Preliminary results on pion form factor at CMD-3

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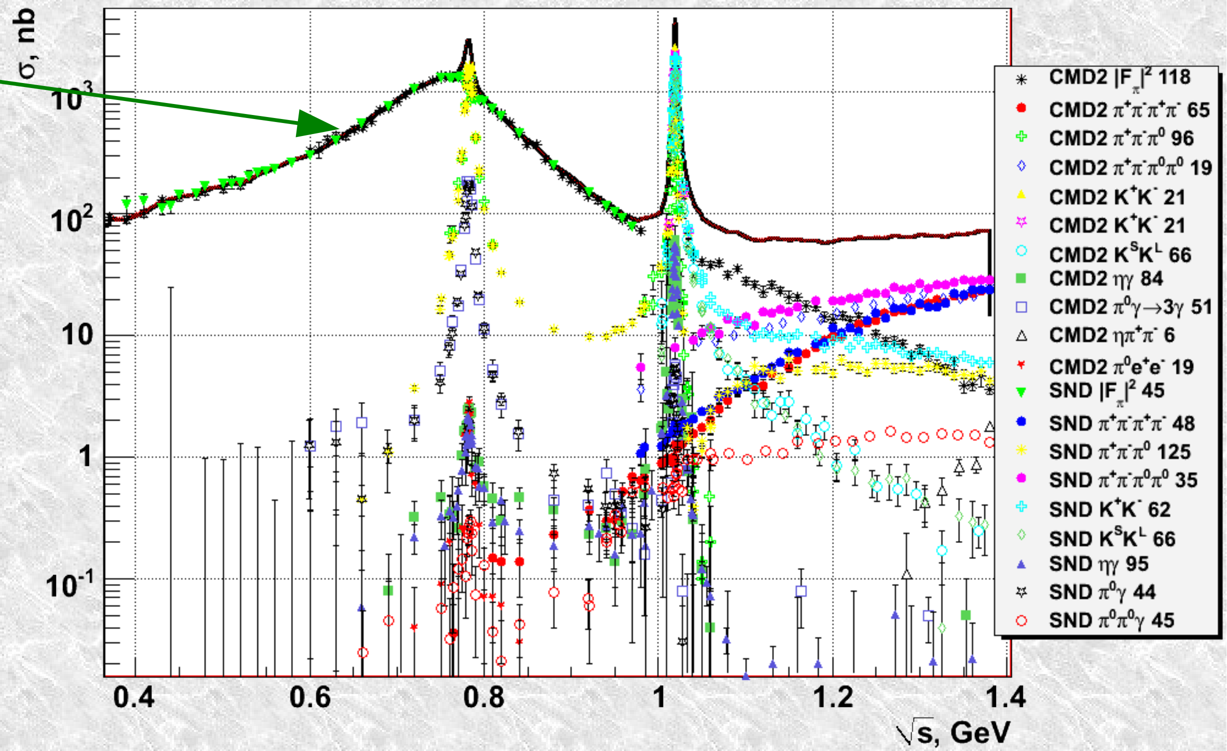
Motivation



Cross section e+e- → π+π-
is the main channel for
e+e- -> hadron production
at 2E < 1 GeV

Total hadronic cross section:

$$R(s)=\frac{\sigma^0(e^+e^-\to\gamma^*\to hadrons)}{\sigma^0(e^+e^-\to\gamma^*\to\mu^+\mu^-)}$$

should be known for calculation of:

$\alpha_{QED}(M_Z)$ - used in precise predictions of EW physics,

(better precision is required in case of ILC physics)

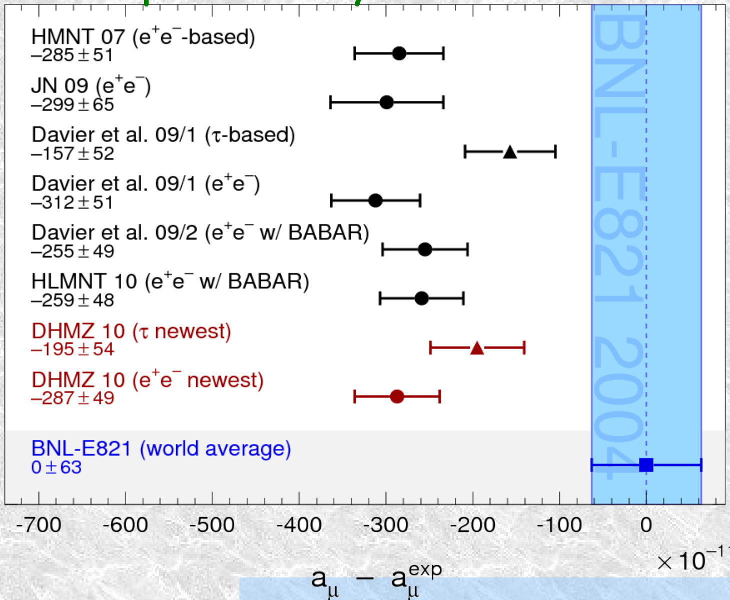
it is essential for the interpretation of precision measurements of:

muon (g-2) - good test of SM

SM prediction for muon g-2

ArXiv:1010.4180,arXiv:1105.3149

Δ Exp - Theory~ 3.3–3.6σ



The anomalous magnetic moment of the muon

$a_\mu^{experimental} = (g-2)_\mu/2$

Experimental world average a_μ = 11 659 208.9 ± **6.3** x 10^{-10}

Theoretical prediction δa_μ = ± **4.9** x 10^{-10}

HLMNT 11

Hadronic content of a_μ calculated

From measured cross-section by dispersion integral

LO hadronic 694.1 ±**4.3** x 10^{-10} HLMNT 11

main channels contribution to precision at √s<1.8 GeV

$\pi^+\pi^-$	505.65 ± 3.09	
$\pi^+\pi^-2\pi^0$	± 1.15	
$\pi^+\pi^-\pi^0$	± 0.99	(mostly from omega region)
.....		

From direct integration
Without model constraints

Light-by-light 10.5 ± **2.6** Prades, de Rafael & Vainshtein need more theory input,

with help of experimental transition form factors

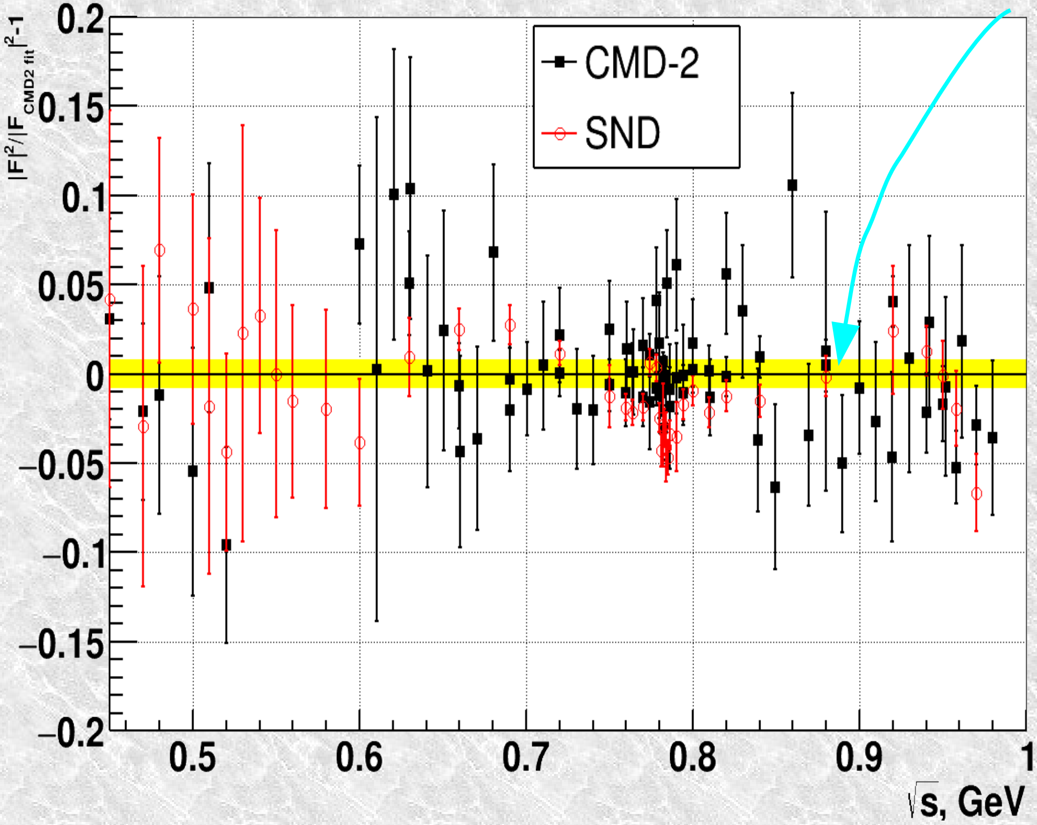
New g-2 experiments at FNAL and J-PARC have plans to reduce error to **1.5x10^{-10}**

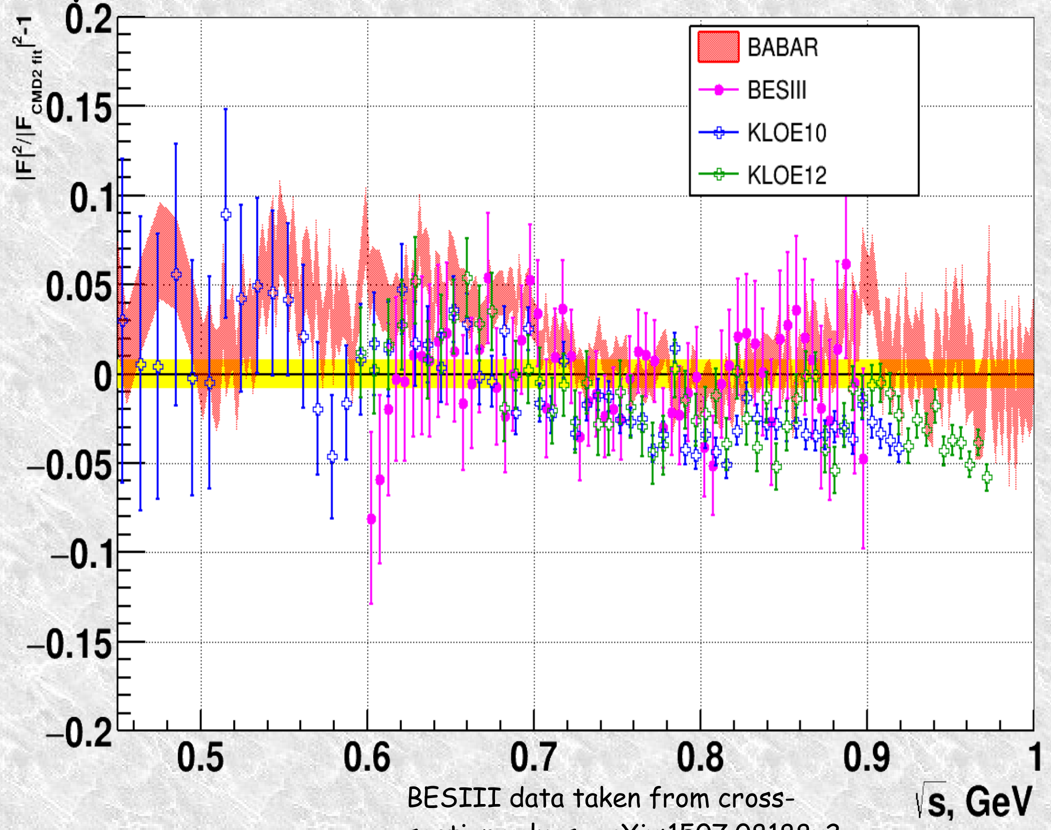
$\pi^+\pi^-$ gives the main contribution to hadronic value and overall theoretical precision of a_μ

Published cross section e+ e− → π+ π−

Relative to CMD-2 fit
yellow band – systematic value

Points, red band:
only statistical error

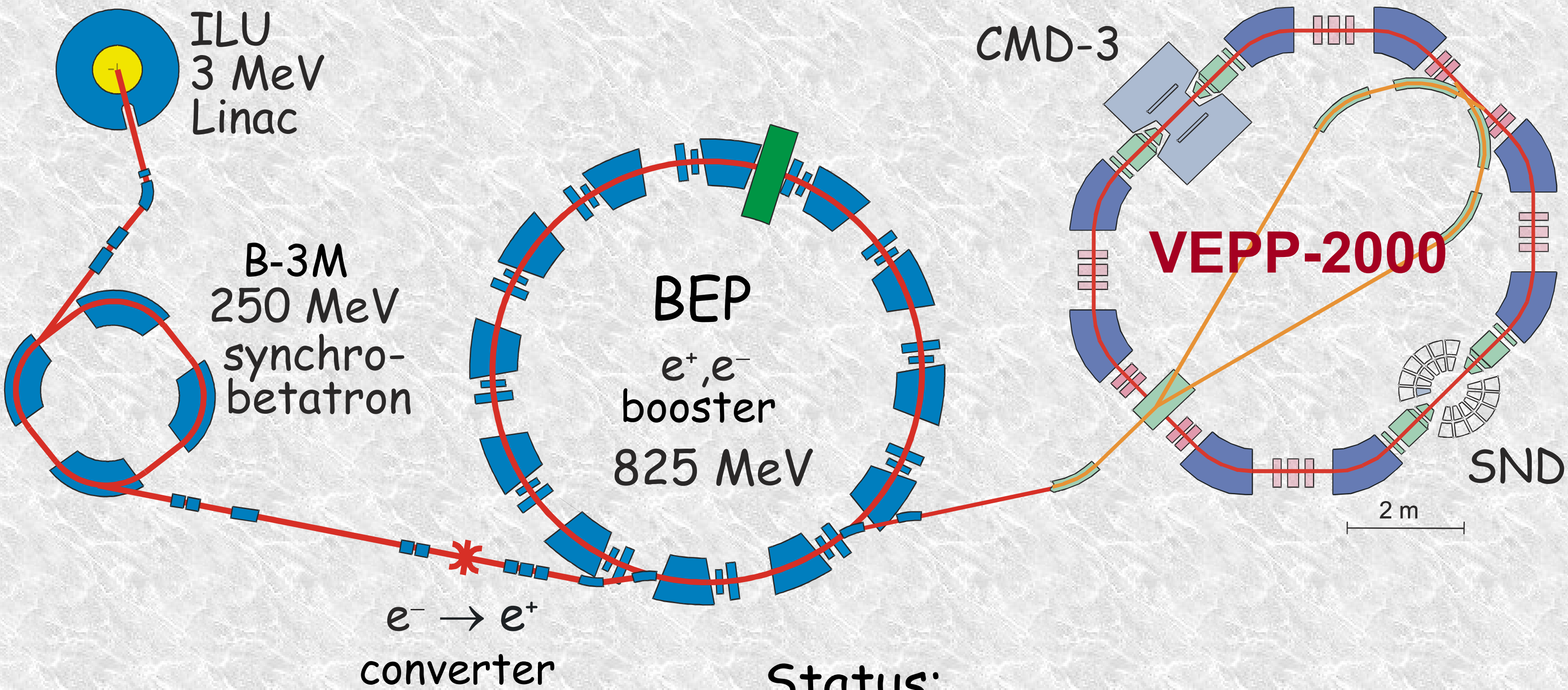




BESIII data taken from cross-section values arXiv:1507.08188v2

Local inconsistencies larger than claimed systematic errors seen

VEPP-2000 collider



- Up to 2 GeV c.m. Energy
- VEPP-2000 uses unique "round beams" optic, which gives additional gain in luminosity and will provide:

  $L=10^{32}\ cm^{-2}s^{-1}$, $\sqrt{s}=2.0$ GeV

Status:

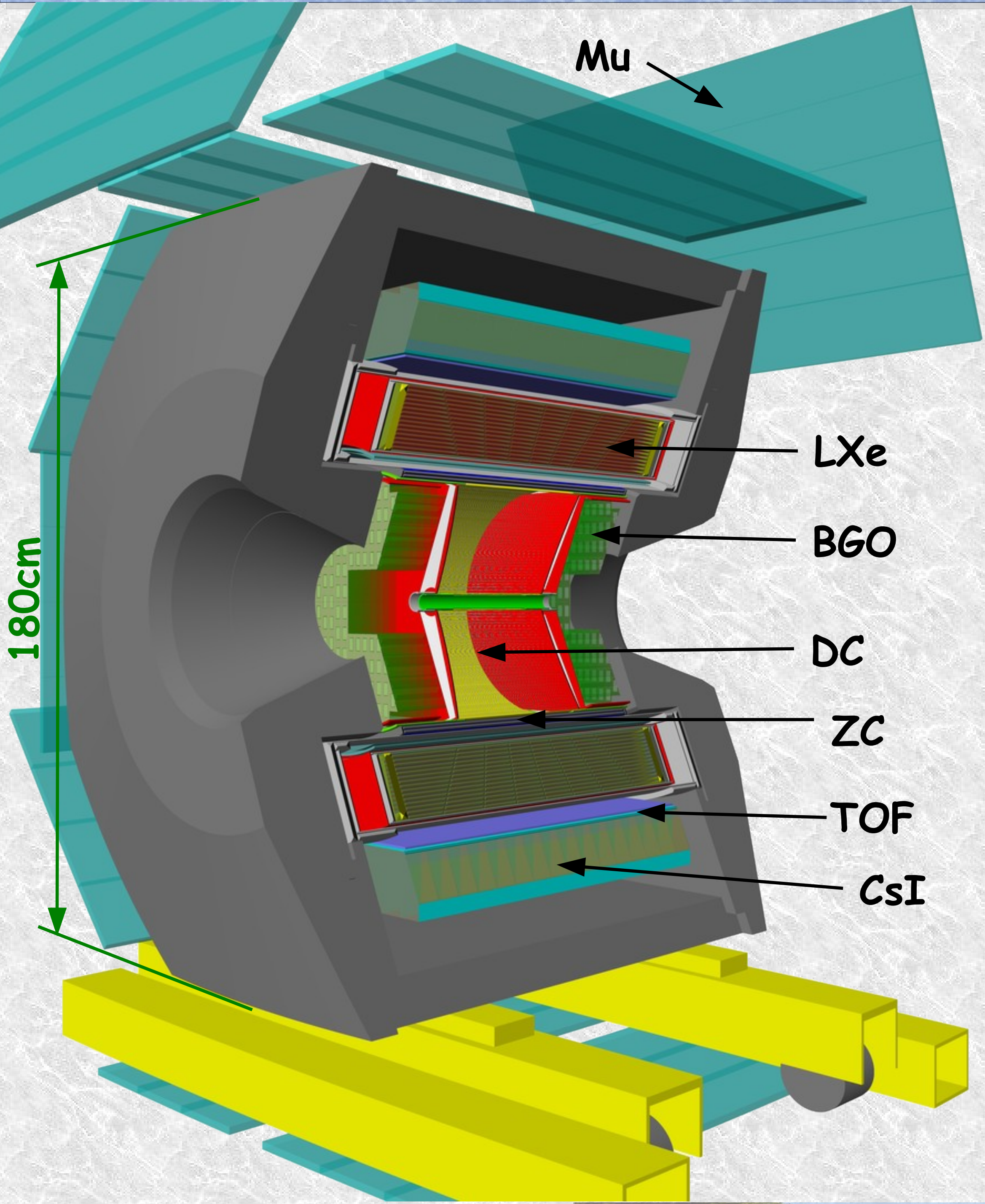
2010 – start of experiments

2013-2015 - upgrade of positron injection facility

Plans:

