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**New Data on  $e^+e^- \rightarrow \pi^+\pi^-$  cross section with CMD-2  
in energy range  $\sqrt{s}=0.37 - 1.38$  GeV**

Collaboration CMD-2

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## Why is it interesting?

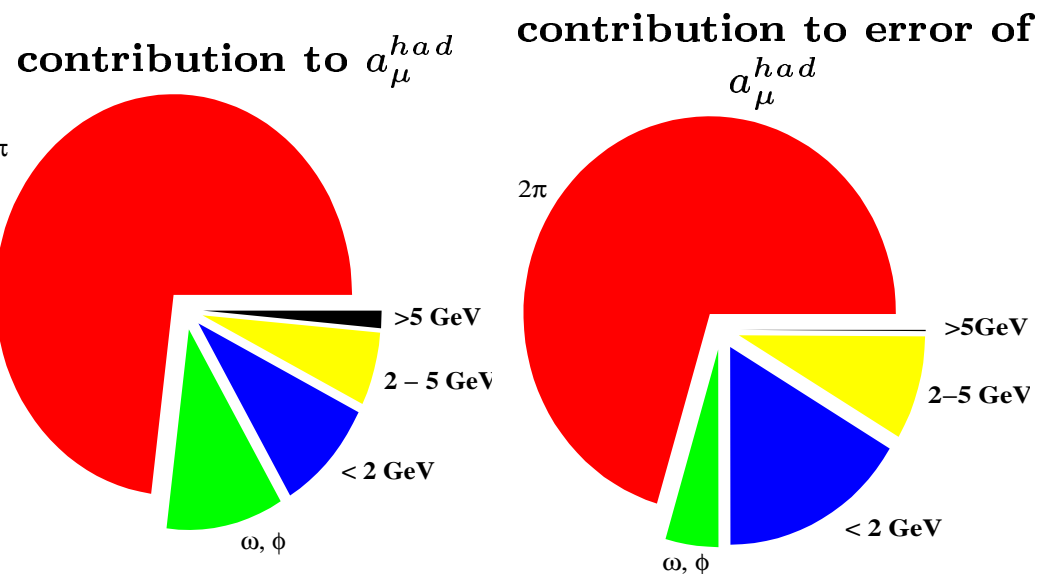
- $\pi$  meson internal structure
- physics of  $\rho, \rho', \rho''$  resonances
- major contribution to hadronic part of the vacuum polarization  
(muon anomalous magnetic moment  $a_\mu = (g - 2)/2$ )

$$a_\mu^{had,1} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^\infty \frac{R(s)K(s)}{s^2} ds \qquad R(s) = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

**About 91% of the total contribution to  $a_\mu^{had}$  comes from  $\sqrt{s} < 1.8$  GeV**  
**73% to  $a_\mu^{had}$  comes from two pion final state**

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

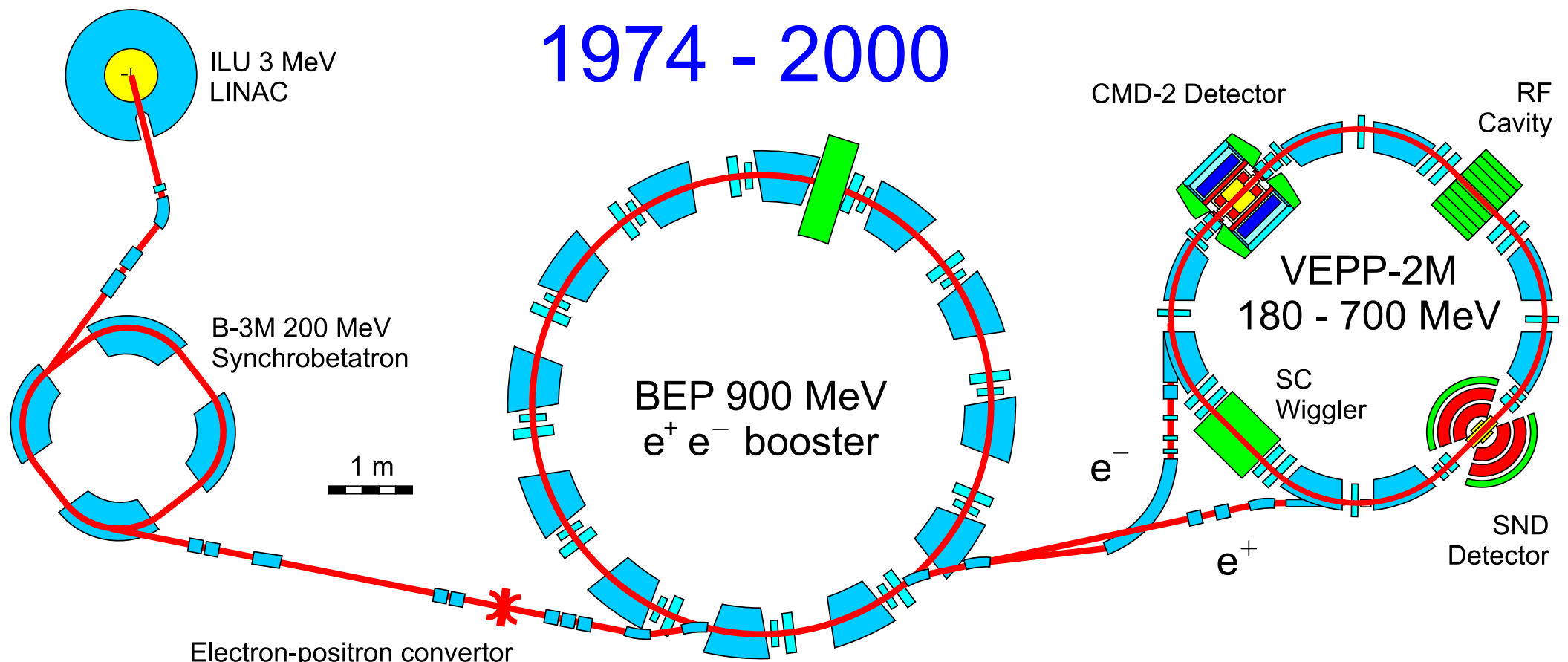
$a_\mu^{SM}$	11 659 180.9	$\pm$	8.0
$a_\mu^{QED}$	11 658 470.6	$\pm$	0.3
$a_\mu^{had,1}$	696.3	$\pm$	7.2
$a_\mu^{had,2}$	-10.0	$\pm$	0.6
$a_\mu^{had,lbl}$	8.6	$\pm$	3.5
$a_\mu^{weak}$	15.4	$\pm$	0.2
			$10^{-10}$



