Experimental input from e^+e^- machines to hadronic contribution to muon (g-2)

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Motivations for precise hadronic cross section measurements

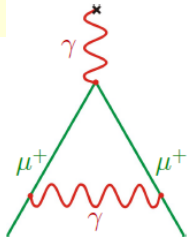
- Tests of perturbative QCD
  - QCD sum rules, quark masses, quark and gluon condensates
  - Higher order QCD corrections - Λ_{QCD}, $\alpha(s)$
- Hadronic corrections to fundamental parameters:
  - Running fine structure constant - $\alpha(M_Z^2)$
  - Anomalous magnetic moment of the muon
- measurement of parameters of light vector mesons ρ, ω, ϕ, ρ', ρ'', …..
- Search of and study of the exotic resonance states (X, Y, Z, …)
- Study of the final states dynamics and test of theoretical models
- comparison with spectral functions of the hadronic tau decays via CVC
- Study of nucleon-antinucleon pair production – nucleon ectromagnetic form factors, search for NNbar resonances, ..

a_μ- SM calculations and experiment

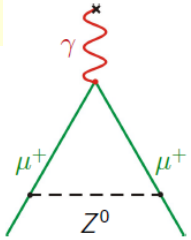
Muon anomaly, $a_m = (g-2)_m/2$

$$a_\mu^{\text{theory(SM)}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{had}}$$

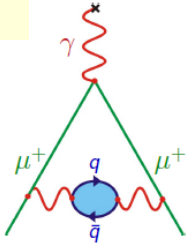
QED



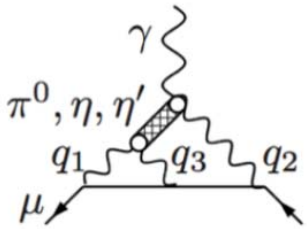
WEAK



HADRONIC



LbL



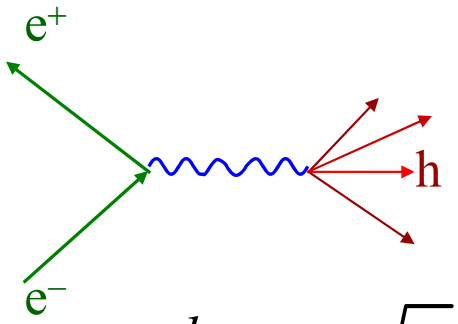
Source	Value (10^{-10})	Uncertainty (10^{-10})
QED	11 658 471.895	0. 008
Weak	15.4	0.2
Hadronic $+ LbL$	693.0	4.9
BNL E821	11 659 208.9	6.4
BNL – SM Theory	28.7	8.0

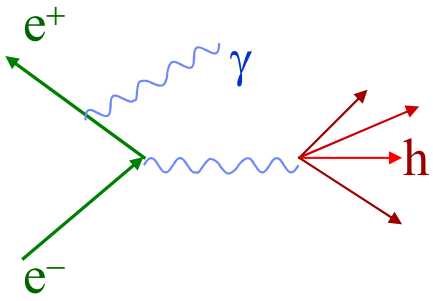
$$a_\mu^{had} = \frac{\alpha^2}{3\cdot\pi^2}\int_{4m_\pi^2}^{\infty} ds \cdot \frac{K(s)}{s}\cdot R(s)$$

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

$a_\mu^{EXP} - a_\mu^{SM} = 3.6\sigma$ **(M. Davier et al., EPJC71(2011)1515)**

Present data: Direct energy scan and ISR



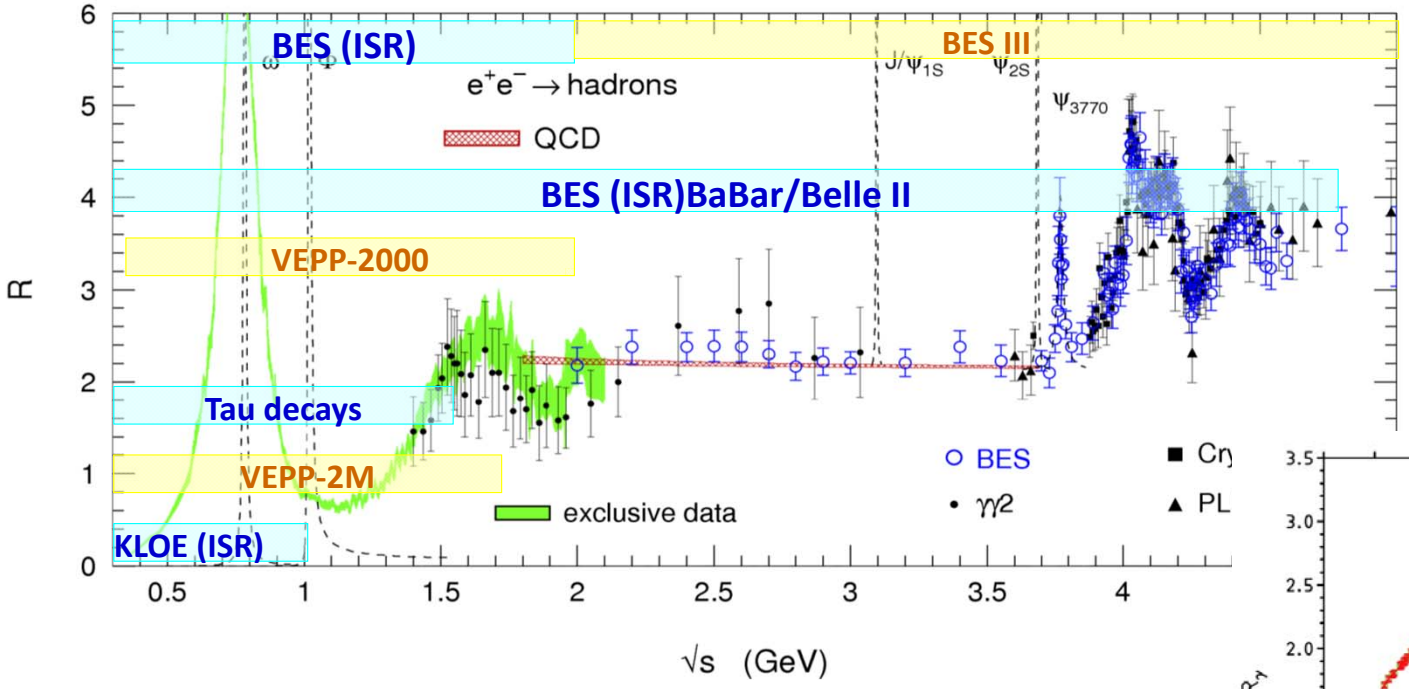


$$E^h_{CM} = \sqrt{s} \qquad E^h_{CM} = M^h_{inv} = \sqrt{\sqrt{s}(\sqrt{s} - 2E_\gamma)}$$

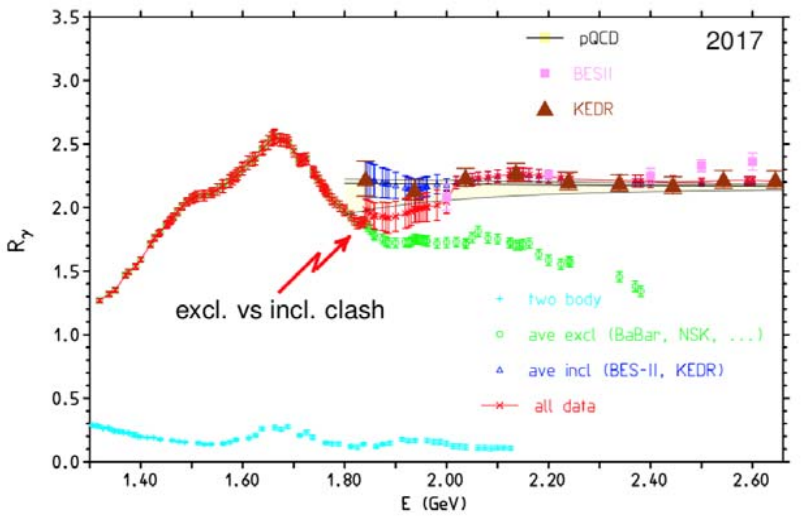
Scan: Novosibirsk – scan (CMD-2/SND at VEPP-2M, 0.36 < √s < 1.4 GeV, CMD-3/SND at VEPP-2000, 2m < √s < 2.0 GeV)
BES, BES II, BES III – Beijing 2-5 GeV

ISR: SLAC – ISR (BaBar at PEPII, 2m < √s < 5 GeV)
Frascati – ISR (KLOE/KLOE-2 at DAFNE, 2m < √s < 1.02 GeV)
BES III

