HVP CONTRIBUTION TO MUON (G-2) AND RECENT RESULTS FROM VEPP-2000

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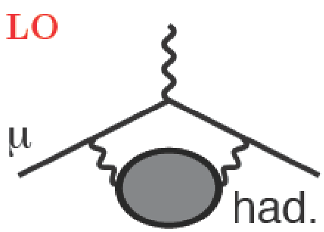
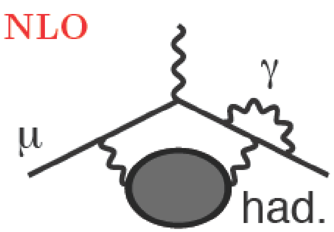
The SM value of a_μ: today

- QED: Kinoshita et al., 2012: up to 5 loops (12672 diagrams). 0.7 ppb
- EW: 2 loops, now Higgs mass is known. 9 ppb
- Hadronic

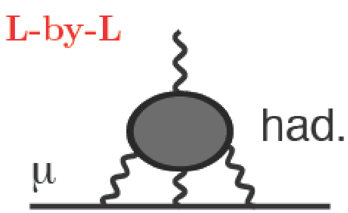
$$a_\mu^{\text{had}} = a_\mu^{\text{had,VP LO}} + a_\mu^{\text{had,VP NLO}} + a_\mu^{\text{had,Light-by-Light}}$$



370 ppb



10 ppb



220 ppb

LBL: model-dependent calculations; improvement is expected from lattice calculations

HVP: the value is based on the hadronic cross-section e^+e^- data; there are effort to get it via lattice calculations.

New experiment at FNAL: 140 ppb

The lowest-order hadronic contribution

The hadronic contribution is calculated by integrating experimental cross-section $\sigma(e^+e^- \to hadrons)$.

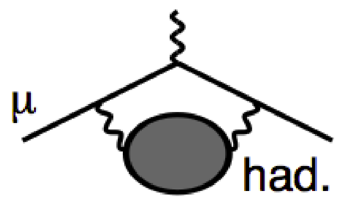
Weighting function $\sim 1/s$, therefore lower energies contribute the most.

Starting from $\sqrt{s} \sim 2\ GeV$ the pQCD estimation of $\sigma(e^+e^- \to hadrons)$ is used. At lower energies only the experimental data are used.

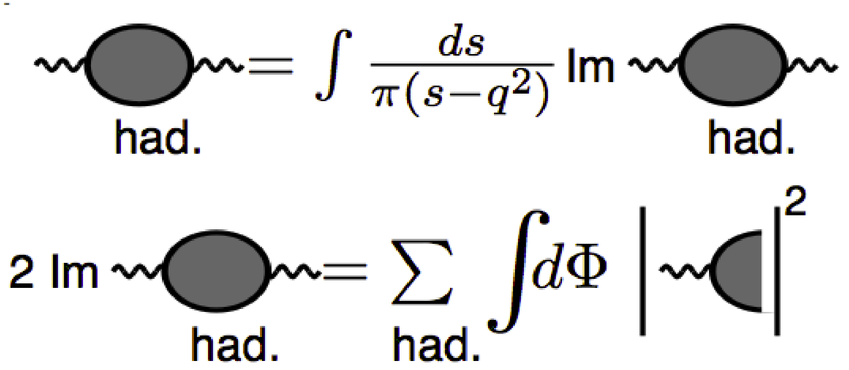
Many sources of data:

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

The diagram to be evaluated:

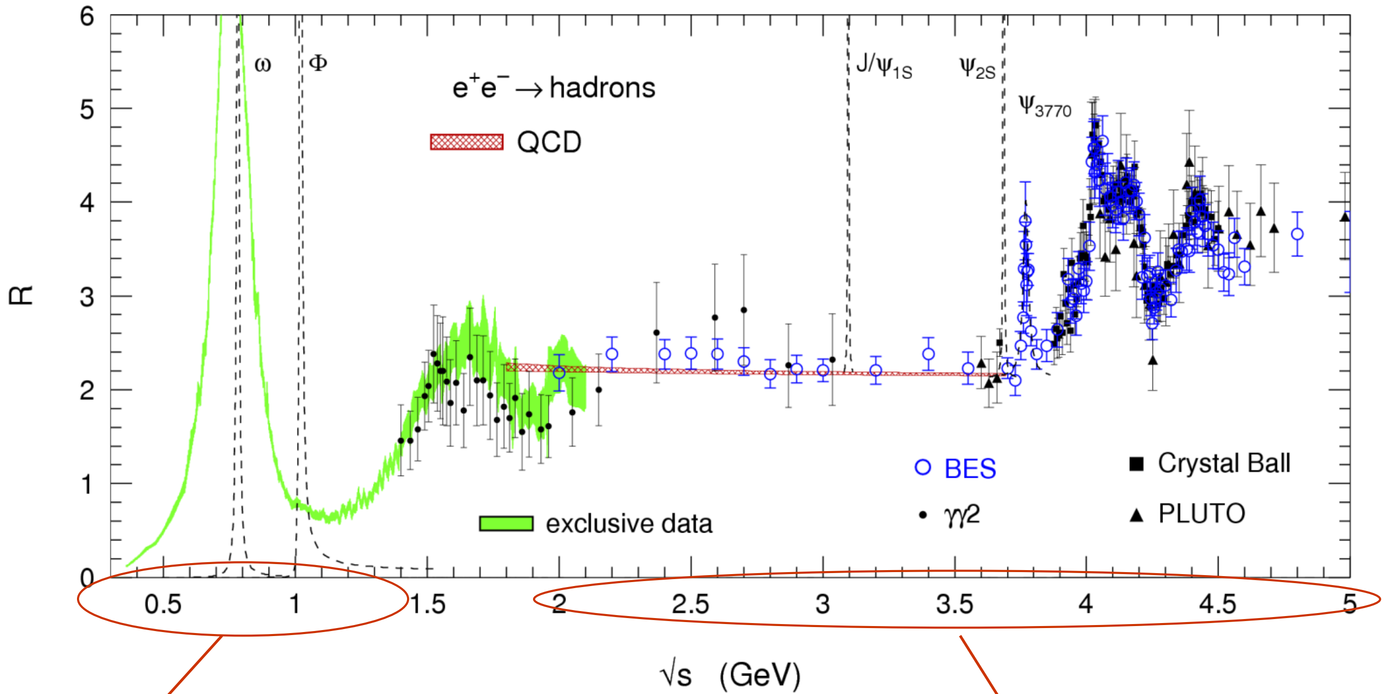


pQCD not useful. Use the dispersion relation and the optical theorem.



$$\boxed{a_\mu^{\text{had,LO}} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\text{th}}}^{\infty} ds\ \frac{1}{s} \hat{K}(s) \sigma_{\text{had}}(s)}$$

Inclusive vs exclusive measurements



Exclusive approach:

• measure each final state separately and calculate the sum

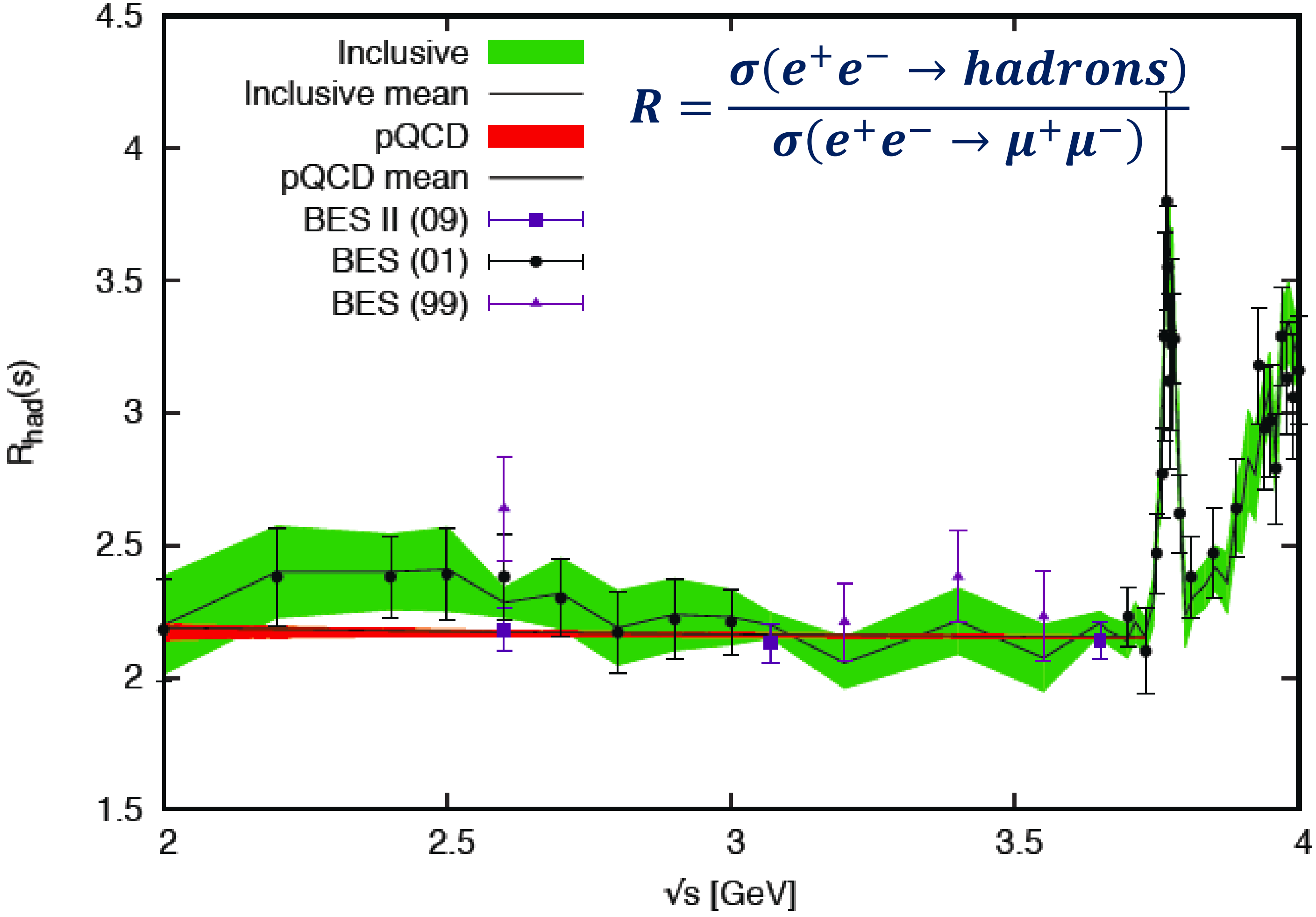
VEPP-2M, VEPP-2000, Babar, KLOE

Inclusive approach:

• select events with any hadron(s) in the final state

BES, KEDR (now)

Inclusive measurement at BES

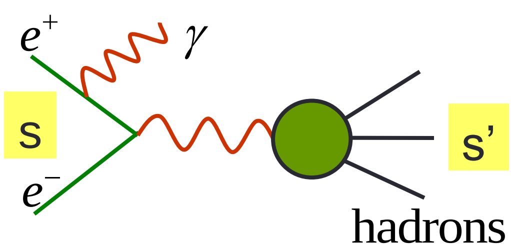


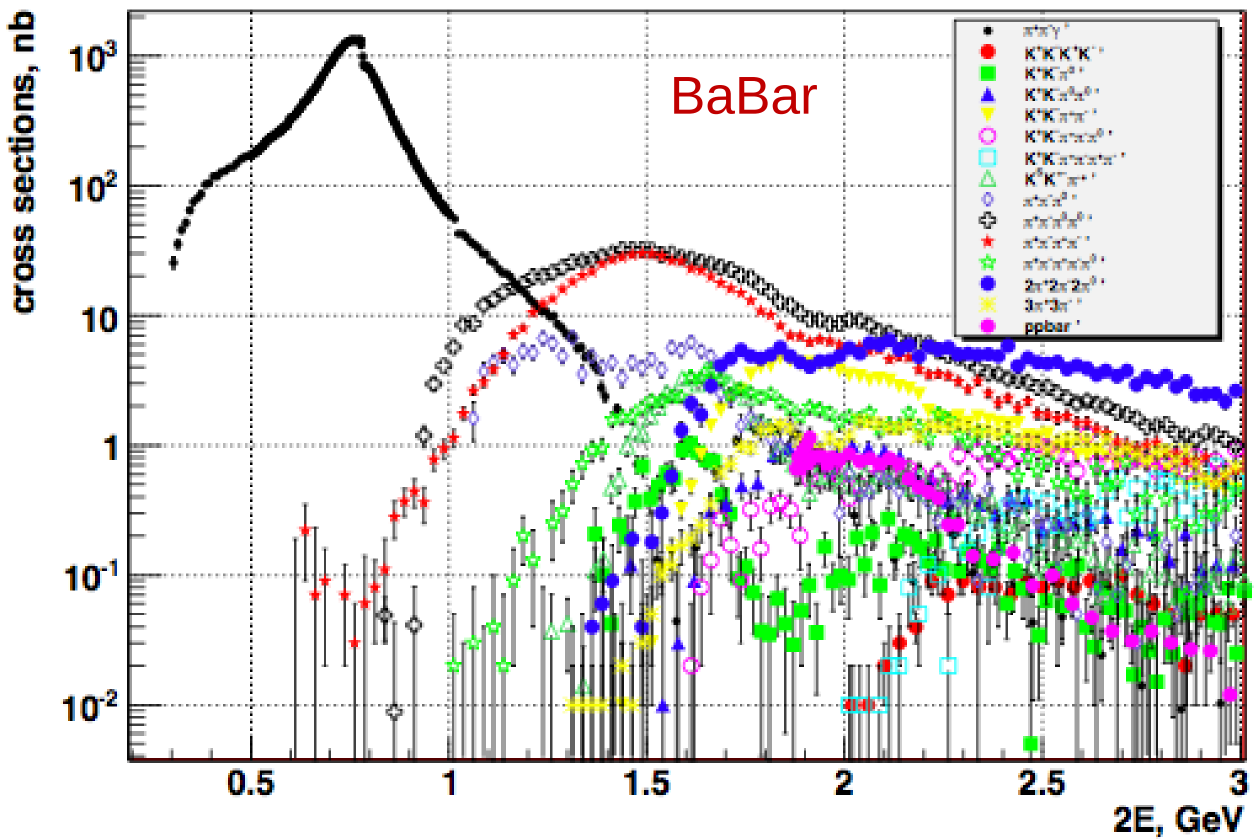
There is ongoing R measurement with KEDR detector at VEPP-4M (Novosibirsk)

ISR approach

New approach to measurement of the hadronic cross-sections was fully developed over last decade: ISR (Initial State Radiation), mainly by BaBar and KLOE.

$$d\sigma(e^+e^- \to \text{hadrons} + \gamma) = H(Q^2, \theta_\gamma) \cdot d\sigma(e^+e^- \to \text{hadrons})$$





Main idea: cross-section is measured in the wide energy range, using events with hard photon, emitted by initial particles.