# VEPP-2M Collider

Beam Energy 180-700 MeV

1974 - 2000



With  $L_{peak} \approx 3 \cdot 10^{30} cm^{-2} sec^{-1}$

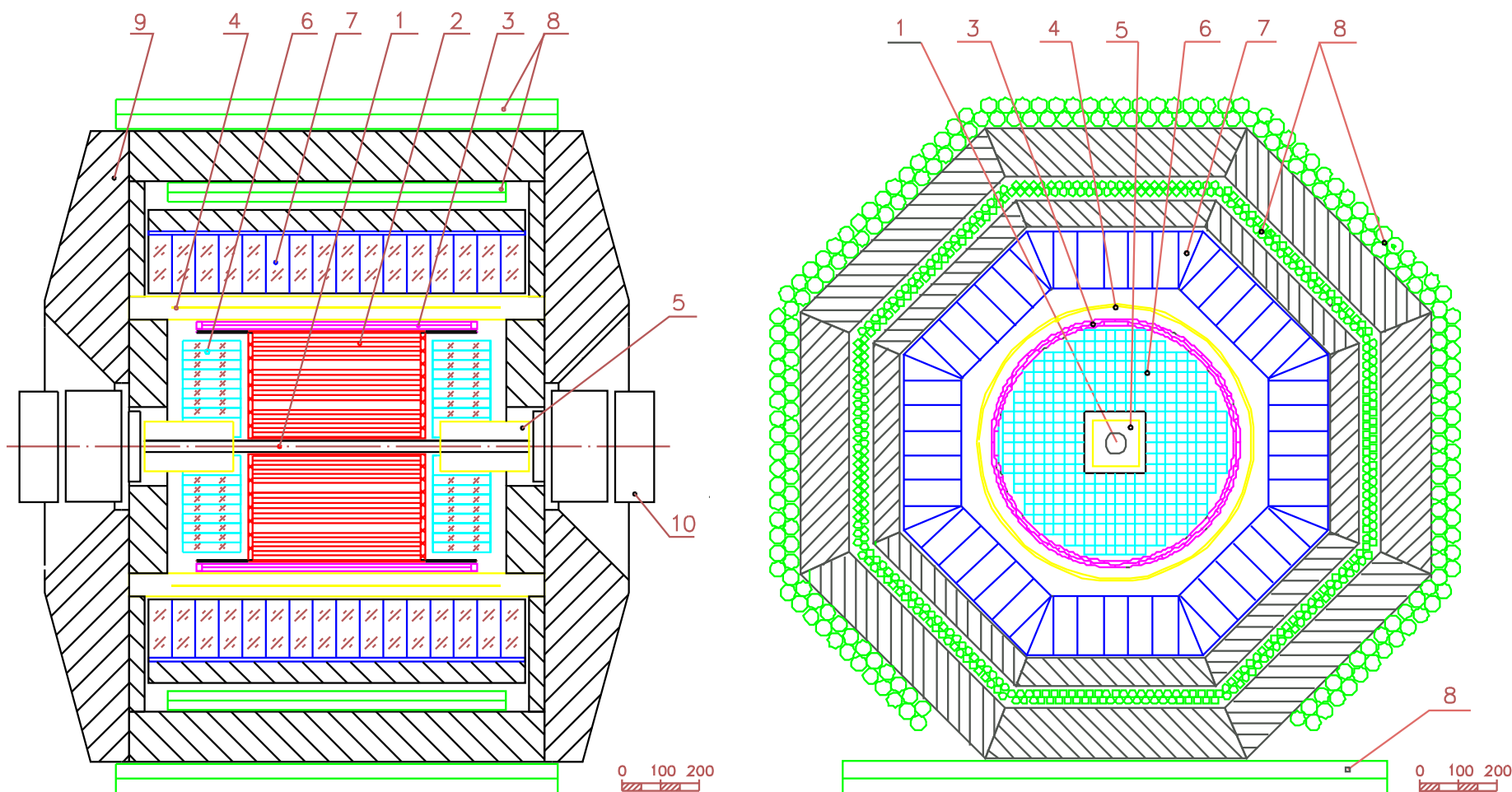
Circumference 18 m

Time between collisions 60 ns

Beam current 50 mA

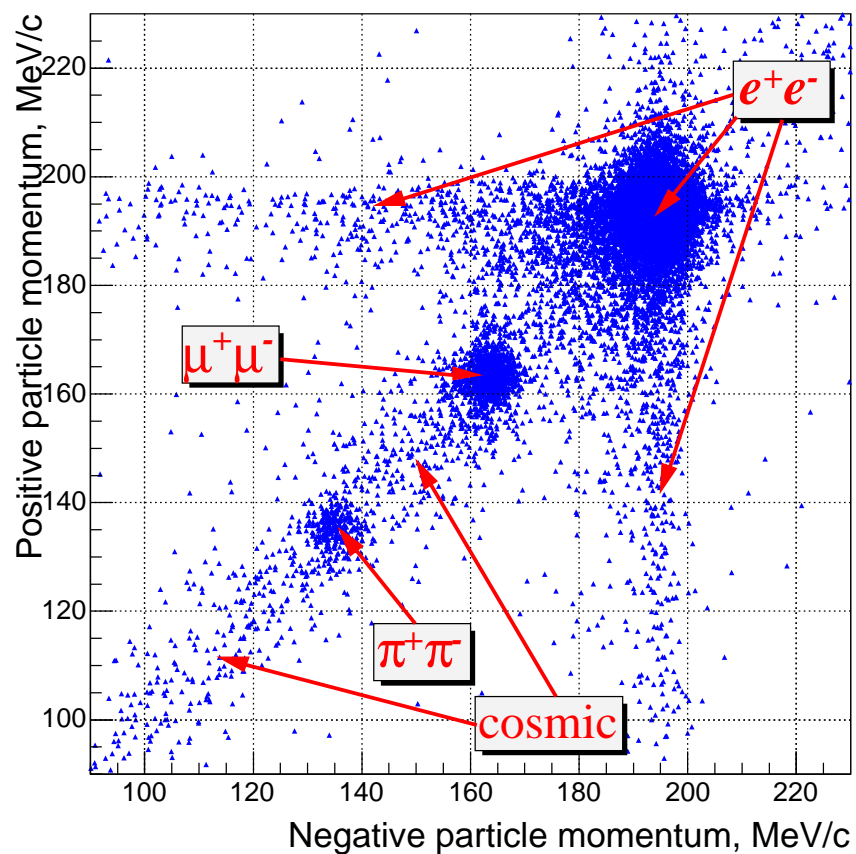
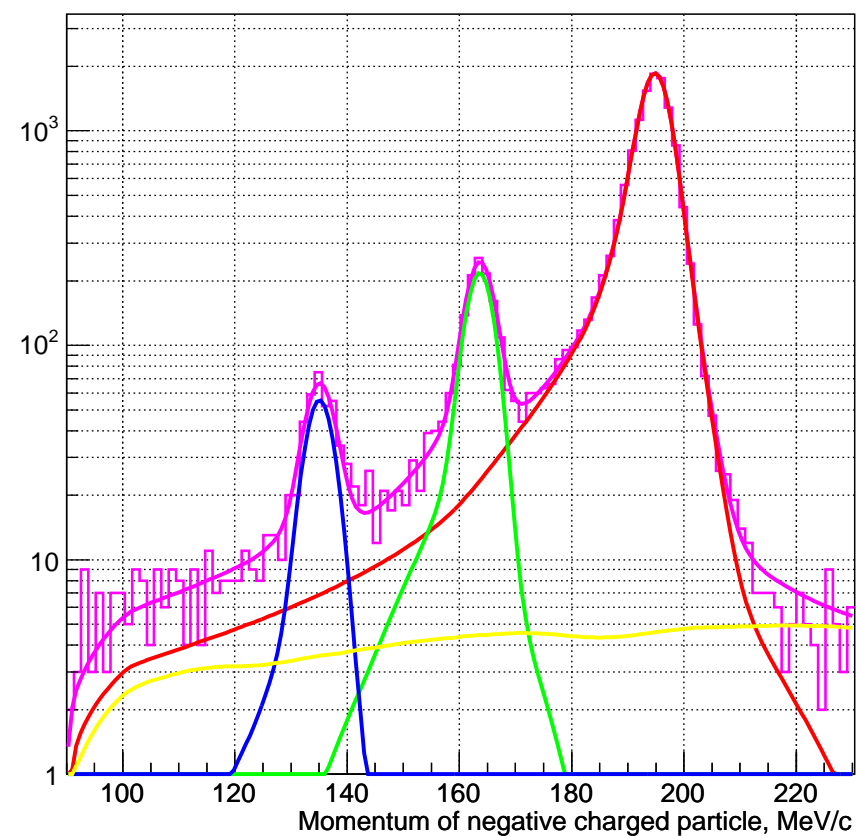
# CMD-2 detector ( 1992-2000)

