CMD-3 measurement of $e^+e^- \to \pi^+\pi^-$

Fedor Ignatov
BINP, Novosibirsk

PhiPsi17, Mainz

R(s), e+e- → hadrons

measurement of R(s) :

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

R(s) is one of the fundamental quantities in high energy physics:
its reflects number of quarks and colors;
used for pQCD tests;
QCD sum rules provide a method of extracting from R(s):
quark masses,quark and gluon condensates, Λ_{QCD}

Through dispersion relations it is essential for the interpretation of precision measurements of:

muon (g-2) - good test of SM

$\alpha_{QED}(M_Z)$ - necessary for precise electroweak predictions

The value and the error of the hadronic contribution to muon (g-2) are dominated by low energy R(s) (<2GeV gives 93% of the value).
$\pi^+\pi^-$ gives the main contribution (73%) to a_μ and its precision

50 years of hadron production at colliders

Volume 25B, number 6 PHYSICS LETTERS 2 October 1967

1 September 1967

Start of e+e- → hadrons measurements

Phys.Lett. 25B (1967) no.6, 433-435

VEPP-2, Novosibirsk

INVESTIGATION OF THE ρ-MESON RESONANCE WITH ELECTRON-POSITRON COLLIDING BEAMS

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Received 1 September 1967

Preliminary results on the determination of the position and shape of the ρ-meson resonance with electron-positron colliding beams are presented.

When experiments with electron-positron colliding beams were planned [1, 2] investigation of the process

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

$$e^- + e^+ \to K^- + K^+$$

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Detector was made from different layers of Spark chambers,
readouts by photo camera

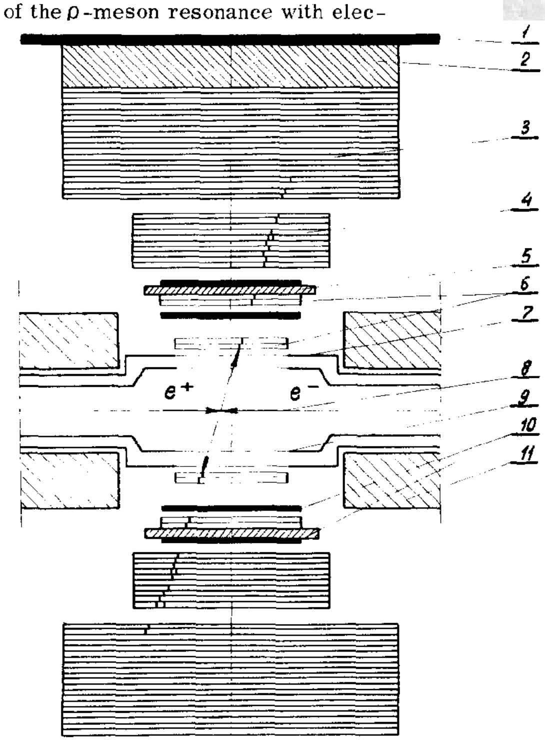


Fig. 1. Spark chambers system:
1) Anticoincidence scintillation counter
2) Lead absorber 20 cm thick
3) "Range" spark chamber
4) "Shower" spark chamber
5) Duraluminium absorber 2 cm thick
6) Thin-plate spark chambers

e+e- → ρ → ππ

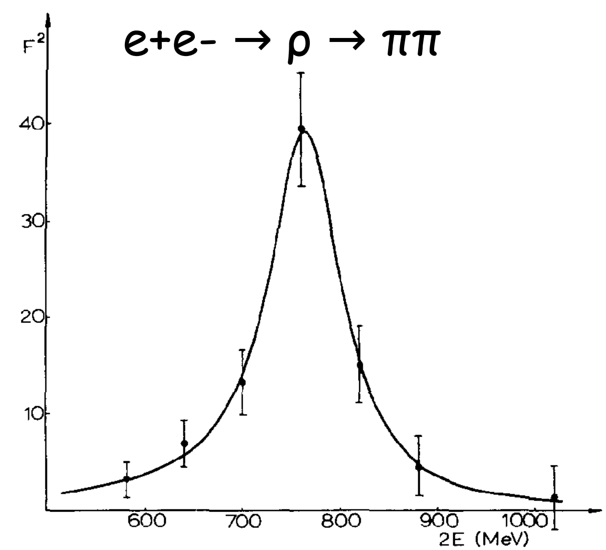
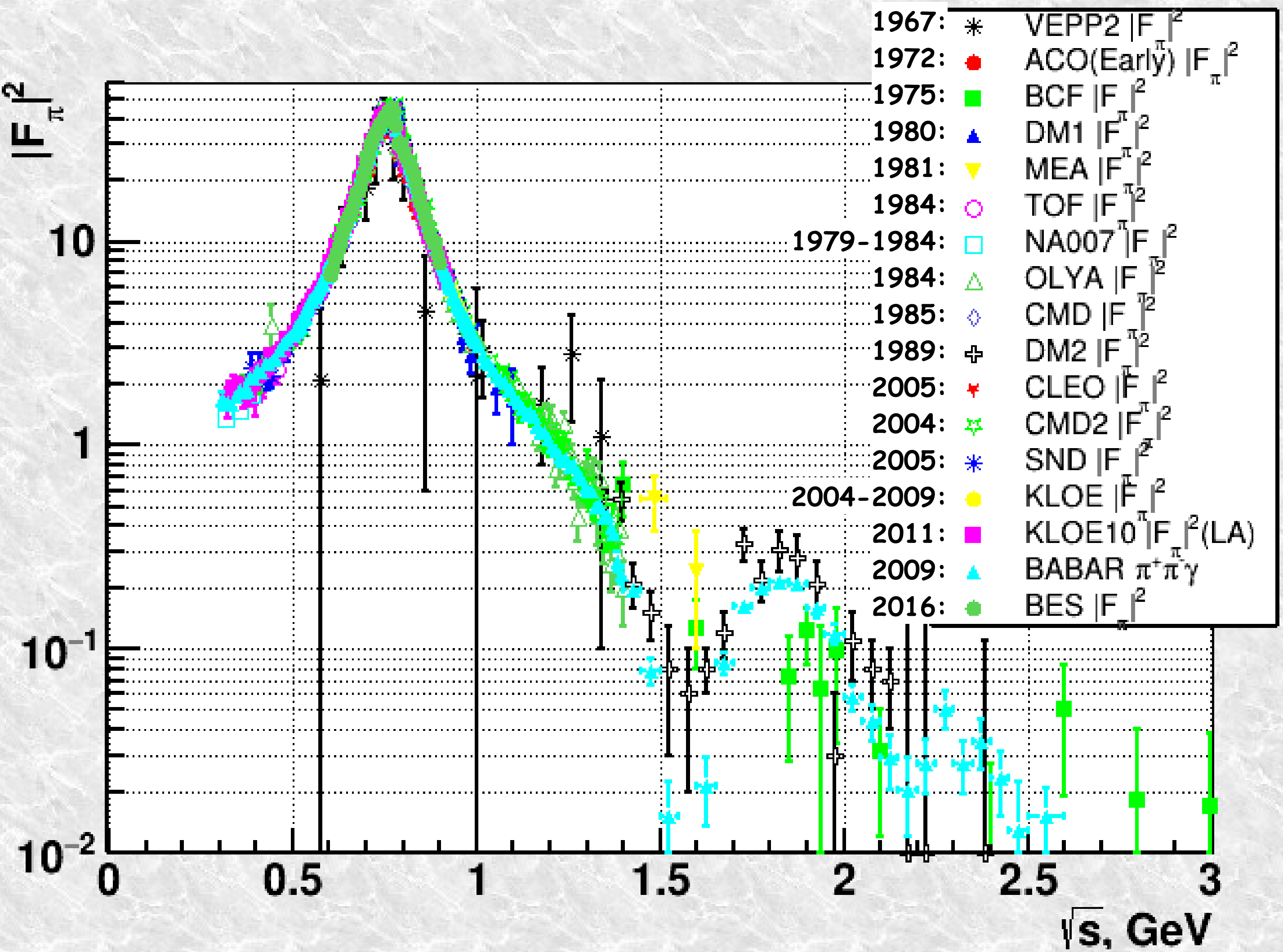


Fig. 2. Experimental values of F^2 (E) approximated by the Breit-Wigner formula.

ment geometry and F- modulus of the form factor for pion pair production [1]. In the case of QED with no other forces F=1. If the particles are produced at the angle 90° with respect to the beam axis then a=18. Integration over the solid angle gives a=20.4.

Rho meson today



New g-2 experiments and future e+e- as ILC require average precision ~0.2%

Before 1985

Low statistical precision

Systematic >10%

NA7 A few points with >1-5%

1985 - VEPP-2M

with more detailed scan

OLYA systematic 4%

CMD 2%

2004 with CMD2 at VEPP-2M

was boost to systematic: 0.6%

(near same total statistic)

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

New ISR method

e+e- → γ + hadron:

KLOE: 0.8%

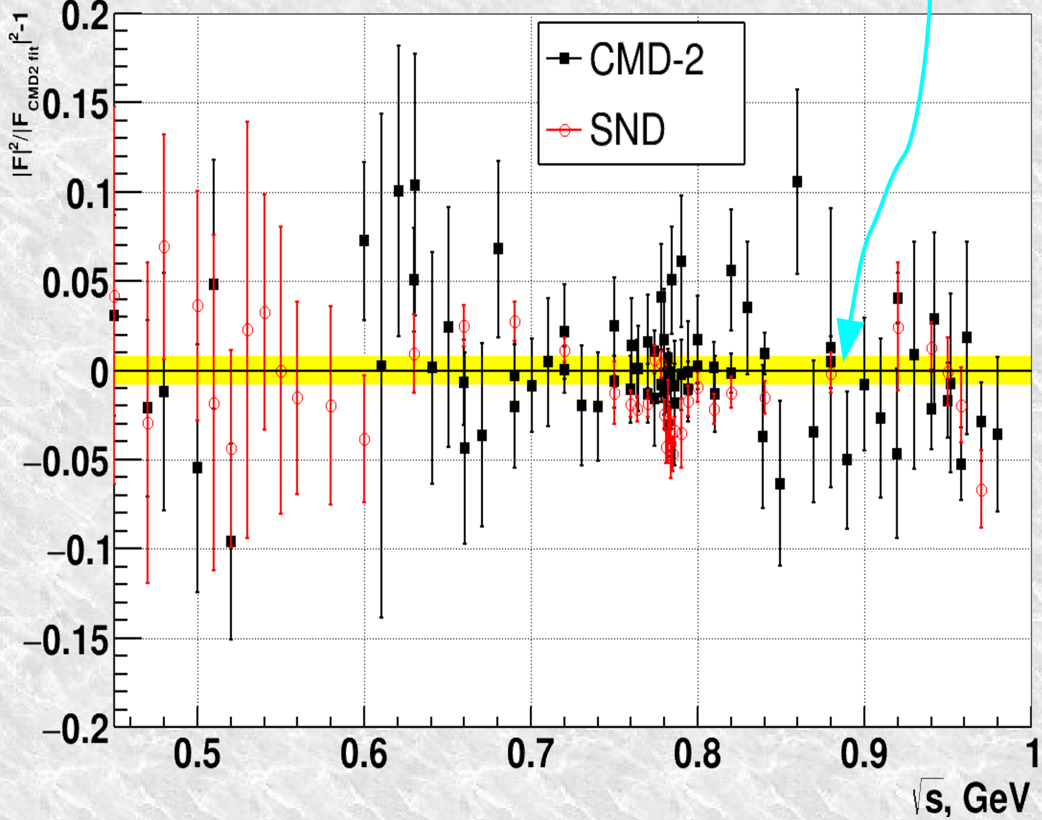
BaBar: 0.5%

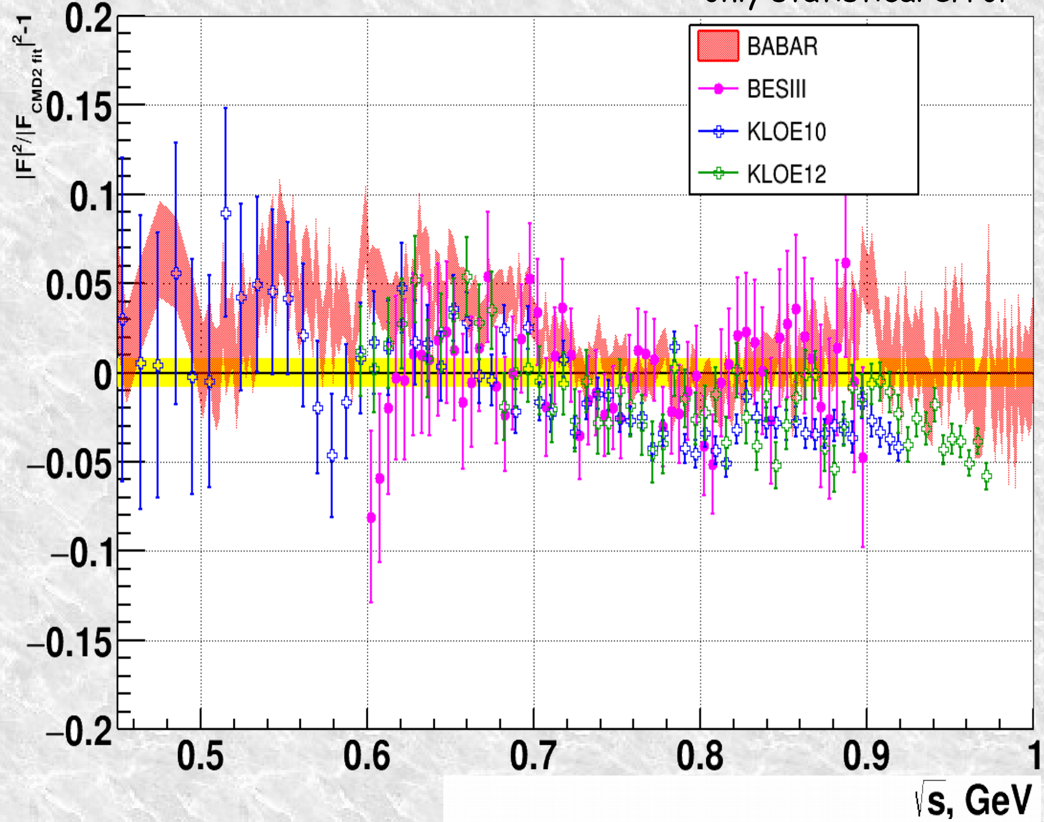
BES: 0.9%

Published cross section e+ e− → π+ π−

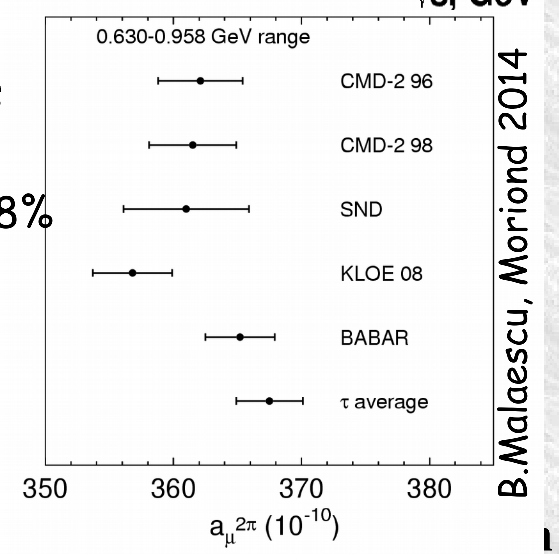
Relative to CMD-2 fit, yellow band – systematic value

Points, red band: only statistical error





Systematic Uncertainties (ρ-region)
CMD2: 0.6-0.8%
SND: 1.5%
BABAR :0.5%
KLOE: 0.8%
BES: 0.9%



