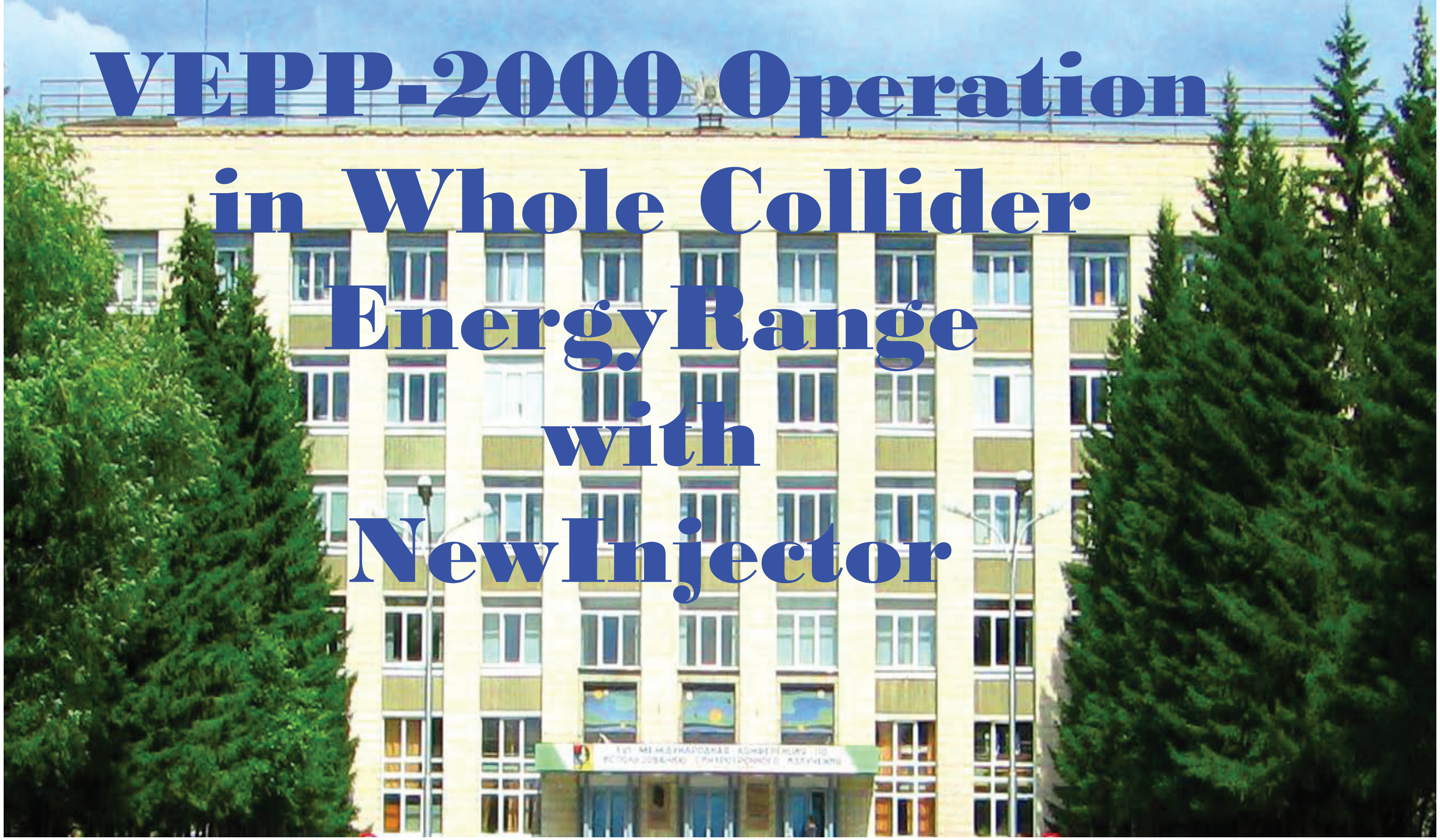
VEPP-2000 Operation in Whole Collider EnergyRange with NewInjector



Yuri Shatunov

on behalf of the VEPP-2000 collaboration

Budker Institute of Nuclear Physics

Novosibirsk State University

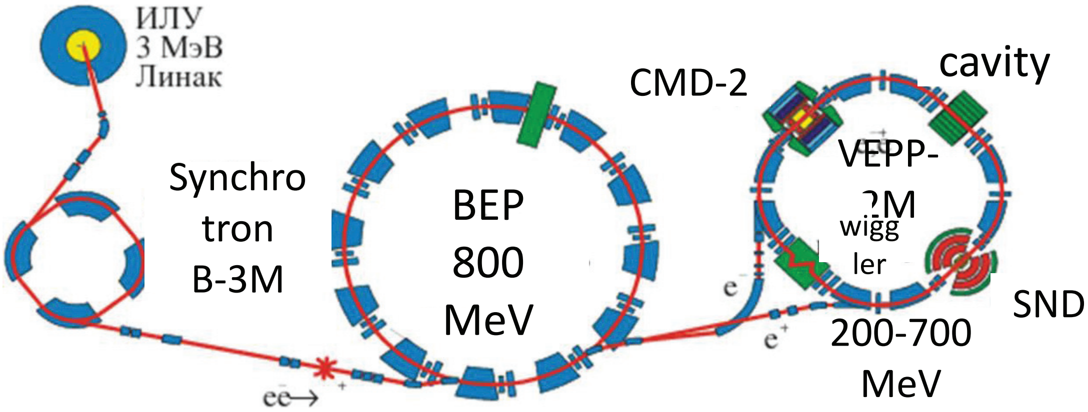
RuPAC 2018

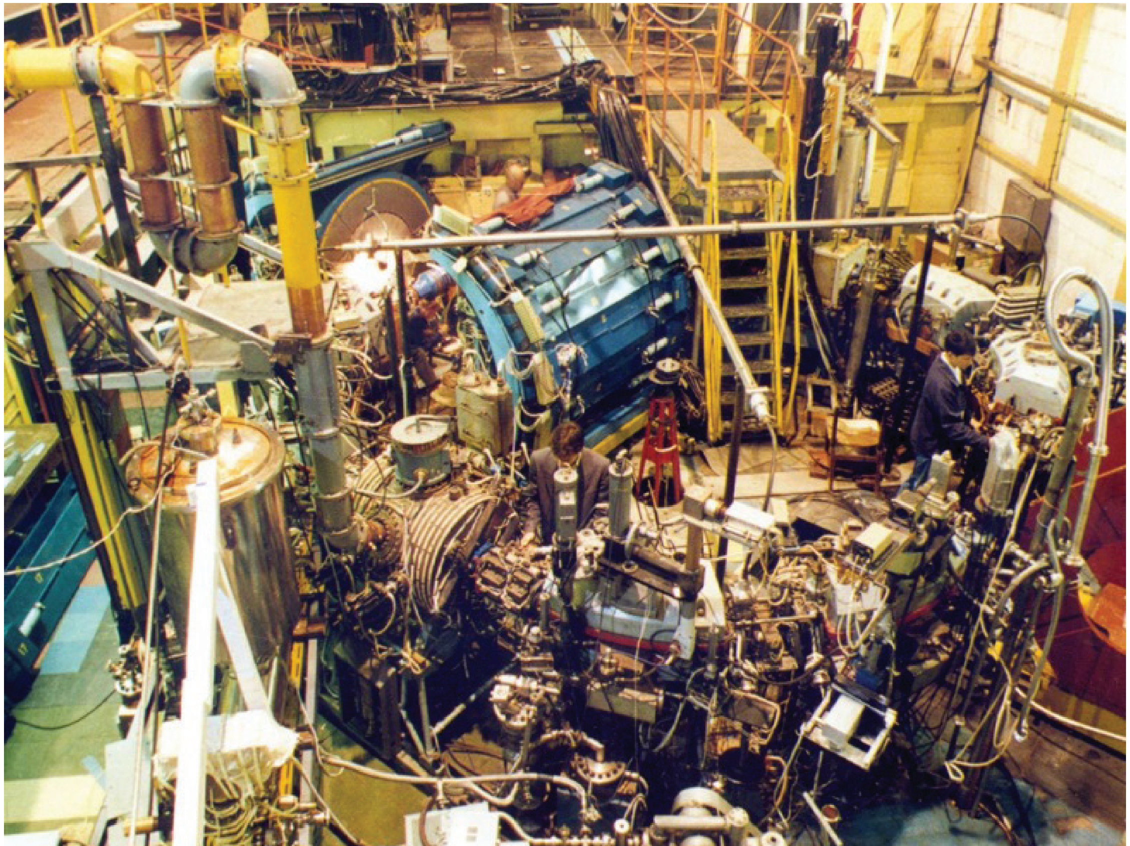
01.10. – 05.10.

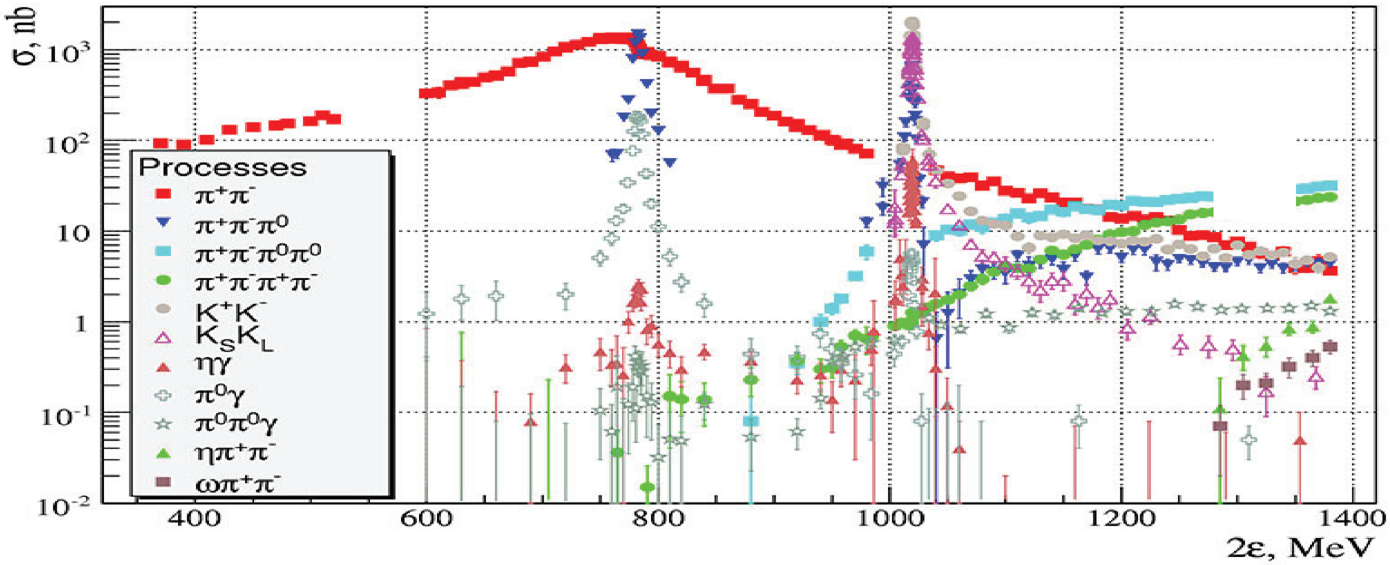
Outline

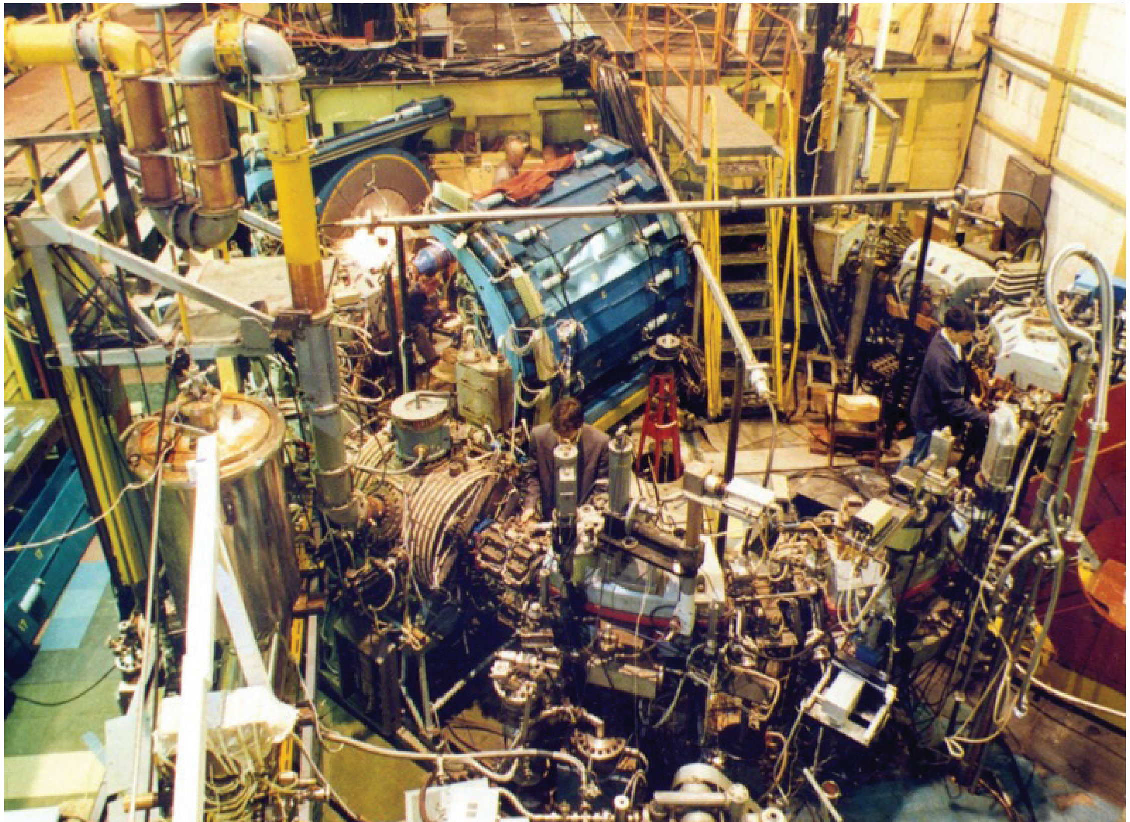
- ❑ Motivation
- ❑ Collider and detectors
- ❑ Collider upgrade
- ❑ Recent results on hadronic cross sections measurements
- ❑ Conclusion

VEPP-2M (1975-2000)



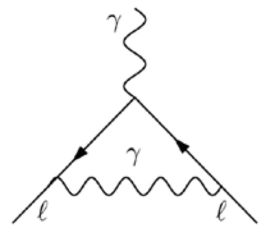


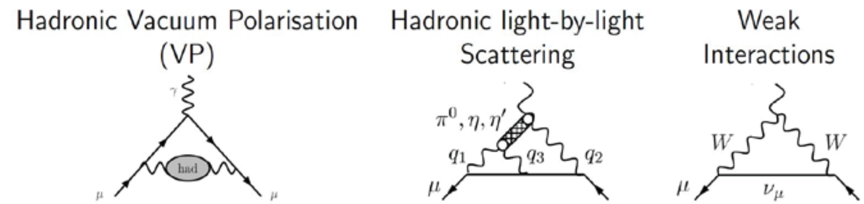

σ, nb
10³
10²
10
1
10⁻¹
10⁻²
400
600
800
1000
1200
1400
2ε, MeV
Processes
π⁺π⁻
π⁺π⁻π⁰
π⁺π⁻π⁰π⁰
π⁺π⁻π⁺π⁻
K⁺K⁻
KsKL
ηγ
π⁰γ
π⁰π⁰γ
ηπ⁺π⁻
ωπ⁺π⁻



$(g-2)/2$ of muon

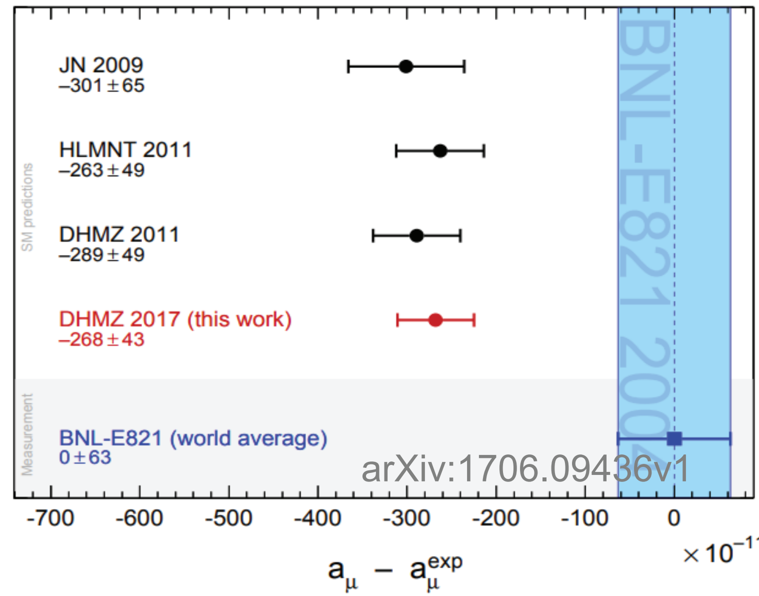
- Magnetic moment of Dirac particle: $\vec{\mu} = g\frac{e\hbar}{2mc}\vec{s}$, gyromagnetic factor g for point-like fermions =2





- Higher order contributions make muon magnetic anomaly $a_\mu \equiv (g-2)/2 \neq 0$

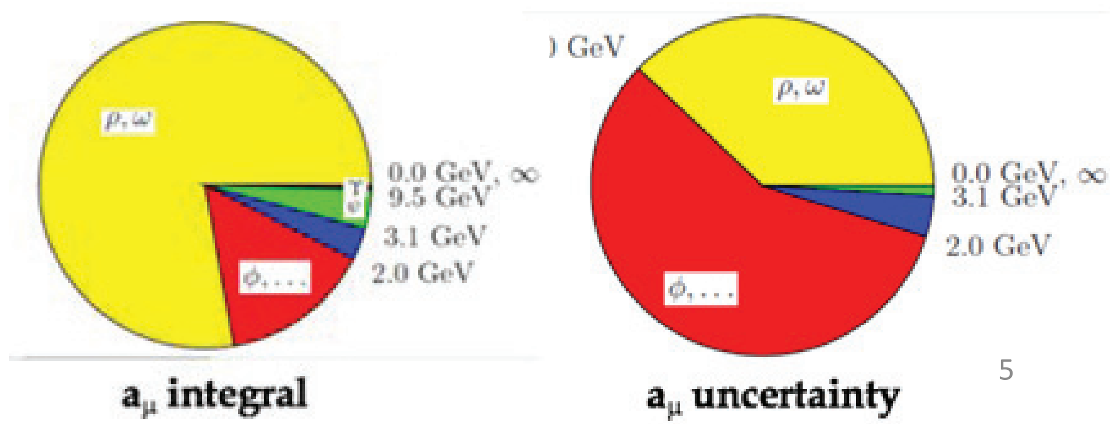
$$\mathbf{a}_\mu^{\text{theory(SM)}} = \mathbf{a}_\mu^{\text{QED}} + \mathbf{a}_\mu^{\text{had}} + \mathbf{a}_\mu^{\text{weak}}$$



- $a^{\text{had,LO}}{}_\mu$ is calculated by integrating experimental $\sigma(e^+e^- \to hadrons)$

$$a^{had}{}_\mu = \frac{\alpha^2}{3\pi^2}\int_{4m^2{}_\pi}^{\infty} ds\,\frac{K(s)}{s}R(s)$$

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



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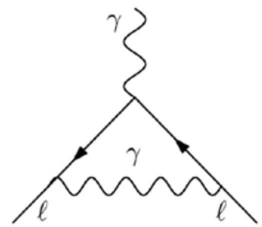

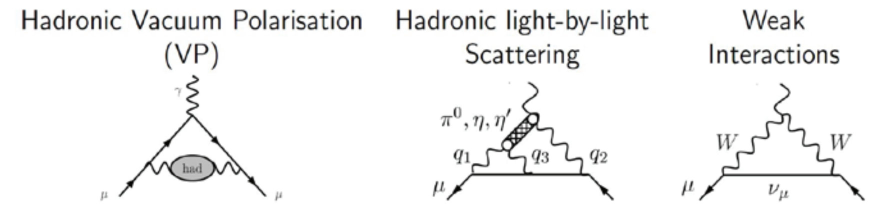

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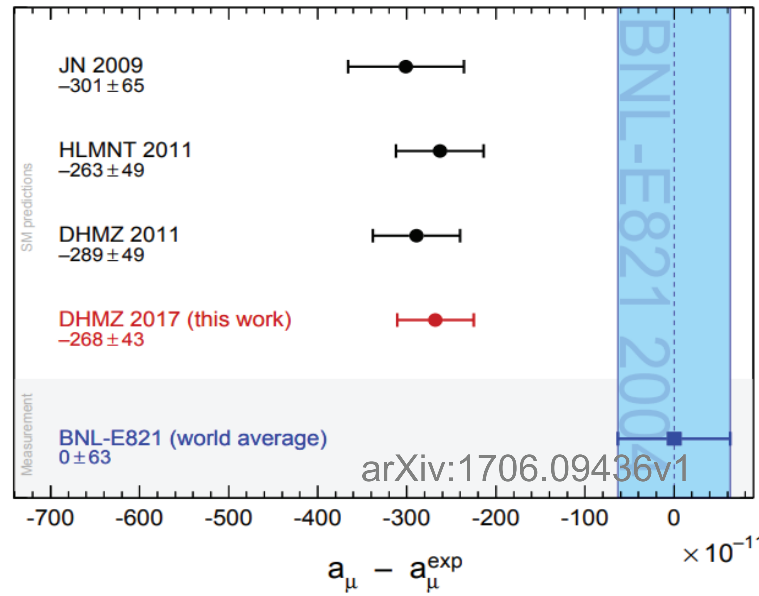
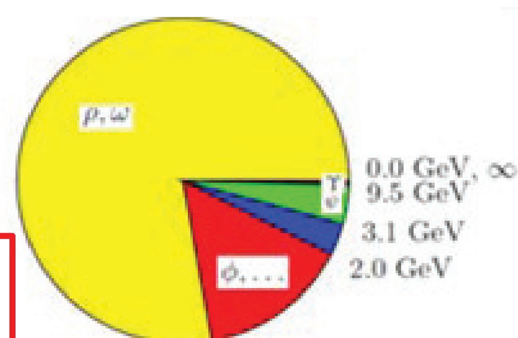
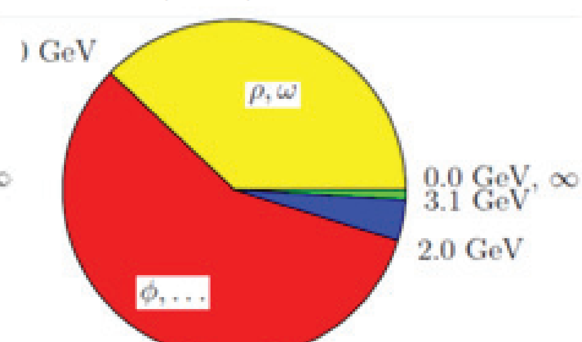


High precision hadronic cross sections measurements in $E_{cm} < 2$ GeV are needed



a_μ integral



a_μ uncertainty

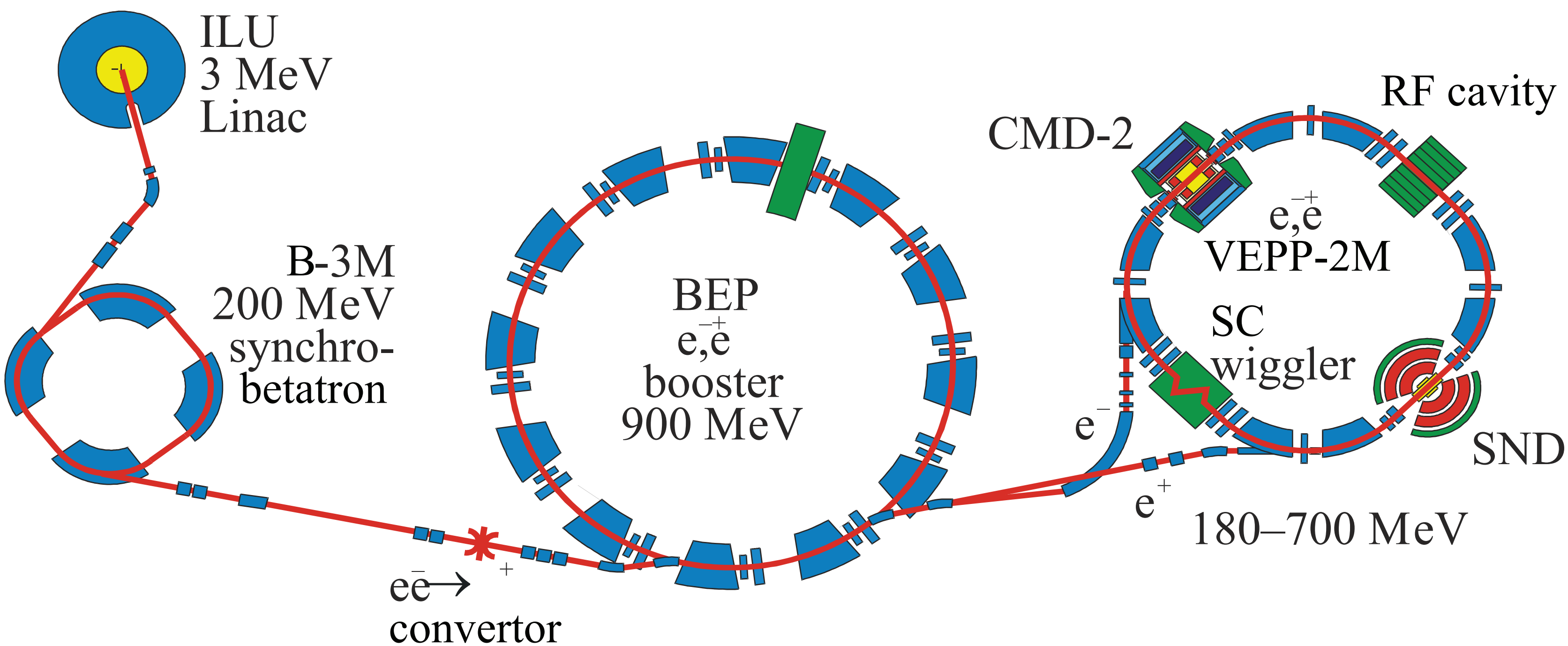
Perspectives for muon (g-2) measurements

Experiment: E969 (FNAL) -> 0.14 ppm
J-PARC (Japan) -> 0.1 ppm

The muon g-2 superconducting coil rolls toward Wilson Hall at Fermilab in Batavia, Illinois on Friday, July 26, 2013.

