RECENT RESULTS FROM THE CMD-3 DETECTOR AT VEPP-2000 COLLIDER

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on behalf of CMD-3 collaboration

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*THE REAL SCIENCE

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НИИЯФ МГУ

Outline

- ❑ **Motivation**
- ❑ **Collider and Detector**
- ❑ **Experiment**
- ❑ **Physics Results**
- ❑ **Conclusion**

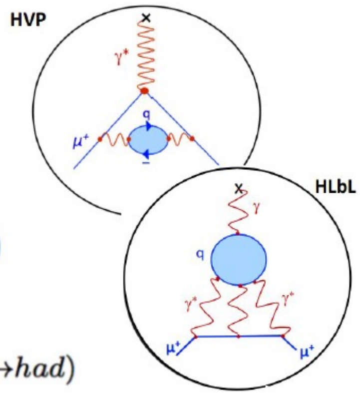
(g-2)/2 of muon (Motivation)

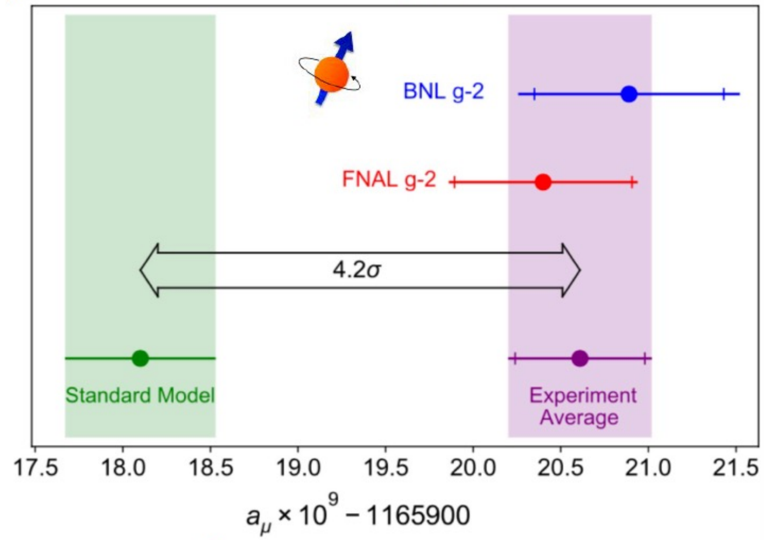
$a_\mu = (g-2)/2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (11\ 659\ 181.0 \pm 4.3) \cdot 10^{-10}$

Kinoshita et al.'12 (11 658 471.808 ± 0.015) · 10^{-10}

Czarnecki et al. (15.4 ± 0.2) · 10^{-10}

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{S}$$





- Optical theorem and analyticity for HVP:

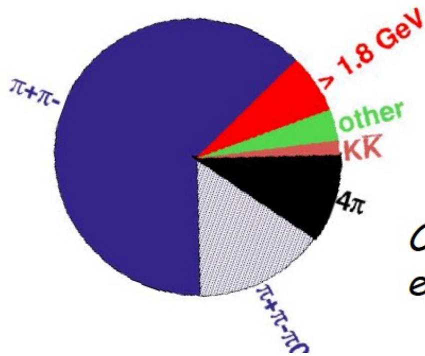
$$\sigma(s)_{(e^+e^-\to had)} = \frac{4\pi}{s}\,\mathrm{Im}\,\Pi_{hadron}(s)$$

$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\,K(s)\cdot\sigma(s)_{(e^+e^-\to had)}$$

- The main contribution is in resonances in low energy region

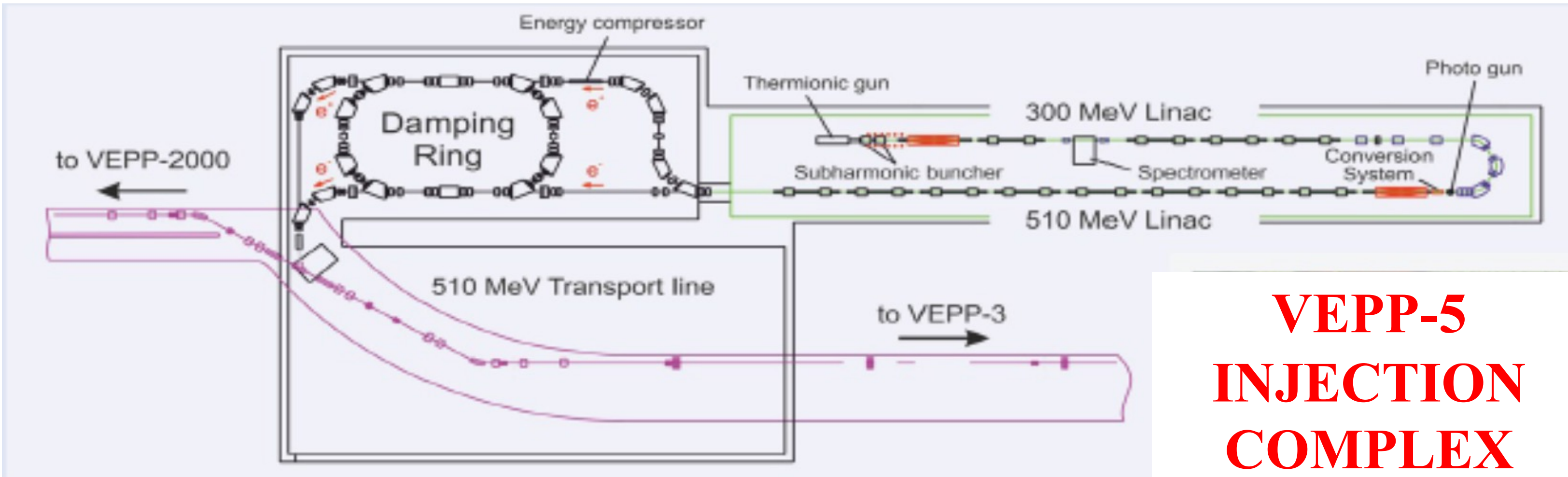
$$K(s) = \int_0^1 dx\,\frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s}$$

- The enhancement at low energy implies that the $\rho\to\pi^+\pi^-$ resonance is dominating in the dispersion integral (~75%). Current precision at 0.6%.



Contributions to HVP error of a_μ

VEPP-2000 Collider



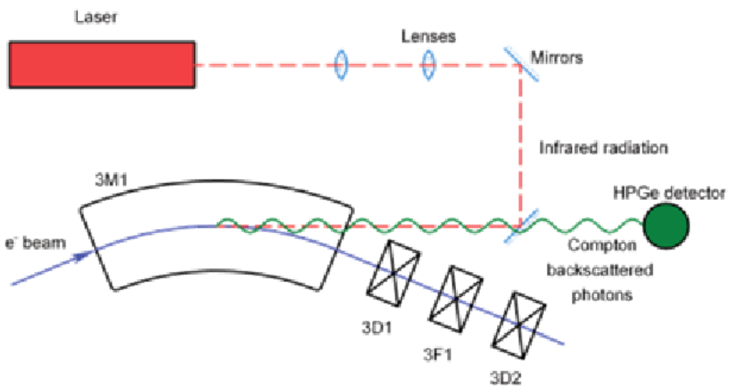
VEPP-5 INJECTION COMPLEX

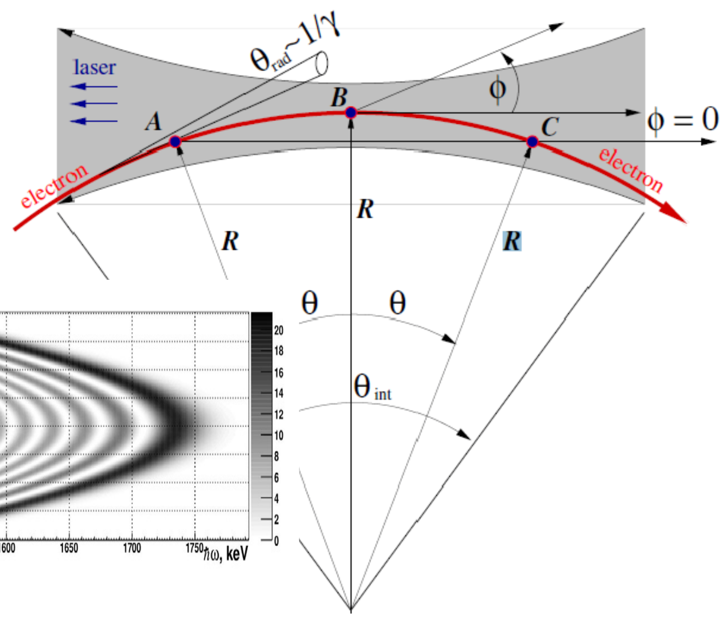
	Parameters at 1 GeV	
	Design	Achieved
Circumference	24.388 m	
Beam energy, MeV	150–1000	160–1005
N of bunches	1×1	
N of particles / bunch	1×10^{11}	0.9×10^{11}
Luminosity, $cm^{-2}s^{-1}$	1×10^{32}	0.5×10^{32}

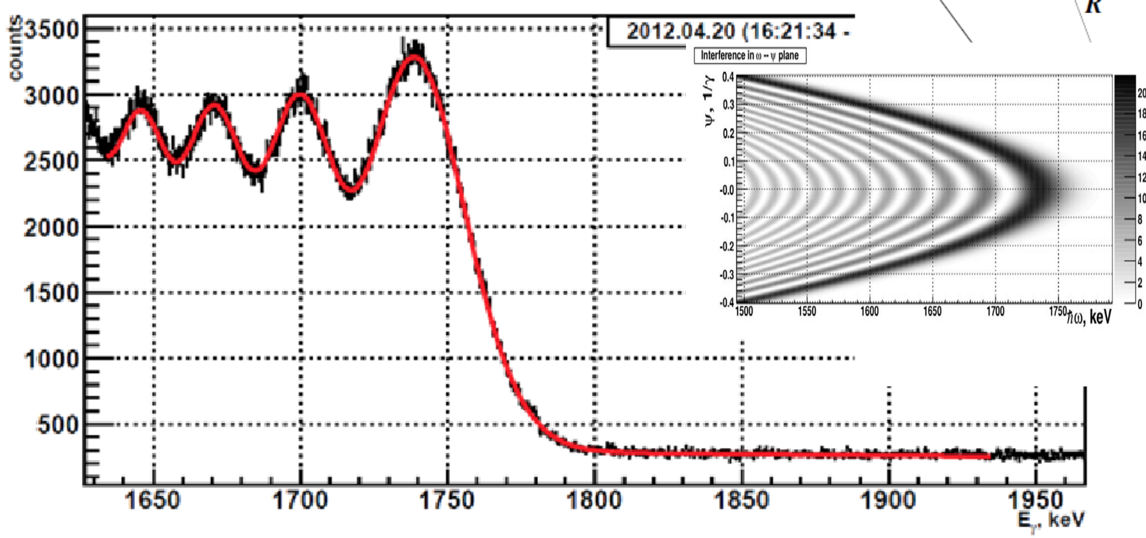
- Round beams concept
- 13 T solenoids for FF
- E_{beam} controled by CBS ($\sigma_{\sqrt{s}} = 0.1$ MeV)

Energy measurement

Starting from 2012, energy is monitored continuously using Compton backscattering