≈100 pb^{-1} per detector per year

CMD-3 Detector

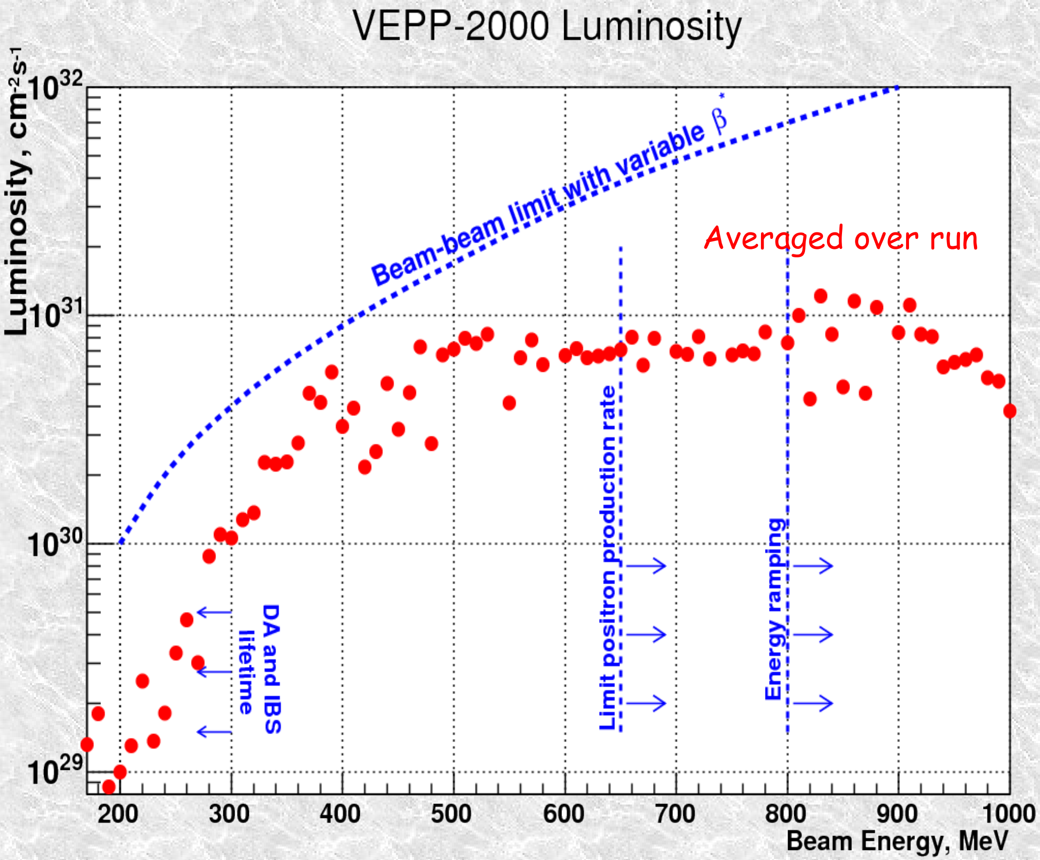


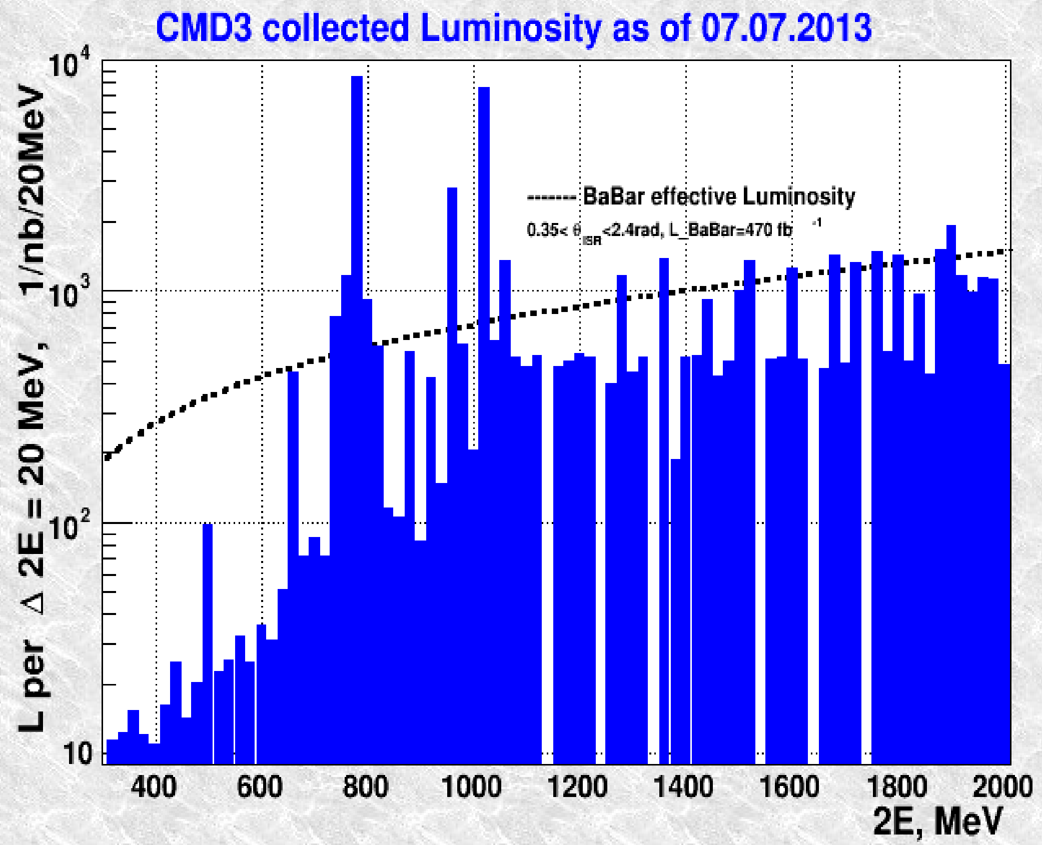
Advantages for this analysis compared to previous CMD-2:

✗ new drift chamber with x2 better spatial resolution, higher B field
- better efficiency
- better momentum resolution

✗ Unique LXe calorimeter with 7 ionization layers with strip readout
- ~2mm measurement of conversion point,
- tracking capability,
- shower profile (from 7 layers + CsI)

Collected Luminosity





The 10^{31} $cm^{-2}s^{-1}$ luminosity at √s=2.0 GeV was reached

Currently the luminosity at high energy is limited by a deficit of positrons and maximum energy of the booster (now 825 MeV), after upgrade it will gain a factor of 10

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

8.3 pb^{-1}	ω - region
9.4 pb^{-1}	< 1 GeV (except ω)
8.4 pb^{-1}	φ - region
34.5 pb^{-1}	> 1.04 GeV

e+e- -> π+π- by CMD3

Very challenging channel as needs to be measured at best systematical precision ~ a few per mil

But... Clean topology of collinear events (mostly without physical background)

Overall corrections at the level of a few percent

Plans to reduce systematic error from 0.6-0.8% (by CMD2) -> 0.35% (CMD3)

3 Key components for this precise measurement:

1) PID - particle separation

2) Acceptance determination
   spatial angle of detection

3) Radiative correction, MC generators

... efficiencies

... beam energy precision

Many systematic studies rely on high statistics

Event selection

- Two charged collinear tracks:

$$|\Delta\varphi| < 0.15, \quad |\Delta\theta| < 0.25$$

$$Q_1 + Q_2 = 0$$

- Vertex position close to interaction point:

$$\rho_{average} < 0.3\,\text{см}, \ |Z_{average}| < 5\,\text{см}$$

$$|\Delta\rho| < 0.3\,\text{см}, \ |\Delta Z| < 5\,\text{см}$$

- Fiducial volume inside good region of DCh:

$$1. < (\pi + \theta^+ - \theta^-)/2 < \pi - 1.$$

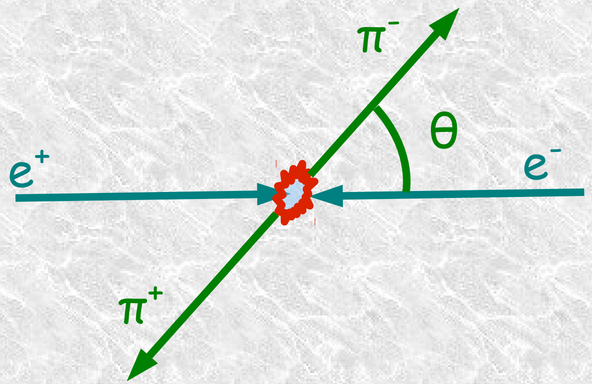
- Quality of selected tracks:

$$\chi^2/ndf < 10, N_{hits} \geq 10$$

- Filtration of low momentum and cosmic background:

$$0.45 E_{beam} < p^+, p^- < E_{beam} + 100\,MeV/c$$

Simple event signature with
2 back to back charged particles



Data sample includes events with: **e+e-, μ+μ-, π+π-, cosmic muons**
Mostly doesn't have any other background at √s <1 GeV

Event separation

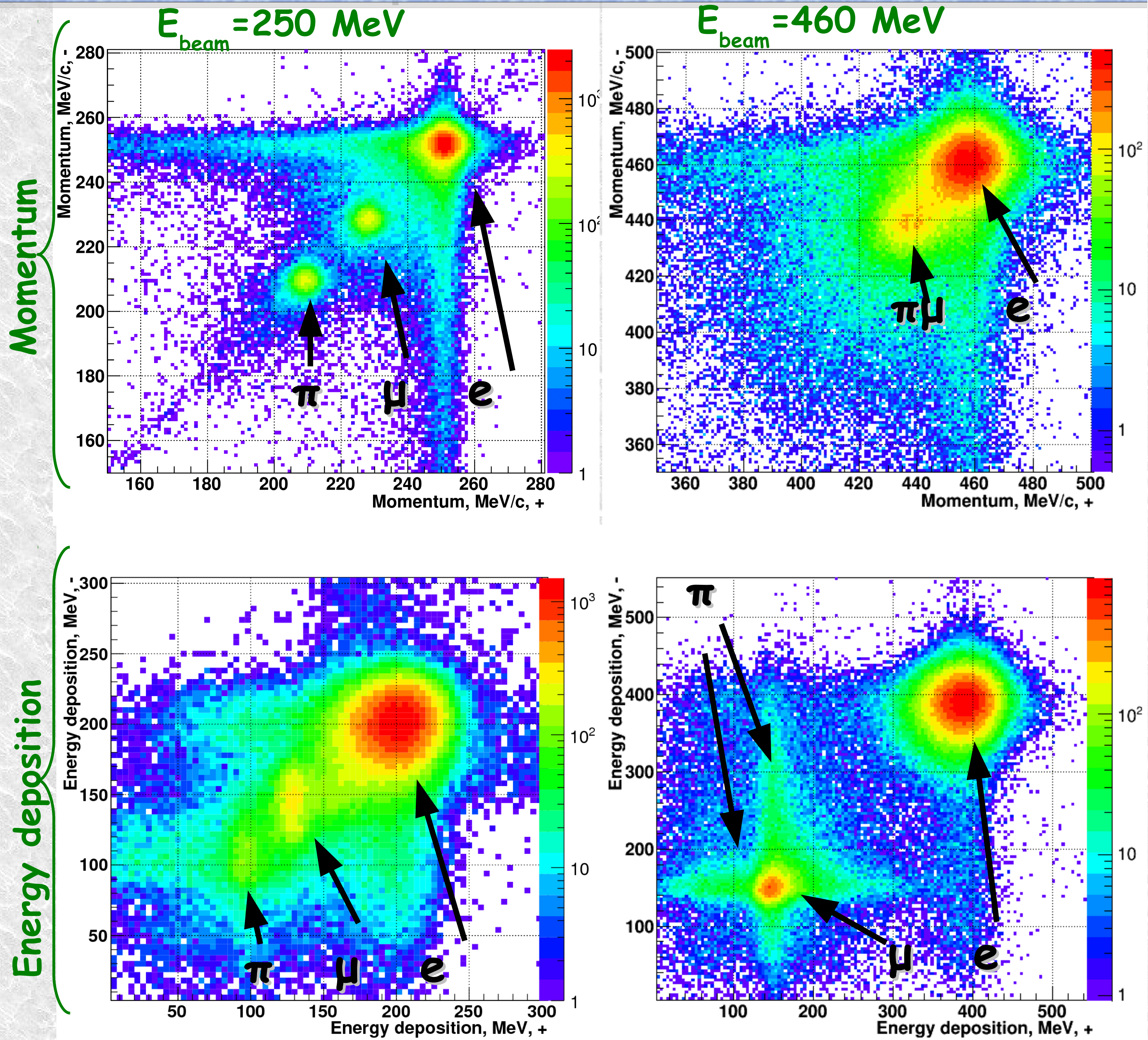
Particle ID can be done by momentum or energy deposition

At low energies momentum resolution of DCh enough to separate different types

At higher energies Electron shower in calorimeter far away from MIPs

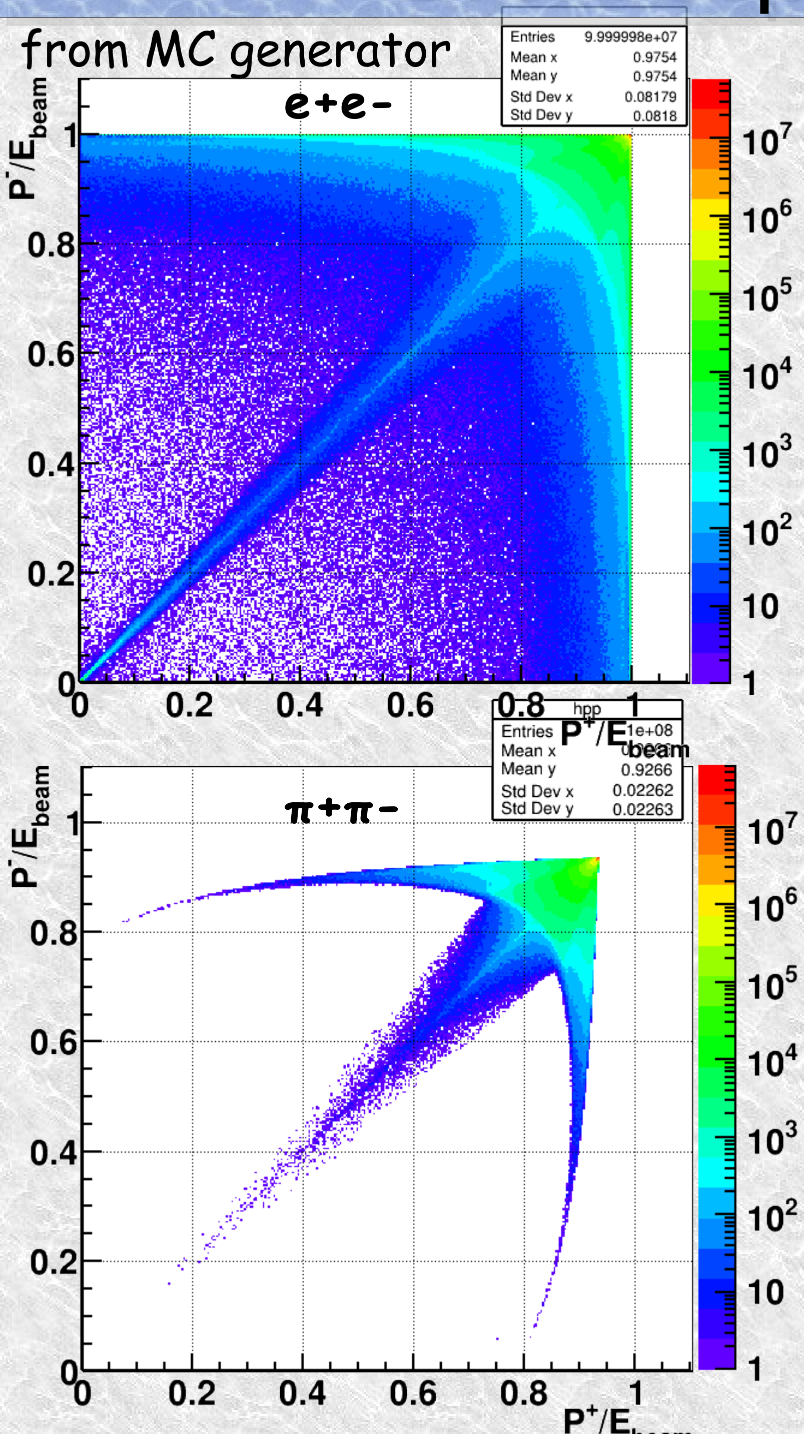
Both methods can be used separately for cross-check

Nμμ can be fixed (or not) from QED



Event separation by momentum

from MC generator



For particle separation:

As input: momentum spectra for ee,ππ,μμ events from MC generator (in applied selection criteria) + cosmic,3π background from data(MC)

Generated distributions are convoluted with detector response function which include (with mostly all free parameters in it):
- momentum resolution,
- bremsstrahlung of electron on vacuum tube,
- pion decay in flight

Nππ/Nee obtained as result of binned likelihood minimization

Event separation by energy deposition

At this moment: Full energy deposition in LXe+CsI calorimeter is used for particle separation

As input: PDF distributions are taken from MC or data itself (fitted by analytical function, and used with some free parameters)

- ✗ Electron - described by mostly free function
- ✗ Muons - from simulation + additional smearing (plan to be taken from data)
- ✗ Pions - from $\varphi \to 3\pi$, $\omega \to 3\pi$ events
- ✗ Cosmic - from data itself (events are selected by vertex position)

