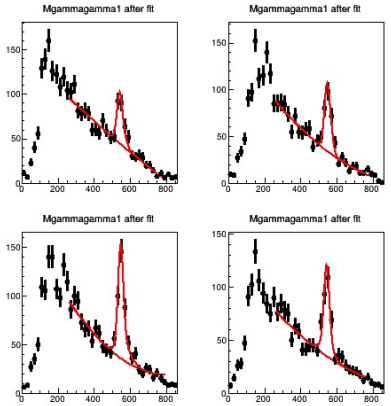
KinFitter developed by Sergey Gribanov is used.

Events $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta$, 2-gauss fit η mass in $\gamma\gamma$

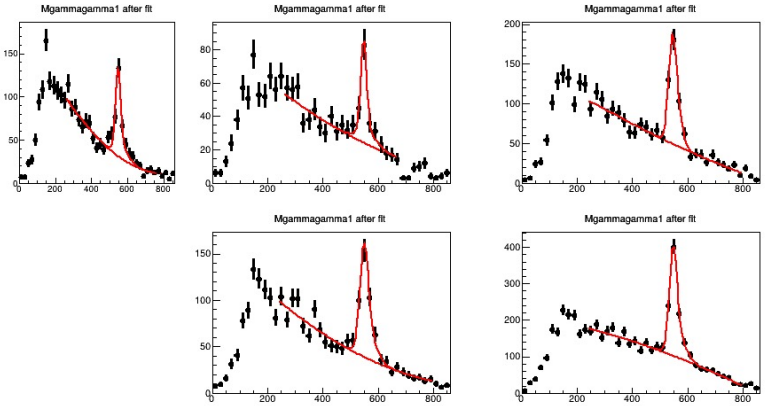
Scan 2022



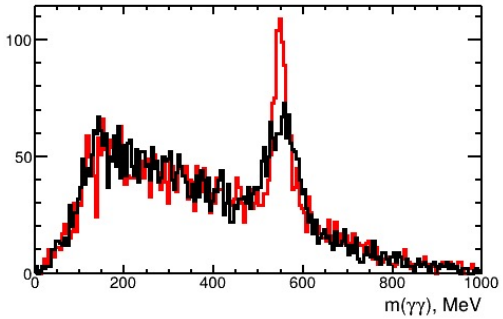
Scan 2020



Scan 2021



Two-photon mass before and after fit

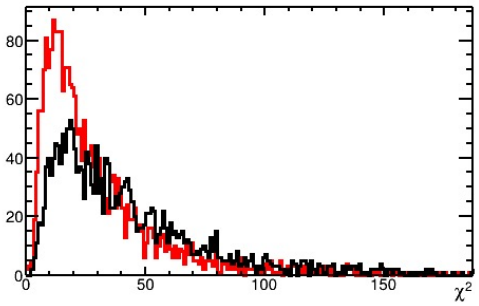


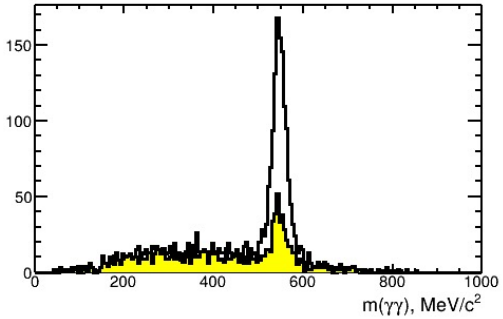
Simulation does not show any background from the $e^+e^- \to \pi^+\pi^-\pi^0\eta$ process to the η peak

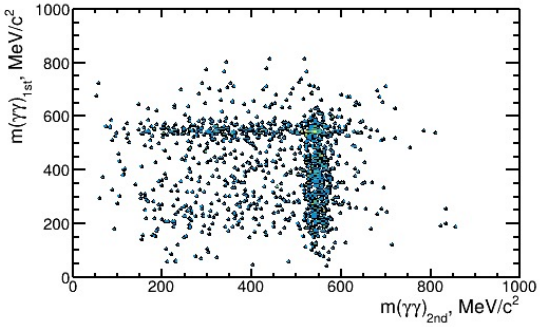
Combinatorial problems - simulation

In the kinematic fit we are looking for the combination with the best $\chi 2$, apply cut on the value (< 100-120), and then plot the di-photon invariant mass to fit to η signal.

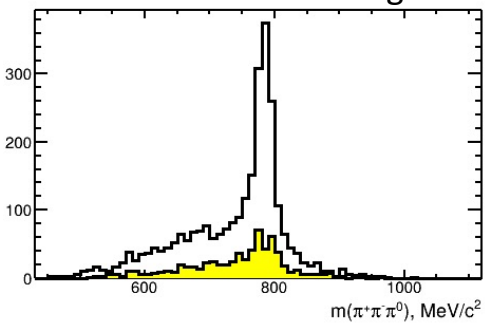
But in the same 6 photon there is another combination with acceptable value of $\chi 2$!!