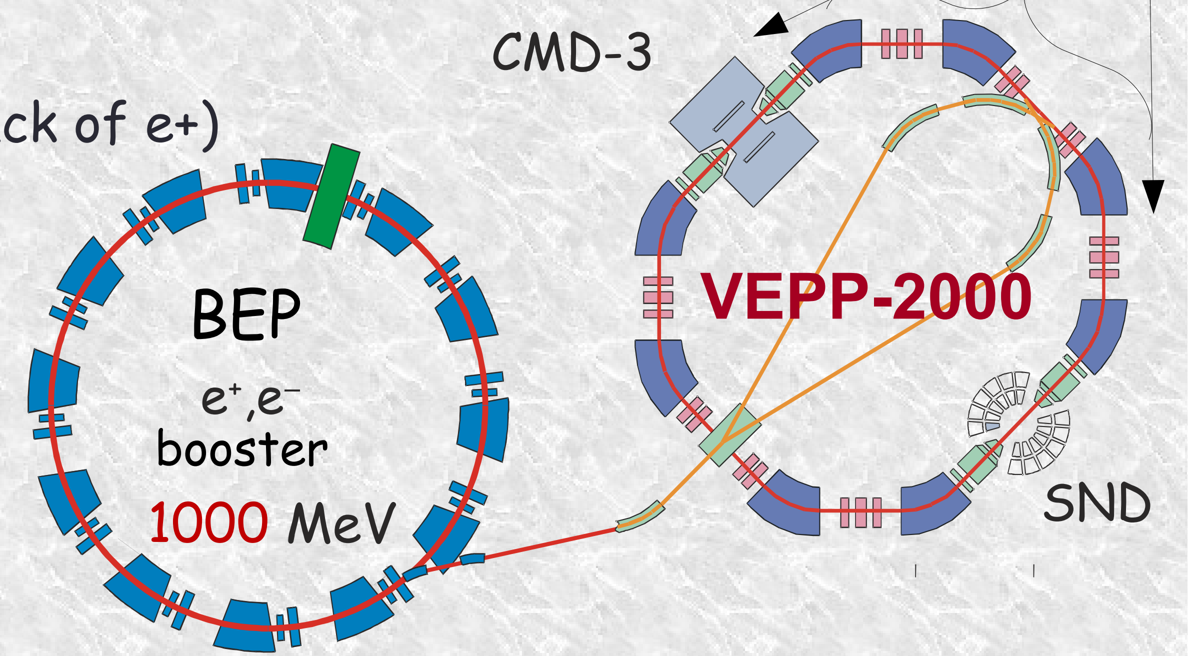
In integral, there is reasonable agreement between existing data sets

But there are local inconsistencies larger than claimed systematic errors → additional scale factor for error of integral value

VEPP-2000 e+e- collider (2E<2 GeV)

- New positron source from 2016 (no luminosity limitation due to lack of e+)

	before	after upgrade
e + /sec	2×10^7	3×10^8
e − /sec	10^9	10^{11}
BEP E max , МэВ	825	1000

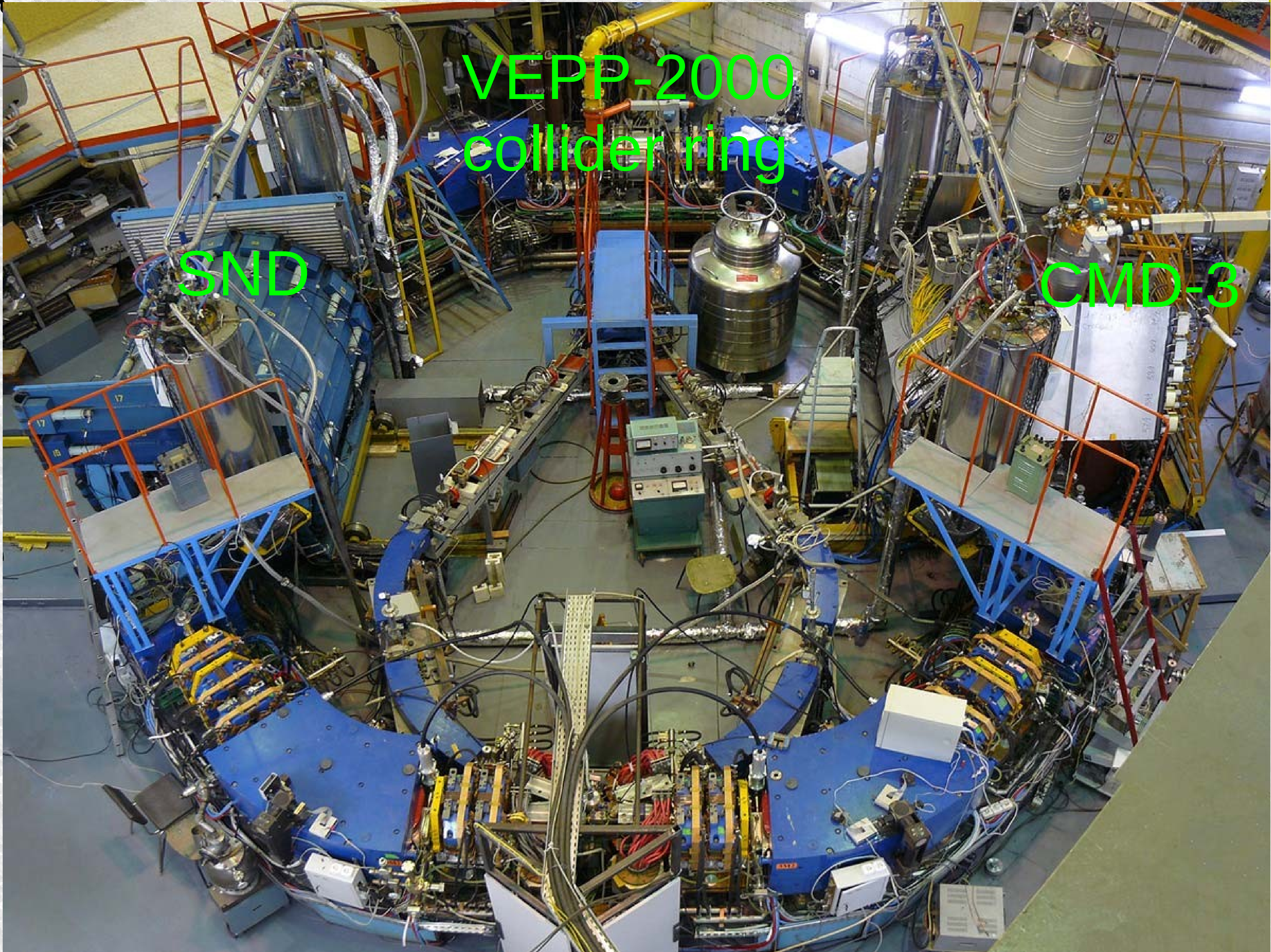


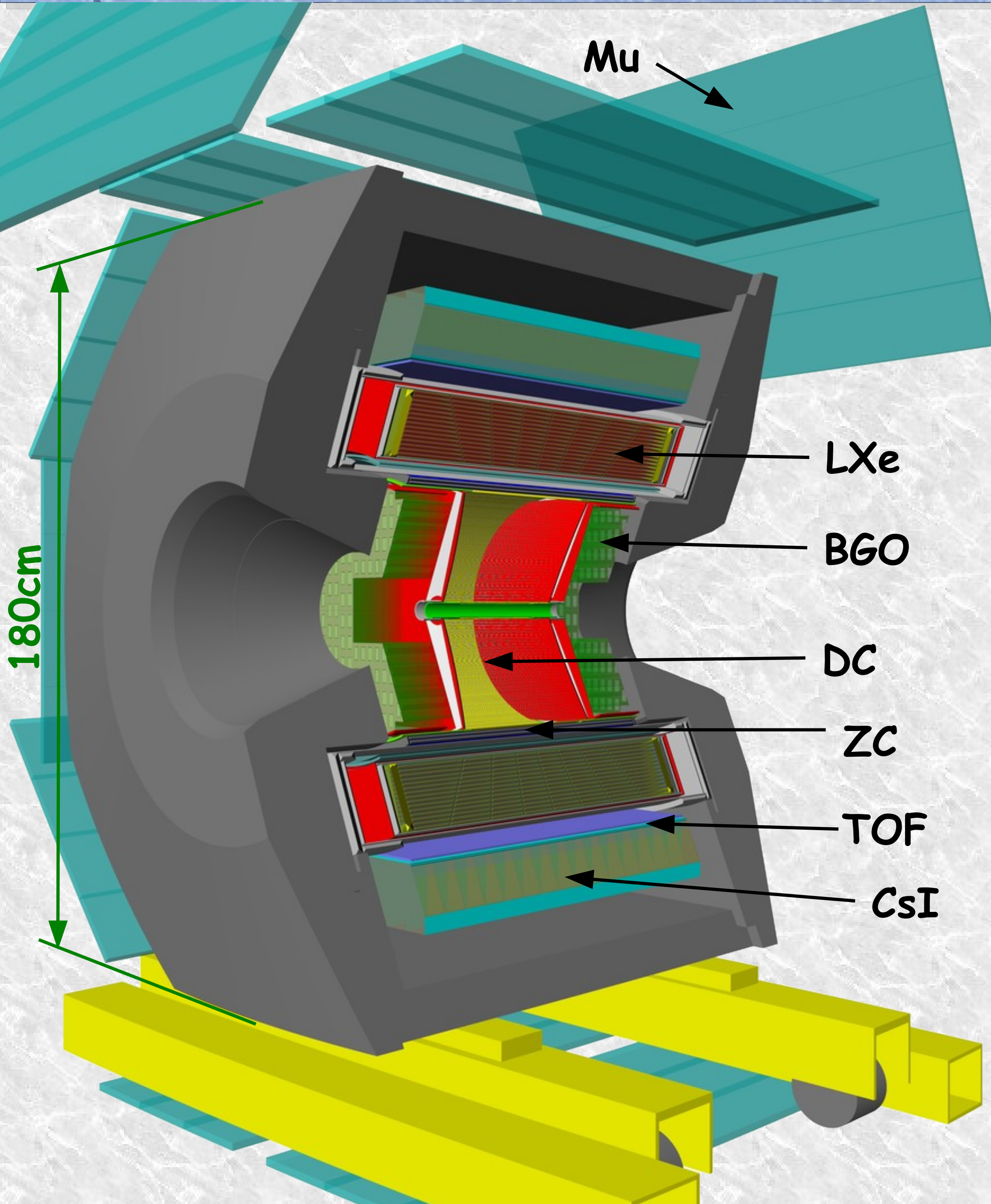
See on: Thursday, afternoon
Dmitry SHWARTZ
"Overview of the BINP accelerator complex"

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


VEPP-2000
collider ring
SND
CMD-3



Advantages compared to previous CMD-2:

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

✗ thicker barrel calorimeter,
- $8.3\ X_0 \rightarrow 13.4\ X_0$
- better particle separation

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

✗ TOF system
- particle id (mainly p, n)

e+e- -> π+π- by CMD3

Very challenging channel as needs to be measured at best systematic 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

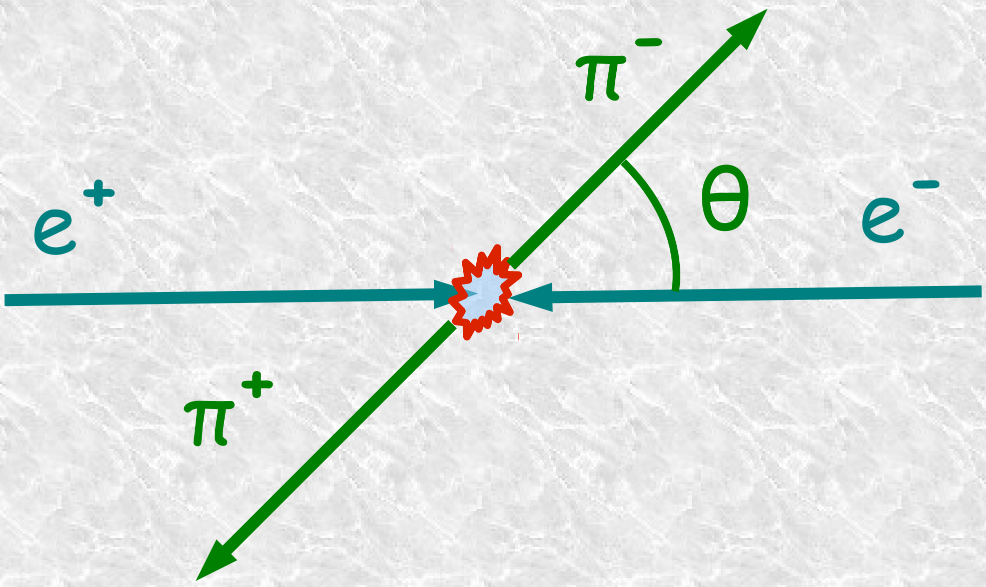
3) Radiative correction, MC generators

... efficiencies

... beam energy precision

Many systematic studies rely on high statistics

Event selection



- Two charged collinear tracks:
  $|\Delta\phi|<0.15,\quad |\Delta\theta|<0.25 \qquad Q_1+Q_2=0$
- Vertex position close to interaction point:
  $\rho_{average}<0.3\,\text{cm},\ |Z_{average}|<5\,\text{cm}$
  $|\Delta\rho|<0.3\,\text{cm},\ |\Delta Z|<5\,\text{cm}$
- 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:
  $0.45\,E_{beam}<p^+, p^-<E_{beam}+100\,\text{MeV}/c$

Data sample includes events with: **e+e-, μ+μ-, π+π-, cosmic muons**

Almost no other background at √s <1 GeV

Event separation

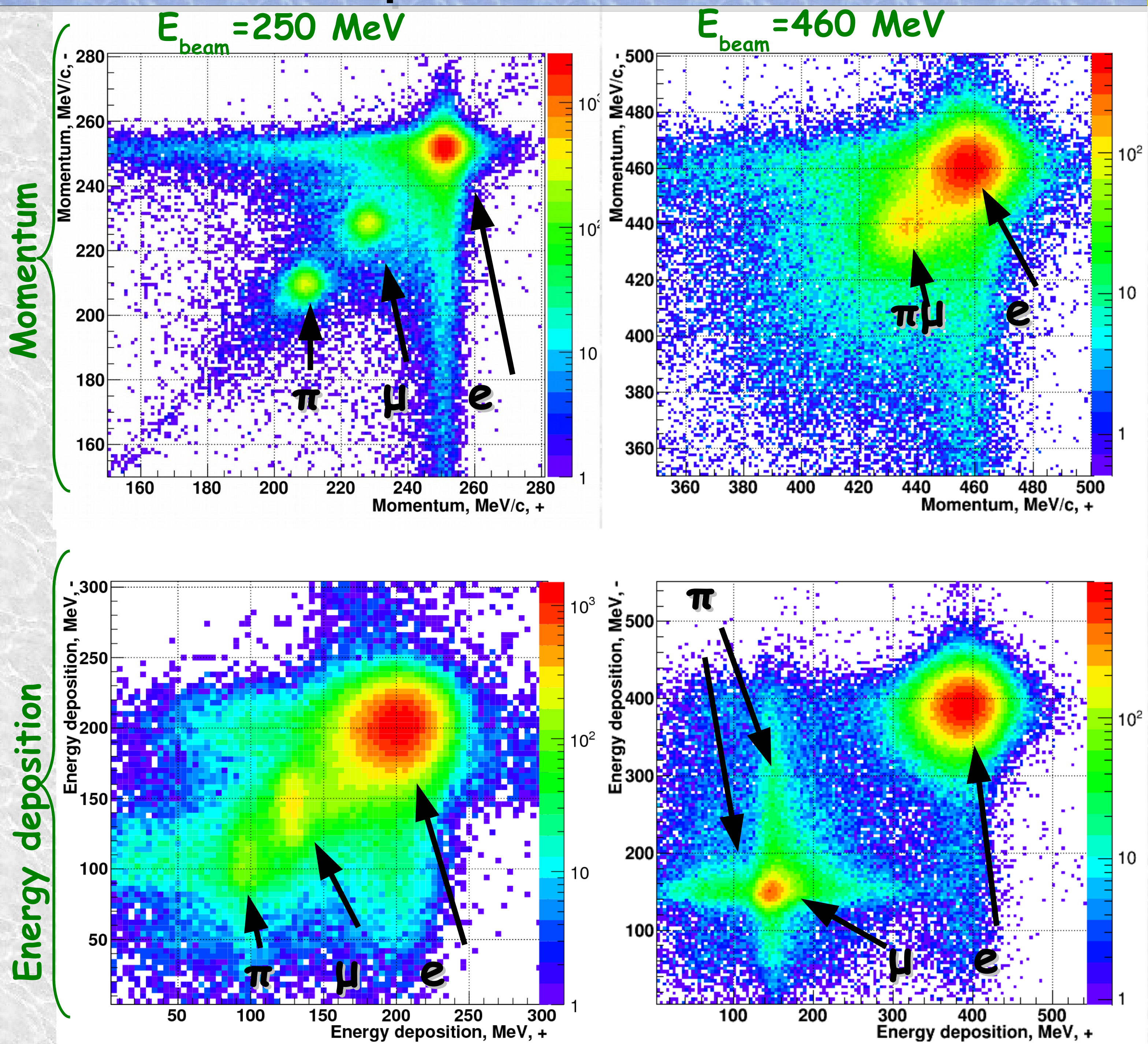
Particle ID can be done by momentum or energy deposition

