Hadronic cross sections measurement with CMD-3 detector

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On behalf of CMD-3 collaboration
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Outline

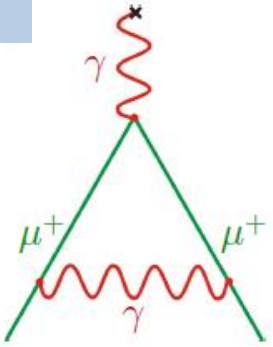
- Collider and detector
- Experiment
- Recent results:
  - Processes with pions
  - Processes with kaons
  - Processes with pions & kaons
  - Other processes
- Summary and perspectives

Motivation

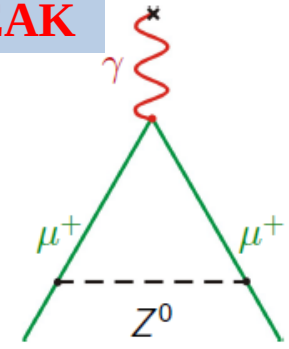
Muon anomaly, $a_m = (g-2)_m/2$

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

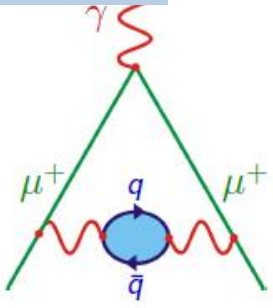
QED



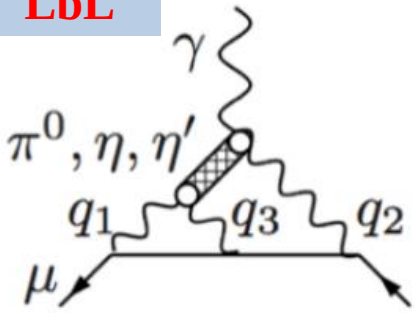
WEAK



HADRONIC



LbL



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

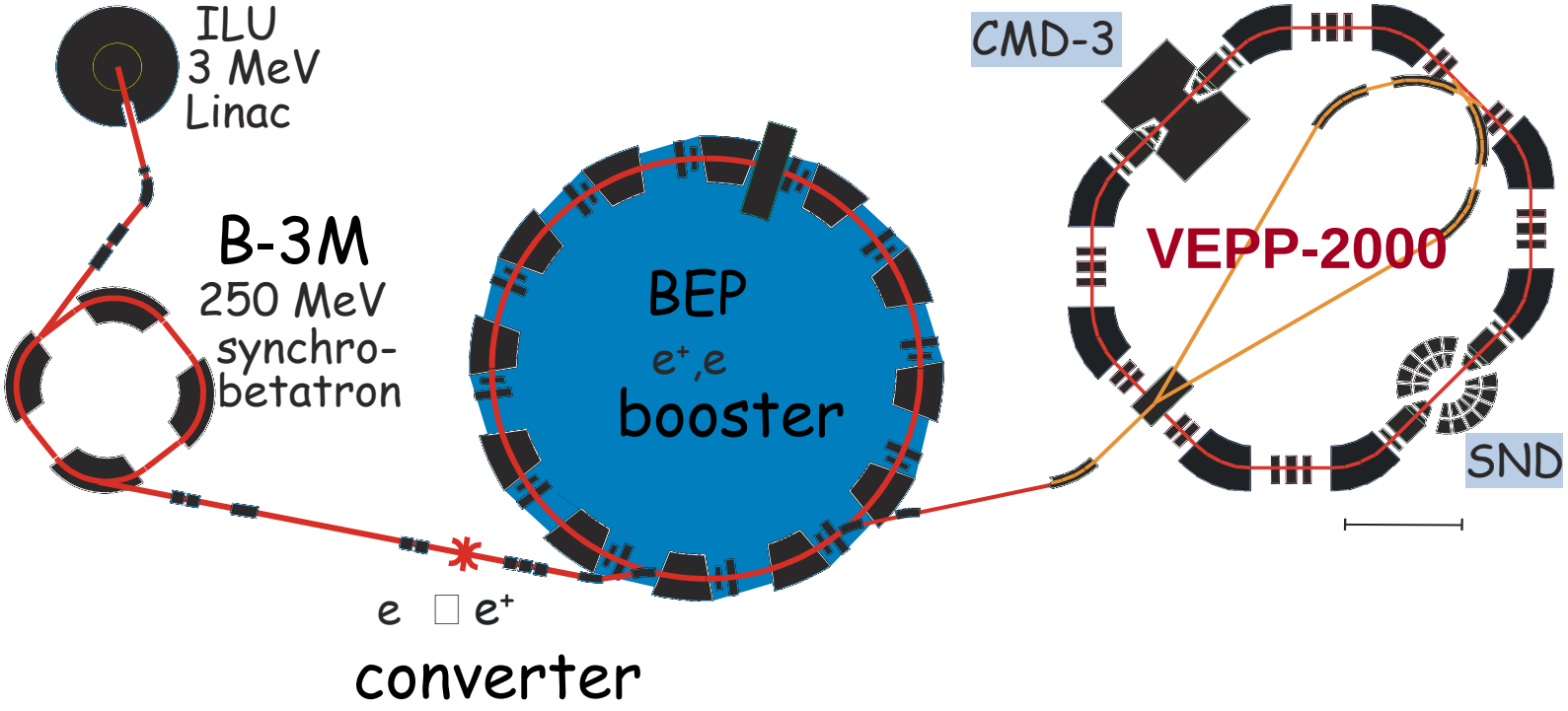
$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

M. Davier et al.,EPJC71(2011)1515

$$a_\mu^{EXP} - a_\mu^{SM} = 3.6\sigma$$

Experimental input is needed! The major contribution to (g-2)/2 coming from VEPP-2000 energy range gives 92% and determines its uncertainty

VEPP-2000 collider (2011-2013)

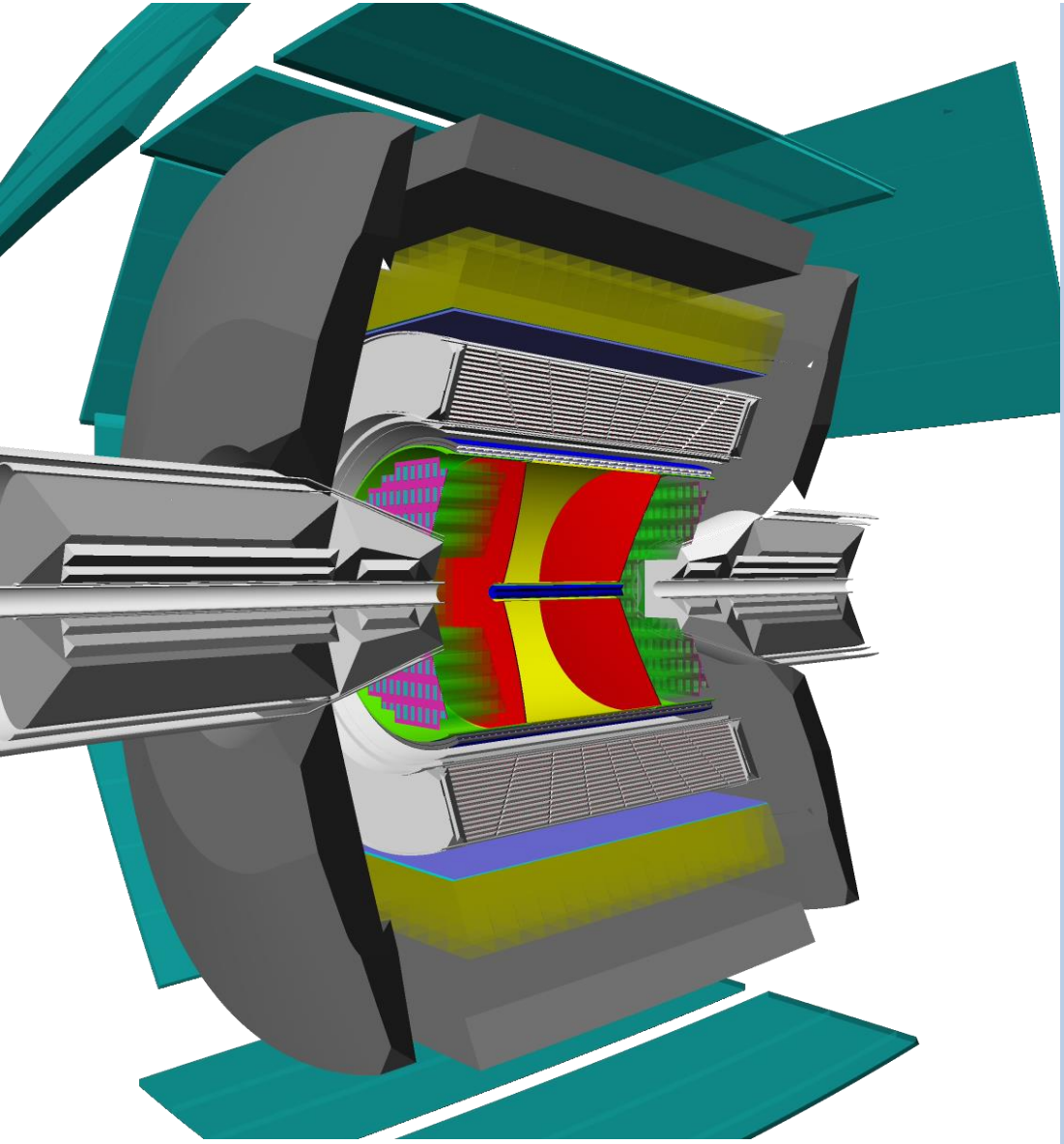


Maximum c.m. energy is 2 GeV, design luminosity is L = 10^{32} 1/cm^{2}s at 2E = 2 GeV

Unique optics with used "round beams", allows to reach higher luminosity

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

CMD-3 detector



DC – 1218 hexagonal cells with sensitive wires, W-Re alloy, 15 μ in diameter, spatial resolution ~ 100μ.

Z-chamber – start FLT, precise determine z-coordinate ~ 500 μ (detector acceptance)

LXe calorimeter thickness 5,1X_0, 196 towers & 1286 strips. Spatial resolution 1 – 2 mm, measurement of conversion point for g's measurement of shower profile

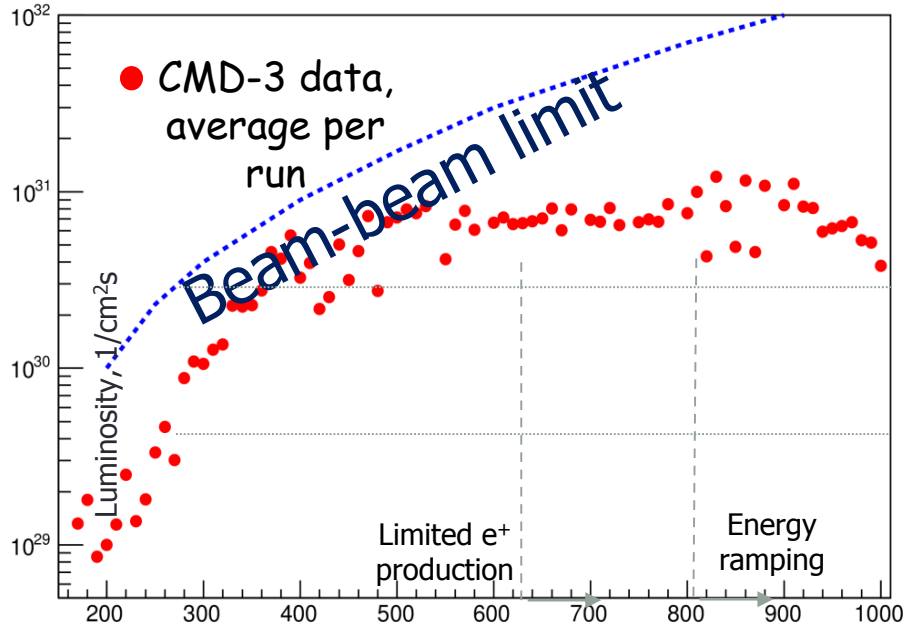
TOF – 16 counters, time resolution ~ 1ns particle id (mainly p, n)

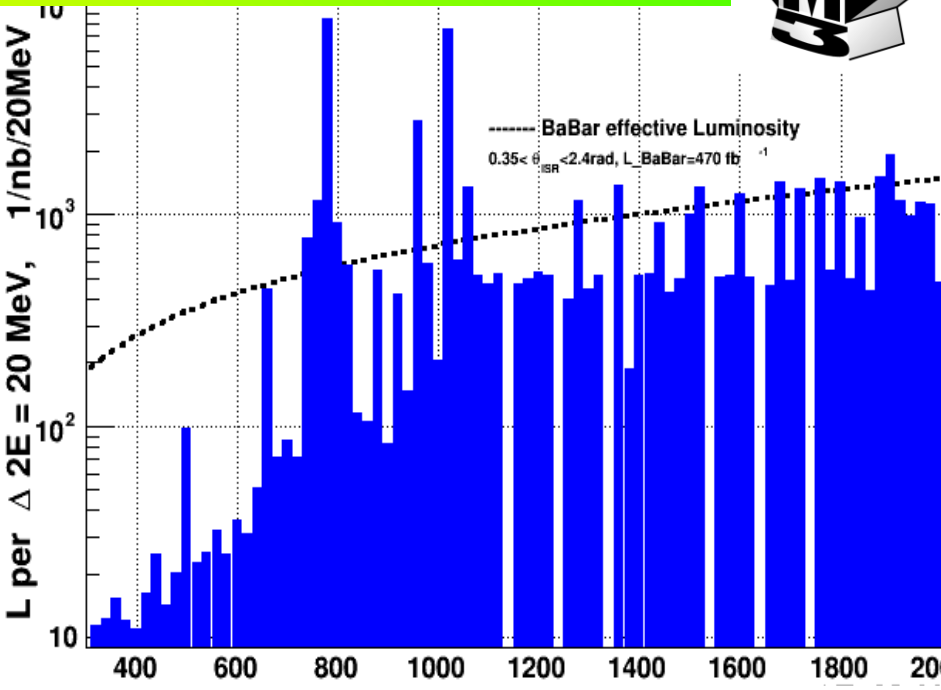
Calorimeter with CsI crystals (~3,5 t), 8 octants, number of crystals - 1152, 8 X_0.

MR system – 8 octants (cosmic veto, ~ 1ns)

Design magnetic field - 1,5 T
(current value 1.3 T)

Collected luminosity





Today the peak luminosity is limited by a deficit of positrons (650 MeV) and limited energy of the booster (higher 825 MeV).

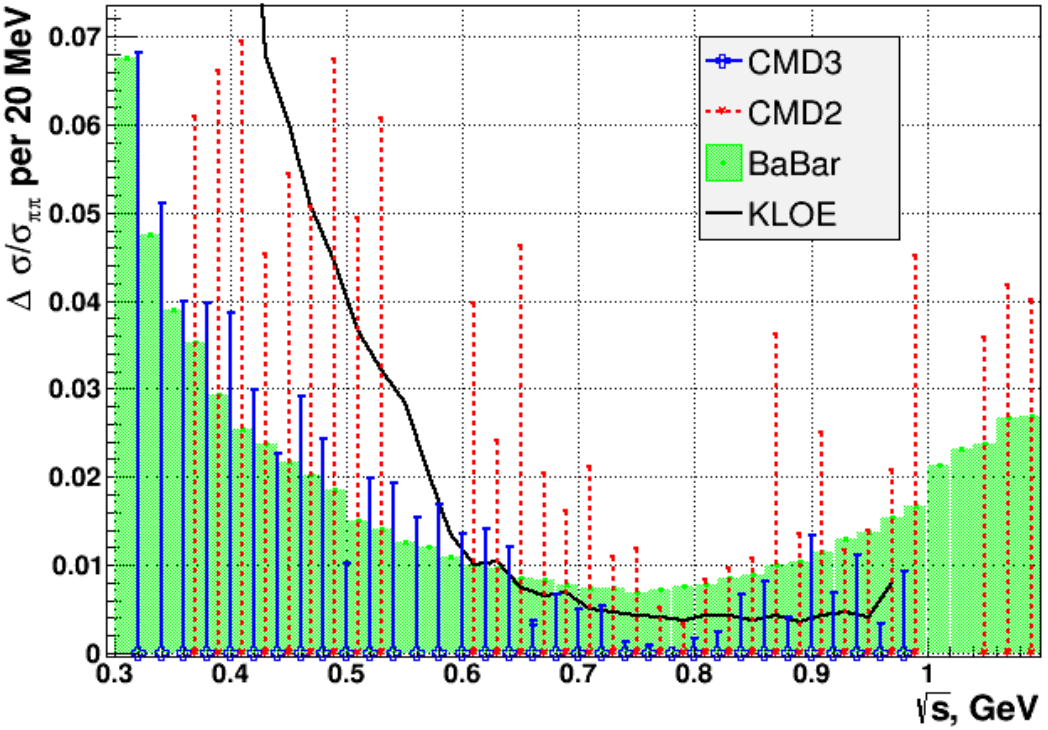
After upgrade (completed) we expect increasing of luminosity by a factor of 10 at maximum beam energy.

