MUON (G-2) AND MEASUREMENT OF HADRONIC CROSS-SECTIONS AT CMD-3

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on behalf of CMD-3 collaboration

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Outline

- History and status of muon g-2
- Hadronic contribution and R(s)
- VEPP-2000 collider and CMD-3 detector
- Recent results

Muon g-2

- Anomalous magnetic moment: $a_\mu = \frac{g_\mu - 2}{2}$
- In the first order $a = 0$, non-zero value comes from higher order corrections
- a_e is measured to 0.24 ppb (*D. Hanneke et al., PRL 100 (2008) 120801*)

$$a_e = (115\,965\,218\,073 \pm 28) \times 10^{-14}\ (0.24\ \text{ppb})$$

- But a_μ is much more sensitive to heavy fields

$$\Delta a_\mu / \Delta a_e \sim \left(m_\mu / m_e\right)^2 \approx 43000$$

- a_μ is measured to 0.54 ppm → about 20 times more sensitive to BSM physics

a_e provides α, a_μ provides SM test

Muon g-2 in Standard Model

- QED: up to 5 loops (12672 diagrams!). 0.29 ppb

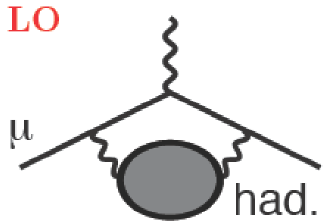
$$a_\mu^{QED} = 116\ 584\ 718.859\ (.026)(.009)(.017)(.006)\ [.034]\ \times 10^{-11},$$

- EW: 2 loops, now Higgs mass is known. 9 ppb

$$a_\mu(\mathrm{EW}) = (153.6 \pm 1.0) \times 10^{-11}$$

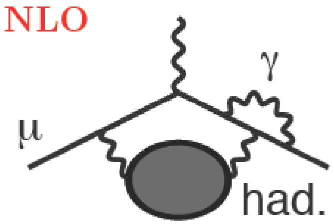
- Hadronic

$$a_\mu^{\mathrm{had}} = a_\mu^{\mathrm{had,VP\ LO}} + a_\mu^{\mathrm{had,VP\ NLO}} + a_\mu^{\mathrm{had,Light-by-Light}}$$



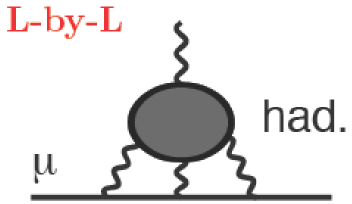
$(6\,923 \pm 42) \times 10^{-11}$

370 ppb



$(-98.4 \pm 0.7) \times 10^{-11}$

10 ppb

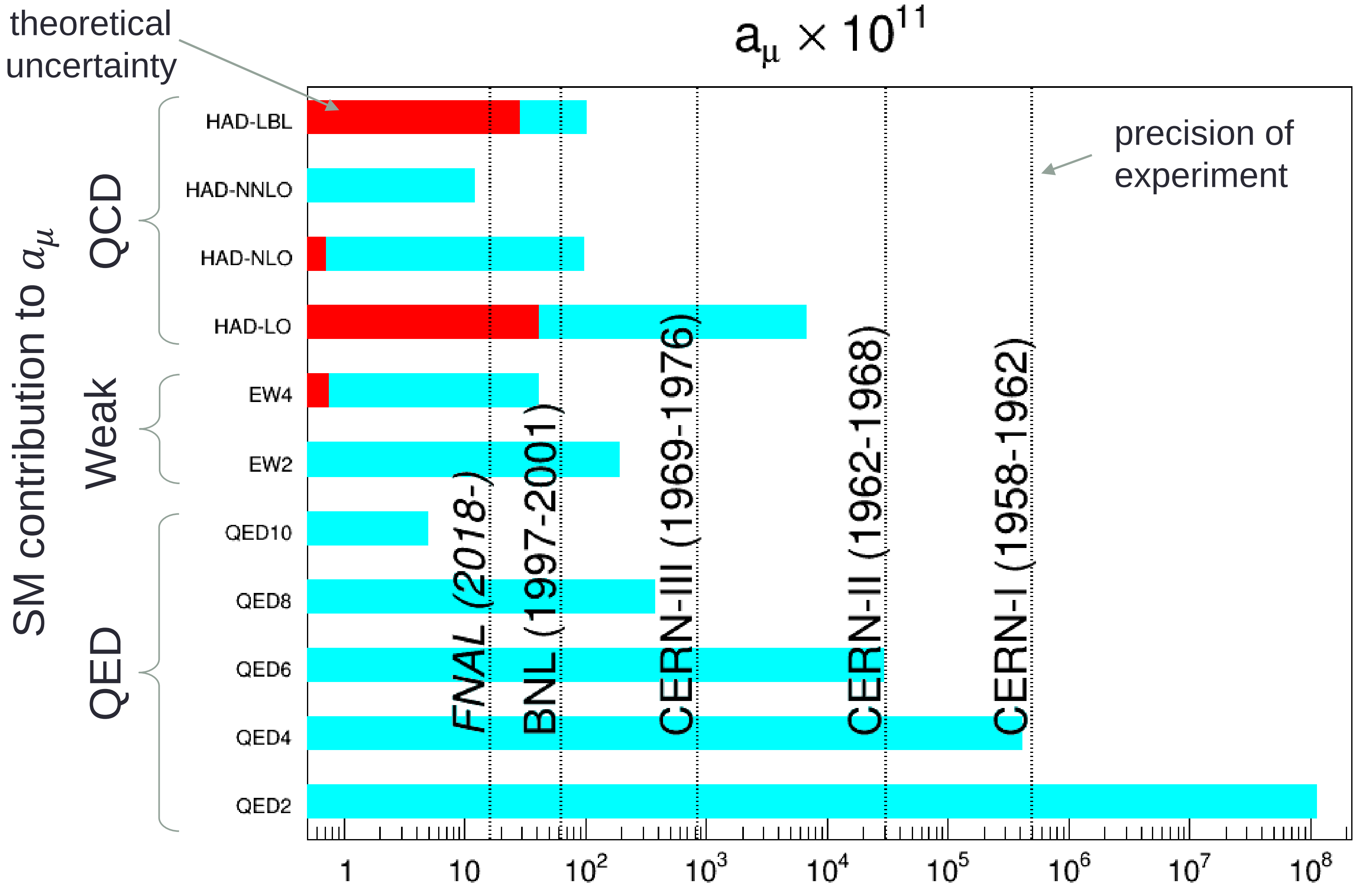


$(105 \pm 26) \times 10^{-11}$

220 ppb

New experiment at FNAL: 140 ppb

History of a_μ measurements



Muon (g-2) today: experiment vs theory

$a_\mu(exp) = 1\,165\,920\,89\,(63) \times 10^{-11}$
(0.54 ppm)

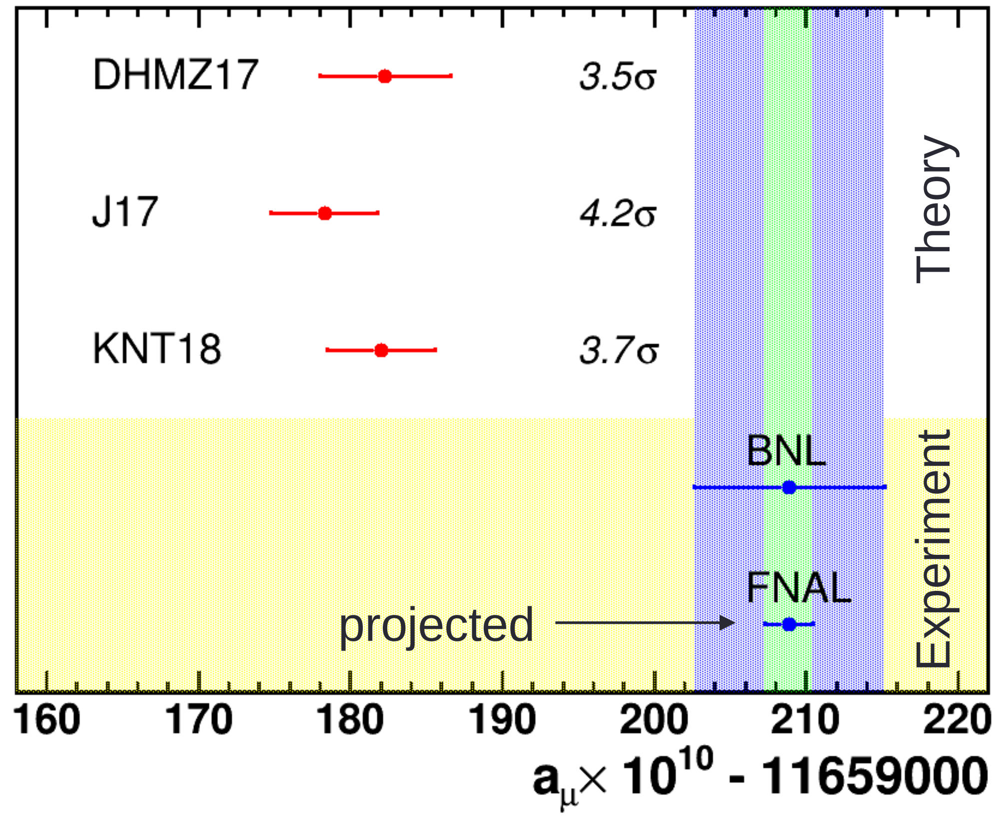
$a_\mu(th) = 1\,165\,918\,21\,(36) \times 10^{-11}$
KNT18 (0.31 ppm)

$\Delta a_\mu(exp - th) = (268 \pm 73) \times 10^{-11}$

Fermilab projections (conservative):

$a_\mu(exp)$ $\rightarrow$ to 0.14 ppm
$a_\mu(th)$ $\rightarrow$ to 0.30 ppm

$\Delta a_\mu(exp - th) \rightarrow$ to $\pm 40 \times 10^{-11}$



New measurement at FNAL

A new experiment to measure muon (g-2) has started data taking in 2018 at Fermilab.

The experiment layout follows CERN-III and BNL design:

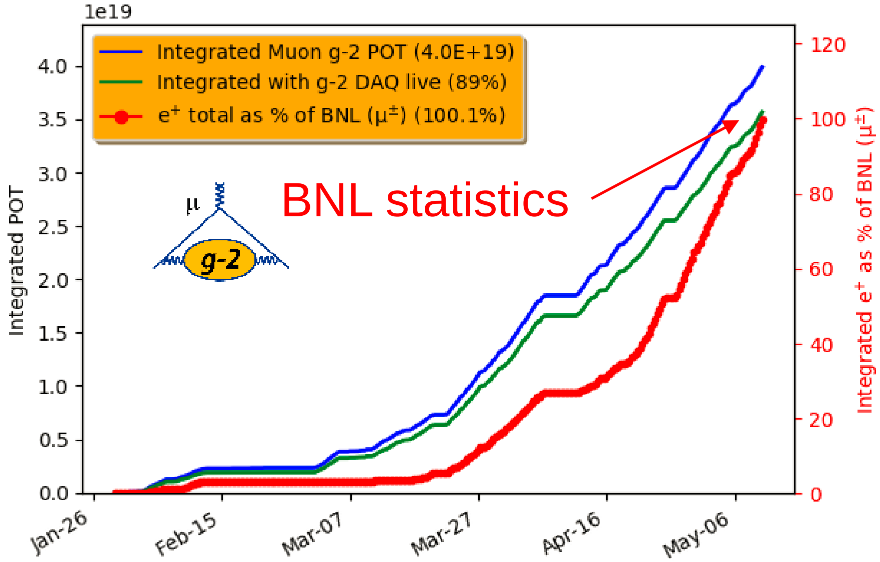
- Storage ring of 7 m radius with ultra uniform magnetic field and quadrupole focusing electric field
- Muons with “magic” momentum of 3.09 GeV/c

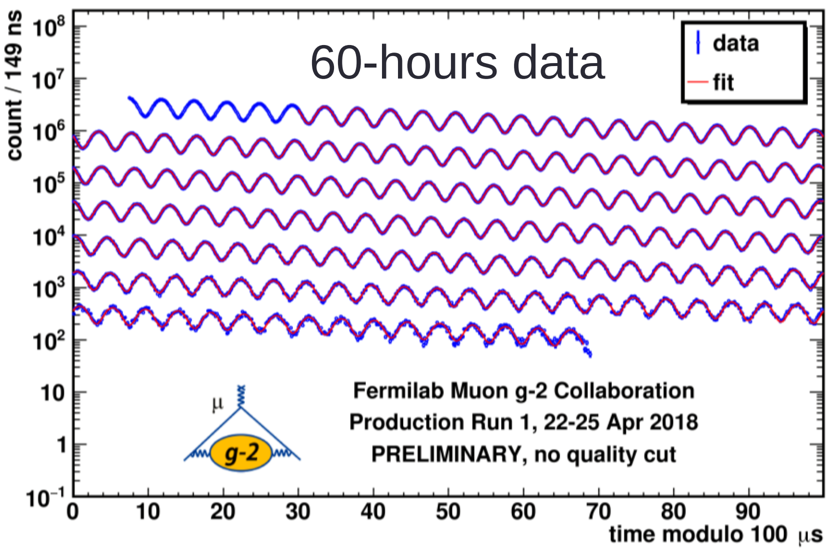
but with numerous improvements.

