Status of the SND and CMD-3 experiments in Novosibirsk

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Experimental Physics Division Seminar, IHEP, CAS
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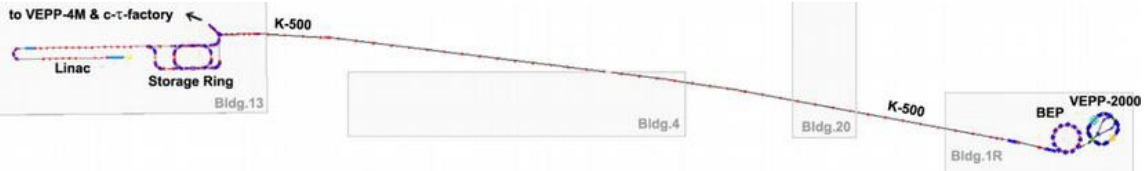
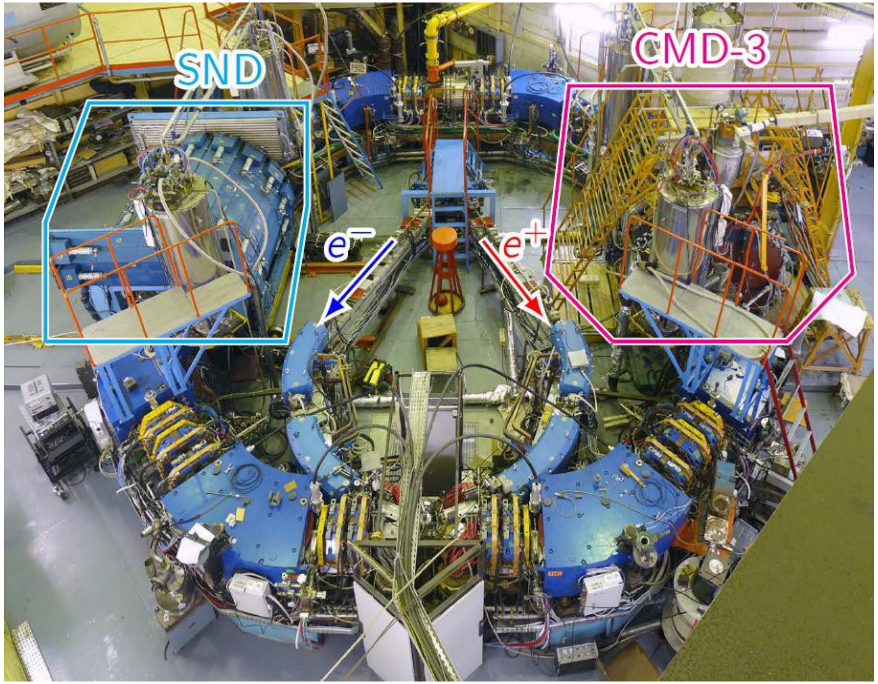
Budker Institute of Nuclear Physics

- **Budker Institute of Nuclear Physics is located in the Novosibirsk scientific center**

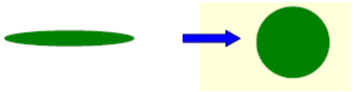
There are two working e+e- colliders in BINP
One of them is VEPP-2000

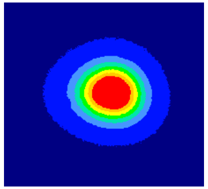
VEPP-2000 e^+e^- collider





Round beams

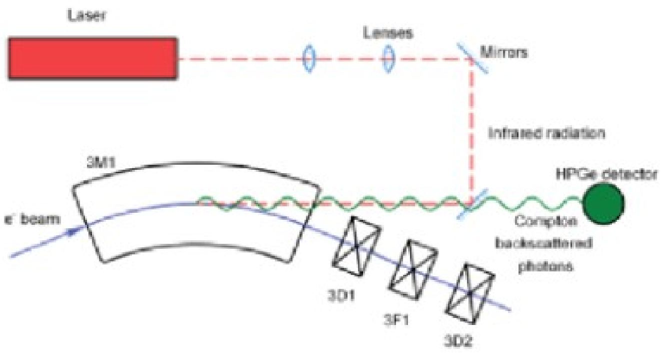


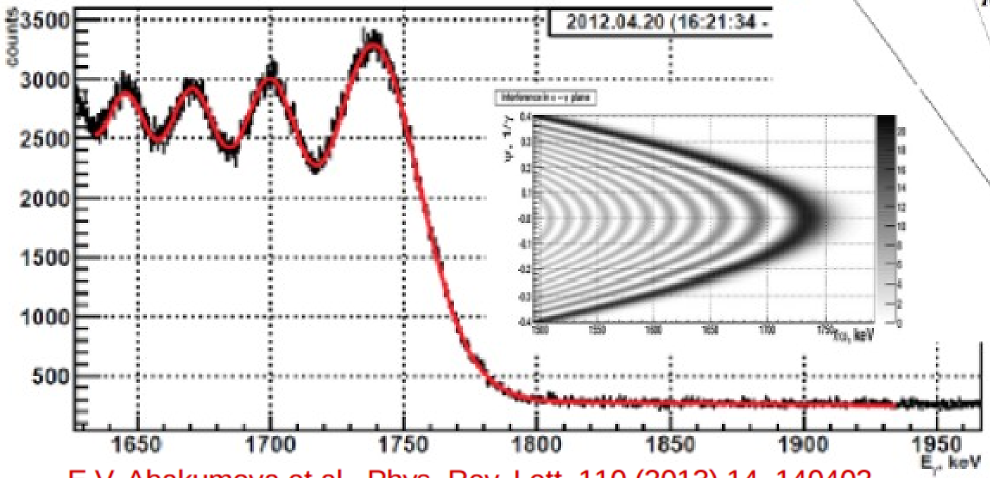


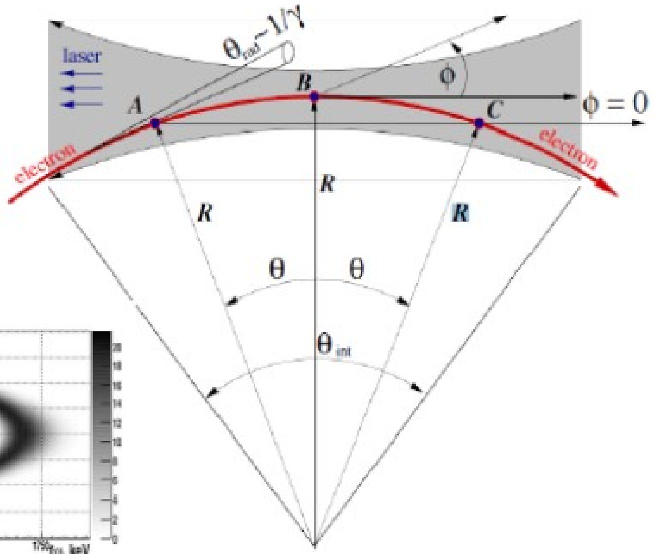
VEPP-2000 parameters:

- c.m. energy 0.3-2.0 GeV
- circumference – 24.4 m
- round beam optics
- Luminosity close to 2 GeV
- $1\text{x}10^{32}$ cm^{-2} sec^{-1} (project)
- $0.8\text{x}10^{32}$ cm^{-2} sec^{-1} (achieved)
- Two detectors: SND and CMD-3

Beam energy measurement



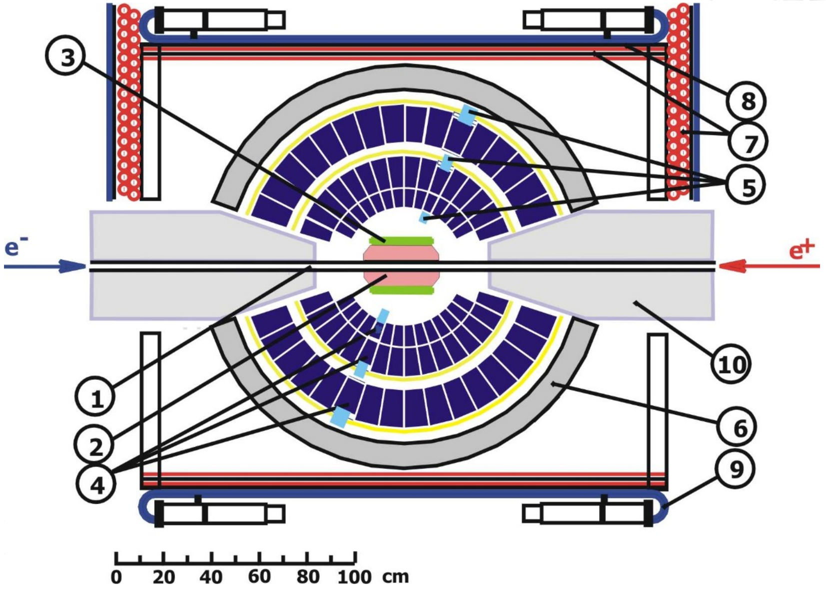


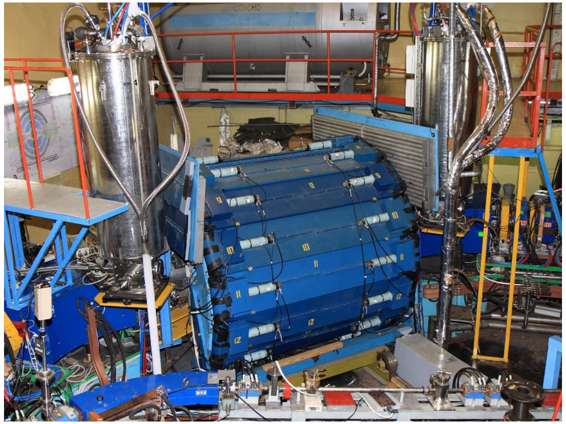


E.V. Abakumova et al., Phys. Rev. Lett. 110 (2013) 14, 140402,
E.V. Abakumova et al.,Nucl.Instrum.Meth. A744 (2014) 35-40