$e^+e^- \to \pi^+\pi^-$ and the hadronic contribution

In units of hadronic contribution:

$$\delta a_\mu^{HVP} = 0.6\%$$

$$\Delta a_\mu(\exp - \text{theory}) \approx 4.0\% \pm 1.1\%$$

Estimated accuracy of Fermilab experiment

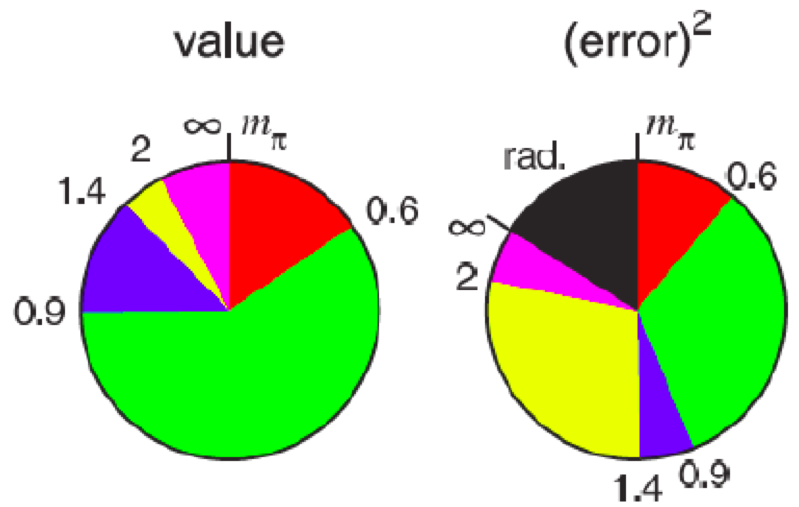
$$\delta a_\mu = 0.25\%$$

Energy range $\sqrt{s} < 2$ GeV contribute >90% of the a_μ^{HVP} value

$e^+e^- \to \pi^+\pi^-$ alone contribute 73% of the value and 0.45% out of 0.6% of the error

VEPP-2000 goal: measure $\sigma(e^+e^- \to \pi^+\pi^-)$ with systematic accuracy of ~0.3% and small statistical errors

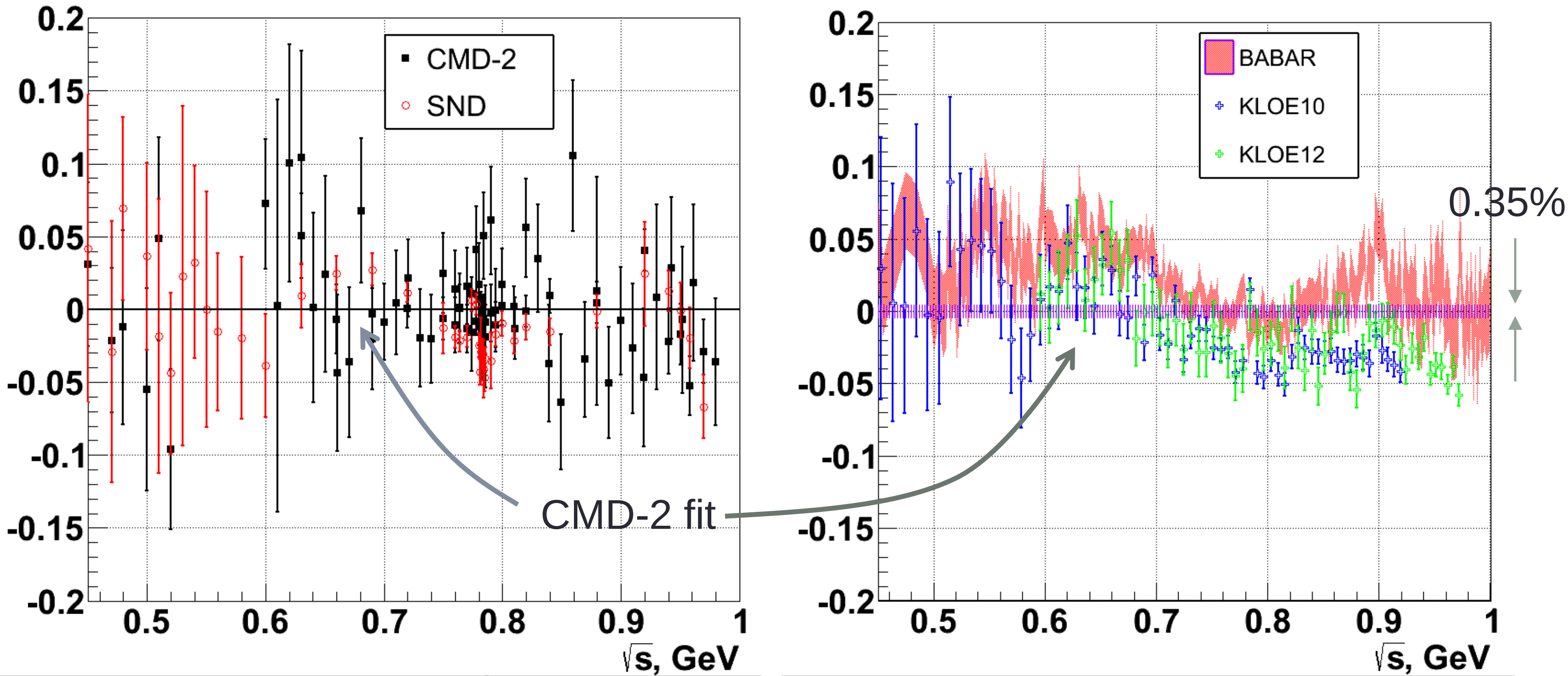
$$a_\mu^{\text{had,LO}} = \frac{m_\mu^2}{12\pi^3}\int_{s_{\text{th}}}^{\infty} ds\, \frac{1}{s}\hat{K}(s)\sigma_{\text{had}}(s)$$



Contribution to the value and error of $a_\mu^{had,LO}$ from different energy ranges

Do existing data agree?

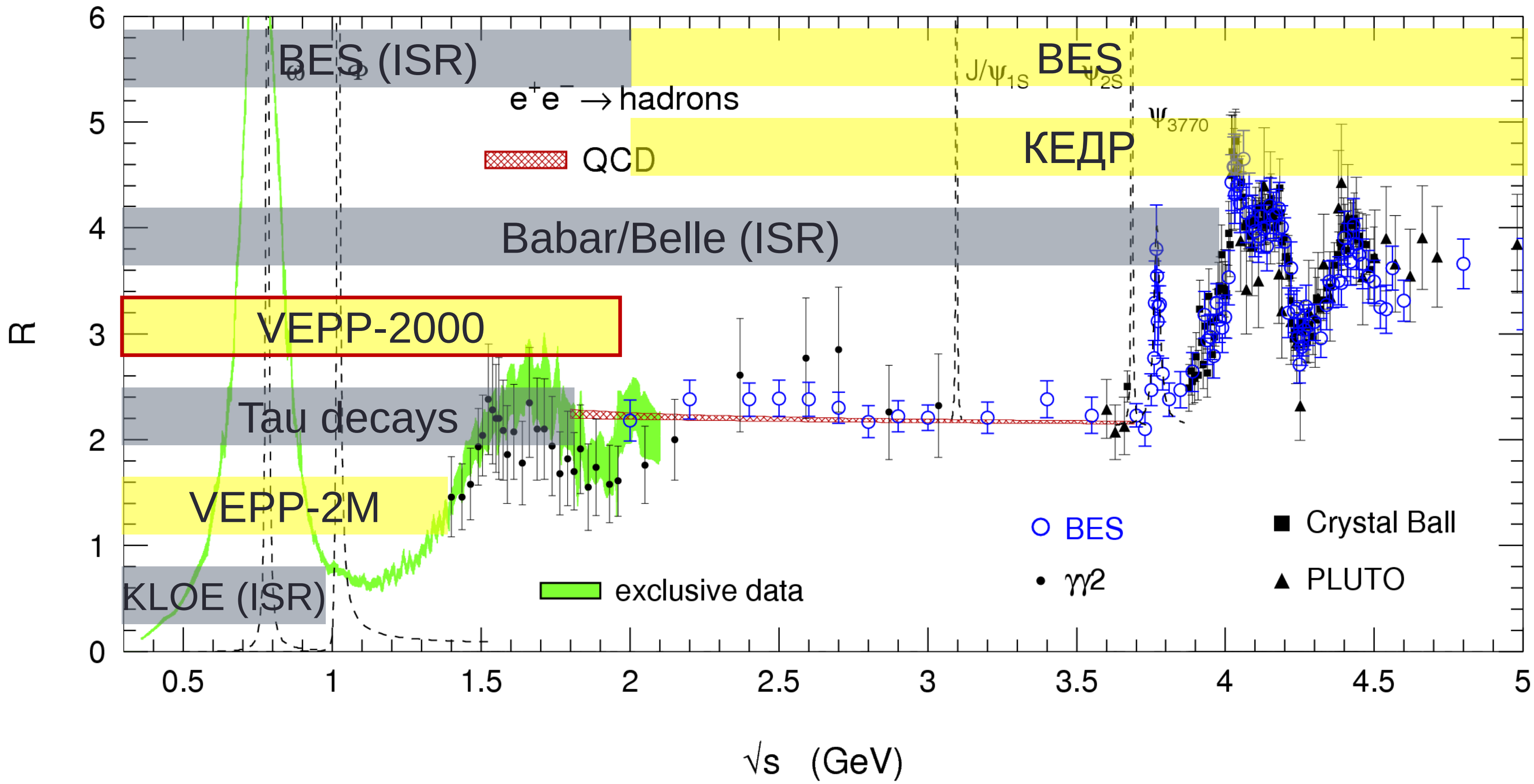
Cross section $e^+e^- \to \pi^+\pi^-$



VEPP-2M data ISR data

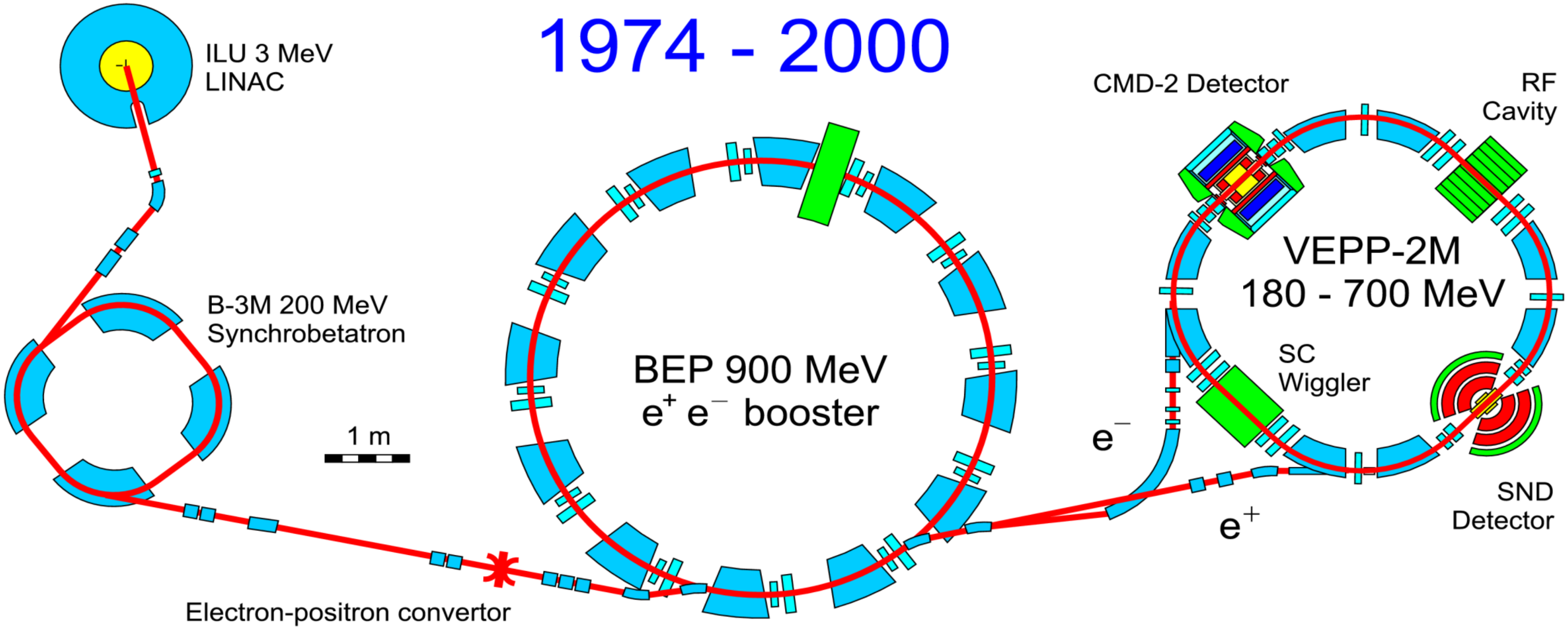
- In integral, there is reasonable agreement between existing data sets
- But there are local disagreements well beyond claimed syst.errors