The experiment aims for 140 ppb precision (x4 over BNL)

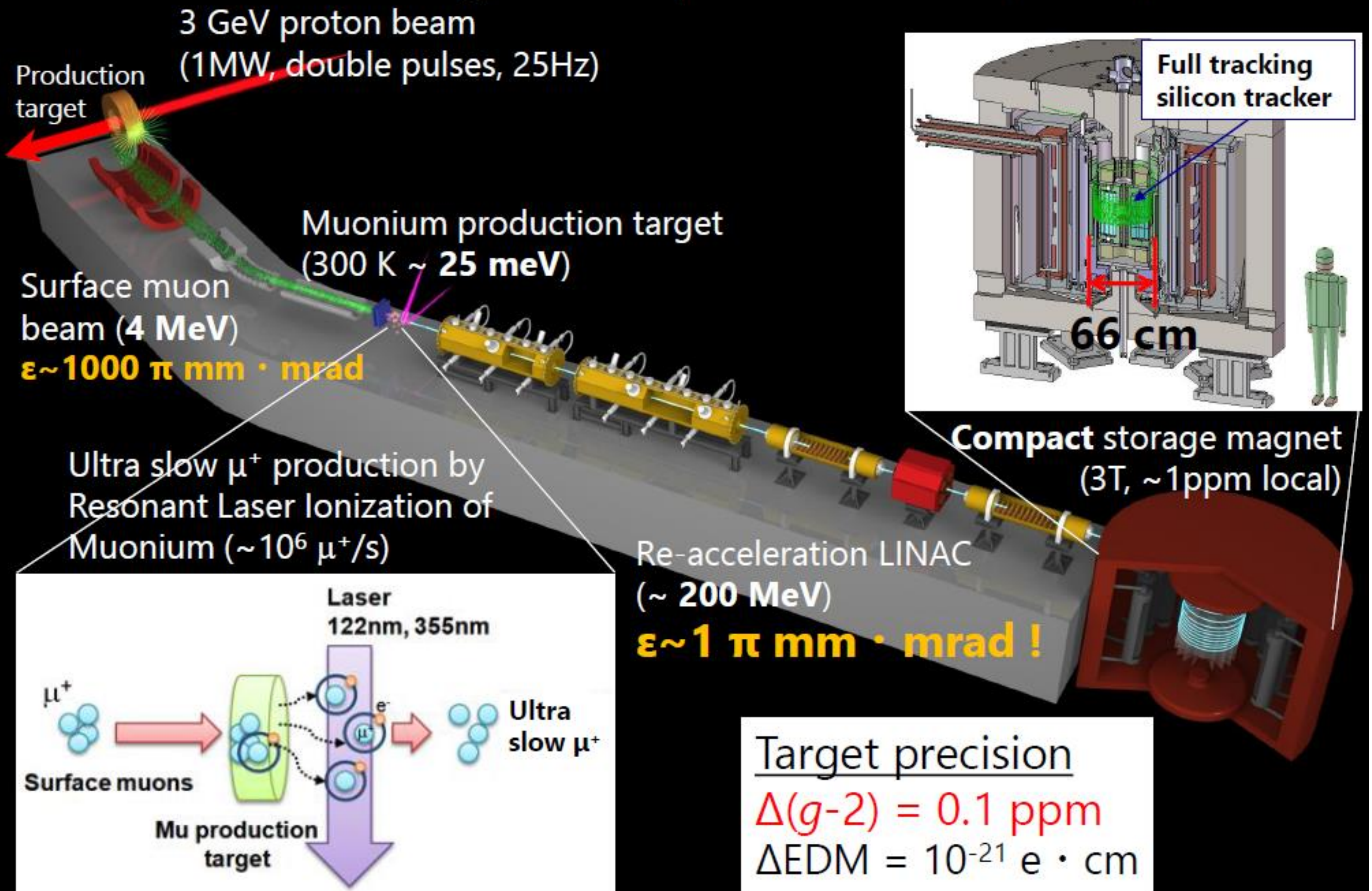
- x20 in statistics
- x2.8 in systematics

BNL level statistics has already been collected!





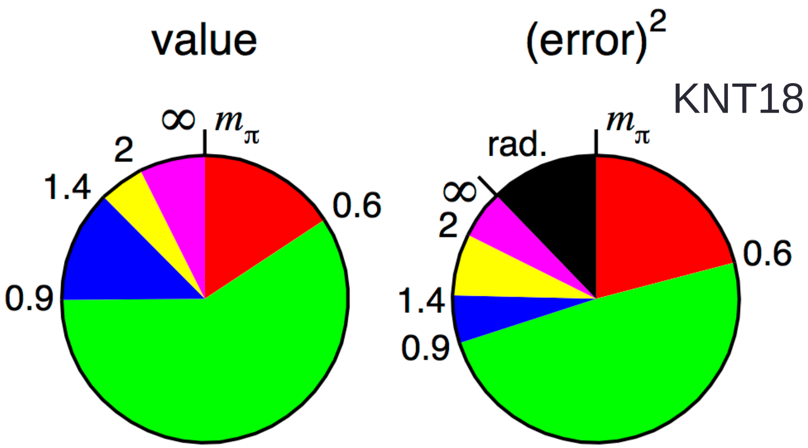
J-PARC *g*-2 experiment (E34)



Leading order hadronic contribution

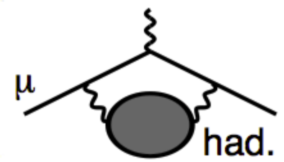
So far, the only method to calculate the hadronic contribution to necessary precision is via dispersion relation - by integrating experimental cross-section $\sigma(e^+e^- \to hadrons)$.

Weighting function $\sim 1/s$, therefore lower energies (≲2 GeV) contribute the most.

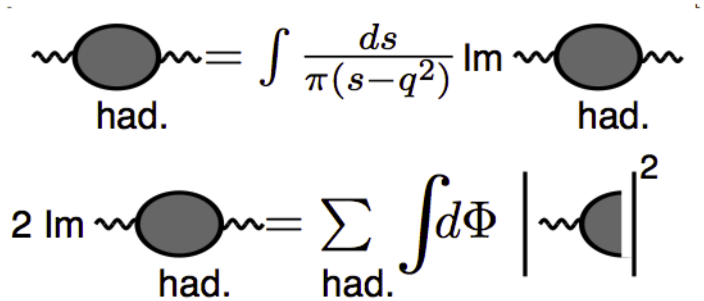


Contribution to the value and error of $a_\mu(had;LO)$ from various energy ranges (in GeV)

The diagram to be evaluated:



pQCD not useful. Use the dispersion relation and the optical theorem.



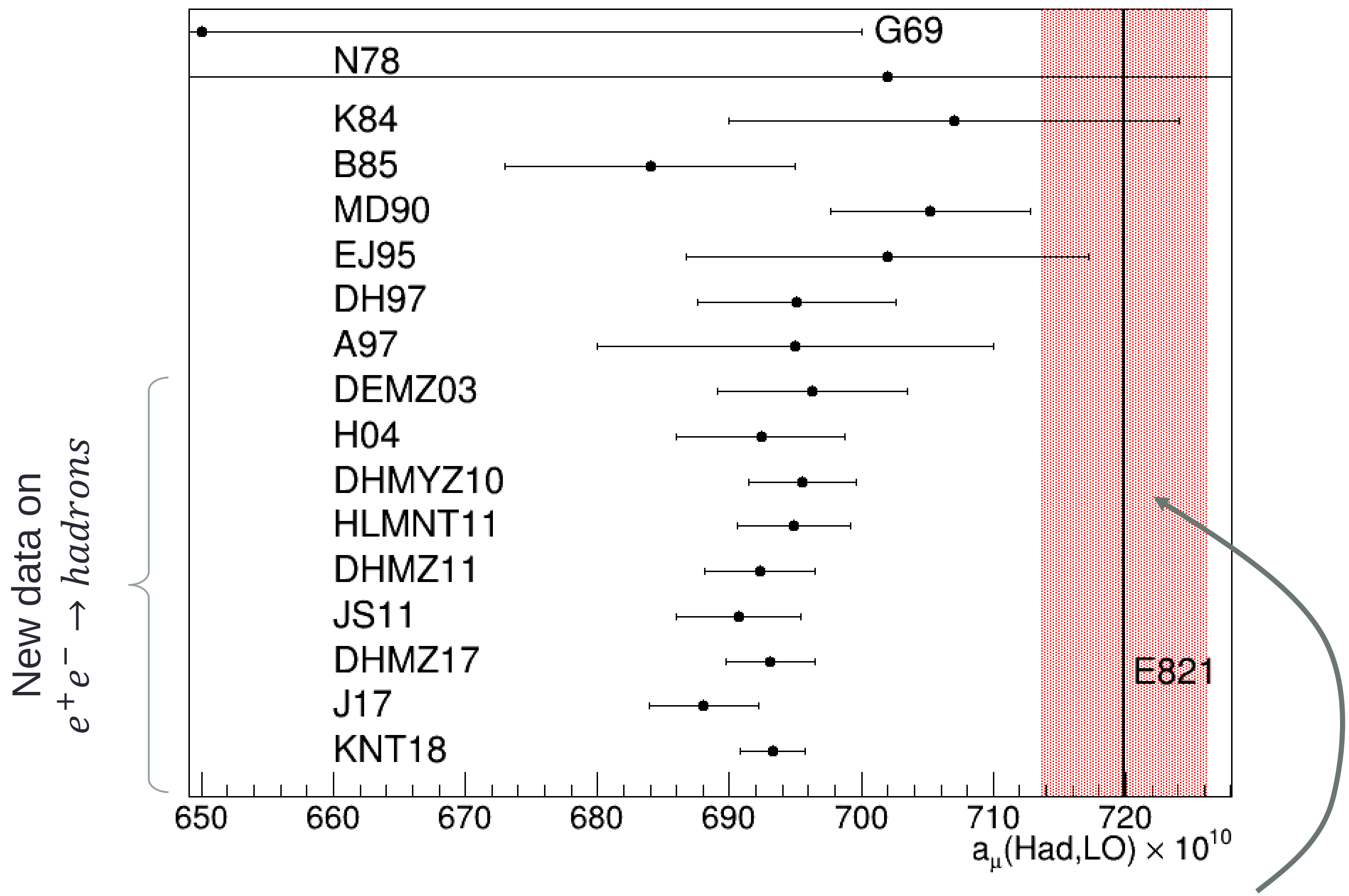
$$a_\mu(had;LO) = \frac{\alpha^2}{3\pi^2}\int \frac{ds}{s} R(s)K(s)$$

measured

$$R(s) = \frac{\sigma^0(e^+e^- \to \gamma^* \to hadrons)}{4\pi\alpha^2/3s}$$

FOM: 140 ppb at FNAL ↔ 0.25% in R(s)

The history of $a_\mu(had; LO)$ calculation

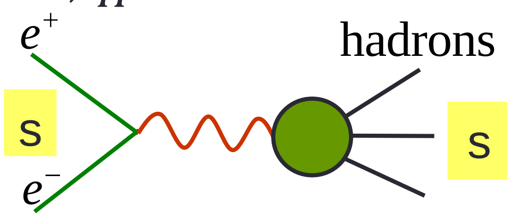


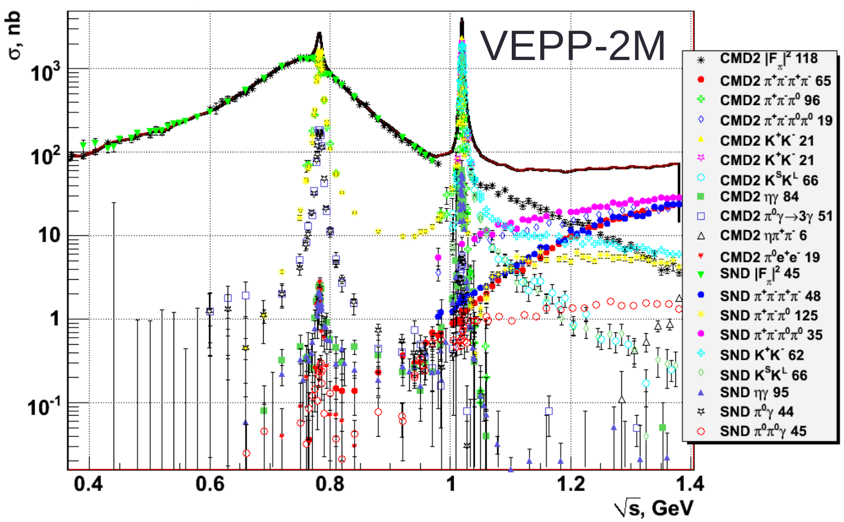
$a_\mu(BNL) - a_\mu(QED) - a_\mu(weak)$

Sources of $\sigma(e^+e^- \to hadrons)$ data

Direct energy scan

- e^+e^- collider, tunable in energy
- Take data at each energy to identify $e^+e^- \to H$