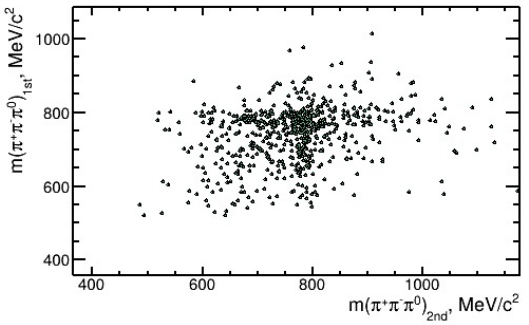






Similar with the ω signal

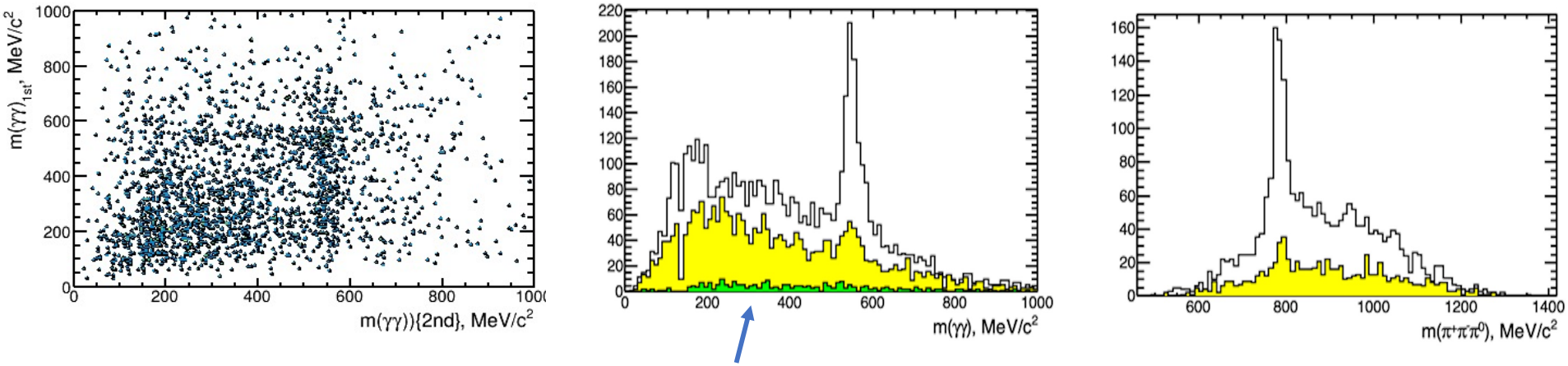




Combinatorial problems - data

In the kinematic fit we are looking for the combination with the best $\chi 2$, apply cut on the value (< 100-120), and then plot the di-photon invariant mass to fit to η signal.

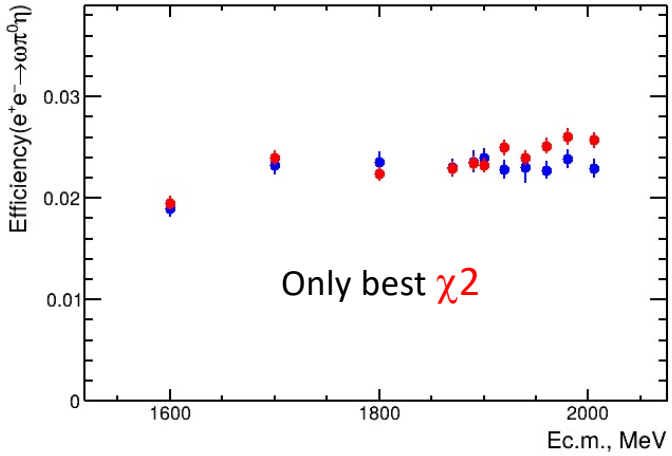
But in the same 6 photon there is another combination with acceptable value of $\chi 2$!! Shown in yellow