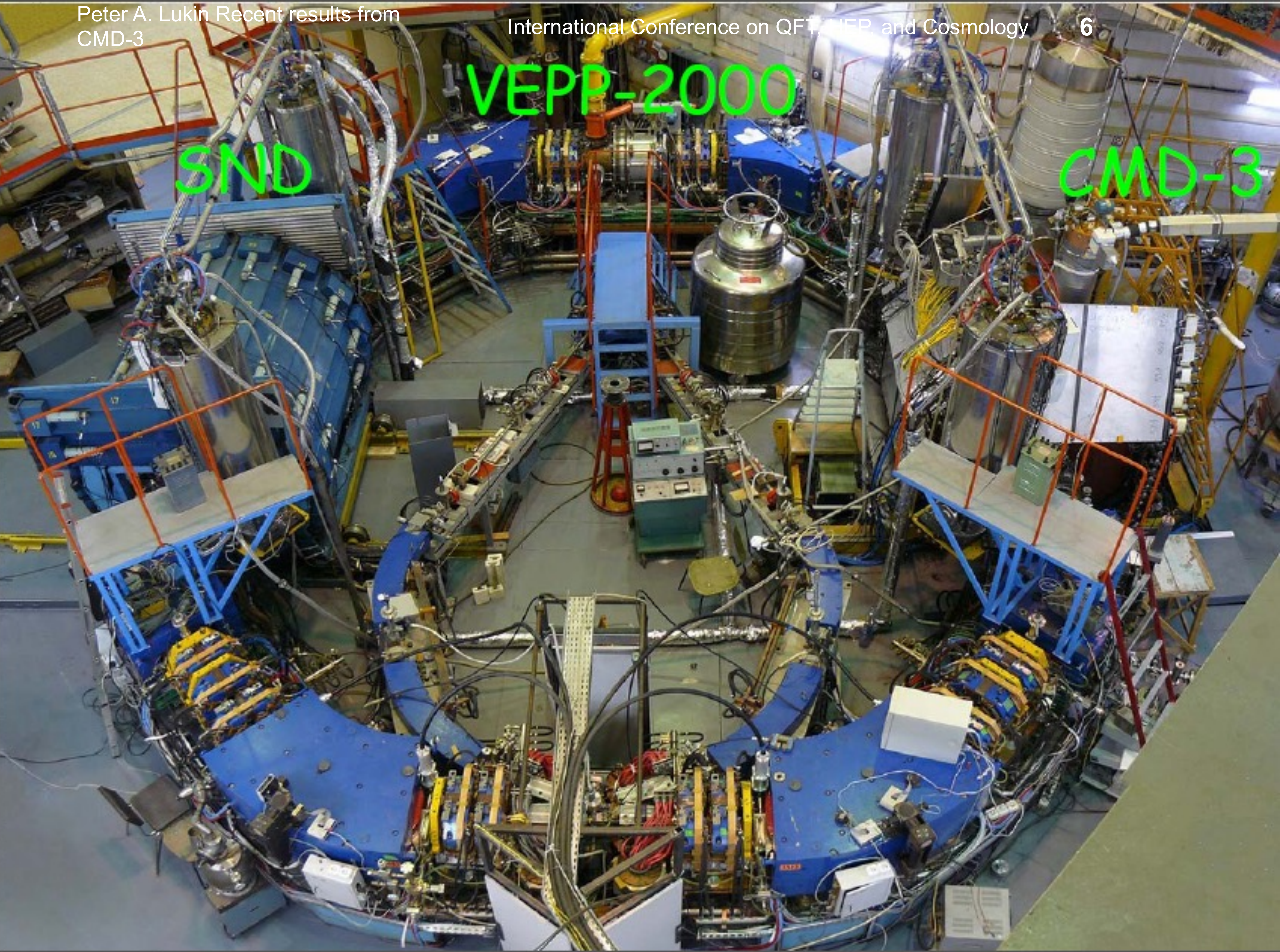




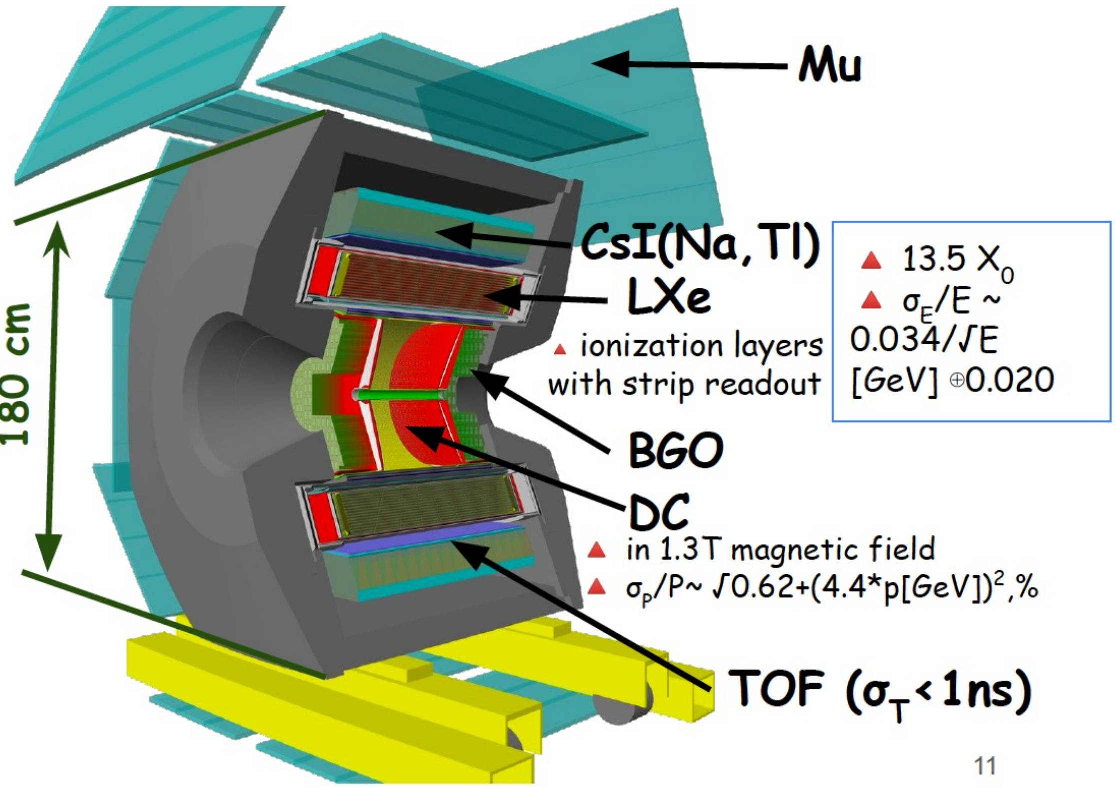


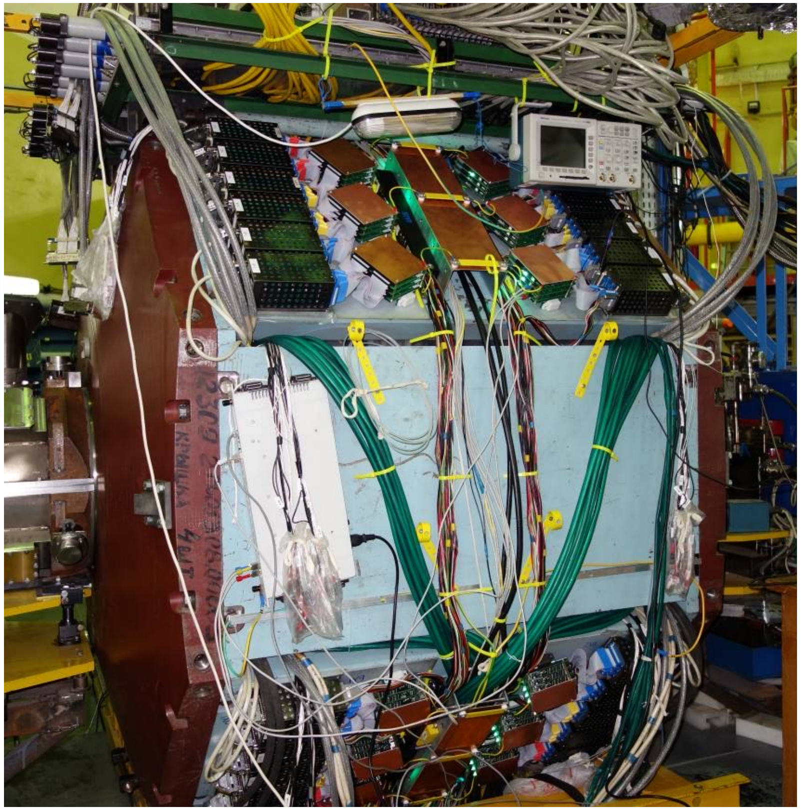
E = 993.662 ± 0.016 MeV

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

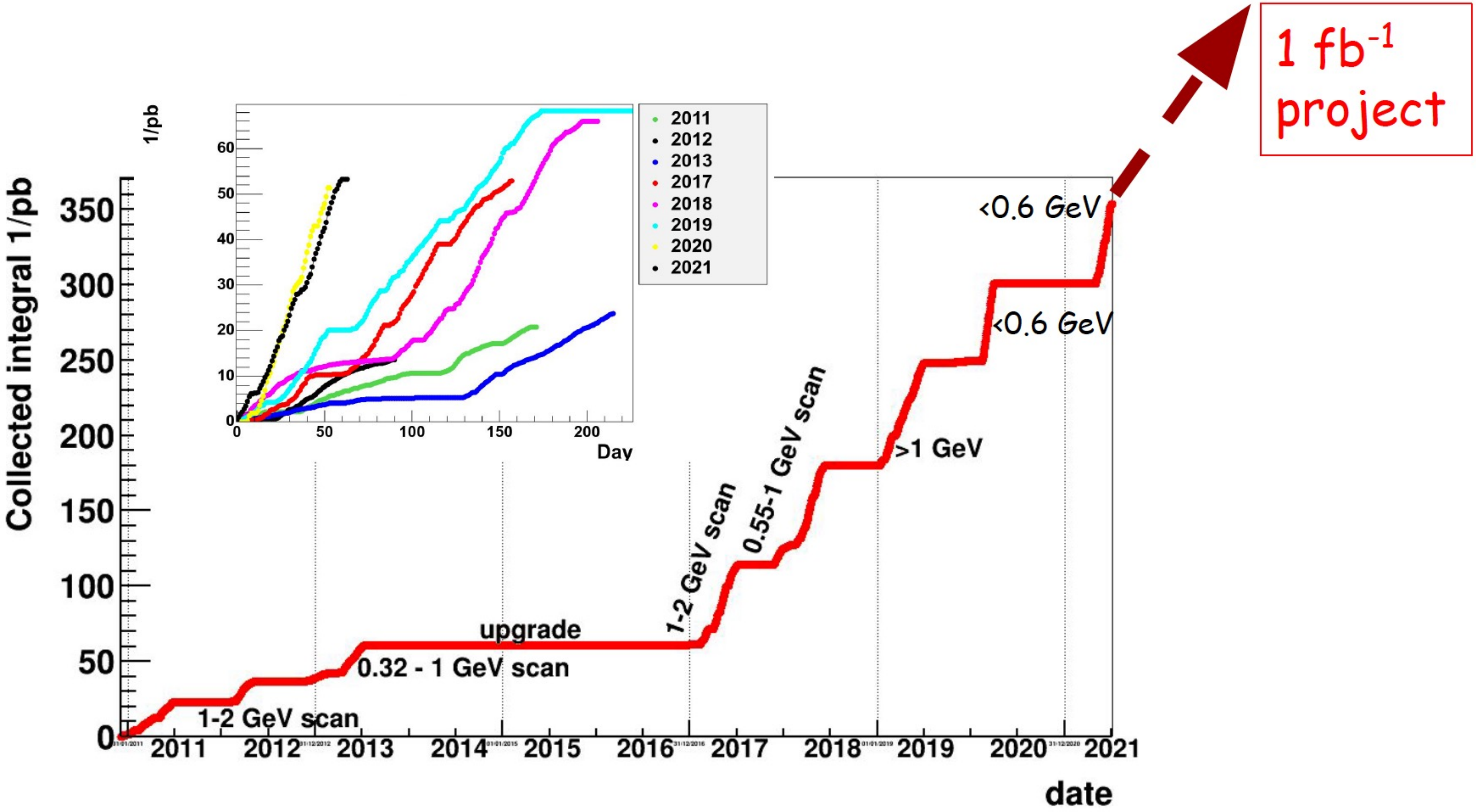

VEPP-2000
SND
CMD-3

Detector CMD-3



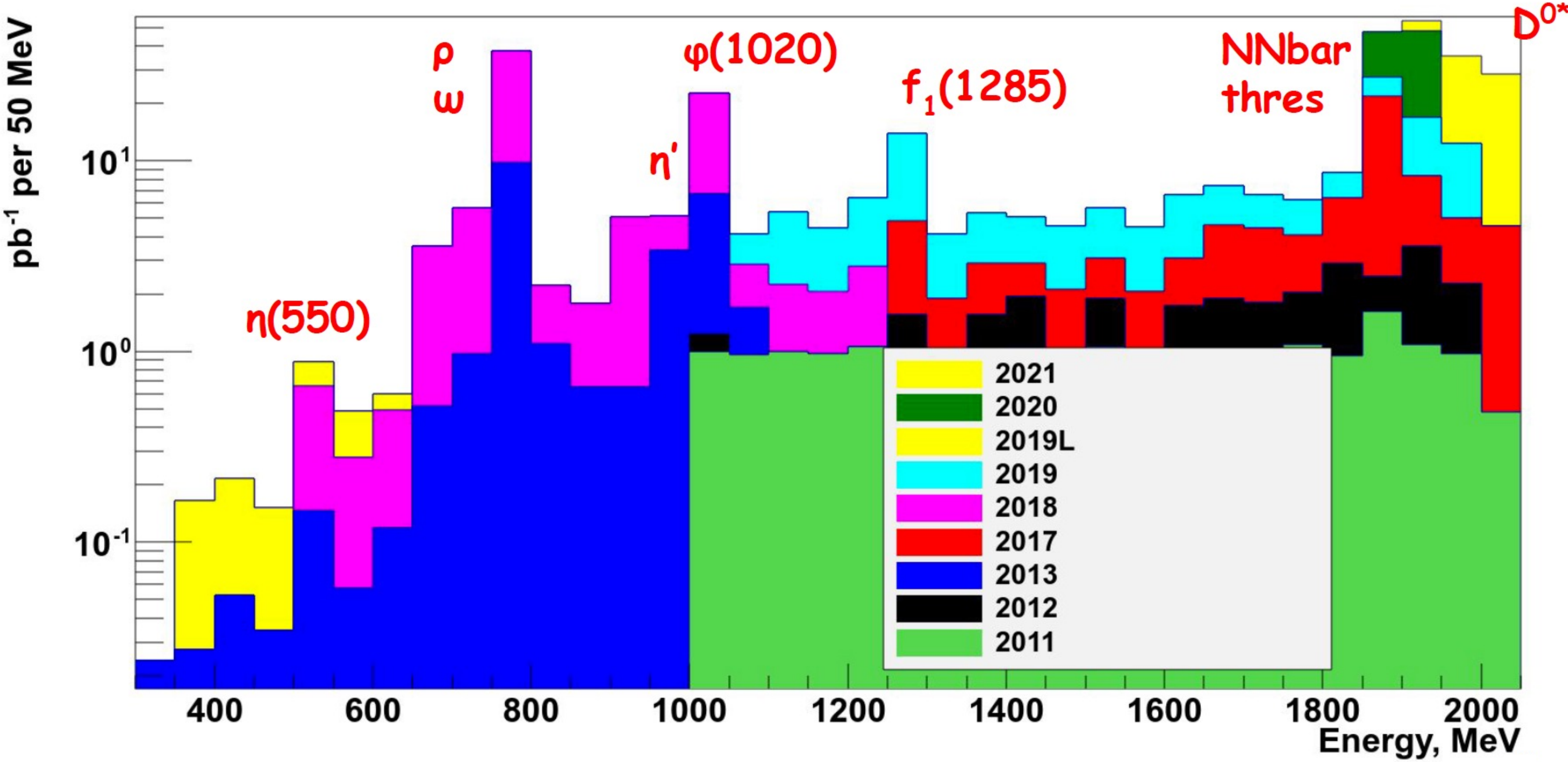


Experiment 2011-2021

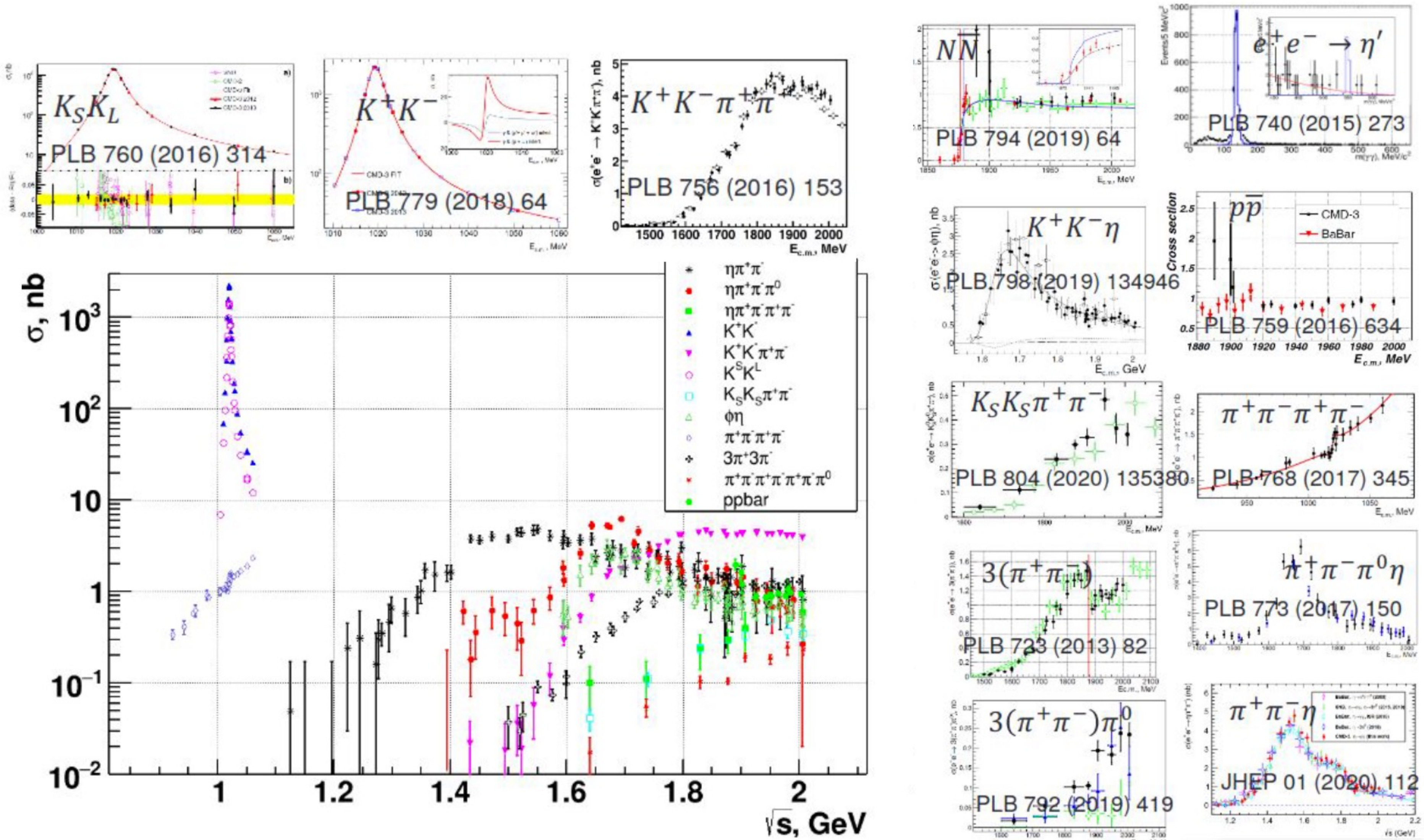


Luminosity Integral collected in 2011-2021 is 370 pb^{-1} and doubled in 2022

Luminosity collected in 2011-2021



CMD-3 published results



Exclusive channels $e^+e^- \to hadrons$

At VEPP-2000 we do exclusive measurement of $\sigma(e^+e^- \to hadrons)$.

published
in progress

- 2 charged

$$e^+e^- \to \pi^+\pi^-, K^+K^-, K_SK_L, p\overline{p}$$

- 2 charged + γ's

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

- 4 charged

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K_SK^*$$

- 4 charged + γ's

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

- 6 charged

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

- γ's only

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

- other

$$e^+e^- \to n\overline{n}, \pi^0e^+e^-, \eta e^+e^-$$

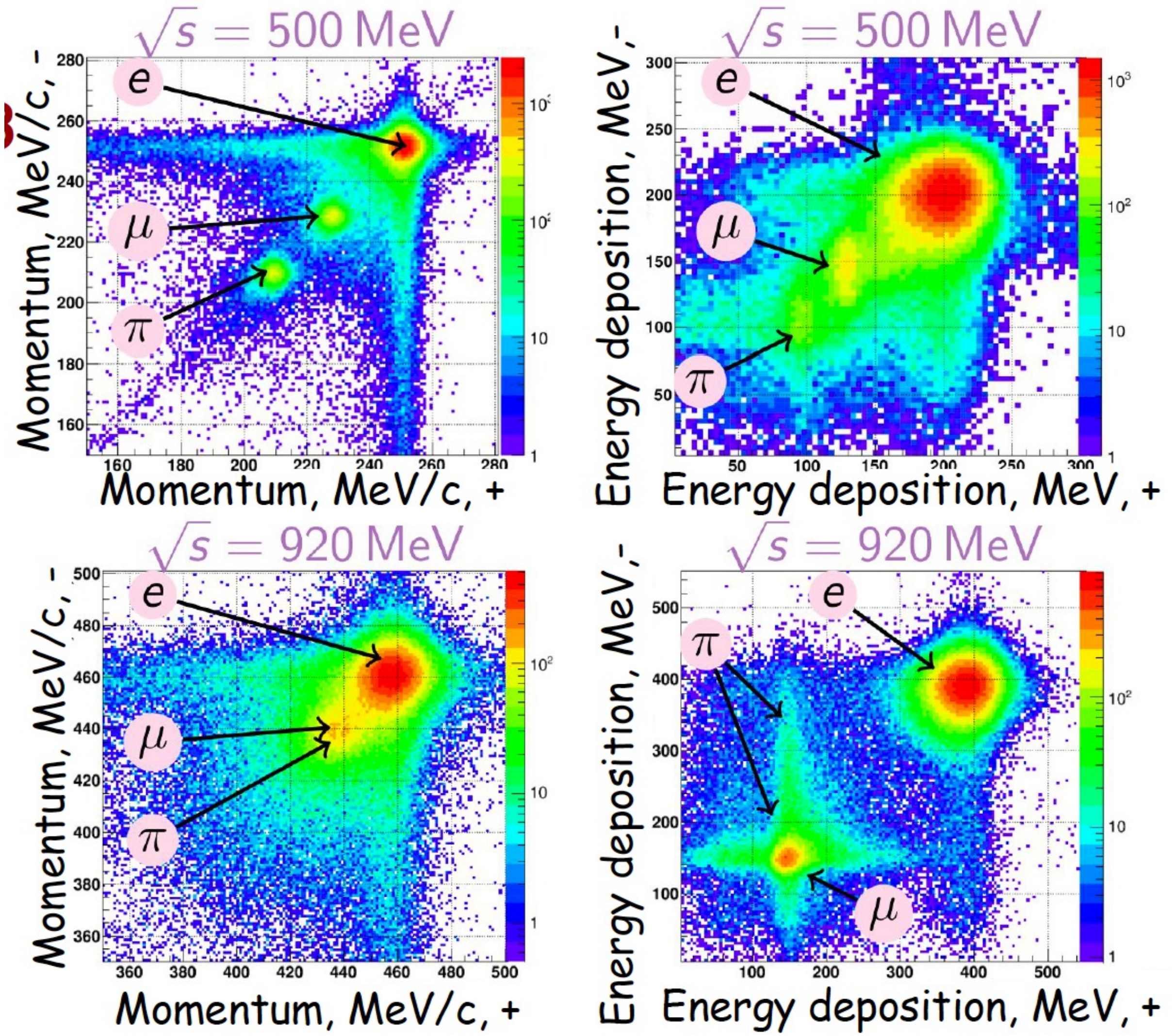
Dominant channel $e^+e^- \to \pi^+\pi^-$