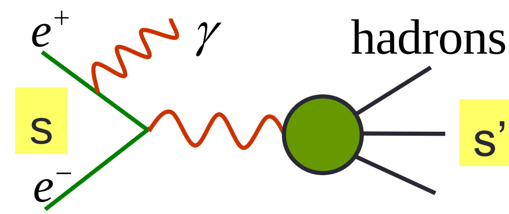


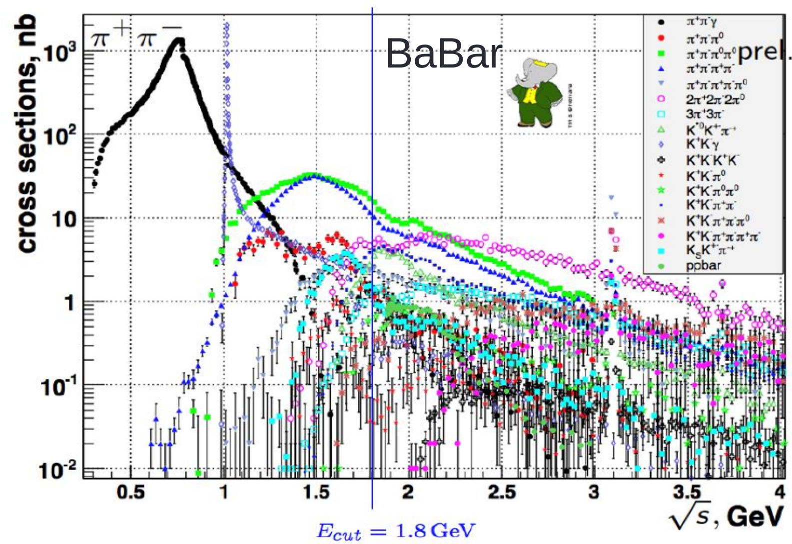
Direct: **CMD-2** and SND (Novosibirsk), (2003-2008)

ISR: **BaBar** (2009-2017), KLOE (2009-2017), BES-III (2016)

Initial state radiation method (ISR)

- e^+e^- collider with high luminosity at fixed energy ("factory")
- Take data at single energy to identify $e^+e^- \to H + \gamma$ and extract $\sigma(e^+e^- \to H)$ at lower energies





Comparison of $e^+e^- \to \pi^+\pi^-$ data

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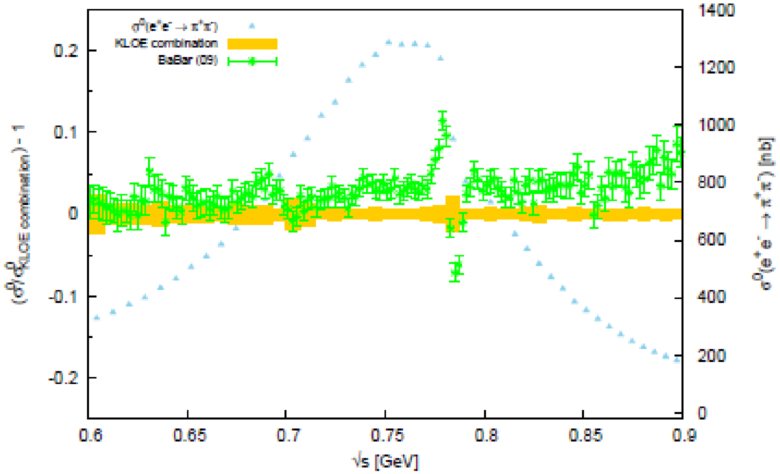
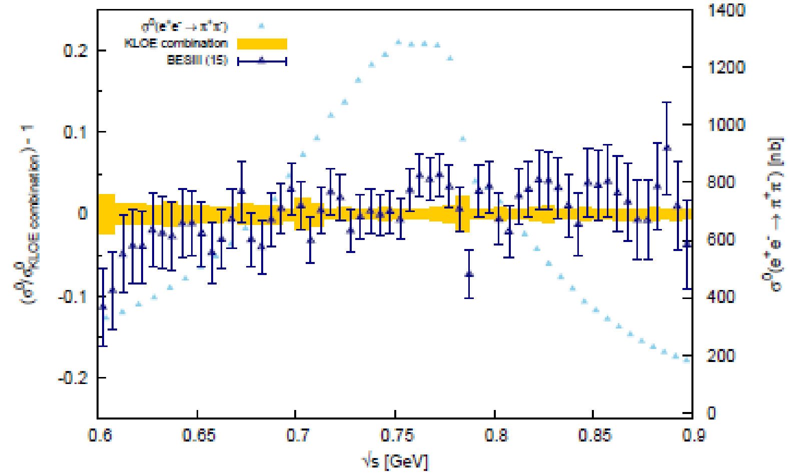
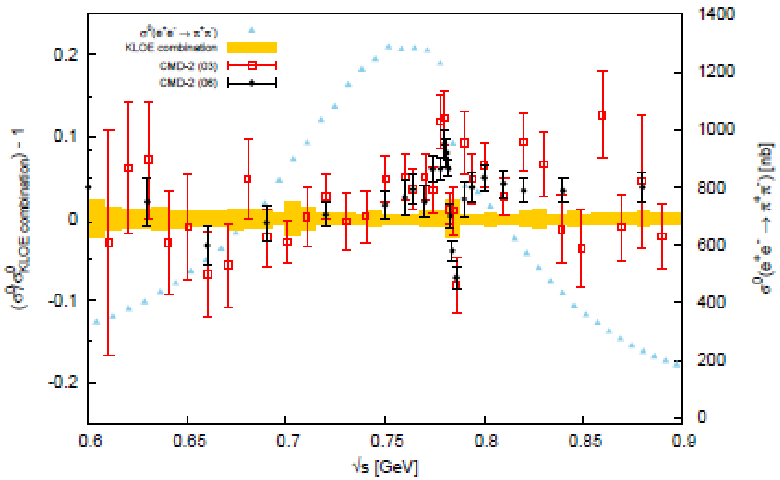


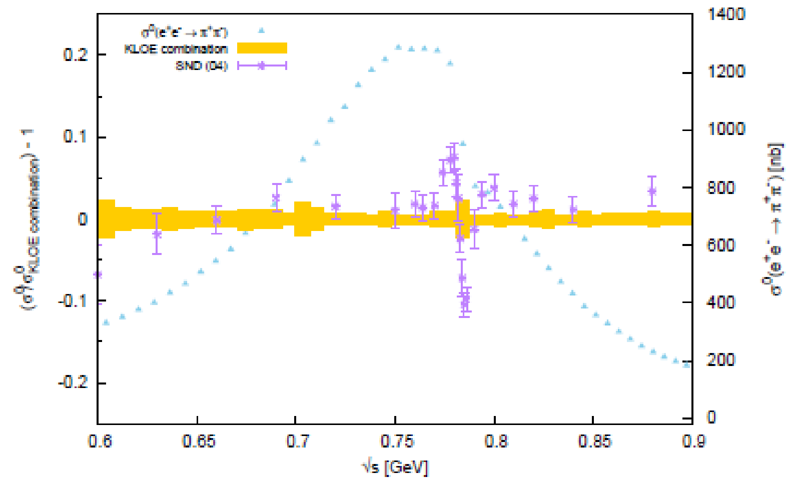
(b) KLOE combination vs. BaBar



(c) KLOE combination vs. BESIII



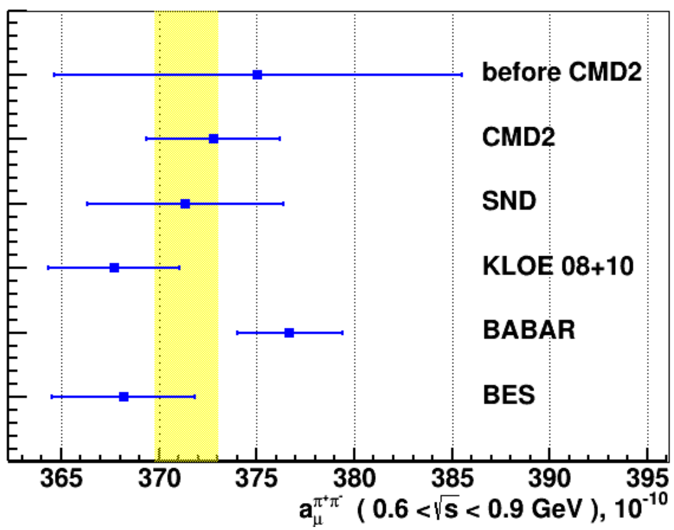
(d) KLOE combination vs. CMD-2



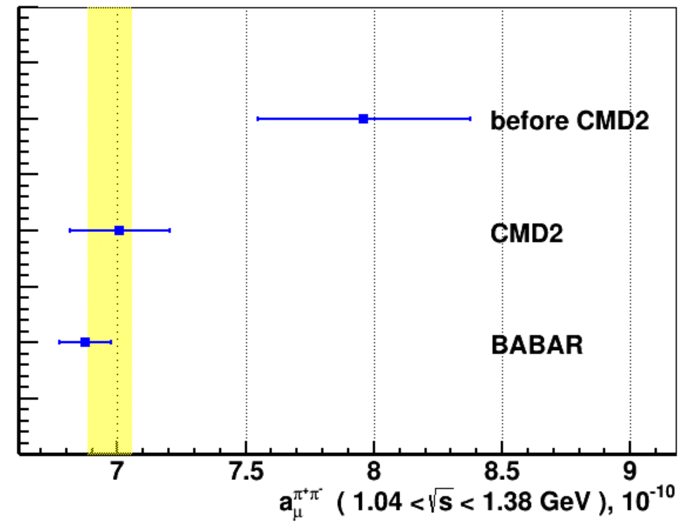
(e) KLOE combination vs. SND

Comparison of contributions to $a_\mu(had;LO)$

ρ meson (0.6-0.9 GeV)



Above ϕ meson (1.04-1.38 GeV)

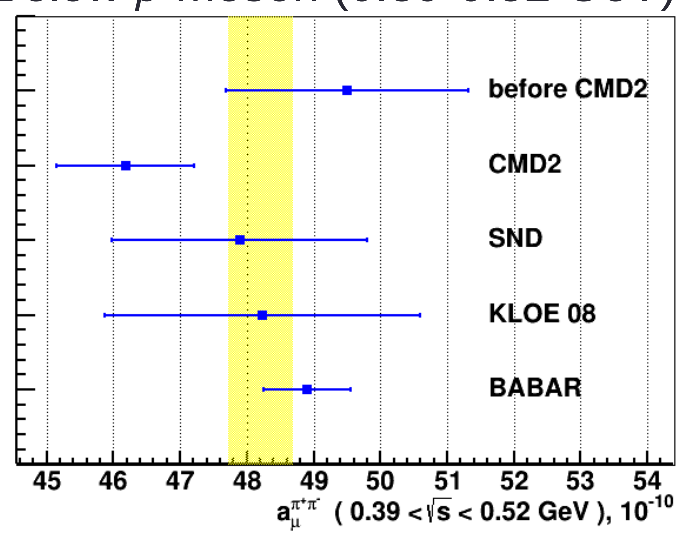


Compared are values of integral:

$$a_\mu(had;LO) = \frac{\alpha^2}{3\pi^2}\int_{E_{min}}^{E_{max}} \frac{ds}{s}\frac{\sigma^0(e^+e^-\to\pi^+\pi^-)}{4\pi\alpha^2/3s}K(s)$$

calculated in different energy ranges and with various data sets

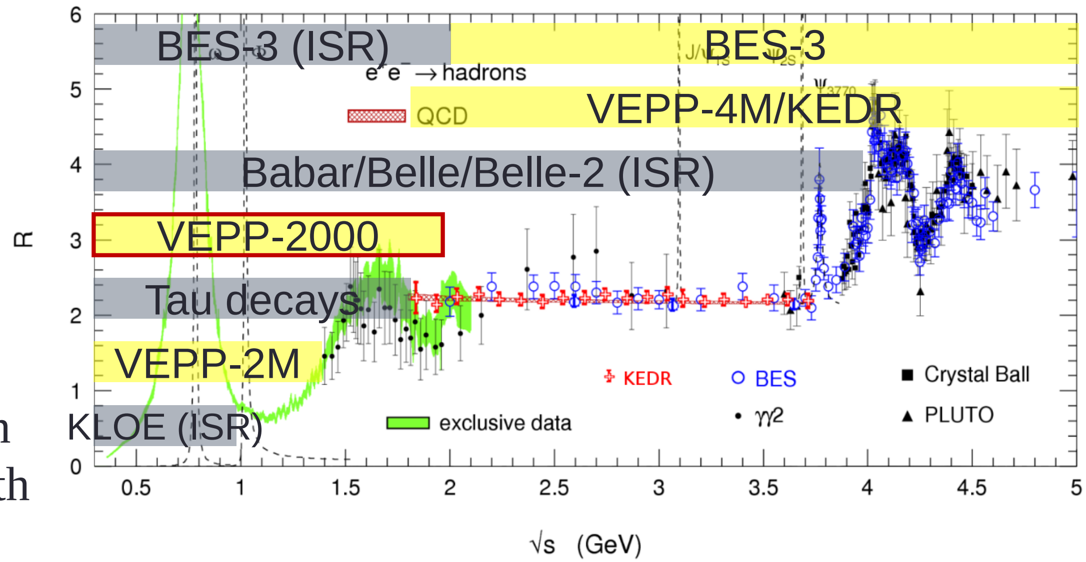
Below ρ meson (0.39-0.52 GeV)