- **Beam energy is controlled using compton backscattering of laser radiation on electron beam**
- **From the fit parameters, the beam energy and beam energy spread are calculated**
- **Accuracy of the beam energy measurement ≈ 0.1 MeV**

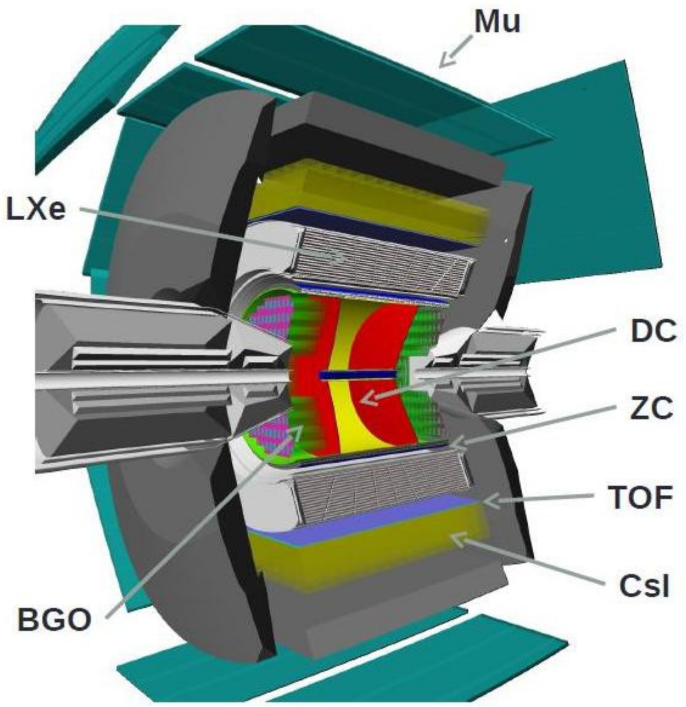
SND detector



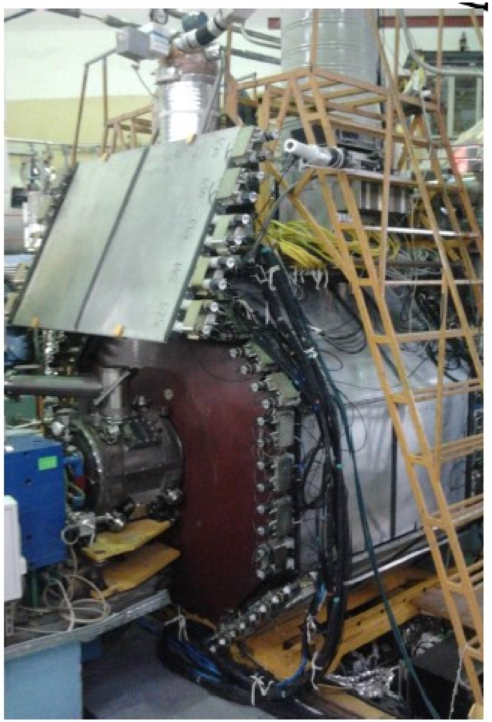


1 – beam pipe, 2 – tracking system, 3 – aerogel Cherenkov counter , 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – iron muon absorber, 7–9 – muon detector, 10 – focusing solenoids.

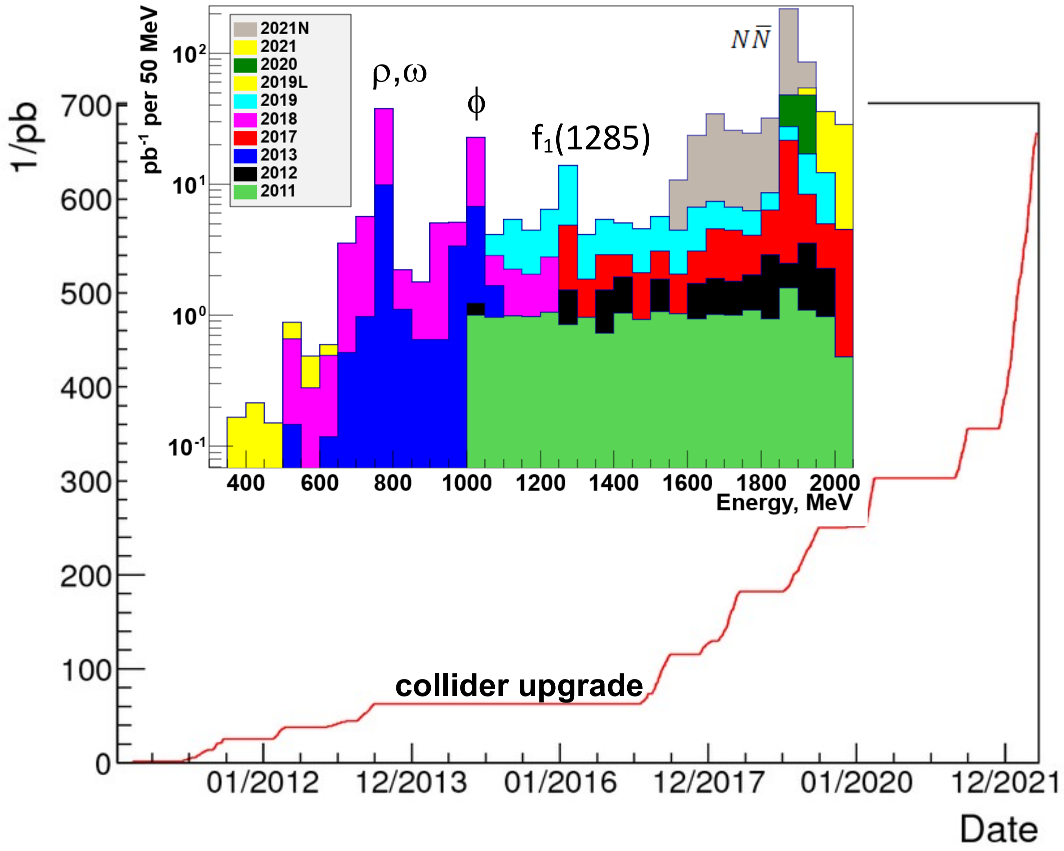
CMD-3 detector



DC– drift chamber
ZC – Z–chamber
LXE – liquid xenon calorimeter
CsI– calorimeter, 1152 crystals
TOF – time of flight system
Mu - muon system
BGO– calorimeter, 680 crystals



Collected data



2010-2013 – experiments, 70 pb^{-1}
2013-2016 – upgrade, new injector
2017-2021 – experiments, 310 pb^{-1}
2022 – the most fruitful year, 270 pb^{-1}

Total integrated luminosity IL≈650 pb^{-1} has been collected by each detector

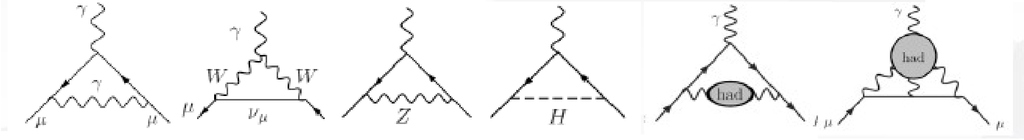
Muon anomalous magnetic moment

Magnetic moment of muon:

$$\vec{\mu} = g \frac{e\hbar}{2mc} \vec{s}$$

- **Gyromagnetic factor g for**
  - **Dirac particles: g = 2**
  - **Higher order contributions (QFT): g ≠ 2**
- **Muon anomaly**

$$a_\mu = \frac{g-2}{2} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL}$$

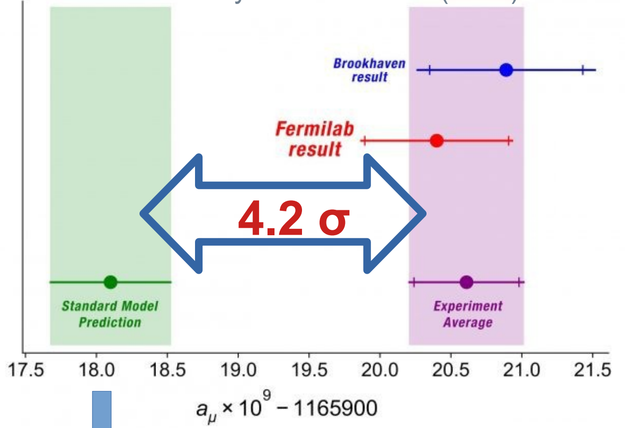


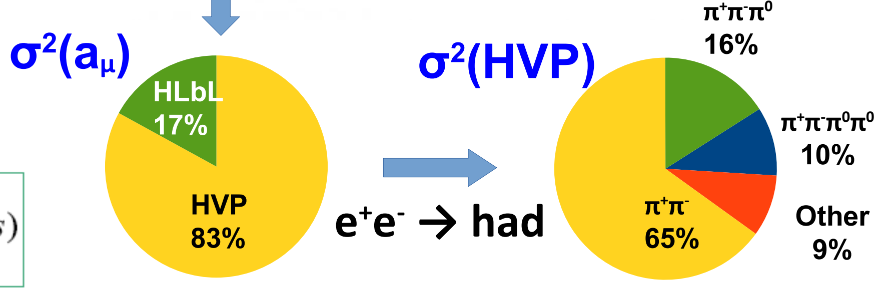
- **New result from FNAL confirms tension with SM (4.2σ!)**
- **Improvement of SM prediction highly desirable**
- **Uncertainty dominated by HVP and HLbL**

$$a_\mu^{had} = \frac{\alpha^2}{3 \cdot \pi^2} \int_{4m_\pi^2}^{\infty} ds \cdot \frac{K(s)}{s} \cdot R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Phys.Rev.Lett. 126 (2021) 141801



