IMPROVING ON HADRONIC CONTRIBUTIONS TO (G-2)/2 OF MUON WITH CMD-3 DETECTOR AT VEPP-2000

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Outline

- Short review of the last generation experiments: CMD-2, SND
- Current status of the accuracy of the hadronic cross sections measurements.
- Main sources of systematic errors due to:
  - Accelerator
  - Detector
  - Theory
- What can we expect in the nearest future:
  - CMD-3
  - SND
- Conclusion

Some features of CMD-2, SND experiments

- Large data sample due to high integrated luminosity and large detectors acceptance (calorimeter covers about 0.9*4π). Detectors collected several millions e^+e^- events (all three detectors)

- Multiple scan (up and down) of the same energy range to avoid possible systematic in energy determination: step (2E) = 10 MeV in the continuum and about 1 MeV near ϕ and ω peaks (CMD-2 and SND)

- Absolute calibration of beam energy using the resonance depolarization method (better than 10^{-4}) $\Rightarrow$ systematic error due to energy uncertainty (CMD-2 and SND) can be neglected

- Excellent energy resolution ($\sigma_E/E \sim$ 1-4%, SND) leads to small background & helps to separate events

Some features of CMD-2, SND experiments

* Detection efficiencies and calorimeter response were studied using “pure” experimental data rather than MC events. Several millions ω and φ meson decays were used, CMD-2 & SND

* Charged and neutral triggers for the same data sample – cross check to monitor triggers efficiencies (CMD-2 & SND)

* Changing events selection criteria to check cross section stability. All detectors carefully studied this item

* Redundancy (cross check possibility) – unstable particles detected via different decay modes ($\pi^0 \to 2\gamma$, $e^+e^-\gamma$; $\eta \to 2\gamma$, $\pi^+\pi^-\pi^0$, $3\pi^0$)

* MC generators based on differential cross sections with precise RC for the processes of e^+e^- annihilation were developed (CMD-2)

How cross sections are measured

Main factors giving dominant contributions to systematic uncertainty for hadronic cross sections

All modes except 2π

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

- Efficiency ε is calculated via Monte Carlo + corrections for detector imperfections
- Integrated luminosity *L* is measured using LAB events
- RC δ accounts for ISR & FSR effects only
- VP effects are included in cross section properties

2π mode

$$|F_\pi|^2 = \frac{N_{\pi\pi}}{N_{ee}} \frac{\varepsilon_{ee}\sigma_{ee}(1+\delta_{ee})}{\varepsilon_{\pi\pi}\sigma_{\pi\pi}^{p.l.}(1+\delta_{\pi\pi})}$$

- Ratio N(2π)/N(ee) is measured directly ⇒ detection inefficiencies are cancelled out in part
- RC accounts for ISR and FSR effects
- Events separation procedure & analysis don't rely on simulation
- Form factor is measured to better precision than *L*

Luminosity measurement

- Precision of luminosity measurement will be improved significantl to better extraction of Bhabha events, increasing detection efficiency and more accurate calculation of the radiative corrections.

- Alternative method to measure luminosity based on the process $e^+e^- \rightarrow \gamma\gamma$. In that case Feynman graph does not contain VP effects. Powerful instrument to arrange cross check and understand systematic.

Source of error	CMD-2	SND	CMD-3
Event separation	0.5%	0.6%	< 0.2%
Fiducial volume	0.2%	0.8%	0.2% or <
Energy calibration	0.2%	0.3%	< 0.2%
Efficiency correct.	1%	0.6%	0.1%
Radiative correct.	0.2%	0.5%	< 0.1%
Total	1.2%	1.3%	0.4% or <

R measurement at CMD-2, SND

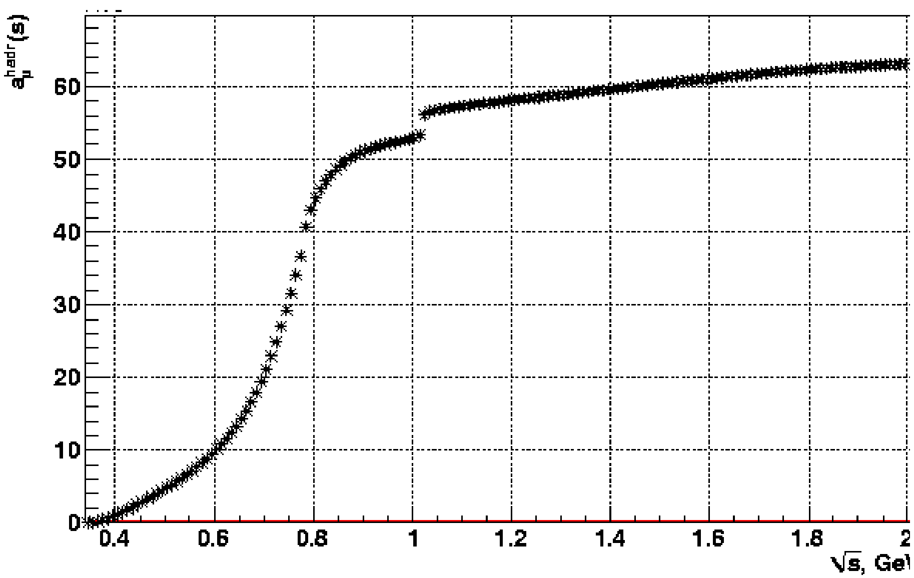
Source of error	CMD-2	SND
Event separation	0.2-0.4%	0.5%
Fiducial volume	0.2% (ZC)	0.8%
Energy calibration	0.1-0.3%	0.3%
Efficiency correction	0.2%-0.5%	0.6%
Pion losses (decay, NI)	0.2%	0.2%
Other	0.2%	0.5%
Radiative corrections	0.4% (0.1%)	0.2%
Total	**0.6%-0.8%**	1.2%

