MEASUREMENT OF $e^+e^- \to \pi^+\pi^-$ CROSS SECTION AT CMD-3

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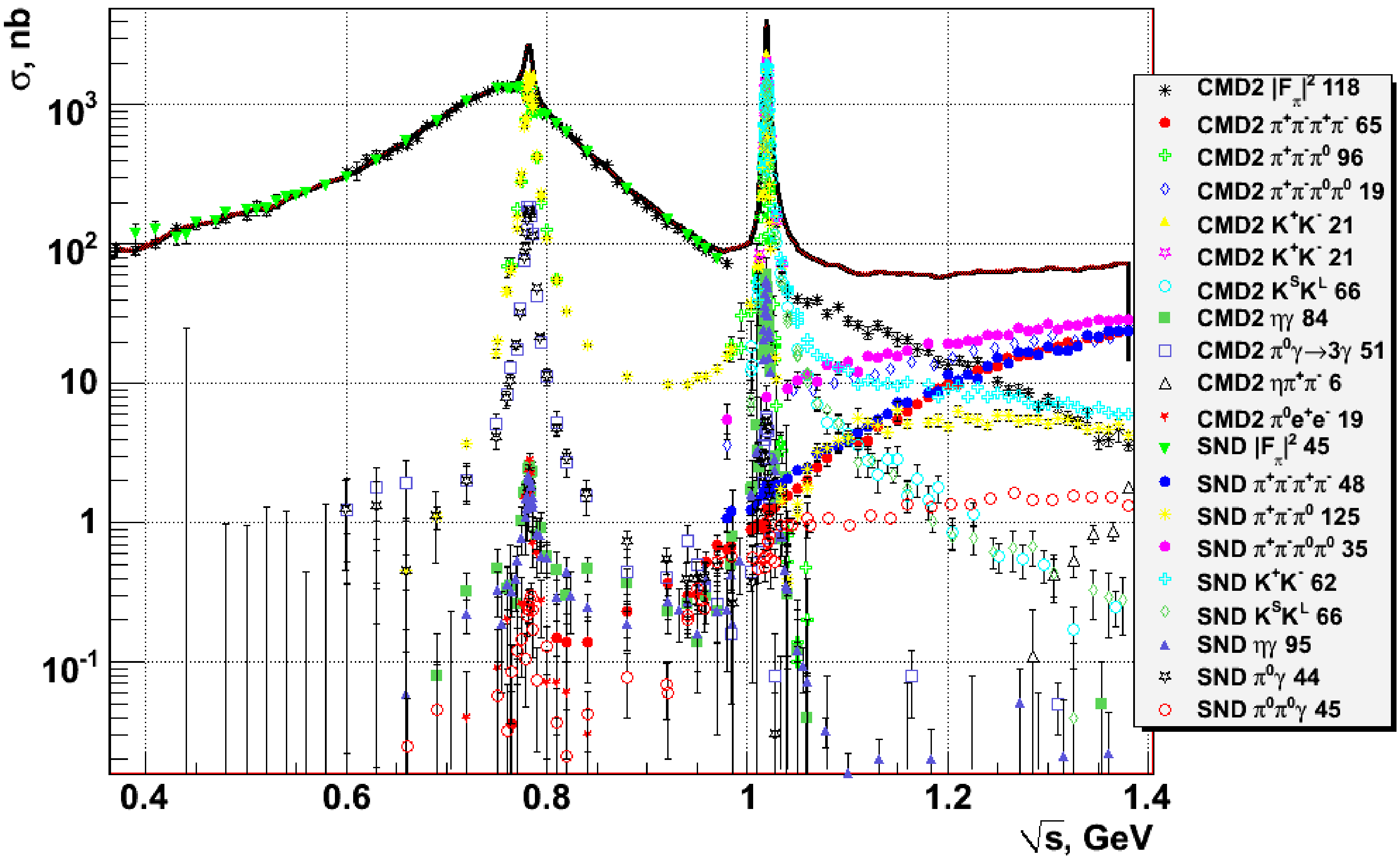
Outline

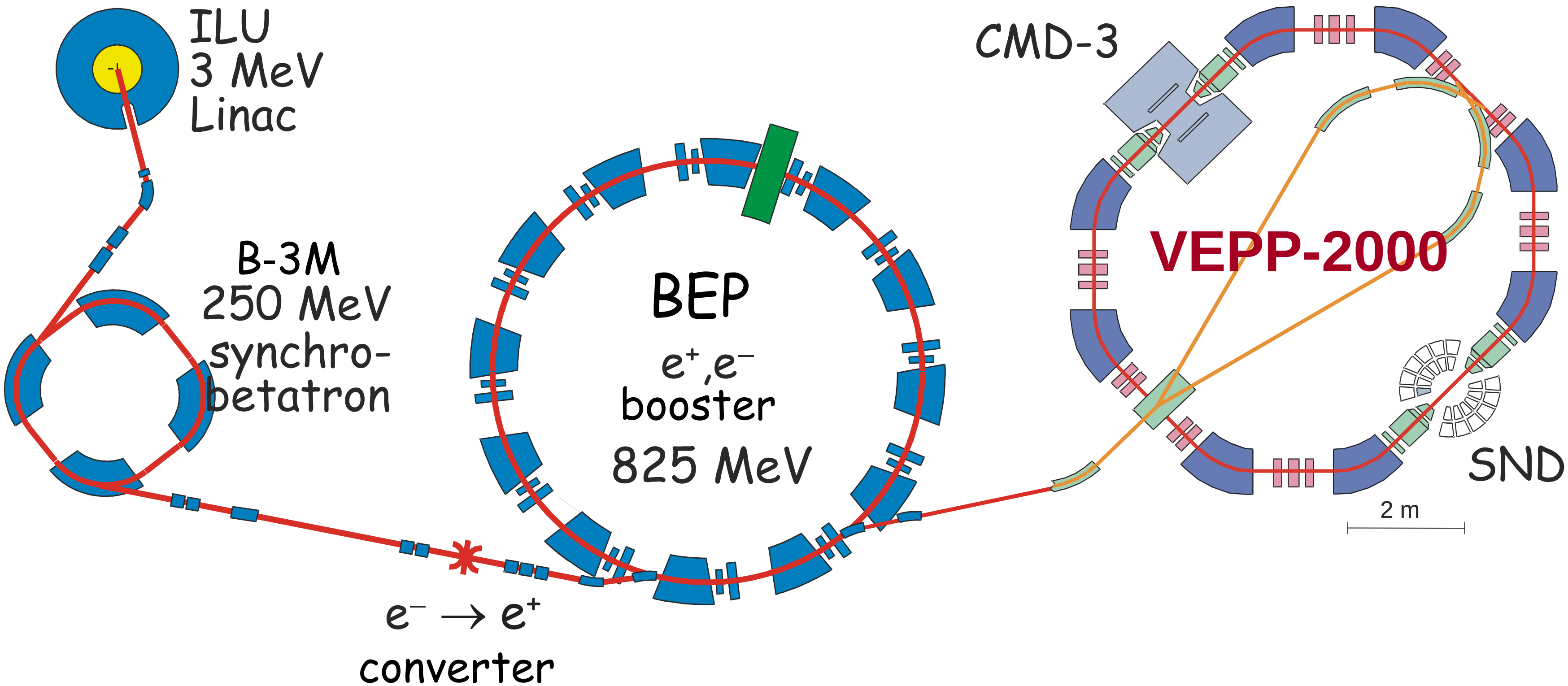
- VEPP-2000
- Detector CMD-3
- Pion formfactor measurement
- Systematic errors

