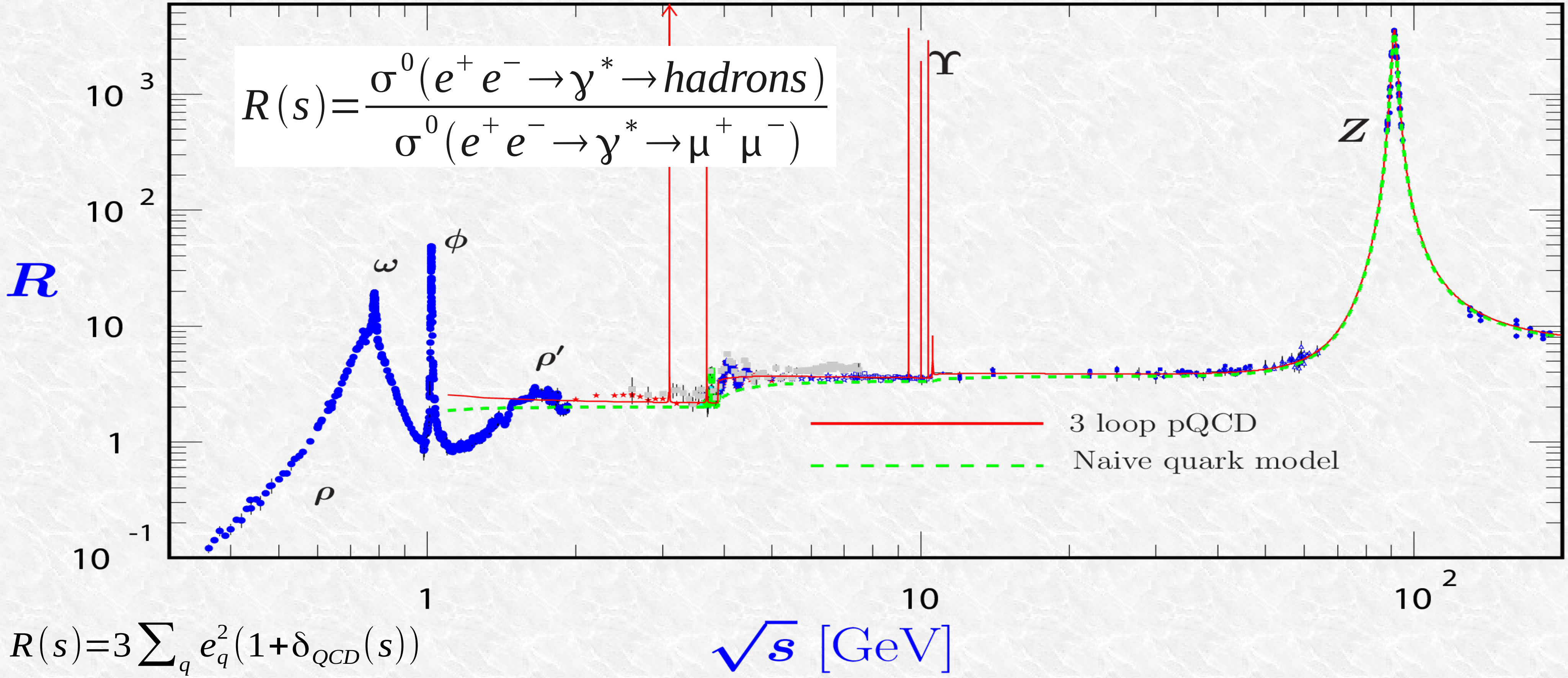
Status of R measurements (direct scan)

Fedor Ignatov
BINP, Novosibirsk

FCCP17, Capri Island

R(s)



$R(s)=3\sum_q e_q^2(1+\delta_{QCD}(s))$

R(s) is one of the fundamental quantities in high energy physics:
its reflects number of quarks and colors → pQCD tests;
QCD sum rules → quark masses,quark and gluon condensates, Λ_{QCD}
Dispersion relations → $\alpha_{QED}(M_Z)$, hyperfine muonium splitting, muon (g-2)

$$a_\mu^{had,LO}=\frac{\alpha^2 m_\mu^2}{9\pi^2}\int_{s_{th}}^{\infty}\frac{1}{s^2}\tilde{K}(s)R(s)ds$$

$$\tilde{K}(s)=0.6\div1.0$$

a_μ^{had} is saturated by low energy R(s) (<2GeV gives 93%) and $\pi^+\pi^-$ gives the main contribution(73%) < 1 GeV

50 years of hadron production at colliders

Volume 25B, number 6 PHYSICS LETTERS 2 October 1967

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

V. L. AUSLANDER, G. I. BUDKER, Ju. N. PESTOV, V. A. SIDOROV, A. N. SKRINSKY and A. G. KHABAKHPASHEV
Institute of Nuclear Physics, Siberian Branch of the USSR Academy of Sciences, Novosibirsk, USSR