VEPP-2000 and R(s)

Now $a_\mu^{had,LO}$ calculation is dominated by ISR measurements

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



ISR and direct scan were never compared to the required level of precision except for $e^+e^- \to \pi^+\pi^-$, where some discrepancies are observed

VEPP-2000 goal: provide direct scan measurement of R(s) up to 2 GeV with high statistics and low systematic

In perfect world we want:

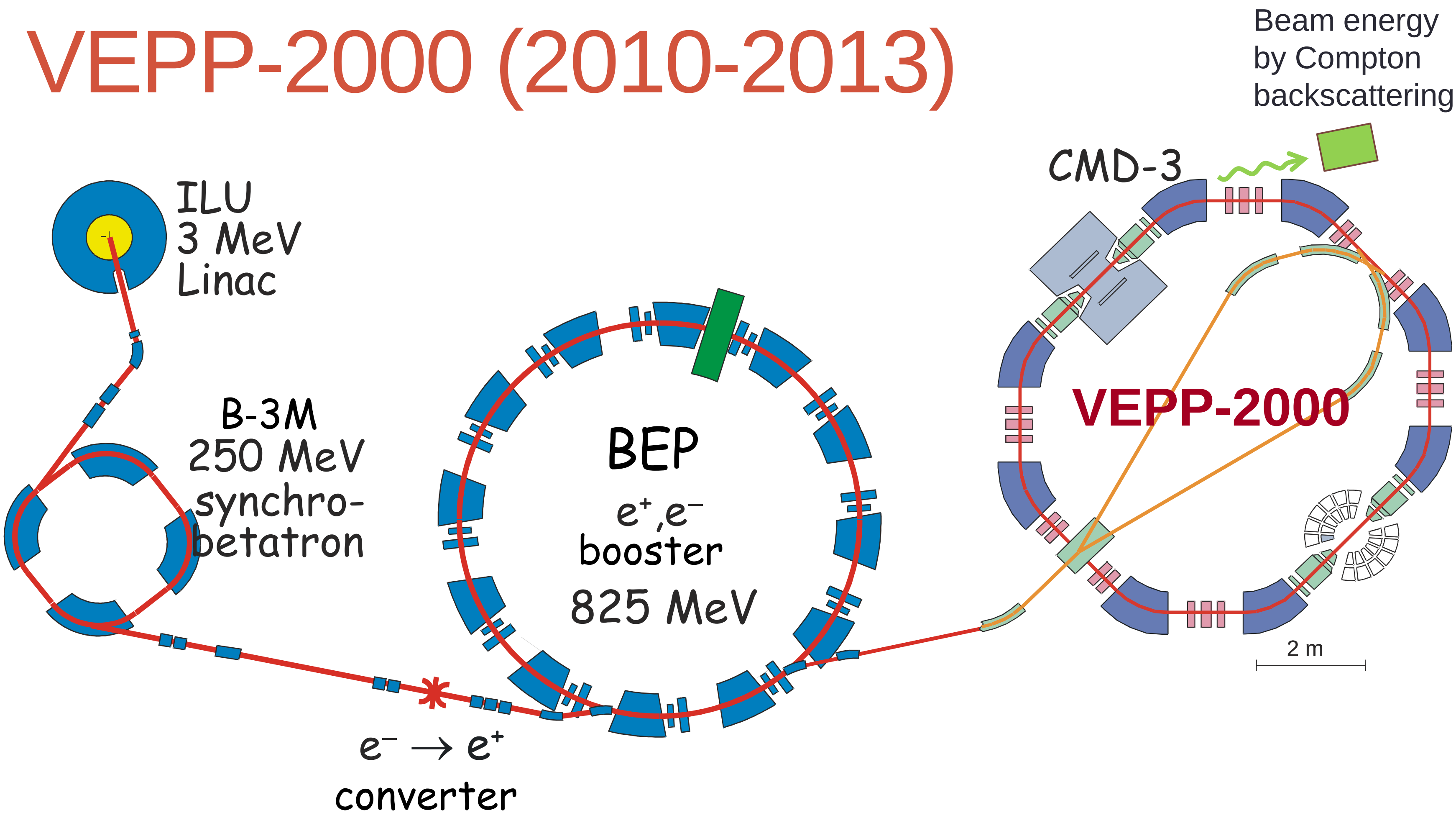
- $a_\mu^{had,LO}$ from direct scan to 0.4%
- $a_\mu^{had,LO}$ from ISR to 0.4%
- $a_\mu^{had,LO}$ from lattice to 0.4%

and they should agree.

Lets set the scale:

- $\Delta a_\mu(exp - th)$ corresponds to $\approx 4\% \cdot a_\mu^{had,LO}$
- FNAL precision of 140 ppb corresponds to $\approx 0.25\% \cdot a_\mu^{had,LO}$

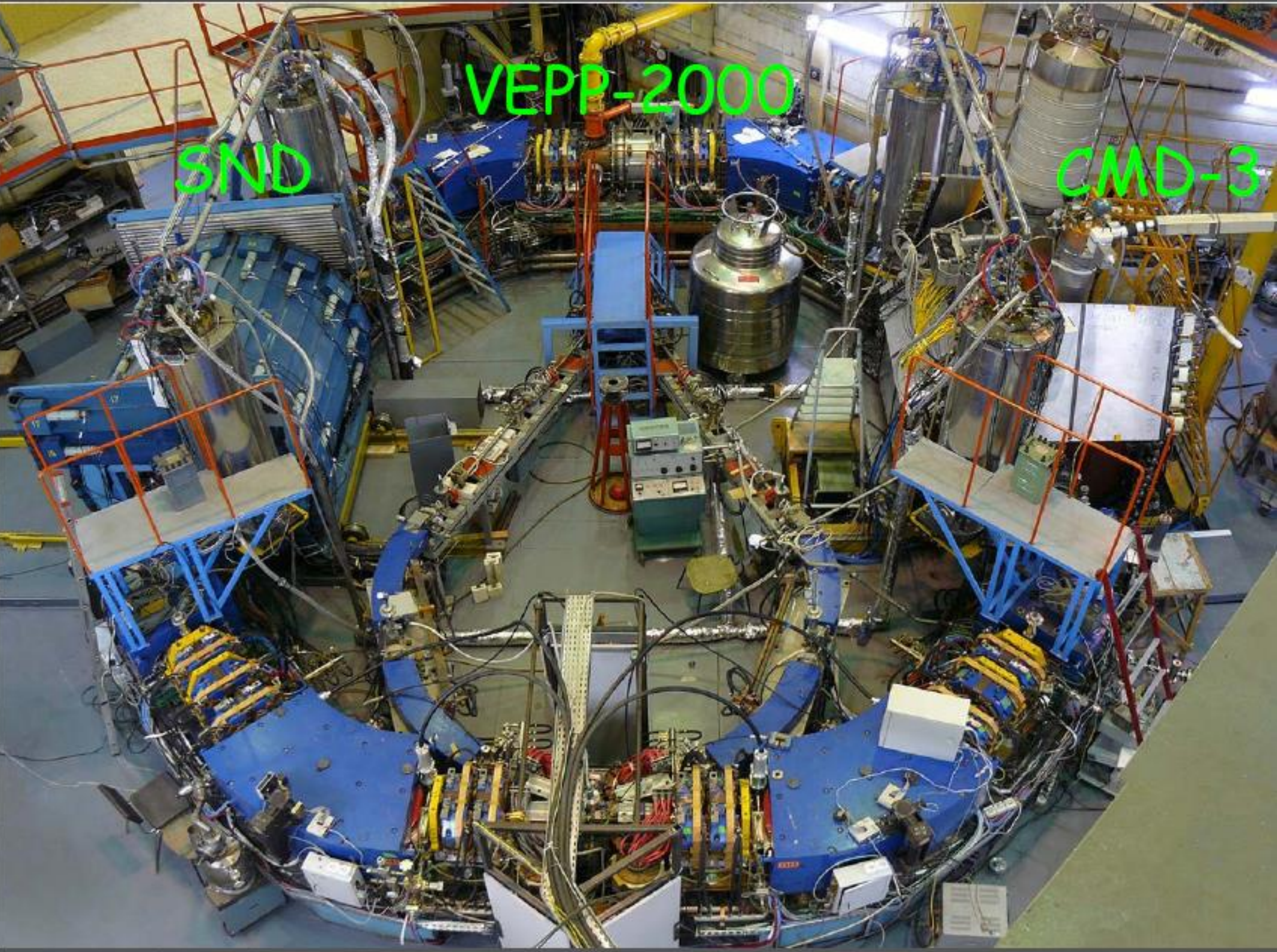
VEPP-2000 (2010-2013)



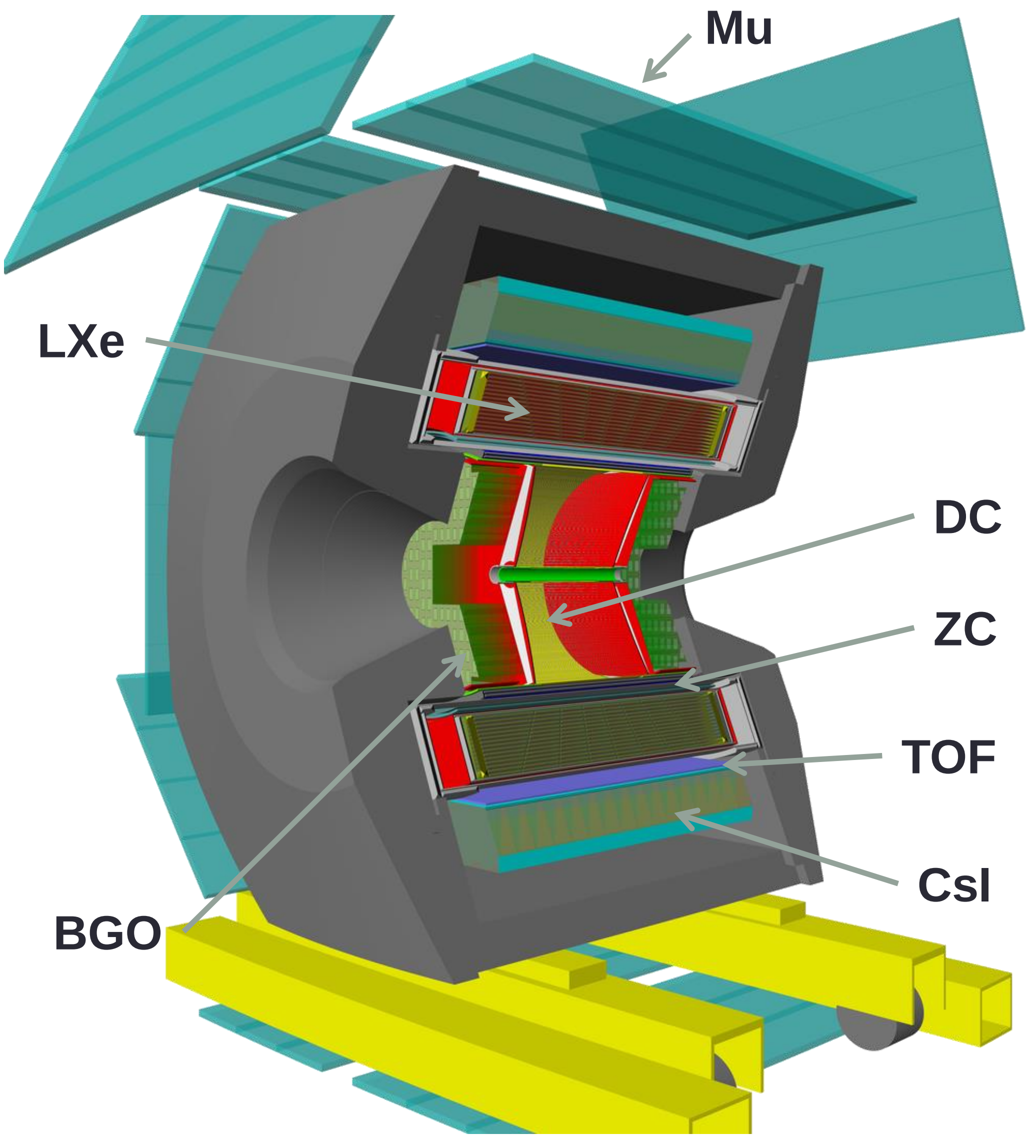
C.m. energy range is 0.32-2.0 GeV; unique optics – "round beams"

