



# Recent results from CMD-3 detector at VEPP-2000 collider

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on behalf of CMD-3 Collaboration

September 2015

# Outline

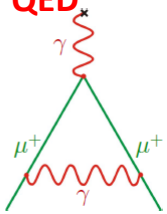
- Motivation
- Collider and detector(s)
- Experiment
- Recent results:
- Perspectives and plans
- Conclusion

# Motivation for low energy e+e-

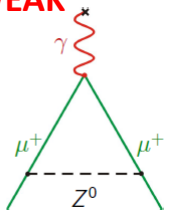
- Magnetic moment of muon: $\vec{\mu} = g\frac{e\hbar}{2mc}\vec{s}$
- Gyromagnetic factor g for
  - Dirac particles (point-like fermions): g = 2
  - Higher order contributions (QFT): g ≠ 2
- Muon anomaly
  - $a_\mu = (g-2)_\mu/2$

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

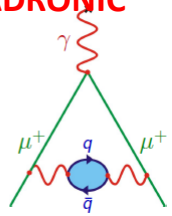
QED



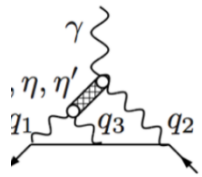

WEAK




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 |

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

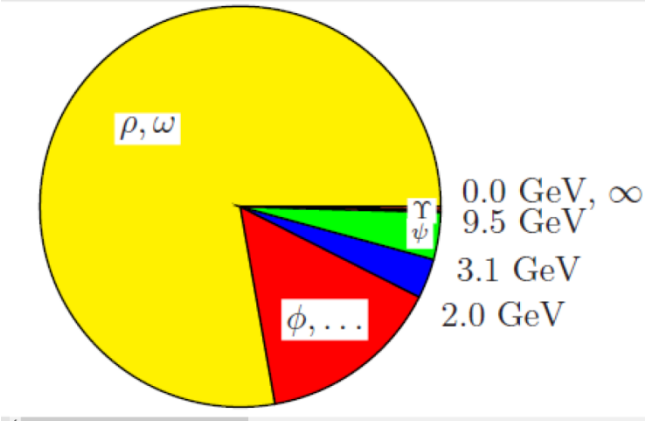
$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

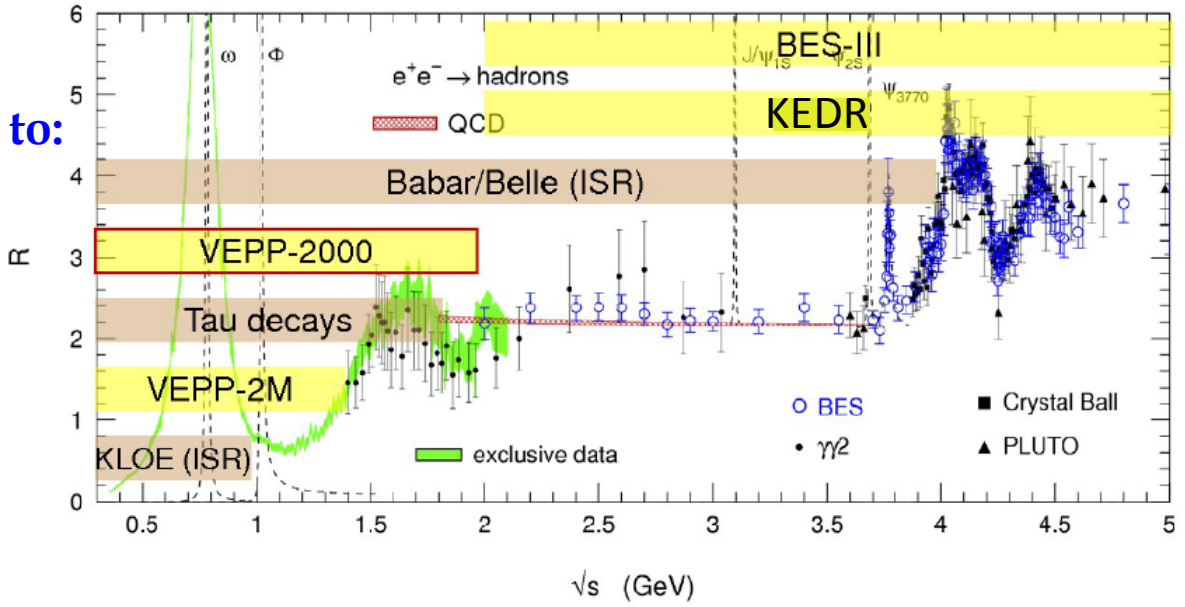
$$a_\mu^{EXP} - a_\mu^{SM} = 3.6\sigma$$ **(M. Davier et al., EPJC71(2011)1515)**

**Low energy contributions are important!**
**Experimental input is needed!**

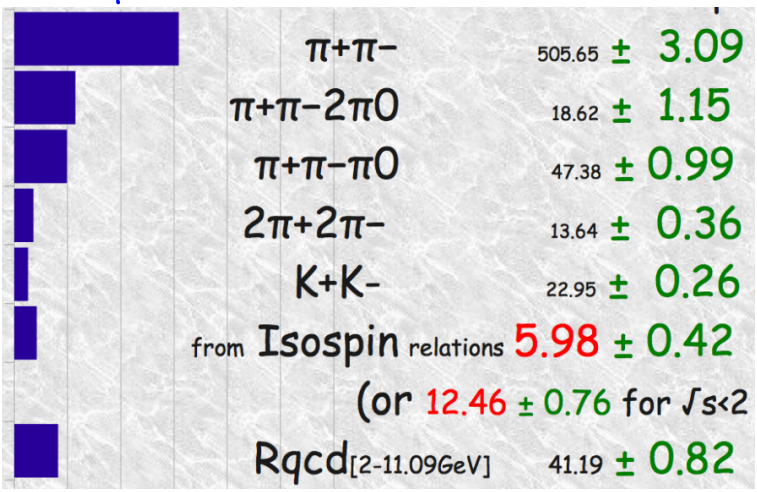
# R measurements at low s

**Contributions of the different energy regions to:**

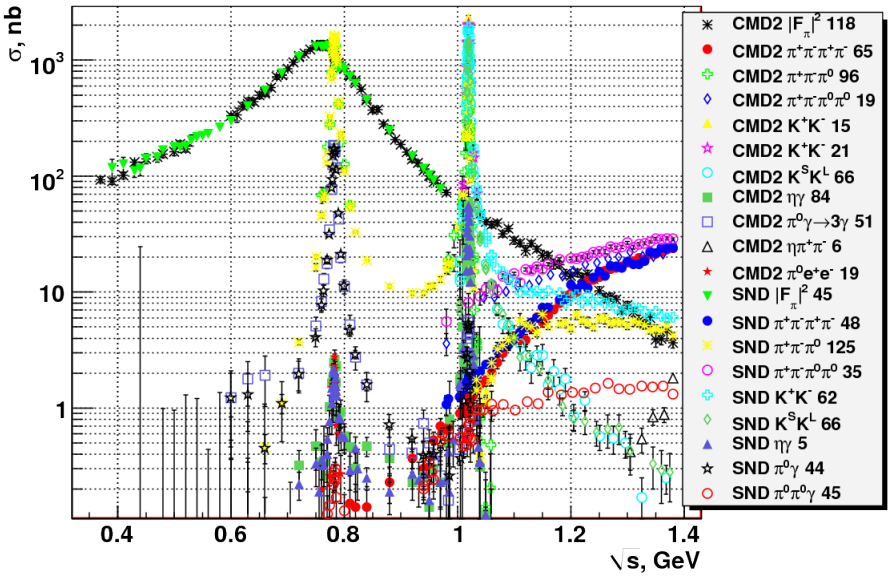



**$a_\mu$ integral**

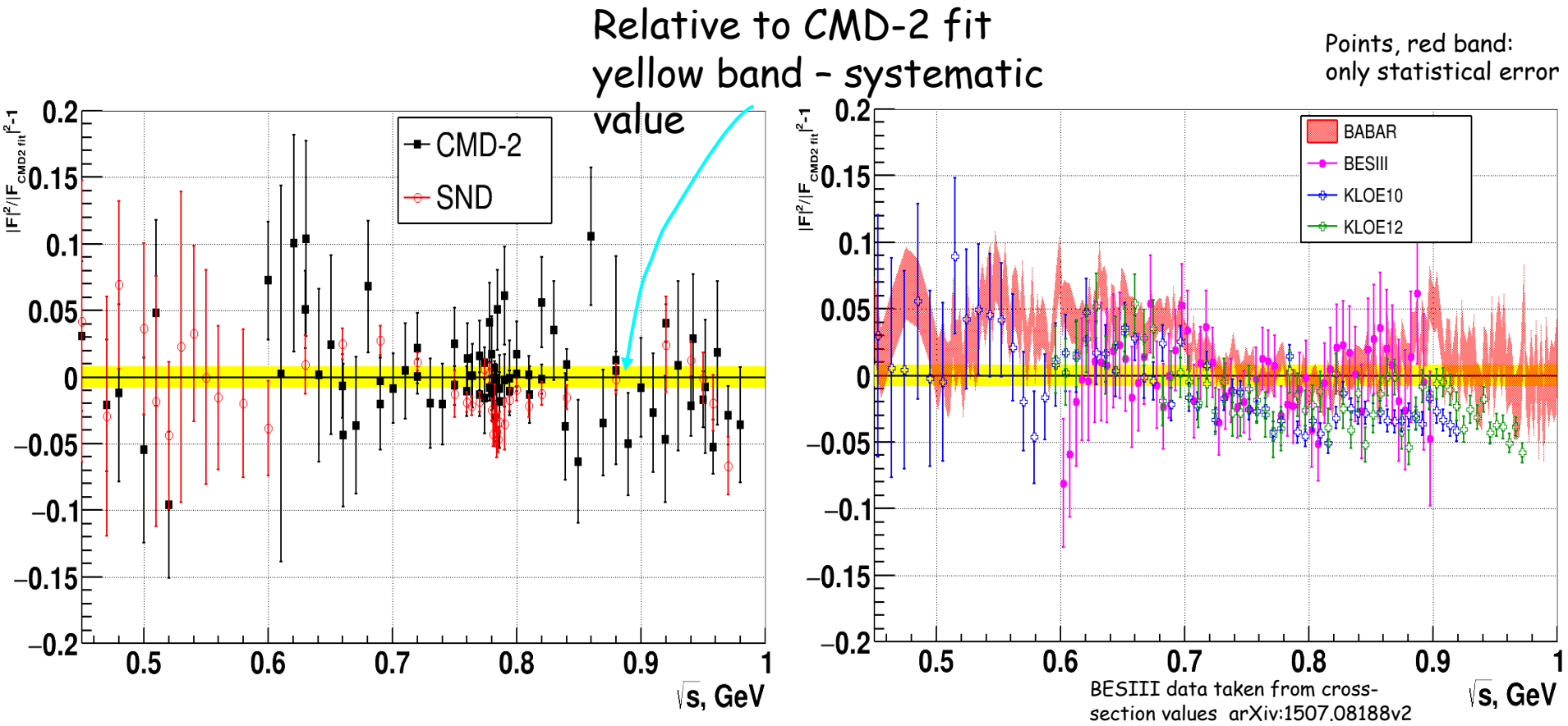



**$a_\mu$ uncetainty**



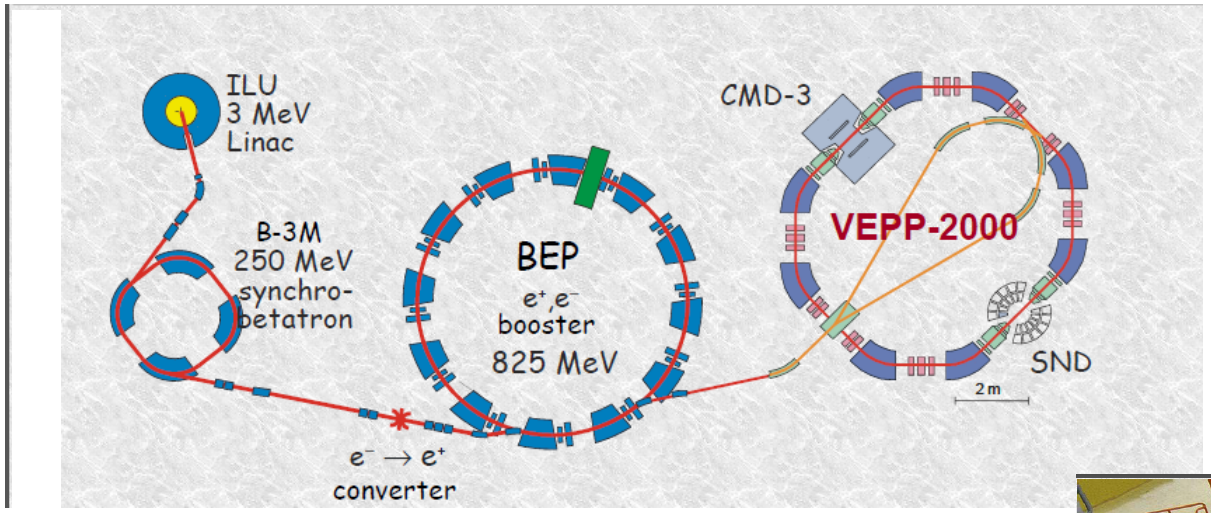

**Precise measurements of $\sigma_{had}$ in $m_{2\pi} < E_{cm} < 2$ GeV are important**

# Published cross section e+ e− → π+ π−



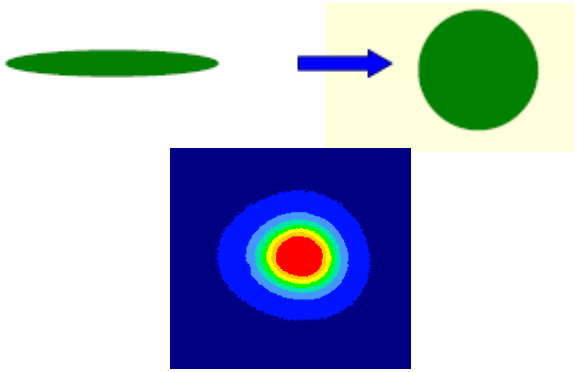

Local inconsistencies larger than claimed systematic errors seen

# VEPP-2000 Collider (2010-2013)



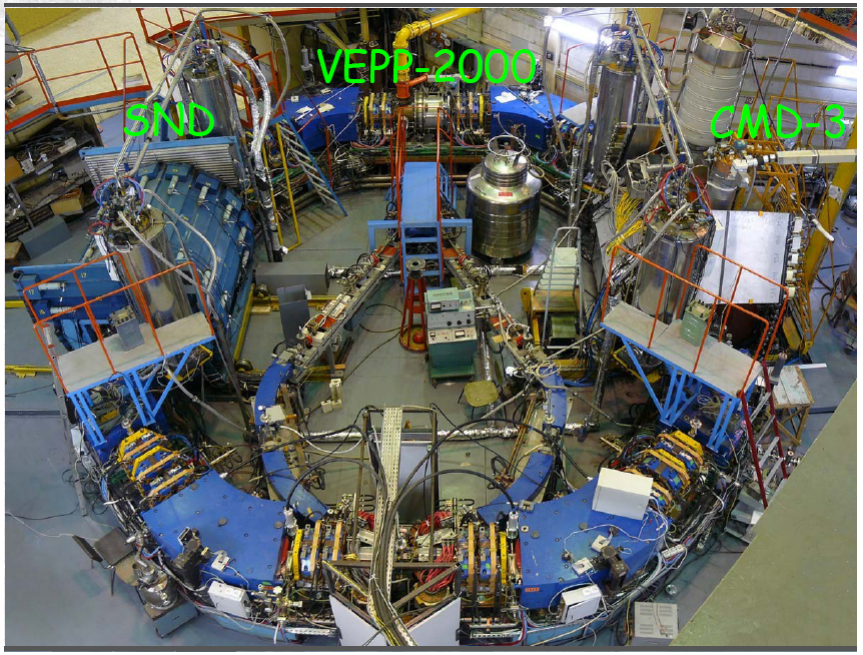

| | VEPP-2M | VEPP-2000 | |
|---|---|---|---|
| E (MeV) | 510 | 510 | 900 |
| Π (cm) | 1788 | 2235 | 2235 |
| $\mathcal{I}^+, \mathcal{I}^-$ (mA) | 40 | 34 | 200 |
| $\varepsilon \cdot 10^5$ (cm · rad) | 3 | 0.5 | 1.6 |
| $\beta_x$ (cm) | 40 | 6.3 | 6.3 |
| $\beta_z$ (cm) | 5 | 6.3 | 6.3 |
| $\xi_x$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

## Main idea: Round Beams

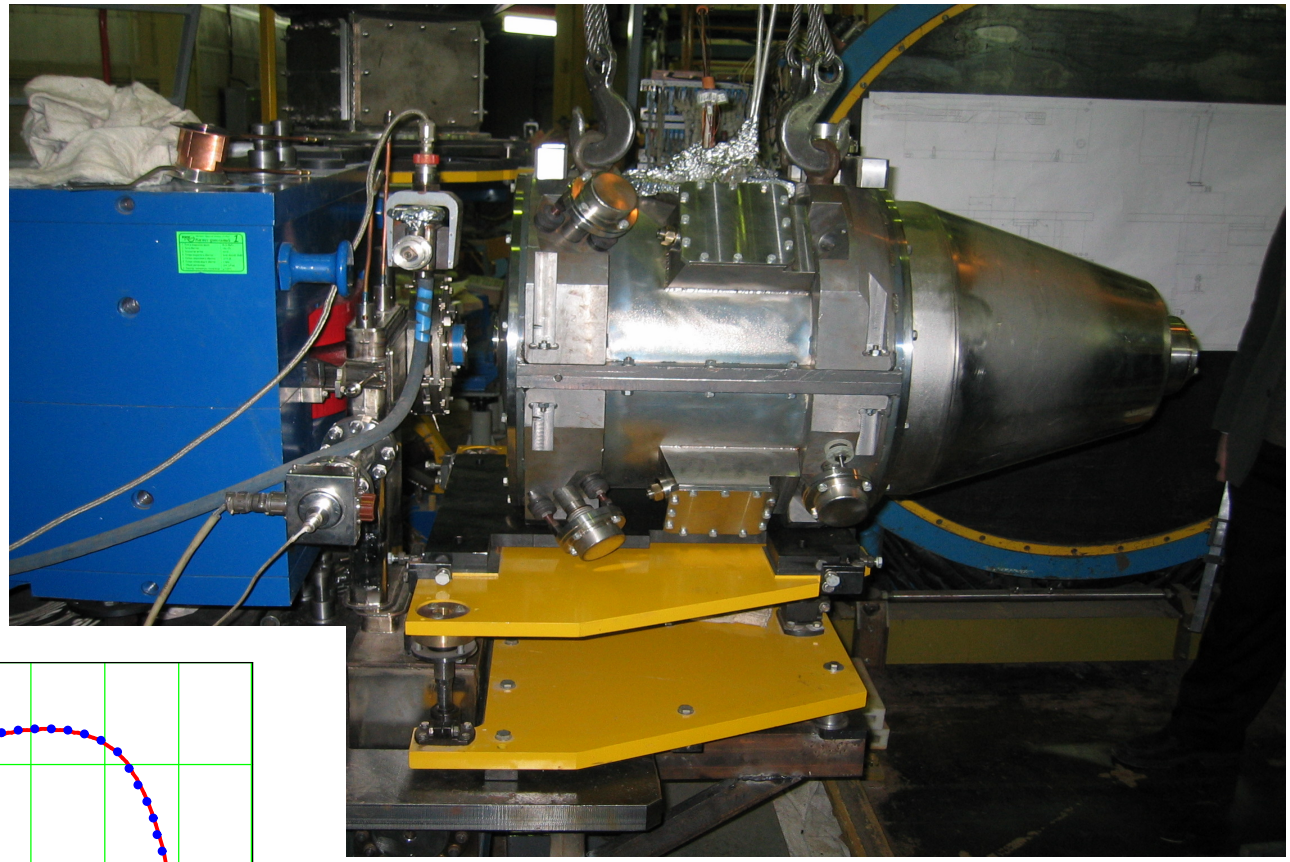


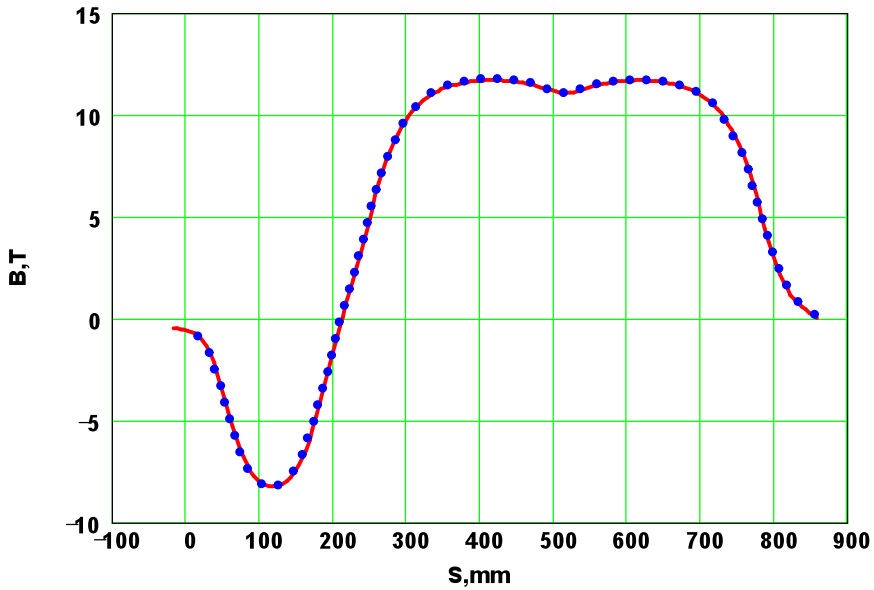
$$L = \frac{\pi\gamma^2 \xi_x \xi_y \varepsilon_x f}{r_e^2 \beta_y^*}\left(1+\frac{\sigma_y}{\sigma_x}\right)^2 \quad \Rightarrow \quad L = \frac{4\pi\gamma^2 \xi^2 \varepsilon f}{r_e^2 \beta^*} \quad \text{(x4)}$$

reduce beam-beam effects $\xi_{x,y} \geq 0.1$ (x4)