VEPP-2M → VEPP-2000

(2001-2007)



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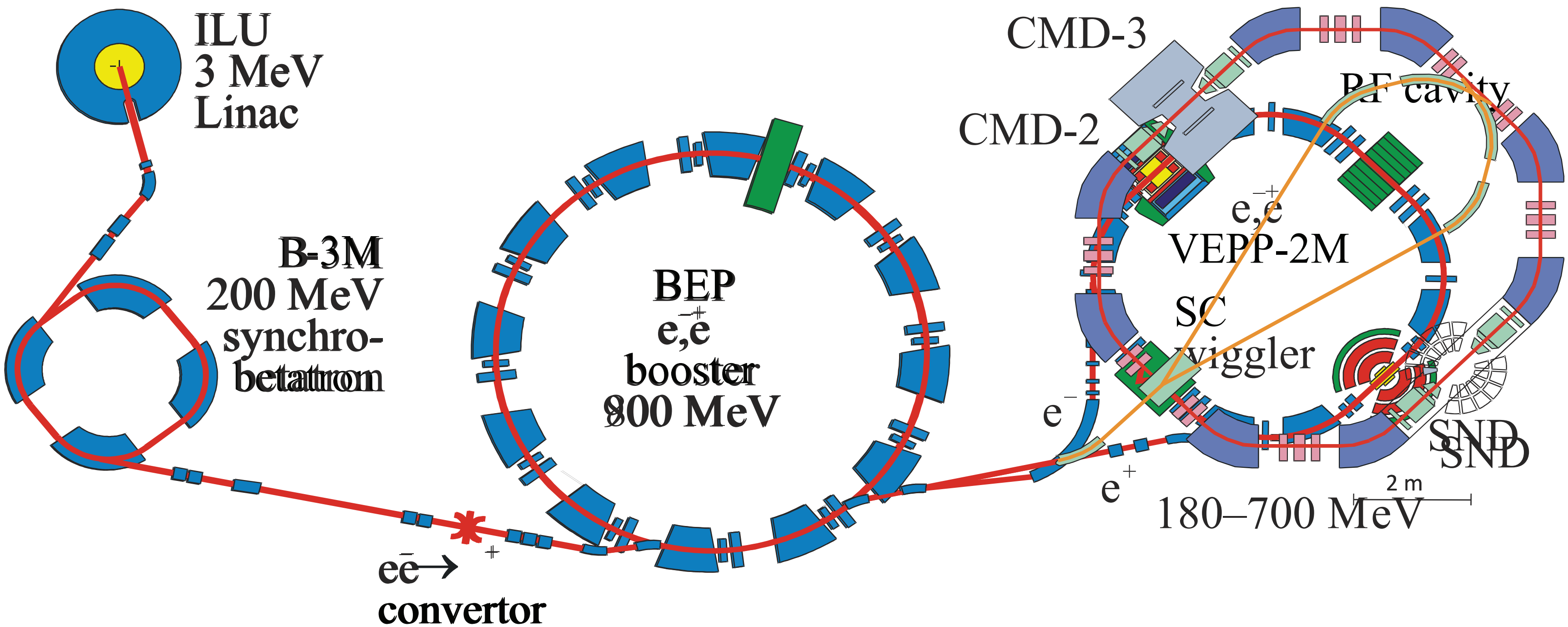
(2001-2007)



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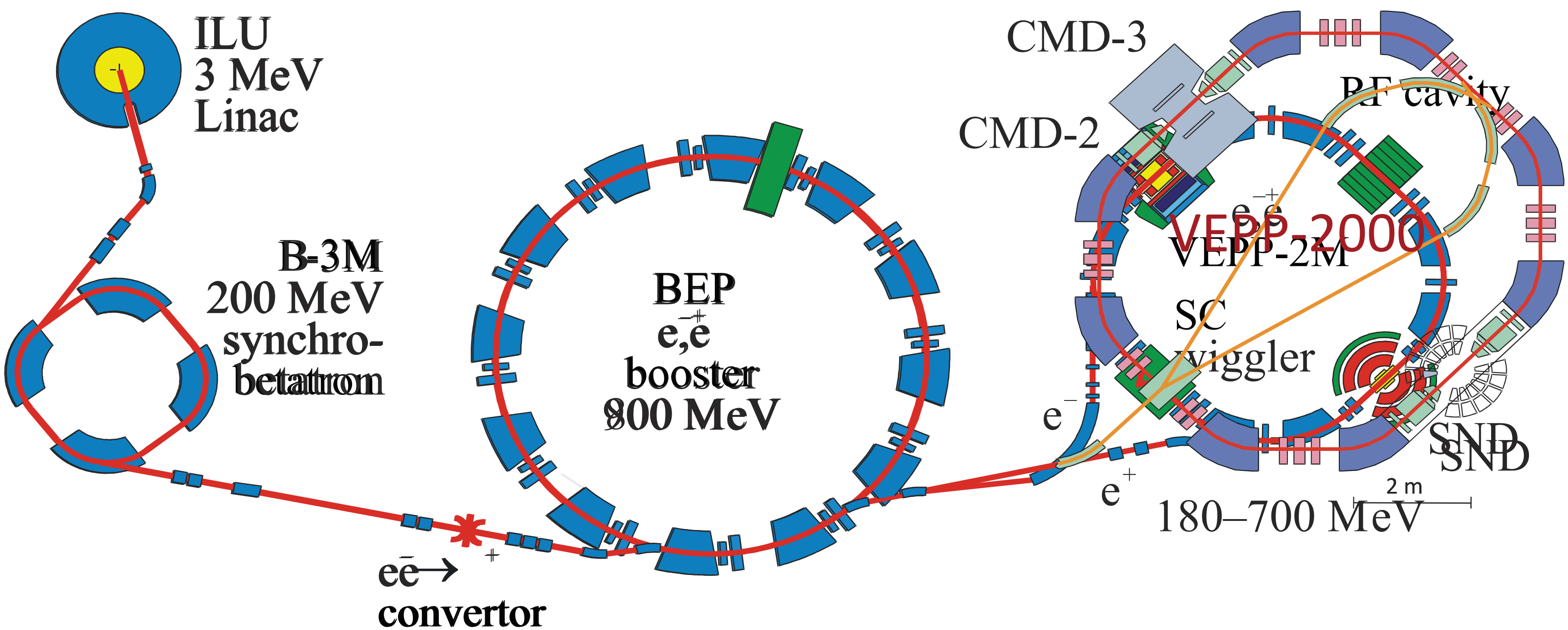

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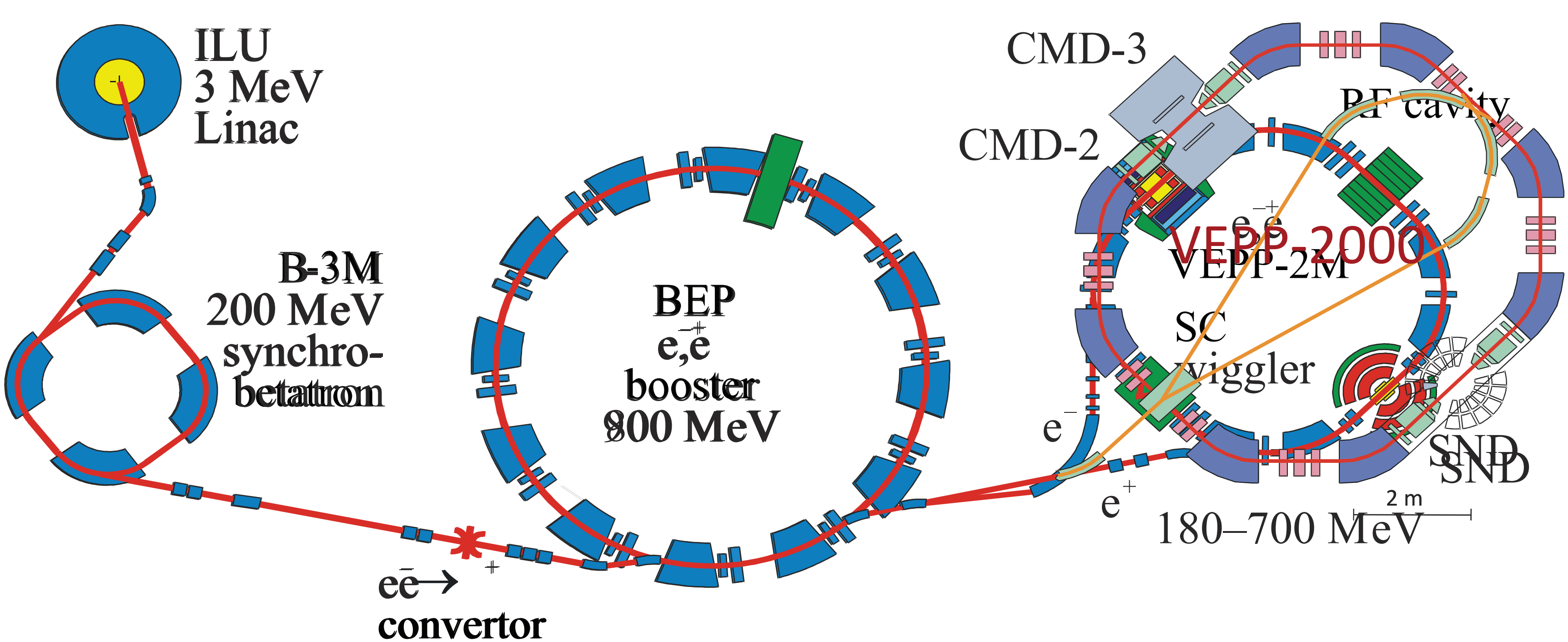
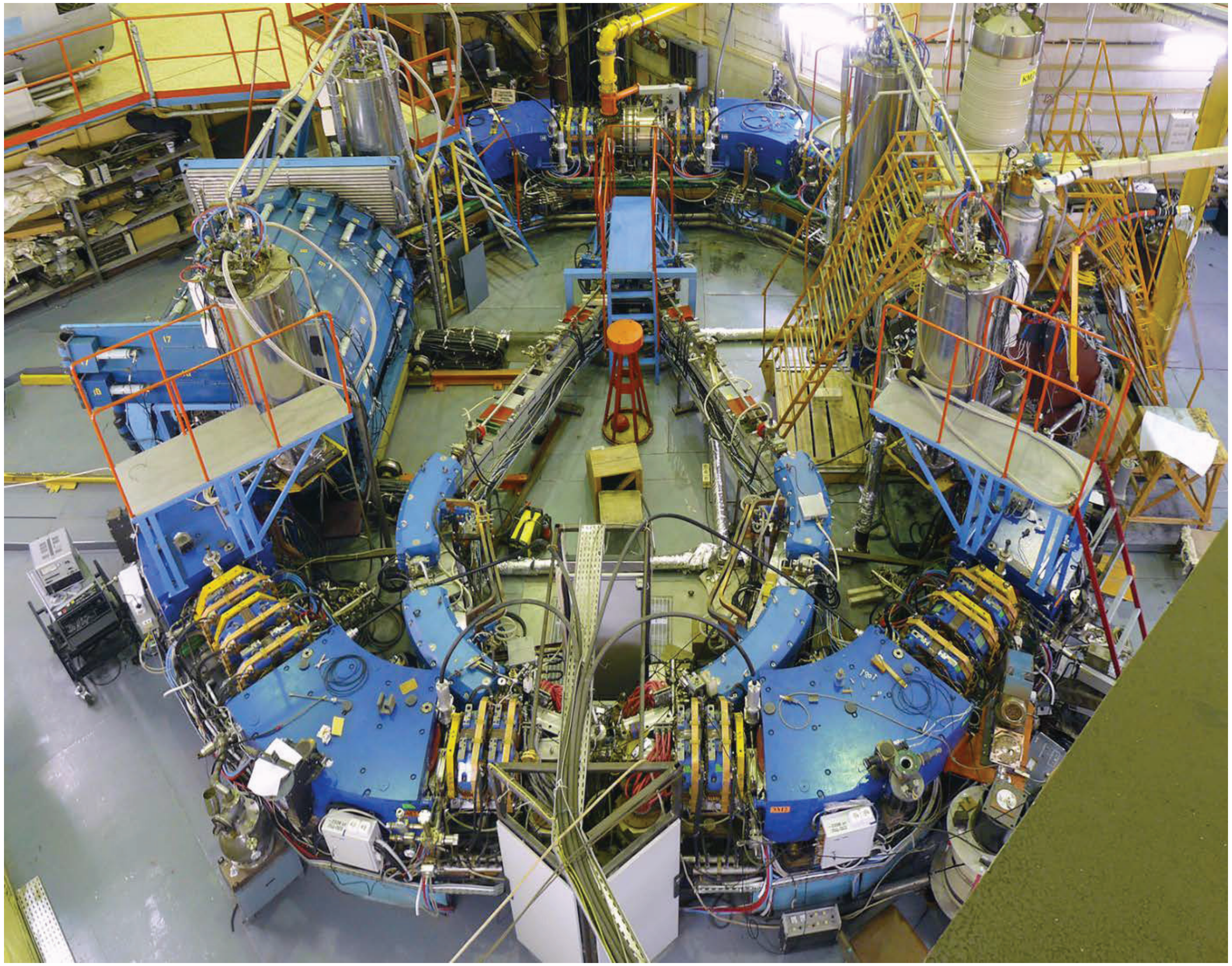
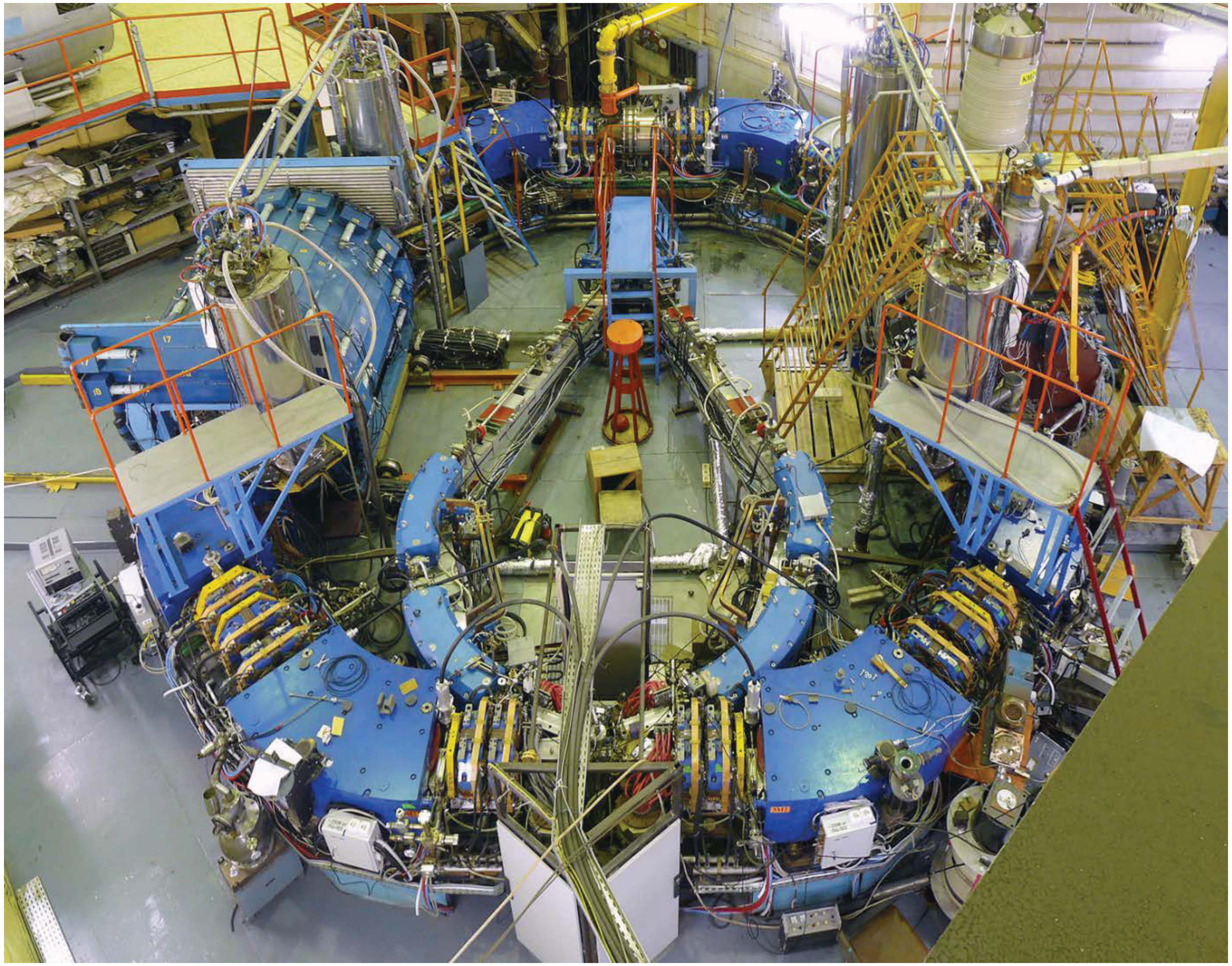


- $E \approx 1$ GeV (per beam)
- $L \approx 1{\times}10^{32}\ cm^{-2}\ sec^{-1}$ (1×1 bunch)



VEPP-2000 overview



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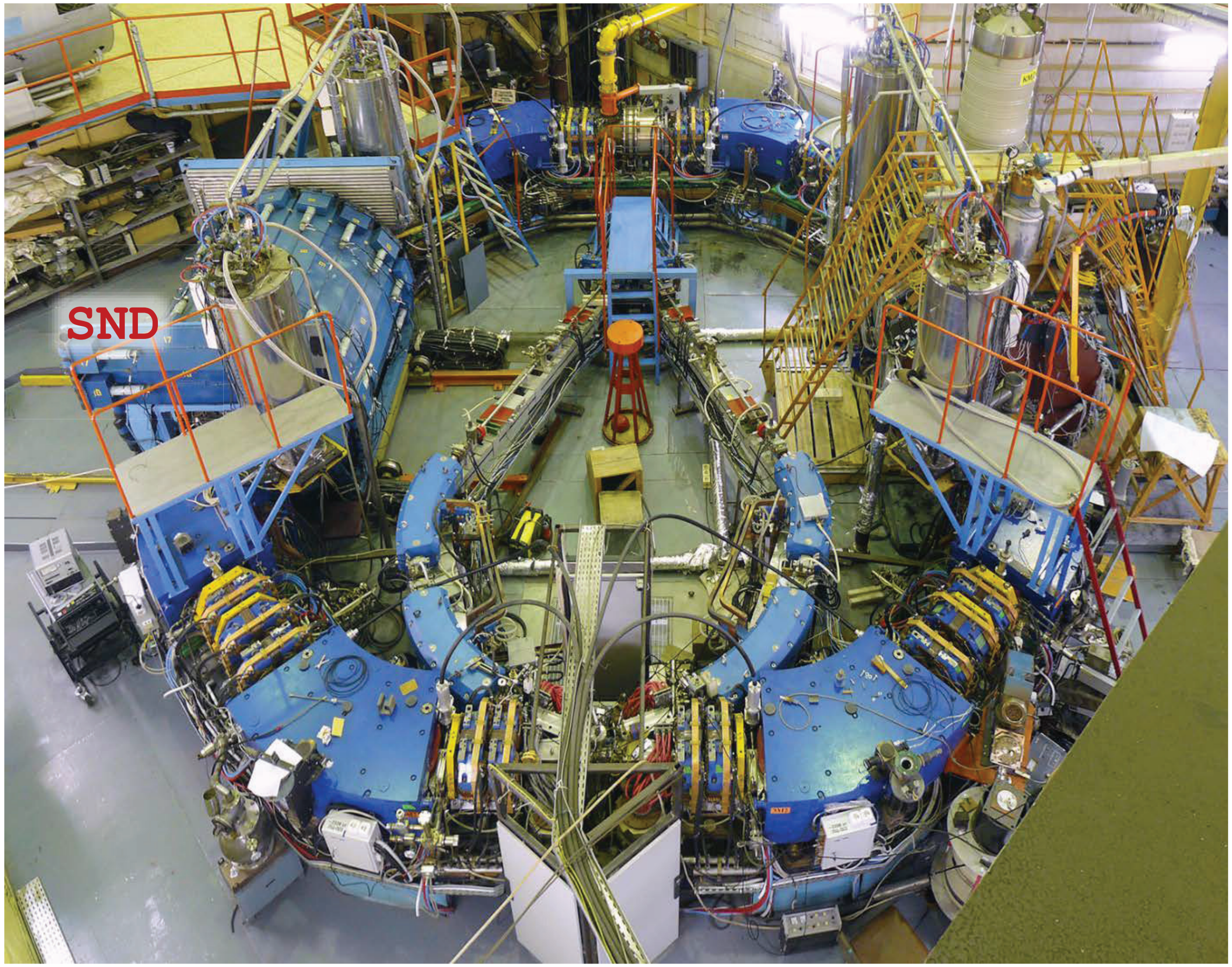
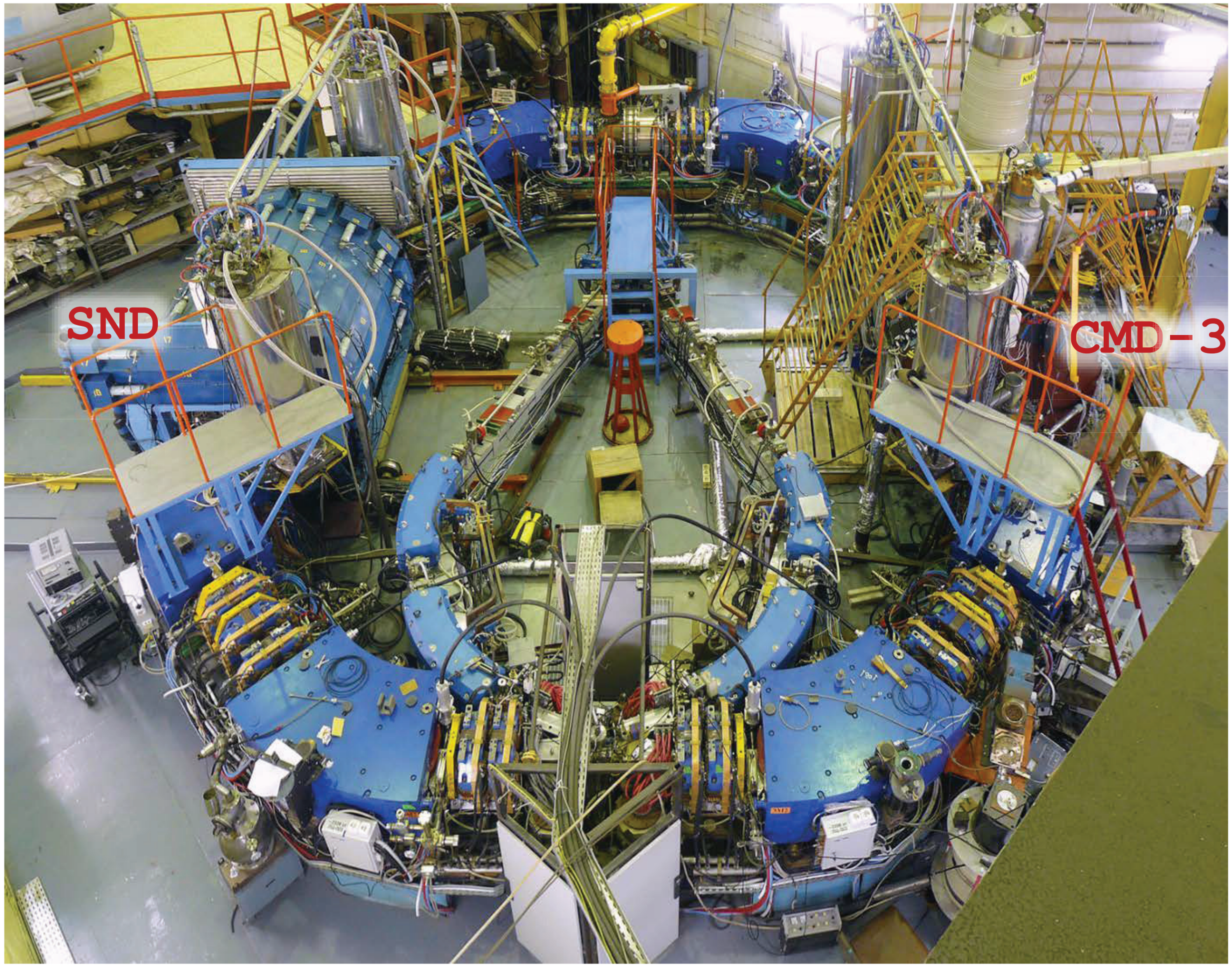
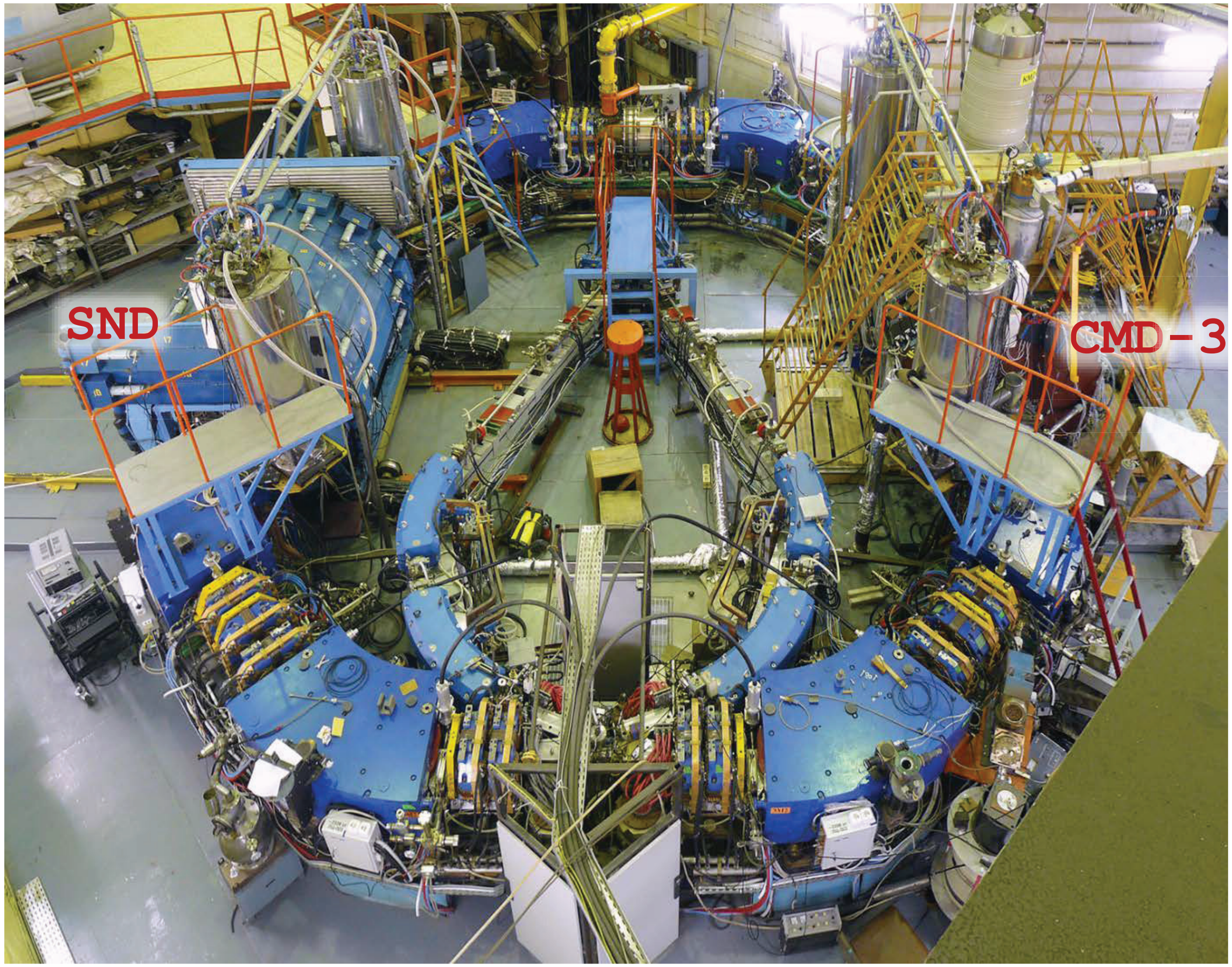