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

$$e^- + e^+ \rightarrow \pi^- + \pi^+$$

$$e^- + e^+ \rightarrow K^- + K^+$$

cor
ter
ide
of
cha
cop

1 September 1967

Start of e+e- → hadrons measurements

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

VEPP-2, Novosibirsk

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

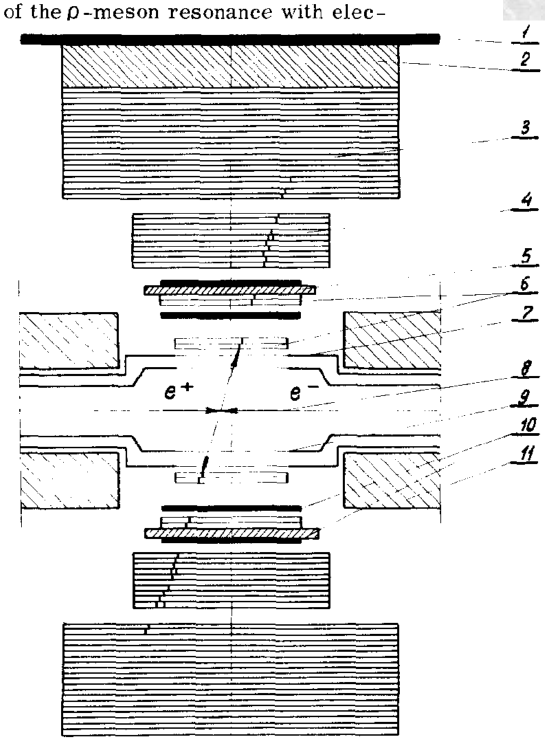


Fig. 1. Spark chambers system:
1) Anticoincidence scintillation counter
2) Lead absorber 20 cm thick
3) "Range" spark chamber
4) "Shower" spark chamber
5) Duraluminium absorber 2 cm thick
6) Thin-plate spark chambers

e+e- → ρ → ππ

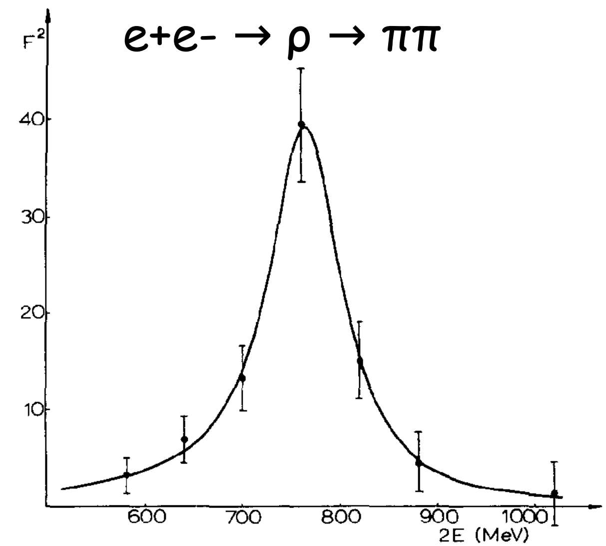
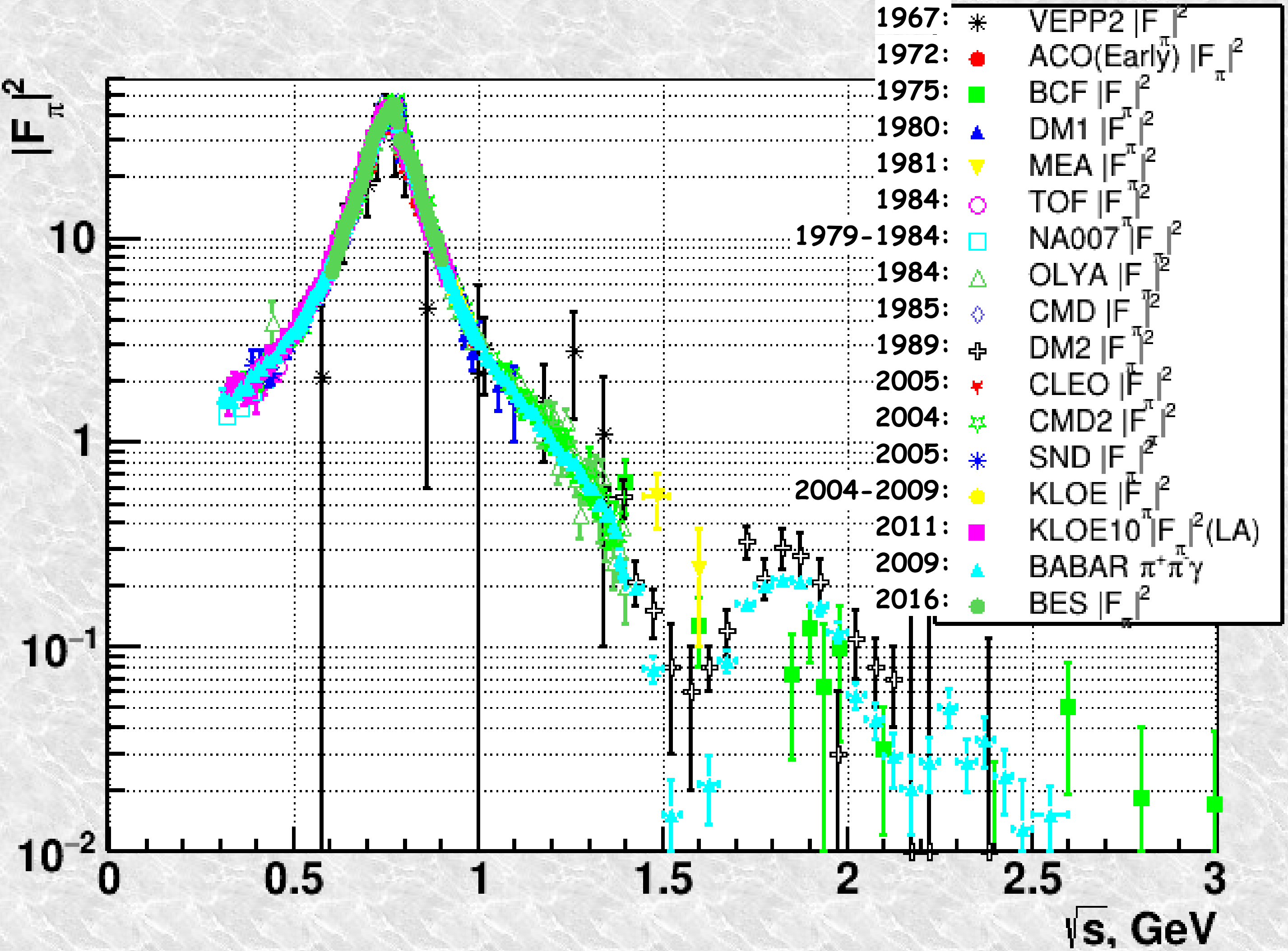