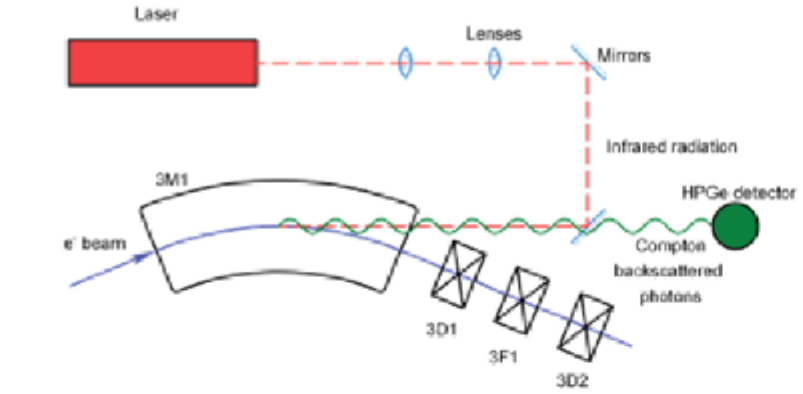


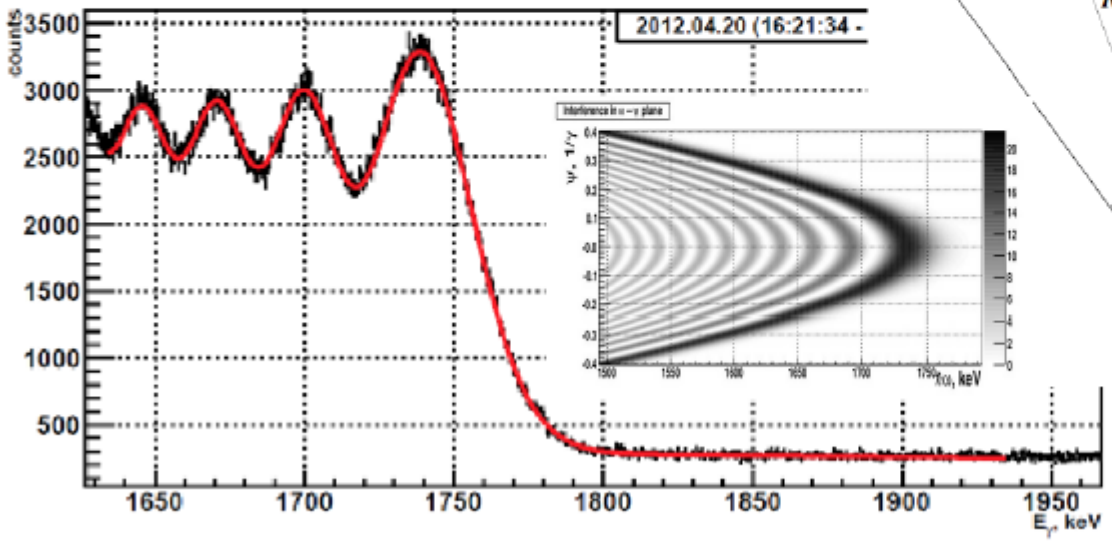
# Solenoid 13.0 T  at VEPP-2000

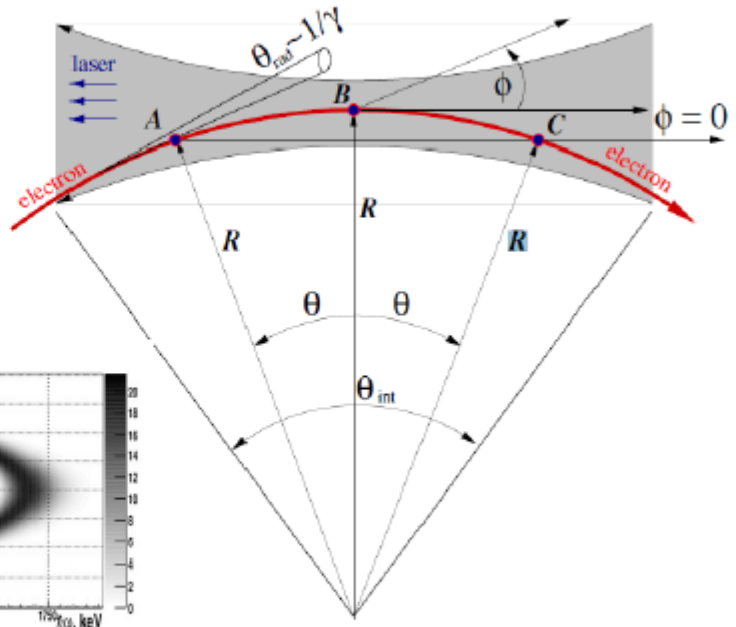




# Compton backscattering beam energy measurement




E = 993.662 ± 0.016 МэВ

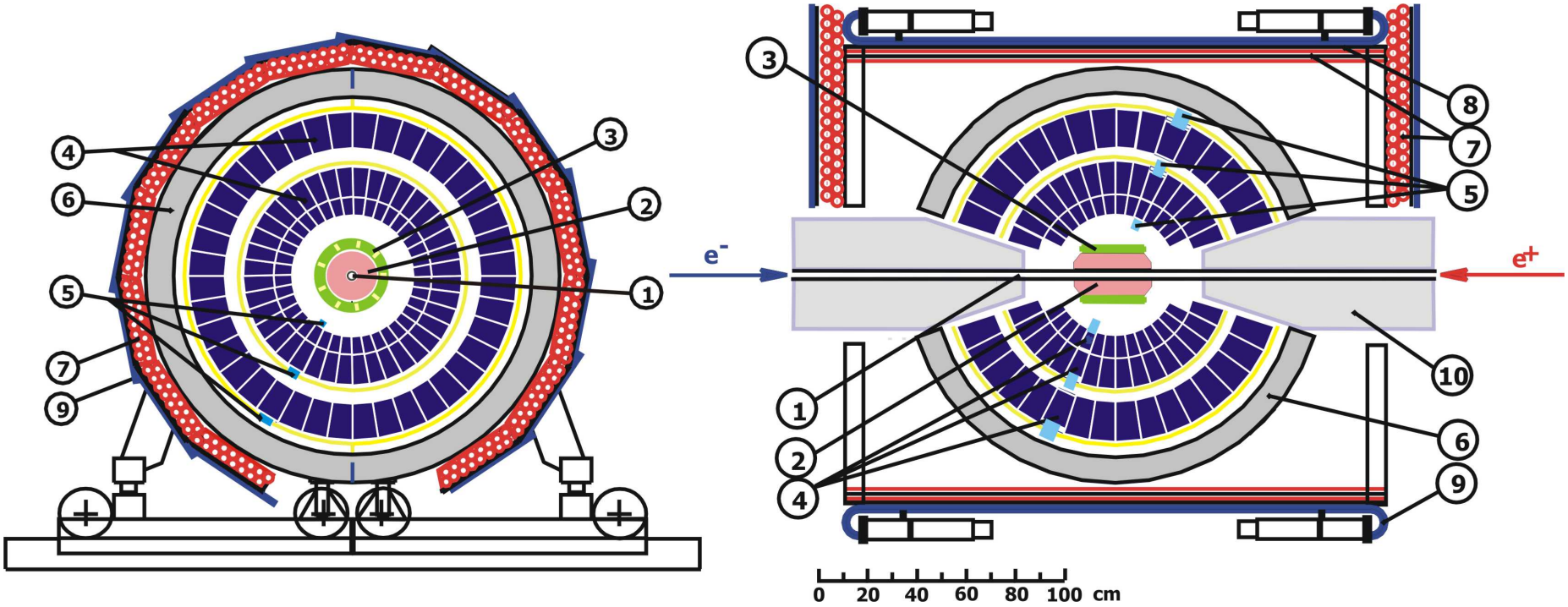
E.V. Abakumova et al., Phys. Rev. Lett. 110 (2013) 14, 140402,
E.V. Abakumova et al.,Nucl.Instrum.Meth. A744 (2014) 35-40

# Physics program at VEPP-2000

1. Precise measurement of the quantity
   $R=\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ – GOAL <1% systematic for major channels
2. Study of hadronic channels:
   $e^+e^- \to 2h, 3h, 4h \ldots$, $h= \pi, K, \eta$
3. Study of 'excited' vector mesons: $\rho'$, $\rho''$, $\omega'$, $\varphi'$,..
4. CVC tests: comparison of $e^+e^- \to$ hadr. (T=1)
   cross section with $\tau$-decay spectra
5. Study of nucleon-antinucleon pair production –
   nucleon electromagnetic form factors,
   search for NNbar resonances, ..
6. Hadron production in 'radiative return'
   (ISR) processes
7. Two photon physics
8. Test of the QED high order processes 2->4,5

Two detectors have been build for the study

# Spherical Neutral Detector



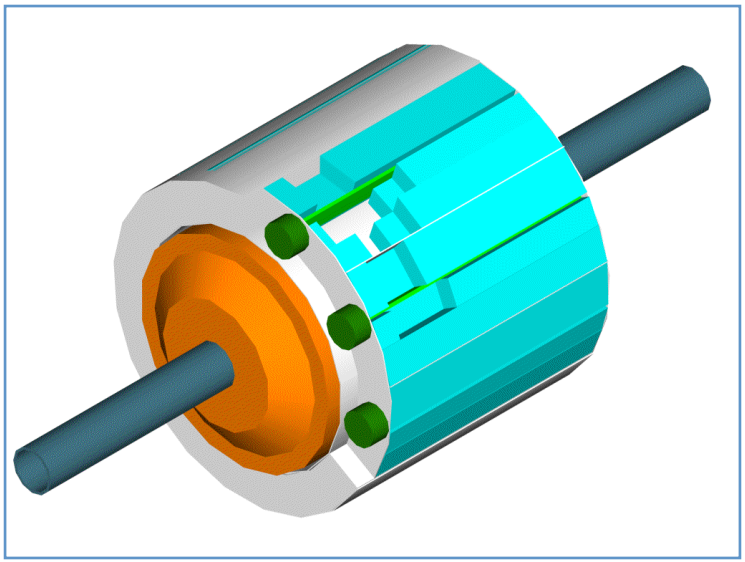

1 – VEPP-2000 vacuum chamber, 2 – tracking system,

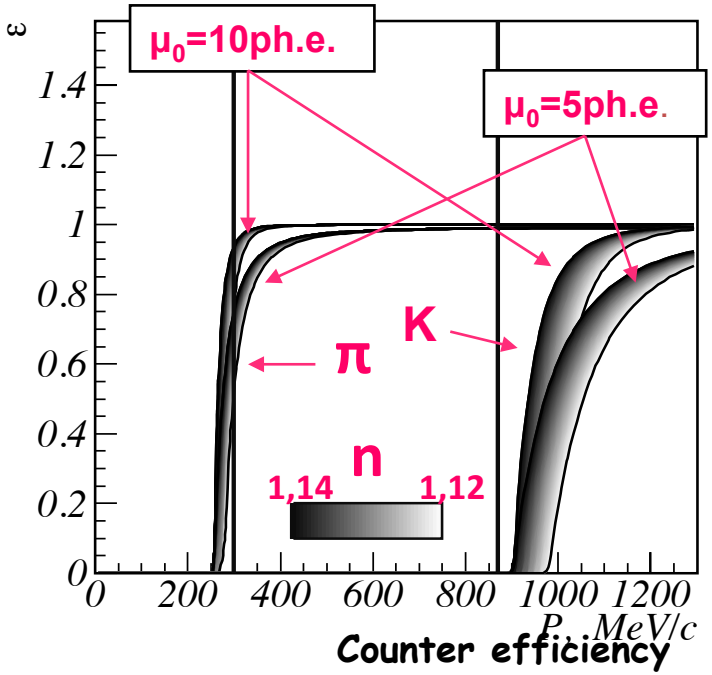
3 – aerogel counters, 4 – electromagnetic calorimeter NaI(Tl), 5 – vacuum phototriodes, 6 – absorber, 7-9 – muon system,

10 – VEPP-2000 phocusing solenoid

# Particle ID Aerogel Counters

## e/π, π/K separation

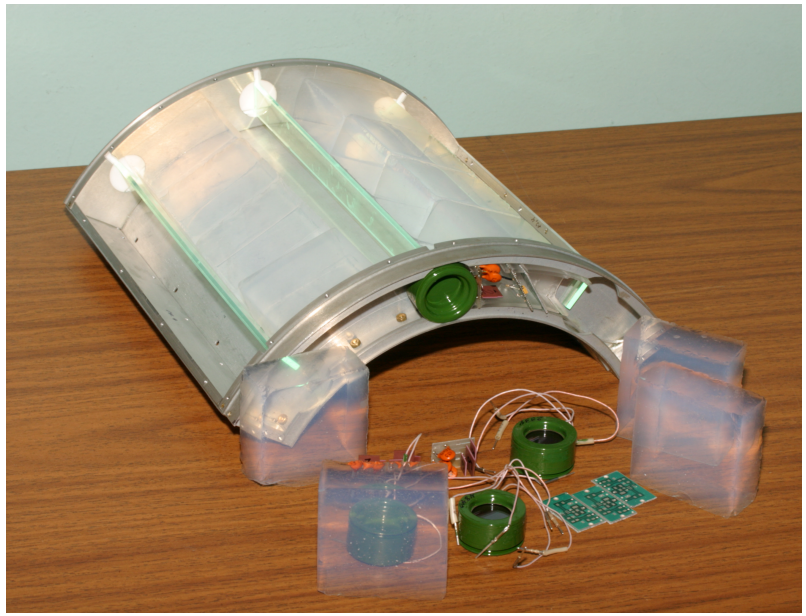





Counter efficiency

$n_{opt}=1.13$

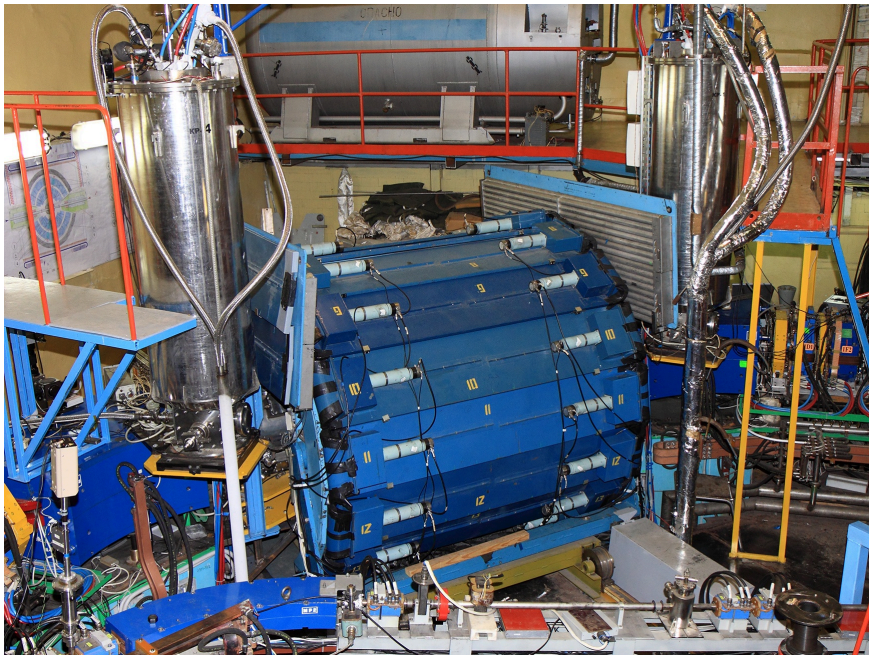
$\bar{N}_{pe}=11.67$

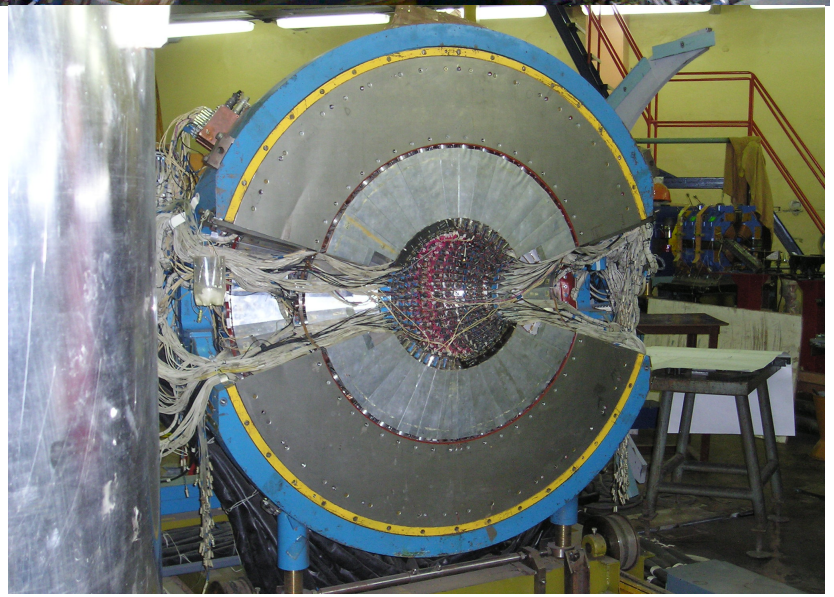


Aerogel + shifter + PMT
Aerogel thickness 31 mm
Shifter turned by 5°
Teflon coverage (R=0.98)

*Nucl.Instrum.Meth.A315:517-520,1992*

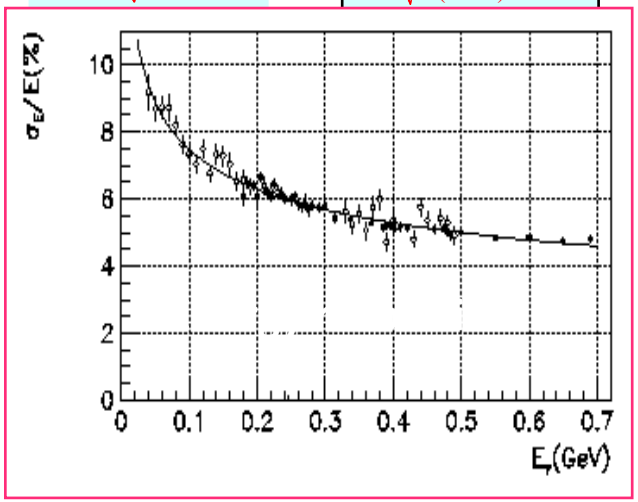
# Spherical Neutral Detector



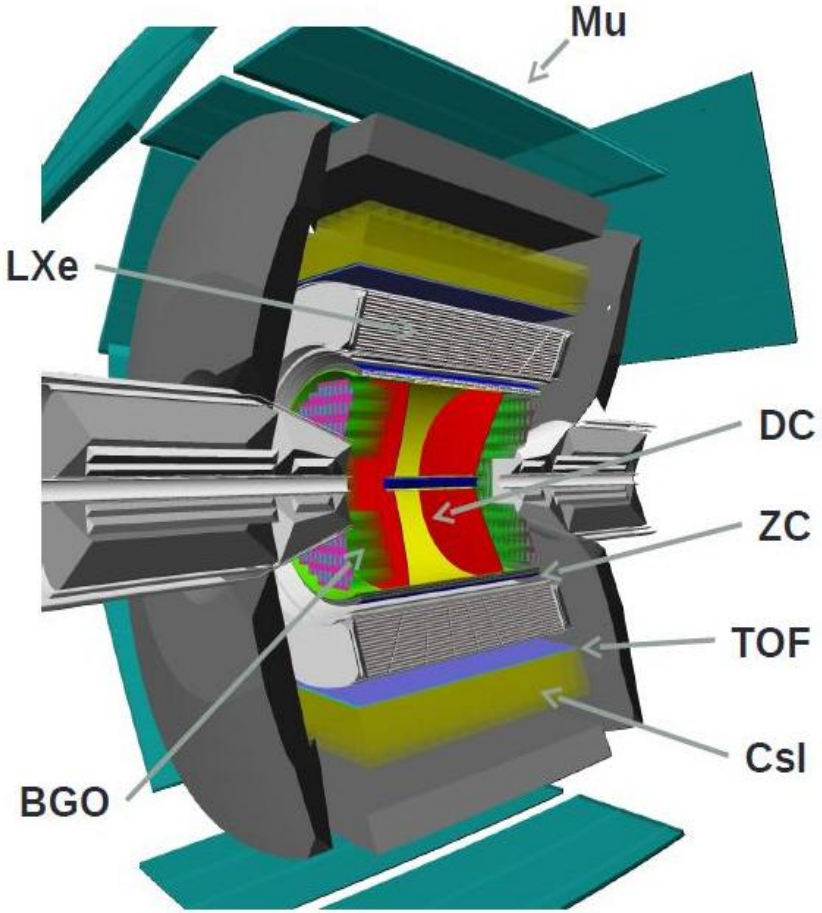


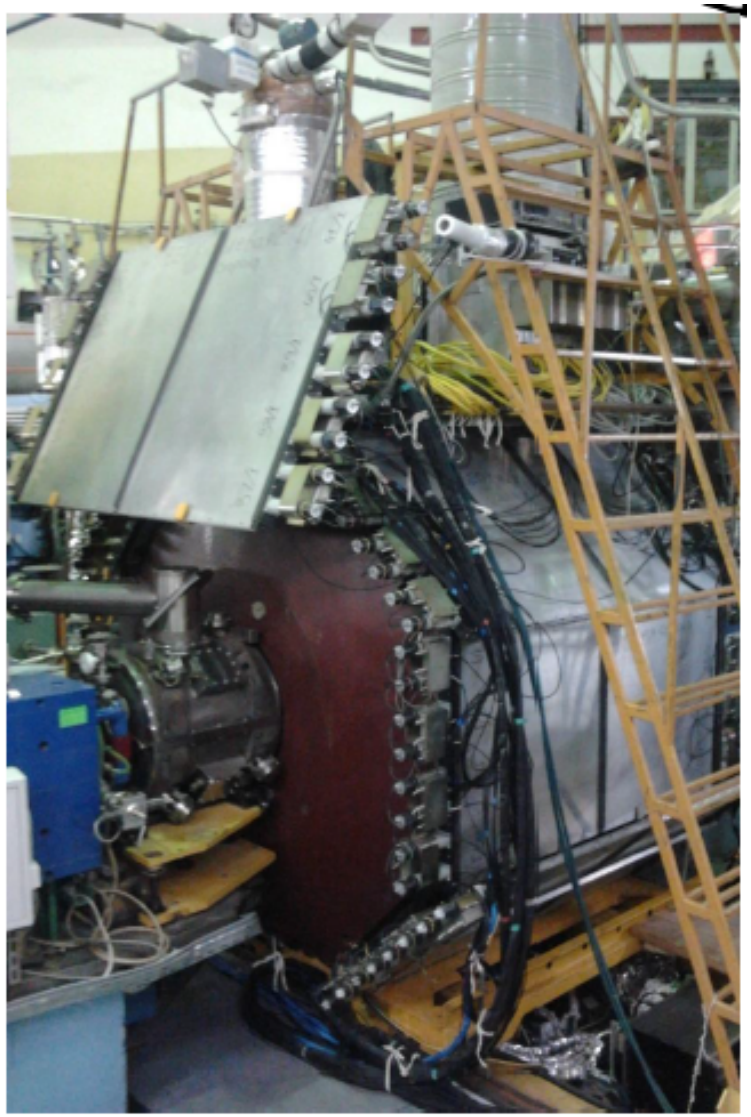
$$\frac{\sigma E}{E} = \frac{4.2\%}{\sqrt[4]{E(GeV)}}$$