## Cryogenic Magnetic Detector



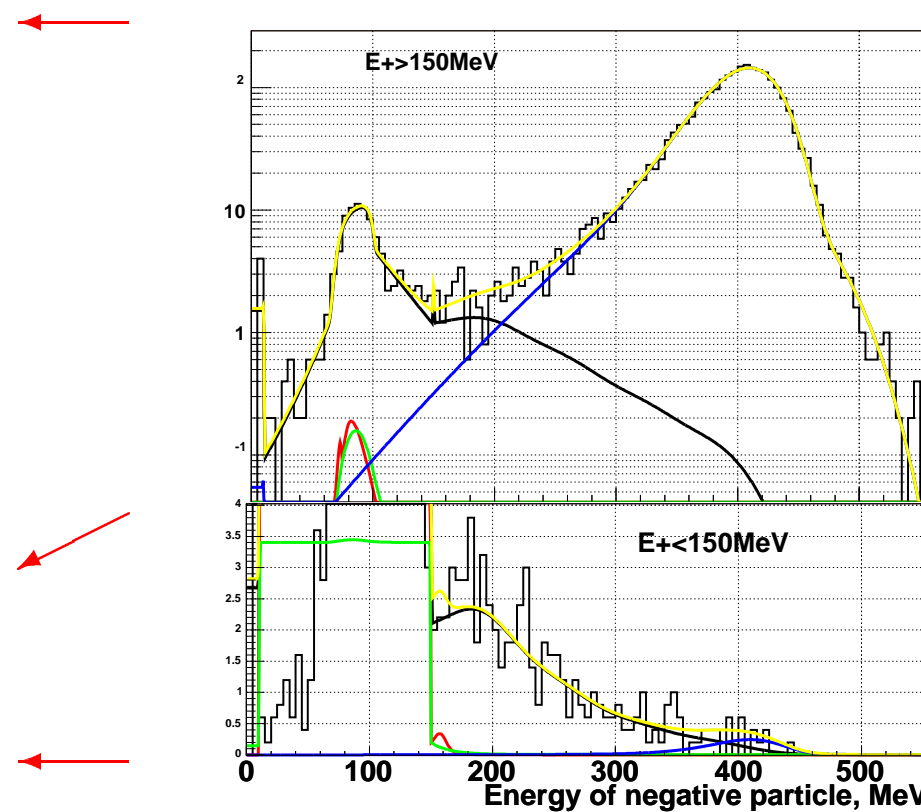
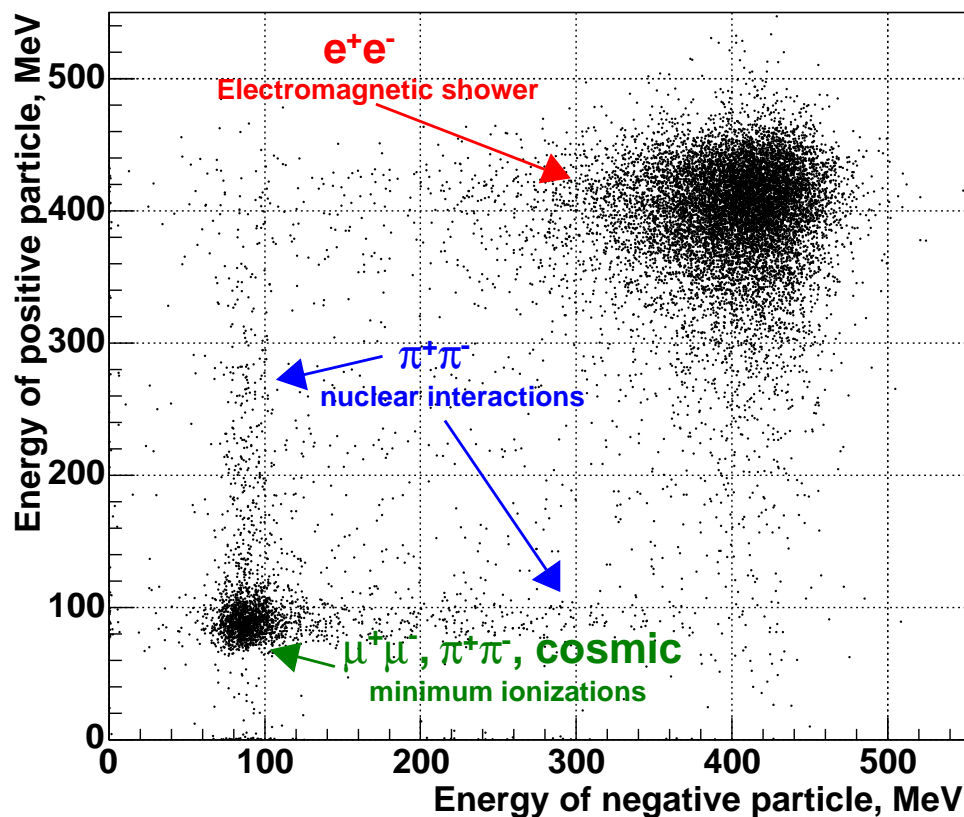
1 — beam pipe, 2 — drift chamber, 3 — Z-chamber, 4 — superconductive solenoid, 5 — focusing solenoid 6 — BGO endcap calorimeter, 7 — CsI barrel calorimeter, 8 — muon system, 9 — magnet yoke, 10 — quadrupole lenses.

# Momentum distribution for particle separation is used at $\sqrt{s} < 0.6\text{GeV}$

**Momentum scatter plot**

**Negative momentum projection**


$$\mathcal{L} = - \sum_{events} \ln \left( \sum_{e,\mu,\pi,bg} \omega_{type} \cdot f_{type}(P^+, P^-) \right), \quad \sum_{type} \omega_{type} = 1$$

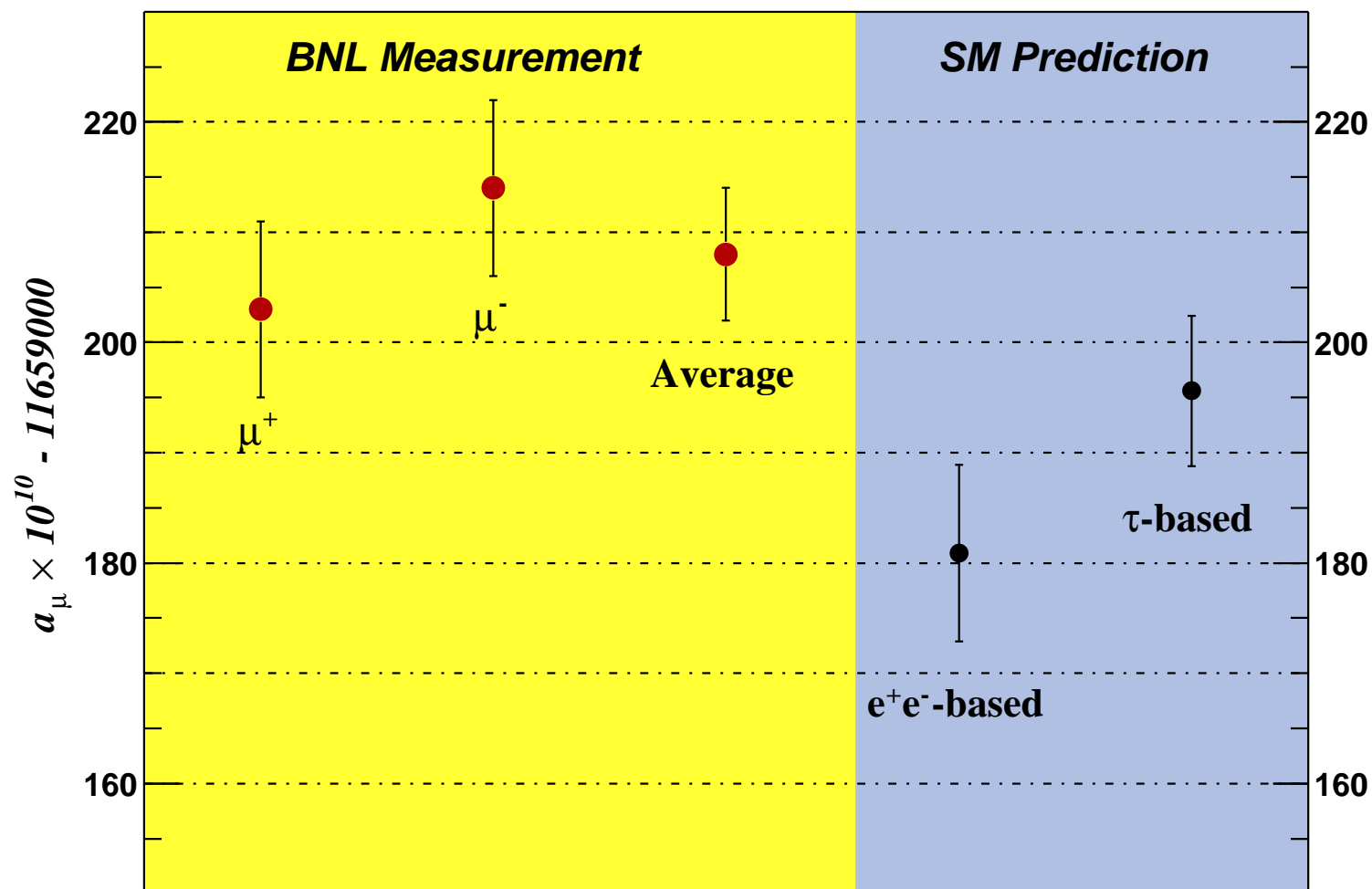
# Energy deposition in CsI calorimeter for particle separation is used at $\sqrt{s} > 0.6\text{GeV}$



$$\frac{N_\mu}{N_e+1} = \frac{\sigma_{ee \rightarrow \mu\mu}^B \cdot (1+\delta_\mu) \cdot \epsilon_\mu}{\sigma_{ee \rightarrow ee}^B \cdot (1+\delta_e) \cdot \epsilon_e} \text{ fixed from QED}$$