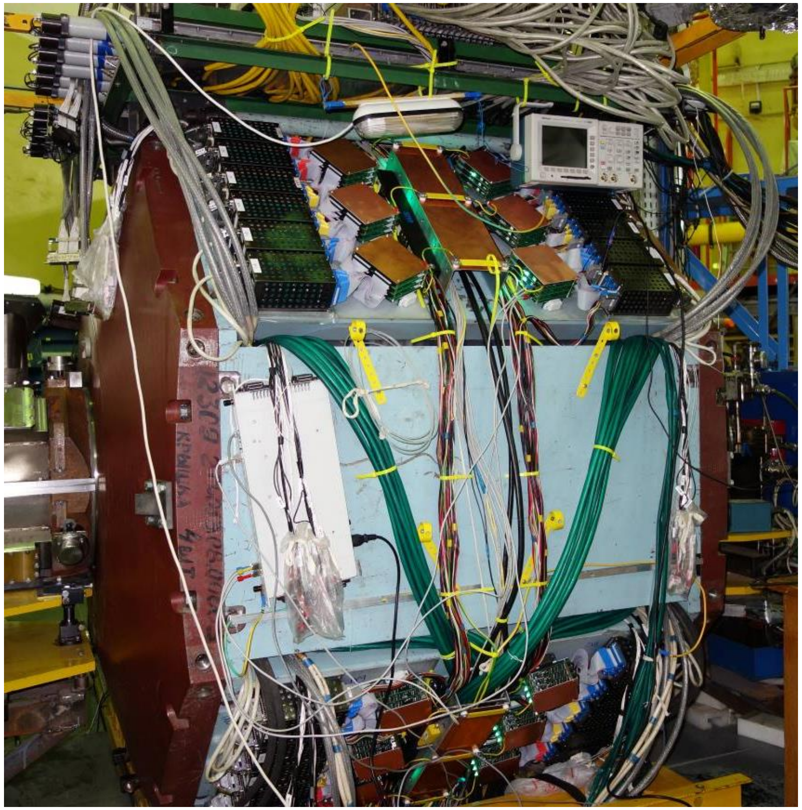
Design luminosity is $L = 10^{32} 1/cm^2 s$ @ $\sqrt{s} = 2$ GeV

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


VEPP-2000
SND
CMD-3

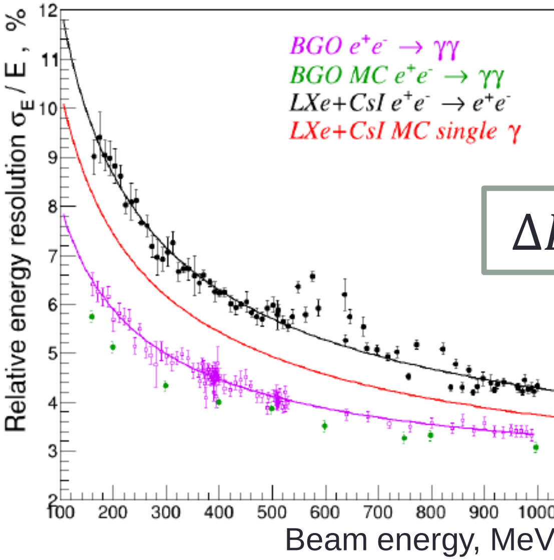
Detector CMD-3



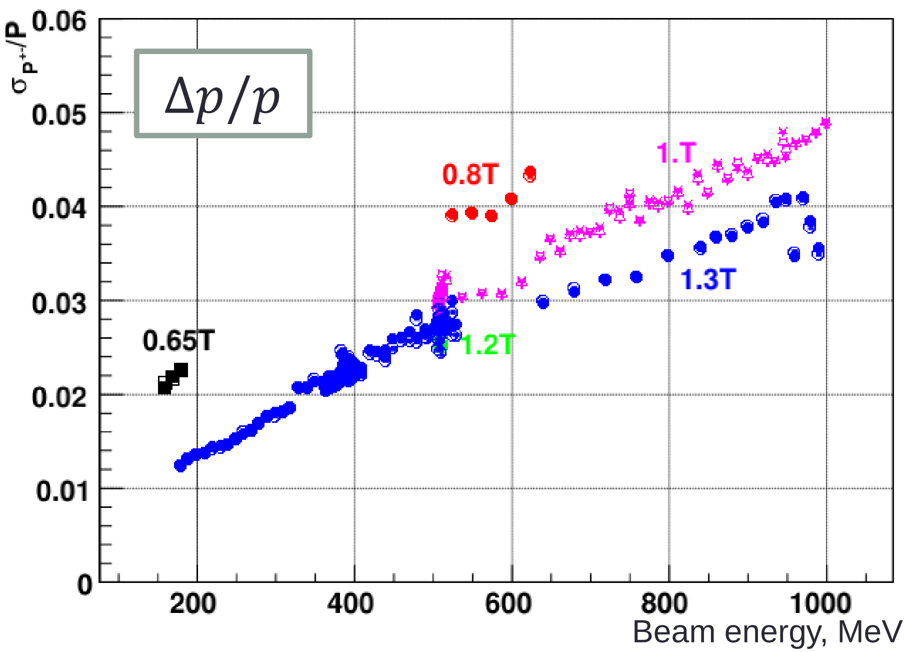


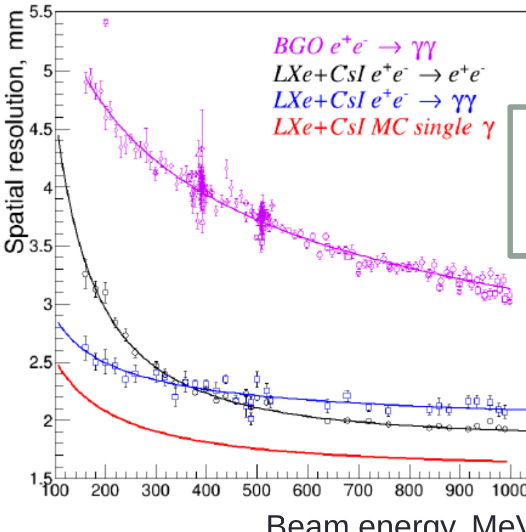
CMD-3 Performance (2011-2013)

- 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



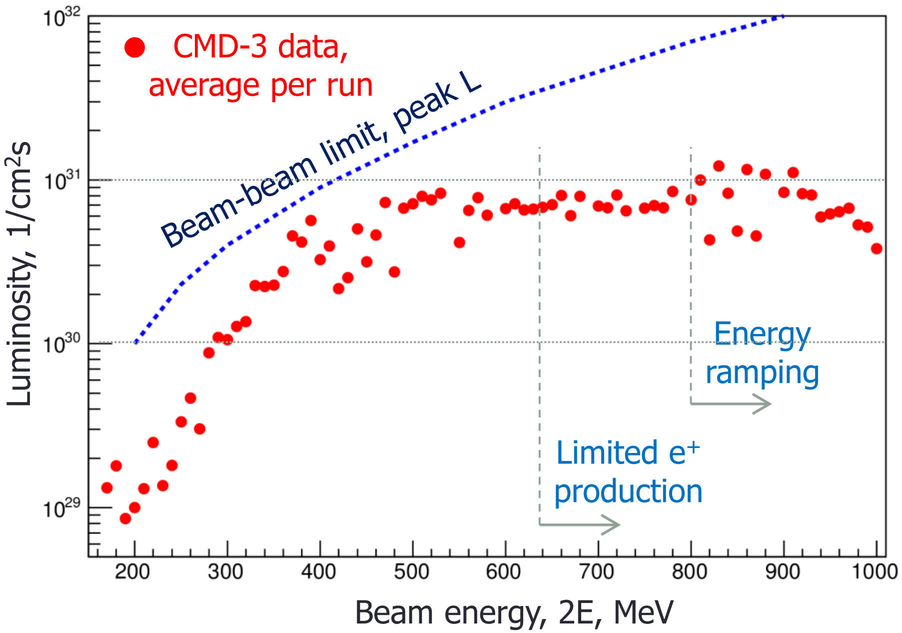
$\Delta E/E$

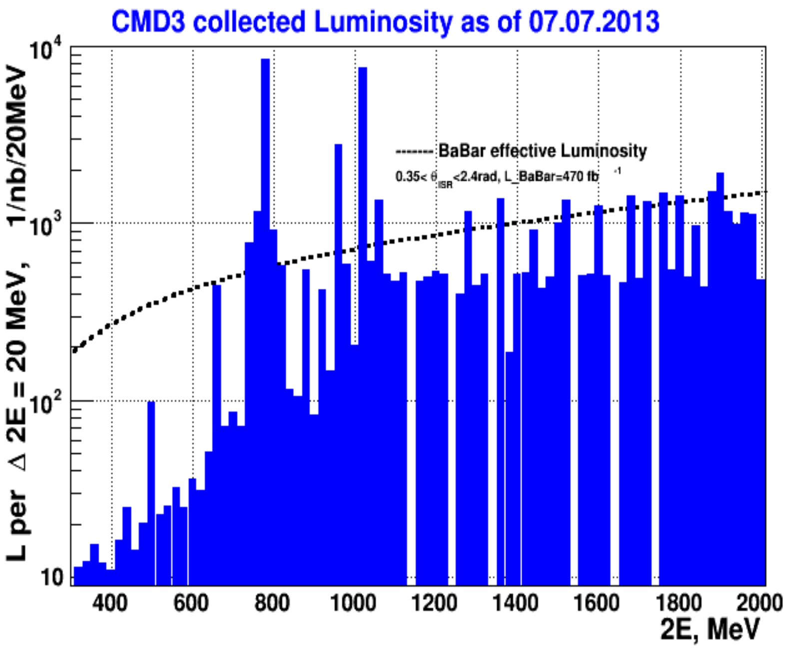




Δx, mm calorimeters

Collected luminosity in 2011-2013





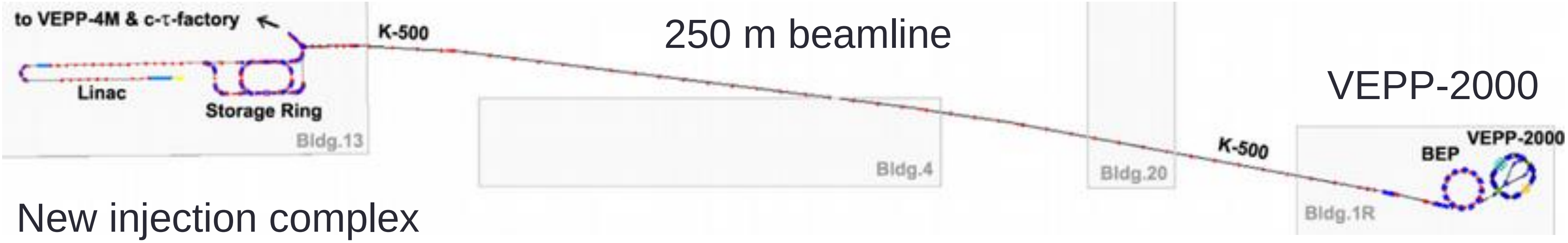
The luminosity was limited by a deficit of positrons and limited energy of the booster.

The VEPP-2000 upgrade has started in 2013.