VEPP-2000 overview



VEPP-2000 overview

Design parameters @ 1 GeV	
Circumference	24.388 m
Beam energy	150 ÷1000 MeV
N of bunches	1×1
N of particles	1×10^{11}
Betatron tunes	4.14 / 2.14
Beta*	8.5 cm
BB parameter	0.1
Luminosity	1×10^{32} cm^{-2}s^{-1}



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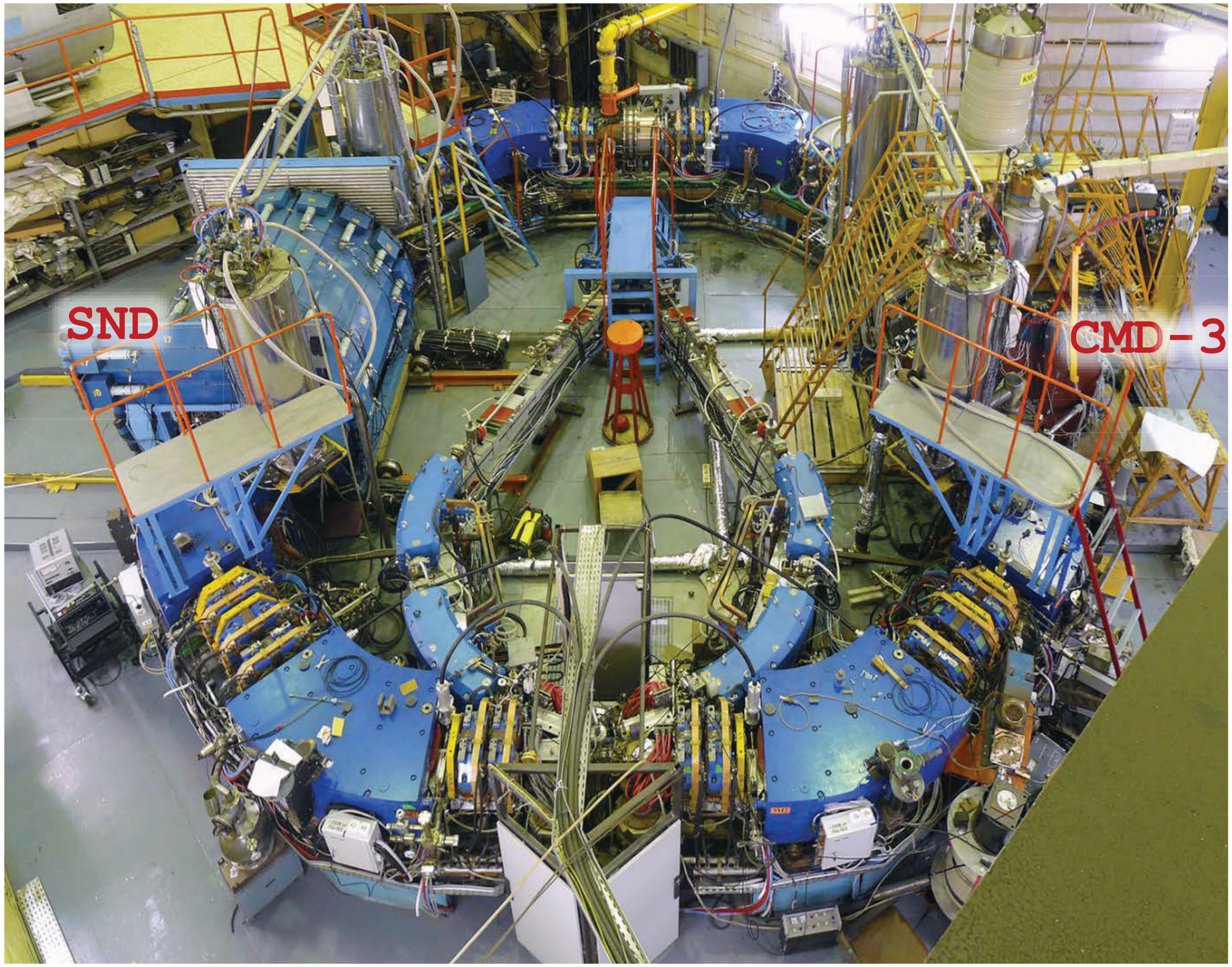

- Round beams concept
- 13 T solenoids for FF
- 2.4 T NC dipoles @ 1 GeV
- CBS for energy control

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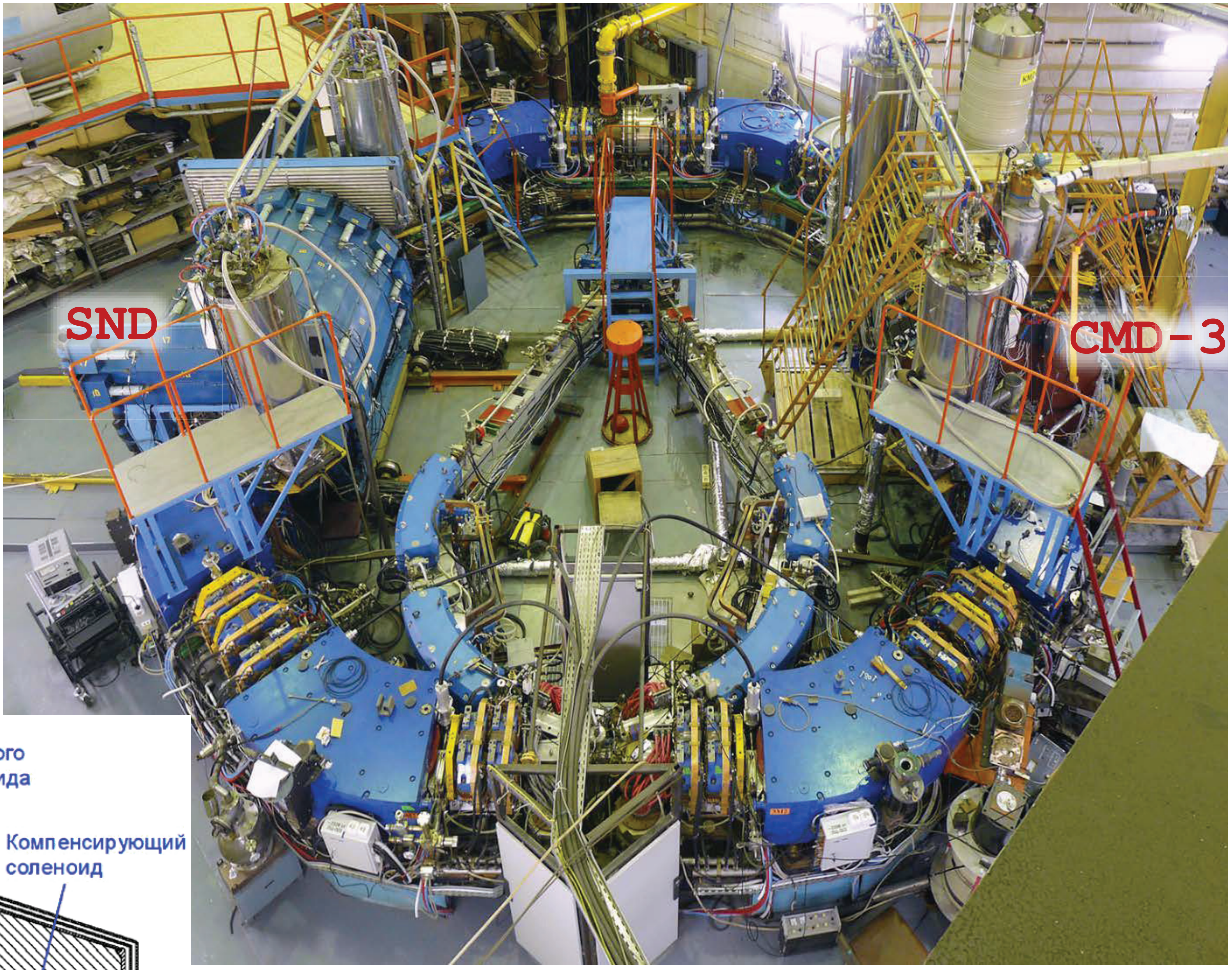

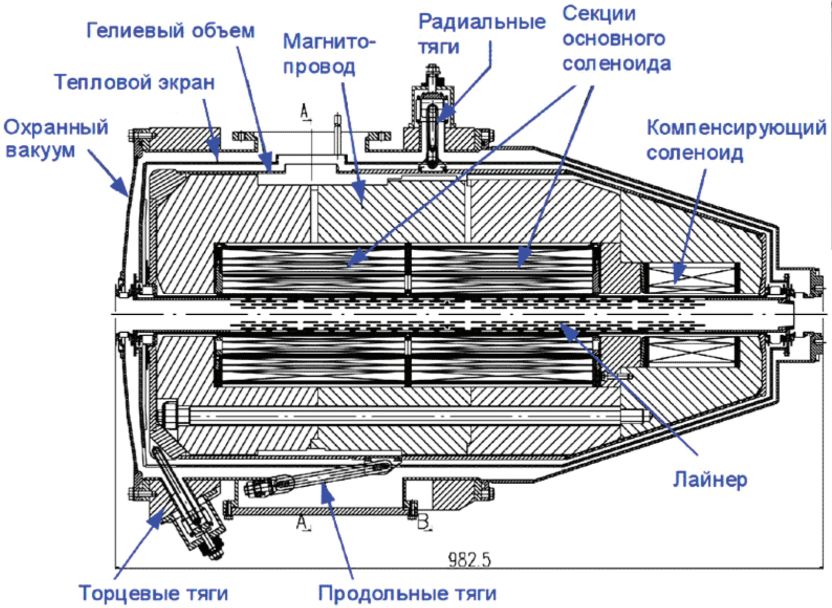

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The concept of Round Colliding Beams

Axial symmetry of counter beam force + X-Y symmetry of transfer matrix IP2IP

⇩

Additional integral of motion (**angular momentum $M_z = x'y - xy'$**)

Particle dynamics remains nonlinear, but becomes 1D

Lattice requirements:

- Head-on collisions!
- Small and equal β-functions at IP: $\beta_x = \beta_y$
- Equal beam emittances: $\varepsilon_x = \varepsilon_y$
- Equal fractional parts of betatron tunes: $\nu_x = \nu_y$

$\beta_x = \beta_y$, $\varepsilon_x = \varepsilon_y$ → Round beam

$\beta_x = \beta_y$, $\nu_x = \nu_y$ → $M_x = M_y$

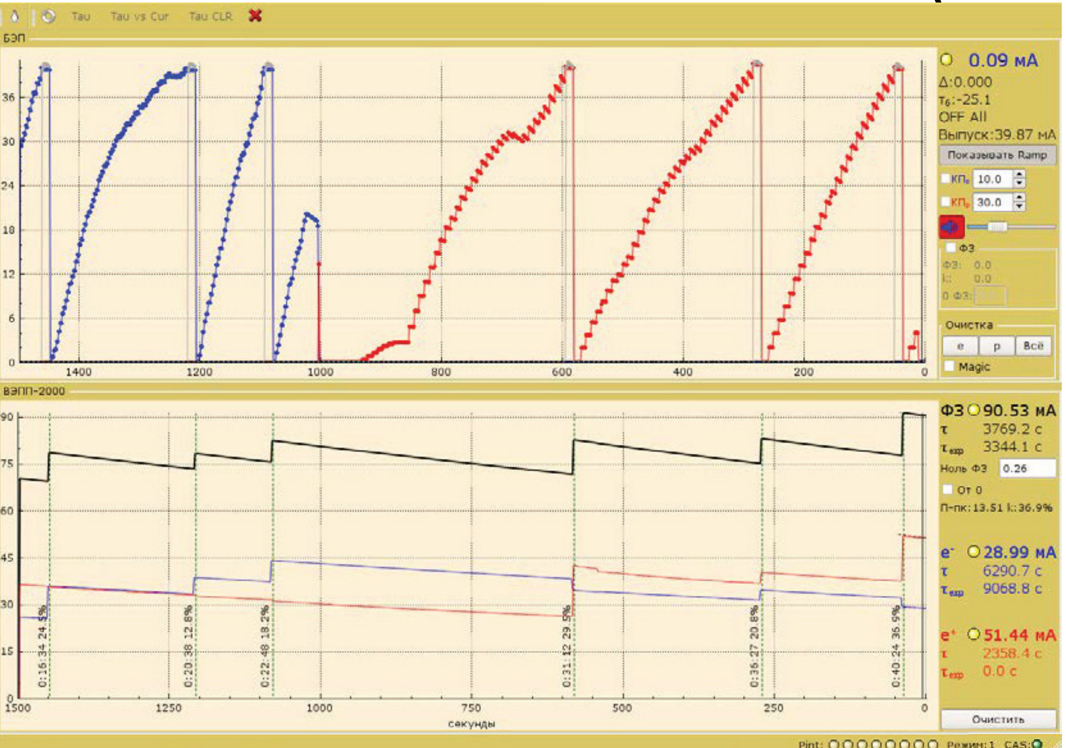
L.M. Barkov, et. al, Proc. HEACC'89, Tsukuba, Japan, p.1385.

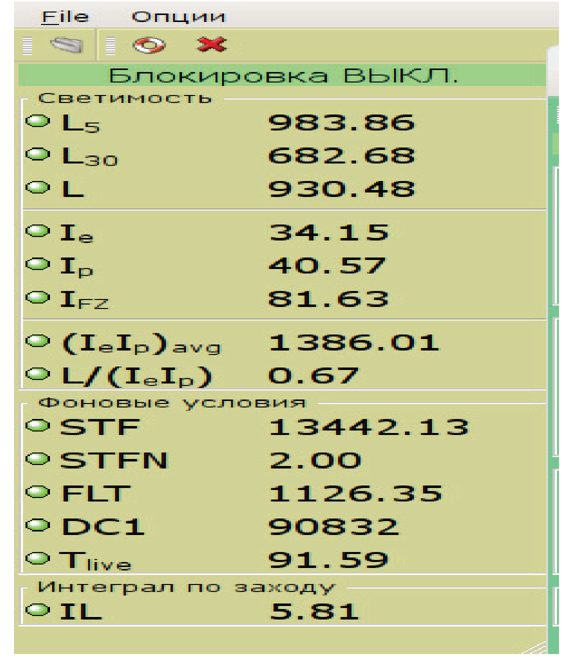
S. Krishnagopal, R. Siemann, Proc. PAC'89, Chicago, p.836.

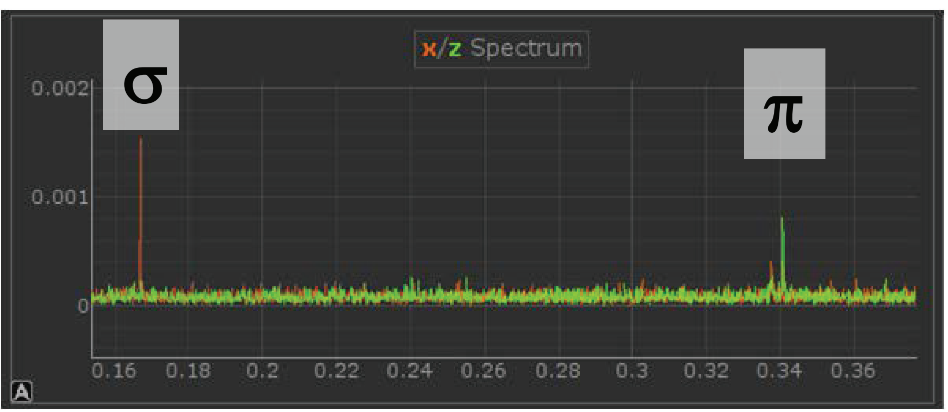
V.V. Danilov et al., EPAC'96, Barcelona, p.1149.

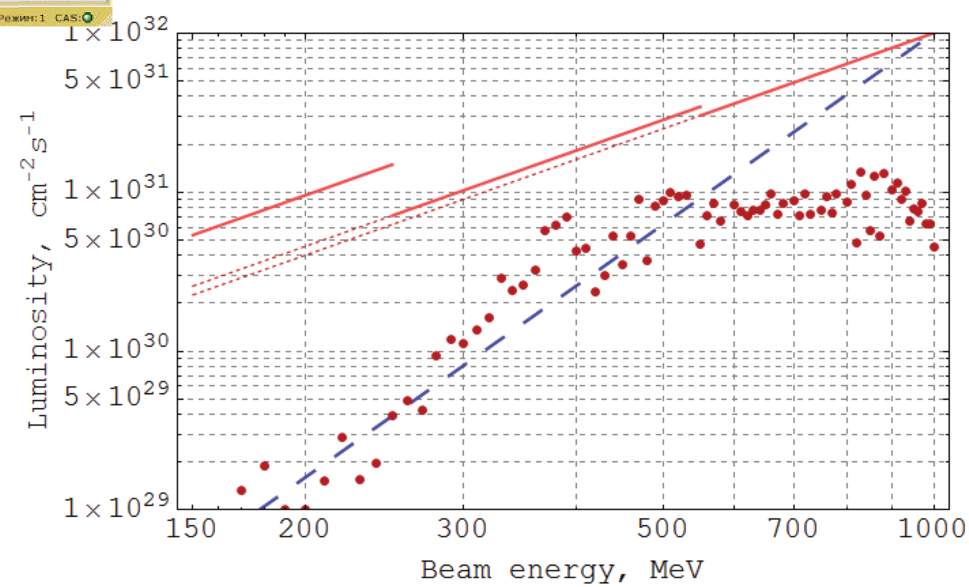
S. Henderson, et al., Proc. PAC'99, New York, p.410.

Светимость (2010-2013 гг.)





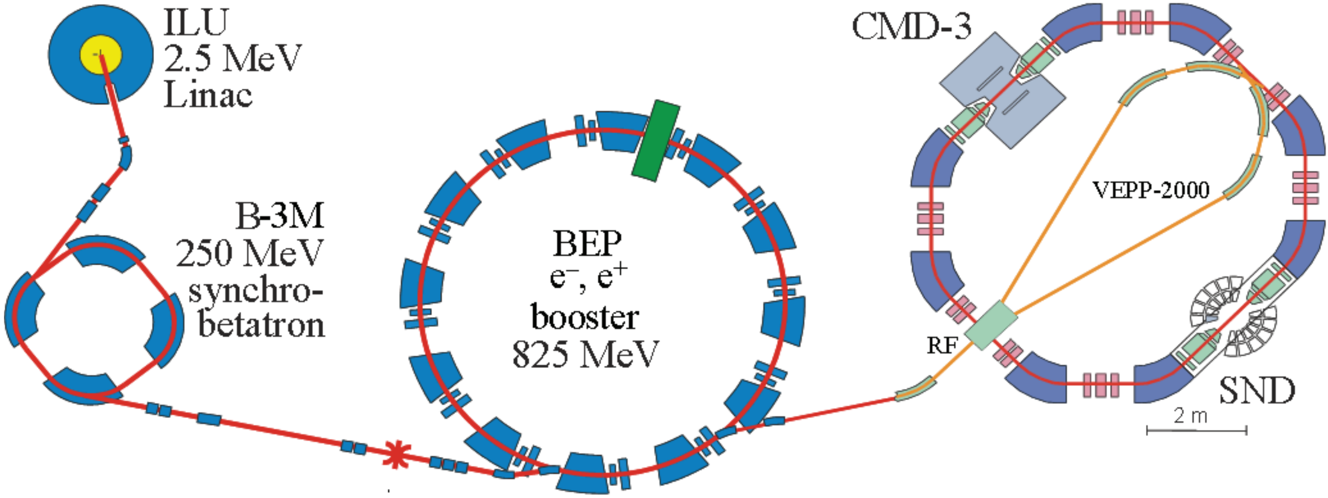




$\Delta\nu = 0.175 \;\rightarrow\; \xi =$ **0.125**/IP

VEPP-2000 complex upgrade

(2014-2017)



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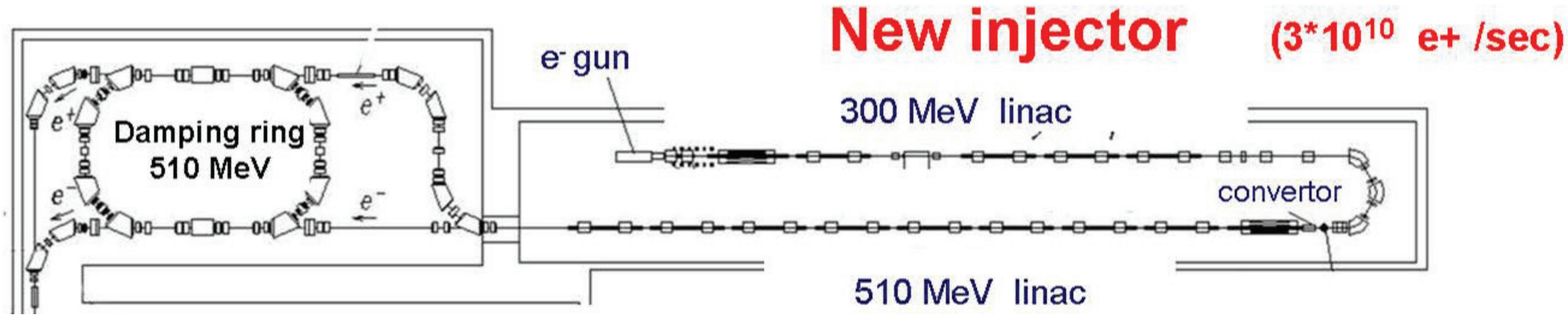

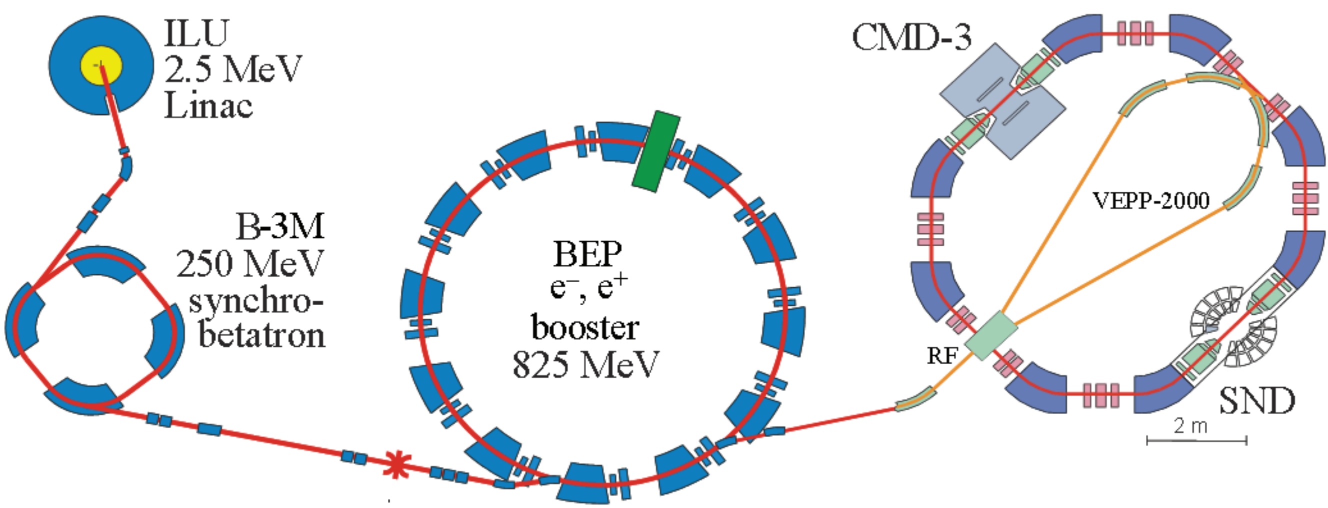

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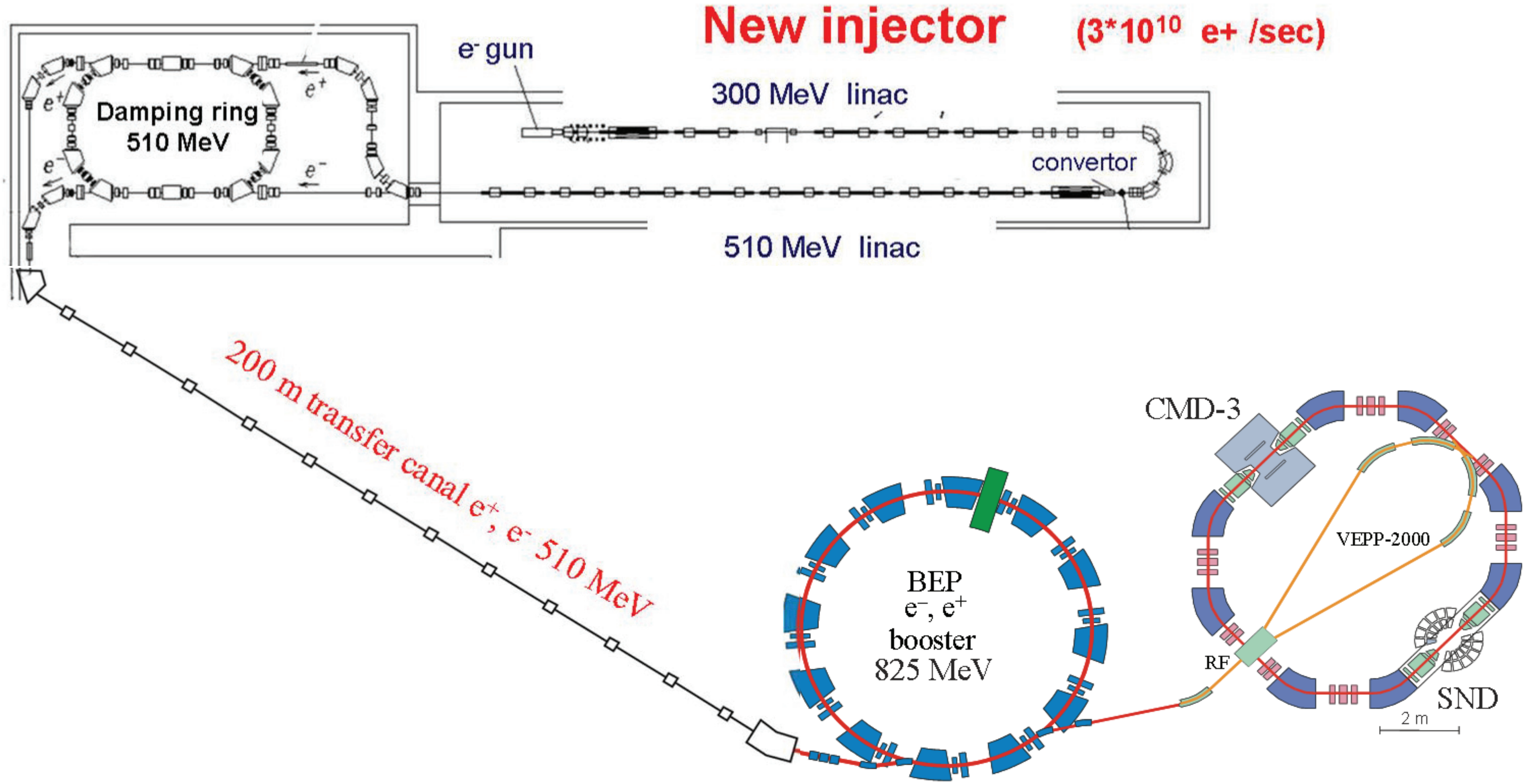