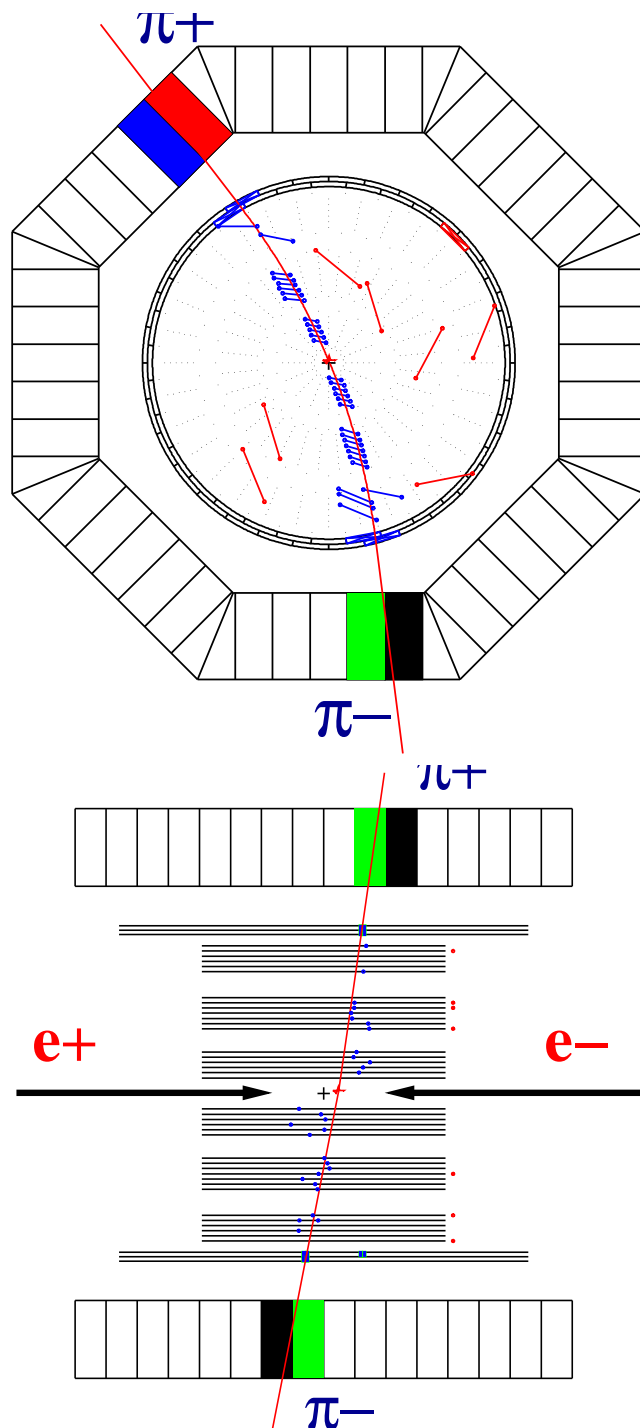
Number of cosmic events from distribution of vertex position

$$\mathcal{L} = - \sum_{events} \ln \left( \sum_{e,\mu,\pi,bg} N_{type} \cdot f_{type}(E^+, E^-) \right) + \sum_{e,\mu,\pi,bg} N_{type}$$

**Anomalous Magnetic Moment ( $a_\mu = (g_\mu - 2)/2$ ) results**


$$a_\mu(\text{Exp}) - a_\mu(\text{Theory}, e^+e^-) = (27.1 \pm 10.0) \cdot 10^{-10} \quad (2.7\sigma)$$

DEHZ'02 M.Davier, S.Eidelman, A.Hocker, Z.Zhang, hep-ph/0208177, hep-ph/0308213

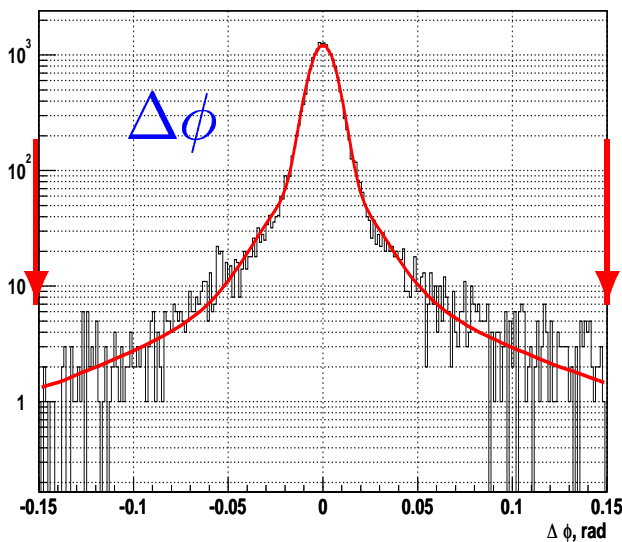


## Collinear Event selection

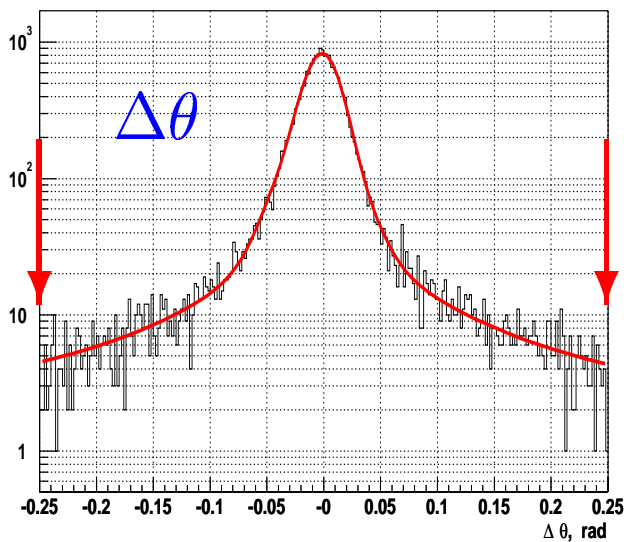
1. One vertex with two tracks,  
 $Q_1 + Q_2 = 0$
2. Vertex position:  
 $\rho_{vtx} < 0.15 \text{ cm}$  ,  $|Z_{vtx}| < 10 \text{ cm}$
3. Tracks collinearity:  
 $|\Delta\phi| < 0.15$  ,  $|\Delta\theta| < 0.25$
4. Minimum Average Momentum:  
 $(p^+ + p^-)/2 > 90 \text{ MeV}/c$  at  $\sqrt{s} < 0.6 \text{ GeV}$   
 $> 200 \text{ MeV}/c$  at  $\rho$ -region  
 And for Charge Kaons Rejection at  $\sqrt{s} > 1 \text{ GeV}$ :  
 $> \max(1.3 \cdot P_K, 325) \text{ MeV}/c$
5. Average polar angle:  
 $1.1 < (\pi + \theta^- - \theta^+)/2 < \pi - 1.1$

