Updated results from CMD-2

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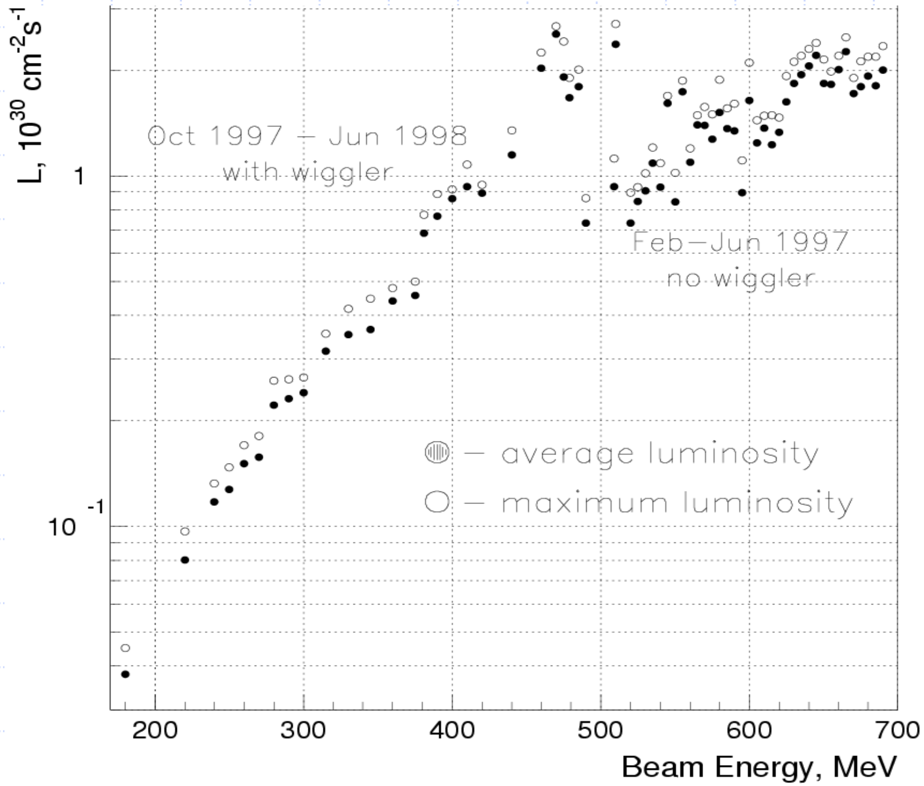
Outline

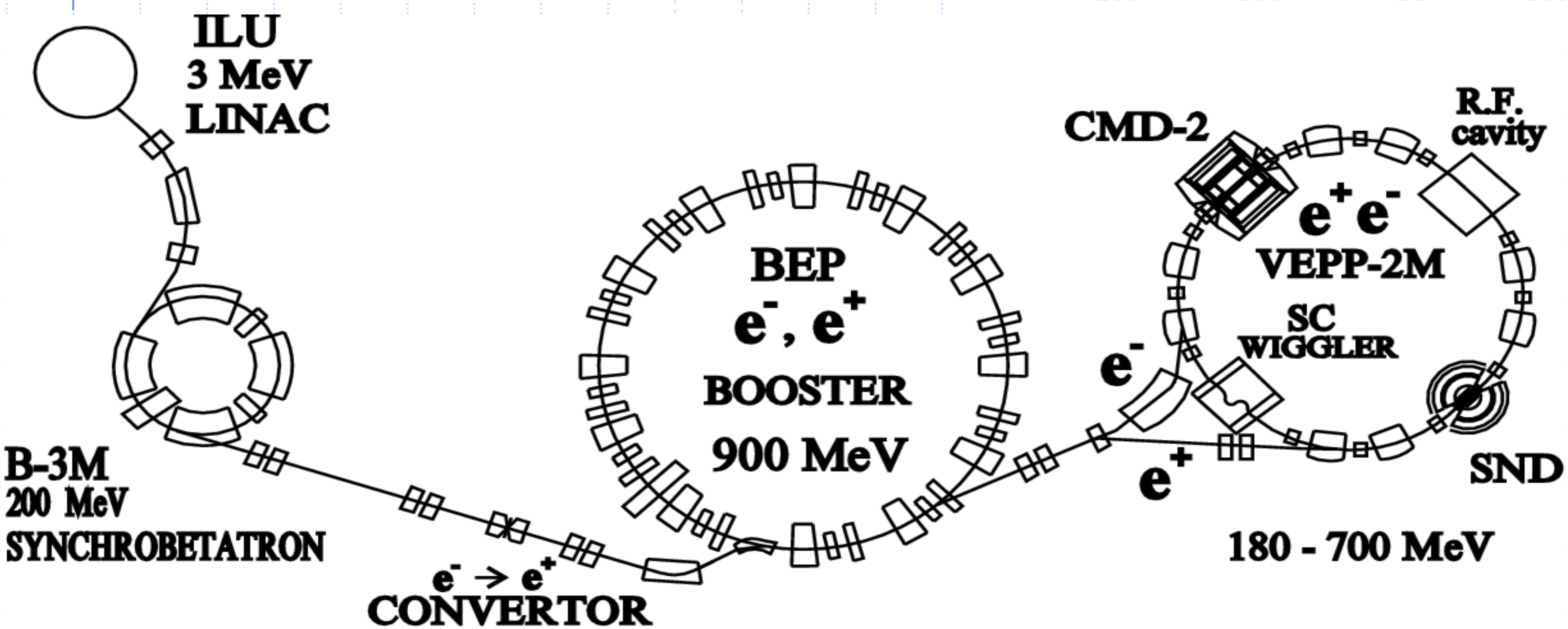
- CMD-2 and SND detectors at VEPP-2M
- Calculations of cross sections $e^+e^- \to e^+e^-(\gamma)$, $\mu^+\mu^-(\gamma)$, $\pi^+\pi^-(\gamma)$ comparison with other programs
- “Dressed” and “bare” cross sections
- Updated results from CMD-2