About 60 pb-1 collected per detector

$\omega(782)$	$8.3\ 1/pb$
$2E < 1$ GeV (except ω)	$9.4\ 1/pb$
$\varphi(1019)$	$8.4\ 1/pb$
$2E > 1.04$ GeV	$34.5\ 1/pb$

VEPP-2000 upgrade (2013-2016)



Collider upgrades:

- x10 more intense positron source
- booster up to 1 GeV (match VEPP-2000)

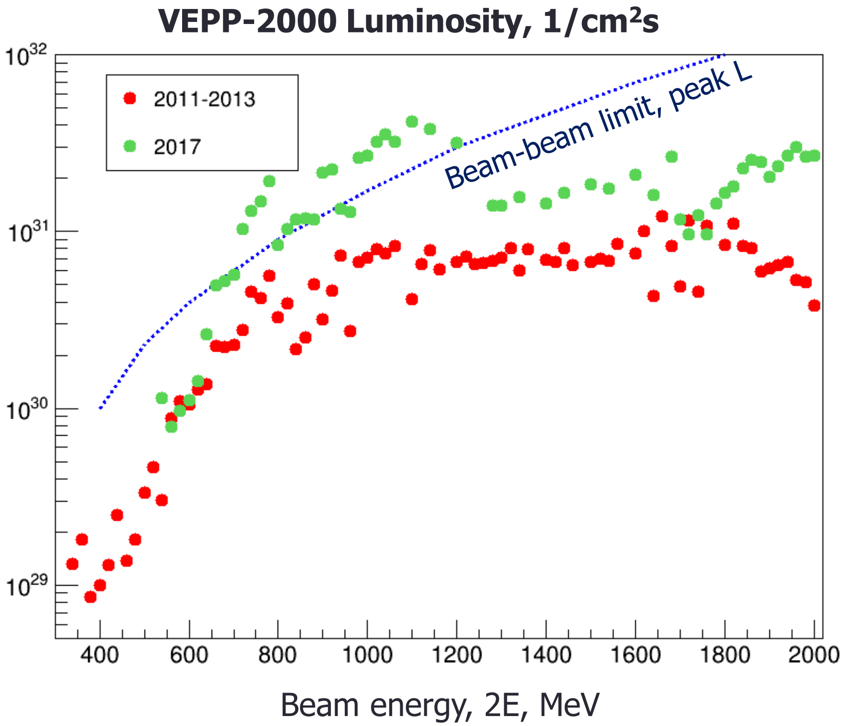
CMD-3 upgrades:

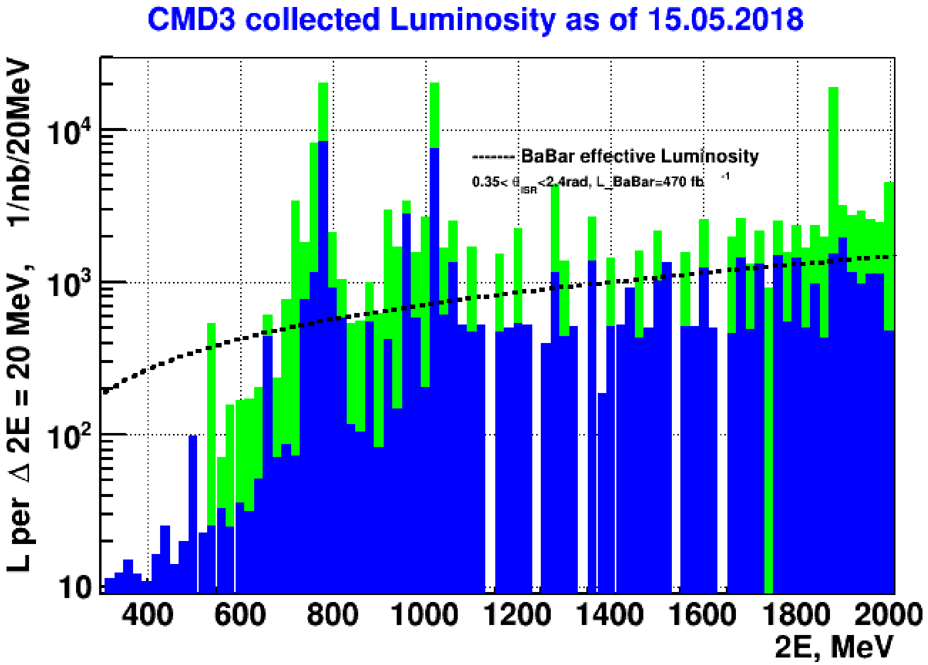
- New electronics for Lxe calorimeter
- New TOF system
- DAQ and electronics upgrades

Detectors resumed data taking by the end of 2016

2017 data taking

2017
2011-2013





In 2017: big improvement in luminosity

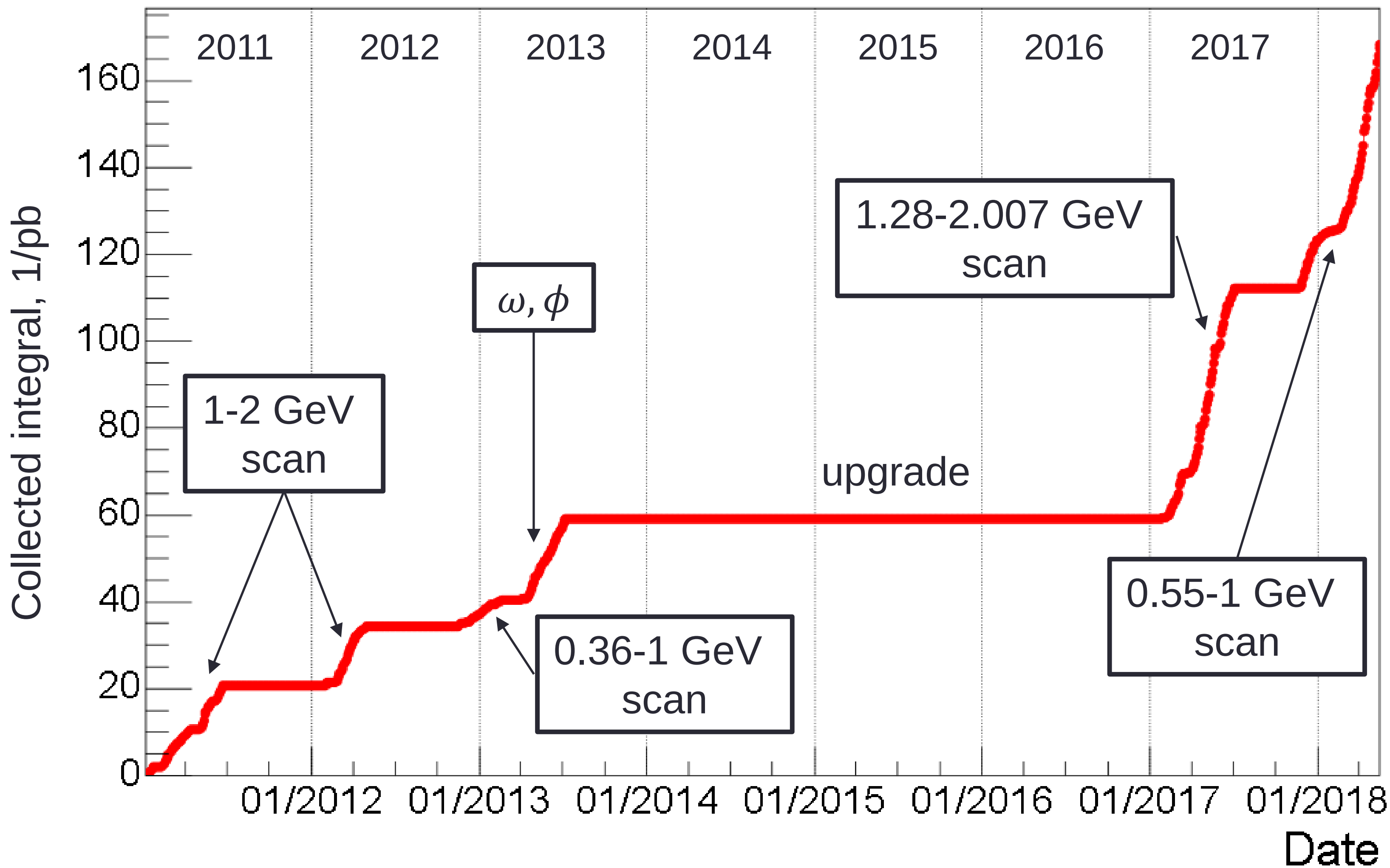
Below 1 GeV: >50 pb^{-1} collected and counting

$0.55 - 1.00$ 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



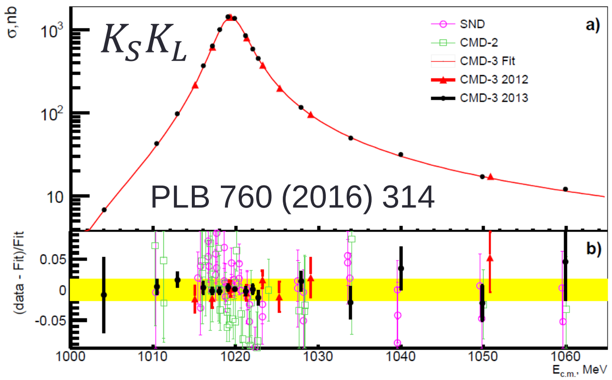
Exclusive channels $e^+e^- \to hadrons$

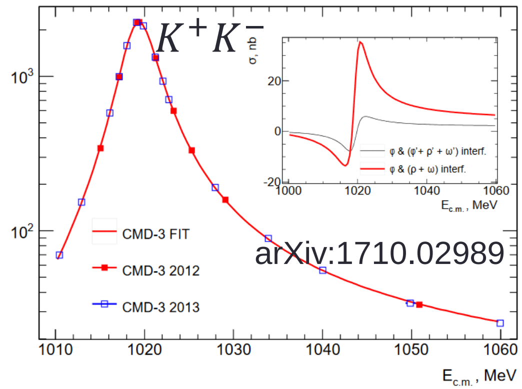
At VEPP-2000 we do exclusive measurement of $\sigma(e^+e^- \to hadrons)$.

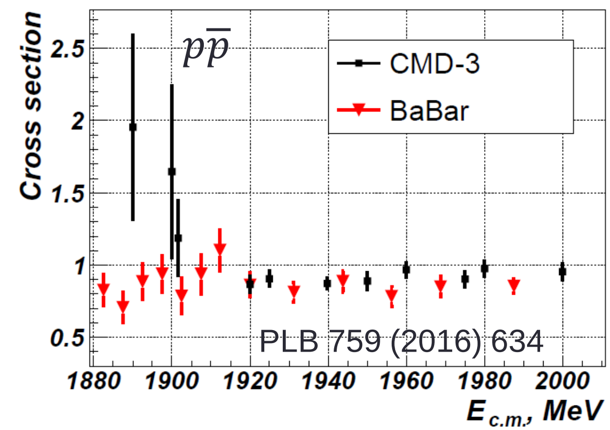
published
in progress

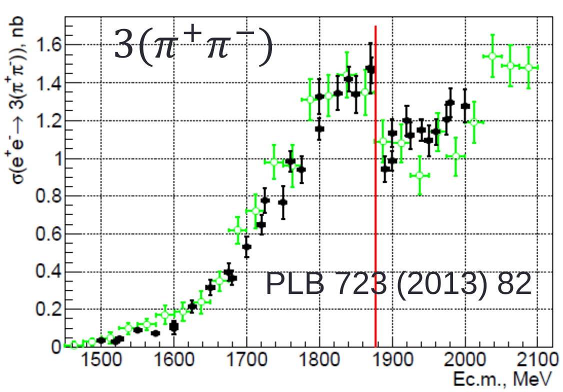
- 2 charged
$$e^+e^- \to \pi^+\pi^-, K^+K^-, K_SK_L, p\bar{p}$$
- 2 charged + γ's
$$e^+e^- \to \pi^+\pi^-\pi^0, \pi^+\pi^-\eta, K^+K^-\pi^0, K^+K^-\eta, K_SK_L\pi^0, \pi^+\pi^-\pi^0\eta, \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$$
- 4 charged
$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K_SK^*$$
- 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
$$e^+e^- \to n\bar{n}, \pi^0e^+e^-, \eta e^+e^-$$