# Collinear Event selection

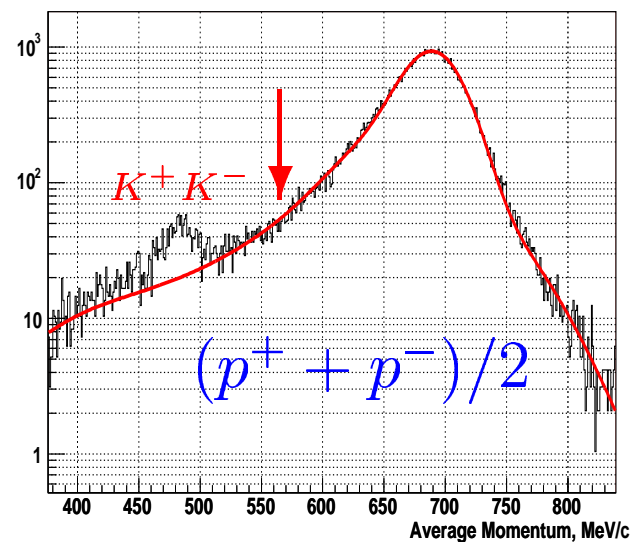
Phi resolution



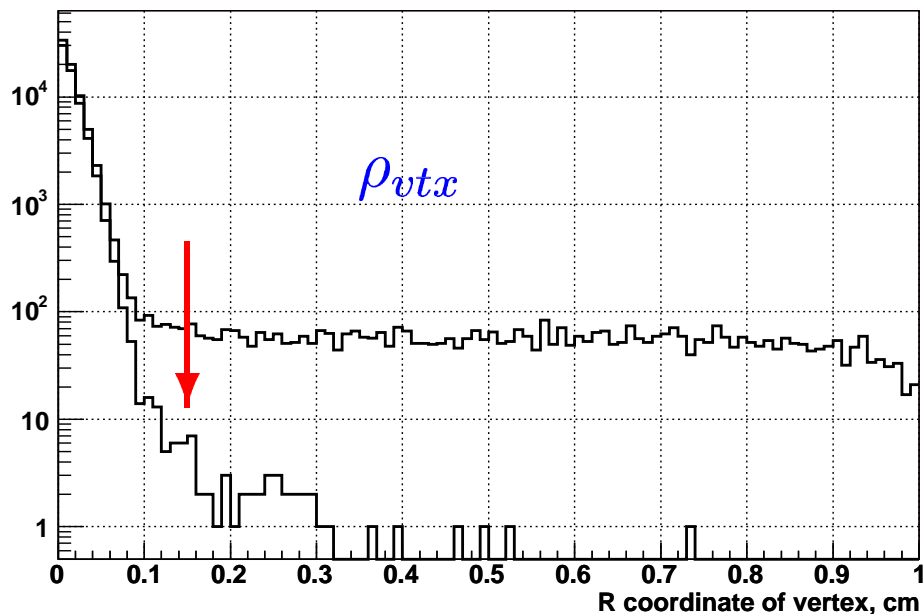
Theta resolution



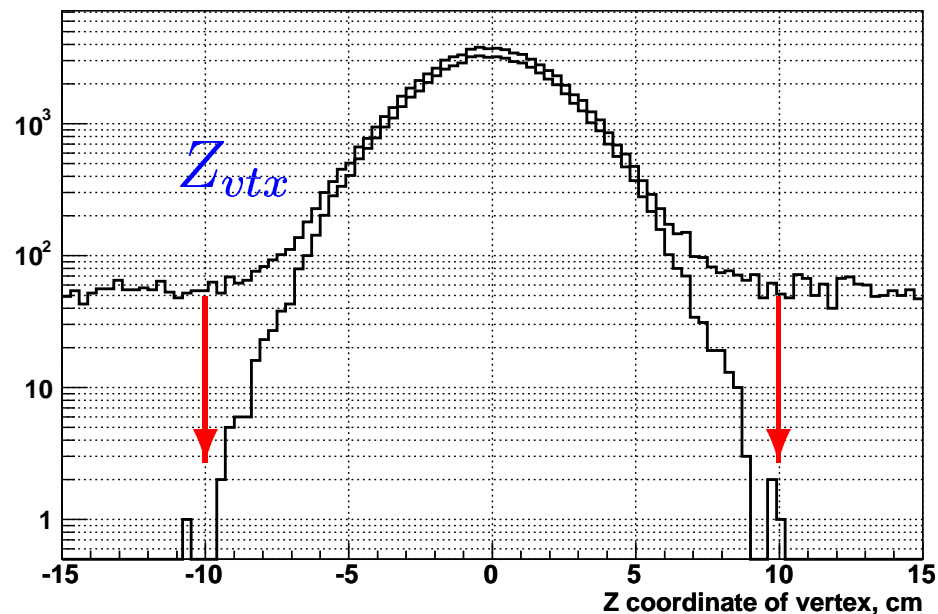
Momentum resolution



Distance to beam



Distance to beam



# Formfactor Calculation

$$|F_\pi|^2 = \frac{N_{\pi\pi}}{N_{ee} + N_{\mu\mu}} \cdot \frac{\sigma_{ee}^B \cdot (1 + \delta_{ee}) \cdot \varepsilon_{ee} + \sigma_{\mu\mu}^B \cdot (1 + \delta_{\mu\mu}) \cdot \varepsilon_{\mu\mu}}{\sigma_{\pi\pi}^B \cdot (1 + \delta_{\pi\pi})(1 - \Delta_{lose}) \cdot \varepsilon_{\pi\pi}} - \Delta_{3\pi,4\pi,K^+K^-}$$

$\sigma^B$  -Born Cross-Section

$\varepsilon$  - efficiency of reconstruction  $\sim 99\%$

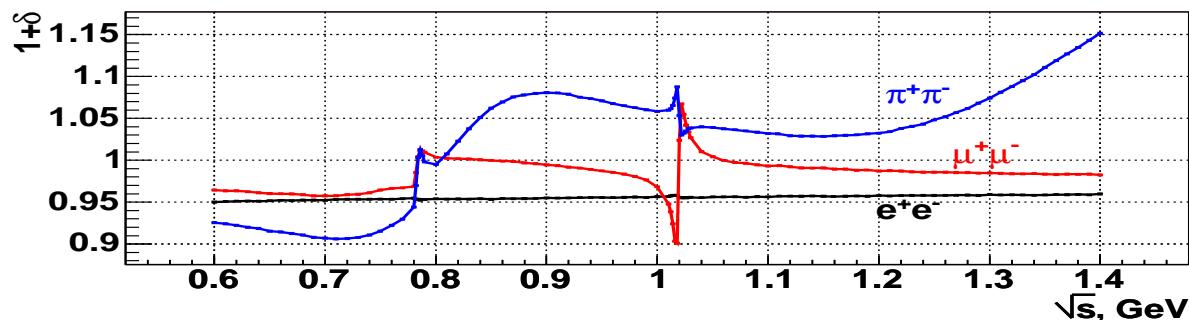
$\Delta_{lose}$  - correction from pion lose  $\sim 3.5\% \div 0.6\%$