Inclusive vs exclusive measurements

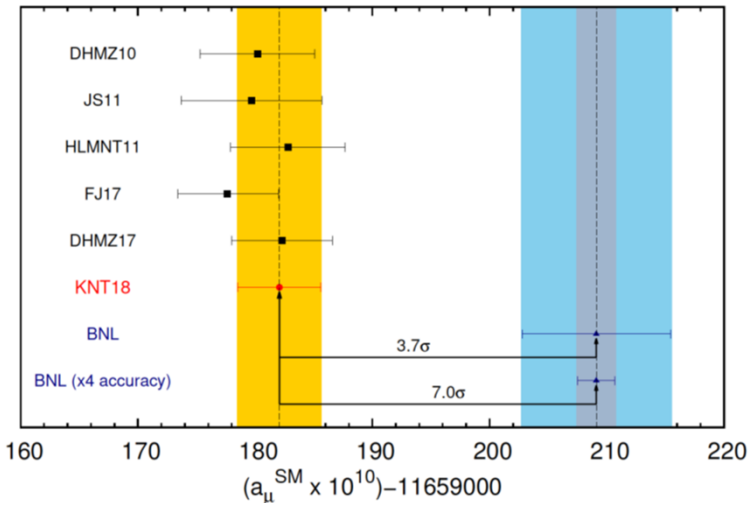


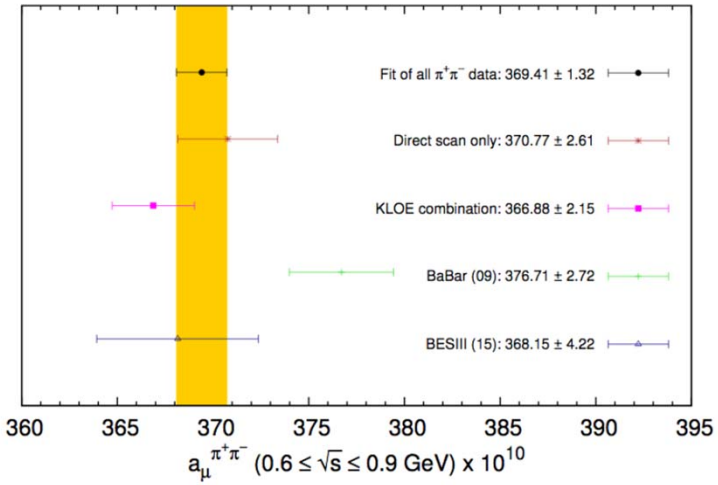
F.Jegerlehner arXiv:1804.07409

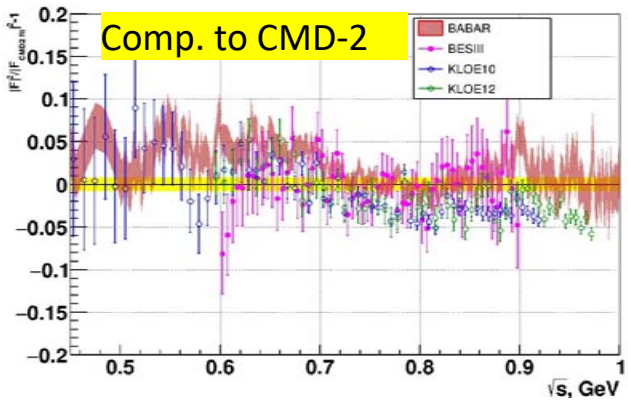


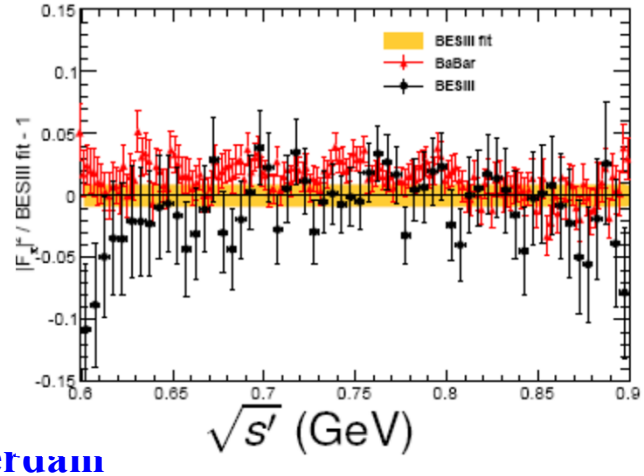
Below 2 GeV R is determined as a sum of the exclusive cross section.
higher ECM – inclusive cross section (systematics?)

Why new more precise measurements are necessary?



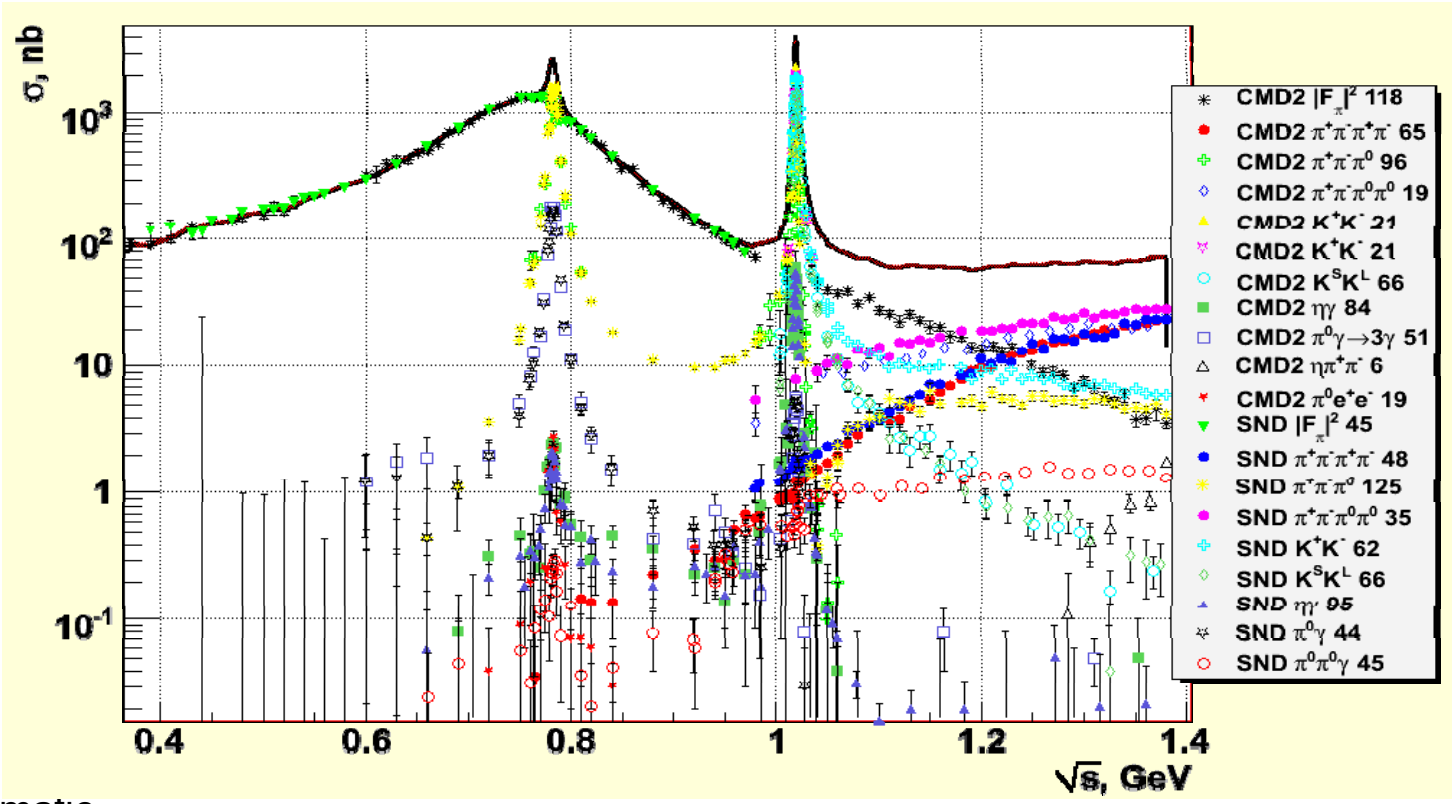






With L≈ 10^{30} $cm^{-2}s^{-1}$ VEPP-2M was pre- ϕ - factory from 1974 to 2000

$$\int Ldt \approx 70\, pb^{-1}$$

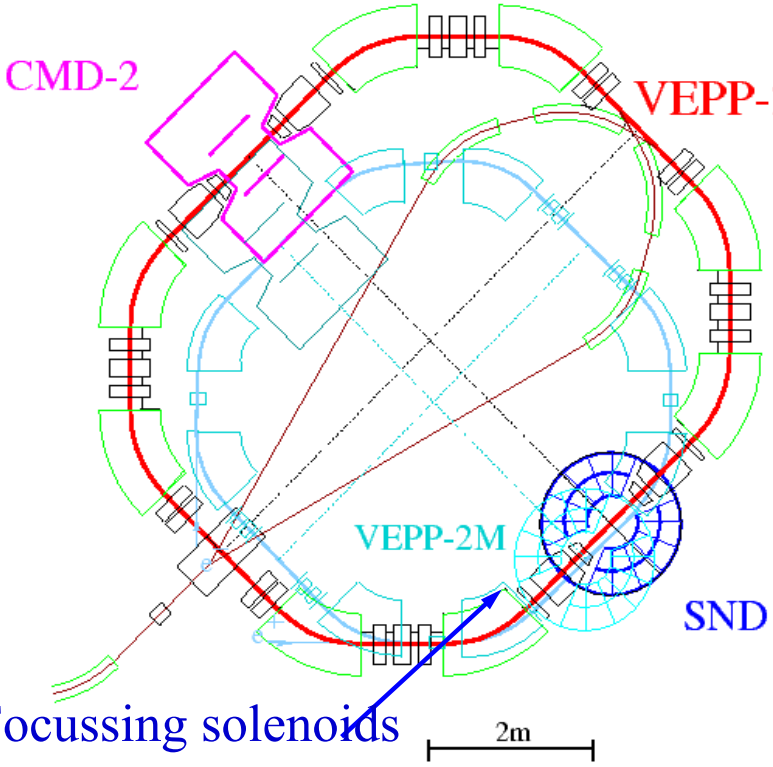


Systematic error:	~0.6-0.7%	1.0%	0.6%	1.5%	1.5 -- 3.5 %	Error of R(s)
Total error:	~ 6 -- 1%	1.5%	1--2%	2.0%	2.5 -- 3.5 %	

Since new experiments at FNAL and JPARC expect to improve the accuracy of muon (g-2) by factor 3, we need in a precision of the hadronic cross section at the level of 0.3%

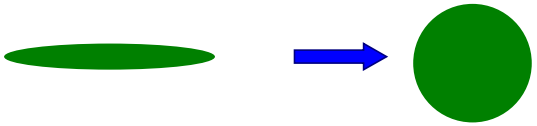
New collider VEPP-2000

2Emax: 1.4 GeV $\rightarrow$ 2 GeV



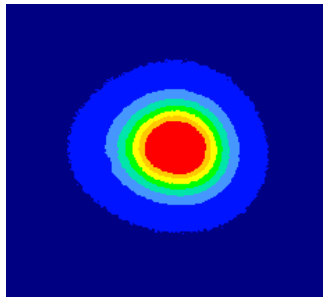
Focussing solenoids
B=12 T

The main idea – round beams!



