Status on pion form factor at CMD-3

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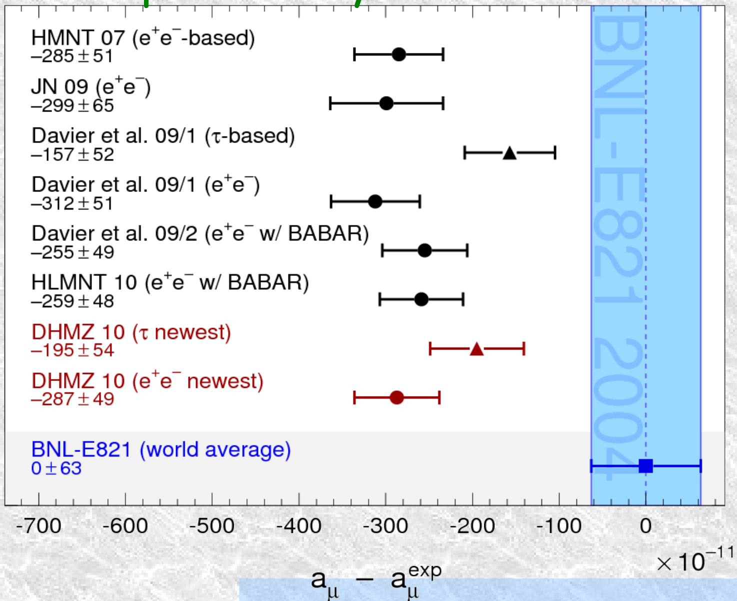
SM prediction for muon g-2

ArXiv:1010.4180,arXiv:1105.3149

The anomalous magnetic moment of the muon

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

Δ Exp - Theory~ 3.3–3.6σ



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

Theoretical prediction δa_μ = ± **4.9** × 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

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

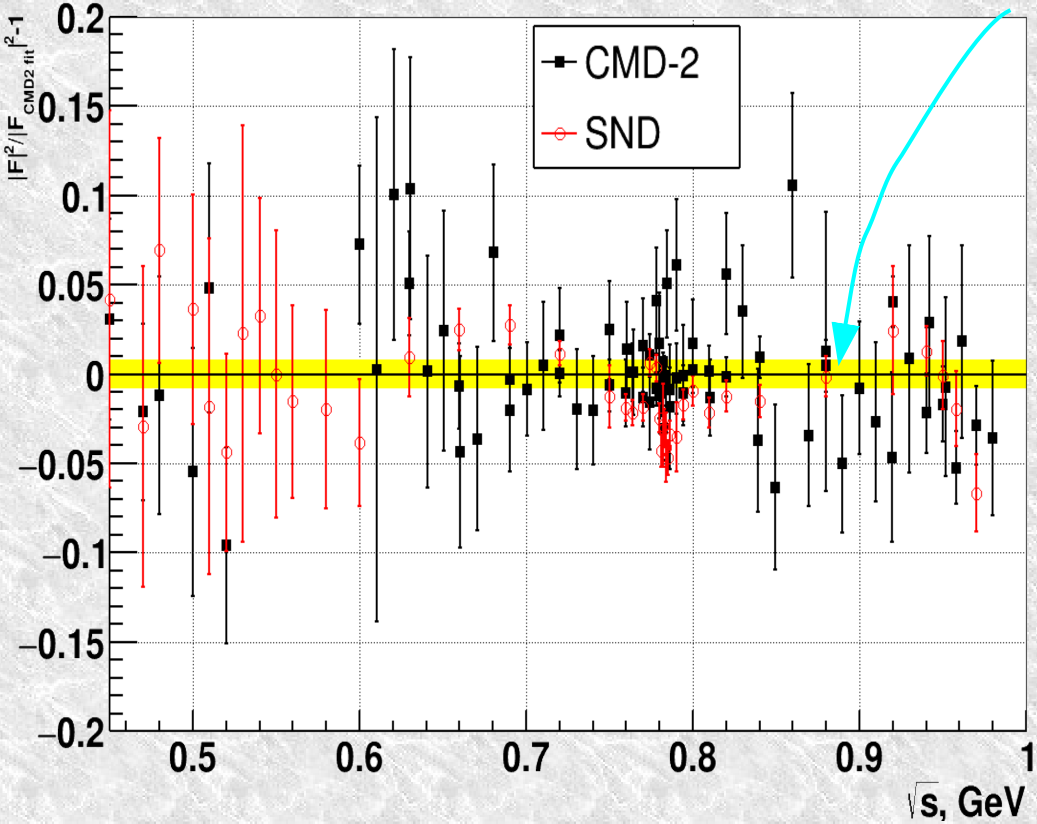
Light-by-light 10.5 **± 2.6** Prades, de Rafael & Vainshtein need more theory input, with help of experimental transition form factors

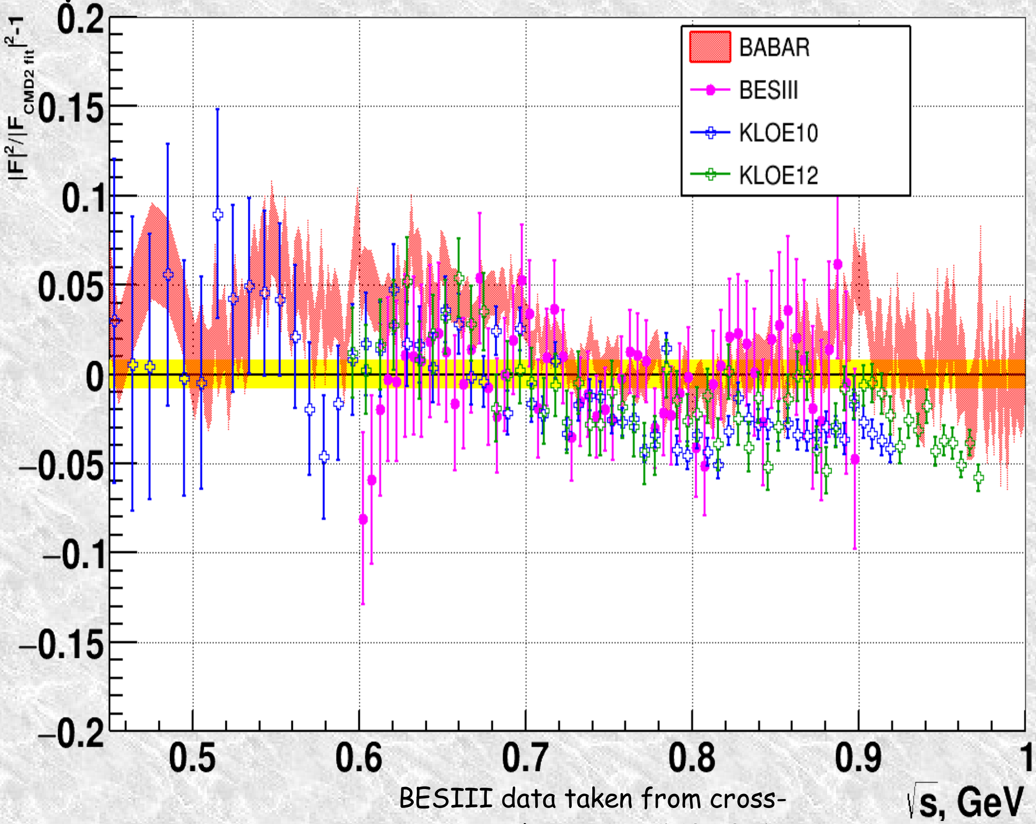
$\pi^+\pi^-$ gives the main contribution to hadronic value and overall theoretical precision of a_μ

Published cross section e+ e− → π+ π−

Relative to CMD-2 fit
yellow band - systematic value

Points, red band:
only statistical error

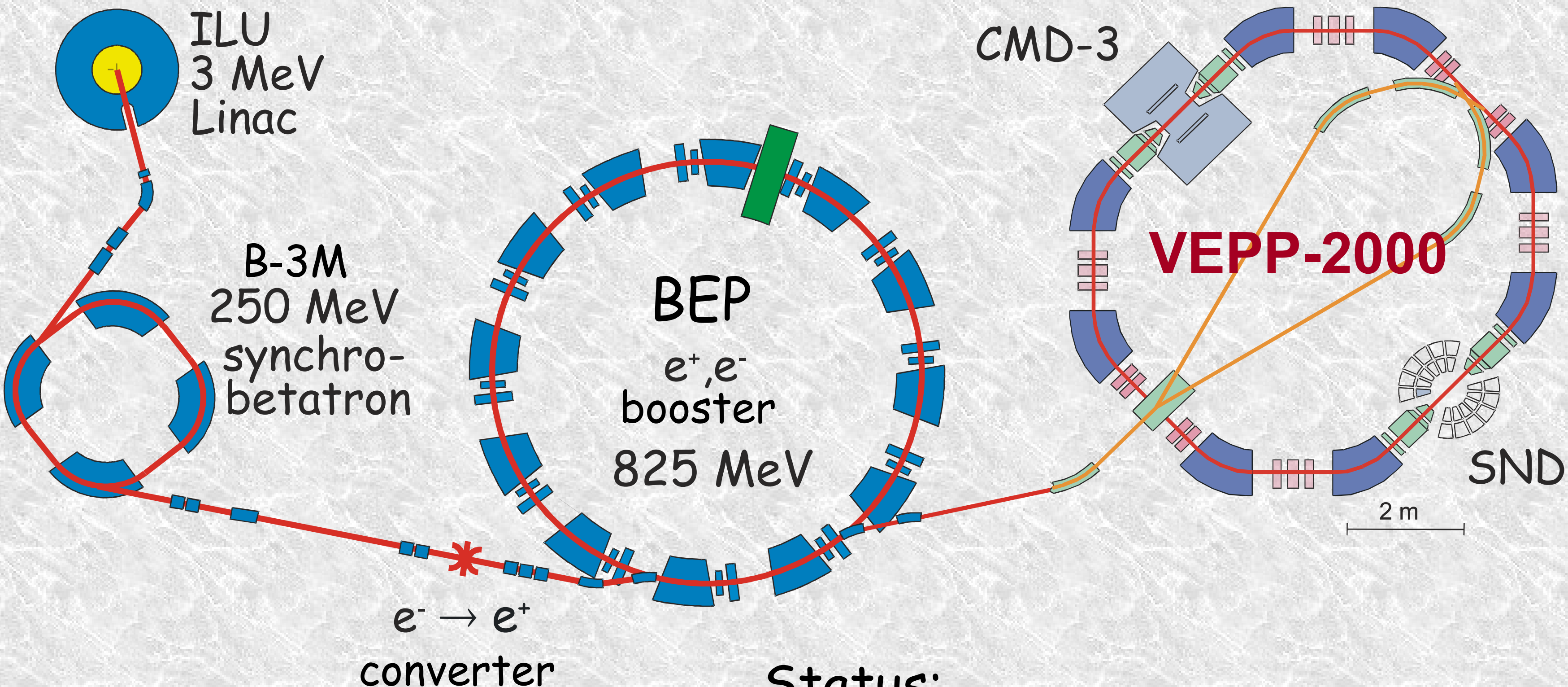




BESIII data taken from cross-section values arXiv:1507.08188v2

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:

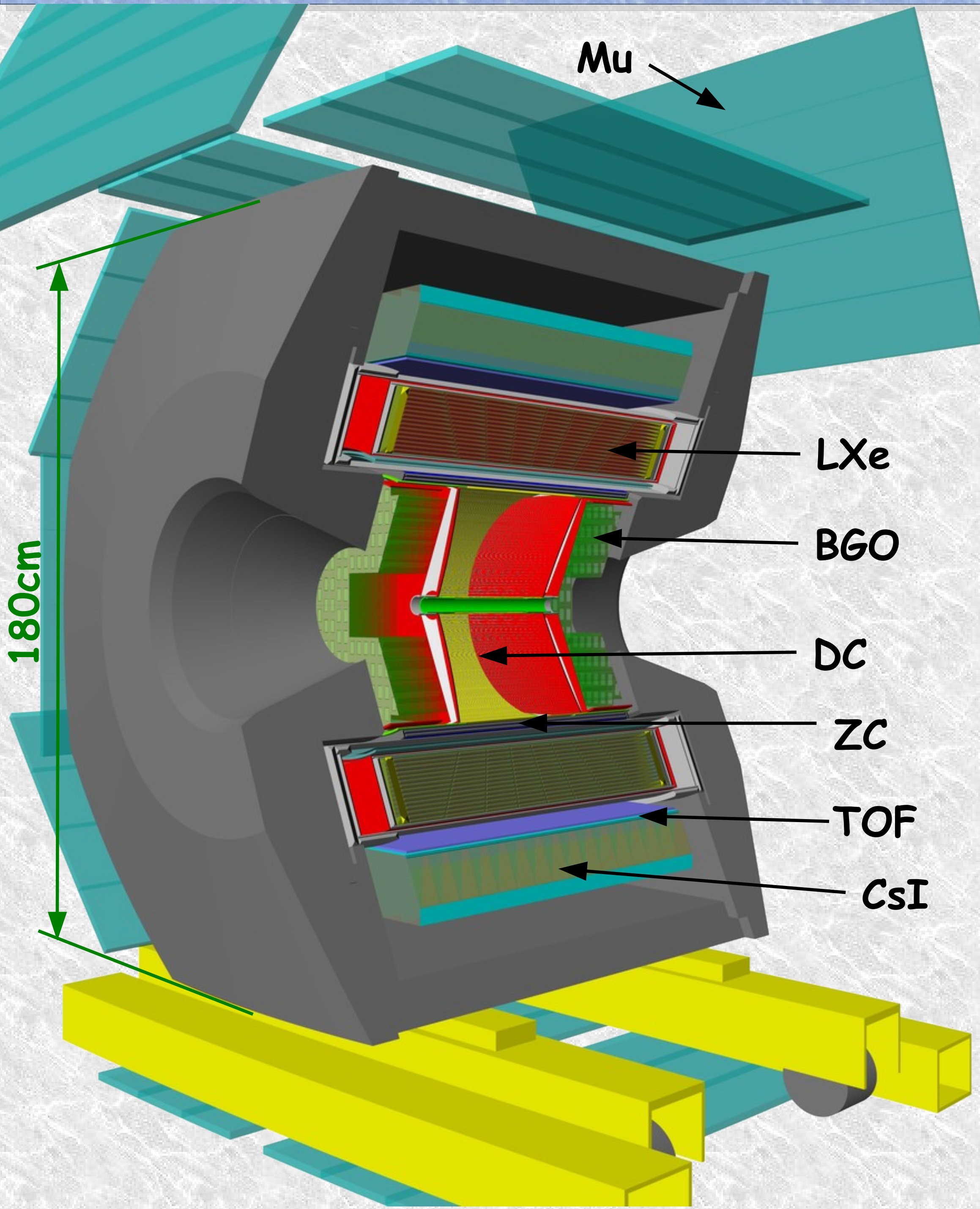
2010 – start of experiments

2013-2015 - upgrade of positron injection facility

Plans:

≈100 pb^{-1} per detector per year

CMD-3 Detector

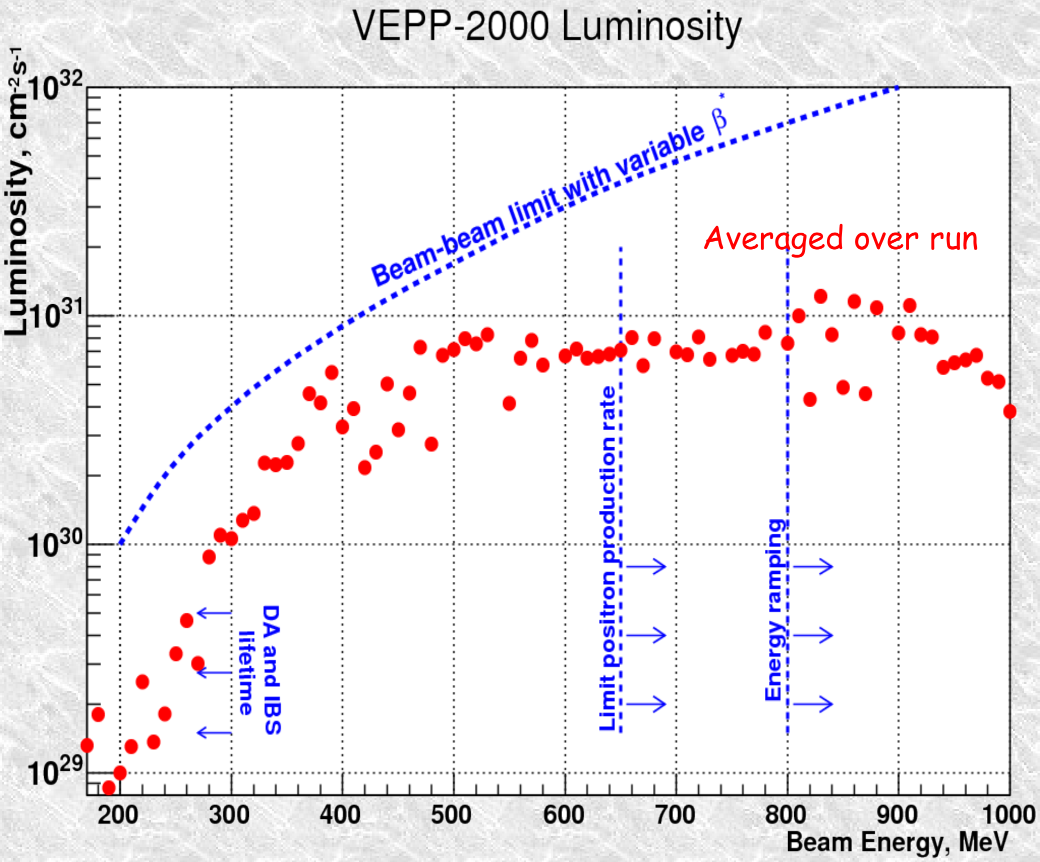


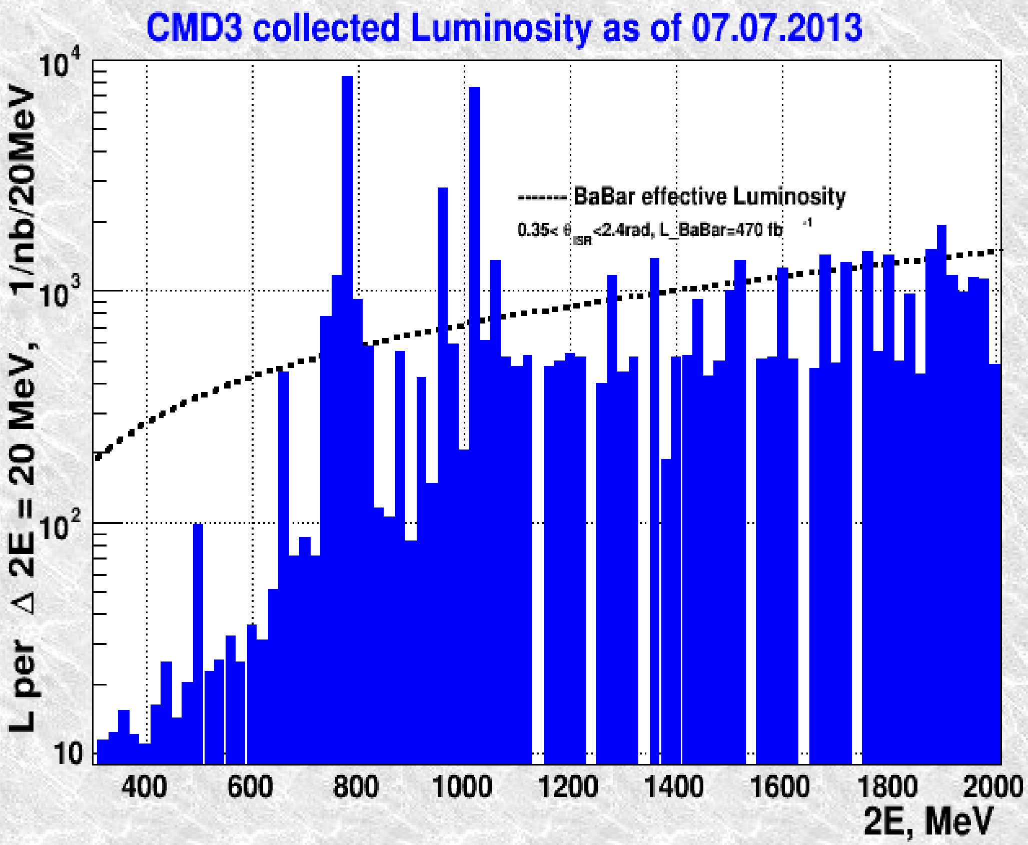
Advantages for this analysis compared to previous CMD-2:

✗ 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 $\sqrt{s}$=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

Event selection

- Two charged collinear tracks:

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

$$Q_1 + Q_2 = 0$$

- Vertex position close to interaction point:

$$\rho_{average} < 0.3\,cm, \quad |Z_{average}| < 5\,cm$$

$$|\Delta\rho| < 0.3\,cm, \quad |\Delta Z| < 5\,cm$$

- Fiducial volume inside good region of DCh:

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

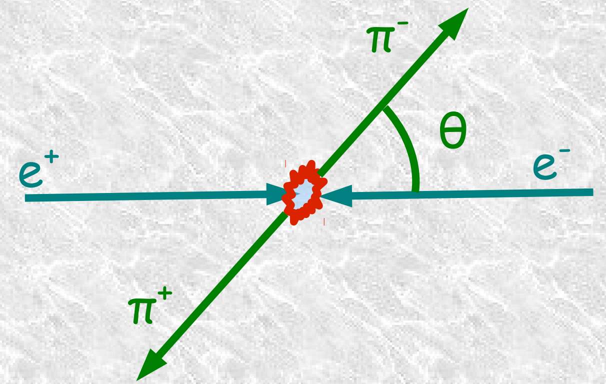
- Quality of selected tracks:

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

- 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 $\sqrt{s} < 1$ GeV

Event separation

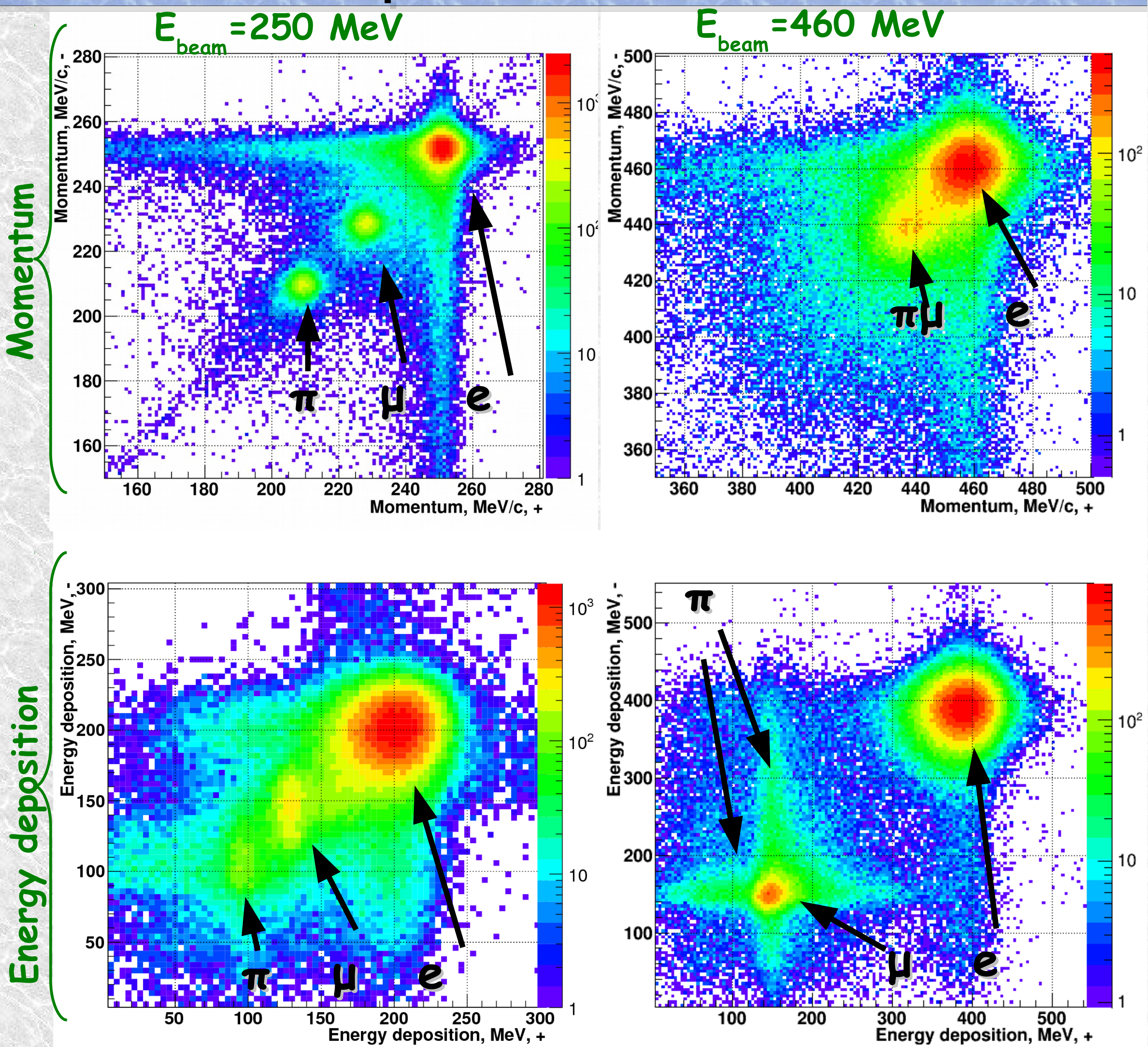
Particle ID can be done by momentum or energy deposition

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

At higher energies Electron shower in calorimeter far away from MIPs

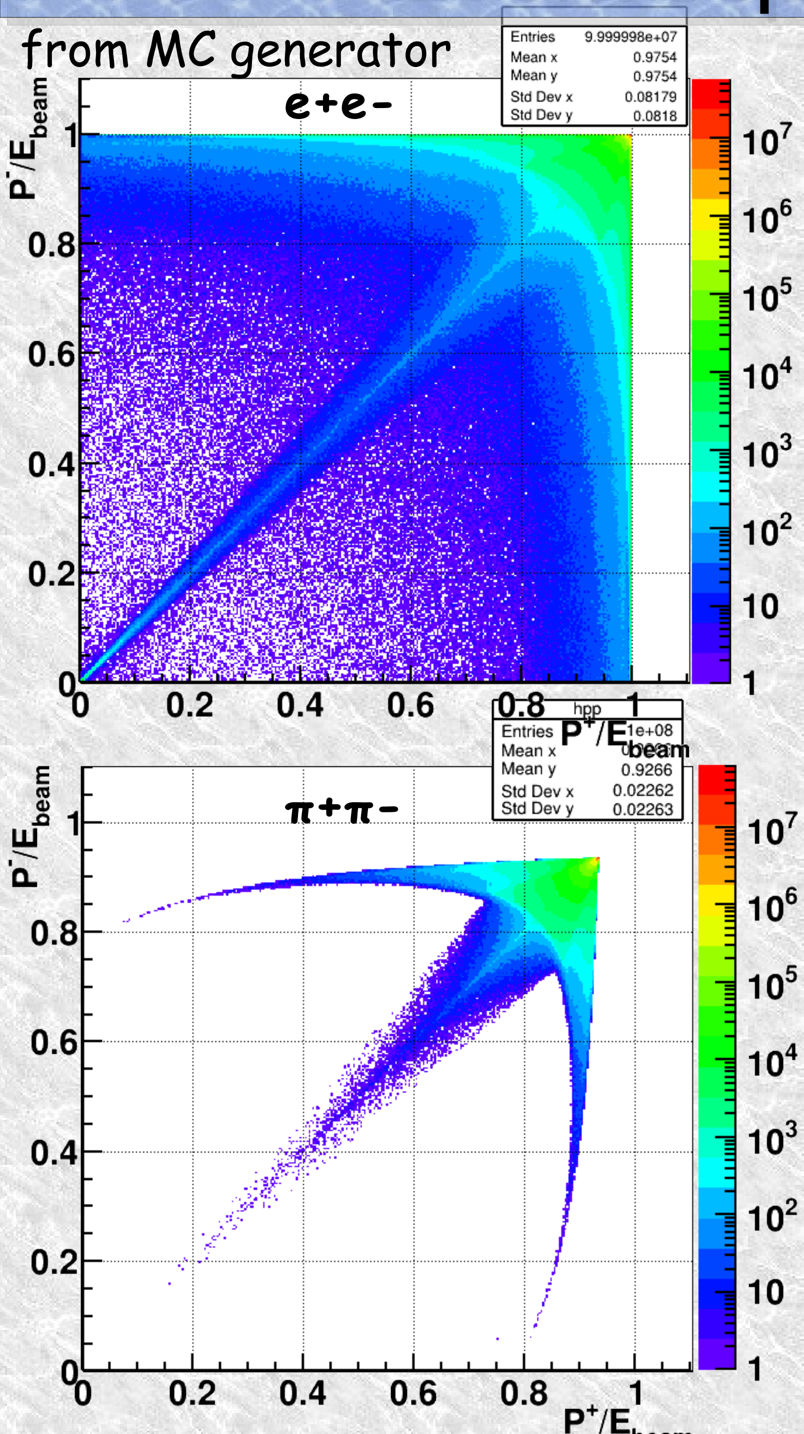
Both methods can be used separately for cross-check