$\Delta_{3\pi,4\pi,K^+K^-}$  - background events

$\sim 0.3\%$  near  $\omega$ -meson,

$\sim 1\%$  above  $\phi$ -meson

$\delta$  - radiation correction

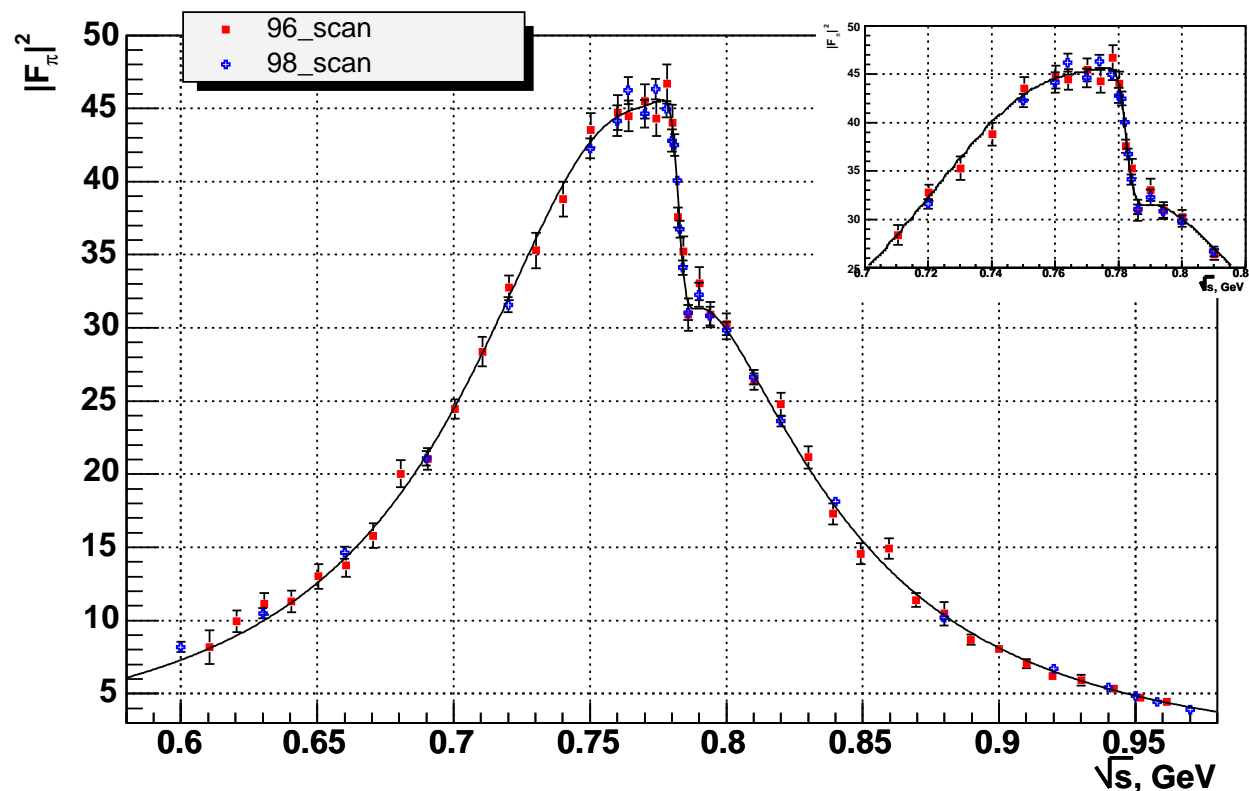


$e^+e^-$	$\mu^+\mu^-$	$\pi^+\pi^-$	cosmic	number of points	energy range, $\sqrt{s}$	
number of events, $10^3$						
164	16	114	17	43	610 $\div$ 960 MeV	Phys.Lett B578:285-289,2004
96	9	4	5	10	370 $\div$ 520 MeV	
710	65	520	19	29	600 $\div$ 960 MeV	
840	81	33	14	36	980 $\div$ 1380 MeV	

## Systematic Errors

source	value		
	$\sqrt{s} = 0.37 \div 0.52$	$0.6 \div 0.96$	$1.04 \div 1.38$ GeV
fiducial volume	0.2 %	0.2 %	0.2÷0.5 %
detection efficiency	0.3 %	0.2 %	0.5÷ 2 %
correction for pion losses	0.2 %	0.2 %	0.2 %
radiative corrections	0.3 %	0.4 %	0.5÷ 2 %
background events	<0.1%	<0.1%	0.6÷1.6 %
energy calibration of collider	0.3 %	0.1 %	0.7÷1.1 %
full event separation	1.0 %	0.2 %	0.5÷3.5 %
	1.2 %	0.6 %	1.3 ÷ 5.0 %
statistic error in point	6 %	1.5 ÷ 4 %	5 ÷ 13 %

# Pion Formfactor (CMD2 data)



The Gounaris-Sakurai parametrization (GS)

$$F_{\pi}(s) = \frac{\text{BW}_{\rho(770)}^{\text{GS}}(s) \cdot \frac{1 + \delta \text{BW}_{\omega}(s)}{1 + \delta} + \beta \text{BW}_{\rho(1450)}^{\text{GS}}(s) + \gamma \text{BW}_{\rho(1700)}^{\text{GS}}(s)}{1 + \beta + \gamma}$$

$600 < \sqrt{s} < 1000 \text{ MeV}$   $\rho, \omega, \rho'$  :  
 $M_{\rho} = 775.65 \pm 0.64 \pm 0.50 \text{ MeV}$   
 $\Gamma_{\rho} = 143.85 \pm 1.33 \pm 0.80 \text{ MeV}$   
 $Br(\omega \rightarrow \pi^+ \pi^-) = 1.30 \pm 0.24 \pm 0.05\%$   
 $\arg \delta = 13.3^{\circ} \pm 3.7^{\circ} \pm 0.2^{\circ}$

Phys.Lett B527:161-172,2002

Phys.Lett B578:285-289,2004

all statistic data at CMD-2  
 only statistic error

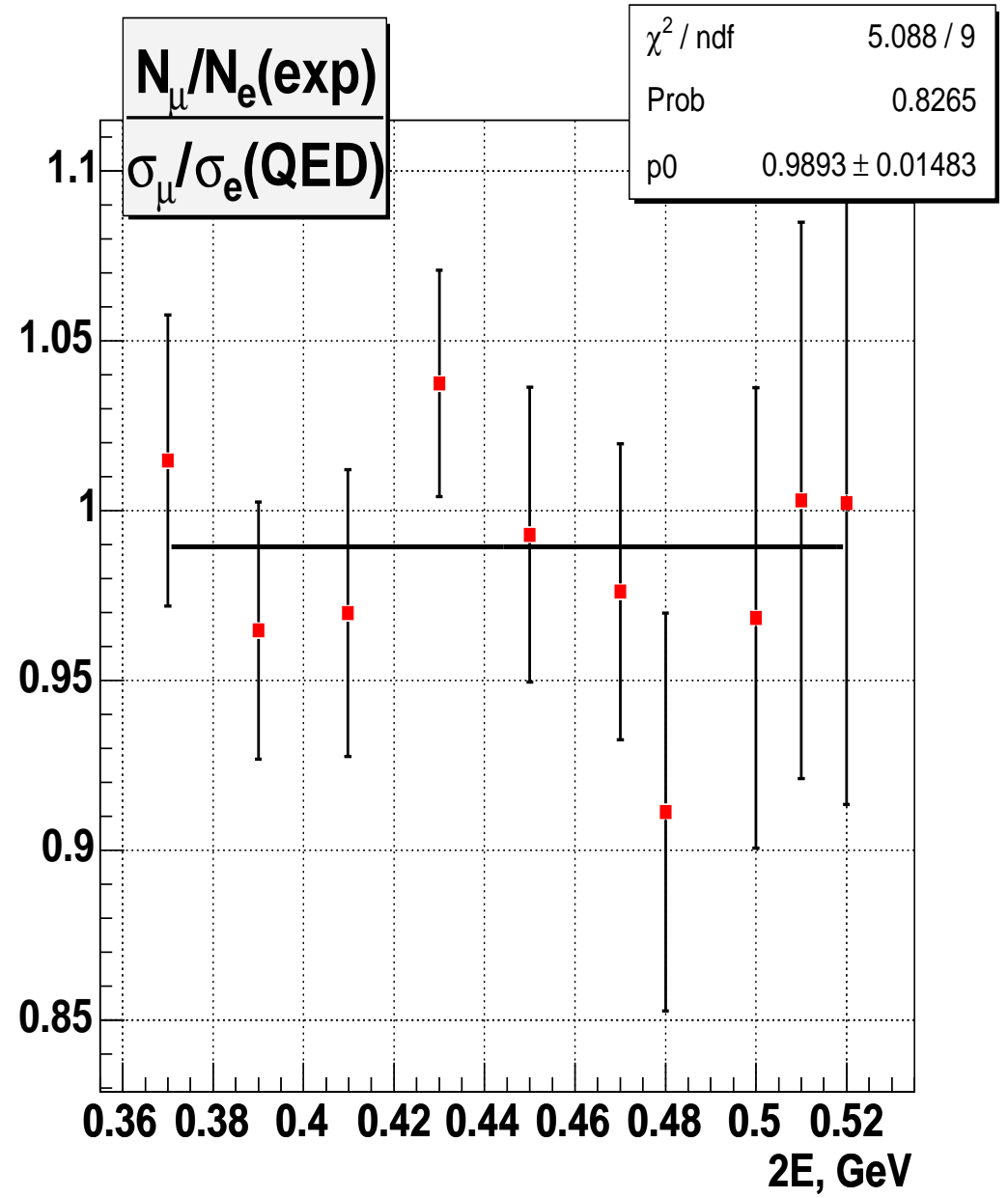
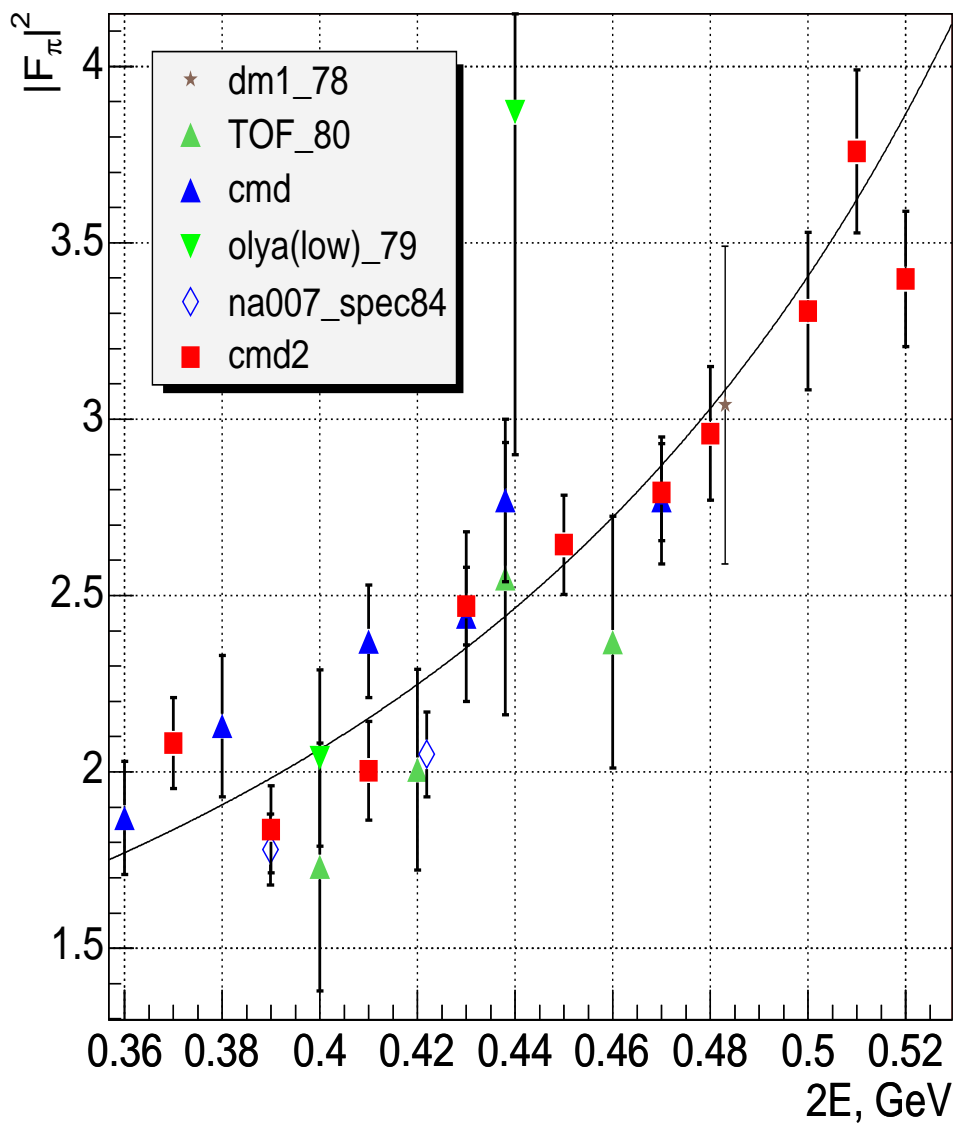
$M_{\rho} = 775.36 \pm 0.46 \text{ MeV}$