$N\pi\pi/Nee$ obtained as result of binned likelihood minimization

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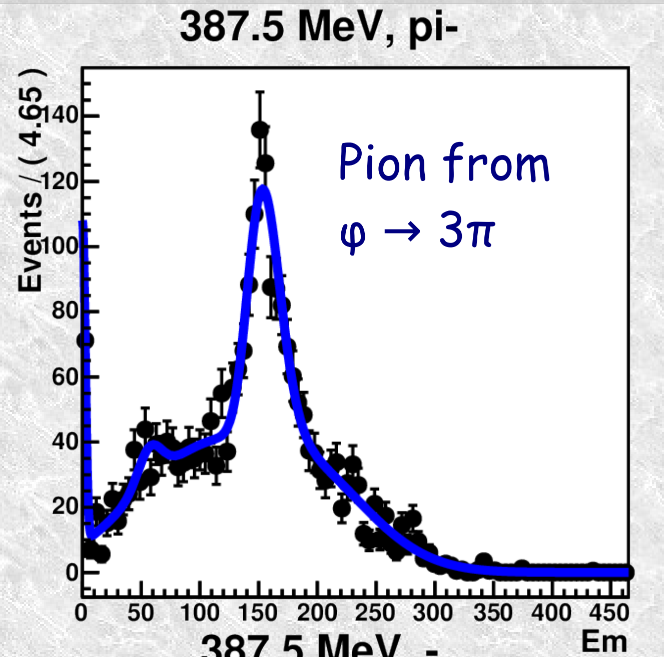
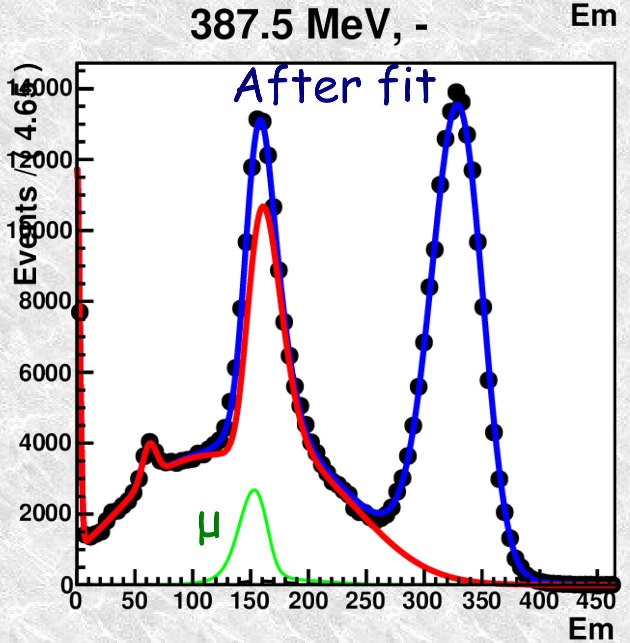
As plans: to exploit information about shower profile (energy deposition in 7 layers of LXe, + CsI)

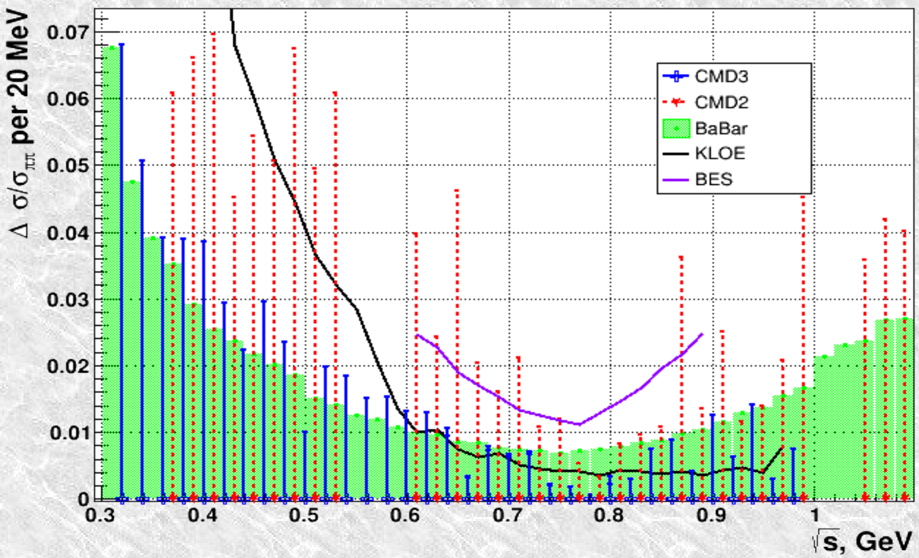
Neural net can be used for event classification

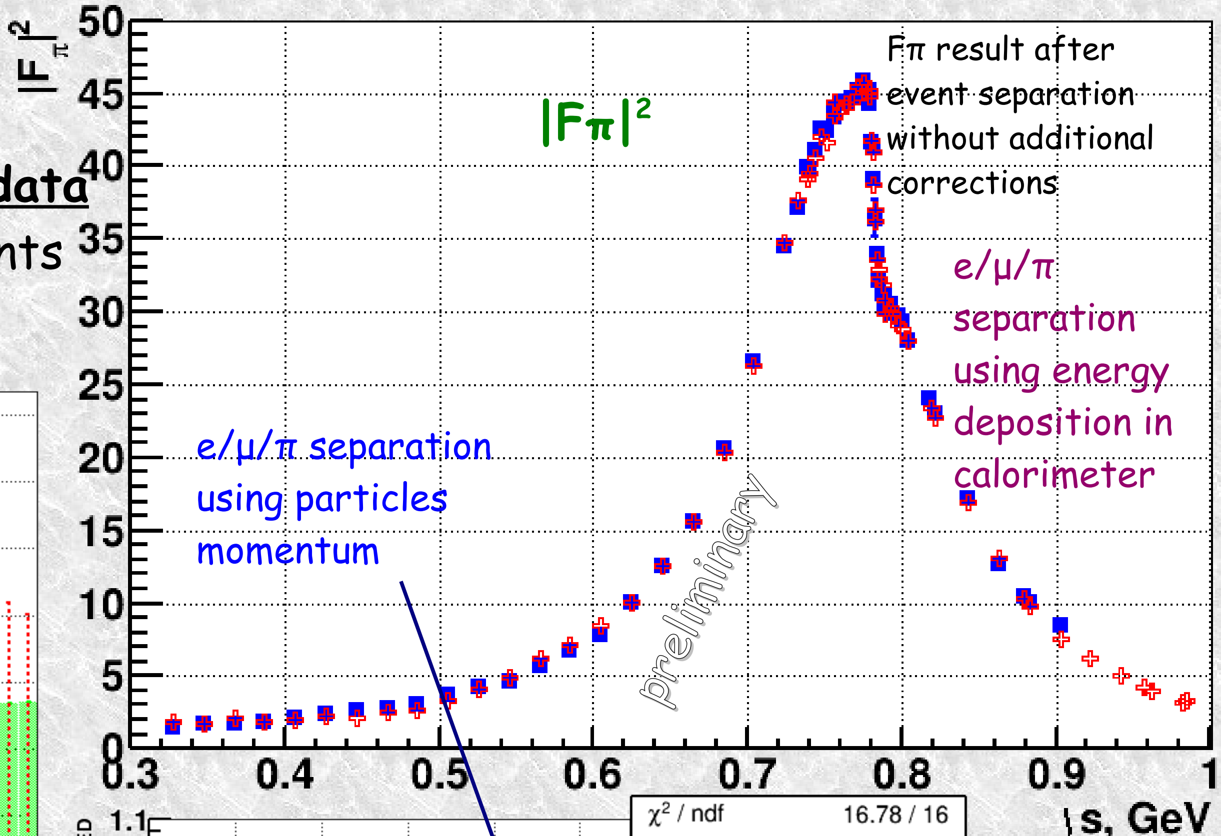


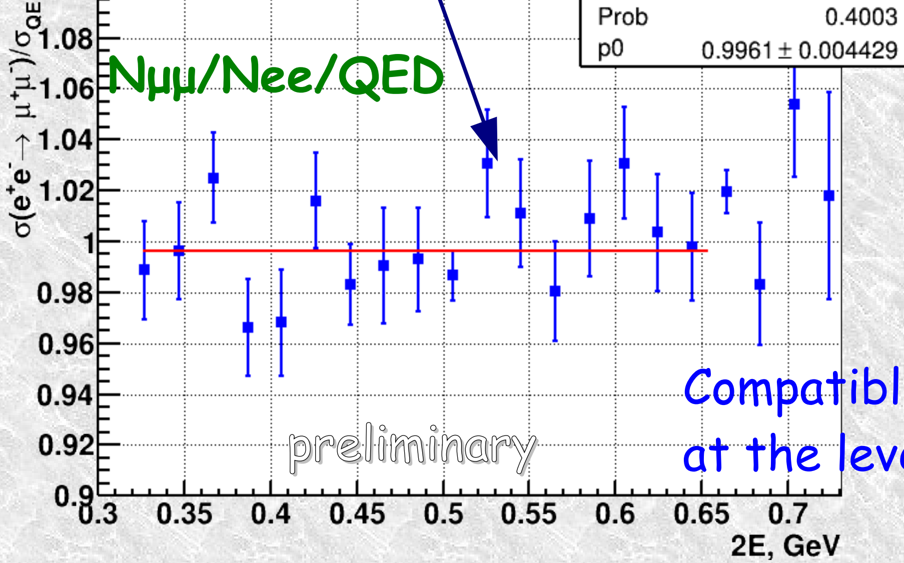


e+e- -> π+π- by CMD-3

Statistical precision of cross section measurement for **2013 data** is at the same level as other experiments and a few times better than at CMD-2



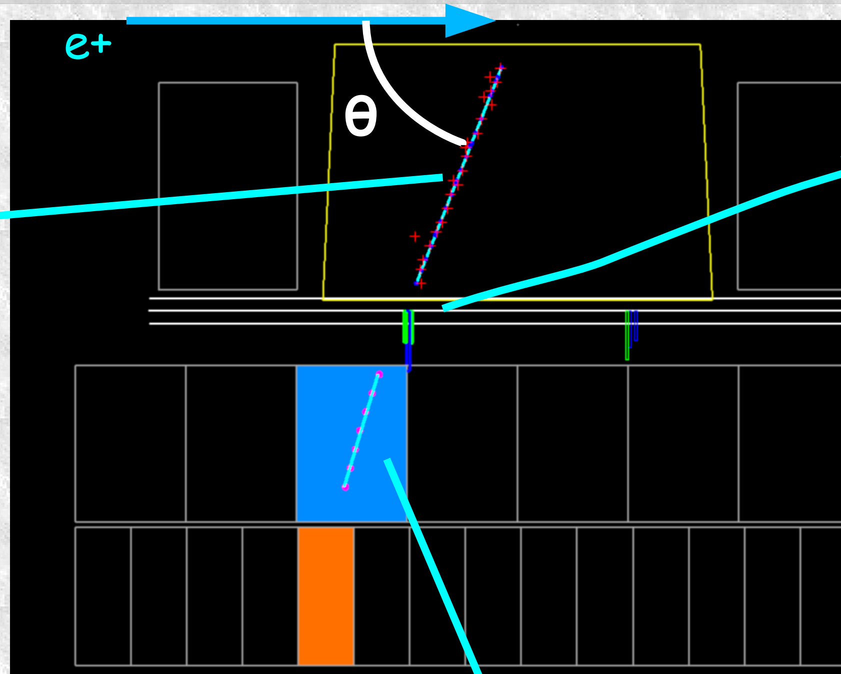




Compatible with QED at the level of 0.5 %

Precision of fiducial volume

Polar angle measured by
DC chamber
with help of charge
division method
(Z resolution ~ 2mm),
Unstable, depends on
calibration and thermal
stability of electronic
Calibration done
relative to ZC (LXe)



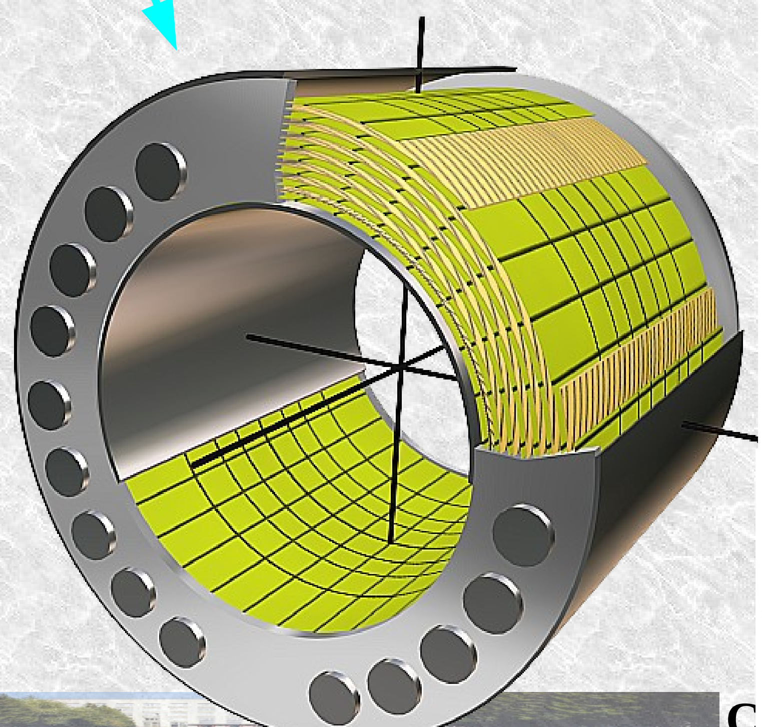
ZC chamber
multiwire chamber
with 2 layers and with strip
readout along Z coordinate

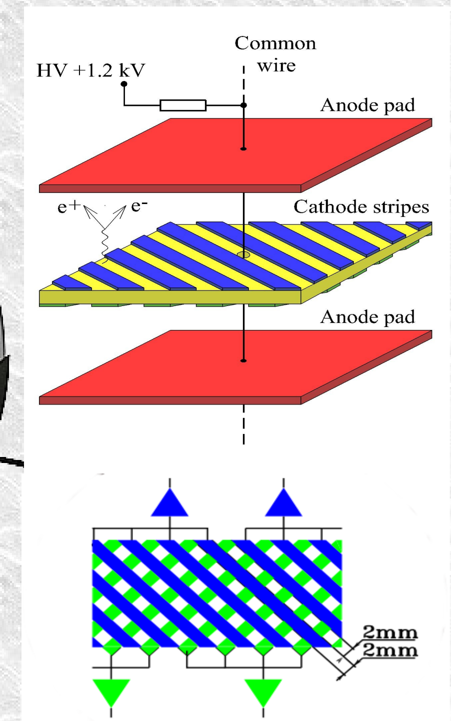
strip size: 6mm
Z coordinate resolution ~
0.7 mm (for θ_{track} ~ 1 rad)

LXe calorimeter
ionization collected in 7 layers with
cathode strip readout,

combined strip size: 10-15 mm
Coordinate resolution ~ 2mm

Both subsystem
with strip precision < 100 μm
give <0.1% in Luminosity determination





Precision of fiducial volume

Polar angle measured by

DC chamber

with help of charge division method

(Z resolution ~ 2mm),

Unstable, depend on calibration and thermal stability of electronic

Calibration done relative to ZC (LXe)

ZC chamber

multi wires chamber with 2 layers and with strip readout along Z coordinate

strips size: 6mm

coordinate resolution ~ 2mm

LXe calorimeter

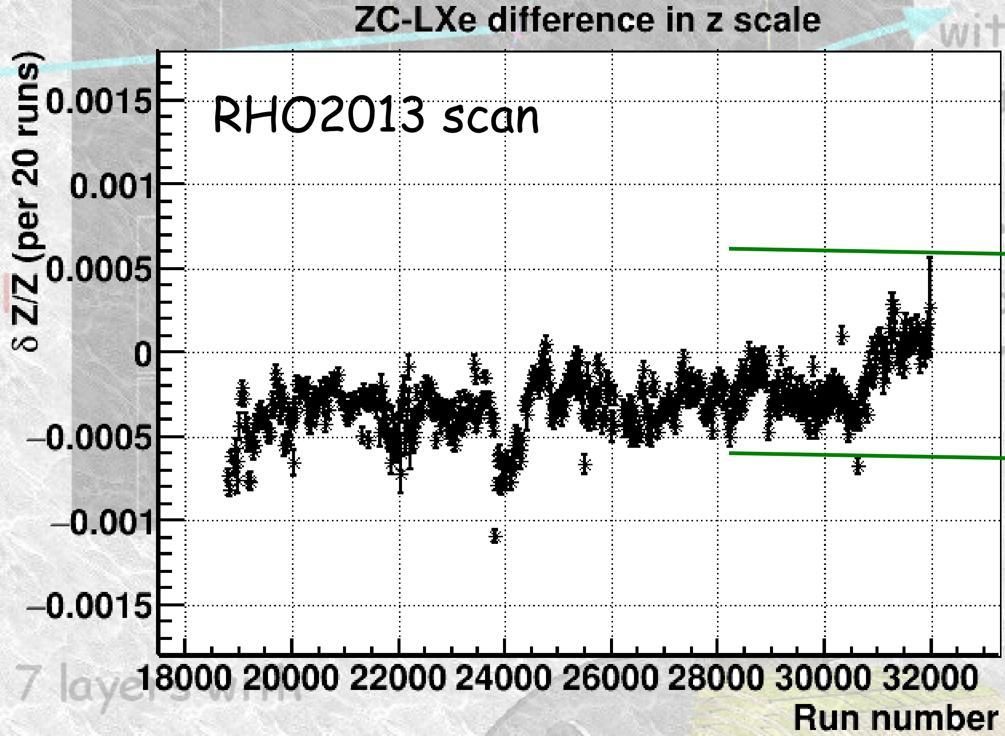
ionization collected in 7 layers with cathode strip readout,

combined strip size: 10-15 mm

Coordinate resolution ~ 2mm

Both subsystem with strip precision < 100 μm give <0.1% in Luminosity determination

Monitoring of z-measurement between ZC vs LXe



±0.1% Luminosity determination at θ>1rad

Variation because of
DCh instability,
different B field,
ZC noise level

MC generators

High experimental precision relies on theoretical precision of MC tools:

Most recent e+e- -> e+e- (gamma) generators
include exact $O(\alpha)$ + some parts from High Order terms:

MCGPJ (VEPP-2000) – accuracy 0.2% for e+e-, π+π- etc
1 real photon (from any particle)
+ photon jets along all particles (collinear Structure function)

BabaYaga@NLO (KLOE,BaBar) - 0.1% for e+e-, μ+μ-
Parton shower approach: n photons with angle distribution
interference for 1 photon radiation

BHWIDE (LEP) – 0.5% (~0.1%?), e+e–
n real photons by Yennie-Frautschi-Suura (YFS) exponentiation method
interference on $O(\alpha)$ level

And there are other generators for different channels:
PHOKHARA (KLOE) μ+μ-, π+π- etc
KKMC (μ+μ-),
etc