Analysis strategy

- 2 tracks with $1 \le \theta \le \pi-1$
- Separation of e/μ/π/cosmic
- Two independent approaches:
  - Separation by momenta
  - Separation by energy depositions

- Binned likelihood minimization:

$$-\ln L = -\sum_{\text{bins}} n_i \ln\left[\sum_{\substack{X=ee,\\ \mu\mu,\,\pi\pi,\\ \text{bg}}} N_X f_X(p^+, p^-)\right] + \sum_X N_X$$



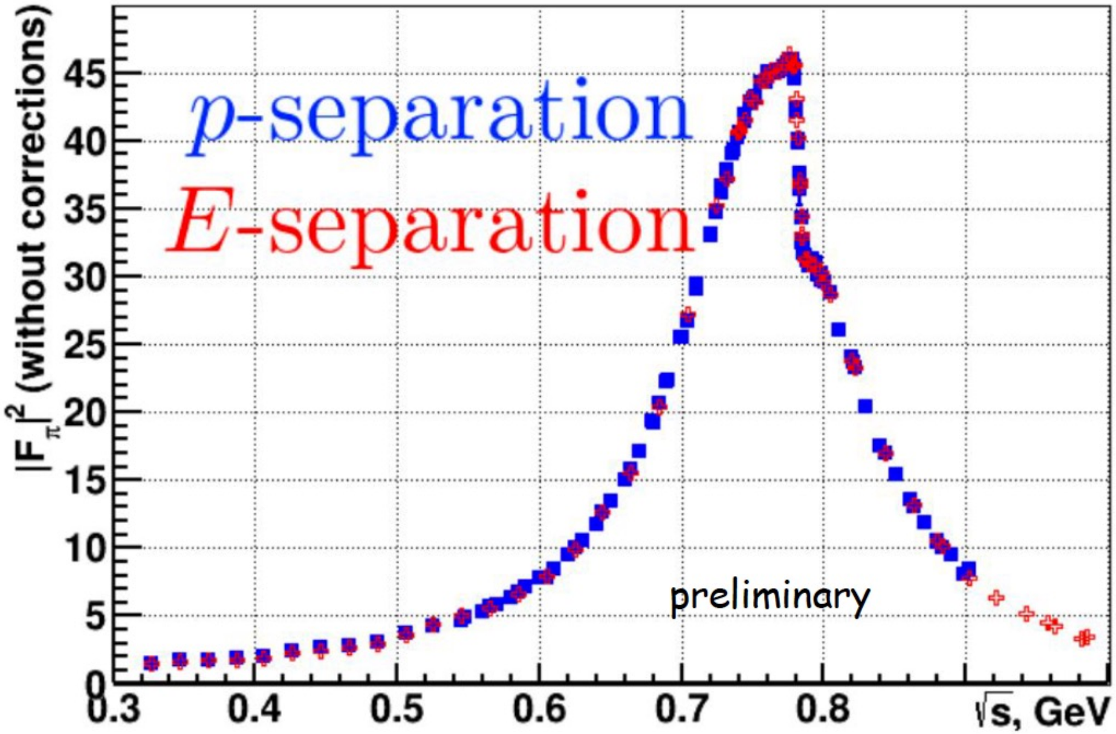
Dominant channel $e^+e^- \to \pi^+\pi^-$

Separation by **momentum**

- take e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ PDFs from MC generators smeared by the detector resolution.
- cosmic PDF from data

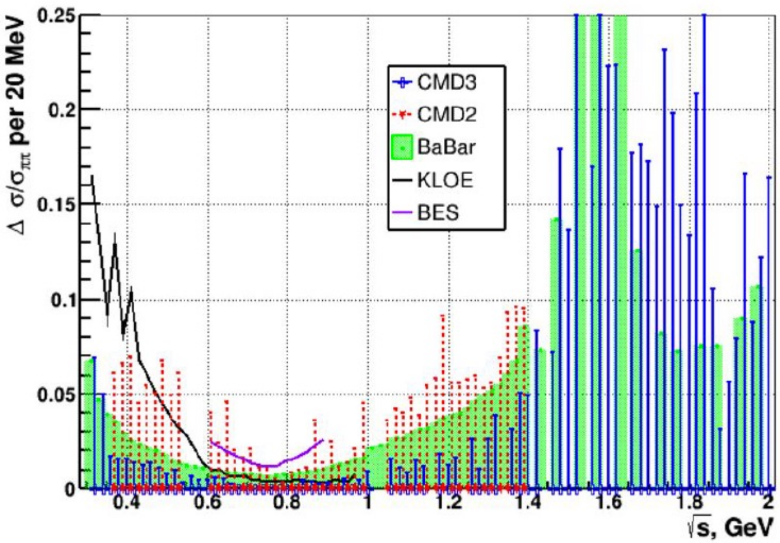
Separation by **energy deposition in LXe**

- No need for PDFs from MC
- Energy deposition includes FSR
- Fit data by analytical functions



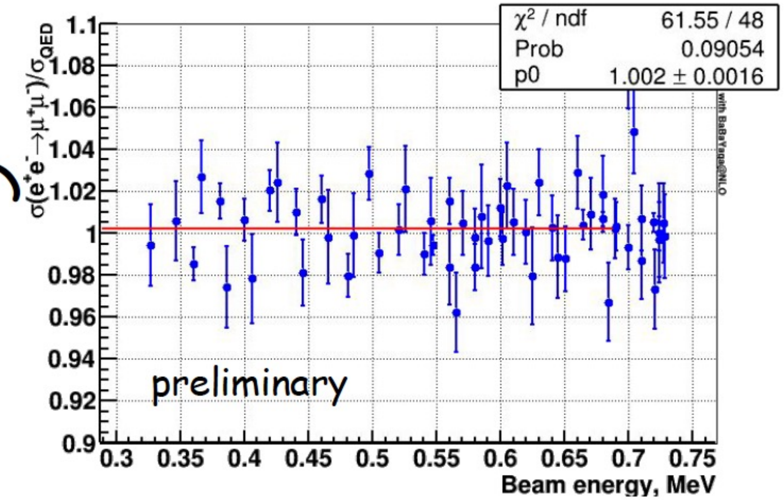
The analysis on its final stages. Additional local consistency checks should be fulfilled. The aim systematic uncertainty is 0.5 %.

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

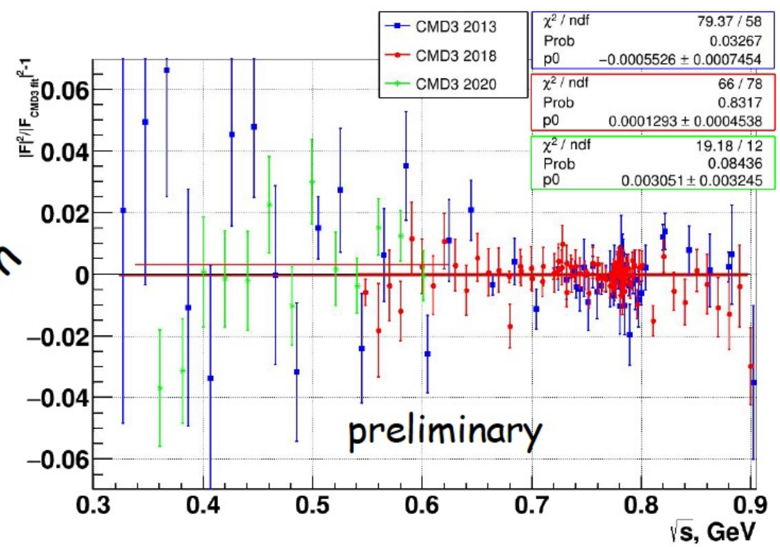


Comparison of statistical uncertainties of cross sections in different experiments

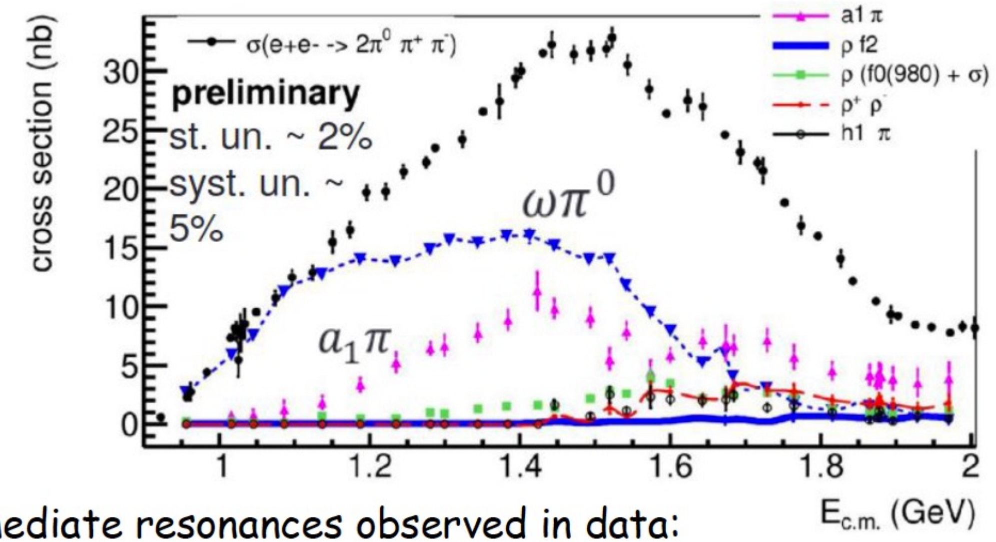
Comparison of $\sigma(e^+e^- \to \mu^+\mu^-)$ with QED



Different seasons comparison



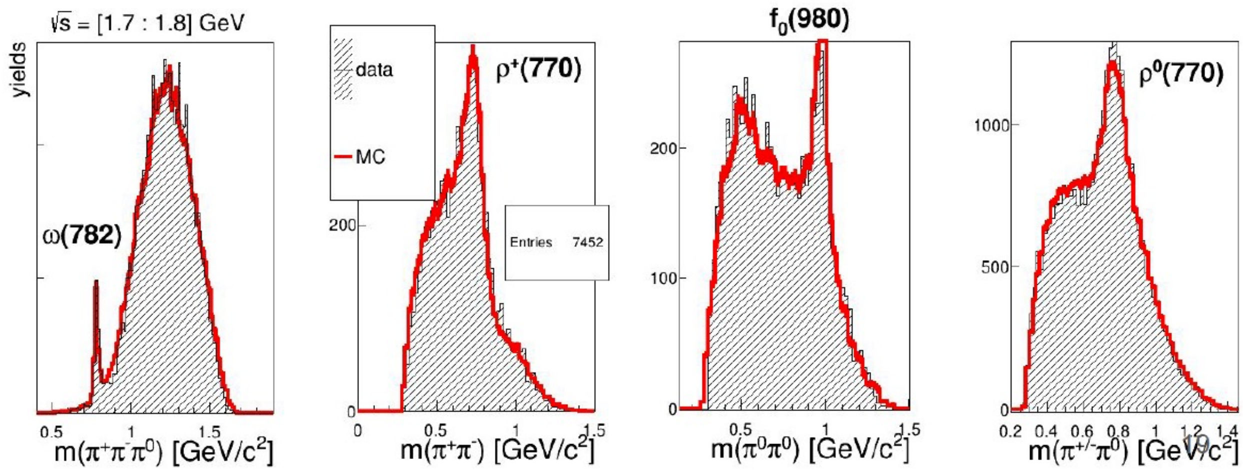
Analysis of $e^+e^- \to 4\pi$



- Simultaneous unbinned amplitude analysis of 150 000 $\pi^+\pi^-\pi^0\pi^0$ events and 250 000 $\pi^+\pi^-\pi^+\pi^-$ events
- Amplitudes accounted for in the likelihood function:

- $\omega[1^{--}]\pi^0[0^{++}]$ (only $\pi^+\pi^-2\pi^0$)
- $a_1(1260)[1^+]\pi[0^-]$
- $\rho[1^{--}]f^0/\sigma[0^{++}]$
- $\rho f_2(1270)[2^{++}]$
- $\rho^+\rho^-$ (only $\pi^+\pi^-2\pi^0$)
- $h_1(1170)[1^{+-}]\pi^0$ (only $\pi^+\pi^-2\pi^0$)

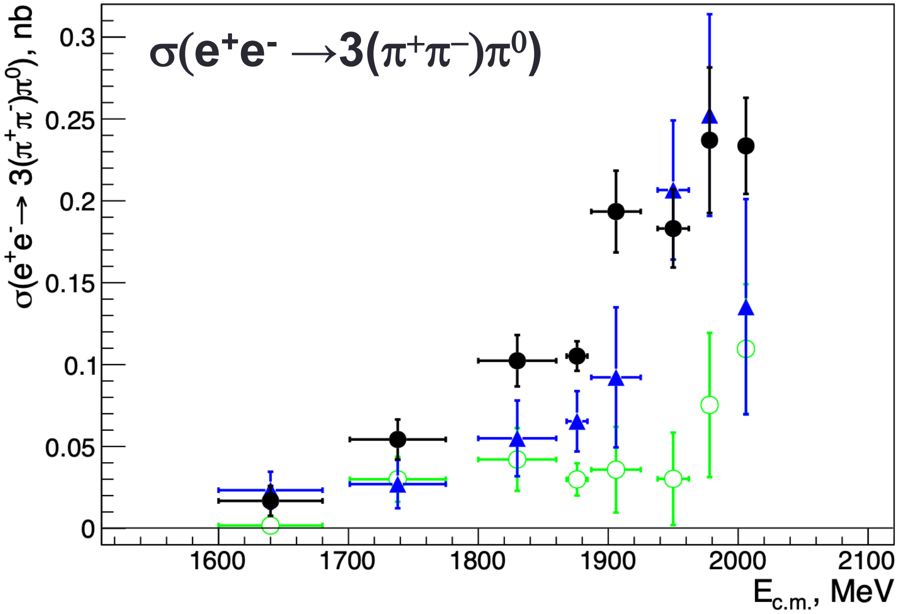
- Intermediate resonances observed in data:

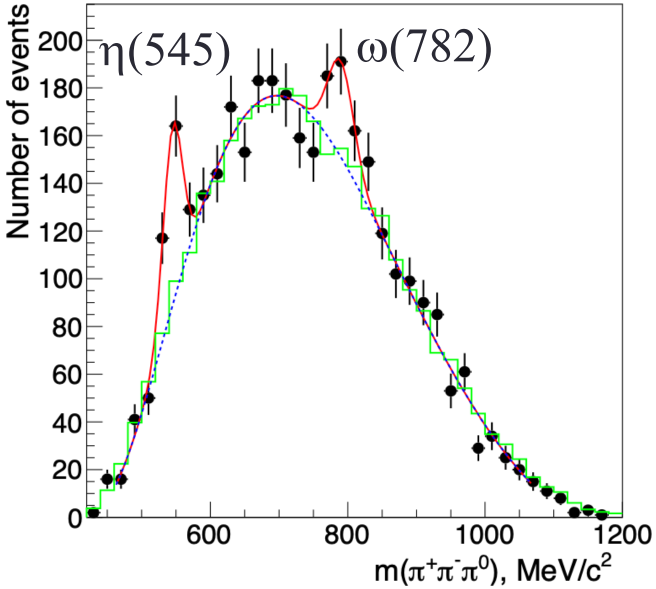


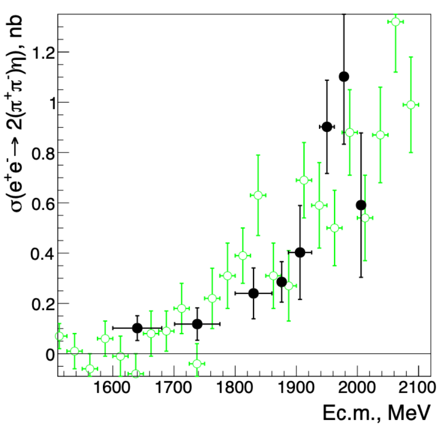
Study of internal dynamics

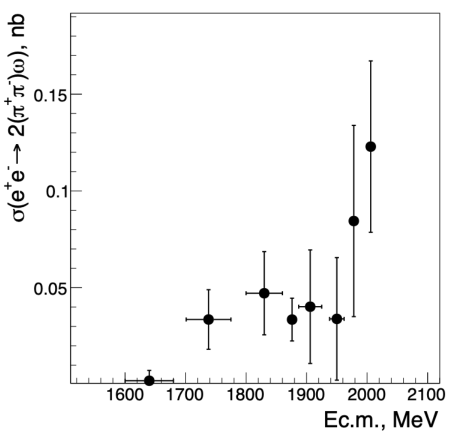
\ intermediate state final state (fs)	1^{--} ρ',ω',φ'...	1^{--} $\rho(770)$	1^{--} $\omega(782)$	1^{--} $\varphi(1020)$	1^{-} $K^*(890)$	1^{+} K1(1270)	1^{++} a1(1260)	1^{++} f1(1285)	0^{+} f0(980)	0^{+} a0(980)	0^{-+} $\eta, \eta'(958)$
$\pi^+\pi^-$	fs	fs	fs	fs							
$\pi^+\pi^-\pi^0$	fs	2π	fs	fs							fs
$\pi^+\pi^-\pi^0\pi^0$	fs	$\pi^\pm\pi^0$, $\pi^+\pi^-$	$\pi^+\pi^-\pi^0$				$\pi^-\pi^0\pi^0$	fs	$\pi^0\pi^0$		
$\pi^+\pi^-\pi^+\pi^-$	fs	$\pi^+\pi^-$					$\pi^-\pi^+\pi^-$	fs	$\pi^+\pi^-$		
5π	fs	2π	3π								fs, $\pi^+\pi^-\pi^0$
6π	fs	$\pi^\pm\pi^0$, $\pi^+\pi^-$					3π				$\pi^+\pi^-\pi^0$
7π	fs		3π								$\pi^+\pi^-\pi^0$
8π	fs										
K^+K^-, KSKL	fs	fs	fs	fs							
$2K\pi^0$, $2K\eta$	fs			2K	$K\pi$						
$2K2\pi$	fs	2π		2K	$K\pi$	$K2\pi$			2π		
$2K3\pi$	fs	2π			$K\pi$			$2K\pi$	2K	2K	
nucleon bar nucleon	fs										
$\pi\gamma$, $\eta\gamma$, $\eta'\gamma$	fs	fs	fs	fs							
πee, ηee, $\eta' ee$	fs	fs	fs	fs							
$\pi^0\pi^0\gamma$, $\pi^0\eta\gamma$	fs		$\pi^0\gamma$	fs					$\pi^0\pi^0$	$\pi^0\eta$	
$\pi^+\pi^-\eta$	fs	fs, 2π		fs				fs			fs
$\pi^+\pi^-\pi^0\eta$	fs	$\pi^+\pi^-$	$\pi^+\pi^-\pi^0$	$\pi^+\pi^-\pi^0$						$\pi^0\eta$	
$\mu^+\mu^-\pi^0$, $\mu^+\mu^-\eta$, $4\pi\eta$, $2\pi 2\eta$	fs										

Analysis of $e^+e^- \to 3(\pi^+\pi^-)\pi^0$









$$\int \mathcal{L}dt = 56.7\ pb^{-1}$$

$$E_{c.m.} = 1.6 - 2.0\ GeV$$

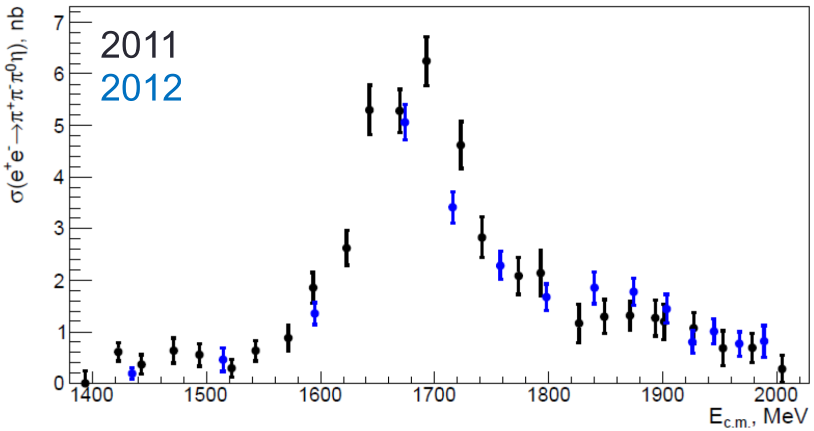
Syst. Error = 13 – 20%

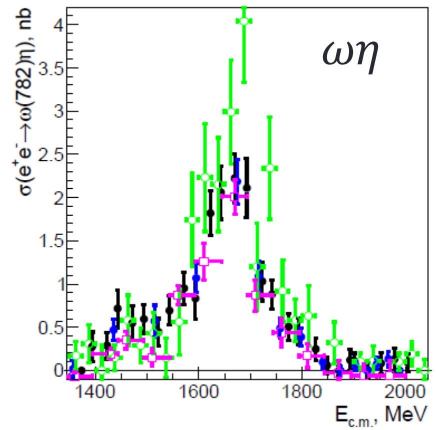
***Phys.Lett.B* 792 (2019) 419-423**

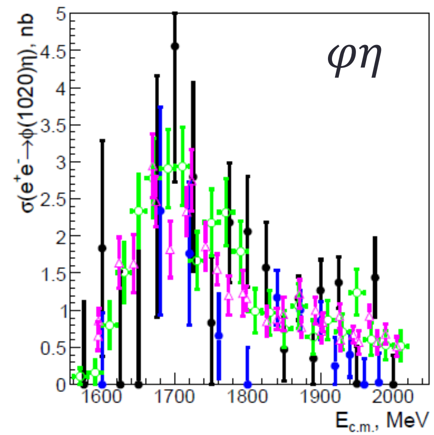
Analysis of $e^+e^- \to \pi^+\pi^-\pi^0\eta$

First measurement of total $e^+e^- \to \pi^+\pi^-\pi^0\eta$ cross section. Systematic error is 15%.

Phys.Lett. B773 (2017) 150-158





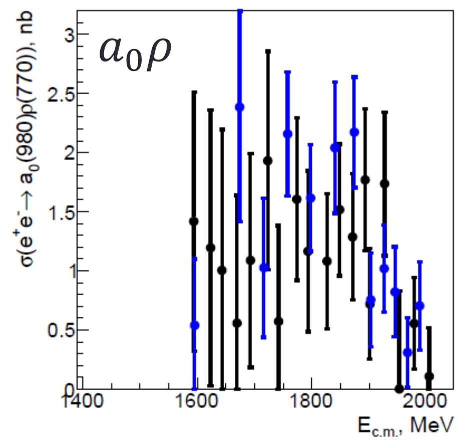


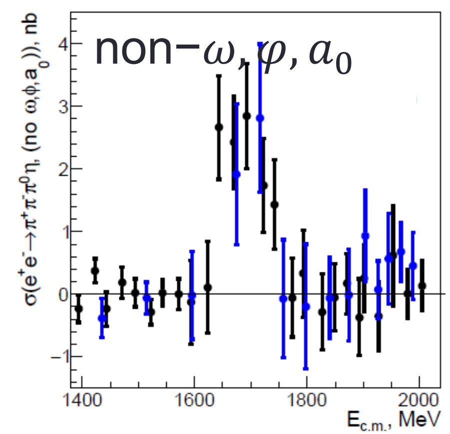
At "low" energies dominated by $e^+e^- \to \omega\eta, \varphi\eta$

At "high" energies dominated by $e^+e^- \to a_0(980)\rho$

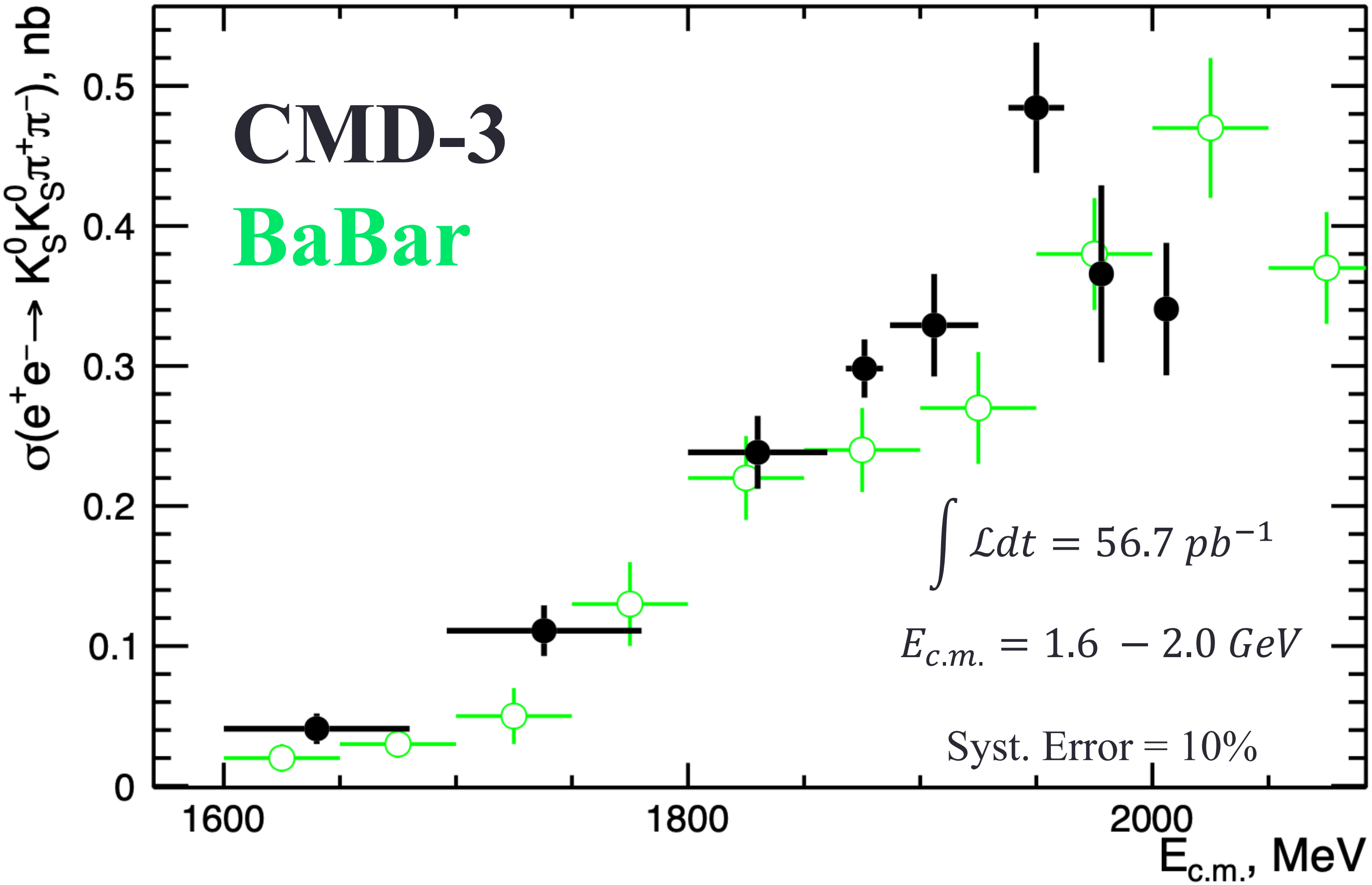
We see non-ω, φ, a_0 contribution
Possible mechanism:

$$e^+e^- \to \omega(1650) \to \rho(1450,1700)\pi \to \rho(770)\eta\pi$$



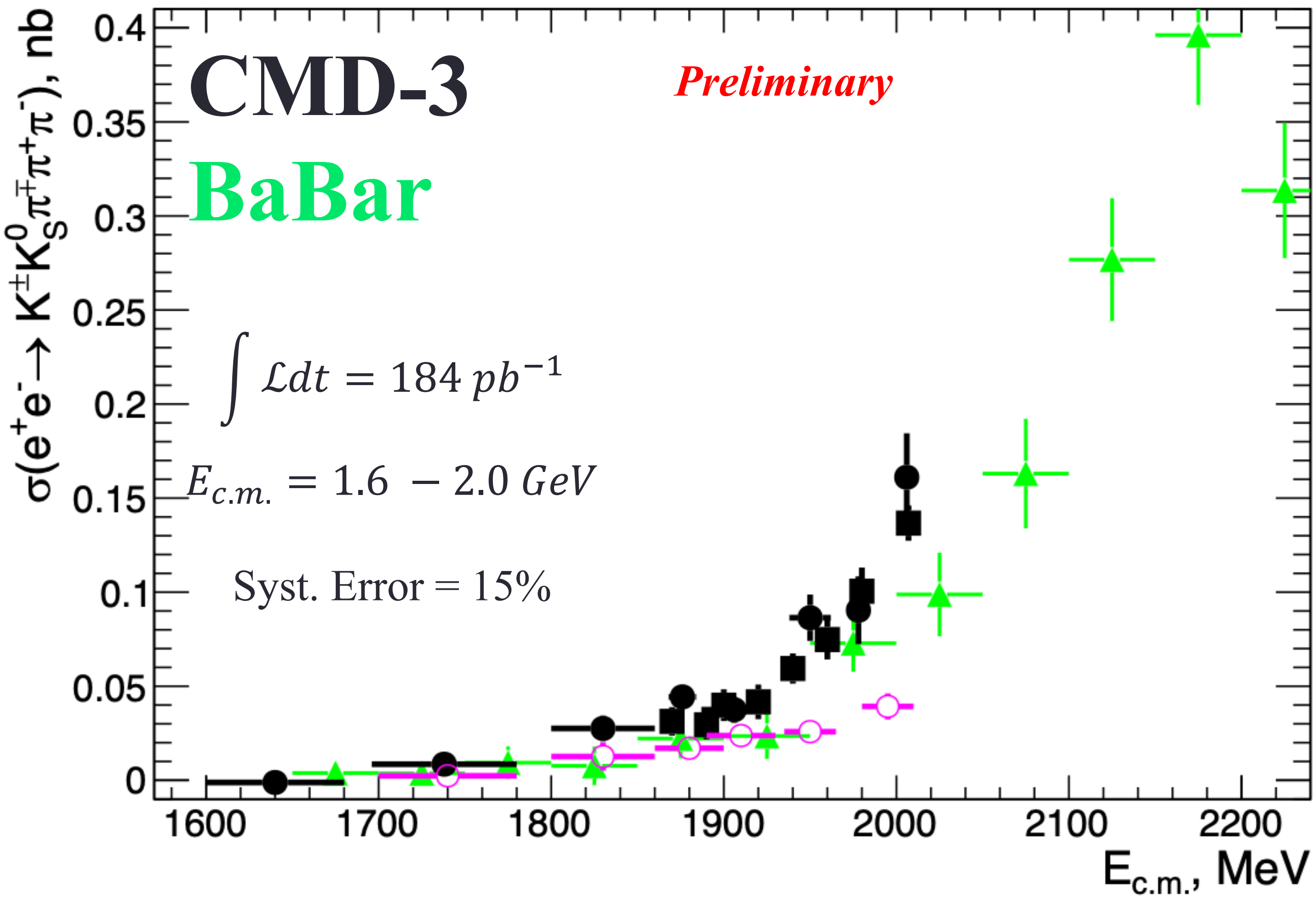


Analysis of $e^+e^- \rightarrow K^0{}_S K^0{}_S \pi^+\pi^-$



Phys.Lett.B 804 (2020) 135380

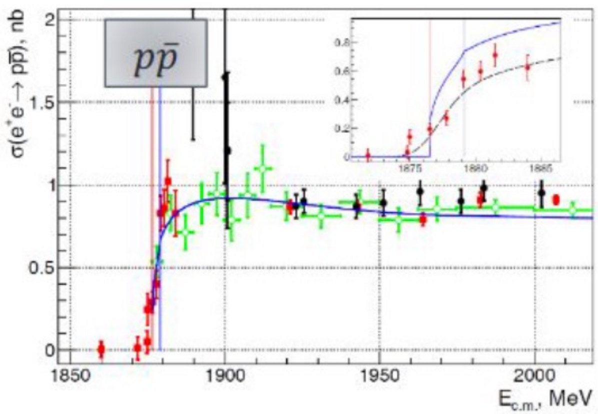
Analysis of $e^+e^- \rightarrow K^0{}_S K^{\pm} \pi^{\mp}\pi^+\pi^-$

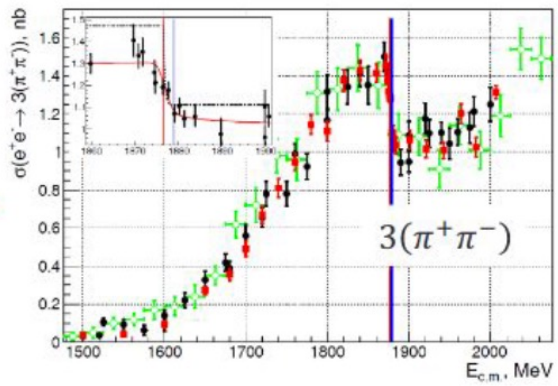


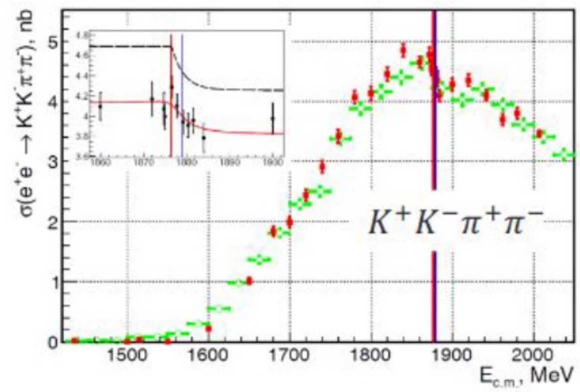
R(s) at nucleon antinucleon threshold

- VEPP-2000: unique ability for detailed scan of ppbar and nnbar threshold.