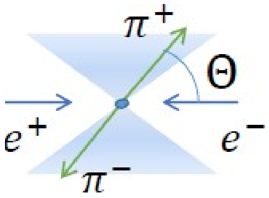


Data from: Phys.Rep 887 (2020) 1-166

Process $e^+e^- \to \pi^+\pi^-$ at SND

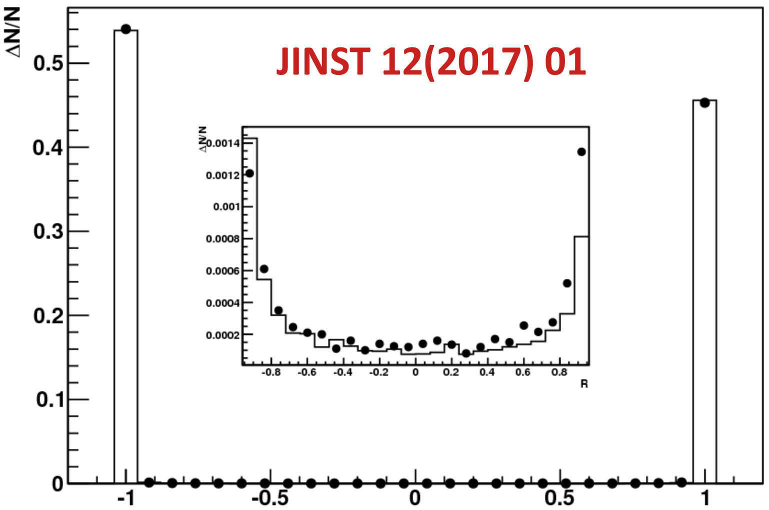
Analisys strategy:

- The collinear $e^+e^- \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ events are selected
- Sorted into two classes: e^+e^- and $\mu^+\mu^-, \pi^+\pi^-$ using machine learning
- $\mu^+\mu^-$ events are subtracted using theoretical cross section



Based on 1/10 of full SND data set

The e/π discriminant parameter



- e/π separation is based on difference in the energy deposition profiles
- Identification efficiencies of e^+e^- and $\pi^+\pi^-$ events is better then 99.5%

Systematic uncertainty on the cross section (%)

Source	< 0.6 GeV	0.6 - 0.9 GeV
Rad. cor.	0.2	0.2
Selection criteria	0.7	0.7
e/π separation	0.3-0.5	0.1
Nucl. interaction	0.2	0.2
μ subtraction	0.3-0.7	0.0-0.2
Total	0.9-1.2	0.8

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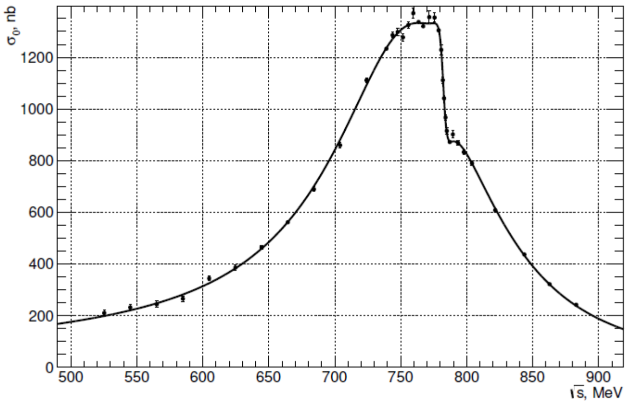
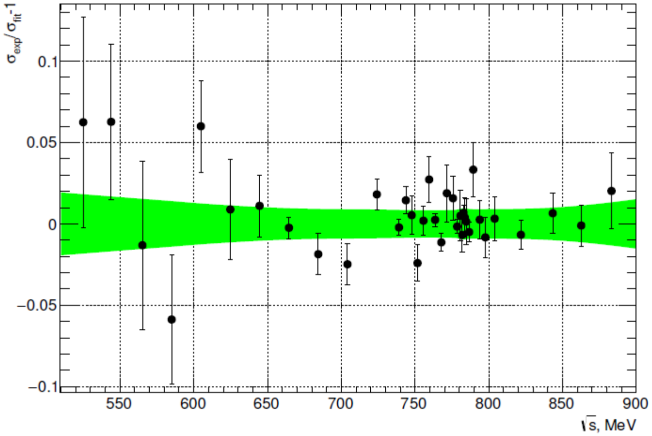
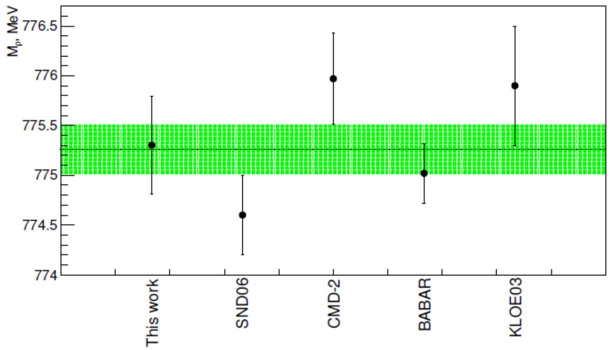
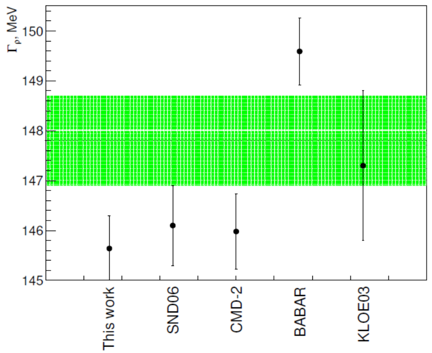
Process $e^+e^- \rightarrow \pi^+\pi^-$ at SND

- The fit to the model based on VMD is performed
- The ρ meson mass obtained from the fit is in agreement with the results of earlier experiments
- The ρ meson width has tension with the value reported by BABAR
- This discrepancy can be partially explained by difference between the fitting models

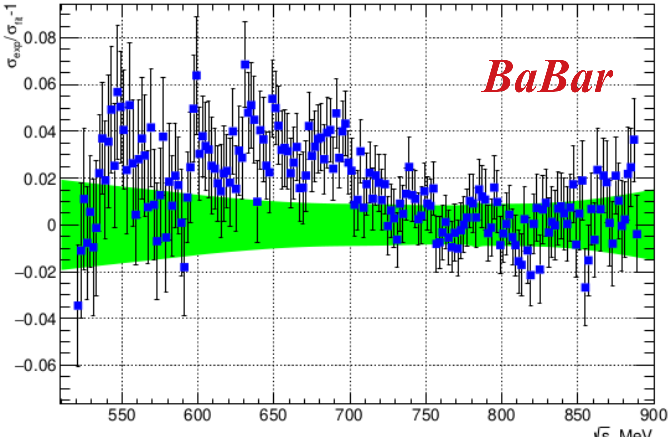


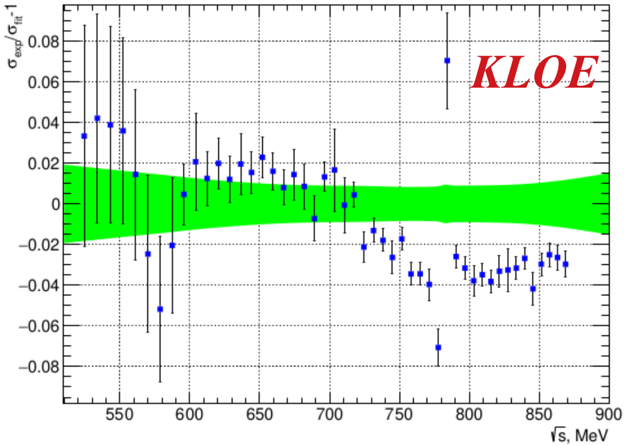




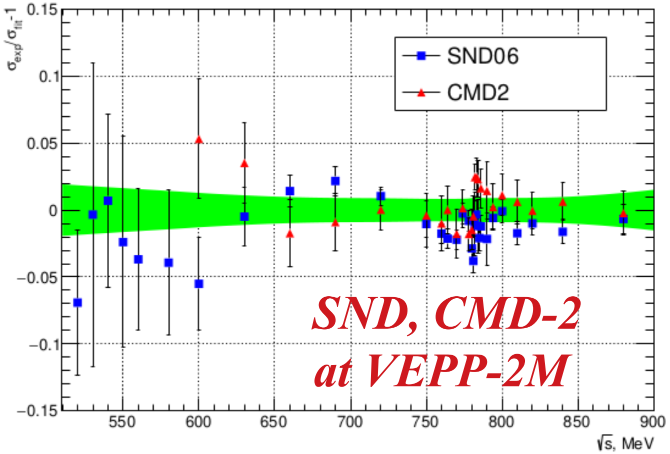


Process $e^+e^- \to \pi^+\pi^-$ at SND





- Hadronic contribution to muon (g-2) is in good agreement for this work, BaBar and priveous SND measurement
- There is a discrepancy with KLOE data



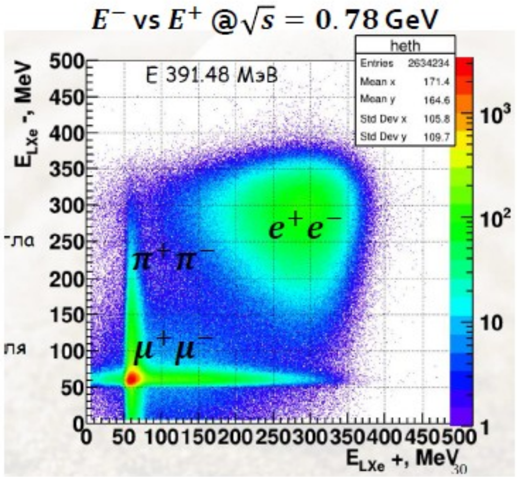
- 3% difference between BABAR and SND data in $0.62 \geq \sqrt{s} \geq 0.7$ GeV
- Deviation between KLOE and SND data is 1-3% at $\sqrt{s} \geq 0.7$ GeV
- Good agreement with previous measuremens from VEPP-2M

Hadronic contribution to muon (g-2)/2 form e+e- $\to \pi^+\pi^-$

	$a_\mu \times 10^{10}$
SND VEPP-2000	409.79±1.44±3.87
SND VEPP-2M	406.47±1.74±5.28
BaBar	413.58±2.04±2.29
KLOE	403.39±0.72±2.50