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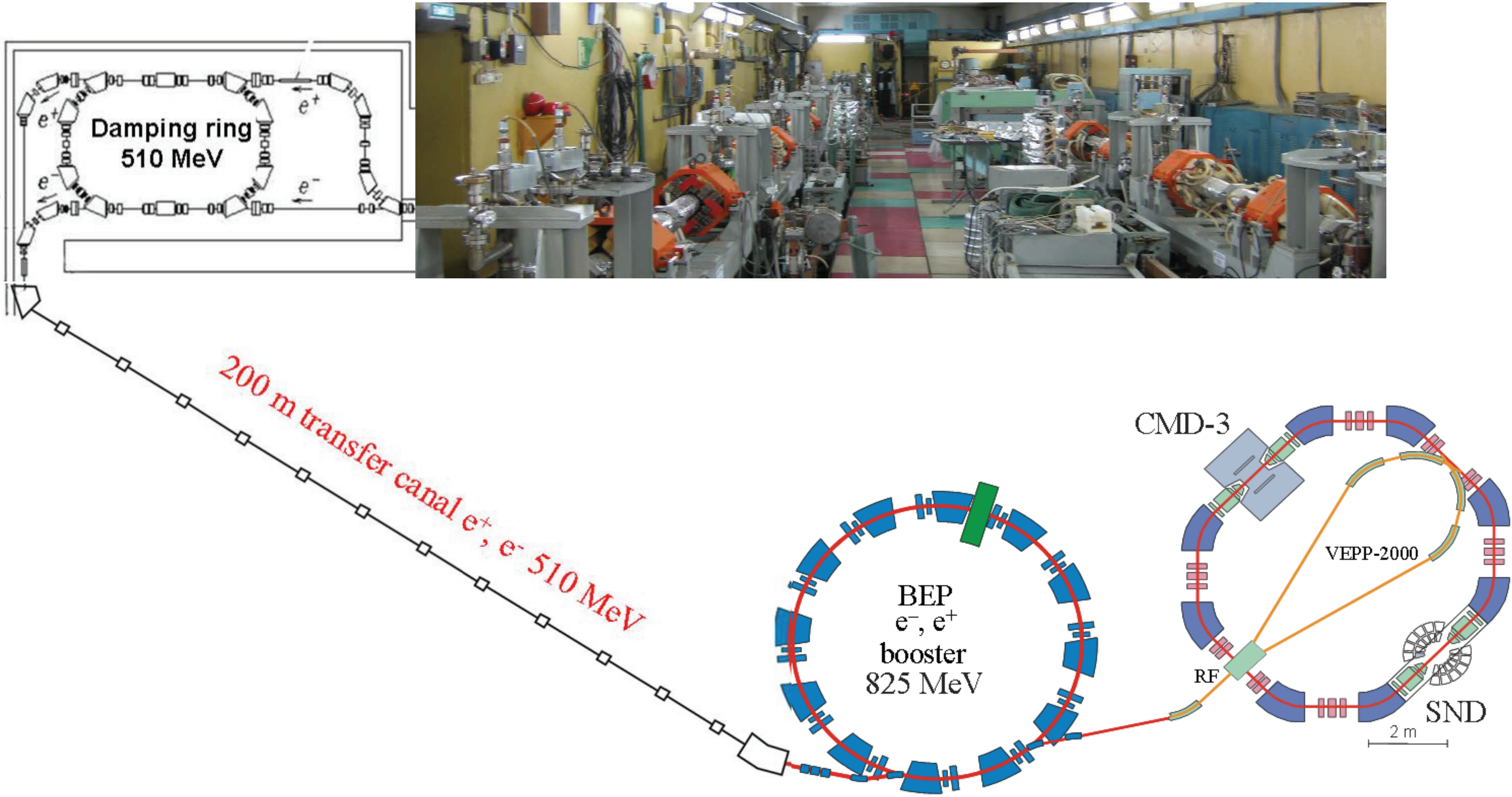

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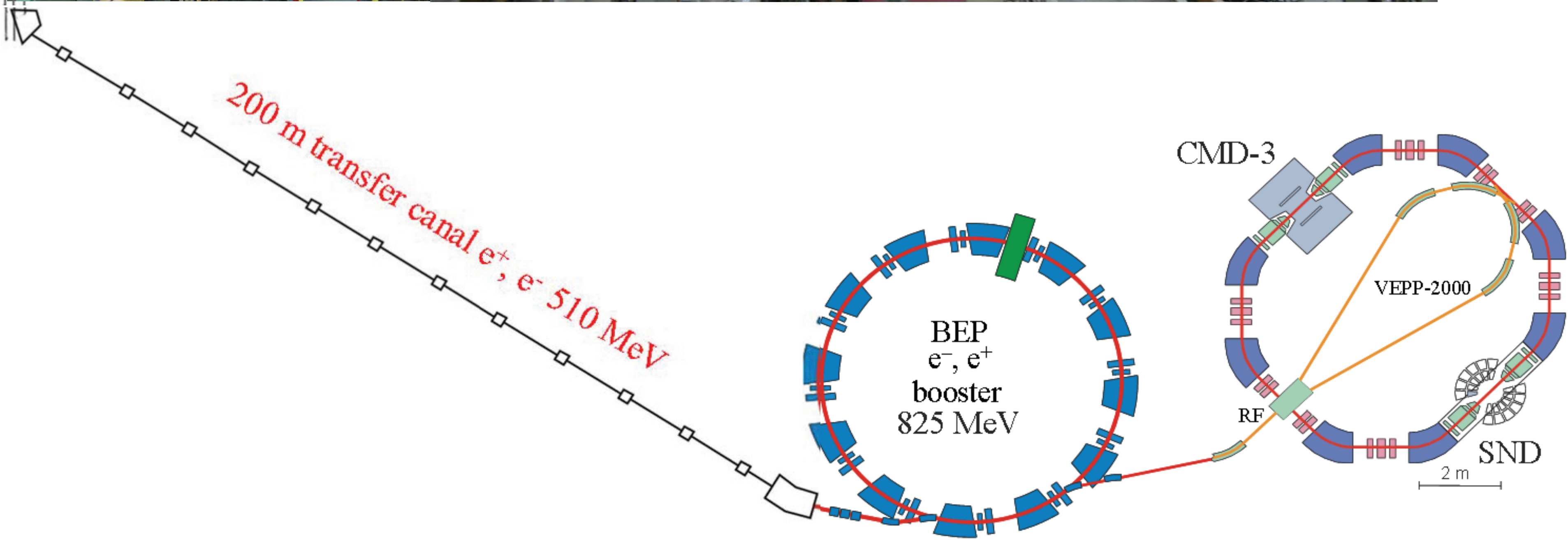

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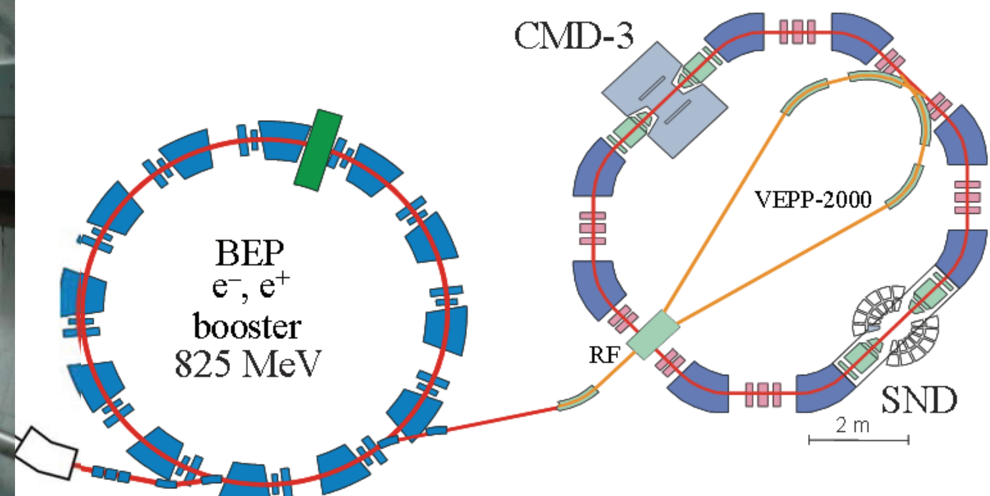

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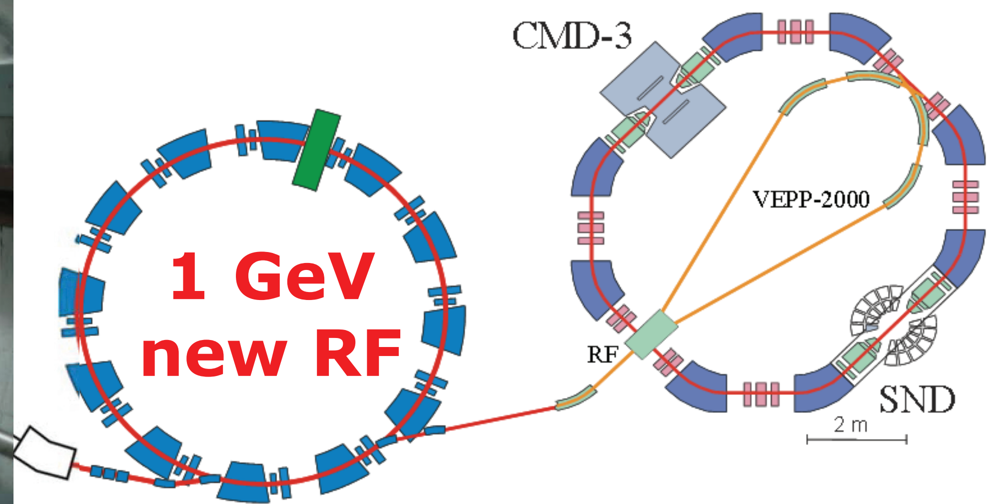

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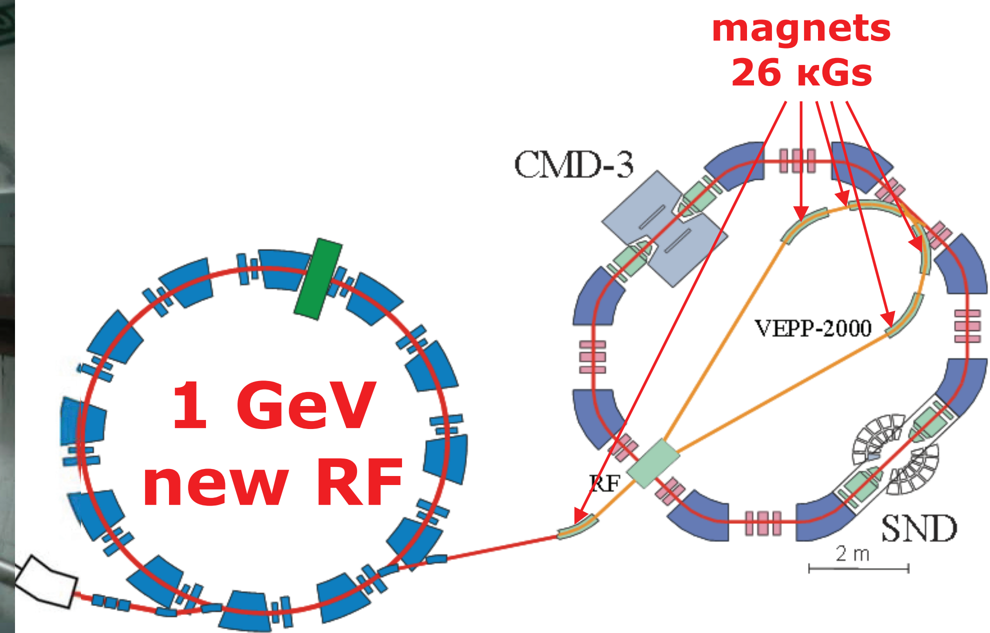
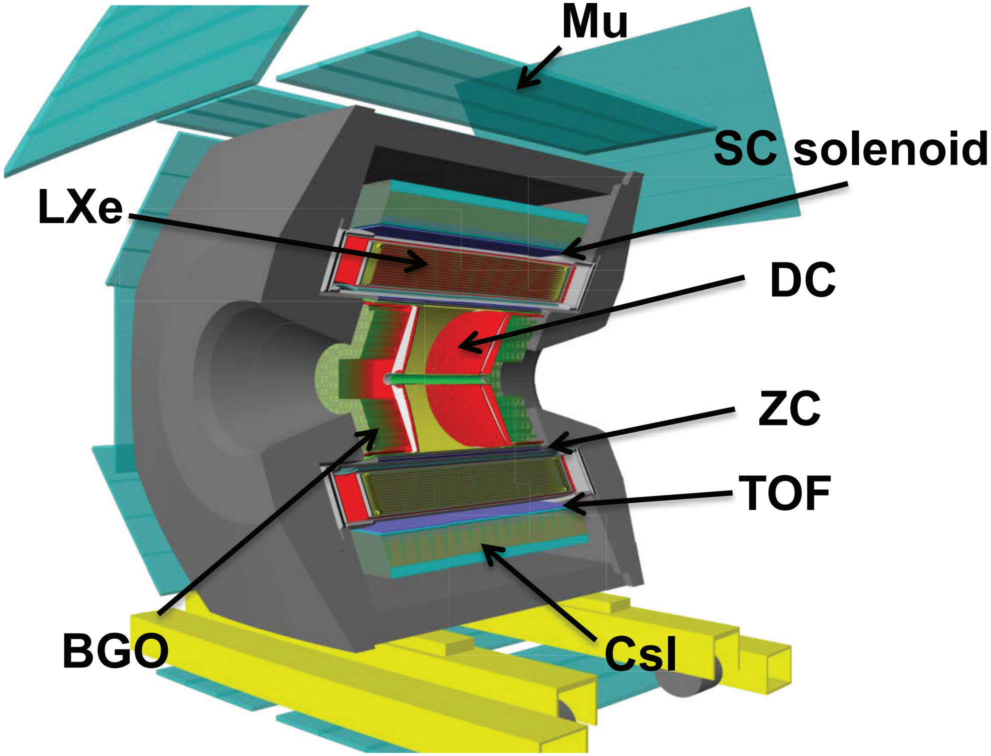
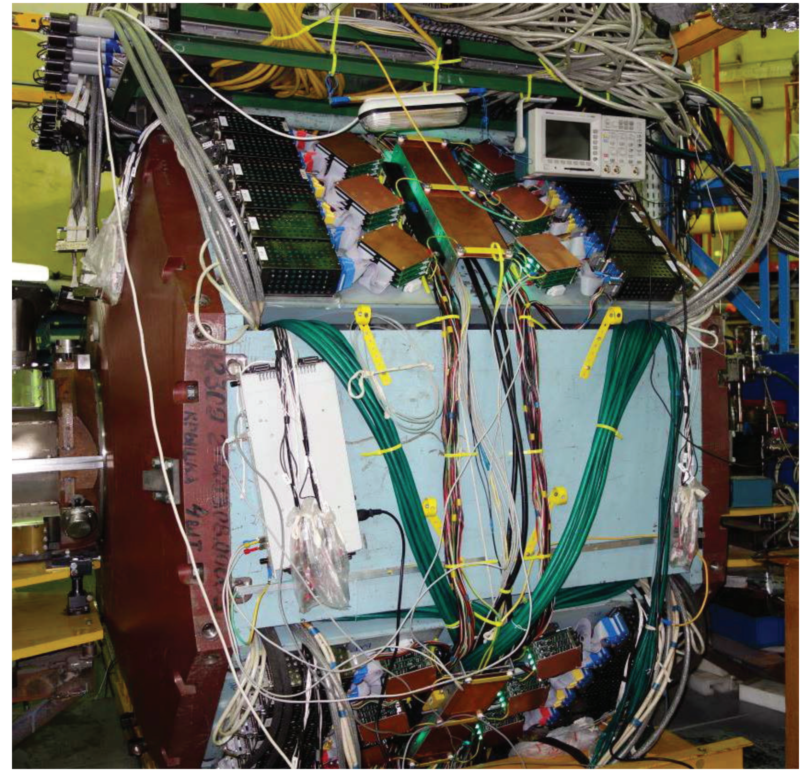


CMD-3 detector & physics program

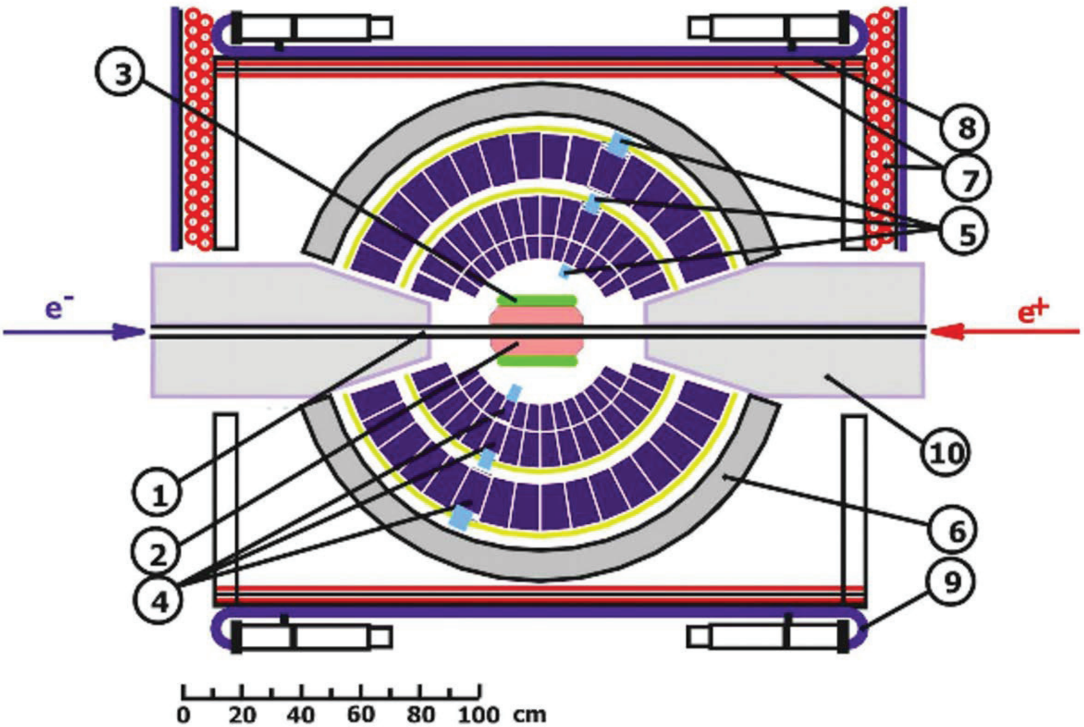




- Precise measurement of $R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$ to achieve <1% systematic for major channels
- Study of exclusive hadronic channels of e^+e^- annihilation, test isotopic relations
- Study of the "excited" vector mesons: $\rho', \rho'', \omega', \phi'$ ...
- Study of $\mathrm{G_E}/\mathrm{G_M}$ for nucleons near threshold
- CVC tests: comparison of isovector part of $\sigma(e^+e^- \to hadrons)$ with τ –decay spectra
- Diphoton physics (e.g. η' production)

SND detector

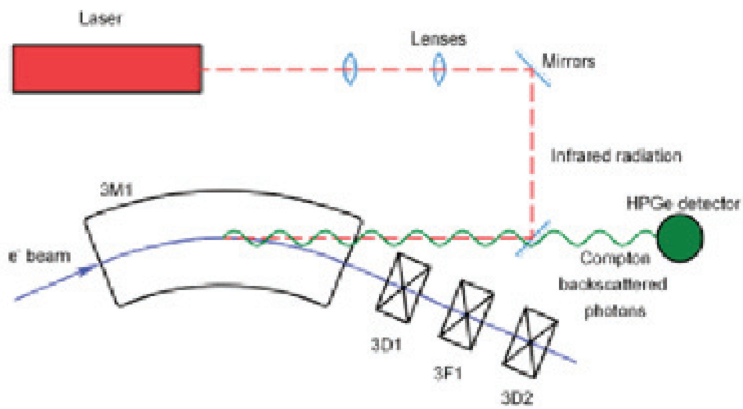
NIM A449 (2000) 125-139



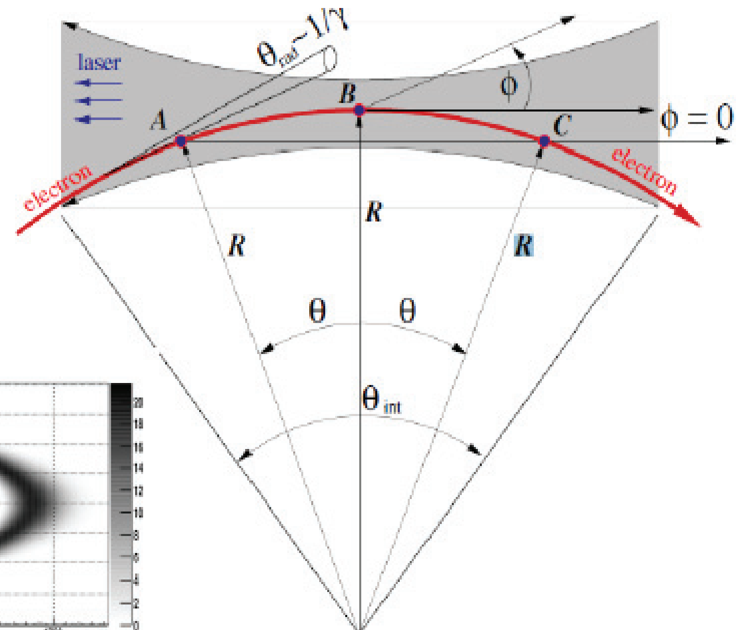
1 – beam pipe, 2 – tracking system, 3 – aerogel Cherenkov counters , 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – iron muon absorber, 7–9 – muon detector, 10 – focusing solenoids.