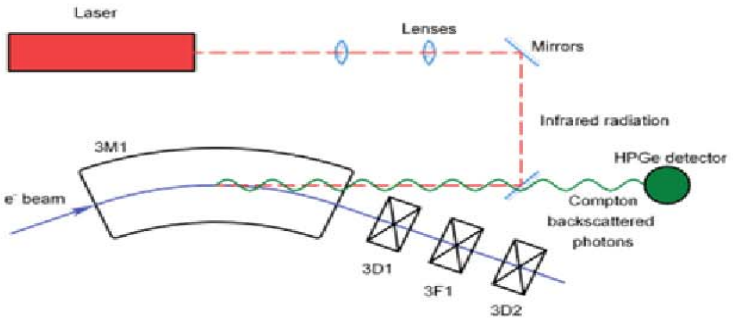
VEPP-2M & VEPP-2000 parameters

	VEPP-2M	VEPP-2000	
E (MeV)	510	510	900
Π (cm)	1788	2235	2235
$\mathcal{I}^+, \mathcal{I}^-$ (mA)	40	34	200
$\varepsilon \cdot 10^5$ (cm · rad)	3	0.5	1.6
β_x (cm)	40	6.3	6.3
β_z (cm)	5	6.3	6.3
ξ_x	0.016	0.075	0.075
ξ_z	0.050	0.075	0.075
$\mathcal{L}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$3 \cdot 10^{30}$	$1 \cdot 10^{31}$	$1 \cdot 10^{32}$

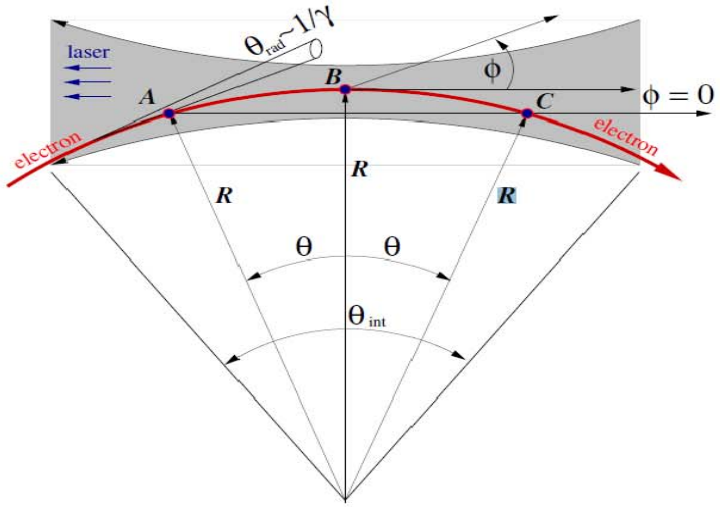


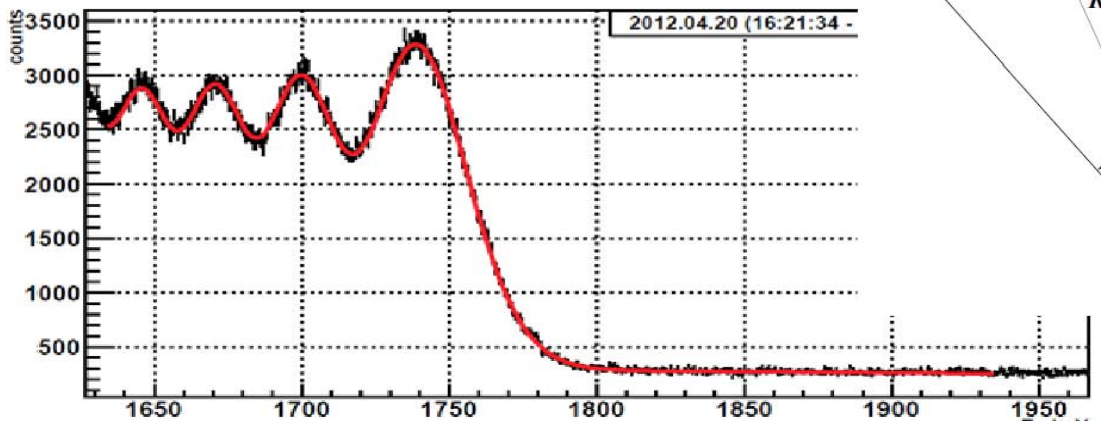
Energy measurement

Starting from 2012, energy is monitored continuously using compton backscattering techneques



Radiation coming from A and C points under angle φ = 0 is interferenced

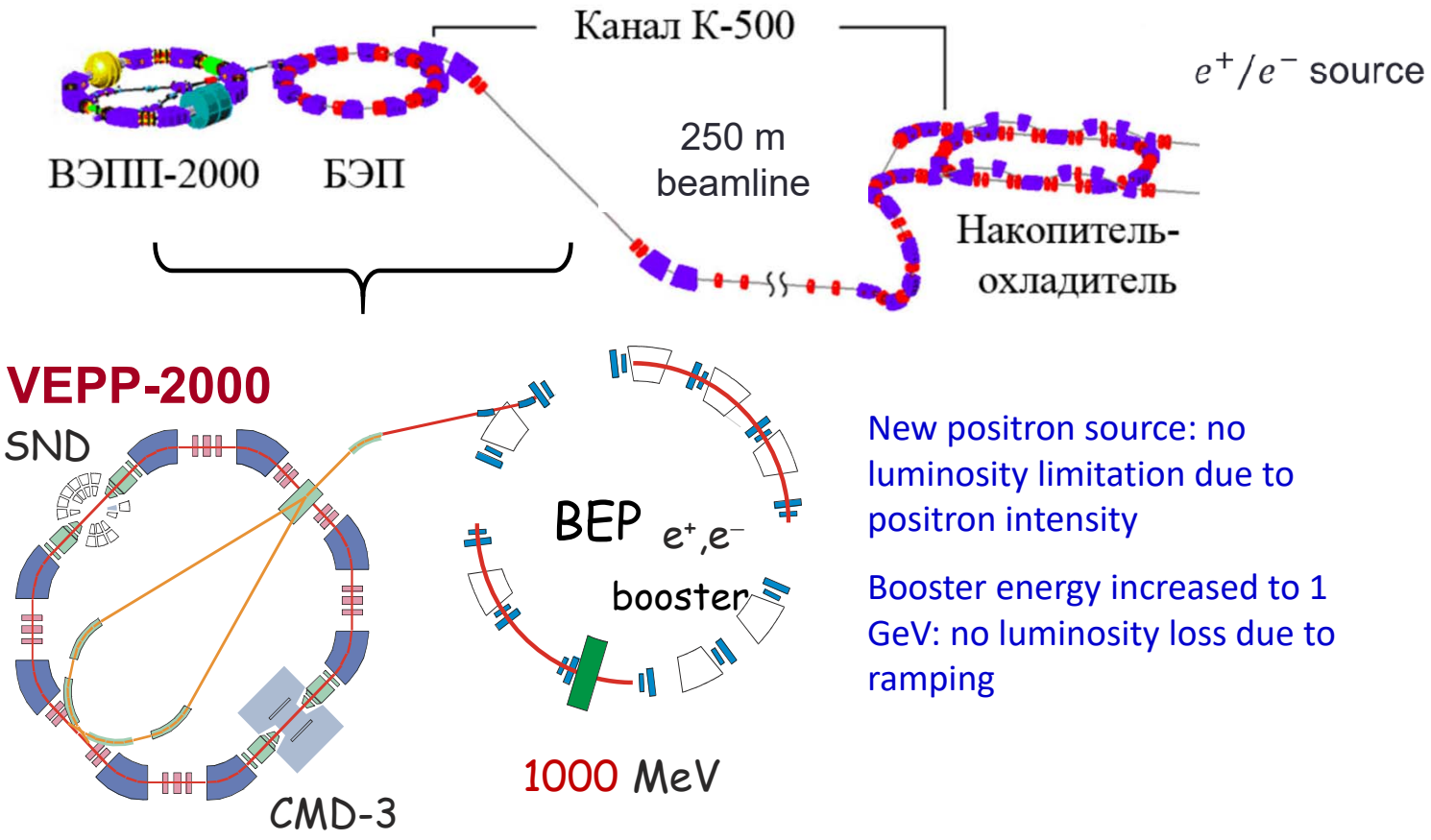




E = 993.662 ± 0.016 МэВ

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

VEPP-2000 after upgrade (from 2017)



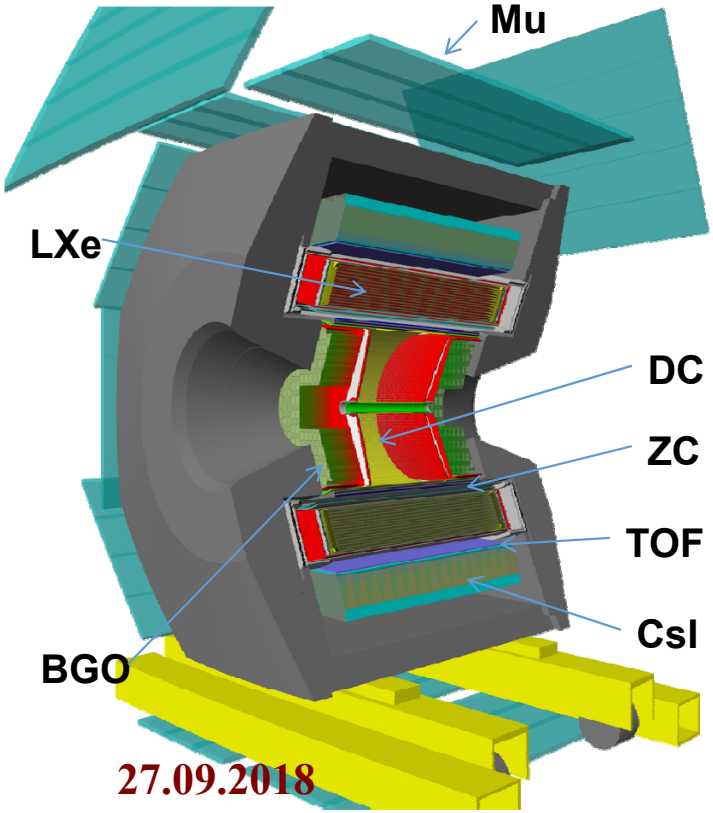
New positron source: no luminosity limitation due to positron intensity