$$\sigma_\phi = \frac{0.82^0}{\sqrt{E(GeV)}} \oplus 0.63^0$$



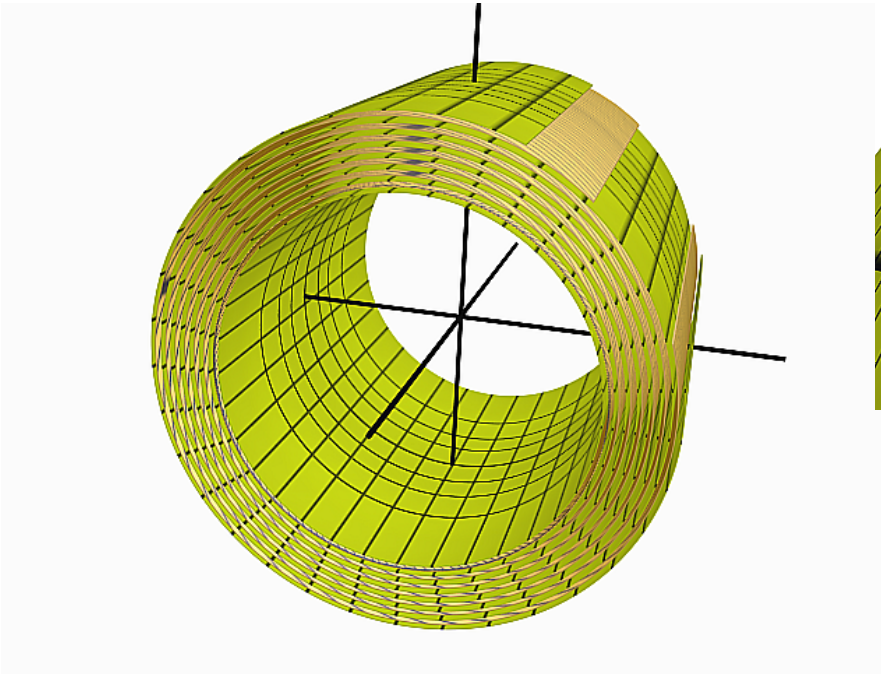
# CMD-3 Detector

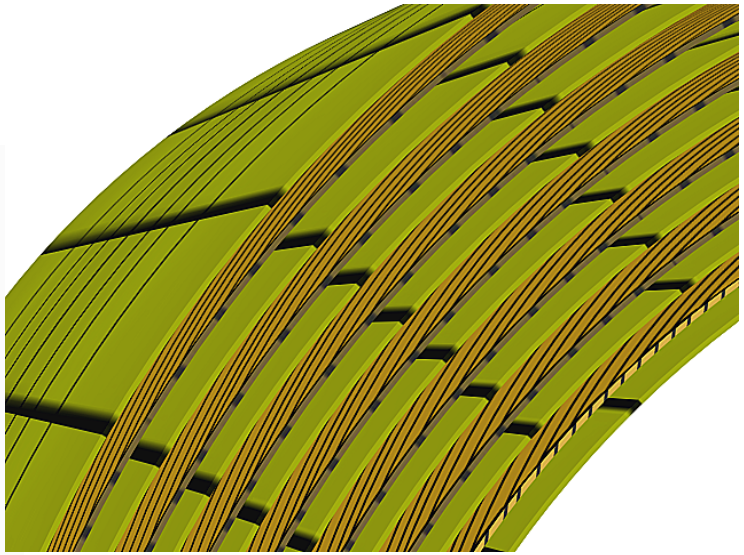


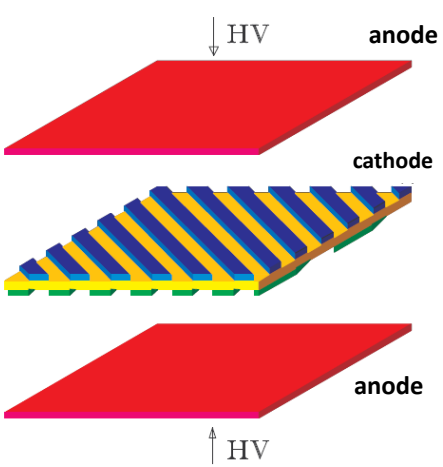
**DC– drift chamber**
**ZC – Z–chamber**
**LXE – liquid xenon calorimeter**
**CsI– calorimeter, 1152 crystals**
**TOF – time of flight system**
**Mu - muon system**
**BGO– calorimeter, 680 crystals**

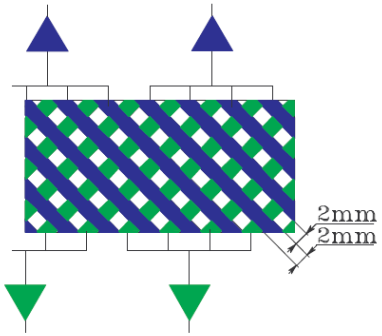
# Calorimeter LXe

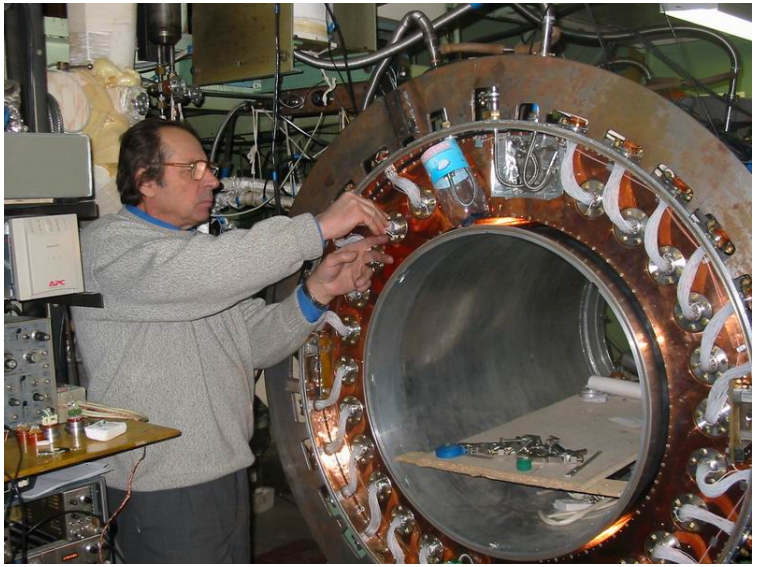




5.7 $X_0$ of LXe (400 liters, 1.2 tons)
14 gaps by 10.2 mm
2124 coordinate strips
264 towers

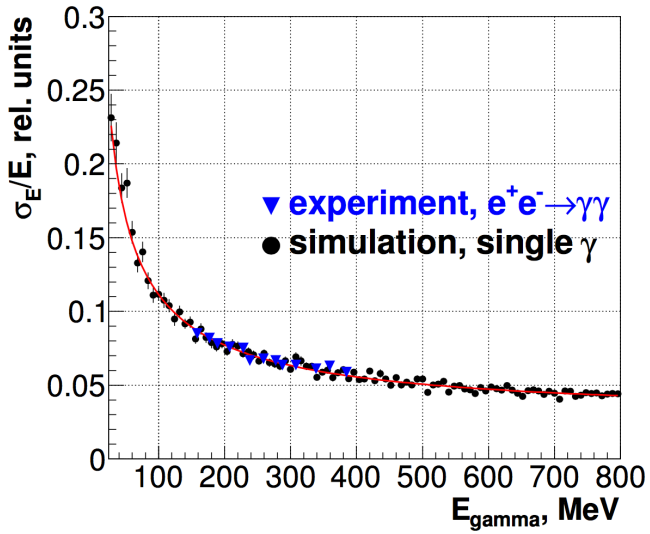


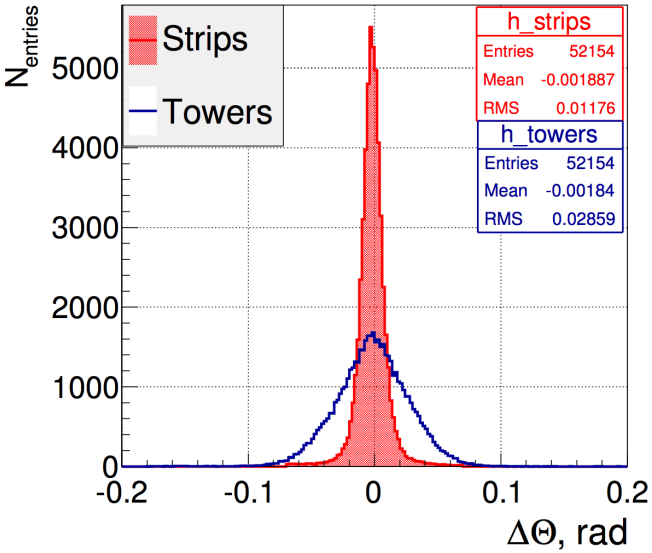



# Calorimeter LXe

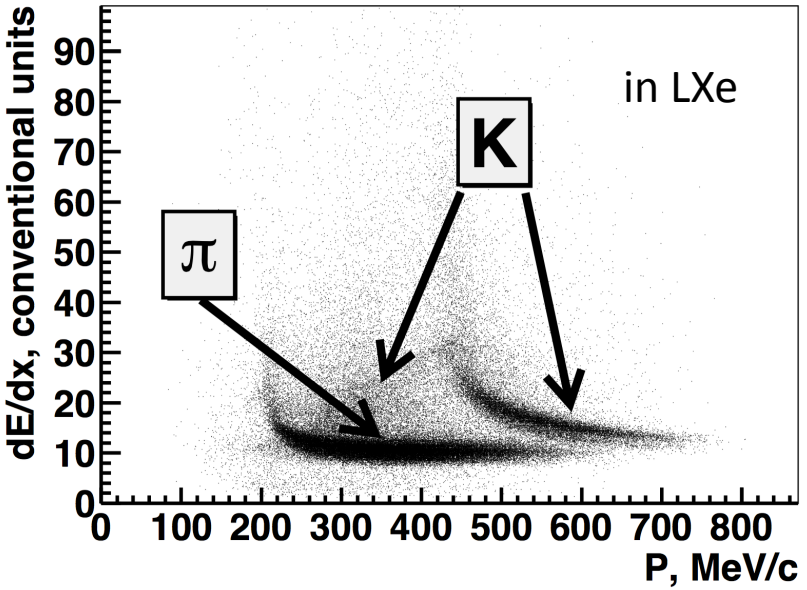
Good energy resolution (in combunation with CsI and BGO)

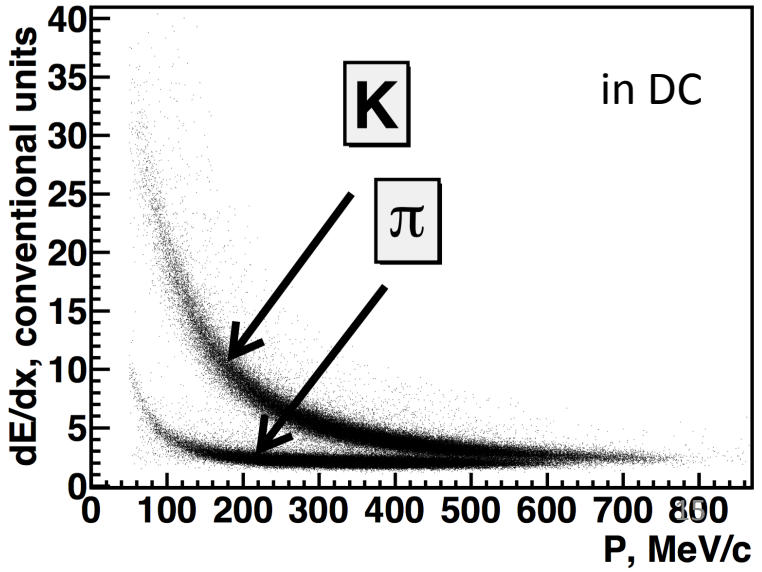



1-2 mm conversion point resolution for photons

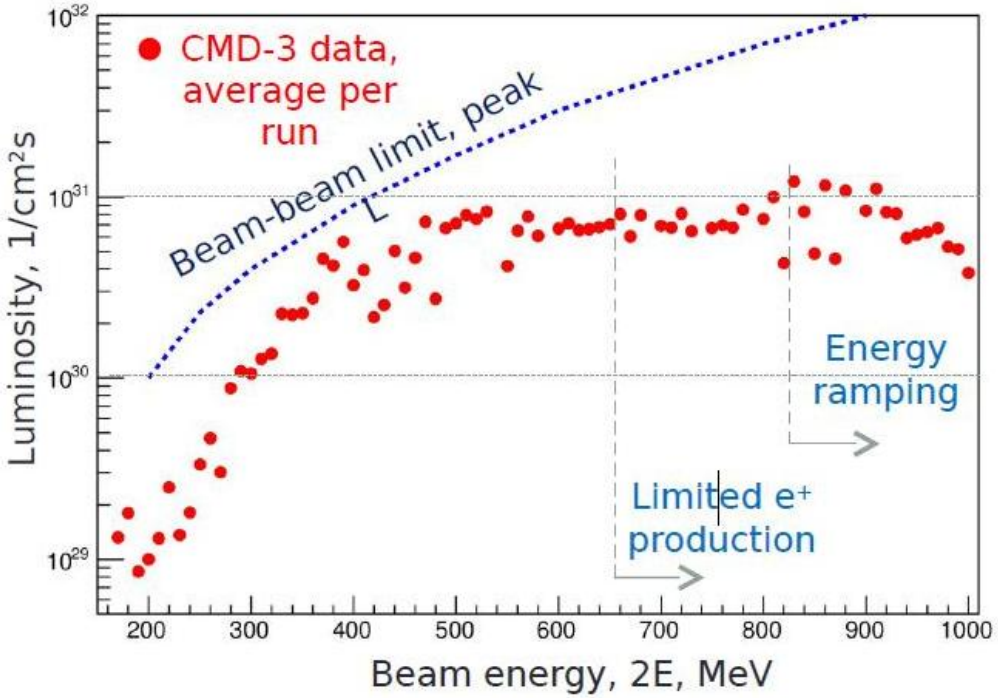


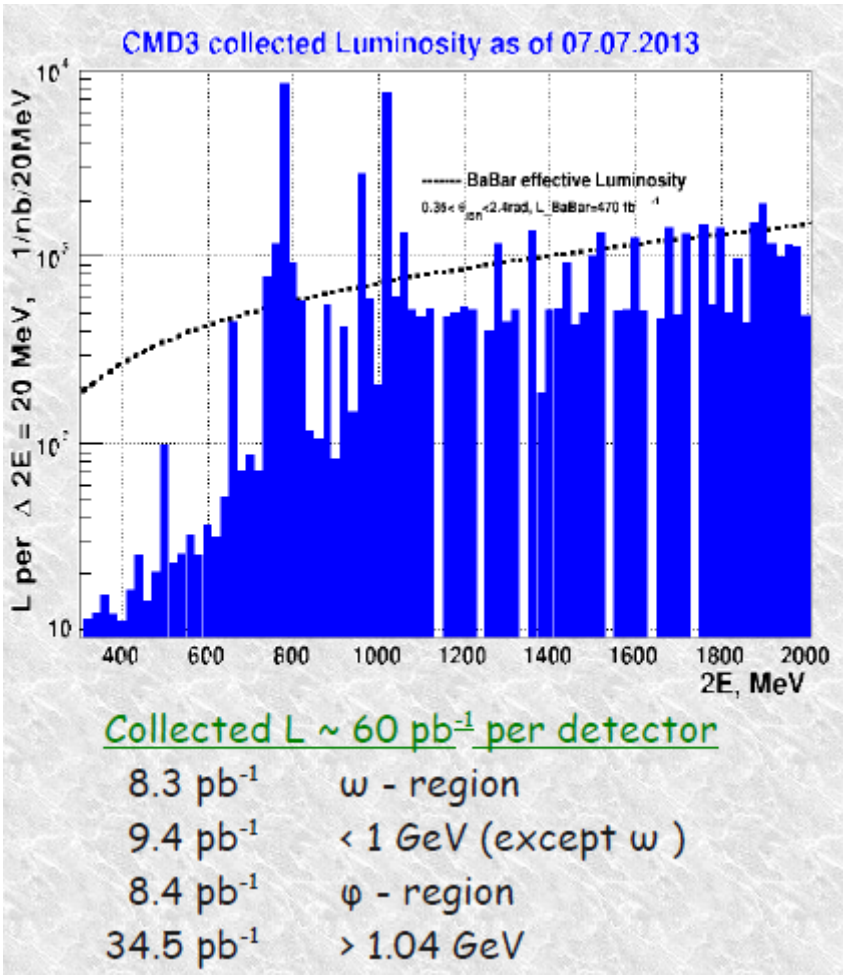

**Additional dE/dx information**



# Collected Luminosity




**The maximum luminosity is $2 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$ at 1.7-1.8 GeV, falling much slower with decreasing energy than before the round beams**

**At high energies luminosity is limited by a deficit of positrons and maximum energy of the booster (820 MeV now)**

Collected L ~ 60 pb$^{-1}$ per detector

| | |
|---|---|
| 8.3 pb$^{-1}$ | ω - region |
| 9.4 pb$^{-1}$ | < 1 GeV (except ω ) |
| 8.4 pb$^{-1}$ | φ - region |
| 34.5 pb$^{-1}$ | > 1.04 GeV |

**In 2013 we reached 2 × 160 MeV, the smallest energy ever measured at $e^+e^-$ colliders**

# SND RESULTS will not be presented in this talk

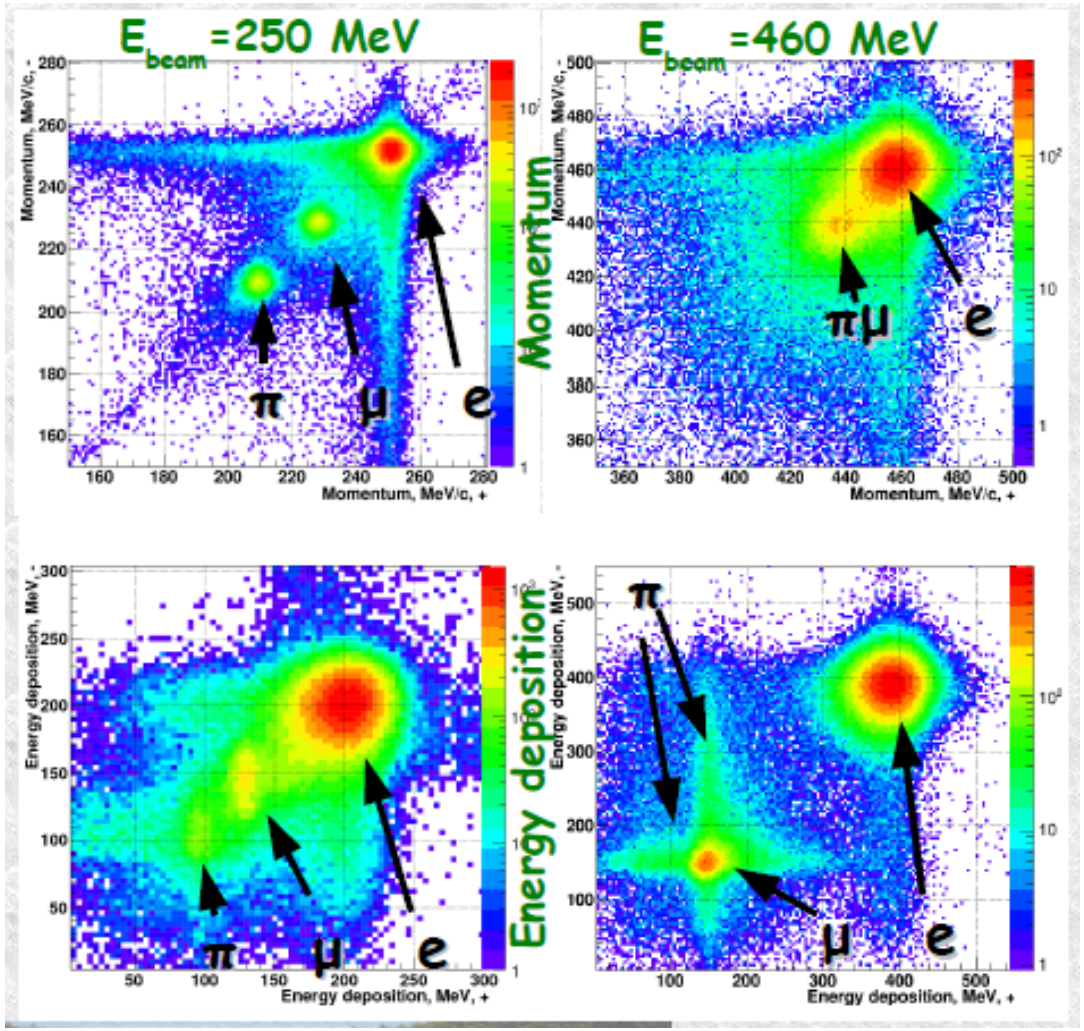
But many reactions are being studying by both detectors