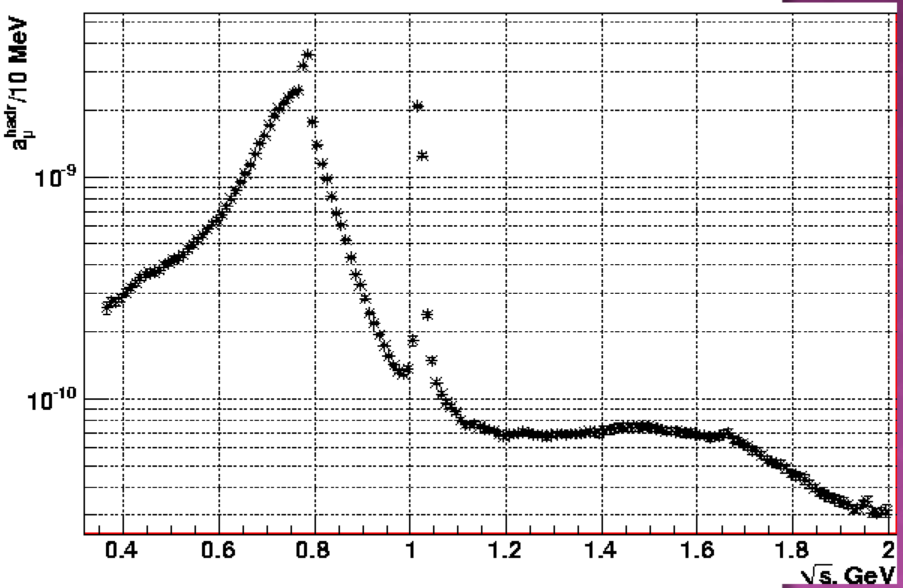
Perspective of R measurement with CMD-3 (for dominant channels)

Source of error	2pi $\sqrt{s}$ < 1 GeV	3pi $\sqrt{s}$ < 2.0 GeV	4pi 2>$\sqrt{s}$>1.1 GeV
Event separation	0.2%	0.2%-0.5%	1% (cuts)
Fiducial volume	0.2% (LXe,0.1%)	0.3%	2% (model)
Energy calibration	< 0.1% (1%)	< 0.1% (1%)	< 0.1% (0.5%)
Efficiency correction	0.1%	0.3%	1% (tr.+ bg.)
Pion losses&NI	0.1%(opt.ass.)	0.4%(opt.ass.)	1%(opt.ass.)
Other	0.2%	(0.3 - 0.7)%	1%
Radiative corrections	0.1%	< 0.3% (ISR)	< 0.3% (ISR)
Total Total (no depolariz.)	0.35% 1.1%	0.8% (1.3 – 1.5)%	2.9% 3%