BabaYaga@NLO vs MCGPJ generators

BabaYaga@NLO used by KLOE, BaBar

MCGPJ used by Novosibirsk group

<u>Selection cuts:</u>

$|\Delta\varphi|<0.15$, $|\Delta\theta|<0.25$

$1< \theta_{average} <\pi -1$

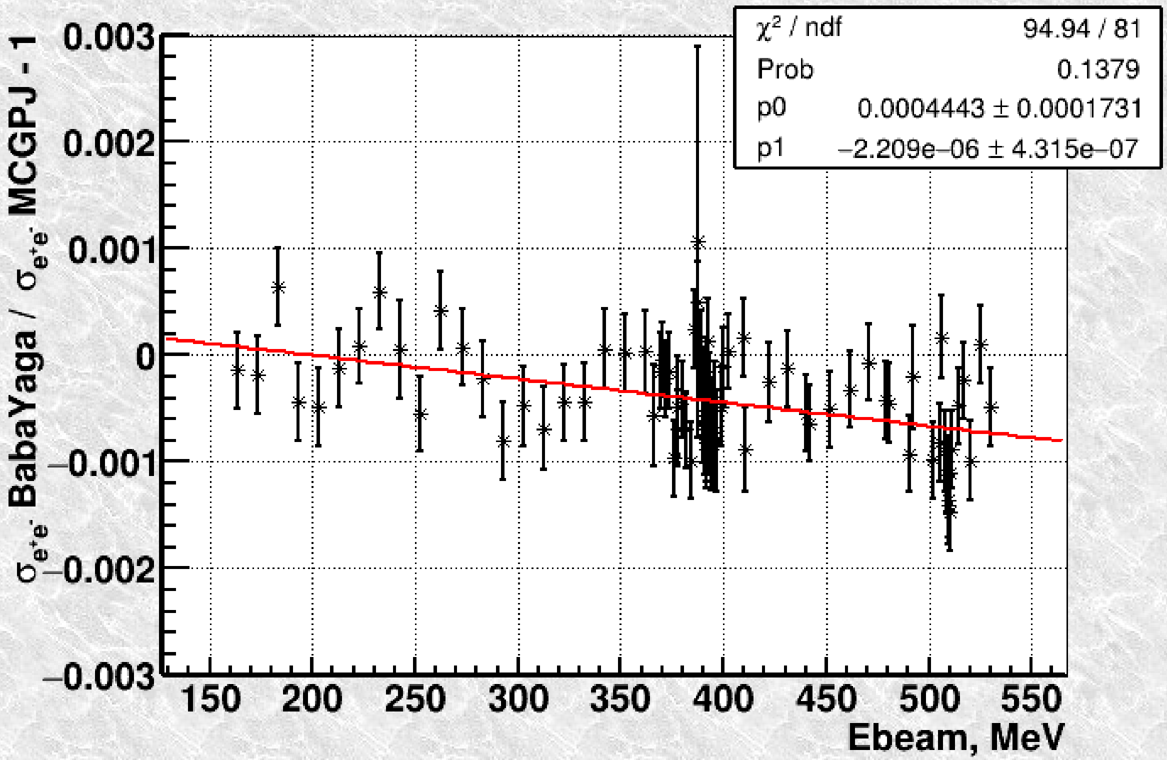
$P^{+-} >0.45 E_{beam}$

<u>Calculated cross-section</u>
<u>at E beam=391.48 MeV</u>

MCGPJ : 751.671 +- 0.034 nb

BabaYaga@NLO : 751.218 +- 0.059 nb

Δ ~ 0.06%



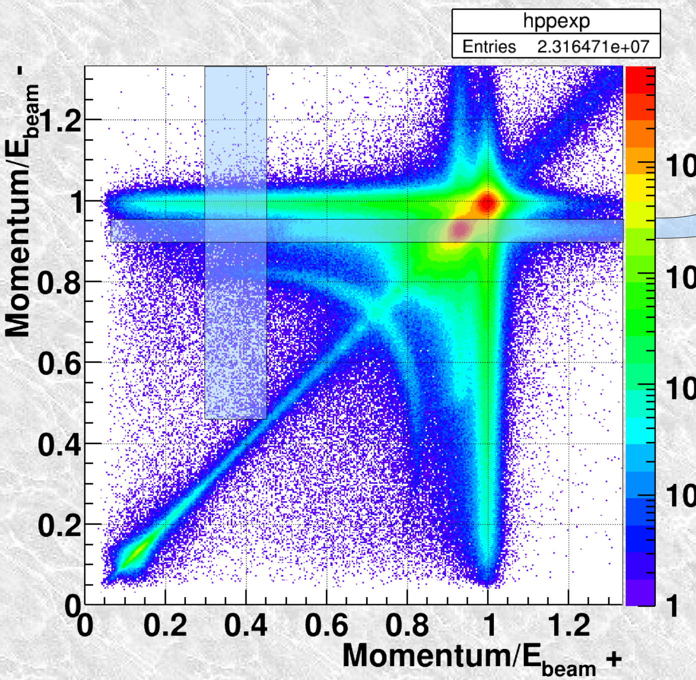
Integrated cross-section
consistent at the level <0.1%

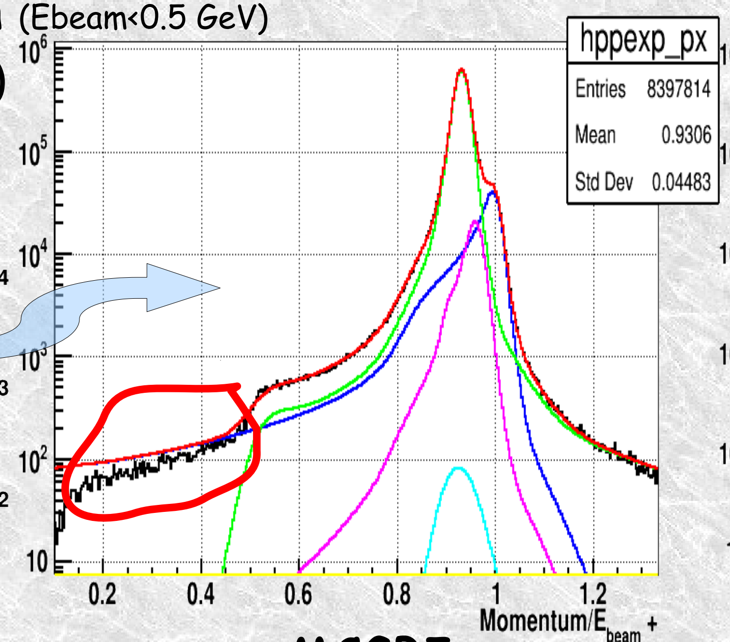
BabaYaga@NLO ~ x1000 slower than MCGPJ

A discrepancy was observed in momentum distribution of experimental data vs fitted functions with input from MCGPJ

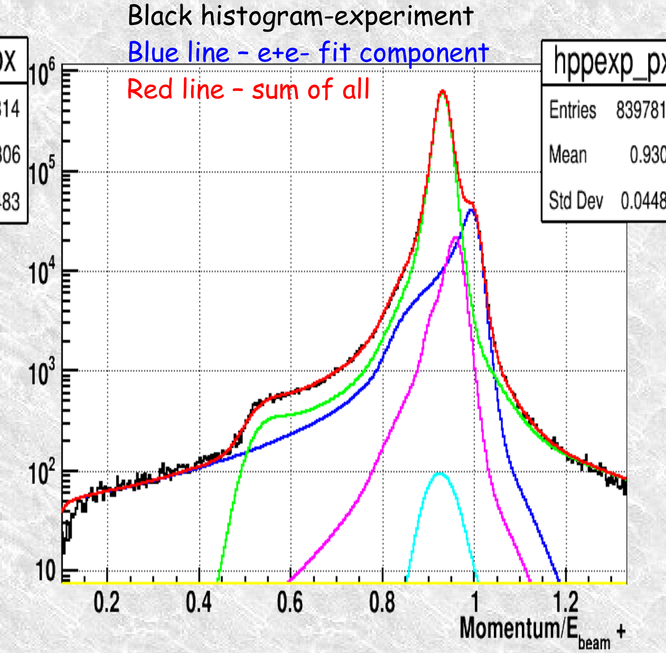
BabaYaga @ NLO vs MCGPJ vs experiment

All events from RHO2013 scan (Ebeam<0.5 GeV)
(~ 10 millions of e+e- and π+π-)

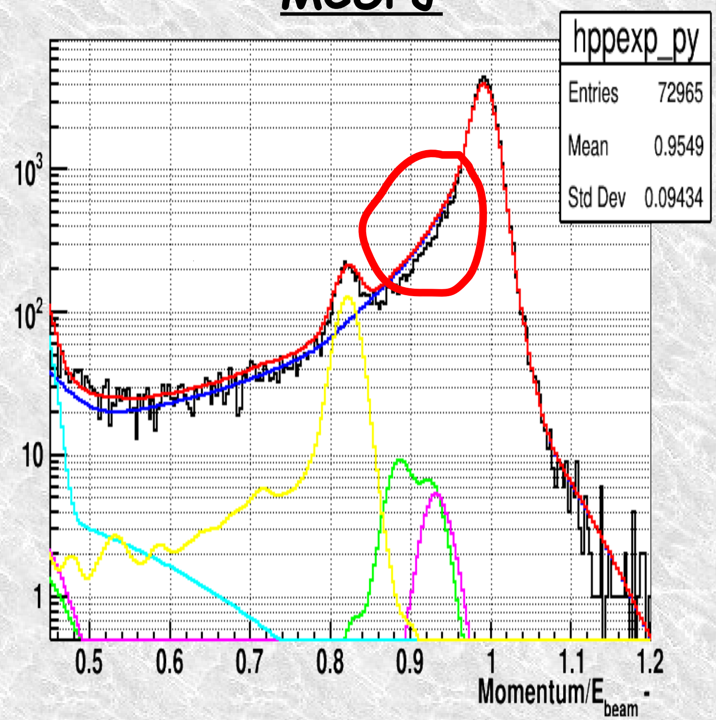


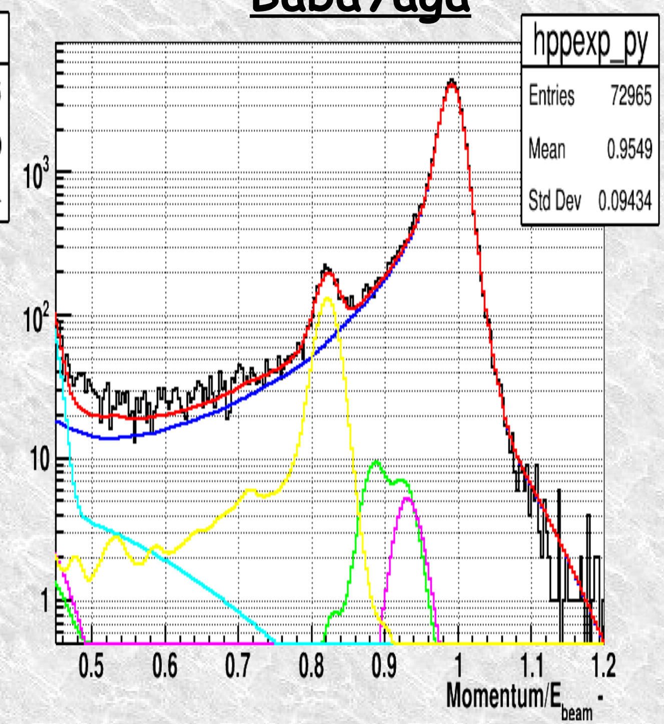


MCGPJ



BabaYaga





BabaYaga better describe experimental data

Looks like MCGPJ should be improved by
adding angular distribution to photon jets

π+π-π0 background

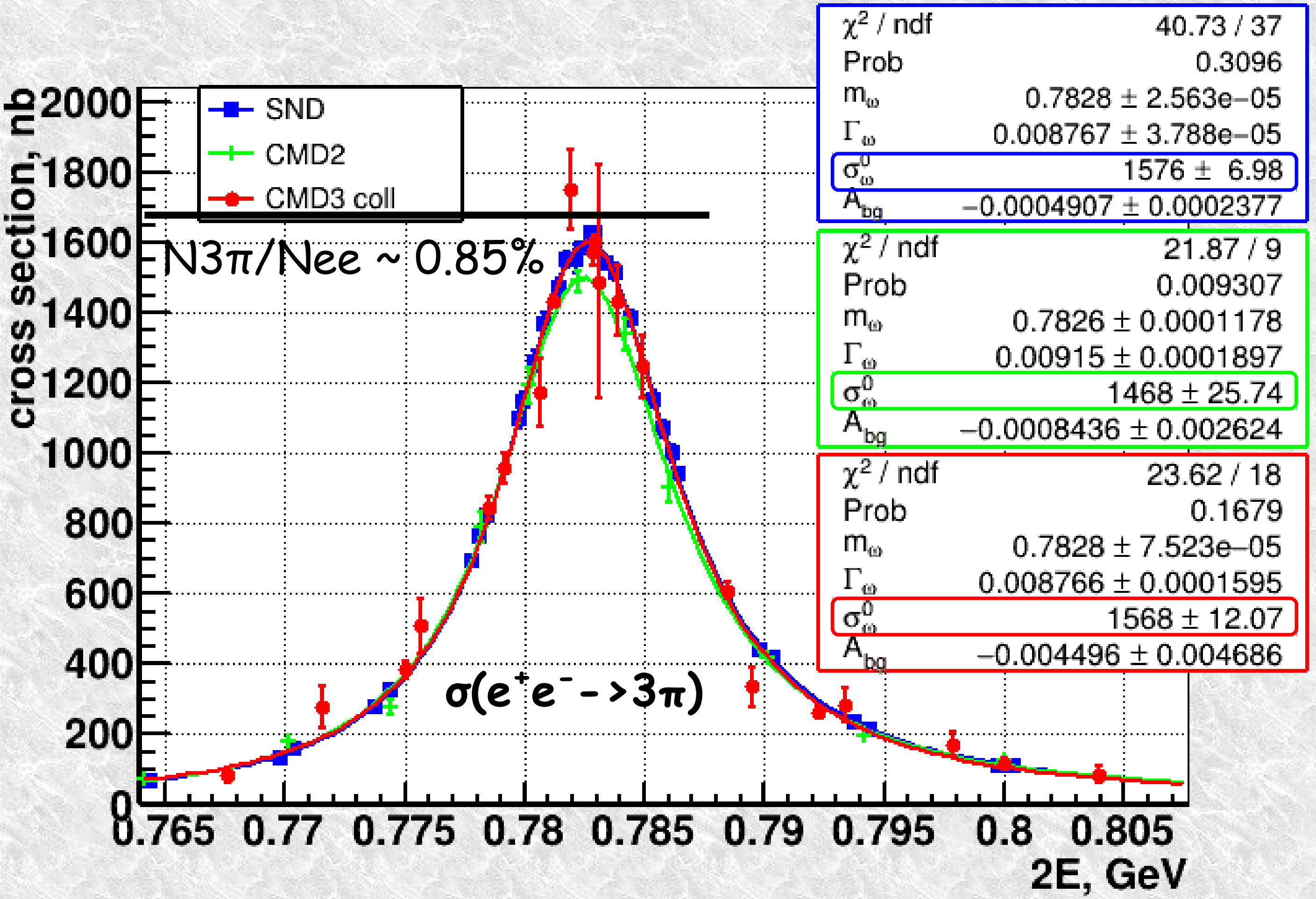
Only significant physical background in selected data sample:

$\pi^+\pi^-\pi^0$ on ω-resonance

Contribution < 1%

This events well seen during particle separation by momentum distributions

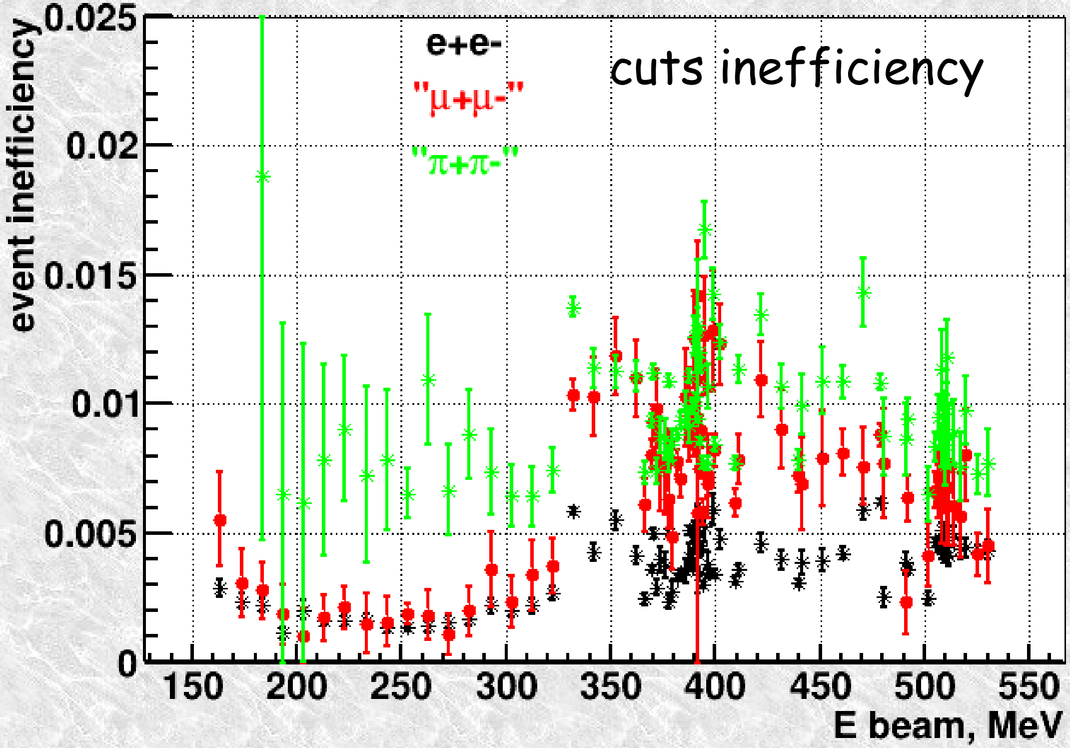
Extracted σ(e^+e^- -> 3π) from collinear events (in phase space model) compatible with published results



ε (3π)=0.4833% acceptance efficiency from simulation by phase space model

efficiencies

<u>Part of track reconstruction inefficiency</u>
from test events
selected only by 2 collinear clusters in calorimeter
-> check if a track was reconstructed or not



Inefficiency ~ 0.2-1%
3-10 times less then was at CMD-2

Pion specific loss of events:
- decay in flight (~6% at 160 MeV)
  (dominated at low energies)
- nuclear interaction on vacuum tube (<1%)

will be checked from $\varphi \to 3\pi$, $\omega \to 3\pi$ events

Systematic e+e- -> π+π- by CMD3

As our grand total(not reached yet)

Our goals are to reach systematic level up to 0.35%:

- e/μ/π separation – 0.2%
  can be checked and combined from different methods
- Radiative corrections - 0.1%
  more proof from data
- Fiducial volume – 0.1%
  controlled independently by LXe and ZC subsystems
- Beam Energy – 0.1 %
  measured by method of Compton back scattering
  of the laser photons(σ_E< 50 keV)
- Pion specific correction – 0.1%
  decay, nuclear interaction taken from data