VEPP-2M collider



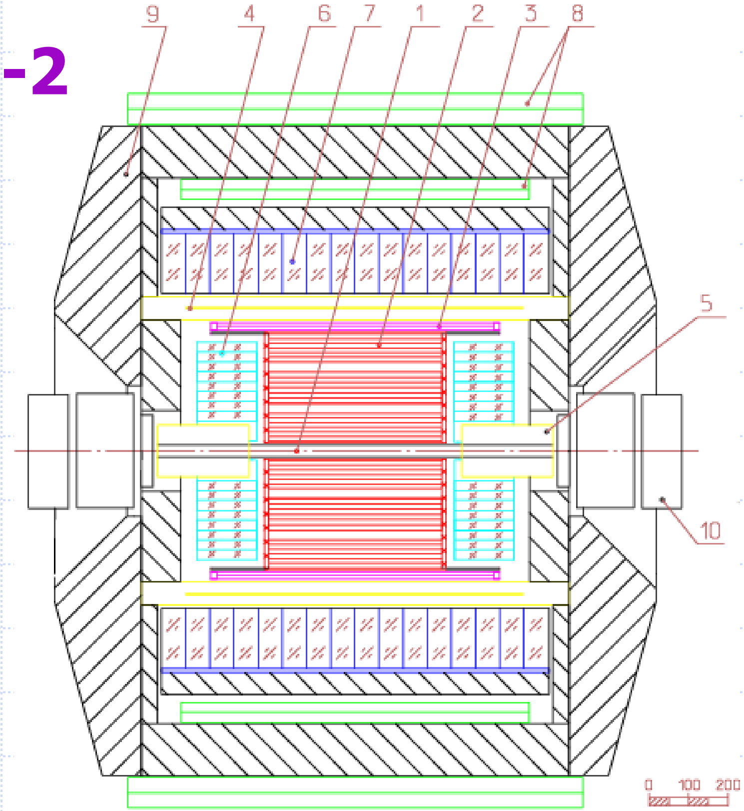
Operating 1974 - 2000

With $L_{peak} \sim 3\times10^{30}$ cm^{-2}s^{-1}
VEPP-2M is a pre-ϕ-factory



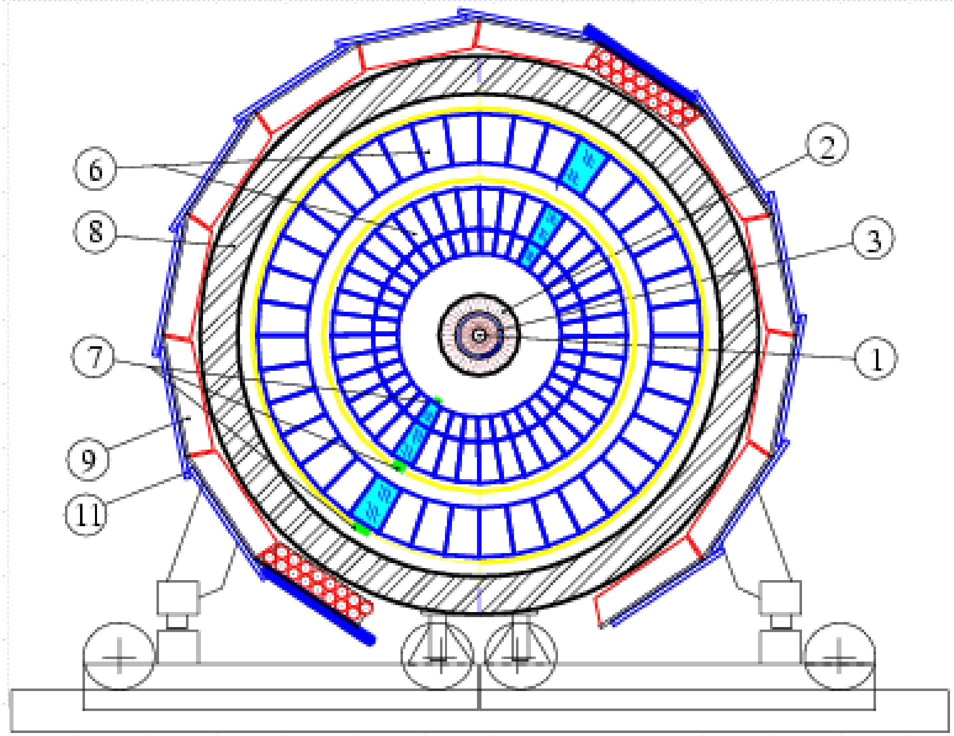
Last generation of detectors at VEPP-2M

CMD-2



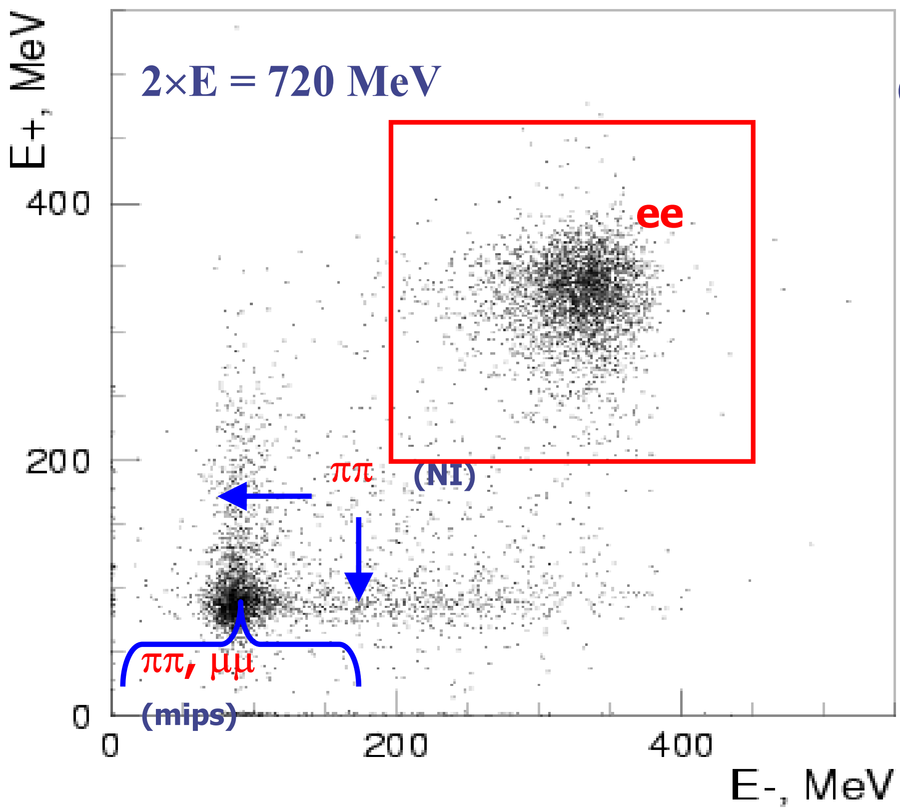
1 – vacuum chamber; 2 – drift chamber; 3 – Z-chamber; 4 – main solenoid; 5 – compensating solenoid; 6 – BGO calorimeter; 7 – CsI calorimeter; 8 – muon range system; 9 – yoke; 10 – quadrupoles

SND



1 – vacuum chamber; 2 – drift chambers; 3 – internal scintillating counter; 6 – NaI crystals; 7 – vacuum phototridoes; 8 – absorber; 9 – streamer tubes; 11 – scintillator plates;

Luminosity measurement



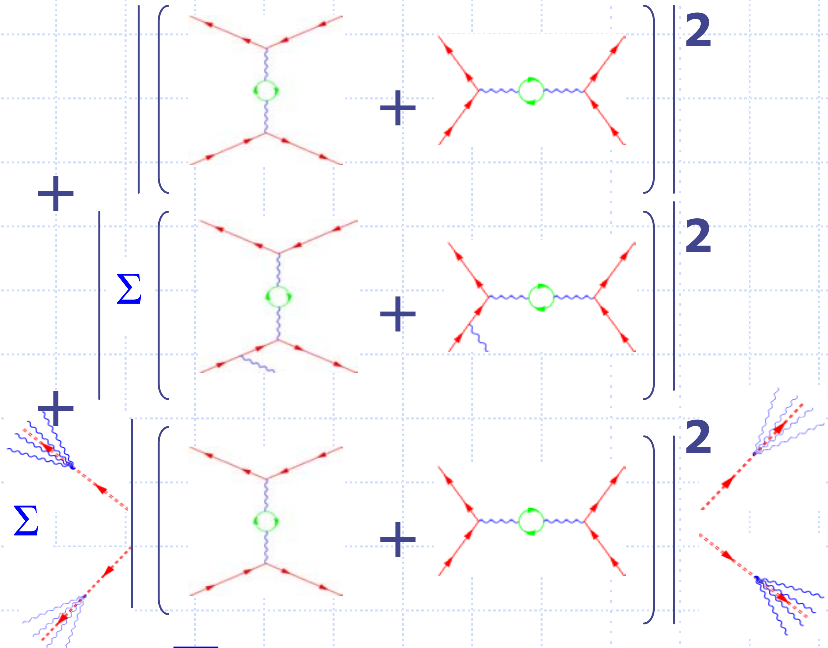
$$L = \frac{N_{ee}}{\sigma(e^+e^- \to e^+e^-(\gamma))}$$

Getting number of N_{ee}

- **Select collinear events in tracking system**
- **Separate e^+e^- events by energy deposition in CsI calorimeter**
    - **Crude separation – number of events in red box**
    - **More precise separation – unbinned fit of energy distribution**

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

$$\sigma^{vis}_{theor}(e^+e^- \to e^+e^-) = \int \ldots \int \frac{D(z_1)..D(z_4)\sigma(z_1,z_2,s)}{\left|1-\Pi(z_1,z_2,s)\right|^2} dz_1..dz_4$$



$- \sum_4$ "compensators"

vacuum polarization by **leptons** and **hadrons** is included by each diagram

precise matrix element for one photon at large angle relatively to initial or final particle ($\theta > \theta_0$, $E > \Delta E$)

along initial or final particles ($\theta < \theta_0$) "jets" described by

D(z) – function giving the probability for electron to have an energy

$E_e = z \times E_{beam}$

E.A.Kuraev and V.S.Fadin, Sov.Jorn.Nucl.Phys. 41(1985)466

where

$$\text{"compensator"} = \int_0^{\pi} \left(\frac{d\sigma}{d\Omega}\right)_\gamma d\Omega_\gamma - \int_0^{\theta_0} \left(\frac{d\sigma}{d\Omega}\right)_\gamma d\Omega_\gamma$$

is required to remove from D(z) the part of cross section caused by emission of one photon at large angles

all terms $\left(\frac{\alpha}{\pi} \ln \frac{s}{m_e^2}\right)^{n_\gamma}$ are taken into account in D functions