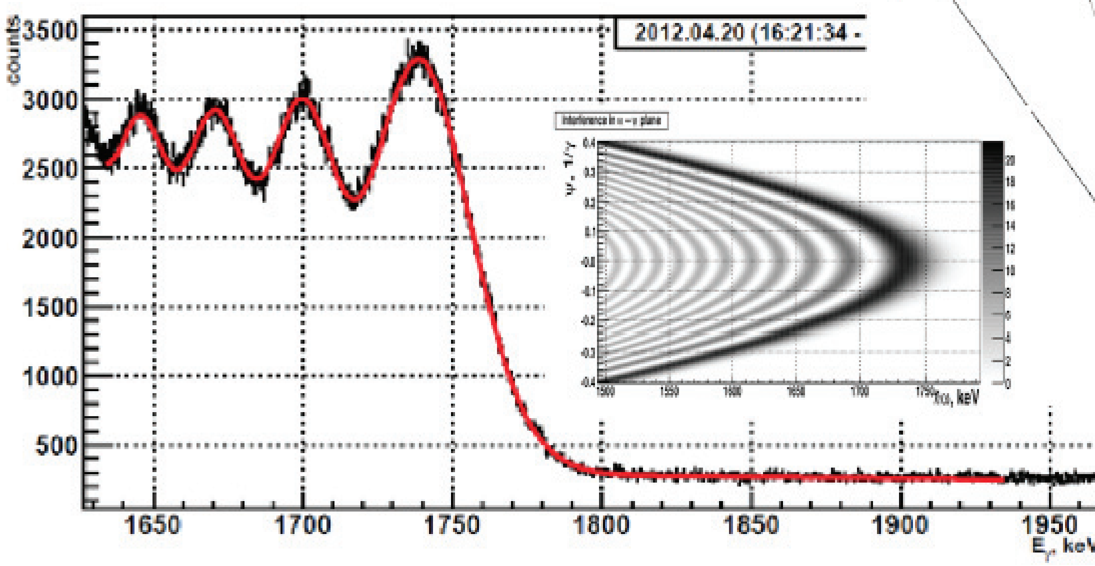
Calorimeter	
Thickness	$13.5\ X_0$
Acceptance	$0.95 \times 4\pi$
Energy resolution	$\frac{\sigma_E}{E} = \frac{0.042}{\sqrt[4]{E[GeV]}}$
Angular resolution	$\sigma_{\phi,\theta} = \frac{0.82^\circ}{\sqrt[4]{E[GeV]}} \oplus 0.63^\circ$
Tracking system	
Acceptance (9 layers)	$0.94 \times 4\pi$
Angular resolution	$\sigma_\phi = 0.55^\circ, \sigma_\theta = 1.2^\circ$
Vertex resolution	$\sigma_R = 0.12cm,$ $\sigma_Z = 0.45cm$
Aerogel counters	
K/π separation	E < 1 GeV

Energy measurement by Compton back scattering



By φ=0 radiation from A and C points are interfered



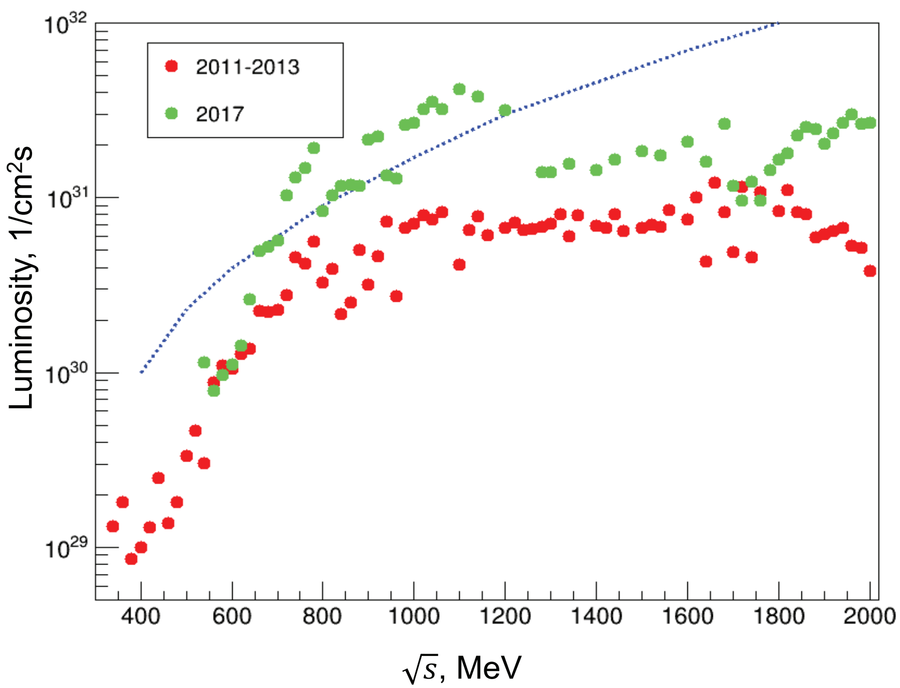


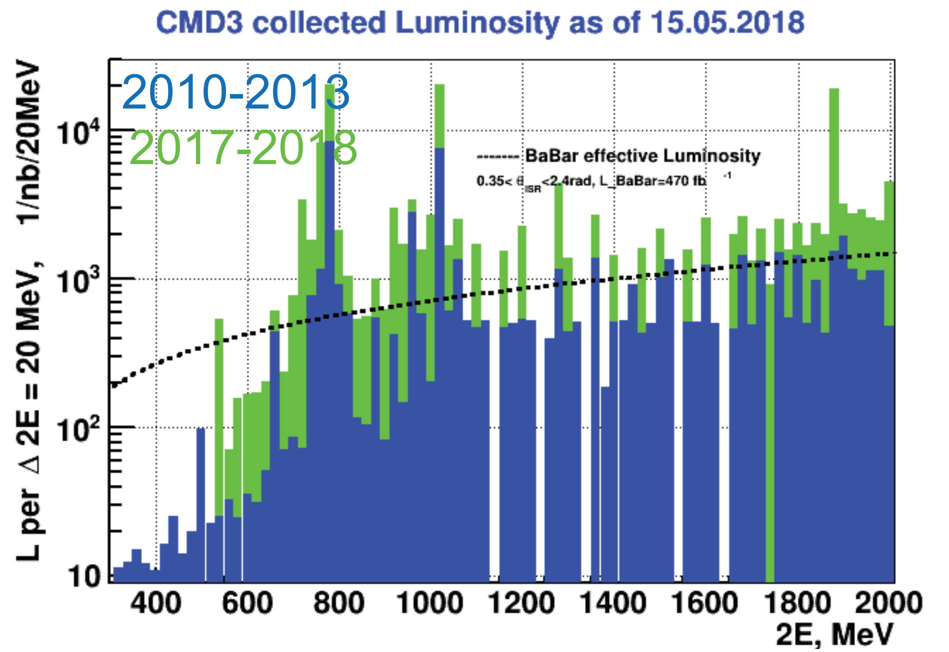
E = 993.662±0.016 MeV

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

In few points this method have been controlled by the resonant beam depolarization

CMD-3: overview of datataking

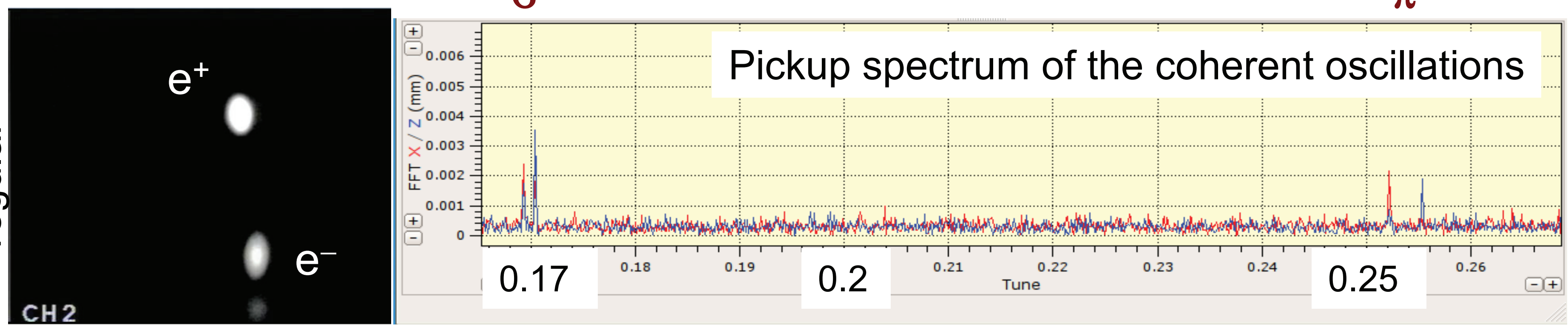


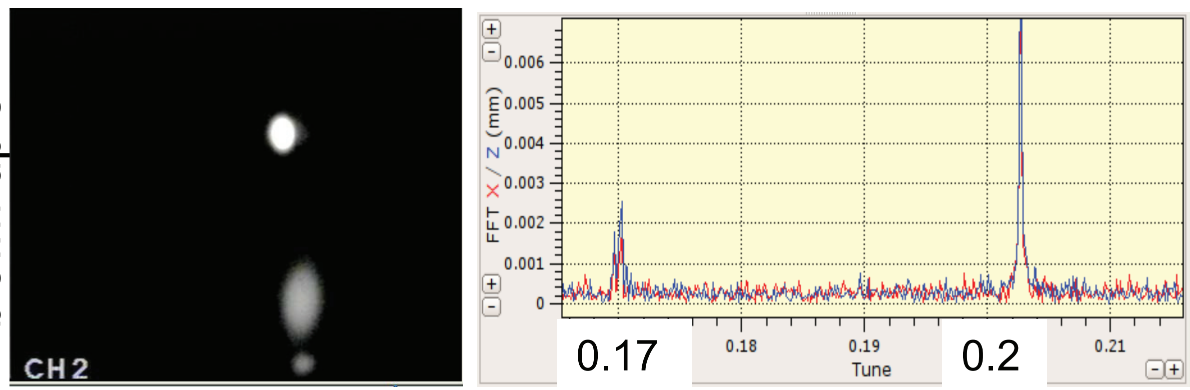


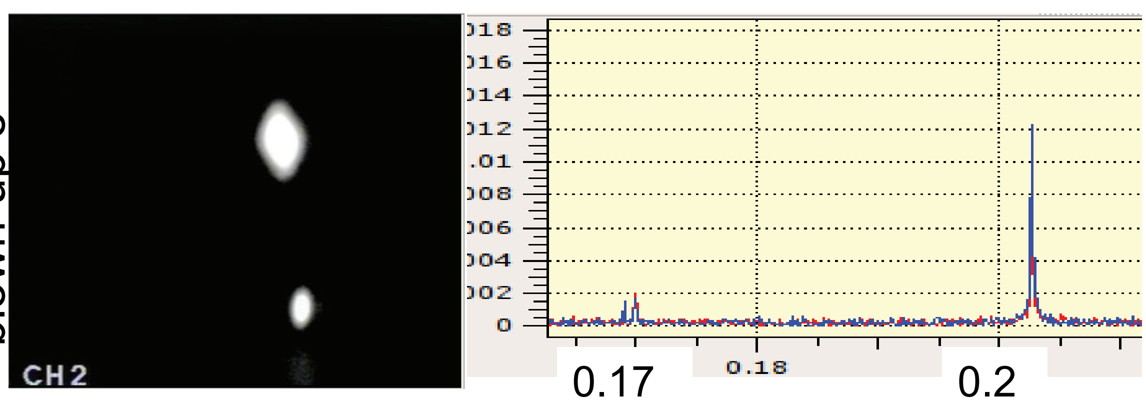
2010-2013 runs	
$\sqrt{s}$ region	L, pb^{-1}
$\omega(782)$	8.3
$\sqrt{s} < 1$ GeV (w/o ω)	9.4
$\phi(1020)$	8.4
$\sqrt{s} > 1.04$ GeV	34.5
Total	60

2017-2018 runs	
$\sqrt{s}$ region	L, pb^{-1}
2.007 GeV ($e^+e^- \to D^{0*}$)	4
$N\bar{N}$ threshold scan	14
Overall 1.28 – 2.007 GeV	50
$\sqrt{s} < 1.0$ GeV	> 50
Total	~100

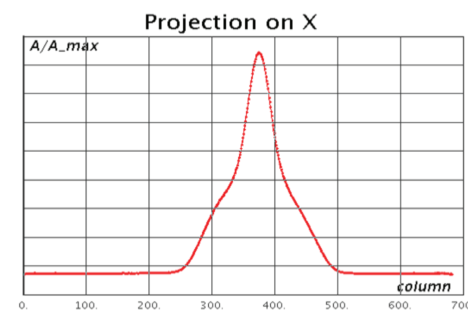
“Flip-flop” effect







E = 240 MeV,
$I_{beam} \sim 5 \times 5$ mA



Coherent beam-beam π-mode interaction with machine nonlinear resonances?

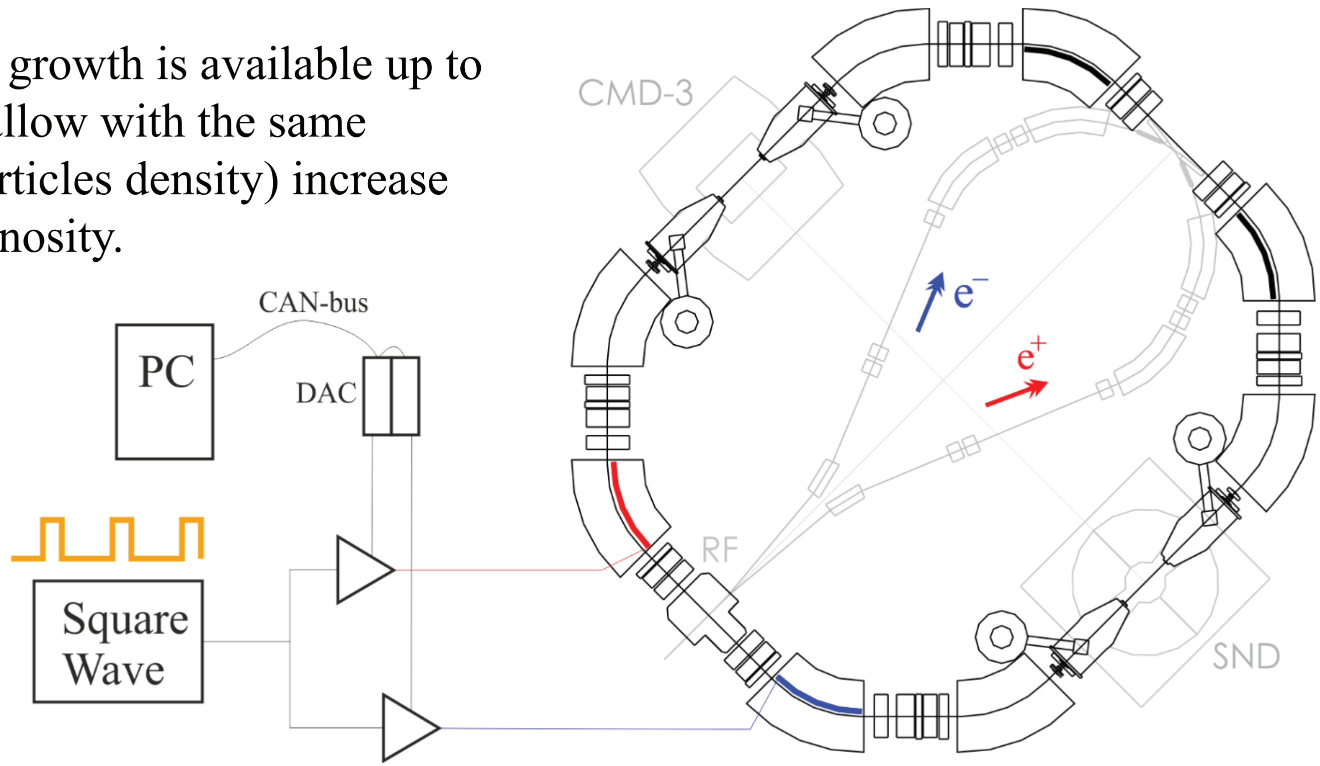
BeamShaker

Kicked bunch oscillations lots decoherence very fast in the presence of counter beam's strongly nonlinear field. Weak and fast kicks should effectively increase the emittance similarly to quantum excitation by wiggler.

At low energies emittance growth is available up to aperture restriction. That allow with the same beam-beam parameter (particles density) increase the beam current and luminosity.

Typical values:
50-100 V, 300 ns, 50 μs

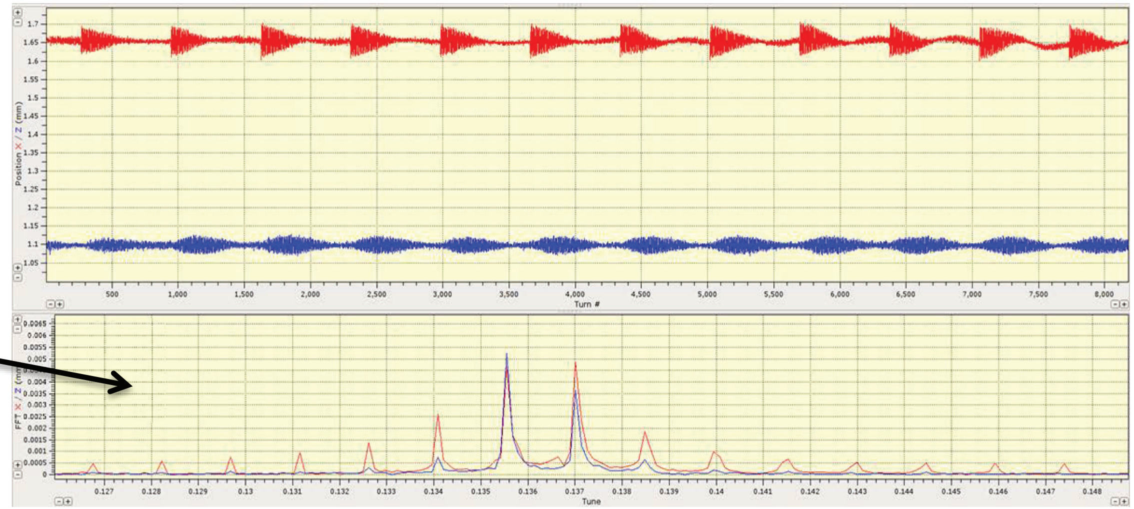
(T_{rev} = 81.4 ns)



Experimentally: permanent excitation of "strong" beam size prevent it from shrinkage to natural value during injection cycle of "weak" beam, or whatsoever. Very effective suppression of flip-flop meta-stable states.
In addition large emittance results in a lifetime enhancement.

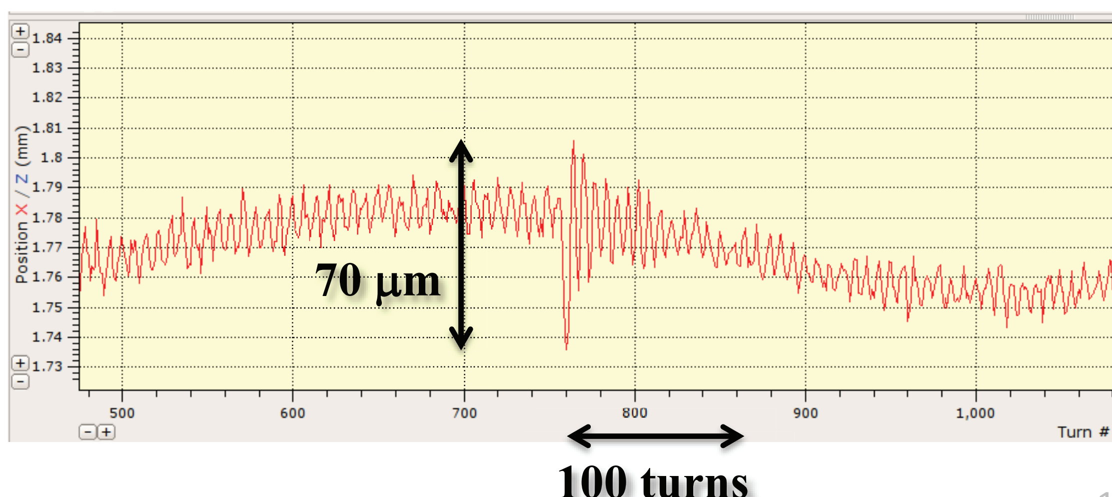
Shaking @ pickup

Pickup signal, without counter beam, 360 MeV



Periodically excited oscillations gives the line spectrum

Pickup signal, with strong counter beam, 274 MeV

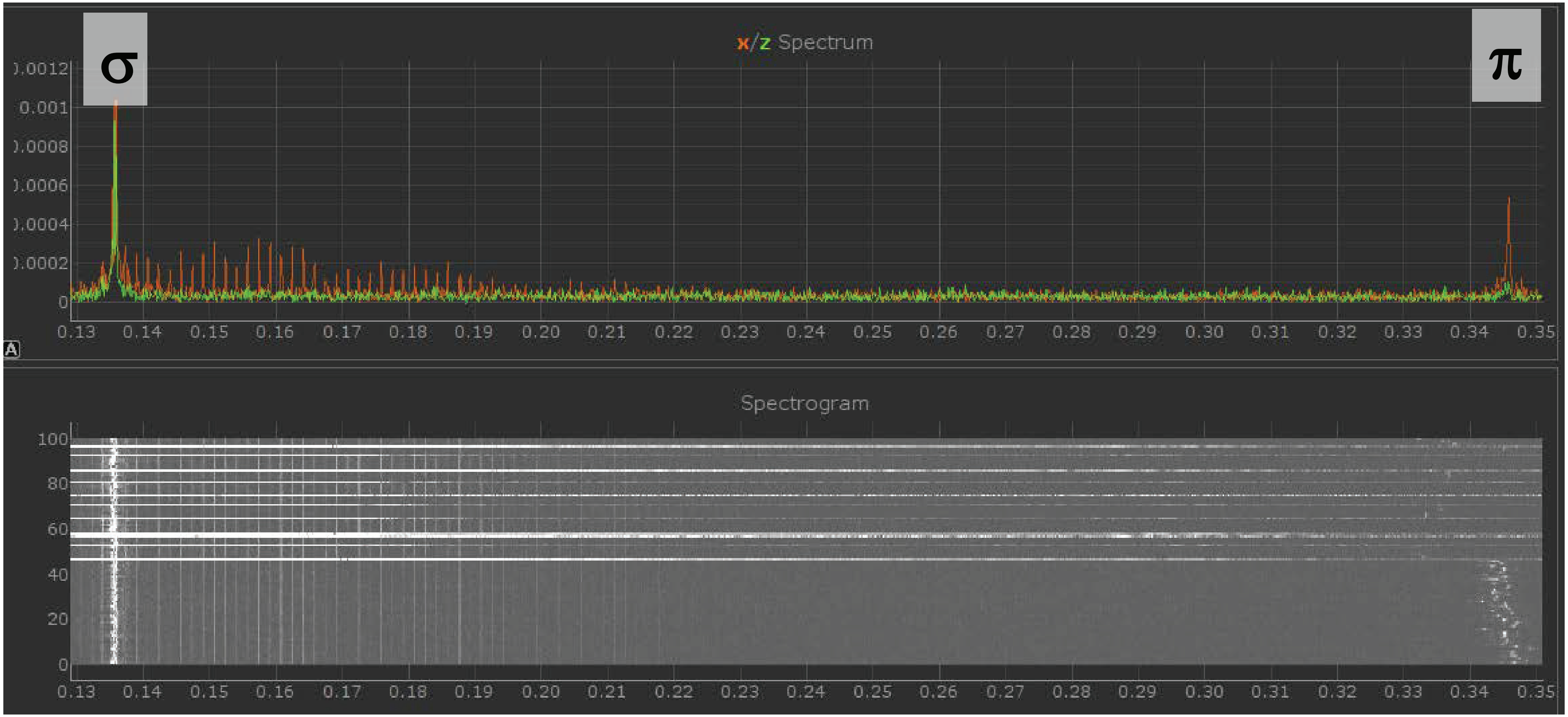


@ 274 MeV:

$\sigma_x = 250\ \mu m$ @ pickup

$\tau_{damp} = 130\ ms = 1.6\times10^6$ turns

Coherent beam-beam spectrum



$$\Delta\nu = \arccos(\cos(\pi\nu_0) - 2\pi\xi\sin(\pi\nu_0))/\pi - \nu_0$$

$\nu_\sigma = 0.135,\ \nu_\pi = 0.345$

$\Delta\nu = 0.21 \ \rightarrow \ \xi =$ **0.17**/IP

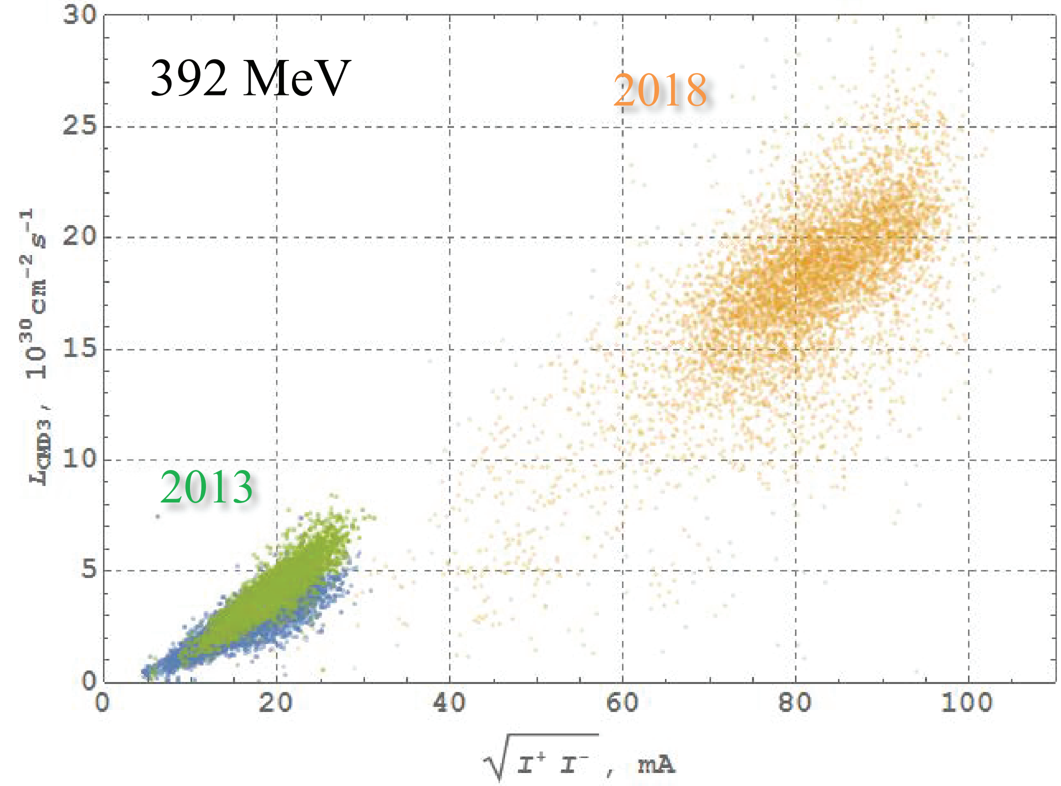
Here the Yokoya factor Y = 1, due to fast kick method of eigen modes excitation and due to short period analysis (studied @ VEPP-2M; simulated for VEPP-2000 by D.Shatilov)

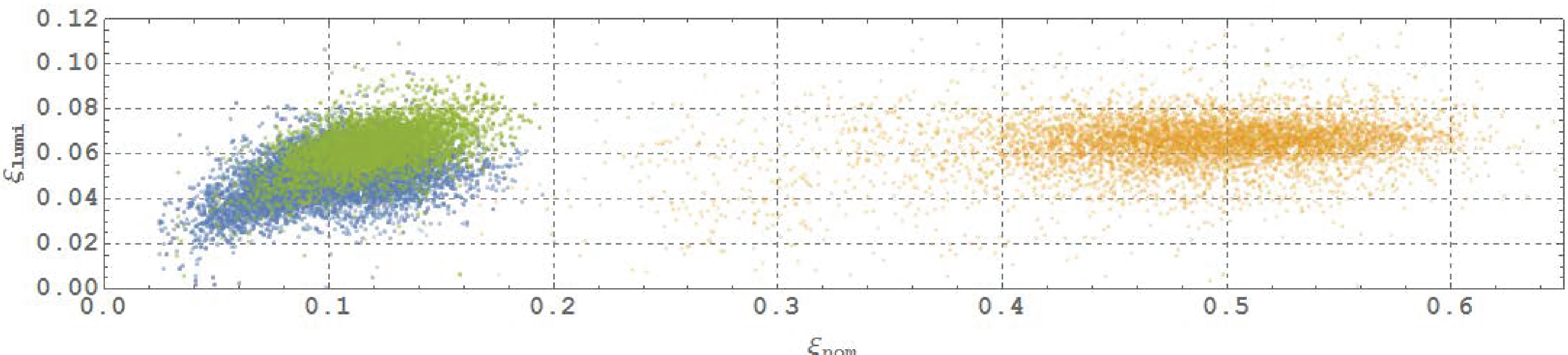
Luminosity and beam-beam parameter

$$\xi_{nom} = \frac{N^- r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{nom}}$$ - normalized beam current

$$\xi_{lumi} = \frac{N^- r_e \beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{lumi}}$$ - “beam-beam parameter”