VEPP-2000 and the world



VEPP-2000: direct exclusive measurement of $\sigma(e^+e^- \to hadrons)$
World-best luminosity below 2 GeV (1 GeV excluded)

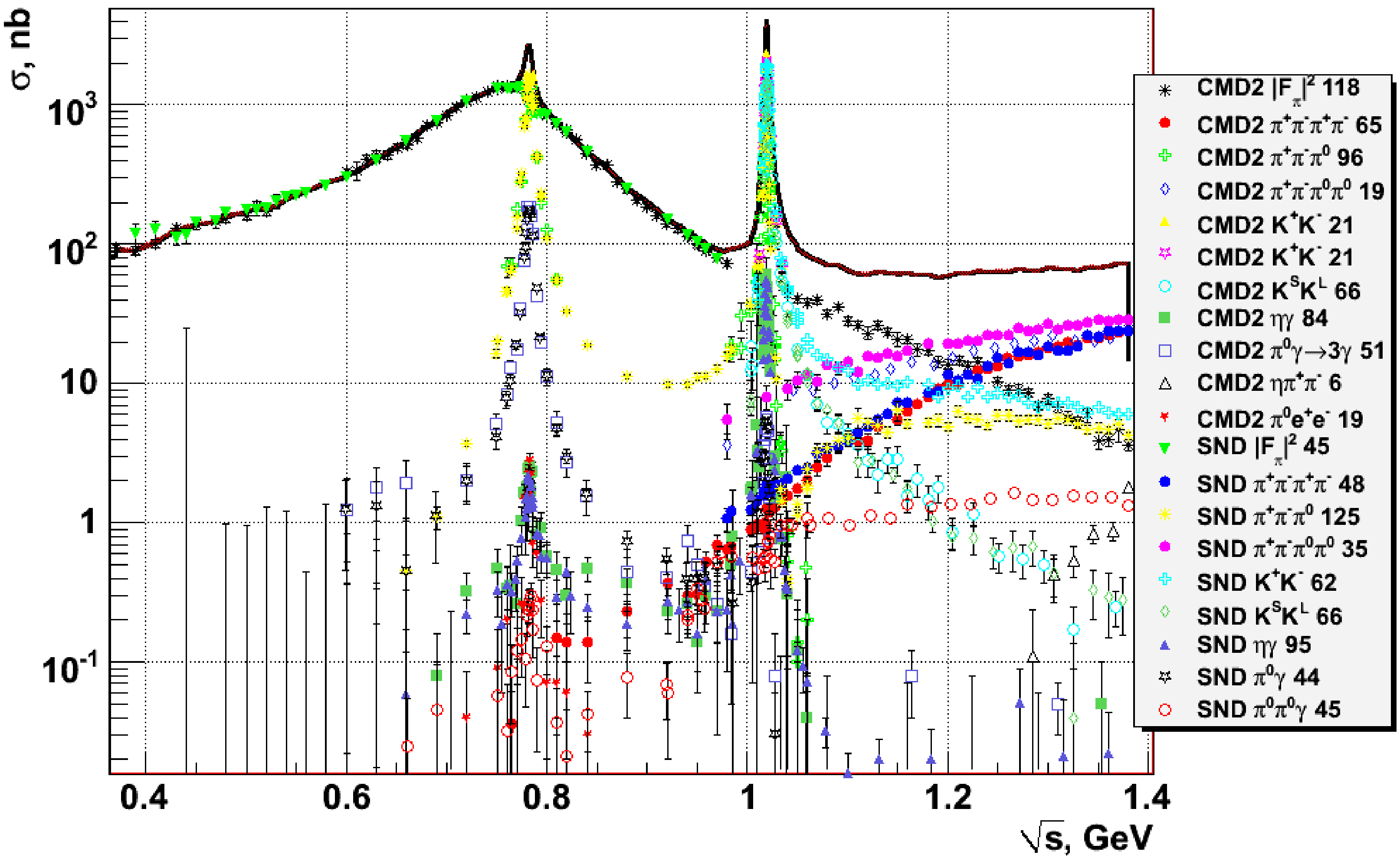
There was VEPP-2M



Energy range: 0.36 – 1.4 GeV

Luminosity up to $5*10^{30}$ $1/cm^2s$

Cross-section measurements at VEPP-2M

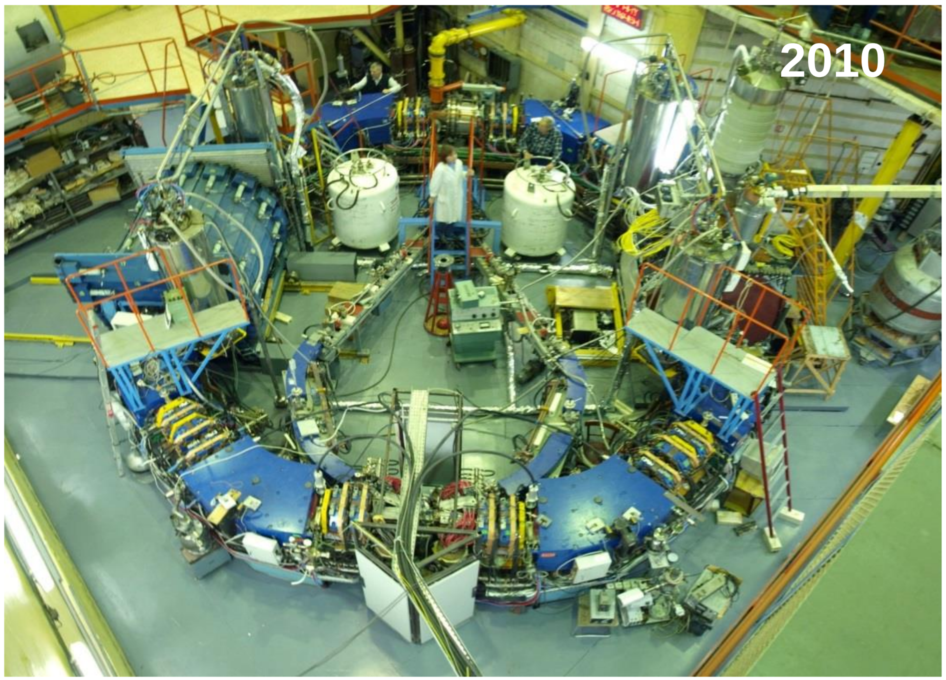


Hadronic cross-section measurements with precision from <1% to ~5%

From VEPP-2M to VEPP-2000

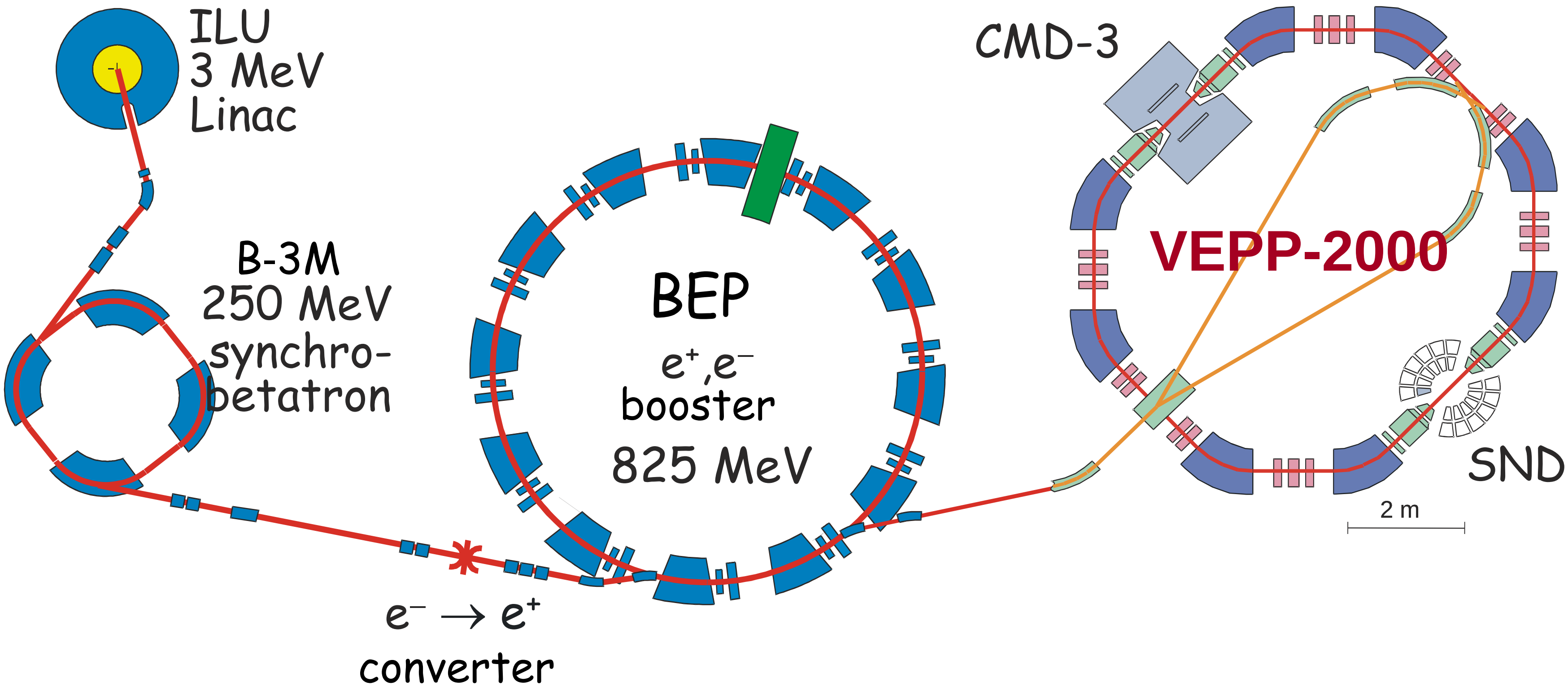
2001 VEPP-2M decommissioned

2010 first engineering run at VEPP-2000 collider with 2 new detectors: CMD-3 and SND



Main VEPP-2000 advantages:
- maximum energy up to 2 GeV
- higher luminosity

VEPP-2000 (2010-2013)



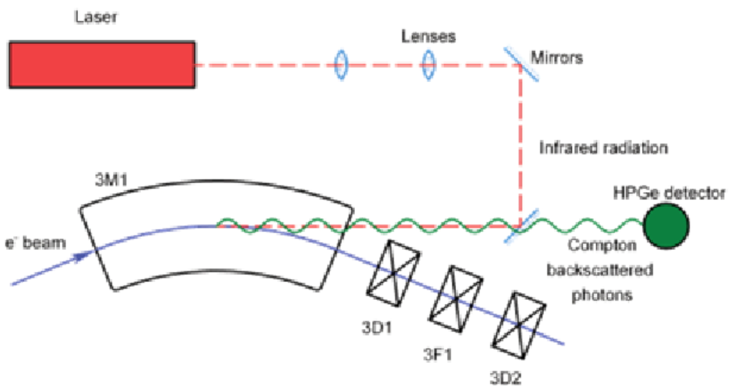
Maximum c.m. energy is 2 GeV, project luminosity is $L = 10^{32} 1/cm^2 s$ at $\sqrt{s} = 2$ GeV

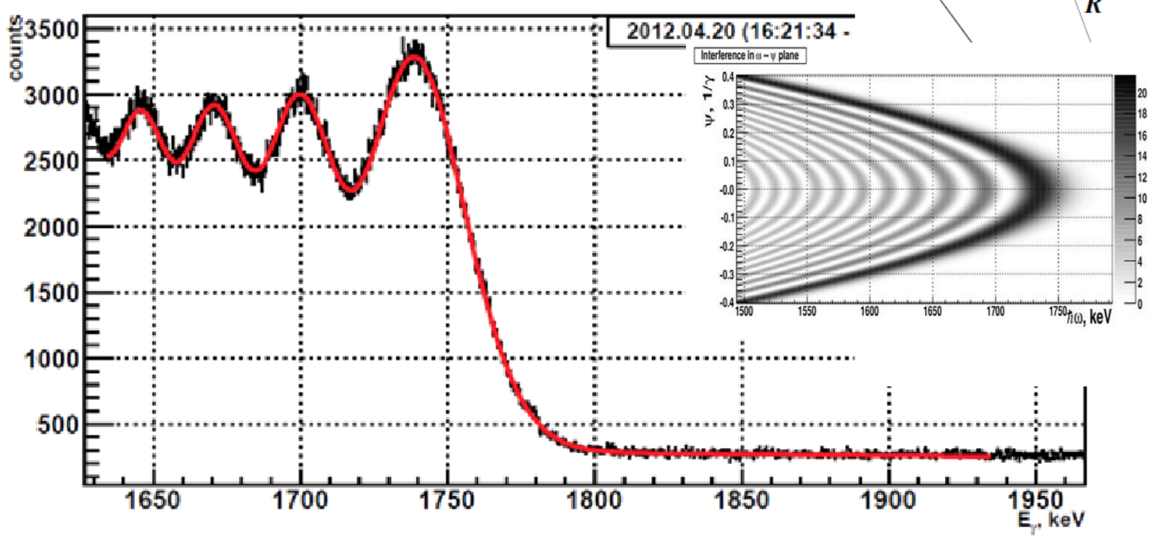
Unique optics, “round beams”, allows to reach higher luminosity