accuracy estimation $\sim 0.2\ \%$

A.B.Arbuzov, E.A.Kuraev et al., JHEP 10 (1997) Mod.Phys.Lett., A13 (1998) 2305

$e^+e^- \to e^+e^-$ code comparison with BHWIDE

S.Jadach, W.Placzek,
B.F.L.Ward hep-ph/9608412

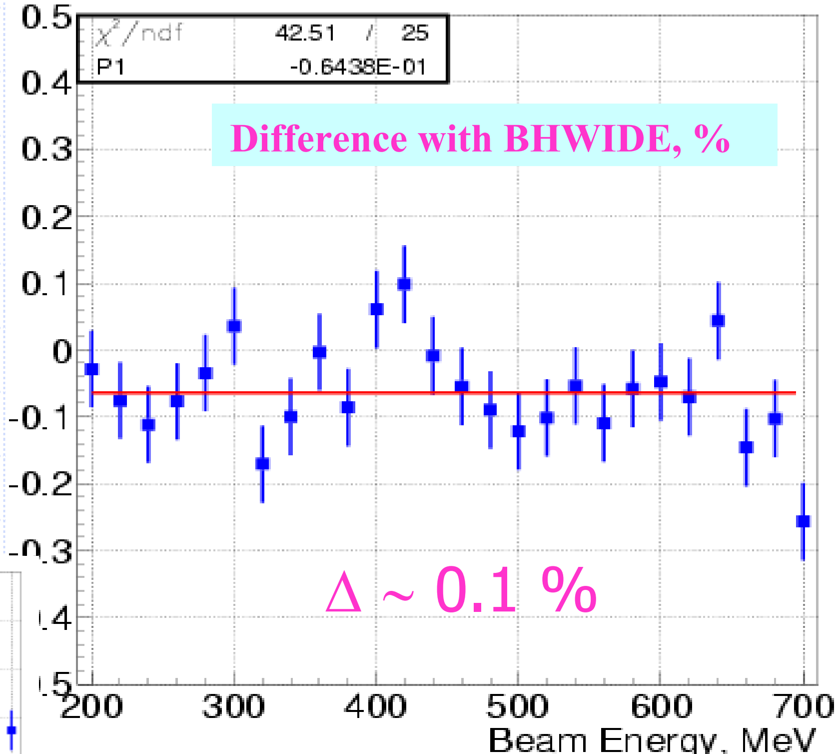
In our selection criteria

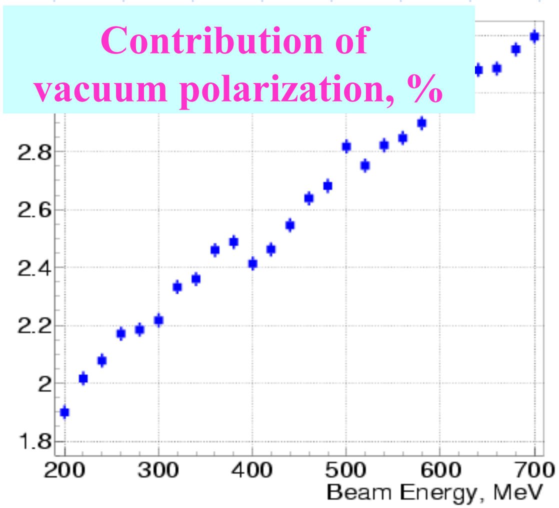
$\Delta\theta < 0.25$

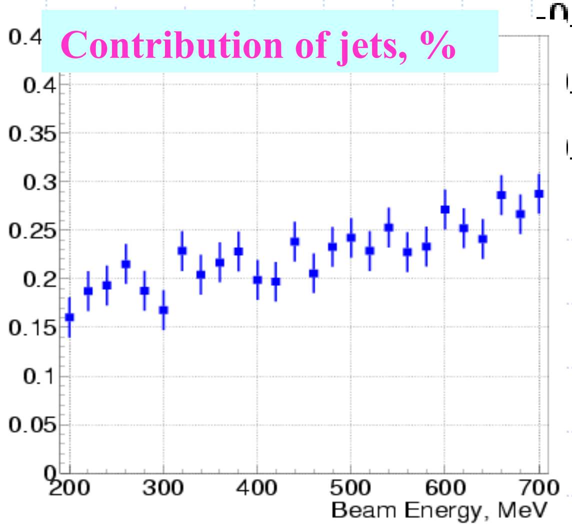
$\Delta\varphi < 0.15$

$1.1 < \theta_{final} < \pi - 1.1$

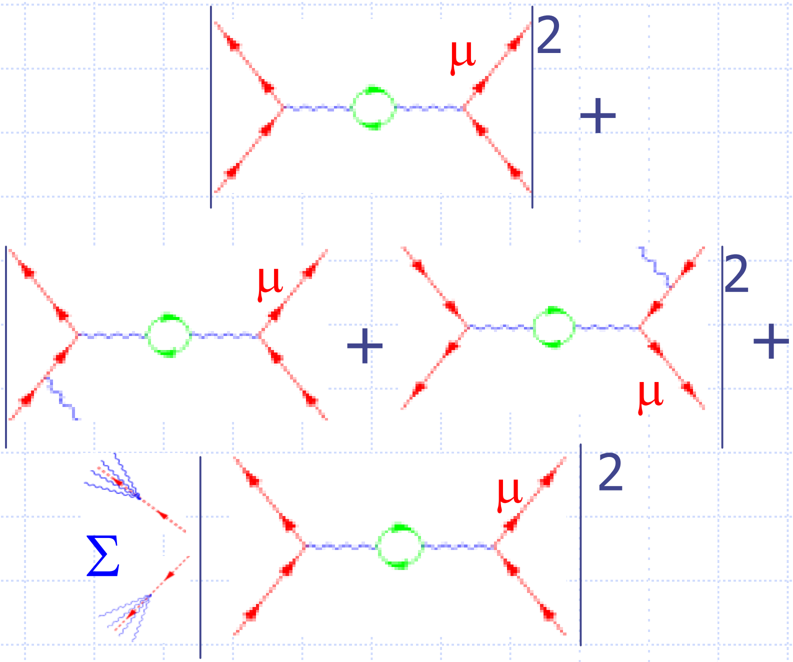
$P^{\pm}_{\perp} > 90$ MeV/c







$e^+e^- \to \mu^+\mu^-$ cross section calculation



$- \sum_{2}$ "compensator"

vacuum polarization by leptons and hadrons is included by each diagram

precise matrix element for one photon at large angle relatively to initial particle ($\theta > \theta_0$, $E > \Delta E$)

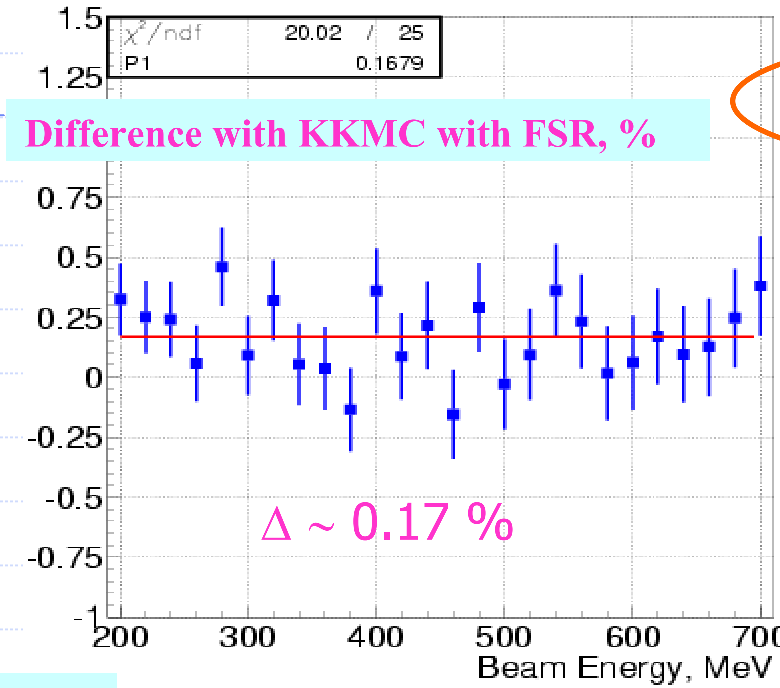
one photon for FSR + Interference

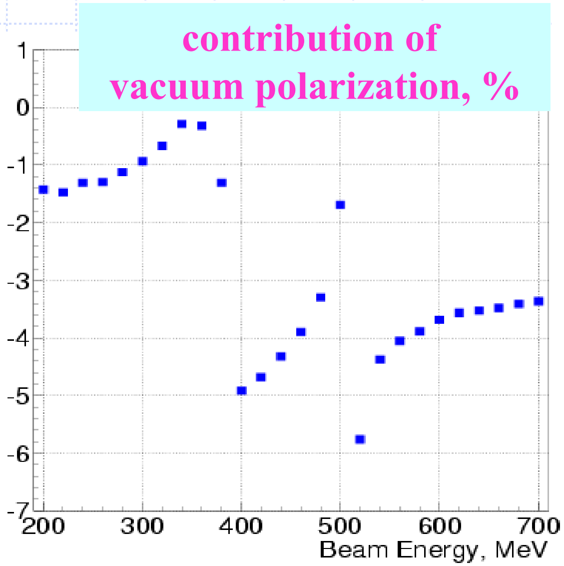
along initial particles ($\theta < \theta_0$) - "jets"

