Update – News from CMD-3

Evgeny Solodov

on behalf of CMD-3 collaboration

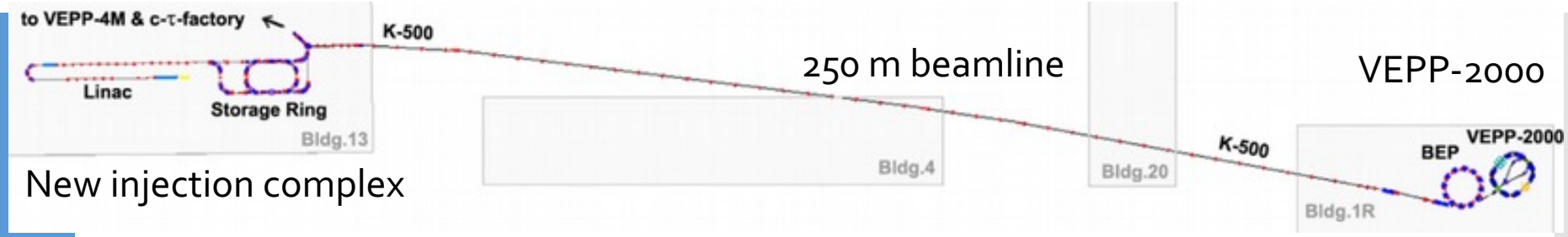
Budker Institute of Nuclear Physics
Novosibirsk, Russia

14th International Workshop on e+e- collision from Phi to Psi

Pisa (Italy)

Lune 8-11, 2026

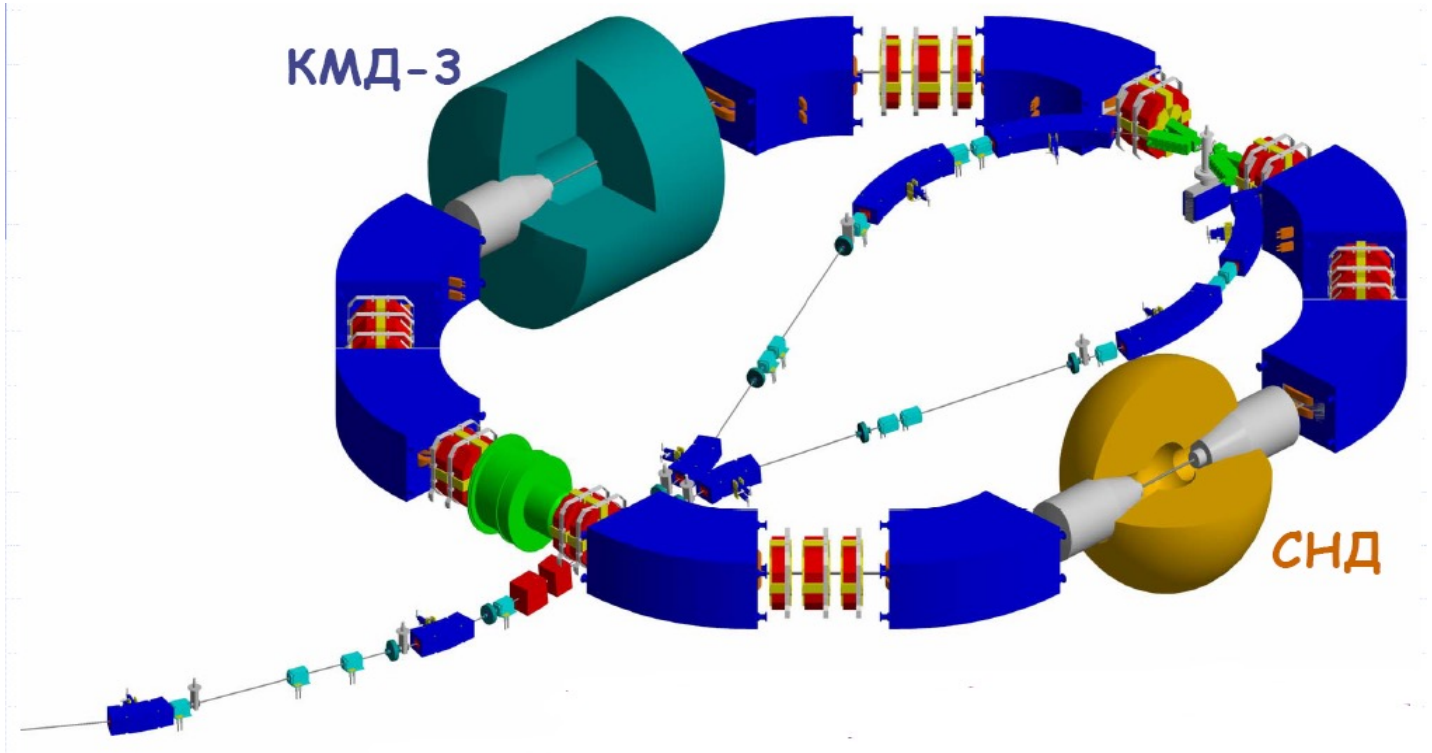
VEPP-2000 (after upgrade 2013-2016)



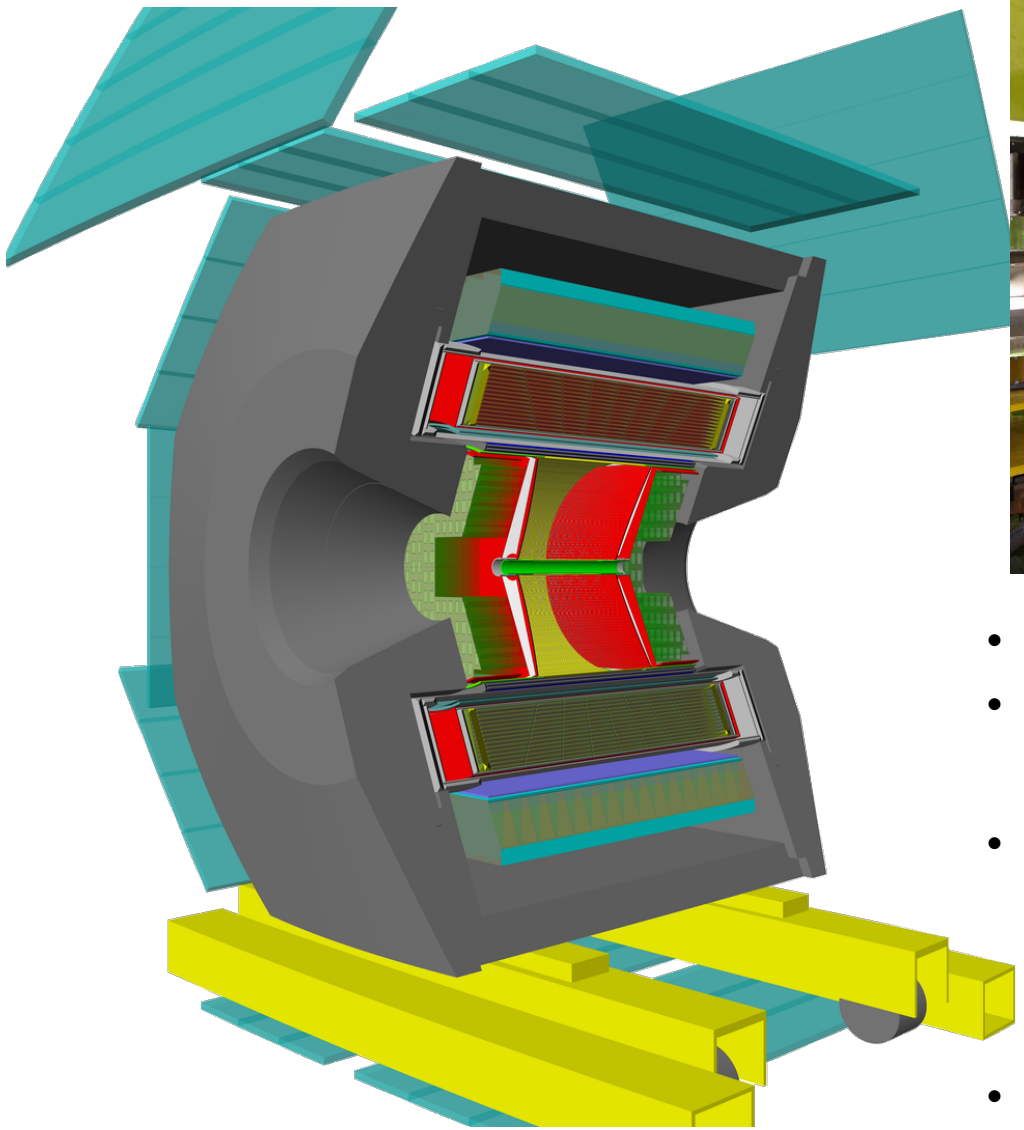
New injection complex

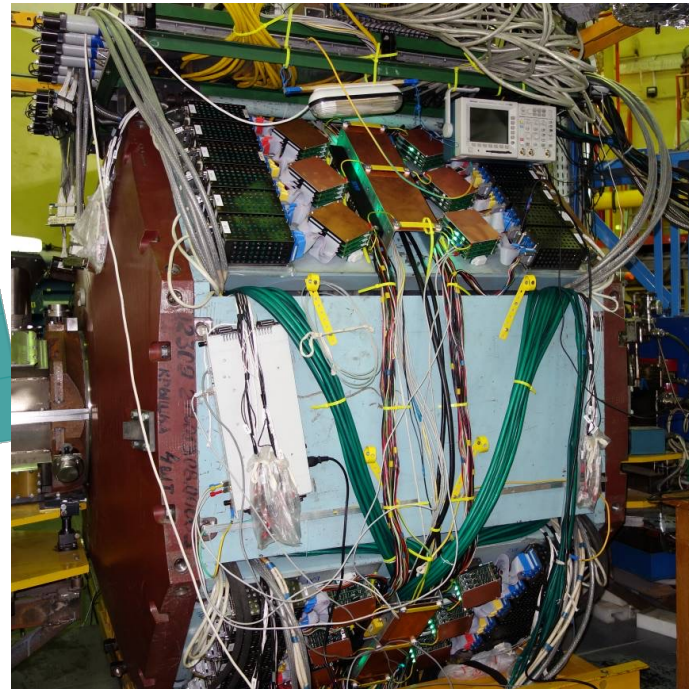
VEPP-2000 parameters:

- 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)



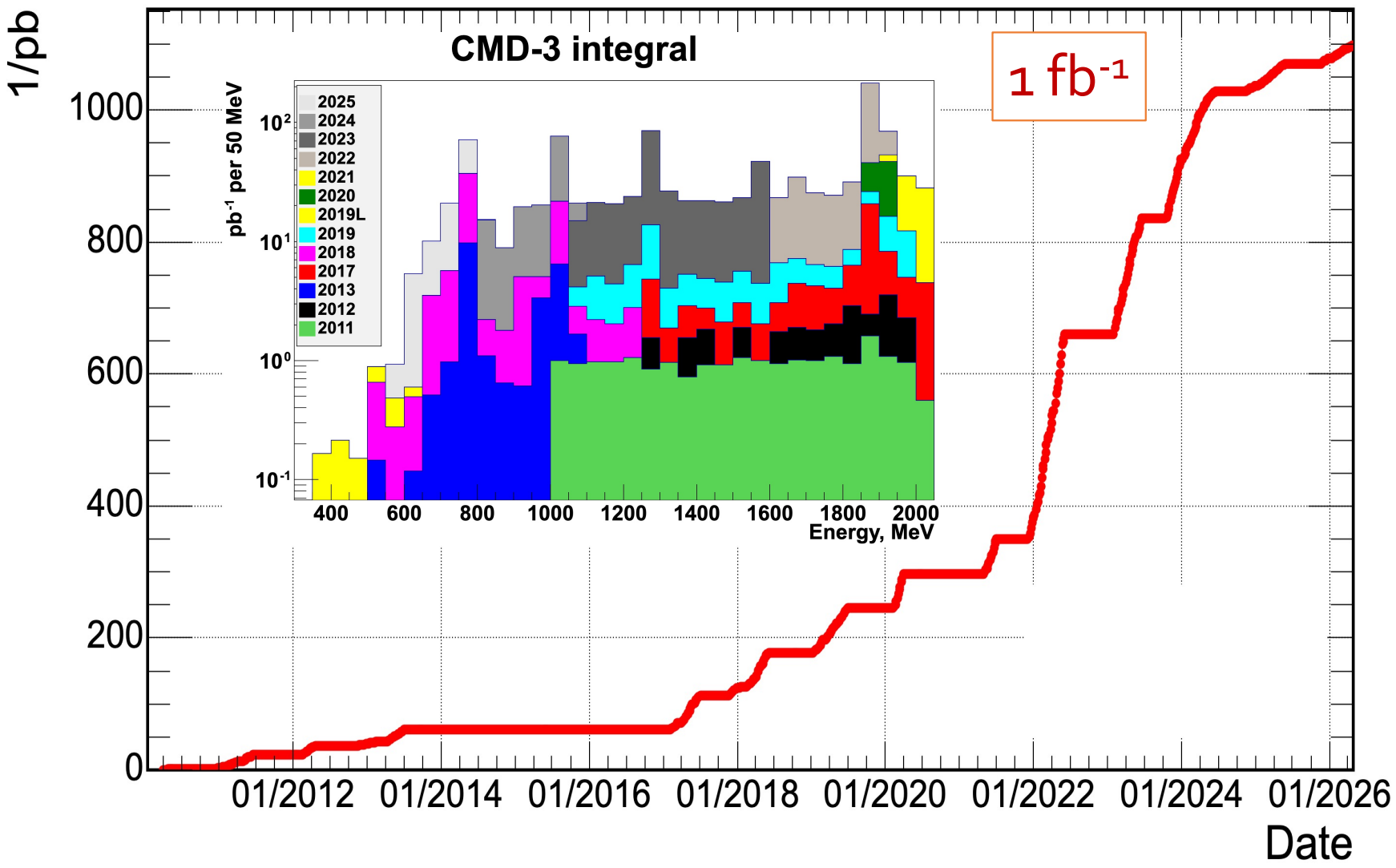
CMD-3 Detector





- Magnetic field 1.0-1.3 T
- Drift chamber
  - $\sigma_{R\varphi} \sim 100\ \mu, \sigma_z \sim 2-3$ mm
- EM calorimeter
  (LXE, CsI, BGO), 13.5 X_0
  - $\sigma_E/E \sim 3\% - 10\%$
  - $\sigma_\Theta \sim 5$ mrad
- TOF
- Muon counters

Collected data



CMD-3 final states under analysis

Signature	Final states (preliminary, published)
2 charged	$\pi^+\pi^-, K^+K^-, K_SK_L, p\bar{p}$
2 charged + γ's	$\pi^+\pi^-\gamma, \pi^+\pi^-\pi^0, \pi^+\pi^-\eta, K^+K^-\pi^0, K^+K^-\eta, K_SK_L\pi^0,$ $K_SK_L\eta, \pi^+\pi^-\pi^0\eta, \pi^+\pi^-2\pi^0, \pi^+\pi^-3\pi^0, \pi^+\pi^-4\pi^0$
4 charged	$\pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K_SK^\pm\pi^\mp, K_SK_L\pi^+\pi^-,$ $K_SK_S\pi^+\pi^-$
4 charged + γ's	$\pi^+\pi^-\pi^+\pi^-\pi^0, \pi^+\pi^-\eta, \pi^+\pi^-\omega, \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0,$ $K^+K^-\eta, K^+K^-\omega$
6 charged	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-, K_SK^\pm\pi^\mp\pi^+\pi^-, K_SK_S\pi^+\pi^-$
6 charged + γ's	$3(\pi^+\pi^-)\pi^0$
Neutral	$\pi^0\gamma, \eta\gamma, \pi^0\pi^0\gamma, \pi^0\eta\gamma, \pi^0\pi^0\pi^0\gamma, \pi^0\pi^0\eta\gamma$
Other	$n\bar{n}, \pi^0e^+e^-, \eta e^+e^-$
Rare decays	$\eta', D^*(2007)^0$, $f_1(1285)$

$$e^+e^- \to \pi^+\pi^-$$

No news

$e^+e^- \to \pi^+\pi^-$ Publications

Phys.Rev.Lett. 132 (2024) 23, 231903

PHYSICAL REVIEW LETTERS **132,** 231903 (2024)

Editors' Suggestion

Measurement of the Pion Form Factor with CMD-3 Detector and Its Implication to the Hadronic Contribution to Muon ($g-2$)

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PHYSICAL REVIEW D **109,** 112002 (2024)

Editors' Suggestion

Measurement of the $e^+e^- \to \pi^+\pi^-$ cross section from threshold to 1.2 GeV with the CMD-3 detector

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(CMD-3 Collaboration)