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

8.3 pb^{-1}	ω-region
9.4 pb^{-1}	region below 1 GeV (except ω)
8.4 pb^{-1}	φ-region
34.5 pb^{-1}	region higher than φ

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

Expected statistical error for 2013 data

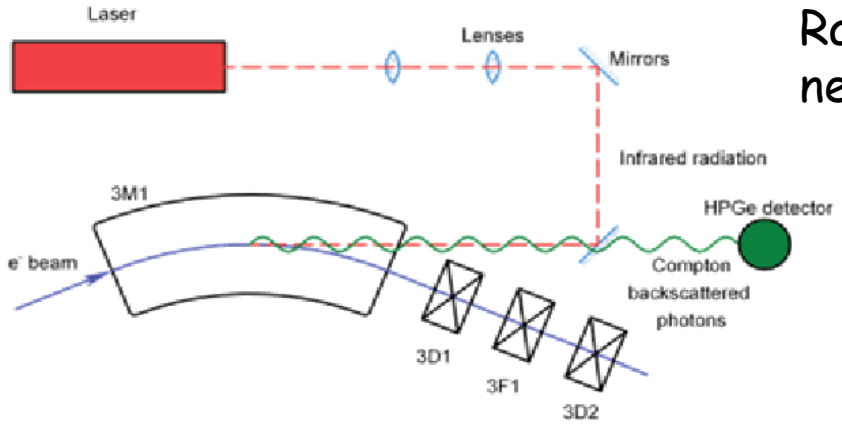


Main sources of systematics:

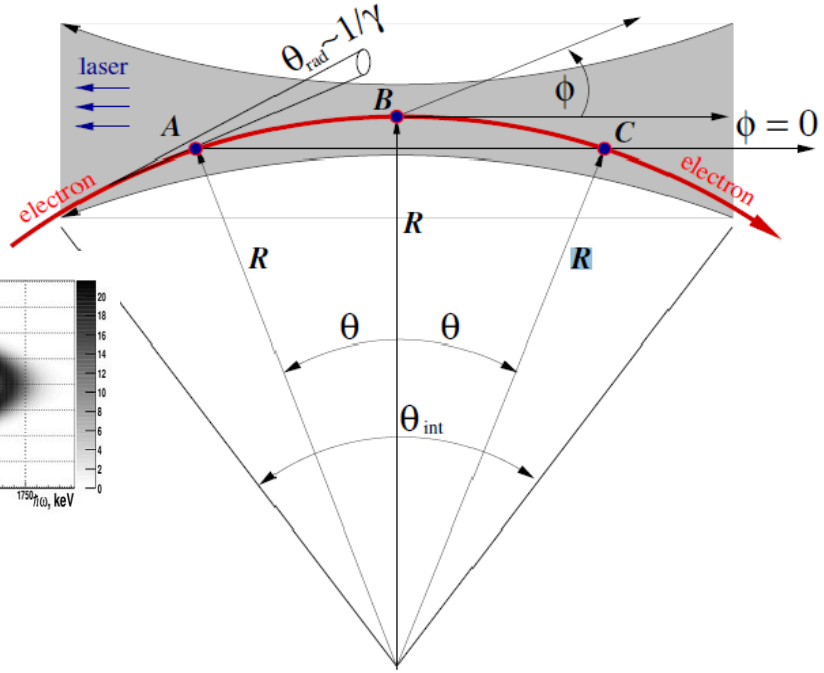
- $e/\mu/\pi$ separation – 0.2% multiple ways to get detector response from data itself.
- Fiducial volume – 0.1% independent systems (ZC & LXe), which can be used to determine fiducial volume with cross check.
- Beam energy – 0.1% constant monitoring with Compton backscattering
- Radiative corrections – 0.1% proof from data.
- Many systematic studies will rely on high statistics.

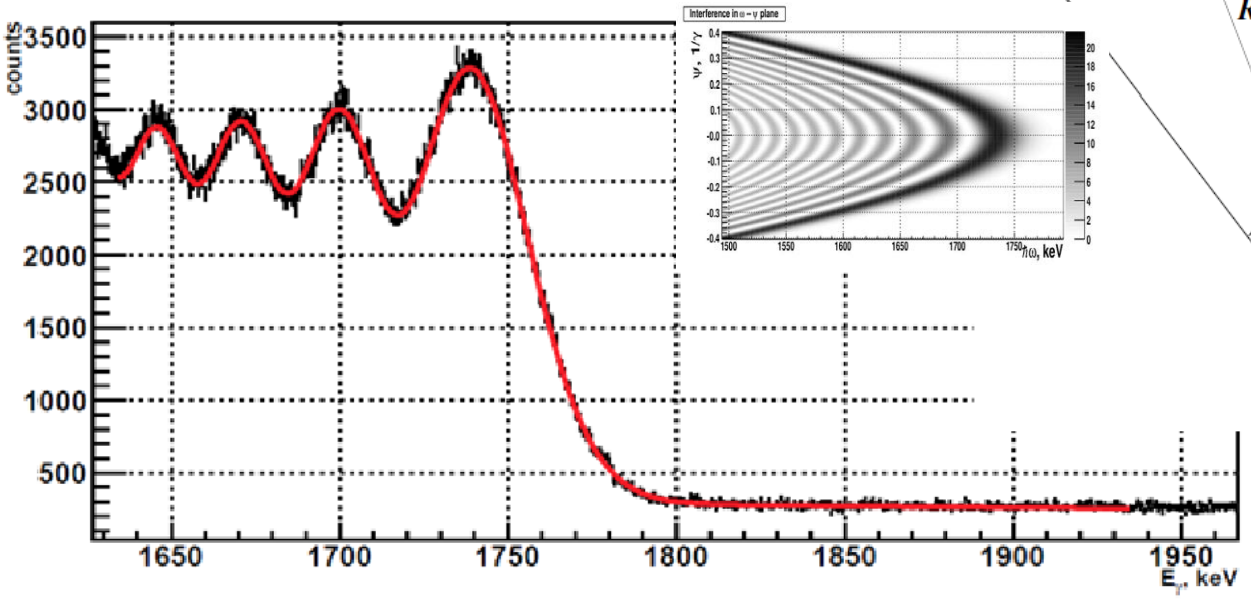
Energy measurement

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



Radiation coming from A and C points near angle θ = 0 is undergone interference



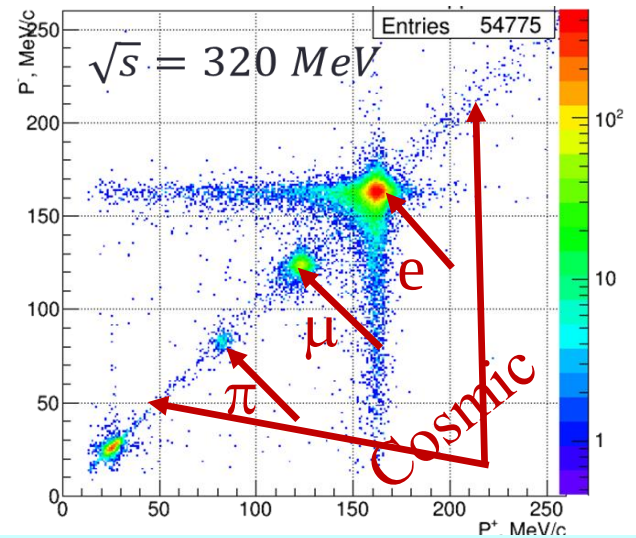


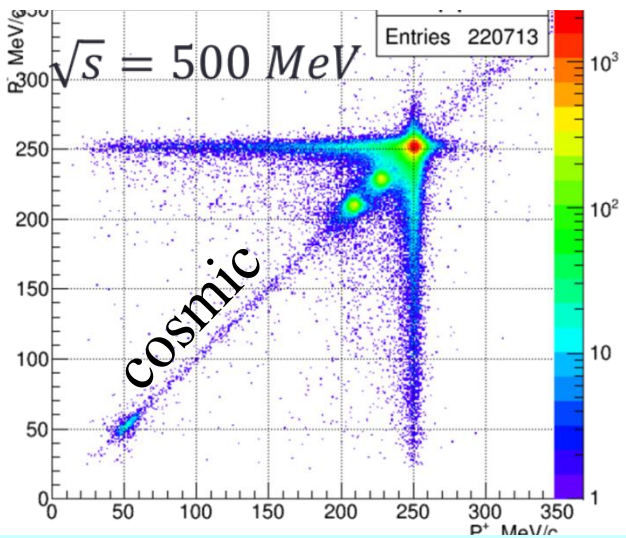
E = 993.662 ± 0.016 MeV

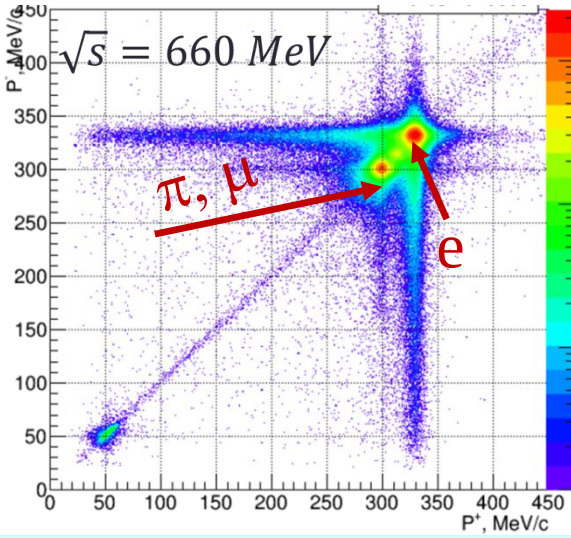
E.V. Abakumova et al.,Nucl.Instrum.Meth. A744 (2014) 35-40

Luminosity determination (e+e- & γγ)