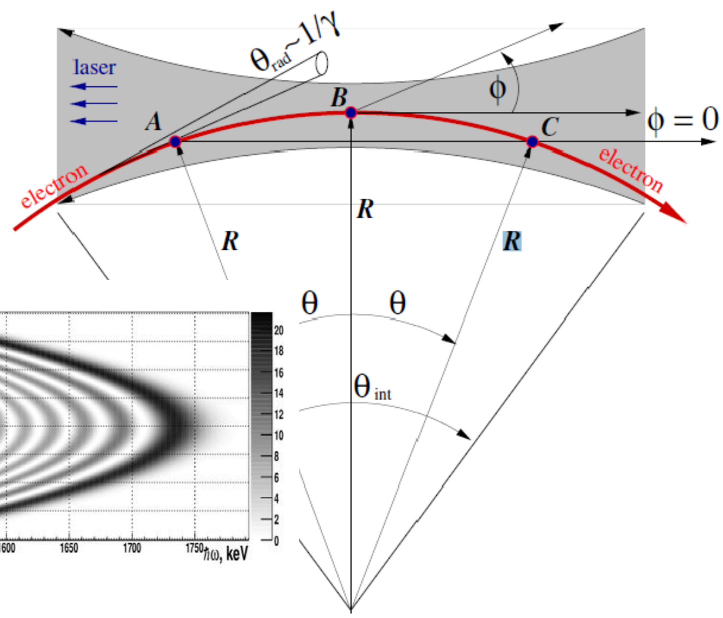
Experiments with two detectors, CMD-3 and SND, started by the end of 2010

Energy measurement

Starting from 2012, energy is monitored continuously using compton backscattering



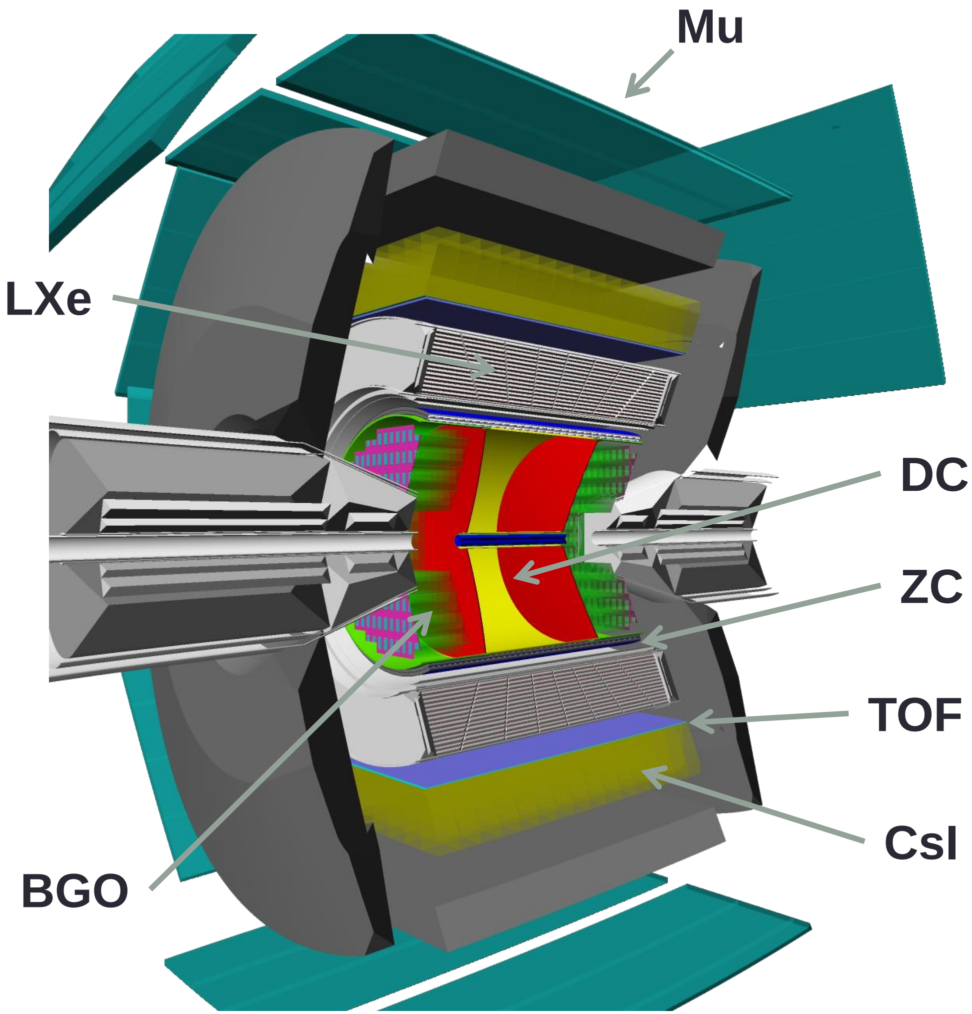




E = 993.662 ± 0.016 MeV

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

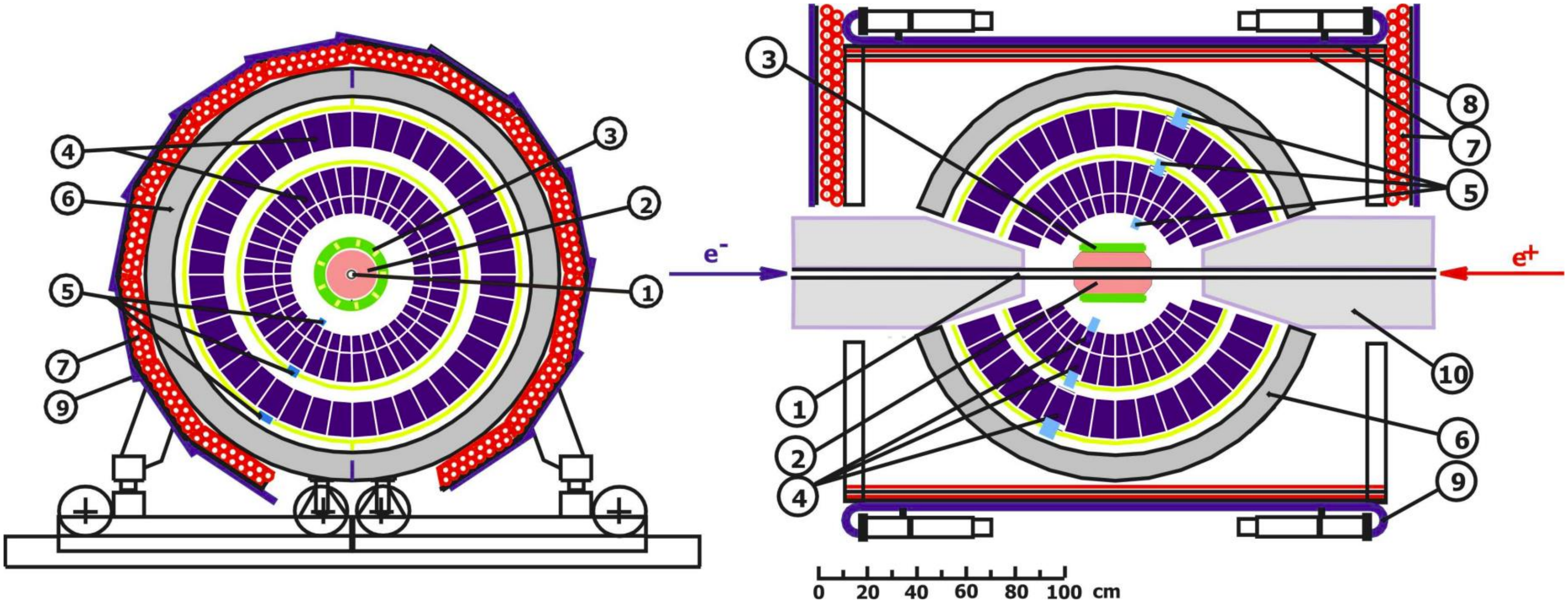
Detector CMD-3



Advantages compared to CMD-2:

- new drift chamber with two times better resolution, higher B field
  better tracking
  better momentum resolution
- thicker barrel calorimeter ($8.3X_0 \rightarrow 13.4\,X_0$)
  better particle separation
- LXe calorimeter
  measurement of conversion point for γ's
  measurement of shower profile
- TOF system
  particle id (mainly p, n)

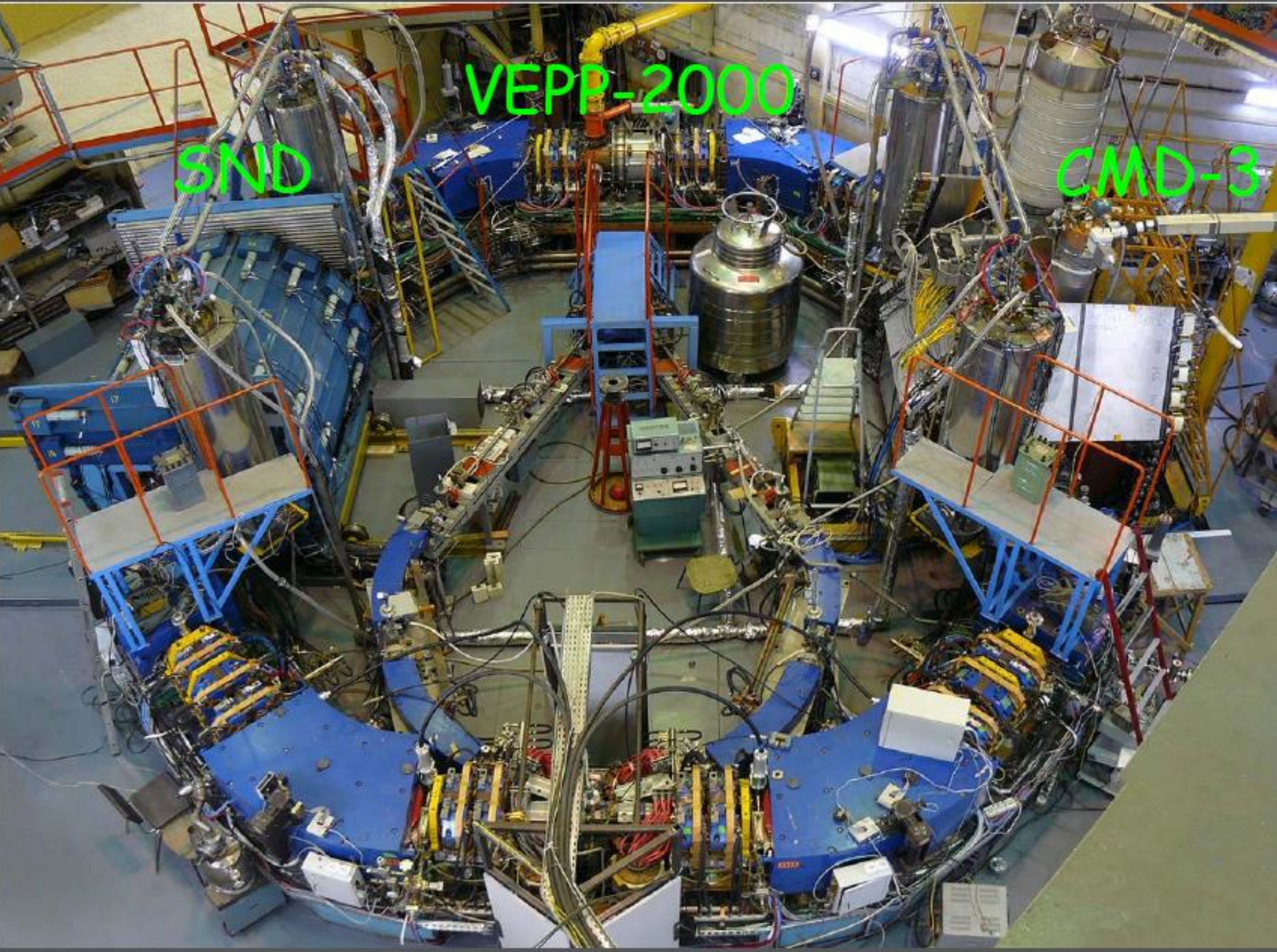
Detector SND



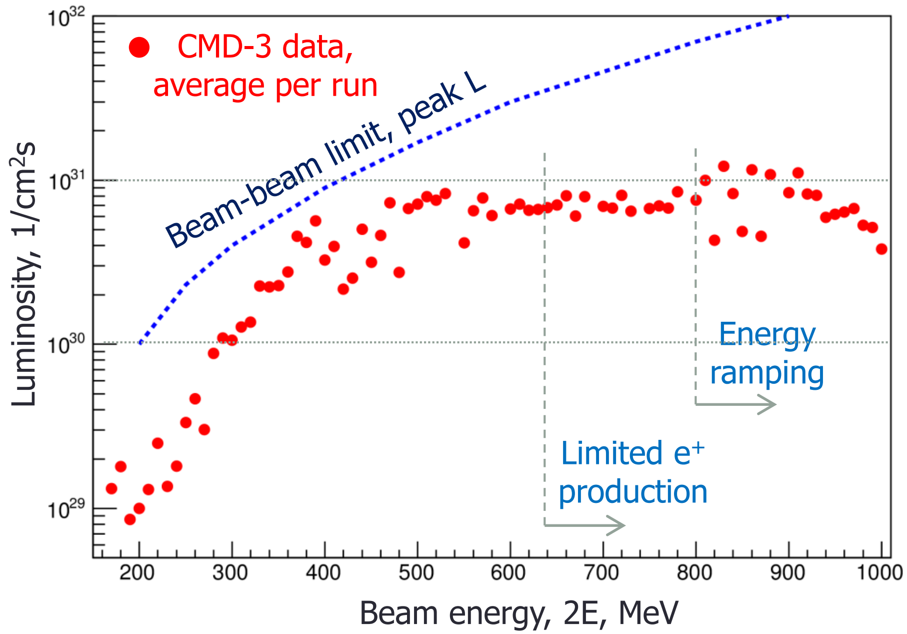
1 – beam pipe
2 – tracking system
3 – aerogel
4 – NaI(Tl) crystals
5 – phototriodes
6 – muon absorber
7–9 – muon detector
10 – focusing solenoid