First publication expected with systematic level ~< 1%

Many systematic studies rely on high statistics

Conclusion

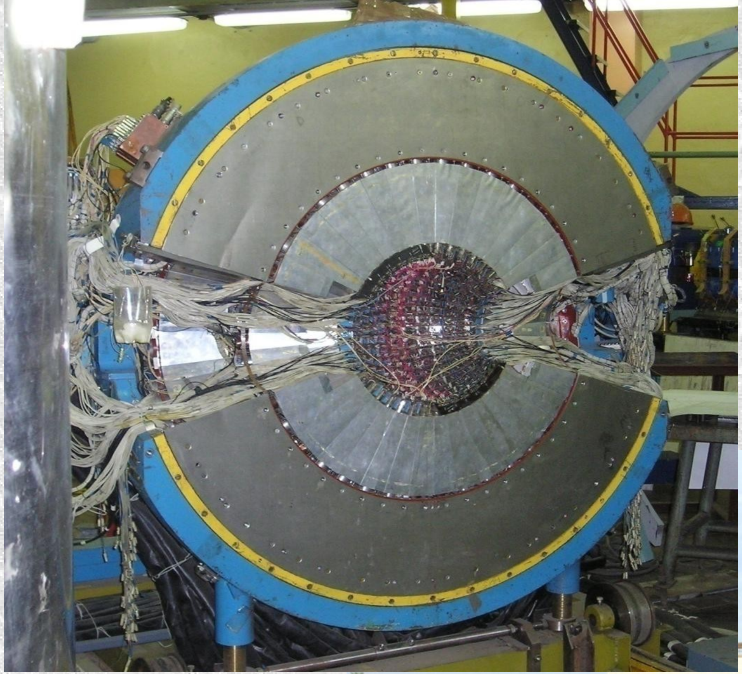
✗ VEPP-2000 collider successfully operates with a goal to get ~ 1fb-1 in 5-10 years which should provide new precise results on the hadron production

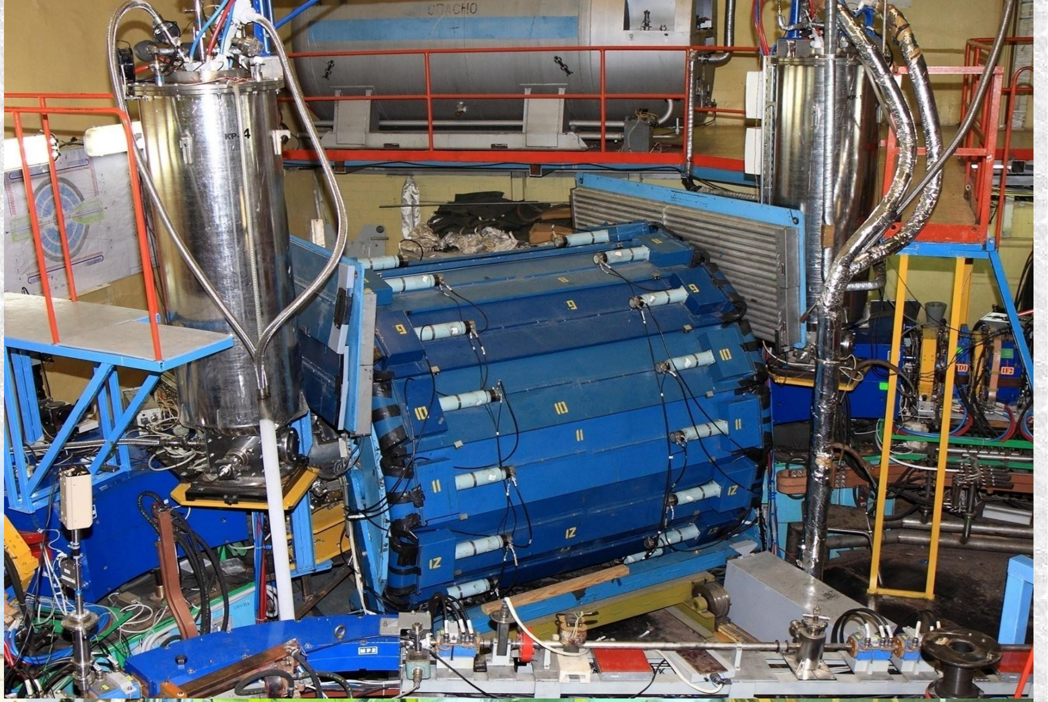
✗ We have upgraded the CMD-3 detector, with much better performance and monitoring of different detector subsystems

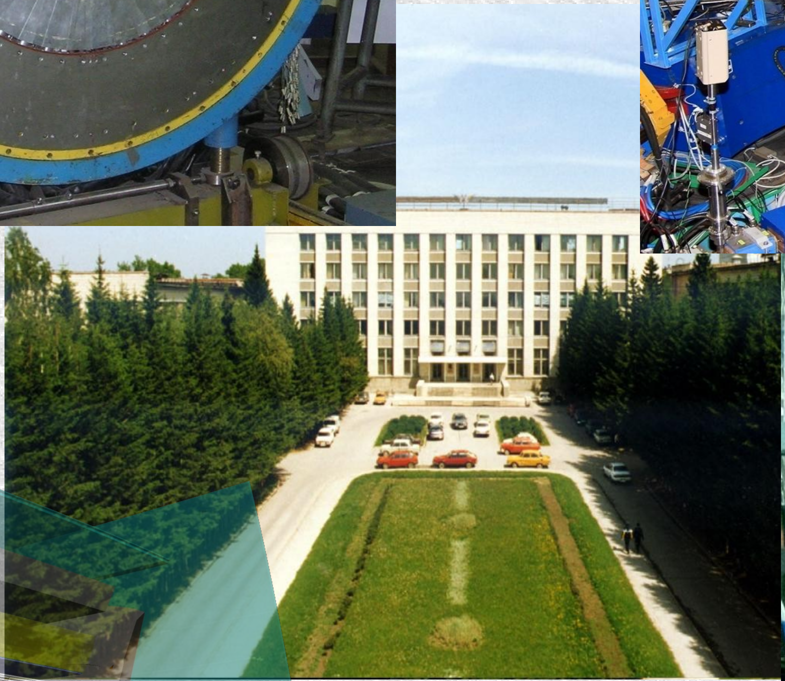
✗ First scan < 1 GeV for $\pi^+\pi^-$ measurement was done

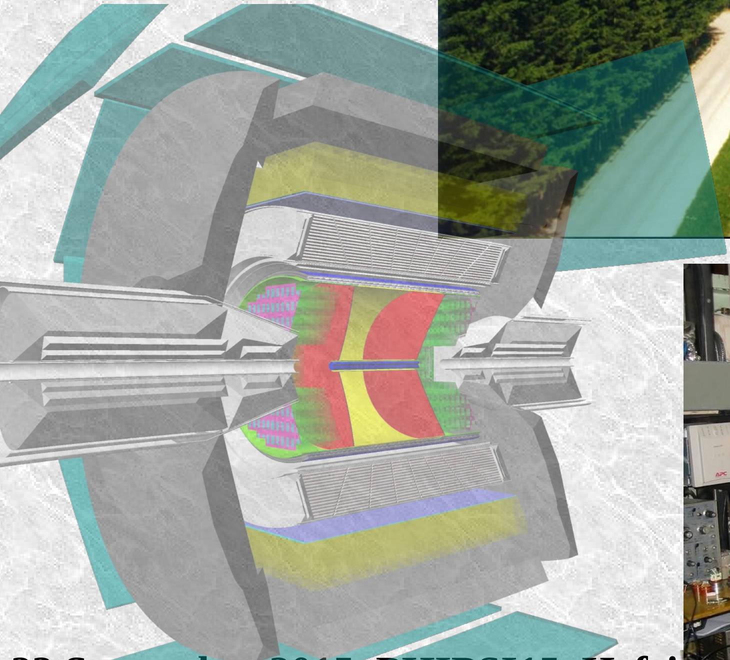
✗ High statistics allow us to study and to control better different systematic contributions, with final goal up to 0.35%

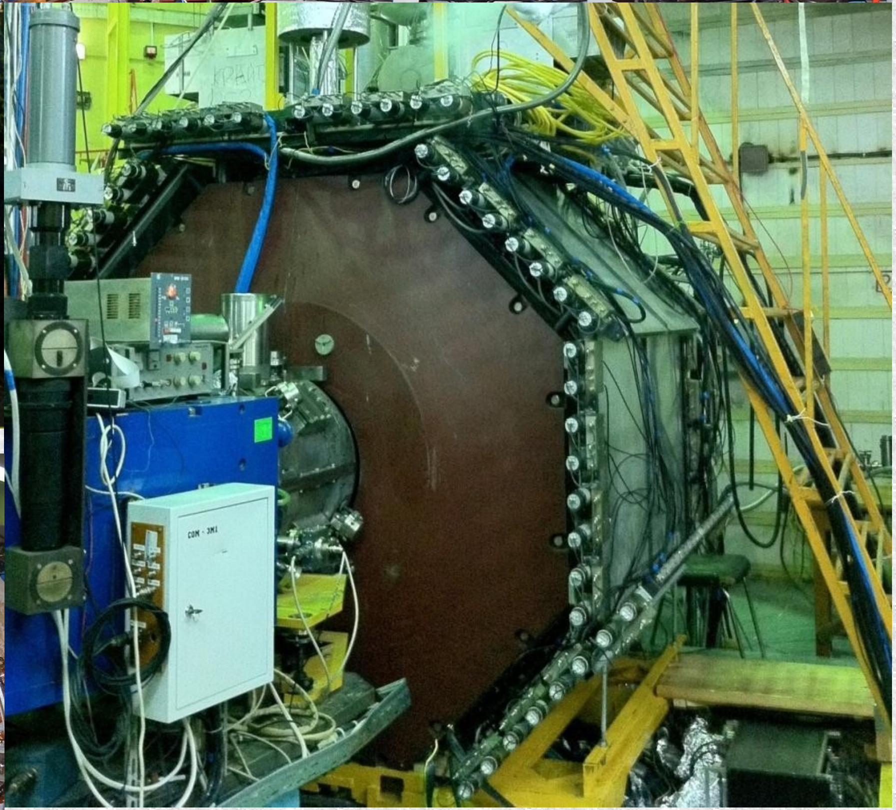
✗ More data expected after VEPP-2000 upgrade with new positron injection facility

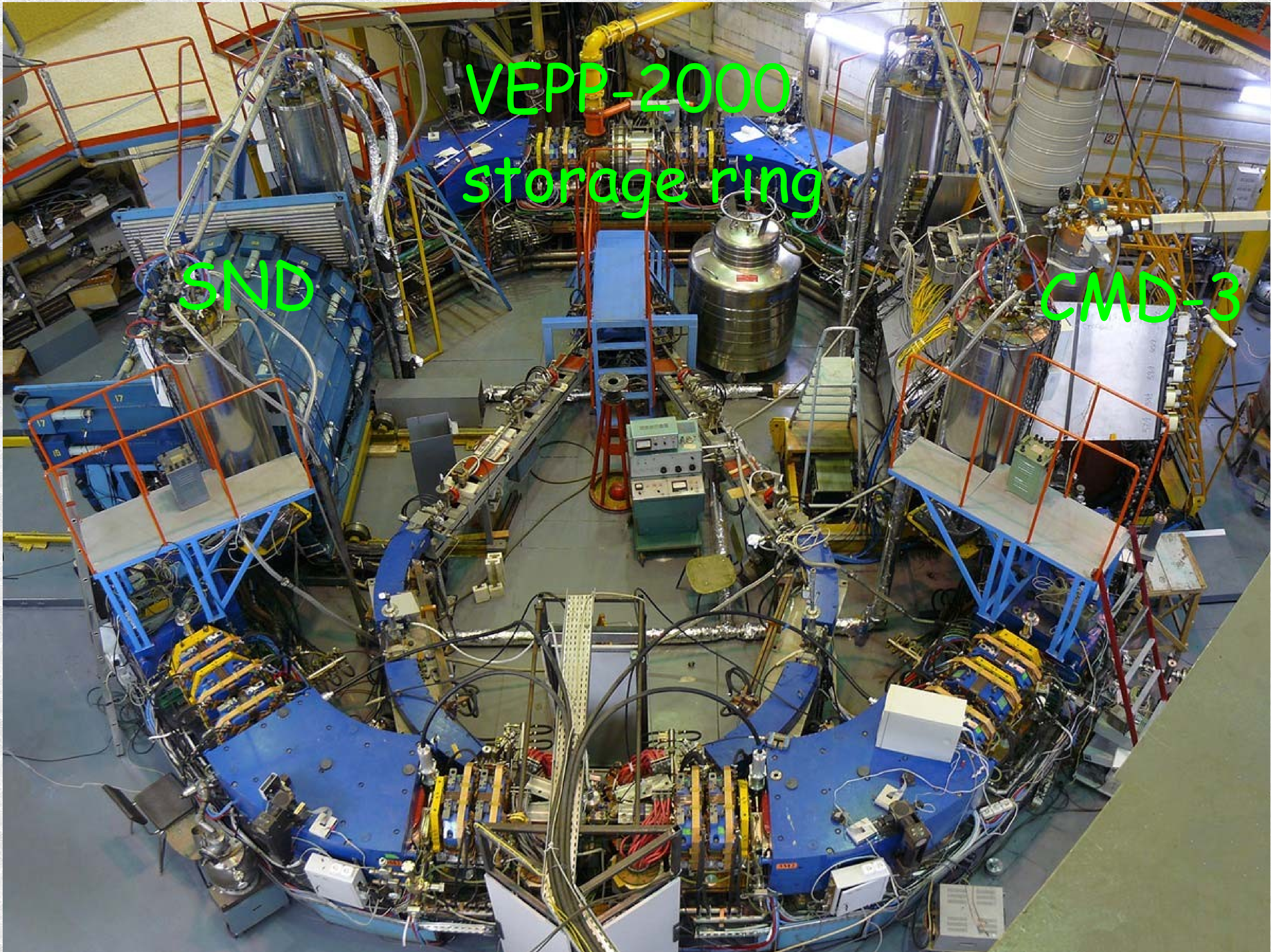











VEPP-2000
storage ring
SND
CMD-3

CMD-3 Detector

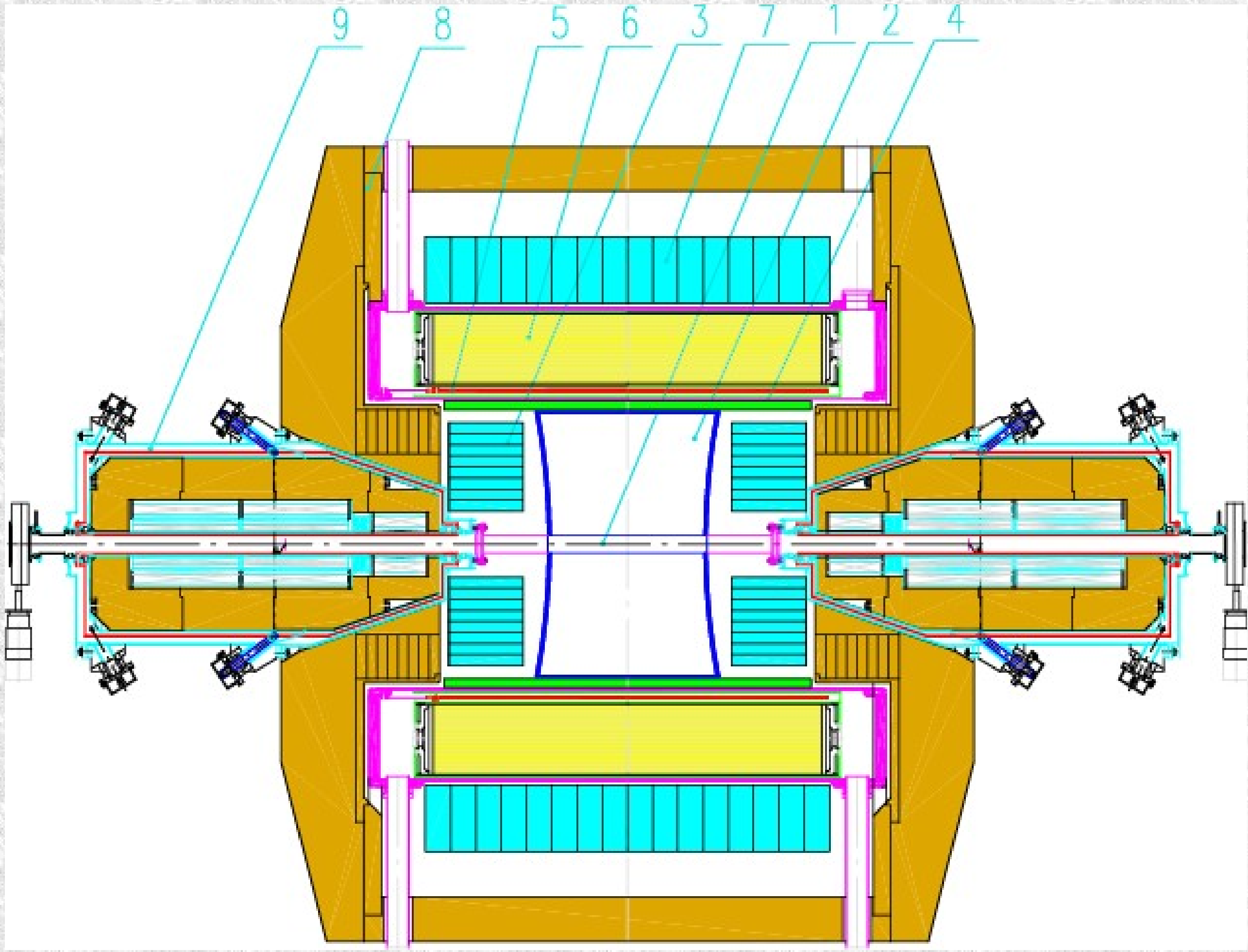
Advantages compared to previous CMD-2:

✗ new drift chamber with x2 better resolution, higher B field
- better tracking
- better momentum resolution