# $e^+e^- \to \pi^+\pi^-$:selection

Main sources of systematics:

- 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




**Goal is 0.35% of systematic accuracy**

# MC generators

High experimental precision relies on theoretical precision of MC tools:

Most recent e+e- -> e+e- (gamma) generators
include exact $O(\alpha)$ + some parts from High Order terms:

MCGPJ (VEPP-2000) – accuracy 0.2% for e+e-, $\pi+\pi-$ etc
1 real photon (from any particle)
+ photon jets along all particles (collinear Structure function)

BabaYaga@NLO (KLOE,BaBar) - 0.1% for e+e-, $\mu+\mu-$
Parton shower approach: n photons with angle distribution
interference for 1 photon radiation

BHWIDE (LEP) – 0.5% (~0.1%?), e+e−
n real photons by Yennie-Frautschi-Suura (YFS) exponentiation method
interference on $O(\alpha)$ level

And there are other generators for different channels:
PHOKHARA (KLOE) $\mu+\mu-$, $\pi+\pi-$ etc
KKMC ($\mu+\mu-$),
etc

# BabaYaga@NLO vs MCGPJ generators

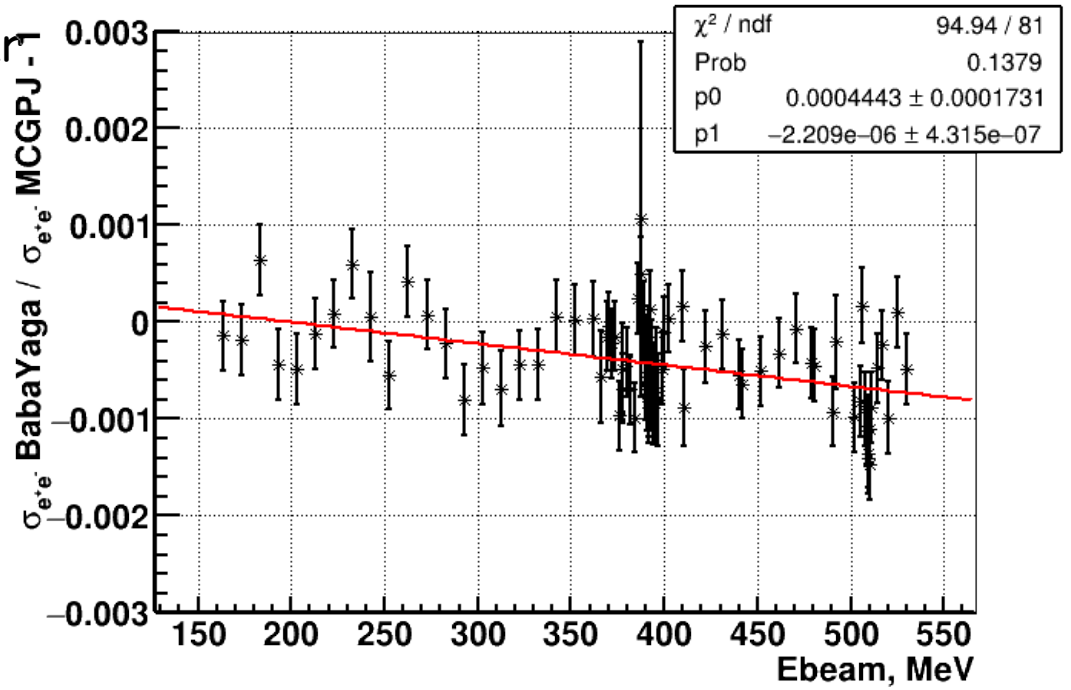
BabaYaga@NLO used by KLOE, BaBar

MCGPJ used by Novosibirsk group

<u>Selection cuts:</u>
$|\Delta\phi|<0.15$, $|\Delta\theta|<0.25$
$1 < \theta < \pi - 1$

$P > 0.45\ E_{beam}$

<u>Calculated cross-section at E beam=391.48 MeV</u>
MCGPJ : 751.671 +- 0.034 nb
BabaYaga@NLO : 751.218 +- 0.059 nb
$\Delta$ ~ **0.06%**



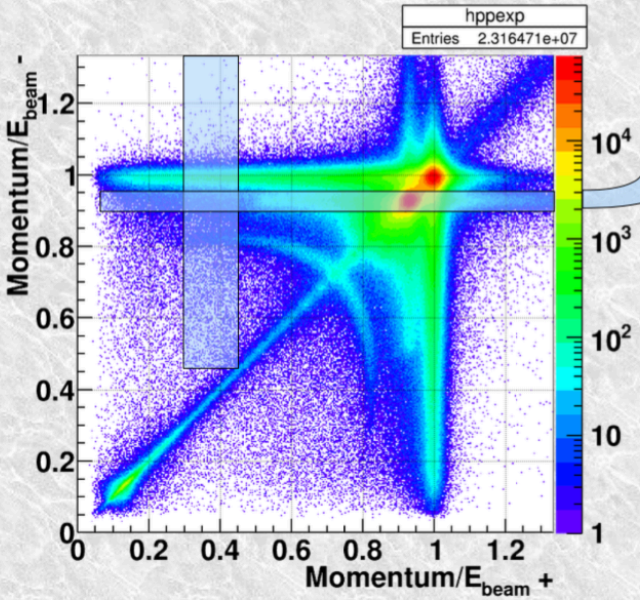

Integrated cross-section consistent at the level <0.1%

BabaYaga@NLO ~ x1000 slower than MCGPJ

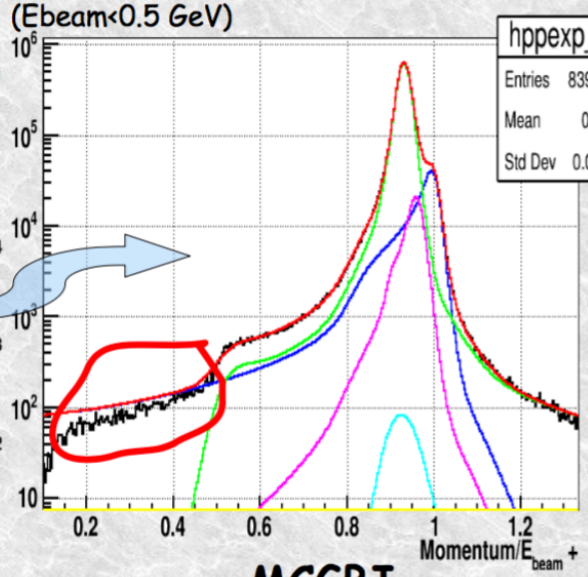
A discrepancy was observed in momentum distribution of experimental data vs fitted functions with input from MCGPJ

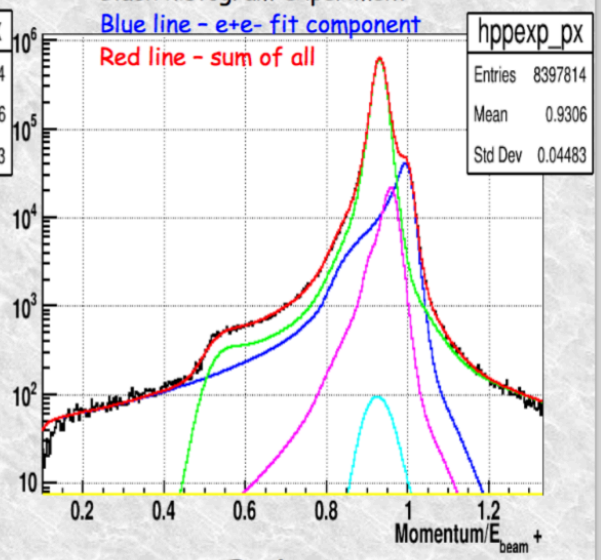
# BabaYaga @ NLO vs MCGPJ vs experiment

All events from RHO2013 scan (Ebeam<0.5 GeV)
(~ 10 millions of e+e- and π+π-)

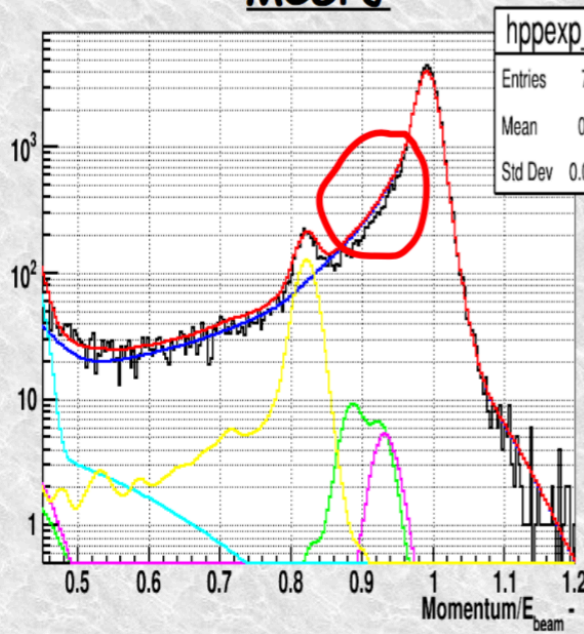



Black histogram-experiment
Blue line – e+e- fit component
Red line – sum of all

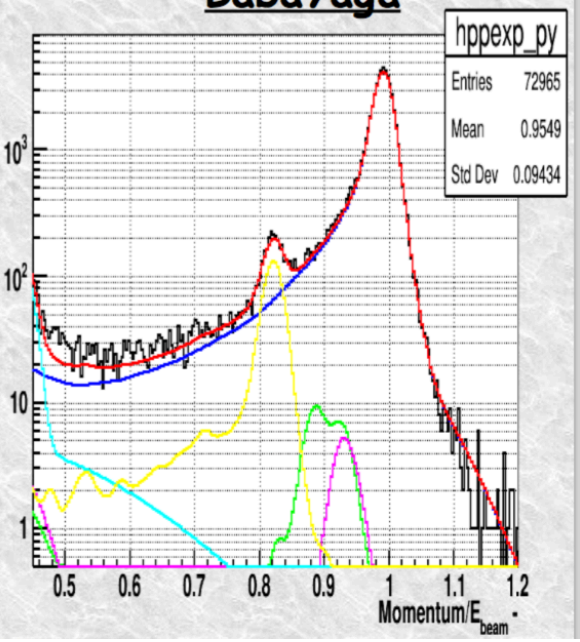



MCGPJ




BabaYaga

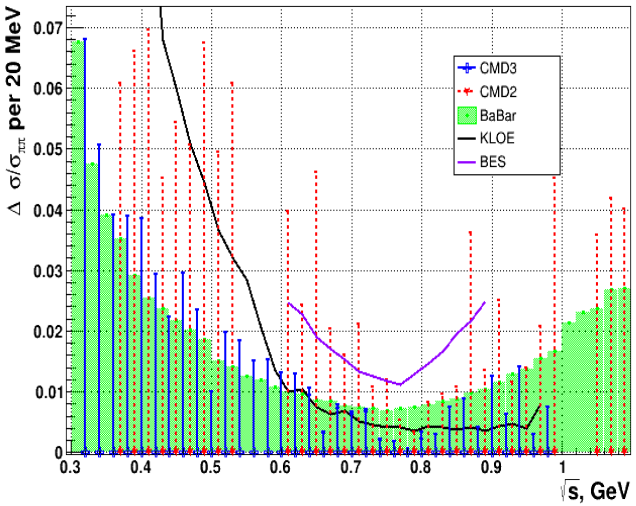


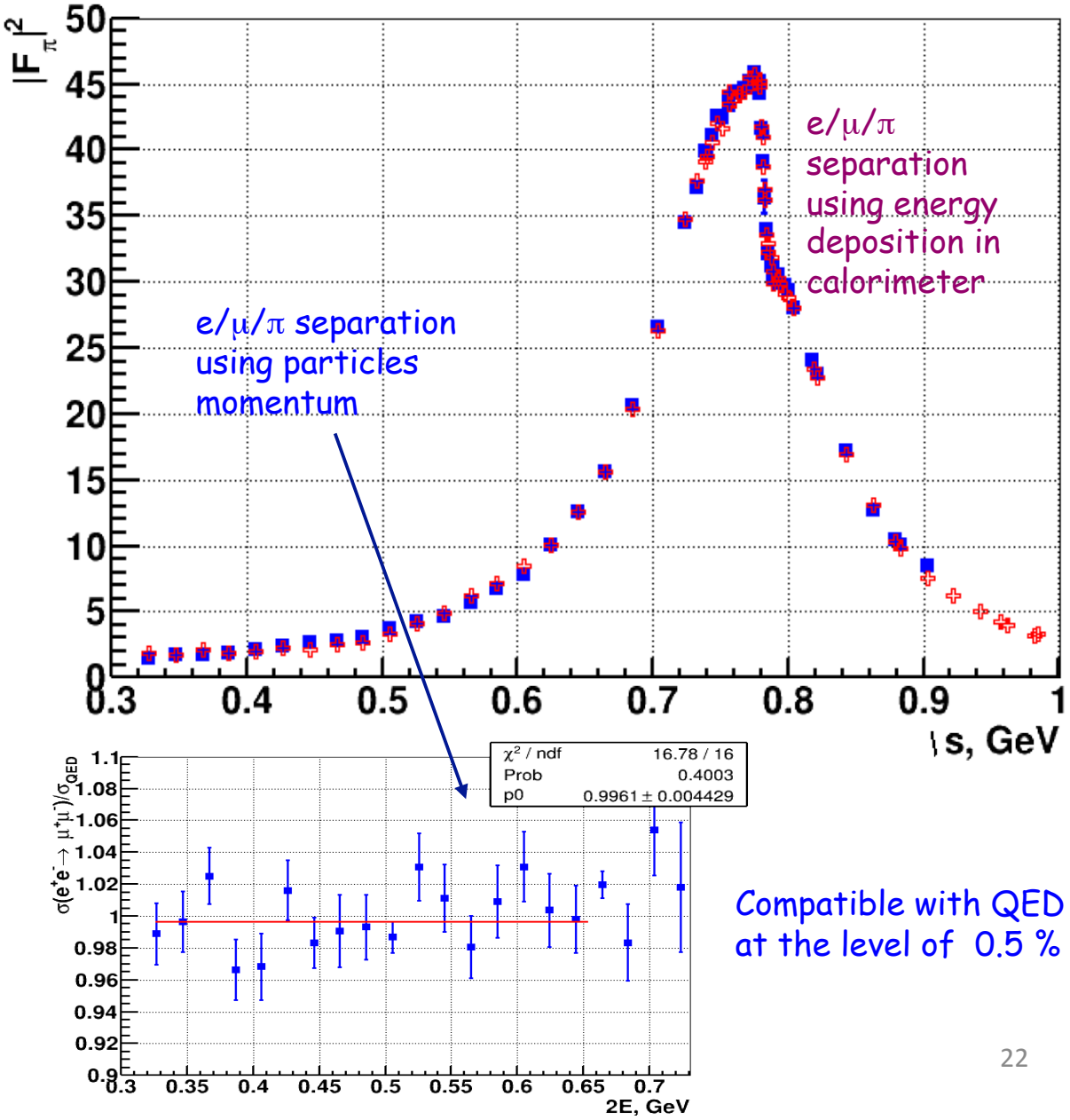

BabaYaga better describe experimental data

Looks like MCGPJ should be improved by
adding angular distribution to photon jets

# $e^+e^- \to \pi^+\pi^-$: preliminary result

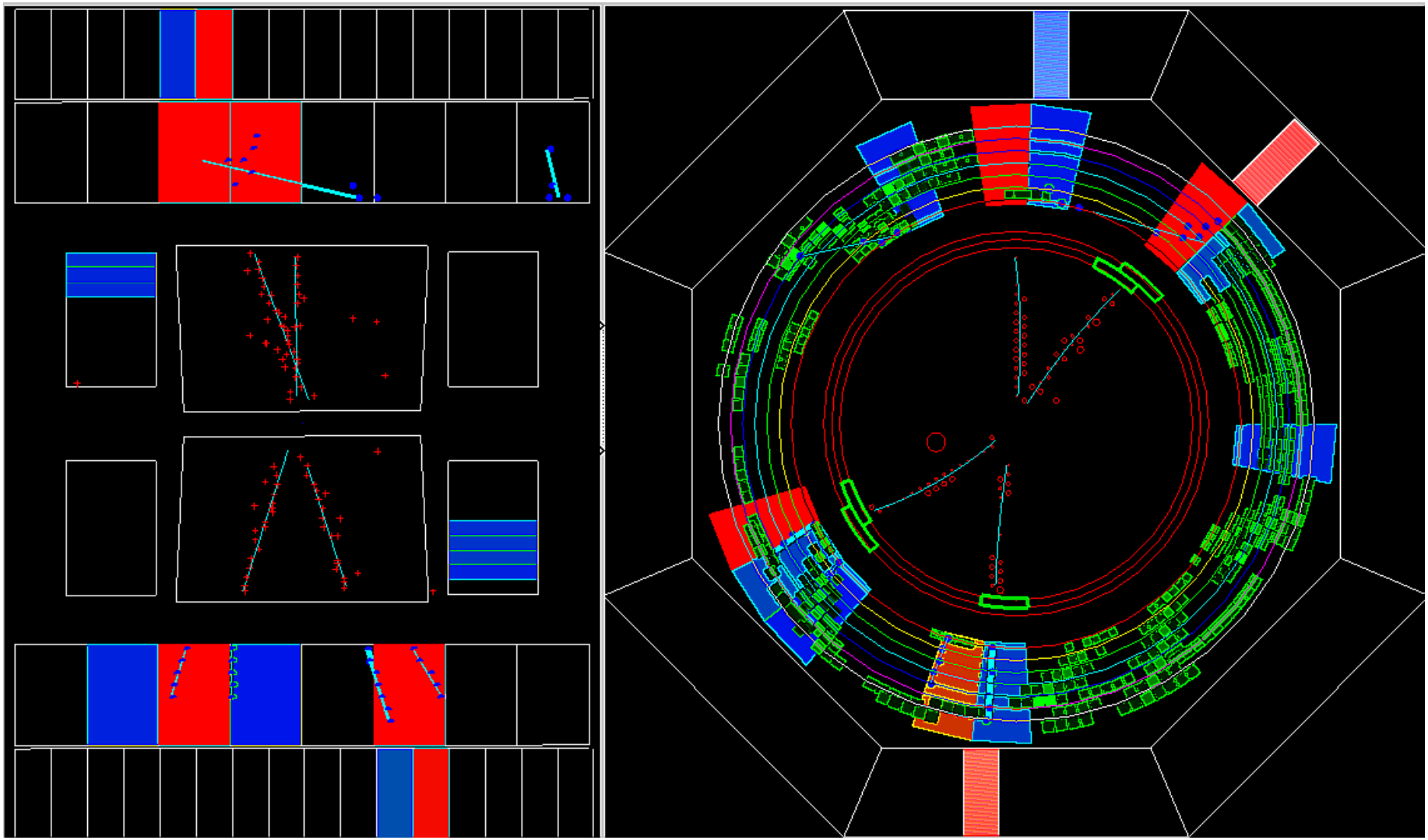
Statistical precision of cross section measurement for **2013 data** is at the same level as other experiments and a few times better than at CMD-2