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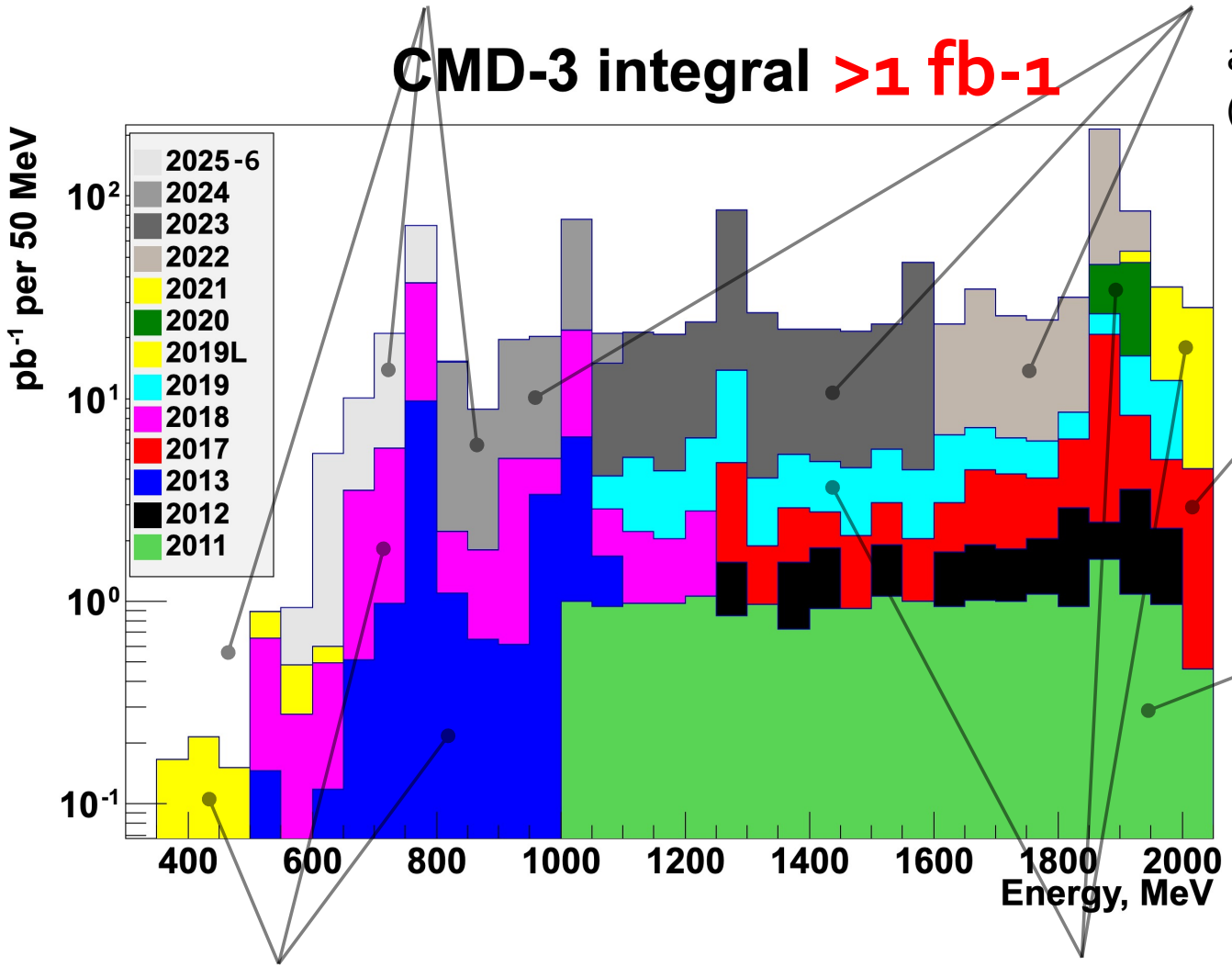
$e^+e^- \to \pi^+\pi^-$

We are canning down to ≲200 MeV with x3 Lumi compare to published data

More data (x3) to be collected (2024-2026(7?))



To be added to analysis (2022, 2023, 2024)

Problem with angle measurement (2017)

Problem with calorimeter electronics (2011, 2012)

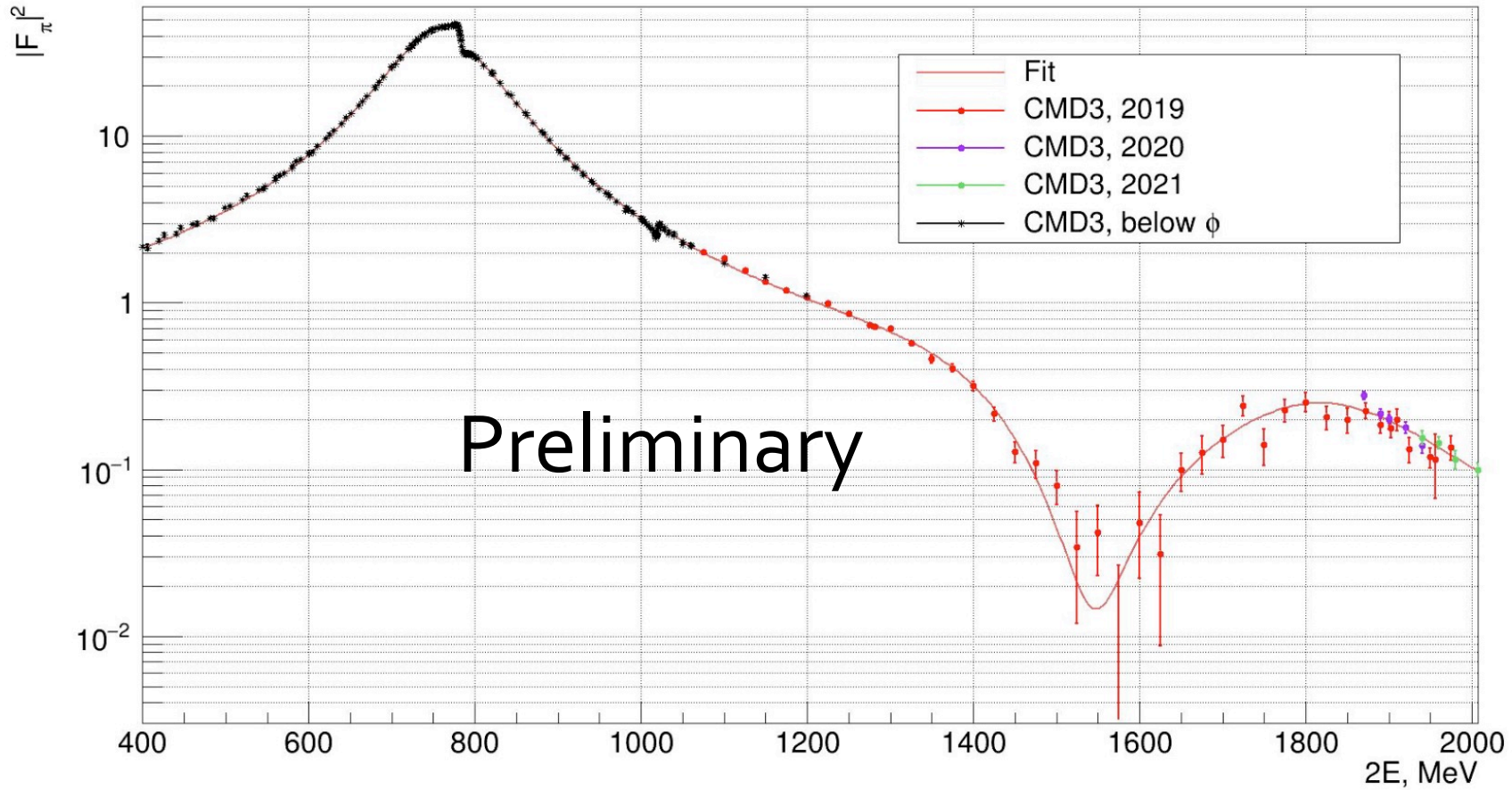
2024 published result (2013, 2018, 2019)

Under analysis (above 1 GeV) (2019,2020,2021)

2025 data were collected with the reverse direction of the beams

$e^+e^- \to \pi^+\pi^-$ 2019-2021 runs analysis above 1 GeV

Intermediate/ preliminary result



Estimated systematic error (preliminary)	0.8%	7%

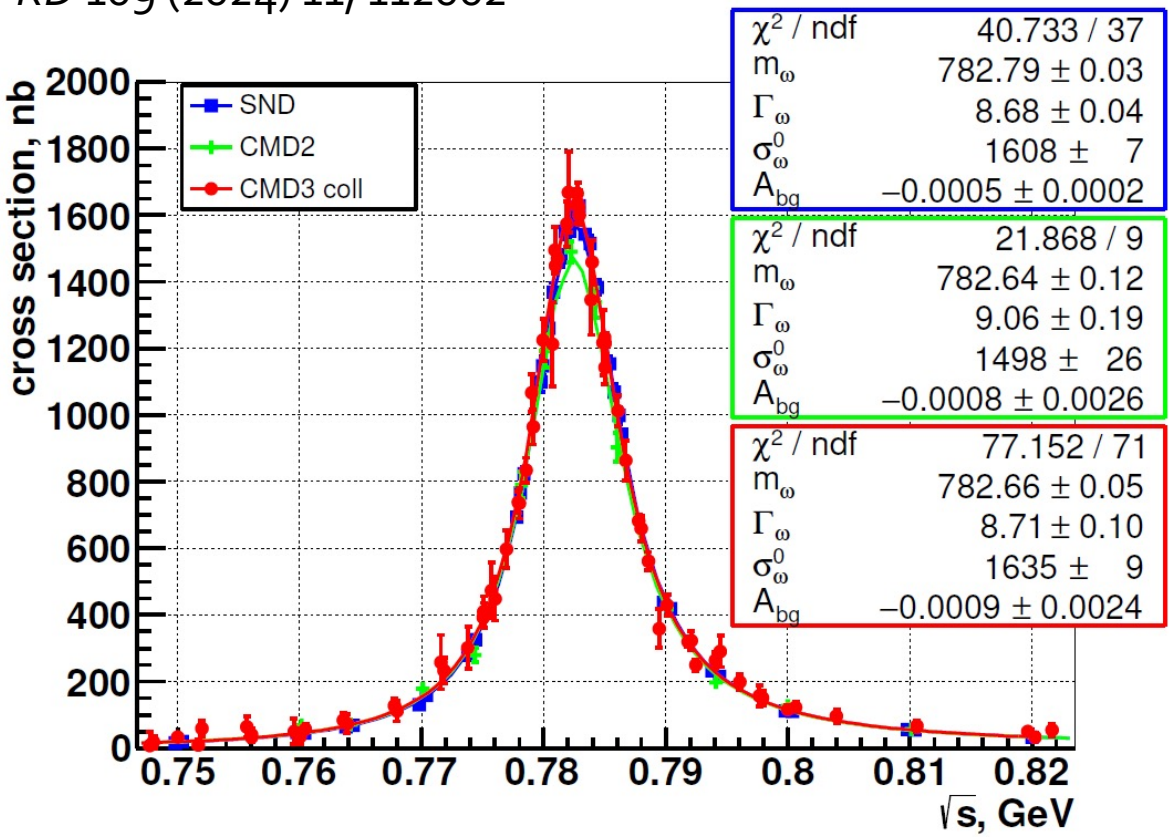
Unfortunately analysis has been frozen – lack of people.
Analysis of 2022-2024 data (x4-5) has not started yet

$$e^+e^- \rightarrow \pi^+\pi^-\pi^0$$

$e^+e^- \to 3\pi$ CMD-3 published result

$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

PRD 109 (2024) 11, 112002



By-product of $e^+e^- \to \pi^+\pi^-$ analysis

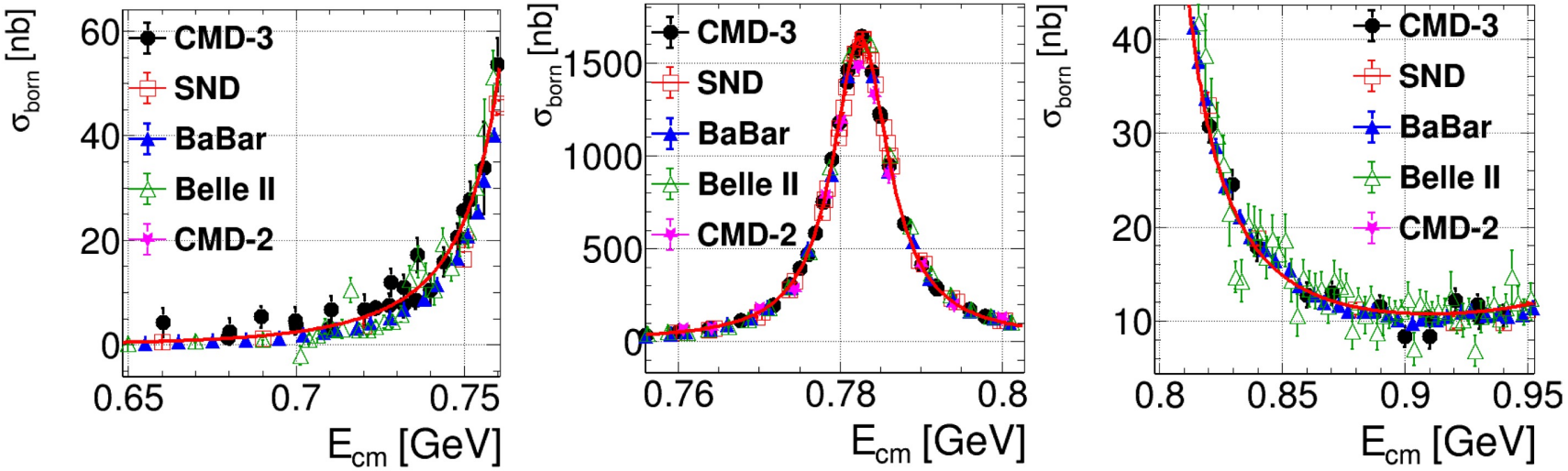
Based on small subset of $e^+e^- \to \pi^+\pi^-\pi^0$ sample ("collinear" selection cuts, π^0 nearly at rest)

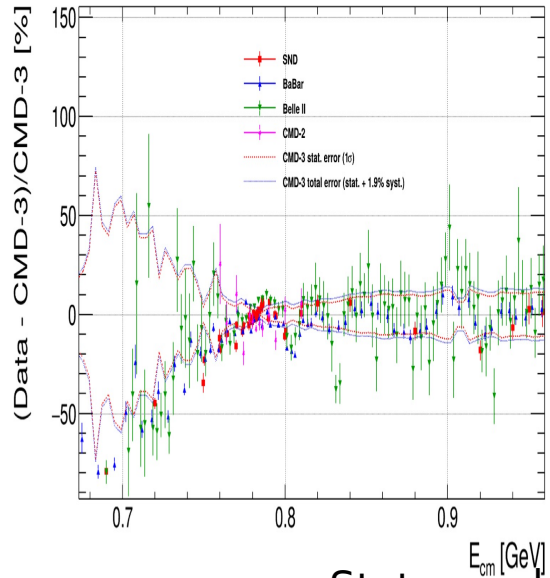
Estimated systematic uncertainty is 3.3%

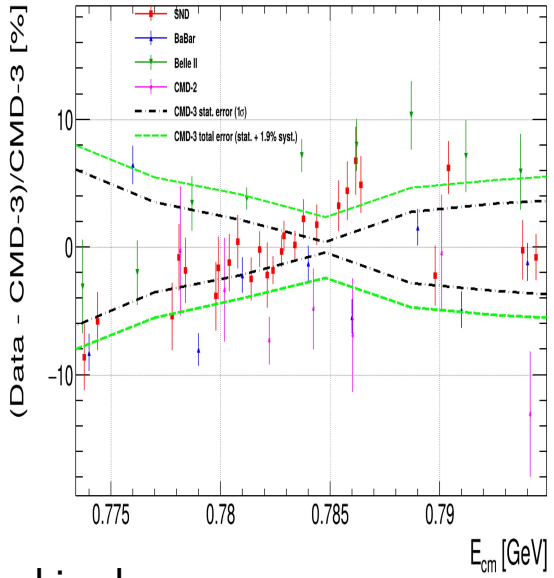
2.2σ tension with CMD-2 measurement

Preliminary

$e^+e^- \to 3\pi$
CMD-3
ongoing
analysis







- $E_{c.m.}$= 0.66 - 0.97 GeV
- $L_{int} \approx 51.4\ pb^{-1}$ (2013,2018)
- $\varepsilon_{MC} \approx 3\%$
- $N_{3\pi} \approx 480k$

Stat.error band is shown

$e^+e^- \to 3\pi$ CMD-3 ongoing analysis

Source	Contribution (%)	Estimation method
Luminosity	1.5 -> ~< 1%	Difference between $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$
Track reconstruction	0.2	Calculation in different selection criteria
π^0 reconstruction	0.5	Comparison with cross section without π^0 reconstruction
Trigger efficiency	<0.1	–
Energy spread	0.3	Calculation of radiative correction without taking account for beam energy spread
Model in MC	< 0.7	Discrepancy with the Phase Space MC
ISR in MC	0.3	Different cross-sections
Selection criteria	0.5	Variation of selection criteria
Background subtraction	0.3	Different event counting procedures

Total systematic uncertainty of cross section: 1.9%

$$a_\mu^{had,3\pi} = \frac{1}{4\pi^3}\int_{s_{\min}}^{s_{\max}} \sigma^{3\pi}_{\text{born}}(s)|1-\Pi(s)|^2 \cdot K(s)\,ds$$

$\sigma^{3\pi}_{\text{born}}(s)$ – Born cross section function after approximation of experimental data

$a_\mu^{had,3\pi}$ in range $0.62 < \sqrt{s} < 1.1\ GeV/c^2$

- **CMD-3** $(44.3 \pm 0.2 \pm 0.8) \times 10^{10}$ **(Function) [Preliminary]**
- BaBar $(42.91 \pm 0.14 \pm 0.55 \pm 0.09) \times 10^{10}$ $(\Delta = (1.4 \pm 1) \times 10^{10}$