Cross-section measurements at VEPP-2M



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

VEPP-2000

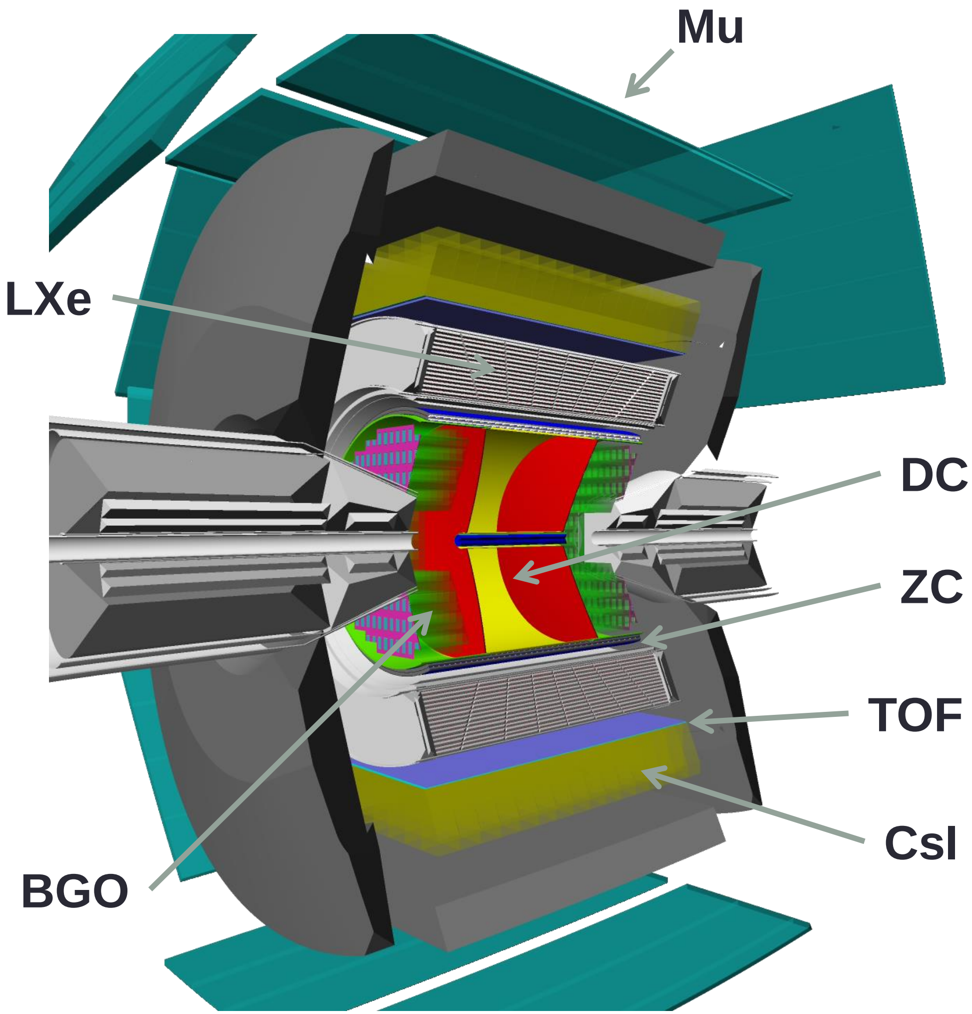


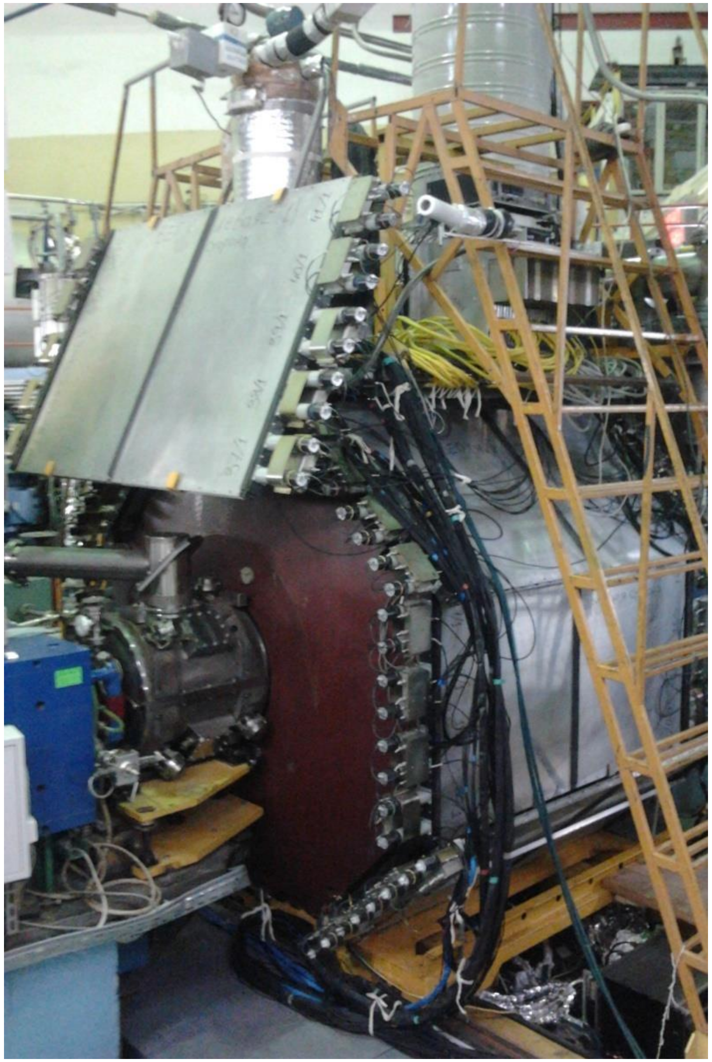
Maximum c.m. energy is 2 GeV, project luminosity is $L = 10^{32} 1/cm^2 s$ at $\sqrt{s} = 2$ GeV