e, μ, π separation based on momentum in DC

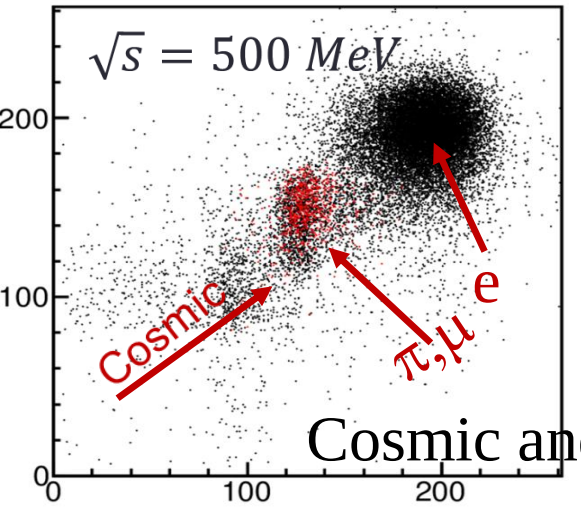


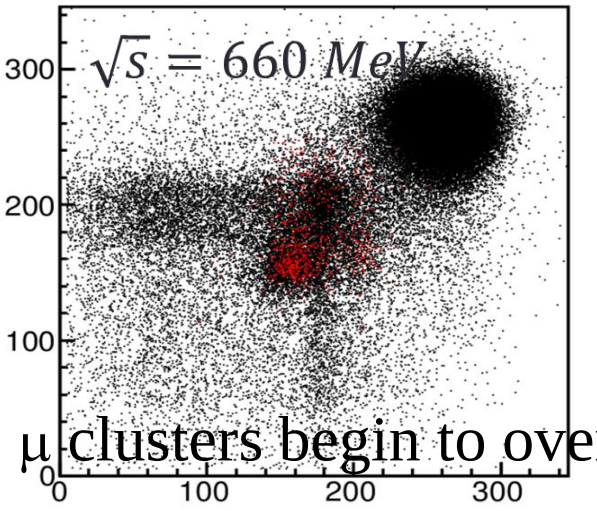


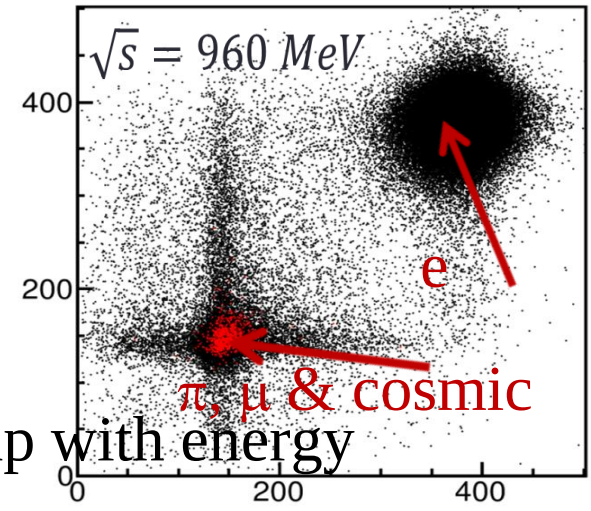


e, μ, π separation based on energy deposition in calorimeter

red dots – simulated muons

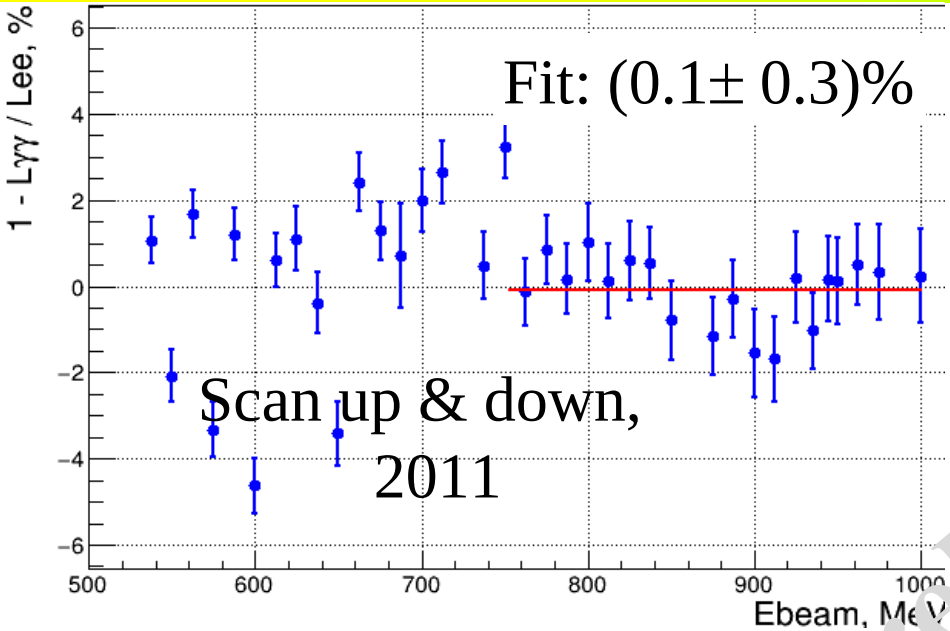


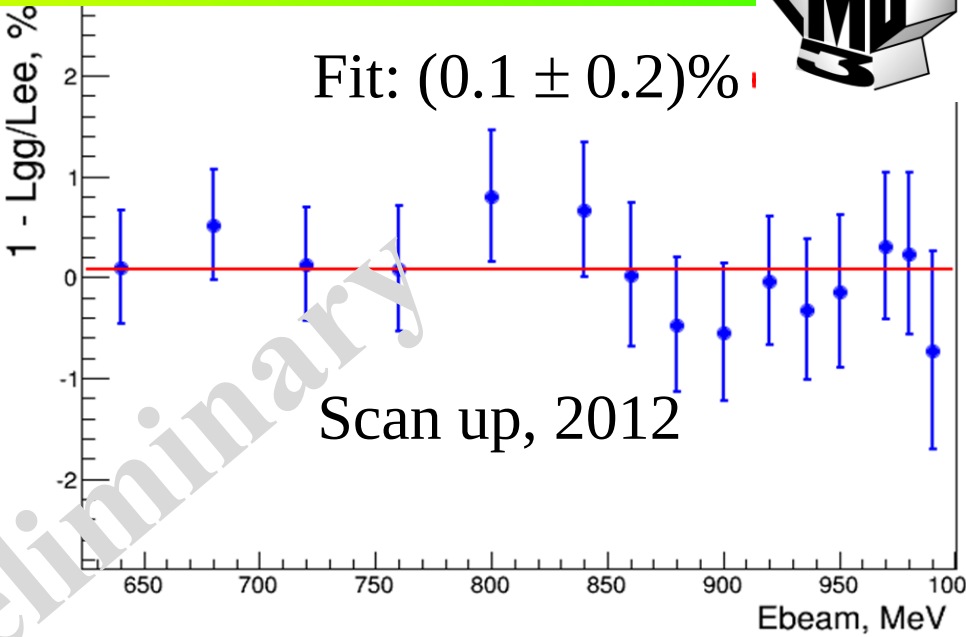


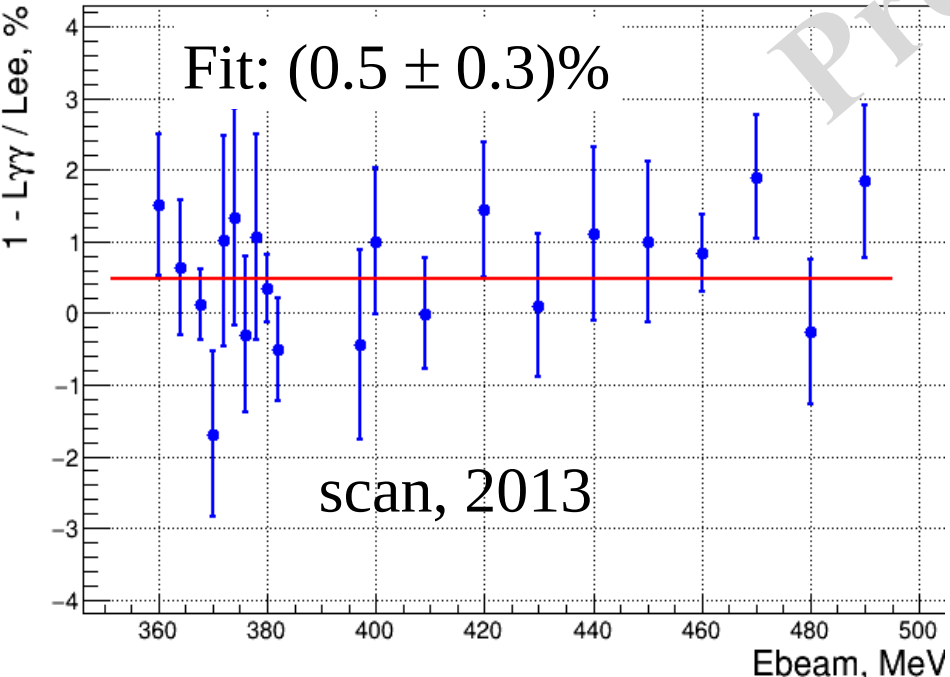


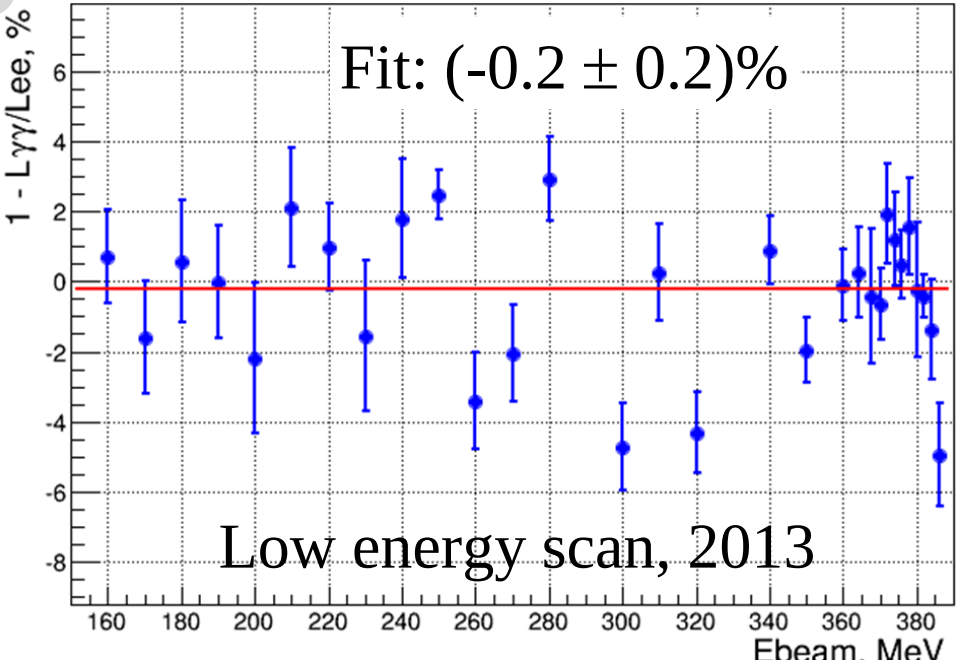
Cosmic and π, μ clusters begin to overlap with energy

Luminosity determination

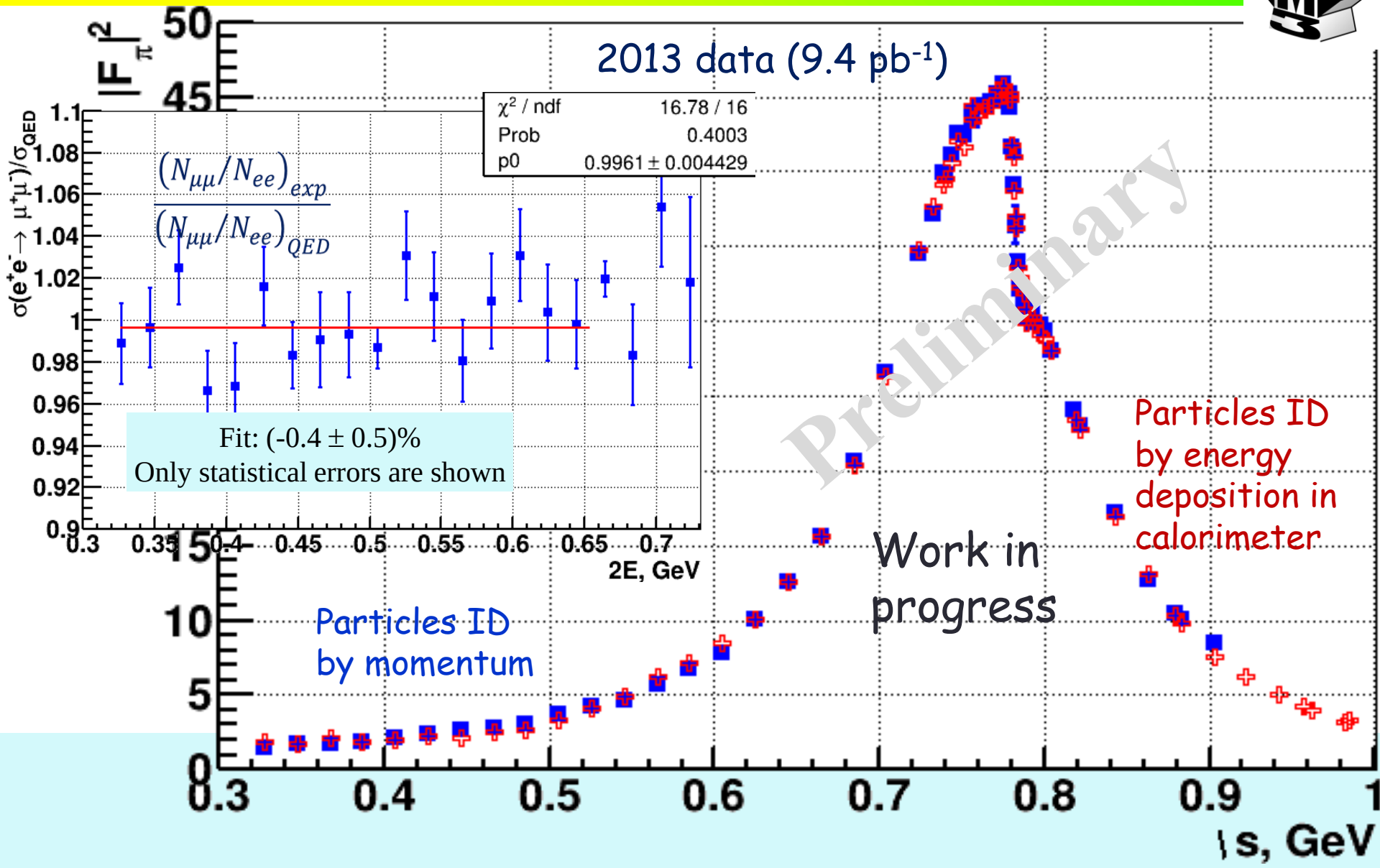






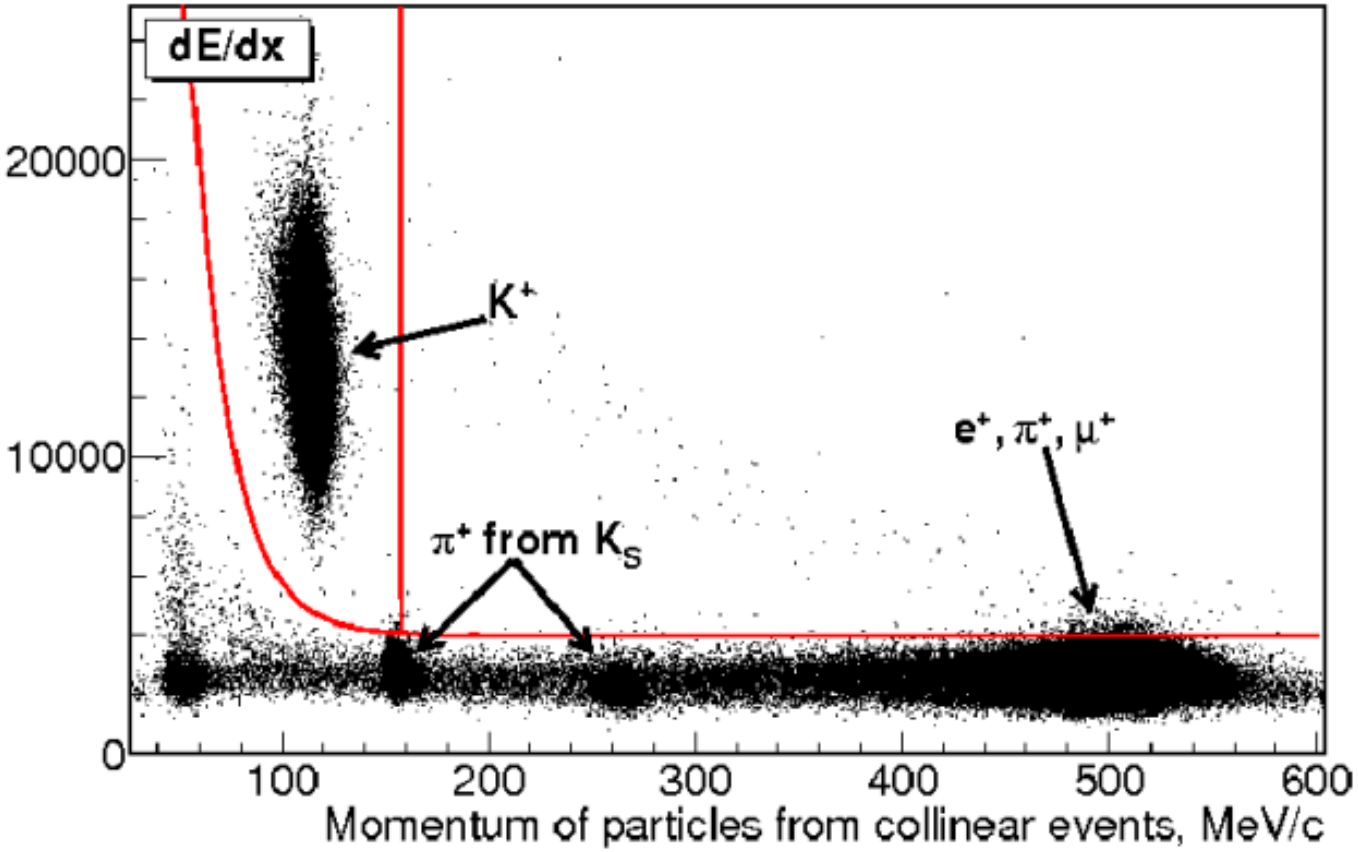


$e^+e^- \to \pi^+\pi^-$


2013 data (9.4 pb-1)
Preliminary
Particles ID by energy deposition in calorimeter
Work in progress
Particles ID by momentum
\s, GeV
|F_π|^2
σ(e+e- → μ+μ-)/σQED
(Nμμ/Nee)exp / (Nμμ/Nee)QED
χ2 / ndf 16.78 / 16
Prob 0.4003
p0 0.9961 ± 0.004429
Fit: (-0.4 ± 0.5)%
Only statistical errors are shown
2E, GeV

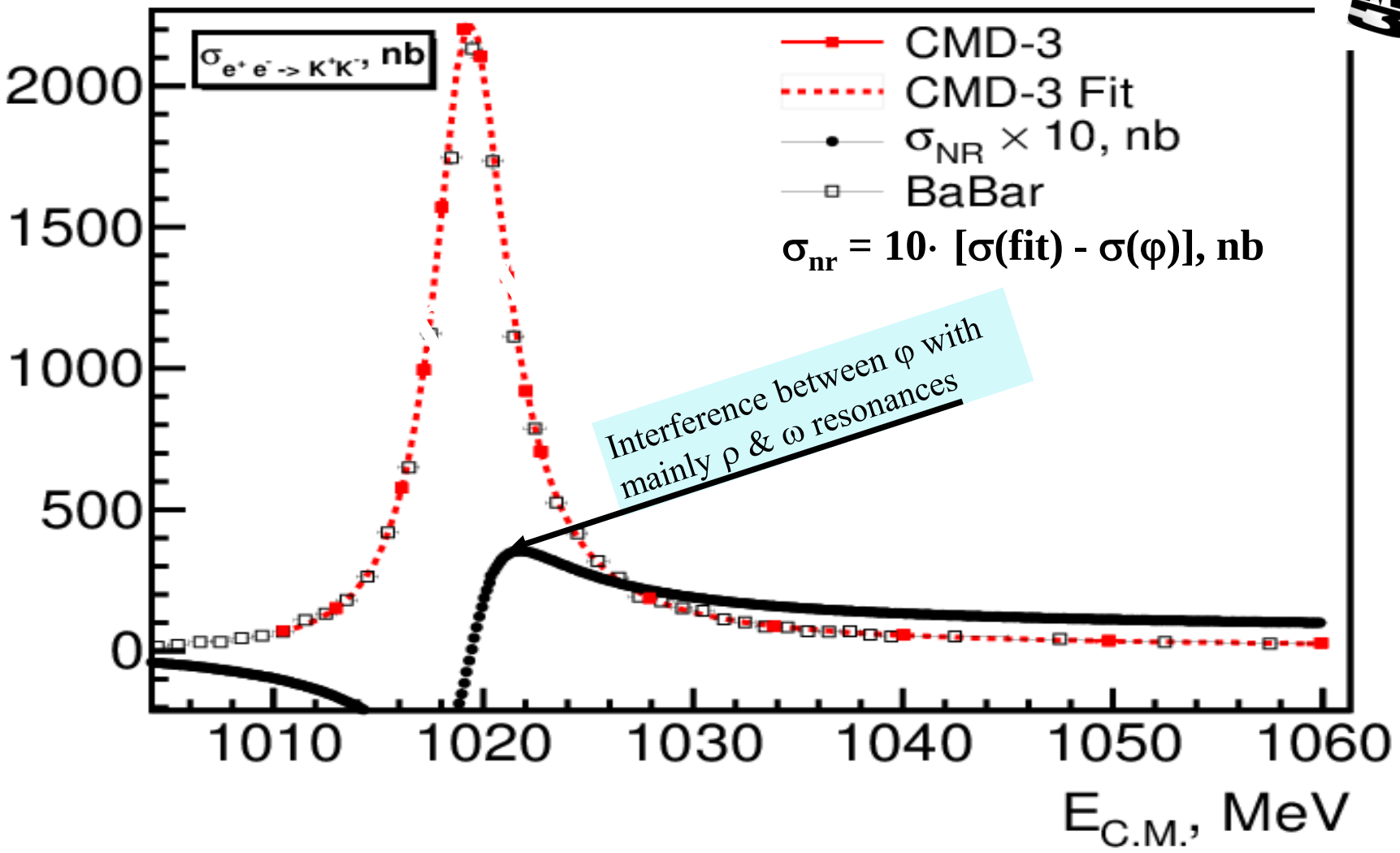
Study of the process $e^+e^- \to K^+K^-$