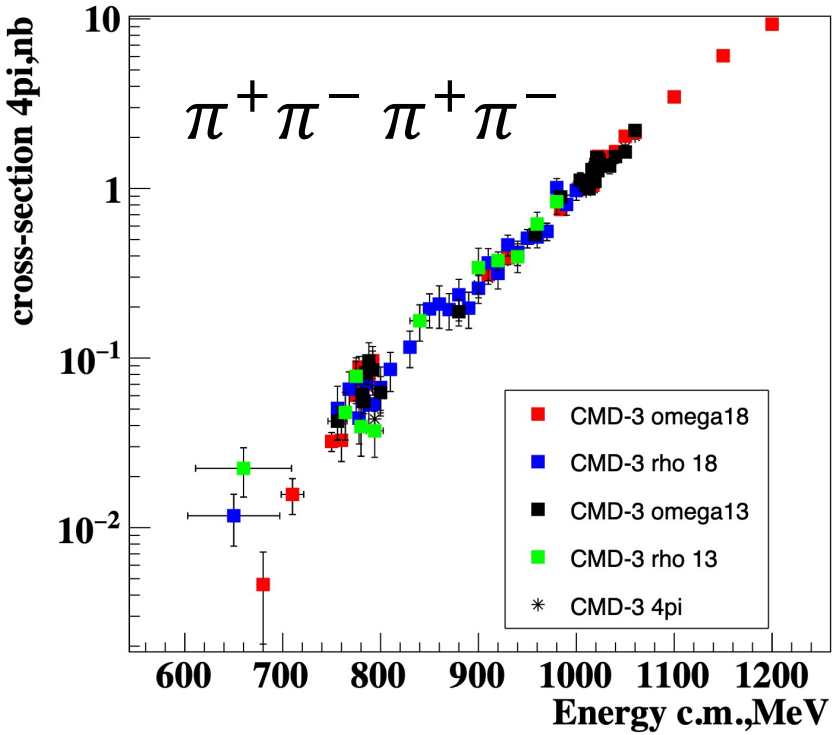
$a_\mu^{had,3\pi}$ in range $0.65 < \sqrt{s} < 0.98\ GeV/c^2$

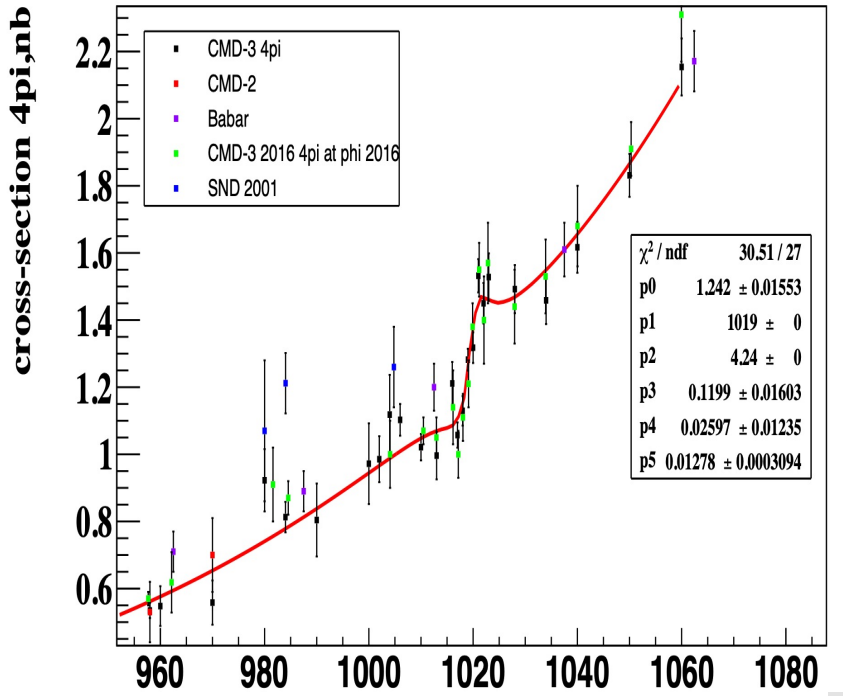
- **CMD-3** $(38.0 \pm 0.2 \pm 0.8) \times 10^{10}$ **(Function) [Preliminary]**
- **CMD-3** $(38.2 \pm 0.2 \pm 0.8) \times 10^{10}$ **(Linear approximation,** $\Delta = (0.2 \pm 1.2) \times 10^{10}$**)**

$$e^+e^- \rightarrow \pi^+\pi^-\,\pi^+\pi^-$$
$$\rightarrow \pi^+\pi^-\,\pi^0\pi^0$$

Preliminary

$e^+e^- \to 4\pi$
CMD-3
ongoing
analysis
(ω, ϕ region)



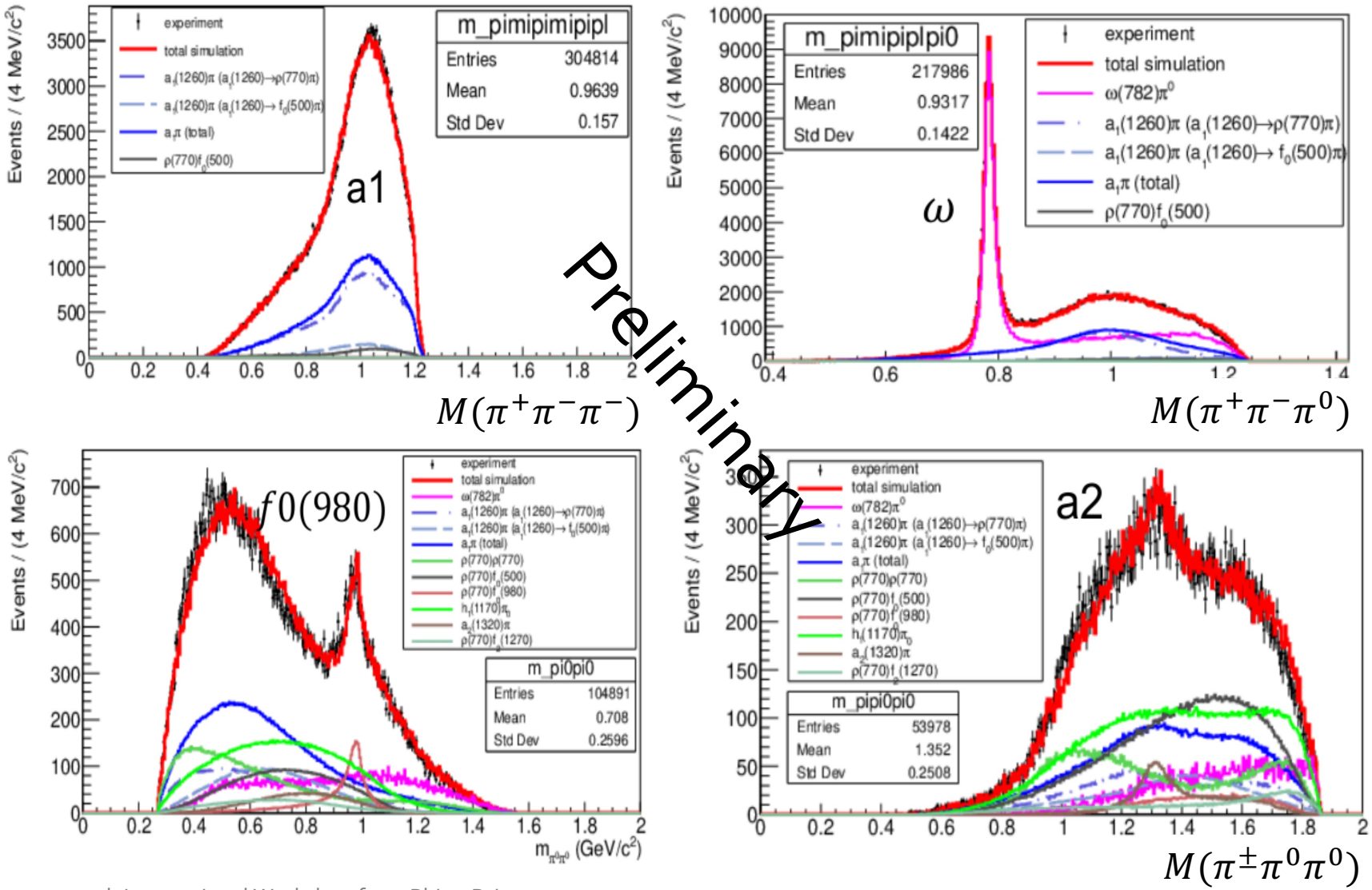


$B(\phi \to \pi^+\pi^-\,\pi^+\pi^-) = (4.5 \pm 1.3) * 10^{-6}$

PDG data $(3.9^{+2.8}_{-2.2}) * 10^{-6}$
CMD-3 2017 - $(6.5 \pm 2.7 \pm 1.6) * 10^{-6}$
Analysis in progress with more recent data
work on systematic uncertainties

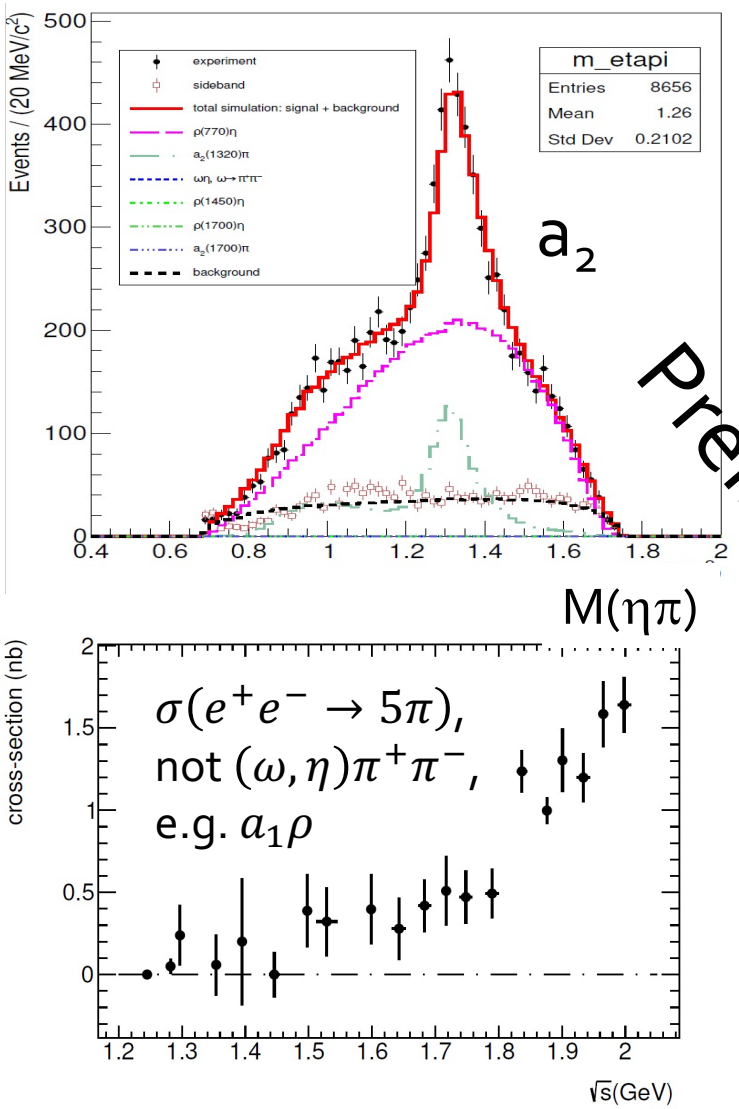
CMD-3 analysis for $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$ above 1 GeV

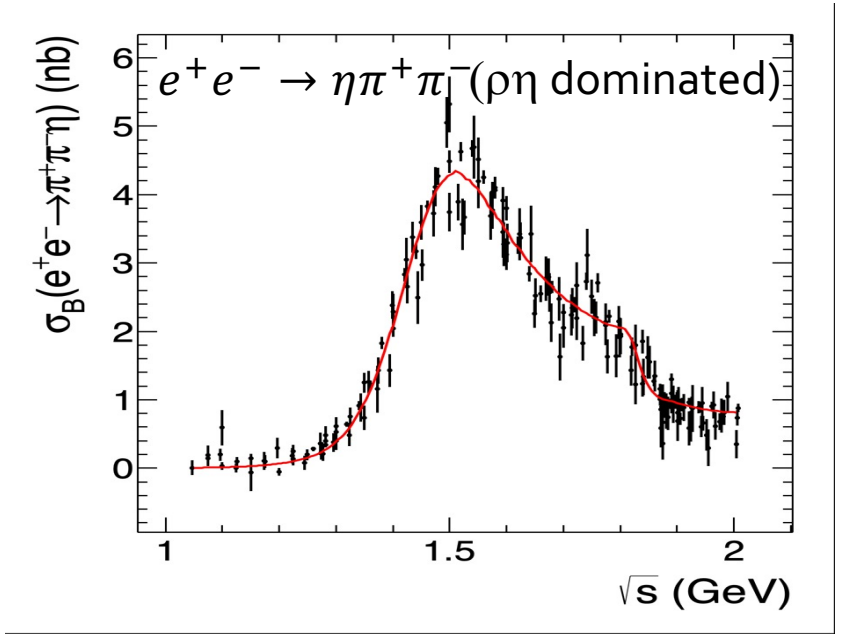
Large data sample allows to perform the amplitude analysis to reduce a model-dependent systematic uncertainties. Work is in progress

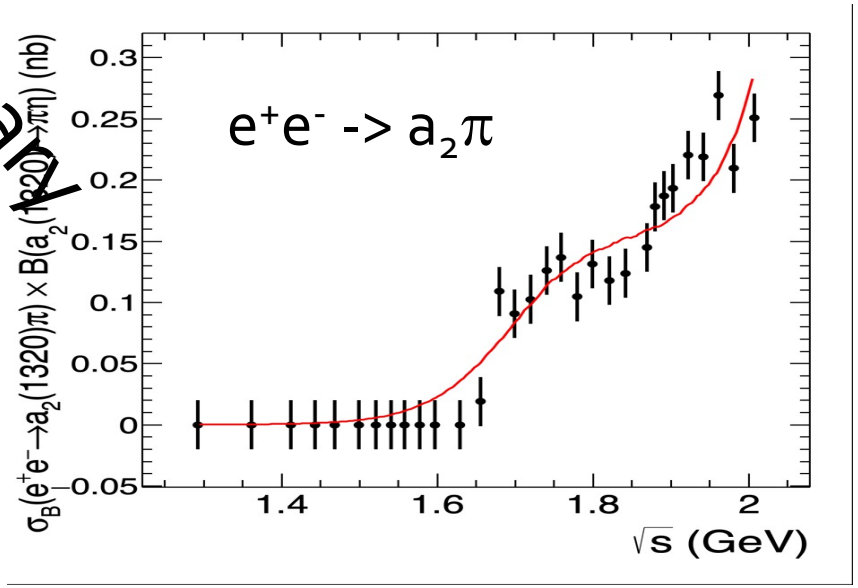


Preliminary results for $e^+e^- \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$, 3π

Amplitude analysis shows a contribution from $a_2(1320)$







Preliminary

$$e^+e^- \rightarrow K_S K_L, K^+K^-$$

CMD-3 measurements of $K_S K_L, K^+K^-$

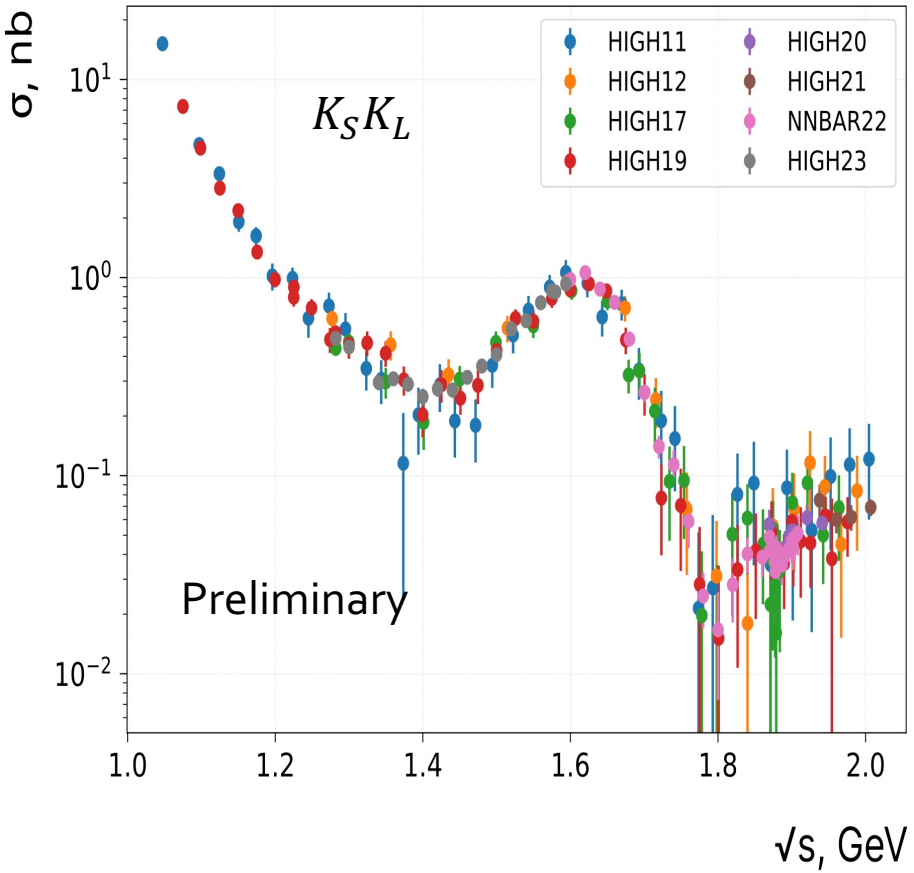
$e^+e^- \to K^+K^-$ PLB 779 (2018) 64

2.0% systematic error
(2.8% at high energy tail)