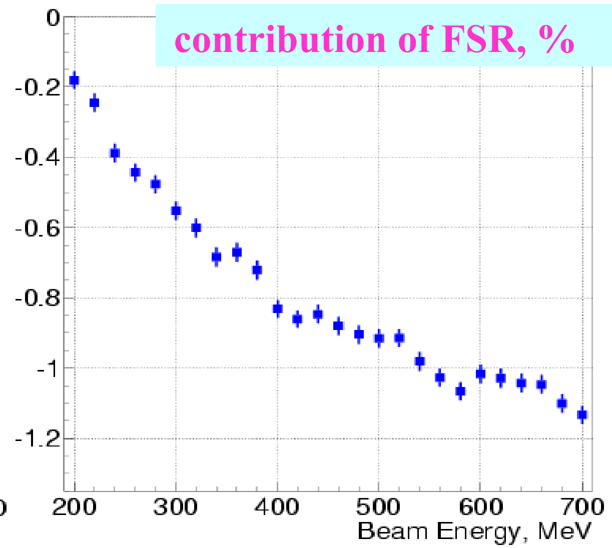
accuracy estimation ~ 0.2 %

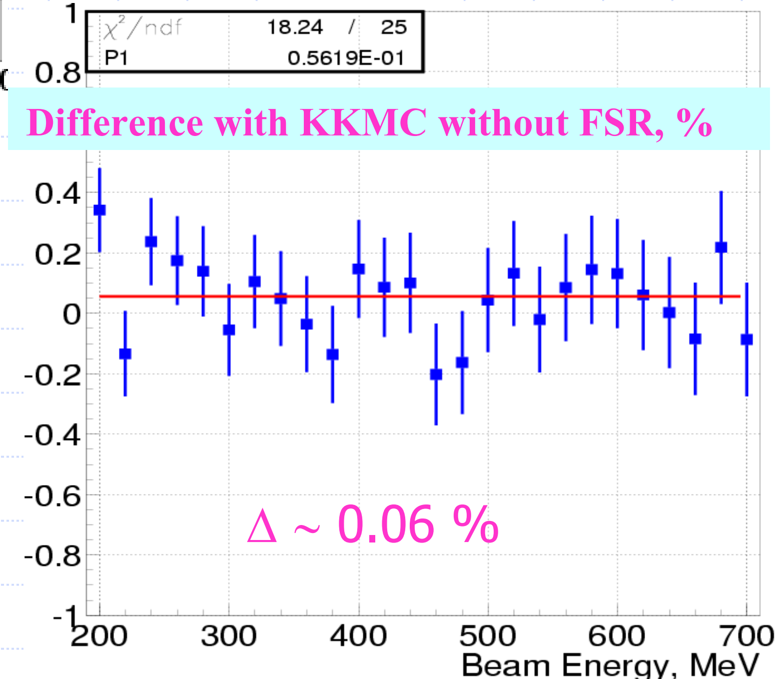
$e^+e^- \to \mu^+\mu^-$ code comparison with KKMC

S. Jadach, B.F.L. Ward, Z. Was, Comput. Phys. Commun. 130:260-325, 2000, hep-ph/9912214

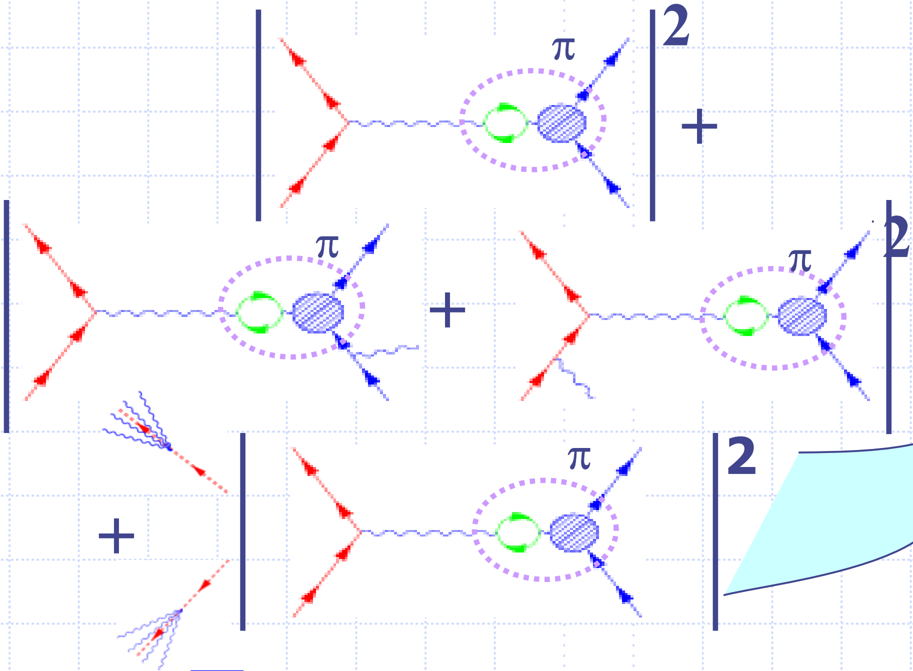




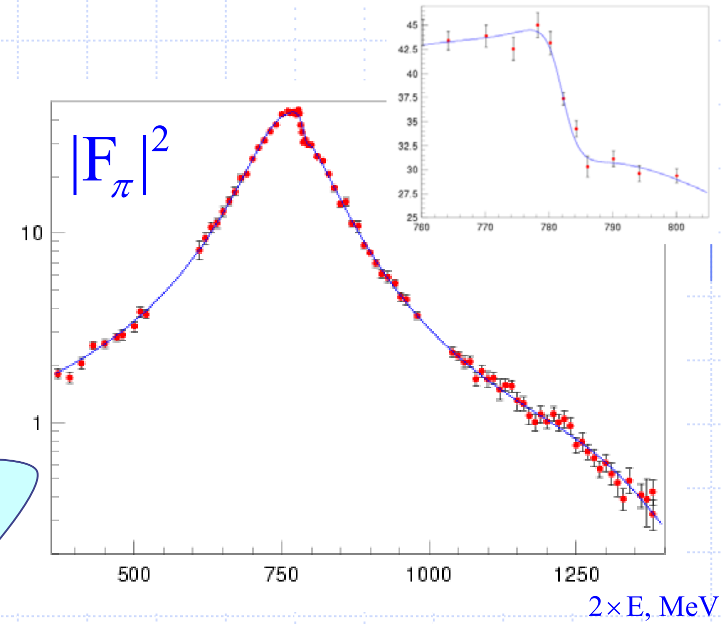




$e^+e^- \to \pi^+\pi^-$ cross section calculation



$$- \sum_{2} \text{"compensators"}$$



Polarization of vacuum by leptons and hadrons is included in resonance: "dressed" cross section

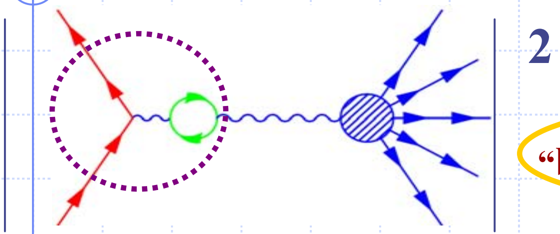
$$|F_\pi|^2_{exp} = \frac{\sigma^{vis}_{exp}(e^+e^- \to \pi^+\pi^-)}{\sigma^{vis}_{theor}(e^+e^- \to \pi^+\pi^-)/|F_\pi|^2_{test}}$$

$e^+e^- \rightarrow \pi^+\pi^-$ code comparison with ...?

No program with the same or better precision

What is R(s) in dispersion relations?

$$\sigma^{vis}_{theor}(e^+e^- \to hadrons) = \int \ldots \int \frac{D(z_1)D(z_2)\sigma(z_1,z_2,s)}{|1-\Pi(z_1,z_2,s)|^2} dz_1 dz_2$$



"bare" cross section

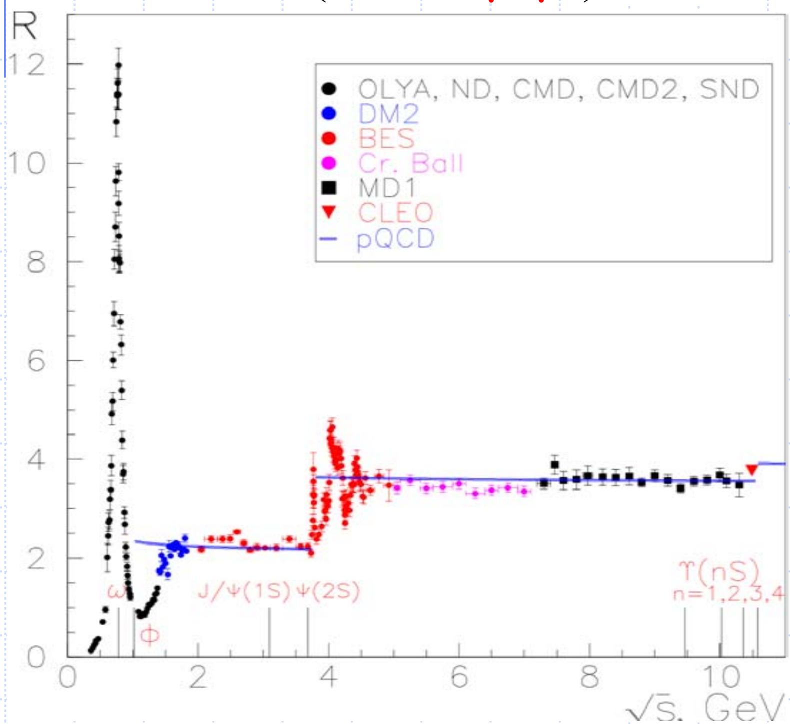
$$R^{\pi\pi}(s) \square |F_\pi(s)|^2 \, |1-\Pi(s)|^2 \left(1 + \frac{2\alpha}{\pi}\Lambda(s)\right)$$