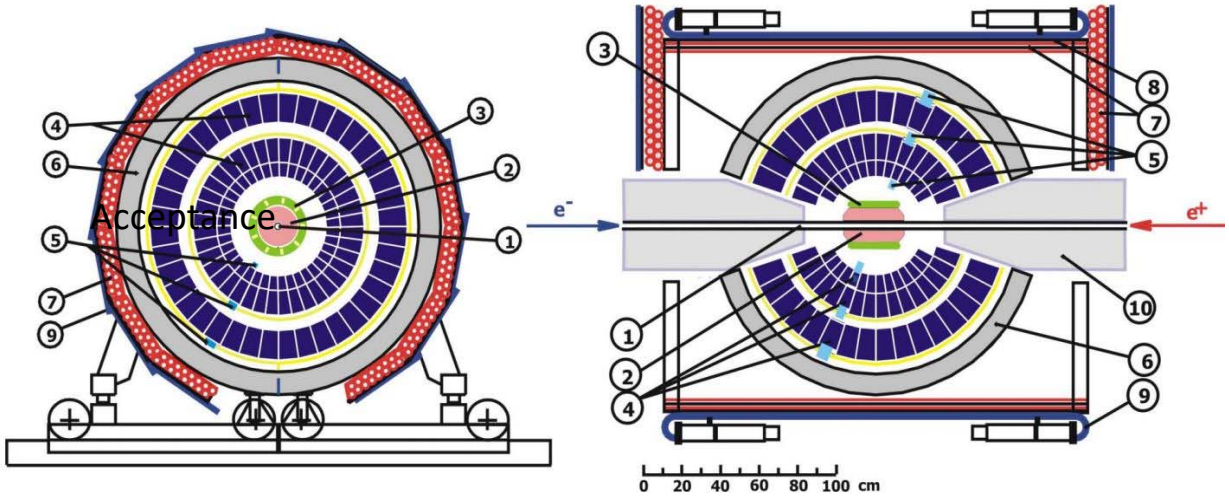
Booster energy increased to 1 GeV: no luminosity loss due to ramping

VEPP-2000 - detectors

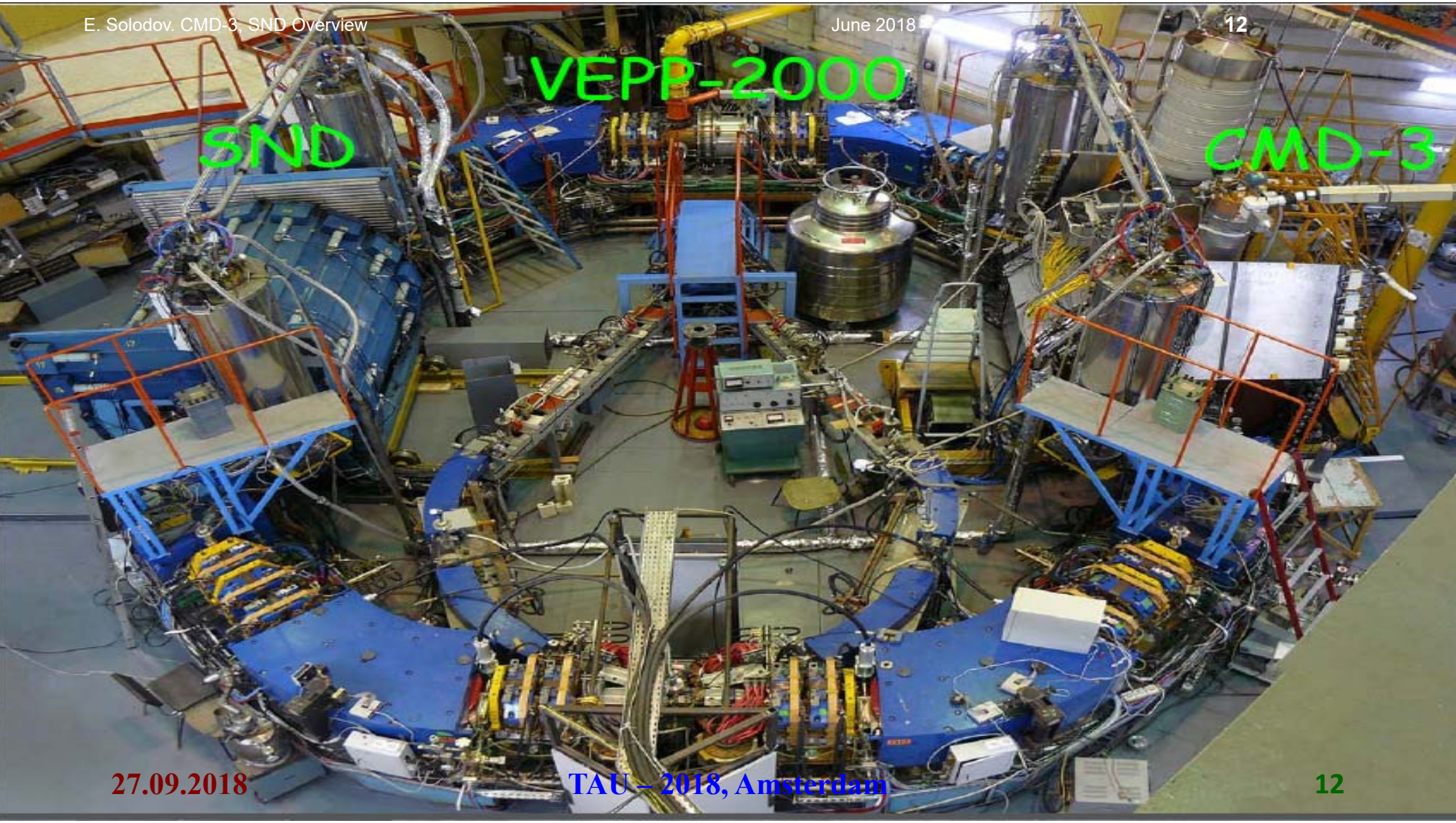
Compact multipurpose detector comprising magnetic spectrometry with high resolution calorimetry

Main advantage: high resolution calorimeter with $0.95 \times 4\pi$ uniform acceptance

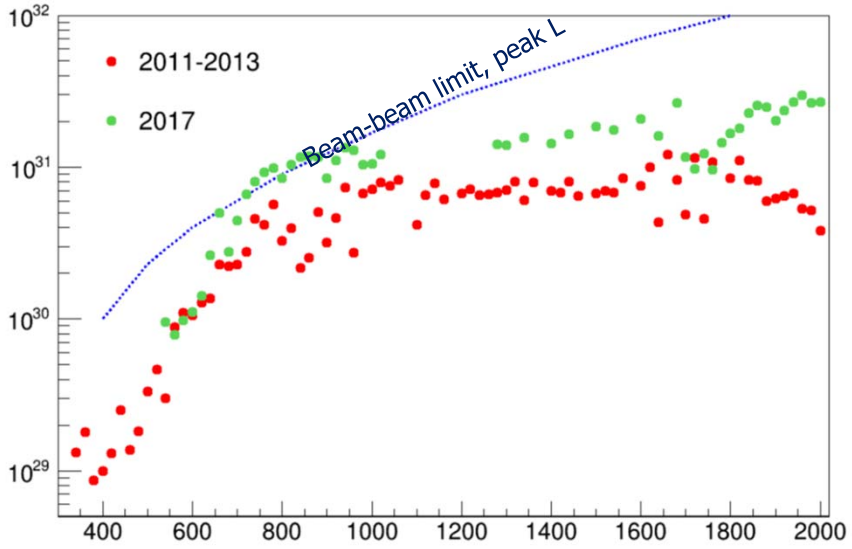


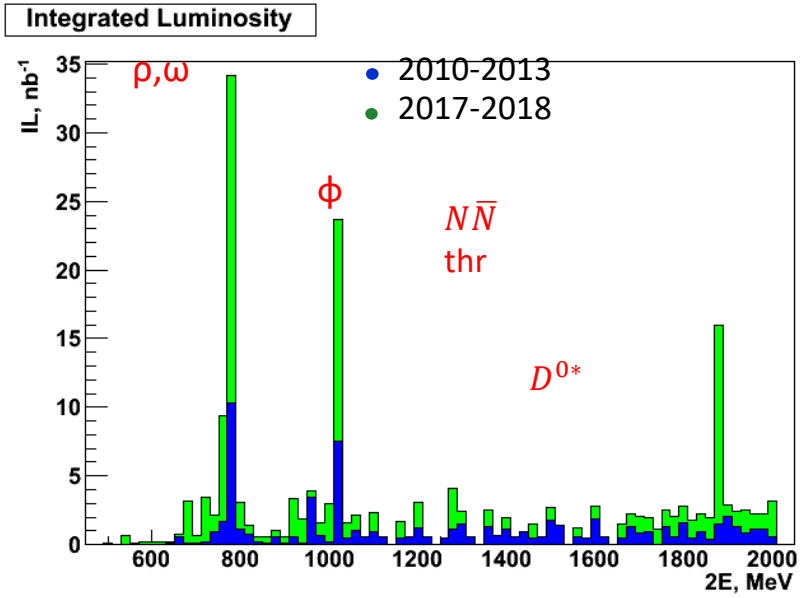


1 – vacuum chamber, 2 – tracking DC, 3 – aerogel n=1.13, 1.05 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – absorber, 7–9 – muon detector, 10 – SC solenoids


VEPP-2000
SND
CMD-3

VEPP-2000 collected Luminosity





2010-2013 ~ 55 pb-1/det.