Hadronic contribution to anomalous magnetic moment of muon

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

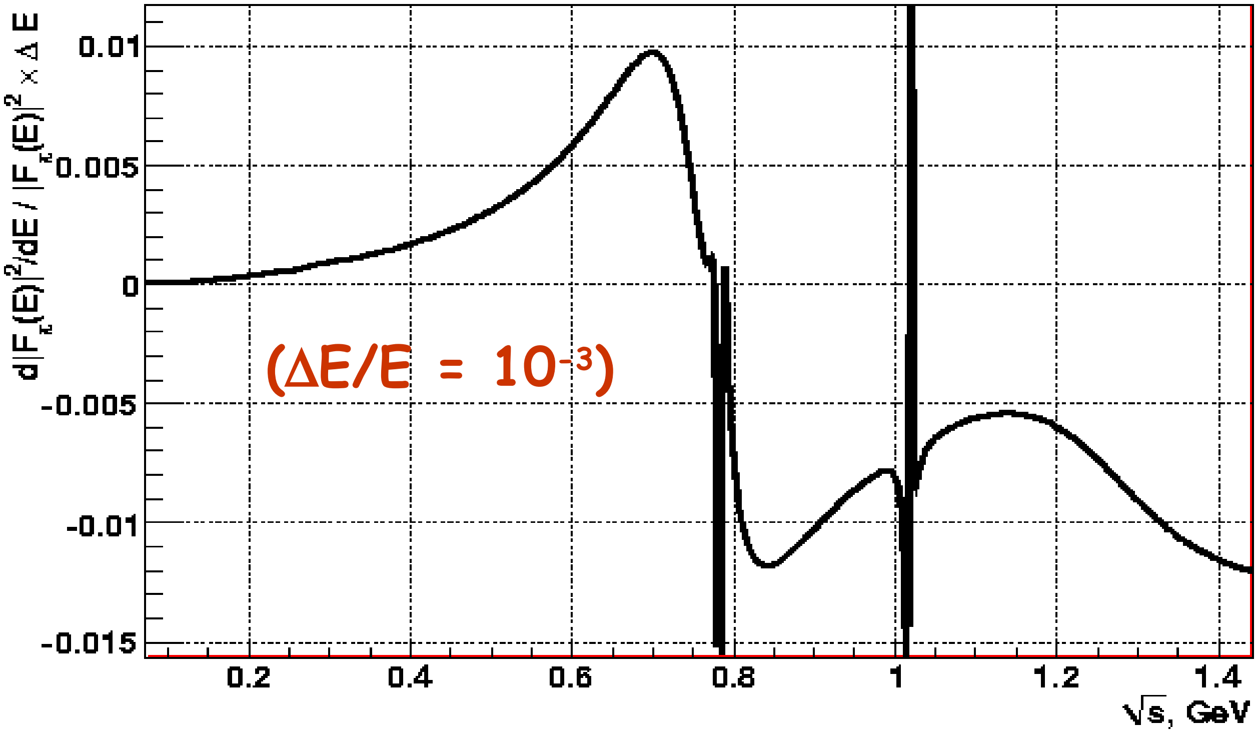




This plot demonstrates how fast integral reaches its asymptotic value ~ 60 ppm. For √s>2 GeV the contribution is about ~ 6 ppm only

Behavior of the integral funct. vs c.m.energy. Sharp slopes of the narrow resonance required energy determination to put down the systematic error

Derivative $d|F_\pi(E)|^2/dE/|F_\pi(E)|^2 \times \Delta E/E$ (accuracy of energy determination)



Derivative jumps up and down inside corridor ±1%, but near ω and φ mesons reaches the values ±6%.

Very important task for machine physicists to determine beam energy with relative accuracy $\Delta E/E \approx 10^{-4}$ or even better

Lay-out of VEPP-2000

Round beam design

revolution time –	82 ns	beam current –	200 mA
beam length –	3.3 c	energy spread –	0.7 MeV
circumference –	24.4 m	beta function in IP	$\beta_x = \beta_z = 4.3$ cm