Process $e^+e^- \to \pi^+\pi^-$ at CMD-3

- Full available statistics in c.m. energy range < 1.2 GeV, three data taking scans
- e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ separation by:
  - 2D fitting of momentum (E < 0.9 GeV)
  - or 2D fitting of energy deposition in LXe (E > 0.55 GeV)
    Most of systematics are uncorrelated!
- Third method for consistency check: by angular distribution

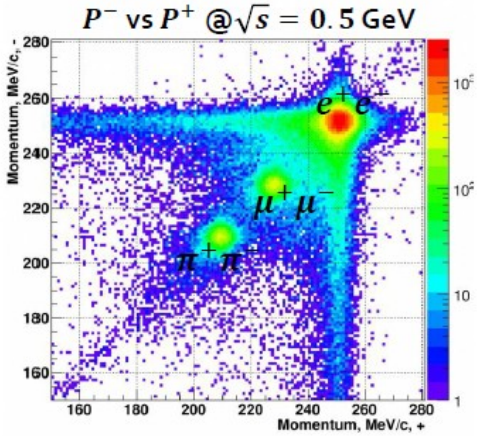


Separation by momentum

PDFs are based on MC
- «Ideal» PDFs are generated using MC
- «Ideal» p.d.f.sare smeared with detector resolution function

Separation by energy deposition

PDFs are mostly empirical
- Construsted using the data
  - Tagged electrons and muons
  - Cosmic muons

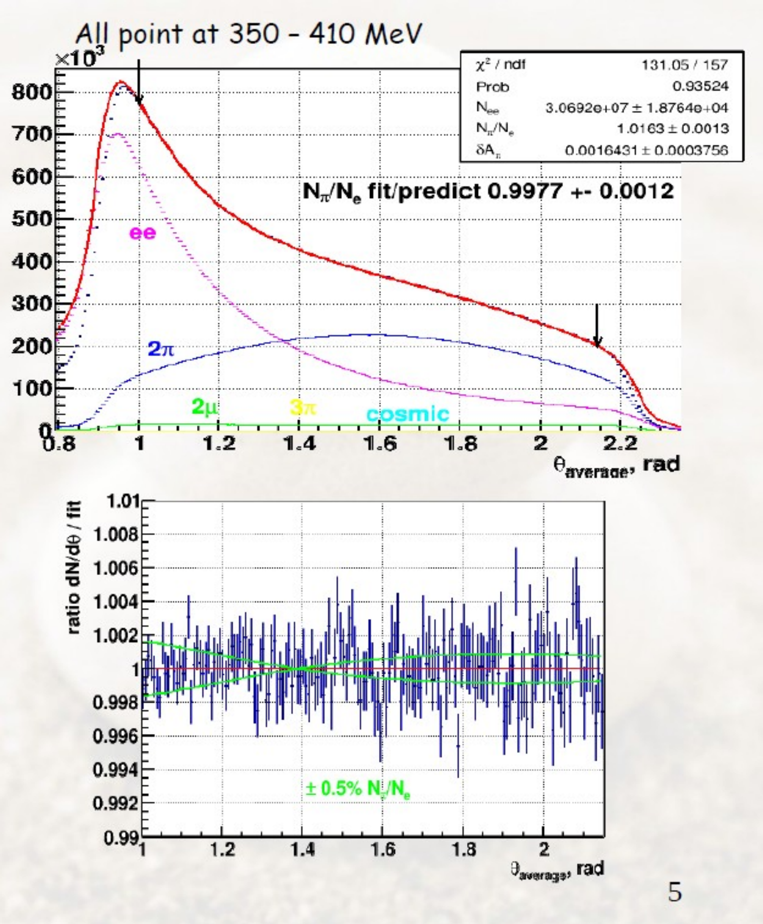


Process $e^+e^- \to \pi^+\pi^-$ at CMD-3

- **Consistency check between three methods in vicinity of ρ meson**

By momentum:
$(N_{\pi\pi}/N_{ee})_{\text{fit/predict}} = 1.0187 \pm 0.0003$
By energy:
$\Delta\, N_{\pi\pi}/N_{ee} = +0.05\% \pm 0.033\%$
By angular distribution:
-free asymmetry:
$\Delta\, N_{\pi\pi}/N_{ee} = -0.23\% \pm 0.12\%$
-fixed asymmetry:
$\Delta\, N_{\pi\pi}/N_{ee} = +0.20\% \pm 0.08\%$

Three methods agree to ~0.2%

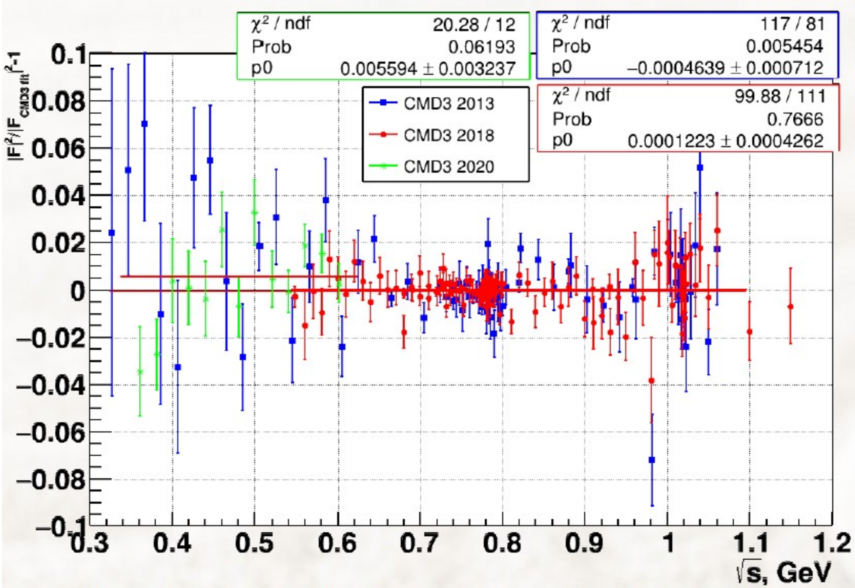


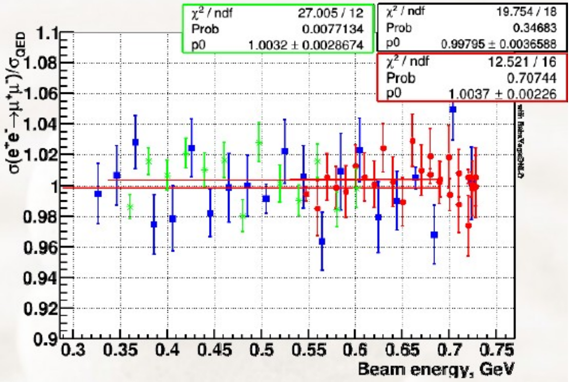
Process $e^+e^- \to \pi^+\pi^-$ at CMD-3

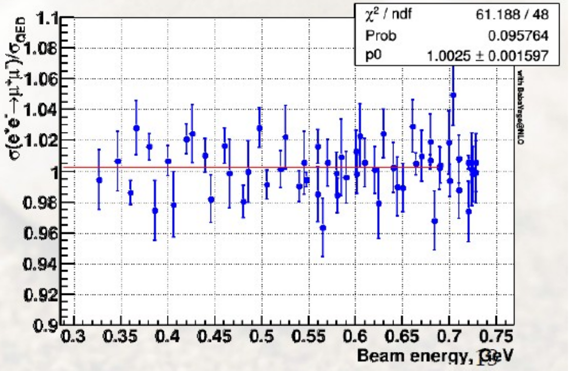
Comparison between different data sets

Comparison of measured $\sigma(e^+e^- \to \mu^+\mu^-)$ to QED

Despite the **quite different experimental condition** in all scans, results are in **good agreement**







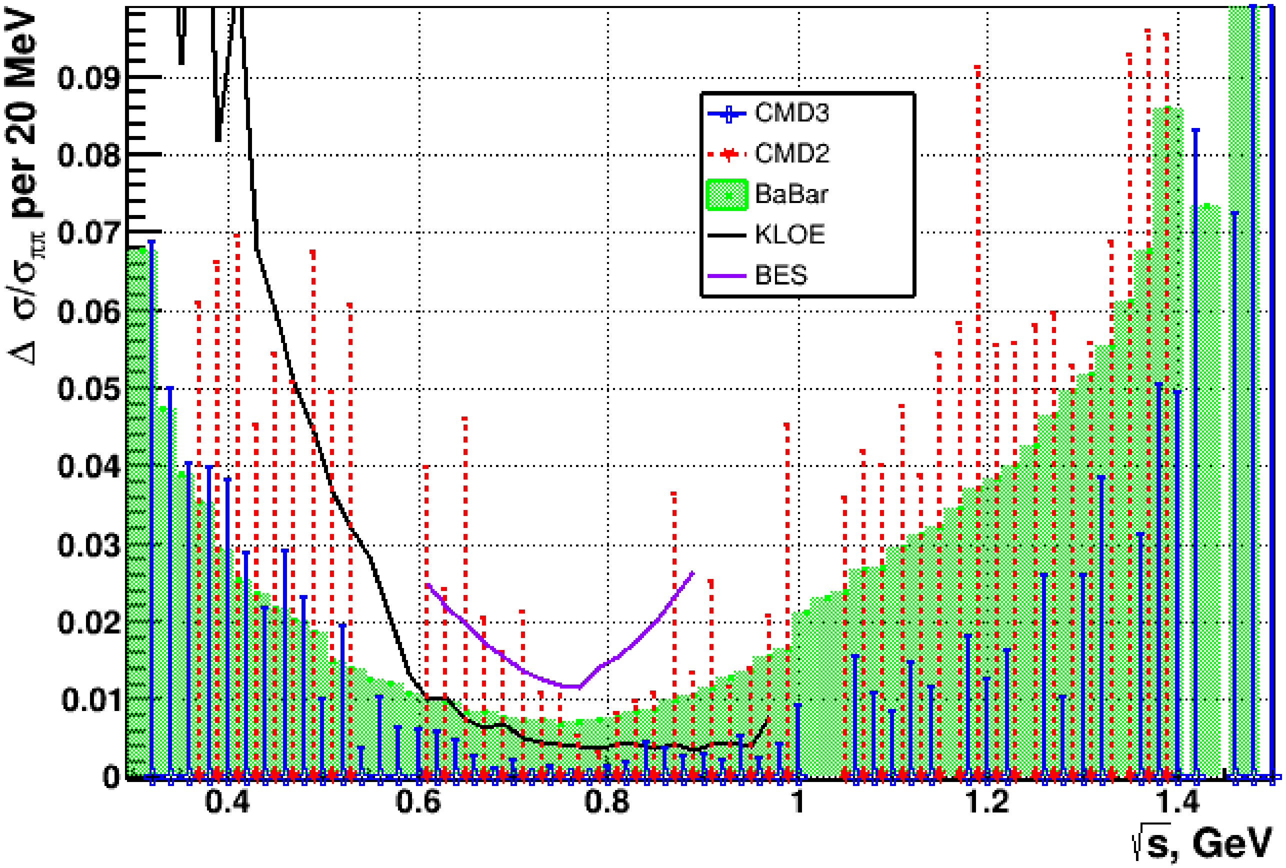
$|F_\pi|^2$ RHO2013/RHO2018 Δ = -0.06 ± 0.08 %