In 2013 we reached 2 × 160 MeV, the smallest energy ever measured at ee colliders

2017-2018 /per detector

$e^+e^- \to D^{0*}$ (2.007 GeV) **pb-1**

$p\bar{p}$ and $n\bar{n}$ threshold 14 pb-1

Overall:

1.28 – 2.007 GeV 50 pb-1

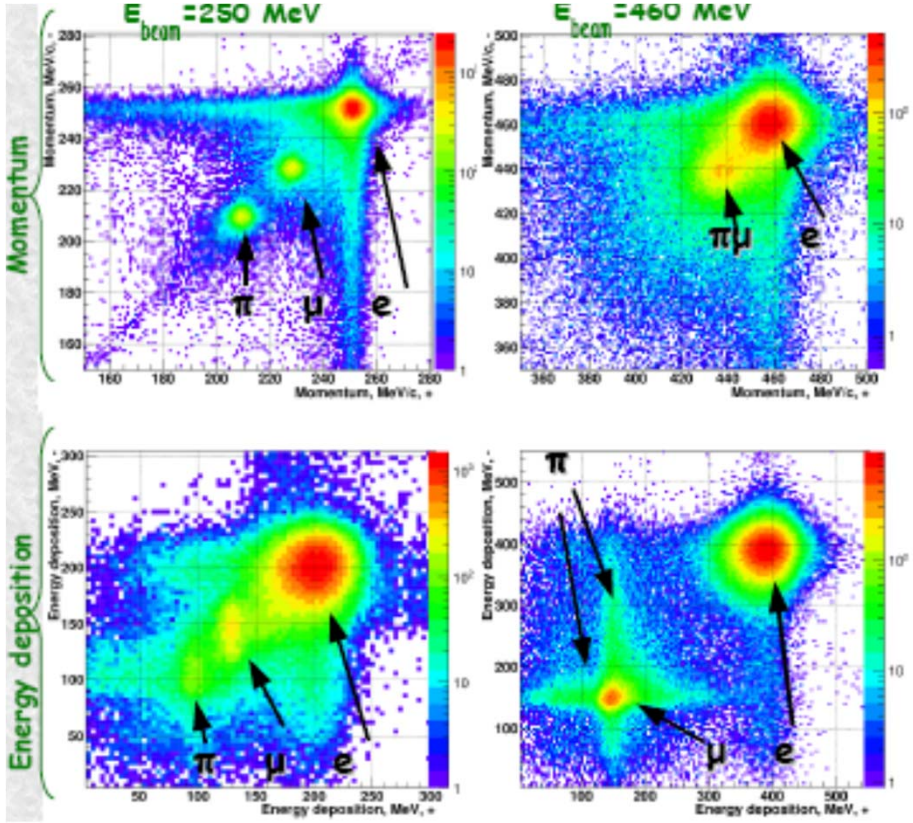
0.55 – 1.00 GeV 70 pb-1

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

Separation of $e^+e^- \to e^+e^-$, $\pi^+\pi^-$, $\mu^+\mu^-$ events by particle momenta and energy deposition in the calorimeter

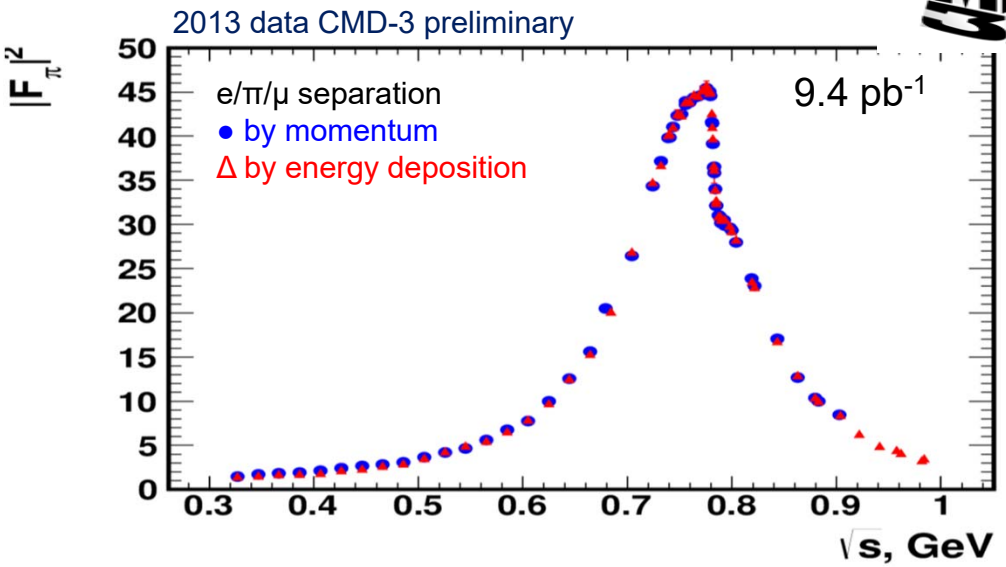
Two charge tracks collinear back-to-back events are selected

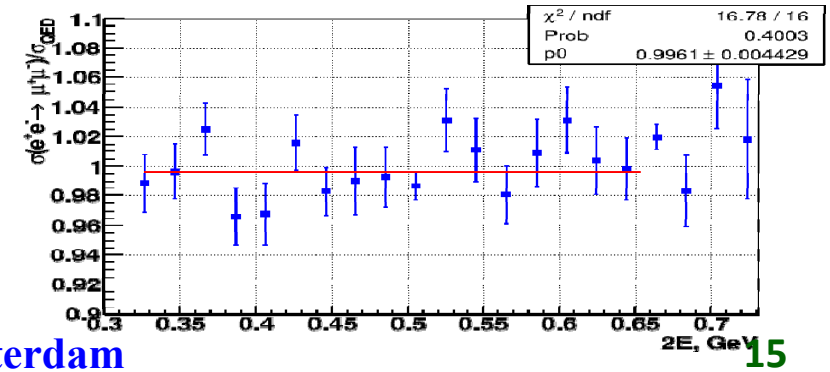
$$|F_\pi|^2 = \frac{N_{\pi\pi}}{N_{ee}} \frac{\sigma^B_{ee}(1+\delta_{ee})\varepsilon_{ee}}{\sigma^B_{\pi\pi}(1+\delta_{\pi\pi})\varepsilon_{\pi\pi}}$$



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

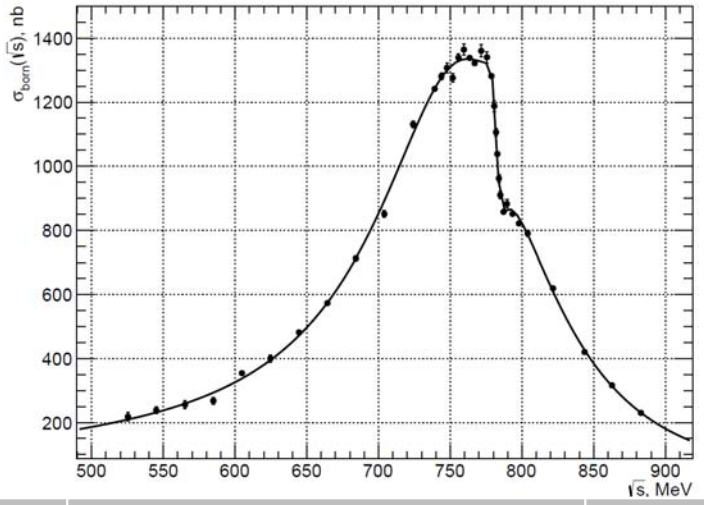
Source	Goal	Current estimation
Radiative Correction	0.2%	0.2% (cross-section) 0.0-0.4% (mom.sep.)
Event separation	0.2%	0.1-0.5% (mom. sep.) ~1.5% (energy sep.)
Fiducial volume	0.1%	ok
Beam energy	0.1%	ok
Pion corrections (decay, nucl.int.)	0.1%	0.1% -nucl. int. 0.6-0.3% decays at low energies
Combined	0.33%	0.4-0.9% (mom.sep.) 1.5% (energy sep.)

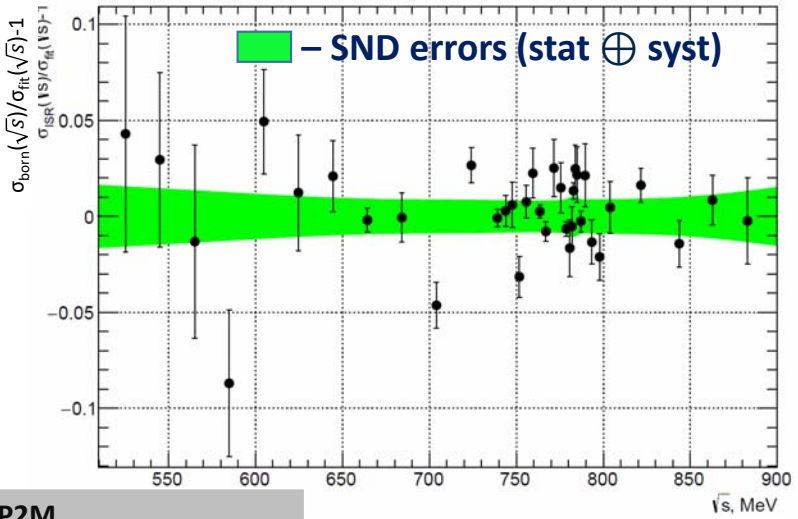




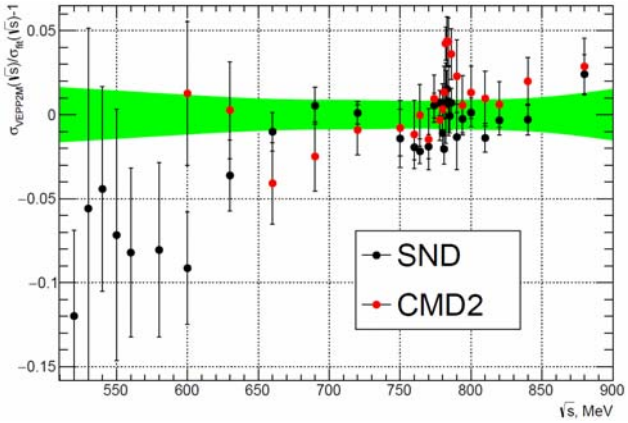
Some corrections are not applied
(result is still “blinded”)
Hope to finalize it later this year