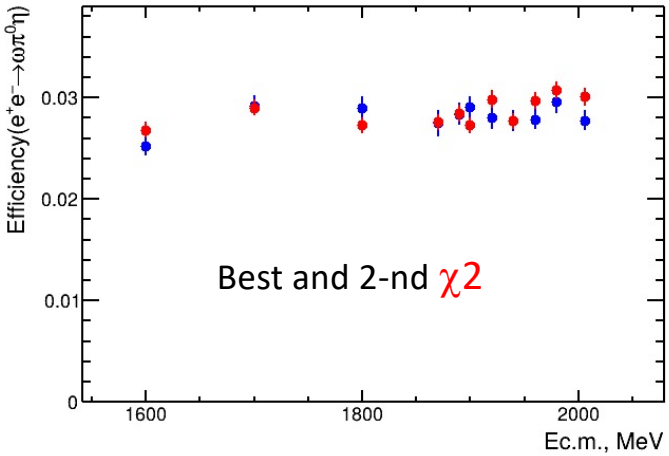


Green – good $\chi 2$ from different 6-photon combination

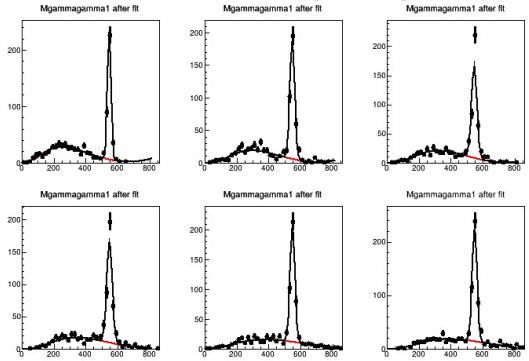
Efficiency from simulation $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta$

The e+e- -> $\omega a_0(980)$ model. Efficiency is determined from η or ω signals. (All η decays are inclued, $\omega \to 3\pi$ only.)

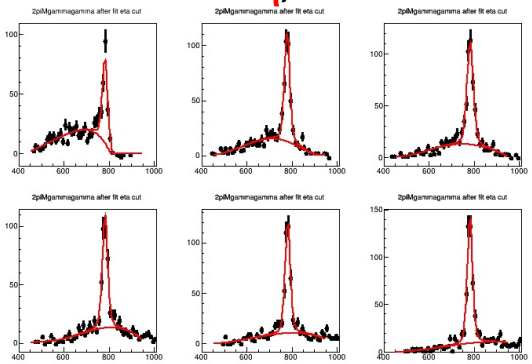




MC e+e- -> $\omega\pi^0\eta$, fit $\eta \to \gamma\gamma$

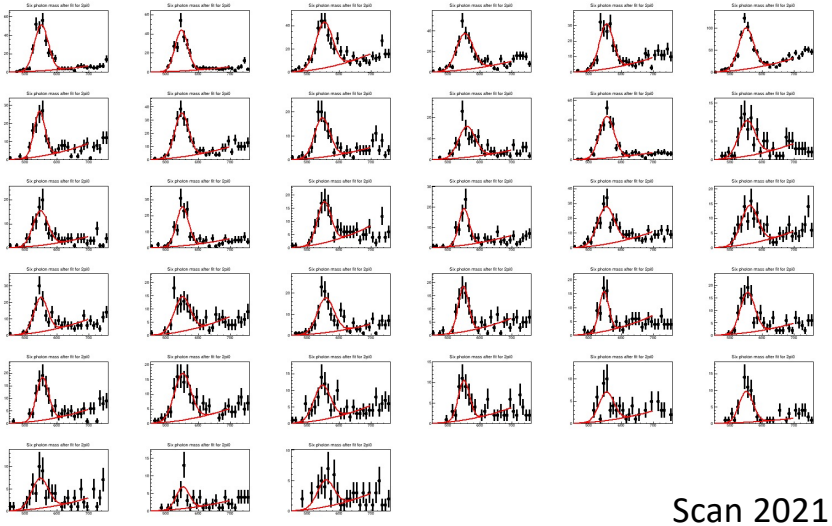


MC e+e- -> $\omega\pi^0\eta$, fit $\omega \to \pi^+\pi^-\pi^0$

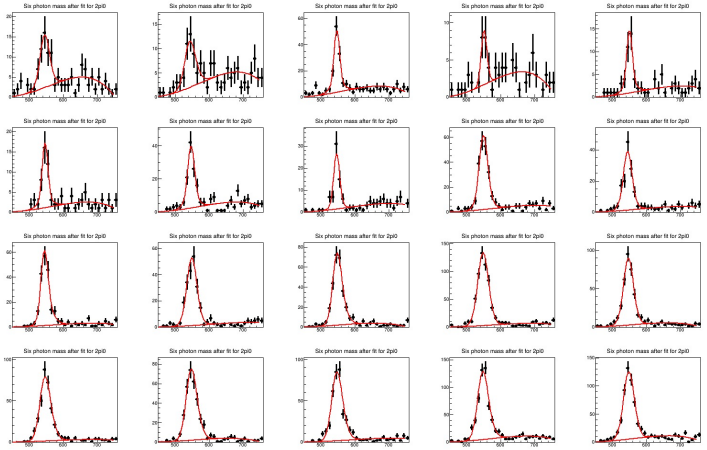


Test process $e^+e^- \to \pi^+\pi^-\eta$, $\eta \to 3\pi^0$

Scan 2023

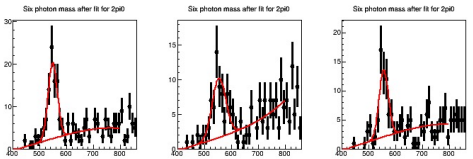


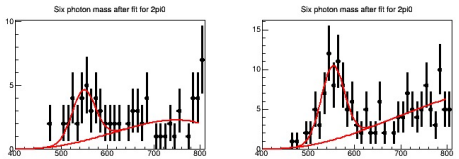
Scan 2022

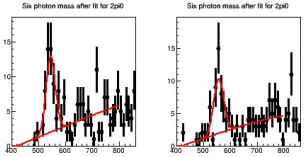


Excellent η signal with very low background!