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

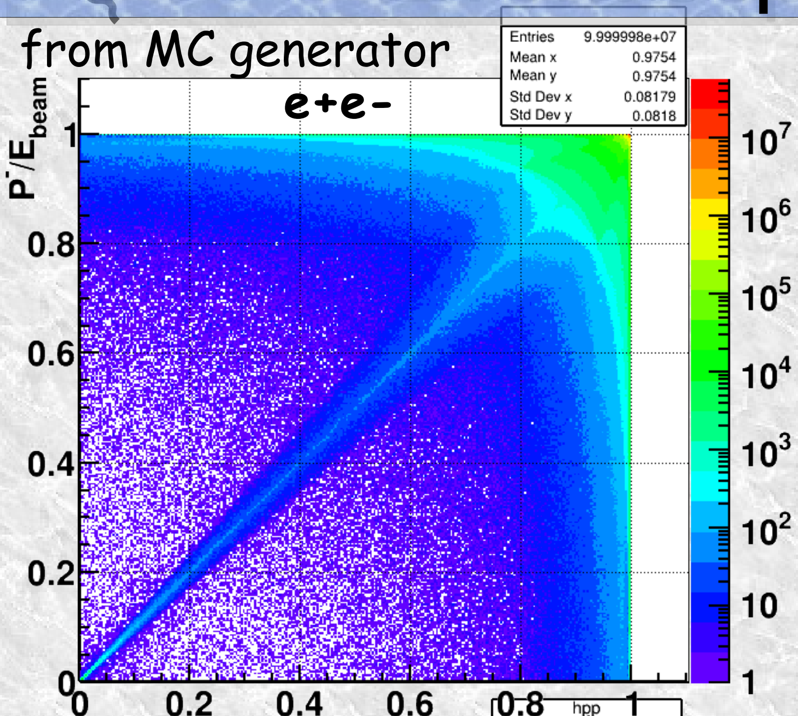
At higher energies Electron shower in calorimeter far away from MIPs

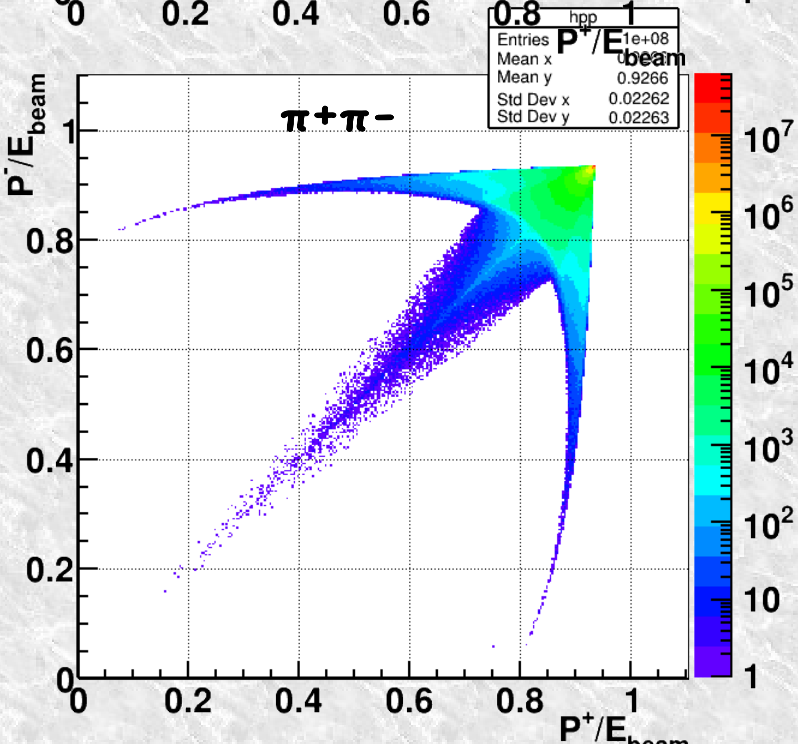
Both methods can be used separately for cross-check

Nμμ can be fixed (or not) from QED



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)

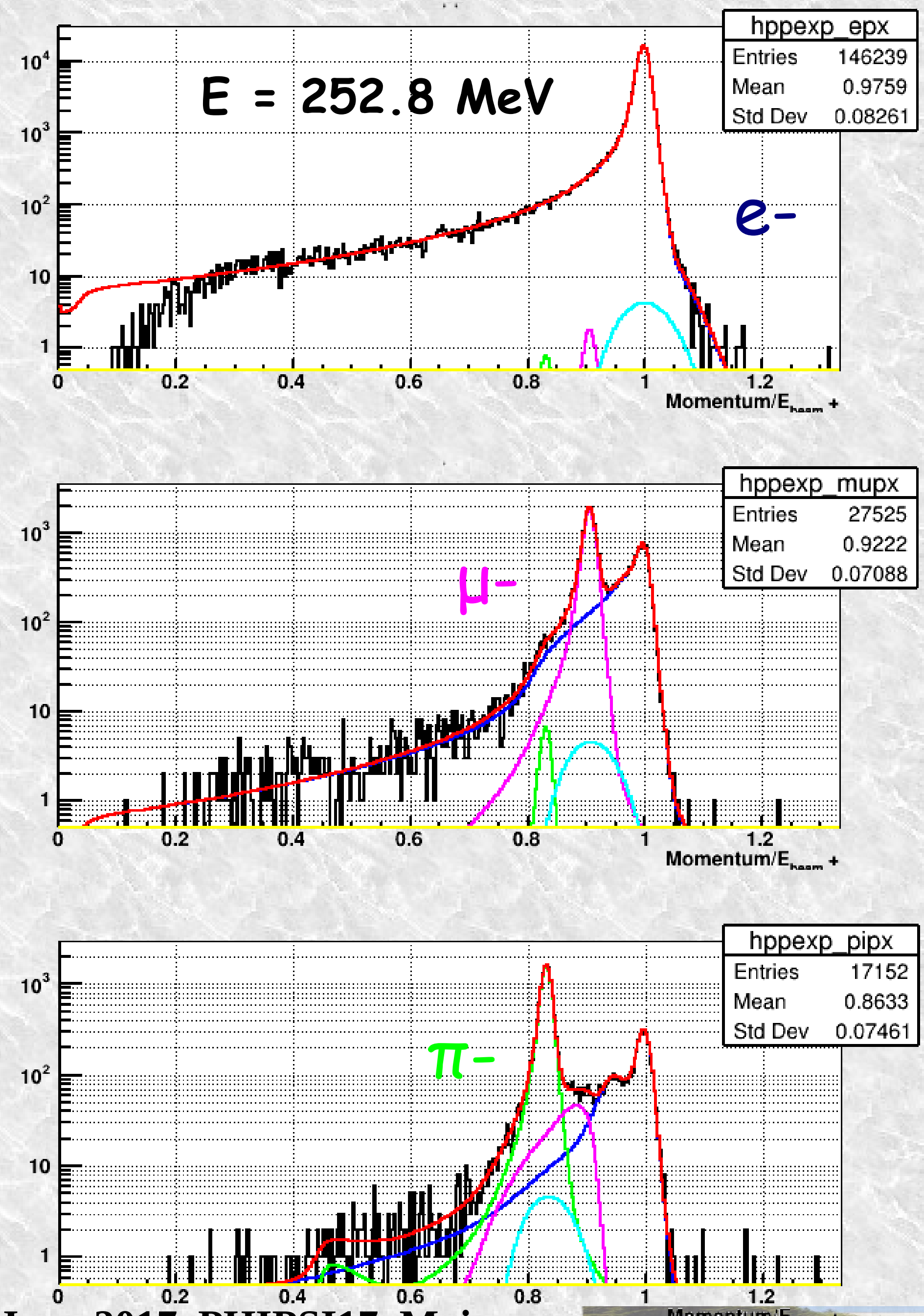
Generated distributions are convolved with detector response function which includes (with mostly all free parameters in it):

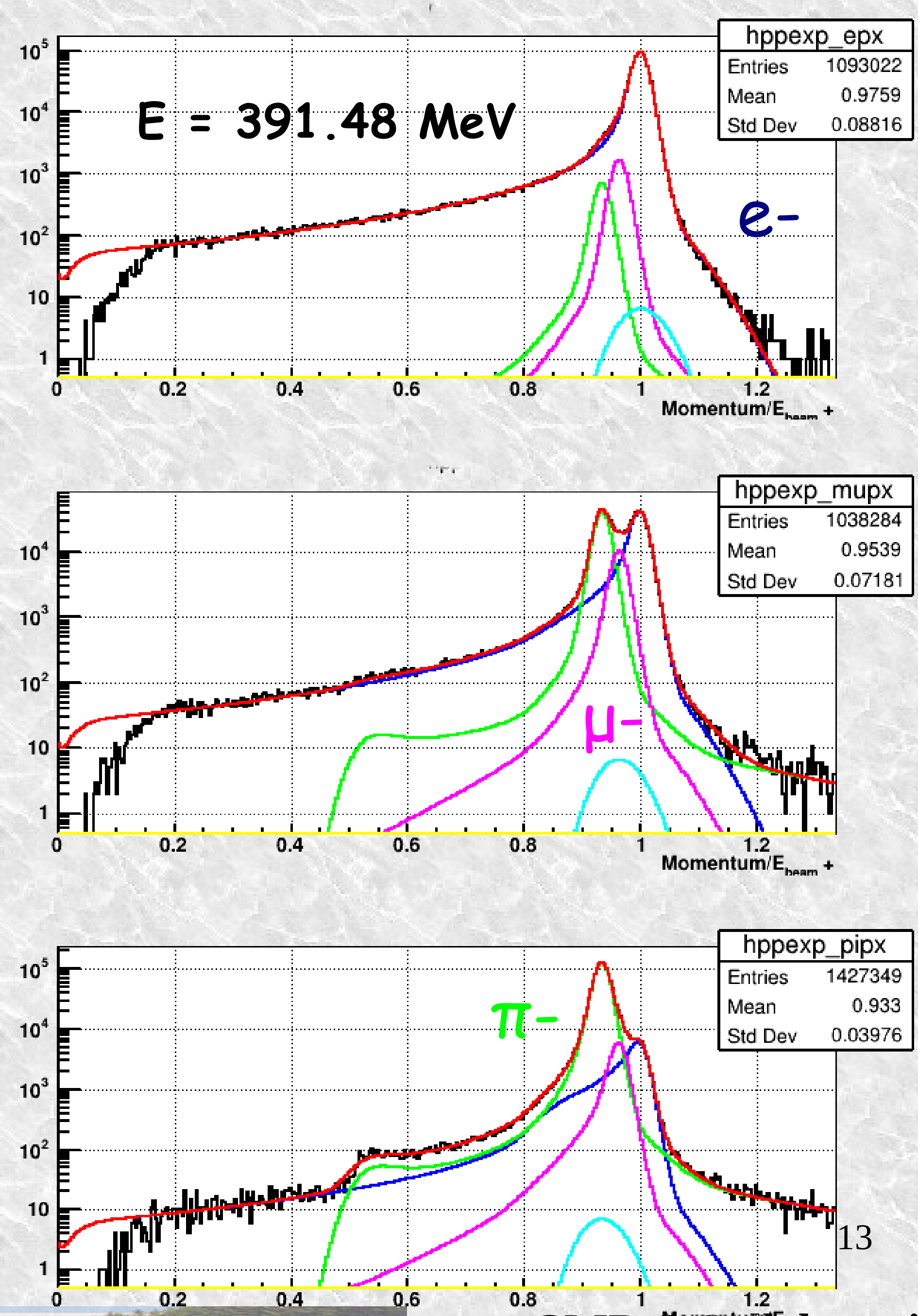
- ✗ momentum resolution,
- ✗ bremsstrahlung of electron on vacuum tube,
- ✗ pion decay in flight

Nππ/Nee obtained as result of binned likelihood minimization

Fit result by momentum

Projection to one charge with different slices over another





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 mostly from data itself (fitted by analytical function, and used with some free parameters)

- Electron - described by mostly free function

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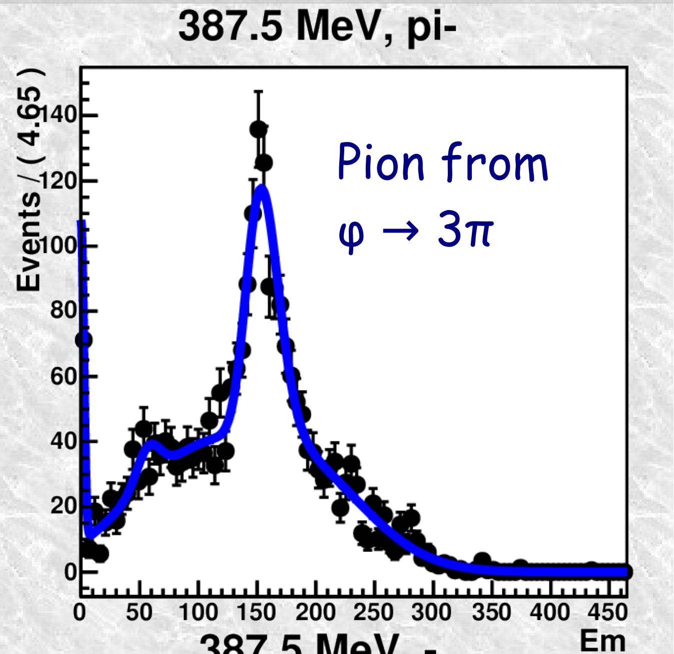
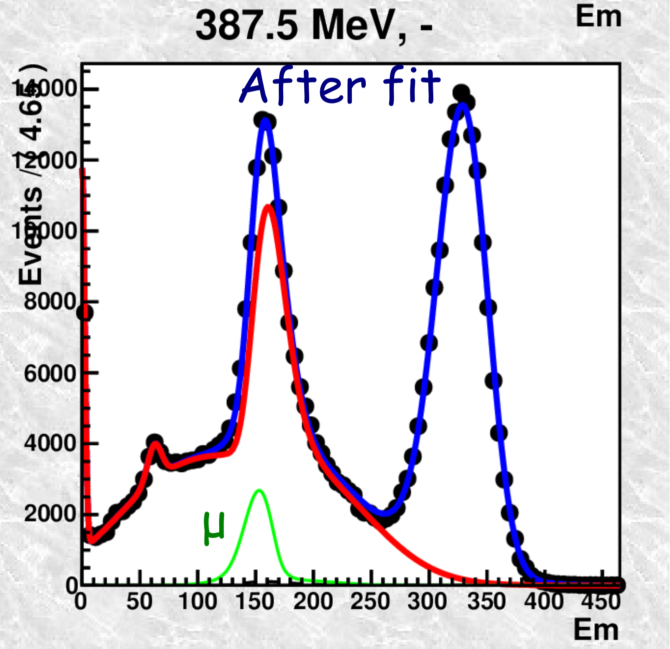
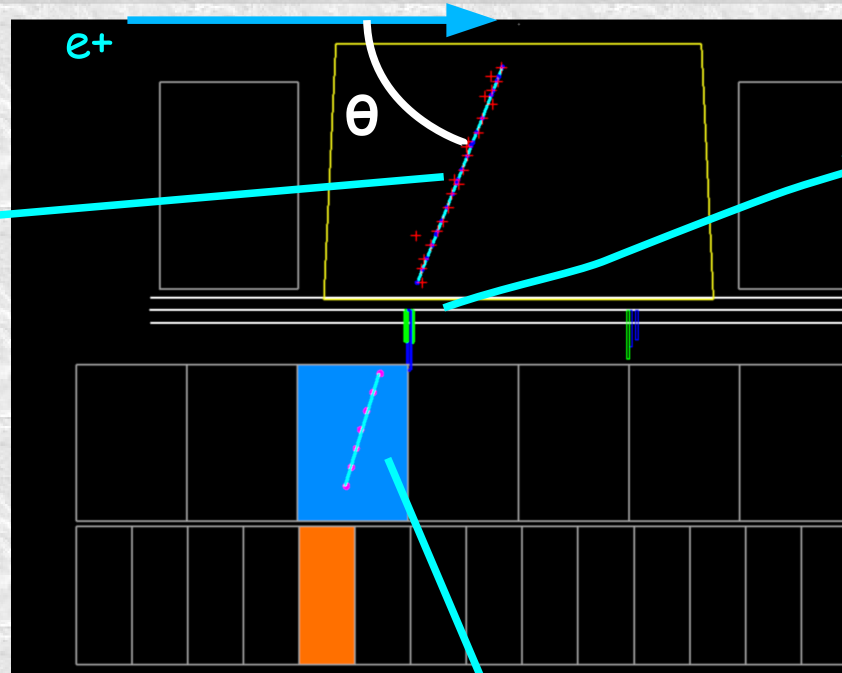
As plans: to exploit information about shower profile (energy deposition in 7 layers of LXe, + CsI)
Neural net can be used for event classification





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)