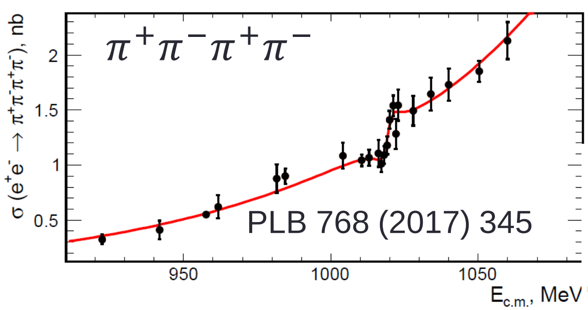
CMD-3 published results from 2011-2013

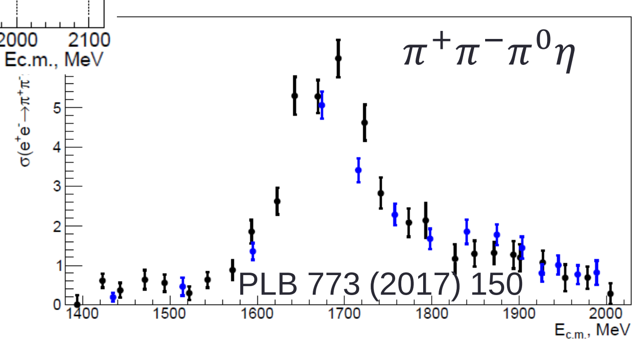


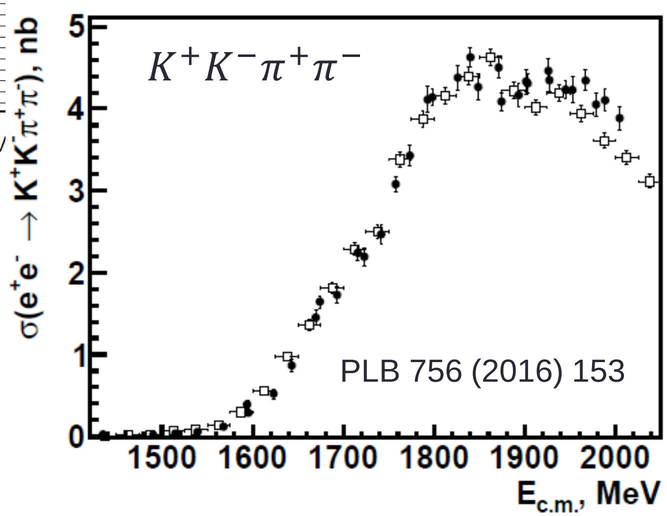






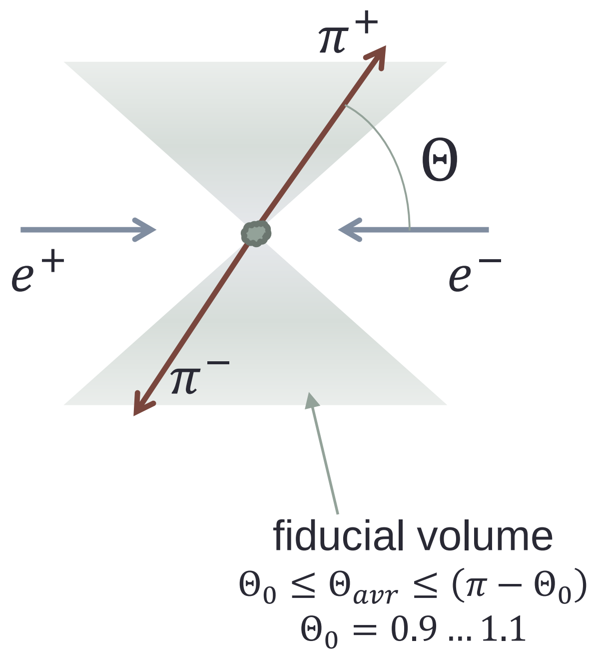






Overview of the $e^+e^- \to \pi^+\pi^-$ analysis

- We select events with 2 back-to-back tracks in the detector at large angle
- Selected event sample consists of $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ pairs and background (mostly cosmic)



Key pieces of analysis to reach high precision:

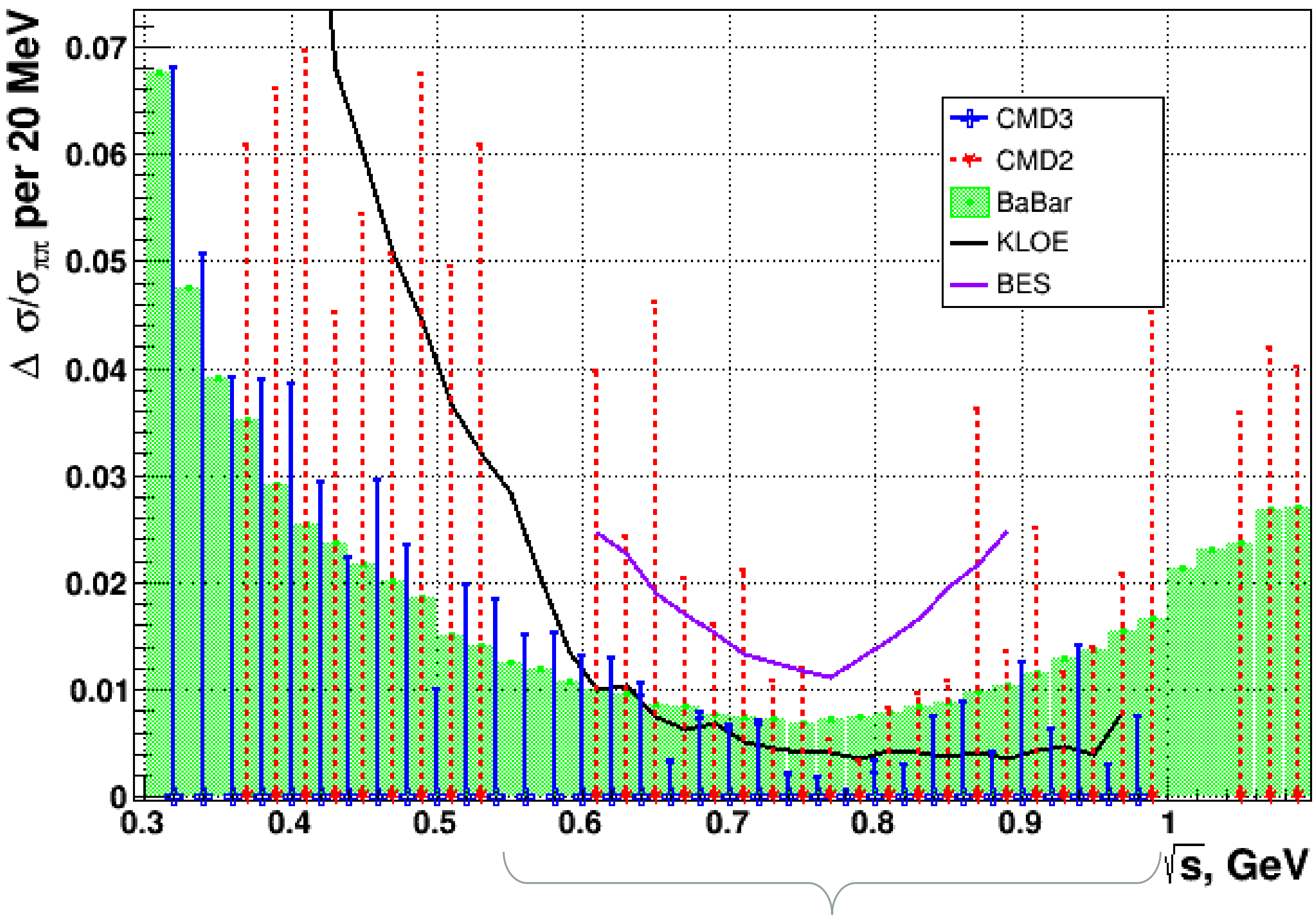
- $e/\mu/\pi$ separation
- radiative corrections
- various pion-specific corrections

Available data:

- 0.32-1.0 GeV (below ϕ):
  - 2013 energy scan – data analysis well in progress
  - 2017-2018 energy scan – we are taking data now
- 1.0-2.0 GeV (above ϕ):
  - 2011-2012 energy scan – no beam energy monitoring
  - 2017 energy scan – data analysis just starting

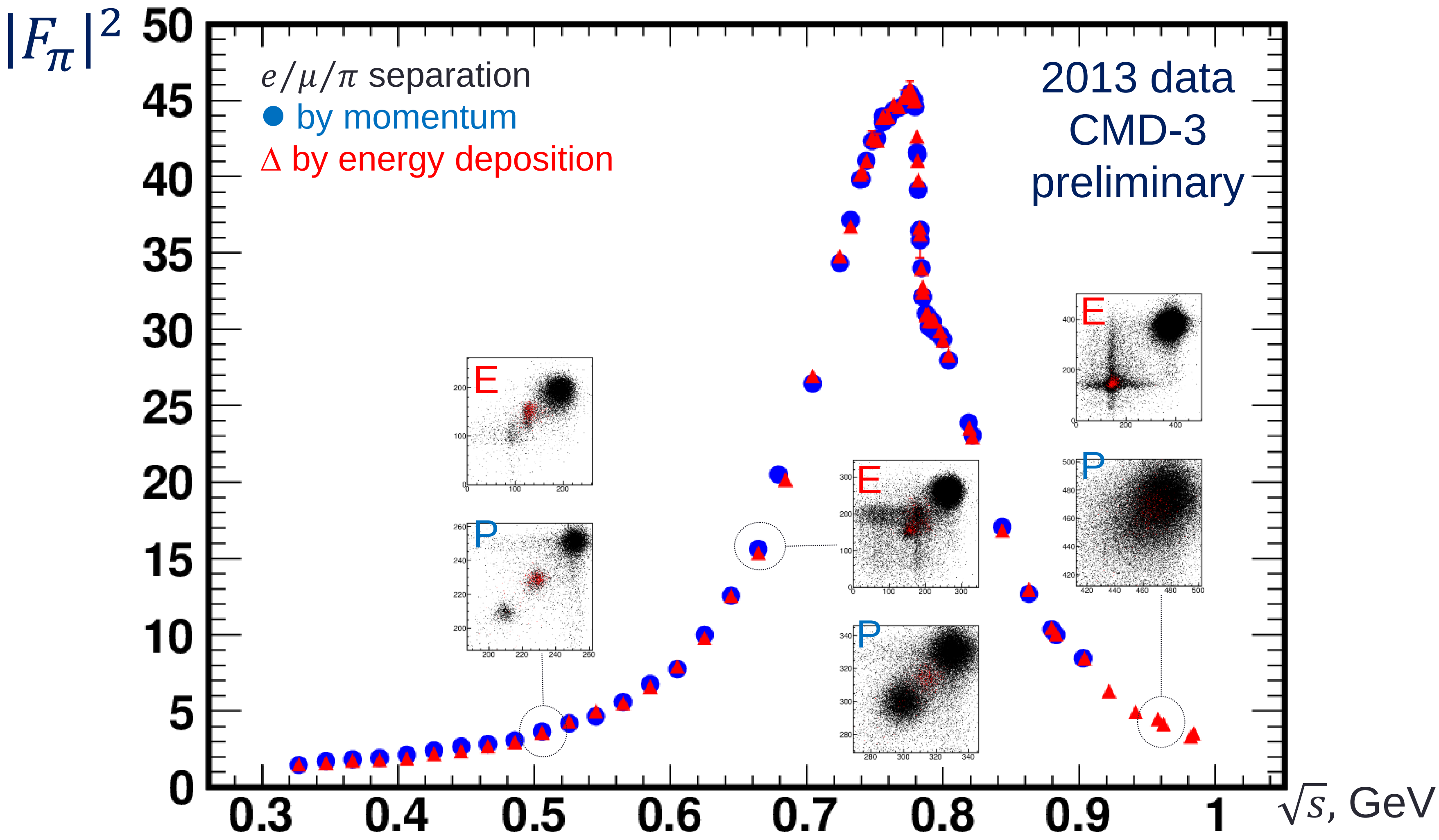
$e^+e^- \rightarrow \pi^+\pi^-$: statistics

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



Already collected x2-3 data in 2017-2018

Preliminary result ("blinded")

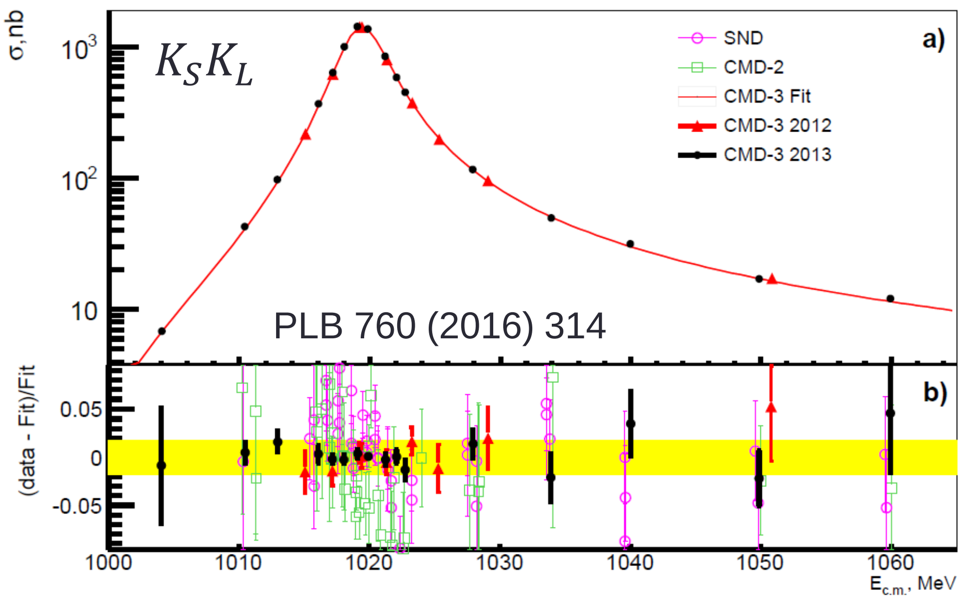


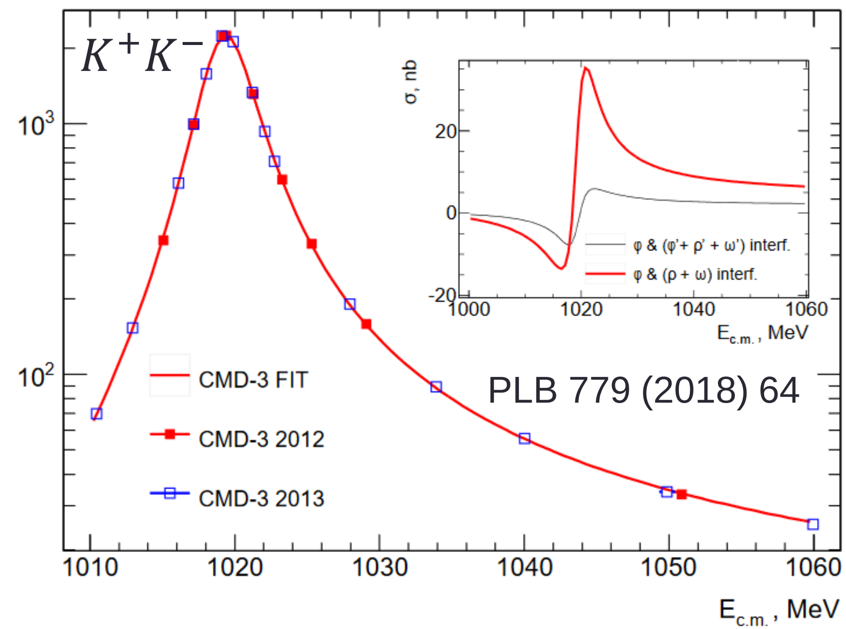
Some corrections are not applied (result is "blinded")