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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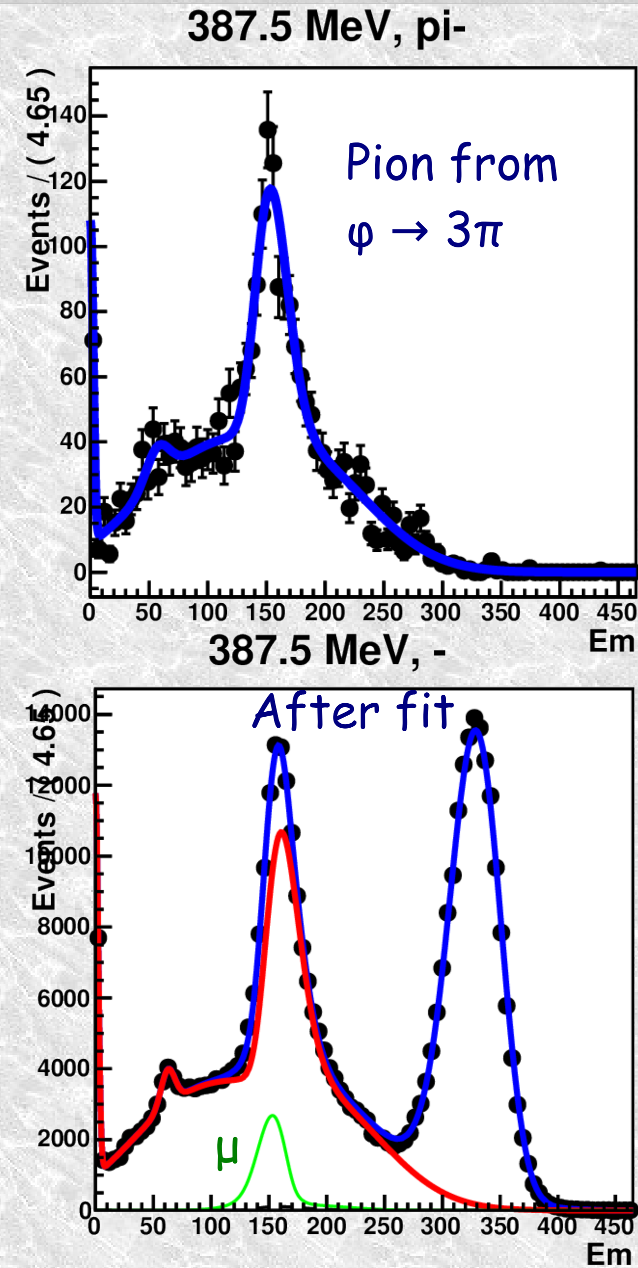
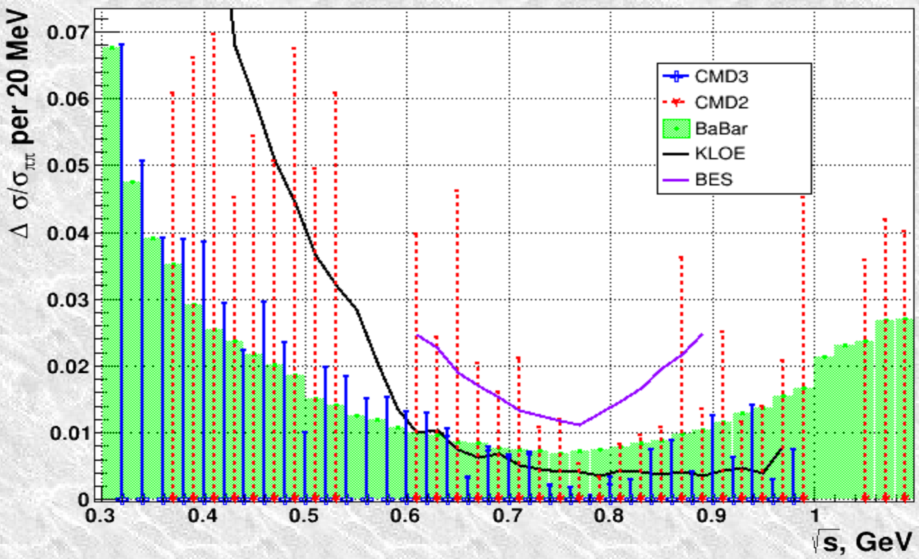
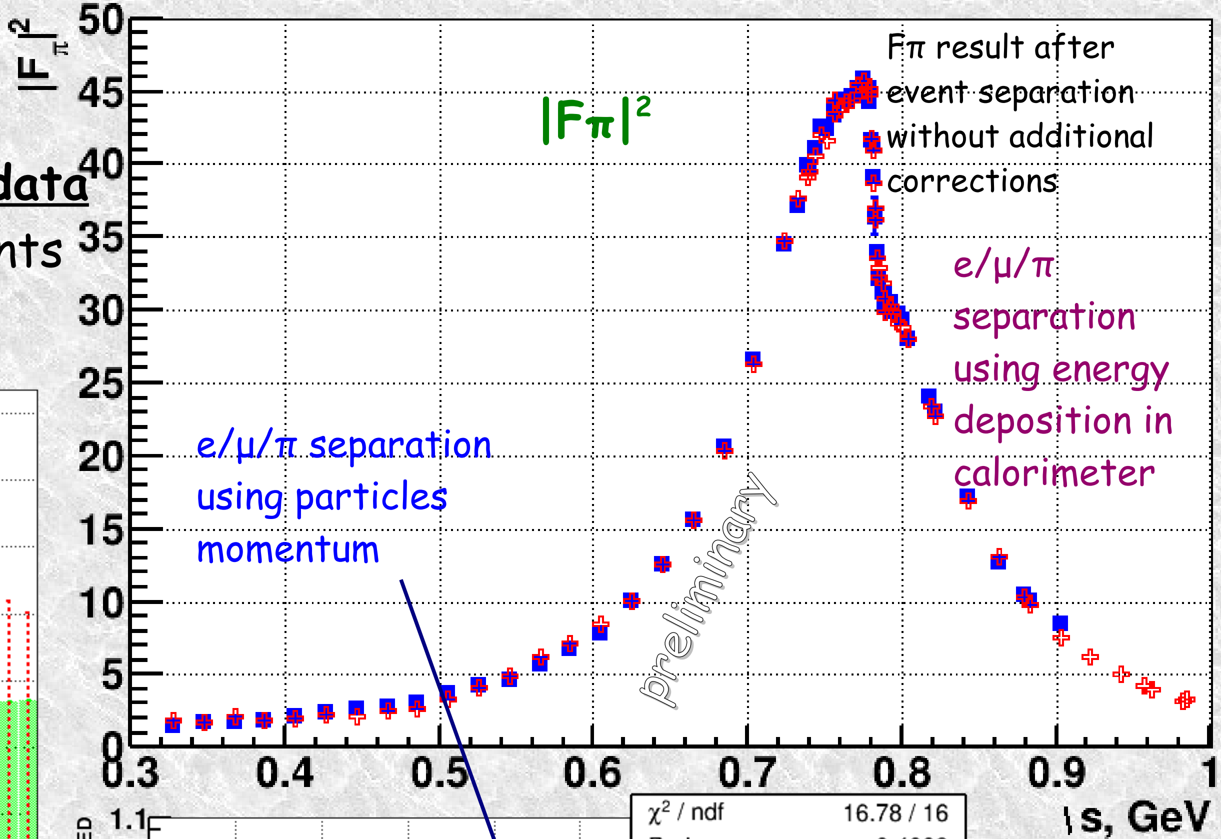
As plans: to exploit information about shower profile (energy deposition in 7 layers of LXe, + CsI)
Neural net can be used for event classification

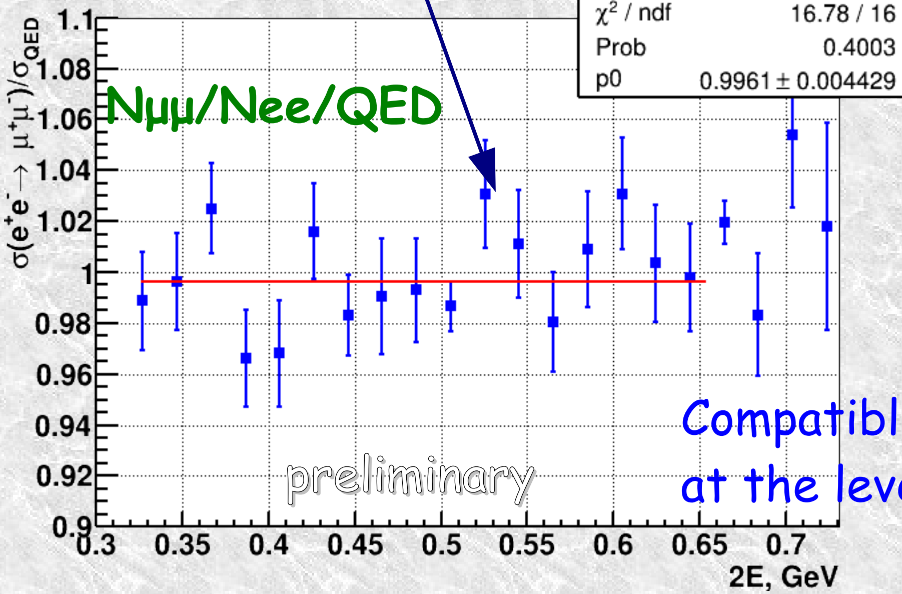


e+e- -> π+π- by CMD-3

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







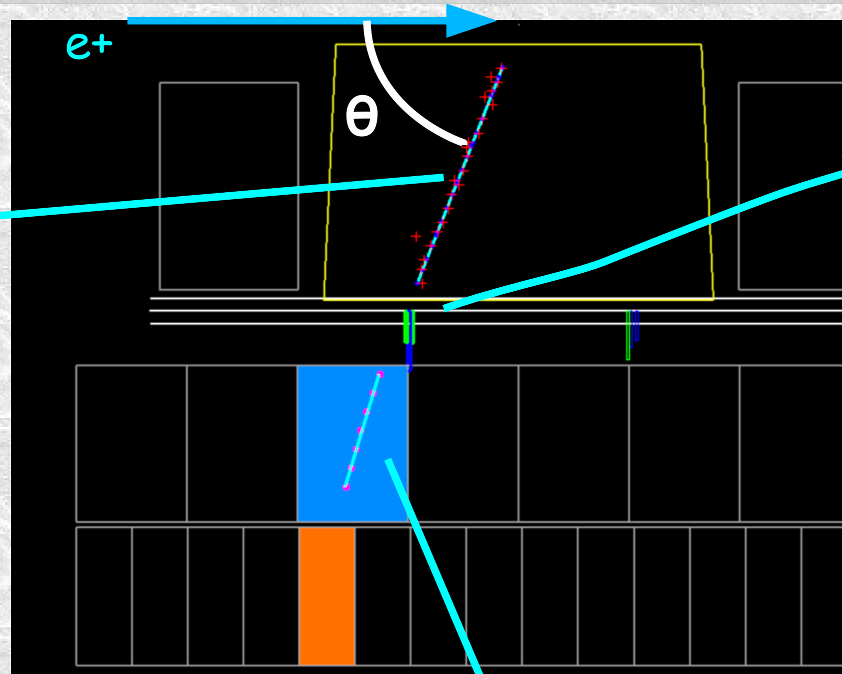
Compatible with QED at the level of 0.5 %

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

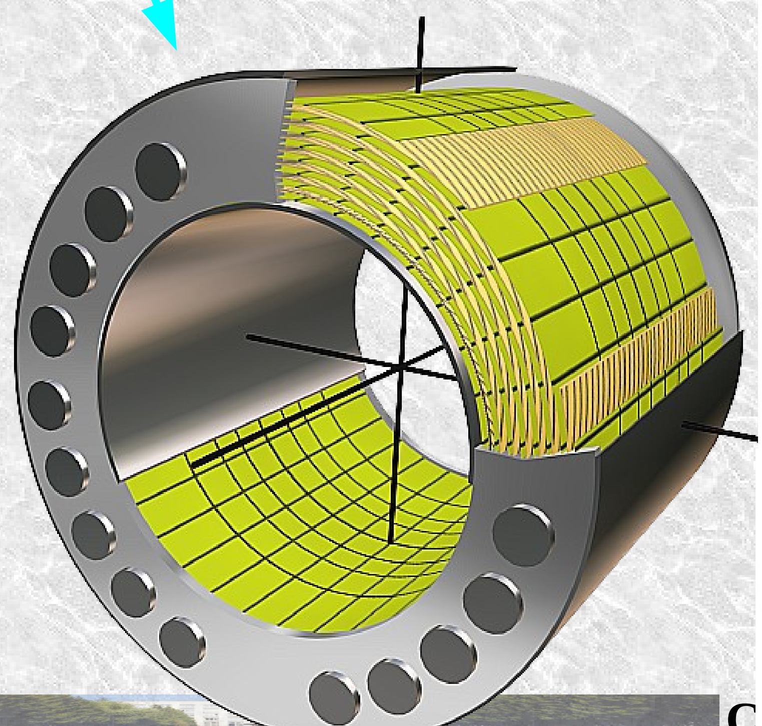
ionization collected in 7 layers with cathode strip readout,

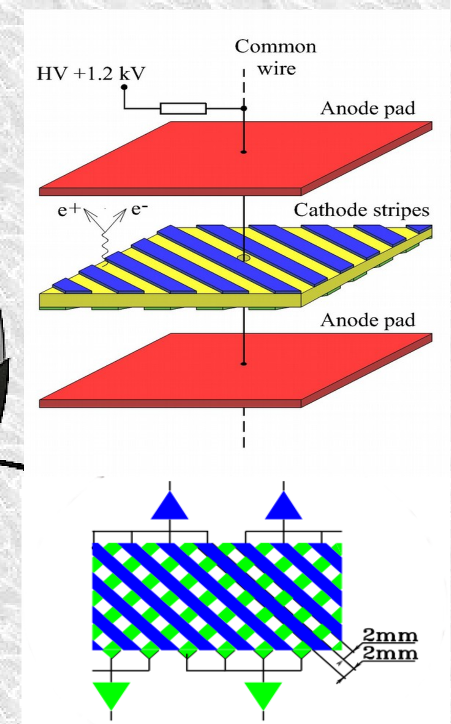
combined strip size: 10-15 mm

Coordinate resolution ~ 2mm

Both subsystem with strip precision < 100 μm

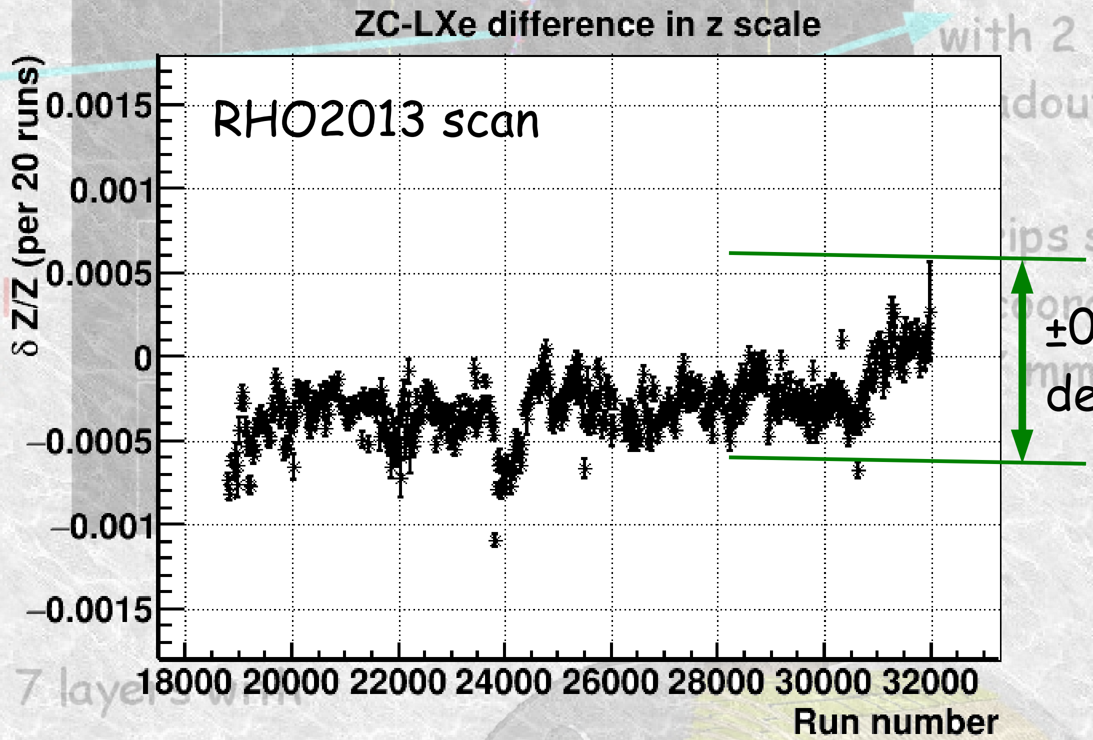
give <0.1% in Luminosity determination





Precision of fiducial volume

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(α) + 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(α) 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>

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

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

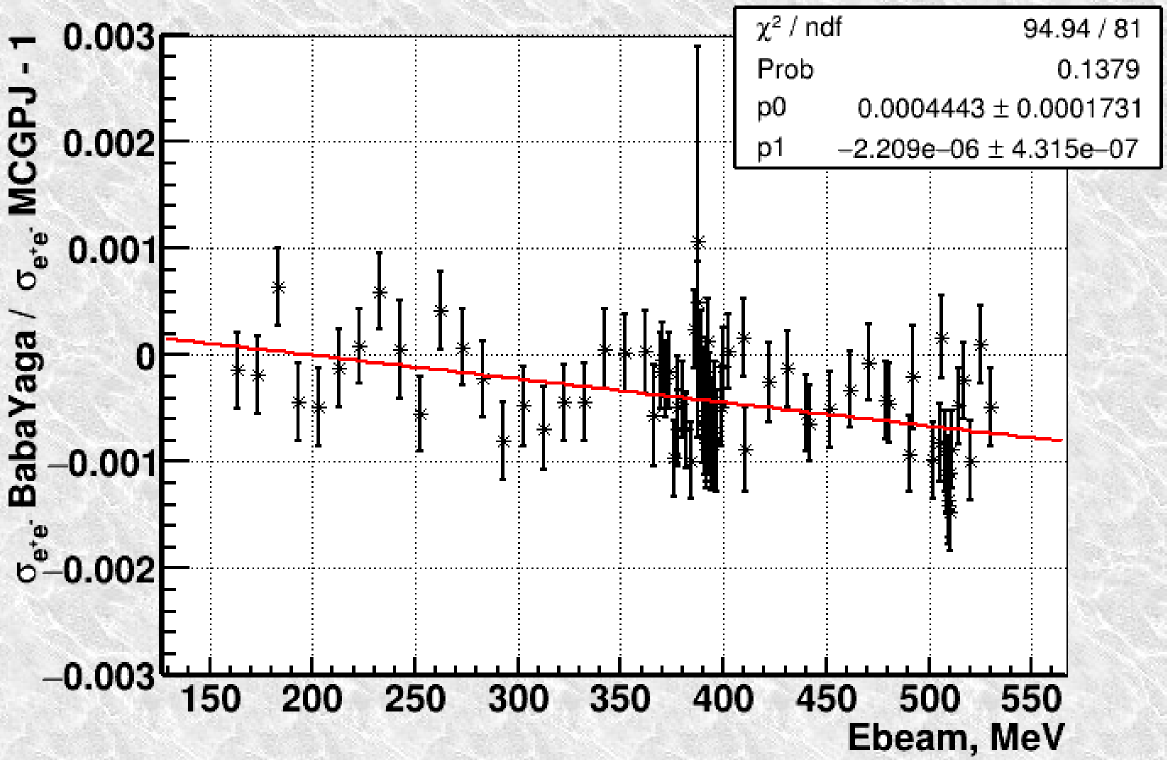
$P^{+-} >0.45\ E_{beam}$

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

MCGPJ : 751.671 +- 0.034 nb

BabaYaga@NLO : 751.218 +- 0.059 nb

Δ ~ 0.06%



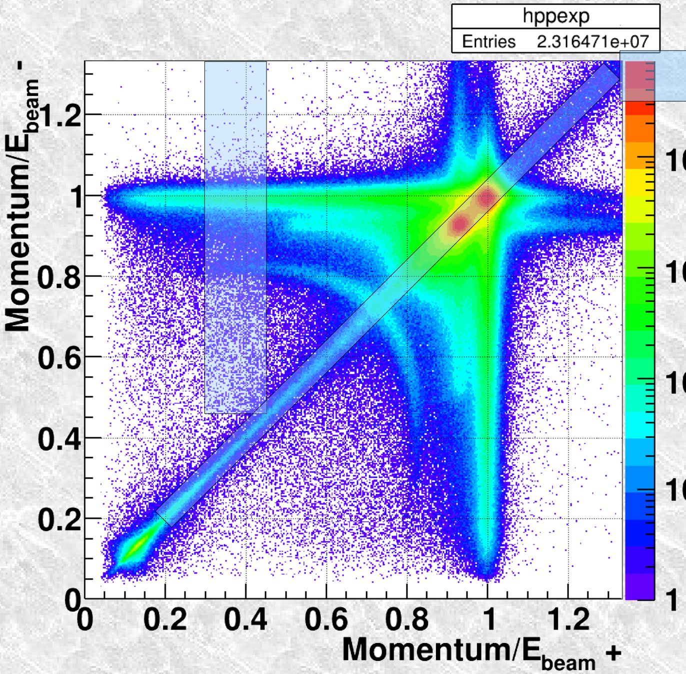
Integrated cross-section consistent at the level <0.1%