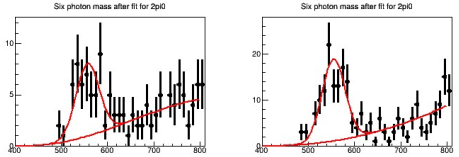
Scan 2021

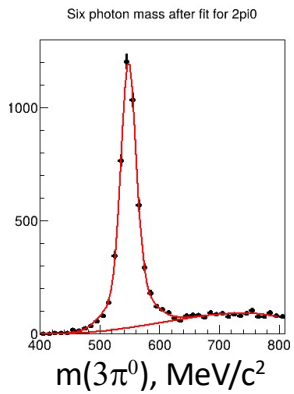






Scan 2020

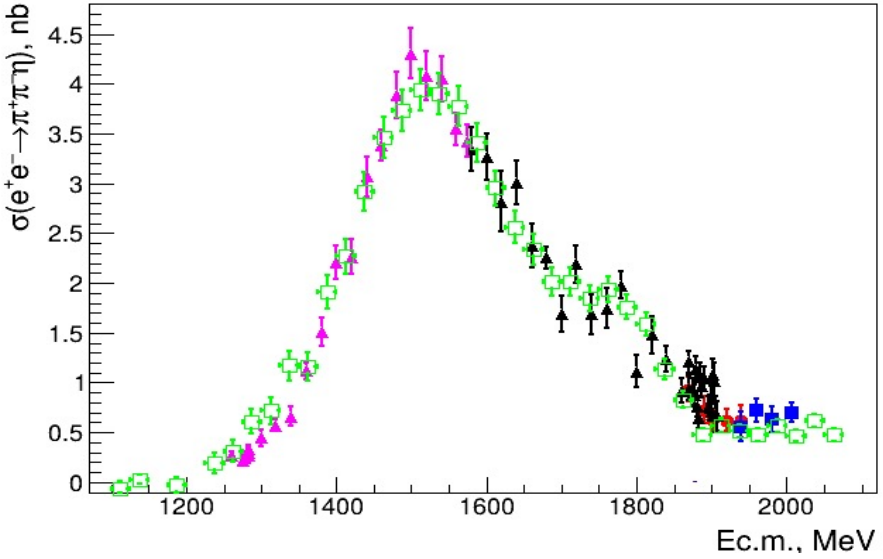


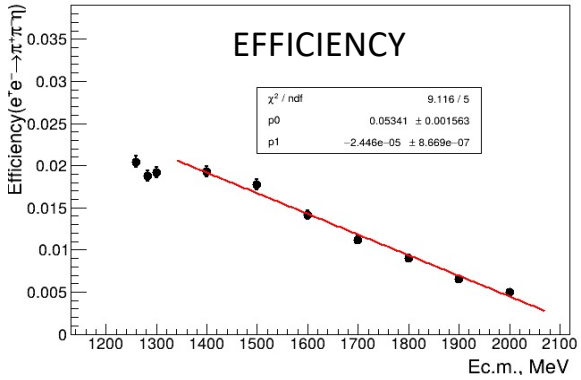


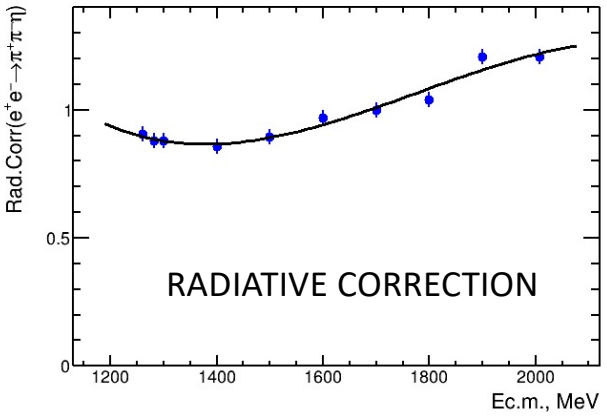
Fit of 2022 points sum. Background distribution is approximate