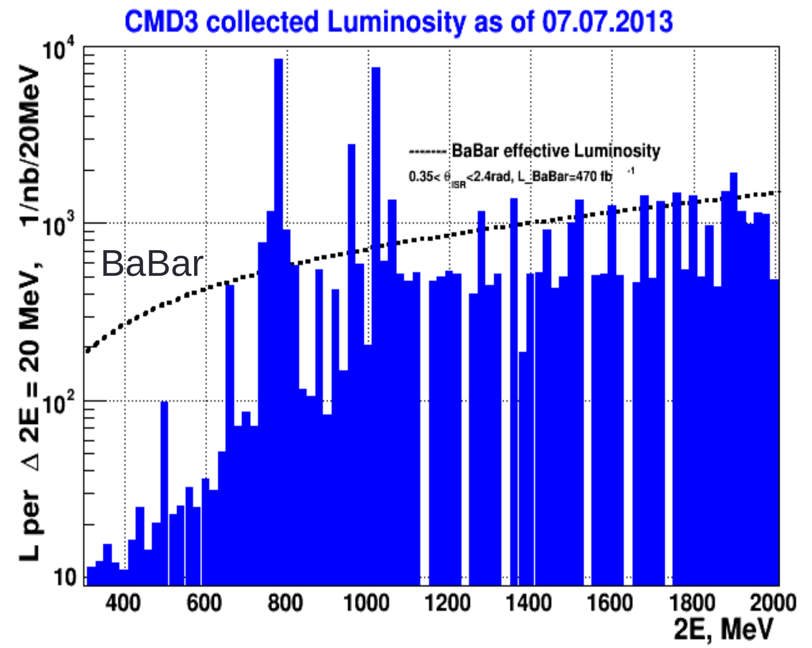
Advantages compared to previous SND:

- new system - Cherenkov counter (n=1.05, 1.13)
  - e/π separation E<450 MeV
  - π/K separation E<1 GeV
- new drift chamber
  - better tracking
  - better determination of solid angle


VEPP-2000
SND
CMD-3

Collected luminosity





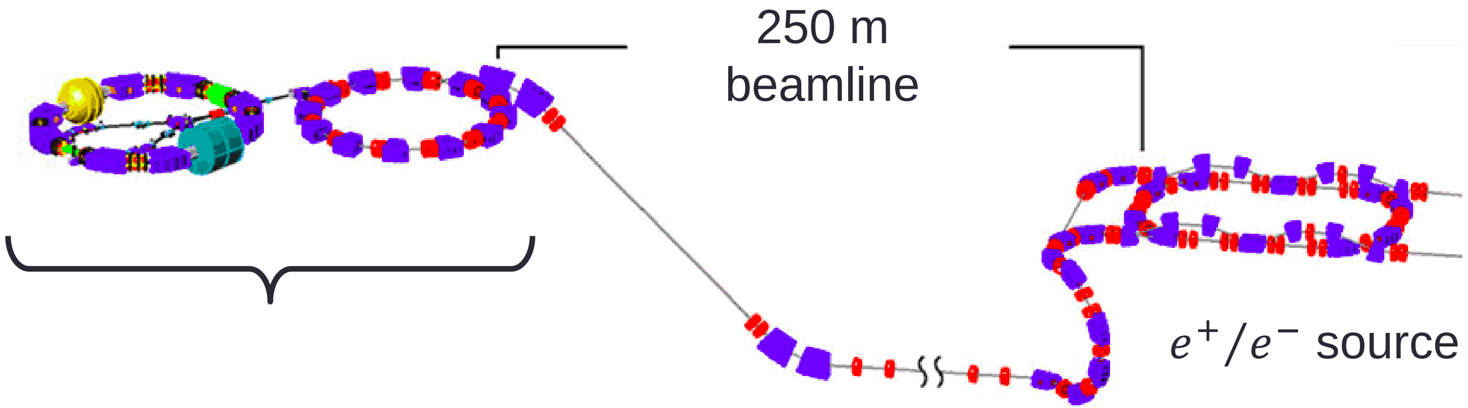
Currently the luminosity is limited by a deficit of positrons (from $E > 650$ MeV) and limited energy of the booster (from $E > 825$ MeV).

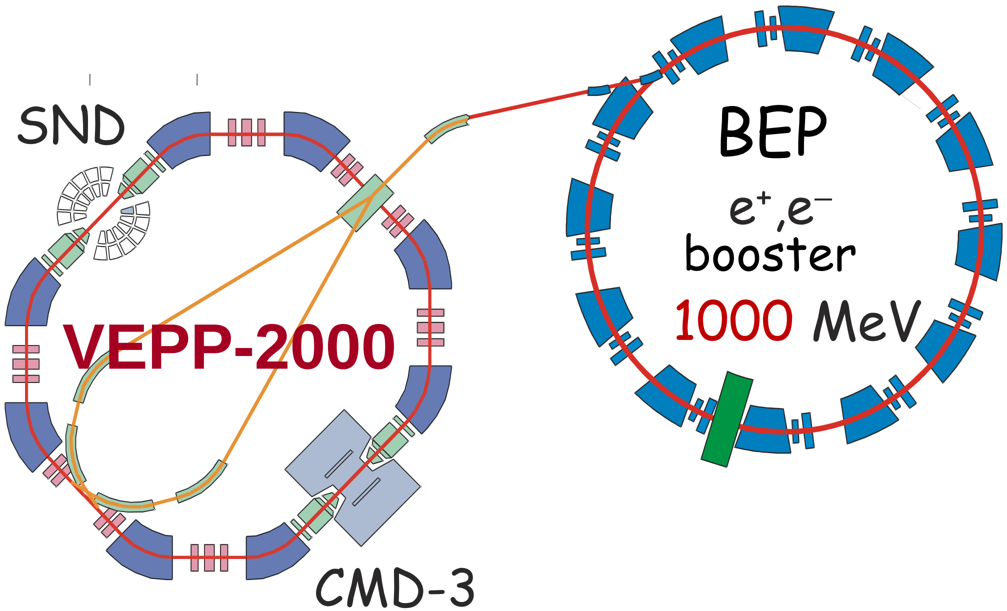
After upgrade (ongoing) we expect luminosity increase by up to factor 10 at maximum energy.

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 after upgrade (2015-)





- New positron source – no luminosity limitation due to lack of e^+
- Booster energy increased to 1 Gev – no deadtime due to energy ramping

Physics program

1. Precision measurement of $R = \sigma(e^+e^- \to hadrons)/\, \sigma(e^+e^- \to \mu^+\mu^-)$
   exclusive approach, up to <1% for major modes
2. Study of hadronic final states:
   $$e^+e^- \to 2h, 3h, 4h, \ldots \quad h = \pi, K, \eta$$
3. Study of vector mesons and theirs excitations:
   $$\rho', \rho'', \omega', \varphi', \ldots$$
4. Comparison of cross-sections $e^+e^- \to hadrons\ (T = 1)$ with spectral functions of τ-decays
5. Study of nucleon electromagnetic formfactor at threshold
   $$e^+e^- \to p\bar{p}, n\bar{n}$$
6. Measurement of the cross-sections using ISR
7. Study of higher order QED processes

Overall, we plan to collect $0.5 \div 1$ 1/fb

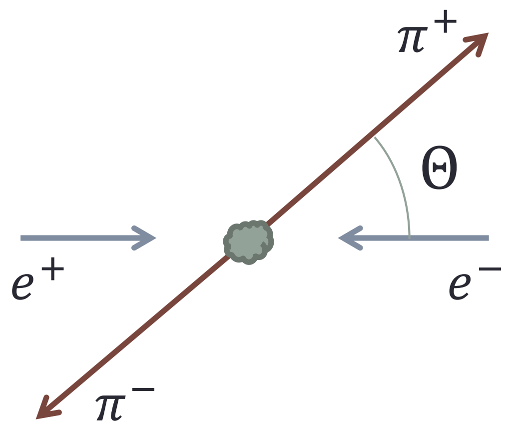
$e^+e^- \to \pi^+\pi^-$ cross section

1. Select final state with 2 back-to-back charged particles

   Cuts: $\mathrm{p_{avr}}, \Delta p, \Delta\Theta, \Delta\varphi$

   Fiducial volume:

   $\Theta_0 \le \Theta_{avr} \le (\pi - \Theta_0)$, $\Theta_0 = 0.9 \ldots 1.1$



2. Identify $e^+e^-, \pi^+\pi^-, \mu^+\mu^-$ and background

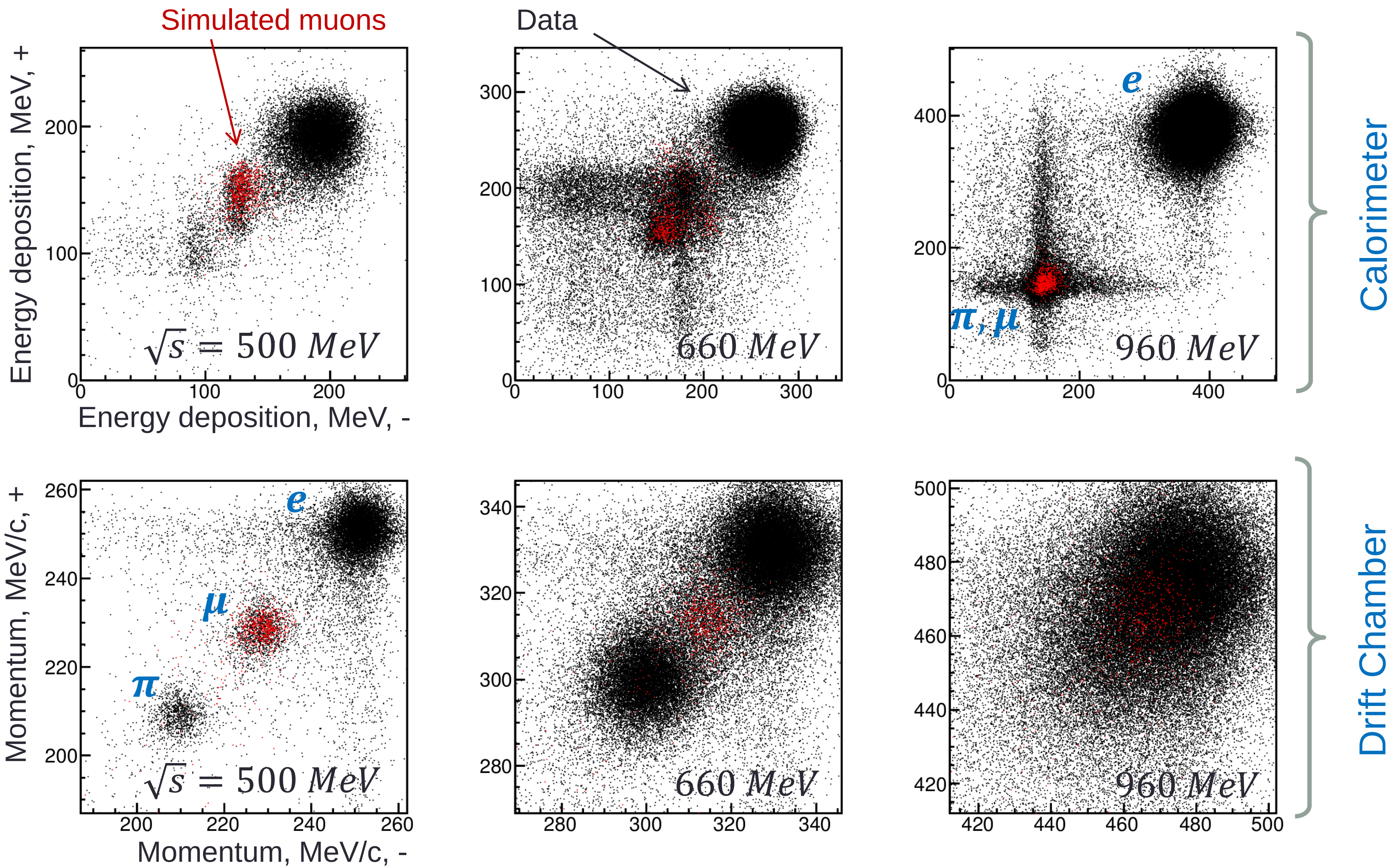
3. Use "master" formula:

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

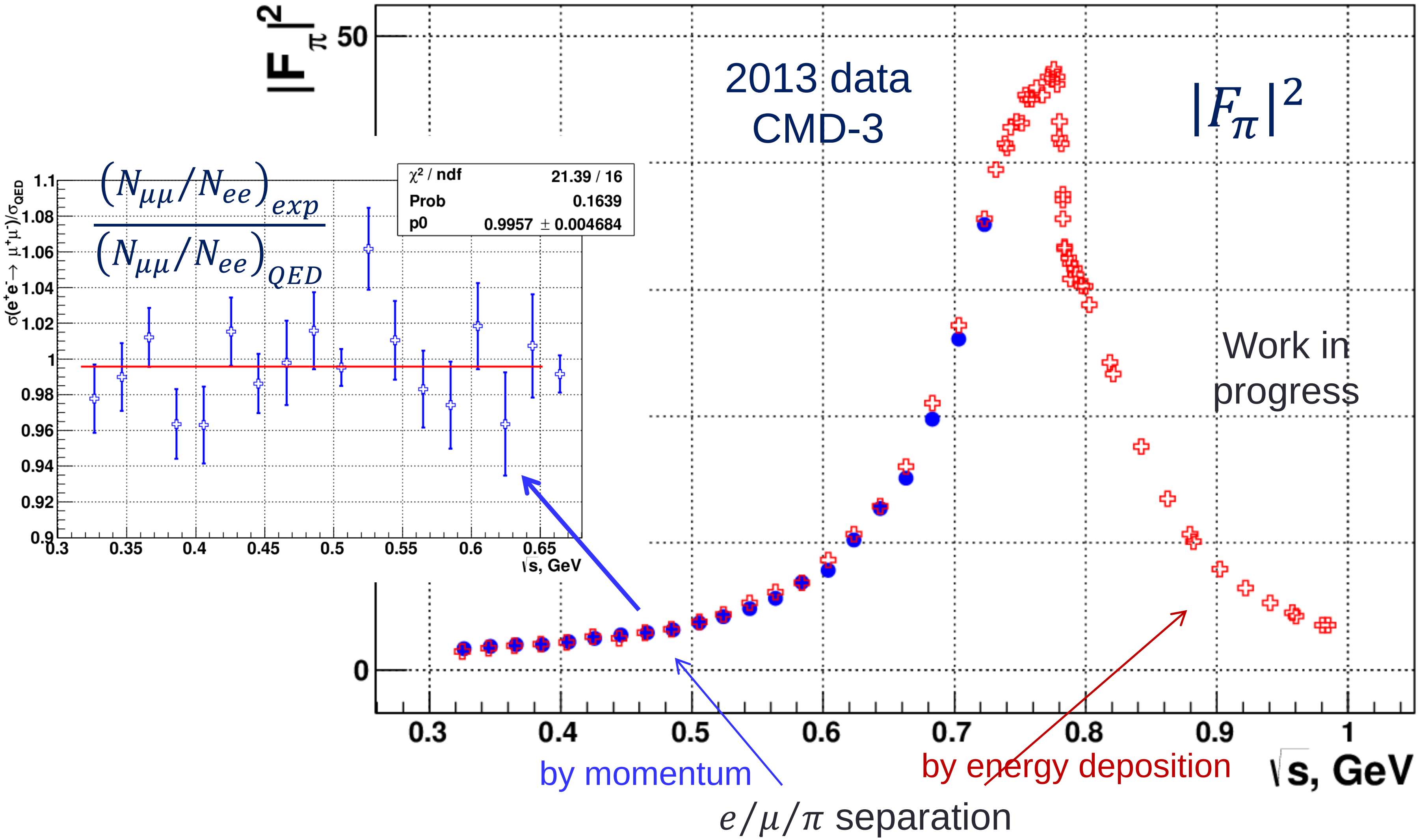
$$\sigma(e^+e^- \to \pi^+\pi^-) = \frac{\pi\alpha^2}{3s}\left(1 - \frac{4m_\pi^2}{s}\right)^{3/2} |F_\pi|^2$$

σ^B_X - "Born" cross-section $e^+e^- \to X$, point-like pions; δ_X - radiative correction; ε_X - detection efficiency (not including acceptance)

$e^+e^- \to \pi^+\pi^-$: e, μ, π separation



$e^+e^- \to \pi^+\pi^-$: VERY preliminary results



$e^+e^- \to \pi^+\pi^-$: statistics and systematics

Main sources of systematics:

- $e/\mu/\pi$ separation – 0.2%

  multiple ways to get detector response from data itself
- fiducial volume – 0.1%

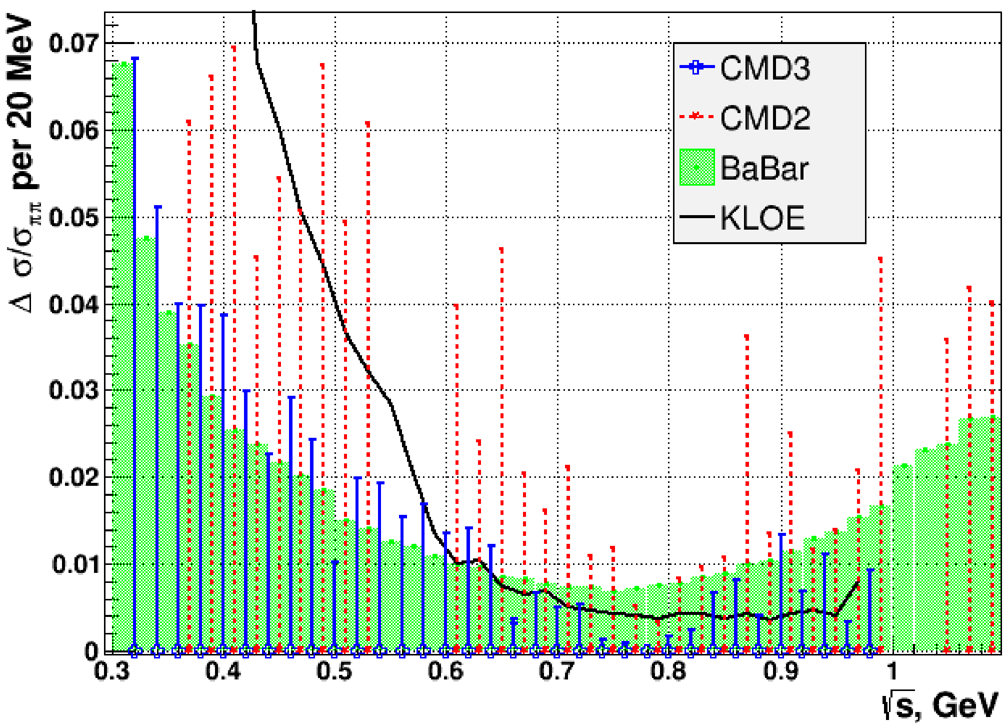
  2 independent systems, which can be used to determine fiducial volume
- beam energy – 0.1%

  constant monitoring with Compton backscattering
- radiative corrections – 0.1%

  proof from data

Many systematic studies rely on high statistics

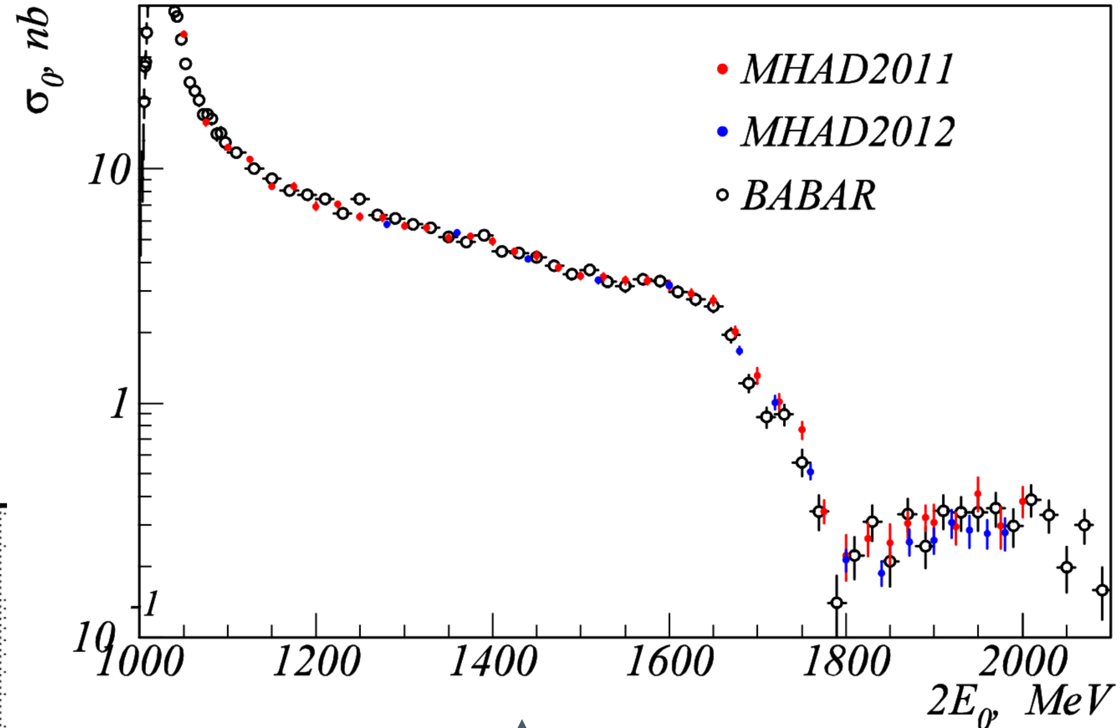
Expected statistical error for 2013 data

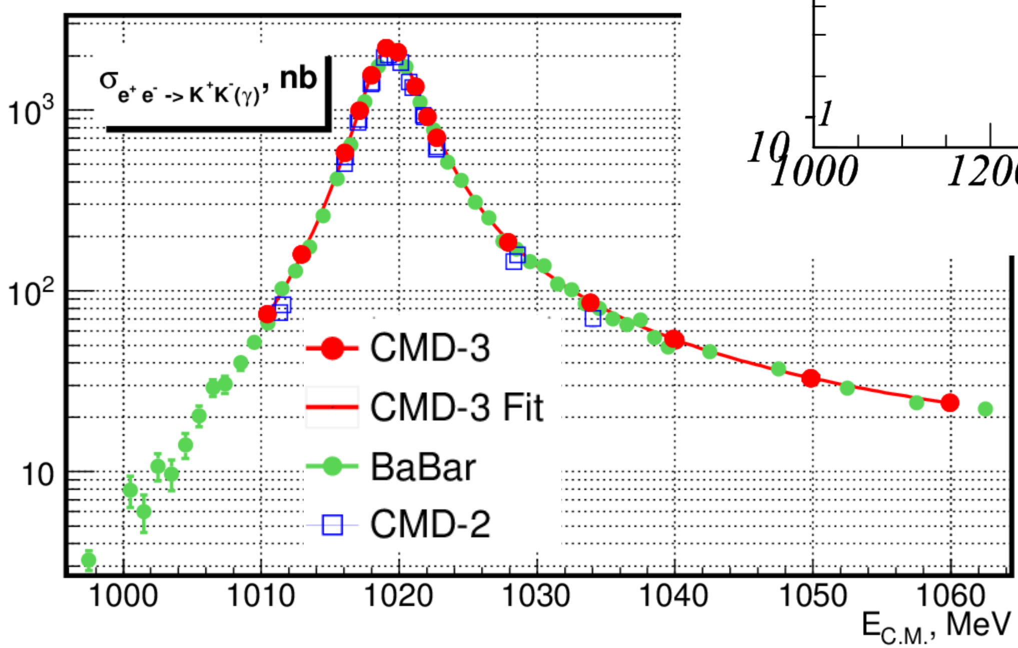


$e^+e^- \to K^+K^-$

CMD-3, @$\varphi(1020)$

There is discrepancy between CMD-2 and BABAR





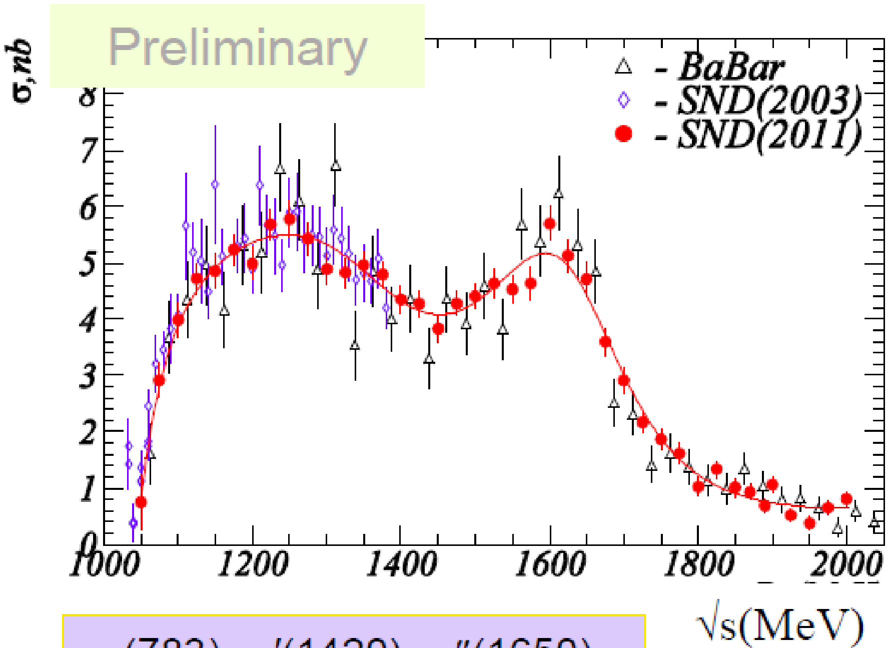
SND, above $\varphi(1020)$

Complicated $\sigma(s)$ due to interference of excited vector resonances

Aerogel Cherenkov counters provide kaons ID

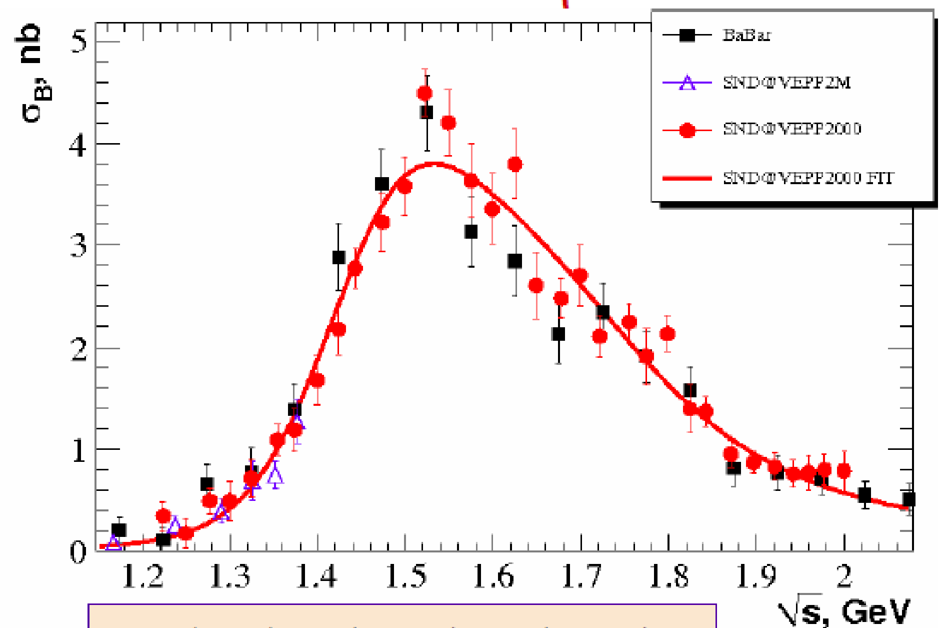
$e^+e^- \to \pi^+\pi^-\gamma\gamma \quad (\gamma\gamma = \pi^0, \eta)$