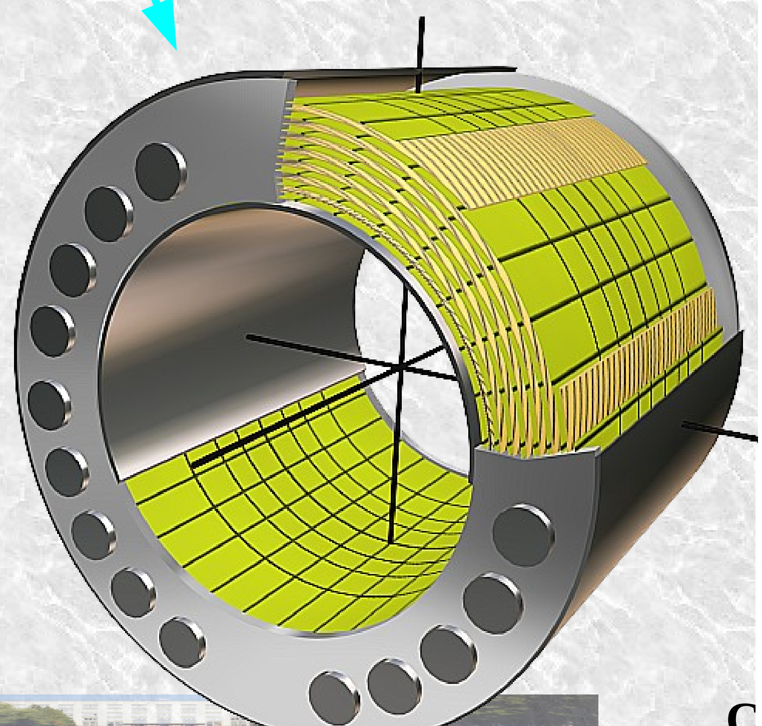


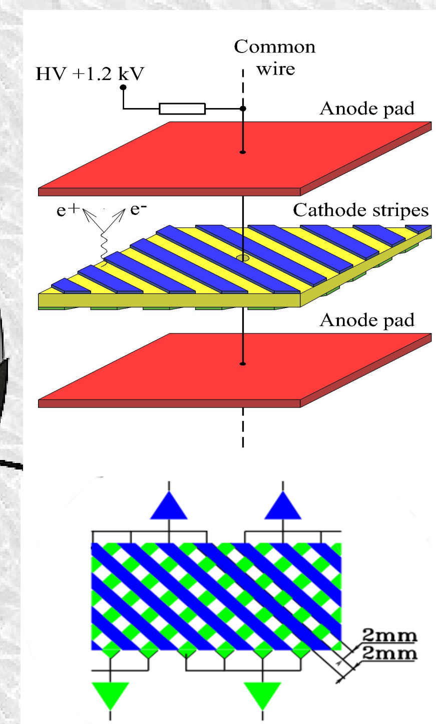
ZC chamber
multiwire chamber
with 2 layers and with strip
readout along Z coordinate

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

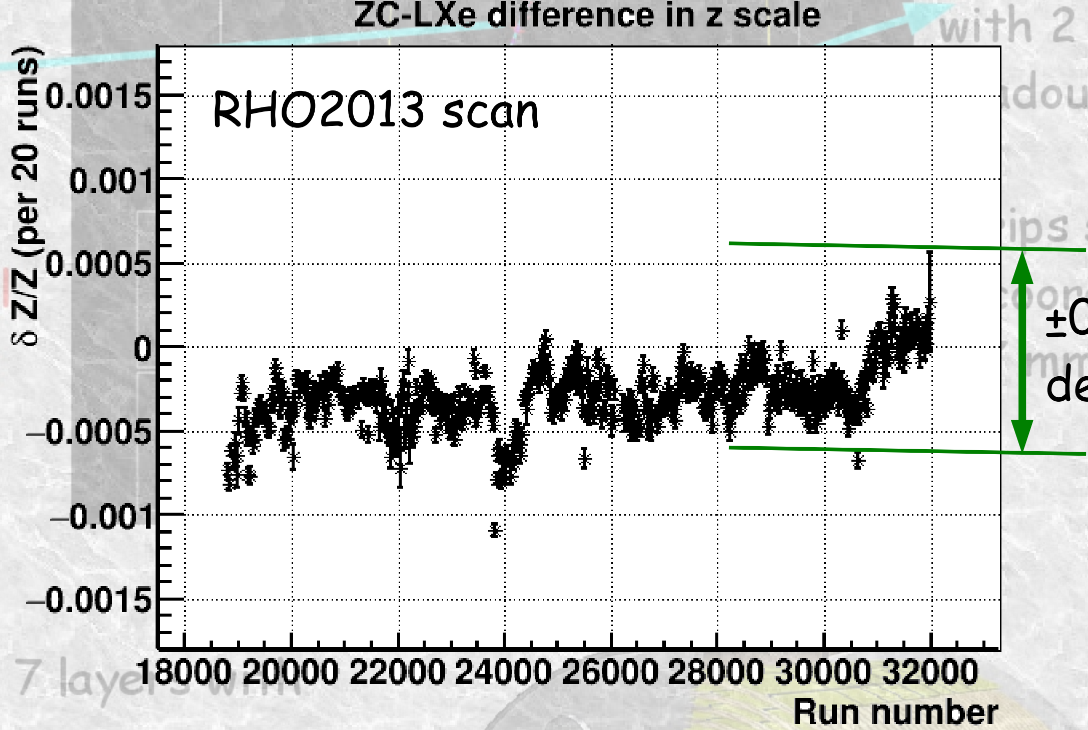




Both subsystem
with strip precision < 100 μm
give <0.1% in Luminosity determination

Precision of fiducial volume

Monitoring of z-measurement between ZC vs LXe



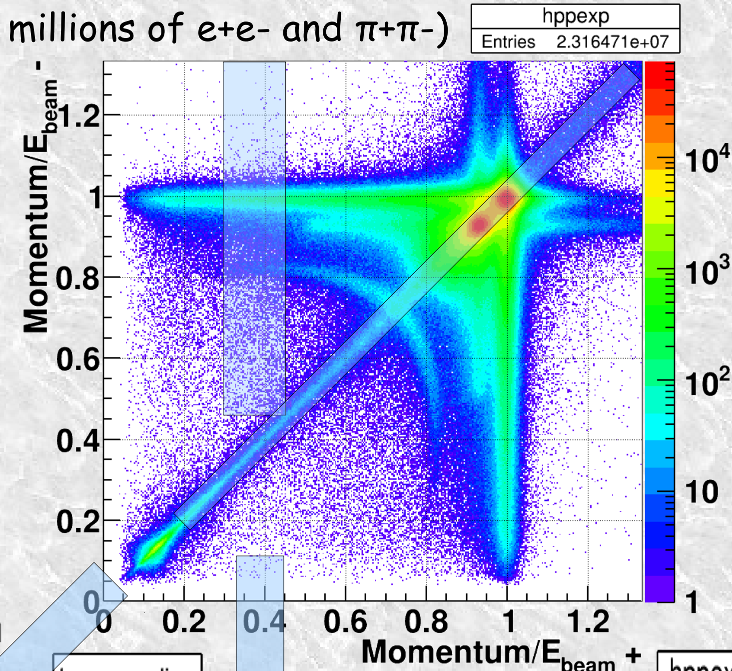
±0.1% Luminosity determination at θ>1rad

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

MC generator, MCGPJ

High experimental precision relies on high theoretical precision of MC tools:

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



MCGPJ generator is used by Novosibirsk group

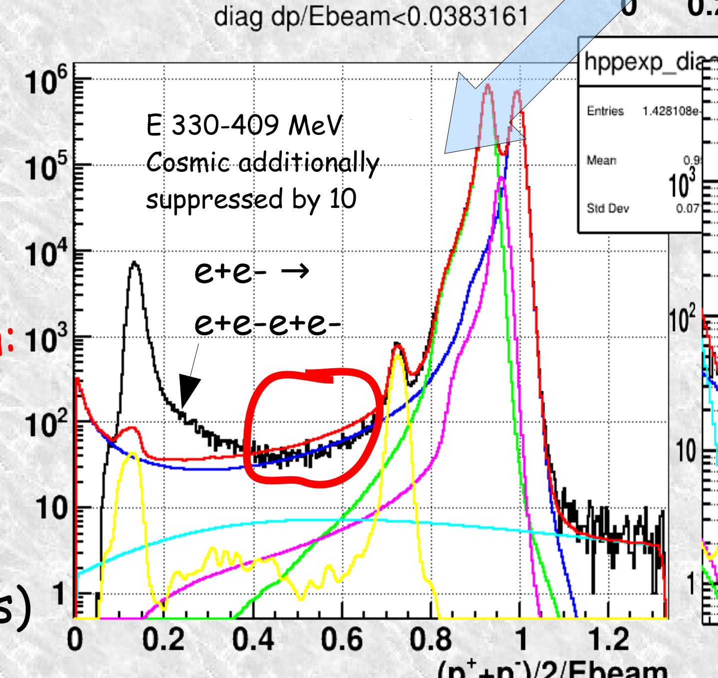
High statistics allowed us to observe
a discrepancy in momentum distribution
of experimental data vs theoretical spectra from MCGPJ

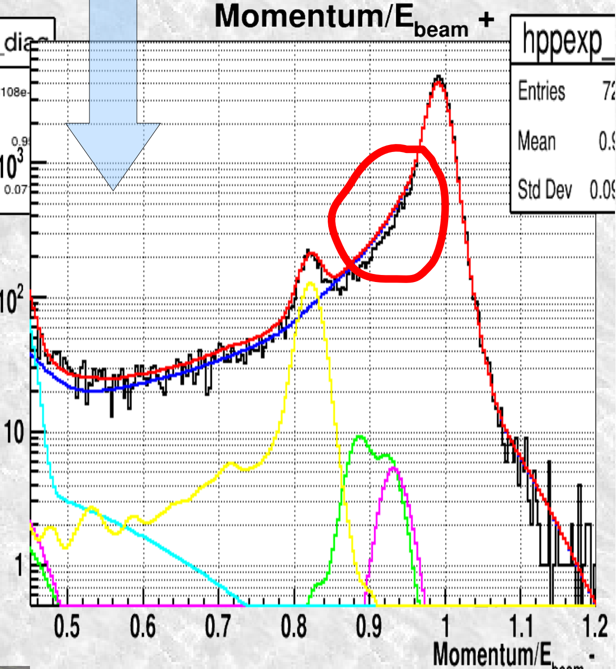
The source of the discrepancy is understood

Several steps for upgrading MCGPJ were done:

photon jet angular distribution,
rebalance of jet compensator,
Structure function for FSR,
...

some question still under inspection:
Matching between
exact Berends 1 photon vs
always 4 jet configuration
(Positive balance of Matrix elements)



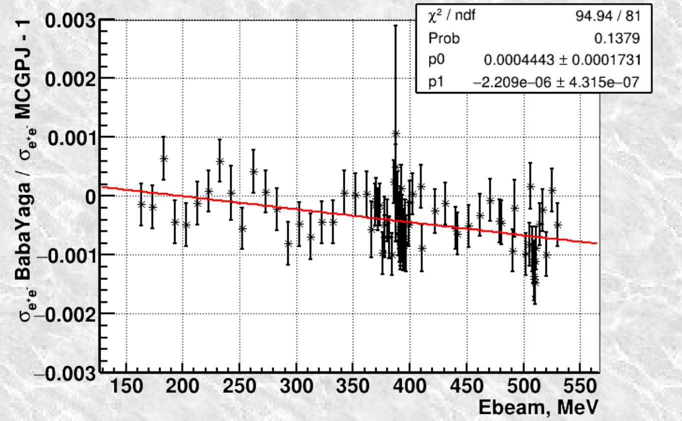


BabaYaga@NLO vs MCGPJ generators

Only two available e+e- → e+e- generators with claimed precision ~ 0.1%

MCGPJ used by Novosibirsk group

BabaYaga@NLO used by KLOE, BaBar



Integrated cross-section was consistent at the level <0.1%

(0.0-0.7% for 2E = 0.15-0.5 GeV)

<u>In 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>

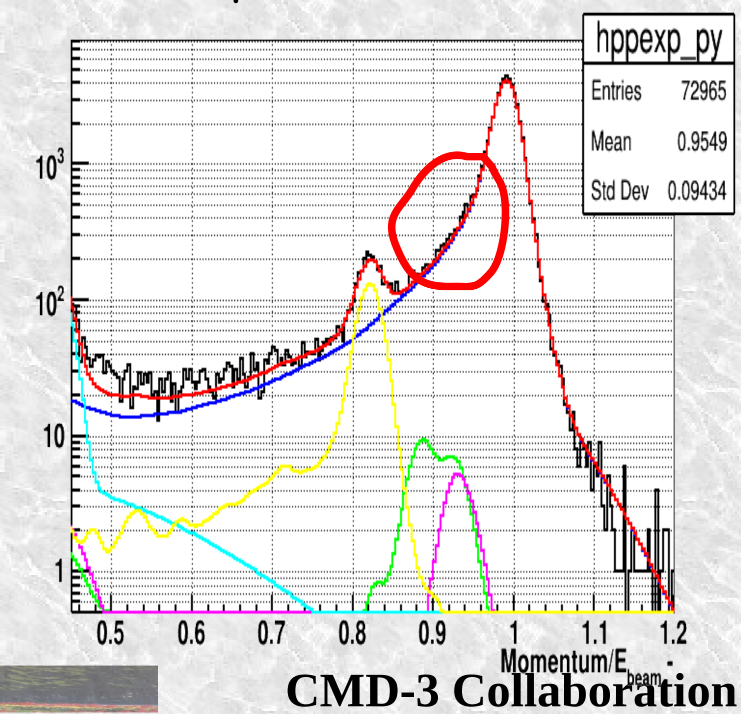
MCGPJ : 751.671 +- 0.034 nb

BabaYaga@NLO : 751.218 +- 0.059 nb

Δ ~ 0.06%

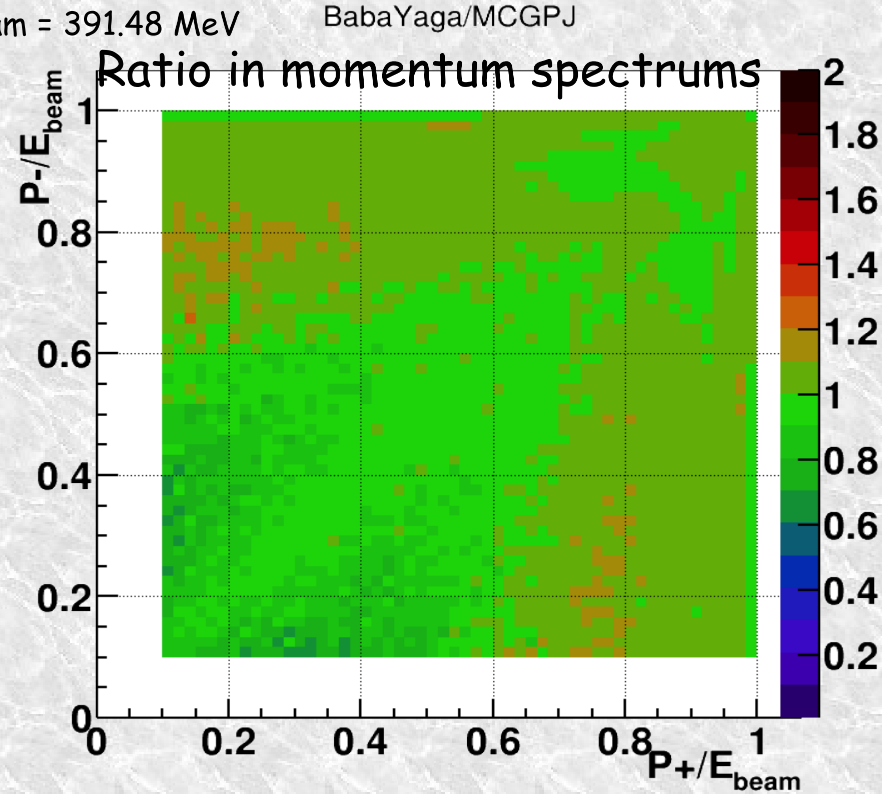
Recent MCGPJ modifications change cross-section: -0.06%