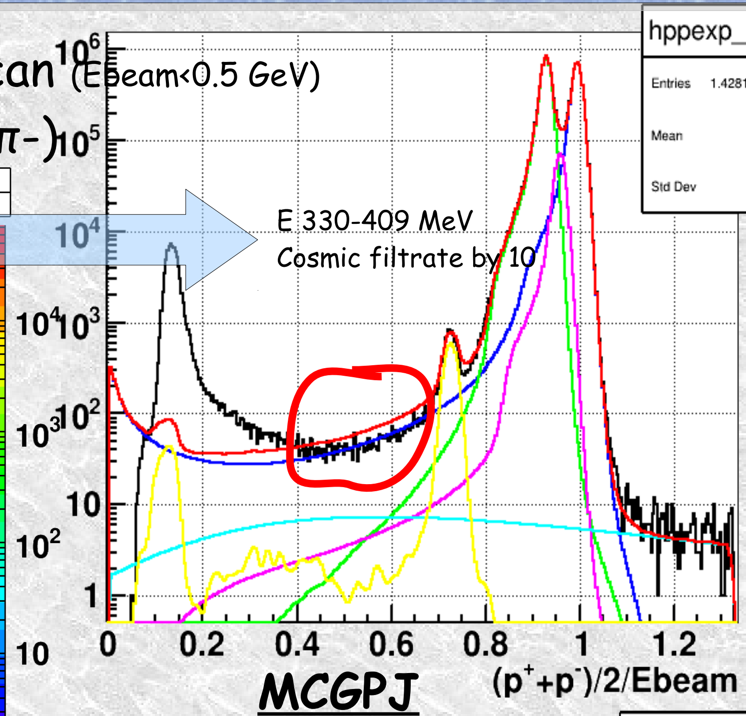
BabaYaga@NLO ~ x1000 slower than MCGPJ

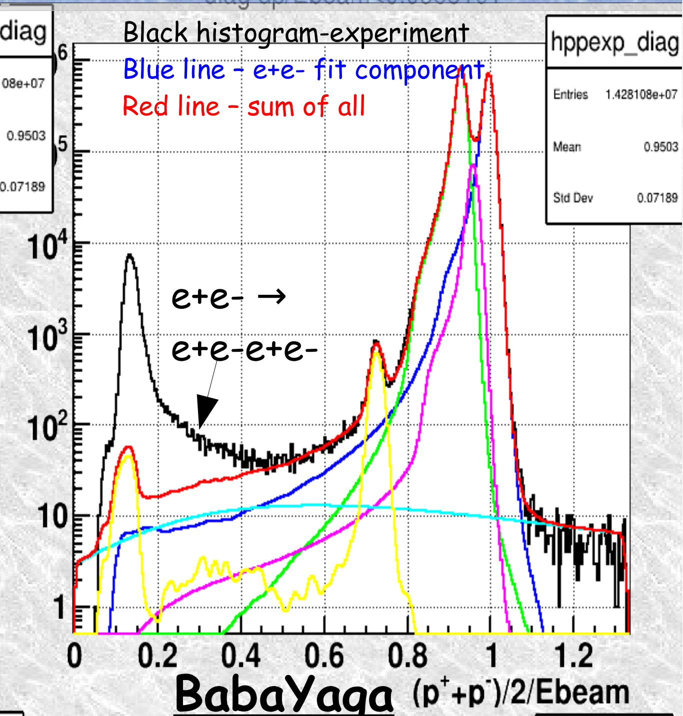
A discrepancy was observed in momentum distribution of experimental data vs fitted functions with input from MCGPJ

BabaYaga @ NLO vs MCGPJ vs experiment

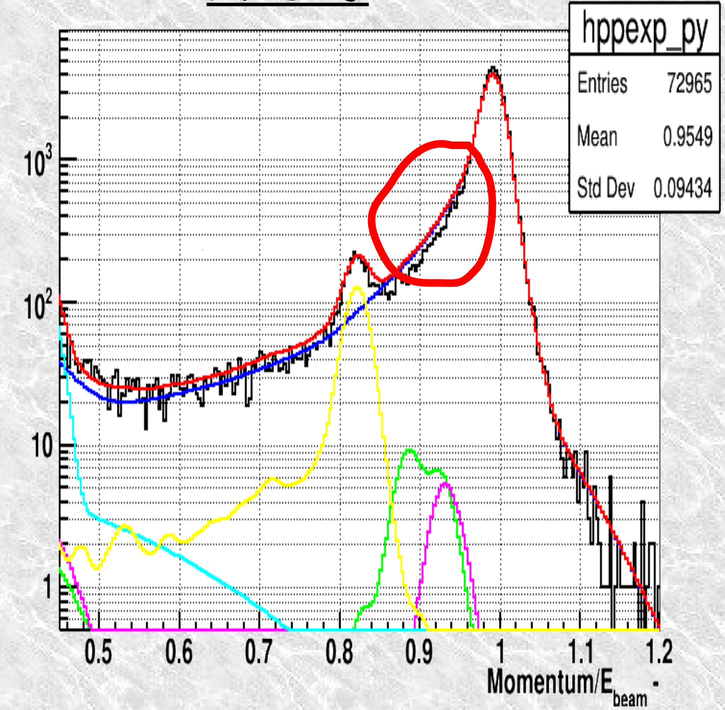
All events from RHO2013 scan (Ebeam<0.5 GeV)
(~ 10 millions of e+e- and π+π-)