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





Parameters	SND & VEPP2000	SND & VEPP2M
m_ρ, MeV	775.925 ± 0.5 ± 0.78	774.6 ± 0.4 ± 0.5
Γ_ρ, MeV	145.686 ± 0.65 ± 1.56	146.1 ± 0.8 ± 1.5
$\sigma(\rho \to \pi^+\pi^-)$, nb	1188.54 ± 4.6 ± 9.5	1193 ± 7 ± 16
$\sigma(\omega \to \pi^+\pi^-)$, nb	32.44 ± 1.3 ± 0.3	29.3 ± 1.4 ± 1.0
$\phi_{\rho\omega}$, degree	112.63 ± 1.41	113.7 ± 1.3 ± 2.0
$B_{\rho\to\pi^+\pi^-} \times B_{\rho\to e^+e^-}$	$(4.892 \pm 0.0154 \pm 0.0391) \times 10^{-5}$	$(4.876 \pm 0.02 \pm 0.06) \times 10^{-5}$
$B_{\omega\to\pi^+\pi^-} \times B_{\omega\to e^+e^-}$	$(1.358 \pm 0.056 \pm 0.011) \times 10^{-5}$	$(1.225 \pm 0.06 \pm 0.04) \times 10^{-5}$



CMD-3 results and analyses ongoing

Published

$K_S K_L$	PLB 760 (2017) 314
K^+K^-	PLB 760 (2017) 314
pp	PLB 759 (2016) 634
$3(\pi^+\pi^-)$	PLB 723 (2013) 82
$\pi^+\pi^-\,\pi^+\pi^-$	PLB 768 (2017) 345
$\pi^+\pi^-\,\pi^0\eta$	PLB 773 (2017) 150
$K^+K^-\pi^+\pi^-$	PLB 756 (2016) 153

Analyses ongoing

$\pi^+\pi^-\,\omega$
$\pi^+\pi^-\,\eta(3\pi)$
$\pi^+\pi^-\,\eta(2\gamma)$
$K^+K^-\,\omega$
$K^+K^-\,\eta$
$K^+K^-\,\pi^0$
$K_S K_L$
$2(\pi^+\pi^-)$
$3(\pi^+\pi^-)\,\pi^0$
$\omega \to \pi^0\,e^+e^-$

Overview of SND results

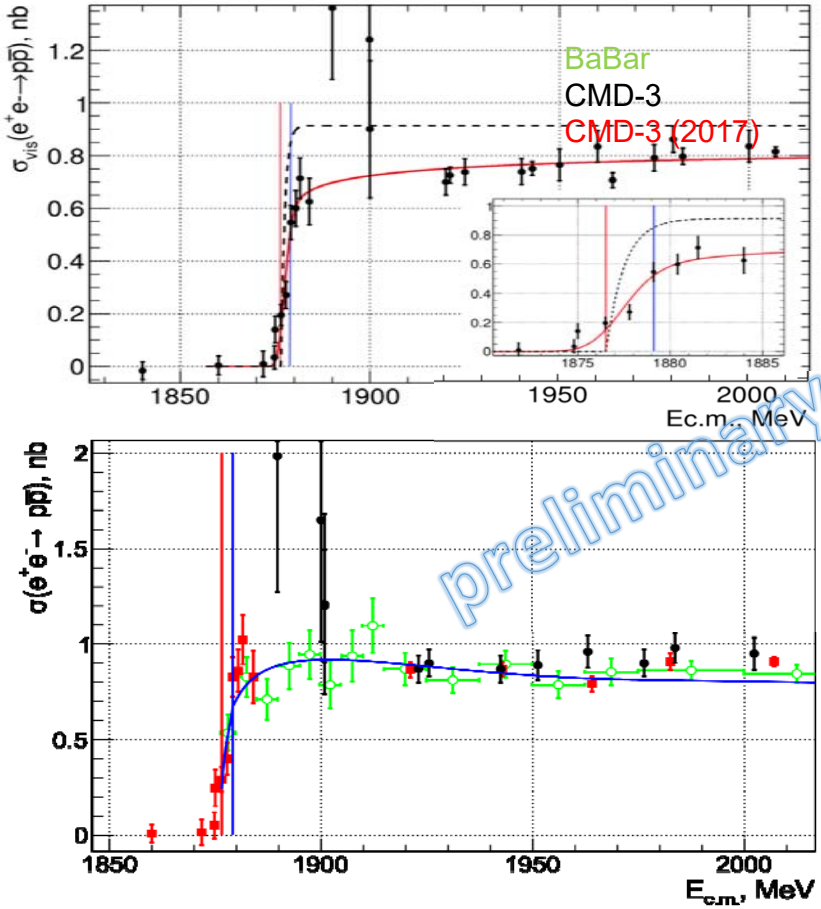
Published

$e^+e^- \to K^+K^-\eta$	Phys. of Atomic Nuclei (2018) v.81(2)
$e^+e^- \to \eta\pi^+\pi^-$	hyPs.Rev. D97 (2018) no.1
$e^+e^- \to K_SK_L\pi^0$	Phys.Rev. D97 (2018) no.3
$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$	Phys.Rev. D94 (2016) no.11
$e^+e^- \to K^+K^-$	Phys.Rev. D94 (2016) no.11
$e^+e^- \to \omega\eta$	Phys.Rev. D94 (2016) no.9
$e^+e^- \to \omega\eta\pi^0$	Phys.Rev. D94 (2016) no.3
$e^+e^- \to \pi^0\gamma$	Phys.Rev. D93 (2016) no.9
$e^+e^- \to \pi^+\pi^-\pi^0$	JETP 121 (2015) no.1
$\eta \to e^+e^-$	JETP Lett. 102 (2015) no.5
$\eta' \to e^+e^-$	Phys.Rev. D91 (2015)
$e^+e^- \to \eta\pi^+\pi^-$	Phys.Rev. D91 (2015) no.5
$e^+e^- \to n\bar{n}$	Phys.Rev. D90 (2014) no.11
$e^+e^- \to \eta\gamma$	Phys.Rev. D90 (2014) no.3
$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$	Phys.Rev. D88 (2013) no.5

In work

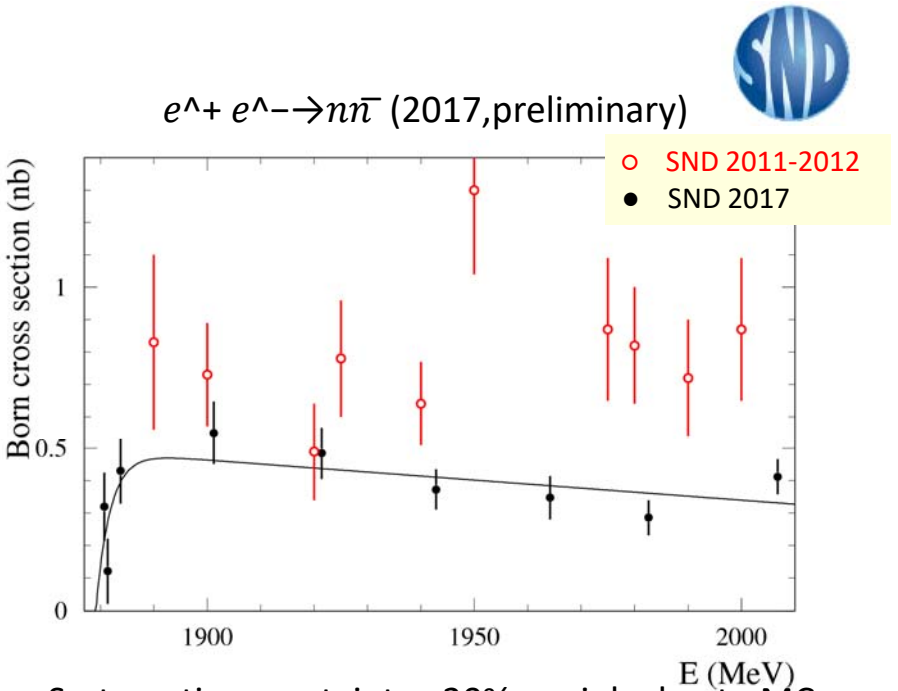
- $e^+e^- \to \pi^+\pi^-$
- $e^+e^- \to n\bar{n}$
- $\eta \to e^+e^-$
- $e^+e^- \to \eta\pi^0\pi^+\pi^-$
- $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$
- $e^+e^- \to K^+K^-\pi^0$
- $e^+e^- \to \omega\pi^0\pi^0$
- $e^+e^- \to 6\pi$
- *etc*

2017: e^+e^- -> pp at NN threshold



A. I. Milstein and S. G. Salnikov, Nucl. Phys. A 977 , 60 (2018)

In 2017 CMD-3 and SND has performed the scan at the NNbar threshold with a step smaller than c.m. machine energy spread (1.2 MeV). The e+e- -> ppbar cross section demonstrate exponentially fast rising in about 1 MeV interval.



Systematic uncertainty ~20%, mainly due to MC

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

arXiv:1808.00145v2

CMD-3 has confirmed fast drop of the cross section, and new scan shows the scale of the drop consistent with ppbar cross section rise ~1 MeV.