"removing" of VP

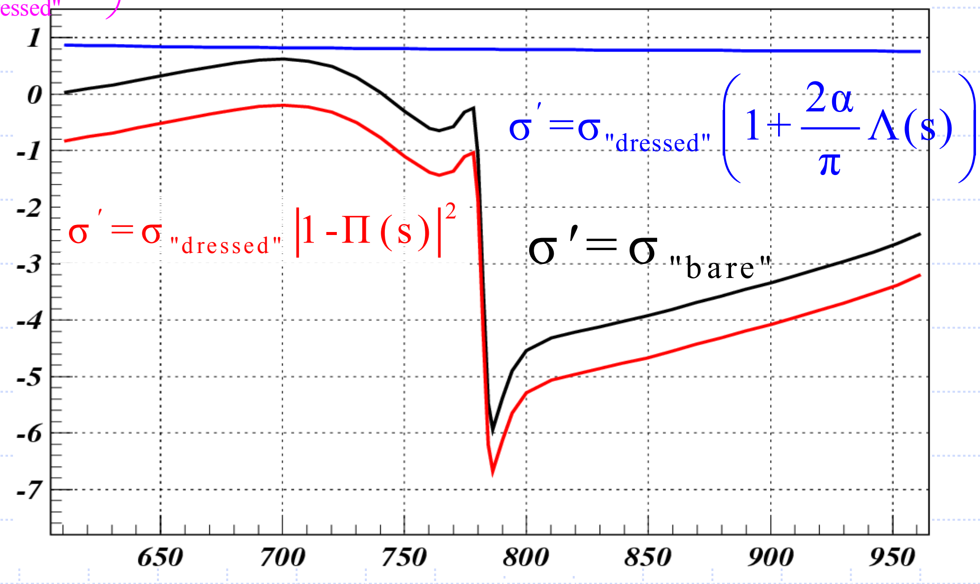
"including" of FSR

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

A.Hoefer et al., hep-ph/0107154
R.Melnikov JMPhys. A16(2001)4591
A.Arbuzov et al.,JHEP 10(1997)



$$\left(\frac{\sigma'}{\sigma_{\text{"dressed"}}} - 1\right), \%$$



Photon vacuum polarization

All available e^+e^- data were used to calculate dispersion integral

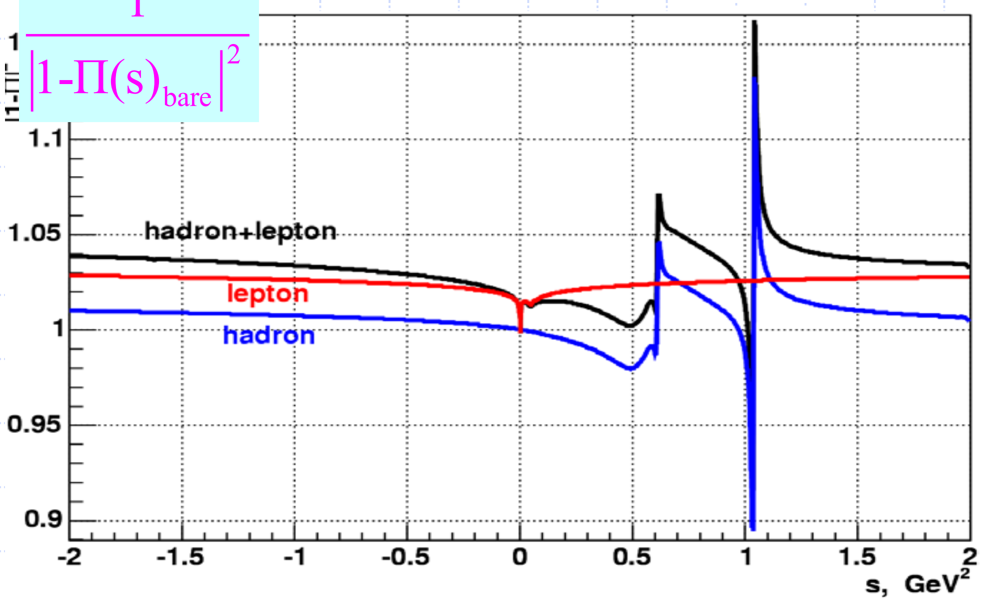
$$\Pi_l(s) = \left(\frac{\alpha}{\pi}\right)\Pi_1(s) + \left(\frac{\alpha}{\pi}\right)^2 \Pi_2(s) + \ldots$$

$\sim 10^{-2}$ $\sim 3\times10^{-5}$

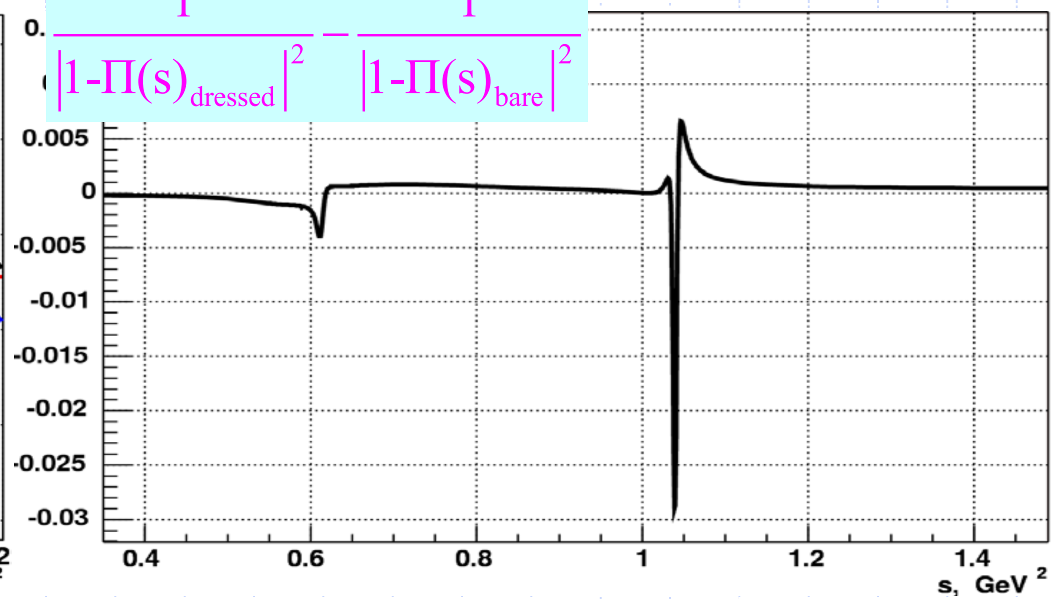
$$\Pi(s) = \Pi_l(s) + \Pi_h(s)$$

$$\Pi(s) = \frac{s}{4\pi^2\alpha}\left(P\int_{4m_\pi^2}^{\infty}\frac{\sigma_{e^+e^-\to\gamma^*\to final}(s')ds'}{s-s'} - i\pi\sigma_{e^+e^-\to\gamma^*\to final}(s)\right)$$

$$\frac{1}{\left|1-\Pi(s)_{bare}\right|^2}$$



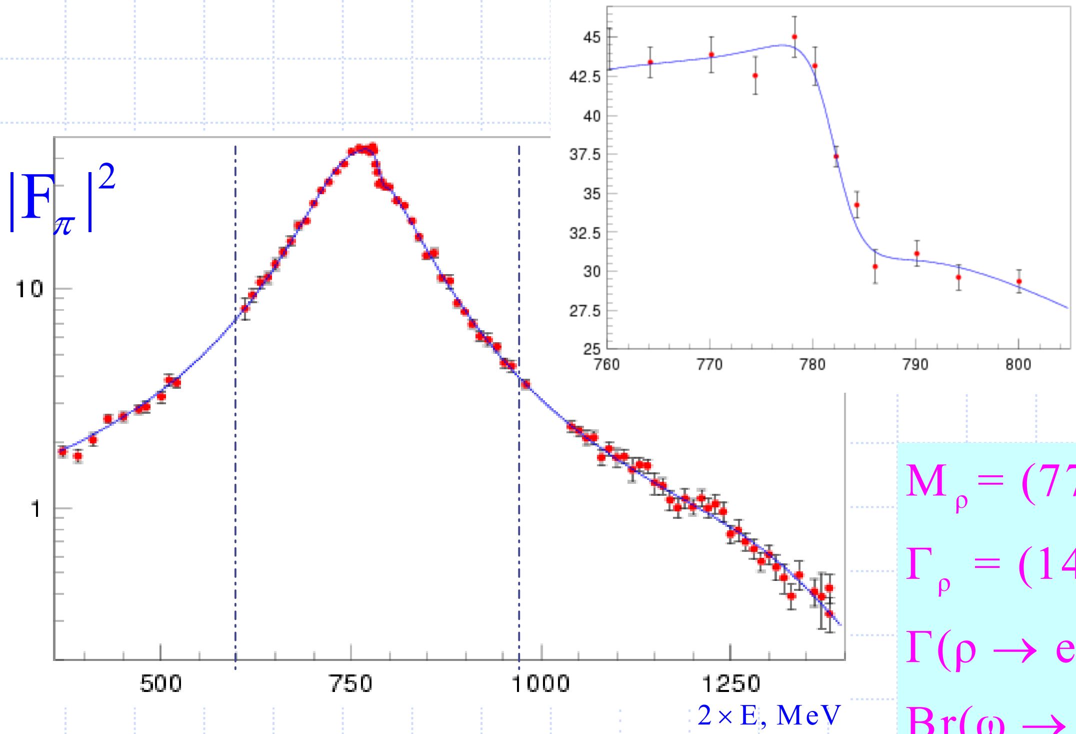
$$\frac{1}{\left|1-\Pi(s)_{dressed}\right|^2} - \frac{1}{\left|1-\Pi(s)_{bare}\right|^2}$$