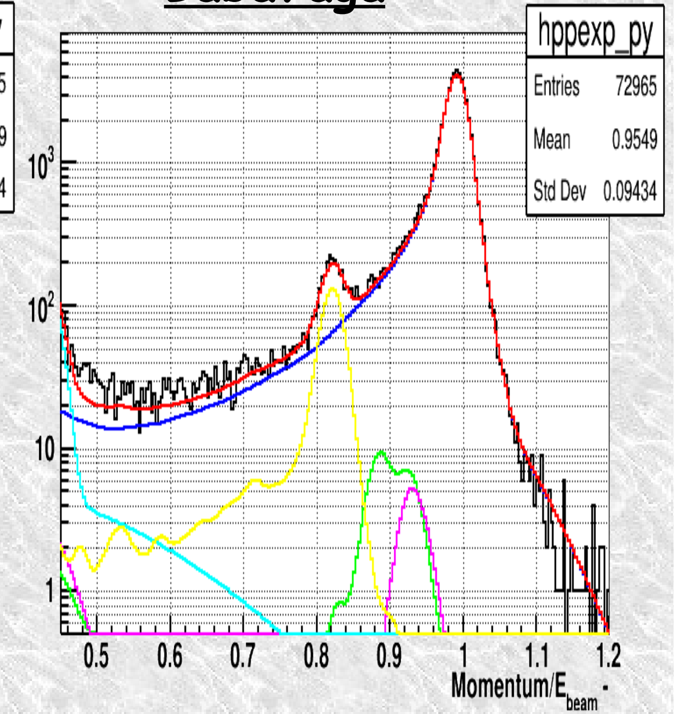






BabaYaga better describe experimental data





MCGPJ should be improved by adding angular distribution to photon jets

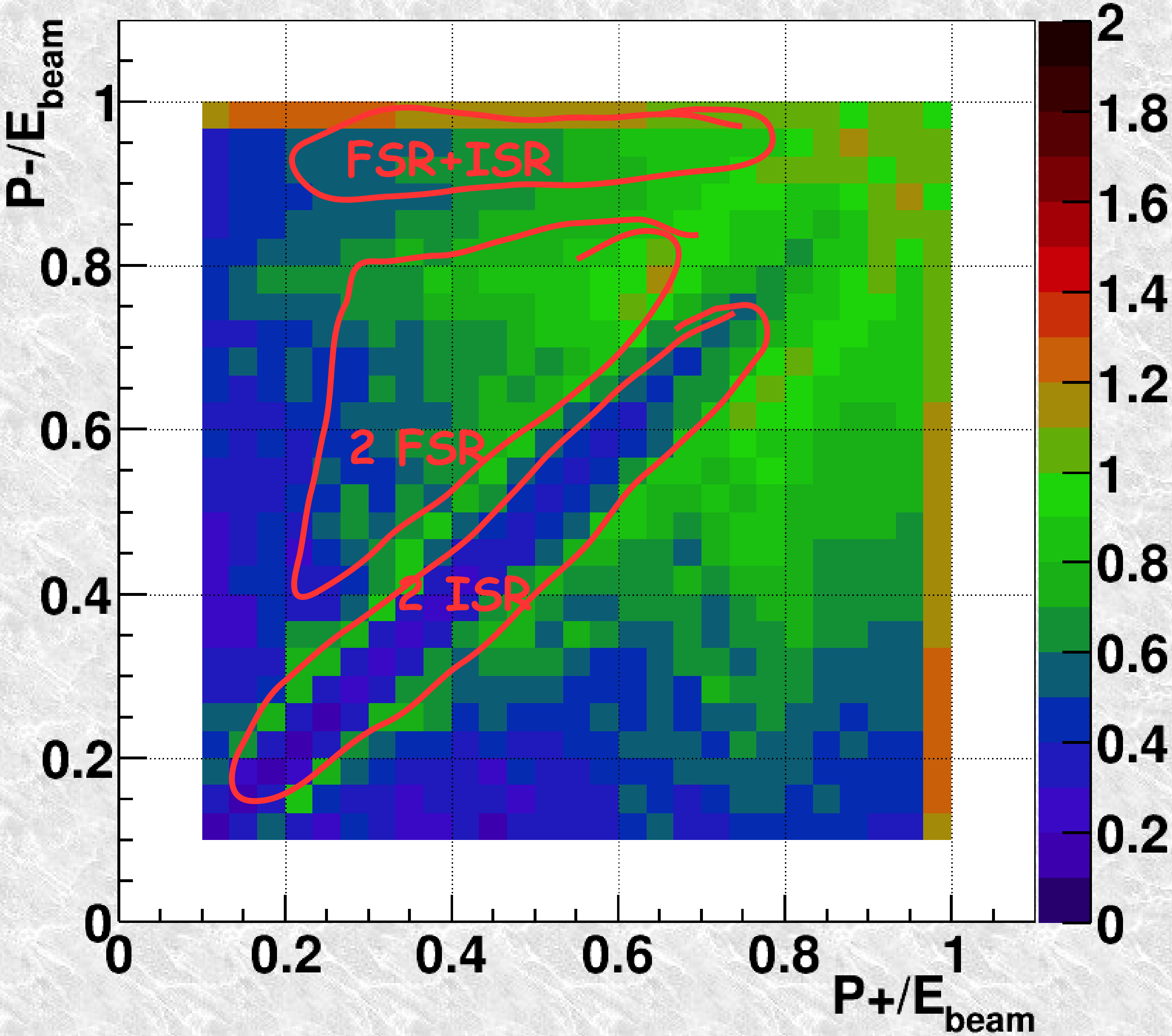
BabaYaga @ NLO vs MCGPJ

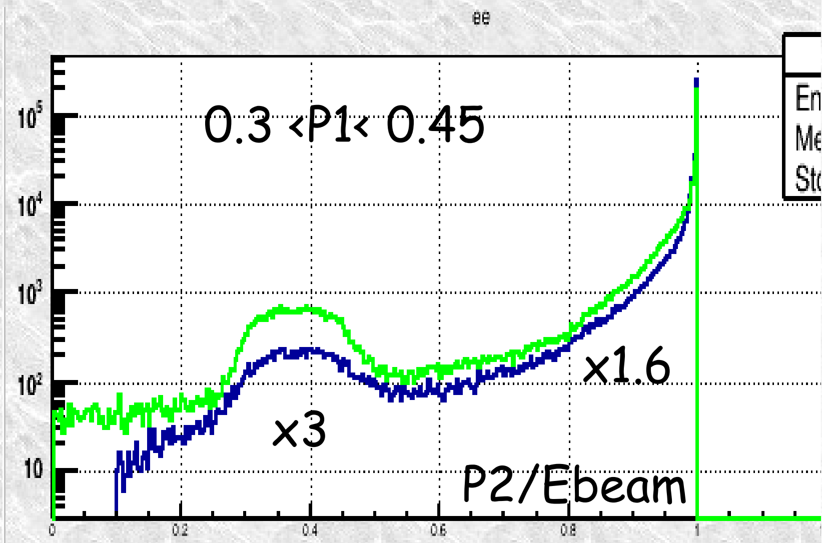
Ebeam = 391.48 MeV

Comparison of momentum spectrum from generators

BabaYaga devided by MCGPJ

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

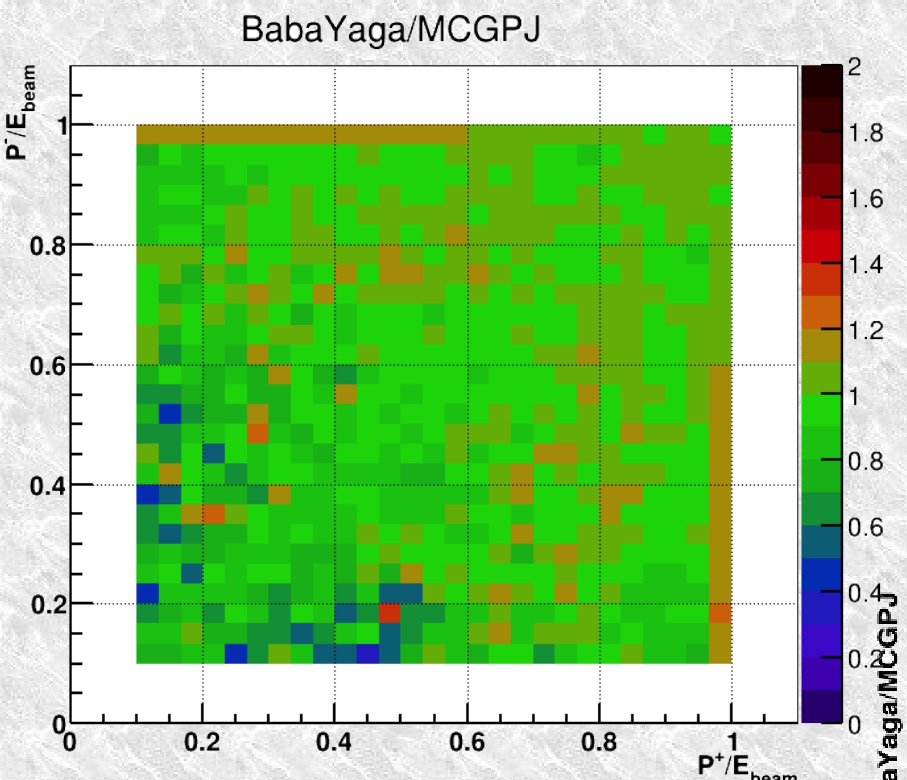


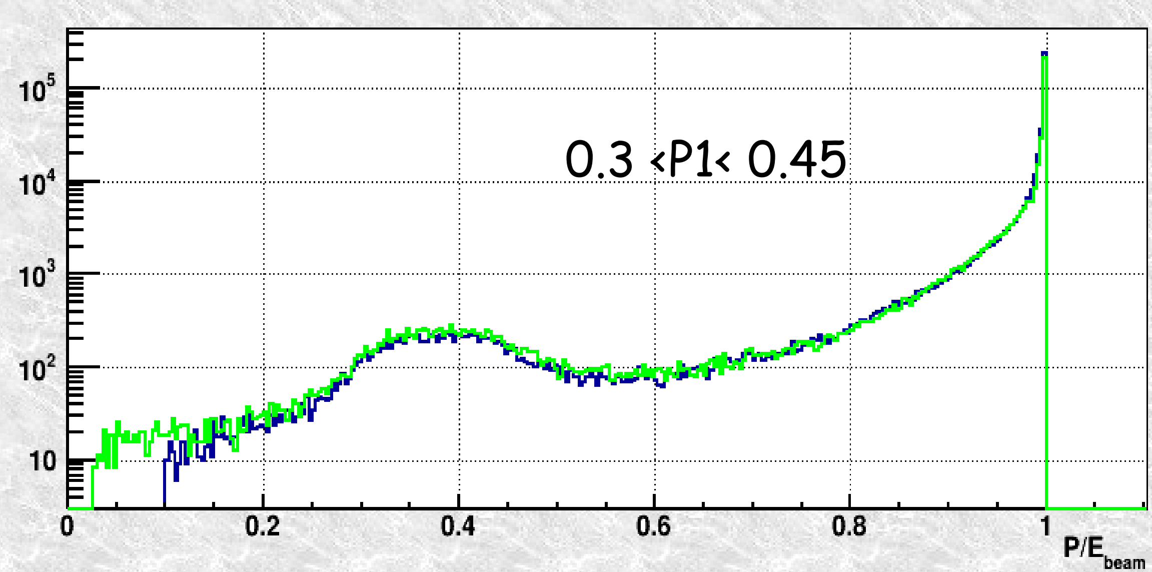


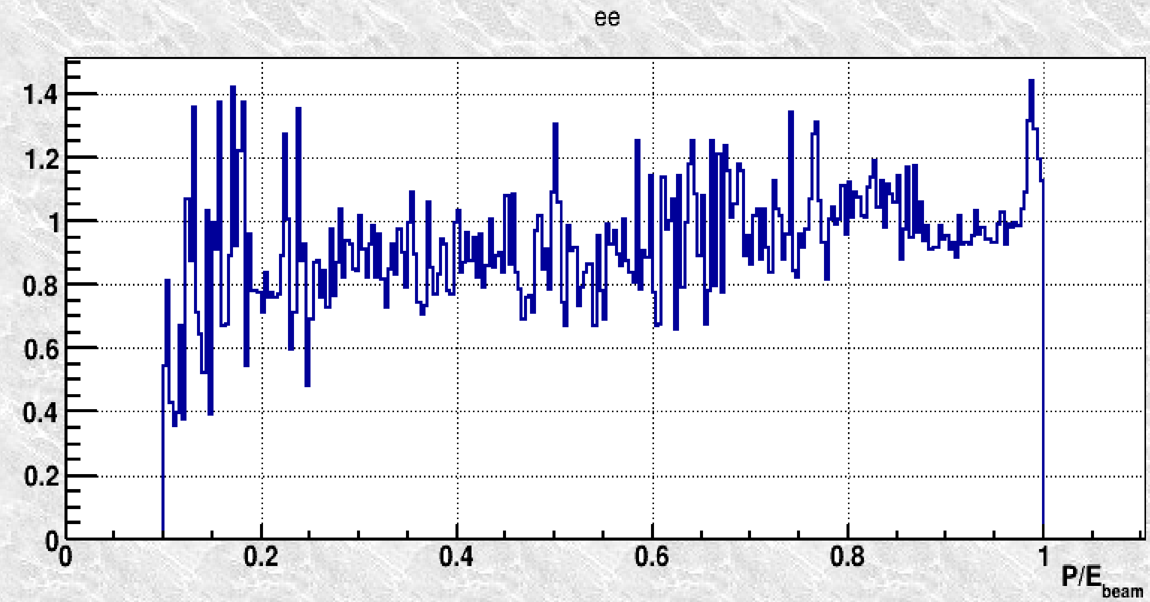
MCGPJ vs BabaYaga

After adding angle distribution for jets

Ebeam = 391.48 MeV







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

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

Also we want to redo "compensator"

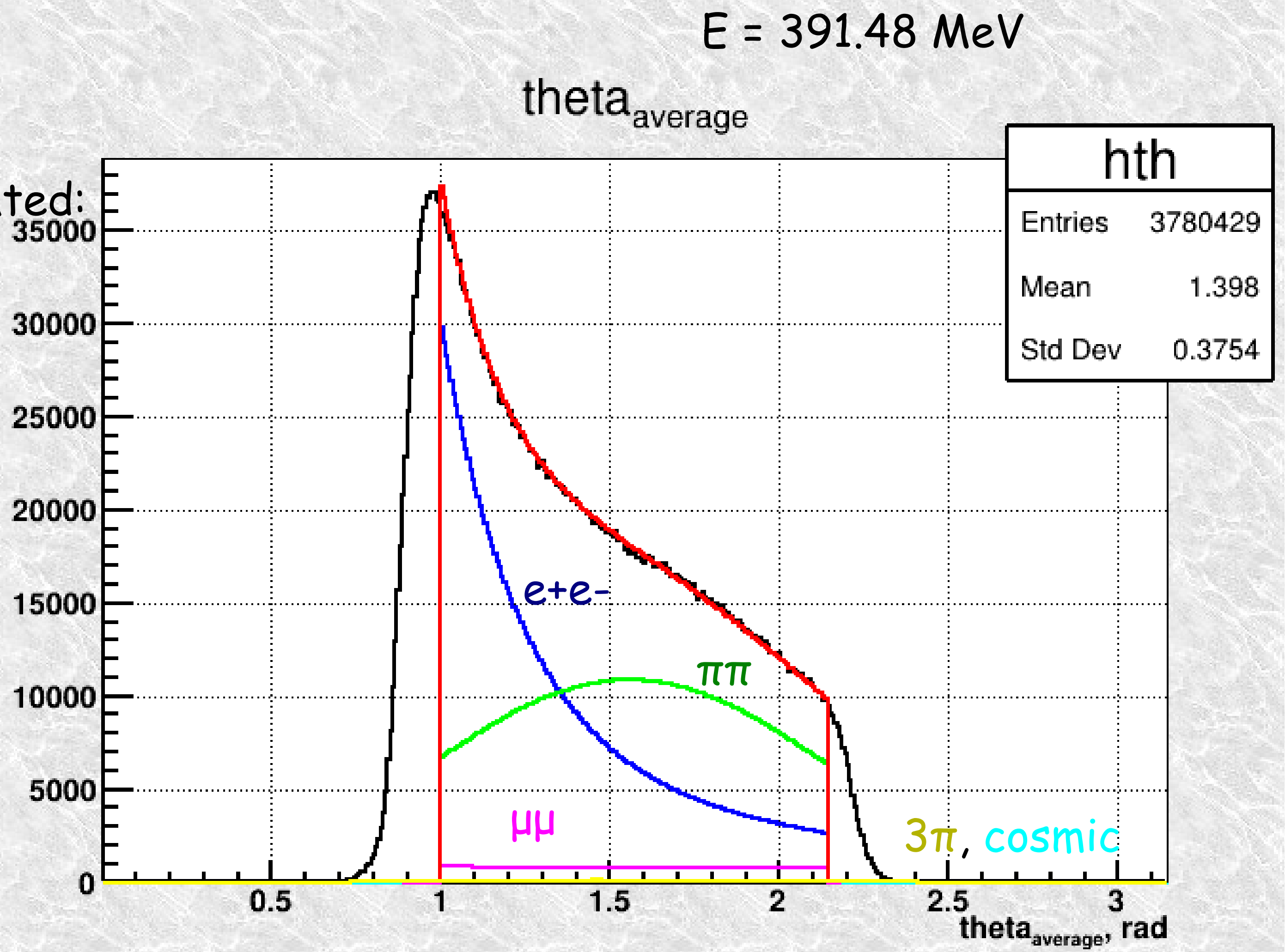
For precision ~<0.1% necessary to have exact $e^+e^- \to e^+e^-\gamma\gamma$ contribution

Theta distribution for separation

First attempt:

In approximation of not correlated:
f(θ) and f(p+,p-)

f(θ)
e+e-,μμ,ππ – from generator
3π — from simulation
Cosmic — from events not in VEPP time phase

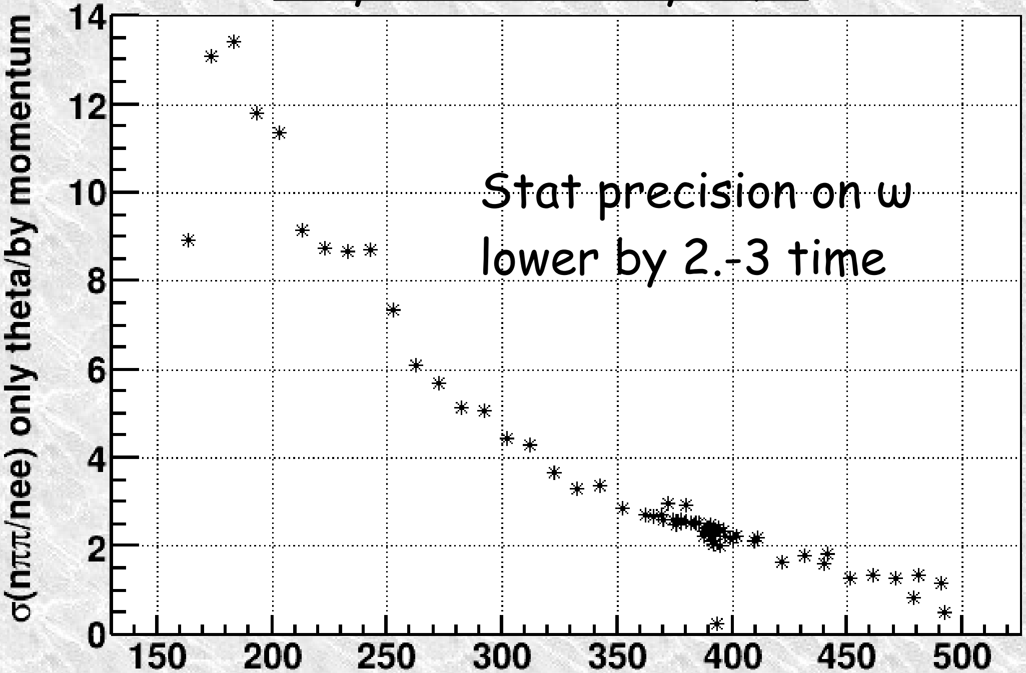


For real usage should be included(as additional parameters):

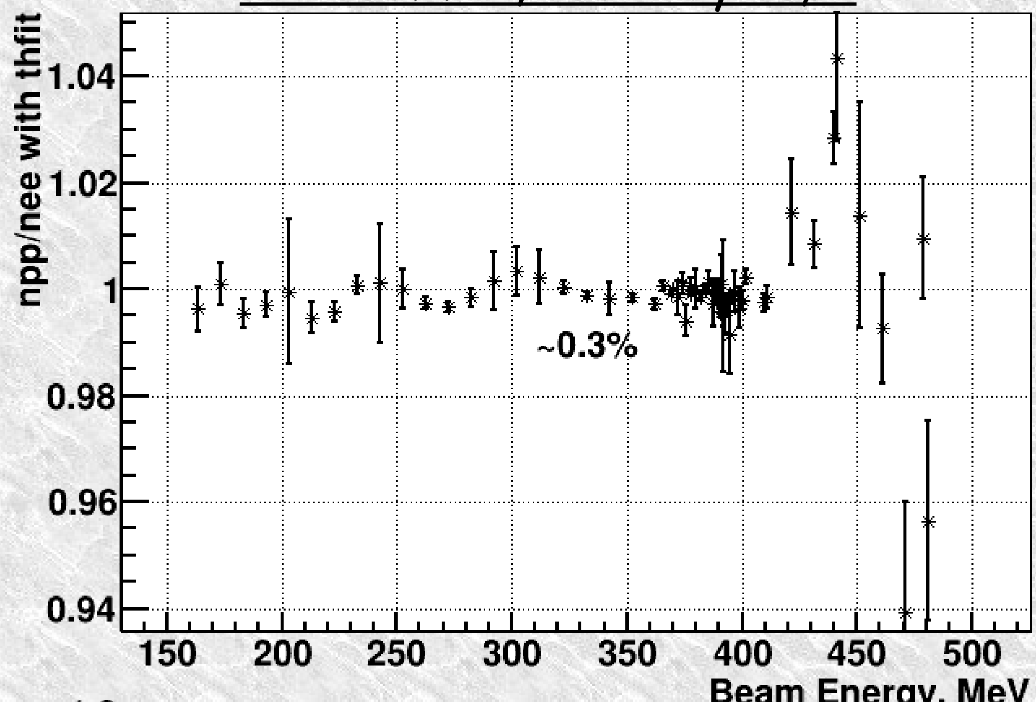
1) z-scale
2) spread from angle resolution
3) efficiency versus theta

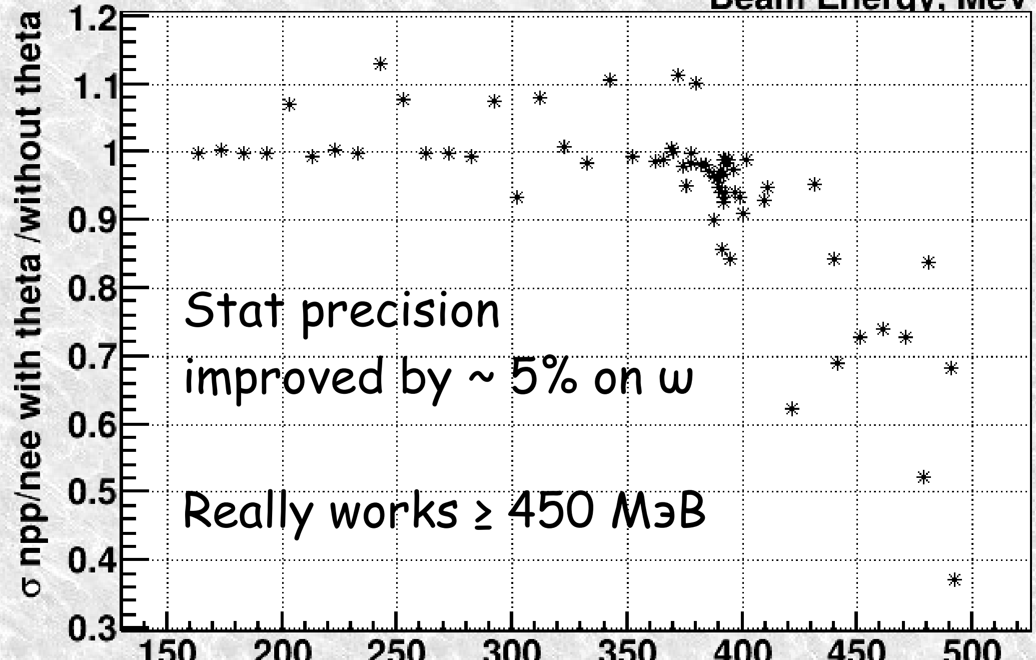
Theta distributions vs momentum separation