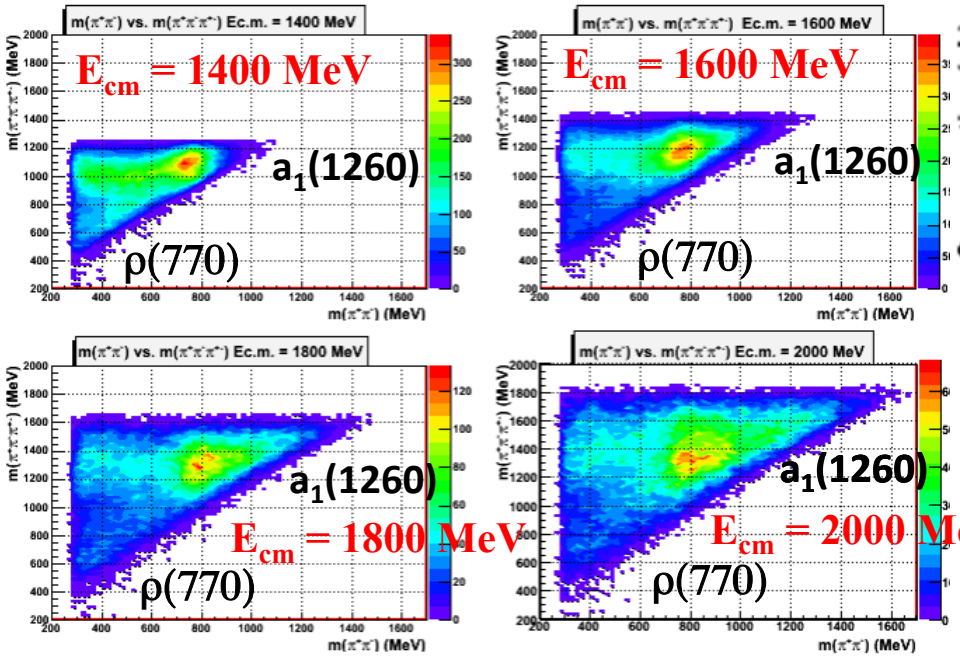

Compatible with QED at the level of 0.5 %

# Example of $e^+e^-$ -> $\pi^+\pi^-\pi^+\pi^-$ from CMD-3

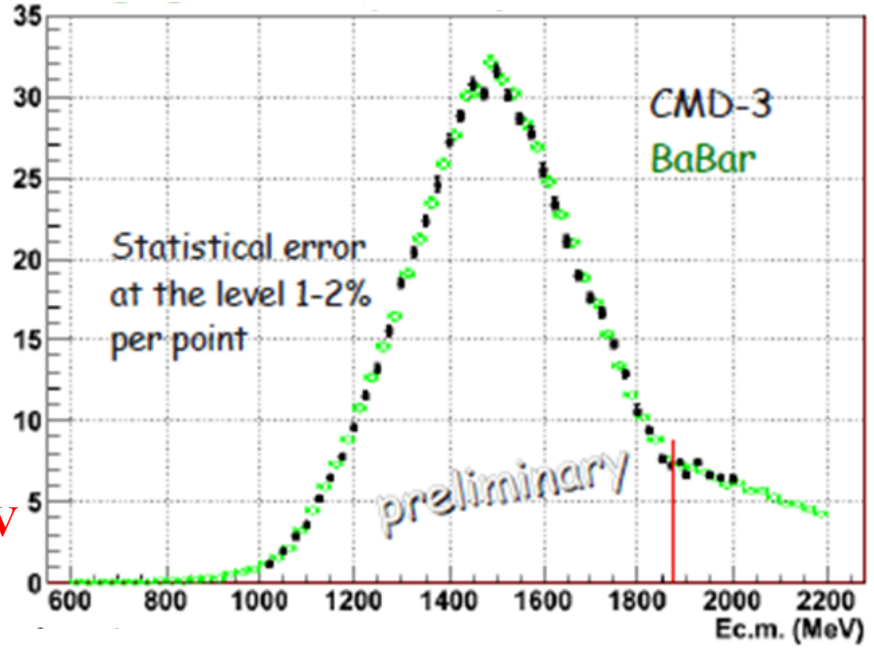


# $e^+e^- \to 4\pi$

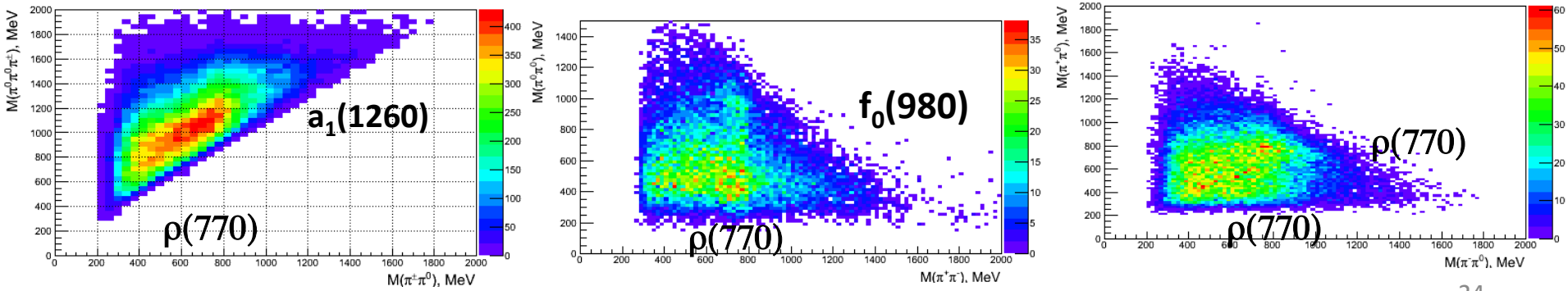
## Dynamics of $e^+e^- \to 2(\pi^+\pi^-)$




## Cross section of $e^+e^- \to 2(\pi^+\pi^-)$

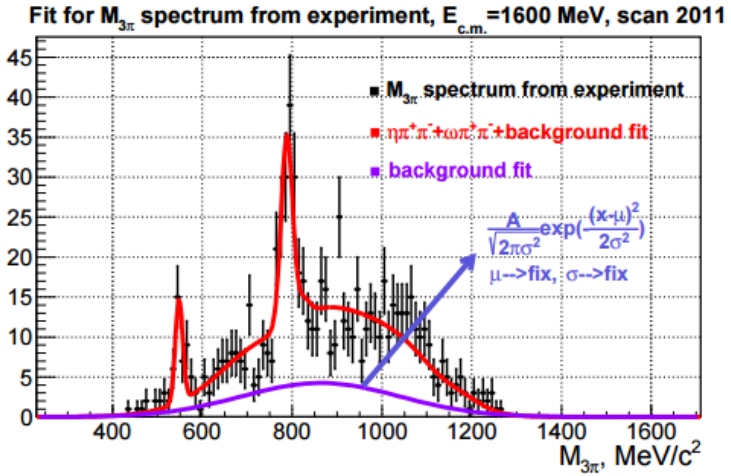


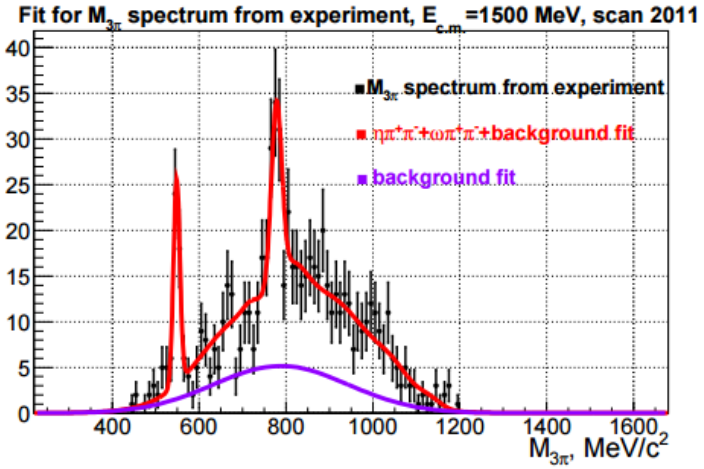

## Dynamics of $e^+e^- \to \pi^+\pi^-\pi^0\,\pi^0$



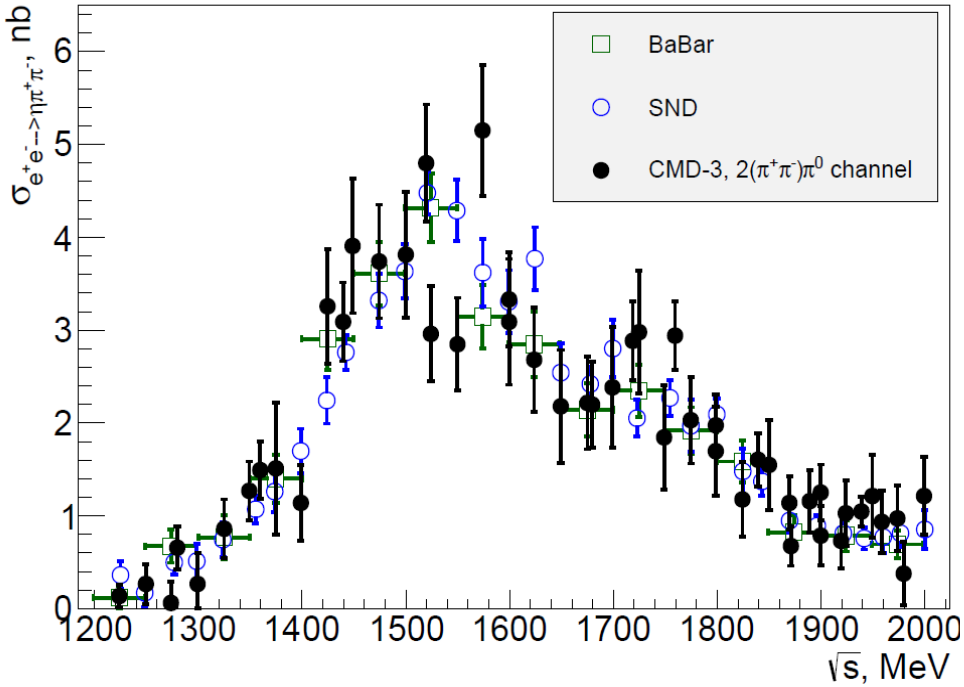
# $e^+e^- \to 5\pi$

## We study $2(\pi^+\pi^-)\pi^0$ final state in intermediate $\eta\pi\pi$ and $\omega\pi\pi$ production

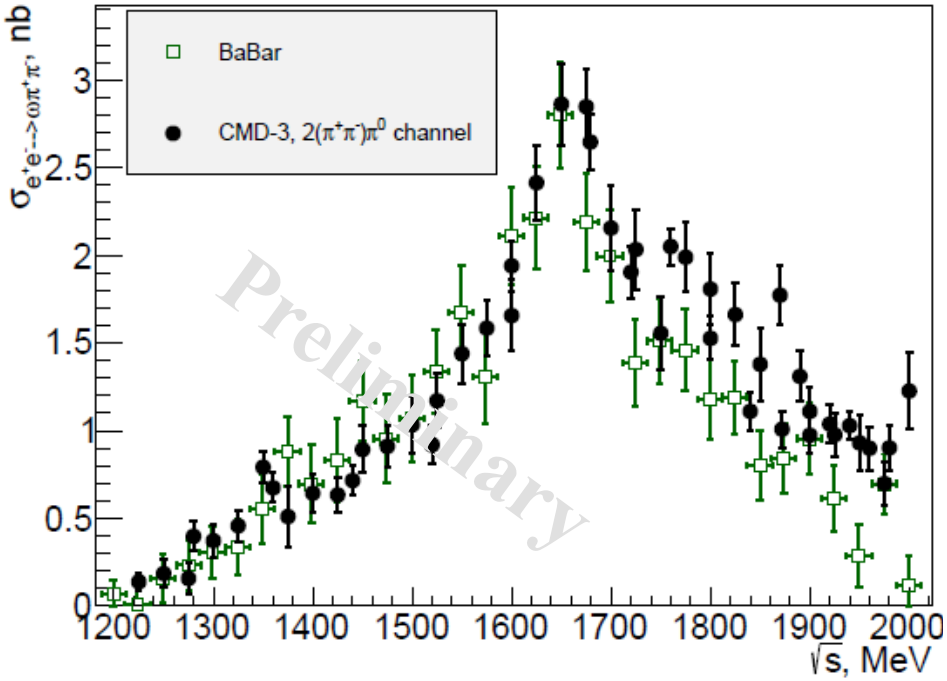


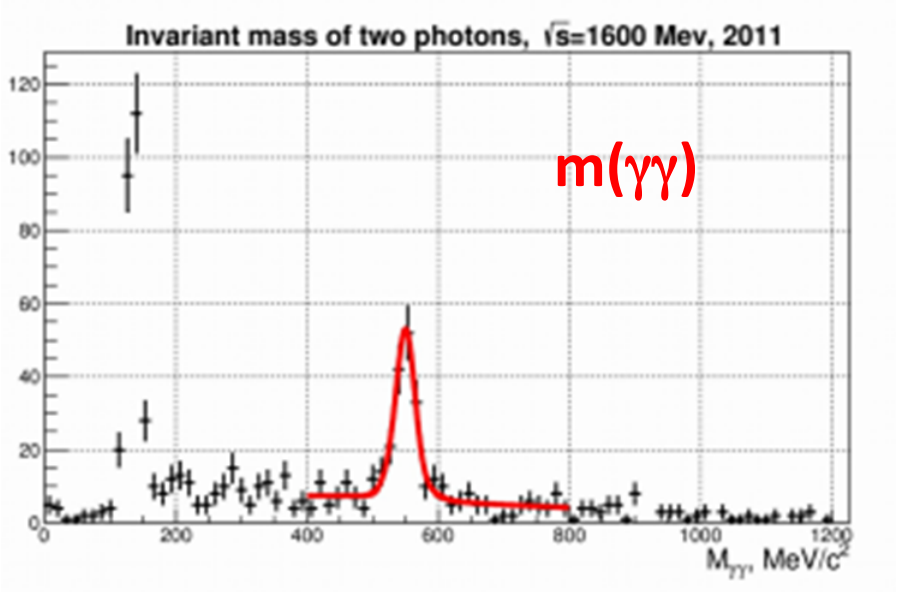

$e^+e^- \to \eta\pi^+\pi^- \to 2(\pi^+\pi^-)\pi^0$

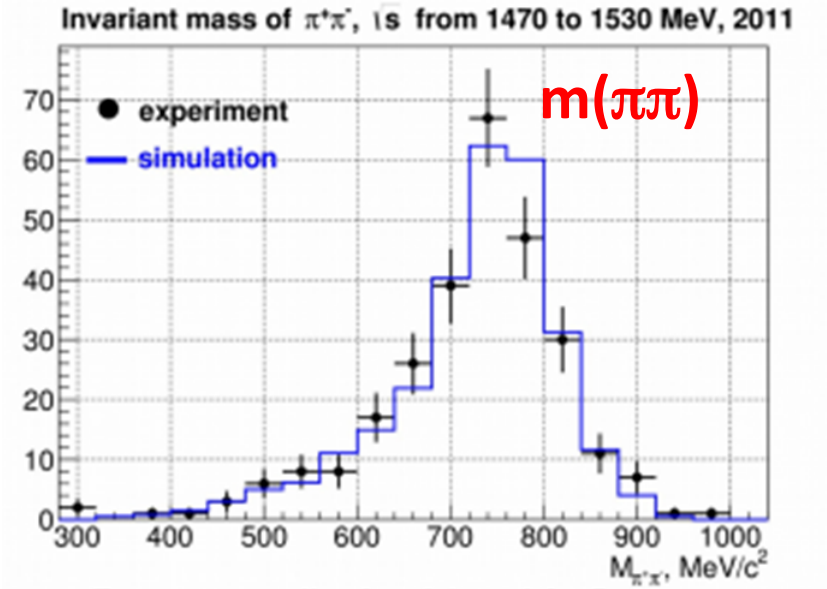


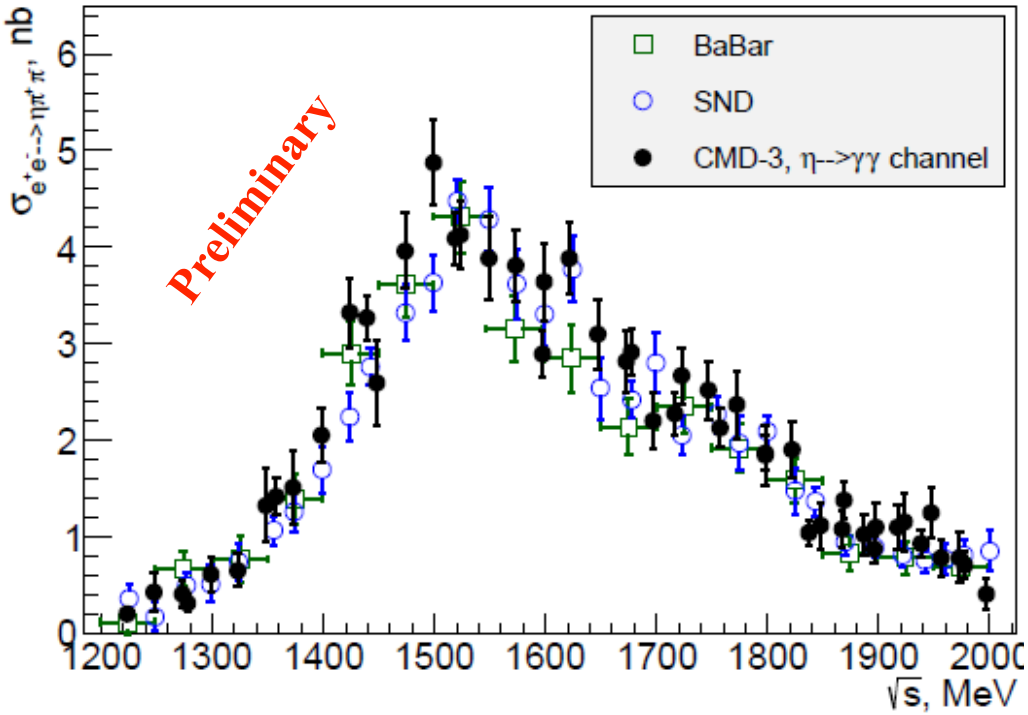

$e^+e^- \to \omega\pi^+\pi^- \to 2(\pi^+\pi^-)\pi^0$



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

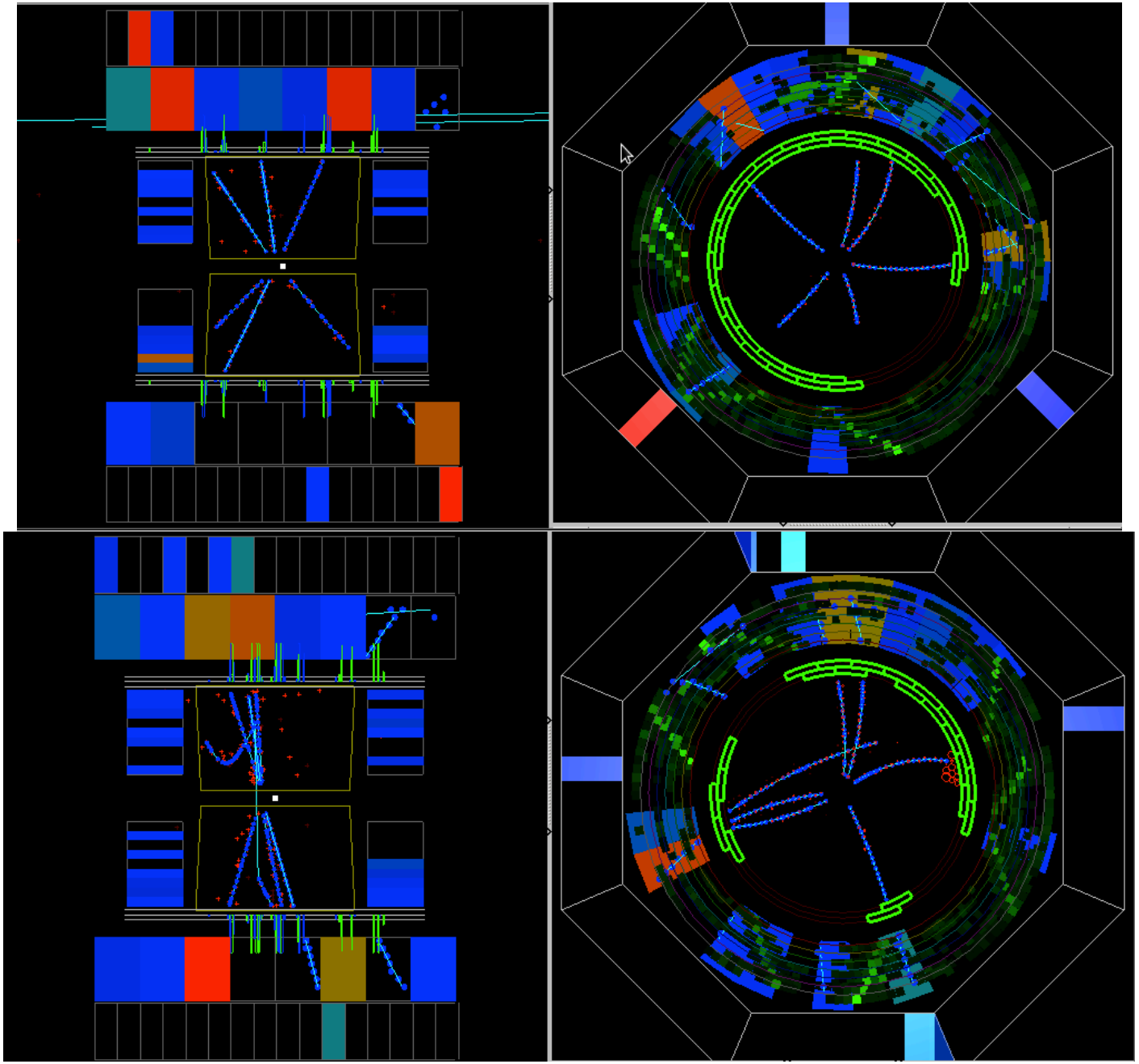


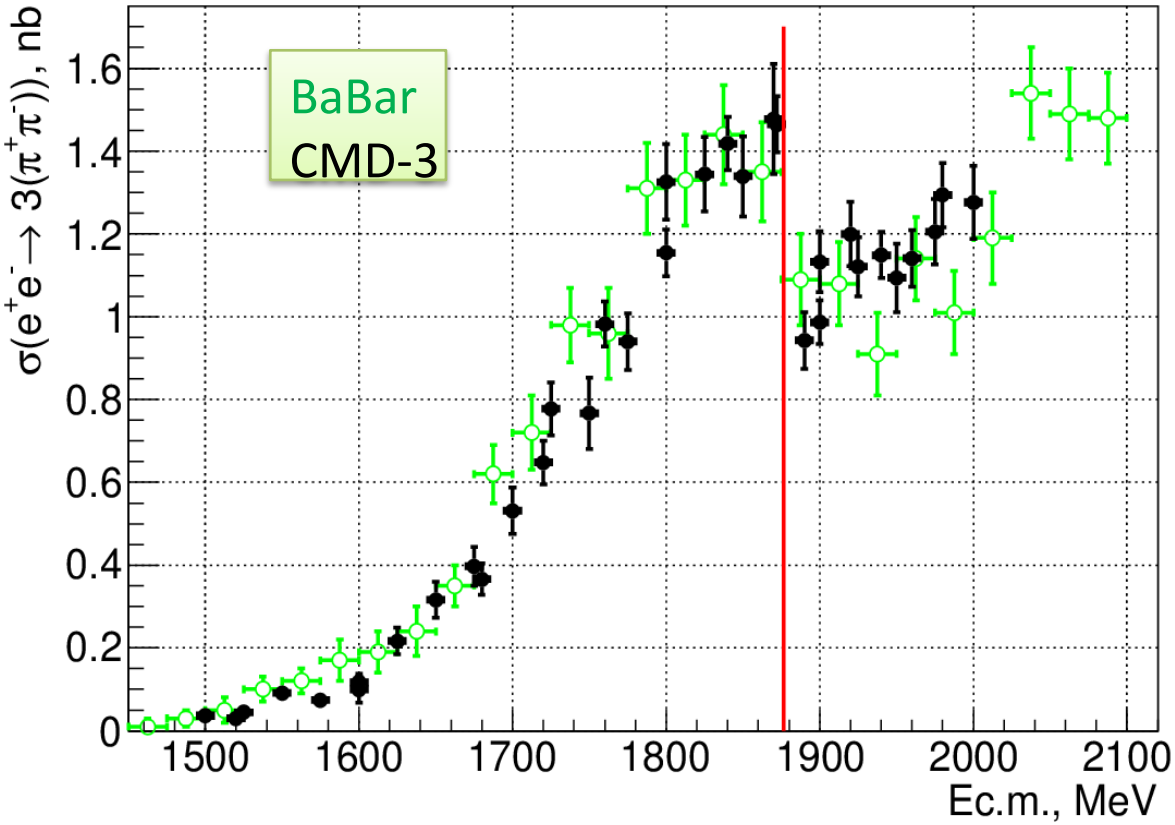




- Decay $\eta \to \gamma\gamma$ is used for the analysis
- Cross section is in agreement with that, measured in $\eta \to \pi^+\pi^-\pi^0$ decay mode
- $e^+e^- \to \eta\rho$ intermediate state dominates
- Futher dynamics study is in progress