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

R.R.Akhmetshin et al., PL B 527(2002) 161

R.R.Akhmetshin et al., hep-ex/0308008



L= 317.3 nb^{-1}

114000 $\pi^+\pi^-$ events in ρ m

$M_\rho = (775.65 \pm 0.64 \pm 0.50)$ MeV ($\downarrow 0.54\sigma$)

$\Gamma_\rho = (143.85 \pm 1.33 \pm 0.80)$ MeV ($\downarrow 0.39\sigma$)

$\Gamma(\rho \to e^+e^-) = (7.06 \pm 0.11 \pm 0.05)$ keV ($\uparrow 1.7\sigma$)

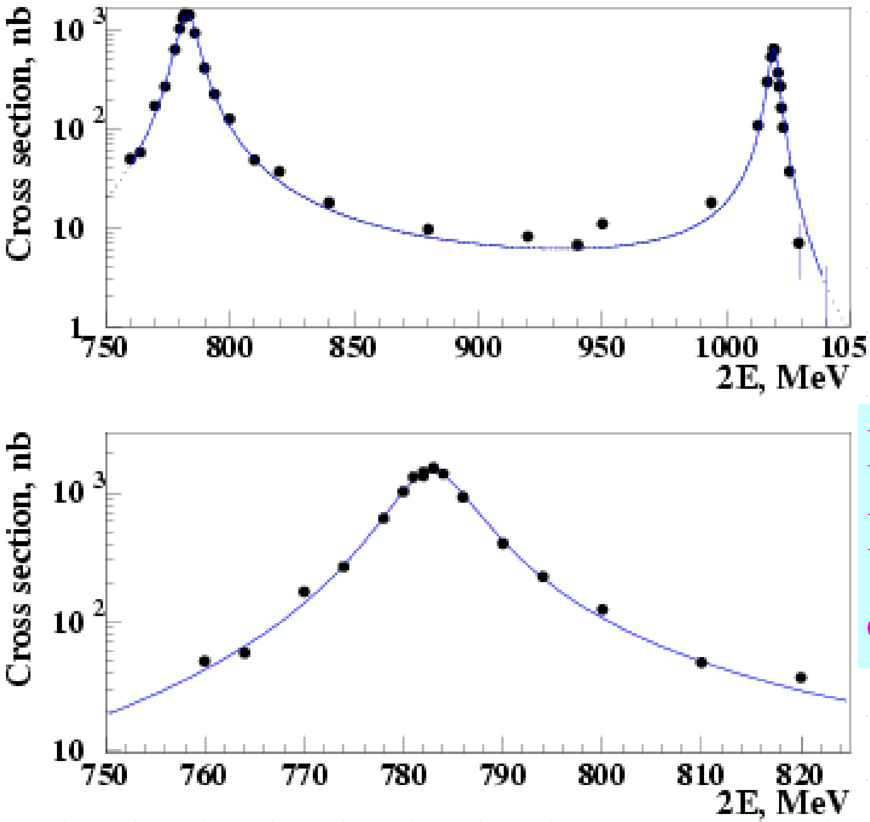
$Br(\omega \to \pi^+\pi^-) = (1.30 \pm 0.24 \pm 0.05)$ % (nc)

$\arg\delta = 13.3^\circ \pm 3.7^\circ \pm 0.2^\circ$ (nc)

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

R.R.Akhmetshin et al., PL B 476(2000) 33

R.R.Akhmetshin et al., hep-ex/0308008



L= 119.6 nb^{-1}

11200 $\pi^+\pi^-\pi^0$ events in ω mes

$M_\omega = (782.68 \pm 0.09 \pm 0.04)$ MeV ($\downarrow$ 0.3 σ)

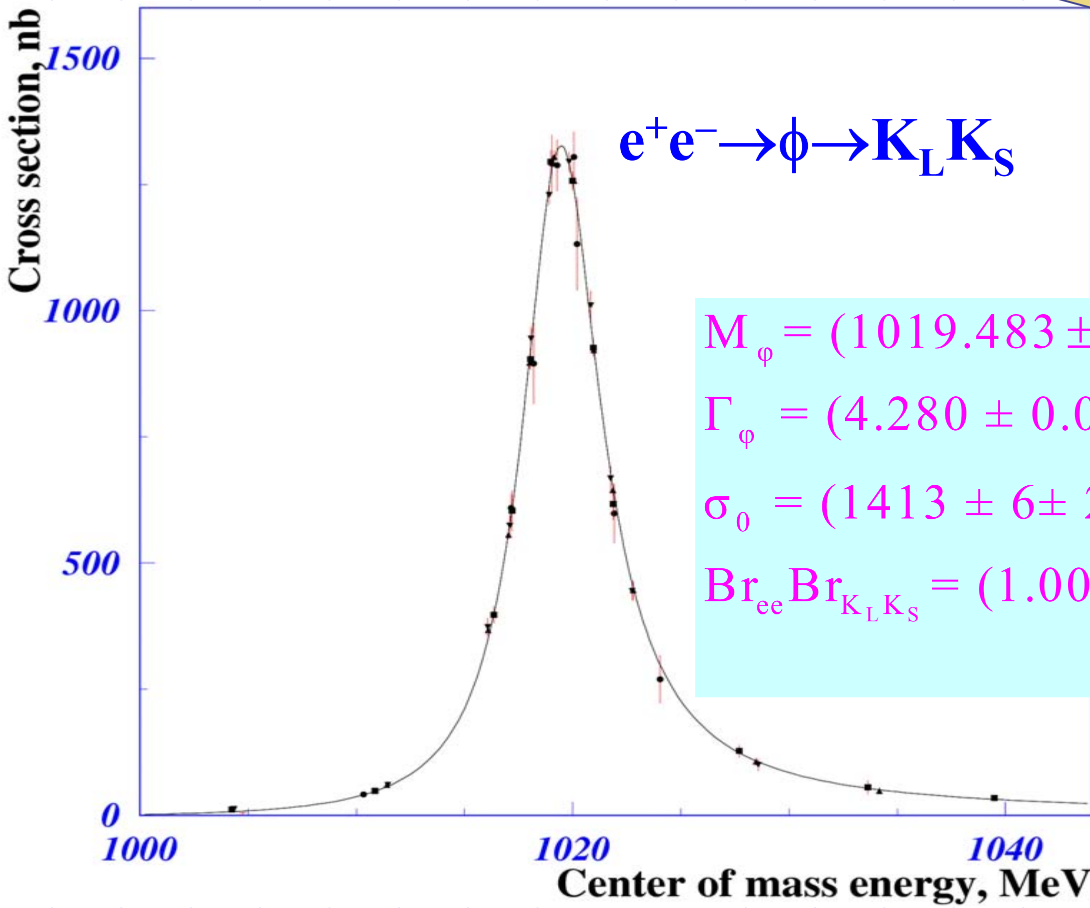
$\Gamma_\omega = (8.68 \pm 0.23 \pm 0.10)$ MeV (nc)

$\sigma_0 = (1495.6 \pm 25.5 \pm 19.4)$ nb ($\uparrow$ 1.2σ)

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

R.R.Akhmetshin et al., PL B 466(1999) 385

R.R.Akhmetshin et al., hep-ex/0308008



$M_\varphi = (1019.483 \pm 0.011 \pm 0.025)$ MeV (nc)

$\Gamma_\varphi = (4.280 \pm 0.033 \pm 0.025)$ MeV (nc)

$\sigma_0 = (1413 \pm 6 \pm 24)$ nb ($\uparrow 1.6\sigma$)