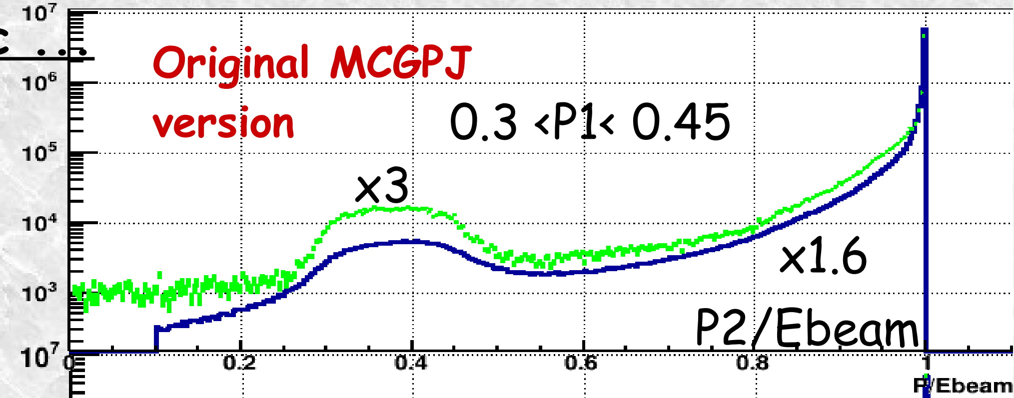
BabaYaga better describes momentum spectrum of experimental data

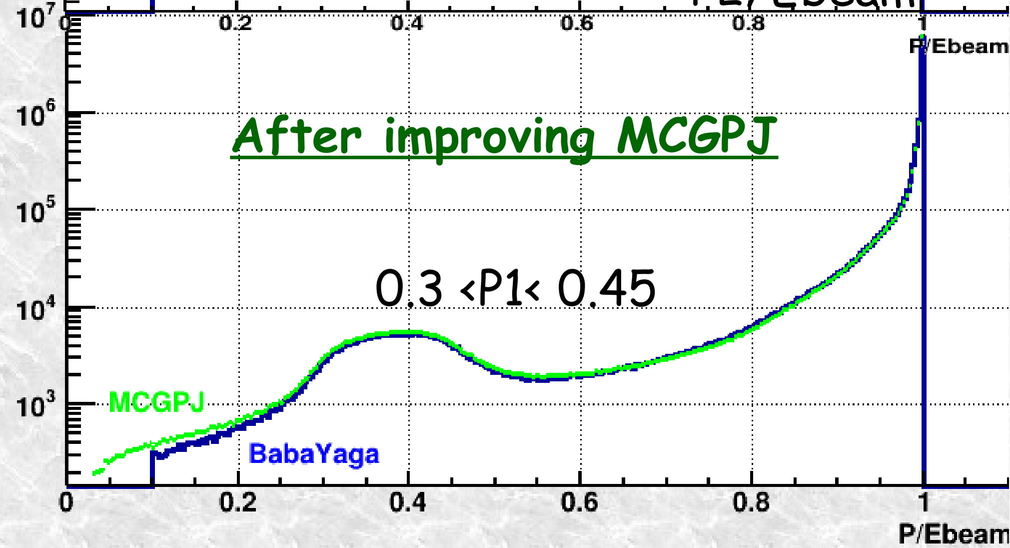


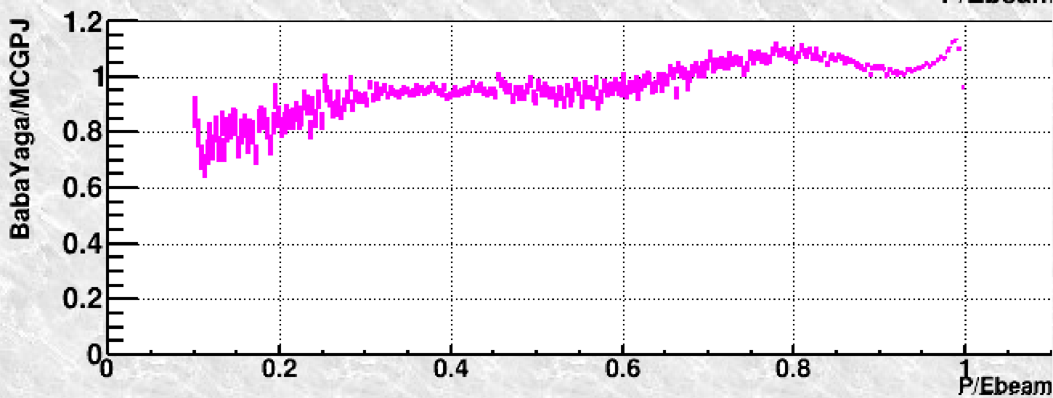
MCGPJ vs BabaYaga spectra

After adding angular distribution for jets, etc ...









Momentum spectrum still disagrees at level ~ 10%

Need more experimental data for cross-check

We need more theoretical help

Result in |Fπ| systematic by momentum

→ 0.0 - 0.4%

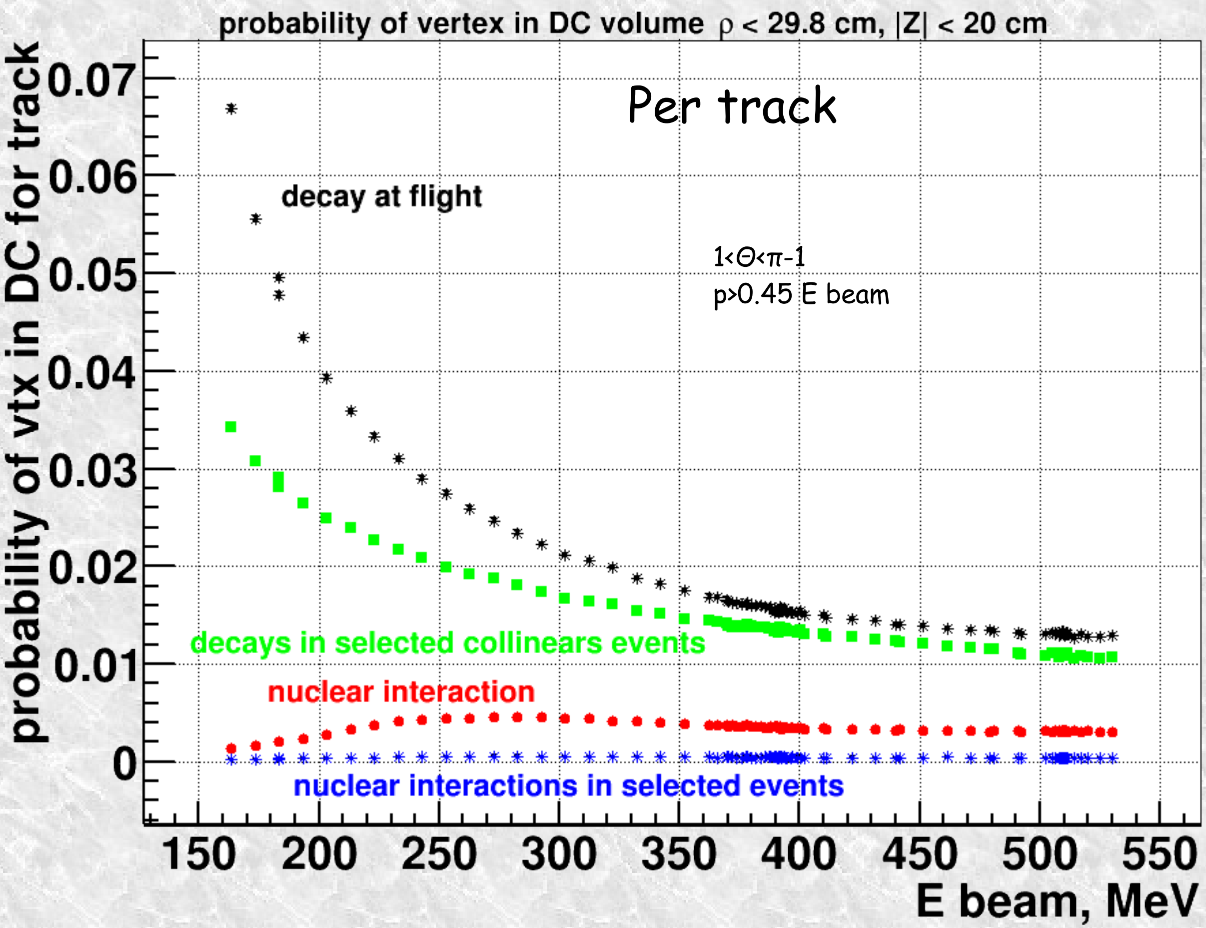
For precision ~<0.1% necessary to have exact e+e-→e+e-(γγ) NNLO generator

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 %

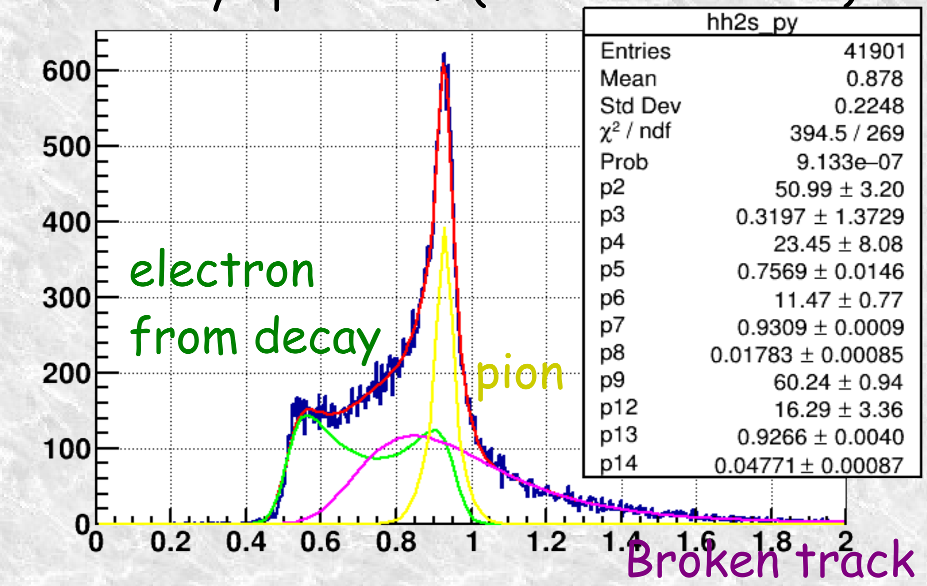
<0.5 % of pions have nuclear interaction in Drift chamber(mostly on vacuum tube),
All events are lost after cuts (survived <0.06%)



Nuclear interaction correction (not depend on detector performance):
Can be taken from simulation(systematic ~ 10%) or can be studied from $\omega \rightarrow 3\pi$

Pion decay inefficiency

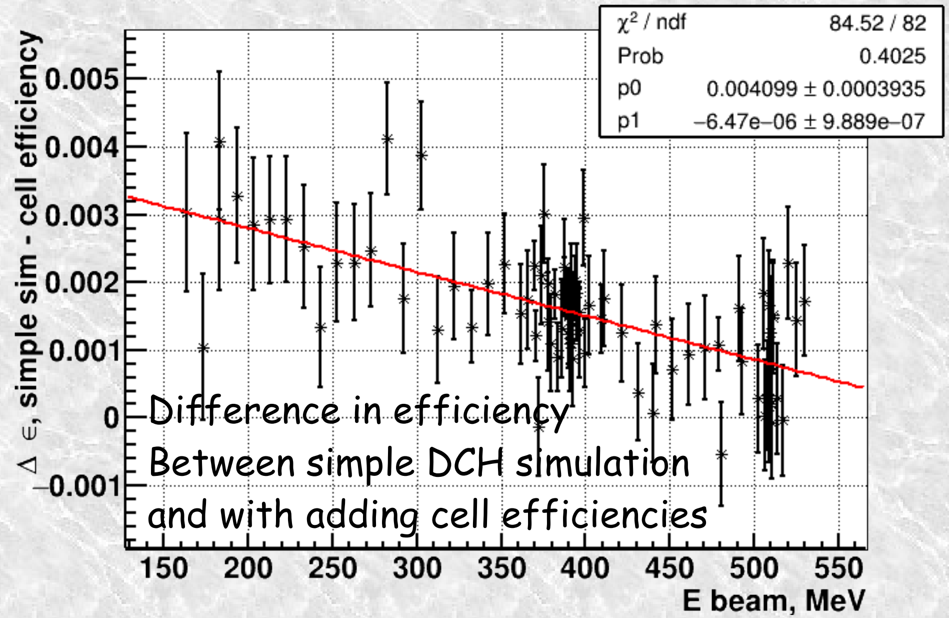
Pion decay spectrum (in selected cuts)



Decay in flight - depends on DCH efficiency

controlled by number of events in tails vs simulation

Simulation: after adding DCH per cells efficiency and amplitudes → 5% change in tails (and also to all decayed tracks)



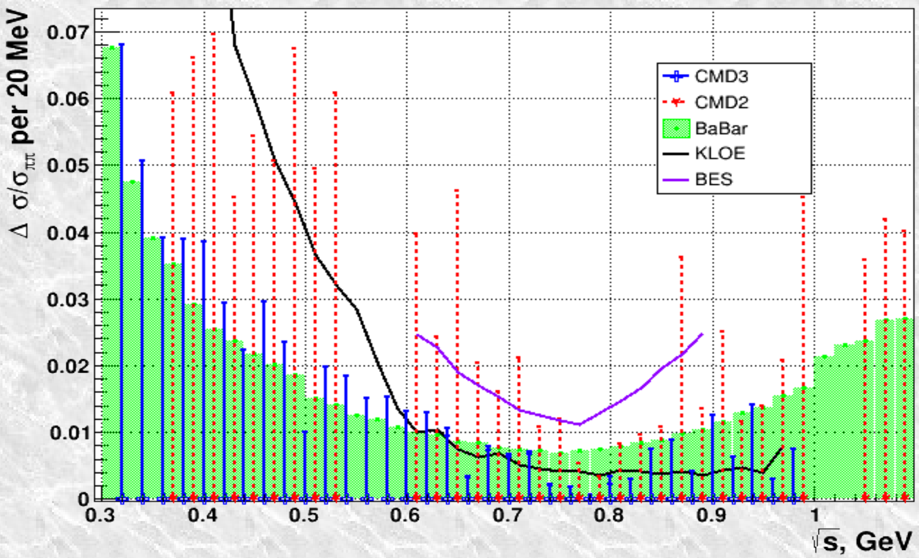
data vs sim efficiency of tails incompatible at ~ 10%

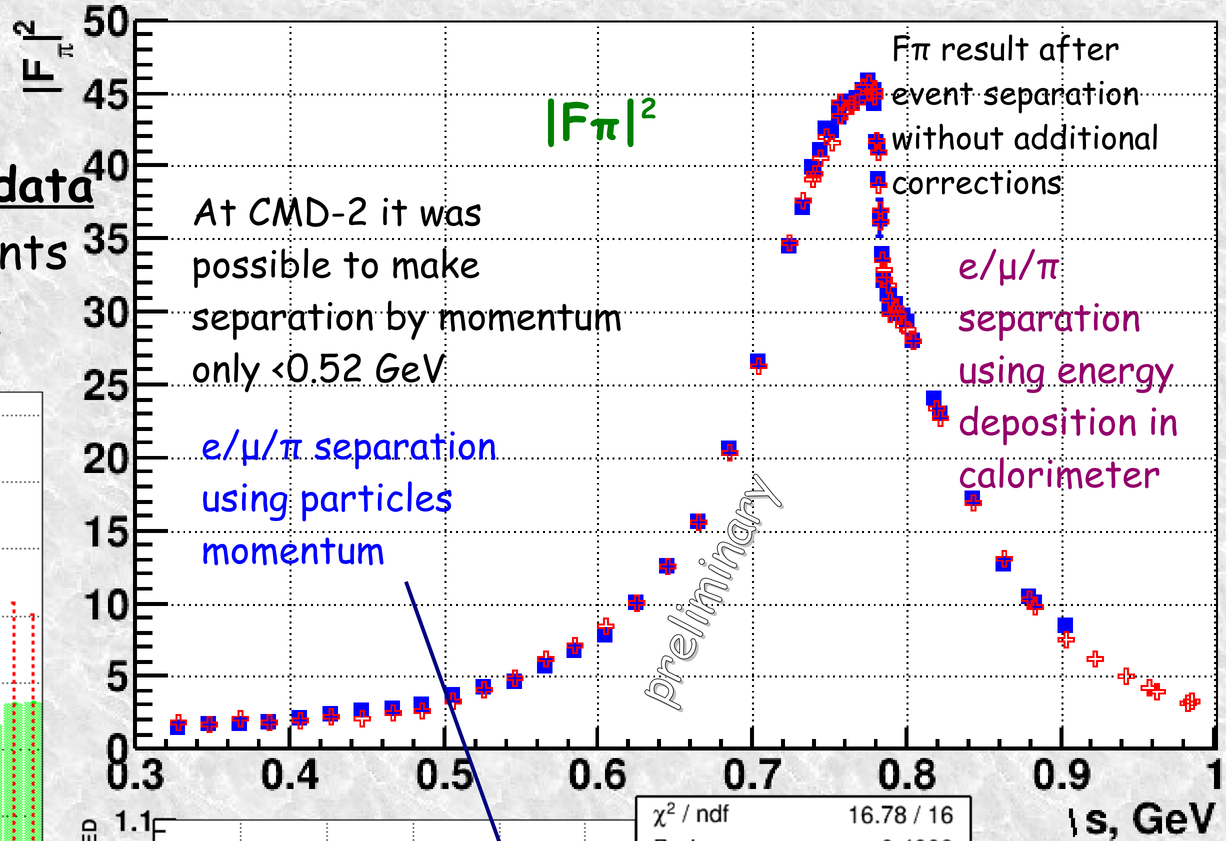
→ 0.6-0.3 % systematic uncertainty of $N\pi\pi$