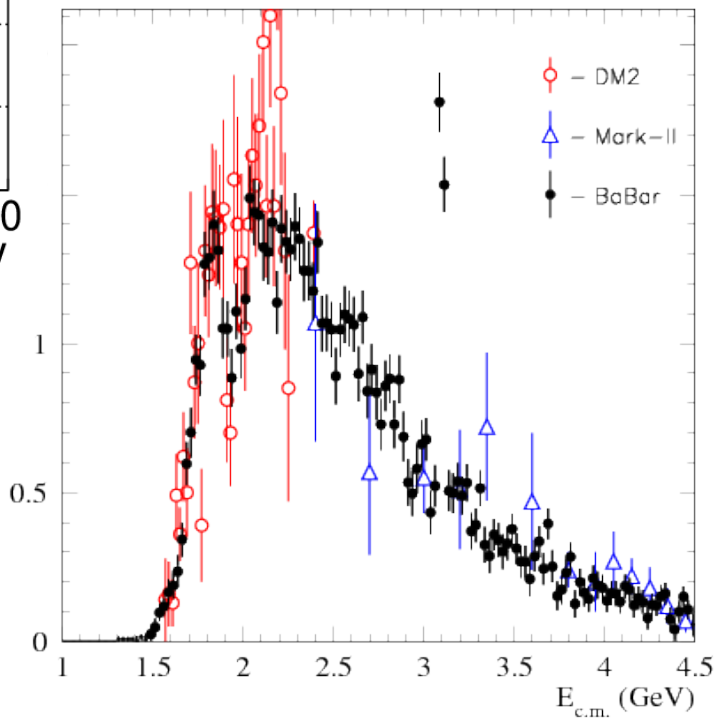
# Examples of $e^+e^-$ -> $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ from CMD-3



# Results for the $e^+e^-$ -> $3(\pi^+\pi^-)$ study



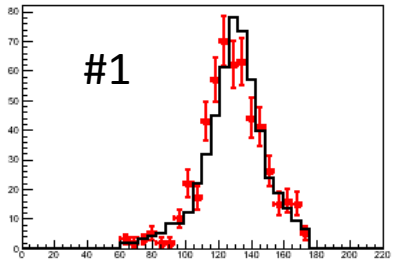

Other data for $e^+e^-$ -> $3(\pi^+\pi^-)$



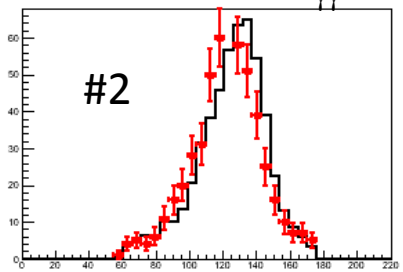

Published: Phys.Lett. B723 (2013) 82-89

# Preliminary results for the $e^+e^-$ -> $2(\pi^+\pi^-\pi^0)$ study

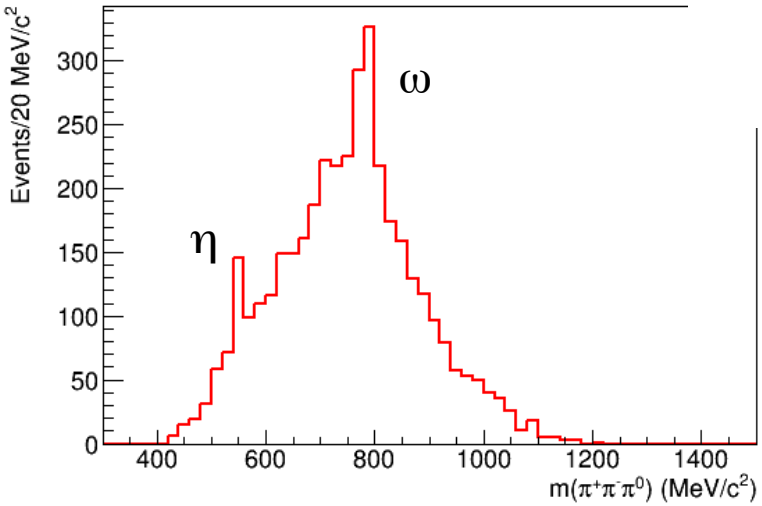
We have relatively clean selection of 2 and 1 $\pi^0$ in addition to four charged tracks

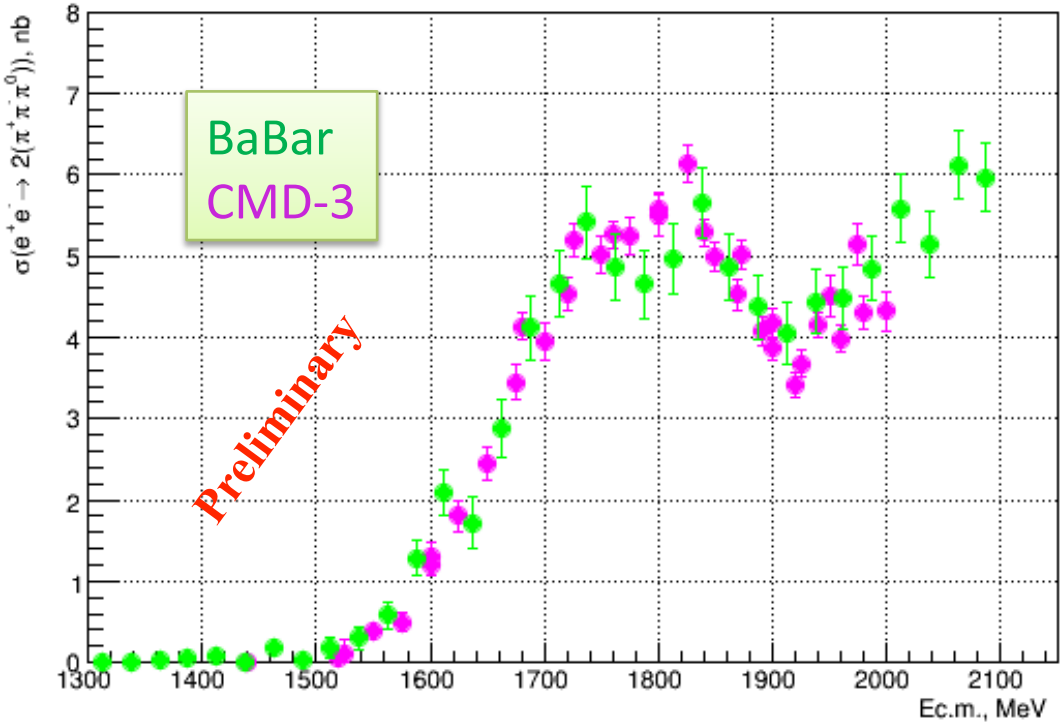



$m_{\gamma\gamma}$, MeV




$m_{\gamma\gamma}$, MeV

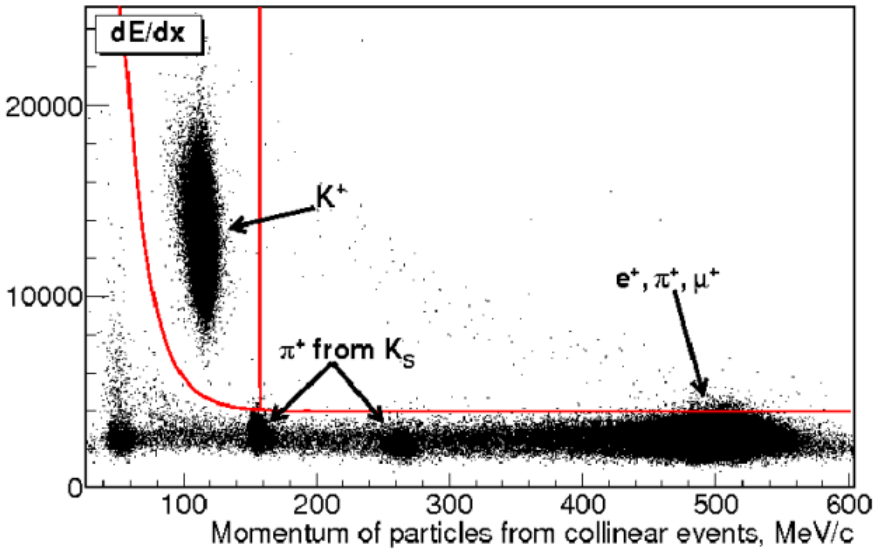


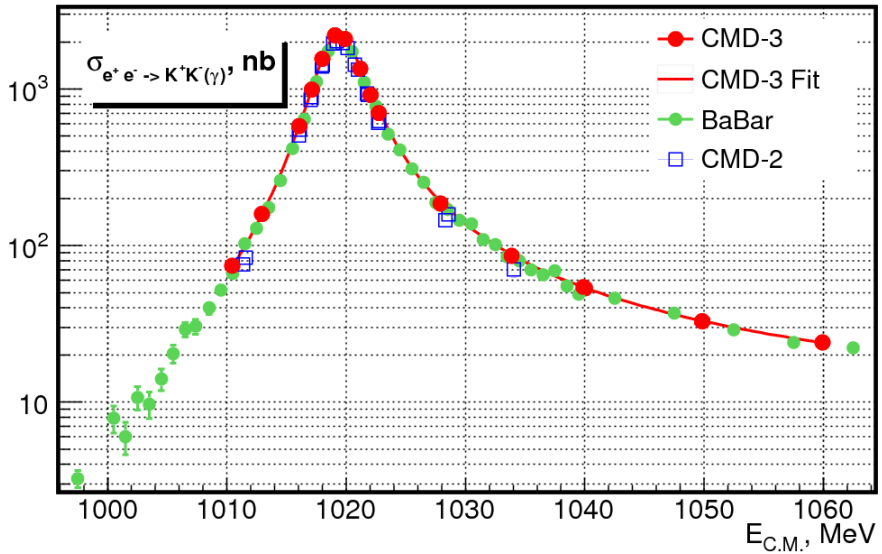




$\omega\eta$, $\phi\eta$, $\rho 4\pi$ intermediate states are seen, systematic errors are under study.

# $e^+e^- \rightarrow K^+K^-$

The study of K+K- production has been made also at energies of the φ-meson mass. The selection of events is made using information from the DC chamber where a pair of charged kaons is reconstructed. Kaons are selected by average energy losses dE/dx of tracks in DC and the average momentum of the pair of tracks.

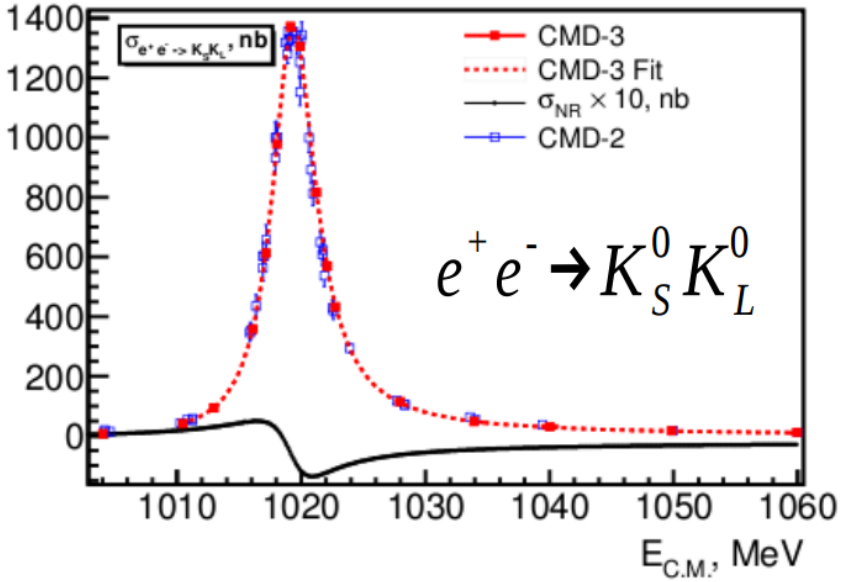



**The measured cross section of the process e+e- → $K^+K^-$ together with the results from CMD-2 and BaBar is shown near ϕ-meson mass energy. The systematic error is about 2.5%**

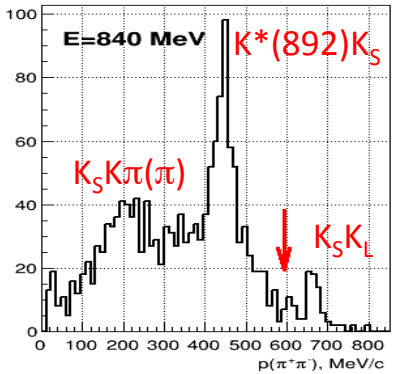
# $e^+e^- \to K_L K_S$

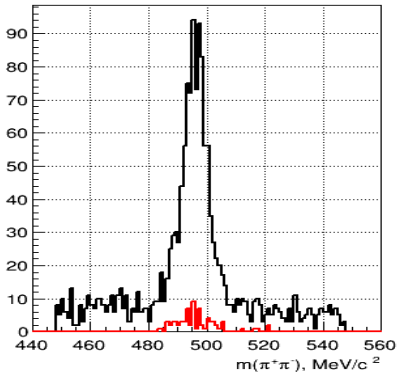
**Process is studied using decay $K_s \to \pi^+\pi^-$**




In $E_{cm}$ = 1100 – 2000 MeV:

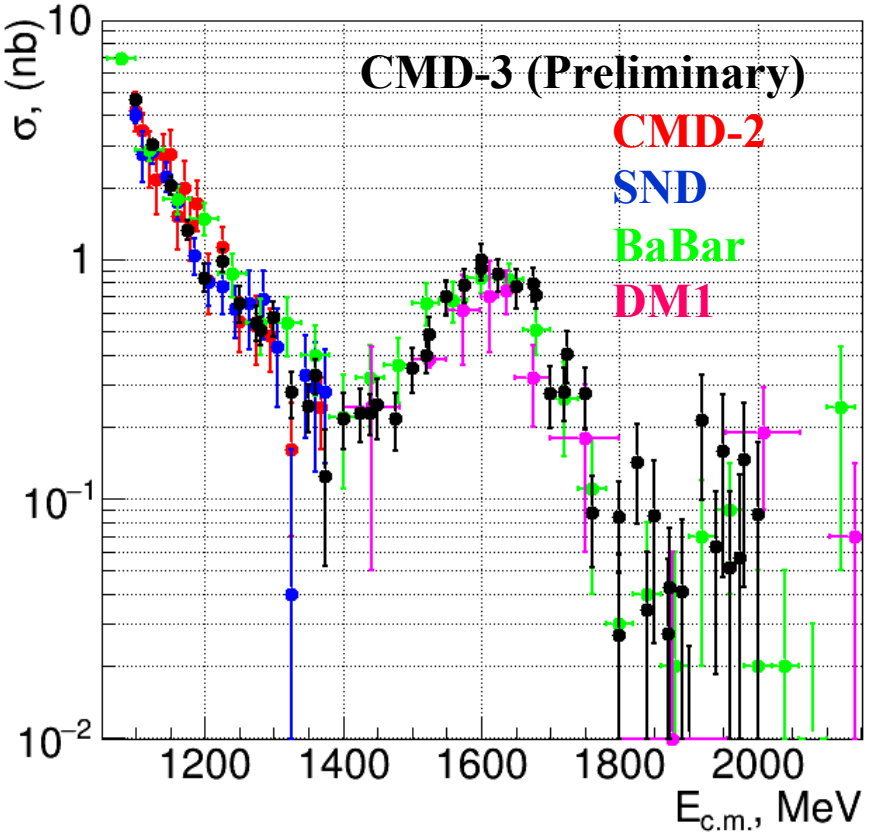
- 54 energy points
- Luminosity integral 32.1 $pb^{-1}$
- 1889 events with fully reconstructed $K_S$



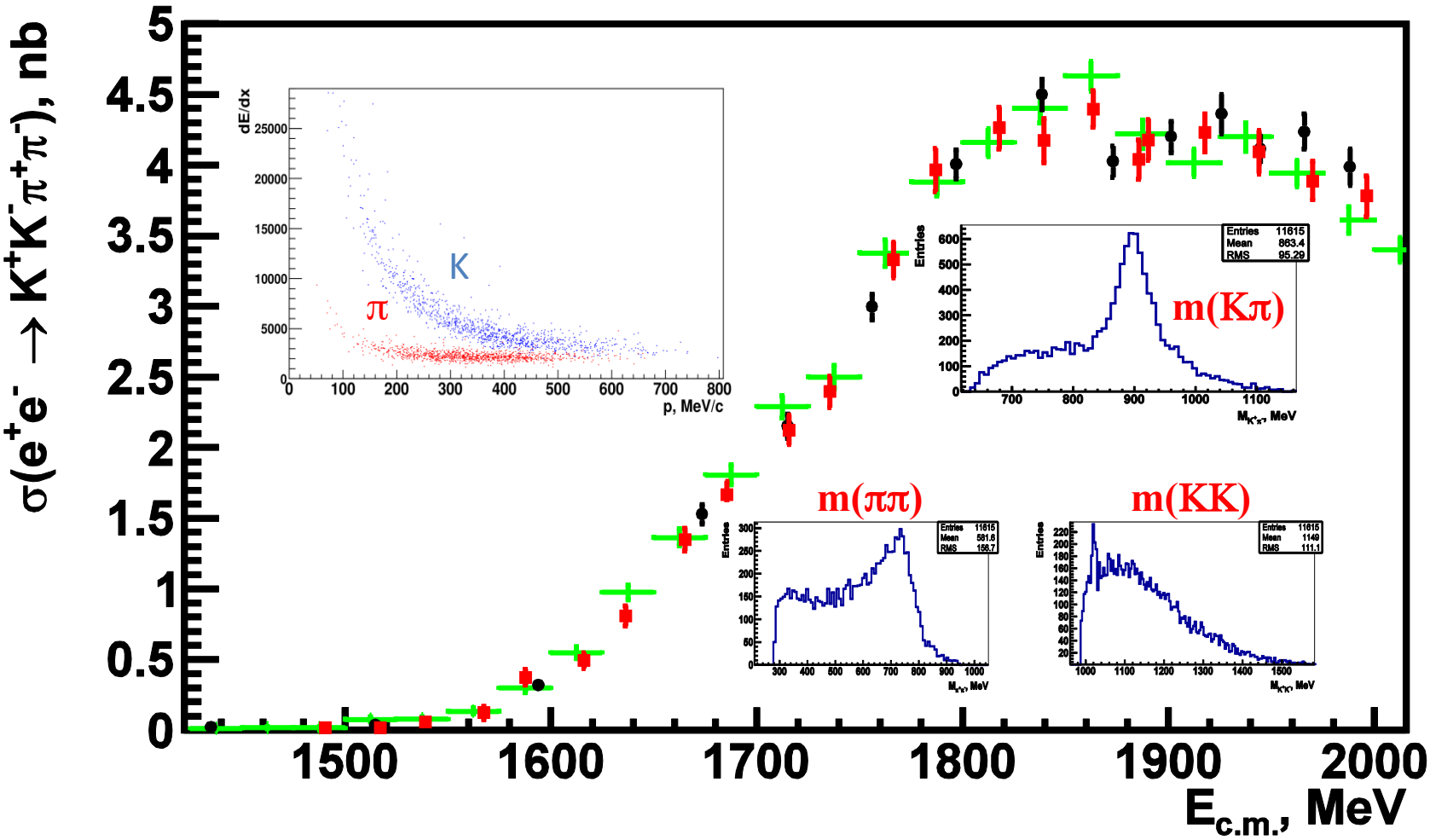




In $E_{cm}$ = 1004 – 1060 MeV:

- 25 energy points
- Luminosity integral 5.9 $pb^{-1}$
- Systematic error is < 2%



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




CMD-3 uses 22 pb-1 in the 1.5-2.0 GeV range with more than 10000 events
Ionization losses in DC provide good K/π separation
Signals from ρ(770), K*(892), ϕ(1020) are seen