Only Theta vs only P+,P-



Theta && P+,P- vs only P+,P-





For precision ~ 0.1%

can be additional cross check of fiducial volume determination

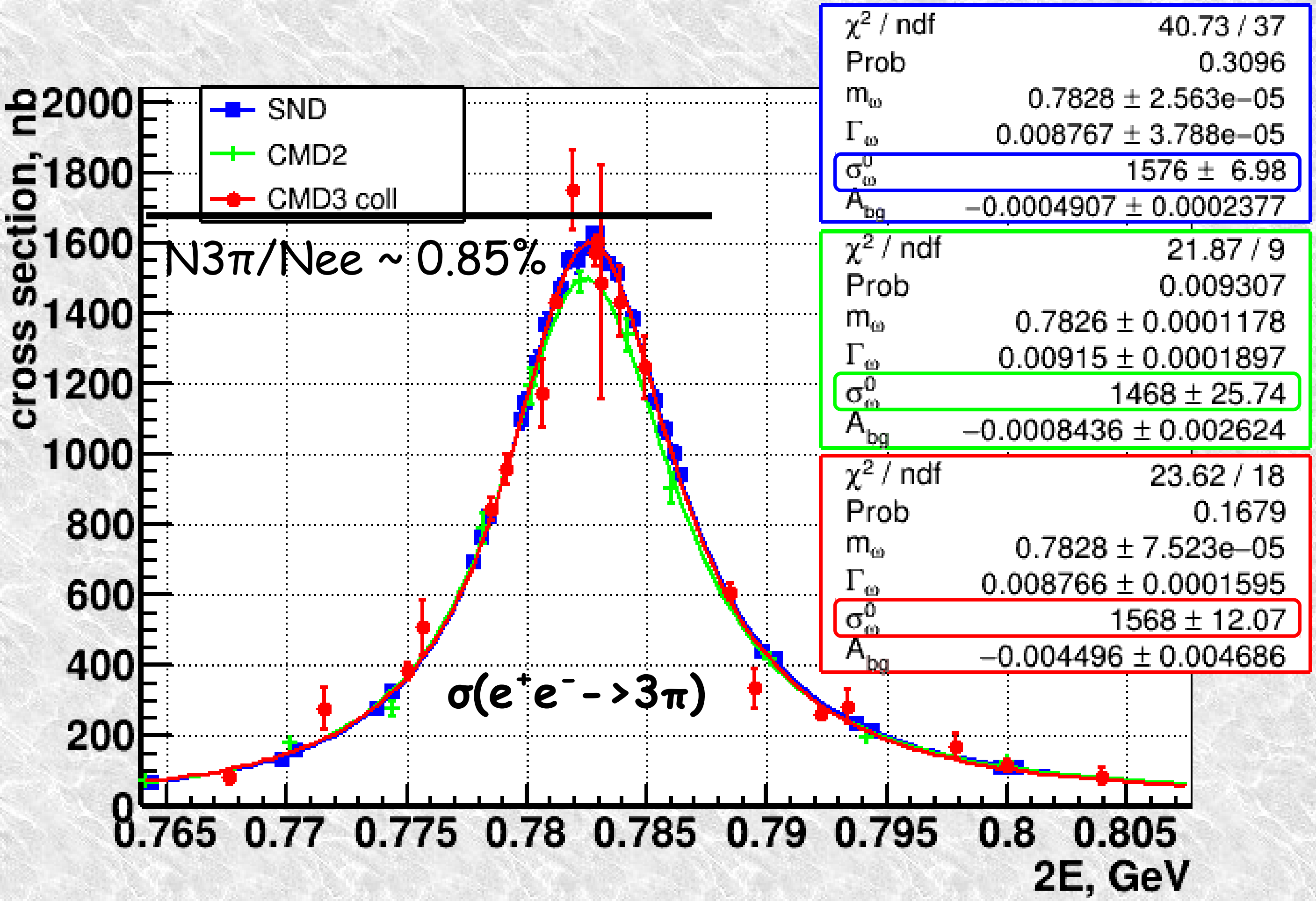
π+π-π0 background

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



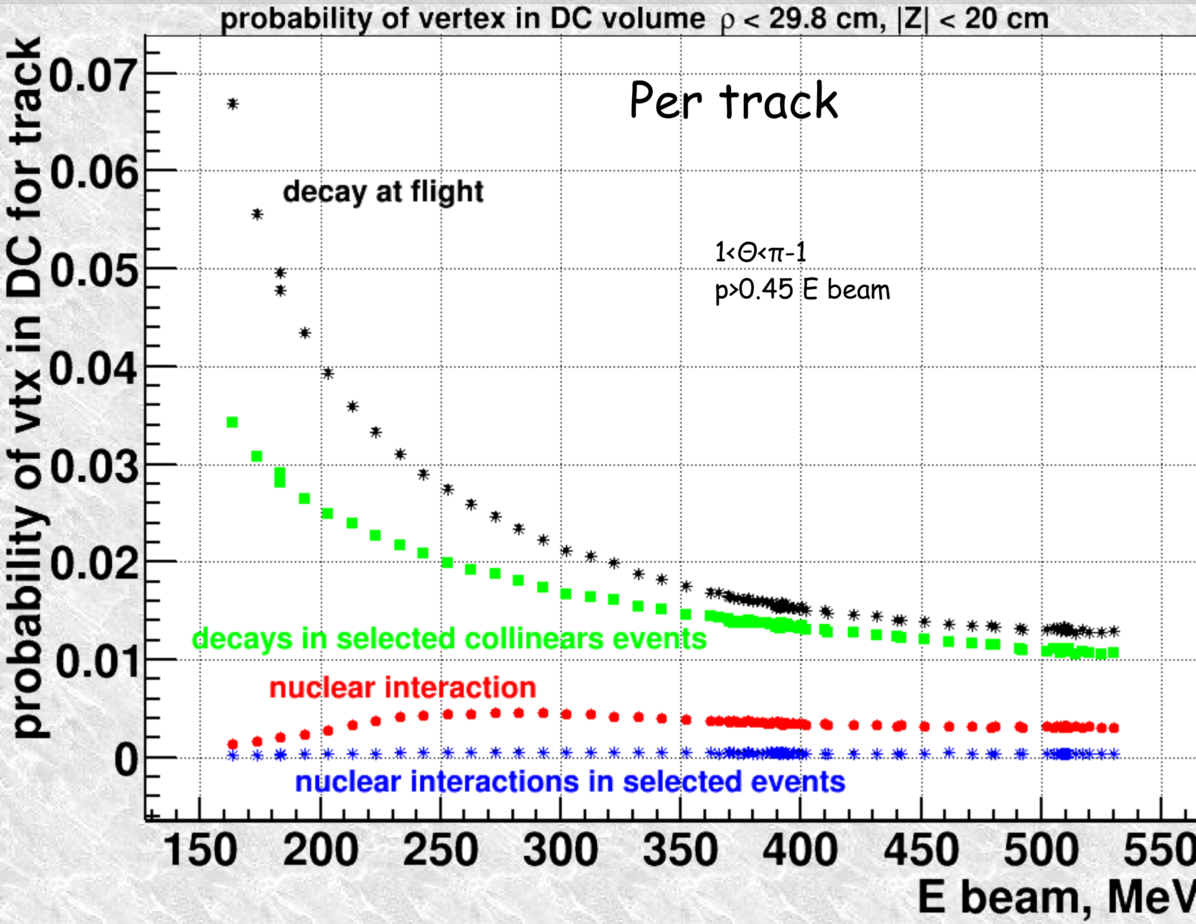
ε (3π)=0.4833% acceptance efficiency from simulation by phase space model

Pion inefficiency

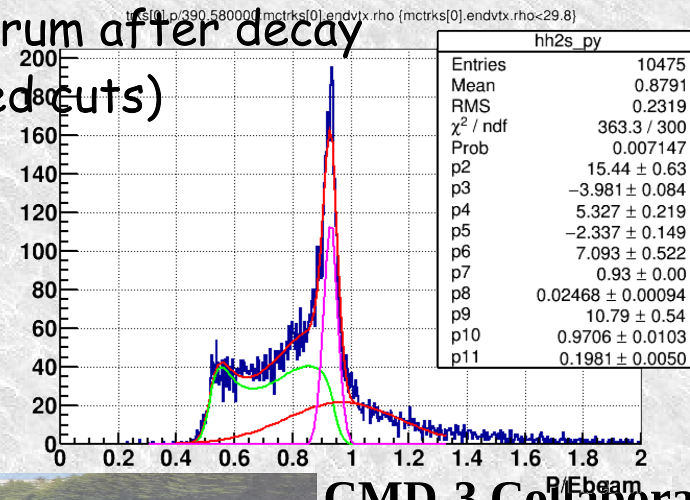
1.5 – 7 % of pions decay in volume of Drift chamber
More than half pass selections

<u>Cuts inefficiencies</u>
E<350 MeV <u>6.5 – 0.5 %</u>
above ~ 0.5 – 0.4 %

<0.5 % of pions have nuclear interaction in Drift chamber(mostly on vacuum tube),
All events are lost after cuts (survived <0.06%)



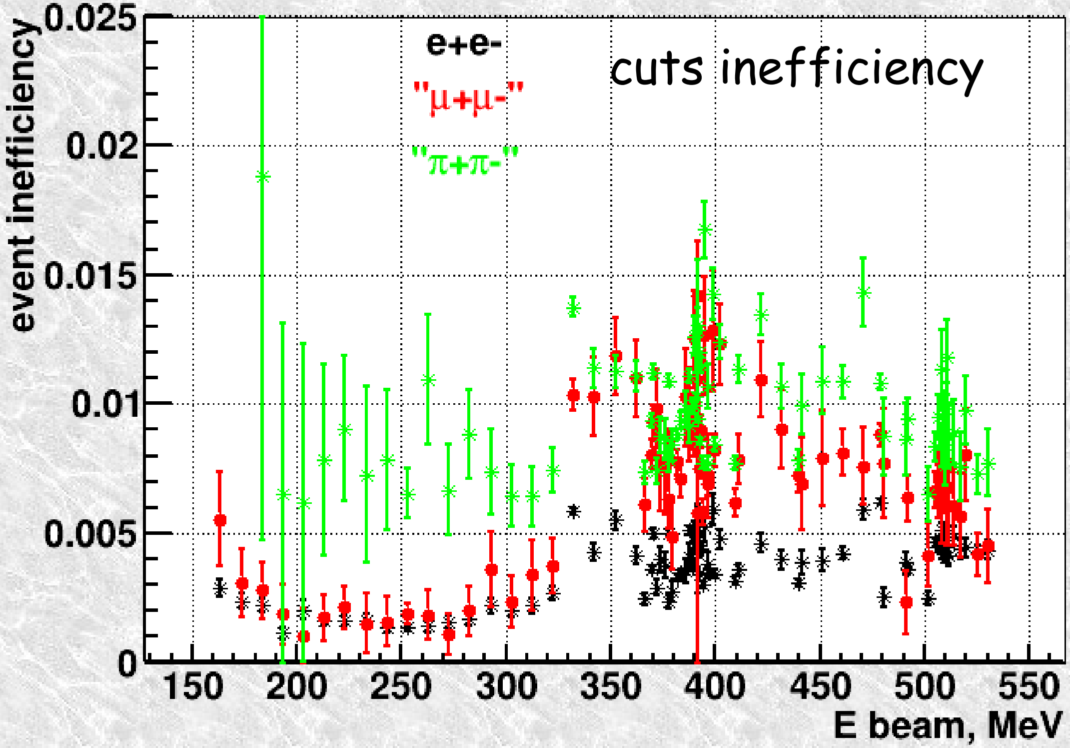
Pion spectrum after decay
(in selected cuts)



Nuclear interaction coorection (not depend on detector perfomance):
from simulation or can be studied from $\omega \to 3\pi$
Decay at flight (depend on detector efficiency):
behavior of momentum spectrum with variation of cuts

efficiencies

Part of track reconstruction inefficiency 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%)

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

Systematic e+e- -> π+π- by CMD3

<u>As our grand total(not reached yet)</u>

<u>Our goals are to reach systematic level up to 0.35%:</u>

- Radiative corrections - 0.1%
- e/μ/π separation – 0.2%
  can be checked and combined from different methods
- 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

0.3% - with current MCGPJ

<u>need precision < 0.07%</u>

<u>Many systematic studies rely on high statistics</u>

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%

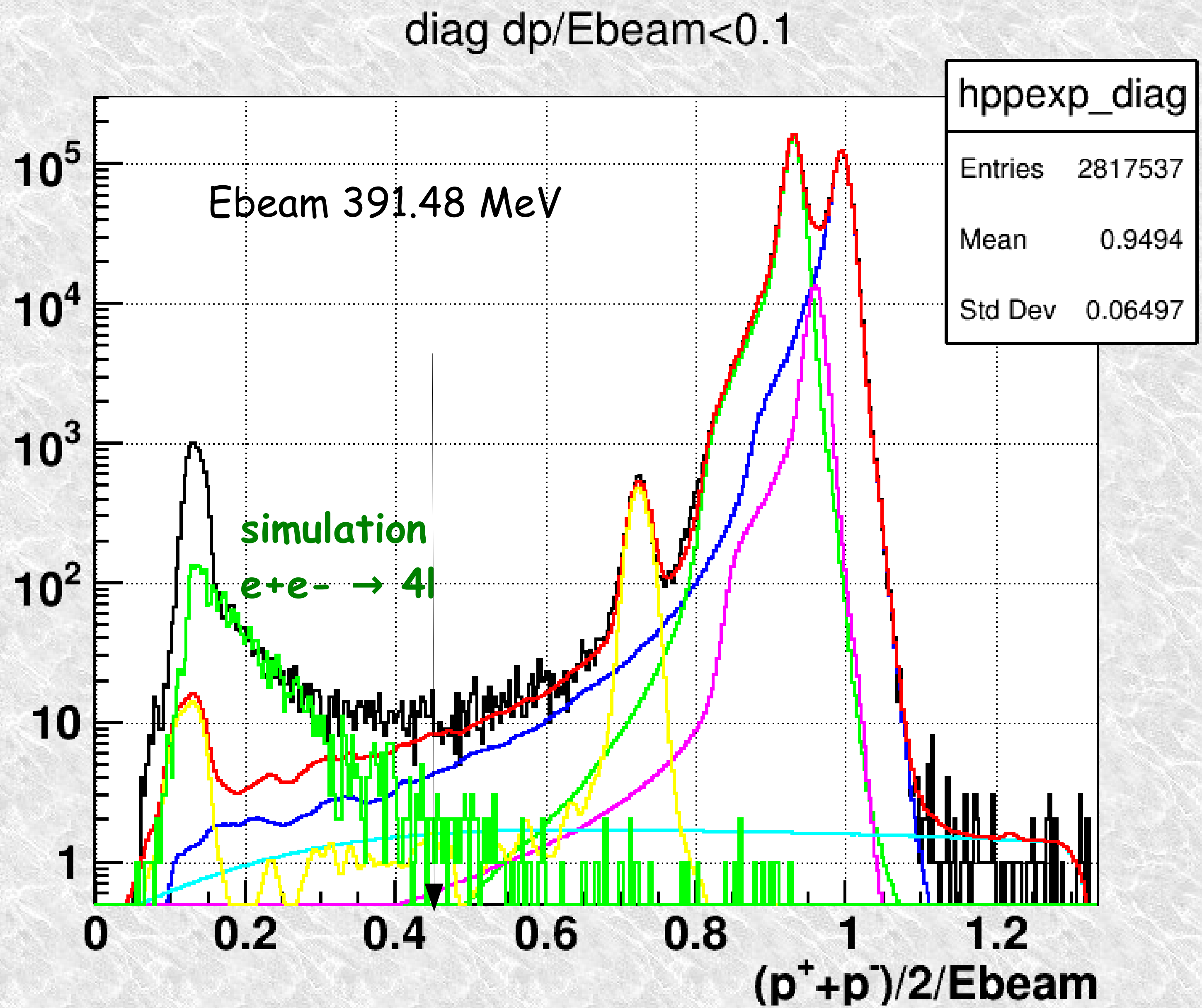
- ✗ More data expected after VEPP-2000 upgrade with new positron injection facility