✗ thicker barrel calorimeter ($8.3X_0$->$13.5X_0$)
- better particle separation

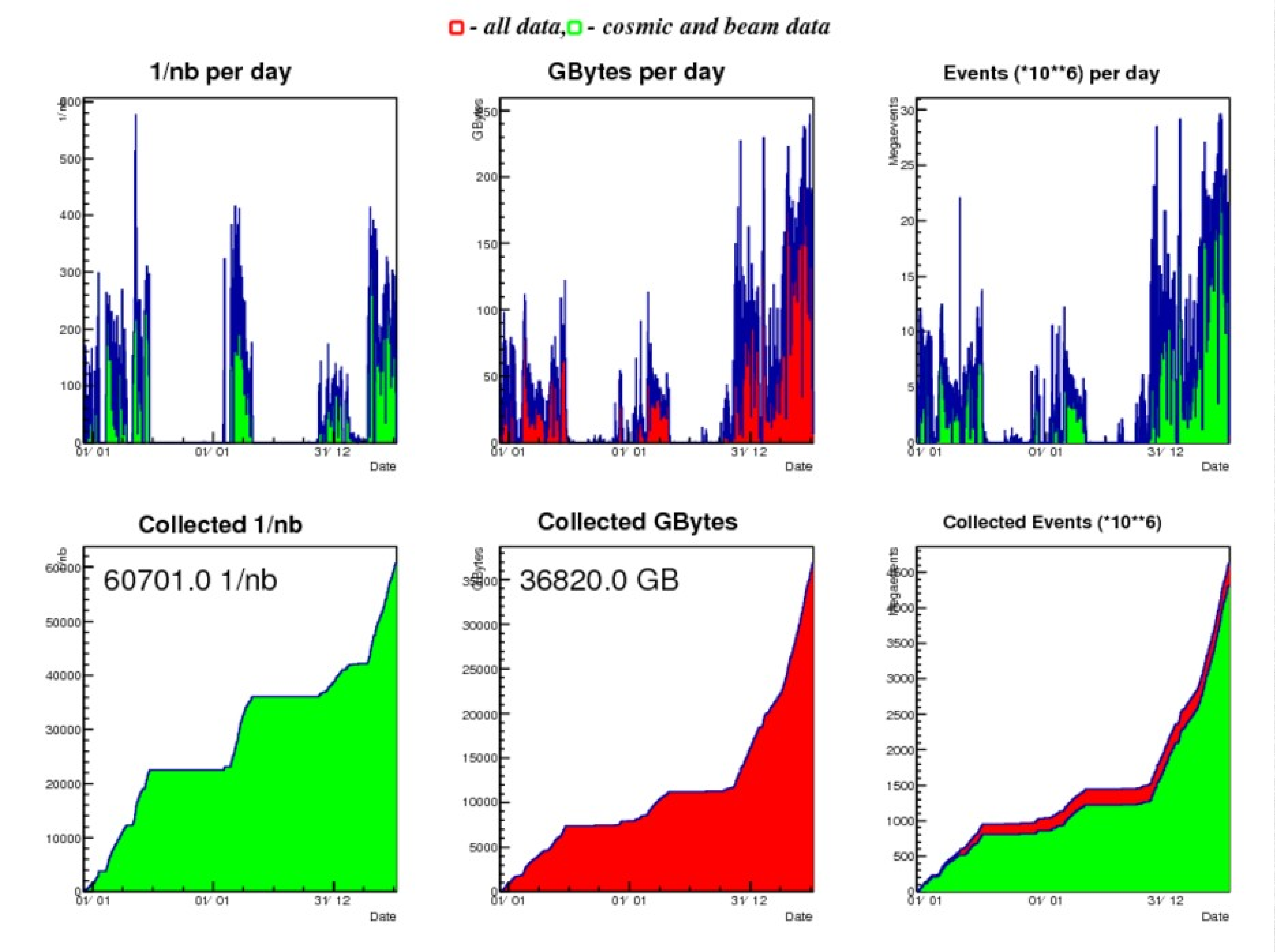
✗ LXe calorimeter
- **~2mm measurement of conversion point for γ's, tracking capability**
- shower profile

✗ TOF system
- time separation for $\bar{n}$

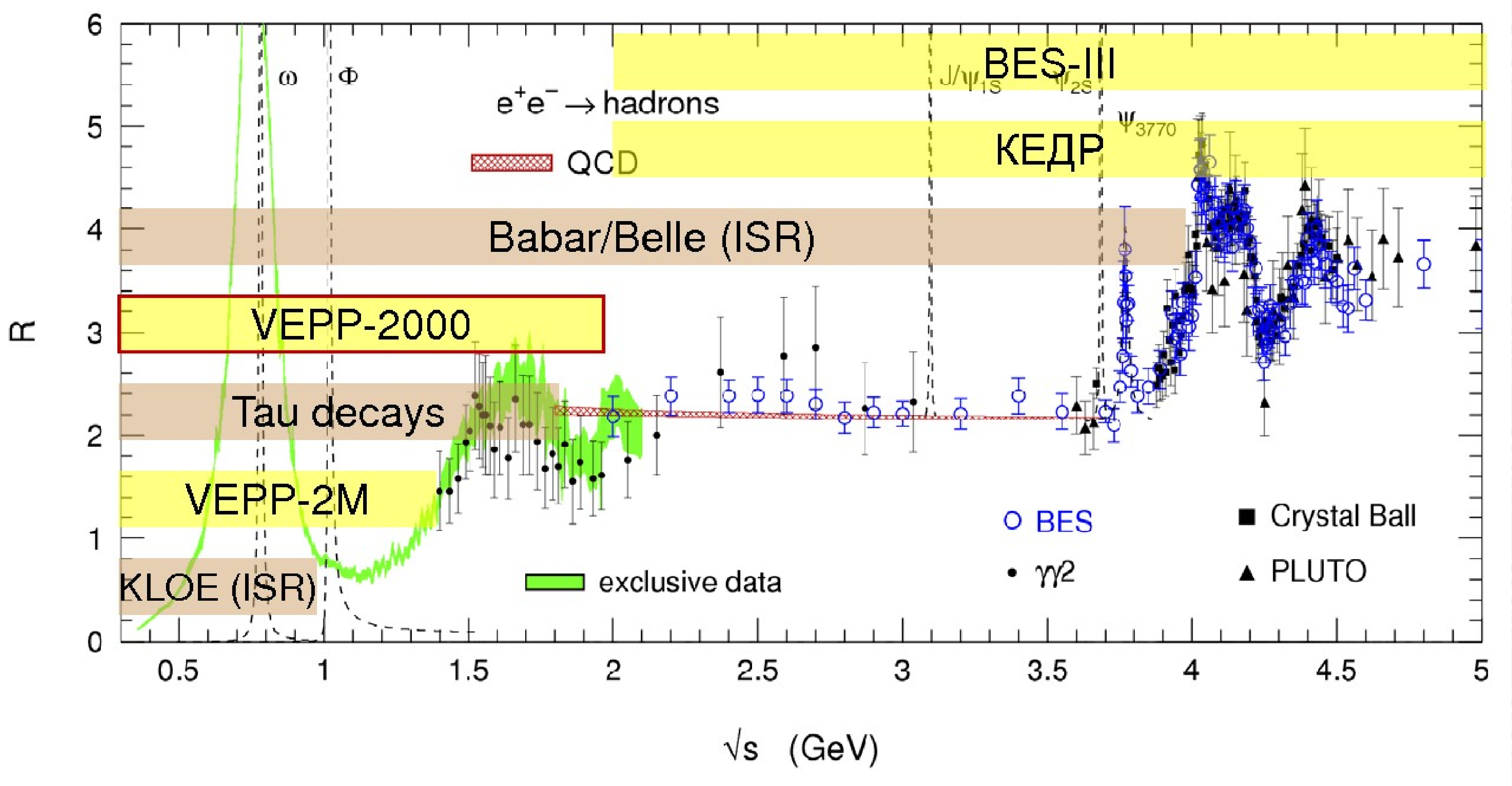


1 – vacuum tube, 2 – drift chamber, 3 – calorimeter BGO (680 crystals), 4 – Z-chamber, 5 – CMD-3 superconducting solenoid, 6 – calorimeter LXe (400 liters), 7 – calorimeter CsI (1152 crystals), 8 – magnet yoke, 9 – solenoids of VEPP-2000, (not shown) muon range and TOF systems

CMD3 data collecting history



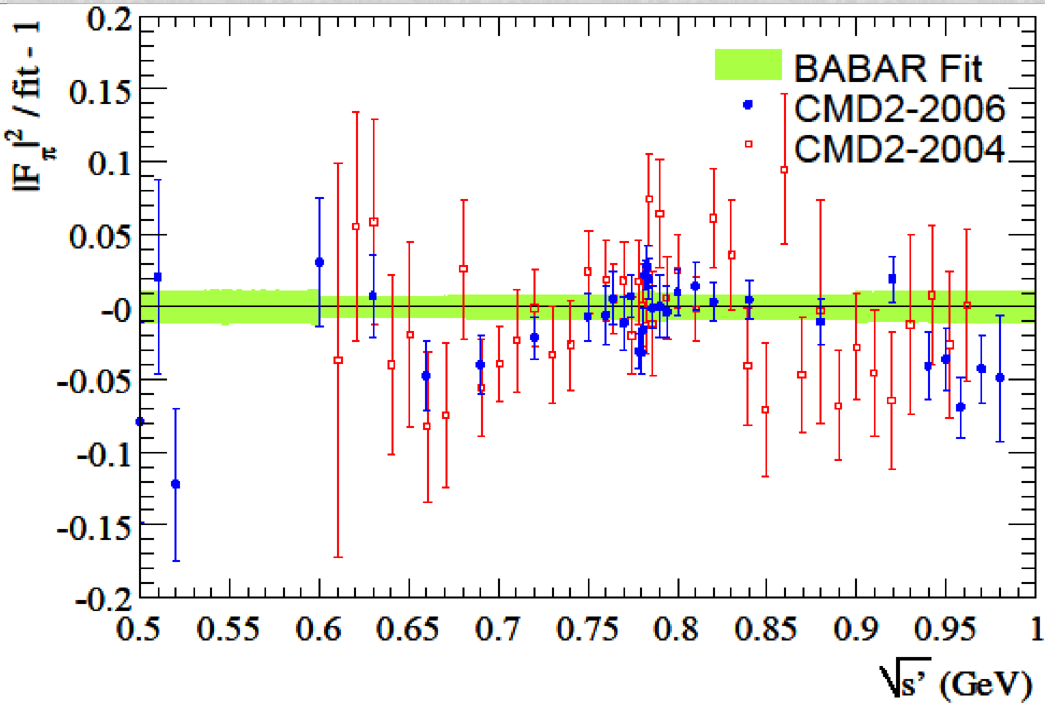
R(s) measurements at low s

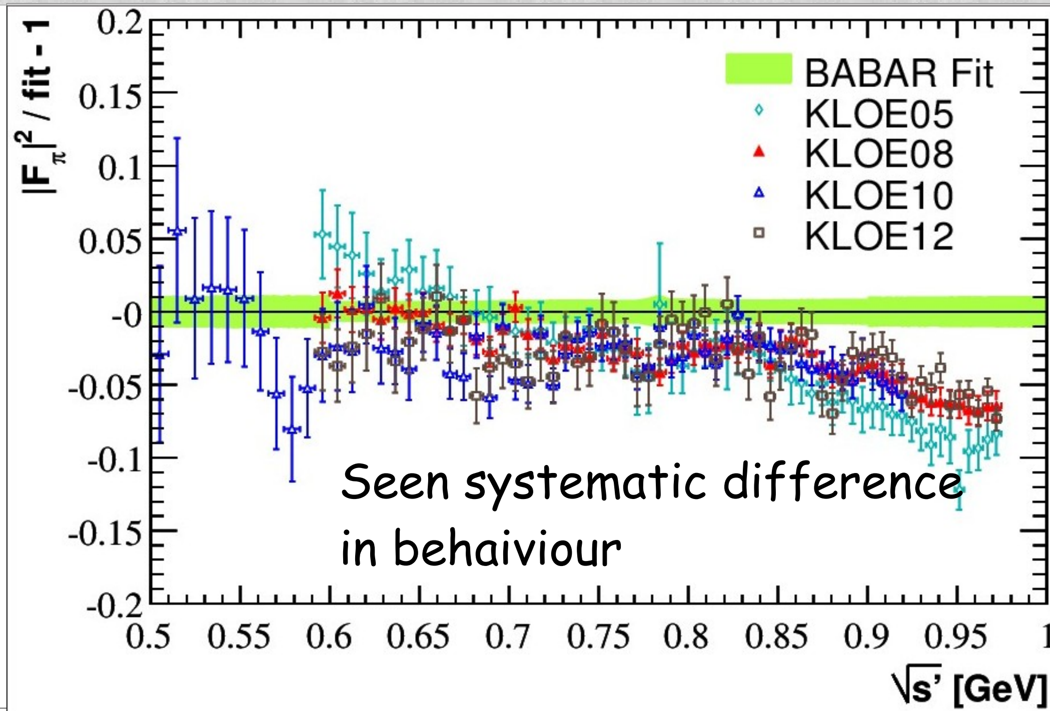


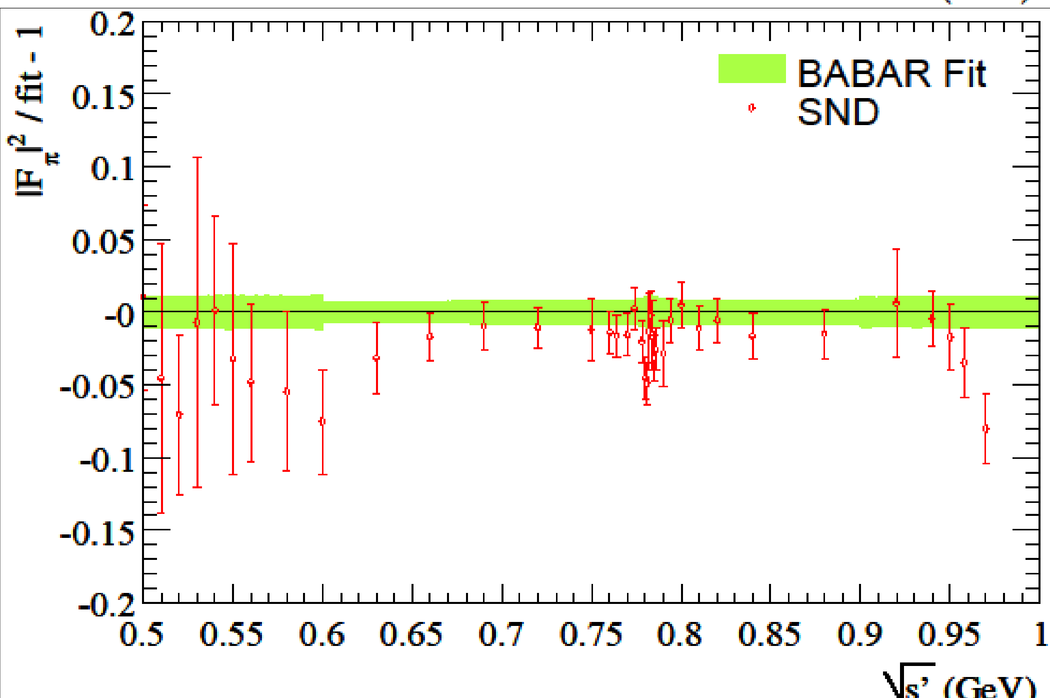
The value and the error of the hadronic contribution to muon (g-2) are dominated by low energy R(s) (<2GeV gives 92% of the value).

$\alpha_{QED}(M_Z)$ – half of error comes from 2E < 4 GeV

π+π- published data

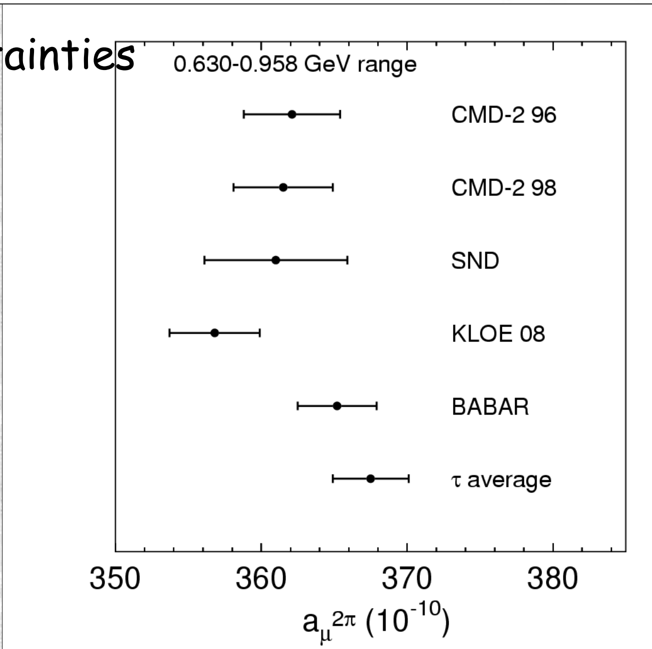






Systematic Uncertainties
(ρ-region)

B A B AR :0.5%
CMD2: 0.6-0.8%
SND: 1.5%
KLOE: 0.8%



B.Malaescu, Moriond 2014

SM prediction for muon g-2

ArXiv:1010.4180,arXiv:1105.3149

$a_\mu^{experimental} = (g-2)_\mu/2$

11 659 208.9 ± **6.3** x 10^{-10} world average

$a_\mu^{theory} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{hadron}$

QED contribution	11 658 471.808 ±0.015	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 ±0.2	Czarnecki et al
NLO hadronic	-9.8 ± 0.1	HLMNT11

Hadronic contributions

From measured cross-section by dispersion integral

From direct integration
Without model constraints
δa_μ

LO hadronic 694.1 **±4.3** x 10^{-10} HLMNT 11

main channels contribution to precision at $\sqrt{s}$<1.8 GeV

$\pi^+\pi^-$	505.65 ± 3.09
$\pi^+\pi^-2\pi^0$	18.62 ± 1.15
$\pi^+\pi^-\pi^0$	47.38 ± 0.99 (mostly from omega region)
$2\pi^+2\pi^-$	13.64 ± 0.36 (BaBar)
K^+K^-	22.95 ± 0.26 (BaBar)

from Isospin relations 5.98 ± 0.42 for not measured $KK\pi, KK2\pi, 2\pi4\pi^0, 2\pi3\pi^0$

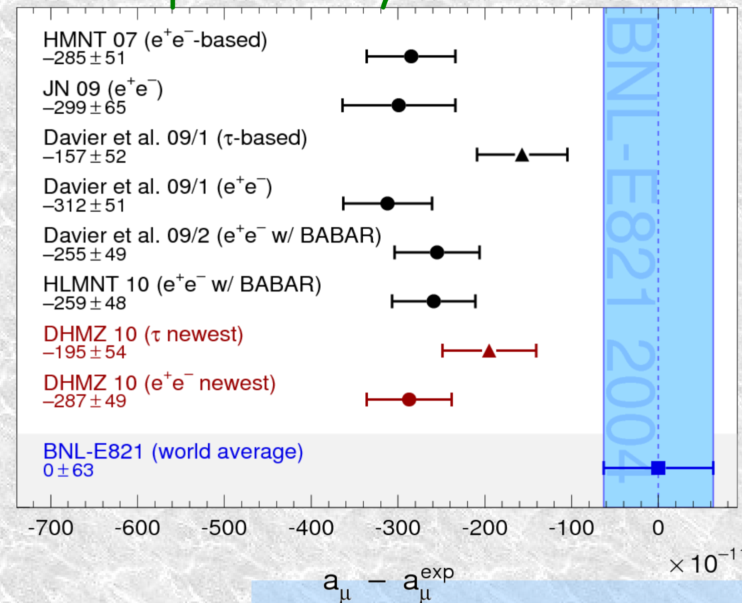
(or 12.46 ± 0.76 for $\sqrt{s}$<2 GeV) (contribution at 1.5-3σ of total error - crucial if something is wrong with used isospin relations)

Rqcd[2-11.09GeV] 41.19 ± 0.82

Light-by-light 10.5 **± 2.6** Prades, de Rafael & Vainshtein need more theory input, probably with help of experimental transition form factors

Theory TOTAL **± 4.9**

Δ Exp - Theory~ 3.3–3.6σ



New g-2 experiments at FNAL and J-PARC have plans to reduce error to **1.5x10^{-10}**

R measurement: systematic errors

What systematic error can be achieved for R measurement at CMD-3?