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

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

Detector CMD-3

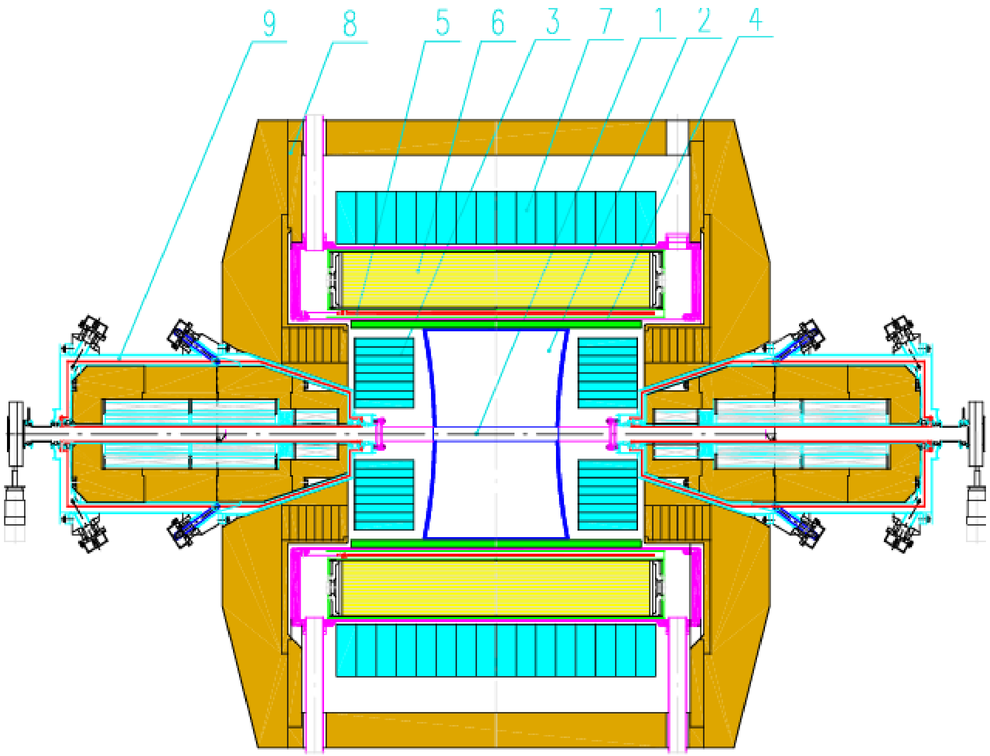




CMD-3 vs CMD-2

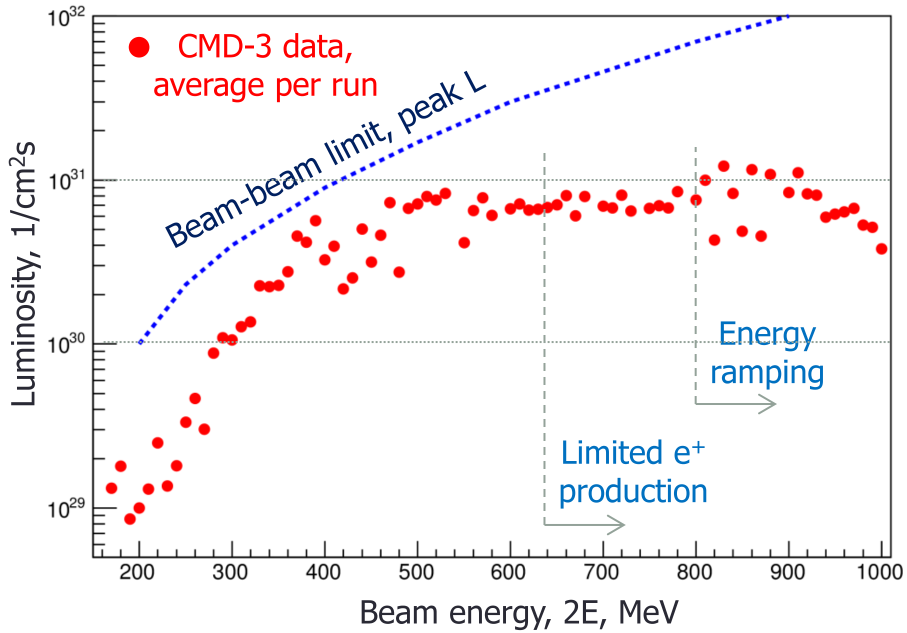
CMD-3 advantages compared to its predecessor CMD-2:

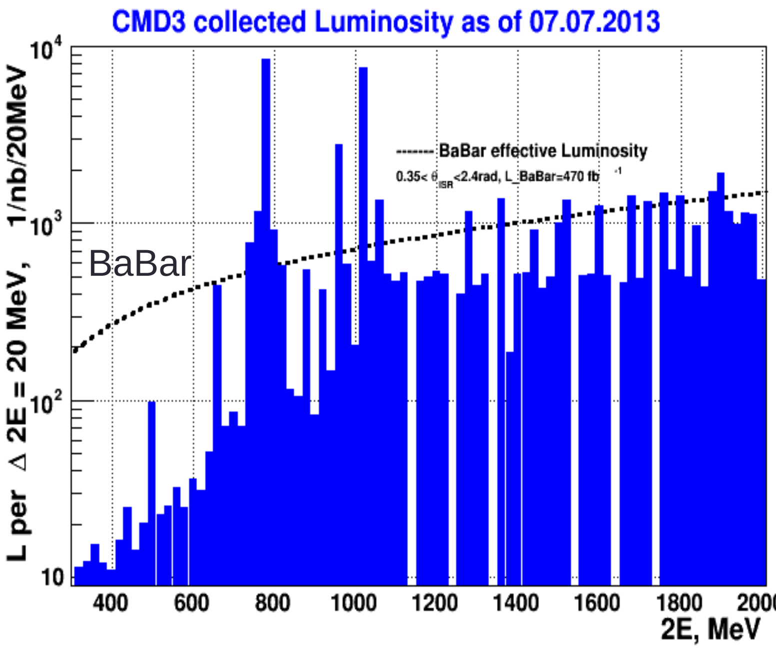
- new drift chamber with two times better resolution, higher B field
  better tracking
  better momentum resolution
- thicker barrel calorimeter ($8.3X_0 \rightarrow 13.4\ X_0$)
  better particle separation
- LXe calorimeter
  measurement of conversion point for γ's
  measurement of shower profile
-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



1 – IP, 2 – drift chamber, 3 – BGO (680 crystals), 4 – Z–chamber, 5 – SC solenoid, 6 – LXe (400 liters), 7 – CsI (1152 crystals), 8 – magnet yoke, 9 – ring solenoids, not shown – muon range system and TOF system

Collected luminosity





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

After upgrade in 2013-2014 we expect luminosity increase by up to factor 10 at maximum energy.

About 60 pb^{-1} collected per detector

$\omega(782)$	$8.3\ 1/pb$
$2E < 1$ GeV (except ω)	$9.4\ 1/pb$
$\varphi(1019)$	$8.4\ 1/pb$
$2E > 1.04$ GeV	$34.5\ 1/pb$

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

It is a challenging channel at CMD-3, because of the high precision.

Reasons to measure pion formfactor yet again:

1. In units of hadronic contribution to $(g-2)_\mu$:
   $\delta a_\mu^{HVP} = 0.6\%$, $\Delta a_\mu(\exp - \text{theory}) \approx 4.0\% \pm 1.1\%$
   $\sigma(e^+e^- \to \pi^+\pi^-)$ attributes to 73% of a_μ^{HVP} and to 0.45% to δa_μ^{HVP}.
2. New experiment at FNAL is expected to measure $(g-2)_\mu$ to 0.25%
3. There is good overall agreement between KLOE, BABAR, CMD-2 and SND, but there are local disagreements.

CMD-3 goal: measure $\sigma(e^+e^- \to \pi^+\pi^-)$ with systematic accuracy of 0.3% and small statistical errors.

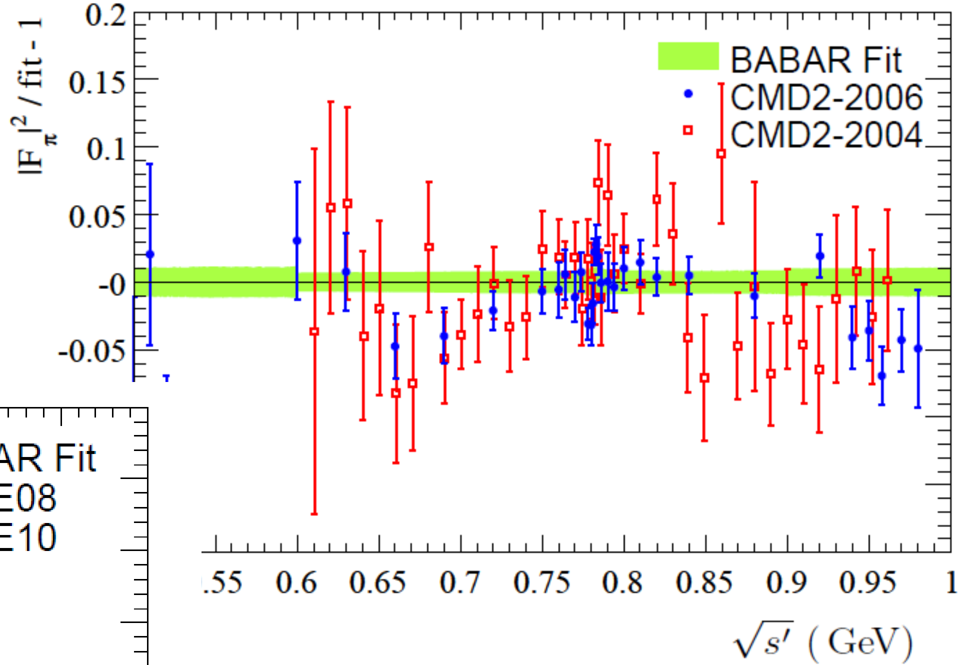
Means to improve systematics:

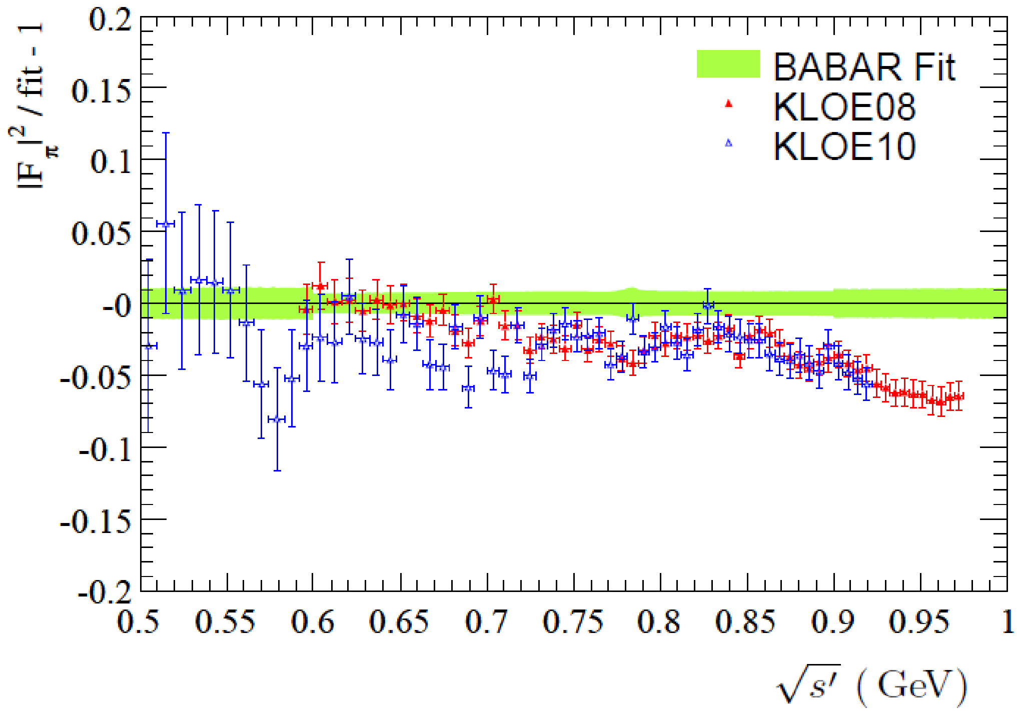
- Better $e/\mu/\pi$ separation – thick multilayer calorimeter, high resolution DC
- Continuous beam energy monitoring
- High statistics – allows to see systematic effects

Do existing measurements agree?

We want agreement on 0.25% level!

- Local statistical power of CMD-2 data is not good enough to judge





- There is serious tension between KLOE and BABAR results (both ISR)
- There is excellent agreement between KLOE'10 and KLOE'12 – very different measurements

The “usual” cross-section formula

The usual way to measure cross-section:

$$\sigma(e^+e^- \to H) = \frac{N_H - N_{bg}}{L \cdot \varepsilon \cdot (1+\delta)}$$

- Luminosity L is measured using Bhabha scattering at large angles
- Detection efficiency ε is calculated via Monte Carlo with corrections for imperfect detector; detection efficiency includes acceptance
- Radiative correction δ often accounts only for initial state radiation

This approach is not optimal for $\sigma(e^+e^- \to \pi^+\pi^-)$:

- normalization final state looks very similar to signal
- acceptance part of detection efficiency is easily calculated
- much more sophisticated calculation of radiative corrections is required

Measurement of 2π cross-section

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

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

   Fiducial volume:

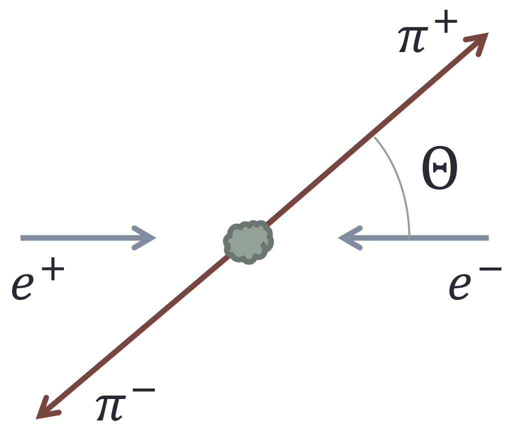
   $\Theta_0 \leq \Theta_{avr} \leq (\pi - \Theta_0), \qquad \Theta_0 = 0.9 \ldots 1.1$

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

3. Use "master" formula:

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

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



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

Separation of $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

Selected event sample consists of $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ final states and cosmic background.

Cosmic background is small (~1%) and easily identified by distance from the tracks to beam axis and interaction point.

Separation of different final states is based on binned likelihood minimization:

- using energy deposition

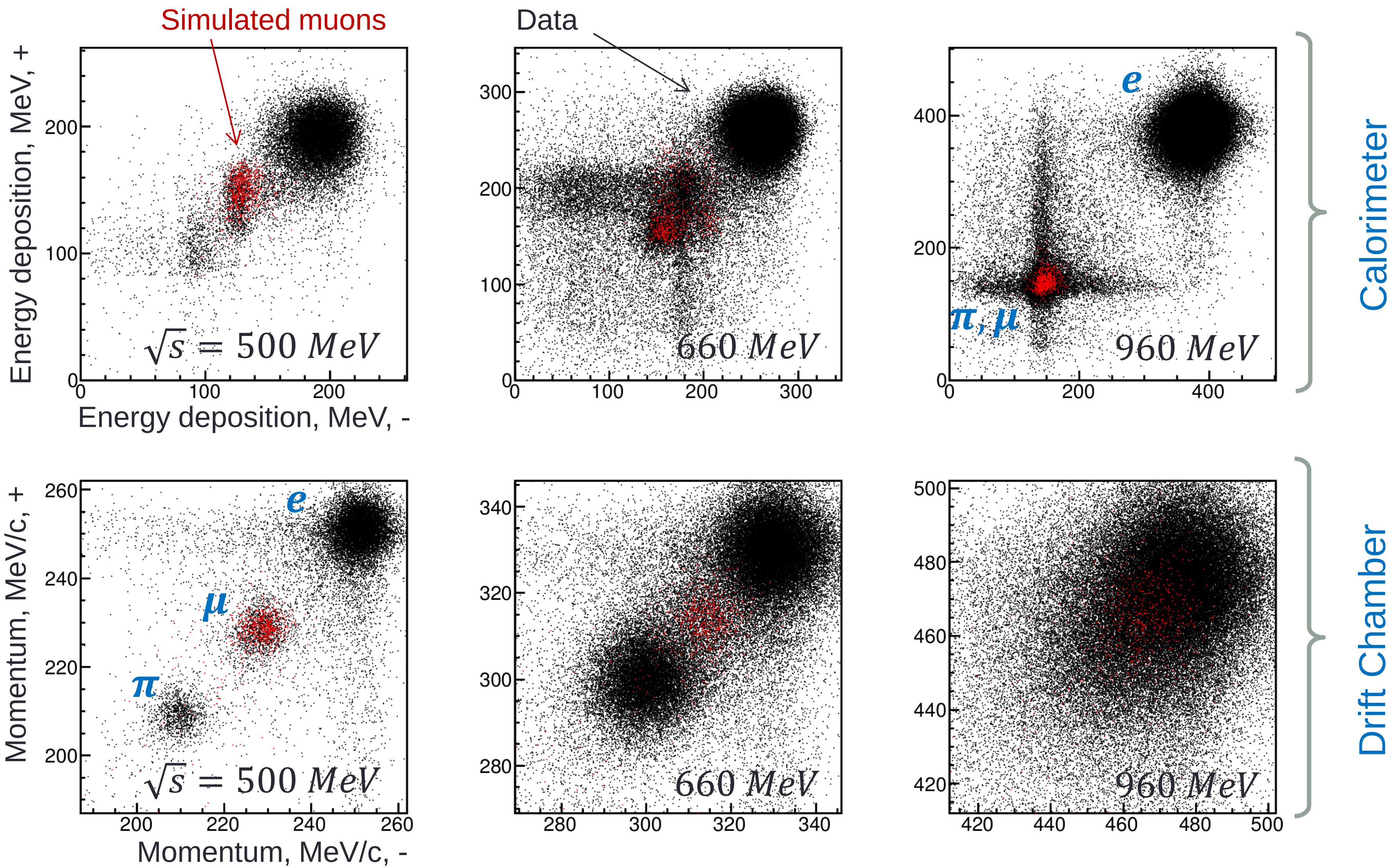
$$-\ln L = -\sum_{bins} n_i \ln\left[\sum_{X=ee,\mu\mu,\pi\pi,bg} N_X f_X(E^+, E^-)\right] + \sum_X N_X$$