RHO2013/LOW2020 Δ = +0.36 ± 0.6 %

$N_{\mu\mu}$/QED Δ = +0.25 ± 0.16 %

Process $e^+e^- \to \pi^+\pi^-$ at CMD-3

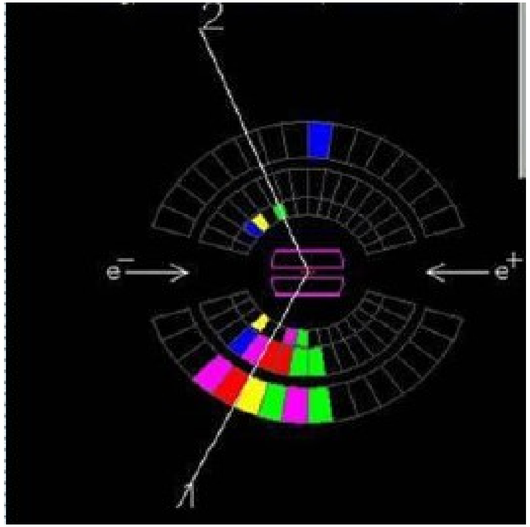
Relative statistical accuracy $\Delta\sigma/\sigma$ of various data sets in 20 MeV energy bins



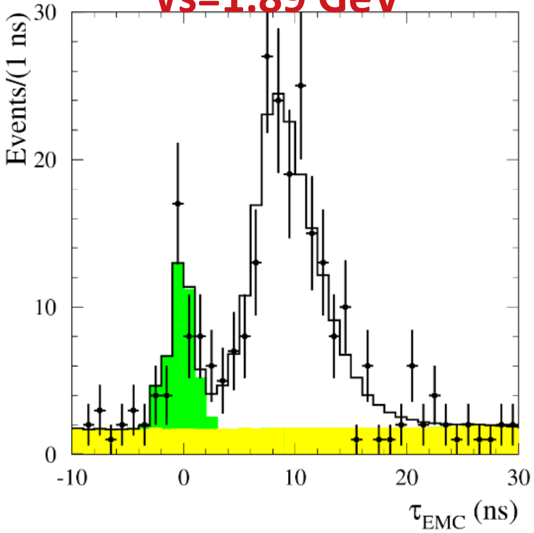
The analysis is on a very last stages. Stay tuned!

Process $e^+e^- \to n\bar{n}$

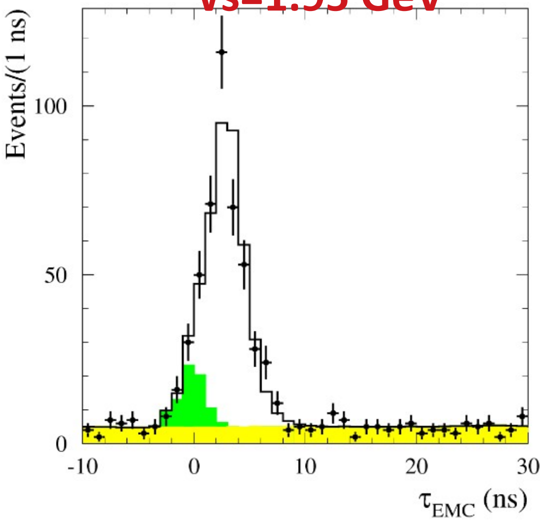
- $e^+e^- \to n\bar{n}$ events at the SND
  - $\bar{n}$ annihilates in electromagnetic calorimeter with big energy deposition
  - n has low energy deposition in calorimeter.
  - $\bar{n}$ has low velocity, its signal in EMC is delayed with respect to typical e^+e^- annihilation event.



√s=1.89 GeV



√s=1.95 GeV



Time of the signal in the electromagnetic calorimeter was used for selection of $e^+e^- \to n\bar{n}$ events

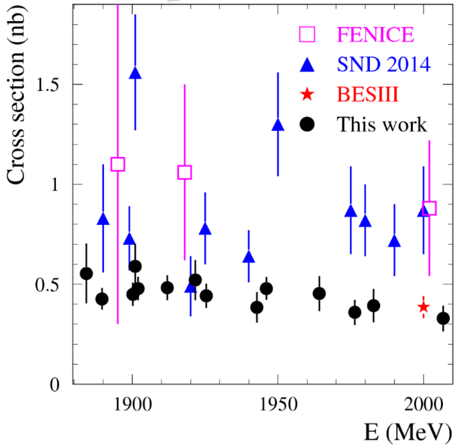
Eur. Phys. J.C 82 (2022) 8, 761

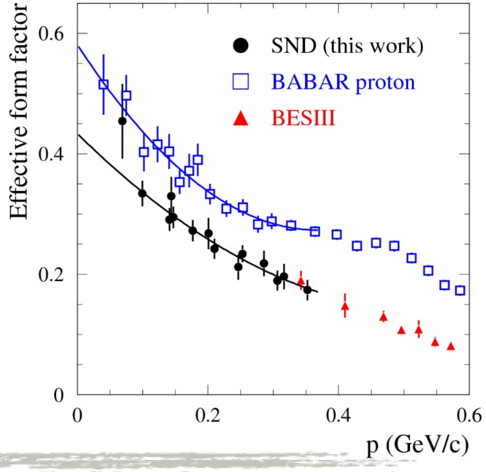
Process $e^+e^- \to n\bar{n}$

- **Detection efficiency and beam background in our previous analysis were underestimated**
- **New result supersedes previous SND measurement of e+e- → $n\bar{n}$ cross section**
- **Near 2 Gev our result is in good agreement with BES III measurement**

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2\beta}{4s}\left[|G_M(s)|^2(1+\cos^2\vartheta)+\frac{1}{\tau}|G_E(s)|^2\sin^2\vartheta\right],\beta=\sqrt{1-4m_N^2/s},\tau=\frac{s}{4}m_N^2$$

$$\sigma(s)=\frac{4\pi\alpha^2\beta}{3s}\left[|G_M(s)|^2+\frac{1}{2\tau}|G_E(s)|^2\right],\qquad F(s)^2=\frac{2\tau|G_M(s)|^2+|G_E(s)|^2}{2\tau+1}.$$





- **Ratio of proton and neutron form factors is 1.3-1.5**

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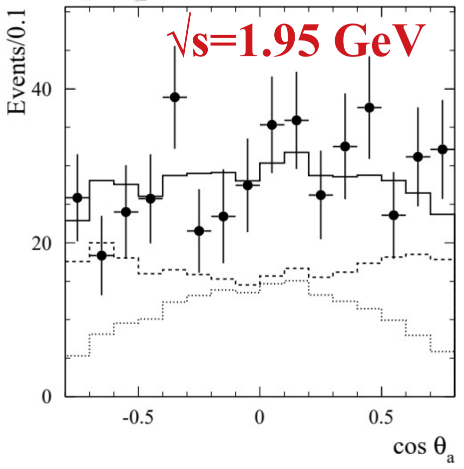
Process $e^+e^- \rightarrow n\bar{n}$

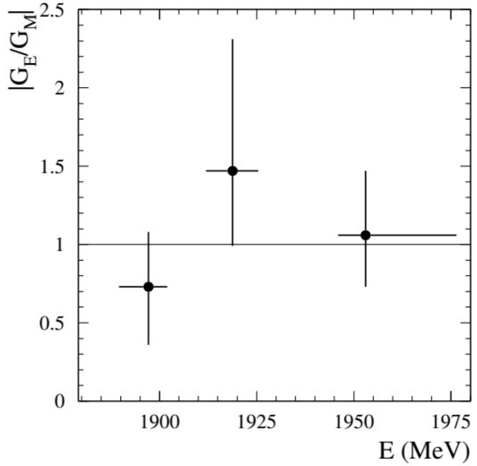
- $|G_E / G_M|$ ratio can be extracted from the measured $\cos\theta$ distribution

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta}{4s}\left[|G_M(s)|^2 (1+\cos^2\vartheta) + \frac{1}{\tau} |G_E(s)|^2 \sin^2\vartheta \right]$$

- SND results agree with the assumption that $|G_E / G_M| = 1$

- But do not contradict larger values $|G_E / G_M| \approx 1.4\text{-}1.5$, observed at BABAR and BESIII