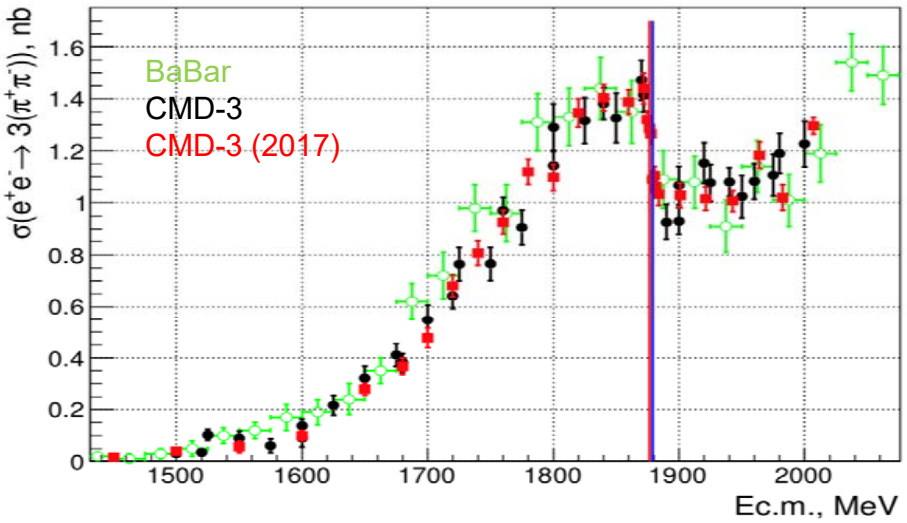


Figure 1: The $e^+e^- \to 3(\pi^+\pi^-)$ cross section measured with the CMD-3 detector at VEPP-2000 in 2017 run (squares). The results of previous CMD-3 measurements [6] are shown by dots, when BaBar measurement [4] are shown by open circles. The lines show the $p\bar{p}$ and $n\bar{n}$ thresholds.

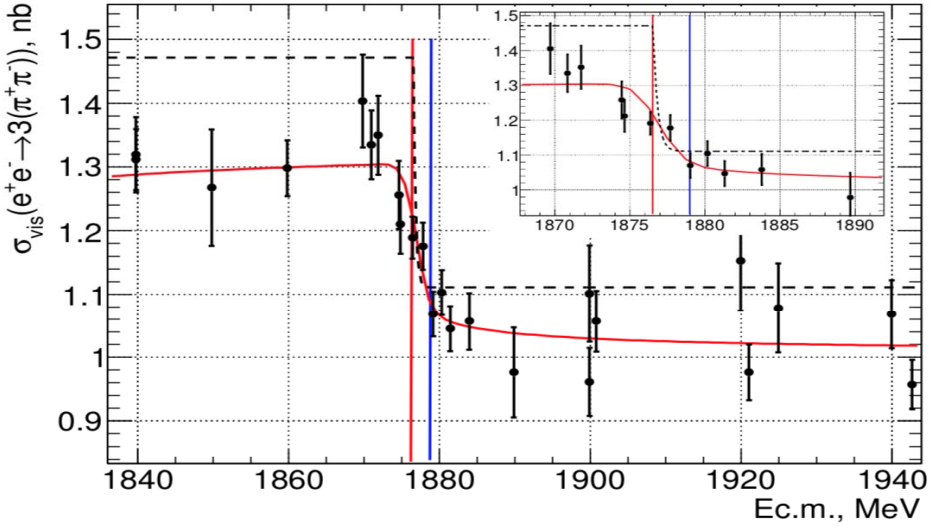
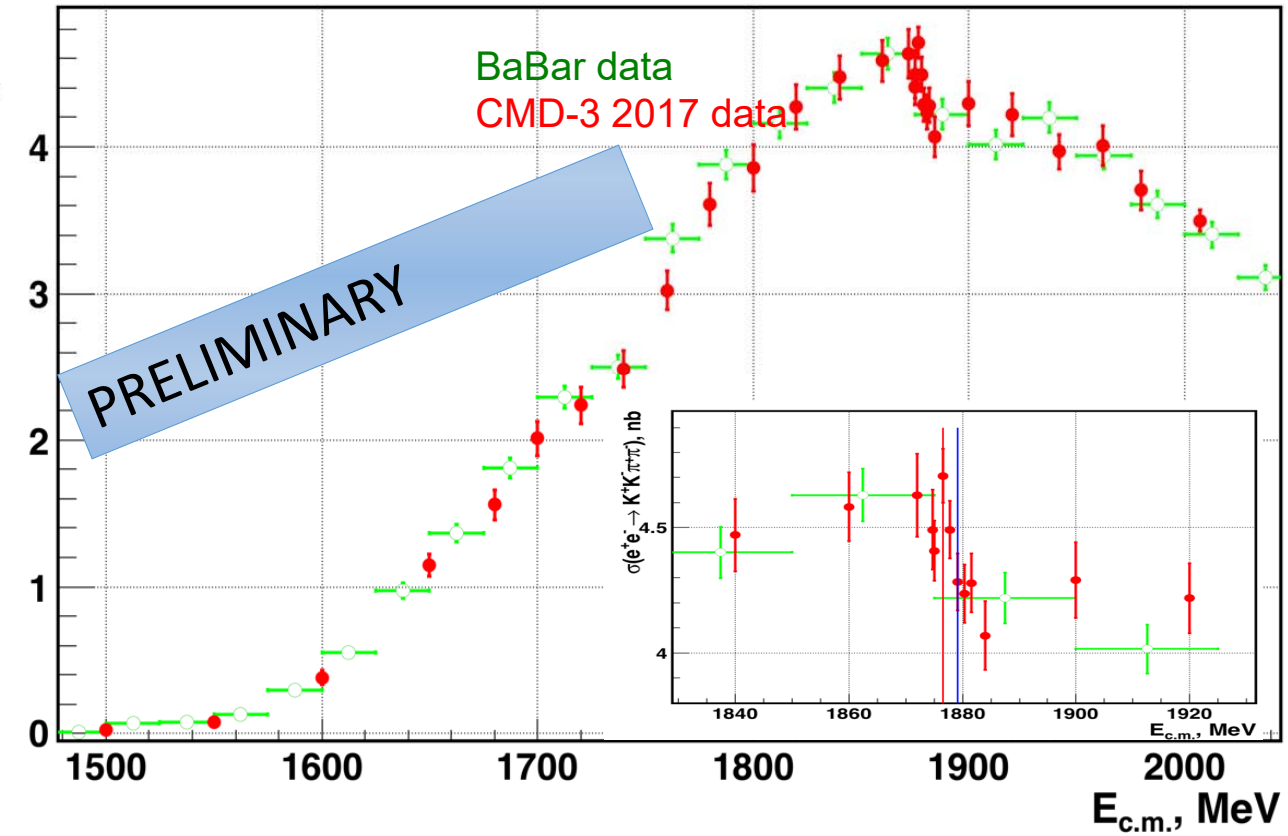


Figure 3: The $e^+e^- \to 3(\pi^+\pi^-)$ visible cross section measured with the CMD-3 detector. Solid curve shows fit with Born cross section (dashed curve) convoluted with 1.2 MeV energy spread and radiation function. The vertical lines show the $p\bar{p}$ and $n\bar{n}$ thresholds.

NEW! Structure in e^+e^- -> $K^+K^-\pi^+\pi^-$



No indication of NNbar threshold in the e^+e^- -> $2(\pi+\pi-)$ reaction!

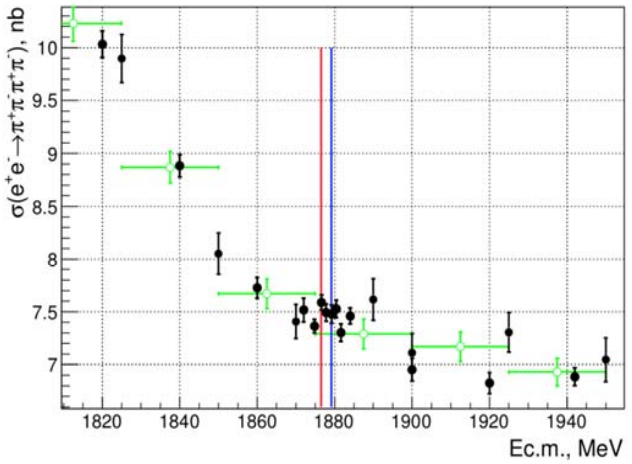
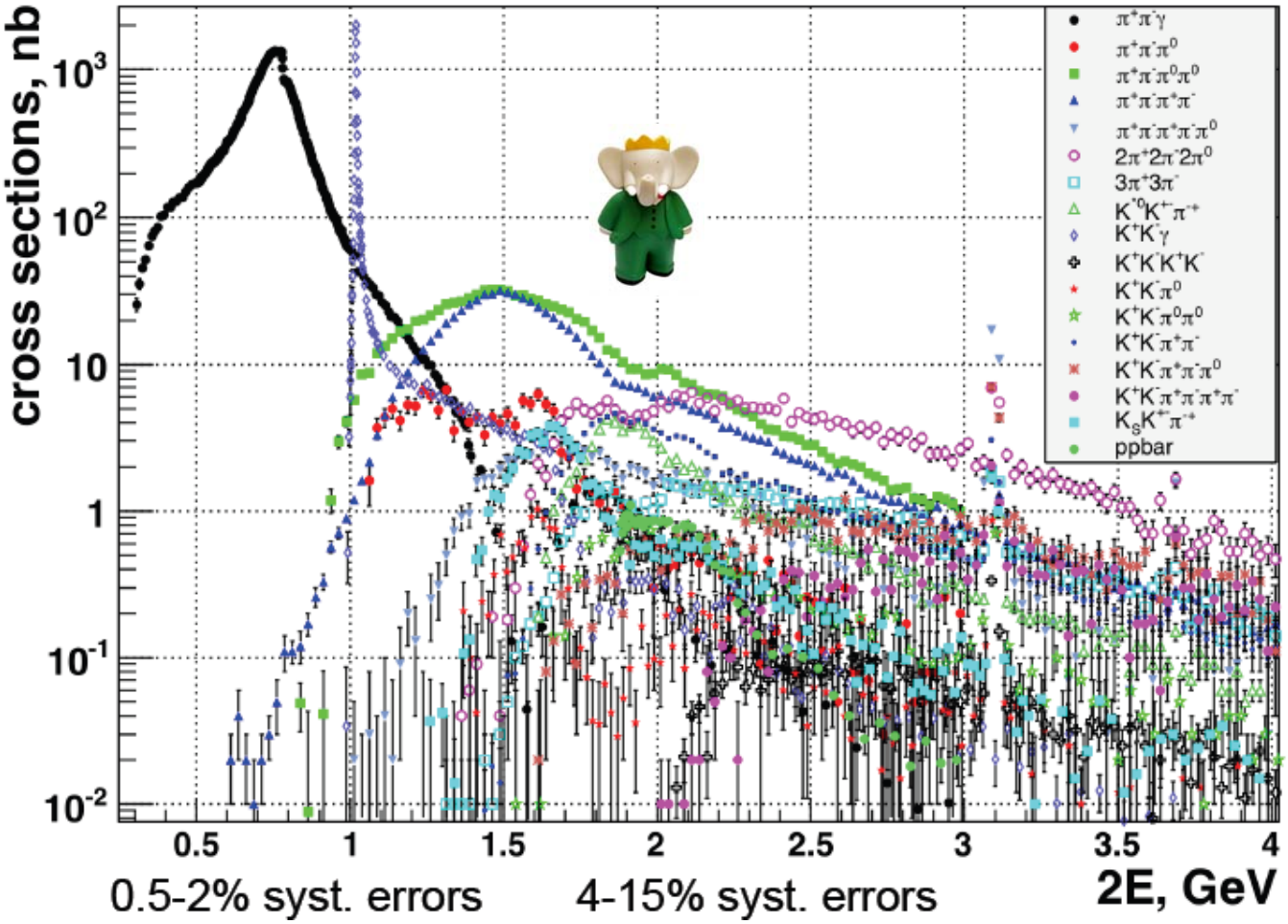