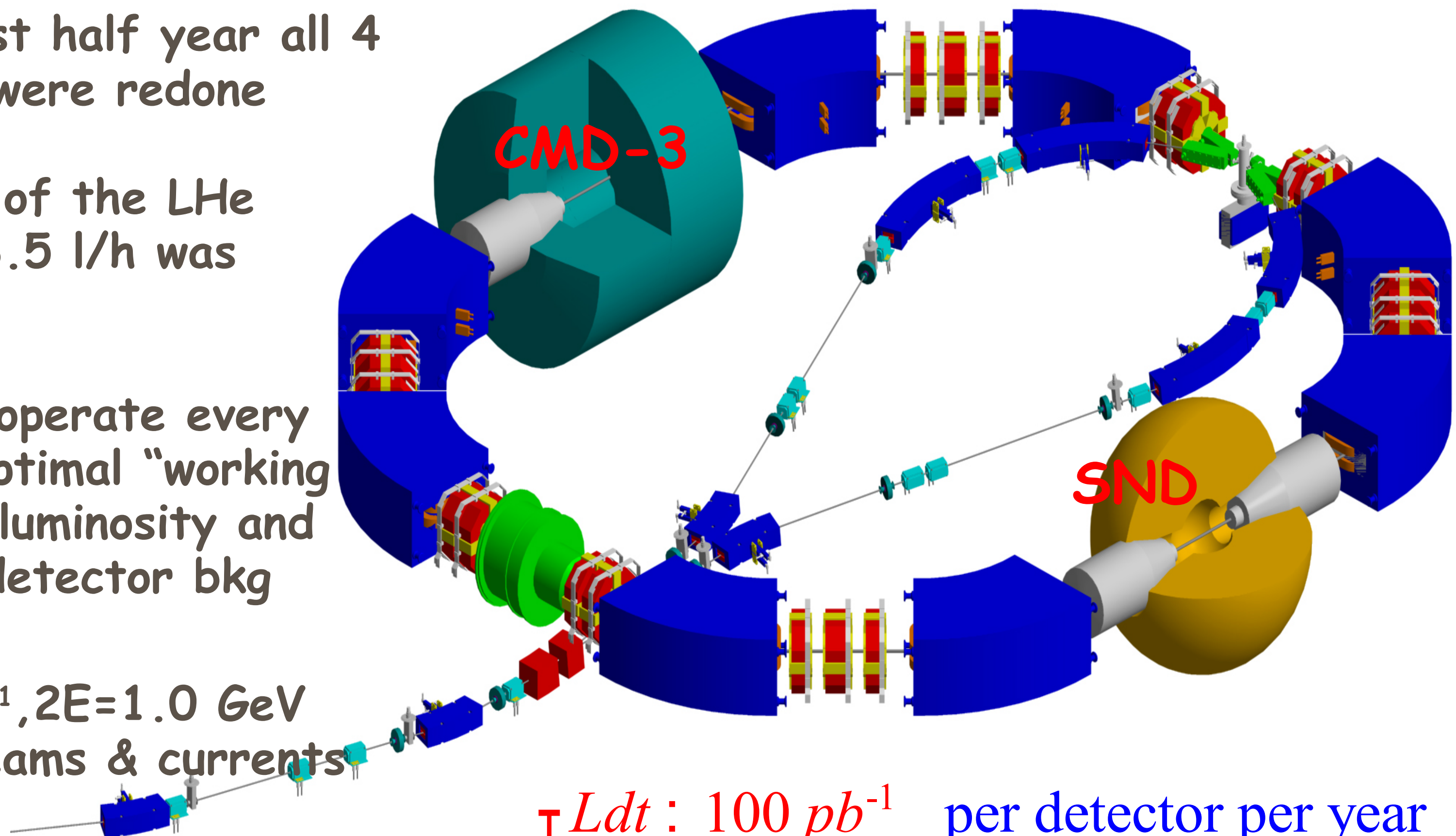
$L = 10^{32}\ cm^{-2}s^{-1}$ at 2E=2.0 GeV $L = 10^{31}\ cm^{-2}s^{-1}$ at 2E=1.0 GeV

During the last half year all 4 SC solenoids were redone

Project value of the LHe consumption 3.5 l/h was achieved

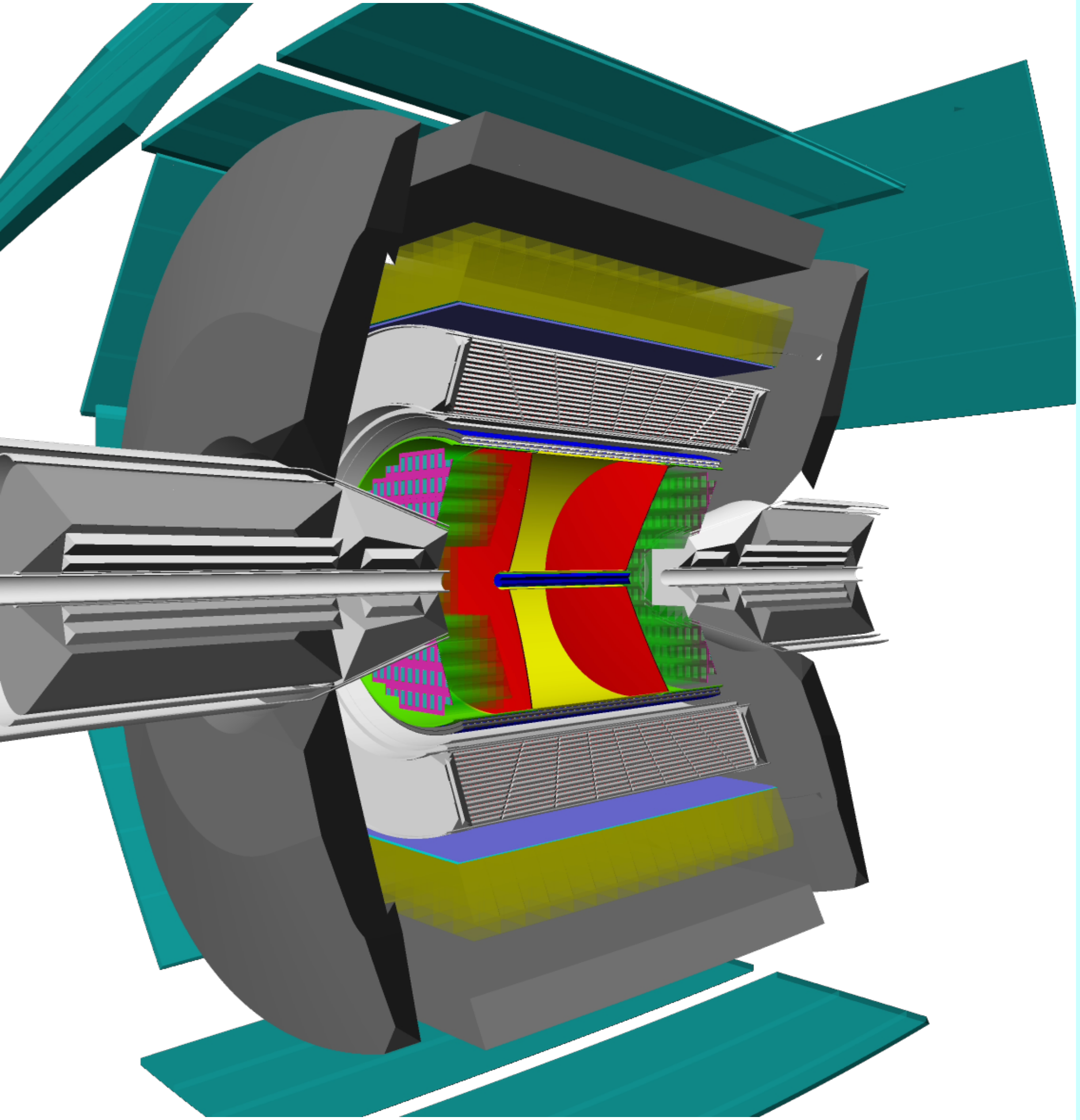
VEPP & SND operate every day to find optimal "working point" as for luminosity and as for small detector bkg