- using momentum ($\sqrt{s} \lesssim 0.66$ GeV)

$$-\ln L = -\sum_{bins} n_i \ln\left[\sum_{X=ee,\mu\mu,\pi\pi,bg} N_X f_X(p^+, p^-)\right] + \sum_X N_X$$

$\pm$ sign reflects energy deposition and momentum of particle with corresponding charge

Separation of $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$



Where to get $f_X(p^+, p^-)$

In order to get number of events with different final states, we need to know 2D p.d.f.s f_X

The momenta p.d.f.s are constructed via MC

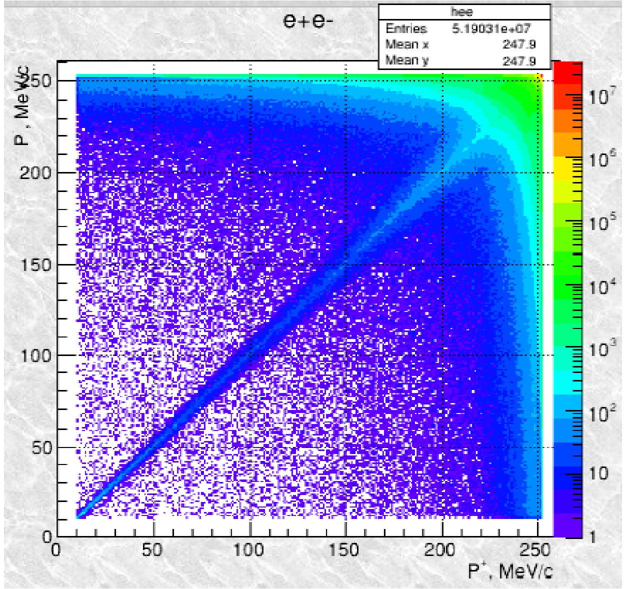
1. The "ideal" distributions are generated using MC generator MCGPJ, which takes into account initial and final state radiation; selection cuts are applied

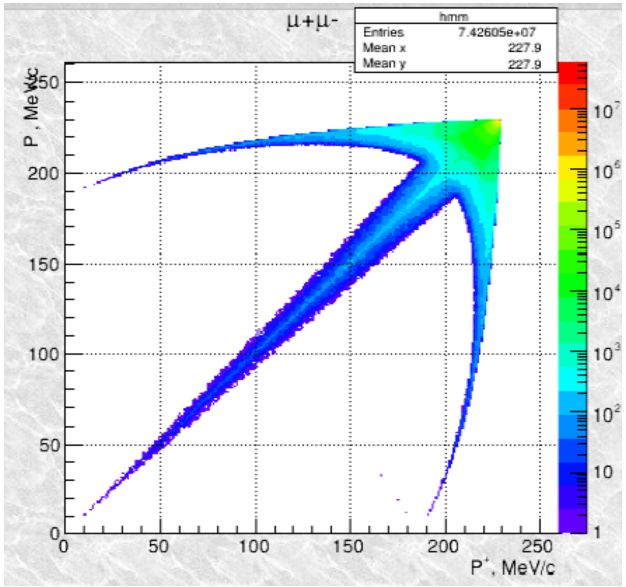
2. The ideal distribution is convoluted with detector response function (DC resolution):