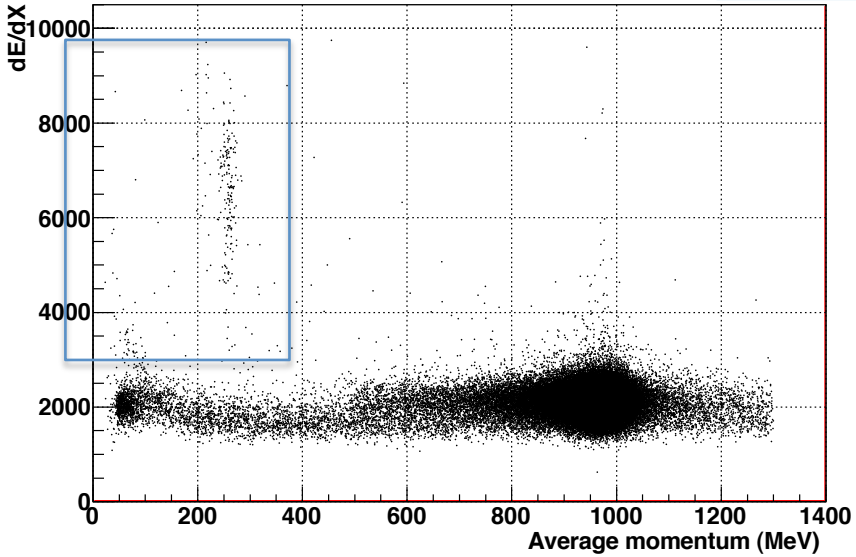
Accepted by Physics Letters B

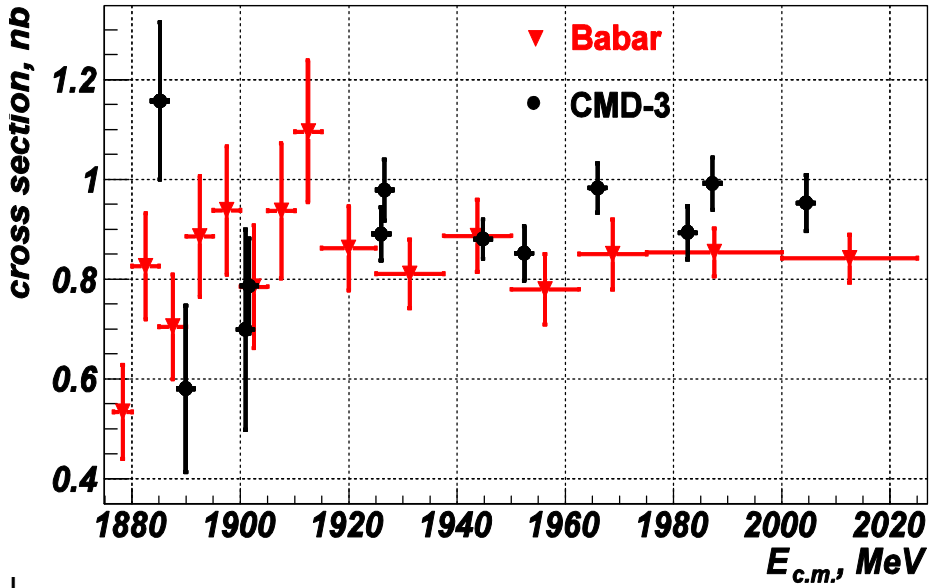
# $e^+e^- \to p^+p^-$

arXiv:1507.08013 [hep-ex]

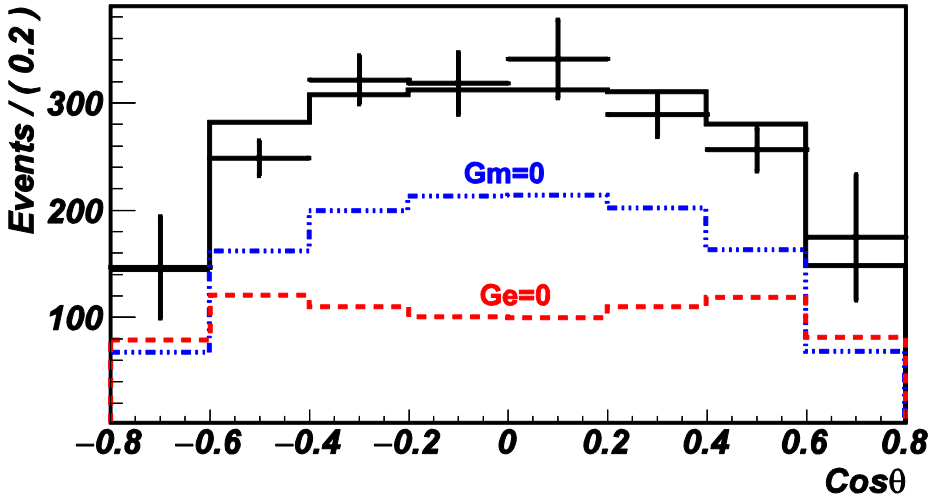
**Accepted by Phys. Lett. B**

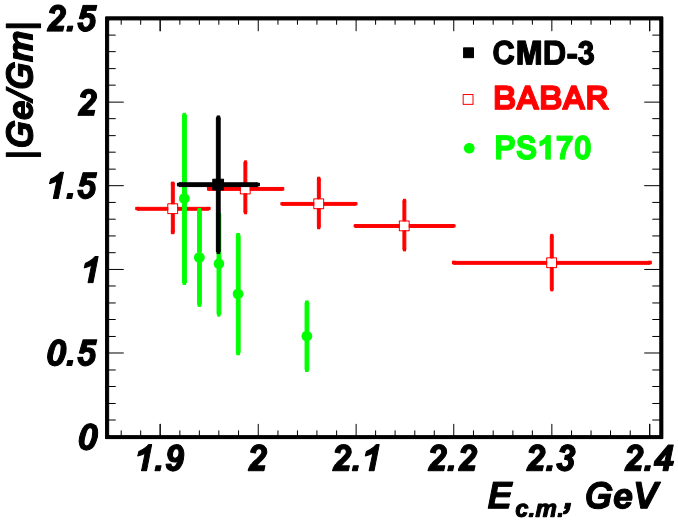
$$\sigma(e^+e^- \to B\bar{B}) = \frac{\alpha^2 \beta C^2}{4m^2}\left(|G_M|^2(1+\cos^2\theta) + \frac{4m_B^2}{m^2}|G_E|^2(1-\cos^2\theta)\right)$$



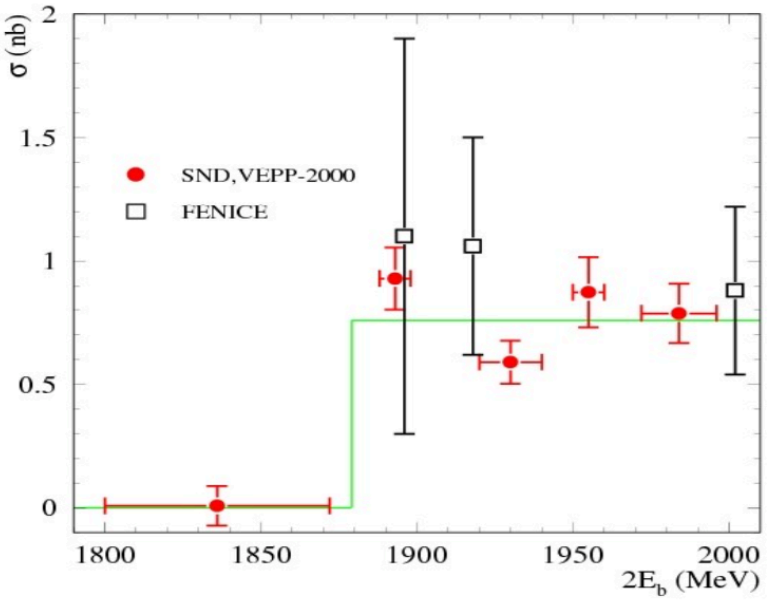




**Angular distribution used to measure $|G_E/G_M|$**



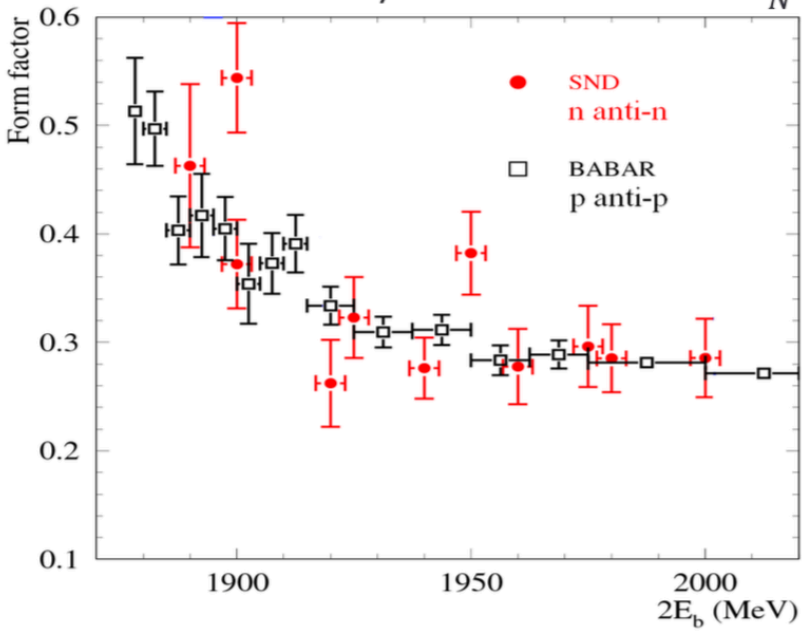
# $e^+e^- \to n\bar{n}$ @ SND



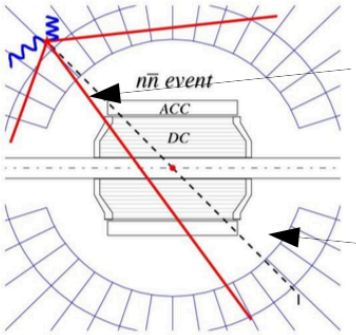

$\sigma_{aver} = 0.8 \pm 0.2$ nb

Effective formfactor

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




Systematics: ~0.25 nb (~30%)




$\bar{n}$

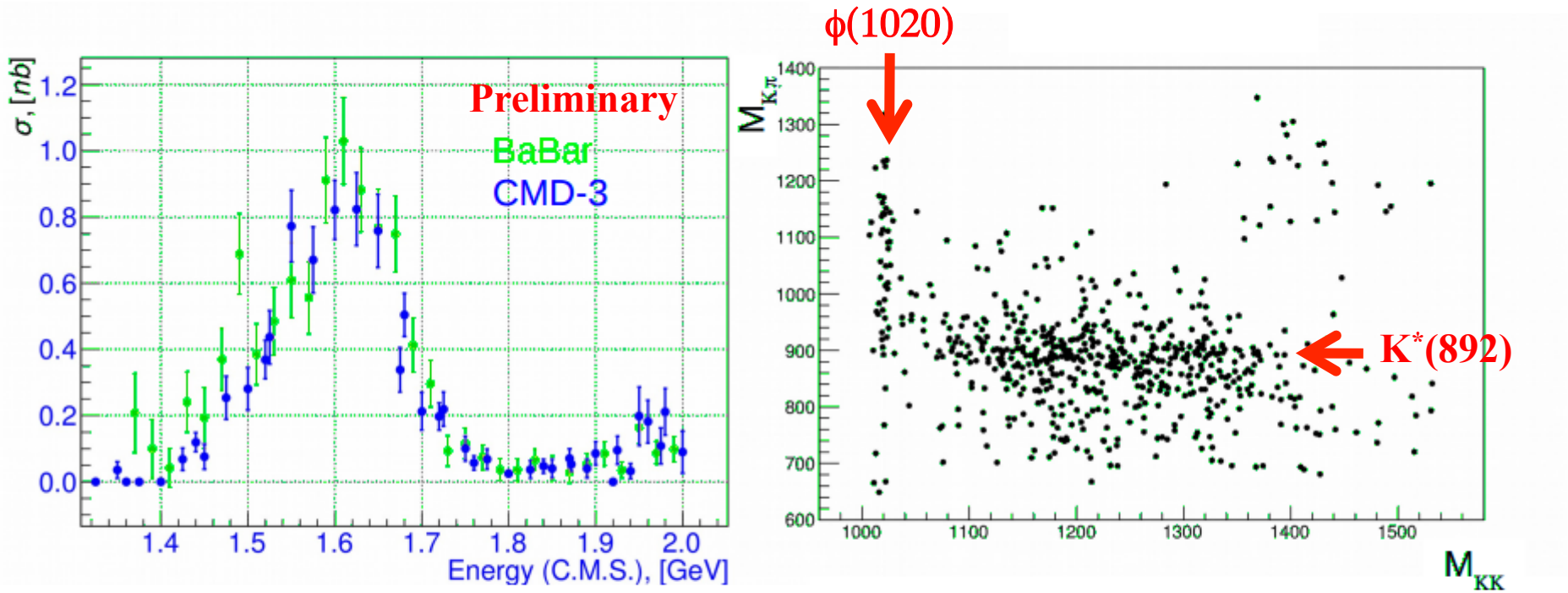
$n$

Signature:
Small energy in calorimeter from n;
"star" from $\bar{n}$ annihialtion in cerenkov/calorimeter

Main features of the cross section:

- cross section has a threshold behavior;
- selected events are delayed by 5-10 nsec;
- cross section is stable under condition variations;
- Uniform φ distribution;
- First and more precise measurement after FENICE;
- **Phys. Rev. D 90, 112007 (2014)**.

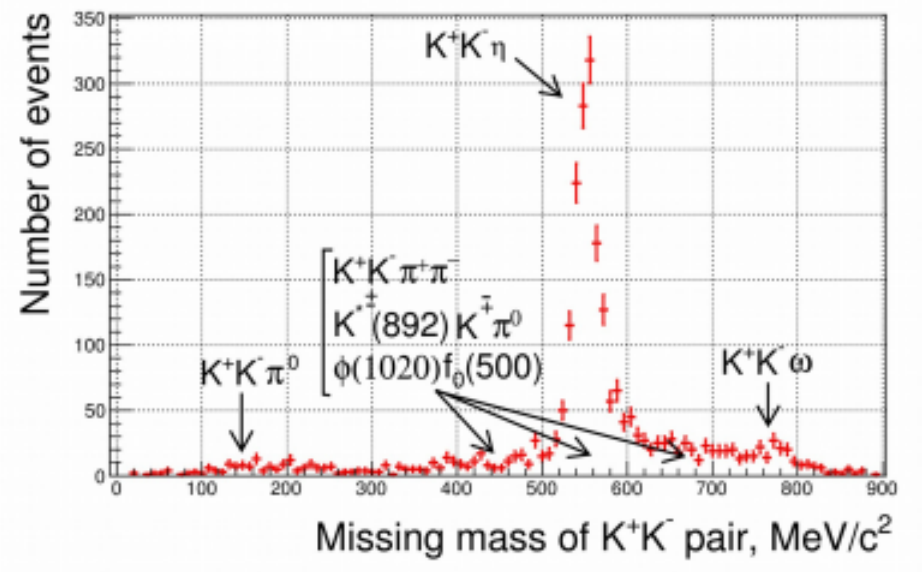
# $e^+e^- \to K^+K^-\pi^0$

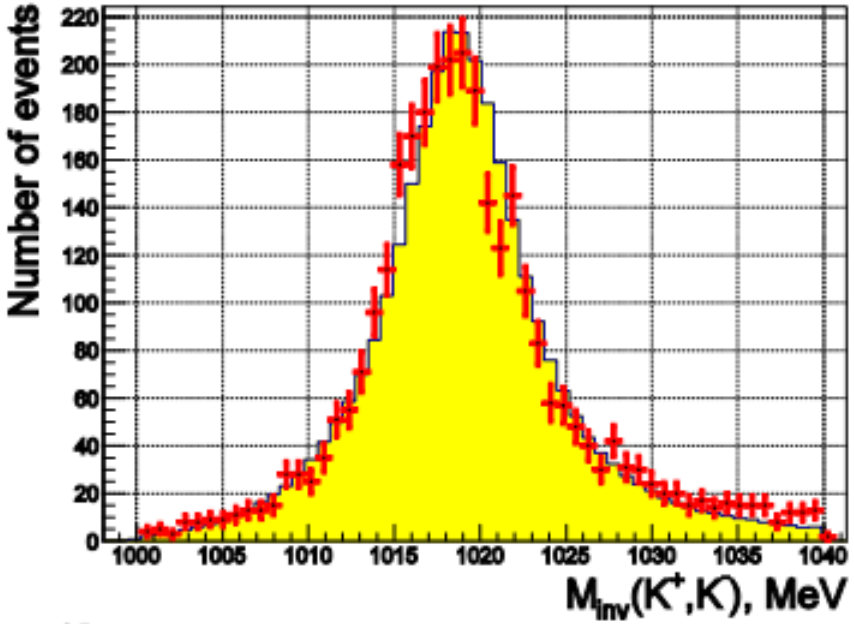



Cross section, very preliminary

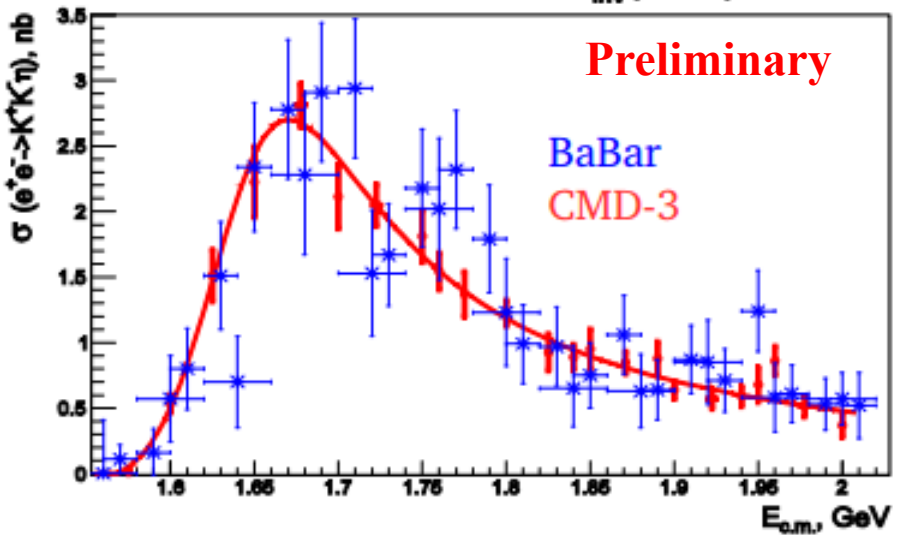
- The Kπ vs. K+K– plot clearly shows the $\phi\pi^0$ and $K^*(892)K$ mechanisms;
- Cross section is consistent with and more precise than BaBar.