The $e^+e^- \to \pi^+\pi^-\eta$ cross section

Our different runs (color) and BaBar data

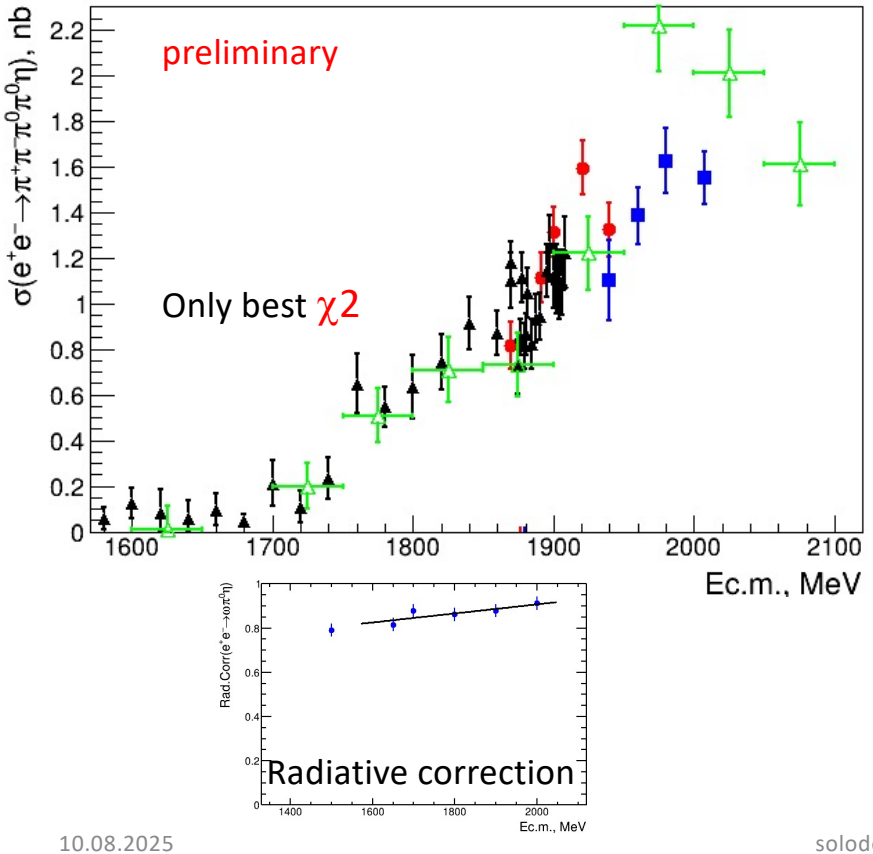


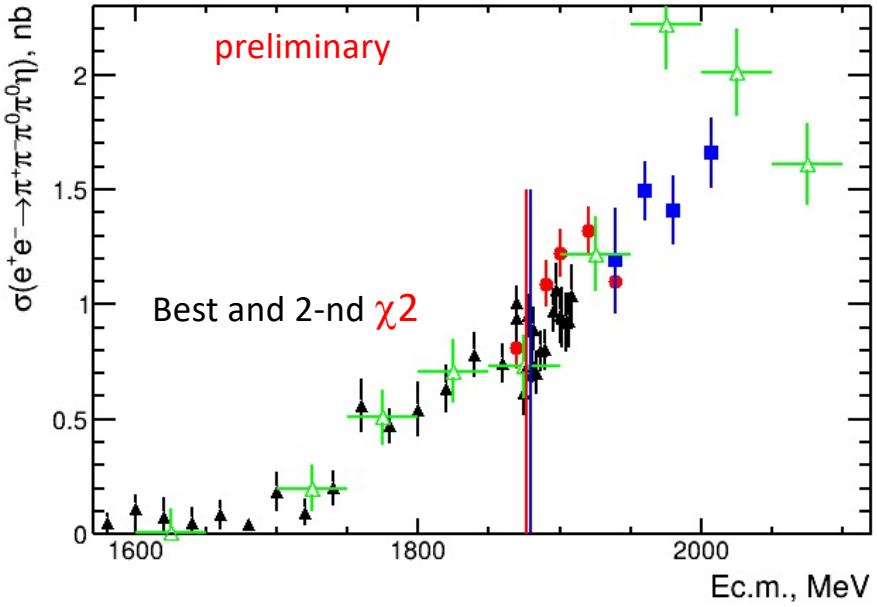




Preliminary – only for illustration. Not all corrections are investigated-included

The $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta$ cross section

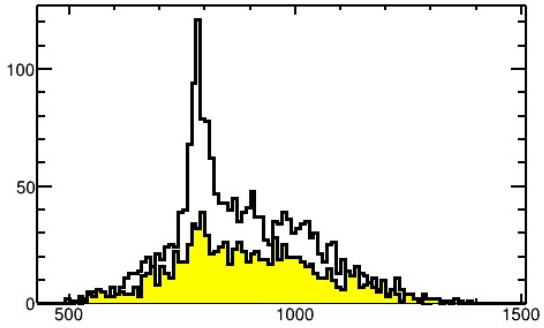




We do not see large difference using 2-nd $\chi 2$ signal
– background level is higher - but correction and systematic uncertainties can be estimated.