The process e+e- → K^+K^- has been studied at energies around φ meson mass. selection is based on information about average energy losses dE/dx in DC and the average momentum of pair tracks



- In E_{cm} = 1004 – 1060 MeV:
- 25 energy points
- Accumulated luminosity 5.9 pb^{-1}

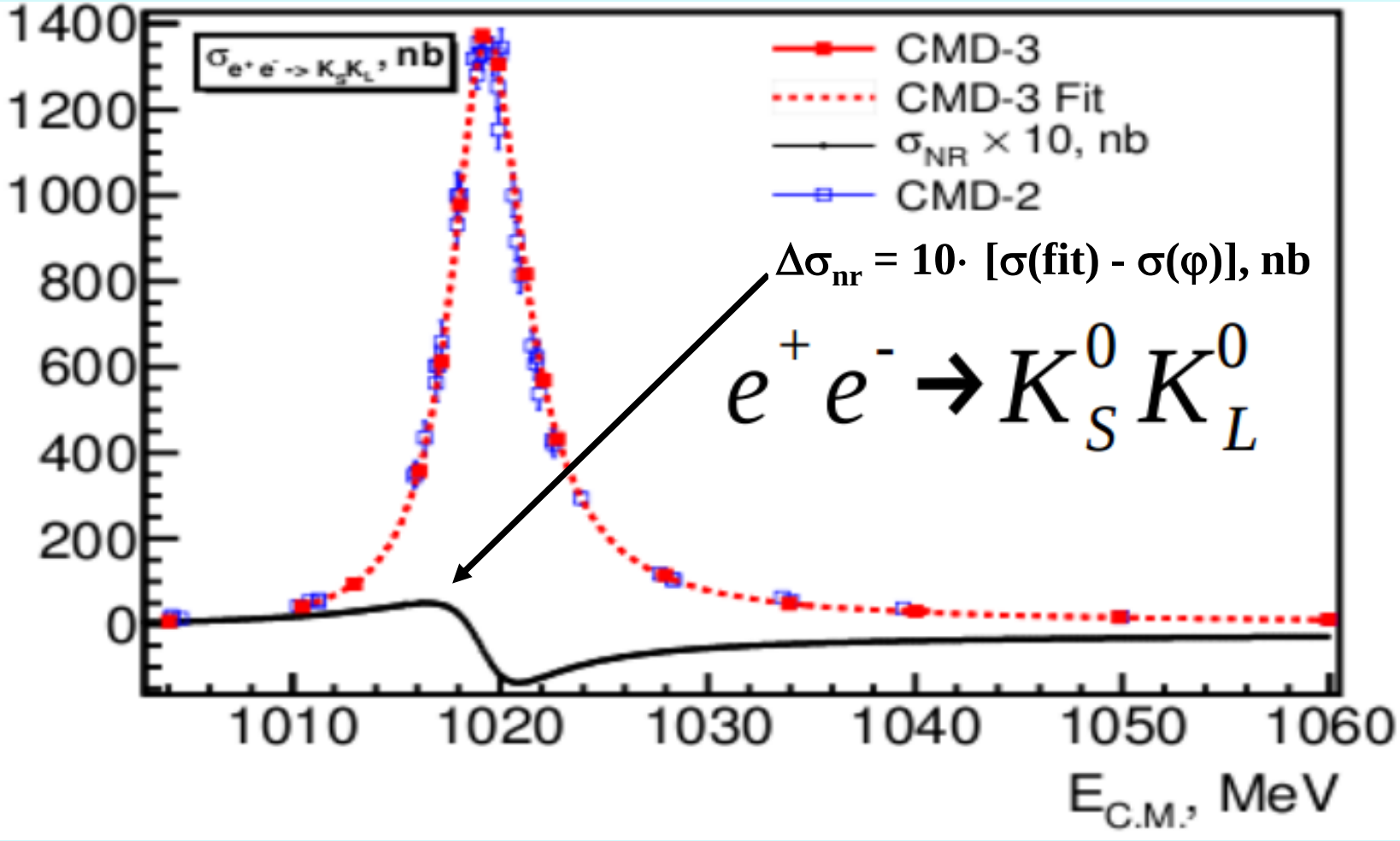
Study of the process $e^+e^- \to K^+K^-$



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

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

This process is studied using decay $K_s \to \pi^+\pi^-$



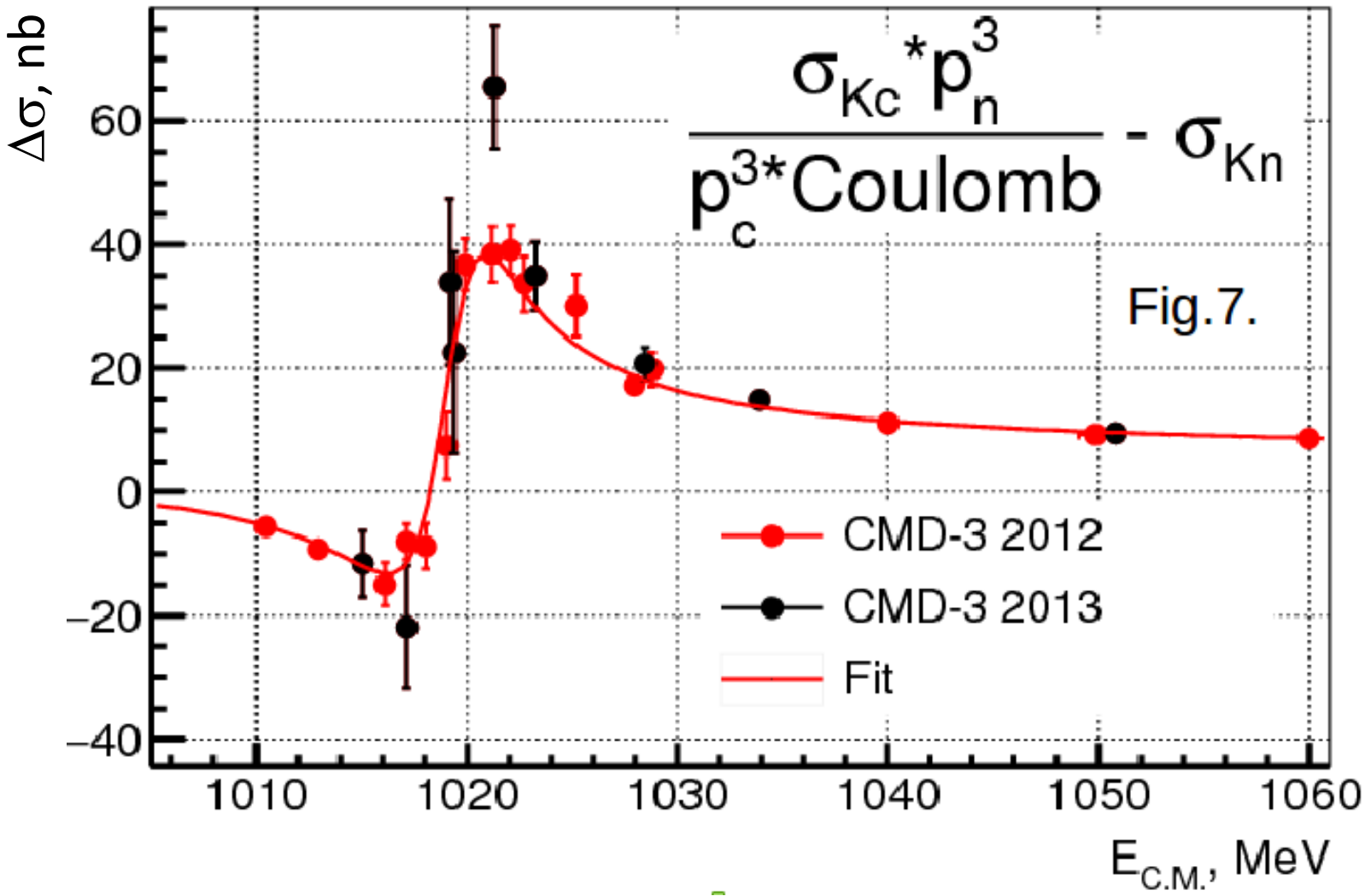
In E_{cm} = 1004 – 1060 MeV: 25 energy points. Collected luminosity ~5.9 pb^{-1}

Systematic error is 2 – 3 %

Published in **Phys.Lett. B760 (2016) 314-319**

The difference of charged and neutral cross-sections normalized to phase space difference as well as Coulomb interaction of charged kaons in final state.

$$\sigma(K^+K^-) \sim |A_{I=0}(\varphi,\omega) + A_{I=1}(\rho)|^2$$
$$\sigma(K_SK_L) \sim |A_{I=0}(\varphi,\omega) - A_{I=1}(\rho)|^2$$



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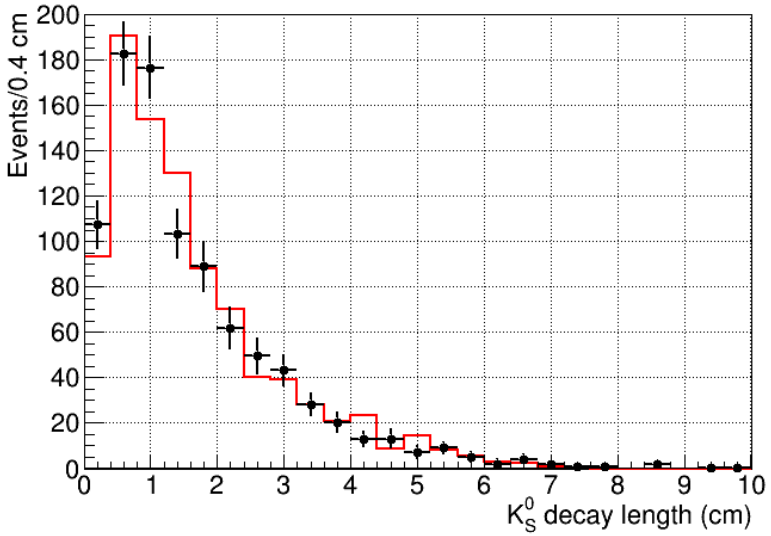
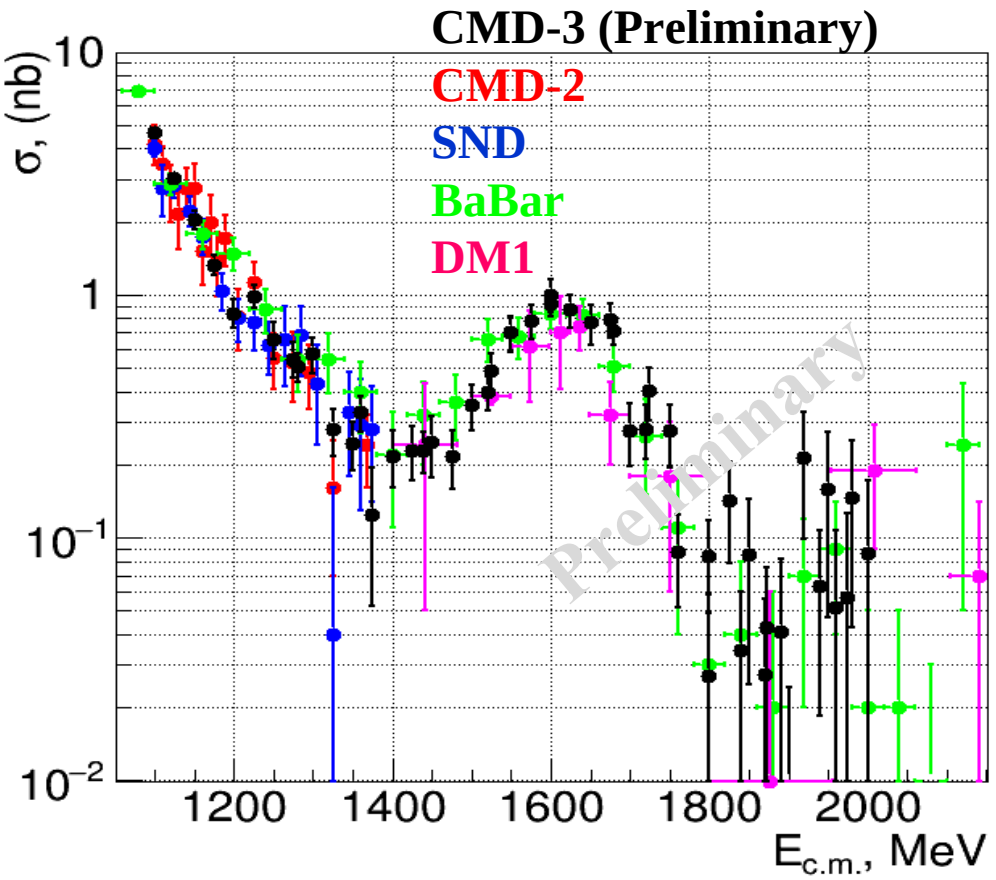




Good agreement with all previous results

In E_{cm} = 1100 – 2000 MeV: 54 energy points

Accumulated luminosity about 32.1 pb^{-1}

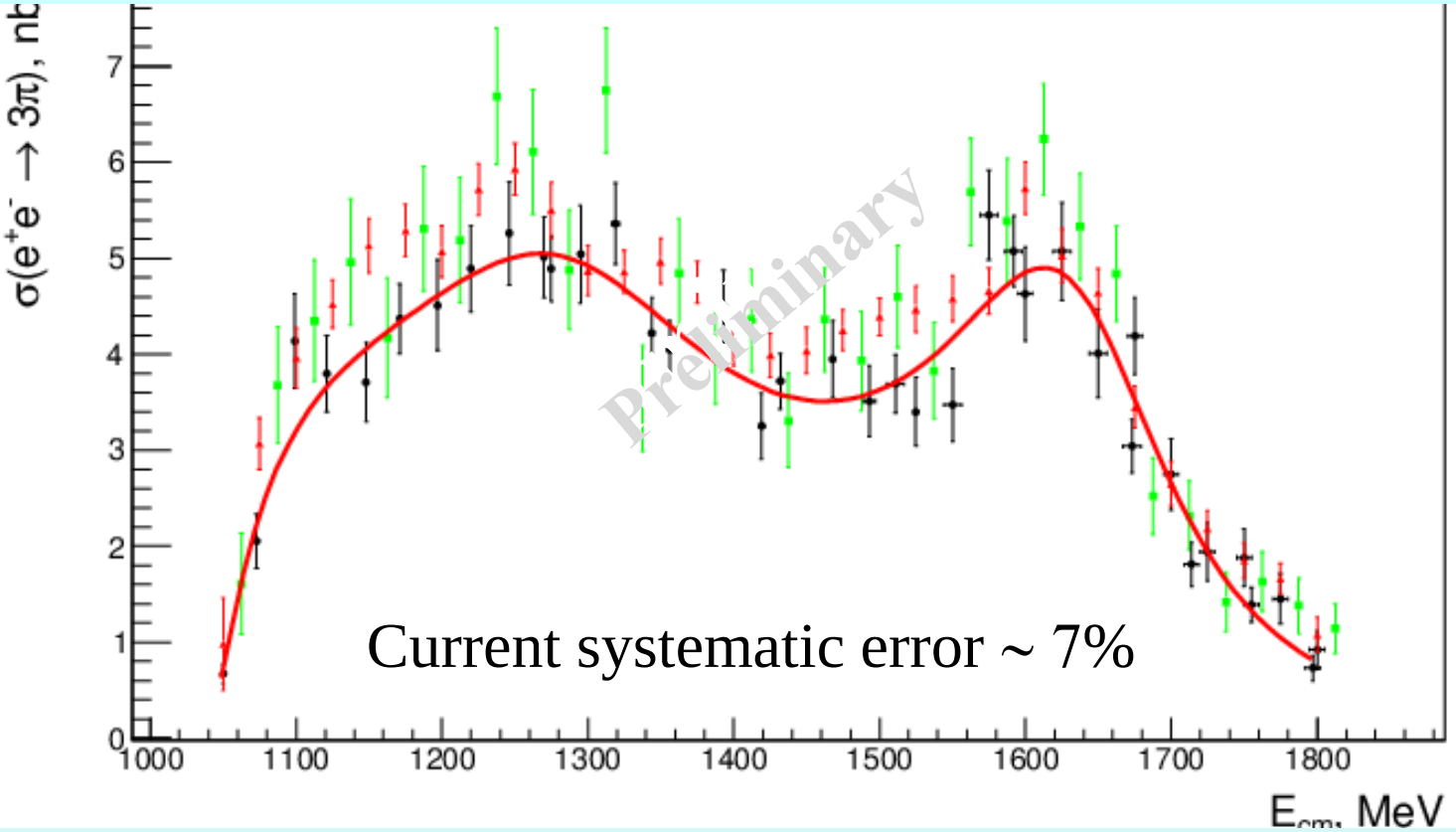
1889 events with fully reconstructed $K_S \to \pi^+\pi^-$