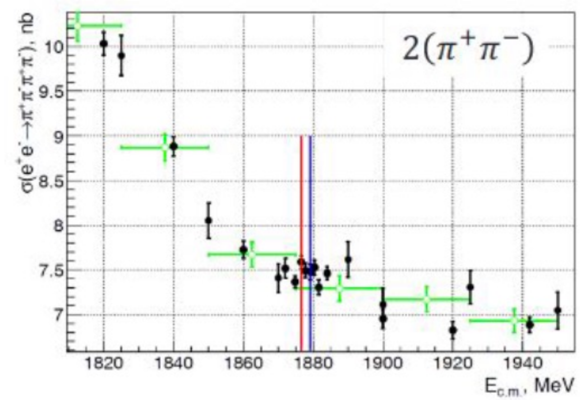
PLB 794 (2019) 64







- observed the sharp change of $e^+e^- \to p\bar{p}$, $3(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$
- width is ~1 MeV – consistent with energy resolution
- puzzle – why there is no change in $e^+e^- \to 2(\pi^+\pi^-)$?



- We plan to do comprehensive study of this energy range

Search for $e^+e^- \to D(2007)^{0*}$

We are trying to probe also charm-physics

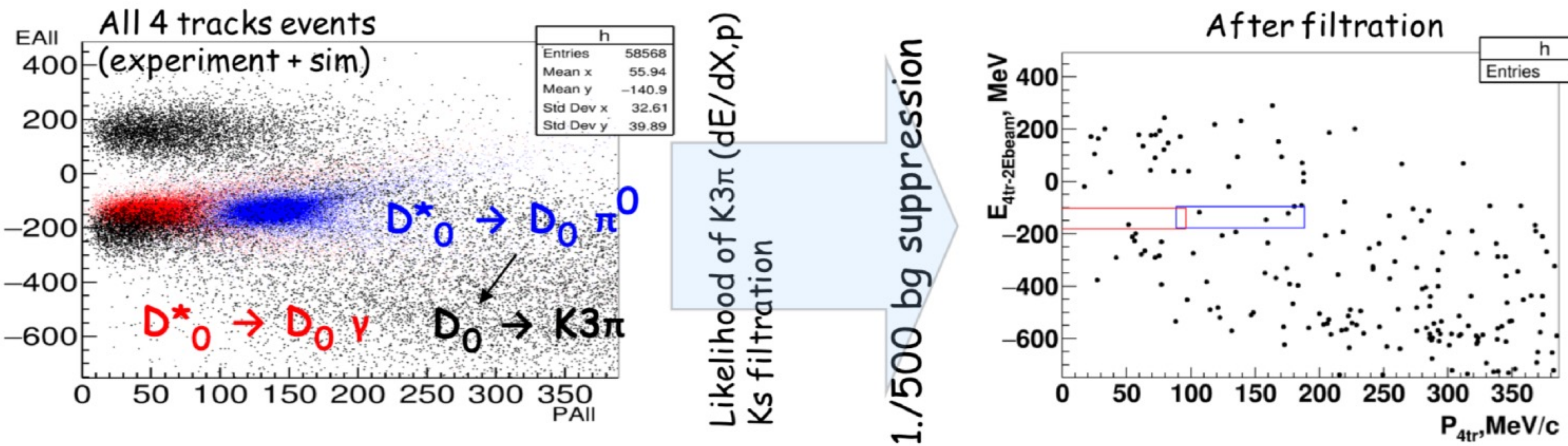
motivation

A. Khodjamirian et al, JHEP11(2015)142 :
SM: Br($D^* \to e^+e^-$) >= $5. \times 10^{-19}$
New Physics with Z' : Br($D^* \to e^+e^-$) < 2.5×10^{-11}

But, they didn't take into account 10^2 - 10^4 factor: detection efficiency and beam energy spread

They did estimation
for e+e- collider with $\int L = 1 fb^{-1}$: Br($D^* \to e^+e^-$) > 4×10^{-13}

VEPP-2000 was able to jump above 2 GeV design machine limit:
At 2017 scan: E=2007 МэВ, L=3.4 πb^{-1}



$D^*_0 \to D_0 \gamma$: Br($D^* \to ee$) < $5.2 \cdot 10^{-6}$
$D^*_0 \to D_0 \pi^0$: Br($D^* \to ee$) < $1.7 \cdot 10^{-6}$

First time UL measurement

Conclusion

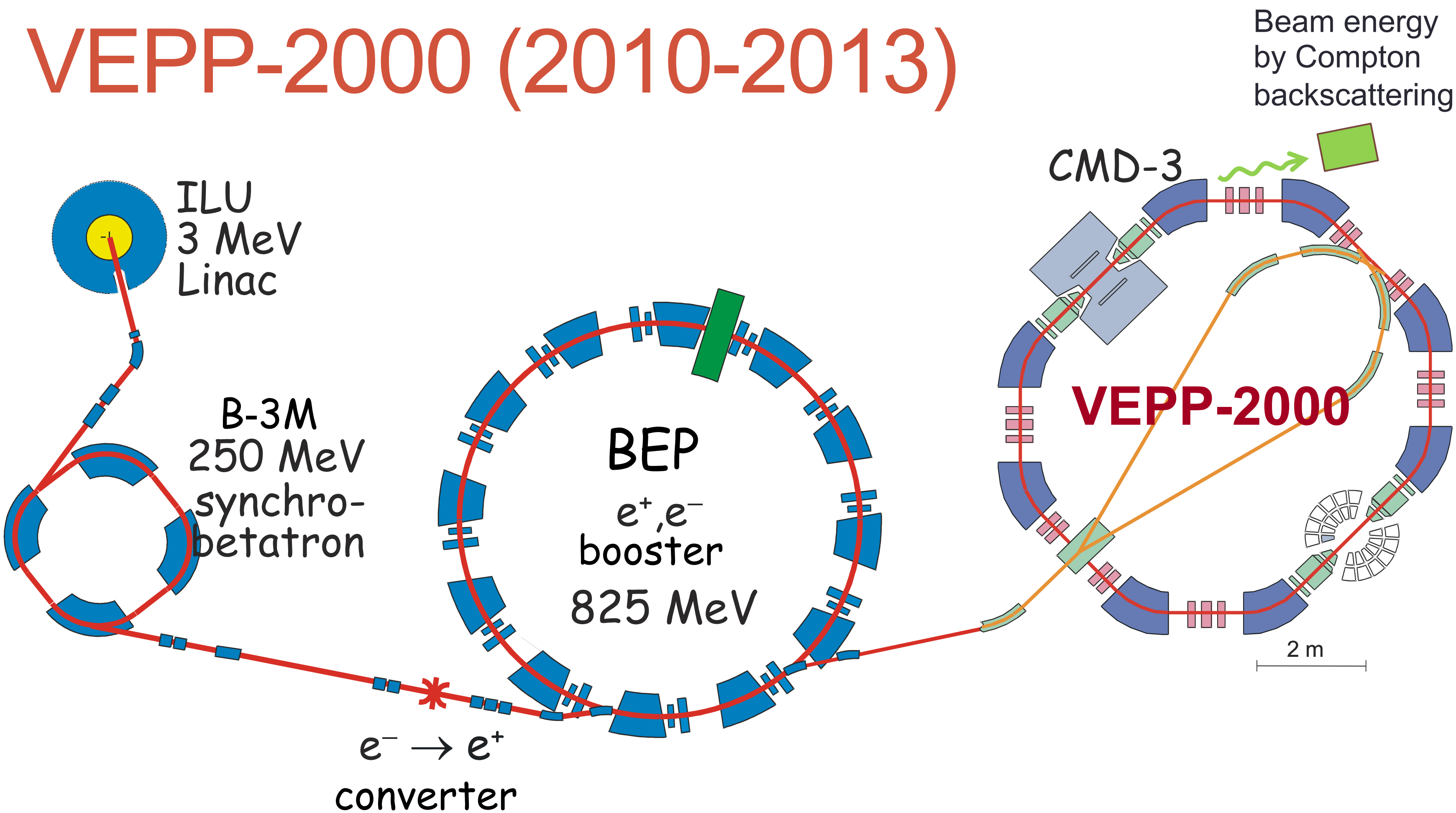
- The VEPP-2000 collider delivered about 370 pb^{-1} of integrated luminosity in the energy range 0.32 – 2.01 GeV to the CMD-3 detector from 2010 – 2021 and doubled the integral in 2022. Today VEPP-2000 is only working on direct scanning of the region for measurement of exclusive $\sigma(e^+e^- \to \text{hadrons})$.
- The VEPP-2000 results will help to reduce error of the hadronic contribution to vacuum polarization and it is independent cross check of ISR data, future lattice, space-like.
- The $e^+e^- \to \pi^+\pi^-$ cross section is measured with systematic uncertainty better than 1%. Publication of a largenumber of precise measurements are expected soon.

Thank You for Your attention!

Stay tuned!

Backup slides

VEPP-2000 (2010-2013)

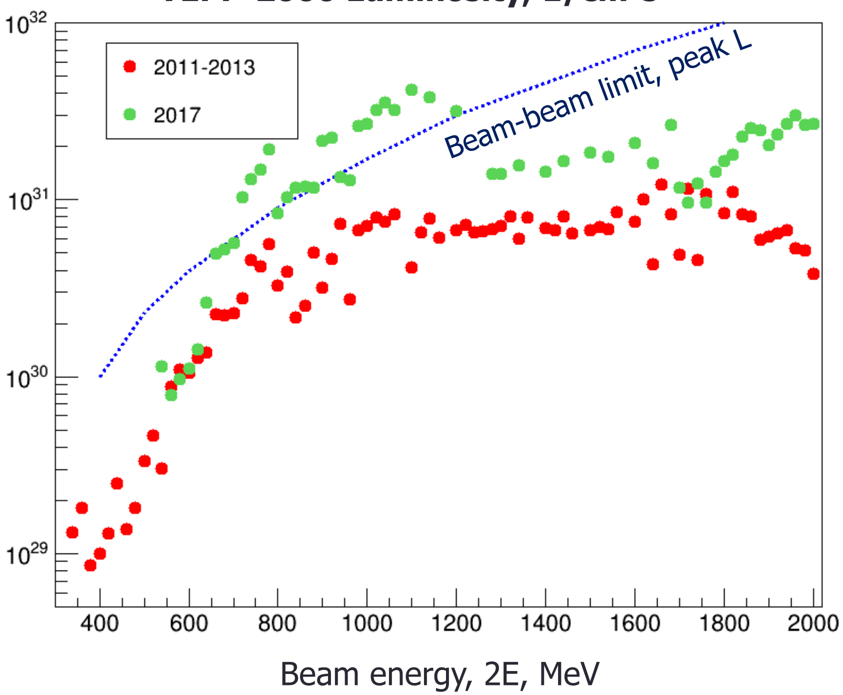


C.m. energy range is 0.32-2.0 GeV; unique optics – "round beams"

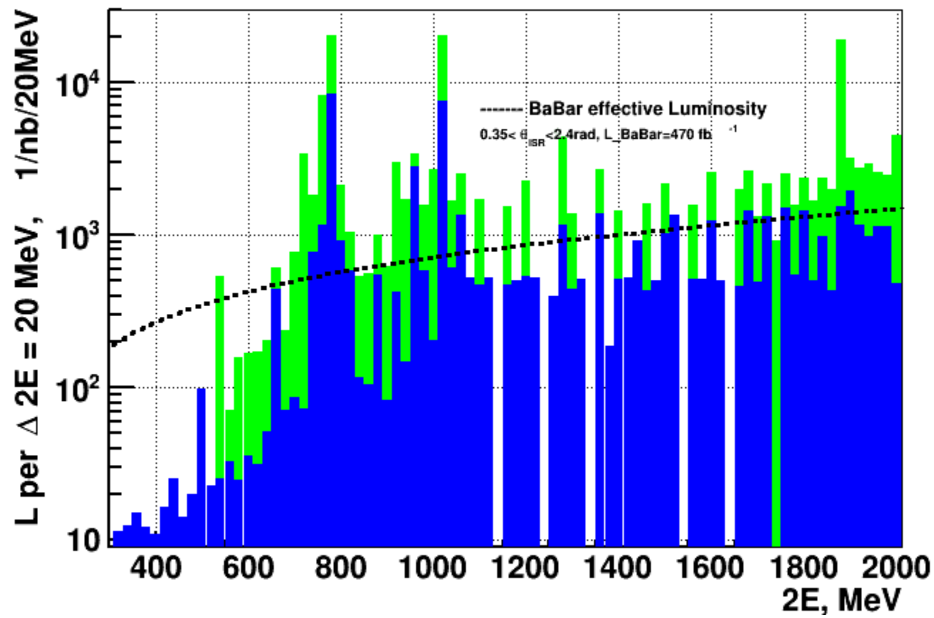
Design luminosity is $L = 10^{32} 1/cm^2 s$ @ $\sqrt{s} = 2$ GeV

Experiments with two detectors, CMD-3 and SND, started by the end of 2010

2017 data taking



2017-2018
2011-2013



In 2017: big improvement in luminosity

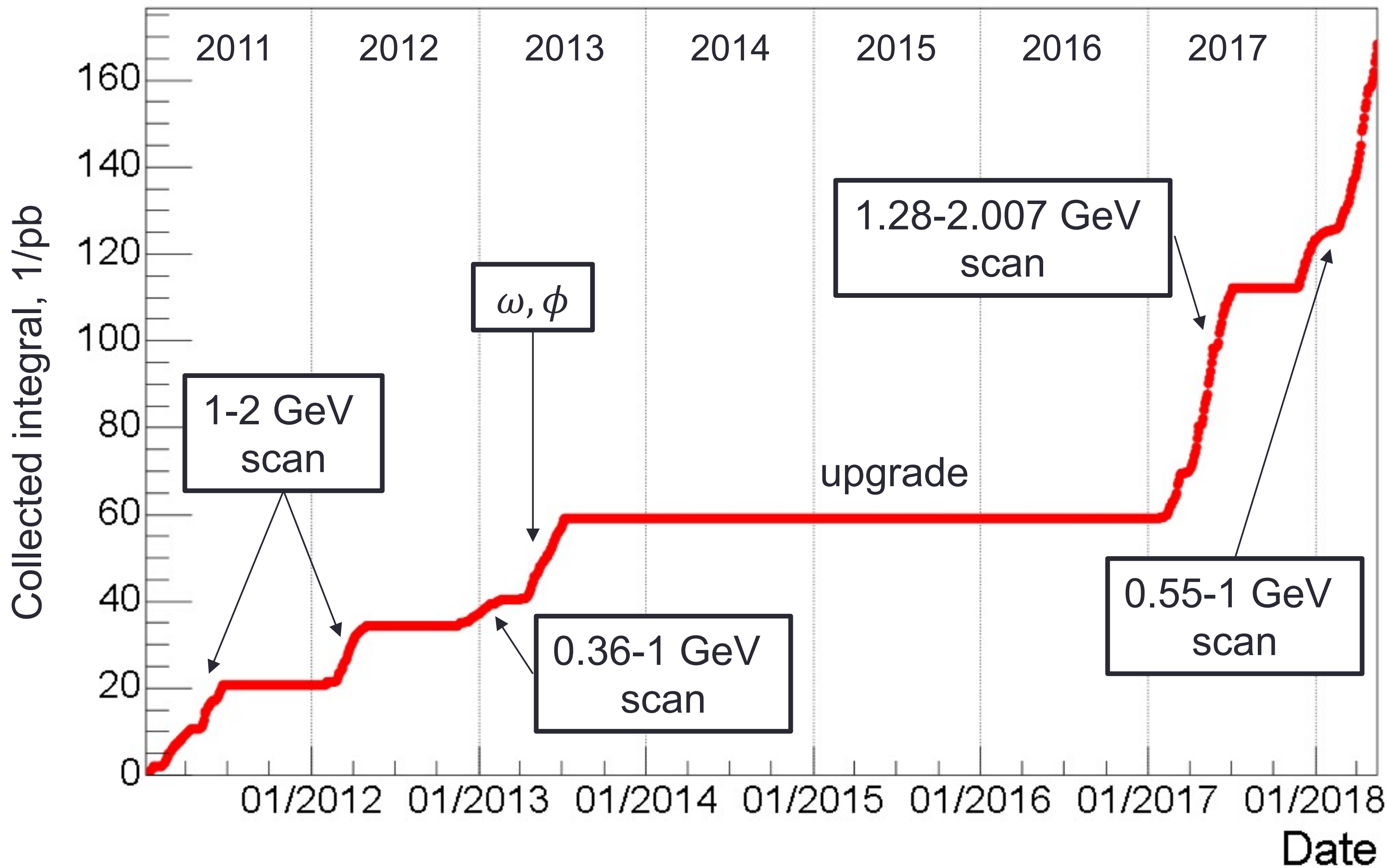
Below 1 GeV: >50 pb^{-1} collected and counting