   e^+e^-: 3 gaussians + bremsstrahlung on beam pipe

   $\mu^+\mu^-, \pi^+\pi^-$: 2 gaussians

Currently, likelihood fit for momenta includes 42 free parameters

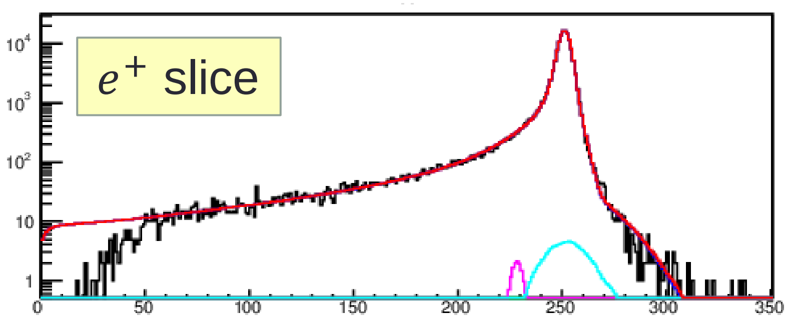


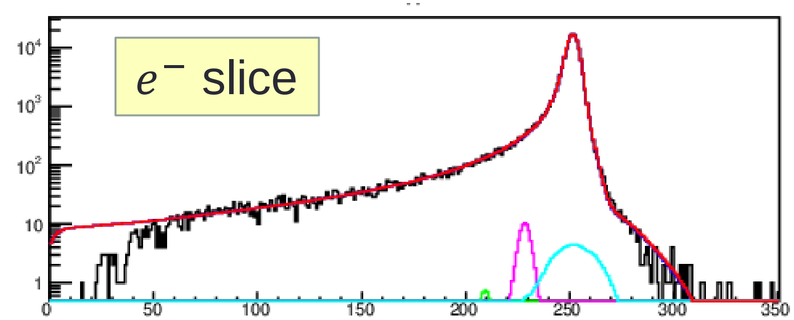


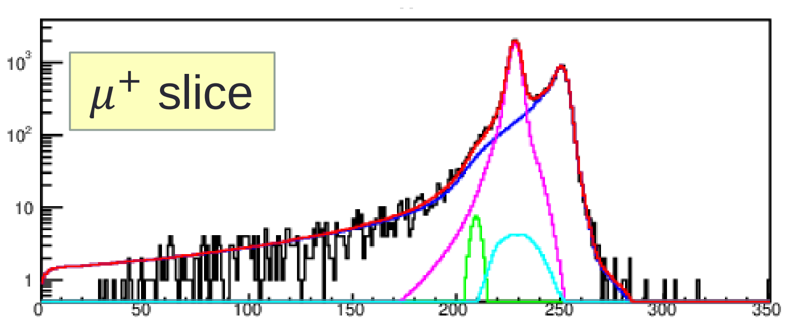
Example of momenta likelihood fit

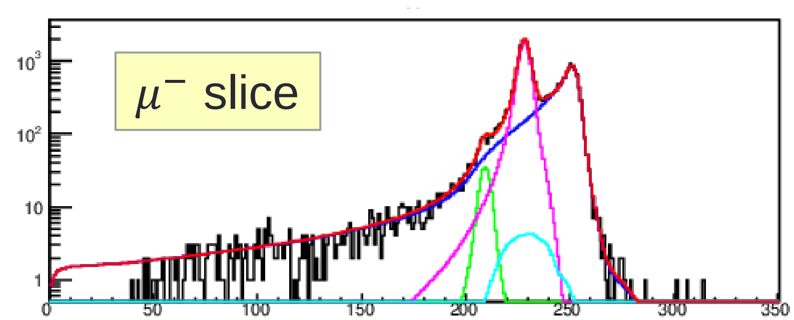
$\sqrt{s}$

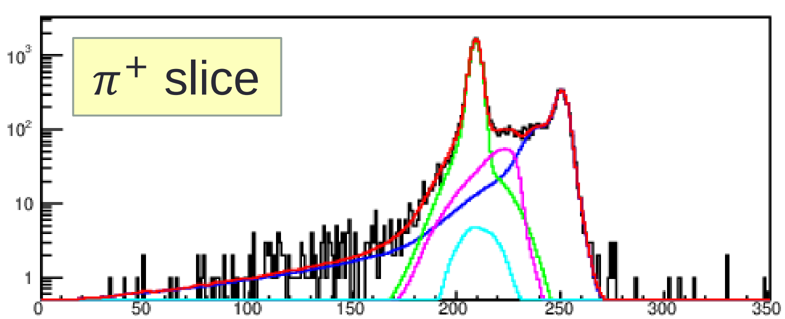
500 MeV

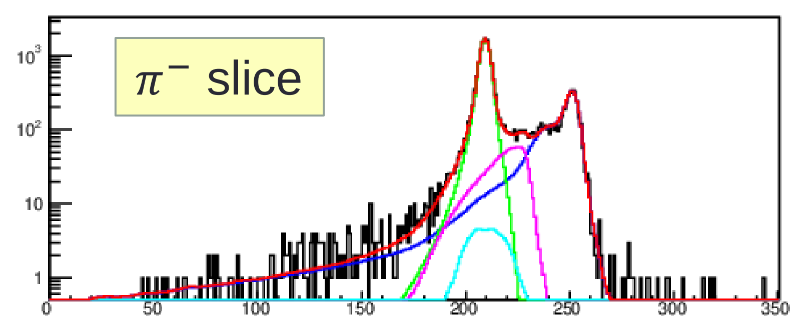












Where to get $f_X(E^+, E^-)$

- Electrons, $f_{ee}(E^+, E^-)$

  From data: tag electron/positron on one side of detector and study response at the opposite side

- Cosmic, $f_{bg}(E^+, E^-)$

  From data: using events with large impact parameter

- Muons, $f_{\mu\mu}(E^+, E^-)$

  From simulation

  Confirm simulation with data using tagged muons; tag by momentum or MVA response for shower profile

- Pions, $f_{\pi\pi}(E^+, E^-)$

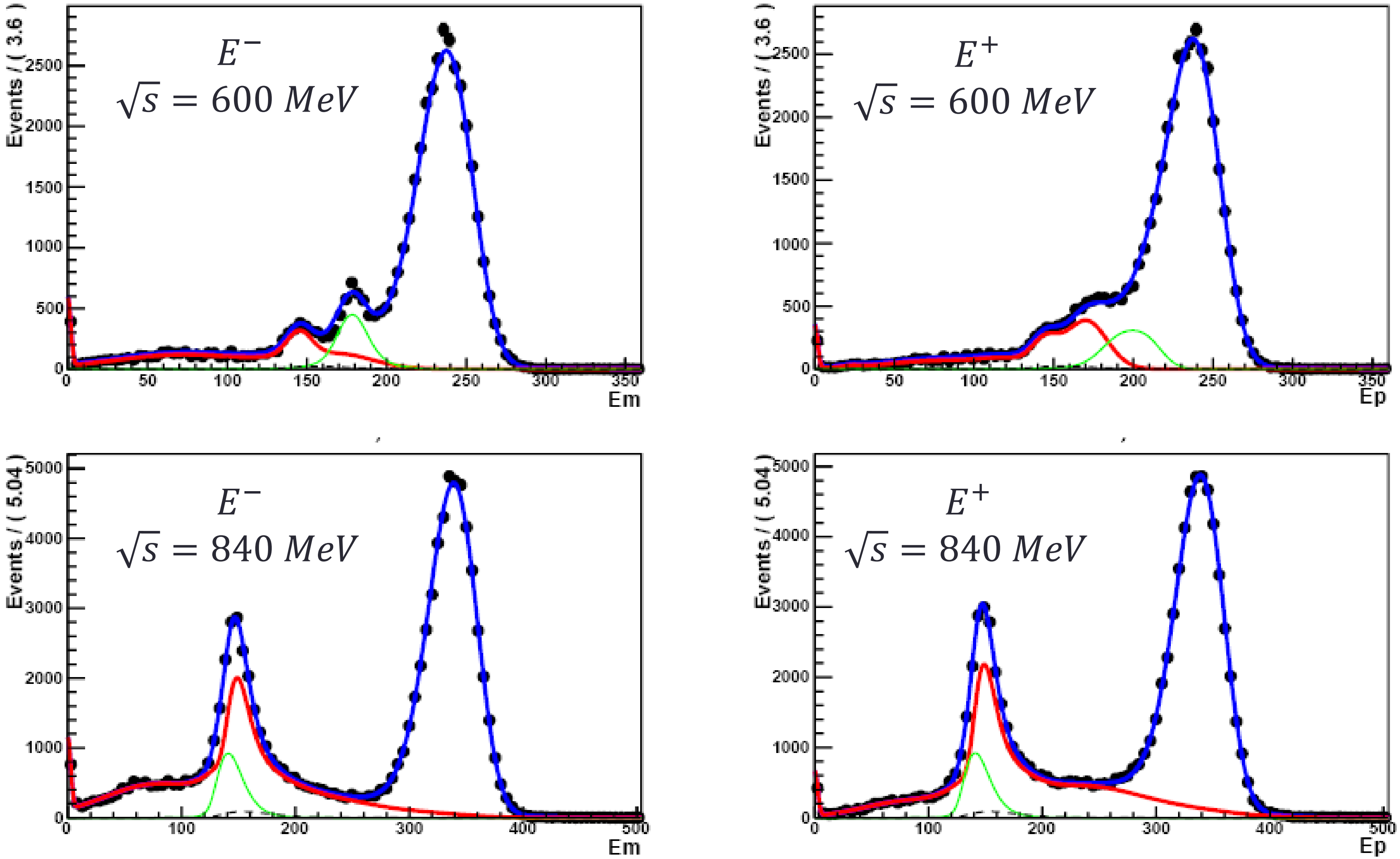
  From data: clean sample of tagged pions from $\varphi \to \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$ decays (we have few million such decays "in bag"). Works only for $\sqrt{s} < 1\ GeV$. From simulation above this energy.