Figure 4: The $e^+e^- \to 2(\pi^+\pi^-)$ cross section measured with the CMD-3 detector. Lines show the $p\bar{p}$ and $n\bar{n}$ thresholds.

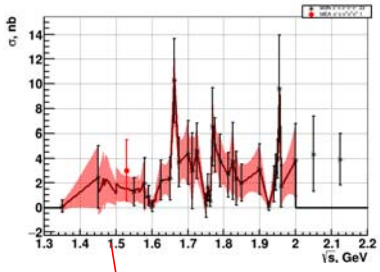
One more channel, where NN threshold structure has been observed!

BaBar ISR analyses

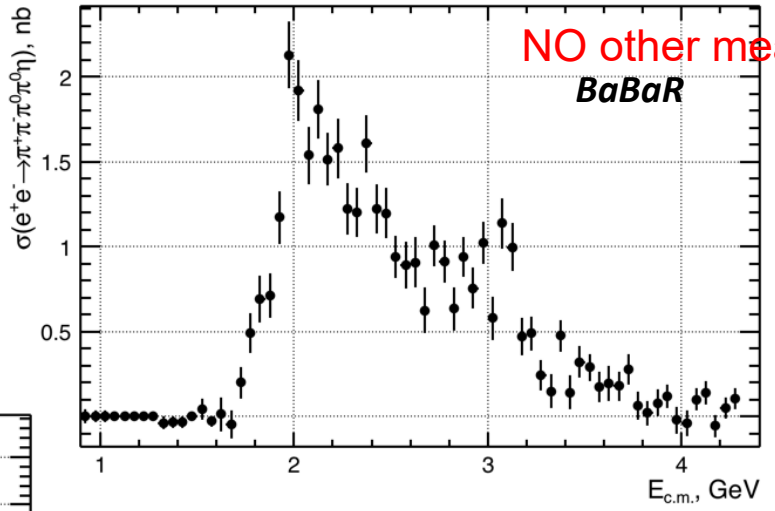
22 final states were studied, ~20 papers on low energy ISR studies were published



Study of the $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0\pi^0\eta$ processes from ISR at *BaBaR* (NEW, preliminary)



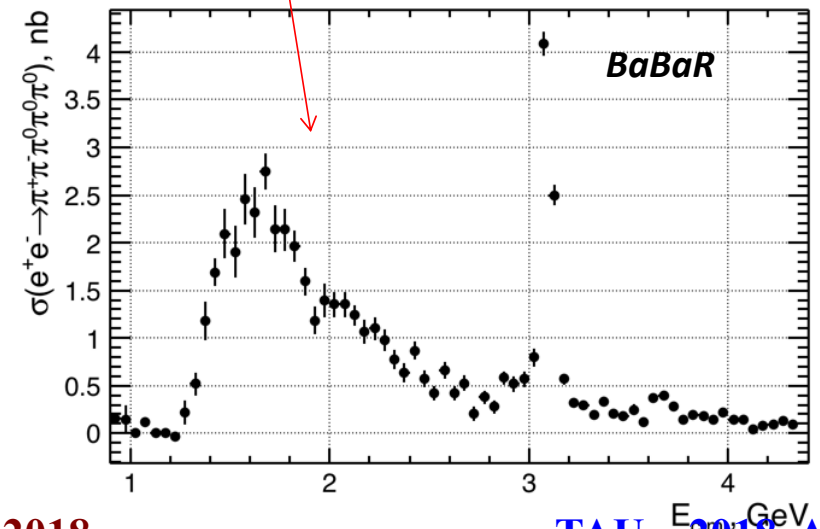
M3N
MEA
1989 !



NO other measurements!

10-13% systematic errors

$\omega\pi^0\pi^0$, $\pi^+\pi^-\eta$, $\omega\pi^0\eta$□ intermediate states

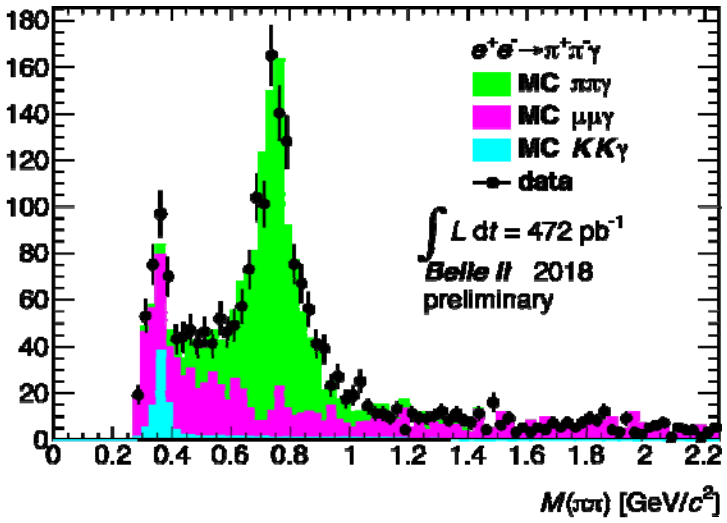


BaBar has a wide program of the hadronic cross section measurement using ISR, including $\pi^+\pi^-$ channel. Analisis is ongoing!

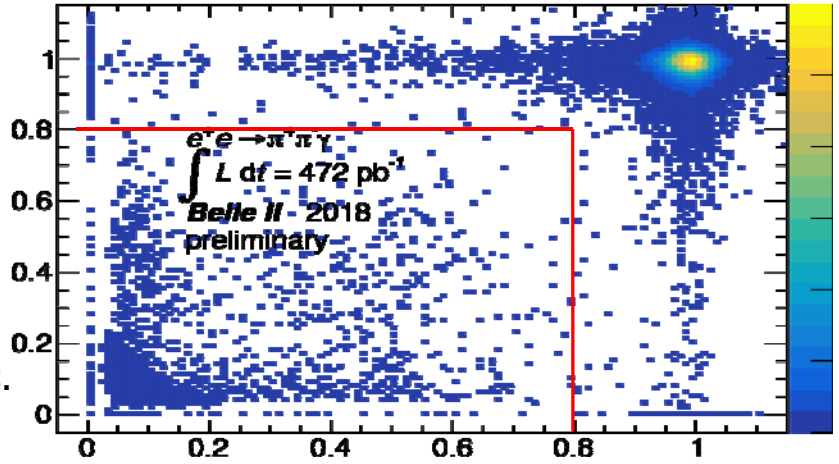
See poster by E. Solodov

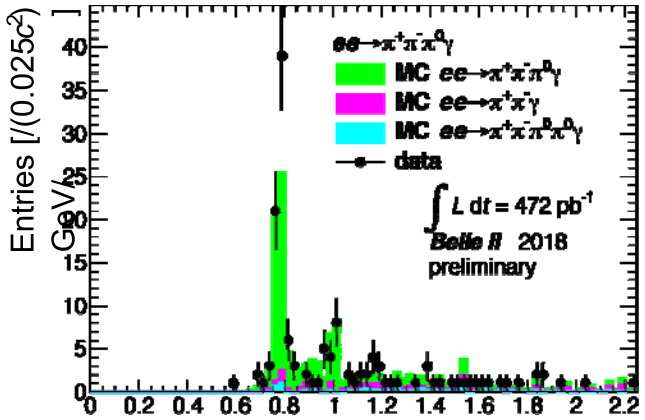
Belle II first look to ISR (Phase II)

Events with one photon
(Eg> 3 GeV, 50 < θ < 110)
and 2 tracks from IP were selected
and 10< Etot <11 GeV.
Analysis done by Y.Maeda



E/p ratio for each of positive and negative charged tracks.





MC cross sections are taken from the Phokhara generator output.

Conclusion

At present a discrepancy between experiment and SM in the muon (g-2) is, probably, the largest among observed.

Two experiments on muon (g-2) measurement are in progress. We anticipate 3-4 times better precision in several years.

The goal of two experiments CMD-3 and SND at VEPP2000 is to provide exclusive measurement of e+e- -> hadrons reactions with high precision in the energy range 0.32 – 2.0 GeV

In 2017 both detectors have collected 50 pb^{-1} in 5 months with c.m. energy scan from 1.68 to 2.0 GeV. At the end of 2017 - beginning of 2018 - 66 pb^{-1} have been collected in 0.55-1.0 GeV

New and more precise experimental data on the hadronic cross section are been waiting from VEPP 2000, BES III, BaBar and Belle II.