$0.55 - 1.00$ GeV	$> 50\ 1/pb$

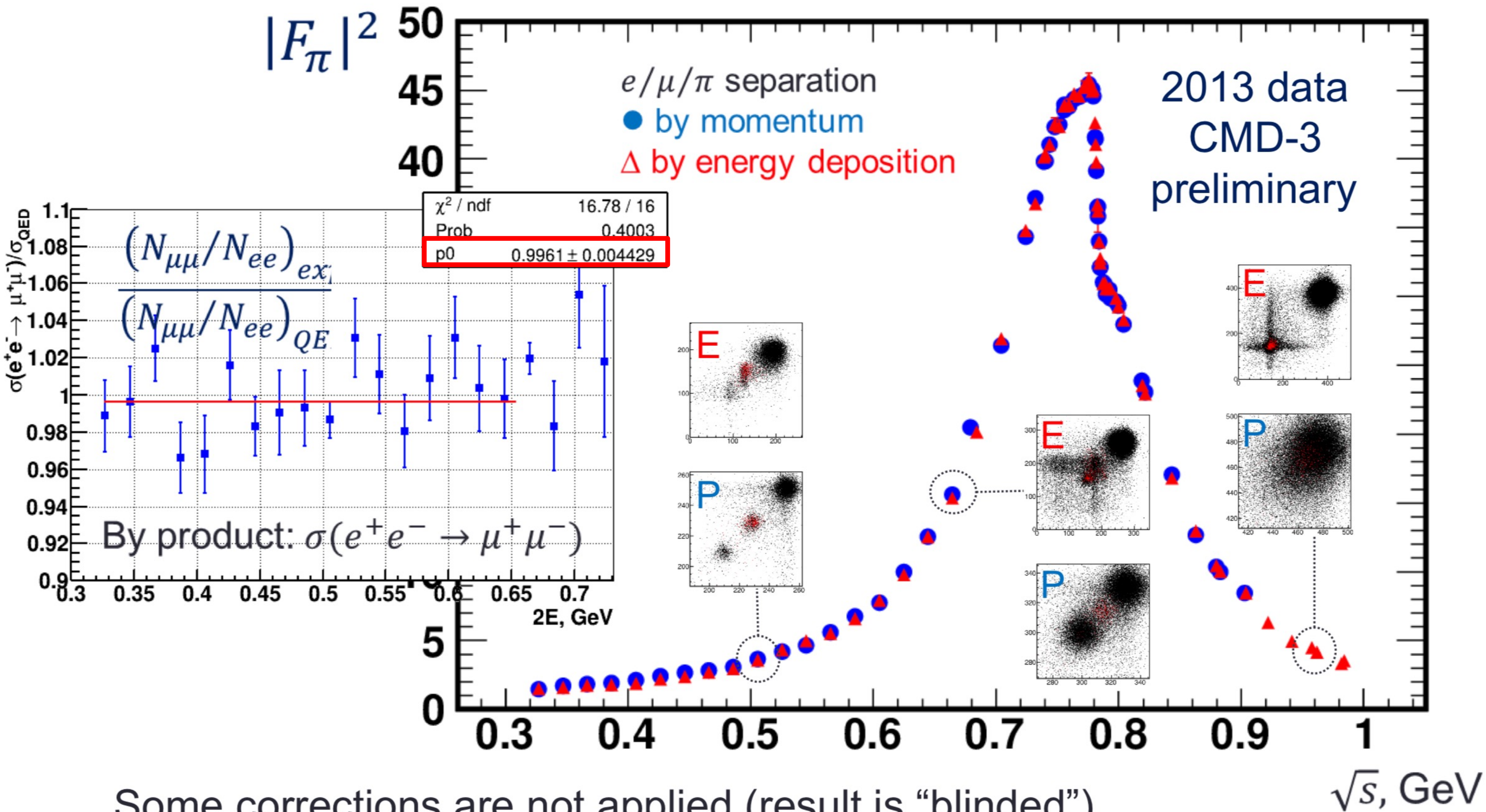
Above 1 GeV: ~50 pb^{-1} collected

2.007 GeV ($e^+e^- \to D^{0*}$)	$4\ 1/pb$
$p\bar{p}$ and $n\bar{n}$ threshold	$14\ 1/pb$
Overall:	
$1.28 - 2.007$ GeV	$50\ 1/pb$

Overview of CMD-3 data taking runs



Dominant channel: $e^+e^- \to \pi^+\pi^-$

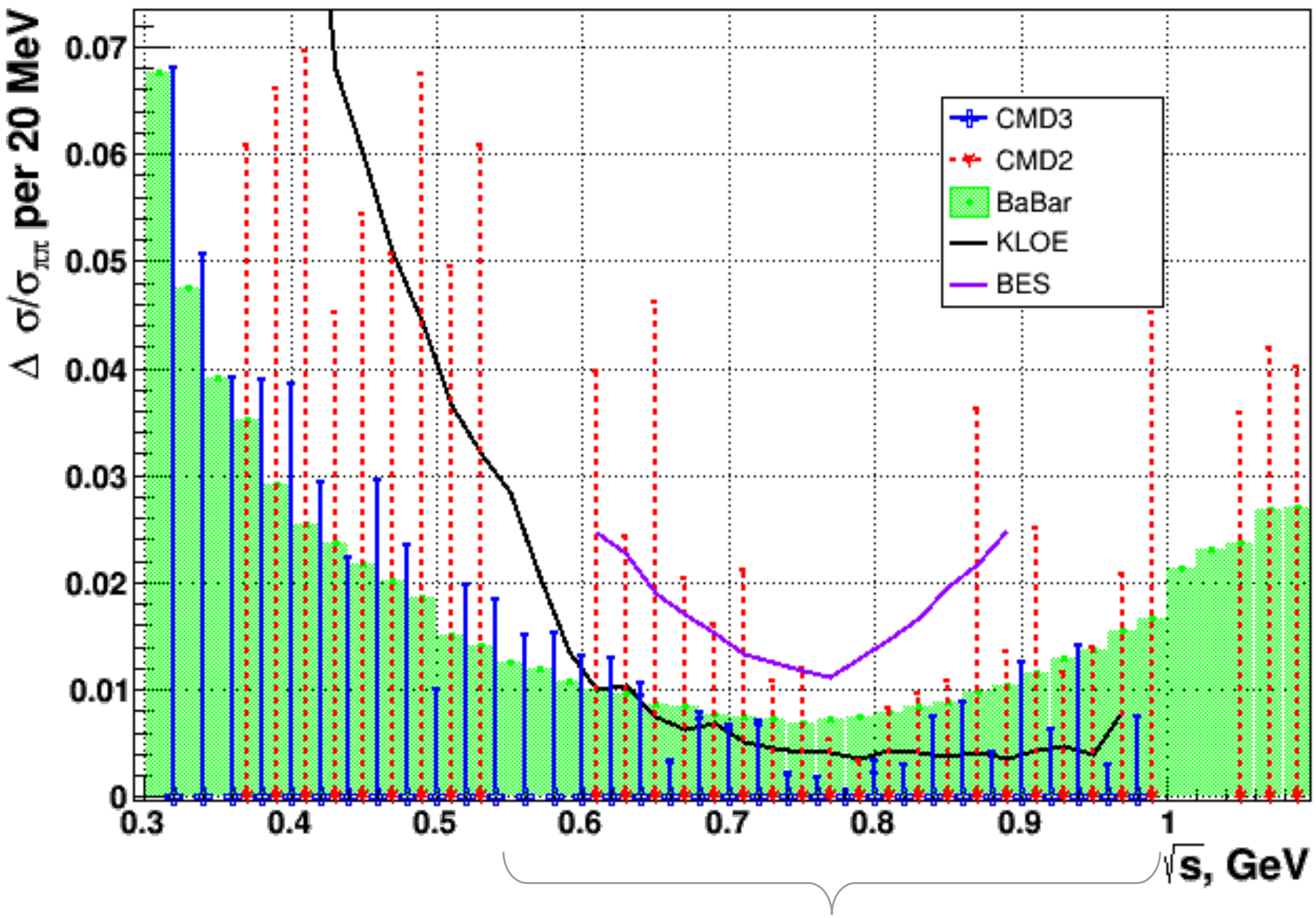


Some corrections are not applied (result is "blinded")

"Open box", when systematics of both methods < 1%
Our goal is to have systematic error at the level ~ 0.33%

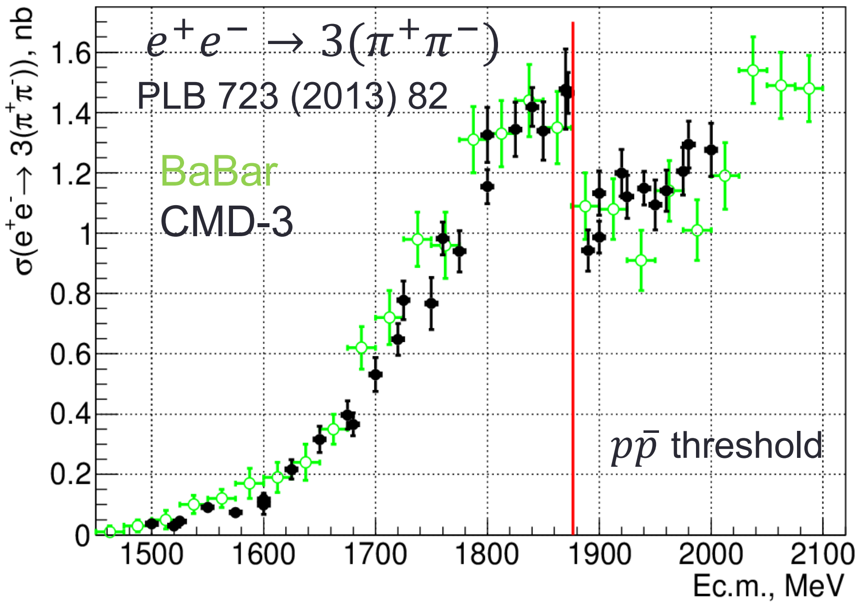
Dominant Channel: $e^+e^- \to \pi^+\pi^-$. Statistics

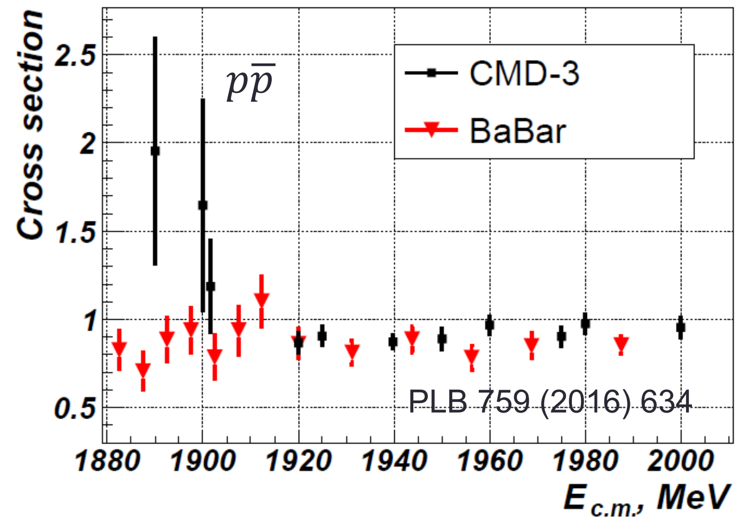
Statistical accuracy $\Delta\sigma/\sigma$ in 20 MeV bins



Already collected x2-3 data in 2017-2018

$R(s)$ at $N\bar{N}$ threshold





One of first results from CMD-3:

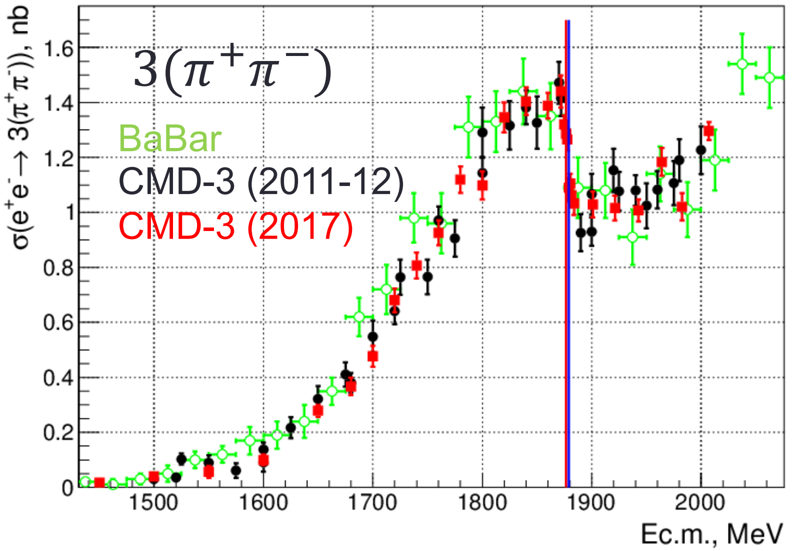
- Sudden drop of $e^+e^- \to 3(\pi^+\pi^-)$ cross section at $N\bar{N}$ threshold
- Confirmed, that $p\bar{p}$ production cross section increases quickly at threshold
- Preliminary studies of dynamics of $e^+e^- \to 3(\pi^+\pi^-)$, hint of energy dependent dynamics in 1.7-1.9 GeV energy range

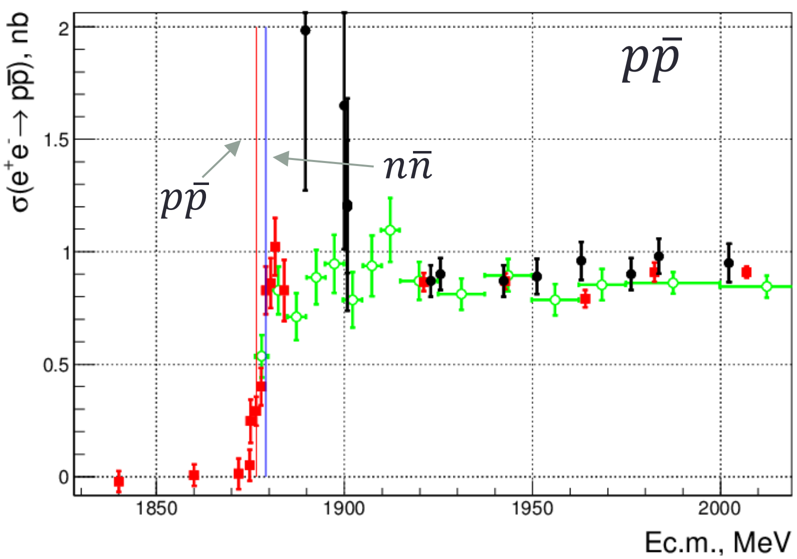
2017: $e^+e^- \to 3(\pi^+\pi^-)$ at $N\bar{N}$ threshold

In 2017, CMD-3 collected 13 1/pb in the narrow energy range around $N\bar{N}$ threshold

- the sharp rise of $e^+e^- \to p\bar{p}$ cross-section is confirmed
- the sharp drop of $e^+e^- \to 3(\pi^+\pi^-)$ cross-section is confirmed
- we see the similar cross-section drop in other channels

arXiv:1808.00145 [hep-ex]





$N\bar{N}$ threshold in $2(\pi^+\pi^-)$ reaction

arXiv:1808.00145 [hep-ex]

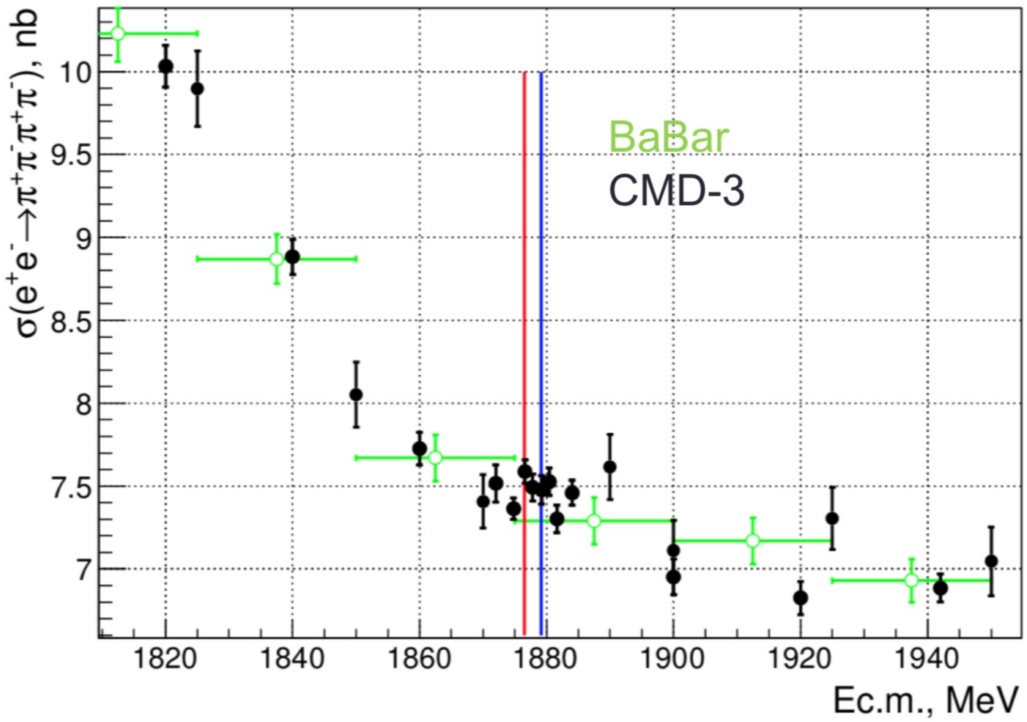


Figure 4: The $e^+e^- \to 2(\pi^+\pi^-)$ cross section measured with the CMD-3 detector. Lines show the $p\bar{p}$ and $n\bar{n}$ thresholds.