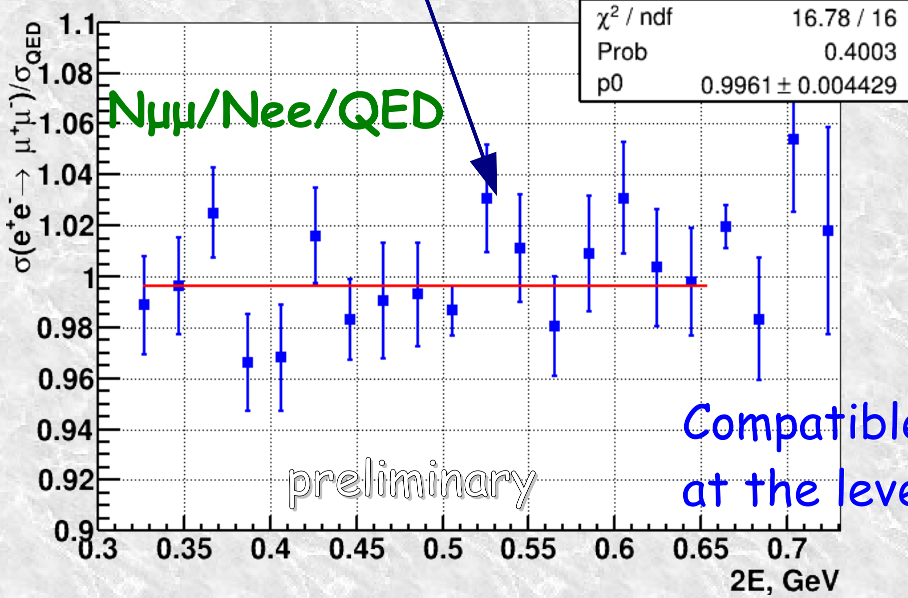
Will be improved with better DCH understanding: next step to introduce noise in simulation (and study of momentum spectrum behavior with variation of cuts)

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 %

Systematic e+e- -> π+π- by CMD3

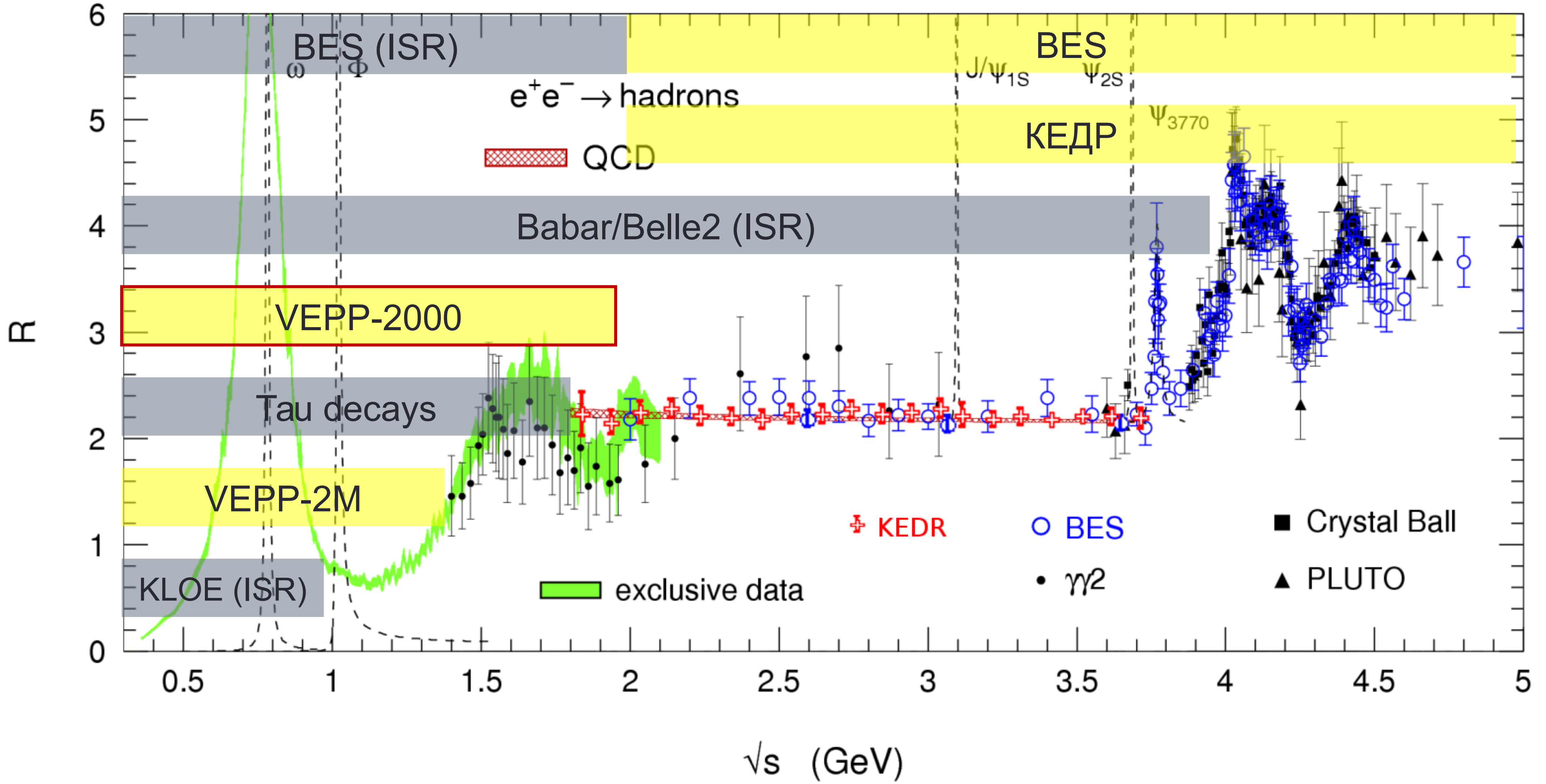
Our goals are to reach systematic level up to 0.35%:	status
✗ Radiative corrections - 0.2%	with current MCGPJ 0.2% - integral cross-section 0.0 – 0.4% - from P spectra
✗ e/μ/π separation – 0.2% can be checked and combined from different methods	~ 0.1 – 0.5% by momentum ~ 1.5% by energy
✗ Fiducial volume – 0.1% controlled independently by LXe and ZC subsystems, angular distribution	✓ ok
✗ Beam Energy – 0.1 % measured by method of Compton back scattering of the laser photons(σ_E< 50 keV)	✓ ok
✗ Pion specific correction – 0.1% decay, nuclear interaction taken from data	~ 0.1 % nuclear interaction 0.6-0.3% pion decay

Many systematic studies rely on high statistics

Conclusion

- VEPP-2000 is running smoothly at $\sqrt{s}$ < 2.00 GeV.
- In 2011-2013 CMD-3 and SND have collected 60 1/pb per detector. Collected integral is similar to the total integral available before.
- Scan at <1 GeV was done in 2013, analysis of $e^+e^- \to \pi^+\pi^-$ is underway
- High statistics allow us to study and to control better different systematic contributions, with final goal up to 0.35%
- In 2013-2016 the collider has been upgraded and data taking was resumed with the ultimate goal of collecting O(1) 1/fb in 5-10 years which should provide new precise results on the hadron production

VEPP-2000 and the world

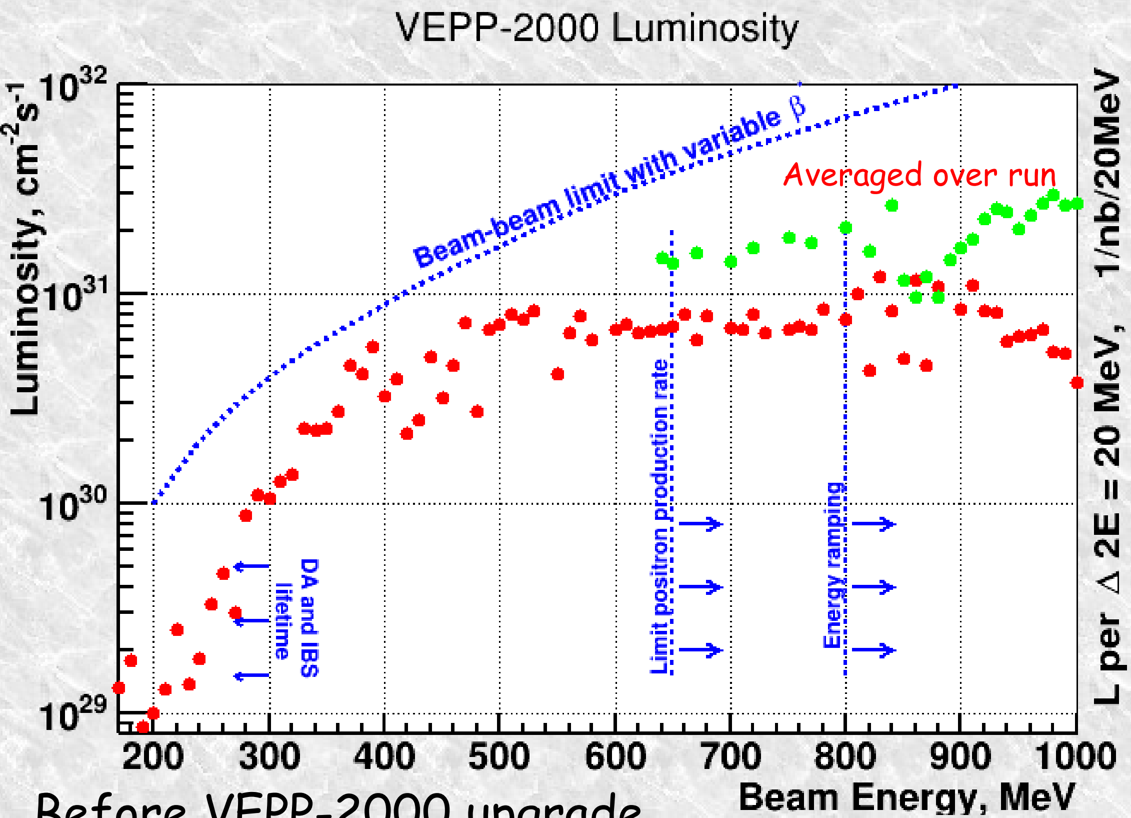


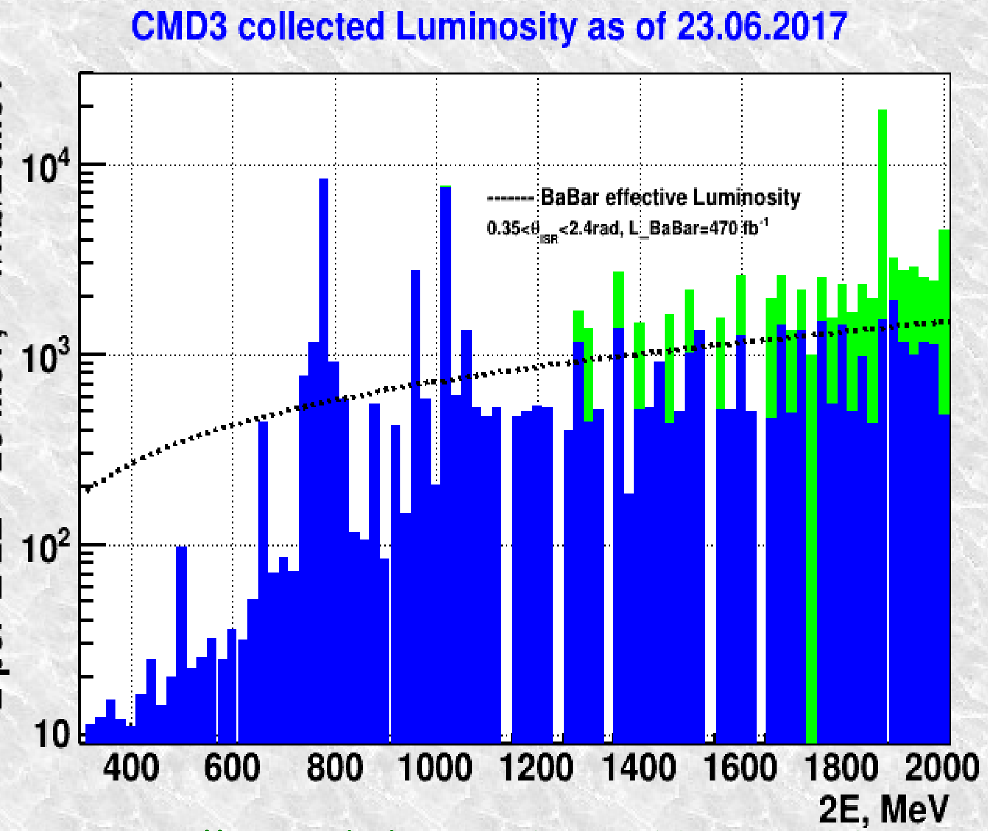
VEPP-2000: direct exclusive measurement of σ (e+e- → hadrons)

Only one working this days on scanning this region

World-best luminosity below 2 GeV (1 GeV excluded – where KLOE outperfom everybody)

Collected Luminosity





<u>Before VEPP-2000 upgrade</u>

The luminosity at high energy was limited by a deficit of positrons (from E > 825 MeV) and limited energy of the booster (from E > 825 MeV)

<u>After upgrade and tuning</u> we expect luminosity increase by up to factor 10 at maximum energy

VEPP is constantly improving luminosity

Usually asked to be slowly by detector side (to work more on better quality of beams)

<u>Collected during 12.2010-07.2013</u>

<u>L ~ 60 pb^{-1} per detector</u>

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

<u>2017 season (up 23 June)</u>

50.7 pb^{-1}	> 1.3 GeV

π+π-π0 background

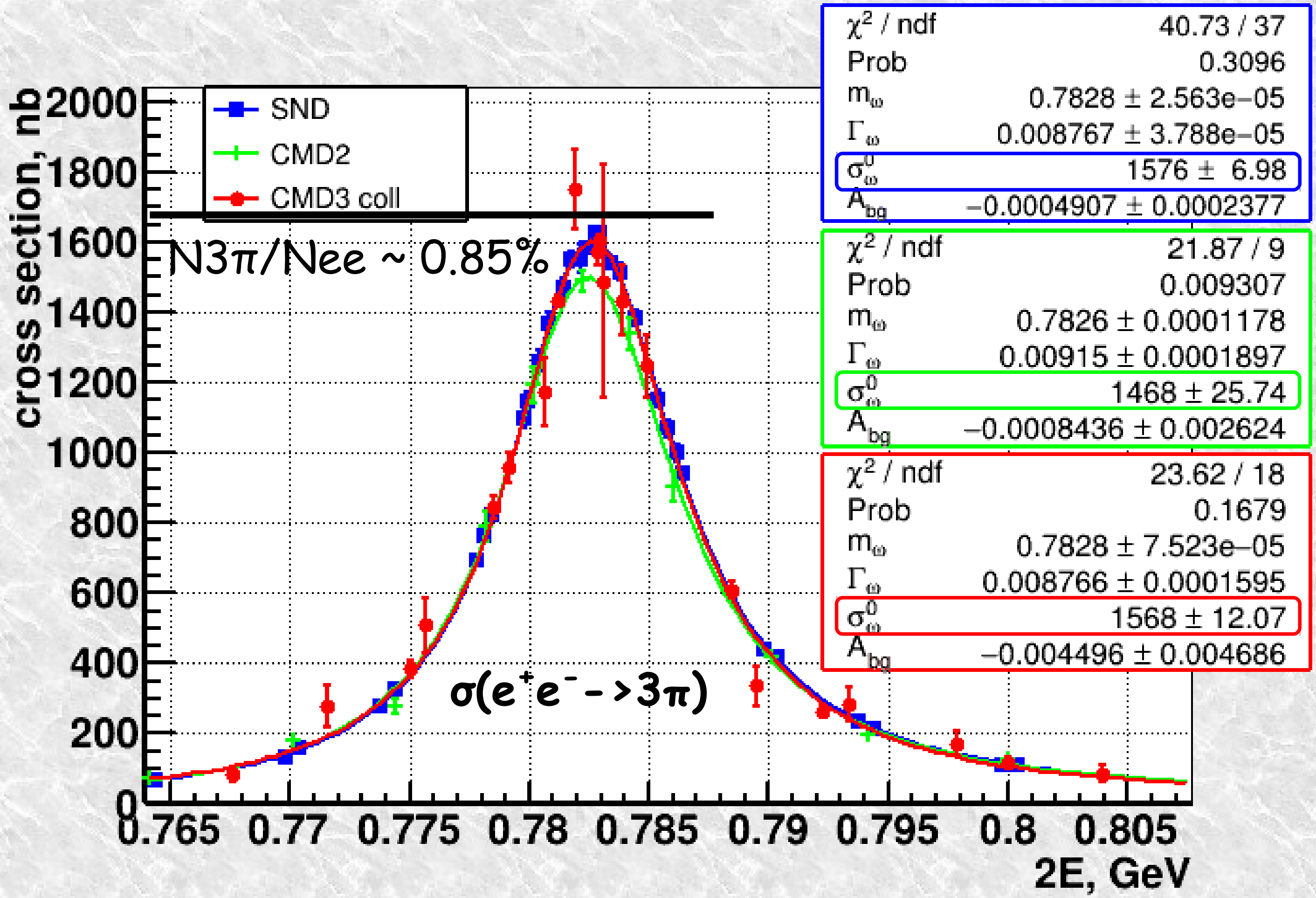
Only significant physical background in selected data sample:

$\pi^+\pi^-\pi^0$ on ω-resonance

Contribution < 1%

This events well seen during particle separation by momentum distributions

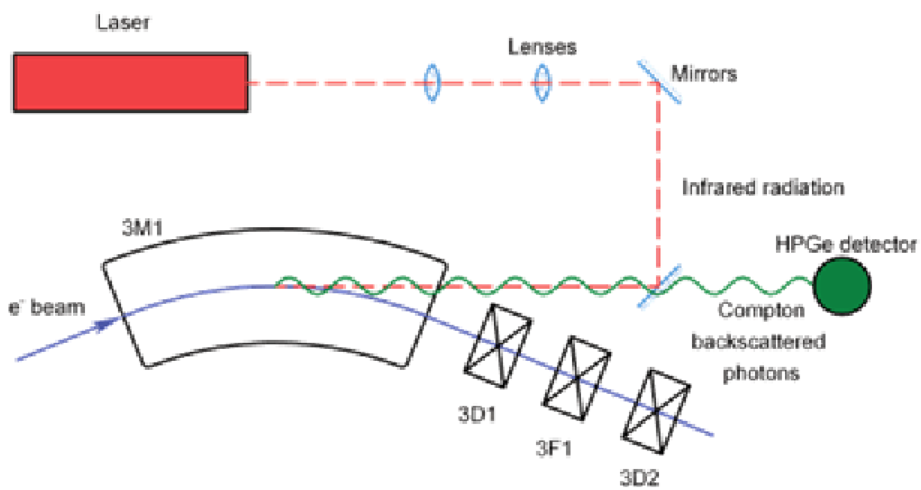
Extracted σ(e^+e^- -> 3π) from collinear events (in phase space model) compatible with published results



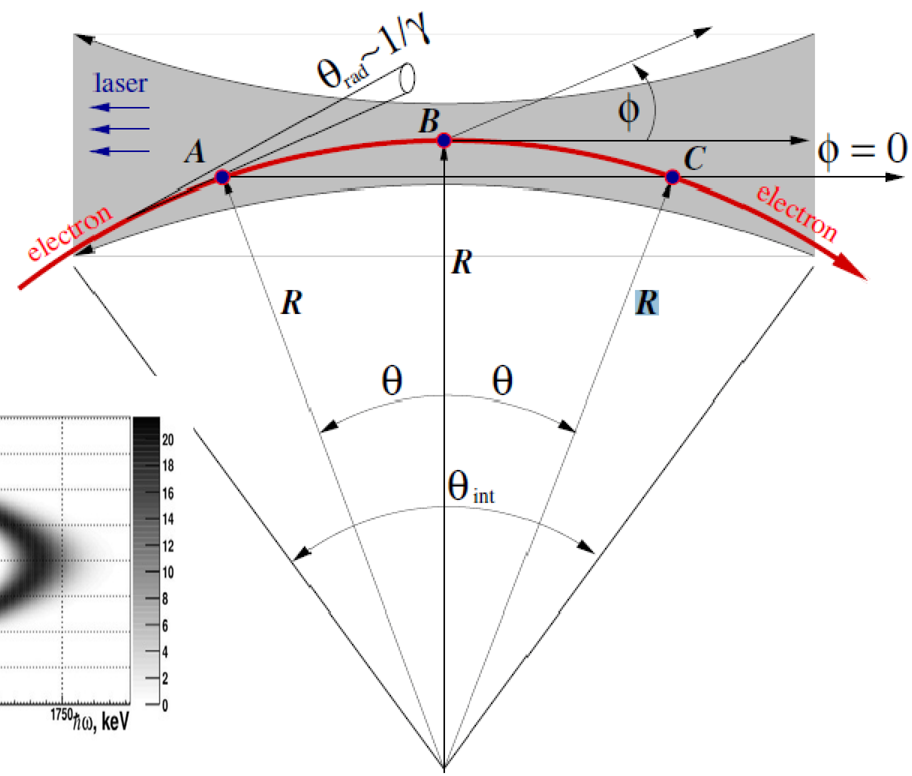
ε (3π)=0.4833% acceptance efficiency from simulation by phase space model

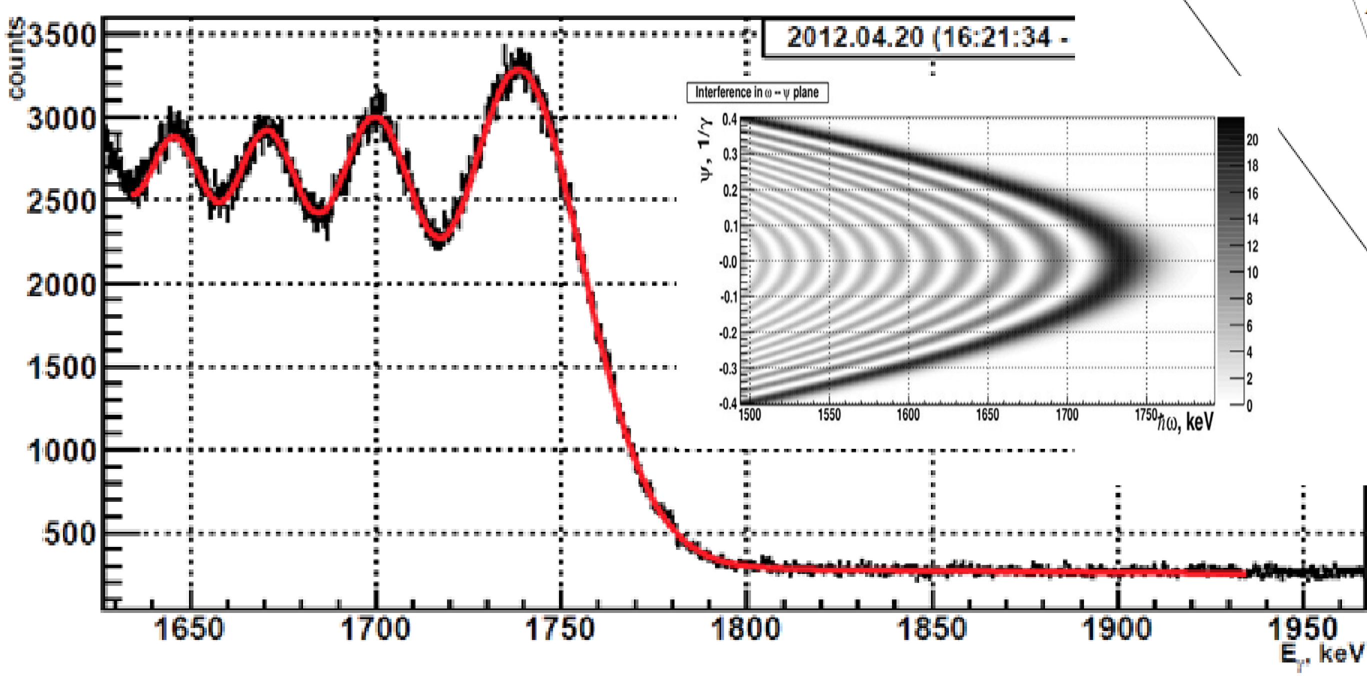
Energy measurement by Compton back scattering

Starting from 2012, energy is monitored continuously using compton backscattering



Interference of photons from A and B





E = 993.662 ± 0.016 МэВ

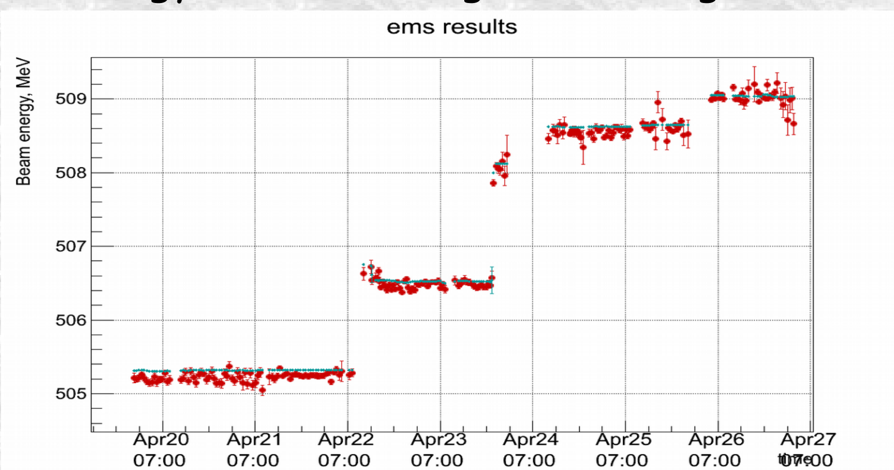
M.N. Achasov et al. arXiv:1211.0103v1 [physics.acc-ph] 1 Nov 2012

Beam energy measurement at VEPP-2000

- Magnetic field control in bending magnets $\delta E/E < 10^{-3}$
  - 8x2 NMR probes, continuous control
  - Absolute calibration using:

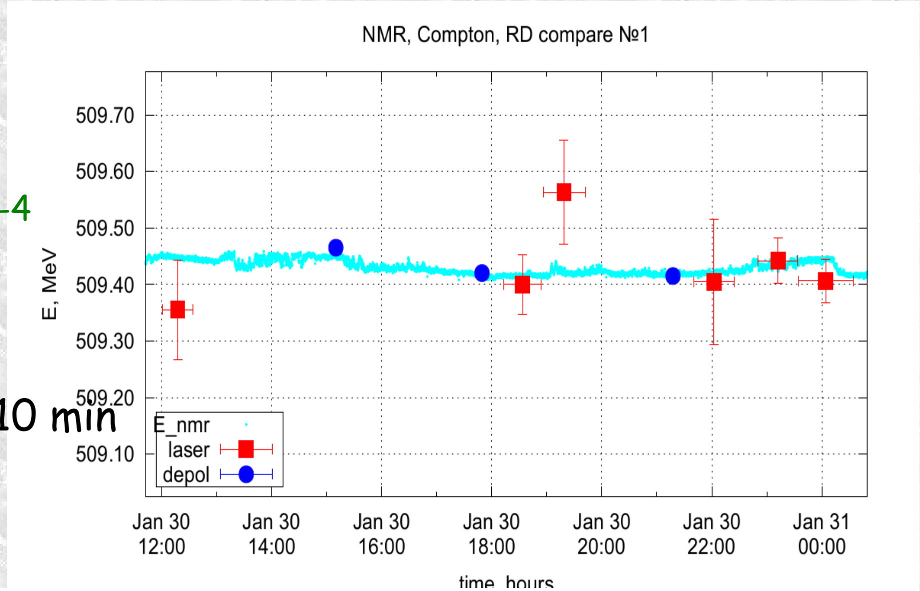
    φ-meson (1019.455 ± 0.020 МэВ),

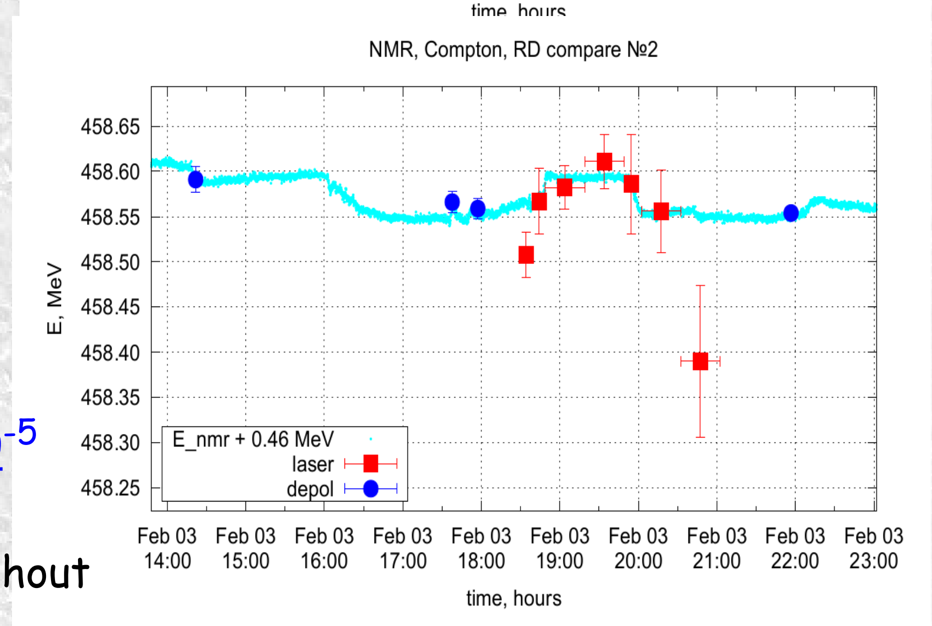
    ω-meson (782.65 ± 0.12 МэВ).
- Measurement of photon energy from back $\delta E/E < 10^{-4}$ scattering laser light
  - Installed in 2012.
  - Needs beam current (20 мА), ~20-50 keV accuracy in 10 min
  - Energy control during data taking.



- Resonance depolarization method $\delta E/E < 10^{-5}$
  - Very high accuracy.
  - Special configuration of VEPP-2000: "warm" optics without CMD-3 field.