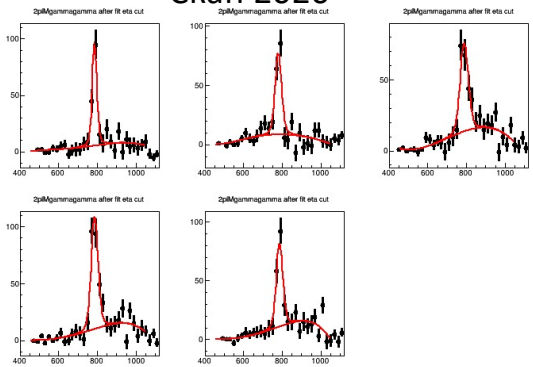
Extracting the $e^+e^- \to \omega\pi^0\eta$ contribution

Selecting signal in $\gamma\gamma$ mass in +-70 МэВ window around η mass, and use 70 МэВ side bands for a background subtraction.
Plot $\pi^+\pi^-\pi^0$ mass (two combinations) and fit ω signal by BW (width 9 МэВ) convoluted with resolution ~15-20 МэВ

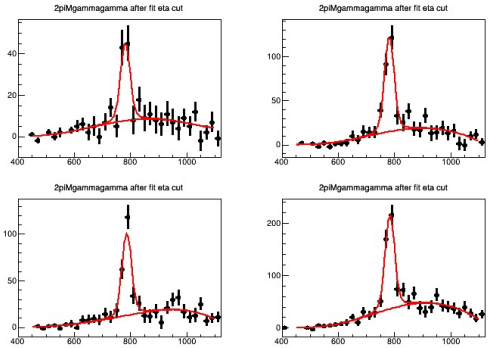


Background from the $\omega\pi^0$,$\omega\eta$
– much larger cross sections