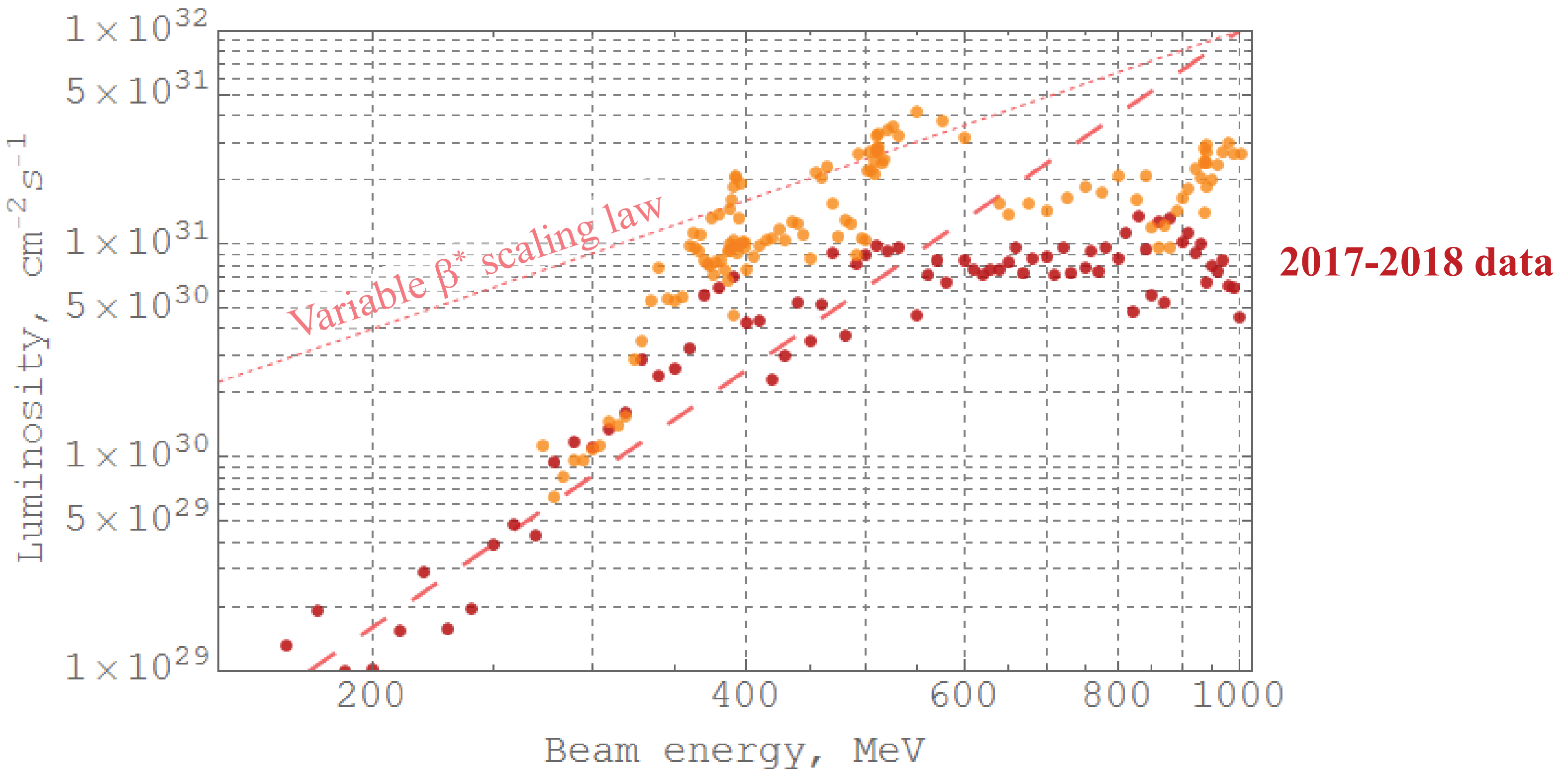
$$L = \frac{N^+ N^-}{4\pi\sigma^{*2}} f_0 = \frac{N f_0 \gamma}{r_e} \frac{\xi_{lumi}}{\beta^*_{nom}}$$





Data collection

CMD-3 luminosity, averaged over 10% of best runs

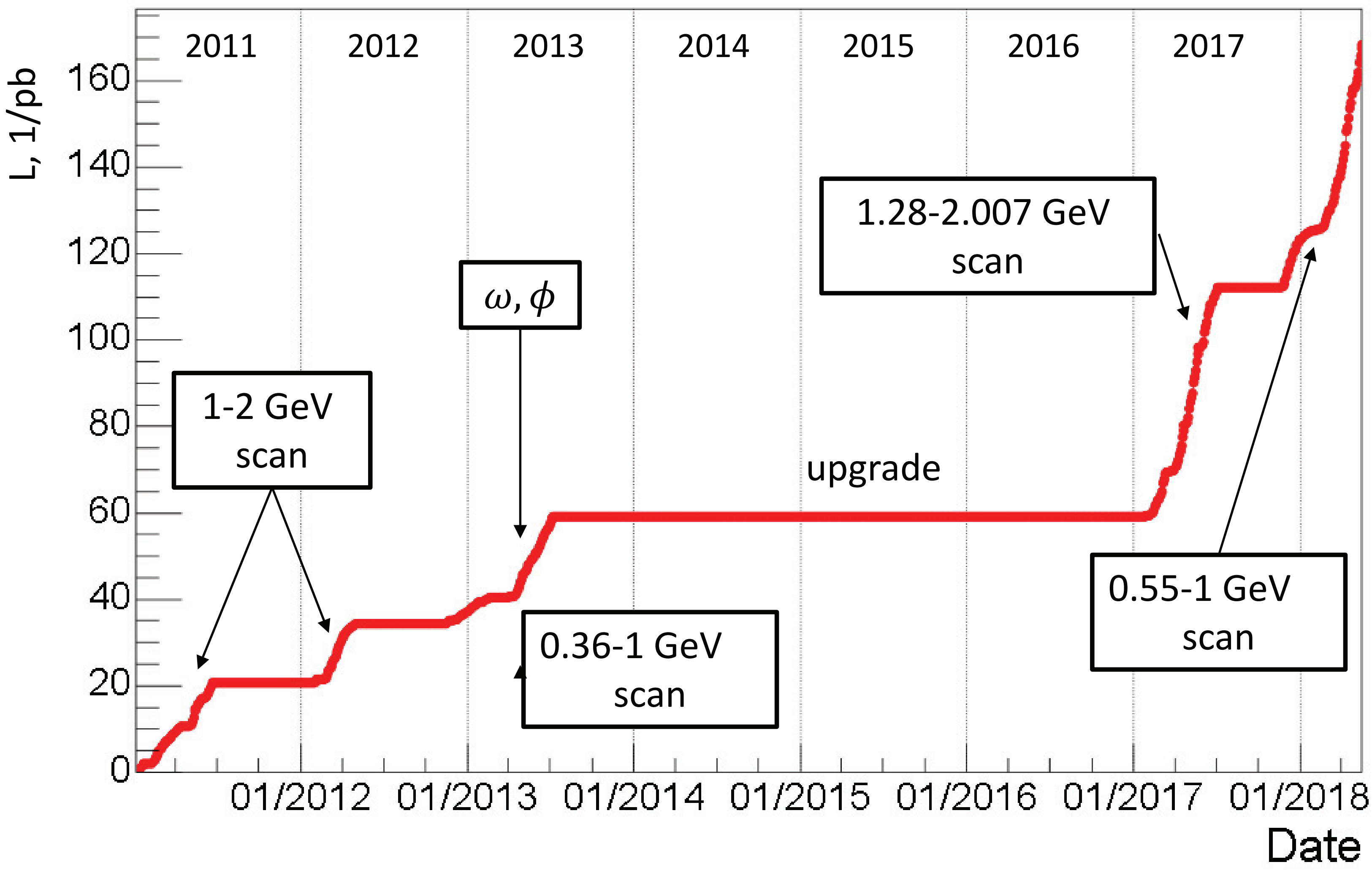


Highest luminosity achieved

$L_{peak} = 5\times10^{31}$ cm^{-2}s^{-1}

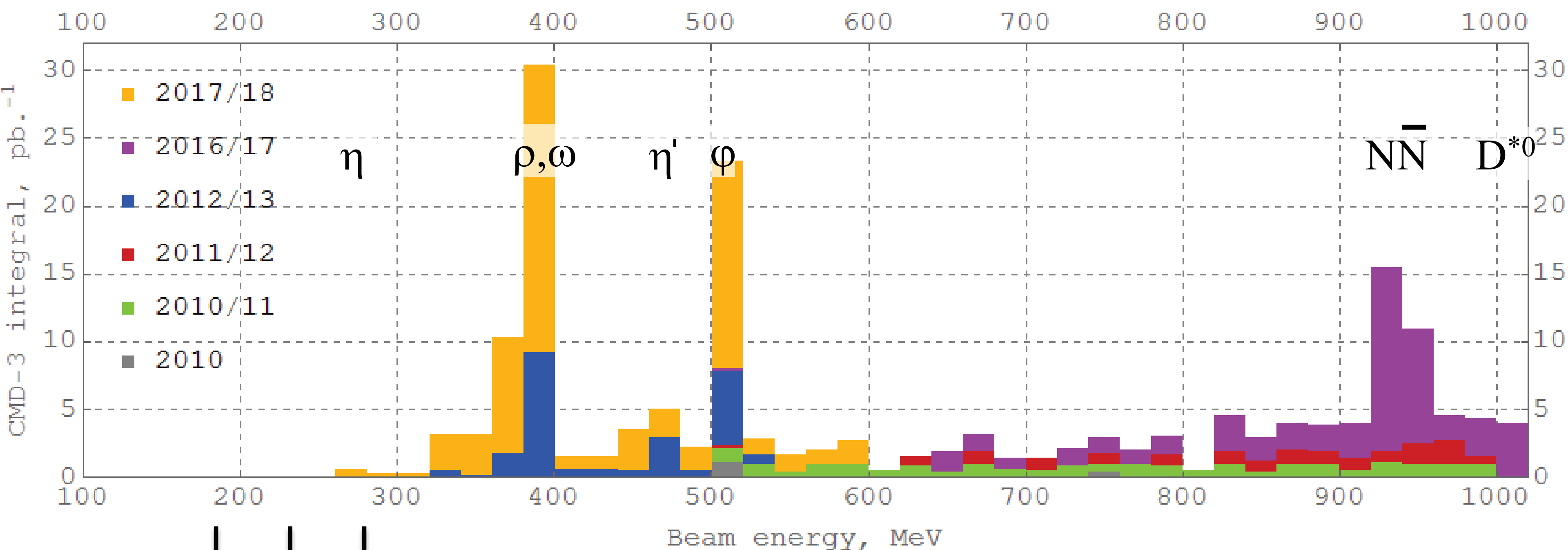
@ 550 MeV

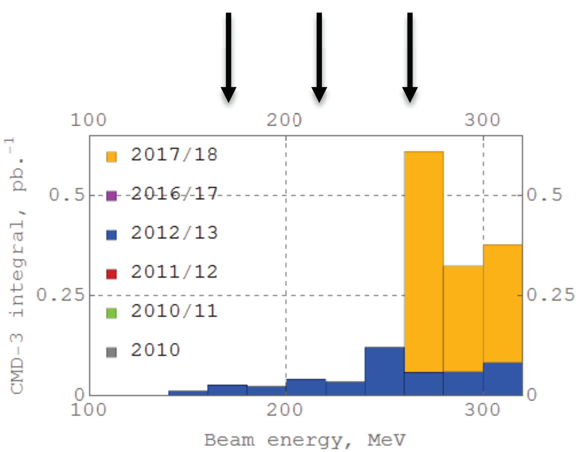
CMD-3: overview of datataking



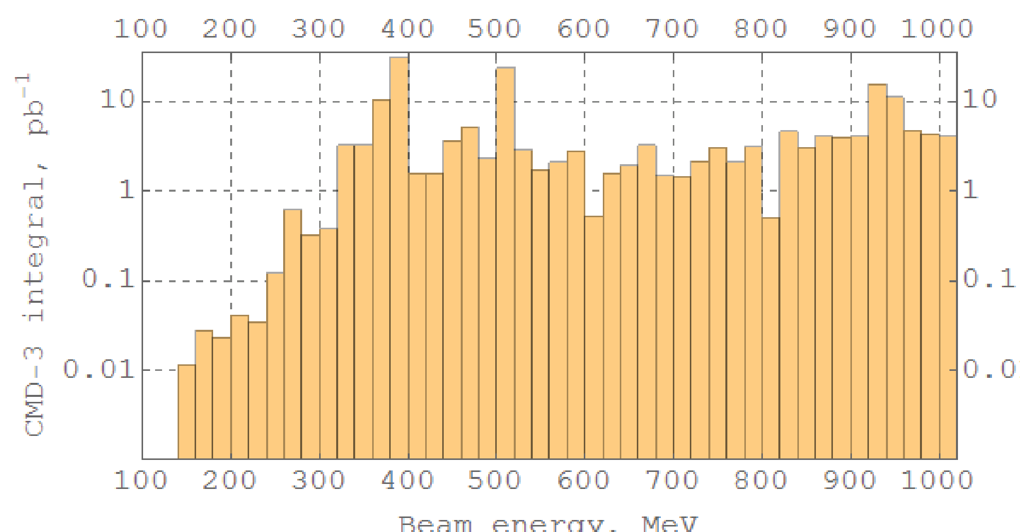
- Data taking will be continued to collect $\sim 1\ \mathrm{fb}^{-1}$ in the next 5-10 years

Total luminosity integral





Lowest energy ever obtained in e^+e^- colliders



Conclusion

- CMD-3 and SND has taken >300 pb^{-1} of data in the whole energy range $0.32 \le \sqrt{s} \le 2.0$ GeV and will take ~2 fb^{-1} in the next years
- The detector subsystems upgrades are planned (endcap and barrel coordinate counters, possibly a new drift chamber)
- New particle identification technique based on the dE/dx in 14 layers of LXe-calorimeter has been developed, and will be applied in the next seasons for K^+K^-, $K^+K^-\pi^0$, $K^+K^-2\pi^0$, $K_SK^{\pm}\pi^{\mp}$ final states analyzes
- This is just a beginning, do not oversleep new interesting results from us!

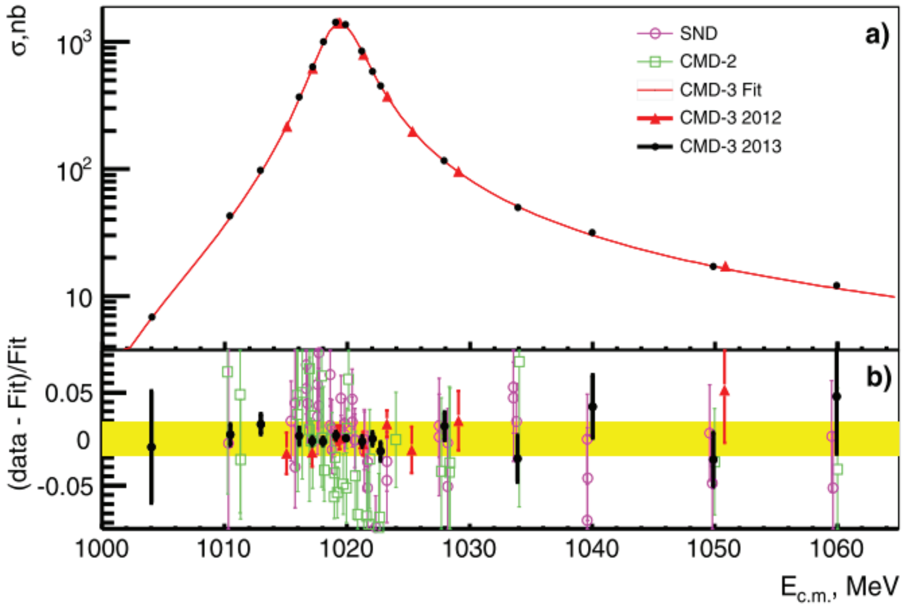
Thank You for Your Attention!

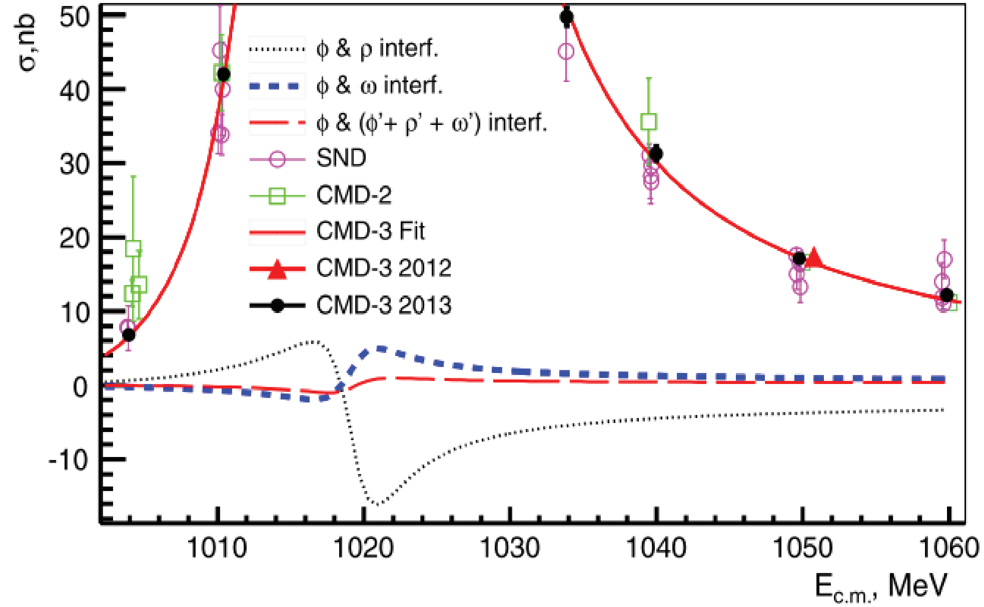
Stay tuned!

Backup slides

$e^+e^- \to K_S K_L$ at ϕ

- The final result published in PLB 760 (2016) 314-319
- Systematic precision ~1.8%





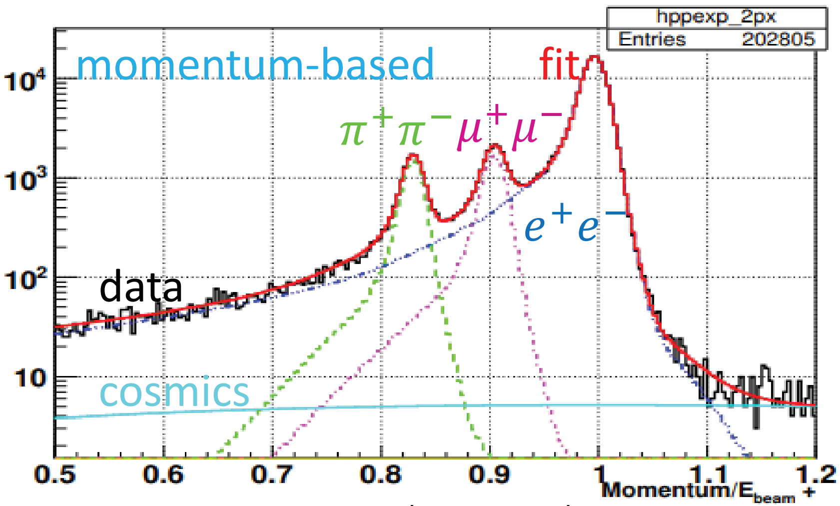
The results of the approximation procedure in comparison with previous experiments.

Parameter	CMD-3	Other measurements
m_ϕ, MeV	1019.457 ± 0.006 ± 0.060 ± 0.010	1019.461 ± 0.019 (PDG2014)
Γ_ϕ, MeV	4.240 ± 0.012 ± 0.005 ± 0.010	4.266 ± 0.031 (PDG2014)
$\Gamma_{\phi\to ee} B_{\phi\to K_S^0 K_L^0}$, keV	0.428 ± 0.001 ± 0.008 ± 0.005	0.4200 ± 0.0127 (BaBar)
$B_{\phi\to ee} B_{\phi\to K_S^0 K_L^0}$, 10^{-5}	10.078 ± 0.025 ± 0.188 ± 0.118	10.06 ± 0.16 (PDG2014)

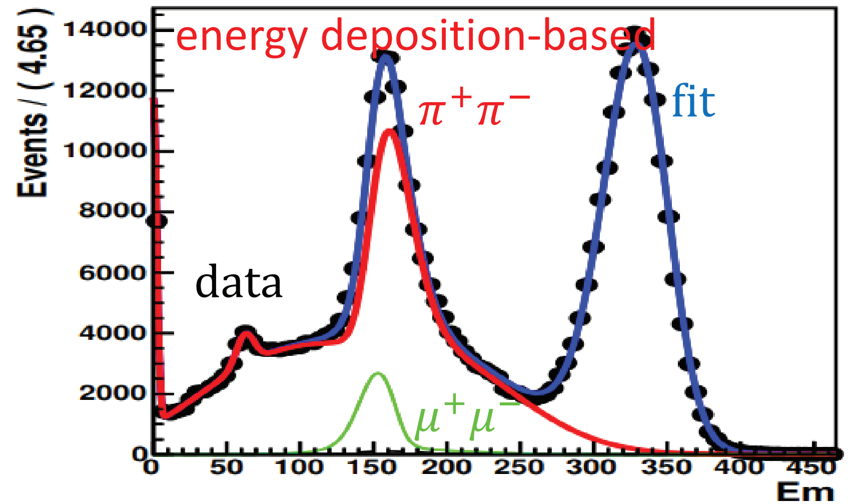
$e^+e^- \to \pi^+\pi^-$: pion formfactor measurement

- In both cases 2D-bin-likelyhood function is constructed, its minimization gives $N_{\pi\pi}/N_{ee}$
- The projections of the fitting functions after minimization:

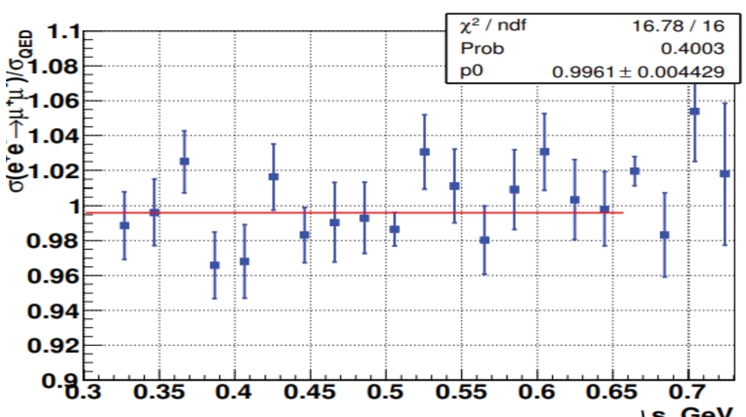
250 MeV

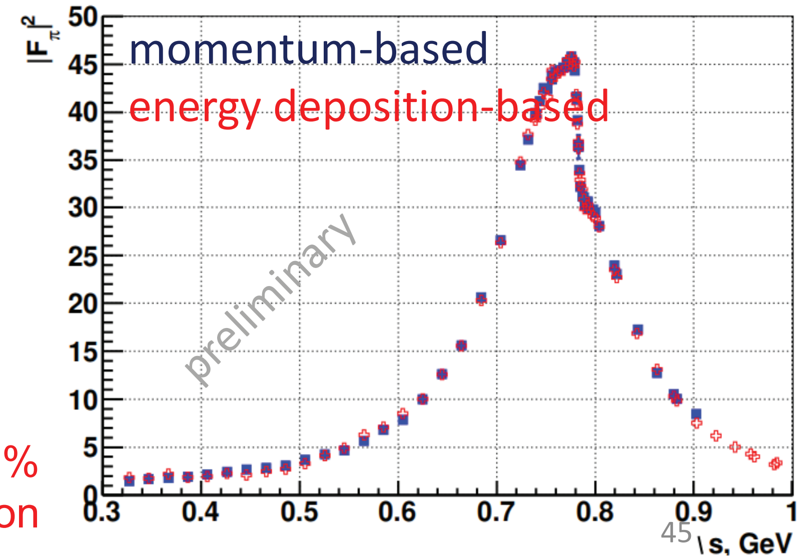


387.5 MeV, -



- Additional test - $\sigma(e^+e^- \to \mu^+\mu^-)$ measurement:

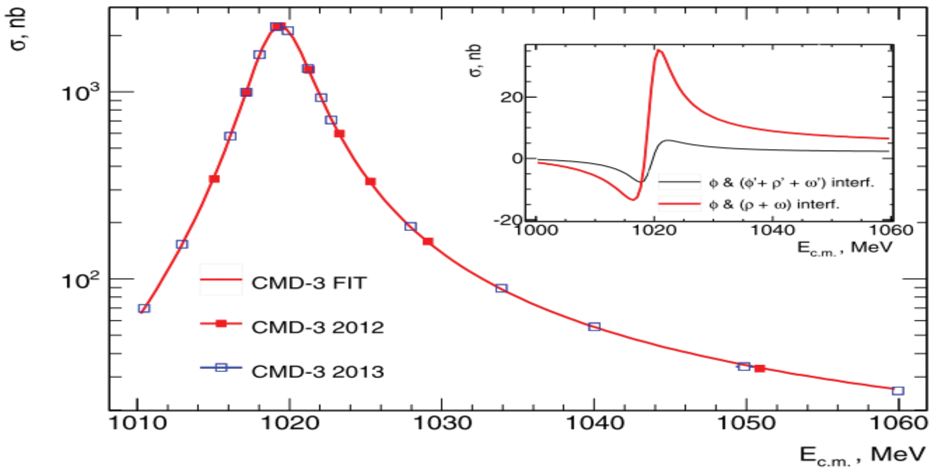




- Currently the systematics is estimated to be 0.4-0.9% (momentum-based) and 1.5% (energy-deposition based), the goal is – 0.35%