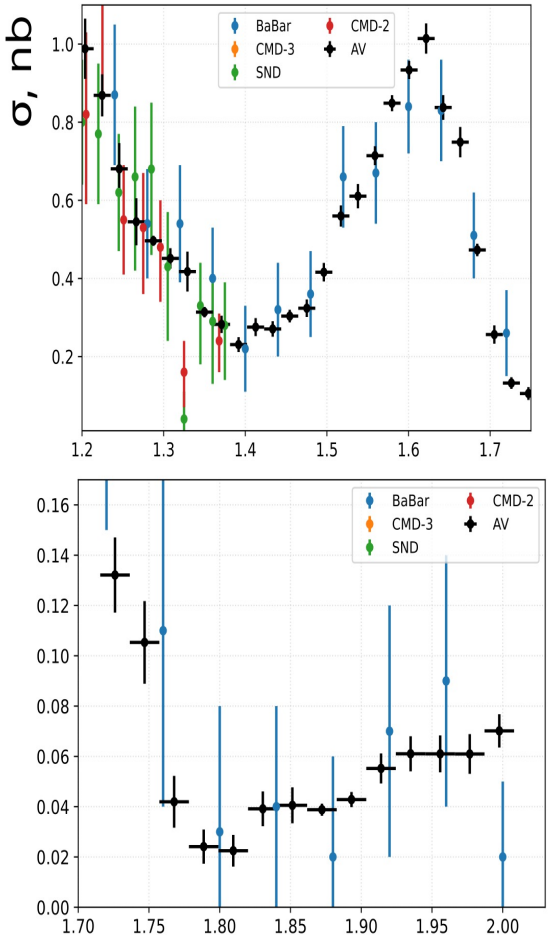
$e^+e^- \to K_S K_L$ PLB 760 (2016) 314

1.8% systematic error

CMD-3 published $K_S K_L, K^+K^-$ at $\varphi(1020)$ only. K^+K^- above φ only preliminary
The data analysis at energies above φ is ongoing for both channels.



σ/20 MeV



Paper for $K_S K_L$ is in preparation

PRELIMARY Paper is in preparation

New resonance is required!

Missing ϕ″ is found!

$$\sigma_{K_S K_L / K^+ K^-} = \frac{\pi \alpha^2 \beta^3}{3s} \left| F_{K^0/K^\pm} \right|^2$$

$$F_{K^0/K^\pm} = F_{I=0} \mp F_{I=1}$$

$$F_{I=0} = \frac{\lambda_0}{s} + \sum_m c_m e^{i\phi_m} \mathrm{BW}(s, M_m, \Gamma_m)$$

$$F_{I=1} = \frac{\lambda_1 e^{i\phi_1}}{s} + \sum_n c_n e^{i\phi_n} \mathrm{BW}(s, M_n, \Gamma_n)$$

Fixed

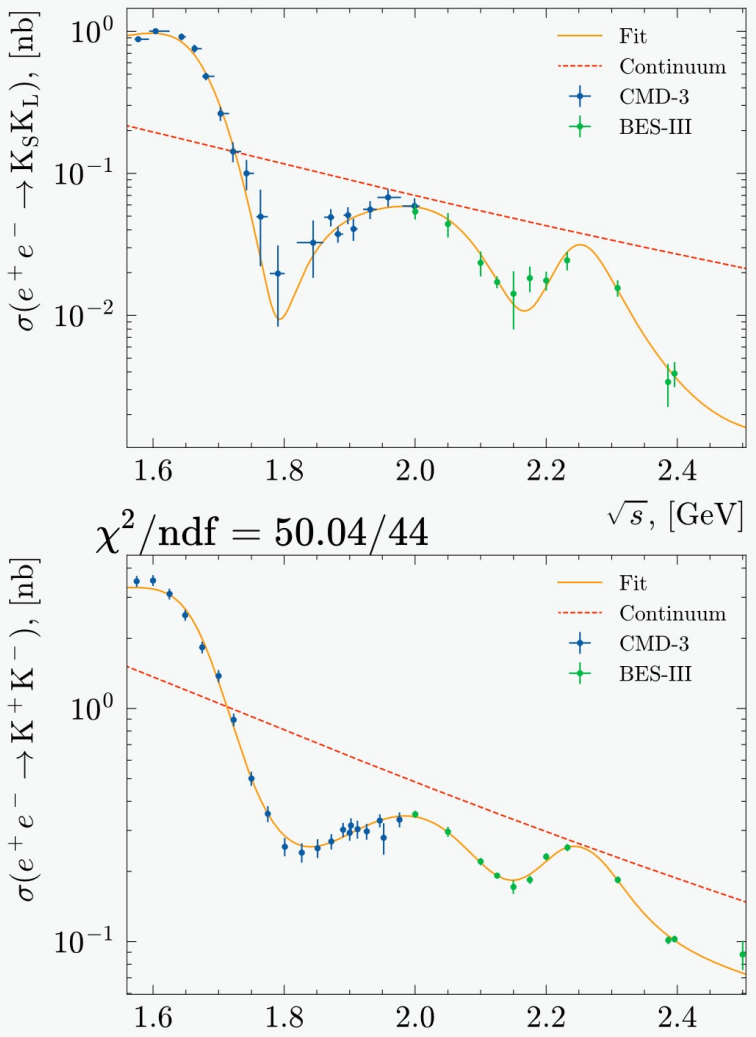
- ρ″ (M=1821 MeV, Γ=316 MeV)
- ρ‴ (M=2270 MeV, Γ=116 MeV)
- φ‴ (M=2239 MeV, Γ=140 MeV)

Free

- φ′ (M~1680 MeV, Γ~150 MeV)
- φ″ (M~2000 MeV, Γ~250 MeV)

→

- φ′ (1.672±0.006 GeV, 0.179±0.011 GeV
- φ″ (2.073±0.022 GeV, 0.281±0.030 Ge

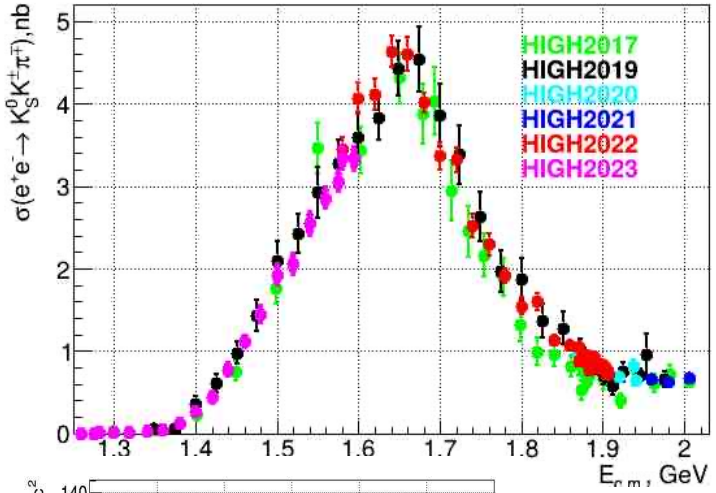


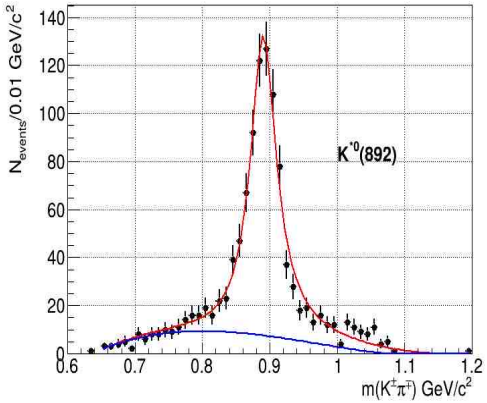
$$e^+e^- \to KK\pi(\pi)$$

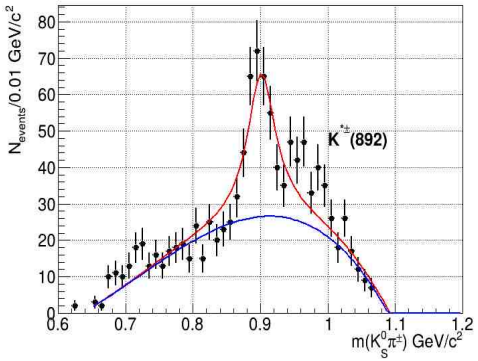
PRELIMINARY

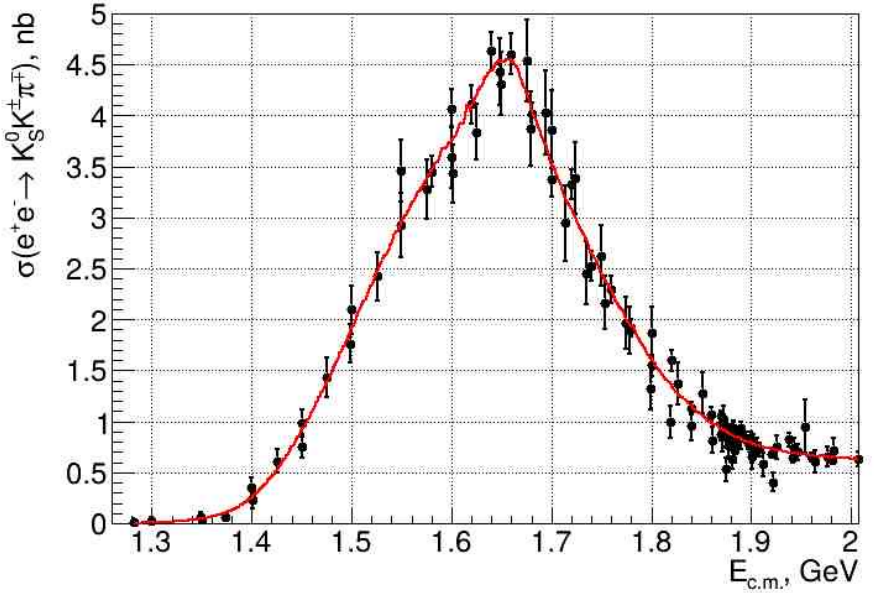
$e^+e^- \to K_S K^\pm \pi^\mp$

In progress









ПАРАМЕТР	ЭТА РАБОТА	PDG
$M_{\phi(1680)}$, МэВ	1652±5	1680±20
$\Gamma_{\phi(1680)}$, МэВ	81±32	150±50
$M_{\rho(1450)}$, МэВ	1577±24	1465±25
$\Gamma_{\rho(1450)}$, МэВ	450±228	400±60
$M_{\rho(1700)}$, МэВ	1800±17	1720±20
$\Gamma_{\rho(1700)}$, МэВ	406±36	250±100

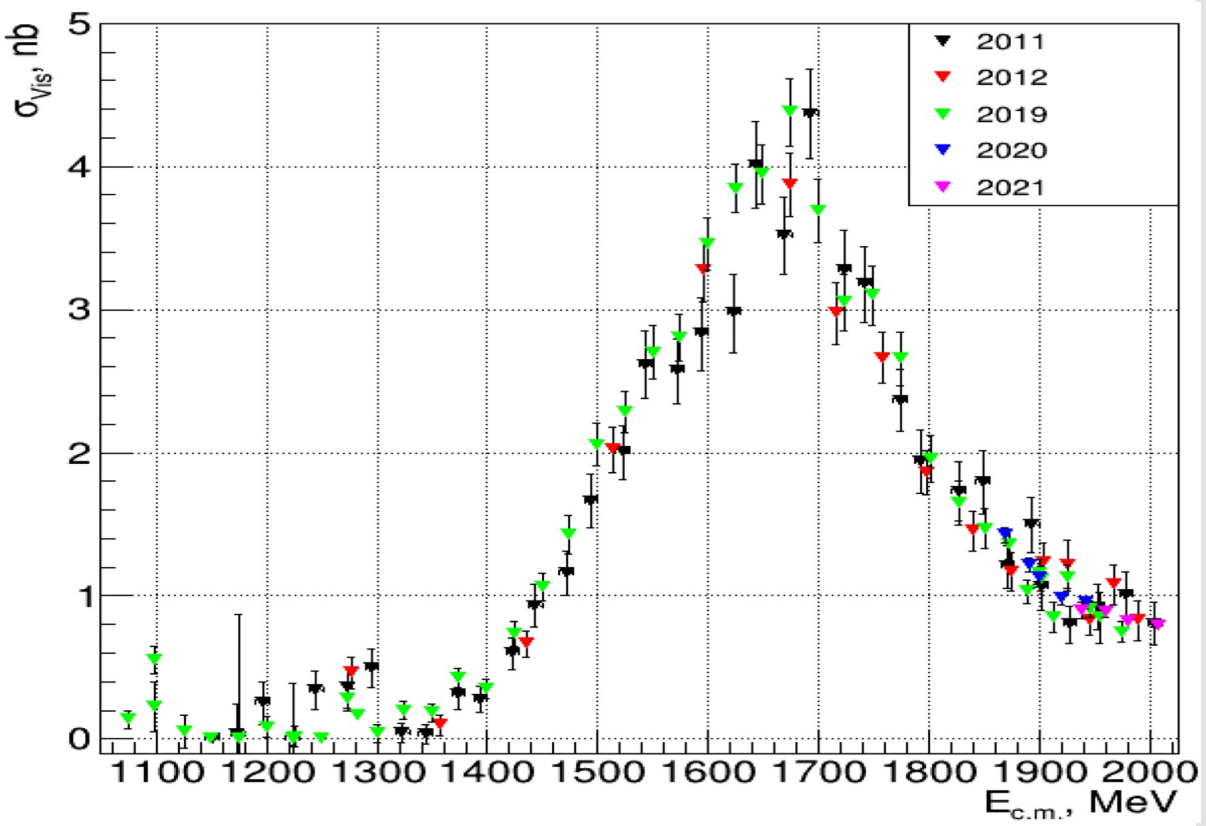
Dominated by $e^+e^- \to K^0\overline{K^{*0}}$ (confirms BaBar)