We continue search for the NNbar threshold indication in other multi-hadron reactions

Conclusion

- The goal of the CMD-3 experiment at the VEPP-2000 is to provide exclusive measurement of $e^+e^- \to hadrons$ from 0.32 to 2.0 GeV
- In 2011-2013 CMD-3 has collected 60 pb^{-1} in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0$ GeV, available at VEPP-2000.
- In 2013-2016 the collider and the CMD-3 detector have been upgraded and the data taking was resumed in 2017 and > 100 pb^{-1} were collected so far.
- Data analysis of exclusive modes of $e^+e^- \to hadrons$ is in progress. Many results have been published.

$\sigma(e^+e^- \to hadrons)$ and the hadronic contribution to a_μ

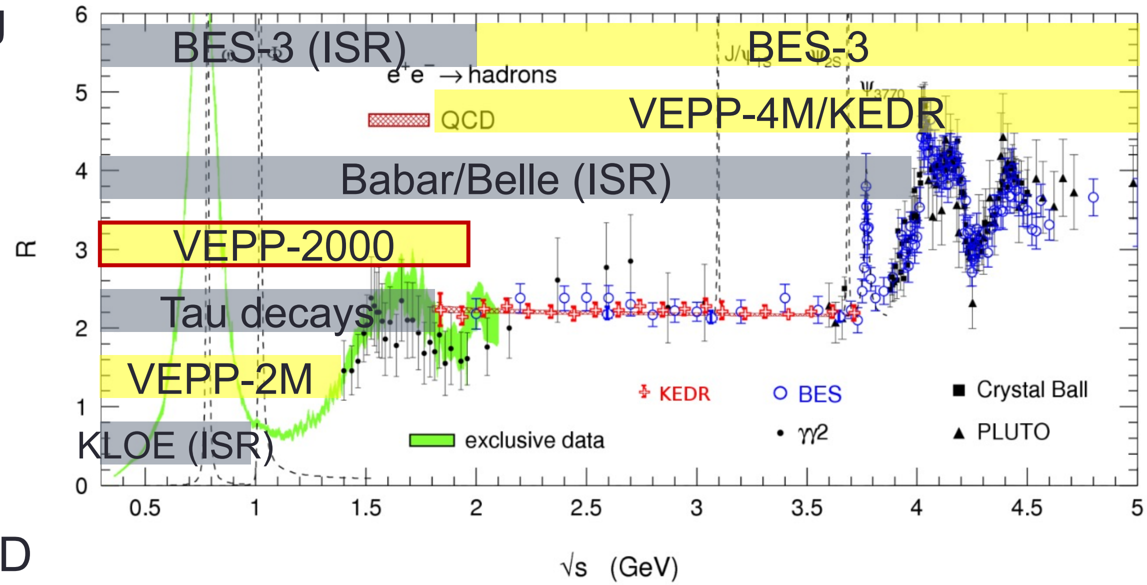
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

So far, the hadronic contribution to a_μ is calculated by integrating experimental cross-section $\sigma(e^+e^- \to hadrons)$.

Weighting function $\sim 1/s$, therefore lower energies contribute the most.

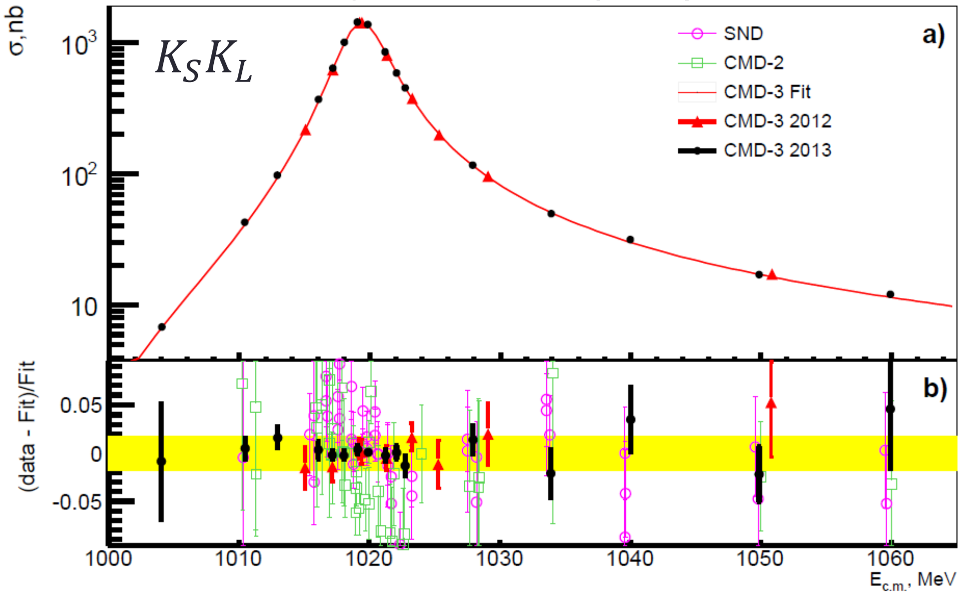
Many sources of data:

- Novosibirsk: CMD-2 and SND (VEPP-2M), CMD-3 and SND (VEPP-2000)
- Factories: Babar, KLOE
- BES-III, KEDR

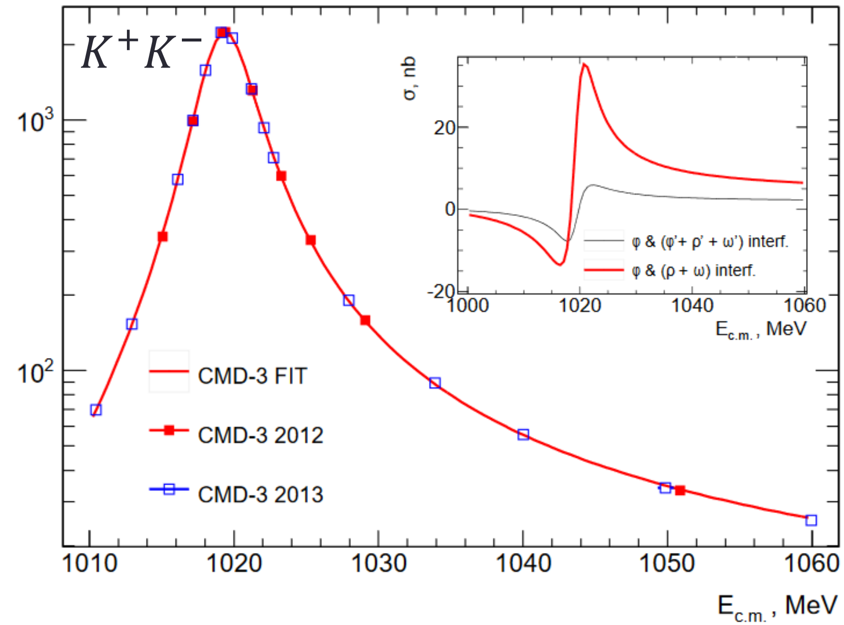


$K_S K_L$ and K^+K^- @$\varphi(1020)$

Phys.Lett. B760 (2016) 314-319



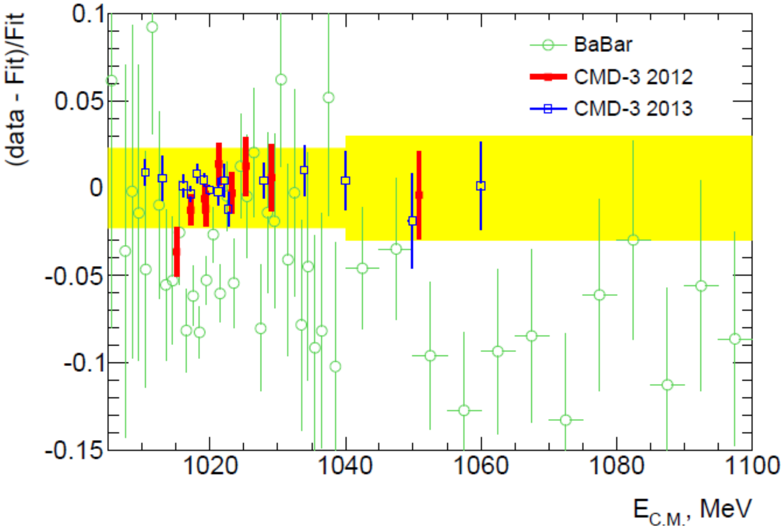
Phys.Lett. B779 (2018) 64-71

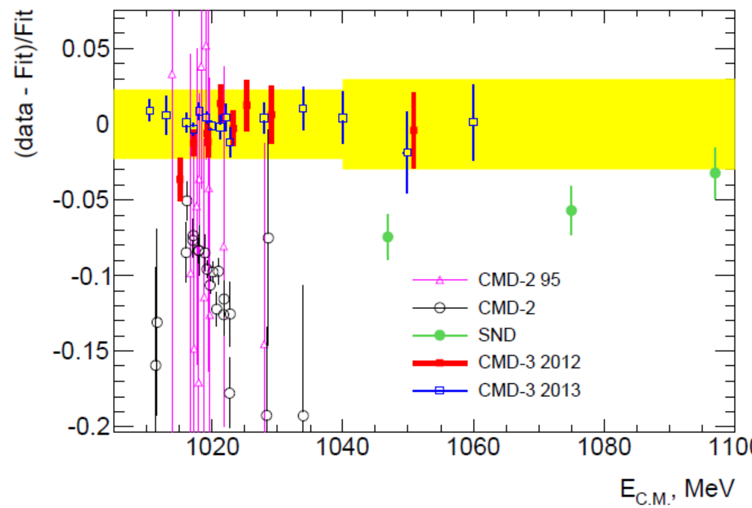


Recent result from CMD-3:

- $K_S K_L$ at φ, systematic precision 1.8%
- K^+K^- at φ, systematic precision 2.0% (2.8%)

K^+K^-: comparison with other measurements





$K_S K_L$ at φ is consistent between different experiments, but there is discrepancy in K^+K^- channel.

New CMD-3 K^+K^- cross-section is above CMD-2 and BaBar, but is consistent with isospin symmetry:

$$R = \frac{g_{\varphi K^+K^-}}{g_{\varphi K_S K_L}\sqrt{Z(m_\varphi)}} = 0.990 \pm 0.017$$

- $R_{SND} = 0.92 \pm 0.03(2.6\sigma)$
- $R_{CMD-2} = 0.943 \pm 0.013(4.4\sigma)$
- $R_{BaBar} = 0.972 \pm 0.017(1.5\sigma)$

Possible explanation: CMD-2 trigger correction was underestimated; due to different trigger configuration there is no such correction at CMD-3

$K_S K_L$ and K^+K^-: $\rho - \varphi$ interference

$\rho - \varphi$ interference can be directly observed:

$$R_{c/n} = \sigma(e^+e^- \to K^+K^-) \times \frac{p^3_{K^0}(s)}{p^3_{K^\pm}(s)} \times \frac{1}{Z(s)} - \delta \times \sigma(e^+e^- \to K_S K_L)$$