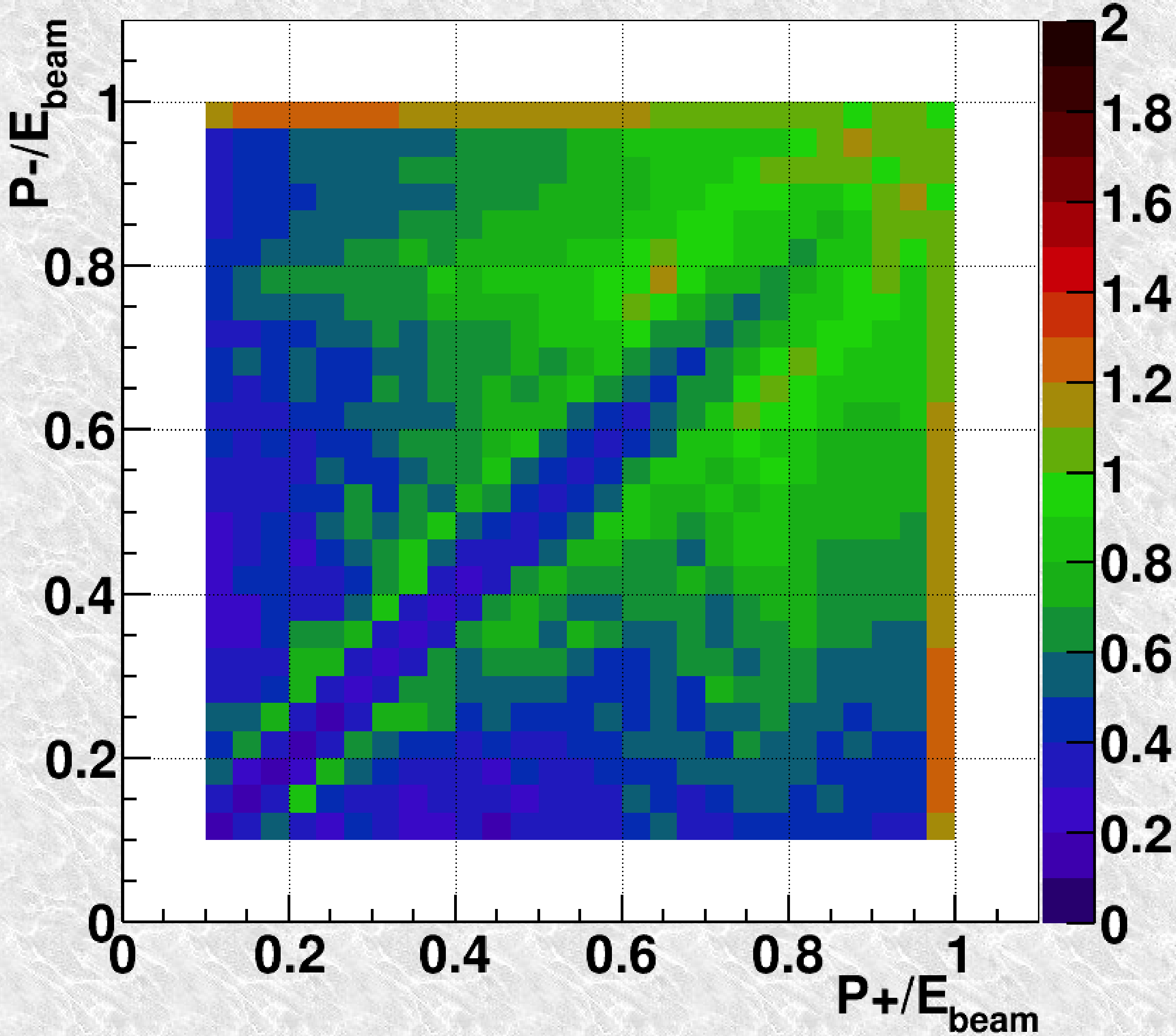
Source of error	CMD2, 2π $\sqrt{s}<1$ GeV	SND, 2π $\sqrt{s}<1$ GeV	CMD2,4π $\sqrt{s}>1.1$ GeV	CMD3, 2π $\sqrt{s}<1$ GeV	CMD3,4π $\sqrt{s}>1.1$ GeV
Event separation	0.2-0.4%	0.5%	2% (cuts)	0.2%	1% (cuts)
Fiducial volume	0.2%	0.8%	3% (model)	0.2%	2% (model)
Energy calibration	0.1-0.3%	0.3%	1%	0.1%	
Efficiency correction	0.2%-0.5%	0.6%	2% (tr+bg)	0.1%	1% (tr+bg)
Pion losses (decay, NI)	0.2%	0.2%		0.1%	
Other		0.5%	2%		0.3% (lum)
Radiative corrections	0.3-0.4%	0.2%	1%	0.1%	1%
Total syst.	0.6-0.8%	1.3%	5%	**0.35%**	**2.5%**
Stat.+Syst.	0.7%	1.5%	7%		

BabaYaga @ NLO vs MCGPJ

Ebeam = 391.48 MeV

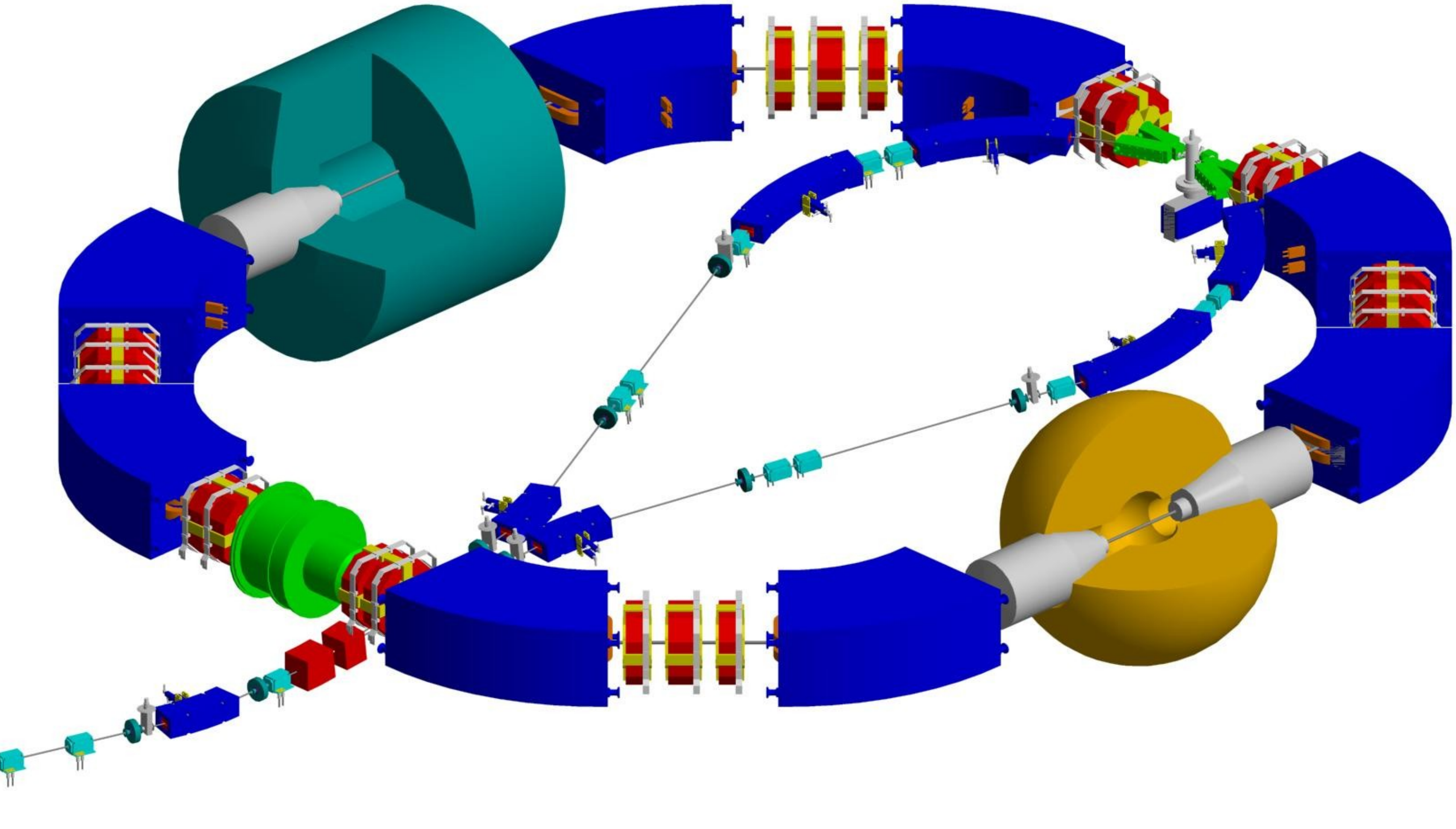
Comparison of momentum spectrum from generators

$\frac{\partial^2 \sigma}{\partial p^+ \partial p^-}$ BabaYaga/MCGPJ

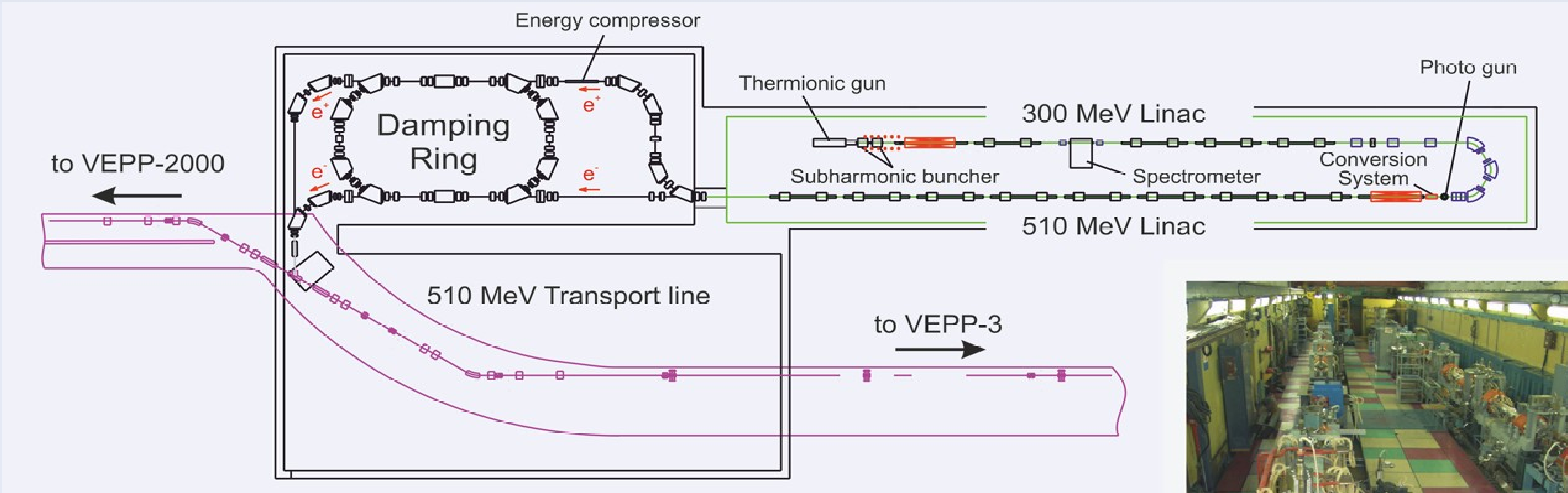


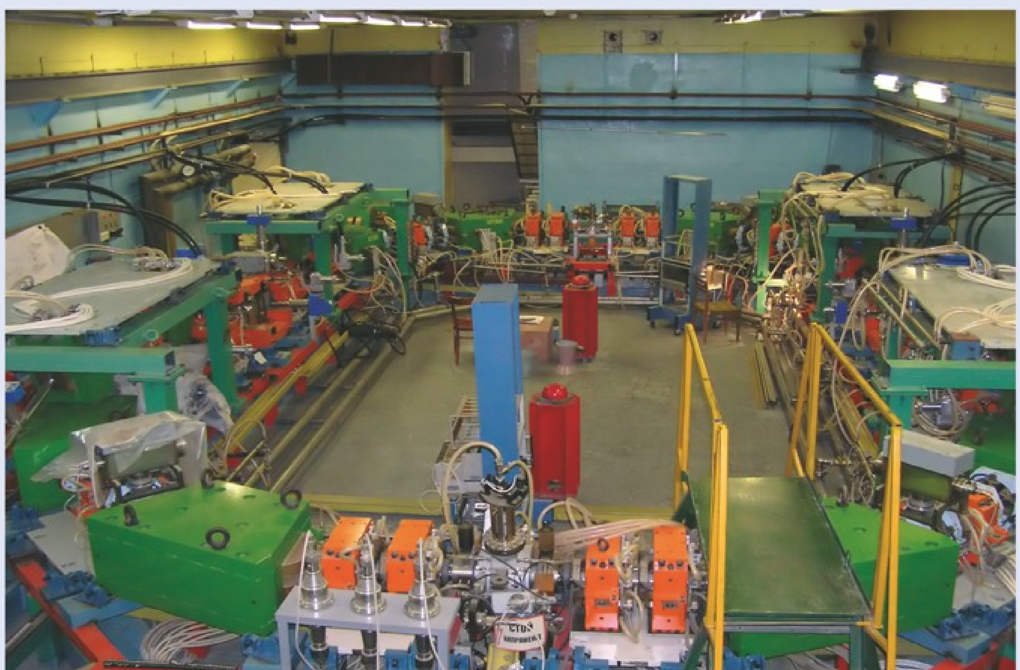
VEPP-2000 parameters

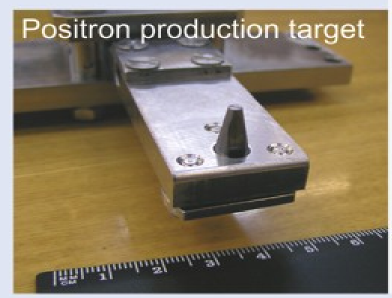
L = 24.39 m
facc= 172 MHz
Vacc= 120 kV
E=0.2 – 1 GeV
Bbend = 2.4 T
Bsol = 13 T
β*=2 – 10 cm
σs = 3 cm
ε=1.4•10-7mrad
νx,z= 2.1; 4.1
α= 0.036
ξ = 0.15
N± = 1011
L=1•1032cm-2s-1



VEPP-5 INJECTION COMPLEX





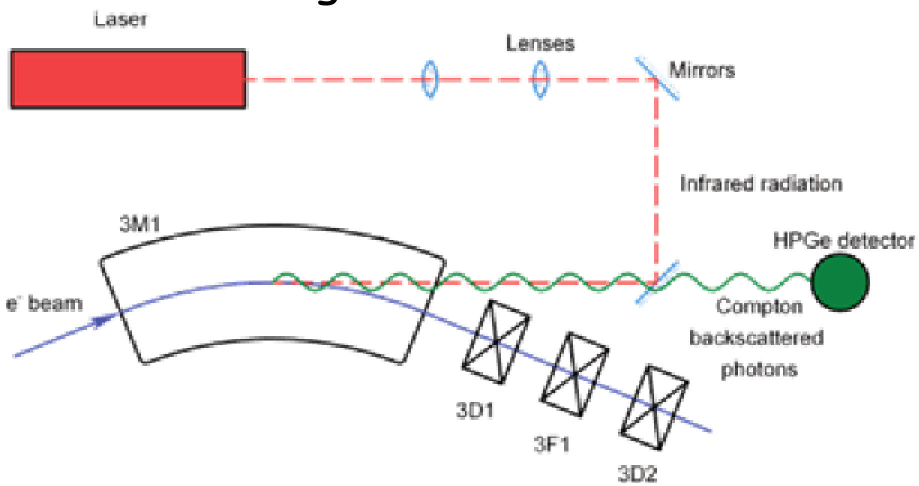


Parameters at E_{beam} = 510 MeV

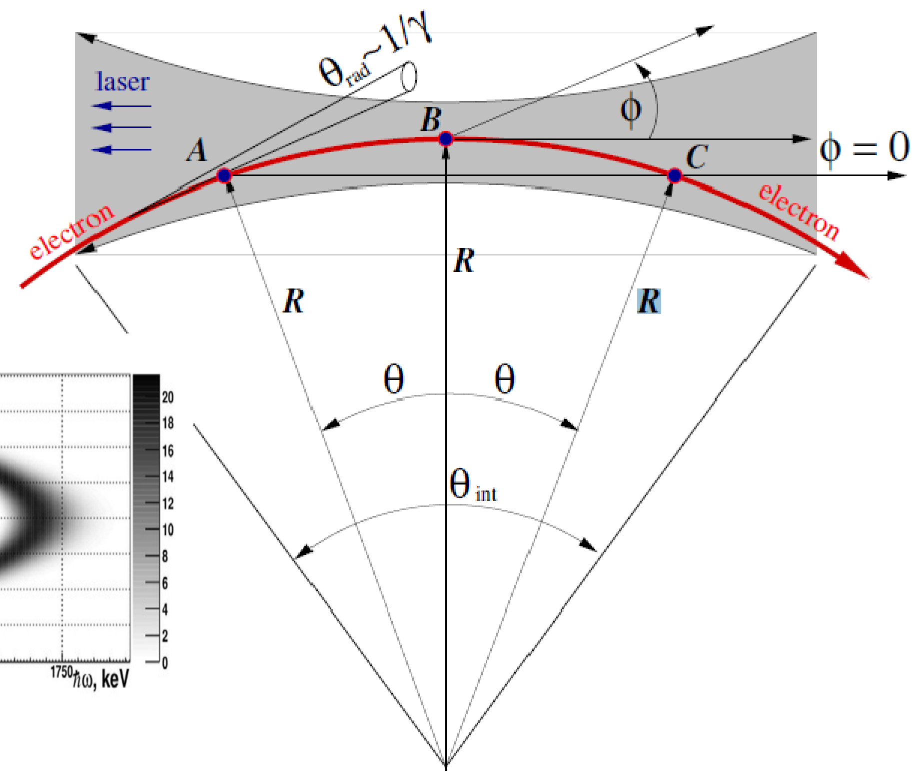
Number of electrons per bunch	$2 \cdot 10^{10}$
Number of positrons per bunch	$2 \cdot 10^{10}$
Repetition rate	1 Hz
Electron bunch energy spread	0.07%
Positron bunch energy spread	0.07%
Vertical emittance	$5 \cdot 10^{-9}$ m·rad
Horizontal emittance	$23 \cdot 10^{-9}$ m·rad