$\Gamma_{\rho} = 143.5 \pm 1.2 \text{ MeV}$

$Br(\omega \rightarrow \pi^+ \pi^-) = 1.47 \pm 0.12\%$

$\arg \delta = 11.0^{\circ} \pm 1.7^{\circ}$

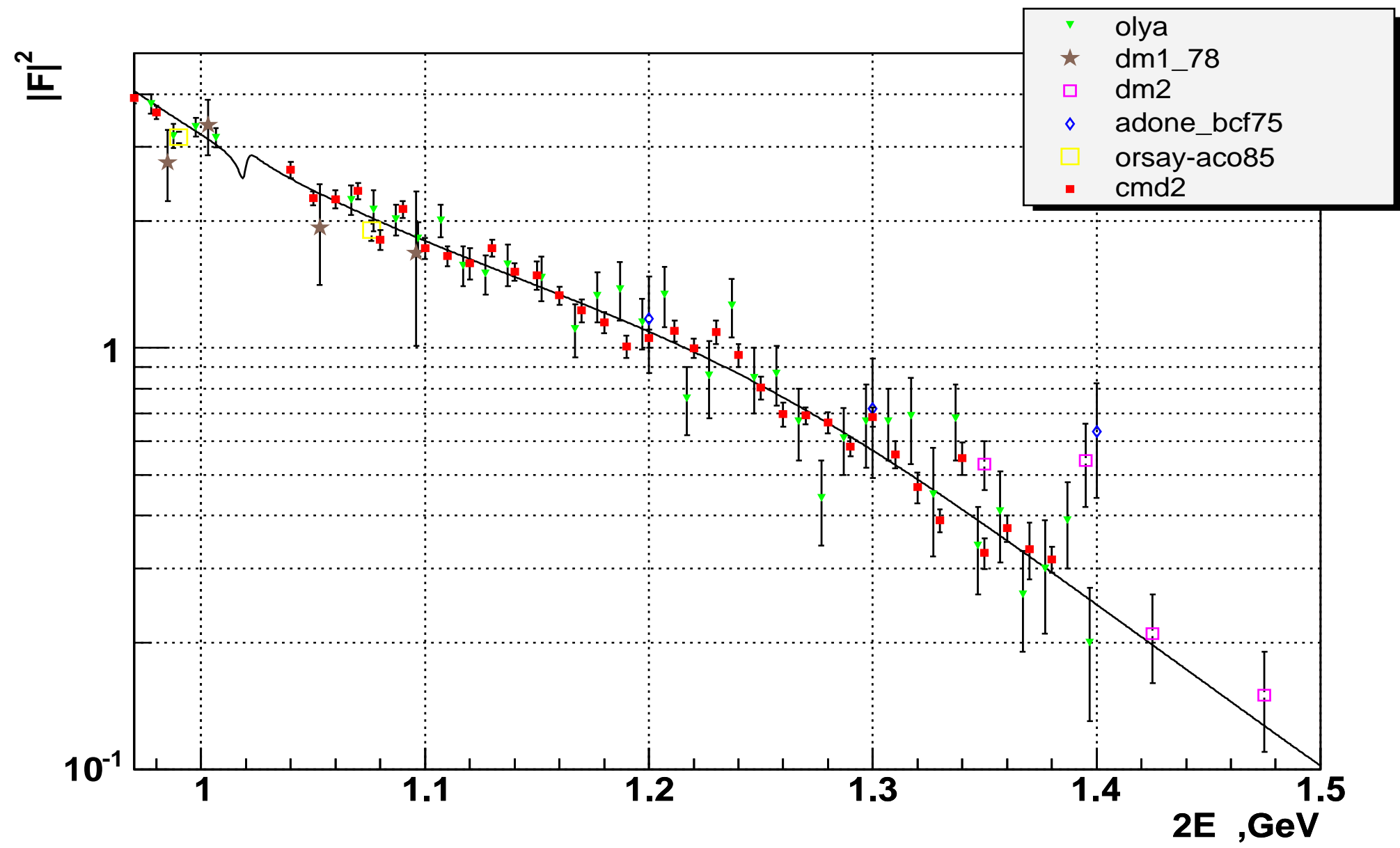
Pion Formfactor at  $\sqrt{s} < 0.6$  GeV