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

- Black points - CMD-3 data (run 2011 & 2012)
- Green points – BaBar data
- Red points – SND data

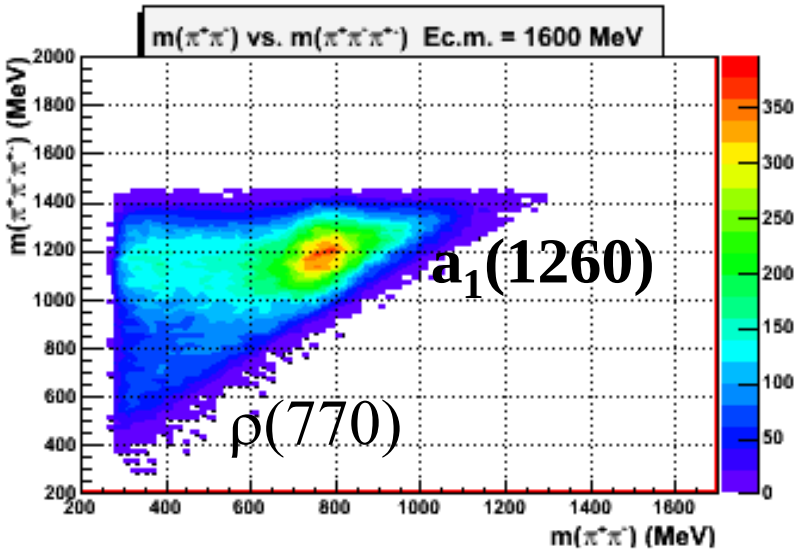
Analysis is based on integrated luminosity ~ 30 pb-1

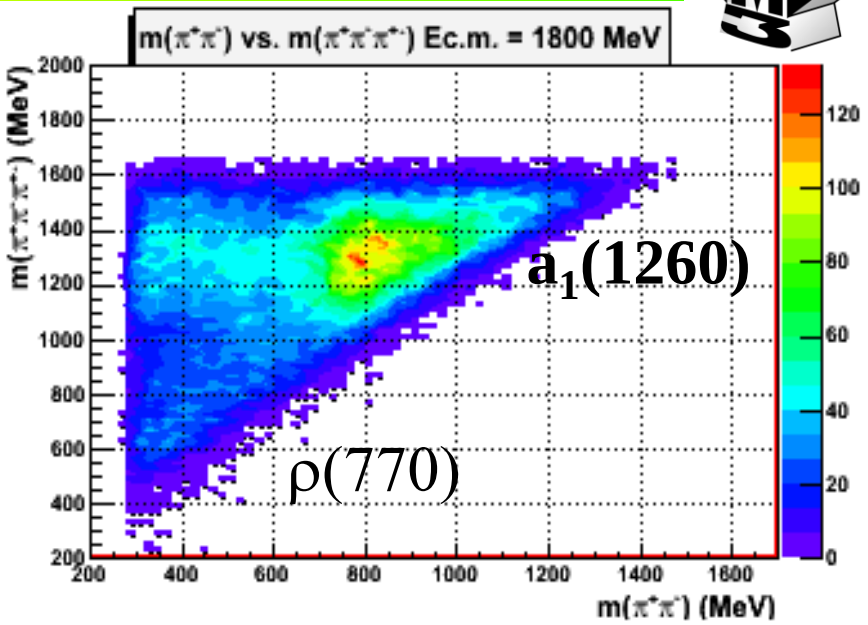
Cross section was measured at 46 energy points

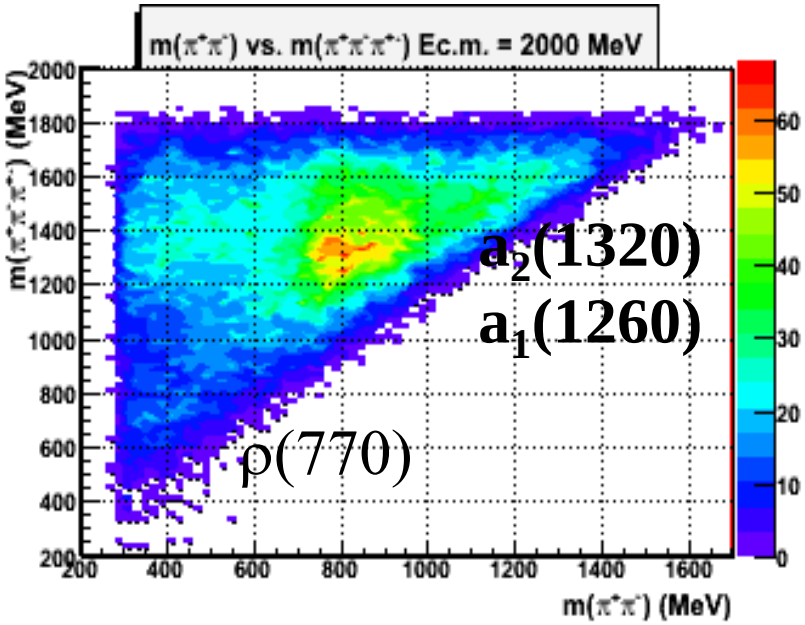


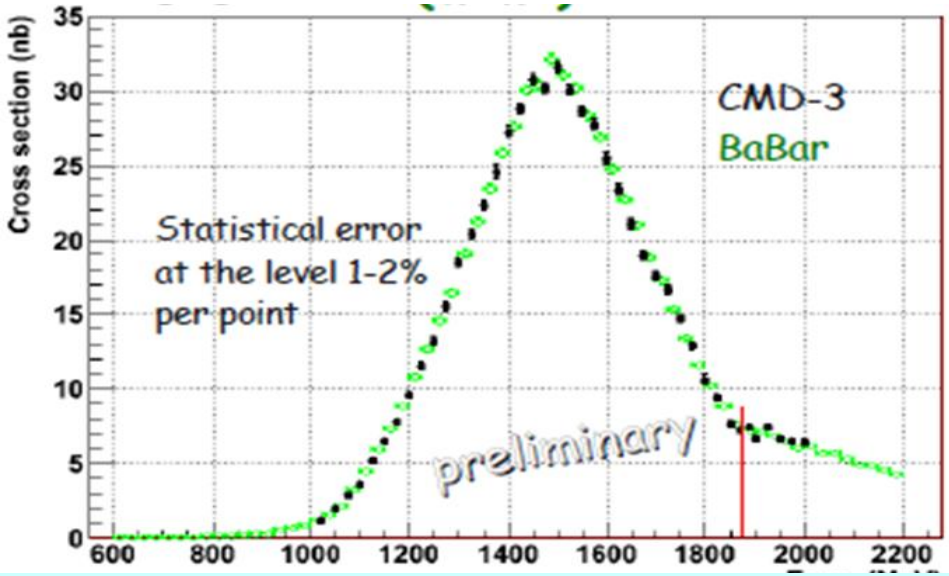
Red fit – sum of amplitudes: ω, φ, φ’, φ’’

Dynamics of $e^+e^- \to 2\pi^+2\pi^-$ & cross section





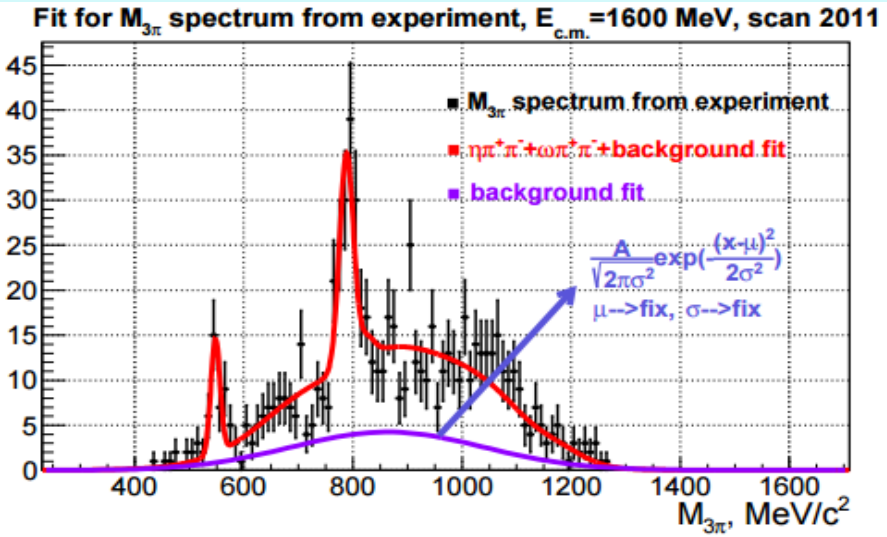


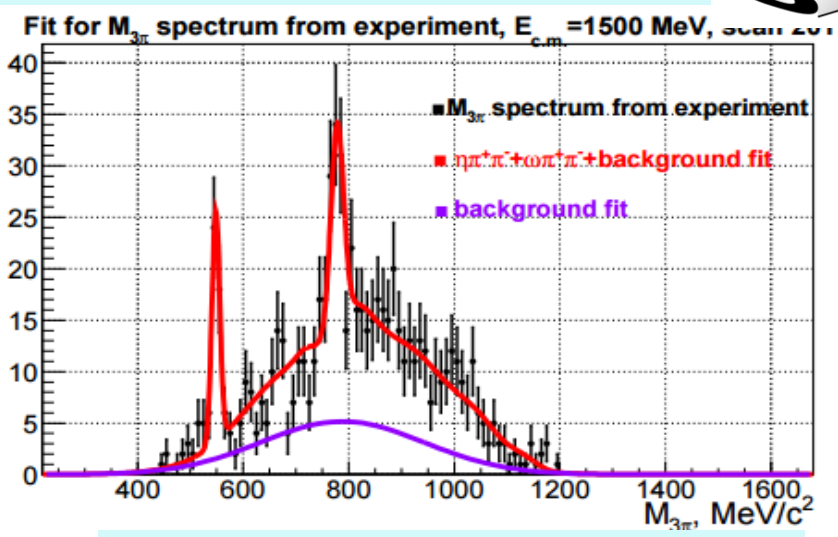


A ρ^0 is always present, $a_1(1260)\pi$ and $a_2(1320)\pi$ are significant

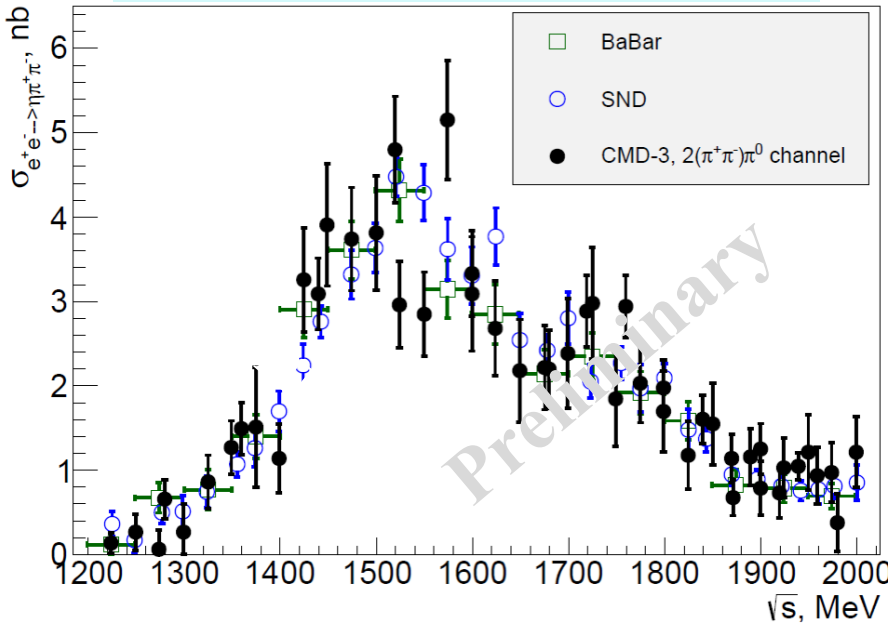
$e^+e^- \to 5\pi$

Study of $2(\pi^+\pi^-)\pi^0$ final state with intermediate $\eta\pi\pi$ and $\omega\pi\pi$ production

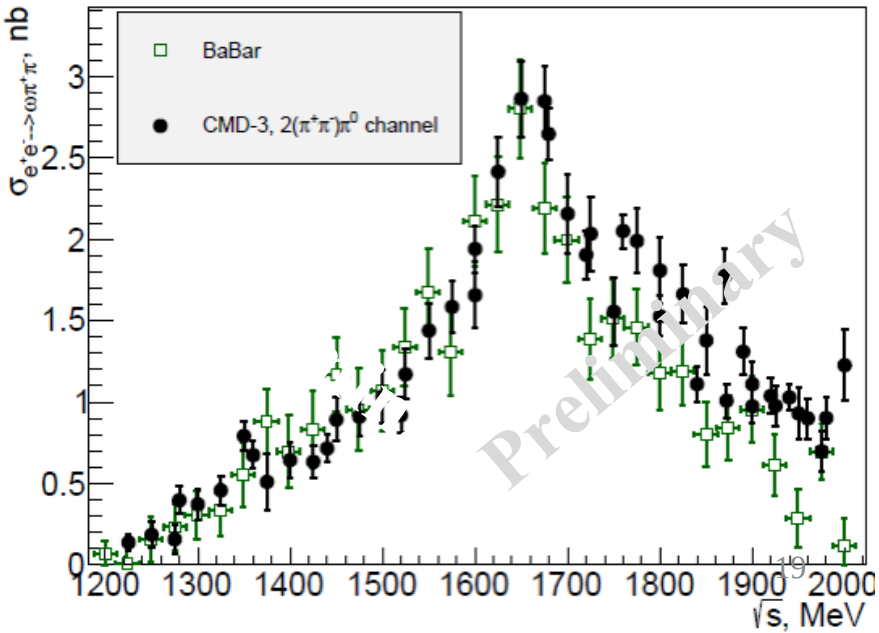




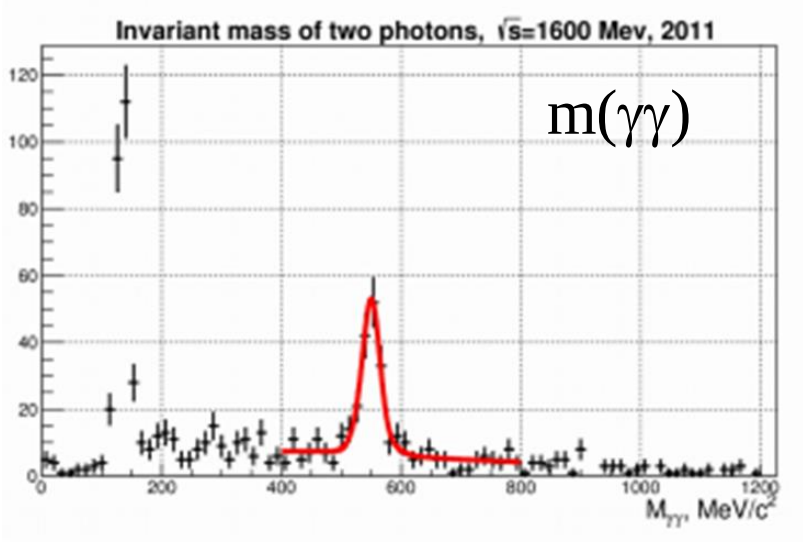
$e^+e^- \to \eta\pi^+\pi^- \to 2(\pi^+\pi^-)\pi^0$