$L \sim 10^{30}\ cm^{-2}s^{-1}$, 2E=1.0 GeV with round beams & currents 4*8 mA² was achieved



$\int L dt \sim 100\ pb^{-1}$ per detector per year

3D view CMD-3 detector



* Z-chamber, LXe & CsI calorimeters, TOF and MR system are inside detector and cosmic tested

* DC is also installed now. Prelim.ampl.and digitizing electronic are ready

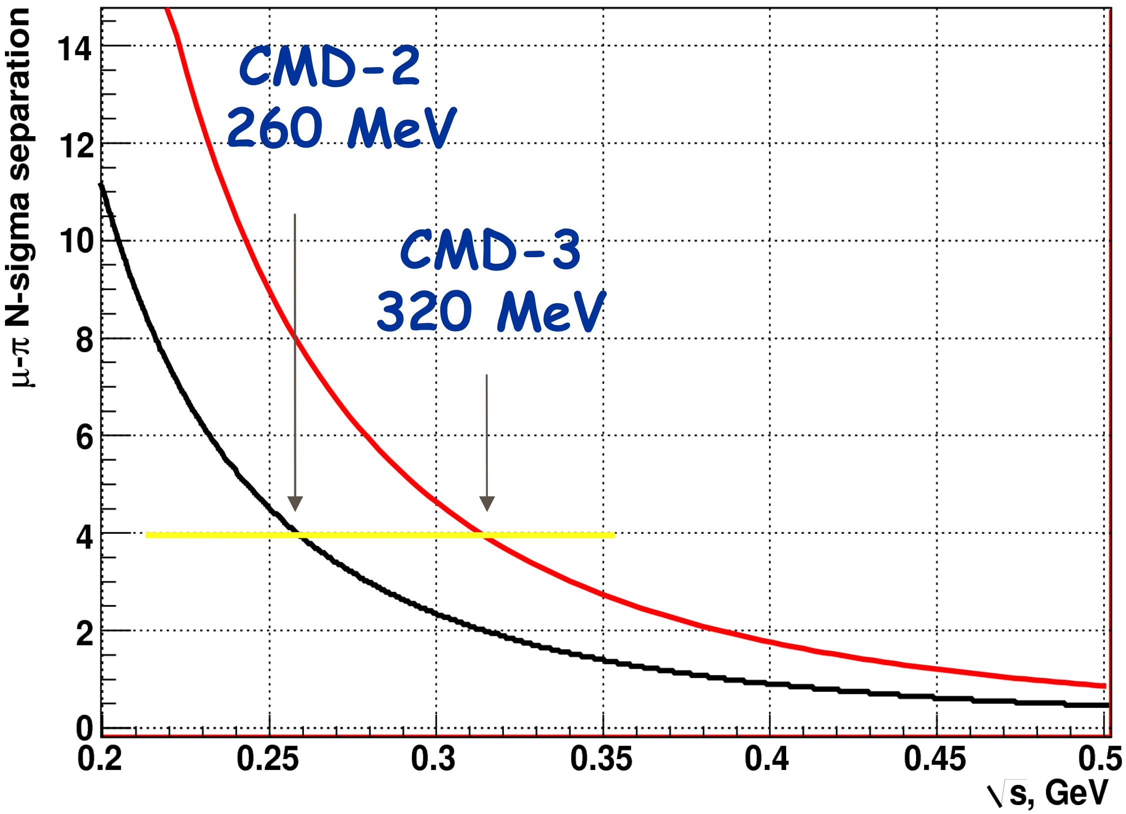
* SC solenoid inside detect. m.f.~ 1.35 T was achieved (projected m.field ~ 1.5 T)