$e^+e^- \to K_S K_L \pi^0$

$\sigma(e^+e^- \to K_S K_L \pi^0)$
CMD-3

Analysis is ongoing …

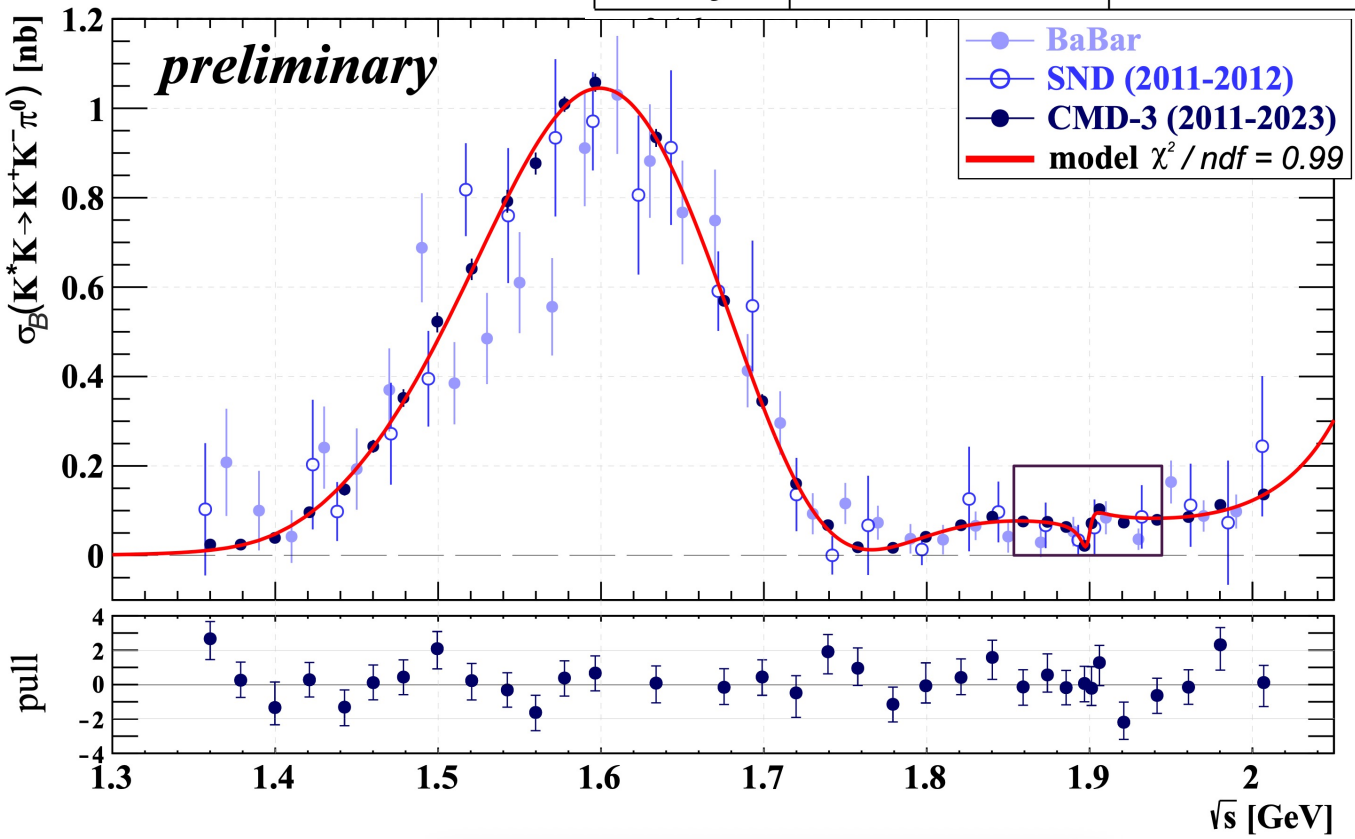
PRELIMINARY



$e^+e^- \to K^+K^-\pi^0$

$\sigma(e^+e^- \to \varphi\pi^0)$ excluded – under separate consideration

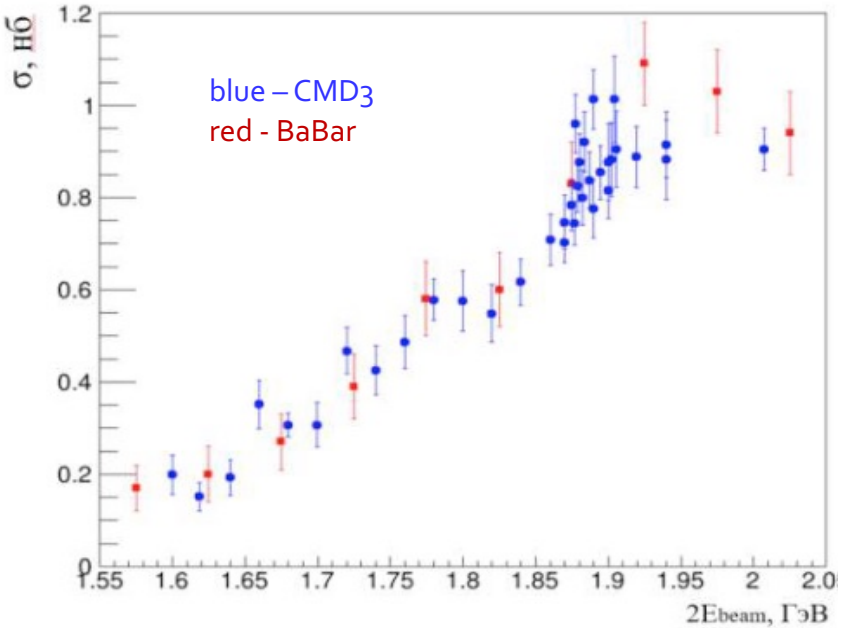
	mass [GeV]	width [GeV]
BW_1	1.752±0.008	0.194±0.01
BW_2	1.598±0.005	0.325±0.015
$\rho(1700)$	1.72 (fixed)	0.25 (fixed)
$\omega(1650)$	1.67 (fixed)	0.315 (fixed)
$\varphi(2170)$	2.175 (fixed)	0.061 (fixed)
BW_3	1.8992±0.0013	0.0069±0.0024



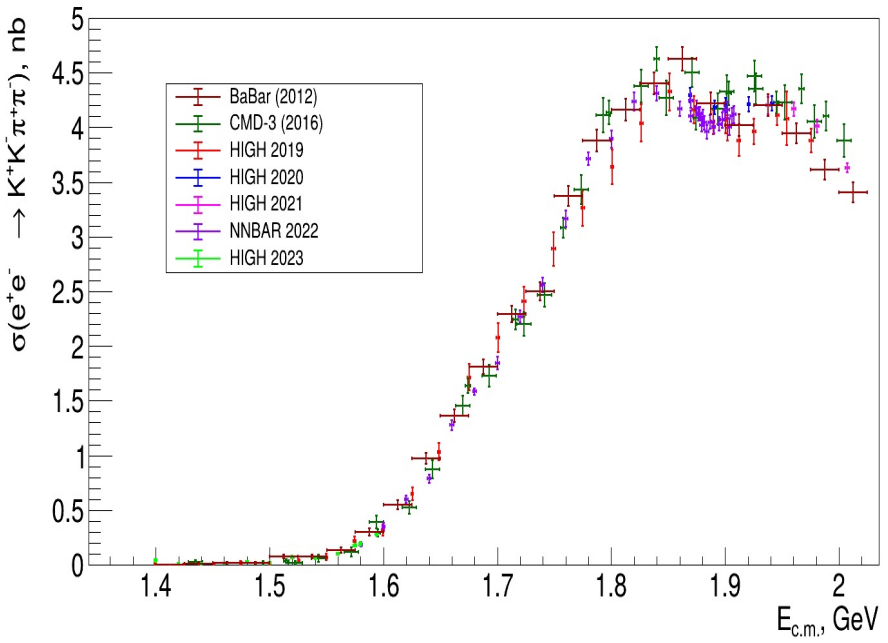
$e^+e^- \to KK\pi\pi$

PRELIMINARY

$e^+e^- \to K_S K_L \pi^+\pi^-$



$e^+e^- \to K^+K^-\pi^+\pi^-$



$$e^+e^- \rightarrow hadrons$$

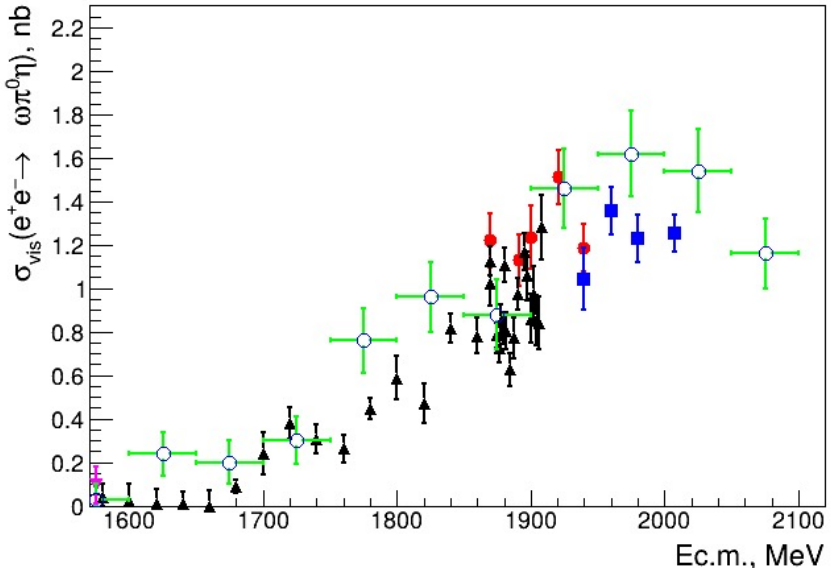
$e^+e^- \to hadrons$

Some number of cross sections for the multihadron reactions havs been published

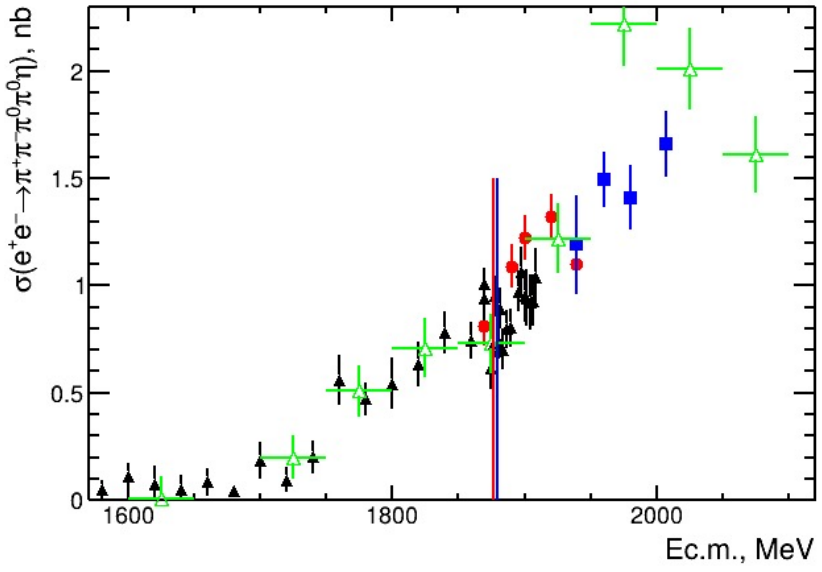
$K_S K^{\pm}\pi^{\mp}\pi^+\pi^-$	PLB 836 (2023) 137606
$K_S K_S \pi^+\pi^-$	PLB 804 (2020) 135380
$3(\pi^+\pi^-)\pi^0$	PLB 792 (2019) 419

New (preliminary) study – paper draft is about to submit to JHEP

$e^+e^- \to \omega\pi^0\eta$



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

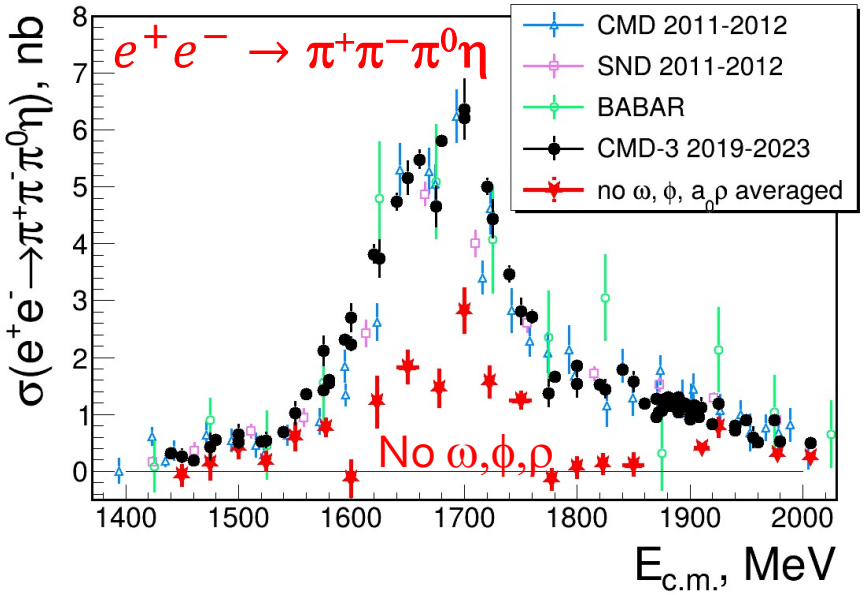


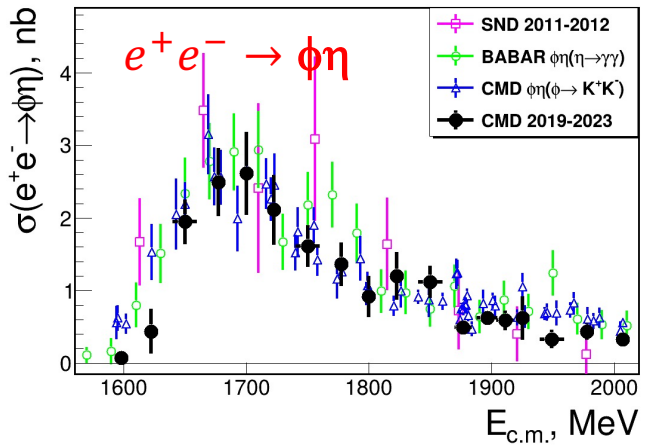
Comparison with the BaBar measurements

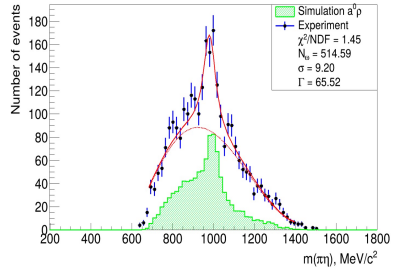
PRELIMINARY

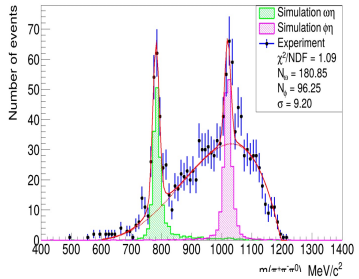
$e^+e^- \to \pi^+\pi^-\pi^0\eta$

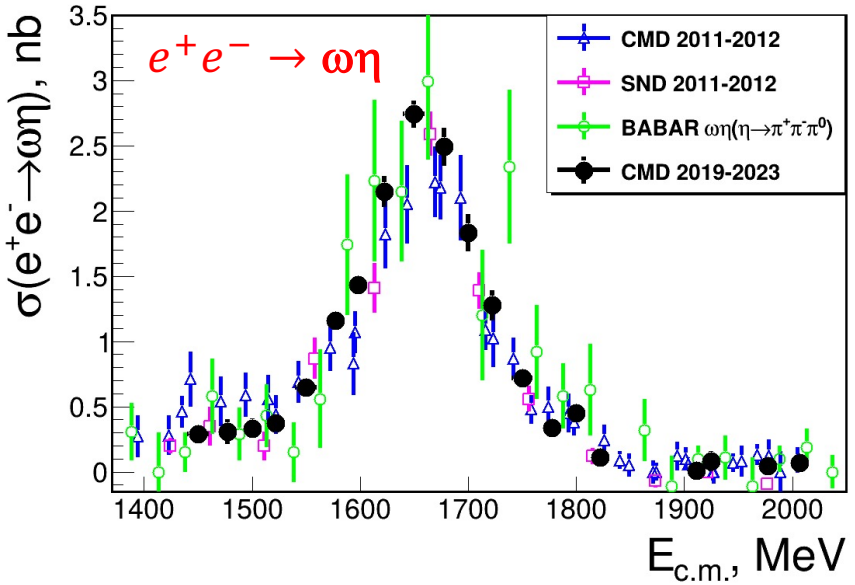
Previous study was published based on 21 pb^{-1} (PLB 773 (2017) 150) .
Now we use 482 pb^{-1}

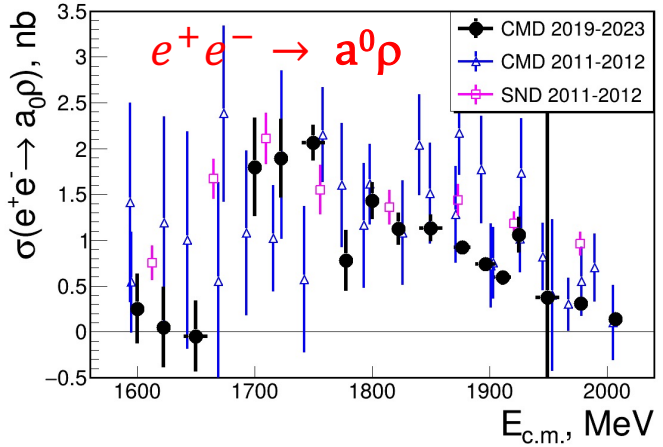












Hadrons study at and around NNbar

Detailed study of the NNbar threshold

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: — 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}

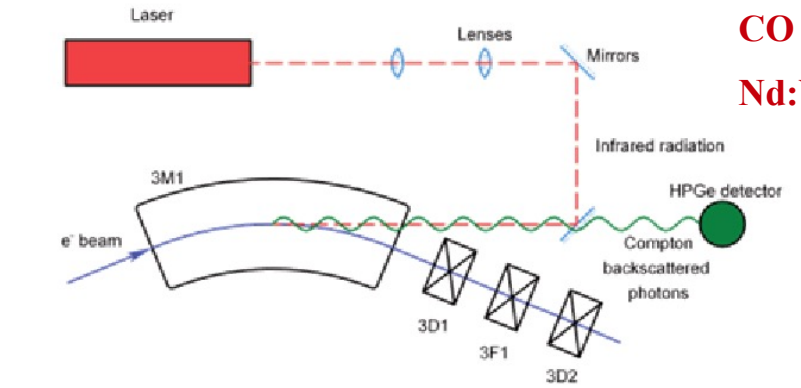
Beam energy measurement

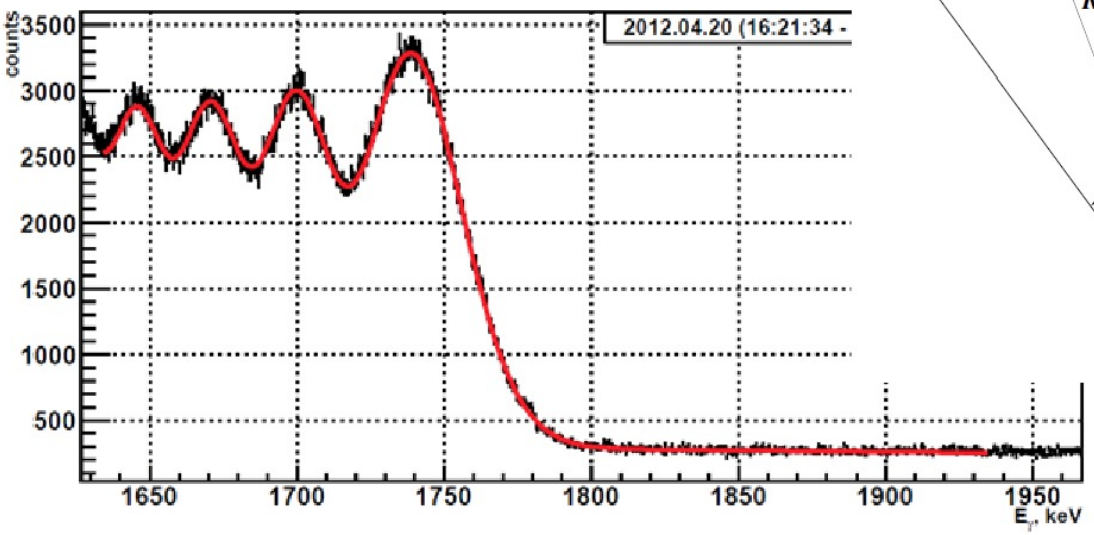
Starting from 2012, beam energy and energy spread are monitored continuously using Compton backscattering system with about 30 keV uncertainty

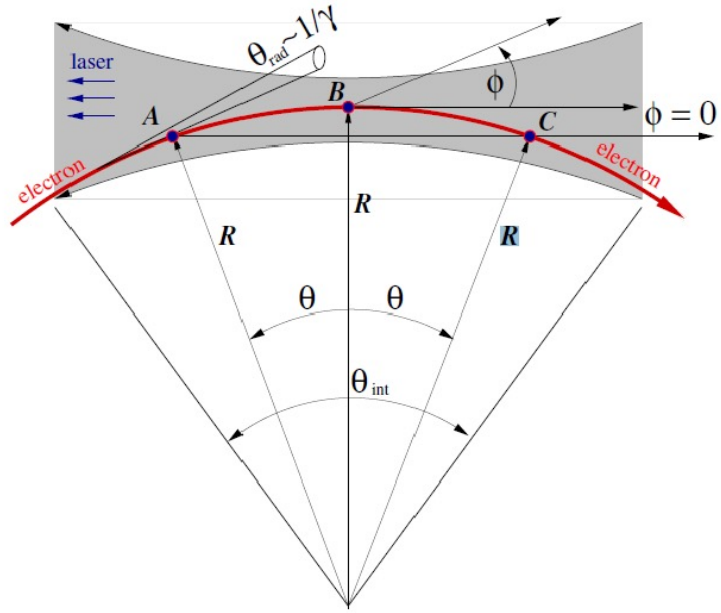
Two sources of photons are used: **ytterbium** and **CO lasers**.