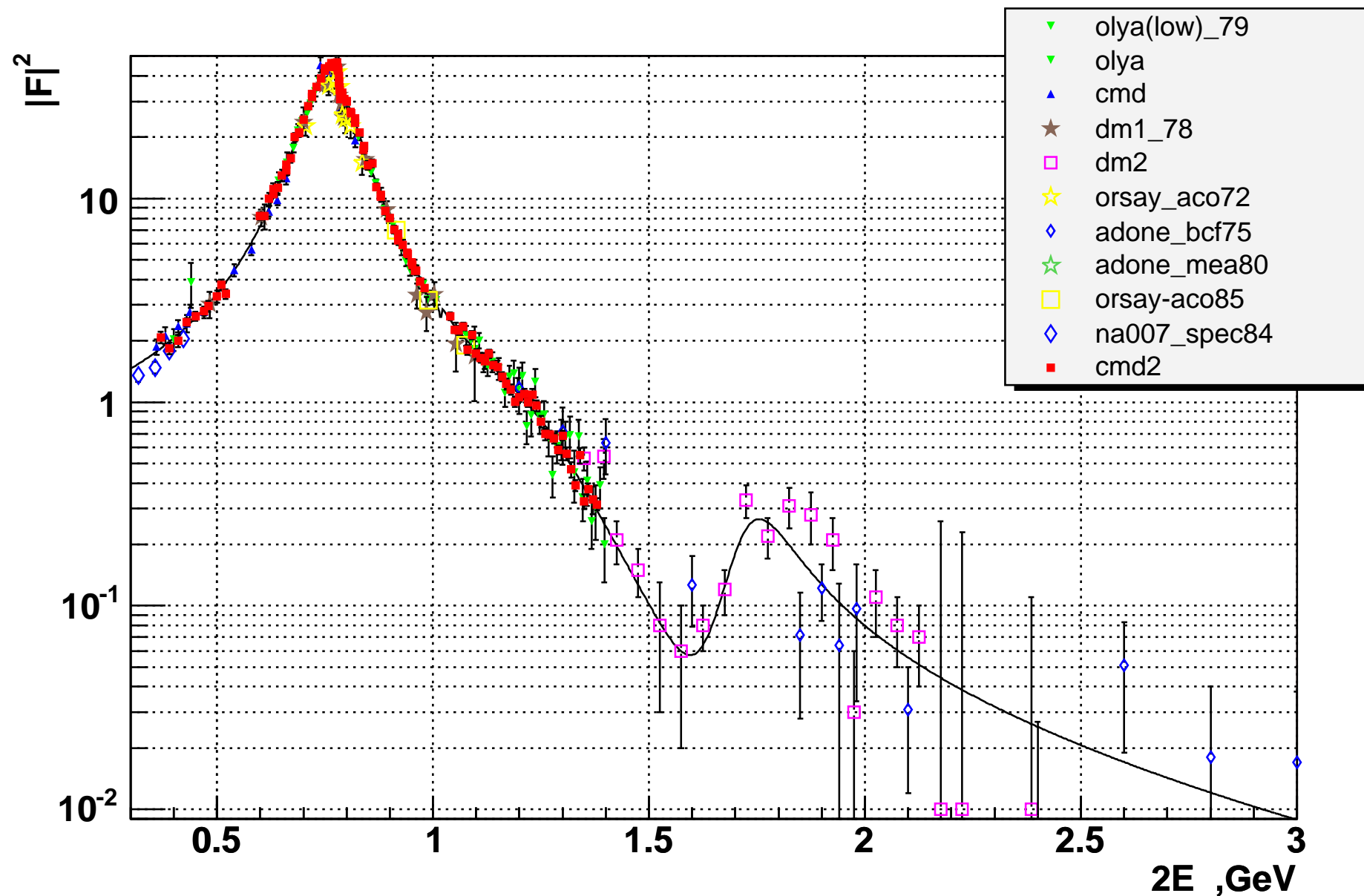
$\chi^2 / \text{ndf}$	5.088 / 9
Prob	0.8265
p0	$0.9893 \pm 0.01483$

$N_\mu/N_e(\text{exp})$   
 $\sigma_\mu/\sigma_e(\text{QED})$

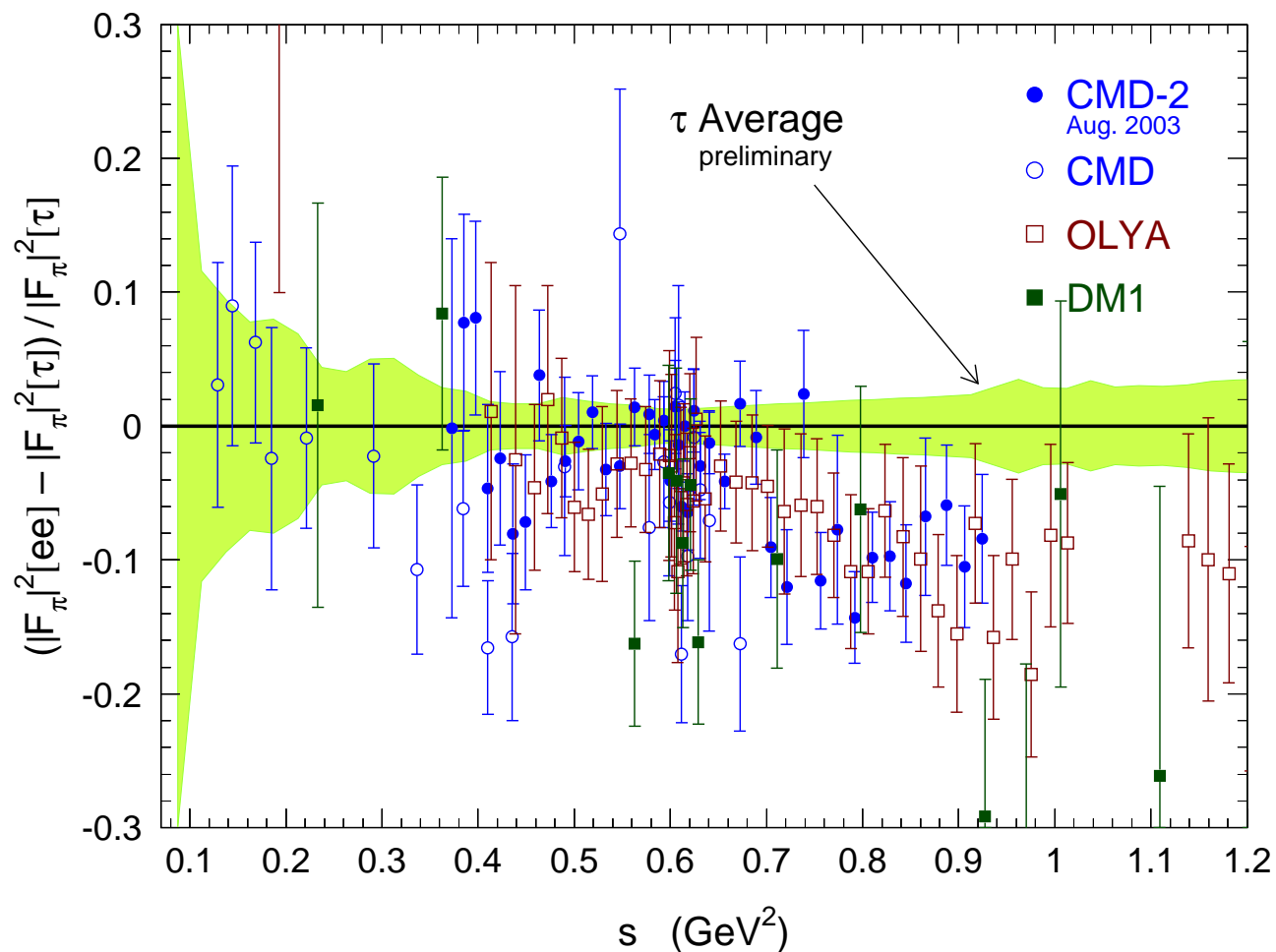
Pion Formfactor at  $\sqrt{s} = 1.02 - 1.38$  GeV



# Pion Formfactor at $\sqrt{s} = 0.37 \div 3. \text{ GeV}$



## Relative comparison of the $\pi^+\pi^-$ spectral functions from $e^+e^-$ and isospin beaking-corrected $\tau$ data



$$a_\mu^{\text{had}} = 696.3 \times 10^{-10} \quad (59.72 \pm 0.6 \text{ ppm}) \quad \text{from } e^+e^-$$

$$a_\mu^{\text{had}} = 711.0 \times 10^{-10} \quad (60.98 \pm 0.5 \text{ ppm}) \quad \text{from } \tau \text{ to } 2\pi \text{ and } 4\pi$$

$$a_\mu(e^+e^-) - a_\mu(\tau) = -14.7 \pm 7.9$$

DEHZ'02, hep-ph/0208177, hep-ph/0308213

## Conclusion

- Contribution at this energy range of  $\pi^+\pi^-$  to  $a_\mu = (g - 2)/2 = (11659208 \pm 6) \cdot 10^{-10}$  :  
 $\Delta a_\mu^{had} = (508.20 \pm 5.53) \cdot 10^{-10}$
- Why spectral function from  $e^+e^-$  and  $\tau$  have different behavior?  
(possibly due to difference in masses and widths of  $\rho^\pm$  and  $\rho^0$  ?)
- The further 2÷10 times improvement of experimental value of  $a_\mu$  need requires the improvement of  $\pi^+\pi^-$  cross-section knowledge.
- KLOE, BABAR and BELLE results for  $e^+e^- \rightarrow \pi^+\pi^-(\gamma)$  will give additional information.
- Experiments with CMD-3 at VEPP-2000  
will provide new data in expanded energy range  $\sqrt{s}=0.36-2$ . GeV.