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



ω(783), ω′(1420), ω″(1650)

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

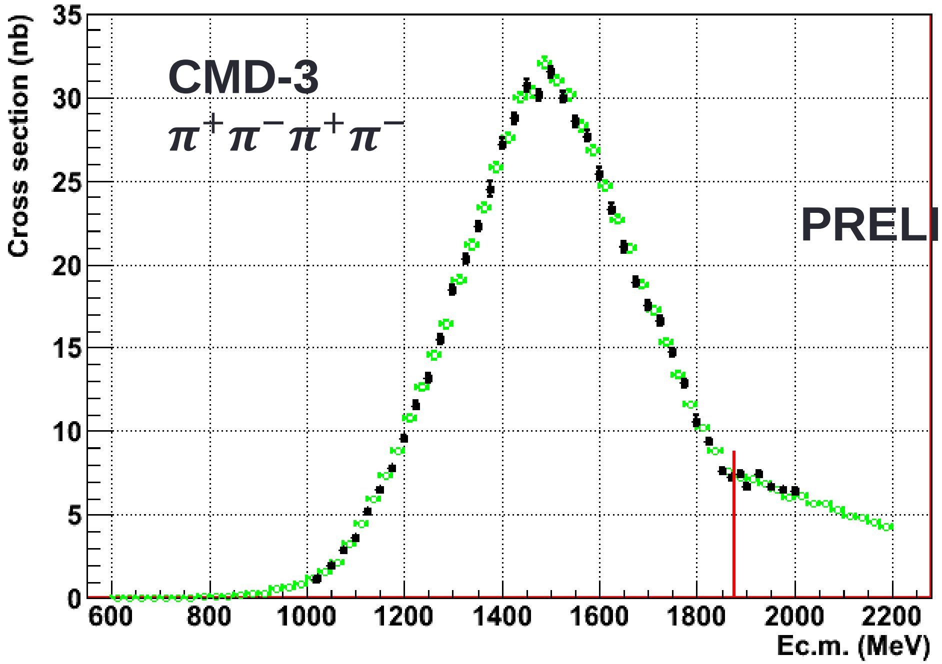


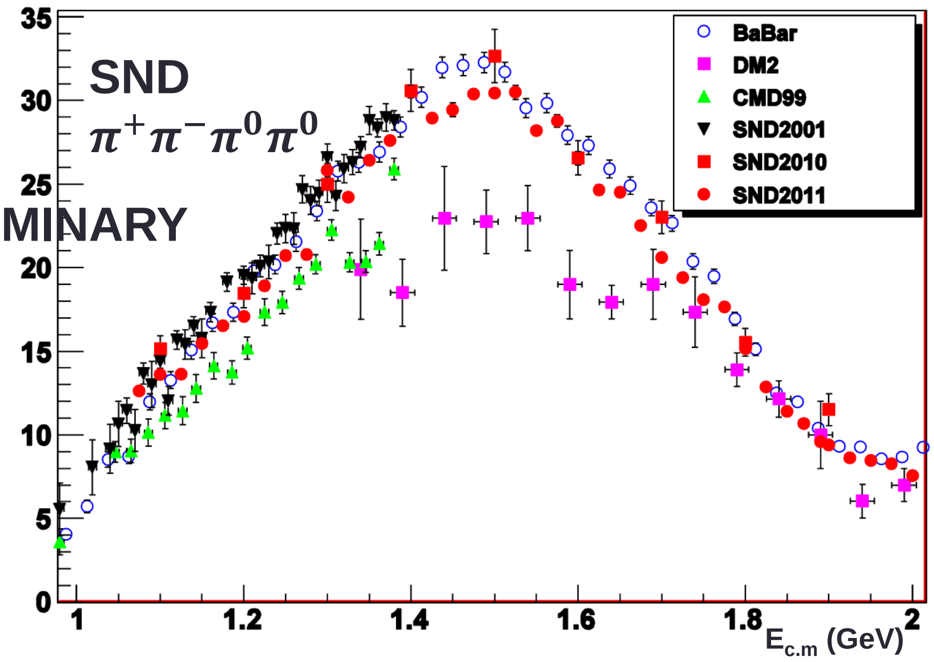
ρ(770), ρ′(1450), ρ″(1700)

Preliminary results from SND, using about 50% of available data.
Estimated systematic error ~5%.

There is ongoing analysis to measure 3π cross section below φ

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

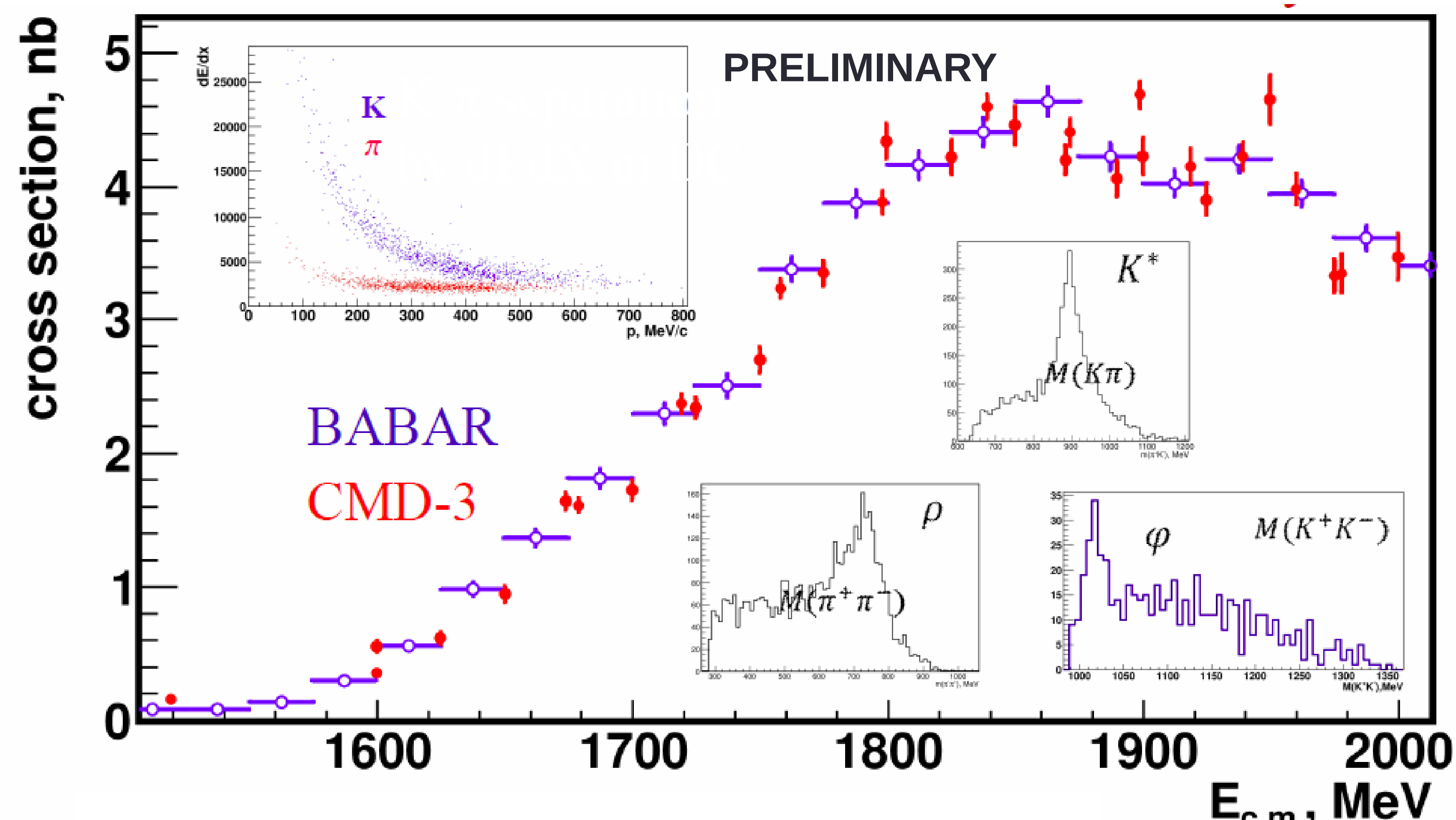




Need to measure these channels to few %.

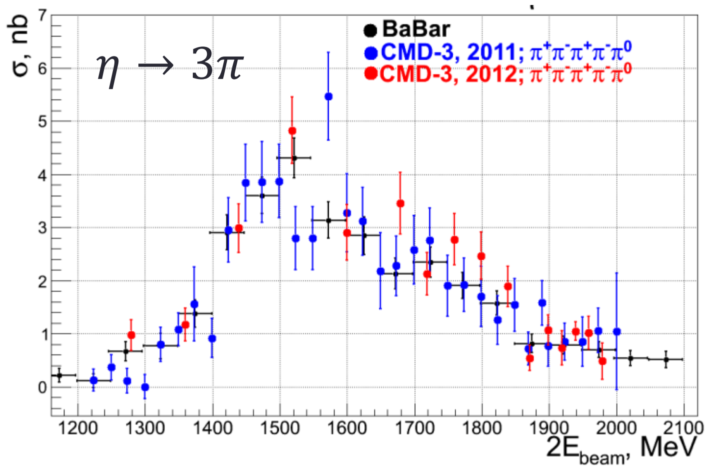
The dominant source of systematic error is the model uncertainty (evaluation of the detector acceptance). High statistics allows for more accurate study of the dynamics.

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

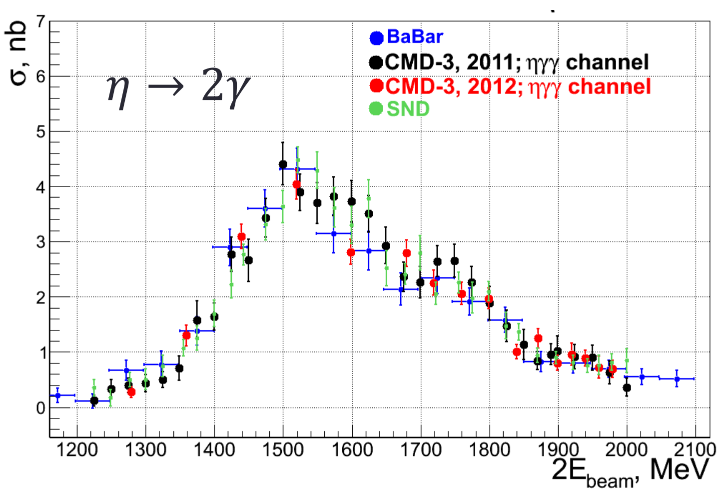


Many intermediate states: $K^*K\pi, \rho KK, \varphi\pi\pi, K^*K^*, \ldots$

$e^+e^- \to 5\pi$



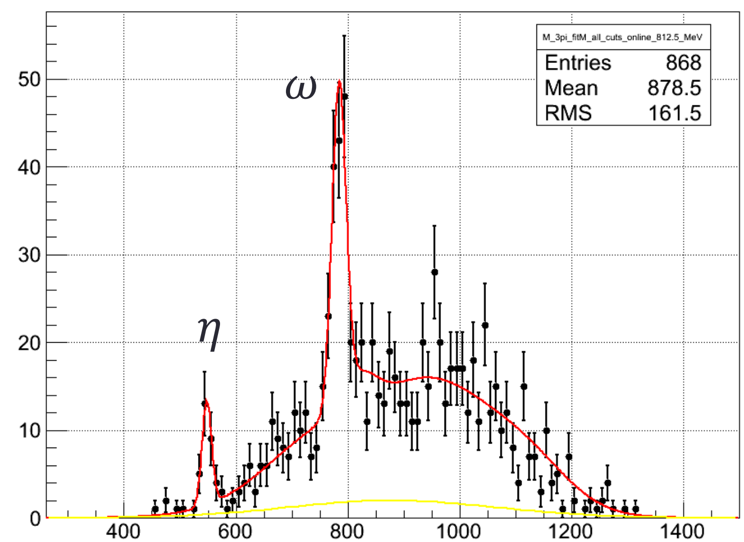
Cross section $e^+e^- \to \eta\pi^+\pi^-$