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

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





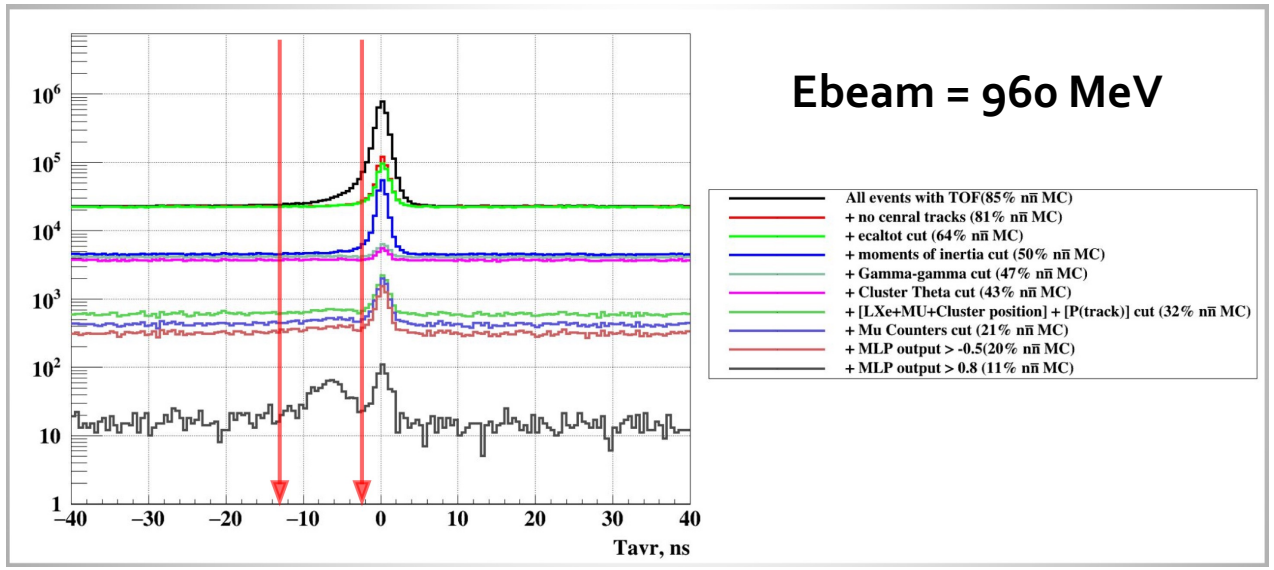


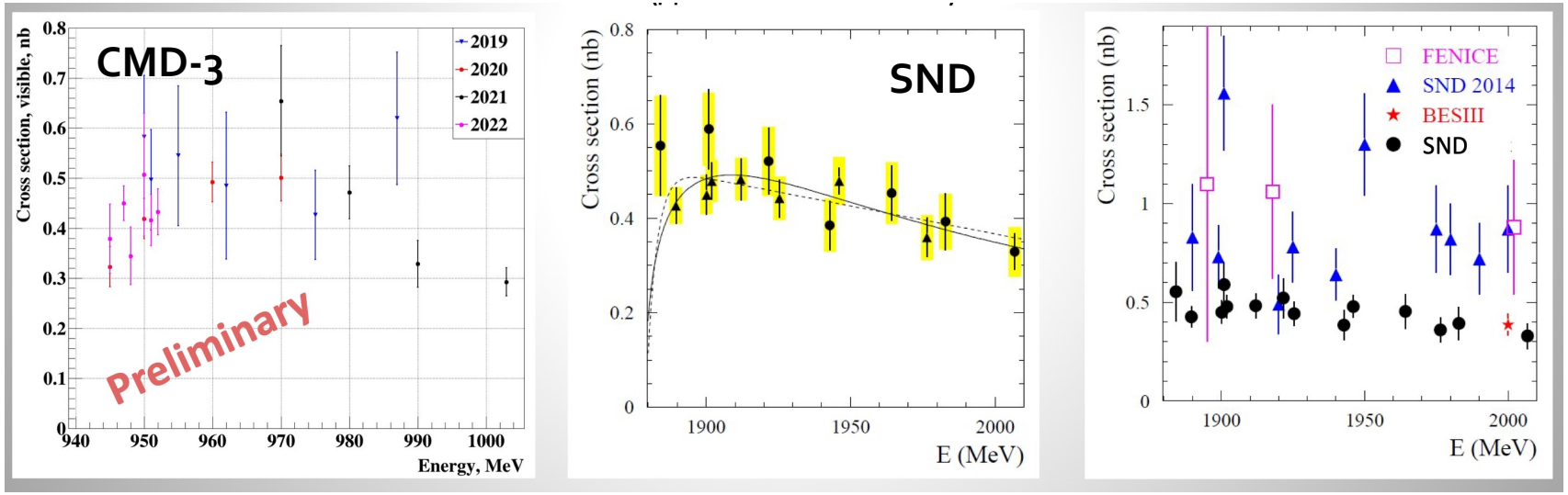
E = 993.662 ± 0.016 МэВ

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

Neutron-anti-Neutron production

CMD-3 Time-Of-Flight system is used with single large cluster in calorimeter: 5-order of background suppression!

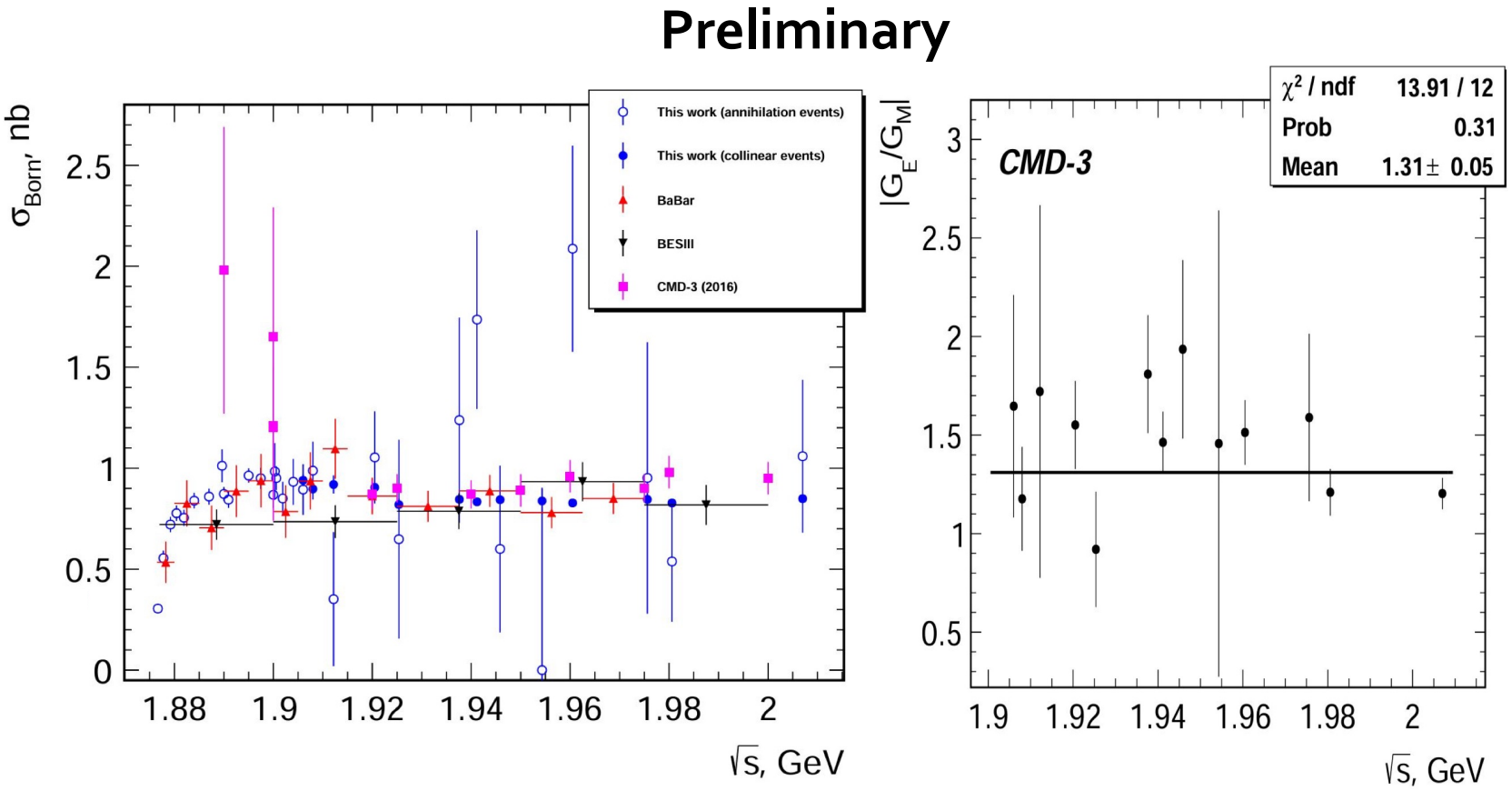




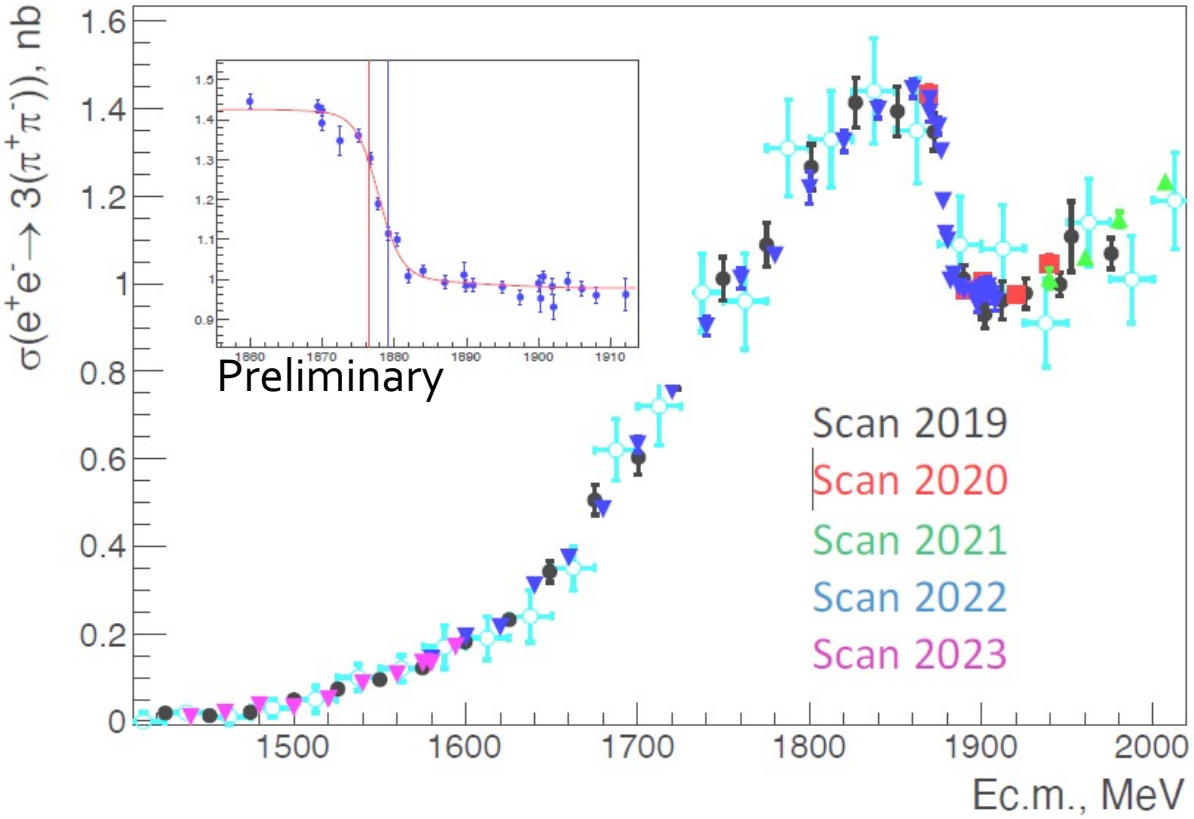
Annihilated in the beam-pipe (and in the DC inner wall) and collinear events in DC are used

Proton-anti-proton production

Previous study was with ~17 times less data Phys. Lett. B 794 (2019) 64–68



$e^+e^- \to 3(\pi^+\pi^-)$



~30% drop in XS!

A "natural" explanation of the effect assumes a virtual appiarance and annyhilation of pbap-nbarn pairs below the threshold and drop of the cross section due to openning real NbarN pair production.

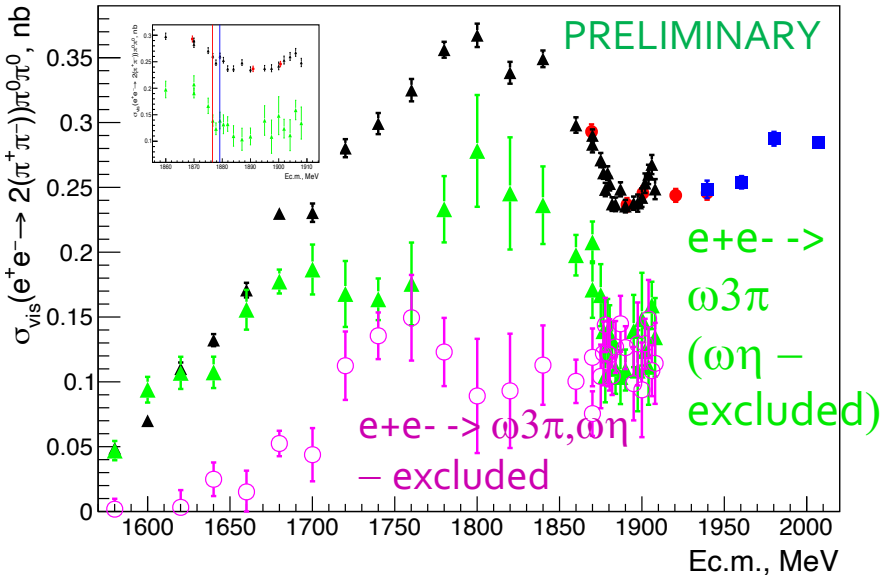
After unfolding fit gives ~30% drop with 1.91+-0.15 MeV shape at 1877.9+-0.13 MeV – exactly between pbarp and nbarn production thresholds.