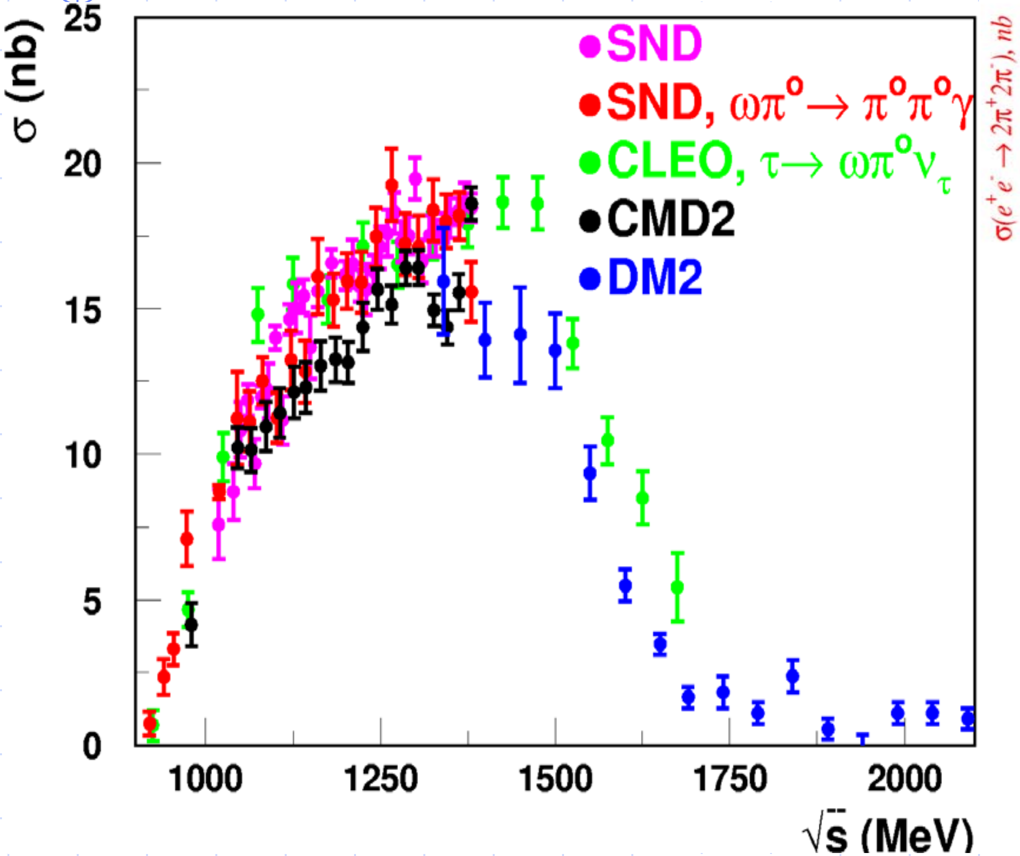
$Br_{ee} Br_{K_L K_S} = (1.001 \pm 0.004 \pm 0.017) \times 10^{-4}$ ($\uparrow 1.6\sigma$)

L= 1294 nb^{-1}

2.72×10^5 $K_L K_S$ events

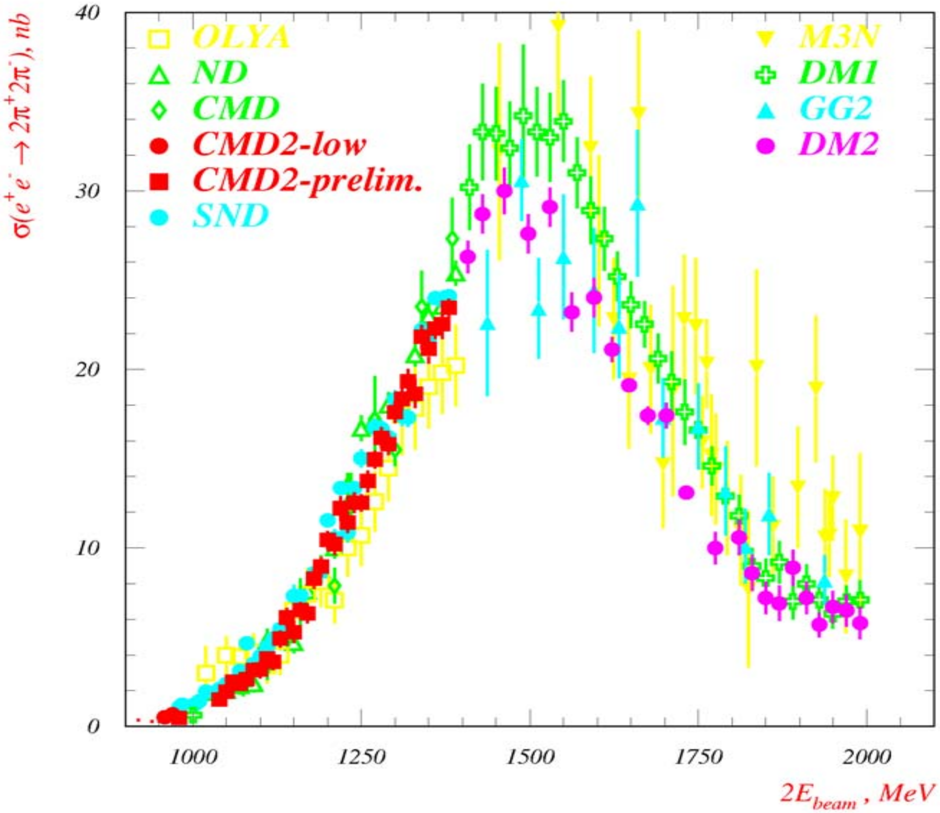
$e^+e^- \to 4\pi$

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



CMD-2 data in 4π channel is lower!

$e^+e^- \to 2\pi^+2\pi^-$



After reanalysis CMD-2 data agrees with SND data

To be published in PL

Neutral kaon mass measurement (preliminary)

$$\int Ldt \simeq 355\, nb^{-1},\ e^+e^- \to K_S^0 K_L^0,\ K_S^0 \to \pi^+\pi^-,\ N_{K_S^0} = 4.9 \cdot 10^4$$

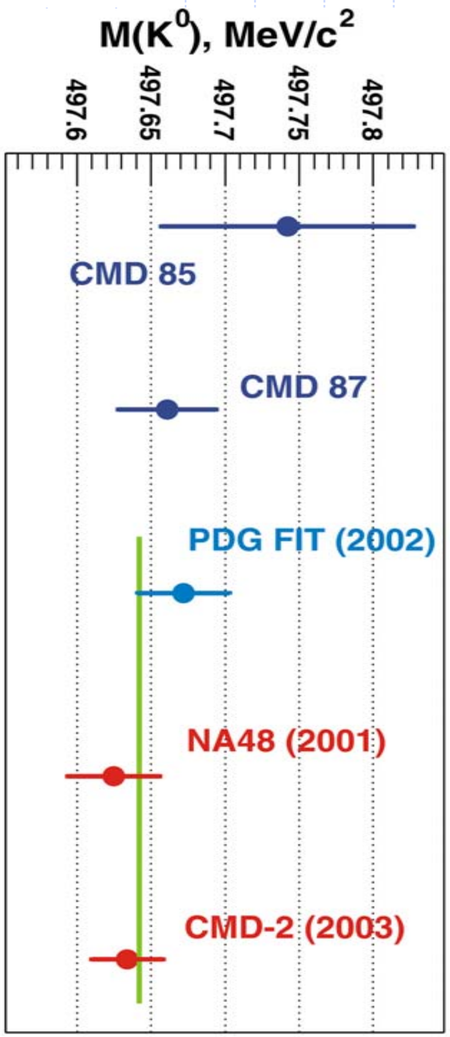
Resonant depolarization beam energy measurement

Systematic due to initial state radiative corrections, beam energy measurement and nonlinearity shift are energy dependent

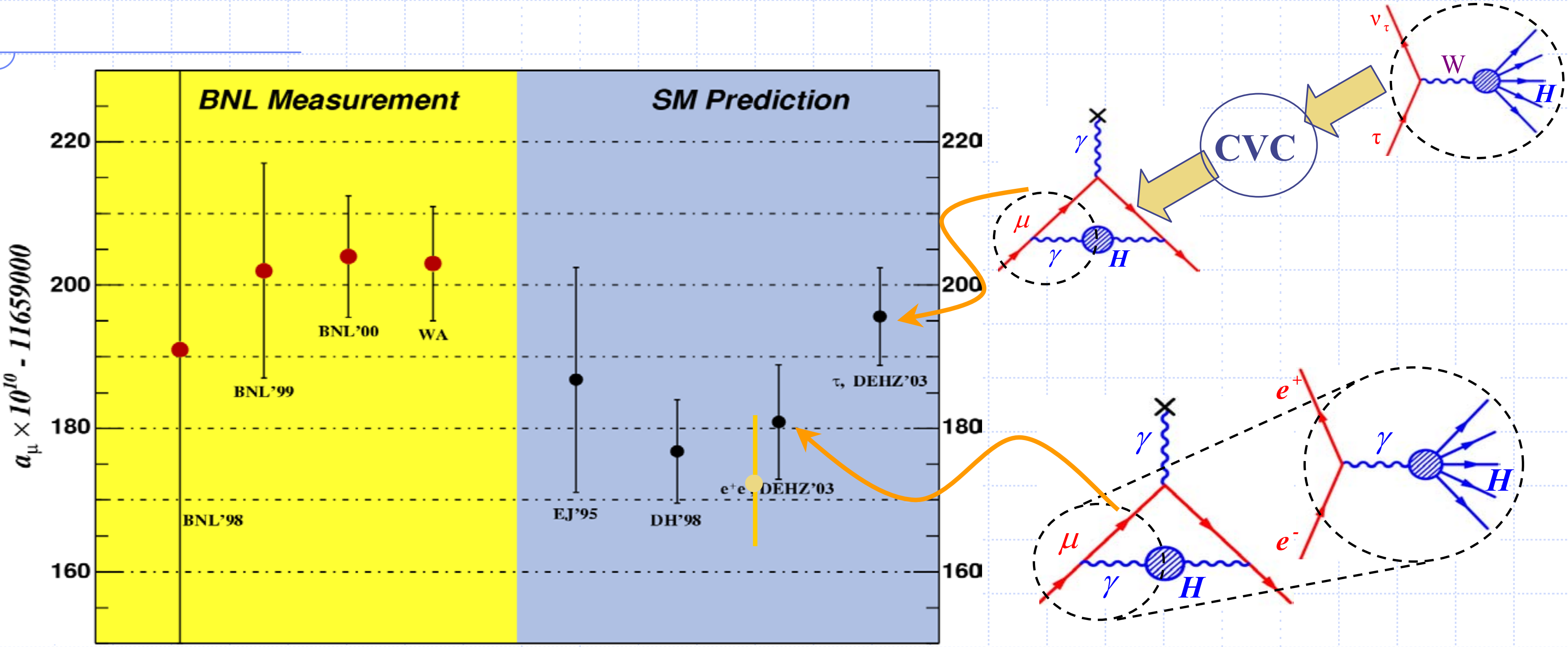
Systematic source	Shift, keV	Error, keV
Beam energy measurement		13 ÷ 19
Energy calibration model dependency		3
Radiative corrections to initial state	– (80 ÷ 630)	2 ÷ 12
Beam energy spread correction	+ 3	0.3
Radiative corrections to final state	– 6	6
Nonlinearity shift	60 ÷ 140	6 ÷ 15
Correction for pion decay in flight	+ 4	3
Background		4
Z-chamber thermal expansion		3
Selection criteria		6
Fit bounds		8
Charged pion mass uncertainty		0.04