Dominated by intermediate ω and η

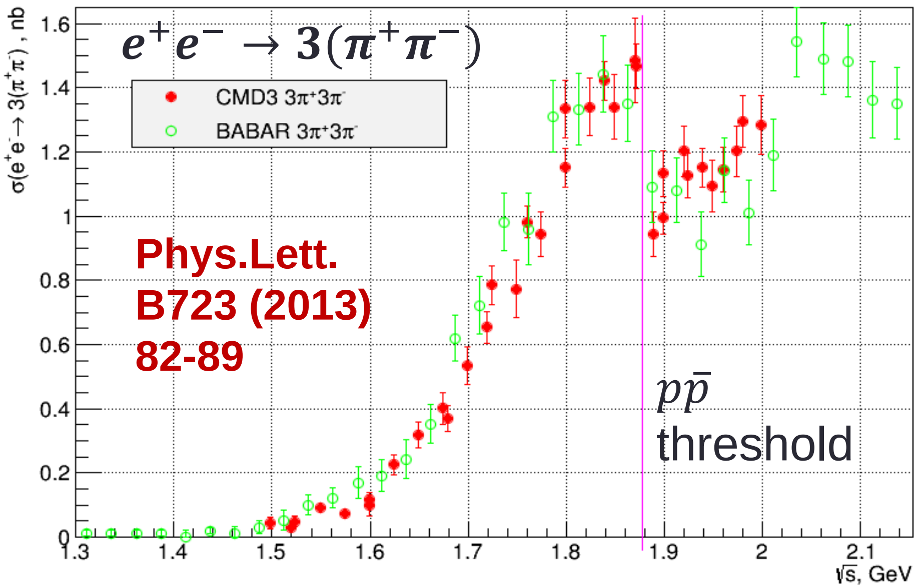
ω and η are observed in several final states, e.g. $\eta \to 3\pi$ and $\eta \to 2\gamma$

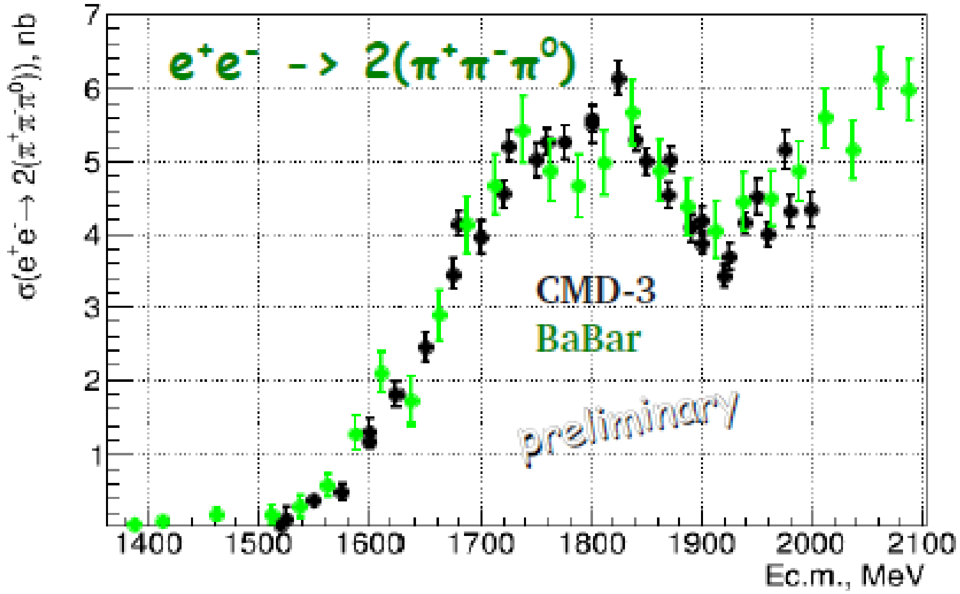
Expected systematic is 10%



Invariant mass of 3π

$e^+e^- \to 6\pi$





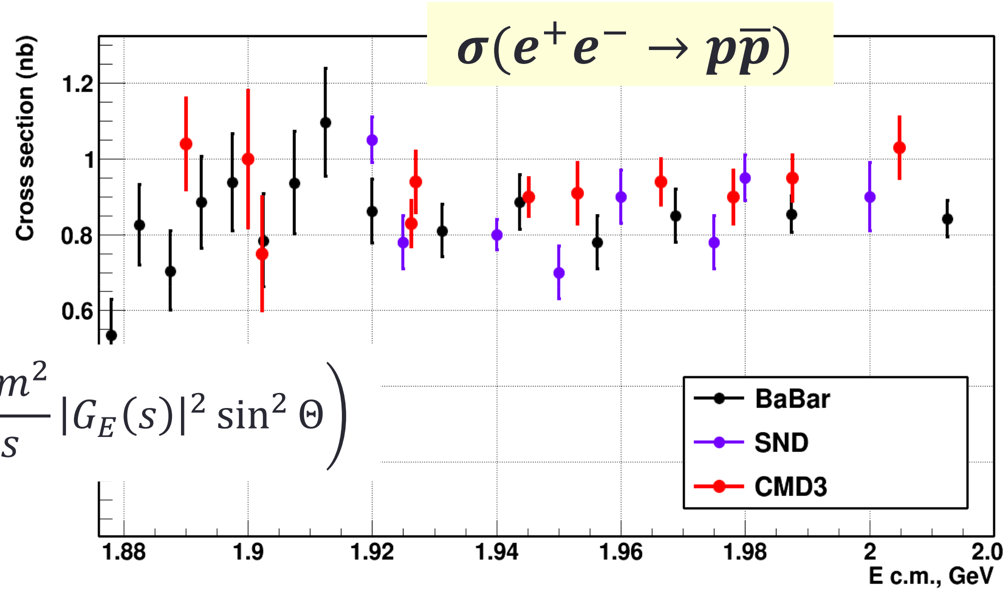
Systematic error is 6%, main source is model dependence. High statistics will help to reduce this error.

Preliminary studies of dynamics of $e^+e^- \to 3(\pi^+\pi^-)$:

- Main production mode: $\rho(770) + 4\pi$ (phase space or f_0(1370))
- Hint of energy dependent dynamics in 1.7-1.9 GeV energy range

$e^+e^- \to p\bar{p}$

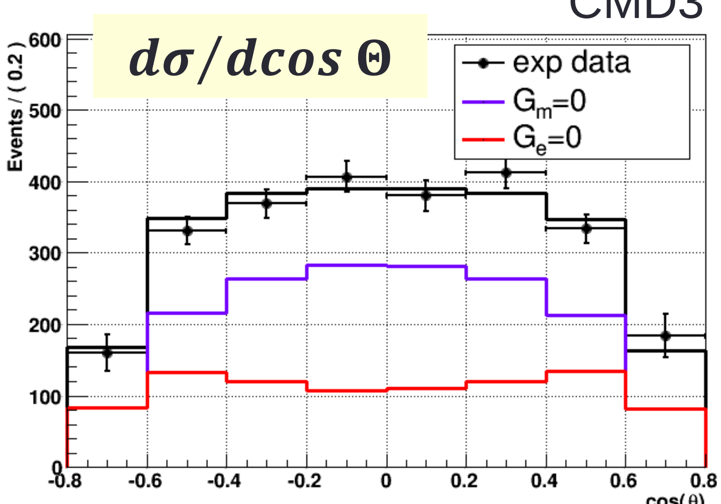
PID by dE/dx, secondaries

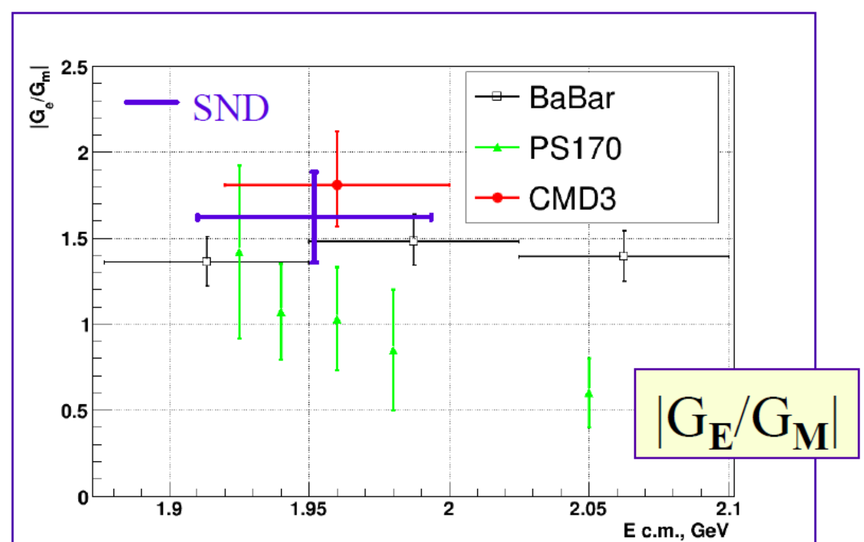


$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left(|G_M(s)|^2(1+\cos^2\Theta) + \frac{4m^2}{s}|G_E(s)|^2 \sin^2\Theta\right)$$

Angular distribution allows to measure $|G_E/G_M|$

CMD3

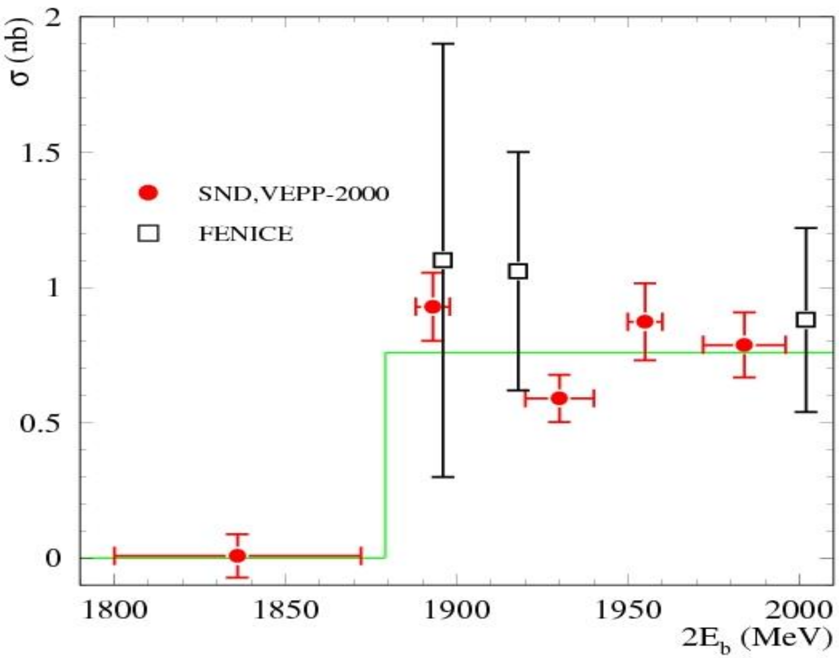




Need more statistics

$e^+e^- \to n\bar{n}$ at SND

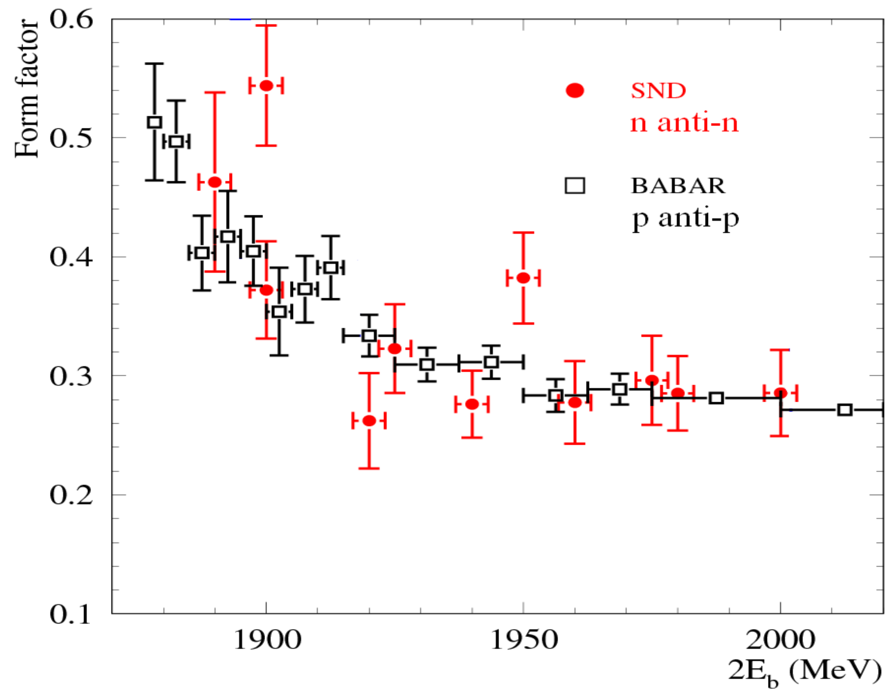
$$\sigma(e^+e^- \to n\bar{n})$$



Phys. Rev. D 90, 112007 (2014)

Effective formfactor

$$|F|^2 = \frac{|G_M|^2 + |G_E|^2/2\tau}{1 + 1/2\tau}, \qquad \tau = \frac{s}{4m_N^2}$$



Conclusion

- In 2011-2013 CMD-3 and SND have collected 60-70 1/pb per detector in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0$ GeV, available at VEPP-2000. Collected integral is similar to the total integral available before.
- Data analysis of many inclusive modes of $e^+e^- \to hadrons$ is in progress. First results ($\omega\pi^0$, 6π, $\eta\gamma$, η') have been published.
- After VEPP-2000 upgrade (scheduled to be finished in 2015) we plan to resume data taking with the ultimate goal of 1 1/fb
- We expect to produce new precise measurements of hadron production R(s), to improve the precision of the hadronic contribution to muon (g-2)