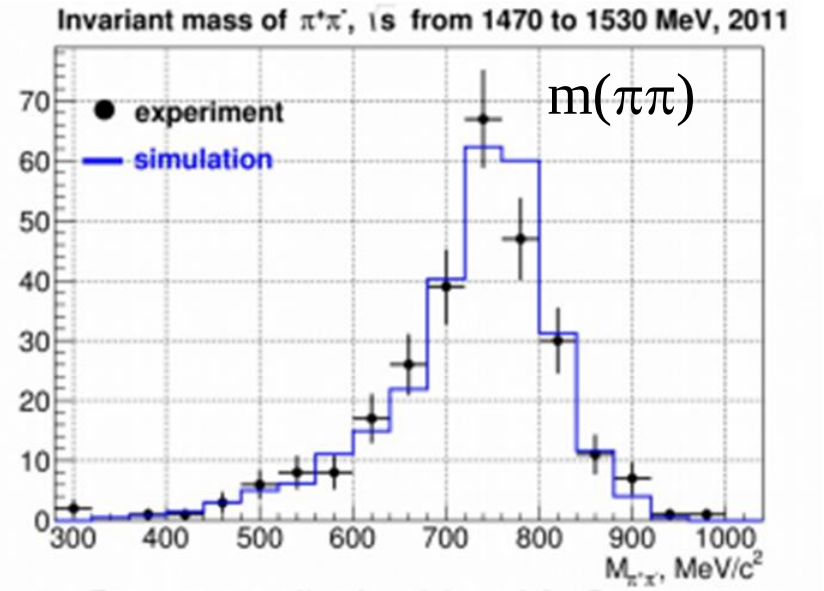


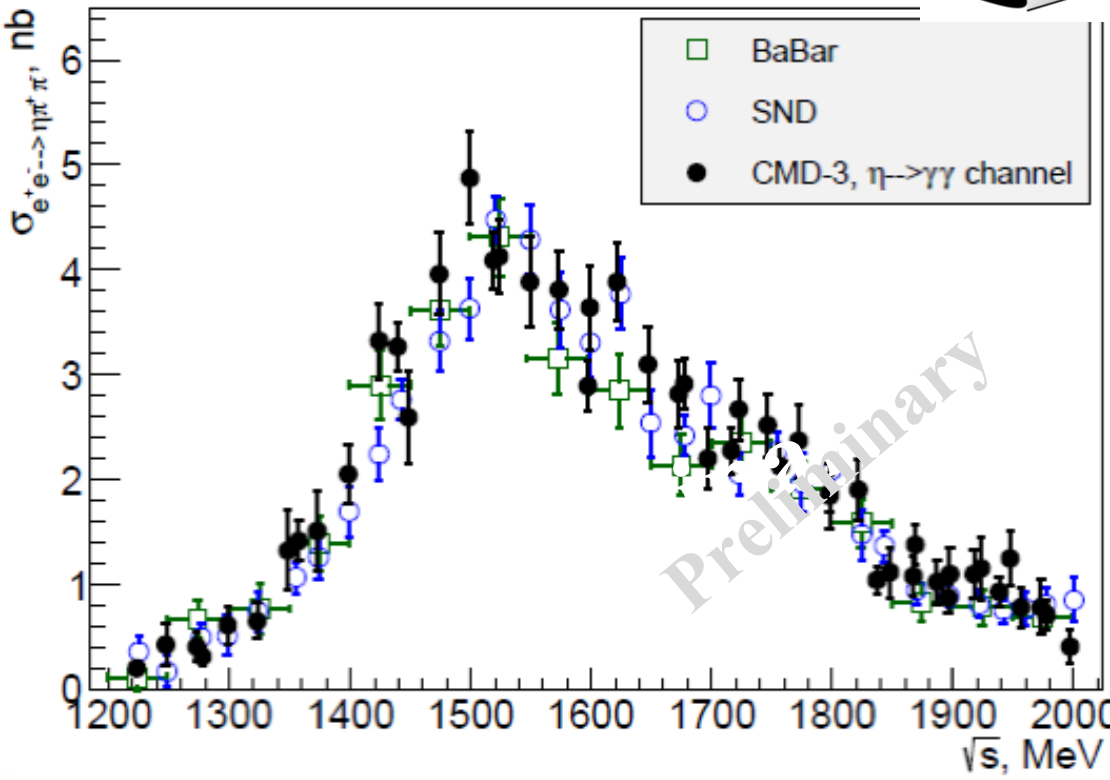
$e^+e^- \to \omega\pi^+\pi^- \to 2(\pi^+\pi^-)\pi^0$



$e^+e^- \to \eta\pi^+\pi^- (\gamma\gamma\pi^+\pi^-)$





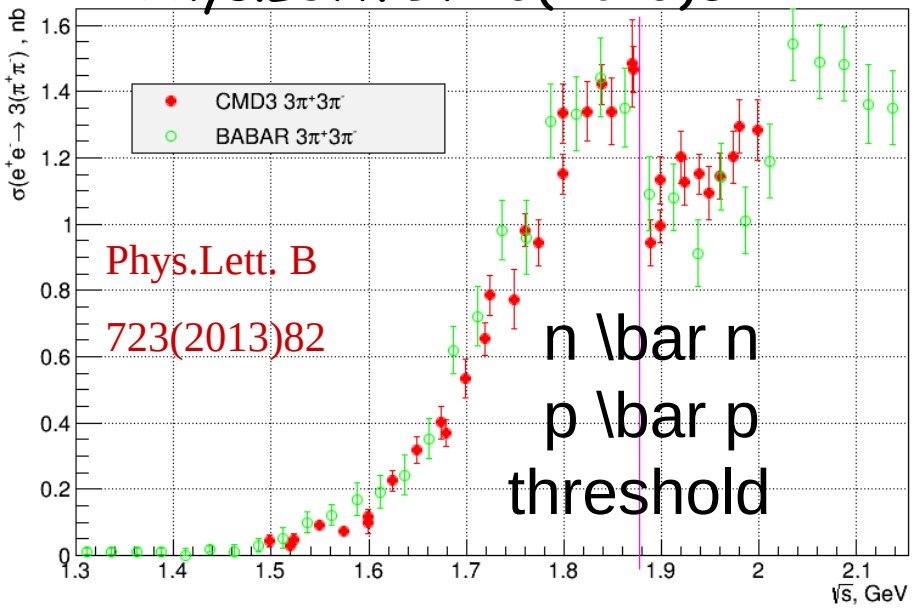


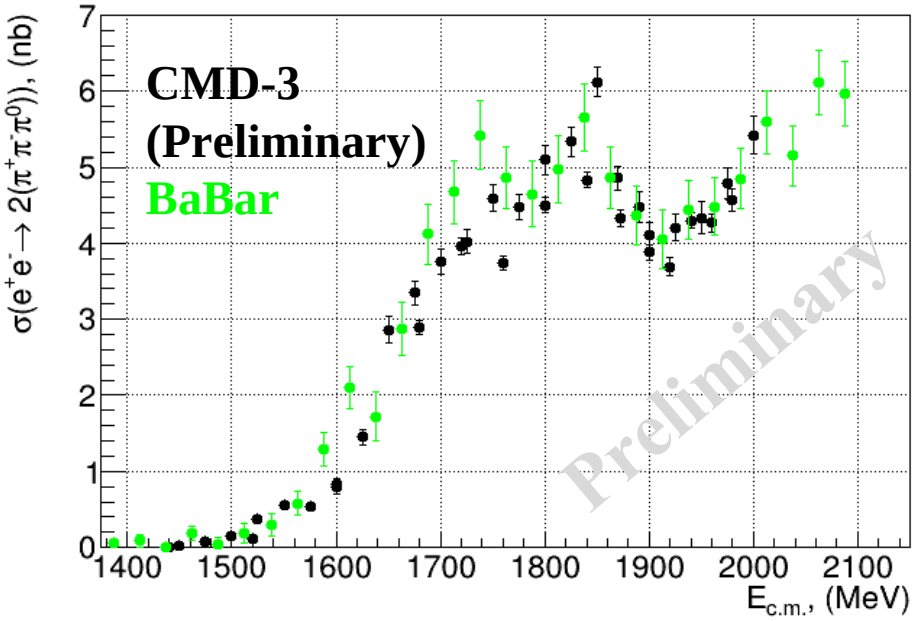
Cross sections are in agreement for both decay modes $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \gamma\gamma$

η and ρ intermediate states dominate.

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

Phys.Lett. B723(2013)82





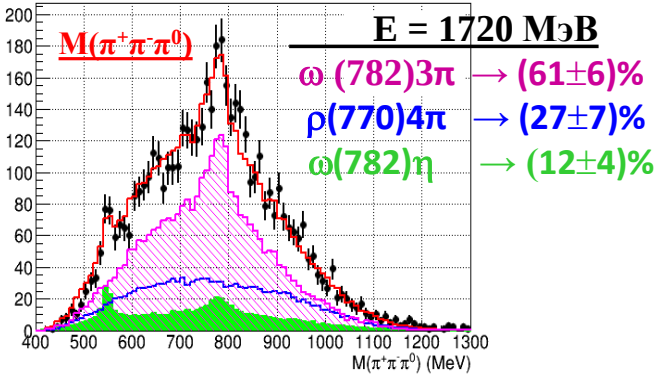
Systematic error is about 6%, main source is model dependence.

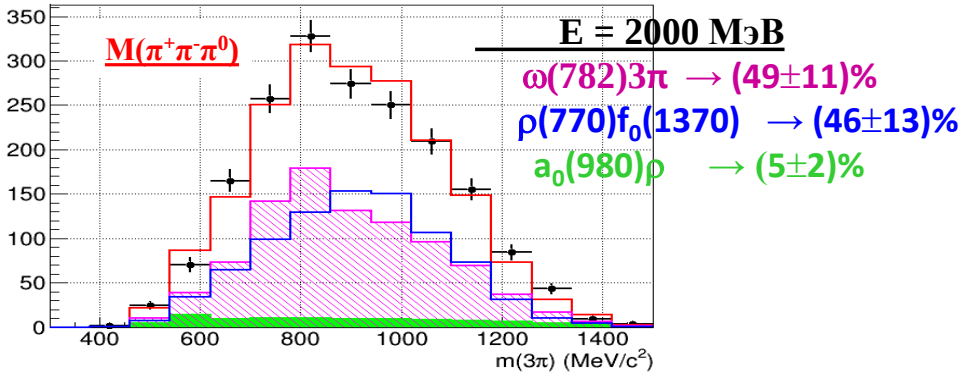
Preliminary studies of dynamics: Hint of energy dependent dynamics in 1.7-1.9 GeV energy range;

In E_{cm} = 1450 – 2000 MeV: 38 energy points,

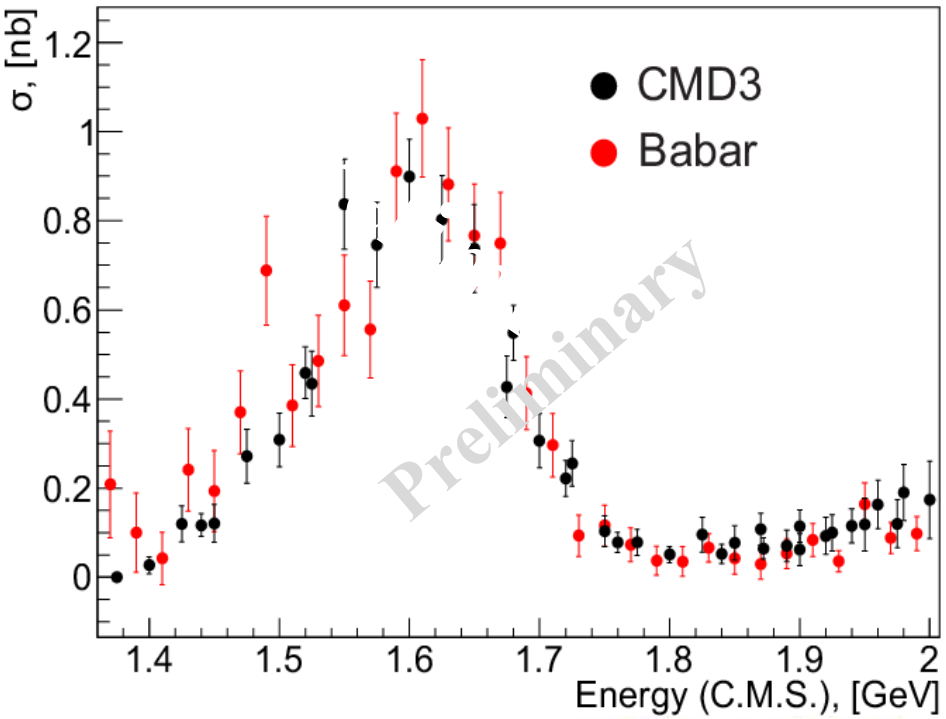
Luminosity integral 23.8 pb^{-1},

10700 fully reconstructed events



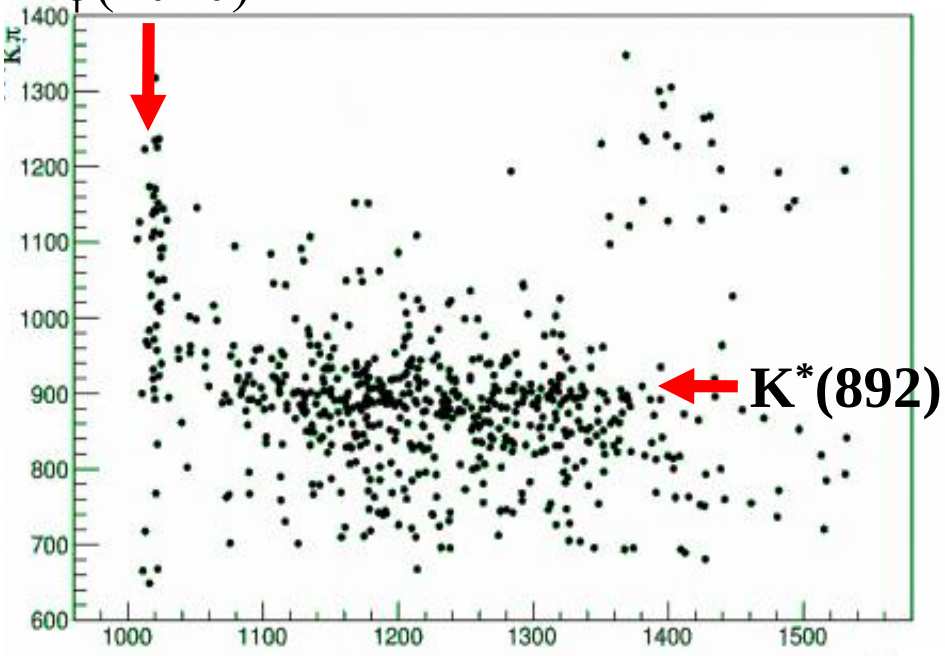


$e^+e^- \to K^+K^-\pi^\circ$



Cross section, very preliminary

φ(1020)

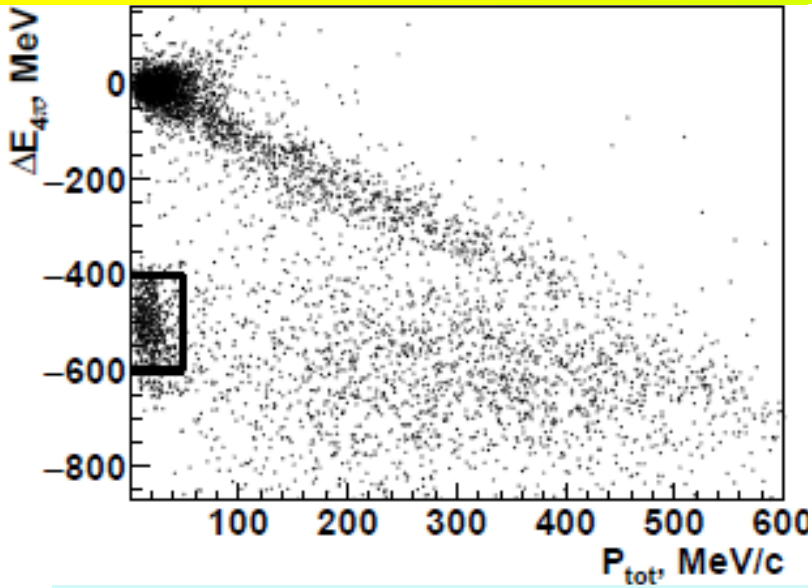


Number of K^* events vs invariant mass of K^+K^-

- Analysis is based on the integrated luminosity34 pb^{-1}
- It is consistent with BaBar but more precise
- Number of selected signal events was found to be 940 ± 57.
- The main physical background comes from the processes: $e+e- \to K^+K^-\pi^0\pi^0$, $\pi^+\pi^-\pi^0$