Best intermediate state matching angular and mass distributions is: e+e- -> $f_0(1500)\rho$ with a mixture of decays $f_0 \to 2(\pi\pi)$, $f_0 \to \rho\rho$, $f_0 \to a_1\pi$ about 3% model-dependent syst.uncertainty can be assigned

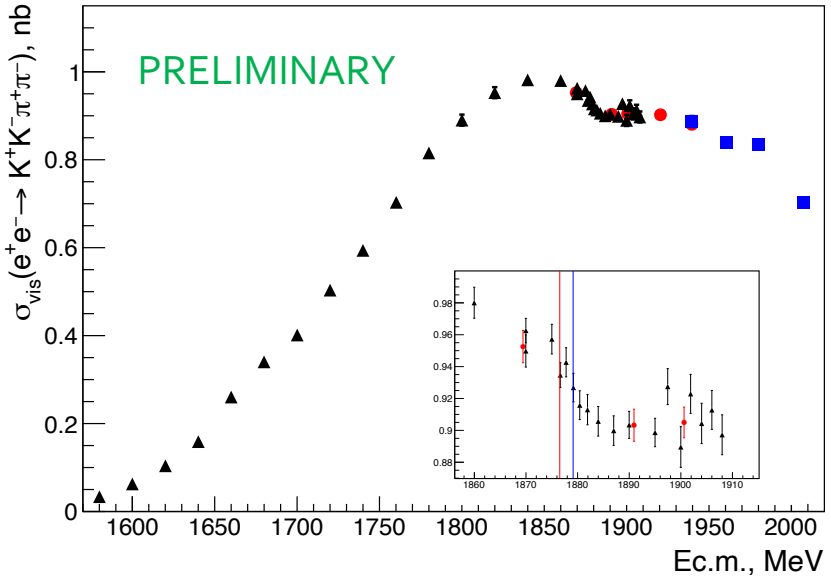
Other channels?

First look to visible (number of events/luminosity) cross sections (no corrections)

$e^+e^- \to 2(\pi^+\pi^-)\,\pi^0\pi^0$



$e^+e^- \to KK\pi\pi$

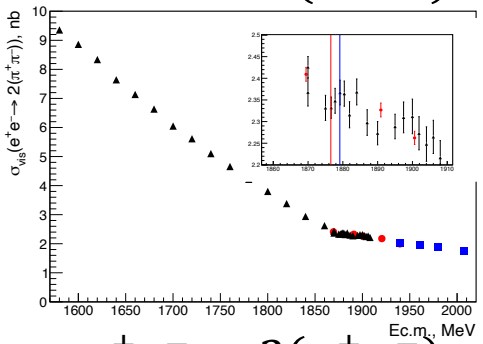


Only these two channels demonstrate an influence of the NNbar threshold to the XS!

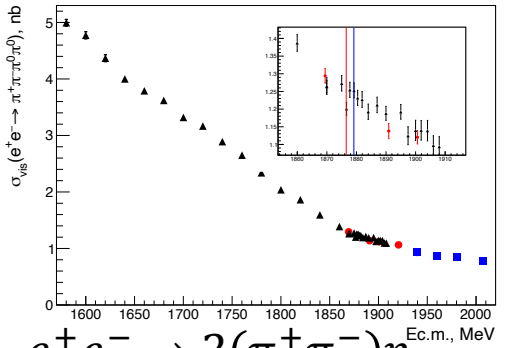
There are no other channels, demonstrating this effect!

Other channels?

$e^+e^- \to 2(\pi^+\pi^-)$

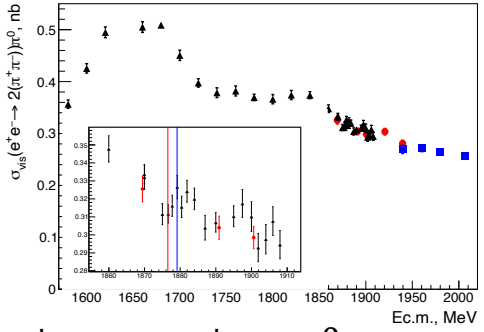


$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

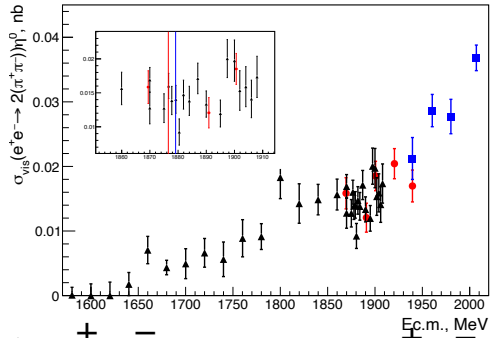


NO IDEAS WHY

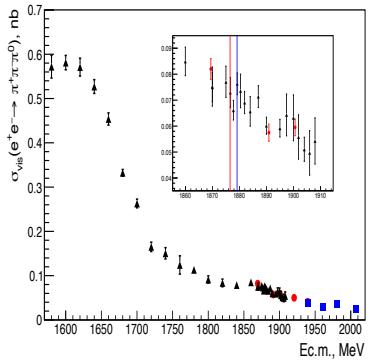
$e^+e^- \to 2(\pi^+\pi^-)\,\pi^0$



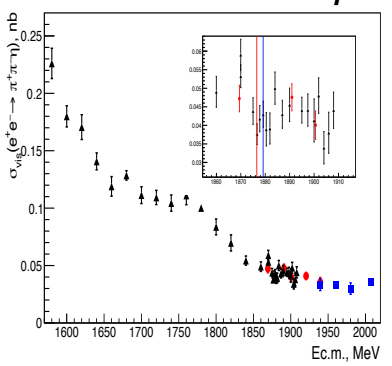
$e^+e^- \to 2(\pi^+\pi^-)\eta$



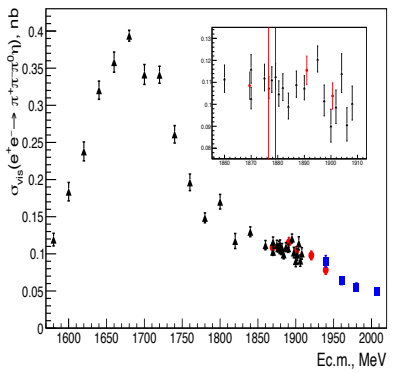
$e^+e^- \to \pi^+\pi^-\pi^0$



$e^+e^- \to \pi^+\pi^-\eta$



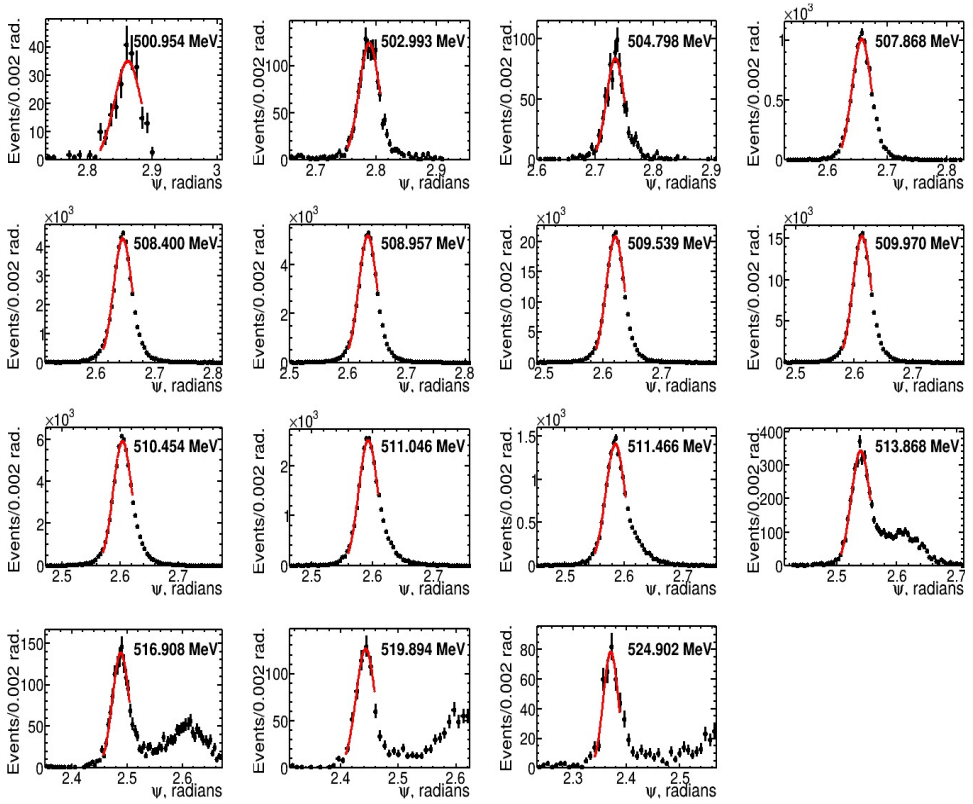
$e^+e^- \to \pi^+\pi^-\pi^0\,\eta$

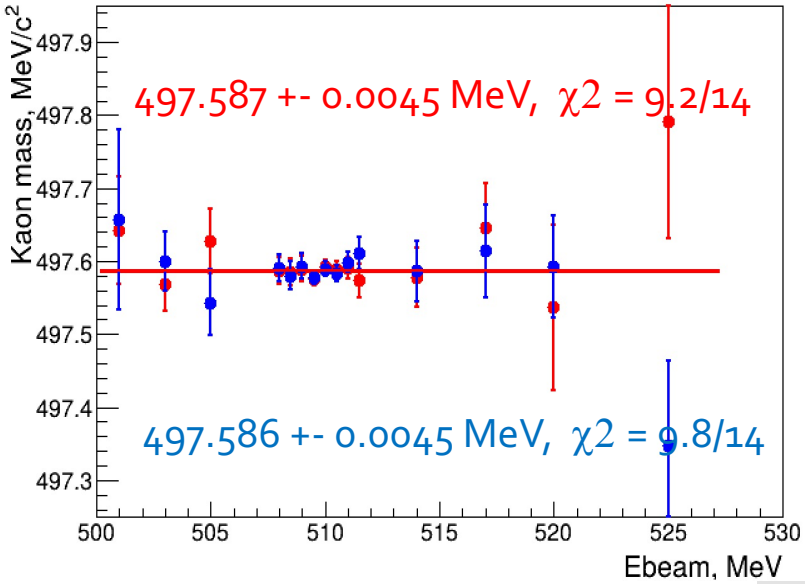


New K⁰ mass measurement

Using edge angle approach for 15 points around ϕ-resonance, and a calibration by the PDG ϕ-resonance mass we obtaine:

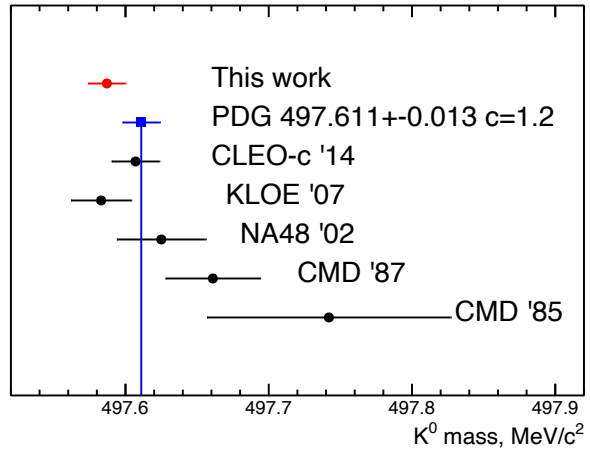
$m(K^0) = 497.587 \pm 0.004(stat) \pm 0.009(syst.calbr) \pm 0.008(syst.cmd)$, MeV/c²



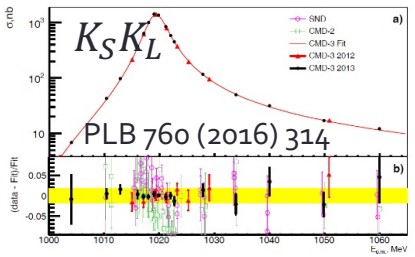


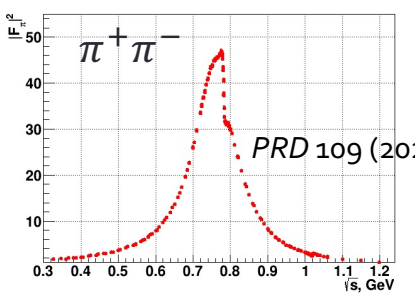
$m(K^0) = 497.587 \pm 0.004(stat.) \pm 0.012(syst.)$

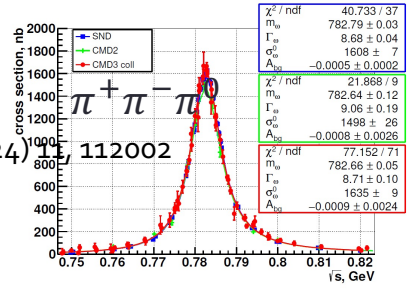
Paper is about to submit to JHEP

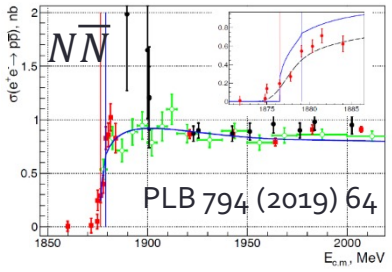


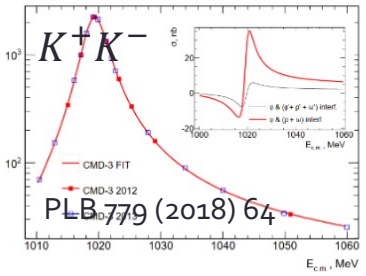
Published CMD-3 results

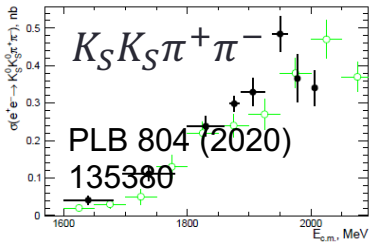


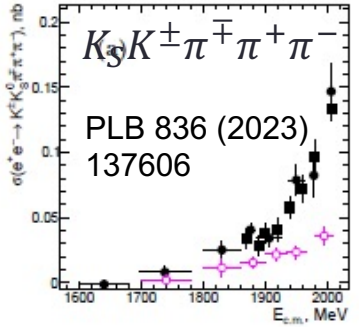


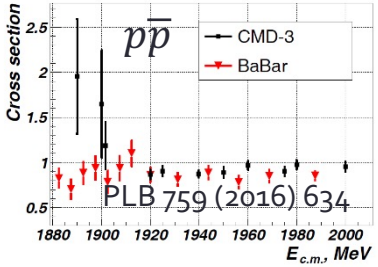


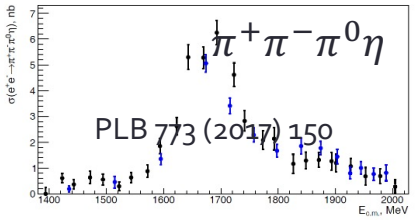


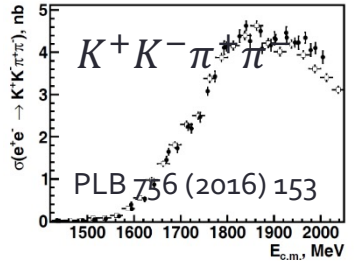


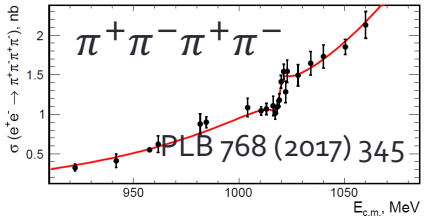


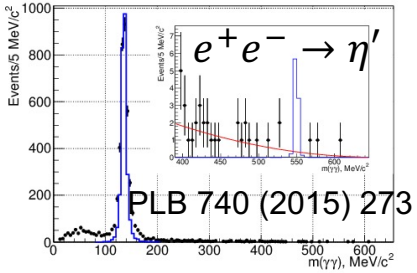


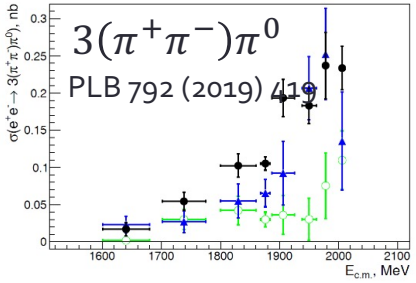


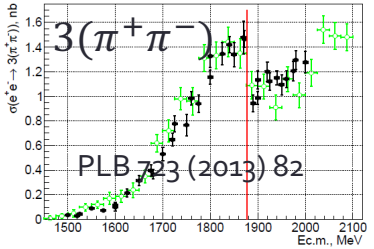


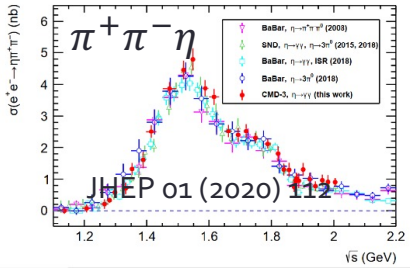


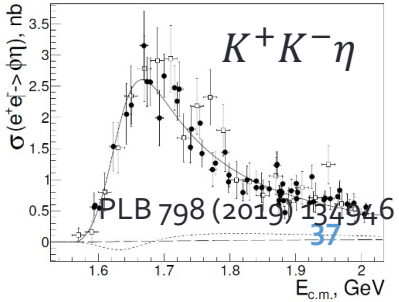












VEPP-2000 /CMD-3 plans

We plan to finish low-energy scan and take some dedicated high energy data over next two years *(potential systematics tests: reverse beams – DONE!, no LXe,…)*