$$M_{K_S^0} = 497.634 \pm 0.016 \pm 0.019\ \text{MeV}/c^2$$

$$M_{K_S^0}^{(fit)} = 497.642 \pm 0.016\ \text{MeV}/c^2$$



g-2 of muon



$e^+e^- \rightarrow$ **hadrons** $\quad a_\mu(\text{exp}) - a_\mu(\text{theor}) = (22.1 \pm 11.3) \times 10^{-10}$ (1.9 σ)

$\tau \rightarrow$ **hadrons**$+\nu_\tau$ $\quad a_\mu(\text{exp}) - a_\mu(\text{theor}) = (\ 7.4 \pm 10.5) \times 10^{-10}$ (0.7 σ)

M.Davier et al., hep-ph/0308213

Conclusion

- Codes for calculations of $e^+e^- \to e^+e^-(\gamma)$, $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^- \to \pi^+\pi^-(\gamma)$ cross sections with accuracy 0.2%

- "Dressed" cross sections for dynamic studies, "bare" cross sections for dispersion relations

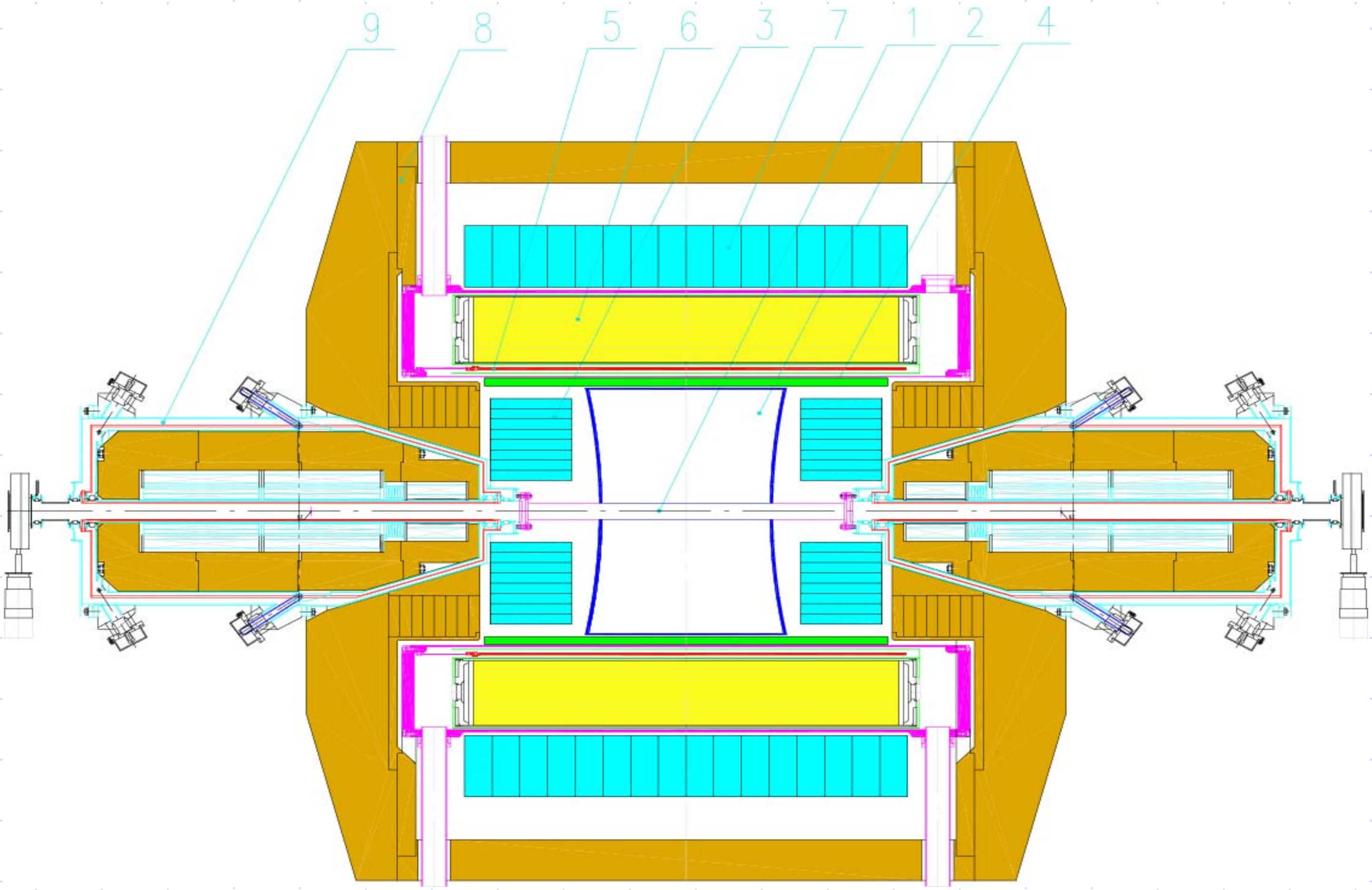
- Updated results have been published hep-ex/0308008

- Good agreement between SM calculations for $(g\text{-}2)_\mu$ based on $e^+e^- \to$ hadrons and $\tau \to \nu_\tau$hadrons with experimental value

CMD-3

System	CMD-2	CMD-3
Drift chamber	512 sensitive wires, $\sigma_{R-\varphi}$=250 μm, σ_Z=5 mm, $\sigma_\theta=1.5\times_{10}{}^{-2}$, $\sigma_\varphi=7\times_{10}{}^{-3}$ $\sigma_{dE/dx}=0.2\times E$	1218 sensitive wires, $\sigma_{R-\varphi}$=140 μm, σ_Z=2 mm, $\sigma_\theta=7\times10^{-3}$, $\sigma_\varphi=4\times10^{-3}$, $\sigma_{dE/dx}=0.15\times E$
Z-chamber	Double layers proportional chamber with cathode strips, anode wires are combined to 2×32 sectors, number of cathode strips – 512, σ_Z=2 mm, σ_t=5 ns, $\Omega=0.8\times4\pi$ steradian.	
Barrel Calorimeter	892 CsI crystals in 8 octants, readout – PMT, thickness – 8.1 X_0, σ_E/E=8.5% at 100÷700 MeV, $\sigma_{\varphi,\theta}$=0.03÷0.02 rad.	1152 CsI crystals in 8 octants, readout – PIN photodiodes, 0.4 m^3 LXe, thickness –5 X_0+8.1 X_0=13.1 X_0, σ_E/E=4.7÷3% at 100÷900 MeV, $\sigma_{\varphi,\theta}$=0.005 rad.
Endcap Calorimeter	680 BGO crystals in 2 endcaps readout – vacuum phototriodes, thickness – 13.4 X_0, σ_E/E=8÷4% at 100÷700 MeV, $\sigma_{\varphi,\theta}$=0.03÷0.02 rad.	680 BGO crystals in 2 endcaps readout – PIN photodiodes, thickness – 13.4 X_0, σ_E/E=8÷3.5% at 100÷900 MeV, $\sigma_{\varphi,\theta}$=0.03÷0.02 rad.
Range system	Streamer tubes, 2 double layers, σ_Z=5 cm	Plastic scintillator counters, σ_t<1 ns
Superconductive solenoid	Magnetic field 1 T, thickness 0.38X_0	Magnetic field 1.5 T, thickness 0.18 X_0

CMD-3



1 – vacuum chamber; 2 – drift chamber; 3 – BGO calorimeter; 4 – Z-chamber; 5 – main solenoid; 6 – LXe calorimeter; 7 – CsI calorimeter; 8 – yoke; 9 – compensating solenoid;

CMD-3