$e^+e^- \to K^+K^-$ at ϕ

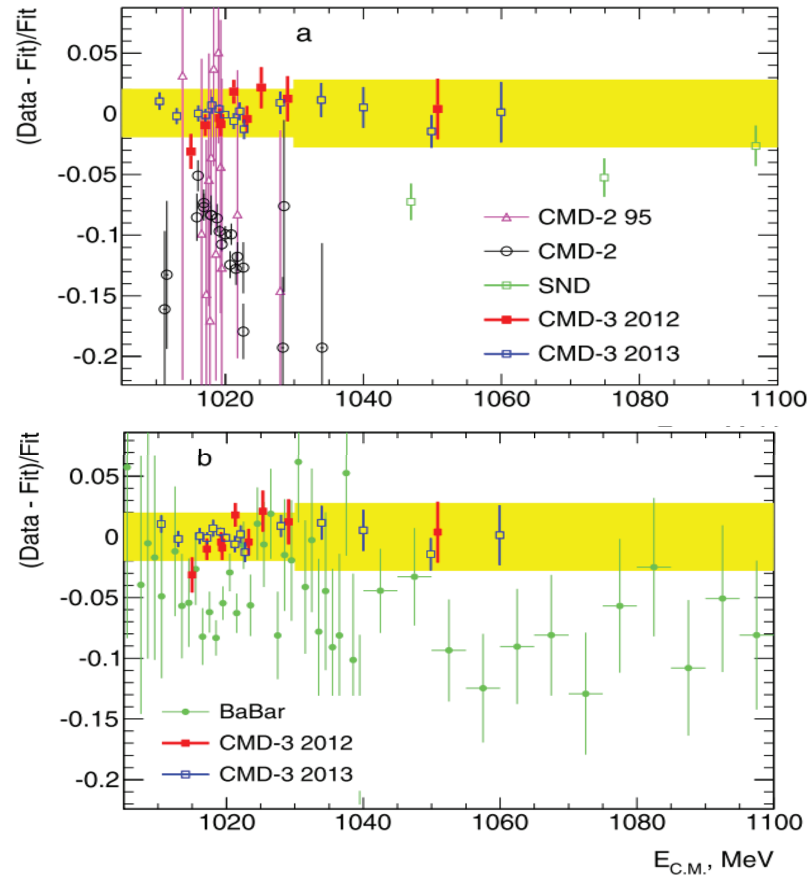
- The final result published in PLB 779 (2018) 64



- Systematic precision ~2.0%
- CMD-3 results are above CMD-2 and BaBar, but are consistent with isospin symmetry:

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

- Comparison with other experiments:



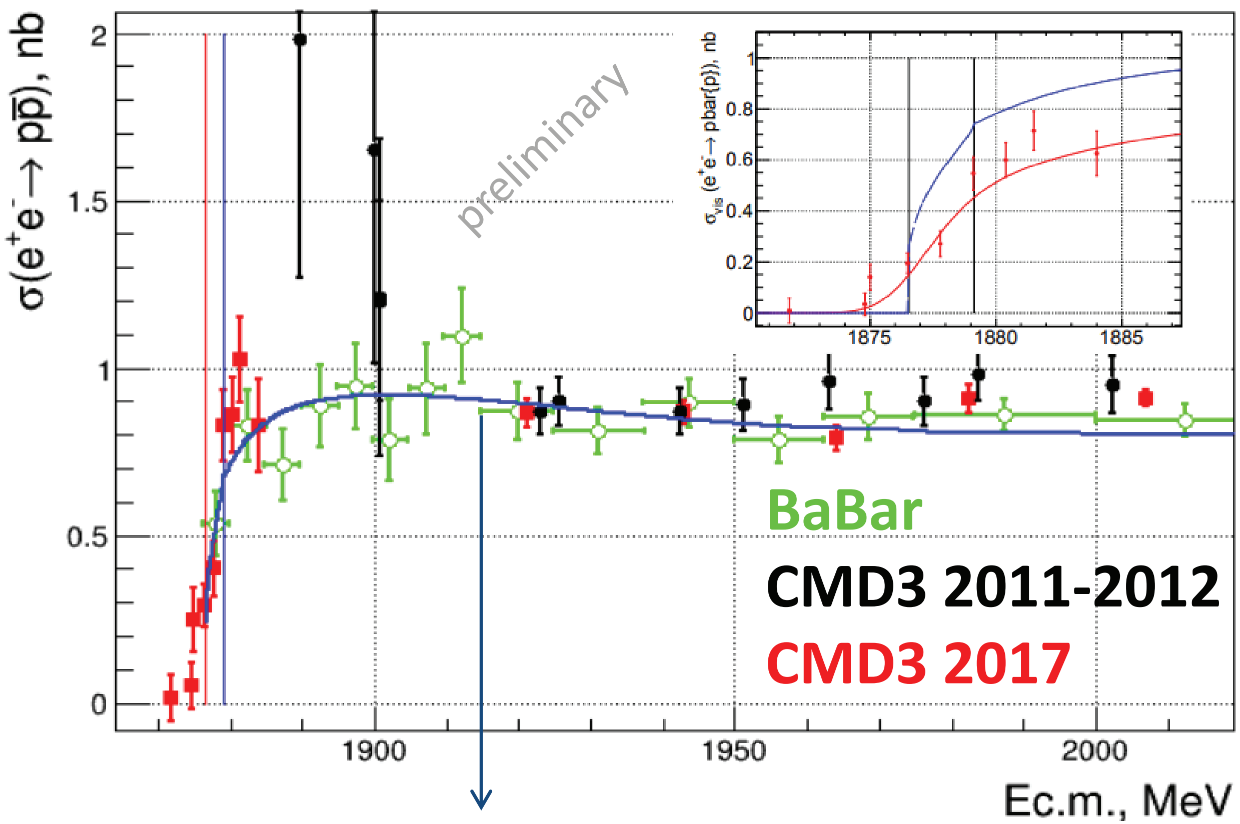
The parameters obtained from a fit of the cross section compared with previous experiments.

Parameter	CMD-3	Other measurements
m_ϕ, MeV	1019.469 ± 0.006 ± 0.060 ± 0.010	1019.461 ± 0.019 (PDG2016)
Γ_ϕ, MeV	4.249 ± 0.010 ± 0.005 ± 0.010	4.266 ± 0.031 (PDG2016)
$\Gamma_{\phi\to ee} B_{\phi\to K^+K^-}$, keV	0.669 ± 0.001 ± 0.022 ± 0.005	0.634 ± 0.008 (BaBar)
$B_{\phi\to ee} B_{\phi\to K^+K^-}$, 10^{-5}	15.789 ± 0.033 ± 0.527 ± 0.120	14.24 ± 0.30 (PDG2016)

Scanning of $N\bar{N}$ threshold

- The 2011-2012-based results $p\bar{p}$ cross section measurements and the results for $\frac{G_E}{G_M}$ ratio were published (PLB 759 (2016) 634). In 2017 a more thorough threshold scan was performed:

arXiv:1808.00145[hep-ex]

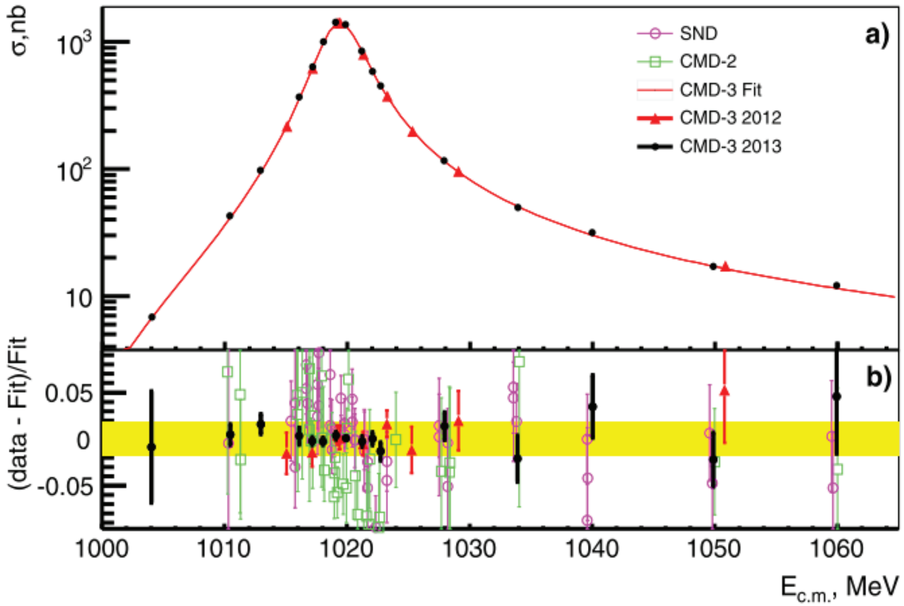


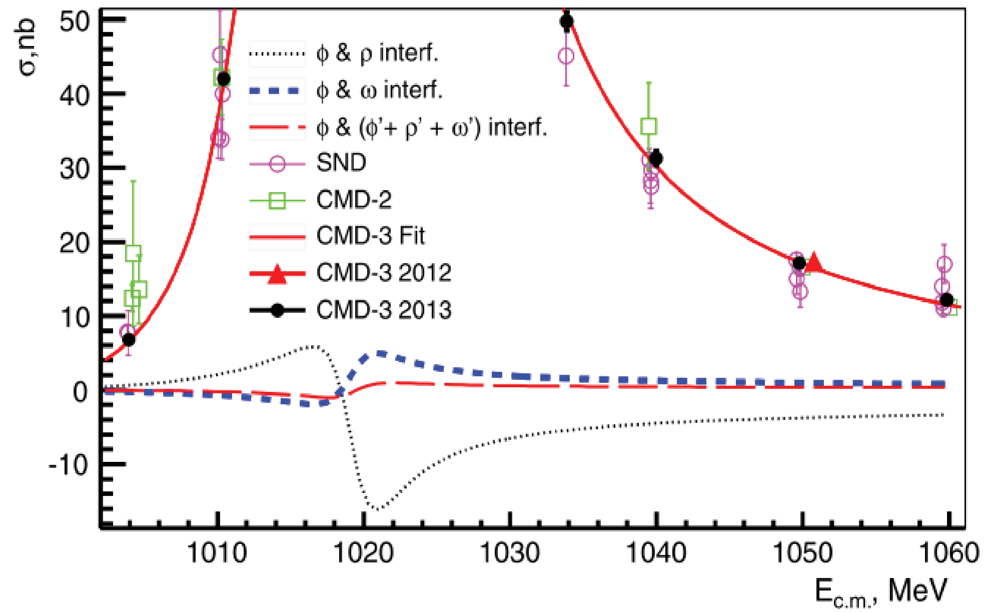
- A solid curve shows the prediction from recent works:

A.I. Milstein and S. G. Salnikov, arXiv:1804.01283v1 [hep-ph]
V. F. 200 Dmitriev, A. I. Milstein and S. G. Salnikov, Phys. Rev. D93, 034033 201 (2016)
A. I. Milstein, S. G. Salnikov, Nucl.Phys. A966, 54 (2017)

$e^+e^- \to K_S K_L$ at ϕ

- The final result published in PLB 760 (2016) 314-319
- Systematic precision ~1.8%





The results of the approximation procedure in comparison with previous experiments.

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m_ϕ, MeV	$1019.457 \pm 0.006 \pm 0.060 \pm 0.010$	1019.461 ± 0.019 (PDG2014)
Γ_ϕ, MeV	$4.240 \pm 0.012 \pm 0.005 \pm 0.010$	4.266 ± 0.031 (PDG2014)
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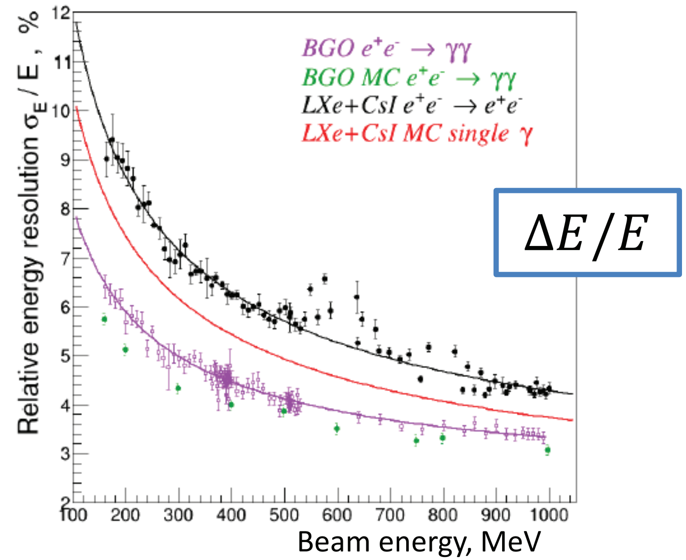
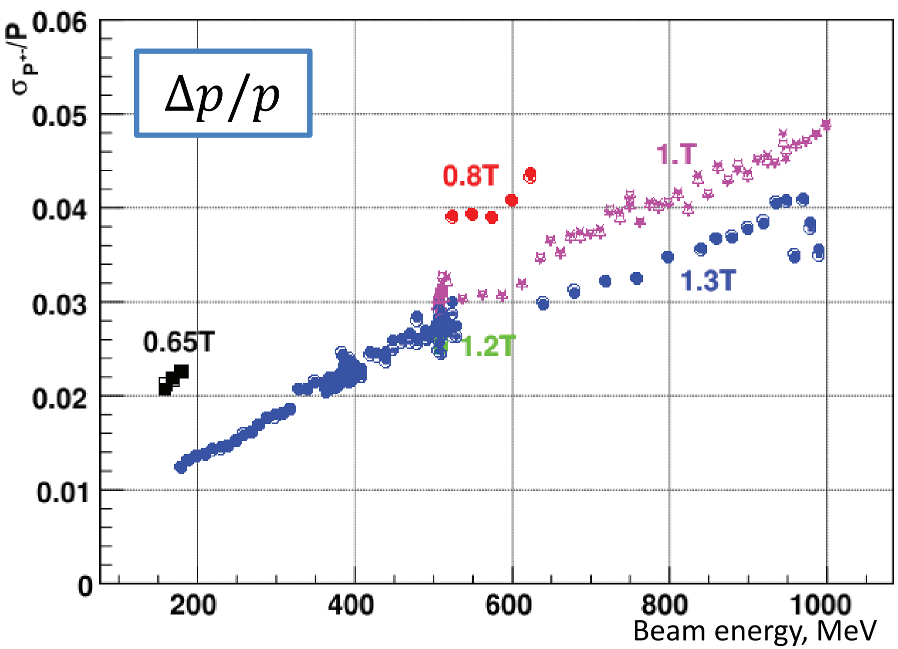
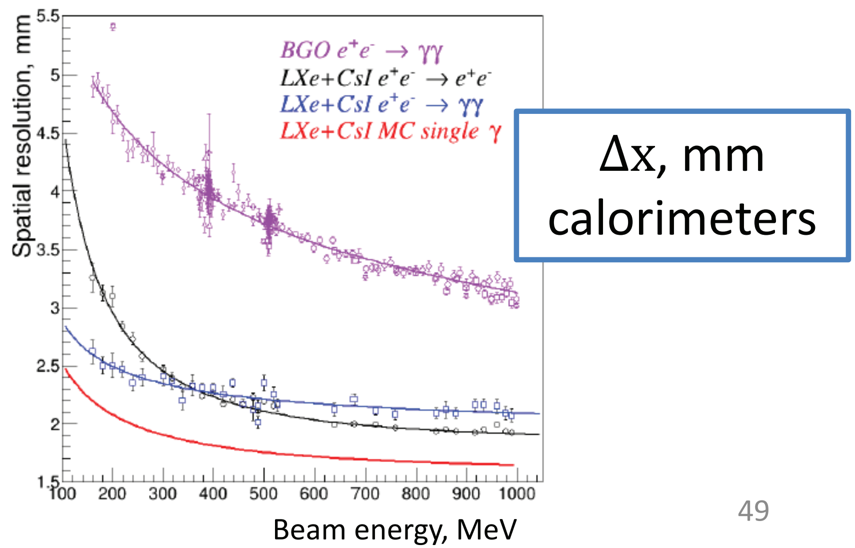
$B_{\phi\to ee} B_{\phi\to K_S^0 K_L^0}$, 10^{-5}	$10.078 \pm 0.025 \pm 0.188 \pm 0.118$	10.06 ± 0.16 (PDG2014)

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

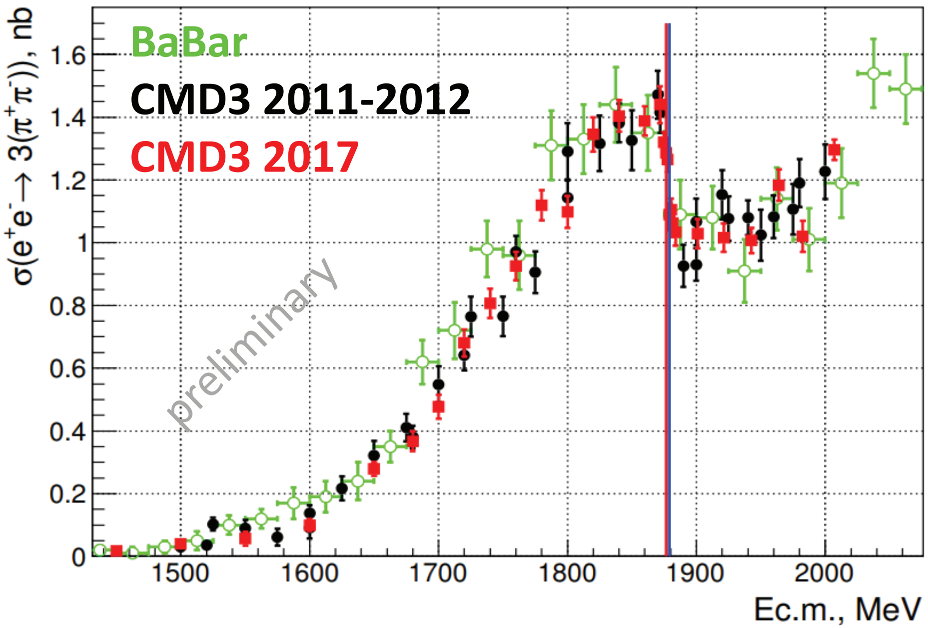


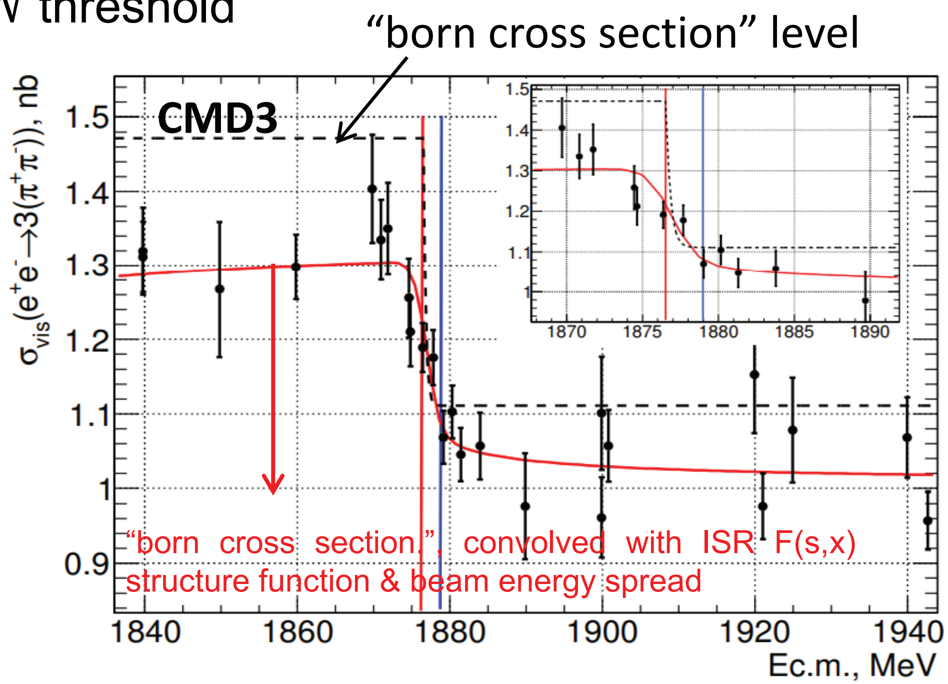




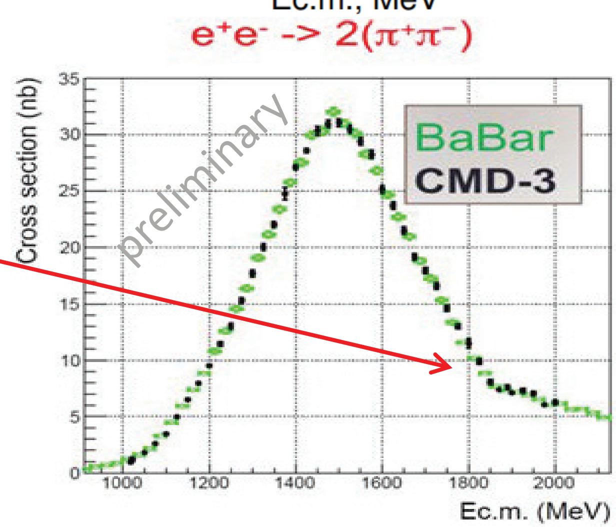
$e^+e^- \to 3(\pi^+\pi^-)$ & $N\bar{N}$ threshold

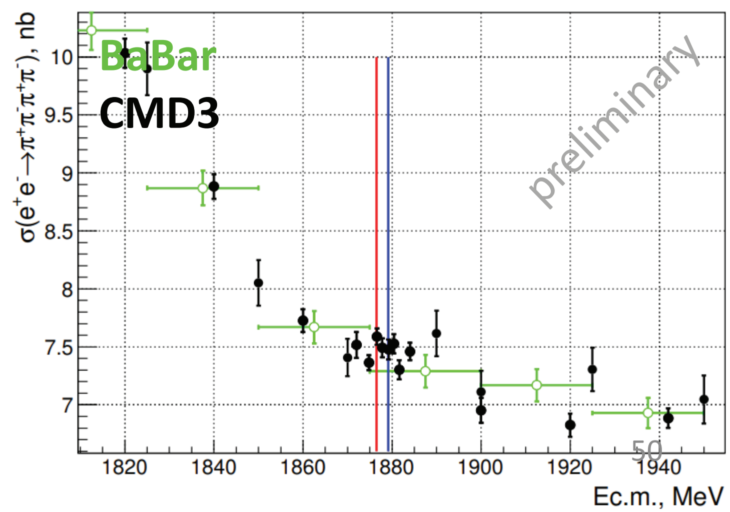
- The 2011-2012-based results were published in PLB 723, 82 197 (2013), new data confirm the drop of the cross section at $N\bar{N}$ threshold





- Curious thing: we see no drop in $\sigma(e^+e^- \to 2(\pi^+\pi^-))$

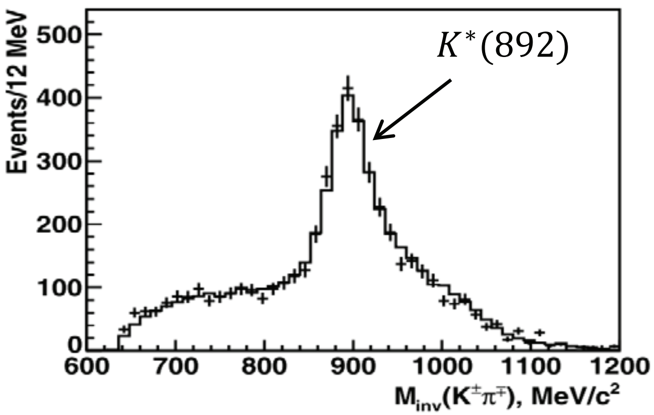


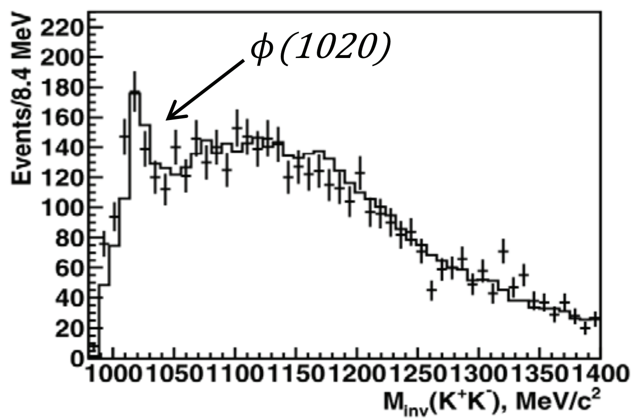


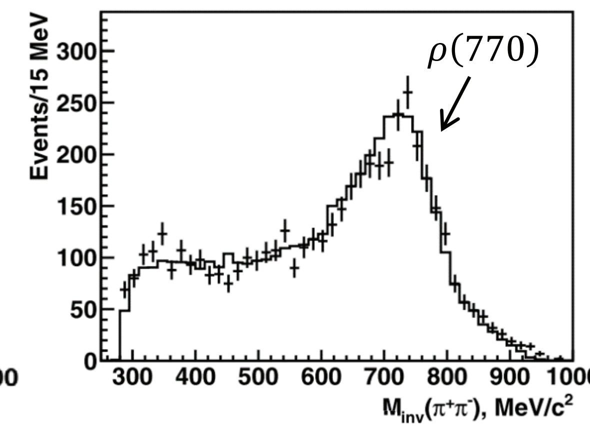
$e^+e^- \to K^+K^-\pi^+\pi^-$ & $N\bar{N}$ threshold

- The major intermediate states were found to be
- $f_0(500)\phi$ & $f_0(980)\phi$,
- $\rho(770)(KK)_{S-wave}$,
- $(K_1(1270,1400)K)_{S-wave} \to (K^*(892)\pi)_{S-wave}K$
- $(K_1(1400)K)_{S-wave} \to (\rho(770)K)_{S-wave}K$

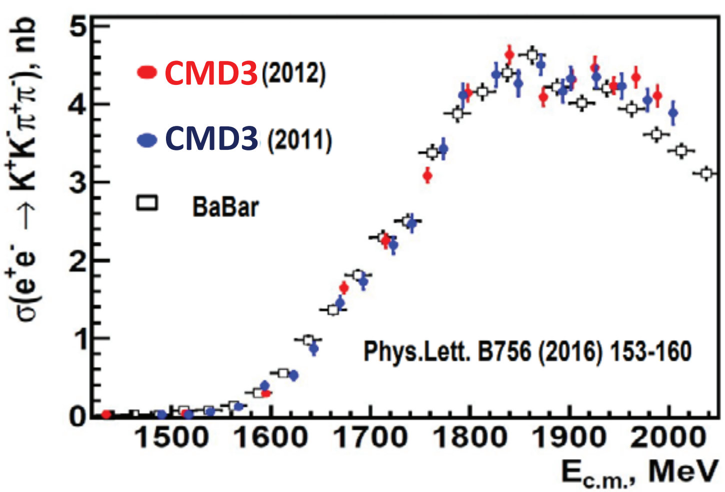
- Their relative amplitudes were found from the unbinned fit of the data:

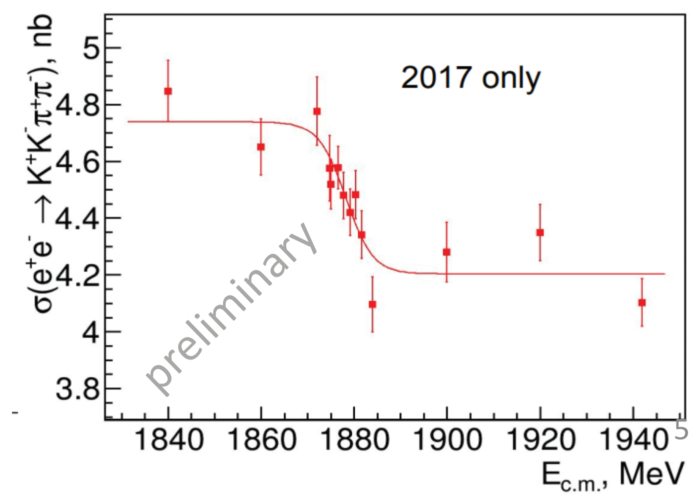






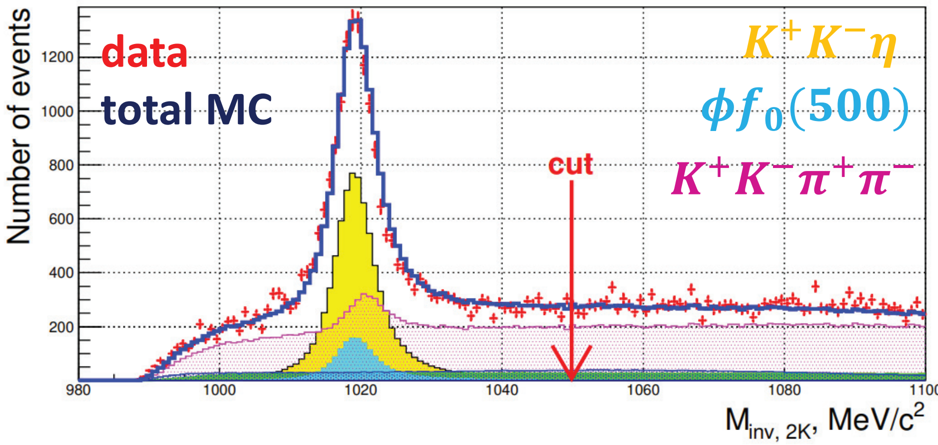
- We see the drop in $\sigma(e^+e^- \to K^+K^-\pi^+\pi^-)$!