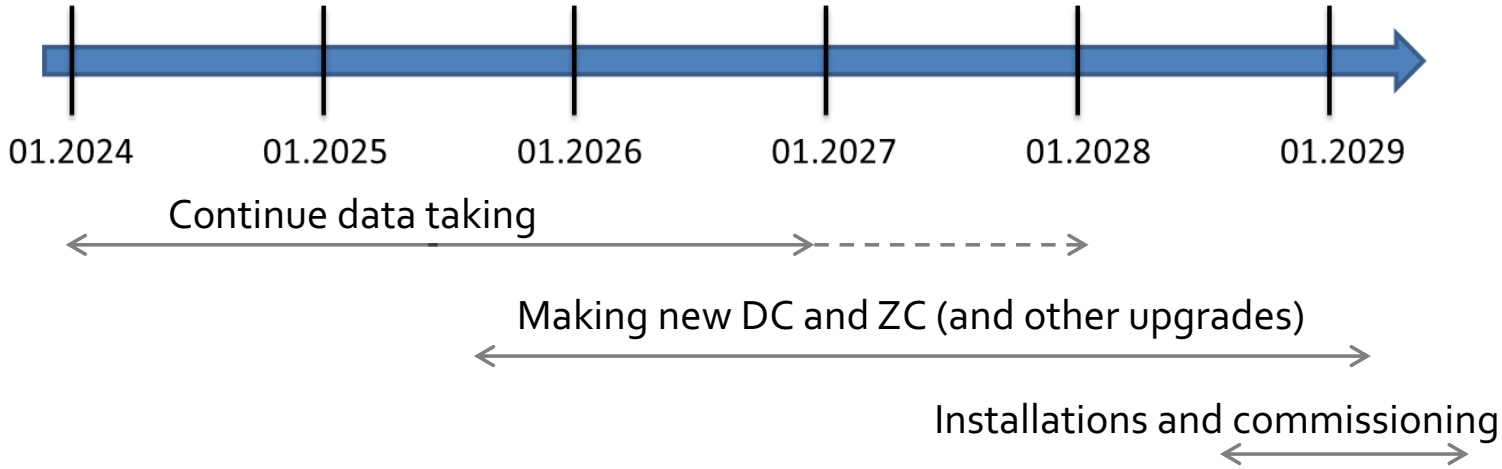
Then we plan to have 1-2 year break for detectors upgrades

CMD-3 planned upgrades:

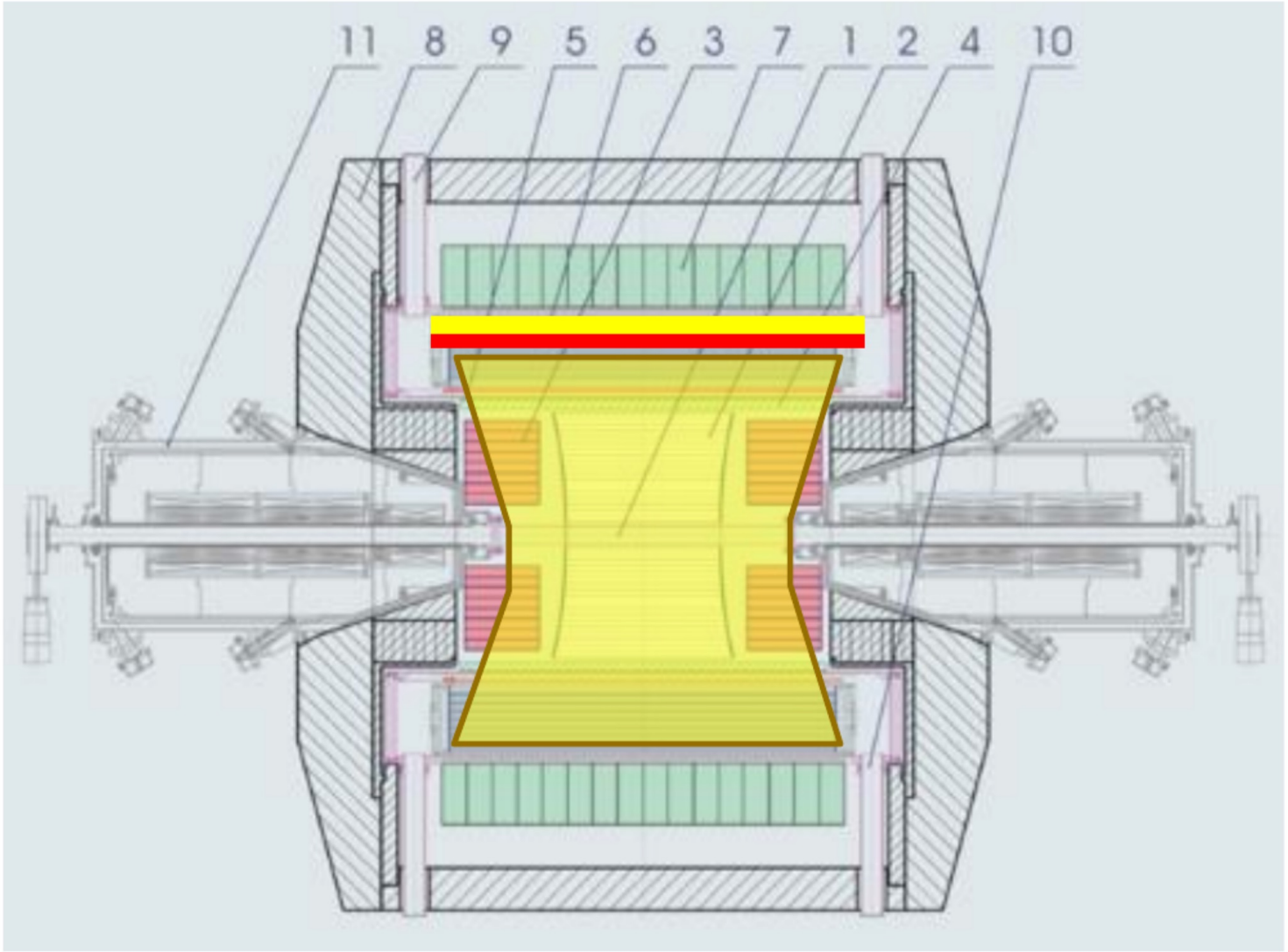
- new drift chamber with semi-conducter strip detector at the inner radius
- new Z-chamber at outer radius
- upgrade of electronics

Various options are discussed: longer DC, larger DC, larger magnetic field,…

The goal is to reach ~0.2-0.3% in $\sigma(e^+e^- \to \pi^+\pi^-)$



Large DC



Claim to have $\pi-\mu$ sepatation by momentum up to 1 GeV
Use semiconducter strip detector at the vacuum pipe and Z-chamber for precision angle measurement

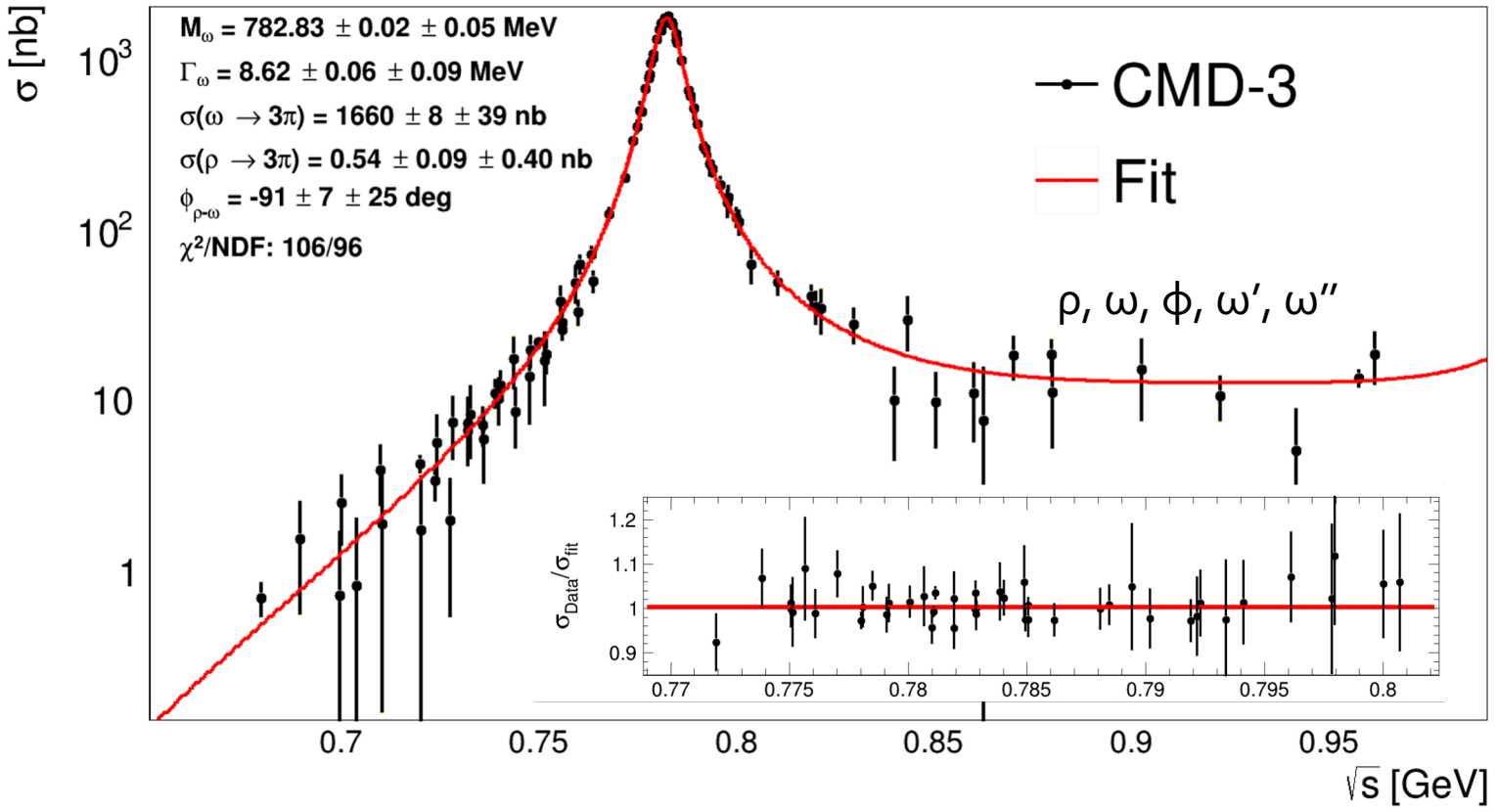
Summary

- The CMD-3 has collected over 1 fb^{-1} of data
- Huge amount of data allows to study tiny effects and rich a percent level of uncertainty – it takes time and delay publications.
- About 20 different analyses are in processing.
- We plan to continue data taking over next ~2 years, with the focus of energies below 1 GeV with 3-4 times more data, and around NNbar threshold.
- Now we are below ω-meson (Ebeam=395 MeV) and starting in October continue the scan down to Ebeam <~200 MeV.
- There are plans for CMD-3 upgrade over next 3-4 years, aimed at measurement of $\pi^+\pi^-$ cross section at the next level of precision (ultimately – to match FNAL)

THANKS

BACK UP

BackUP


M_ω = 782.83 ± 0.02 ± 0.05 MeV
Γ_ω = 8.62 ± 0.06 ± 0.09 MeV
$\sigma(\omega \to 3\pi)$ = 1660 ± 8 ± 39 nb
$\sigma(\rho \to 3\pi)$ = 0.54 ± 0.09 ± 0.40 nb
$\phi_{\rho-\omega}$ = -91 ± 7 ± 25 deg
χ^2/NDF: 106/96
CMD-3
Fit
ρ, ω, ϕ, ω′, ω″
σ [nb]
10^3
10^2
10
1
0.7
0.75
0.8
0.85
0.9
0.95
√s [GeV]
$\sigma_{Data}/\sigma_{fit}$
1.2
1.1
1
0.9
0.77
0.775
0.78
0.785
0.79
0.795
0.8

Insights into CMD2/CMD3 difference

- We don't have means to do a full scale CMD-2 analysis – we can only get some hints about the potential sources of difference
- The radiative corrections are not the suspects.
- Suspect #1. Subtraction of cosmic background

  At CMD-3 we've developed better method to count cosmic background. Now we know that CMD-2 method had unaccounted systematic error (but we can't estimate it).

  The CMD-2 cosmic background was much larger:6% - 15% compare to 0.12% for CMD-3
- Suspect #2. Event separation based on energy deposition

  CMD-3: LXe only ($5X_0$) and full calo ($13X_0$), observed very different behavior/systematics; might be able to take CsI only data

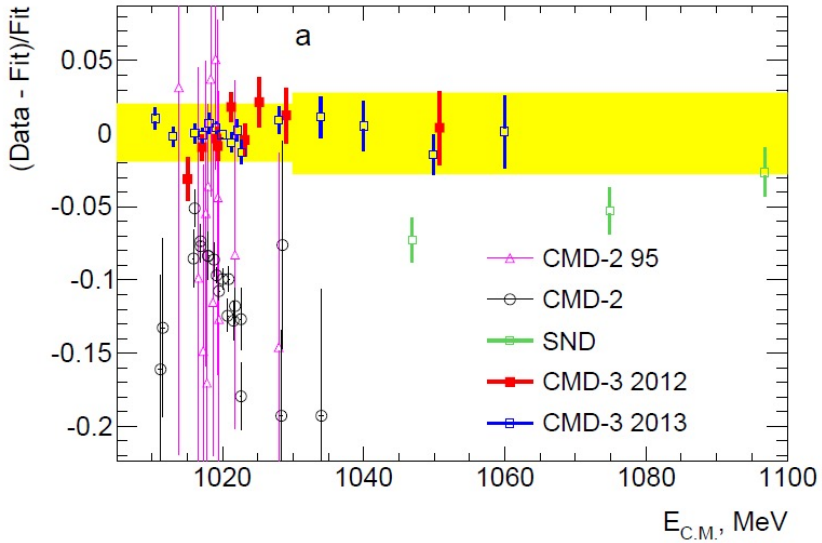
  CMD-2: CsI only ($8X_0$), systematics were estimated
- Suspect #3. Trigger. (correction was small, but could be …)

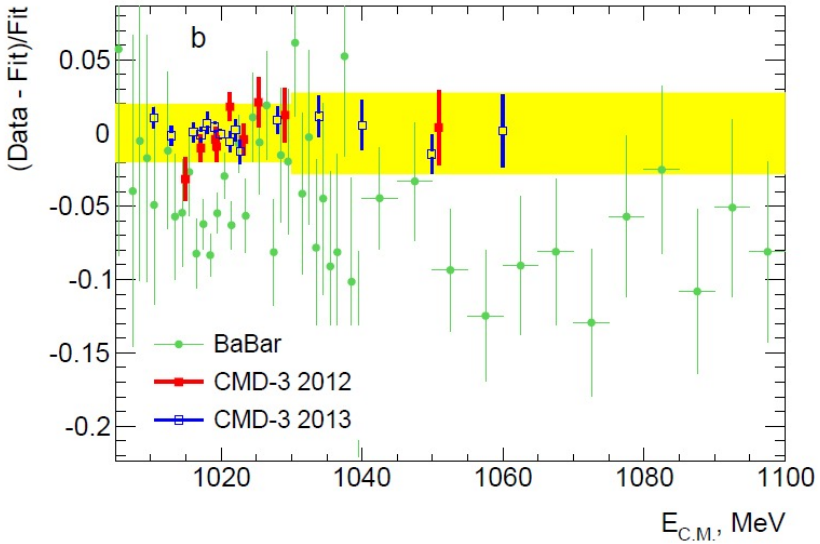
  Cmd2 had only one trigger with DC (4-6 superlayers), Z-chamber (2 layers) and CsI calorimeter with 40 MeV threshold in coincidence. Efficiency was studied assuming no correlations for π^+ and π^-. Correlated missing of both tracks could be – we have it with CMD-3

All above was discussed at the previous presentations – we did not see large effects

K^+K^- CMD3 / CMD2

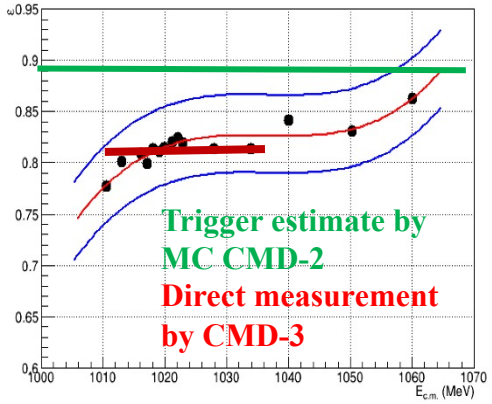
(example of trigger influence)



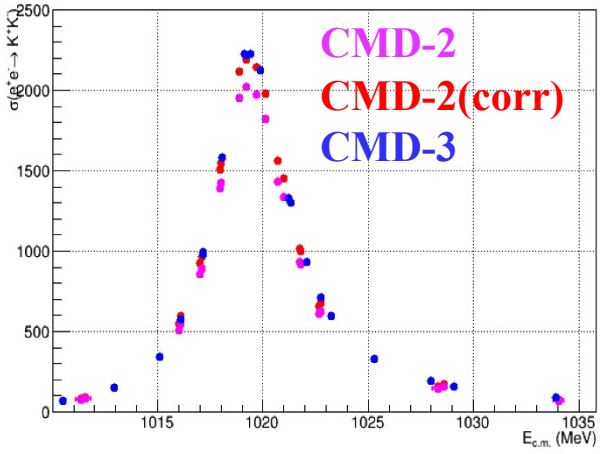


CMD-2 measured K^+K^- cross section ~10% lower than CMD-3

Suspect: trigger efficiency. At CMD-2 it was estimated by MC. At CMD-3 we've measured it and found 9.5% bias to CMD-2 estimate.



Measured CMD-2 trigger efficiency for K^+K^-



Effect of the correction on K^+K^- cross section

Not published