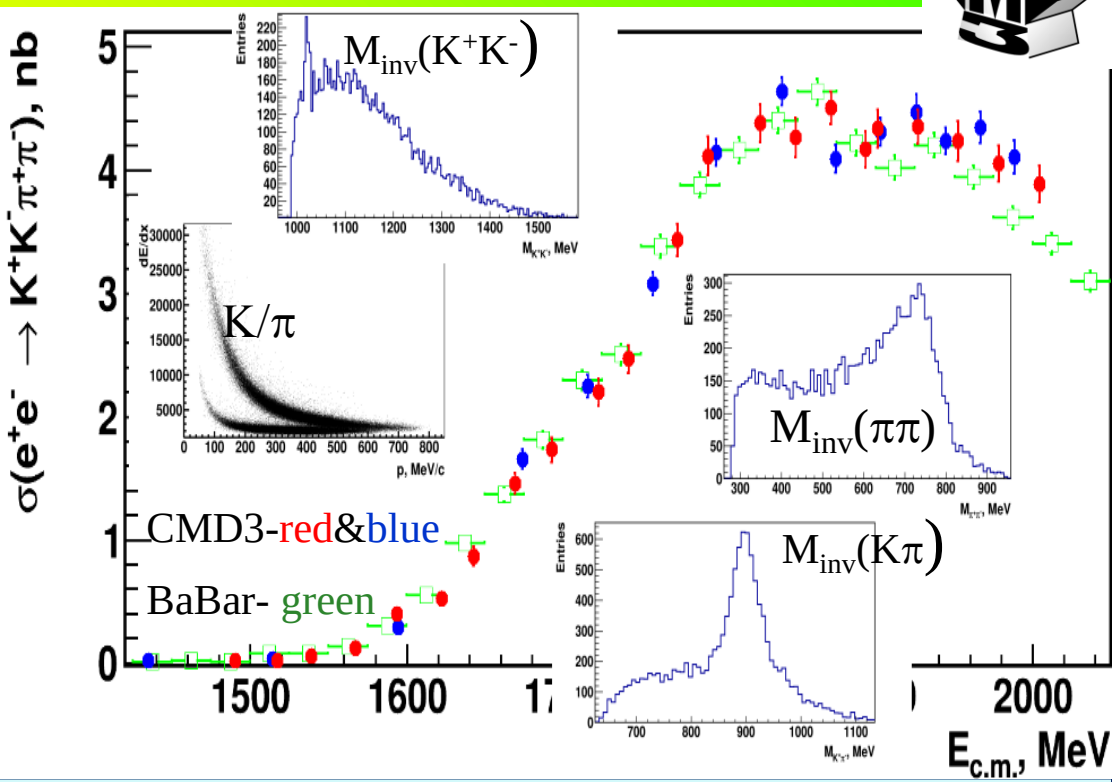
- Two intermediate states are clearly seen: $\varphi\pi^\circ$ and K*(892)K mechanism
- Detection efficiency according to SIM was around 12% ~ 18% with energy
- The current systematic uncertainty is estimated as 10%

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



$\Delta E = E_1 + E_2 + E_3 + E_4 - 2E_{beam}$

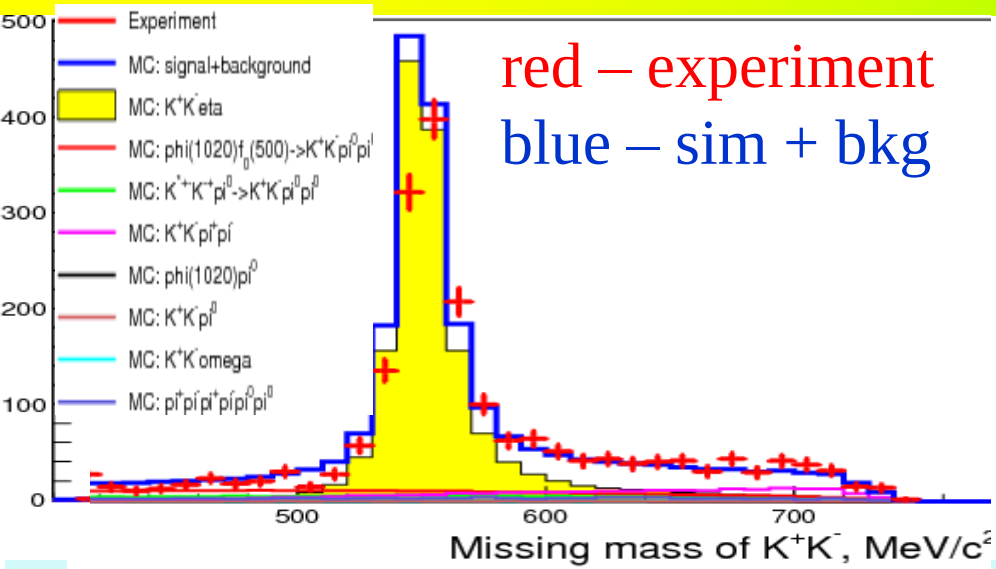
$\mathbf{P}\tau o\tau = |\mathbf{P}_1 + \mathbf{P}_2 + \mathbf{P}_3 + \mathbf{P}_4|$



- CMD-3 studies uses 22 pb^{-1} between 1.5 and 2 GeV, more than 20000 events with 3 and 4 tracks were selected for analysis;
- Ionisation losses in DC dE/dx provide good K/π separation;
- Analysis of $\pi^+\pi^-$, $K^\pm\pi^\mp$, K^+K^- inv. Masses clear shows signals from π^0, $K^{*0}(892)$ and $\phi(1020)$;
- Many different mechanisms seen: $K_1(1270)K \to K2\pi K$, $K^*(892)K\pi$, $K_1(1400)K \to K^*(892)\pi K$, $\varphi\pi^+\pi^-$.

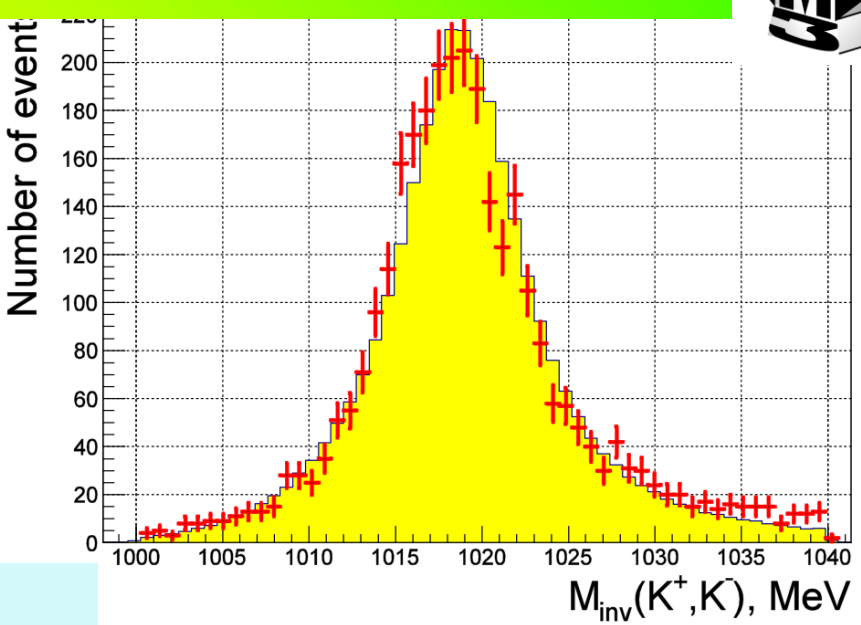
Recently published in Phys.Lett. B756 (2016)153-160

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

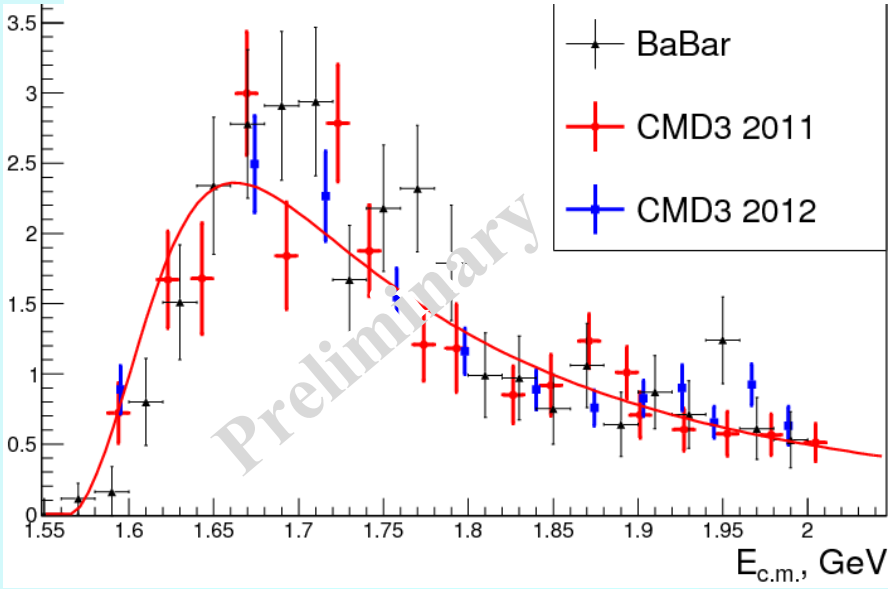


red – experiment

blue – sim + bkg

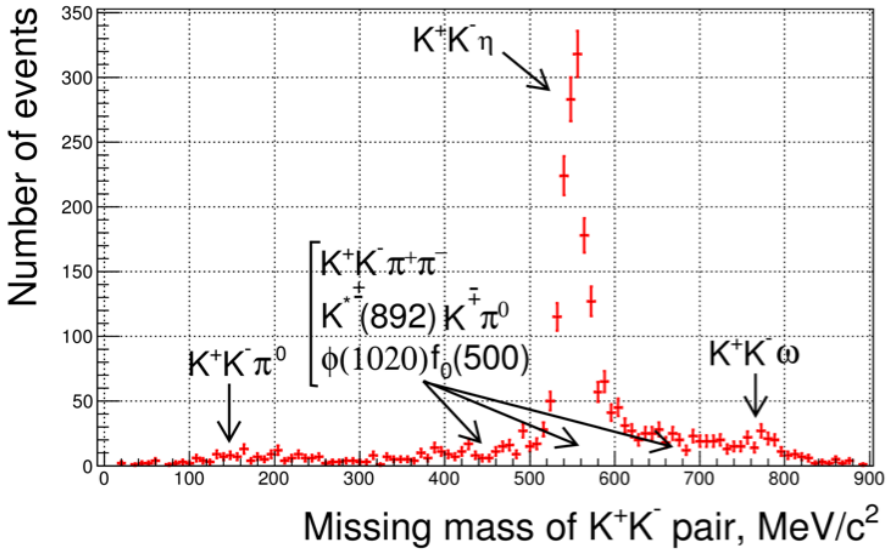


- A data sample of 22 pb^{-1} collected in 2011-2012 is used at energy points between 1.57 - 2.0 GeV
- Analysis: dominant $\varphi\eta$ signal, studies of nonresonance $K^+K^-\eta$ is needed
- Background with numerous physical components is seen
- The data sample includes 1268 ± 43 signal events

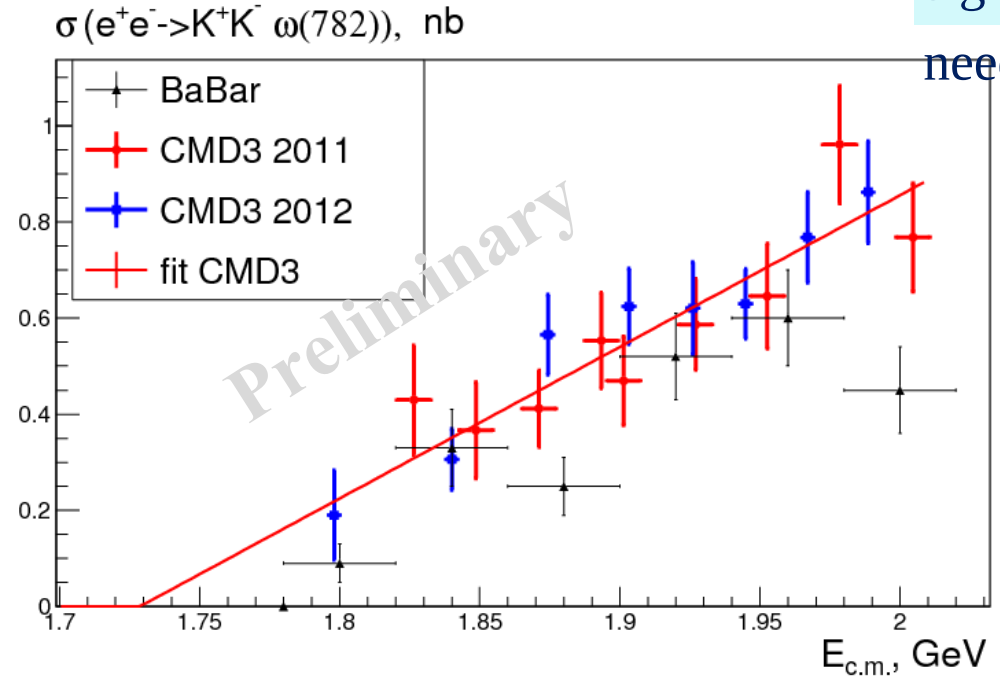


XS $e^+e^- \to \varphi(1020)\eta$

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

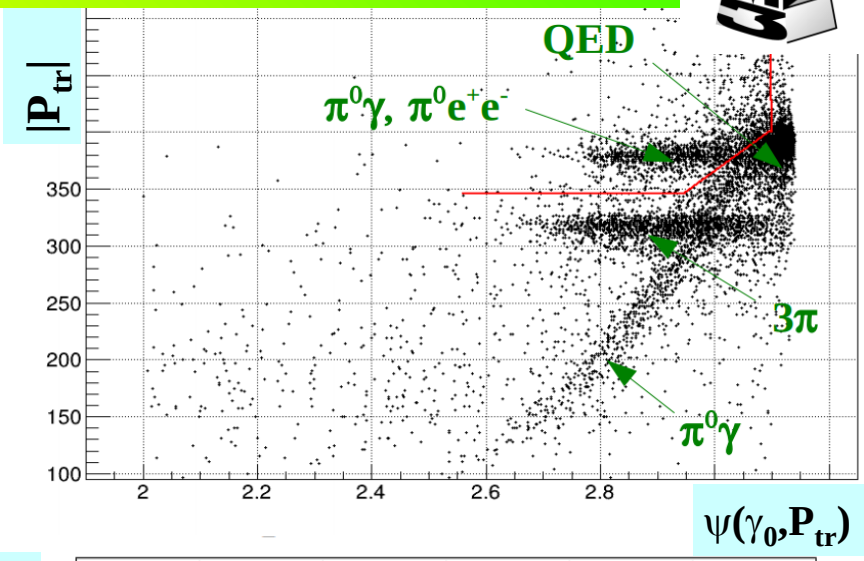


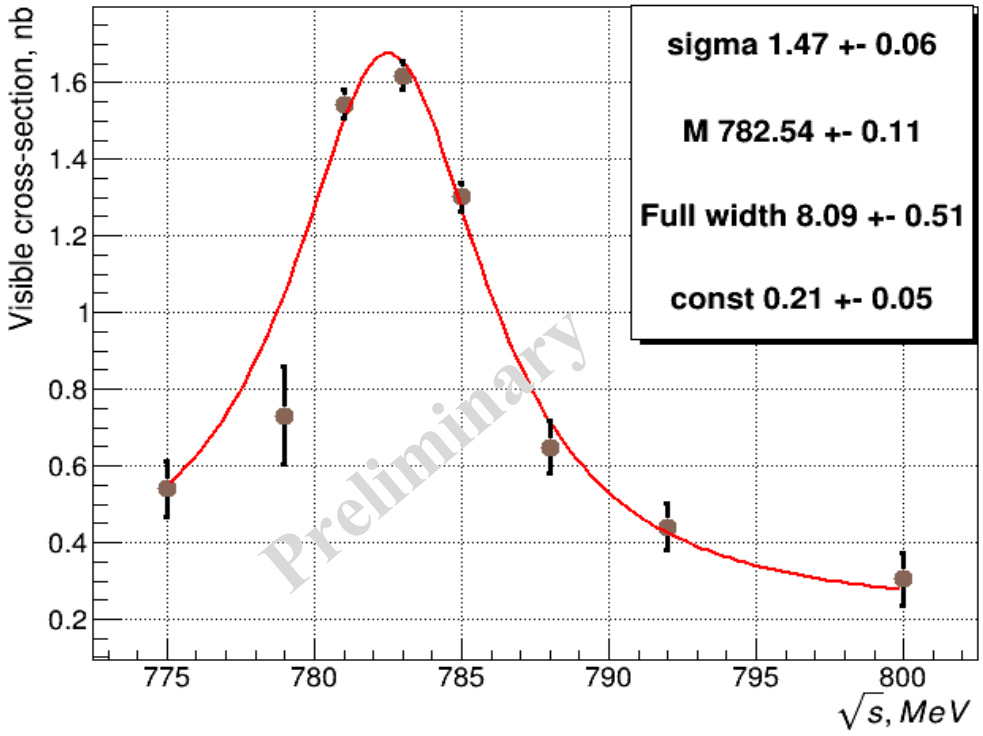
- A data sample of 12 pb^{-1} collected in 2011-2012 is used to study $e^+e^- \to K^+K^-\omega$;
- Selected number of signal events 899 ± 37
- XS was measured at 16 energy points between 1.84 - 2.0 GeV
- Analysis emphasizes the dominant $K^+K^-\omega$ signal, studies of nonresonance $K^+K^-\omega$ needed