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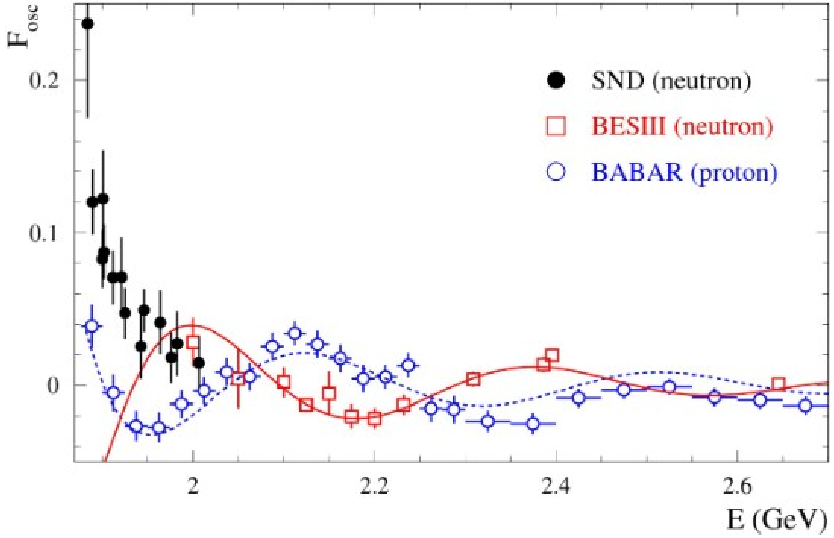
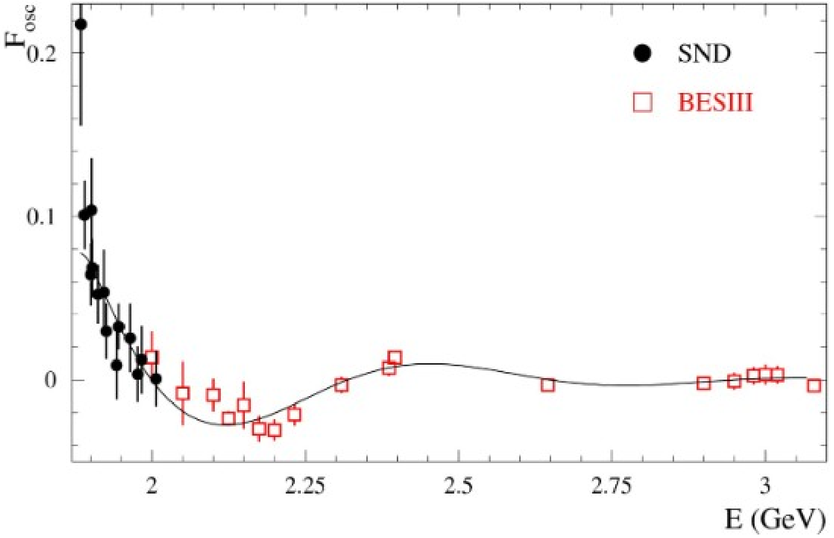
Process $e^+e^- \to n\bar{n}$





Sinusoidal modulation was observed in nucleon effective form factors in BABAR and BESIII experiments. SND and BESIII data fit with significantly lower oscillation frequency.

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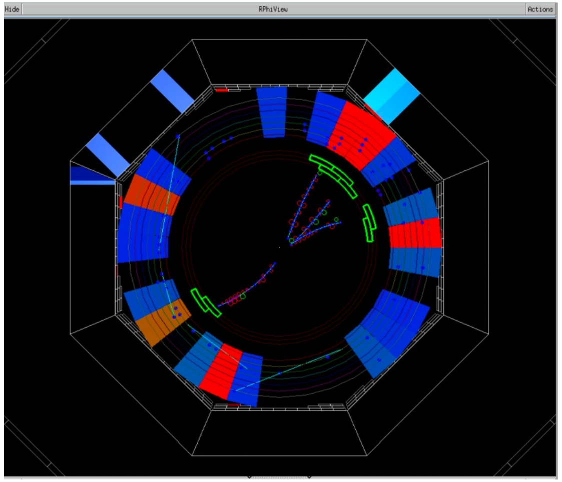
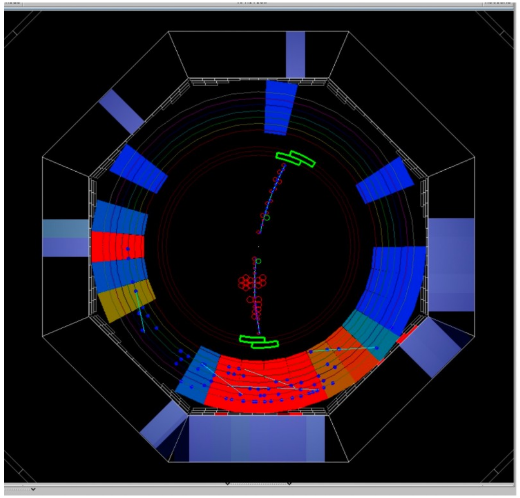
$p\bar{p}$ threshod scan



Anti-protons close to the production threshold are seen as an annihilation star at the vacuum beam pipe (or in the DC inner wall)+ large energy deposition in the calorimeters.

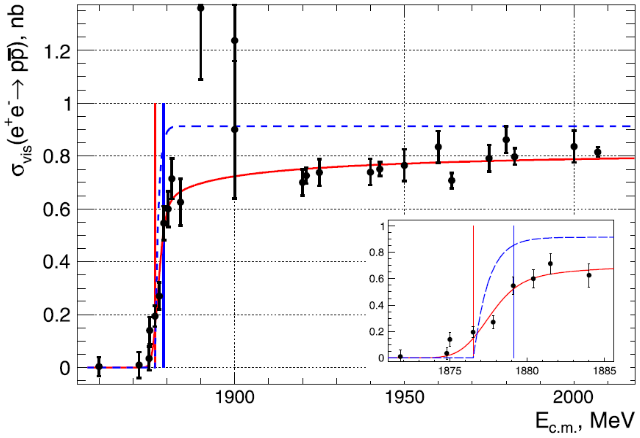
Above 1.9 GeV they are seen as collinear pp-bar tracks in DC



Fit to exponrntially saturated function gives σ_{th} = 0.78±0.28 MeV

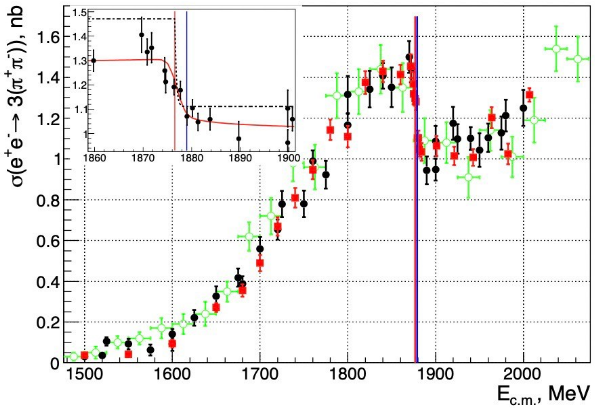
Beam energy spraed 0.95±0.1 MeV

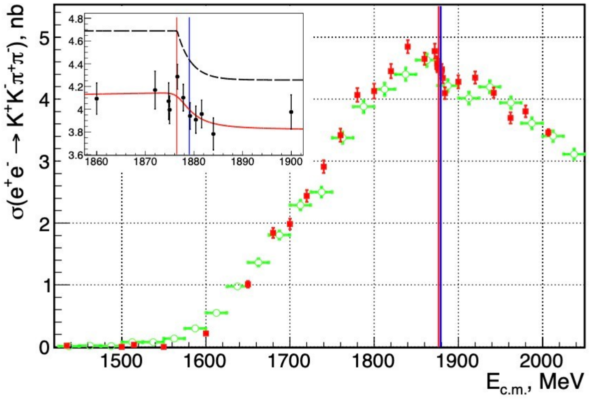
Phys. Lett. B 723 (2013) 73
Phys. Lett. B 794 (2019) 64–68



Fast increase near the threshold

$p\bar{p}$ threshod scan

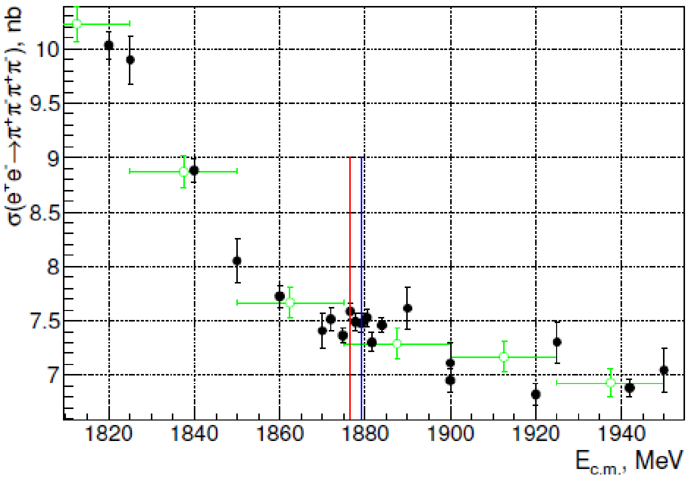




Phys. Lett. B 723 (2013) 73

Phys. Lett. B 794 (2019) 64–68

- **There is a sharp drop in cross sections $e^+e^- \to 3(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$ near pp-bar threshold**
- **Nothing like that for $e^+e^- \to 2(\pi^+\pi^-)$**
- **Simultanious fit of all three channels by exponentialy rising (drop) functions gives:**
  E_{th} = 1876.87±0.10±0.11 MeV
  σ_{th} = 0.31±0.25±0.15 MeV
  χ^2/ndf = 66/60
- **σ_{th} consistant with zero**

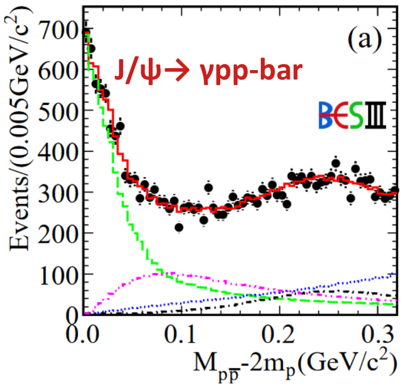


- **The idea, that signal in the hadronic cross section is proportional to the annihilation rate of $p\bar{p}$ to this final state does not work!**
- **Observation the «dip» in $K^+K^-\pi^+\pi^-$ indicates on complicated production dynamics**