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




- A data sample of 22 $pb^{-1}$ collected in 2011-2012 is used to study $e^+e^- \to K^+K^-\eta$;
- 23 c.m. energy points between 1.57 and 2.0 GeV;
- Analysis method empasizes the dominant $\phi\eta$ signal, studies of non-resonant $K^+K^-\eta$ needed;
- Rich background with numerous components seen;
- The data sample includes 1600 events of the signal and about 600 background events;

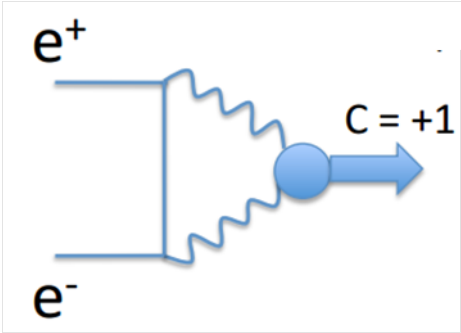


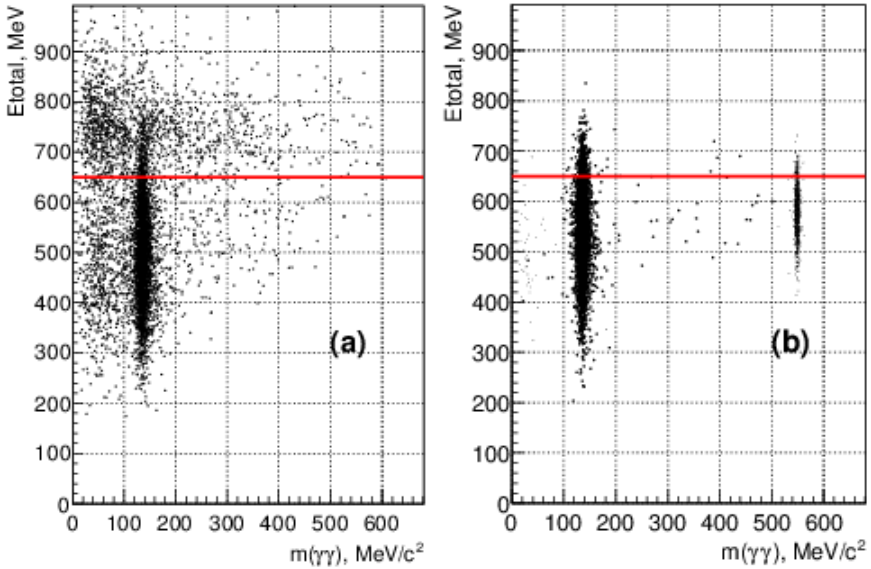

Cross-section $e^+e^- \to K^+K^-\eta$

# $e^+e^- \to \eta'(958)$

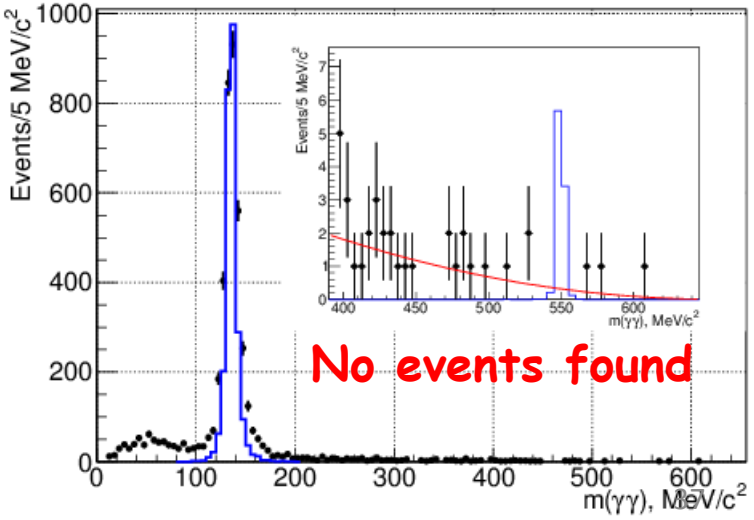
**Phys. Lett. B740(2015) 273.**

Dedicated physics run @ $E_{cm} = M_{\eta'}$
Integrated Luminosity is 2.69 $pb^{-1}$
Decay $\eta' \to \eta\pi^+\pi^- \to \pi^+\pi^-\gamma\gamma$ was used



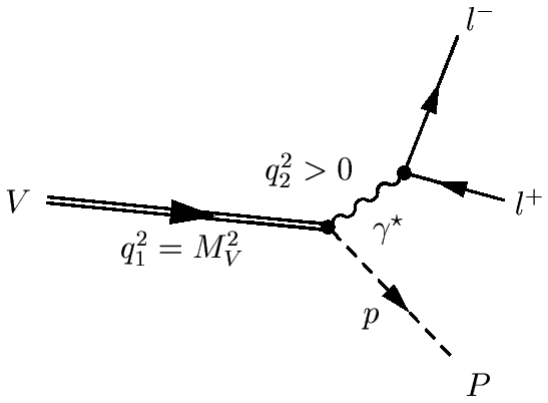




$$Br(\eta' \to e^+e^-) = Br(\eta' \to \gamma\gamma)\frac{\alpha^2}{2\beta}\left(\frac{m_e}{m_{\eta'}}\right)^2\left[\ln\left(\frac{1+\beta}{1-\beta}\right)\right]^2$$



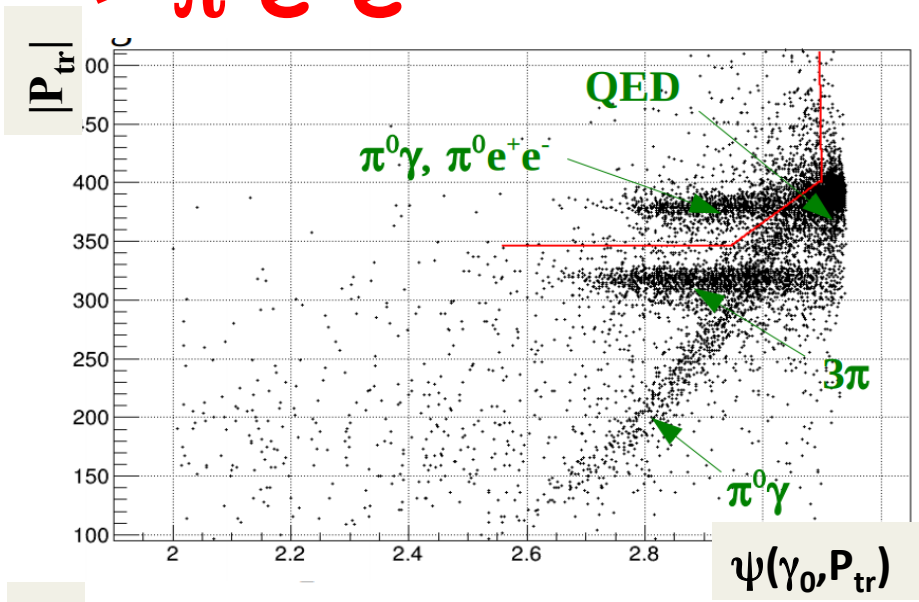

$\Gamma(\eta' \to e^+e^-) < 0.0024$ eV (90%CL) - CMD-3
$\Gamma(\eta' \to e^+e^-) < 0.0020$ eV (90%CL) - SND
$B(\eta' \to e^+e^-) < 5.6\times10^{-9}$ (90%CL) - SND+CMD-3
$B(\eta' \to e^+e^-) = 3.7\times10^{-11}$ – Theory (no FF)

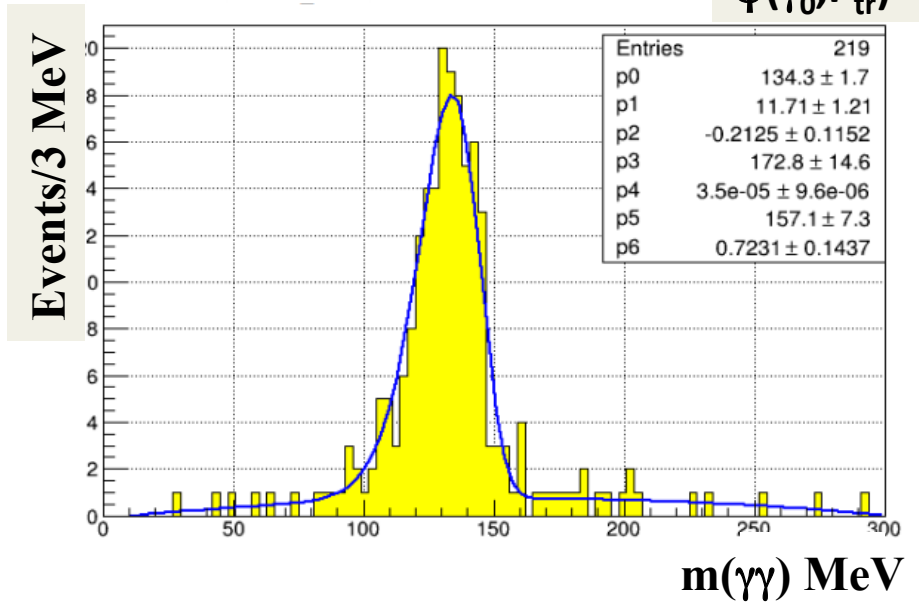
# $e^+e^- \to \omega \to \pi^0 e^+e^-$



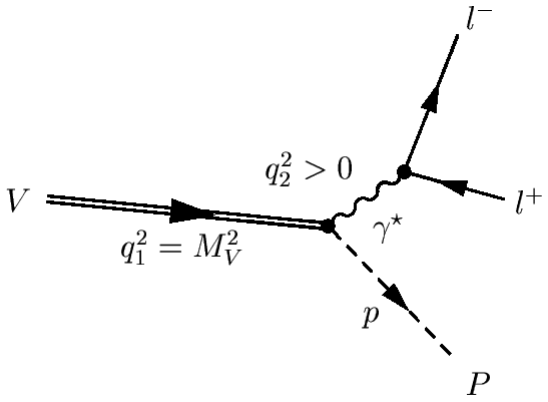

The total momentum of charged particles $|\mathbf{P_{tr}}|$ vs angle between the most energetic photon direction. This plot separates contributions from many processes. Red line presents the selection criteria

Invariant mass of two photons for selected events. Fit with the function describing signal and background is used to determine the number of signal events.



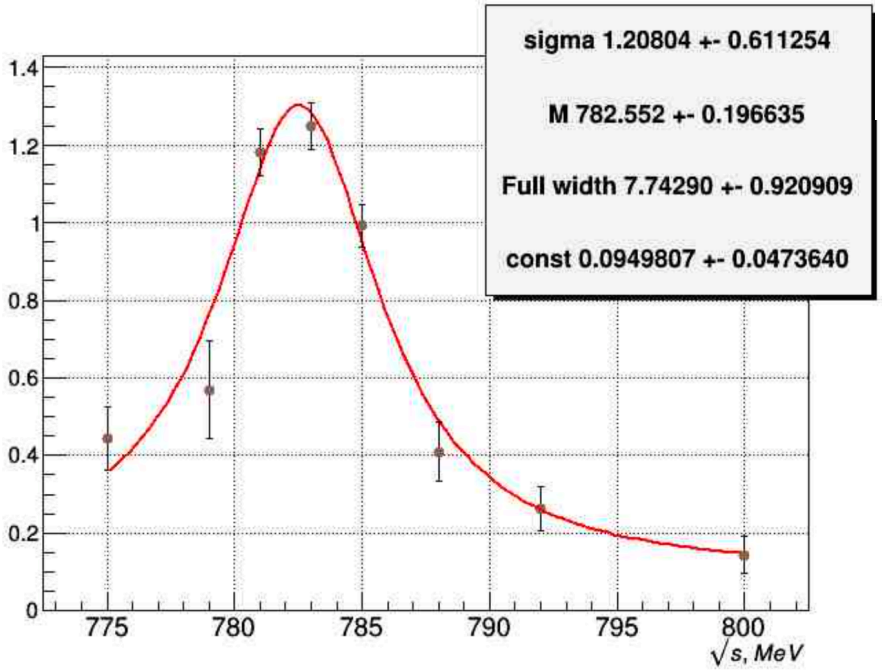
# $e^+e^- \to \omega \to \pi^0 e^+ e^-$




PRELIMINARY

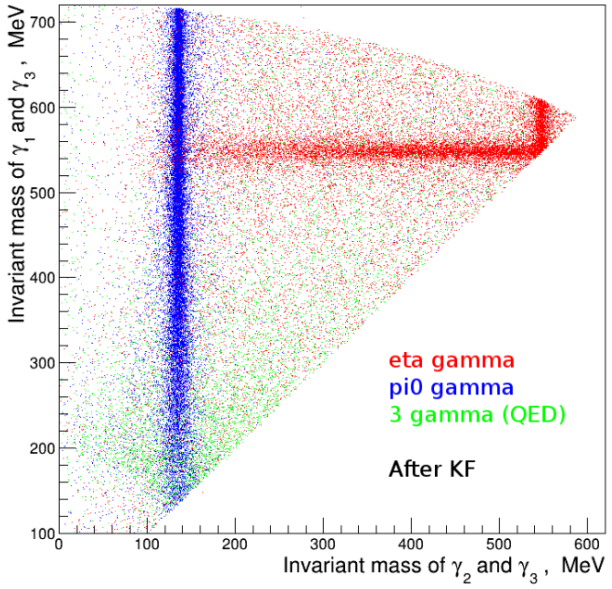
| Experiment | Br($\omega \to \pi^0 e^+ e^-$) | events | data, $pb^{-1}$ |
|---|---|---|---|
| ND | $(5.9 \pm 1.9) \cdot 10^{-4}$ | 43 | |
| CMD-2 | $(8.19 \pm 0.71 \pm 0.62) \cdot 10^{-4}$ | 230 | 3.3 |
| SND | $(7.61 \pm 0.53 \pm 0.64) \cdot 10^{-4}$ | 613 | 9.8 |
| CMD-3 | $(7.22 \pm 0.39) \cdot 10^{-4}$ $(stat.)$ | 1228 | 10 |

Table 1: Results from current and other experiments.




Work is in progress

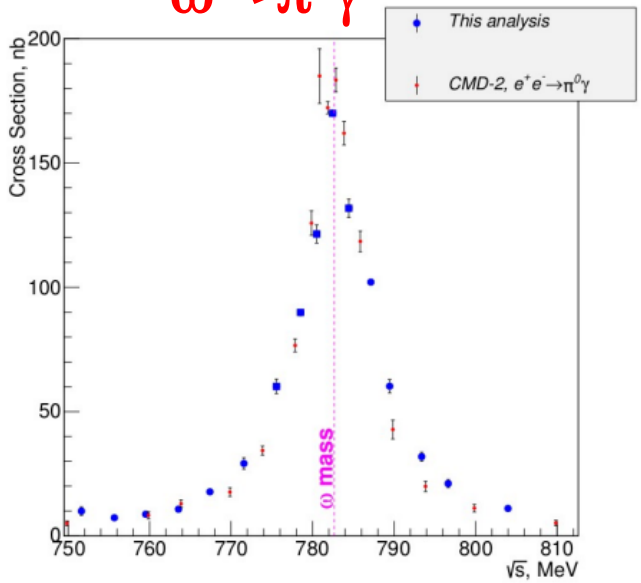
# $e^+e^- \to \pi^0\gamma,\eta\gamma \to 3\gamma$




Processes are under study in the center-of-mass energy range 750 – 1030 MeV using experimental data collected in 2013.
The kinematic reconstruction procedure is applied to all sets of three of photons in event. The procedure uses the energy-momentum conservation and assumes the common initial point of photons. The set of photons with the minimal $\chi^2$ value is used in analysis.

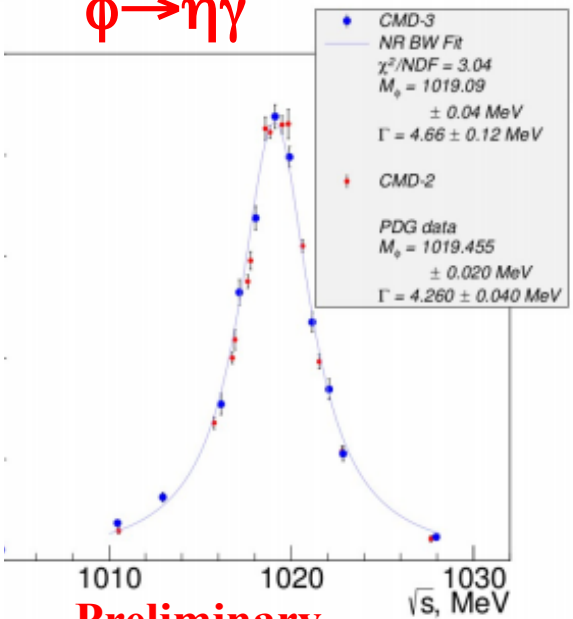
The main physics background in the whole energy range is the three photon annihilation of an $e^+e^-$ -pair.

$\omega \to \pi^0\gamma$



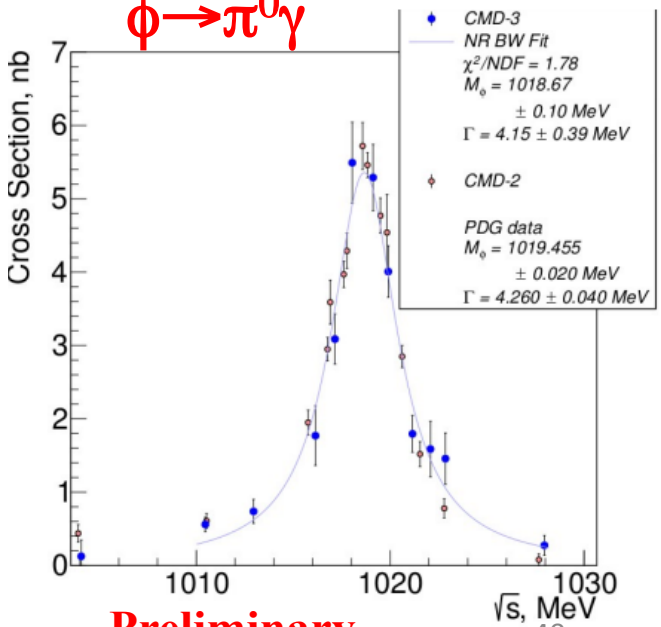

Preliminary

$\phi \to \eta\gamma$




Preliminary

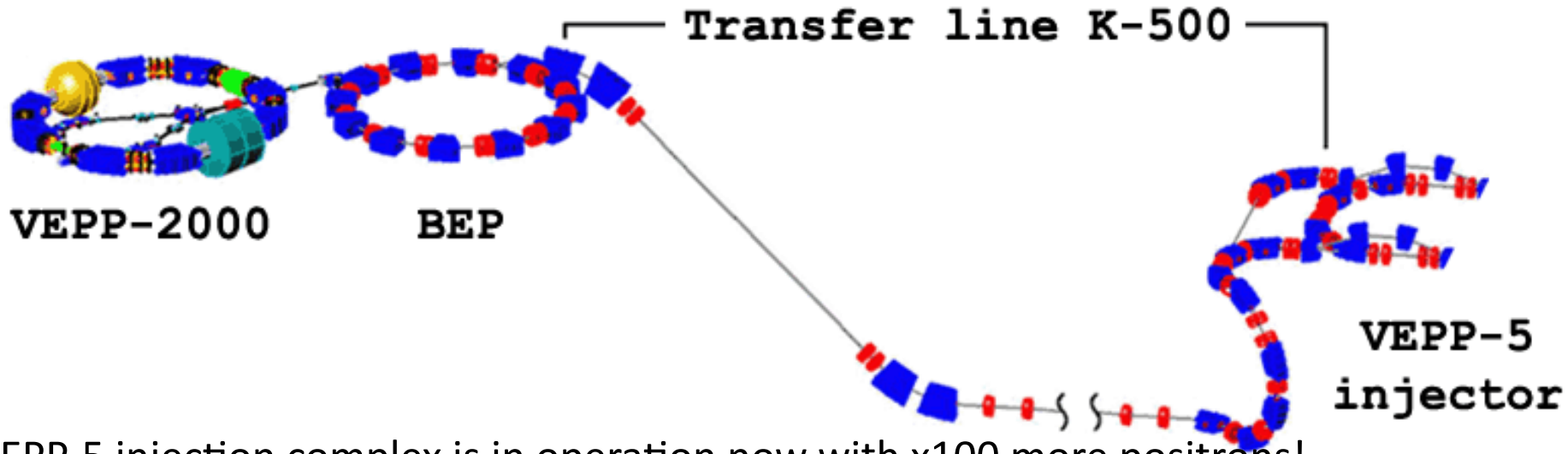
$\phi \to \pi^0\gamma$




Preliminary

# Plans and perspectives

**The collider complex and both detectors are upgraded for next run.**




•VEPP-5 injection complex is in operation now with x100 more positrons!

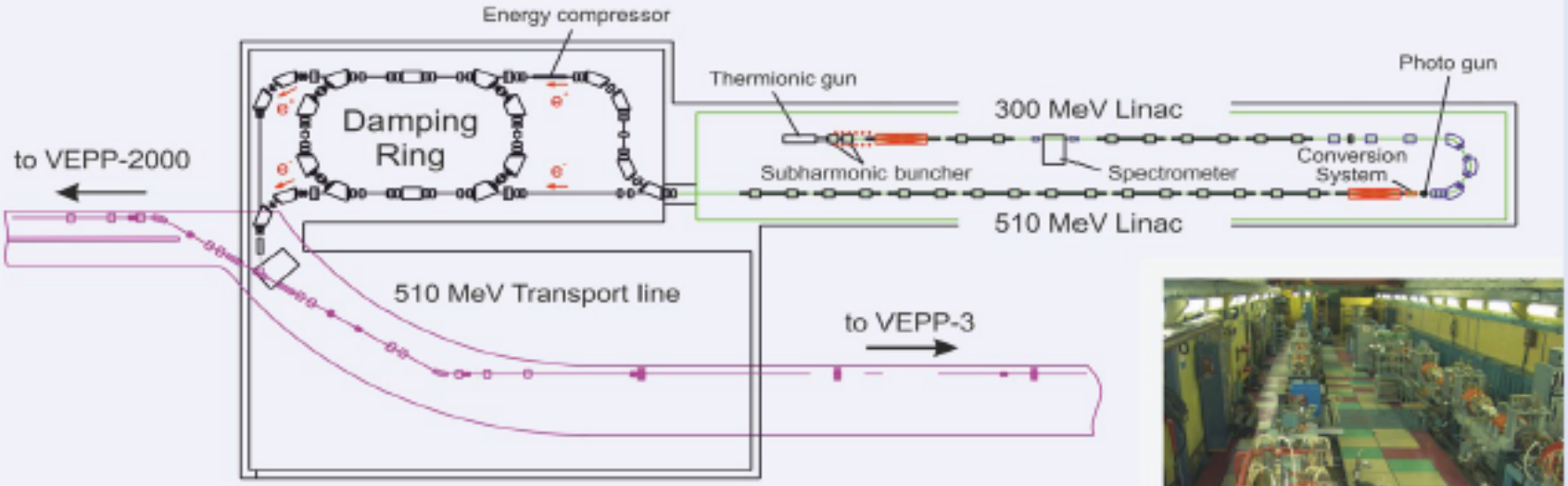
• Maximum energy in buster BEP is increased to 1 GeV

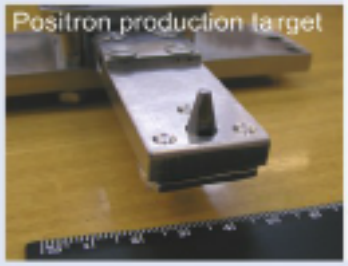
• Additional inflectors are installed to VEPP-2000 to accept 1 GeV trickle injection

• Transfer line is ready, e- and e+ beams have been injected to buster!

• Both detector DAQs are upgraded to accept x10 luminosity (background?)

# VEPP-5 INJECTION COMPLEX




Parameters at $E_{beam}$ = 510 MeV

| | |
|---|---|
| Number of electrons per bunch | $2 \cdot 10^{10}$ |
| Number of positrons per bunch | $2 \cdot 10^{10}$ |
| Repetition rate | 1 Hz |
| Electron bunch energy spread | 0.07% |
| Positron bunch energy spread | 0.07% |
| Vertical emittance | $5 \cdot 10^{-9}$ m·rad |
| Horizontal emittance | $23 \cdot 10^{-9}$ m·rad |

# Conclusion

- VEPP-2000 collider successfully operated at $\sqrt{s} = 2m_{\pi} - 2$ GeV with $L_{max} = 2 \times 10^{31}$ cm$^{-2}$s$^{-1}$ – data collected are good for new study

- CMD-3 detector has good enough performance and monitoring of different detector subsystems

- The measured cross sections have the same or better statistical precision than that from previous experiments

- VEPP-2000 upgrade is underway with new positron injection facility and upgraded booster, which will increase luminosity by factor of x10 at 2E = 2 GeV with a goal to get 1 fb$^{-1}$ in 5 – 10 years, which should provide new precise results on the hadron production