Unlike momenta, there is rather small "native" correlation between E^+ and E^-, but they strongly correlate through common angle:

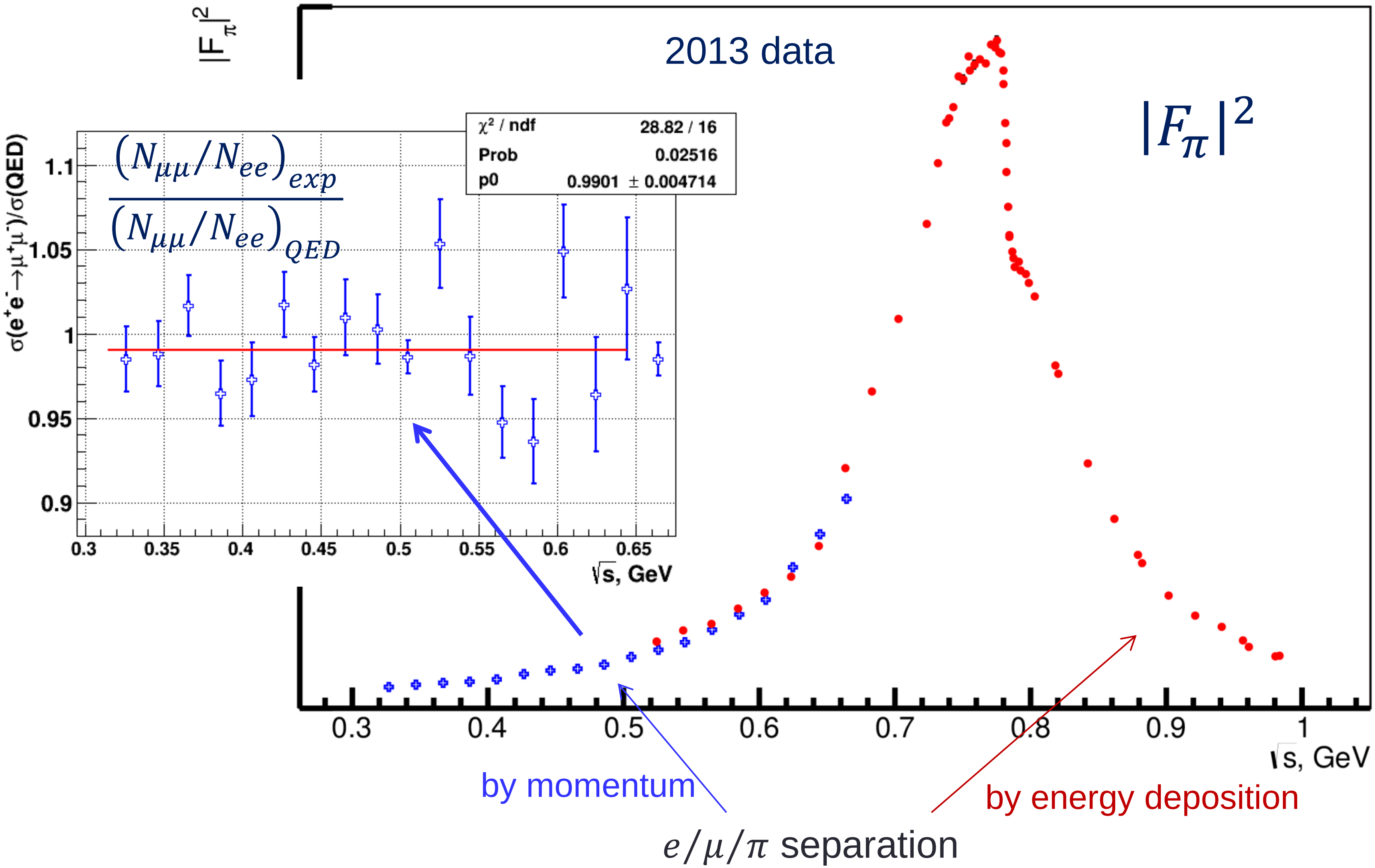
$$f(E^+, E^-) \approx f^+(E^+, \Theta) \cdot f^-(E^-, \Theta)$$

It might be necessary to introduce Θ to likelihood fit

Example of energy deposition likelihood fit



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



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

Main sources of systematics:

- $e/\mu/\pi$ separation – 0.2%

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

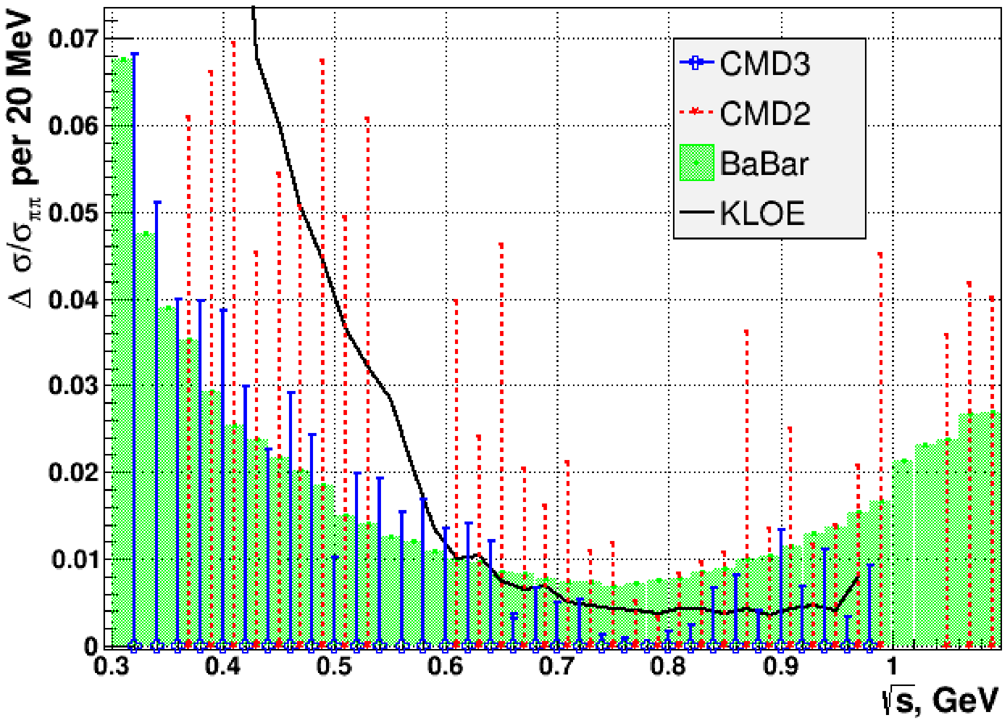
  2 independent systems, which can be used to determine fiducial volume
- beam energy – 0.1%

  continuous monitoring with Compton backscattering
- radiative corrections – 0.1%

  check from data

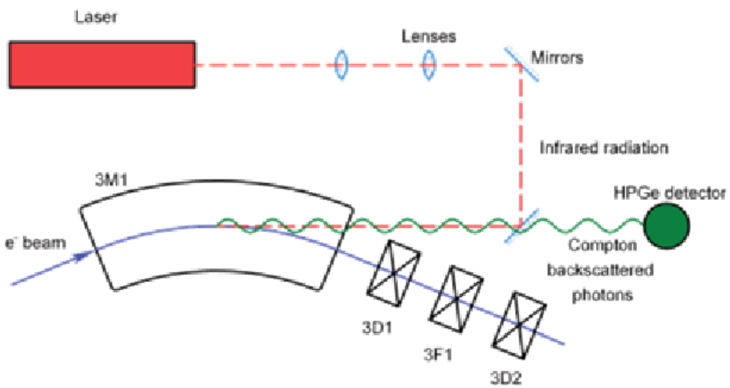
Many systematic studies rely on high statistics

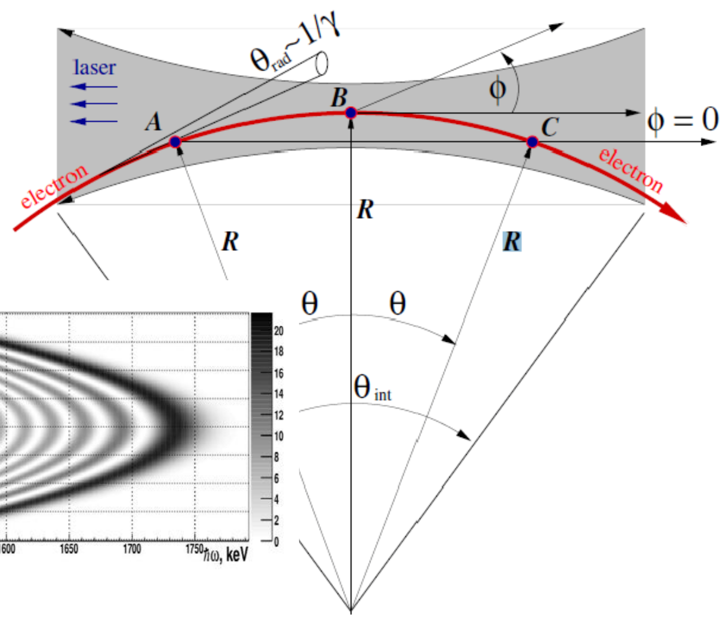
Expected statistical error for 2013 data