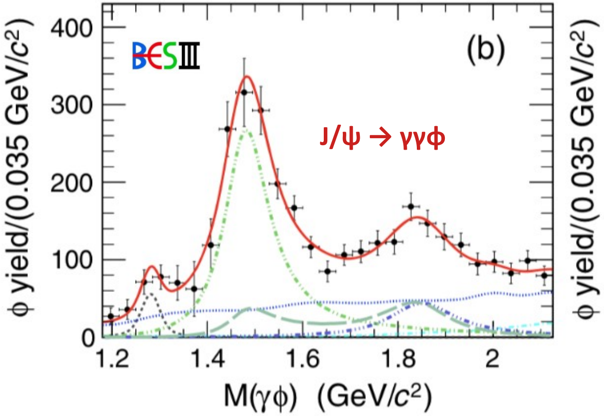
J/ψ radiative decay

- Something very similar happends with J/ψ radiative decays
- It is usually explained by X(1835) resonance with $J^{PC} = 0^{-+}$
- If effects in $e^+e^- \rightarrow X$ and $J/\psi \rightarrow \gamma X$ connected, there should be more complicated explanation

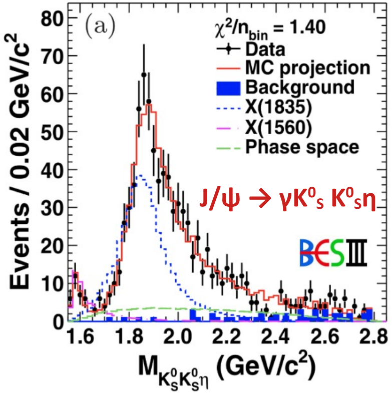
Phys.Rev.Lett. 108 (2012) 112003



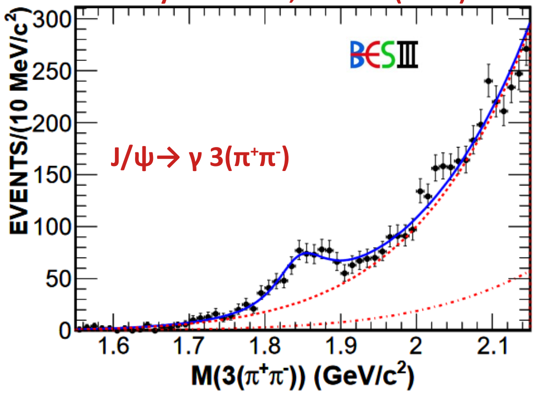
Phys. Rev. D97, 051101 (2018)



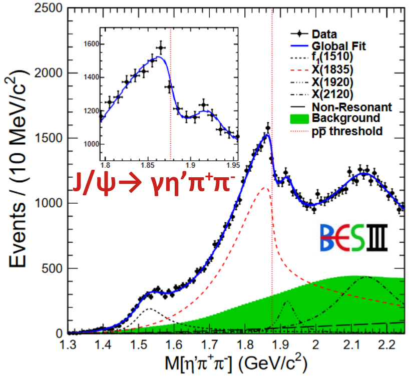
Phys. Rev. Lett. 115, 091803 (2015)



Phys.Rev. D88, 091502 (2013)

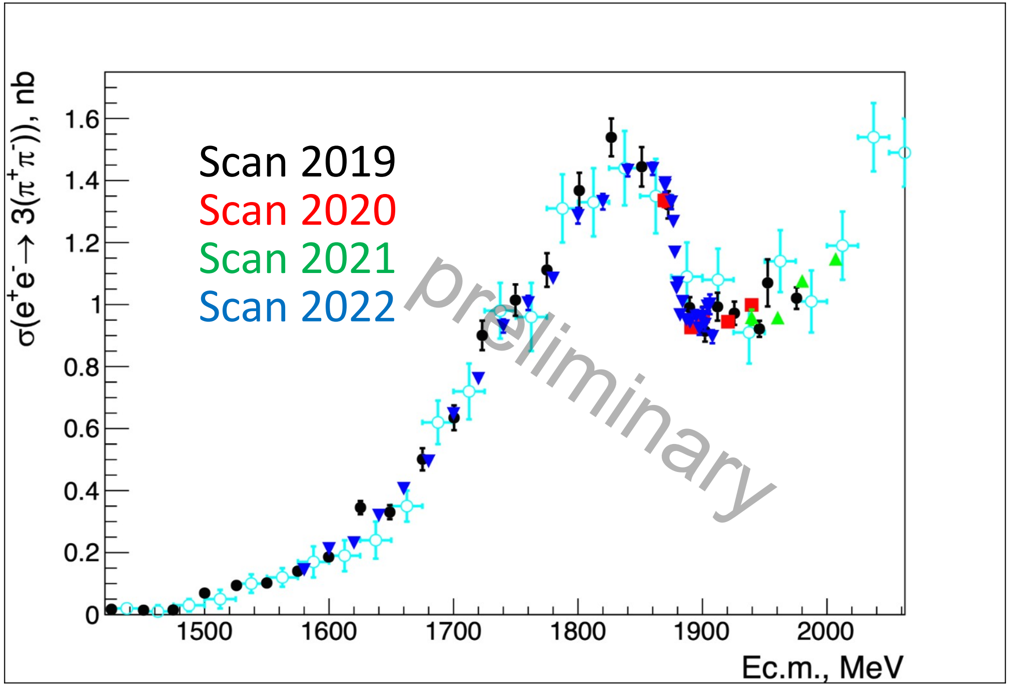


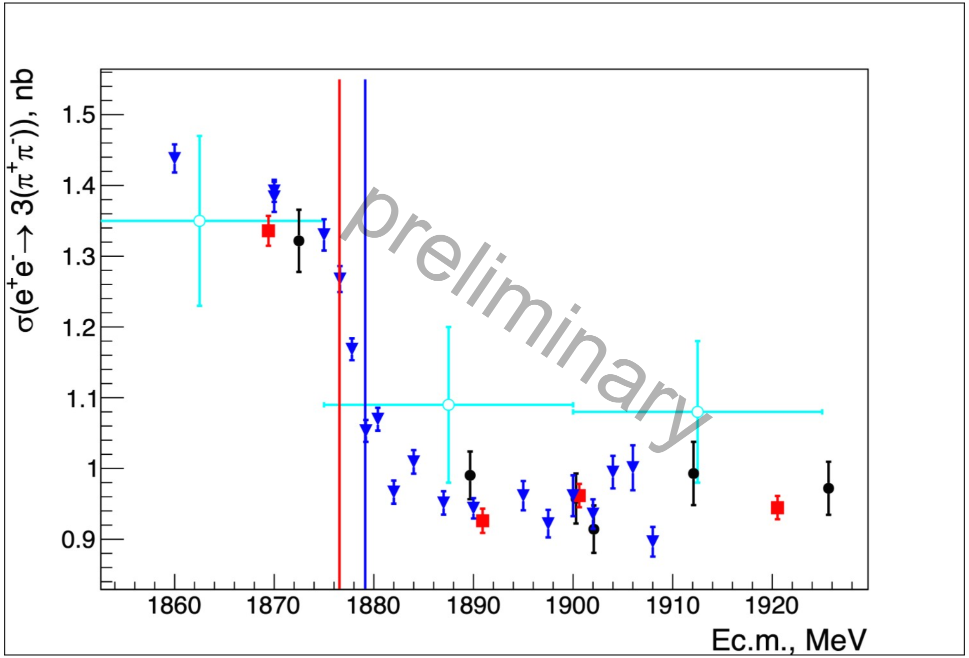
Phys. Rev. Lett. 117, 042002 (2016)



$p\bar{p}$ threshod scan

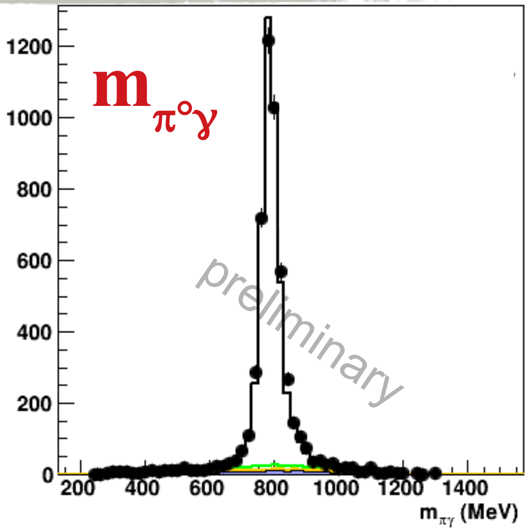
First preliminary results from CMD-3 confirms a fast cross section changing

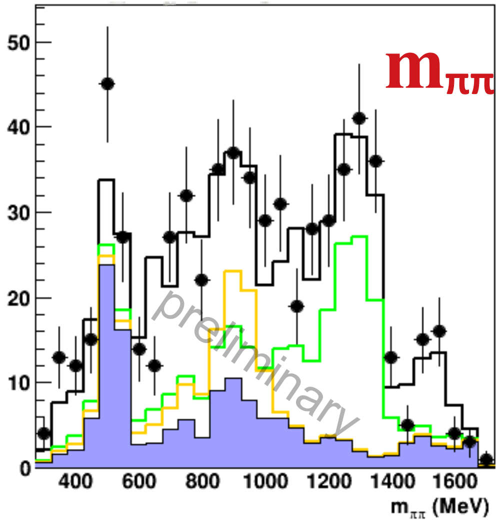




Process $e^+e^- \to \pi^0\pi^0\gamma$

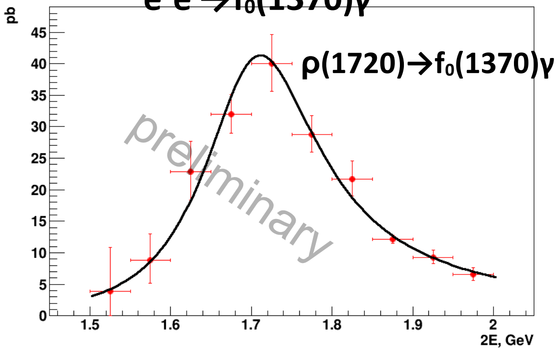
- Dominant intermediate mecanism is $e^+e^- \to \omega\pi^0$
- There are also contributions from radiative decays, which can be interpreted as the decay of $\rho(1720) \to f_0(1370)\gamma$ and $\phi(1680) \to f_0(980)\gamma$