Methods comparison:

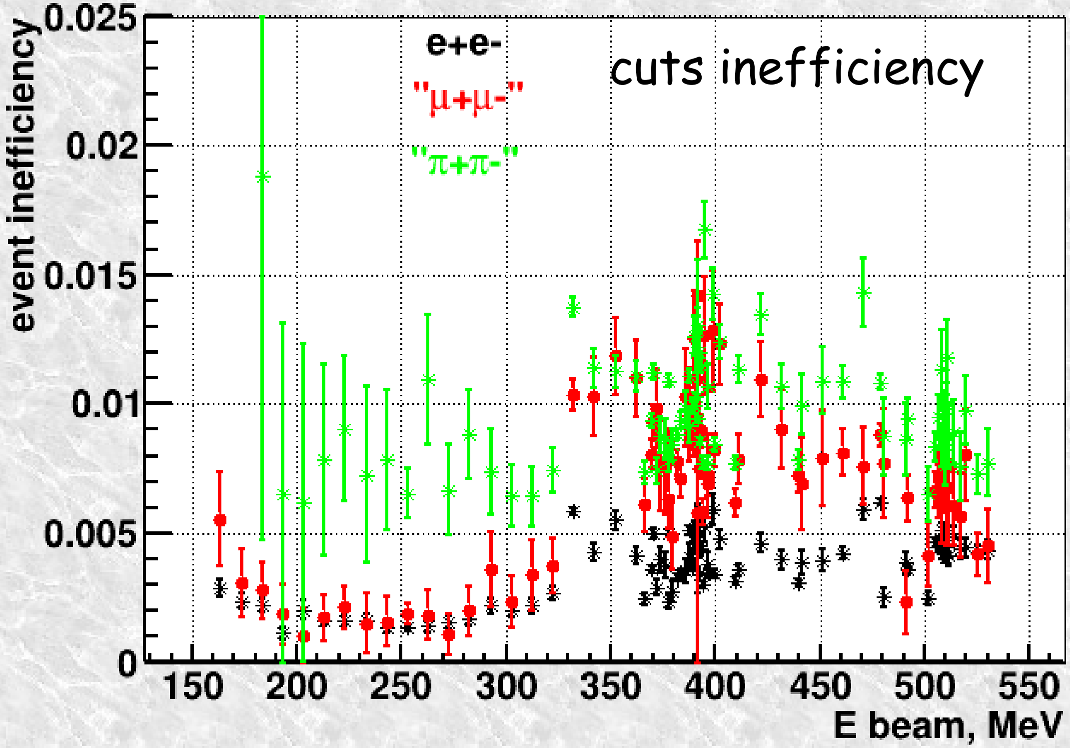




efficiencies

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

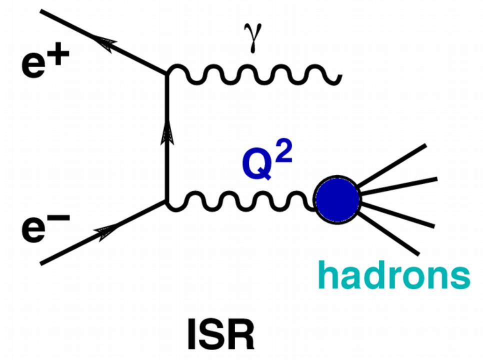


Pion specific loss of events:
- decay in flight (~6% at 160 MeV) (dominated at low energies)
- nuclear interaction on vacuum tube (<1%)

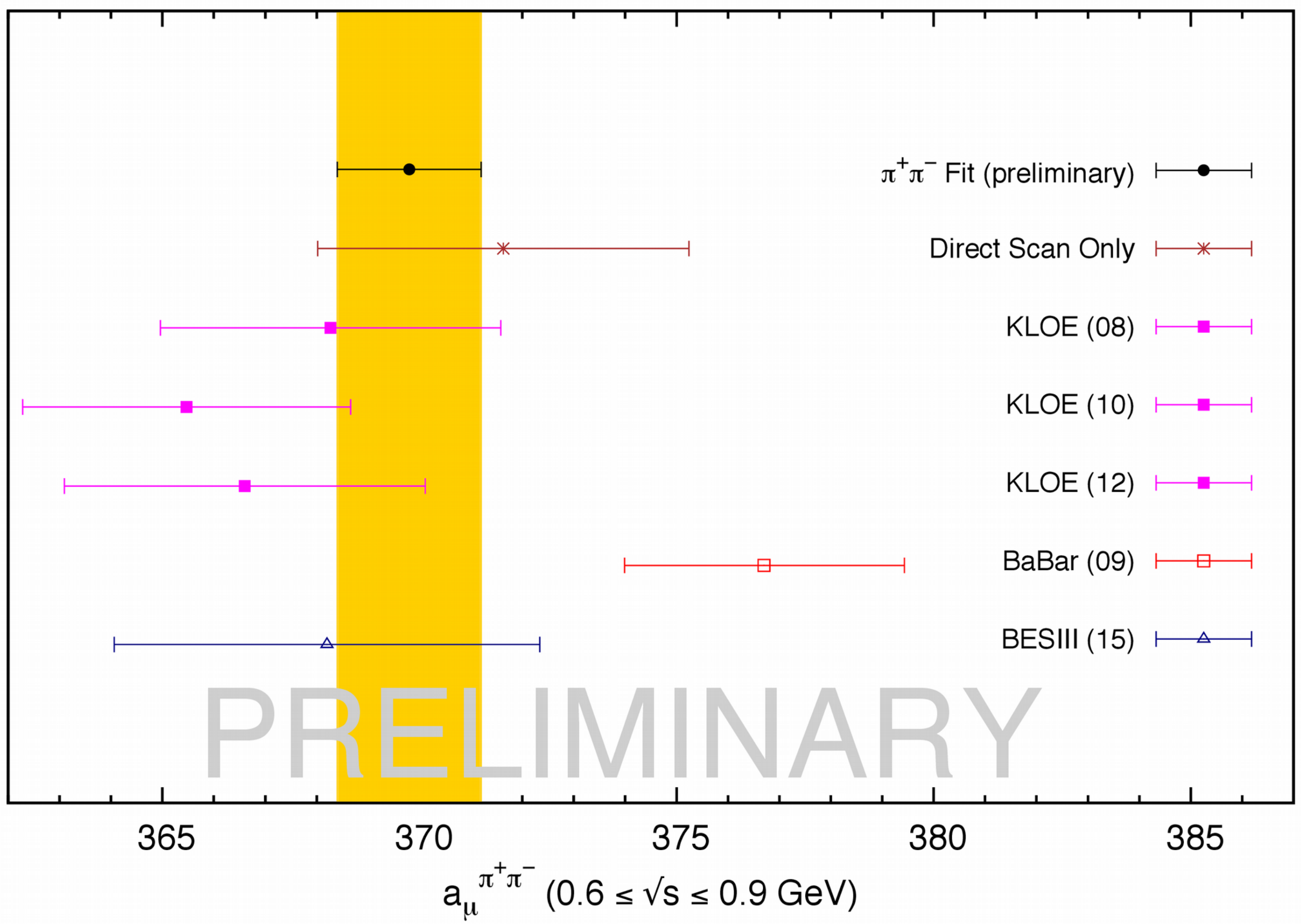
Can be checked from $\varphi \rightarrow 3\pi$, $\omega \rightarrow 3\pi$ events

HVP: HLMNT -> HKMNT in preparation

$\pi^+\pi^-$ channel: + KLOE12, + BES III from Rad. Ret.:



Prel. HKMNT combination w. full cov.-matrices:



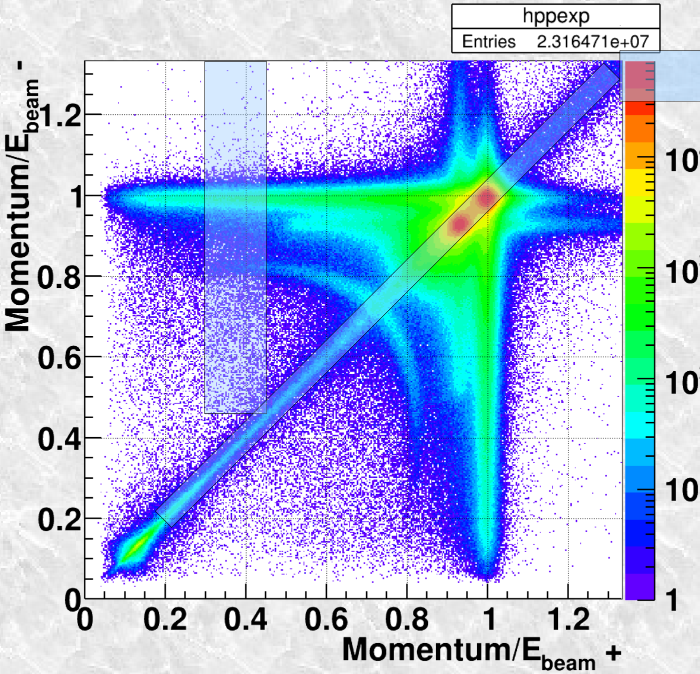
- χ^2_{min}/d.o.f. = 1.4
- further improvements expected from CMD-3, more also from BaBar?

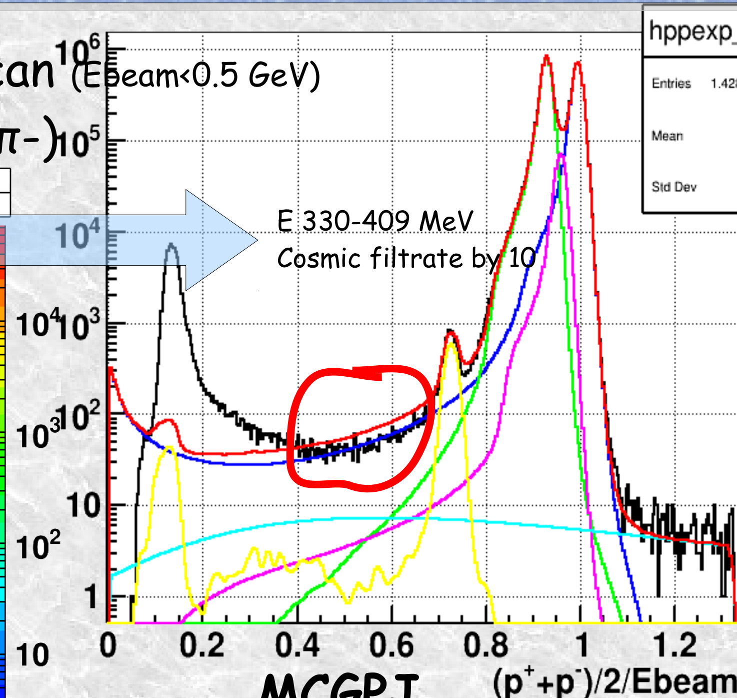
➔ see Simon Eidelman's talk on CMD-3

➔ Yaquian Wang's talk on BES III π FF & ISR

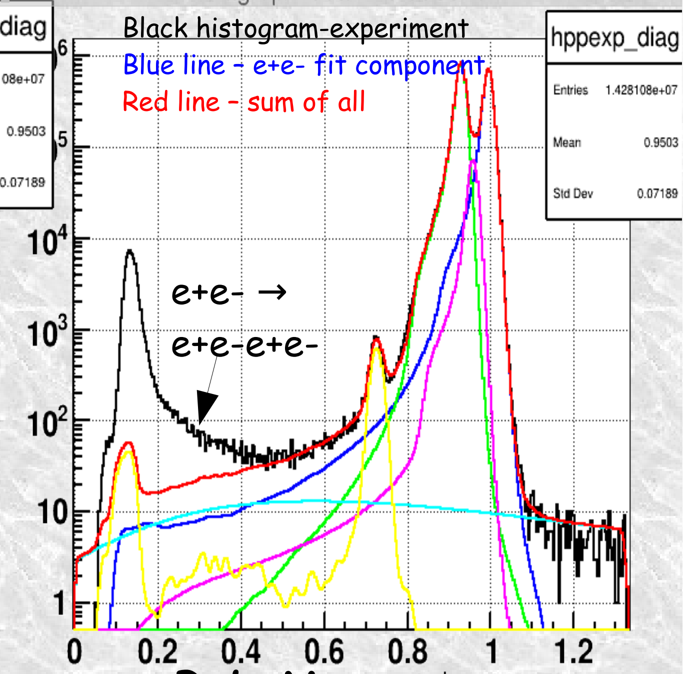
BabaYaga @ NLO vs MCGPJ vs experiment

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

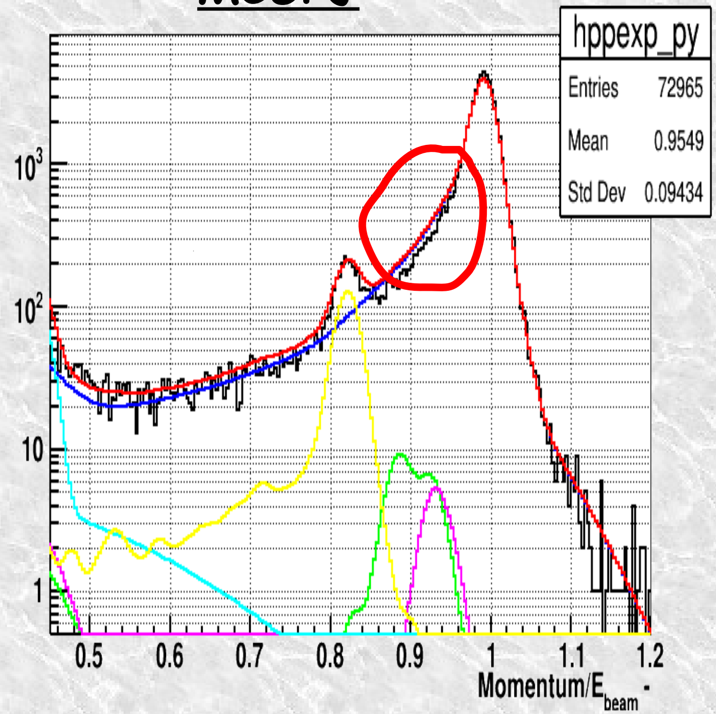


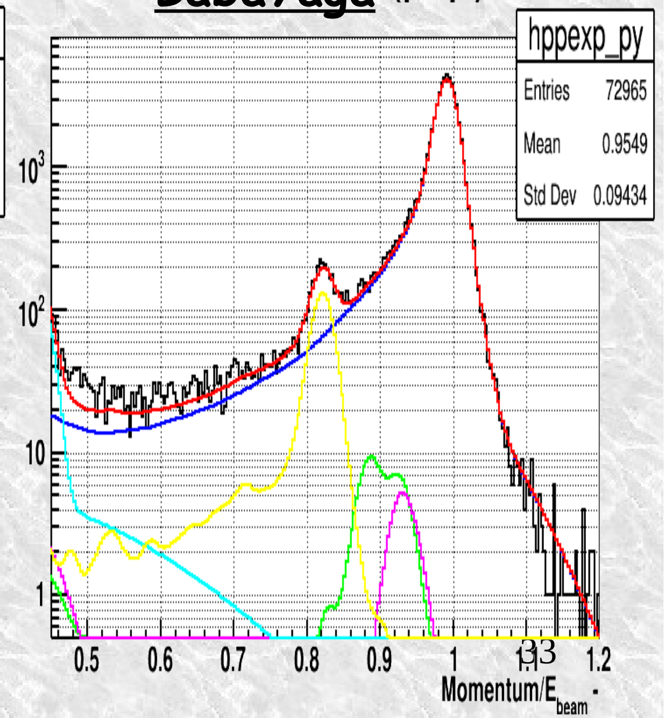


MCGPJ



BabaYaga





BabaYaga better describe experimental data
MCGPJ modification was done with adding angular distribution to photon jets (some question still under inspection)

SM prediction for muon g-2

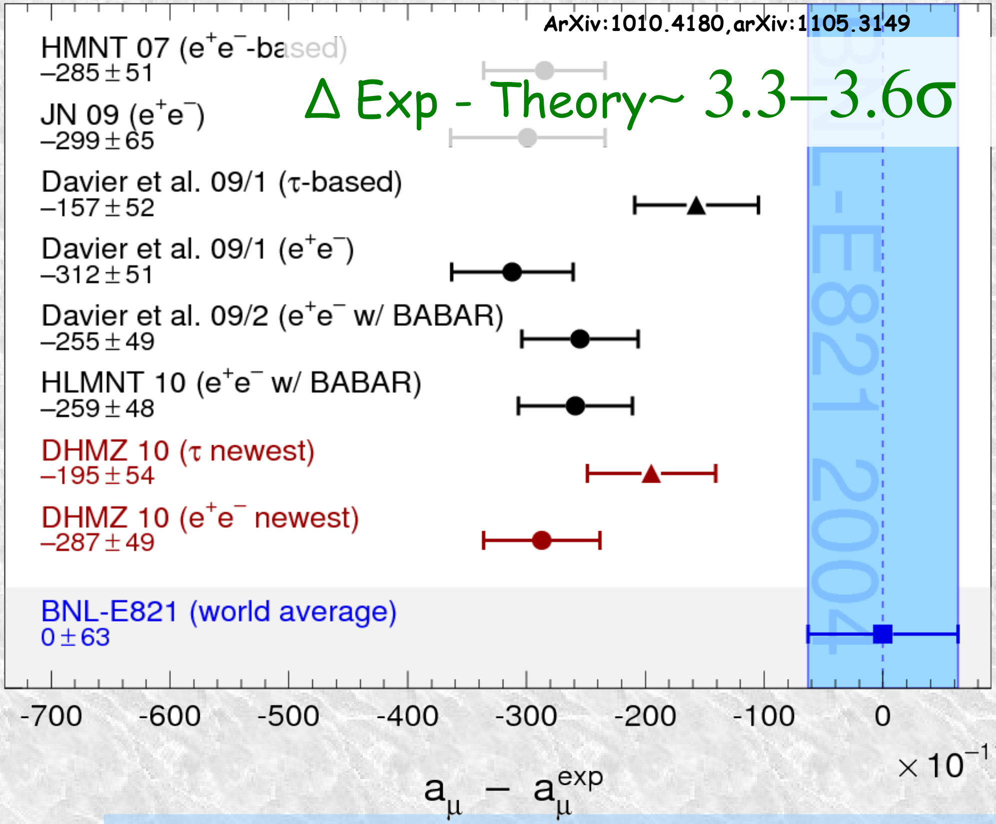
Experimental world average

a_μ = 11 659 208.9 ± 6.3 x 10^{-10}

Theoretical prediction

δa_μ = ± 4.9 x 10^{-10}

(HLMNT 11)



Δ Exp - Theory~ 3.3–3.6σ

Hadronic content of a_μ calculated

From measured cross-section by dispersion integral

LO hadronic 694.1 ±4.3x 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)
.....		

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 need more theory input, with help of experimental transition form factors

The value and the error of the hadronic contribution to muon (g-2) are dominated by low energy R(s) (<2GeV gives 93% of the value).

$\pi^+\pi^-$ gives the main contribution (73%) to a_μ