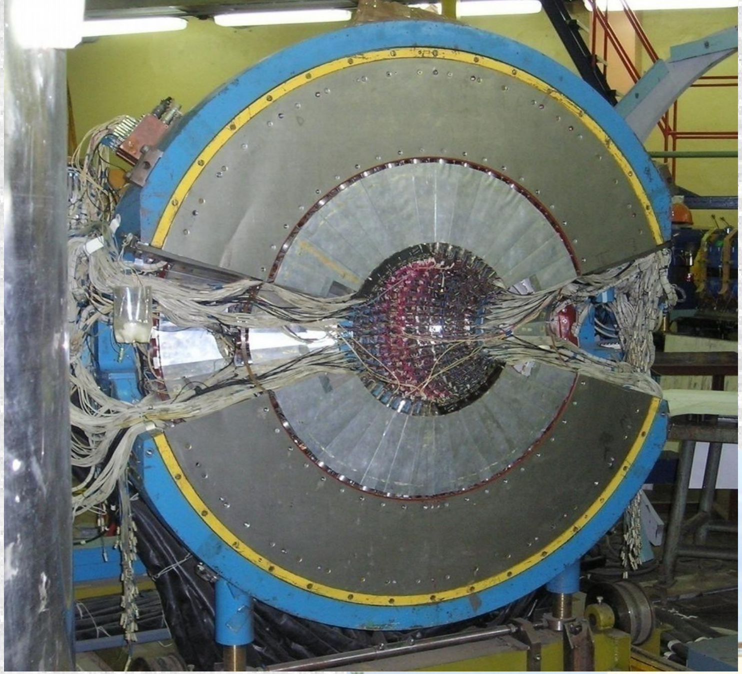
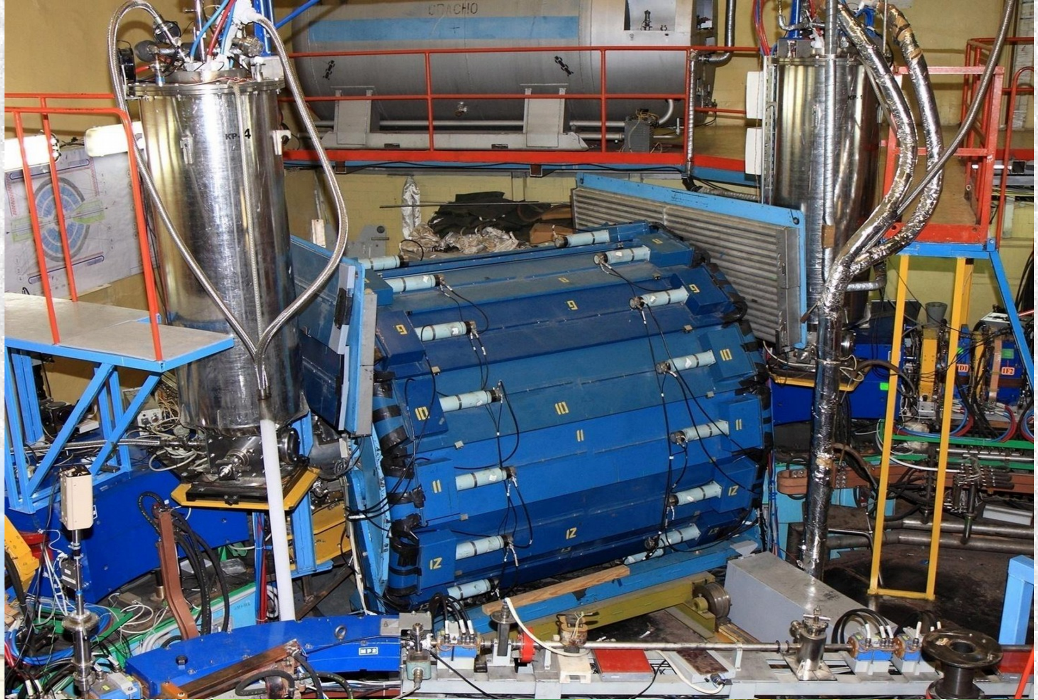
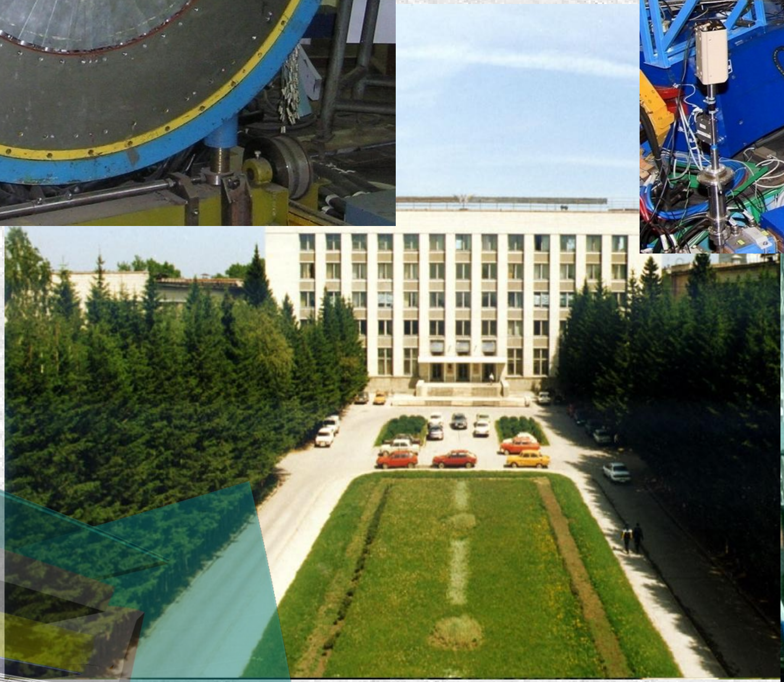
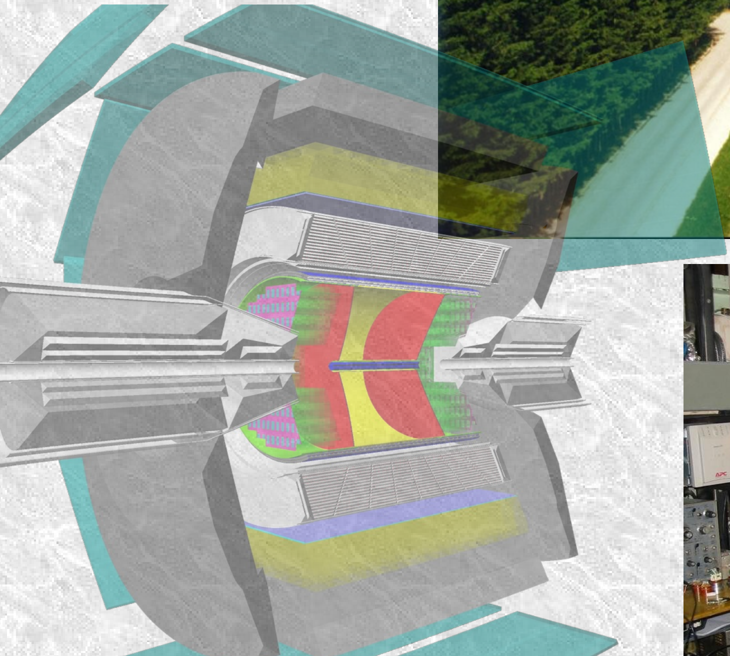
e+e- → e+e-e+e-

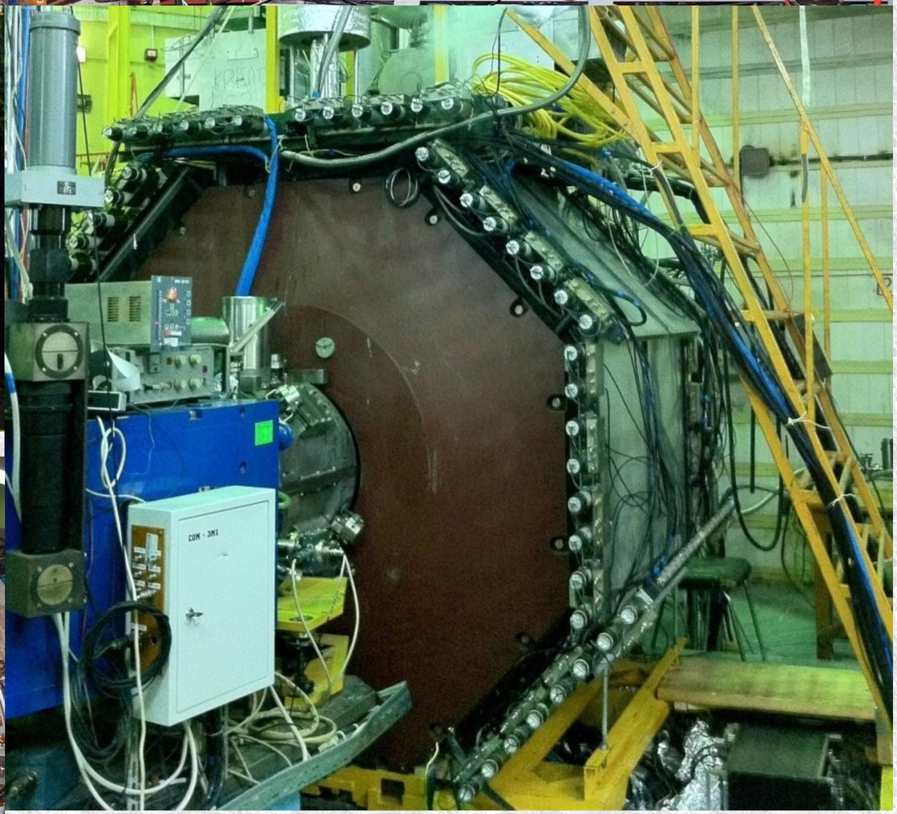
Diag36 generator (1986)
F.A.Berends et al.
http://inspirehep.net/record/238520

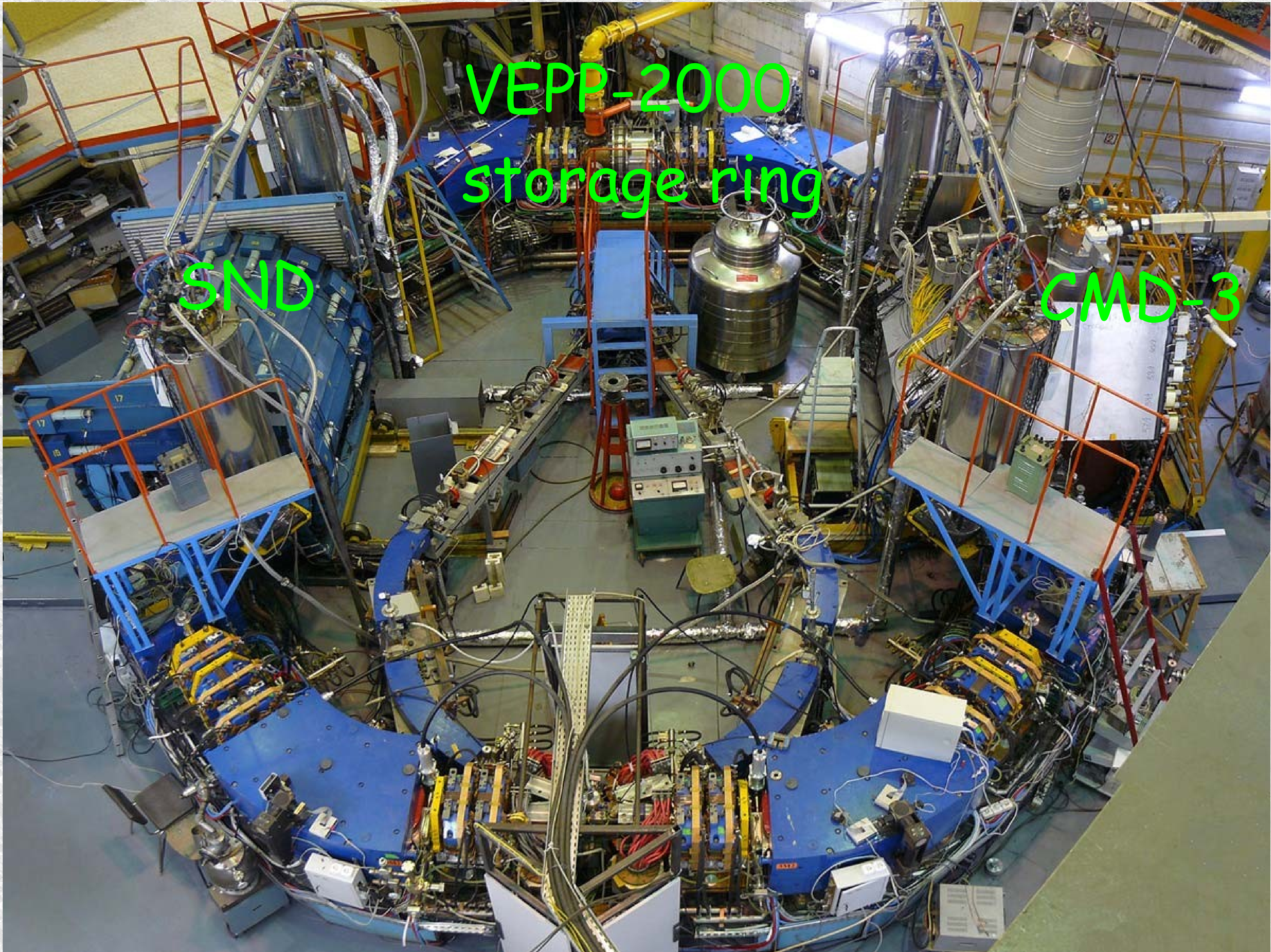
All diagrams for 4 lepton in final state

Main contribution from 2 photon annihilation







VEPP-2000
storage ring
SND
CMD-3

SM prediction for muon g-2

ArXiv:1010.4180,arXiv:1105.3149

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

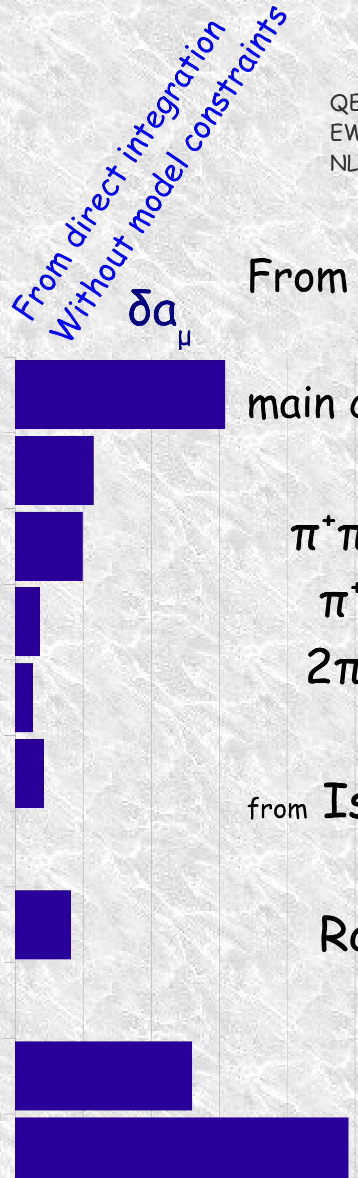
11 659 208.9 ± **6.3** x 10^{-10} world average

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

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



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	
$\pi^+\pi^-2\pi^0$	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 $KK\pi, KK2\pi, 2\pi4\pi^0, 2\pi3\pi^0$

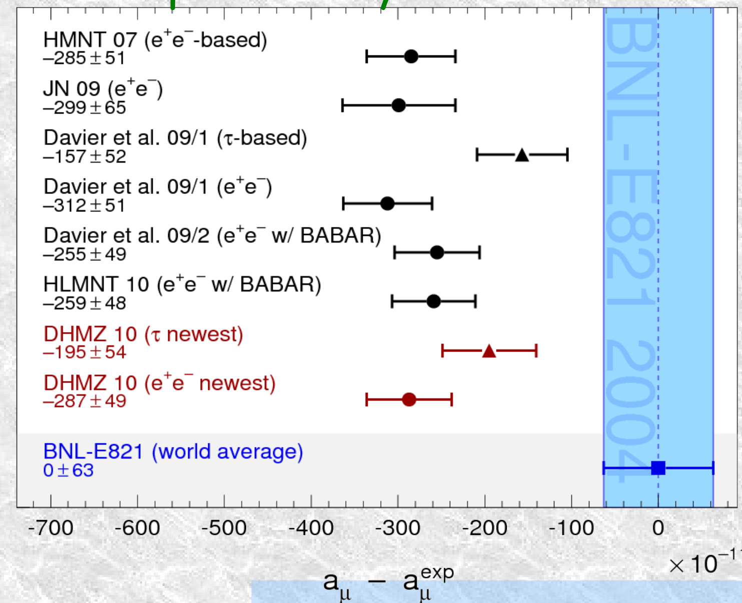
(or 12.46 ± 0.76 for √s<2 GeV) (contribution at 1.5-3σ of total error - crucial if something is wrong with used isospin relations)