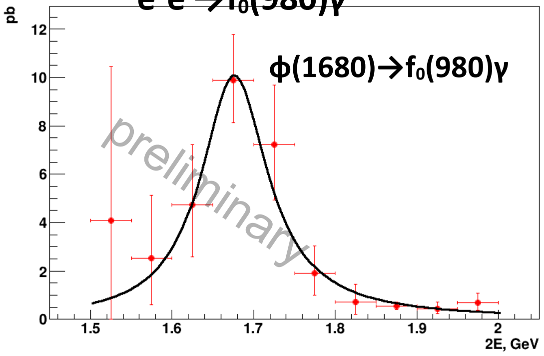
Cross section

$e^+e^- \to f_0(1370)\gamma$



Cross section

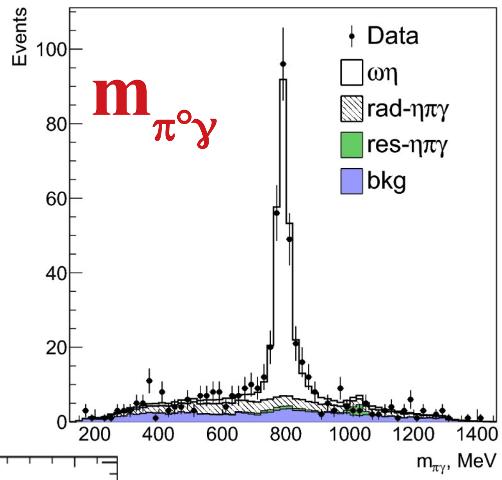
$e^+e^- \to f_0(980)\gamma$

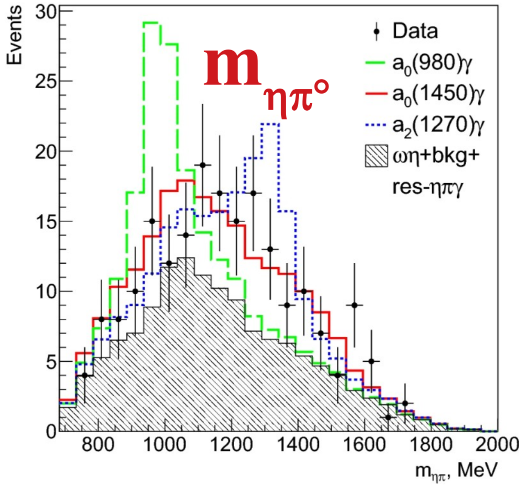


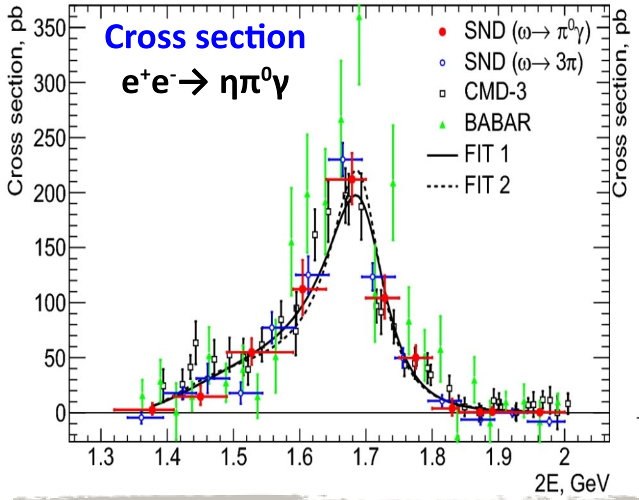
- $f_0(980)$ is one of the candidates for exotic QCD state
- $f_0(1370)$ together with $f_0(1500)$ and $f_0(1710)$ can have a mixture of glueball

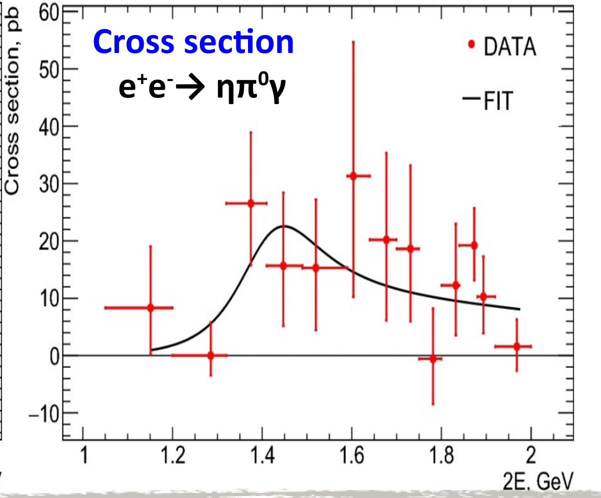
Process $e^+e^- \to \eta\pi^0\gamma$

- Process $e^+e^- \to \eta\pi^0\gamma$ was studied in energy region $\sqrt{s}$ =1.05–2.00 GeV for the first time
- Dominant intermediate mecanism is $e^+e^- \to \omega\eta$
- Contributions from radiative decays: $e^+e^- \to V', V'' \to a_0(980)\gamma$, $a_0(1450)\gamma$, $a_2(1320)\gamma$ are expected









- The process $e^+e^- \to \eta\pi^0\gamma$ is not completely described by the hadronic intermediate states $e^+e^- \to VP$
- Significance of this contribution is 5.6σ
- It is well described by radiative process $e^+e^- \to a_0(1450)\gamma$

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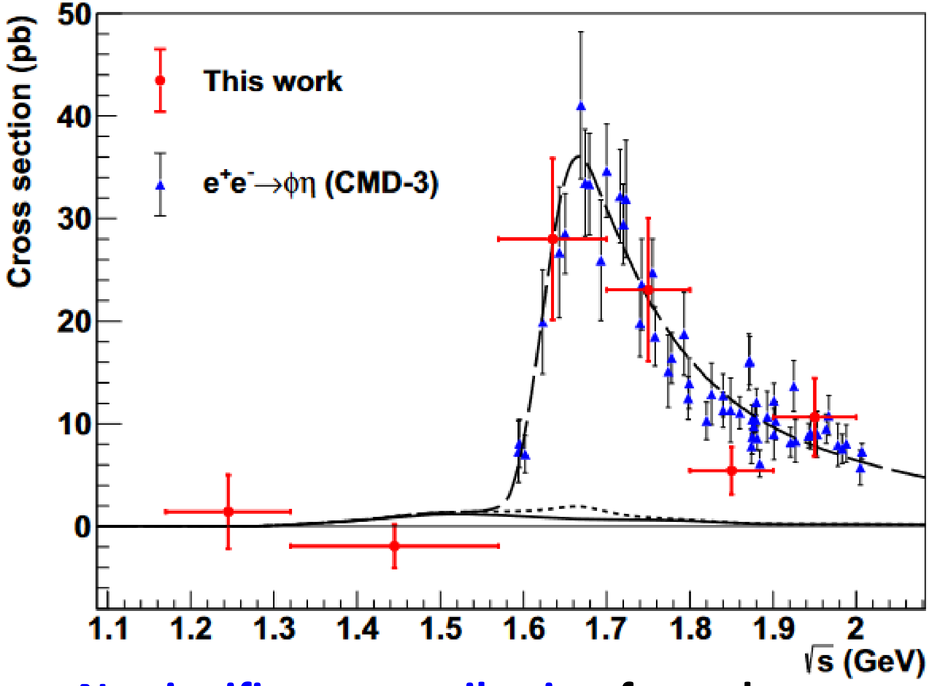
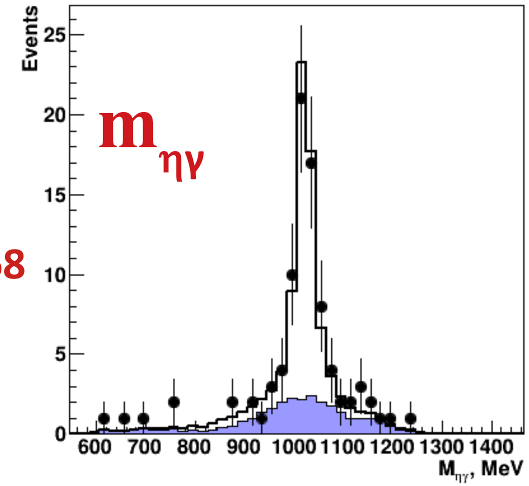
Process $e^+e^- \to \eta\eta\gamma$

- Process $e^+e^- \to \eta\eta\gamma$ was studied in energy region $\sqrt{s}$ =1.17–2.00 GeV for the first time
- Dominant intermediate mecanism is $e^+e^- \to \phi\eta$
- Contributions from radiative decays:
- $e^+e^- \to V', V'' \to f_0(1500)\gamma$, $f_2'(1525)\gamma$
- are expected
- Measured $e^+e^- \to \eta\eta\gamma$ cross section is consistent with the sum of contributions from the $e^+e^- \to \phi\eta$, $e^+e^- \to \omega\eta$ и $e^+e^- \to \rho\eta$
- processes.



Eur. Phys. J. C 82 (2022) 2,168



- No significant contribution from the radiative decays has been found.
- In the energy region of f(1680) and r(1700) resonances the upper limit for the radiative decays is 11 pb (90% CL).

Thank you for your attention!