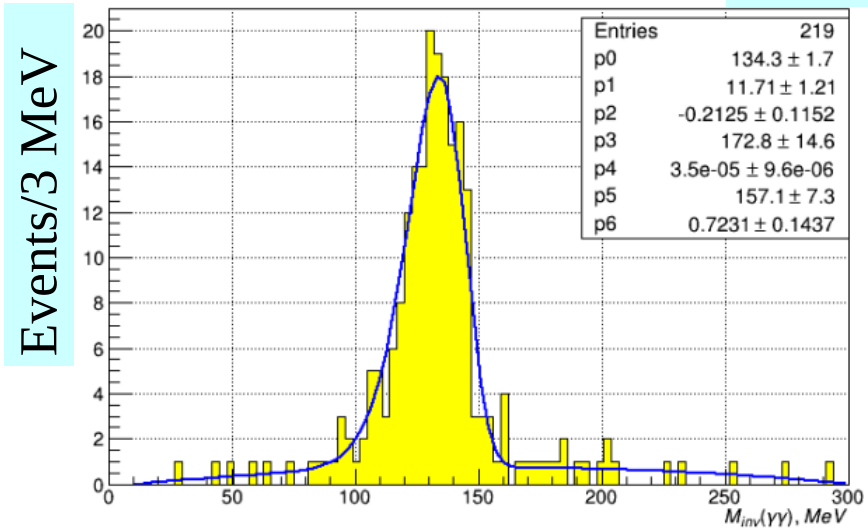


$e^+e^- \to \omega \to \pi^0 e^+e^-$

The total momentum of charged particles $|\mathbf{P}_{tr}|$ vs angle between the most energetic photon and $\mathbf{P}_{tr}$.
Red line presents the selection criteria (right plot).
About 1383 signal events were selected.



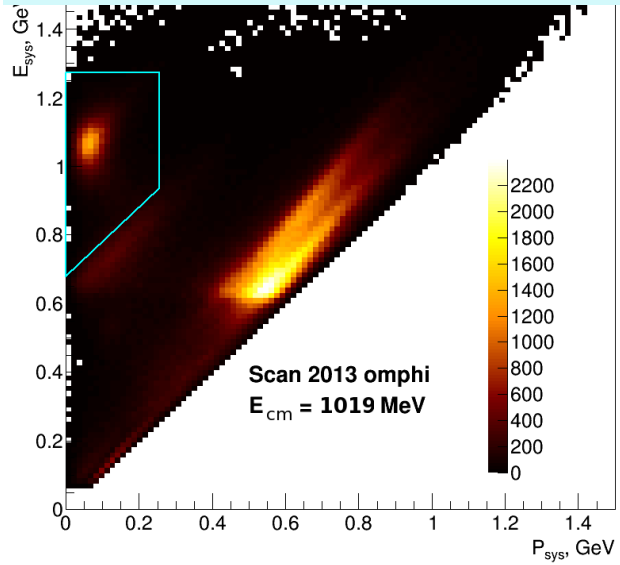




The analysis is still in progress. Our statistics is enough to decrease statistical error twice with respect to the previous CMD-2 result: Br(ω→π°e+e-) = (8.8±0.35)10^{-4}. Additionally with better detector performance we hope to reach the most precise result also for the ee →π°ee channel.

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

- Processes are under study in CMS energy range 750-1030 MeV. Data were collected
- Main physics background is two gamma annihilation with one radiated photon



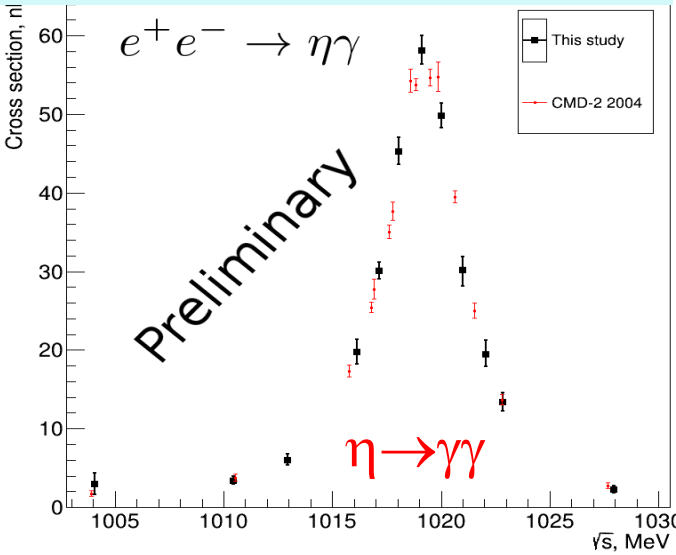
$E_{syst} = (E\gamma_1 + E\gamma_2 + E\gamma_3)/2E_{beam} \sim 1$

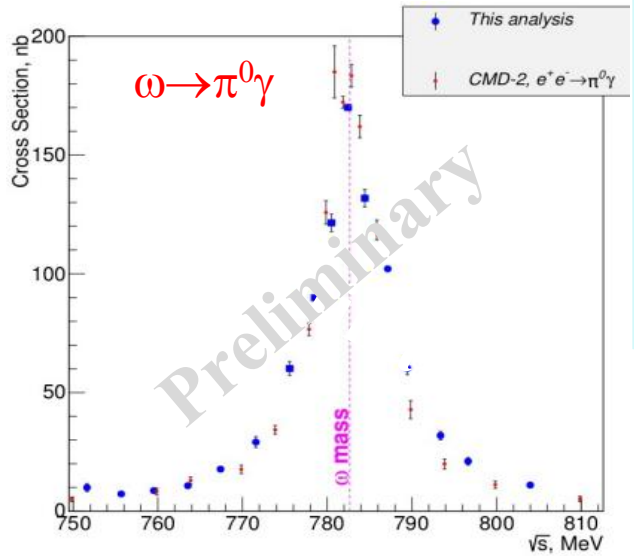
$Psyst = |\vec{p_1} + \vec{p_2} + \vec{p_3}| \sim 0$

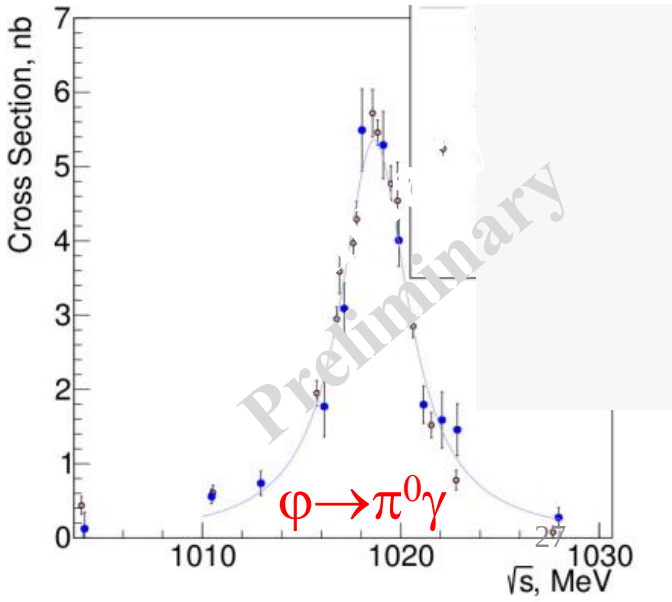
Kinematic reconstruction is applied to all events with three photons

Common initial points of photon production was assumed

The combination of three photons with a minimal χ^2 value is used in analysis

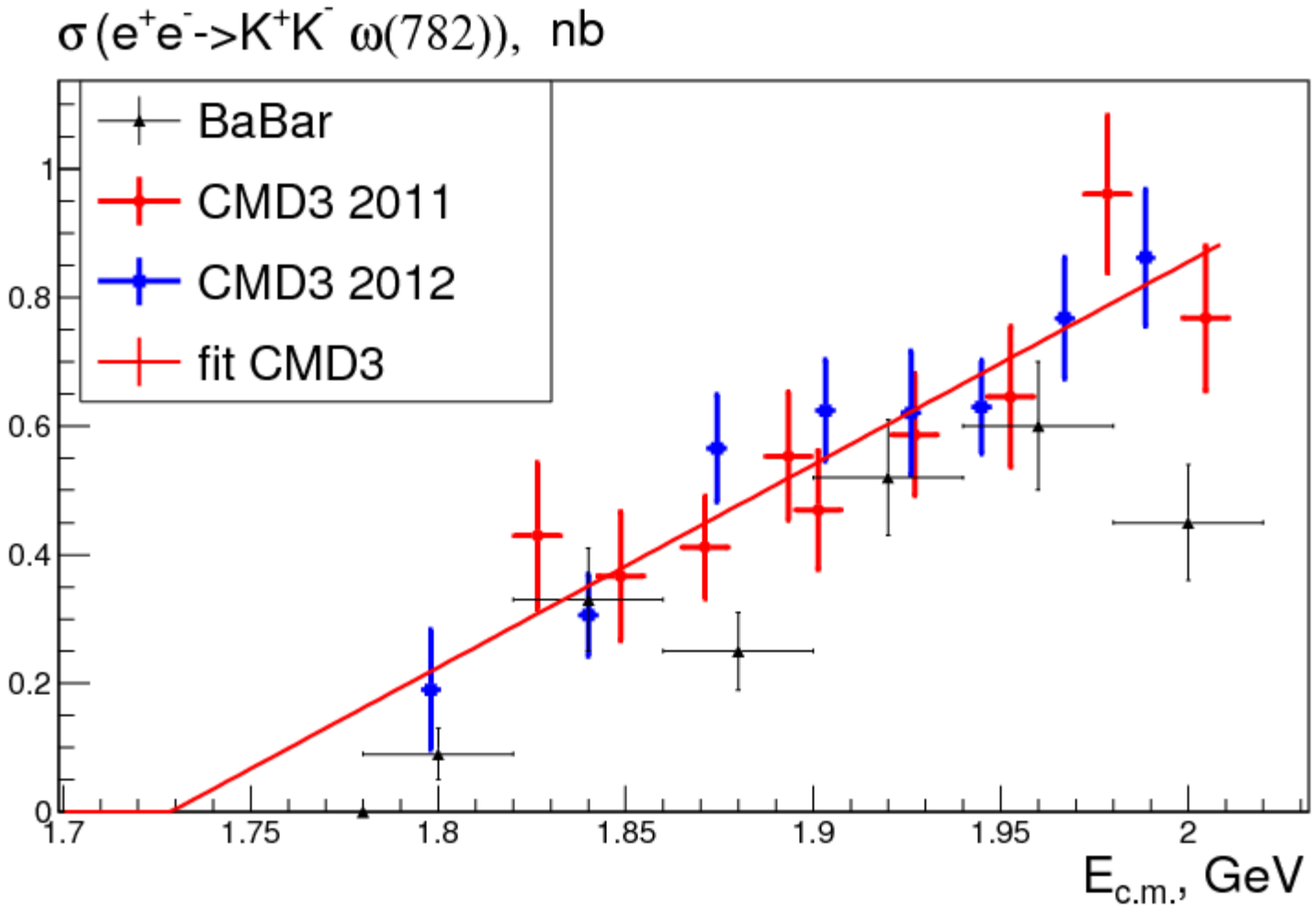






Summary and nearest perspectives

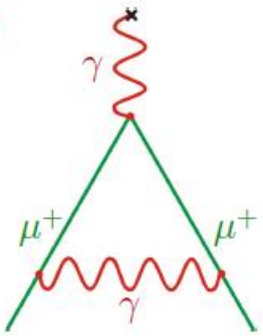
- VEPP-2000 successfully operated at $\sqrt{s} = 2m_\pi$ -2 GeV with $L_{max} = 2x10^{31}$ cm^{-2}s^{-1} and collected about 60 pb^{-1} per detector.
- CMD-3 detector has good enough performance and monitoring of different detector subsystems.
- Cross sections measured have the same or better statistical precision with respect to previous CMD-2 experiments.
- CMD-3 results will provide high accuracy, compatible or better than ISR measurements, the tentative goals are 0.3% (0.5%) for $\pi^+\pi^-$ and ~3% for multibody modes.
- VEPP-2000 upgrade is underway with new positron injection facility, which will increase luminosity at least by factor of 10.
- We start analysis of the multihadron processes with Ks in final states: $K_SK^{0*} \to K_SK^{\pm}\pi^{-+}$, $K^{*\pm}K^{-+} \to K_S\pi^{\pm}K^{-+}$, $K^{*\pm}K^{*-+} \to K_S\pi^{\pm}K^{-+}\pi^0$ and so on
- Various studies of transition form factors are in progress: $e^+e^- \to \pi^0\gamma, \eta\gamma, \pi^0e^+e^-, \eta e^+e^-$.
- We plan to get data with integrated luminosity of about 1-2 fb^{-1} in 5 – 10 years, which should provide new precise results on multihadron production.
- Upgrade of the new positron injection facility completed
- We are expecting soon the new luminosity


σ (e+e-->K+K- ω(782)), nb
BaBar
CMD3 2011
CMD3 2012
fit CMD3
0
0.2
0.4
0.6
0.8
1
1.7
1.75
1.8
1.85
1.9
1.95
2
Ec.m., GeV

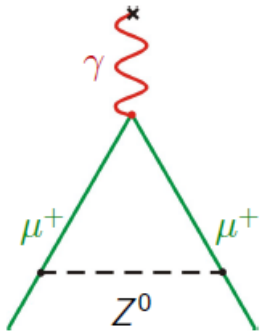
Motivation

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

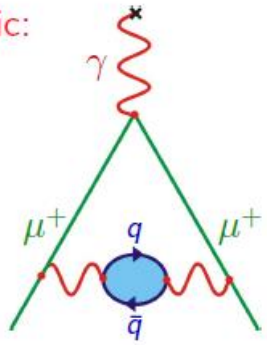
QED:



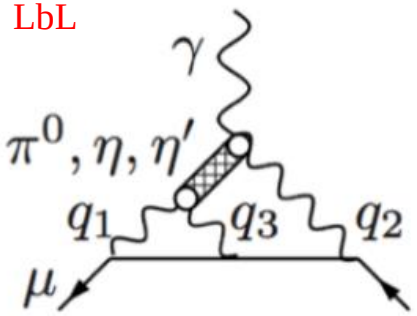
weak:



hadronic:



LbL



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

$$a_\mu^{EXP} - a_\mu^{SM} = 3.6\sigma$$

M. Davier et al., EPJC71(2011)1515

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

Major contribution to (g-2)/2 coming from VEPP-2000 energy range gives 92% and determine it's uncertainty