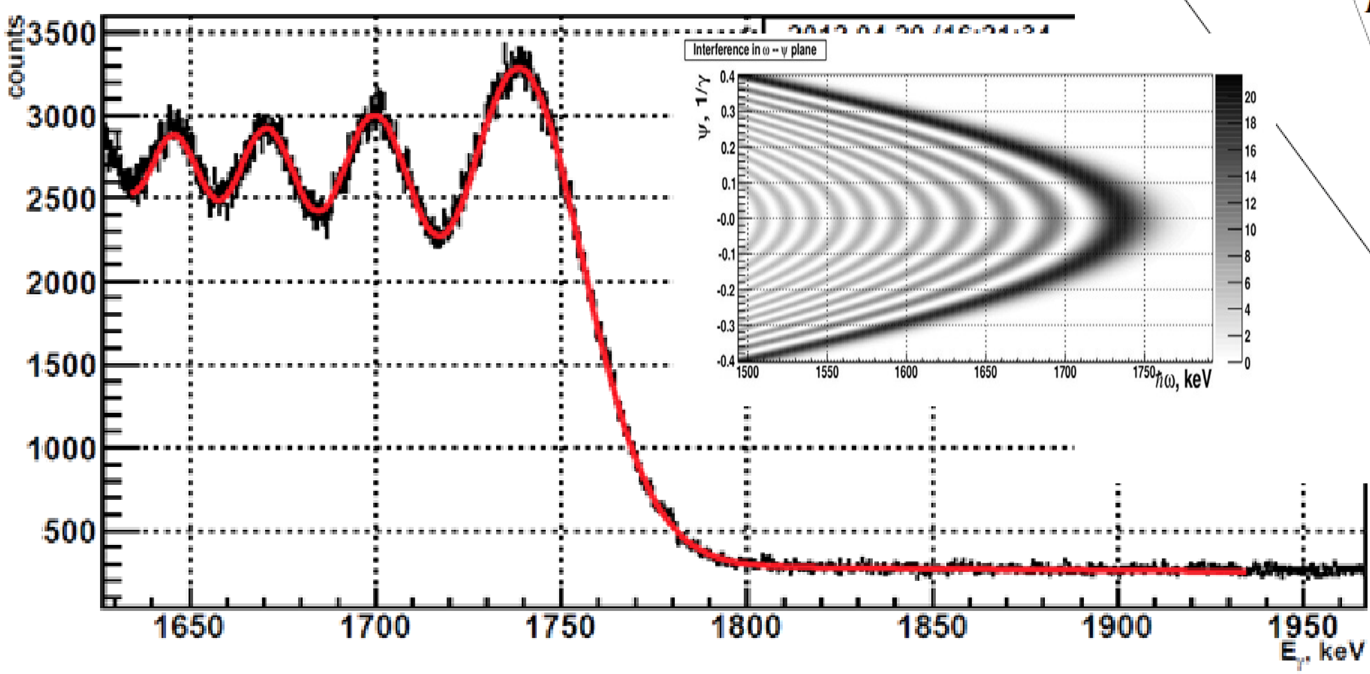
Energy measurement by Compton back scattering

Starting from 2012, energy is monitored continuously using compton backscattering



Излучение из точек A и C под углом φ = 0 интерферирует



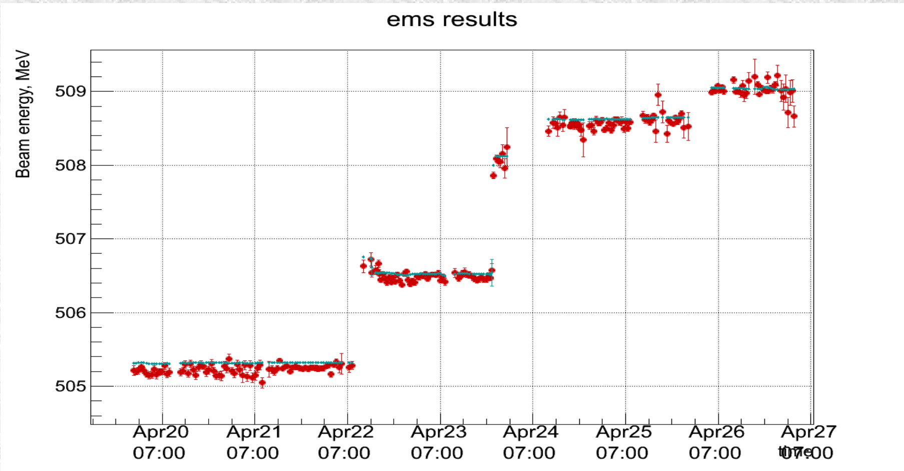


E = 993.662 ± 0.016 МэВ

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

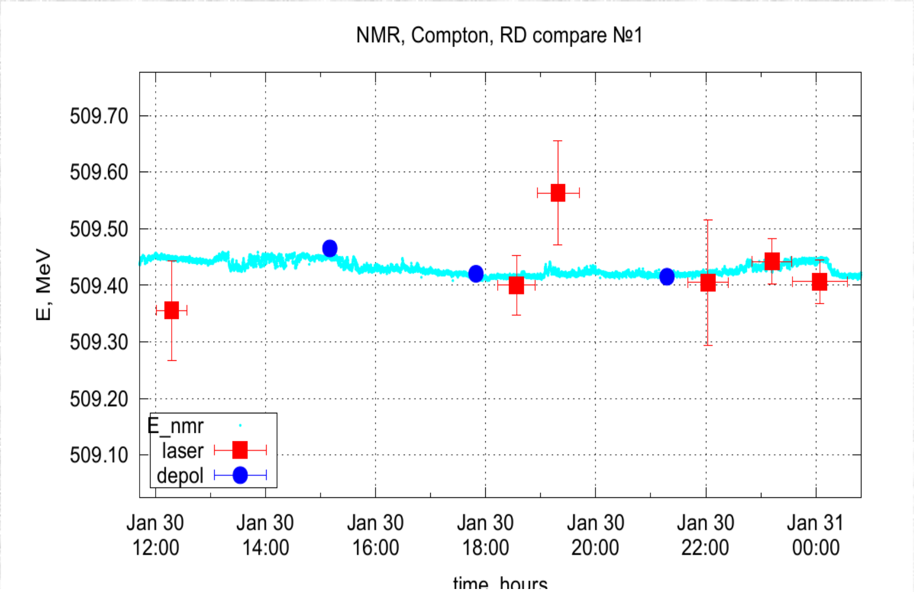
Beam energy measurement at VEPP-2000

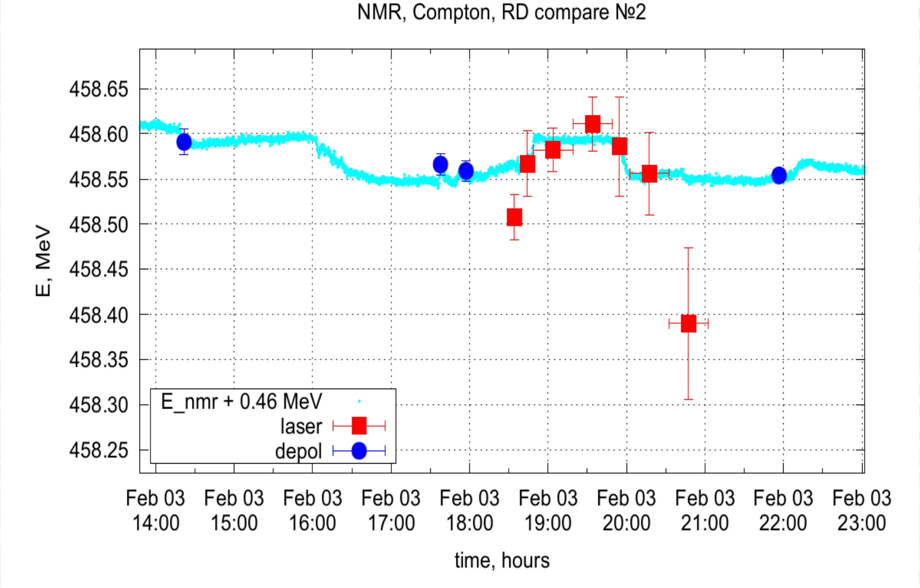
- Magnetic field control in bending magnets
  - 8x2 NMR probes, continuous control
  - Absolute calibration using:
    φ-meson (1019.455 ± 0.020 МэВ),
    ω-meson (782.65 ± 0.12 МэВ).
- Measurement of photon energy from back scattering laser light
  - Installed in 2012.
  - Needs beam current (20 мA), ~20-50 keV accuracy in 10 min
  - Energy control during data taking.



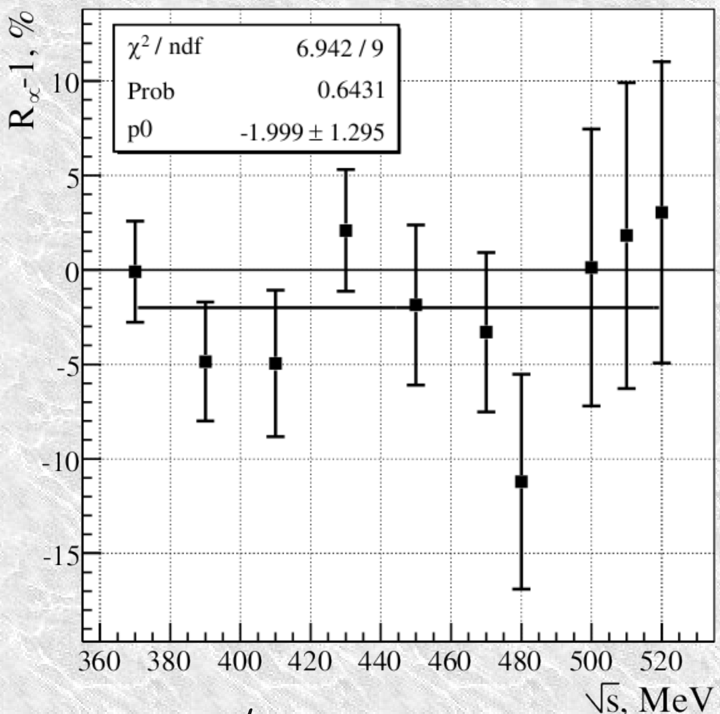
- Resonance depolarization method
  - Very high accuracy (δE/E < 10-5).
  - Special configuration of VEPP-2000: "warm" optics without CMD-3 field.

Methods comparison:

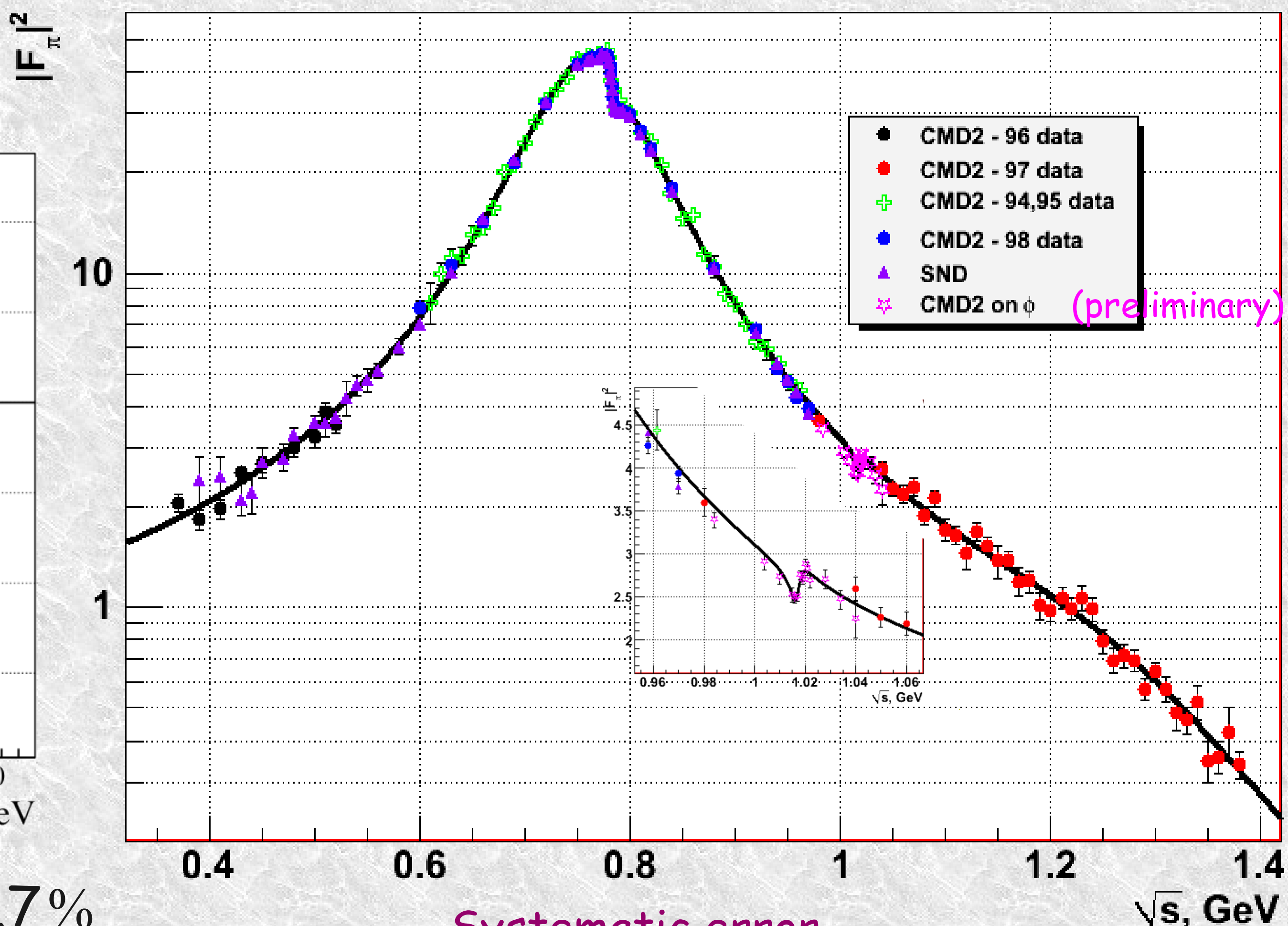




Pion formfactor



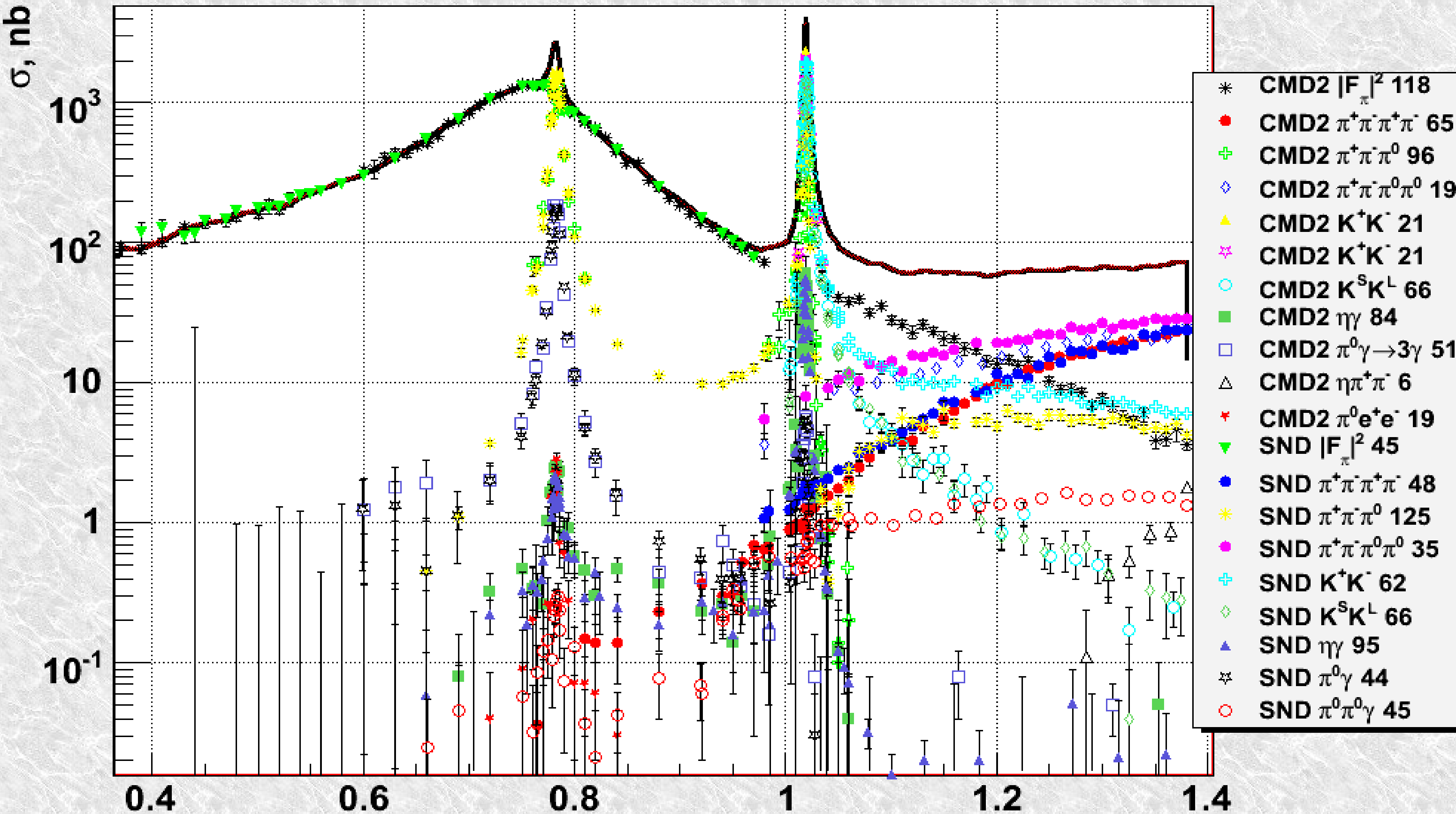
$$\frac{\sigma^{measuared}_{\mu^+\mu^-}}{\sigma^{QED}_{\mu^+\mu^-}} - 1 = -2 \pm 1.3 \pm 0.7\,\%$$



Systematic error

CMD2	0.7%	0.6% (95)/ 0.8% (98)	1.2-4.2%
SND	3.2%	1.3%	

Inclusive Hadronic Cross-Sections with CMD2&SND



Combined precision of R(s) from CMD2&SND

Systematic error:	~0.6-0.7%	1.0%	0.6%	1.5%	1.5 -- 3.5 %
Total error:	~ 6 -- 1%	1.5%	1--2%	2.0%	2.5 -- 3.5 %

The uncertainty in a_μ(had) was improved by factor 3 as the result of VEPP-2M measurements