* Map of magnetic field inside DC was measured

* Plan to be ready data taking by fall 2009

π/μ/e separation based on charged particle momentum

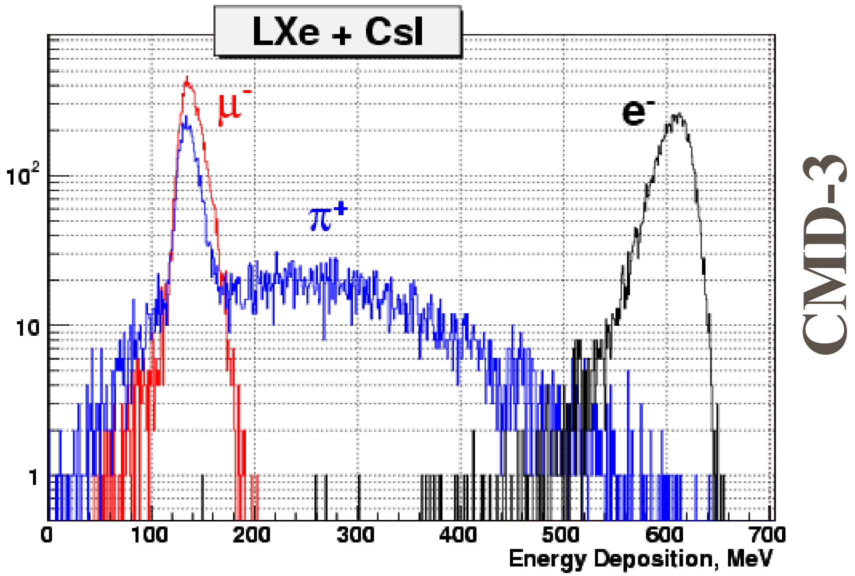
Comparison CMD-3 momentum resolutions with respect to CMD-2

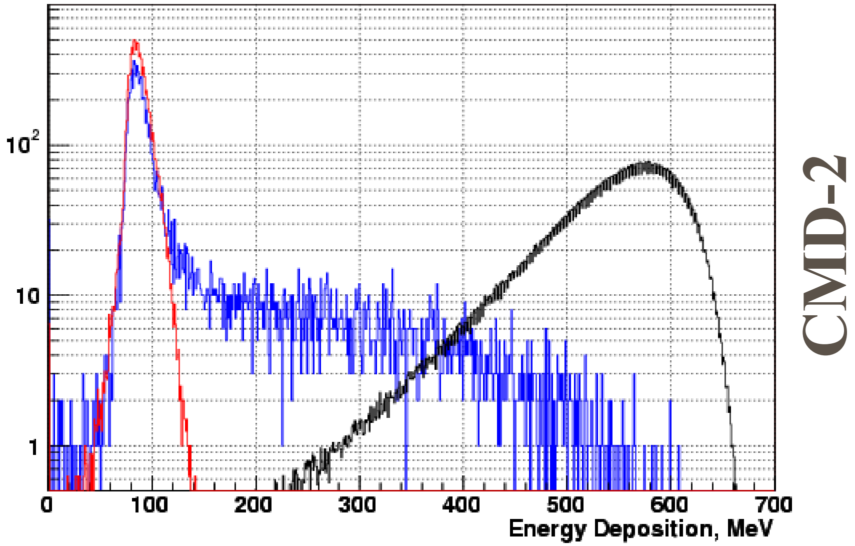


Vertical axis – number of standard deviations between average momentum of pions and muons

- DC resolution is better by factor of 2.5 (already achieved)
- Magnetic field will be 1.5 times grater (already achieved)
- π/μ/e separation based on momentum will be possible up to √s = 2*320 MeV - close to the ρ-meson peak

π/μ/e separation based on energy deposition in calorimetrs





- Energy resolution of barrel part will be improved ($8X_0 \rightarrow 15X_0$)
- Part pions "looks" like muons will be suppress to the level 10% (was 25% at CMD-2). We can try π/μ separation based on energy deposition (for two tracks ~ 1%)
- Information of energy deposition in depth of calorimeter provide at least additional factor of two for π/μ separation

Fiducial volume

1. **Z-chamber**: In first approach we will have the same z-coordinate resolution ⇒ the accuracy of the fiducial volume determination will not change. At polar angles θ ~ 60° $\sigma_z \approx 0.7$ mm & system. shift is smaller 0.1 mm. For LAB events it leads to acceptance uncertainty about 0.2%.