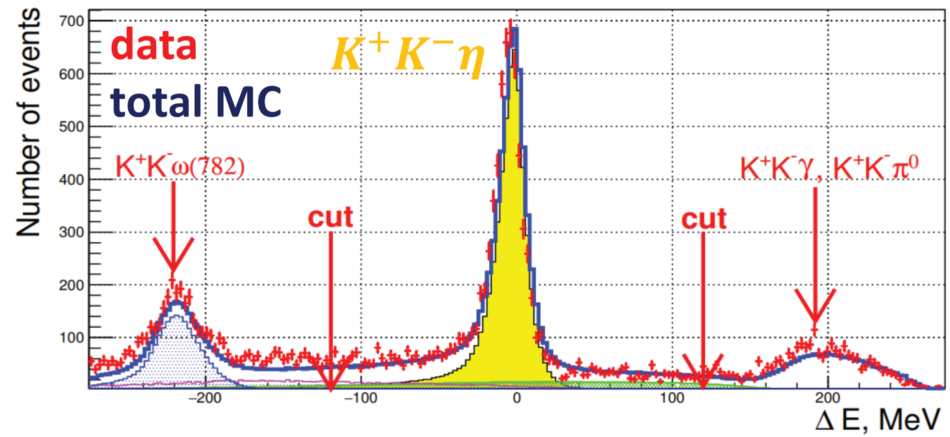
$e^+e^- \to K^+K^-\eta, K^+K^-\omega$

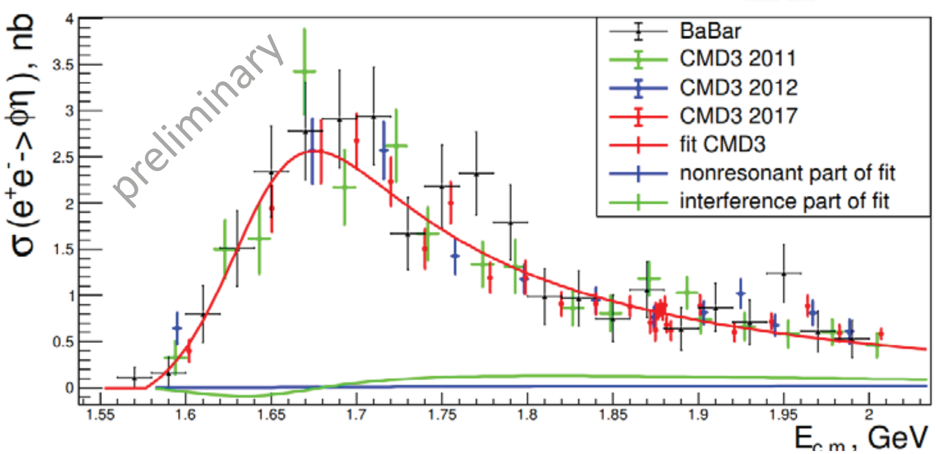
- The dominant mechanism was found to be $e^+e^- \to \phi(1680) \to \phi\eta$ => the case for $\phi(1680)$ parameters measurement from cross section fitting



- η was considered as a recoil particle:

$$\Delta E = \sqrt{\vec{p}^{\,2}_{K^-} + m_K^2} + \sqrt{\vec{p}^{\,2}_{K^+} + m_K^2} + \sqrt{(\vec{p}_{K^-} + \vec{p}_{K^+})^2 + m_\eta^2} - E_{\text{c.m.}}$$

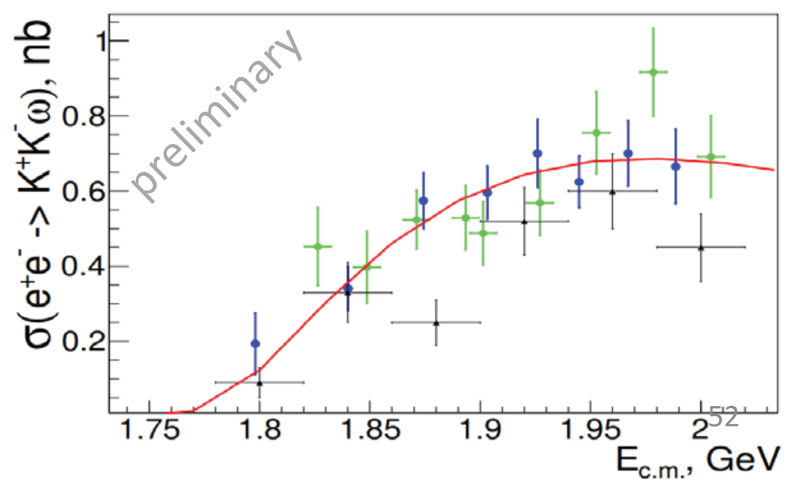




ϕ' parameters from fit

Parameter	Value (CMD-3/BaBar)
χ^2/n.d.f	91.3/60 = 1.55 / 184.9/144 = 1.28
$\Gamma_{ee}^{\phi'}\mathcal{B}(\phi' \to \phi\eta)$,eV	100±11 / 154±32
$m_{\phi'}$,MeV	1682±5 / 1709±19
$\Gamma_{\phi'}$,MeV	199±26 / 325±68

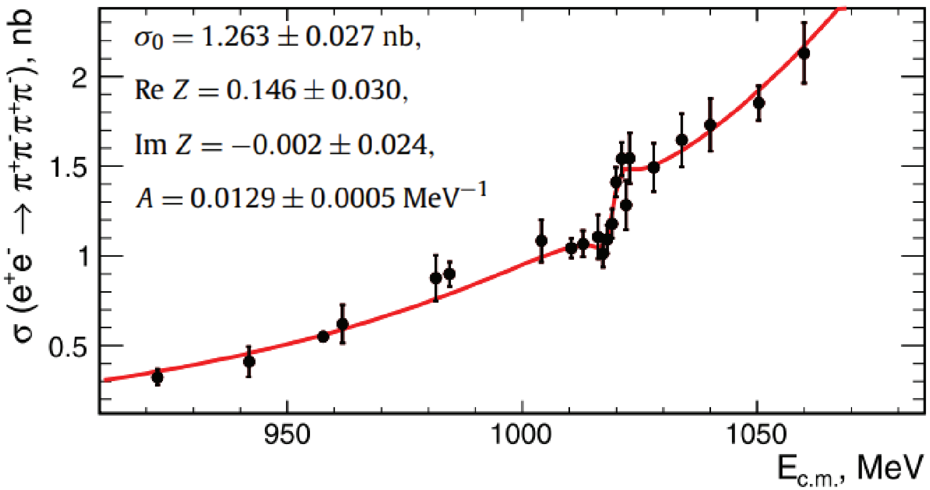
Similarly the $\sigma(e^+e^- \to K^+K^-\omega(782))$ was measured:



Other results

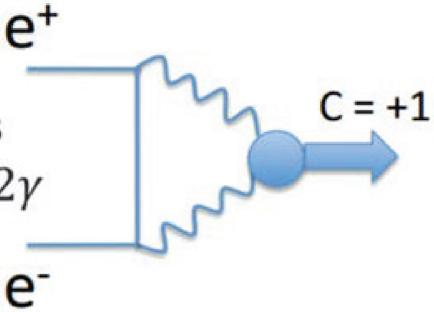
- Study of $e^+e^- \to 2\pi^+2\pi^-$ in the range (PLB 768 (2017) 345–350)

$$\sigma(\mathrm{E_{c.m.}}) = \sigma_0 \cdot f(\mathrm{E_{c.m.}}) \cdot \left|1 - Z \cdot \frac{m_\phi \Gamma_\phi}{m_\phi^2 - \mathrm{E_{c.m.}^2} - i\mathrm{E_{c.m.}}\Gamma_\phi}\right|^2 \quad f(\mathrm{E_{c.m.}}) = e^{A(\mathrm{E_{c.m.}} - m_\phi)}$$



- Search for $e^+e^- \to \eta'(958)$ (PLB 740 (2015) 273–277)

C-even resonances can be produced via 2γ

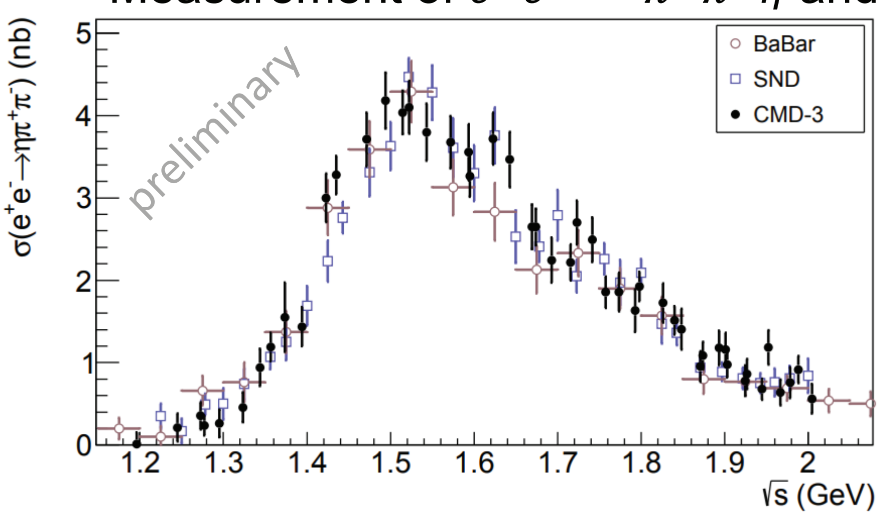


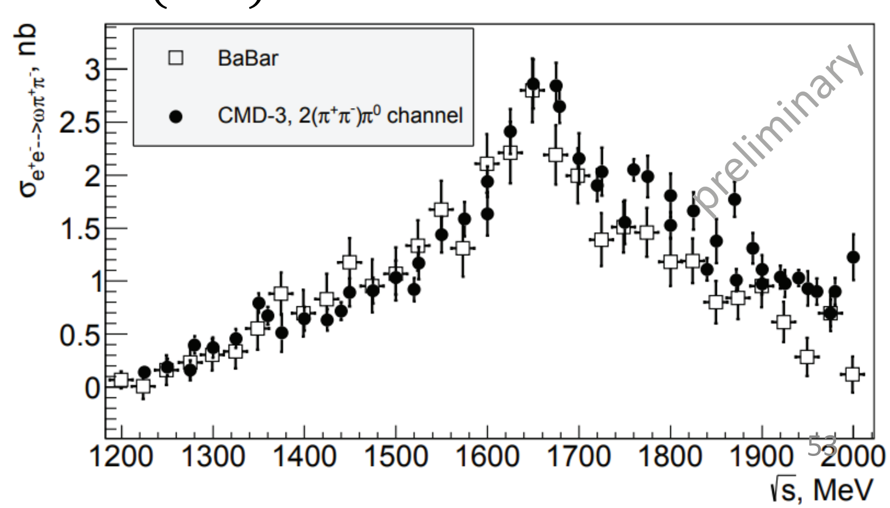
$$Br(\eta' \to e^+e^-) = Br(\eta' \to \gamma\gamma)\frac{\alpha^2}{2\beta}\left(\frac{m_e}{m_{\eta'}}\right)^2\left[\ln\left(\frac{1+\beta}{1-\beta}\right)\right]^2$$

B($\eta' \to e^+e^-$) < 1.2 10^{-8} (90%CL) - CMD-3

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

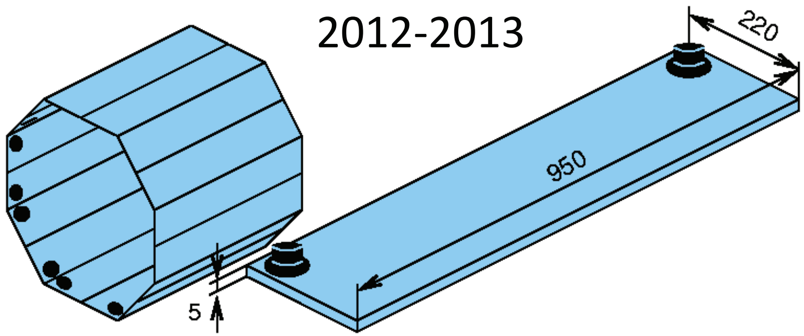
- Measurement of $e^+e^- \to \pi^+\pi^-\eta$ and $\pi^+\pi^-\omega(782)$ cross sections:



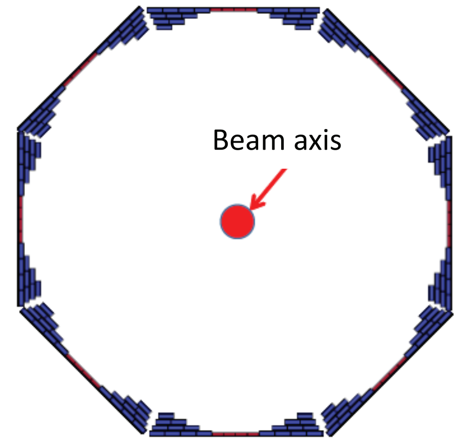


New TOF system

“Old” TOF
2012-2013

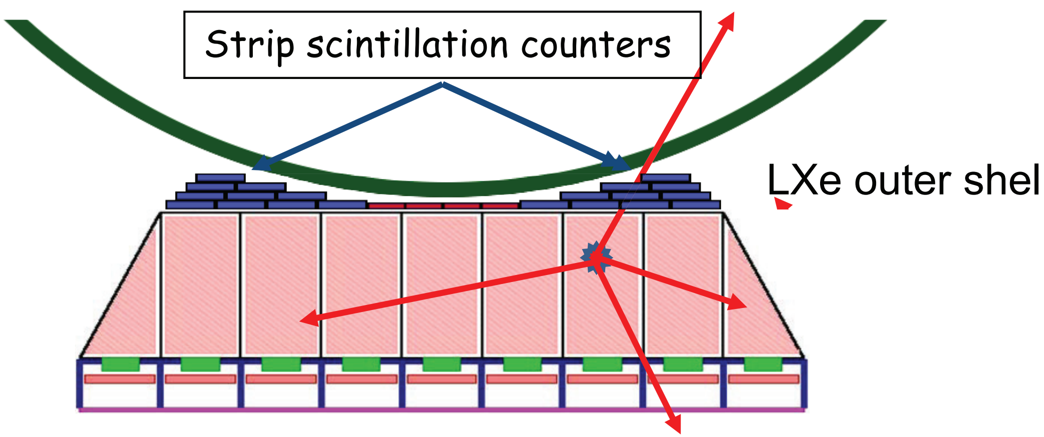


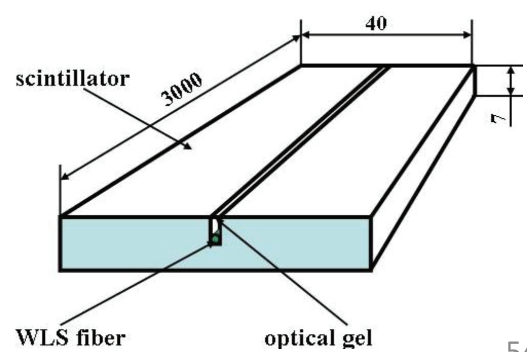
“New” TOF (2017-)



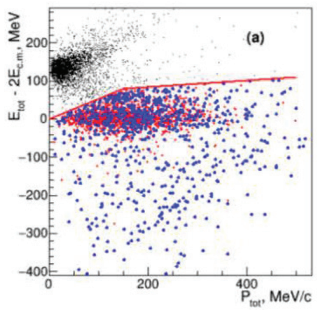
In 2013-2016 the TOF system was completely replaced

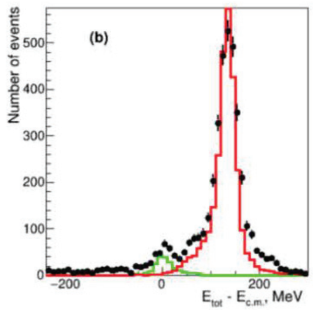
- More granulated (16 counters → 175 counters)
- 0.8 ns resolution per counter



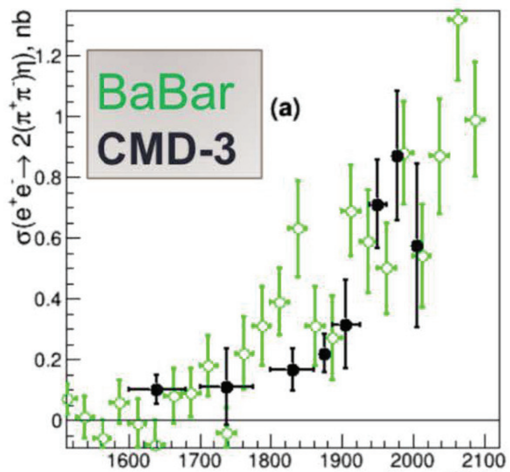


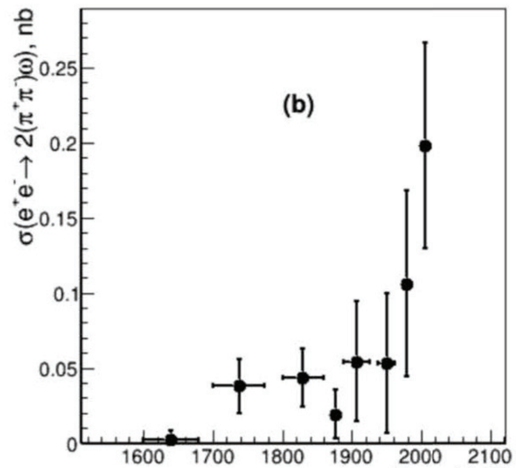
The most hottest result $e^+e^- \to 3(\pi^+\pi^-)\pi^0$

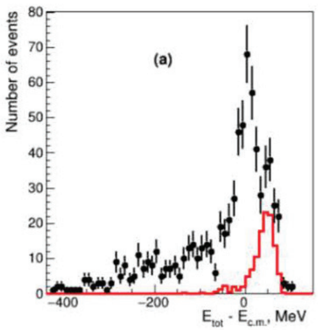


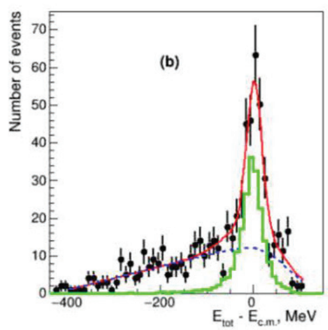


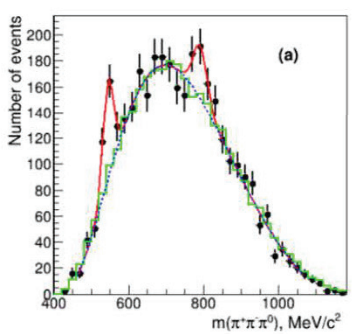
Based on 56 pb^{-1} in 1600-2000 MeV









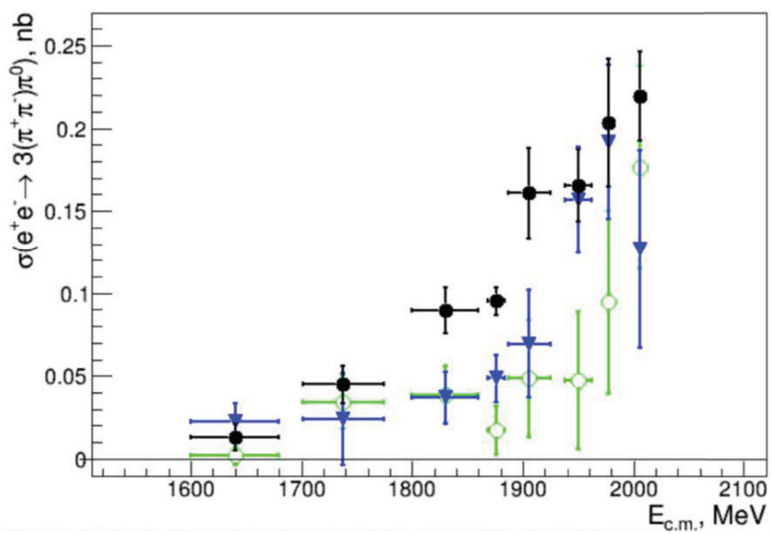


Dominated by

ω4π

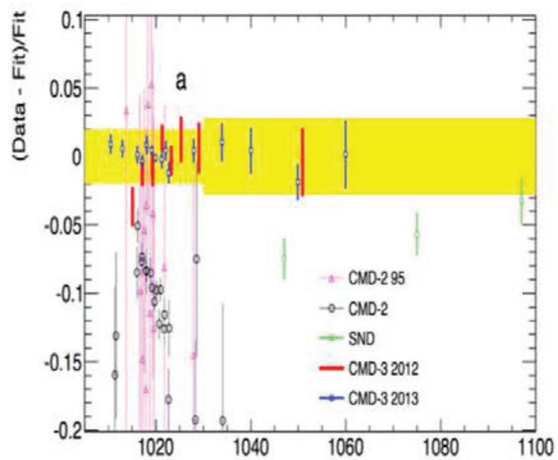
η4π

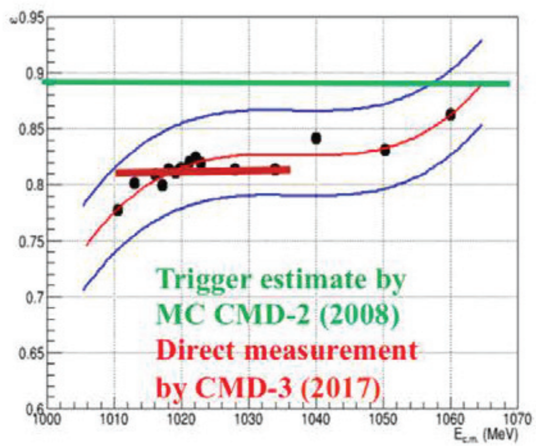
Publications are in preparations

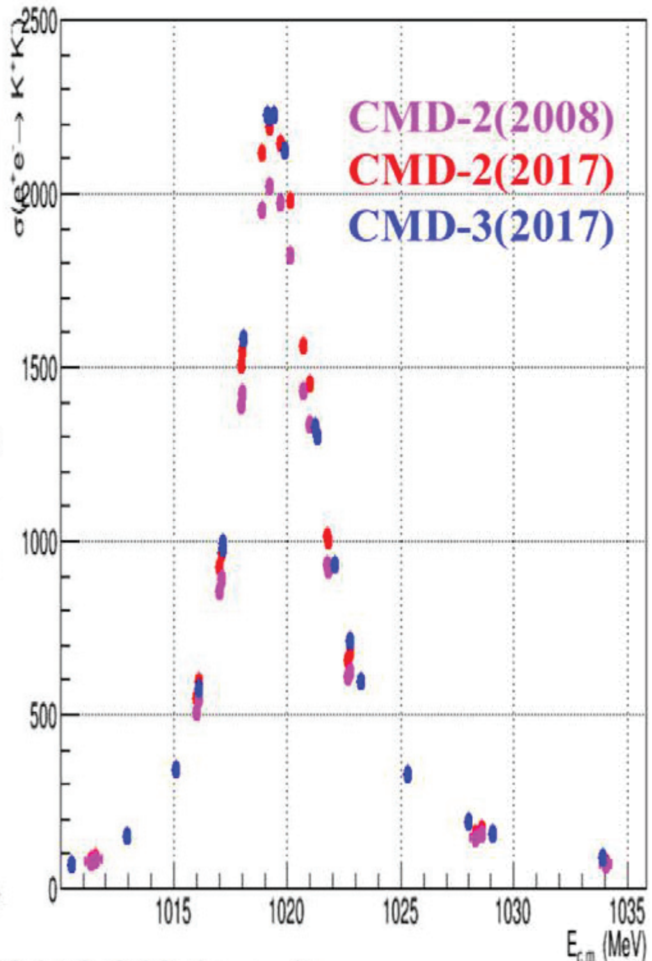


Correction to K^+K^- at ϕ

- We observe large discrepancy between CMD-2 and CMD-3 data.
- CMD-2 has trigger DC+Z-chamber+CsI calorimeter energy deposition – no cross check! Kaons stop in first wall and only decays and interactions provide trigger.
- CMD-3 has only DC hits in trigger, but all information from Z-chamber(the same!) and calorimeter.
- We can directly measure trigger efficiency of CMD-2.
- Corrected data should be published soon







Trigger correction $(1+\delta)_{trig} = 1.094 \pm 0.040$ (сист.)