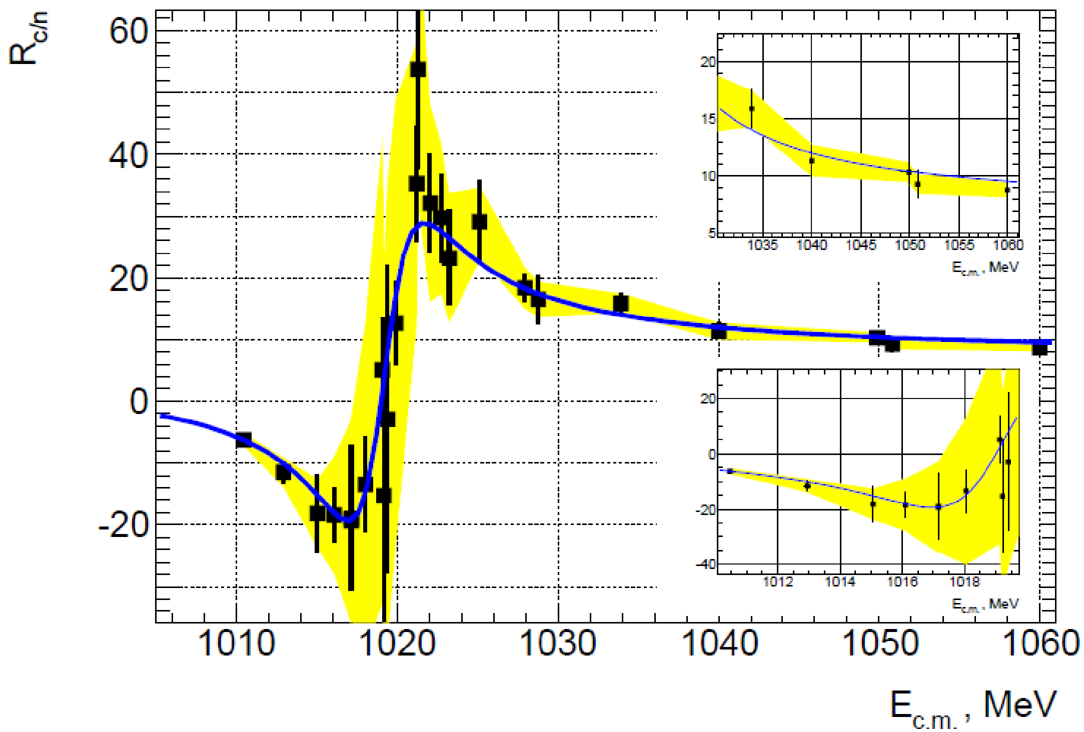
- $r_{\rho,\omega} = 0.91 \pm 0.04$

deviation of SU(3) relations

$$g_{\omega K^+K^-} = g_{\rho K^+K^-} = -g_{\varphi K^+K^-}/\sqrt{2}$$

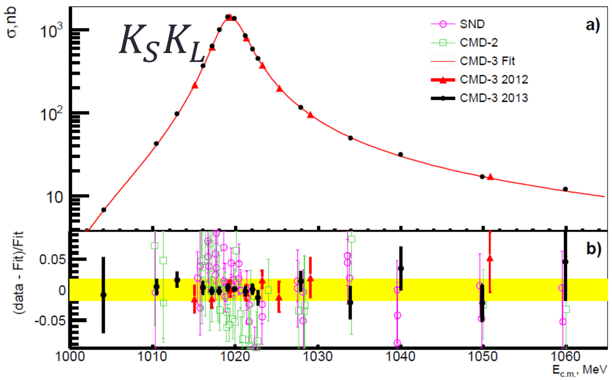
- $\delta = 0.989 \pm 0.003$

test of systematic errors

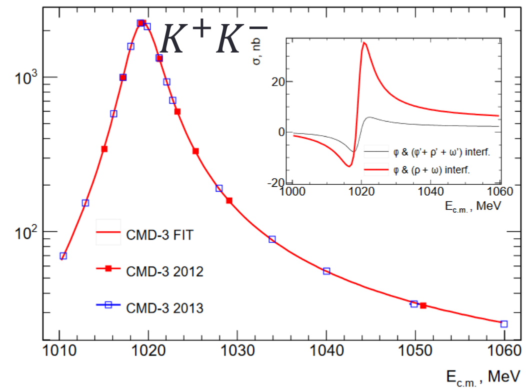


CMD-3 published results from 2011-2013

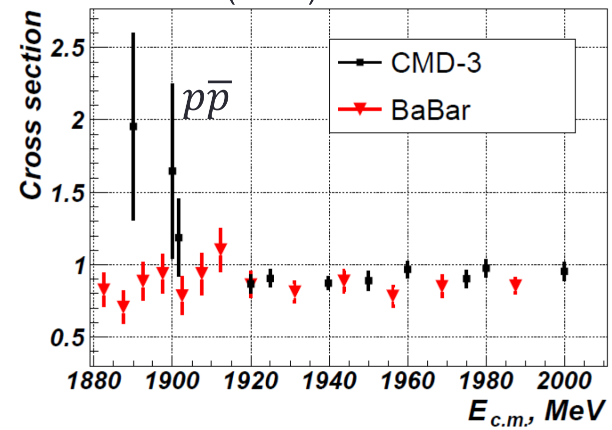
PLB 760 (2016) 314



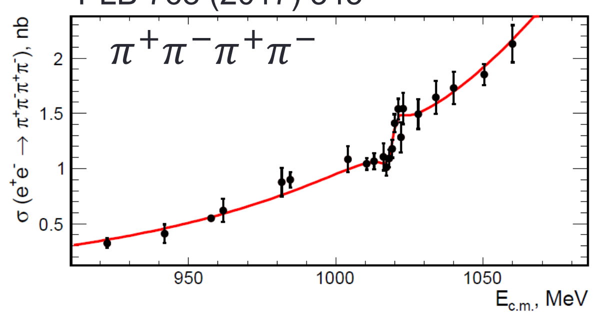
PLB 779 (2018) 64



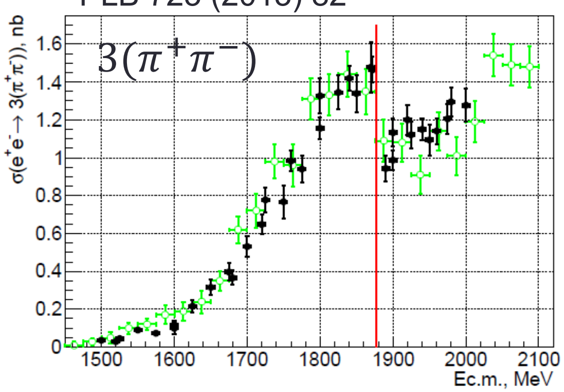
PLB 759 (2016) 634



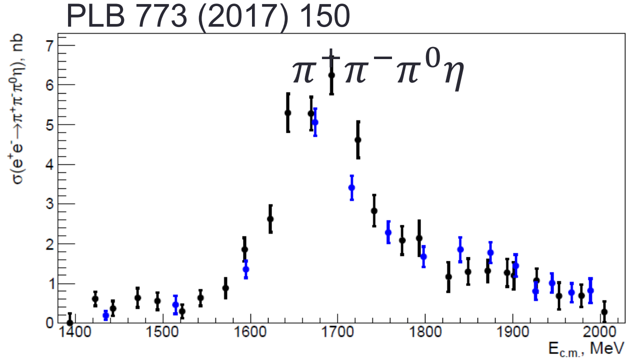
PLB 768 (2017) 345



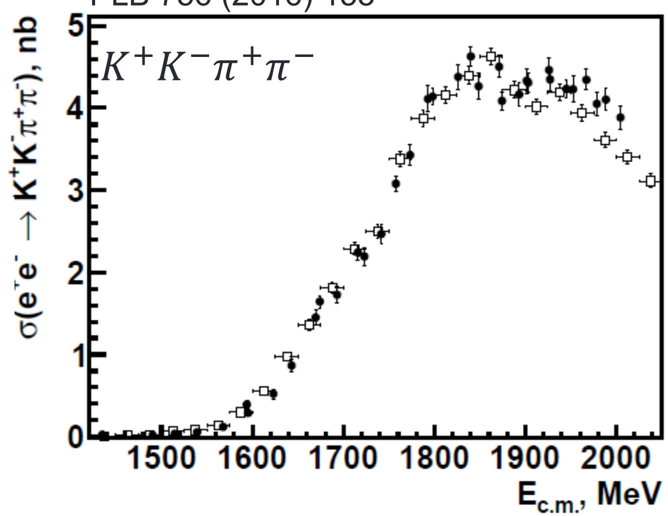
PLB 723 (2013) 82



PLB 773 (2017) 150

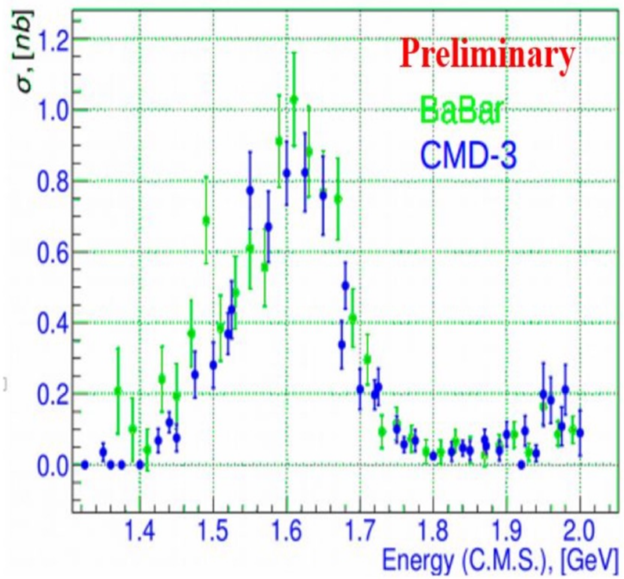


PLB 756 (2016) 153

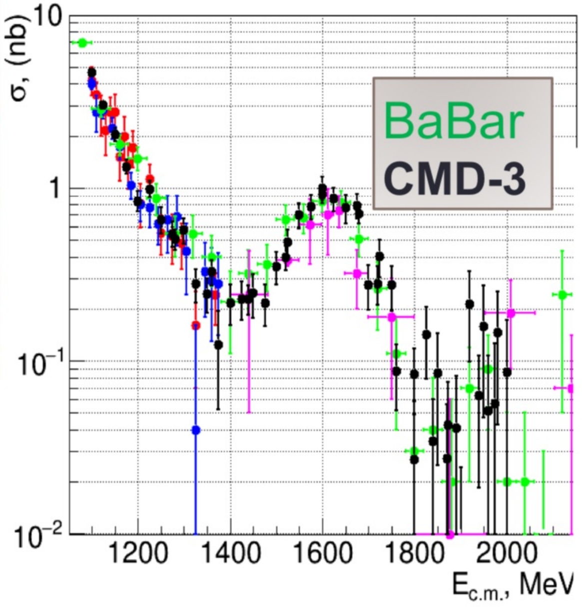


More CMD-3 preliminary results from 2011-2013

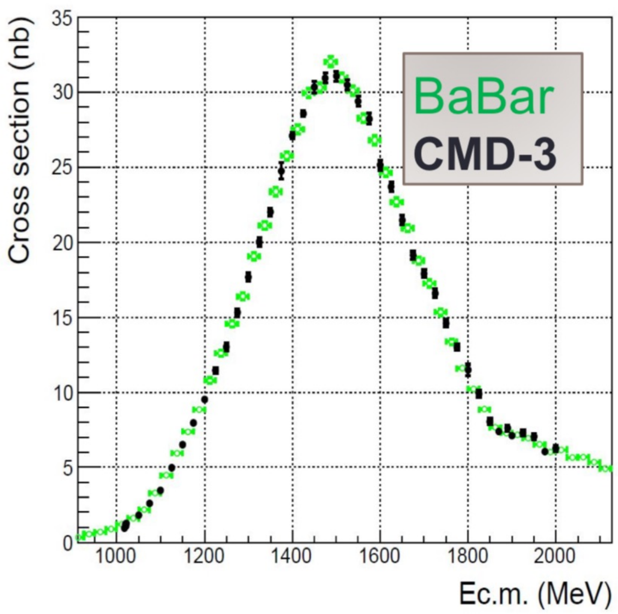
$e^+e^- \to K^+K^-\pi^0$



$e^+e^- \to K_SK_L$



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



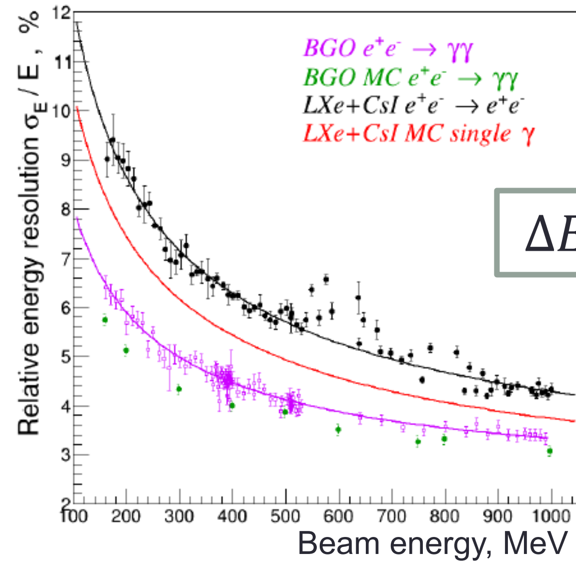
Analysis in progress

$e^+e^- \rightarrow \pi^+\pi^-$: systematics

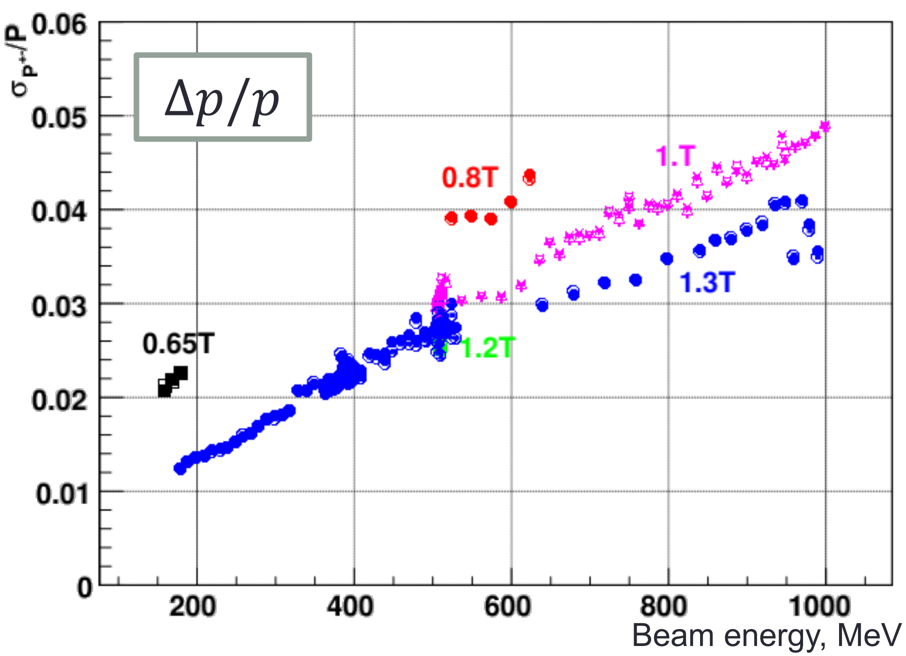
Source	Goal	Current estimation	Comment
Radiative correction	0.2%	0.2% (cross-section) 0.0-0.4% (mom.separation)	To-do: more MCGPJ improvement, comparison to data
Event separation	0.2%	0.1-0.5% (mom.separation) ~1.5% (energy separation)	To-do: improve energy separation
Fiducial volume	0.1%	ok	Two independent subsystems to fix fiducial volume
Beam energy	0.1%	ok	Continuous monitoring via Compton backscattering
Pion corrections (decay, nucl.int.)	0.1%	0.1% - nucl.interations 0.6-0.3% - decays al low energies	To-do: improve reconstruction of decay events
Combined	**0.33%**	**0.4-0.9% (mom.sep.)** **1.5% (energy sep.)**	**open box when both <1%**

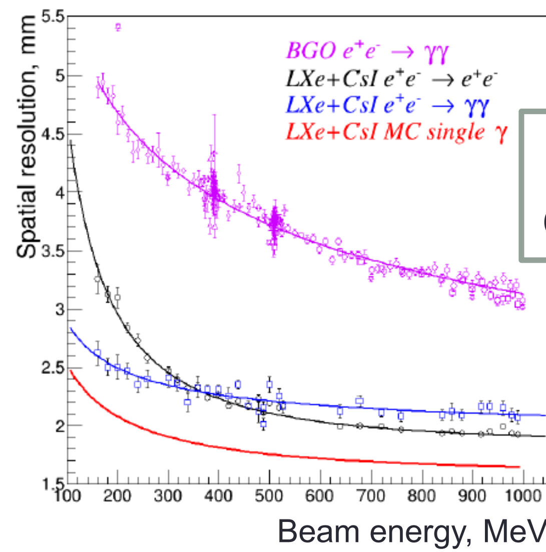
CMD-3 Performance (2011-2013)

- 1.0-1.3 T magnetic field
- Tracking: $\sigma_{R\varphi} \sim 100\ \mu, \sigma_z \sim 2-3$ mm
- Combined EM calorimeter (LXE, CsI, BGO), 13.5 X_0
  - ➢ $\sigma_E/E \sim 3\% - 10\%$
  - ➢ $\sigma_\Theta \sim 5$ mrad



$\Delta E/E$

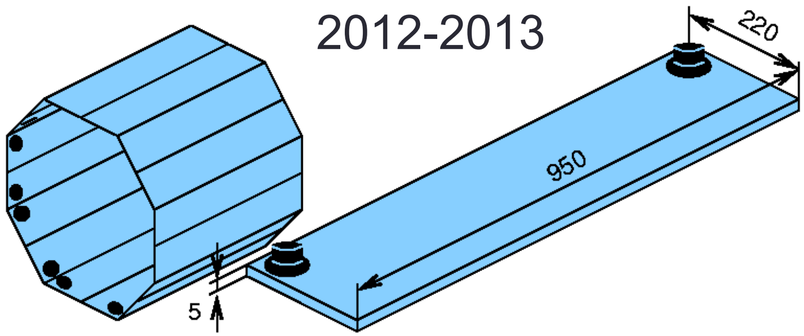




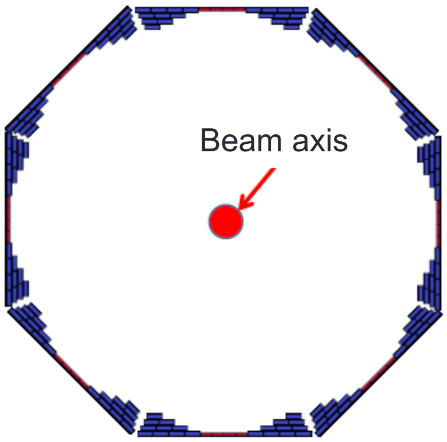
Δx, mm calorimeters

New TOF system

“Old” TOF
2012-2013

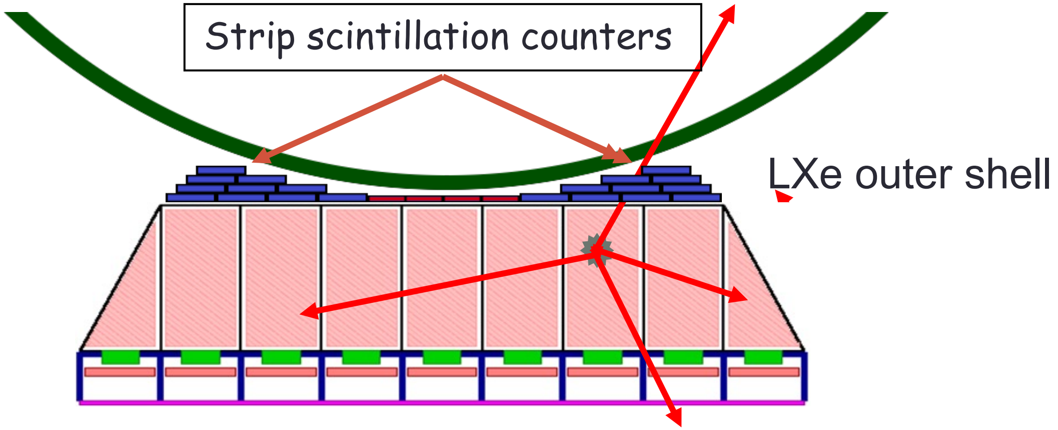


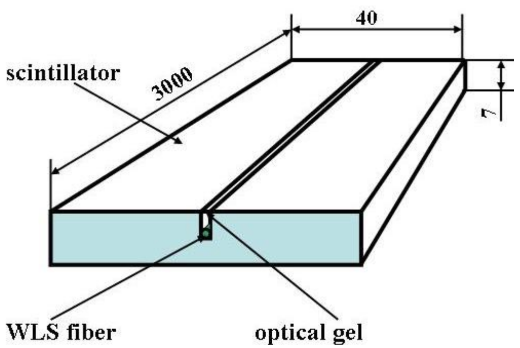
“New” TOF (2017-)



In 2013-2016 the TOF system was completely replaced

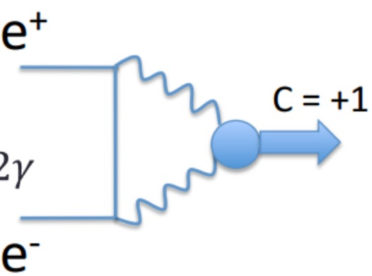
- More granulated (16 counters → 175 counters)
- 0.8 ns resolution per counter





Search for e+e- → η'(958)

Phys.Lett. B740 (2015) 273-277



C-even resonances can be produced via 2γ

Theory: assuming real γ

$$B(\eta' \to e^+e^-) = 3.7 \cdot 10^{-11}$$

γ virtuality and transition form factor can enhance it

New limit:

$B(\eta' \to e^+e^-) < 5.6\times10^{-9}$ (90%CL) - SND+CMD-3

Dedicated data taking at $\sqrt{s} = M_{\eta'}$

Continuous beam energy monitoring is crucial