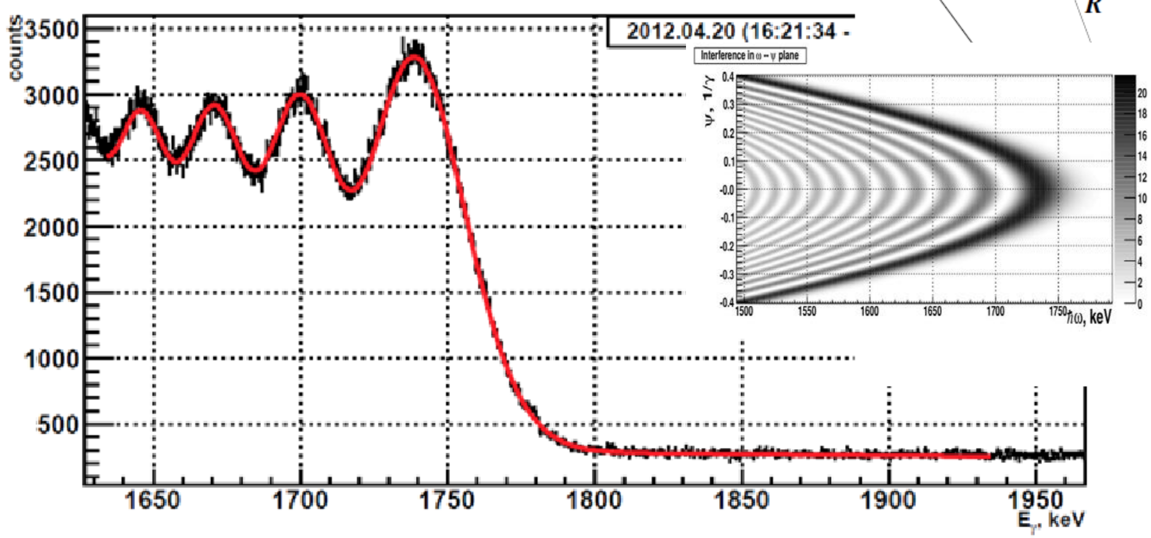


Energy measurement

Starting from 2012, energy is monitored continuously using Compton backscattering







E = 993.662 ± 0.016 MeV

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

Radiative corrections

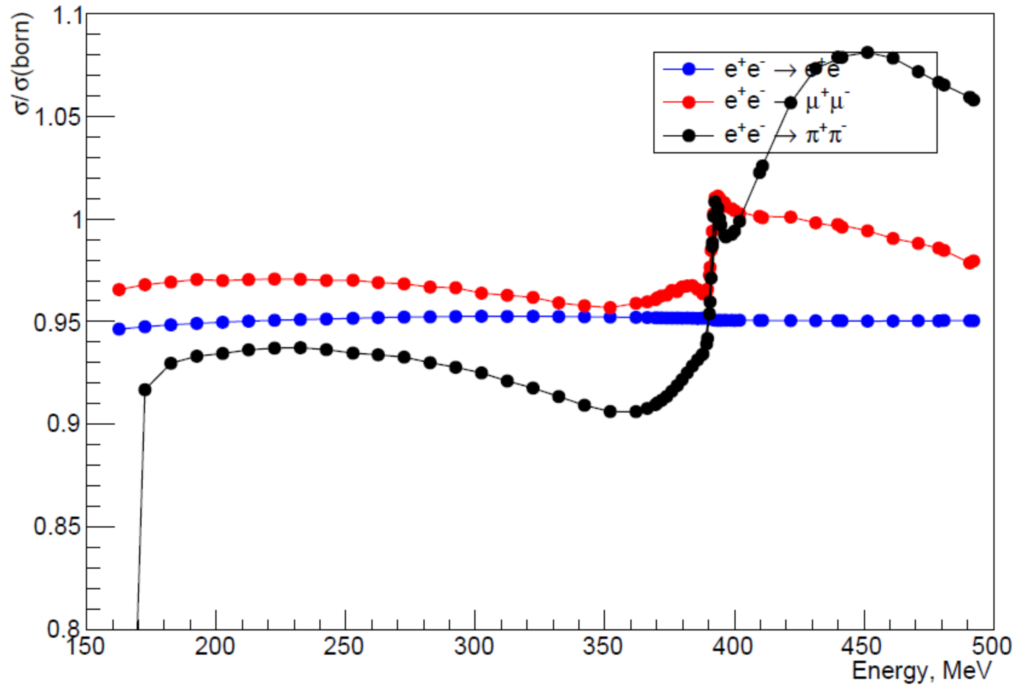
Radiative corrections are large ~10%

Need to know to ~0.1% (absolute)

Most of existing generators claim necessary accuracy.

How to check that?

1. Compare generator MCGPJ, we use, with alternative high-precision generators (BABAYAGA, KKMC, BHWIDE, PHOKHARA)
2. Compare experimental radiative tails in p, $\Delta\Theta$, $\Delta\varphi$,… with what is predicted from MC



Radiative corrections for 2013 data for particular selection cuts

Radiative corrections (2)

Need to be careful with what is taken into account when calculating $\delta_{\pi\pi}$

- Hadron spectroscopy: vacuum polarization (VP) is the part of the cross-section ("dressed"), final state radiation (FSR) is not
- Cross-section used in R: FSR is the part of the cross-section, VP is not ("bare")
- Measured number of events includes VP and part of FSR allowed by the event selection

We measure two kinds of cross-sections:

- $\sigma_{\pi\pi}, |F_\pi|^2$: "dressed" cross-section $e^+e^- \to \pi^+\pi^-$

  Ratiative correction includes FSR contribution, allowed by selection cuts, but does not include VP

  This cross-section is used to get M_ρ, Γ_ρ,…
- $\sigma^0_{\pi\pi(\gamma)}$: "bare" cross-section $e^+e^- \to \pi^+\pi^-(\gamma)$

  Calculated from $\sigma_{\pi\pi}$ as $\sigma^0_{\pi\pi(\gamma)} = \sigma_{\pi\pi} \cdot |1 - \Pi(s)|^2 \cdot \left(1 + \frac{\alpha}{\pi}\Lambda(s)\right)$

  Used to get R

  remove VP ($|1 - \Pi(s)|^2$)

  add FSR ($\left(1 + \frac{\alpha}{\pi}\Lambda(s)\right)$)

Detector efficiencies

Trigger efficiency:

- CMD-3 has two independent modes to trigger collinear events
- Main mode, “charged”, is highly efficient and uses only tracking data
- Many intermediate trigger arguments are readout, allowing for detailed monitoring of efficiency

Reconstruction efficiency:

- track reconstruction is highly efficient (>99%)
- monitored using test events

Efficiencies, specific for particular final state

- e^+e^-: bremsstrahlung on beam pipe (~1%)
- $\pi^+\pi^-$: decay in flight
  hadronic interactions with the beam pipe material (~1%)
- These corrections are calculated via MC and tested from data

Conclusions

- In 2013 CMD-3 collected large data set with $\sqrt{s} < 1$ GeV
- The expected precision for $\sigma(e^+e^- \to \pi^+\pi^-)$ is at the level or better of the best existing measurements
- The existing data sample with $\sqrt{s} > 1$ GeV is collected without beam energy monitoring system
- After VEPP-2000 upgrade (scheduled to be finished in 2014) we plan to collect more data in the whole energy range