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**

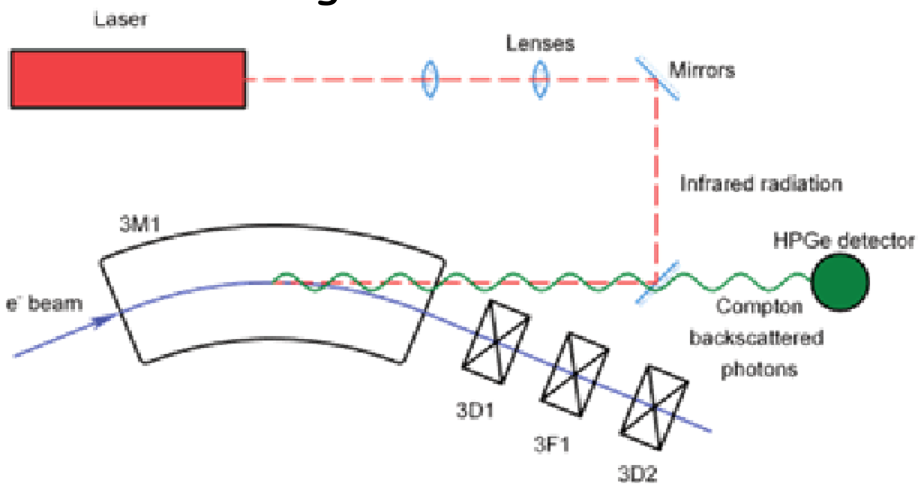
Δ Exp - Theory~ 3.3–3.6σ



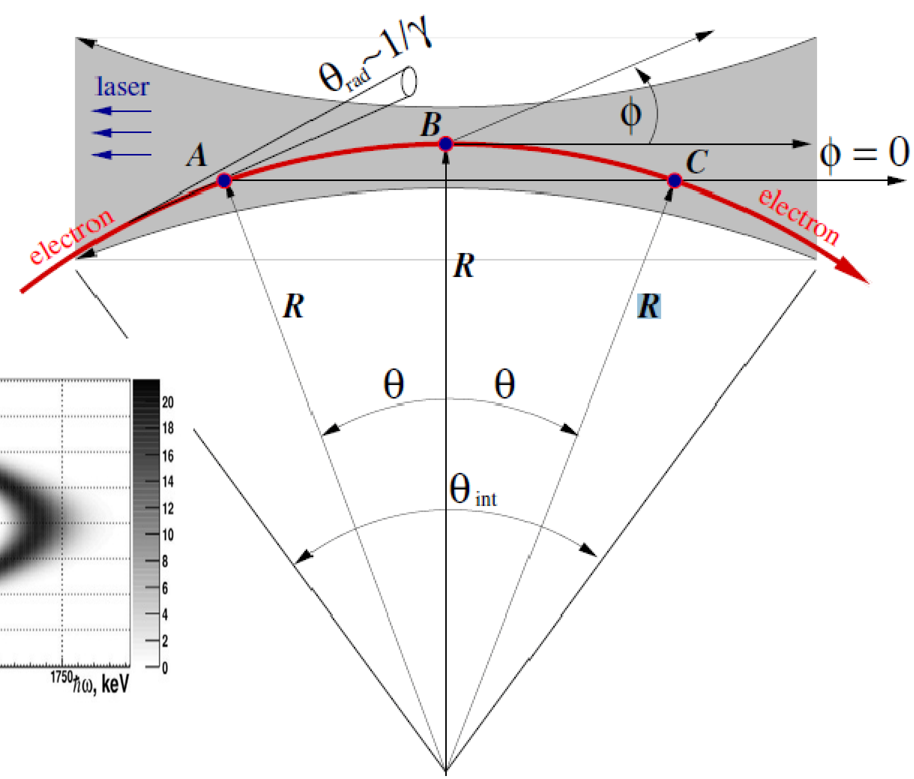
New g-2 experiments at FNAL and J-PARC have plans to reduce error to **1.5x10^-10**

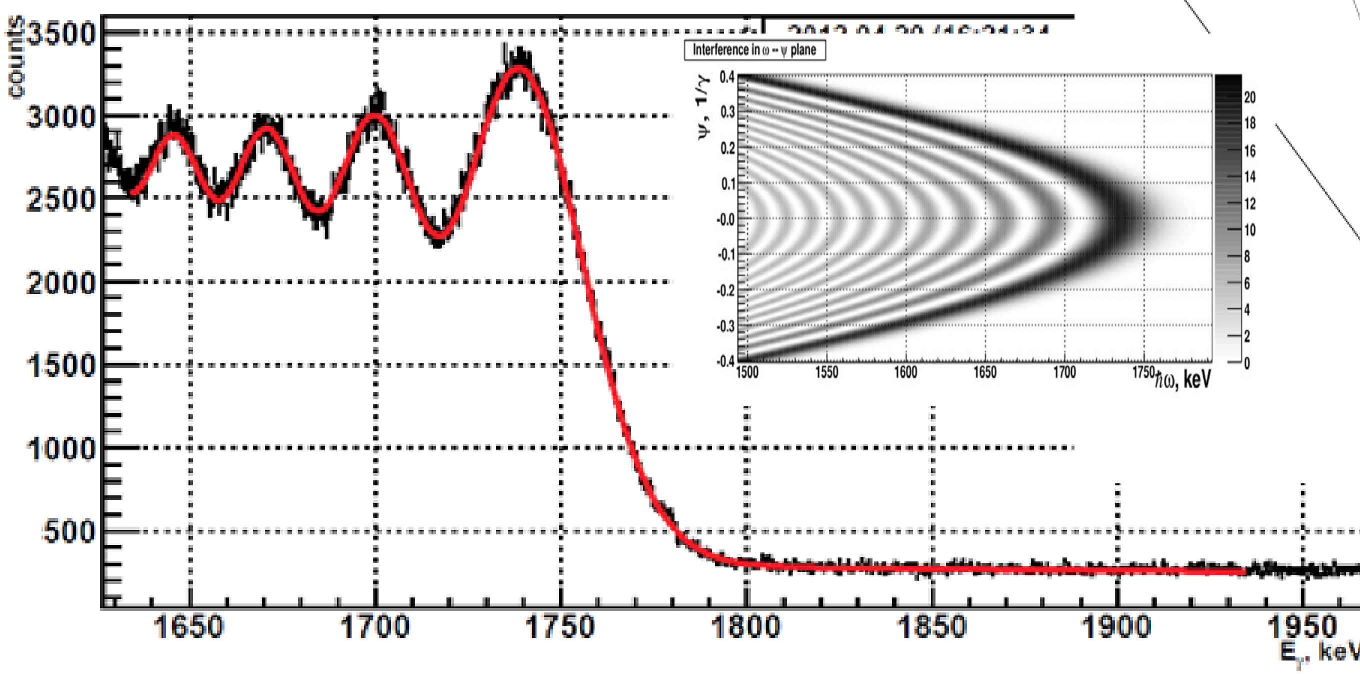
Energy measurement by Compton back scattering

Starting from 2012, energy is monitored continuously using compton backscattering



Излучение из точек А и С под углом φ = 0 интерферирует



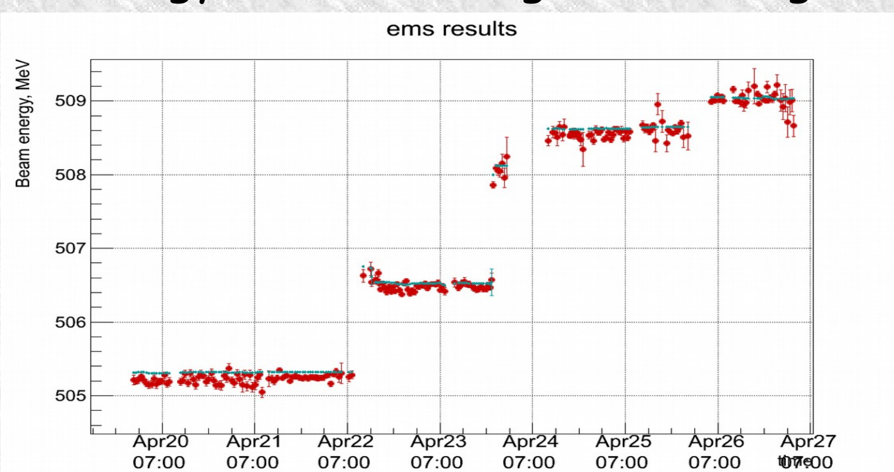


E = 993.662 ± 0.016 МэВ

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

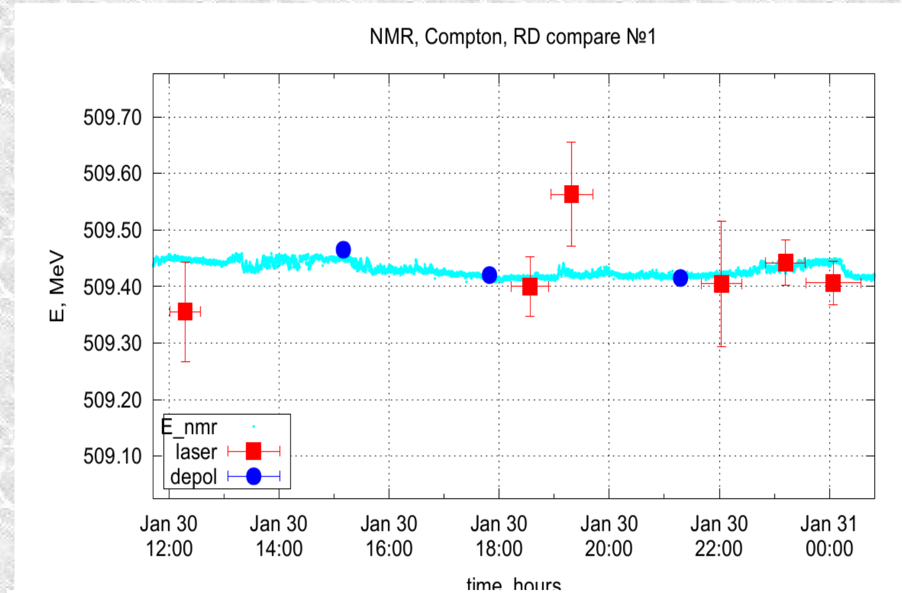
Beam energy measurement at VEPP-2000

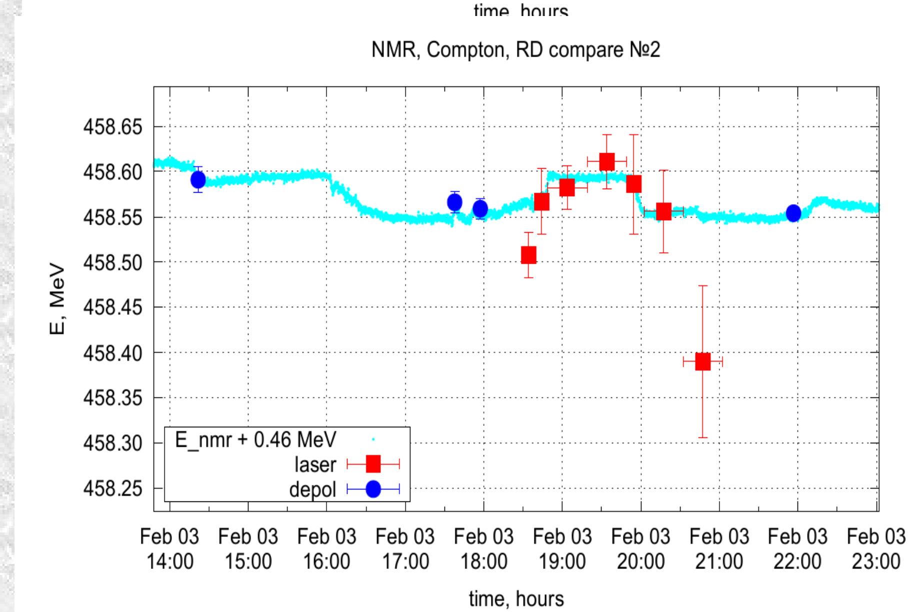
- Magnetic field control in bending magnets
  - 8x2 NMR probes, continuous control
  - Absolute calibration using:
    φ-meson (1019.455 ± 0.020 МэВ),
    ω-meson (782.65 ± 0.12 МэВ).
- Measurement of photon energy from back scattering laser light
  - Installed in 2012.
  - Needs beam current (20 мA),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



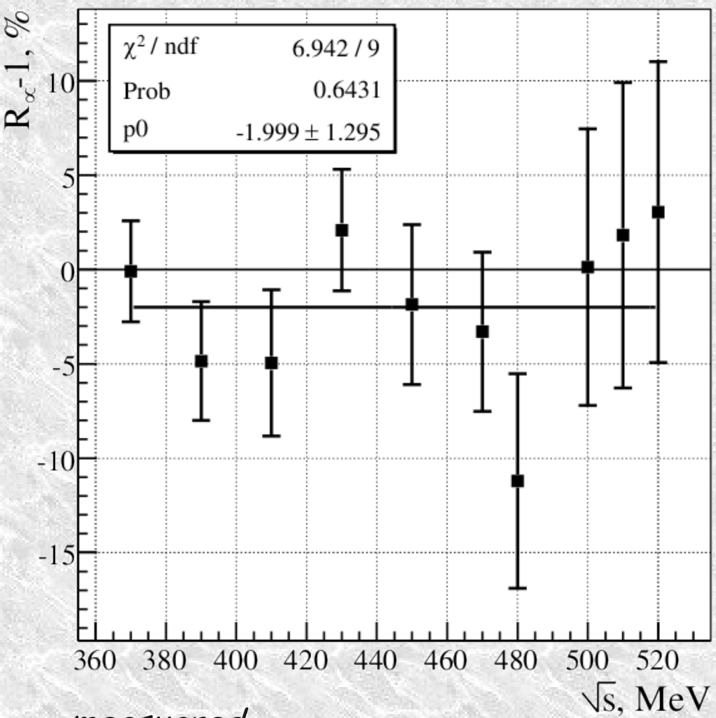
- Resonance depolarization method
  - Very high accuracy (δE/E < 10-5).
  - Special configuration of VEPP-2000: “warm”

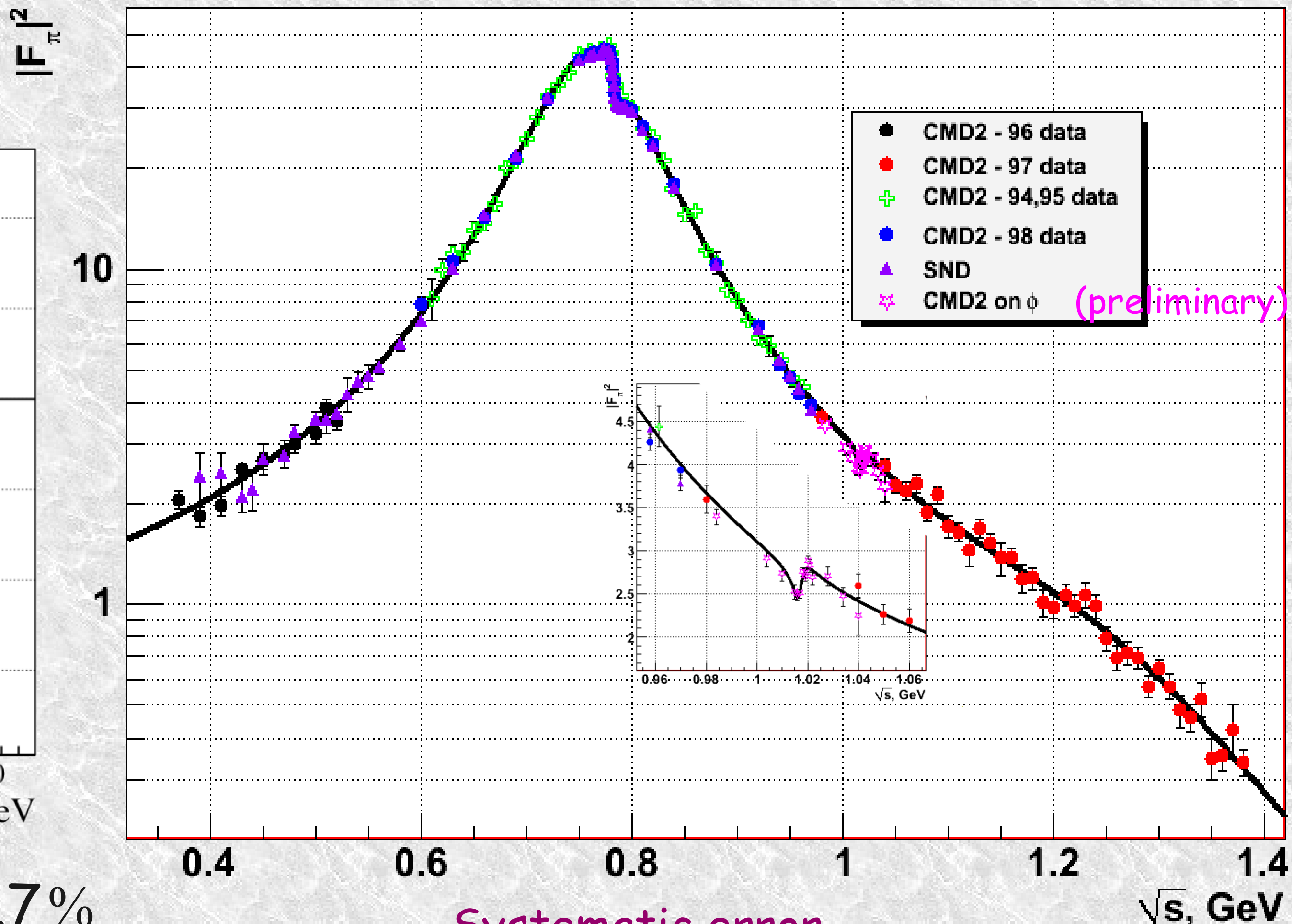
Methods comparison:





Pion formfactor





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

Systematic error

CMD2: 0.7% — 0.6% (95)/ 0.8% (98) — 1.2-4.2%

SND: 3.2% — 1.3%