$e^+e^- \to \pi^+\pi^-$: 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.)**	

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

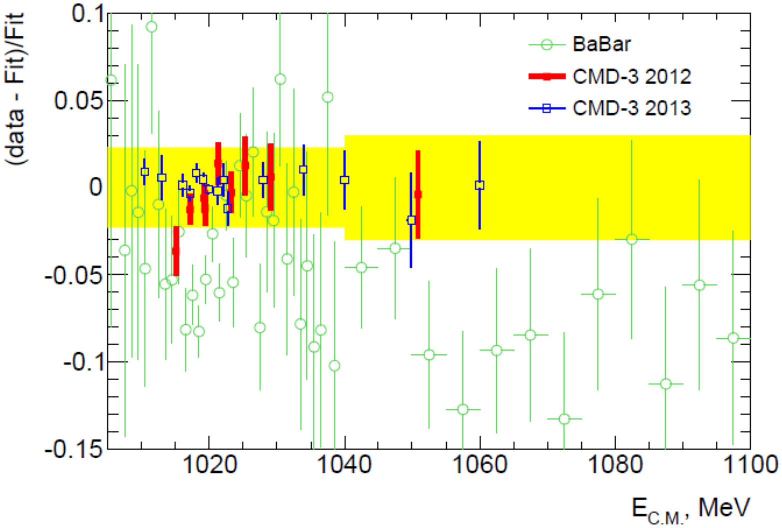


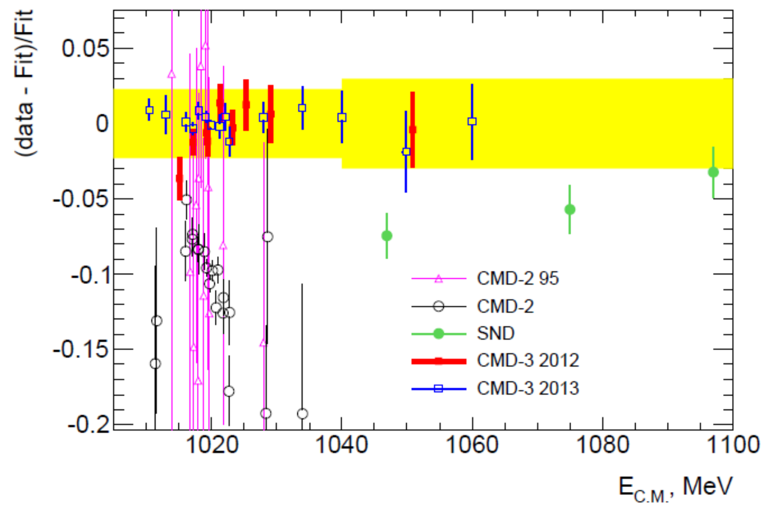


Recent result from CMD-3:

- $K_S K_L$ 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:

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

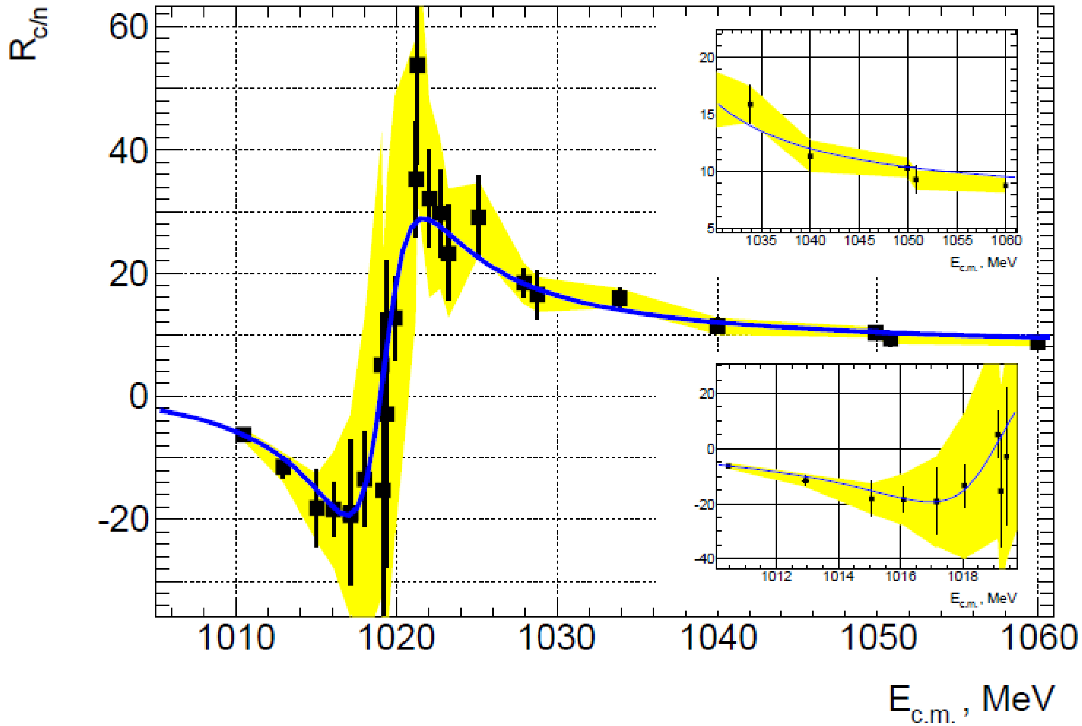
- $r_{\rho,\omega} = 0.91 \pm 0.04$

deviation of SU(3) relations

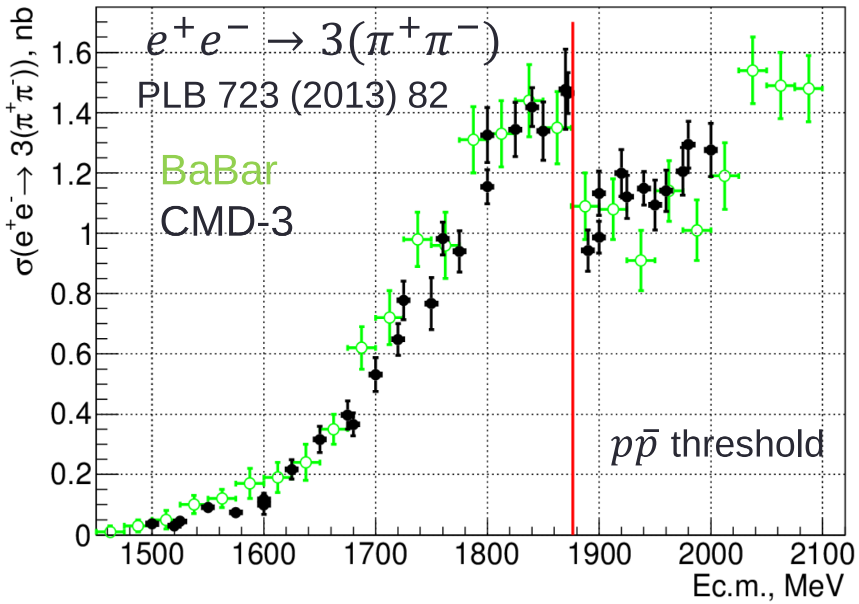
$$g_{\omega K^+K^-} = g_{\rho K^+K^-} = -g_{\varphi K^+K^-}/\sqrt{2}$$

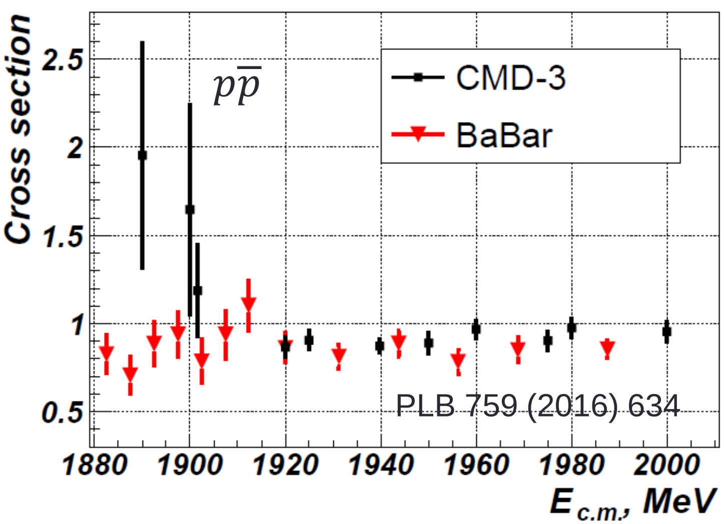
- $\delta = 0.989 \pm 0.003$

test of systematic errors



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





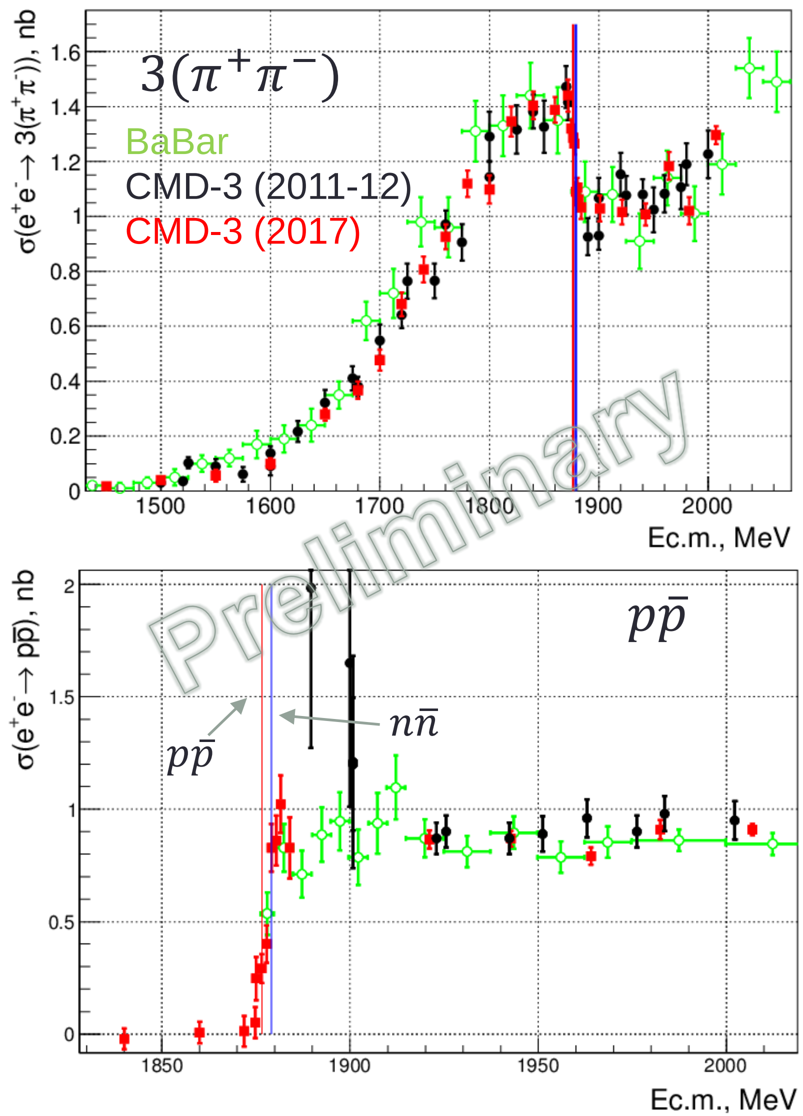
One of first results from CMD-3:

- 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 ($K^+K^-\pi^+\pi^-$) and don't see it in $\pi^+\pi^-\pi^+\pi^-$



Conclusion

- We are eagerly waiting for the result of the new measurement of muon (g-2) at Fermilab
- The goal of two experiments at VEPP-2000, CMD-3 and SND, is to provide exclusive measurement of $e^+e^- \to hadrons$ from 0.32 to 2.0 GeV. In particular, it is used to calculate the hadronic contribution to muon (g-2).
- In 2011-2013 CMD-3 has collected 60 1/pb 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. >100 1/pb were collected so far.
- Data analysis of exclusive modes of $e^+e^- \to hadrons$ is in progress. Many results have been published.