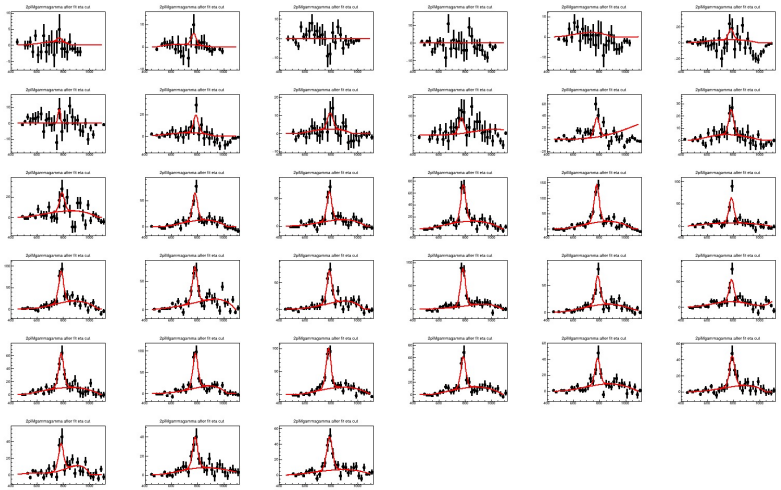
Скан 2020



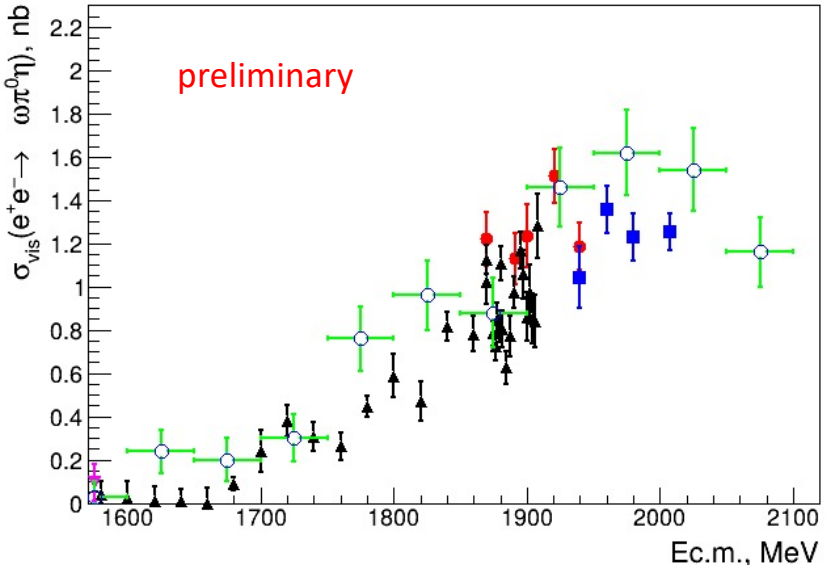
Скан 2021



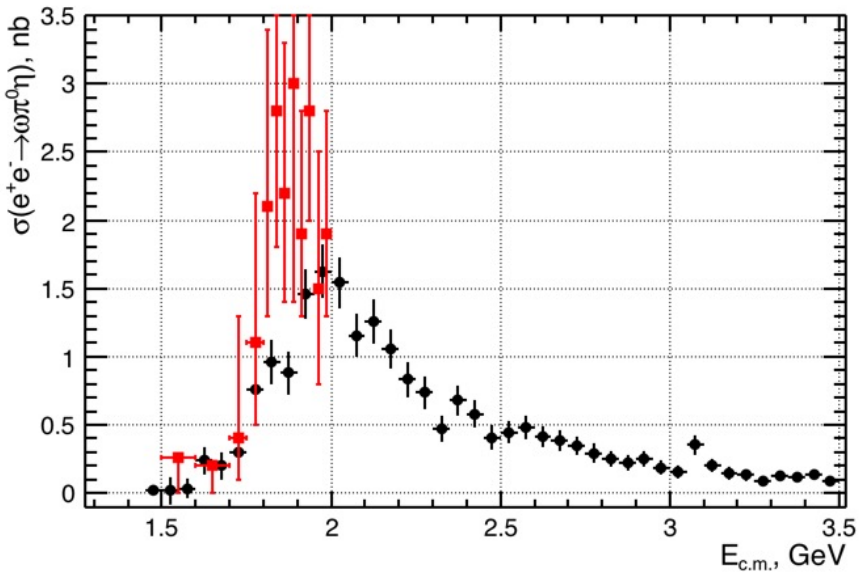
Скан 2022



The $e^+e^- \to \omega\pi^0\eta$ cross section



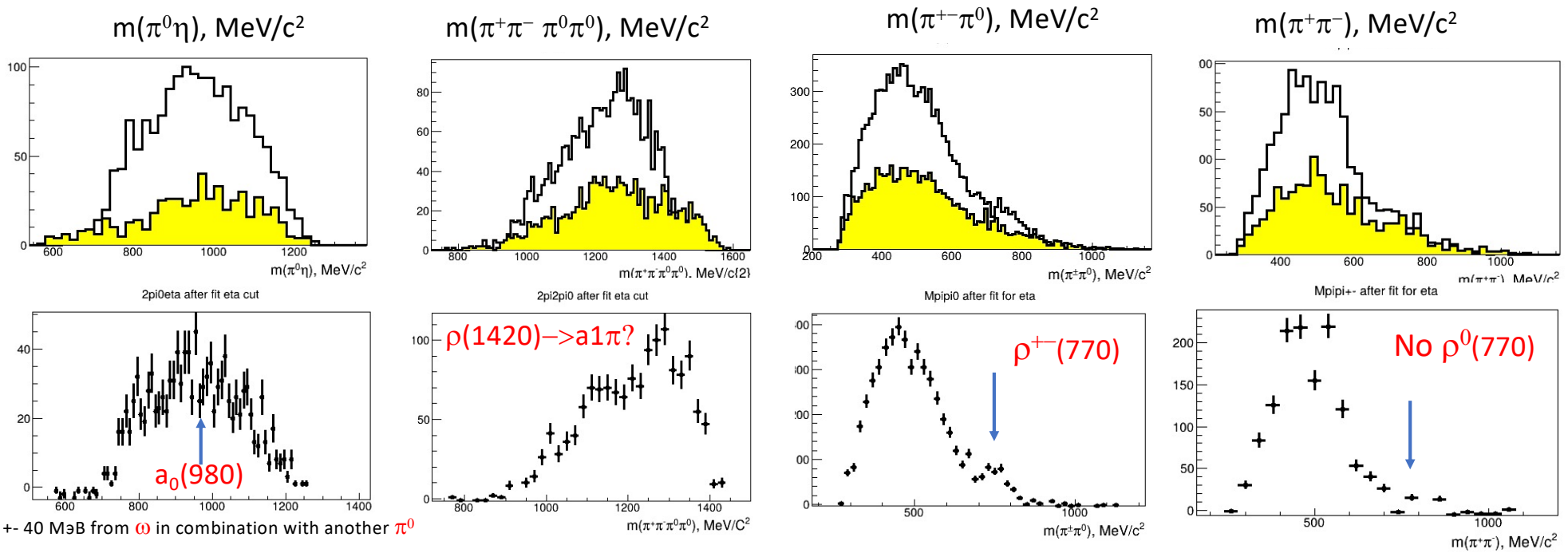
БаБар и СНД



A little bit below BaBar, but BaBar, probably had problem with background subtraction – point are below the threshold

The e^+e^- –> $\omega\pi^0\eta$ is below $\pi^+\pi^-\pi^0\pi^0\eta$: what else?