- **LXe calorimeter**: For normal incident particles θ ~ 90° $\sigma_z \approx 0.9$ mm, but systematic shift is still unknown. Cross check capability will be in hand. Very possible we can improve the accuracy of the acceptance measurement by factor of 1.5. We assume that fiducial volume will be determined at least with the same accuracy (or better) as we had at CMD-2.
- **Huge statistics**: Help to study systematic of z-coordinate determination in DC & to improve the accuracy of DC calibration procedure. Study in detail angular distributions of multi hadrons events must help to choose model for simulation. Besides we will be able to select "pure" $\mu^+\mu^-$ events and study acceptance and measure luminosity with them

Radiative corrections

What we have and what we can expect in the nearest future

1. Channel e+e- → e+e-: BHWIDE (LEP, 0.5%), MCGPJ (CMD-2, 0.2%, LO) photon jet radiation in collinear region

   BabaYaga (KLOE, 0.1%, LO + NLO) used parton shower approach.
2. Plan to implement in MCGPJ the NLO corrections and put down theoretical systematic error to 0.1%. This work is in progress now with Dubna, E.Kuraev and A.Arbuzov.
3. Channels e+e- → μ+μ-, τ+τ-: KKMC generator was redone for low energies, 0.1%. MCGPJ (CMD-2, 0.2%). B.Smith, M.Voloshin: PL B 324 – all enhanced second order corrections contribute not more than 0.02% and quickly decrease when energy increase
4. Channel e+e- → γγ MCGPJ (CMD-2, 0.2%). Very important for luminosity measurement – cross check possible. ISR only. Feynman graphs do not contain VP effects
5. Channel e+e- → π+π-, K+K-: MCGPJ (CMD-2, 0.2%). ISR & FSR are taken into account. Experimental evidences are required to prove validity of s-QED application for pions & kaons.
6. VP effects are calculated with accuracy better than 0.05% and do not contribute to final systematic error

Detection & trigger efficiencies

1. Efficiency of track reconstruction in DC will be better than 98% with uncertainty < 0.1% (CMD-3 & new SND)

2. Trigger efficiency close to 100%. Charged & neutral triggers for the same data sample – powerful instrument to monitor trigger stability and it's real efficiency (CMD-2 & CMD-3)

3. Bremsstrahlung of electrons (positrons) on the wall of the machine vacuum chamber. We had correction about 0.5% ($\sqrt{s}$<1GeV). Plan to have the same accuracy at VEPP-2000.

4. Optimization of selection criteria for collinear events:
Polar angle – compromise for every detector.
Threshold on transverse momentum of charged particles in DC.
Choice of the optimal acollinearity angle between tracks in DC.
Choice of the energy threshold for particles to be detected in calorimeters.

5. π^0 reconstruction – main source of systematic error for processes with π^0 in FS. LXe calorimeter will significantly put down this error

Physics with ISR at VEPP-2000

- ISR will provide the "scan" full energy range at the same time

- Statistic will have the same level as we had at CMD-2, if project luminosity 10^{32} $cm^{-2}c^{-1}$ will be achieved