Use combinations of 970-1003 energy points from 2021. Plot masses. Subtract background using side bands



No significant signal from $\omega a_0(980)$.

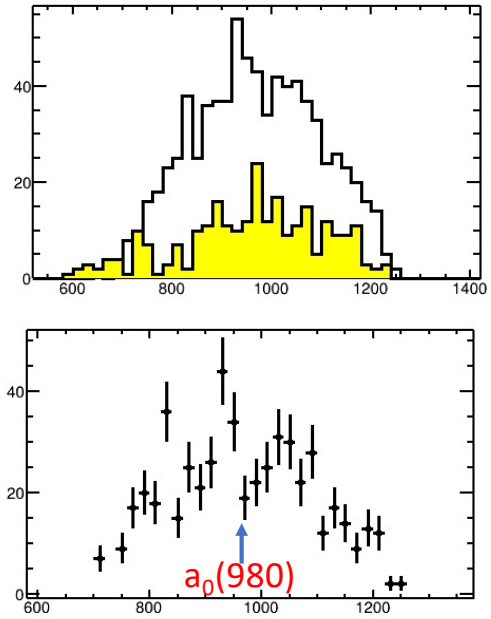
We have signal from $\rho^{+-}(770)$, but no signal from ρ^0. Could be $\rho(1420)\eta \to \rho^{+-}\pi^{-+}\pi^0\eta$?

May be $\rho^+\rho^-\eta$, but not enough phase space at our energies.

The e^+e^- –> $\omega\pi^0\eta$ is below $\pi^+\pi^-\pi^0\pi^0\eta$: what else?

Only E=1003 MeV (2021 ~25 pb^{-1}). Plot masses. Subtract background using side bands

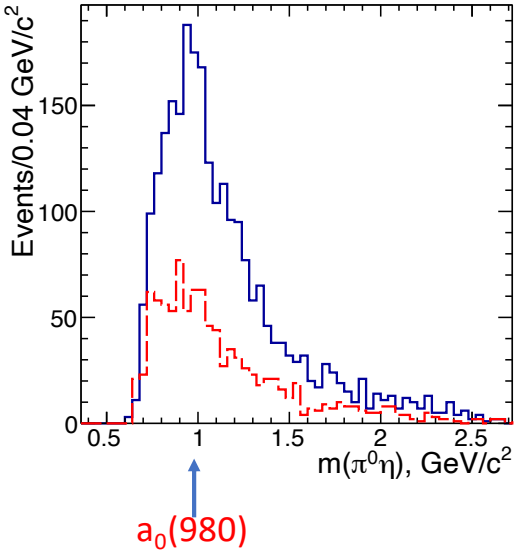
$m(\pi^0\eta)$, MeV/c^2

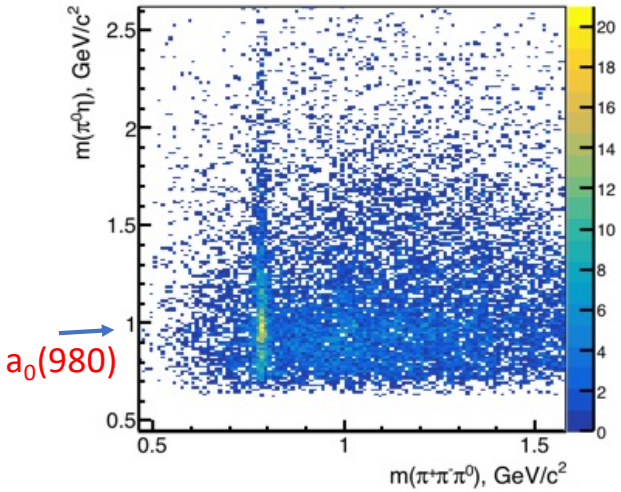


+- 40 МэВ from ω in combination with another π^0

Could be an interference?

Plots from BaBar paper





At 1003.5 МэВ probably we have a small indication of the $\omega a_0(980)$ (BaBar has seen this signal at higher energies).

Conclusion

- Relatively sucsessful extraction of events with 6 photons for the $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\,\pi^0$ and $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta$ reactions - efficiency ~2-3% (including Br η)
- Efficiency should be 1.5-2 times better, when new procedure for the photon finding using LXe strips would be finalized (not shown here).
- The $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta$ and $e^+e^- \to \omega\pi^0\eta$ cross sections have been obtained in agreement with BaBar with better precision.
- We observe the $e^+e^- \to \rho^{+-}\pi^{-+}\,\pi^0\eta$ process contribution
- Work on the systematic uncertainties estimate is in progress
  – expecting around 10-15%.
- Simulation with $\omega a_0(980)$ shows relatively small model-dependent uncertainty.
- Detailed amplitude analysis needs more data.

Thanks