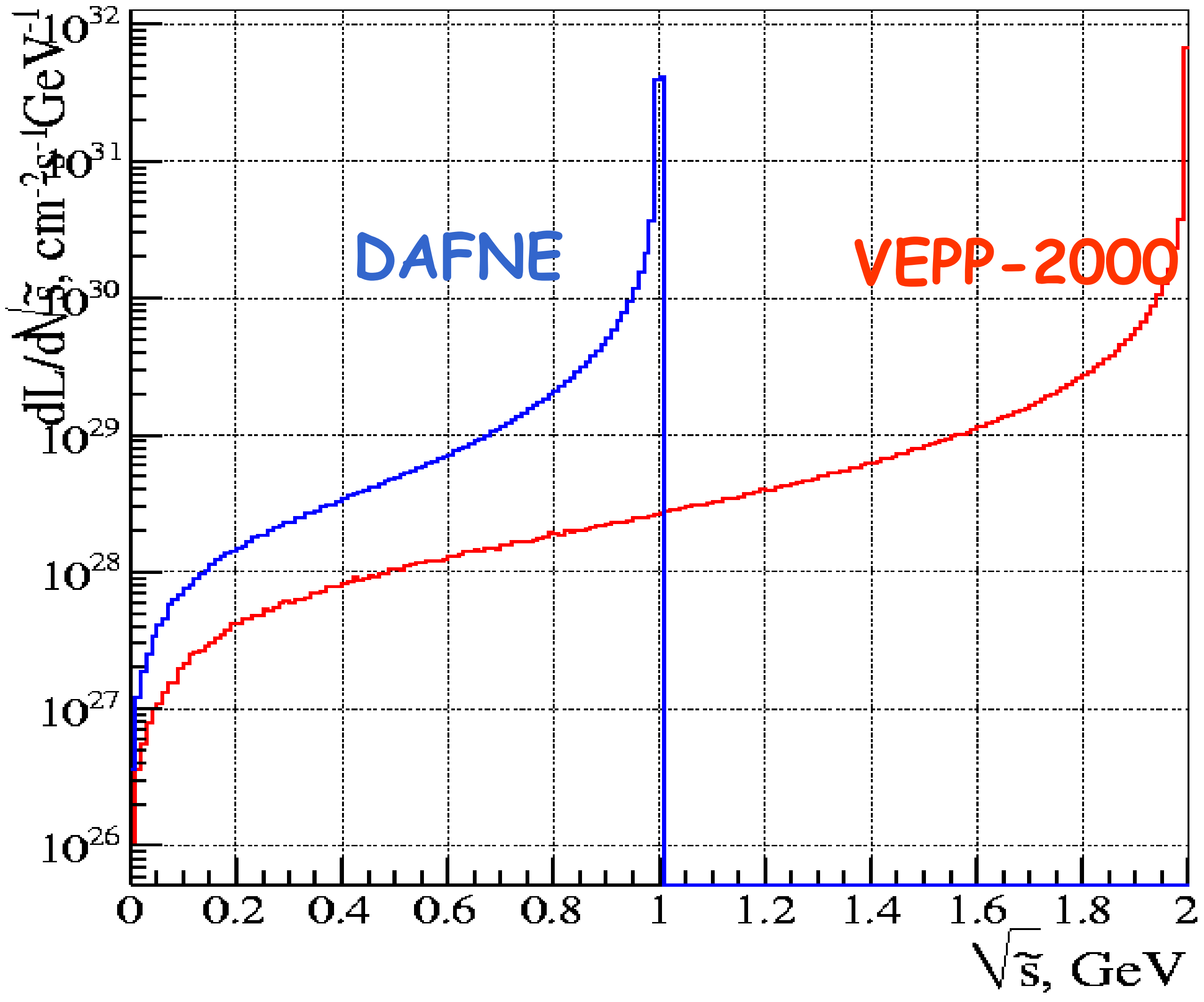
- Trigger & reconstruction efficiencies, detector imperfection will be at the same moment identically for full energy range.

- We will have capability to arrange cross check with result of the direct scan experiment. It allows better understand and estimate the systematic. CMD-3 aim to achieve (0.2-0.3)%.

- Cross sections measurement of the process e+e- must confirm the validity of this method & have to allow to determine energy scale and accuracy.

- It is possible to divide energy range in such a way that determine hadronic cross section between points corresponding to direct scan experiment to fill empty energy gaps which naturally arise with direct scan experiment.

Luminosity with ISR at VEPP-2000



Conclusions

1. Despite decades of experiments, precise studies of e^+e^- annihilation into hadrons at low energies are still interesting and can provide a lot of important information

2. In a few years new precision data from CMD-3 and SND working at VEPP-2000 as well as with ISR at DAFNE and B–factories are expected

3. Progress is particularly expected for the channel $e^+e^- \to \pi^+\pi^-$, where systematic uncertainty 0.3% plan to be achieved (CMD-3)

4. MC generators with precise RC were done :
   $e^+e^- \to e^+e^-$, BHWIDE (0.5%), MCGPJ (0.2%) and BabaYaga (0.1%)
   $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$, KKMC (0.1% redone for low energy), MCGP (0.2%)
   $e^+e^- \to \pi^+\pi^-$ and K^+K^-, MCGPJ (0.2%)

5. Only ISR is taken into account for the processes with neutral particles in final state: $e^+e^- \to \gamma\gamma$, $K_l K_s$, $\pi^0\gamma, \eta\gamma, \eta'\gamma$, $\omega\pi^0$, MCGPJ(0.2%)

Conclusions

6. Measurement of beam energy with relative accuracy better than 10^{-4} are extremely needed (resonance depolarization techniques only)

7. To have enough statistic ~10^5 at every energy point (~100) machine luminosity about 10^{31} $cm^{-2}s^{-1}$ around ρ meson is required

8. To illuminate possible systematic error in hadronic cross sections more accurate and independent measurements (CMD-3 & SND) are necessitated

9. Efforts of theorists are required to build models to describe in detail energy dependence of cross sections with 4 & more pions in FS

10. Luminosity and trigger efficiency must be measured in different channels at the same data sample to arrange cross check for better systematic study

THANK YOU FOR ATTENTION

Questions and discussion