Fig. 2. Experimental values of F^2 (E) approximated by the Breit-Wigner formula.

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 + hadrons

(limited only by systematic):

KLOE: 0.8%

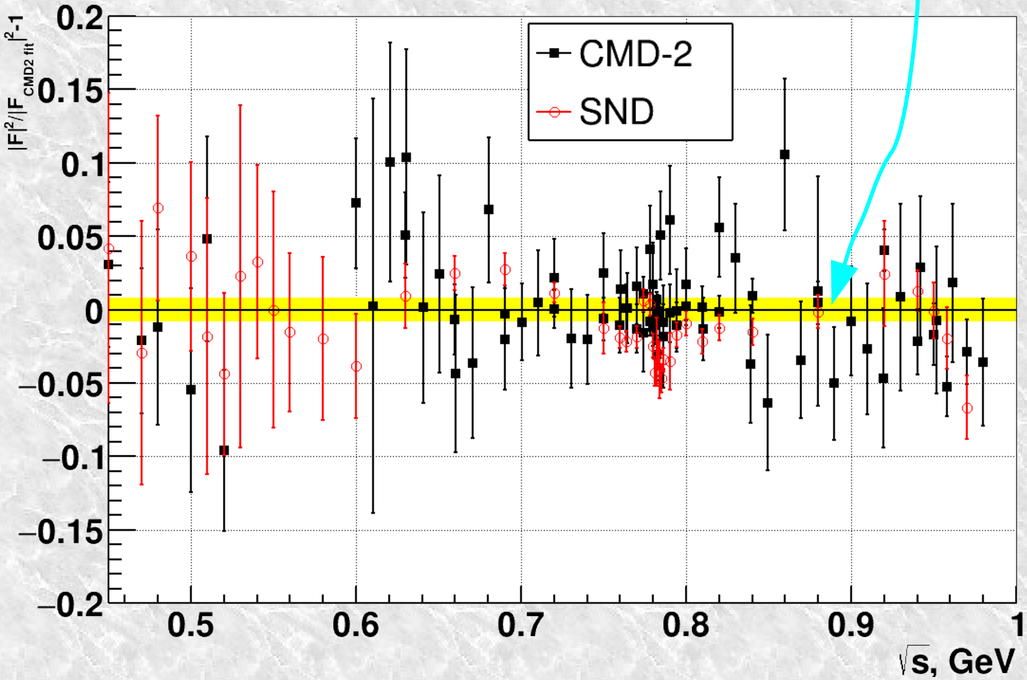
BaBar: 0.5%

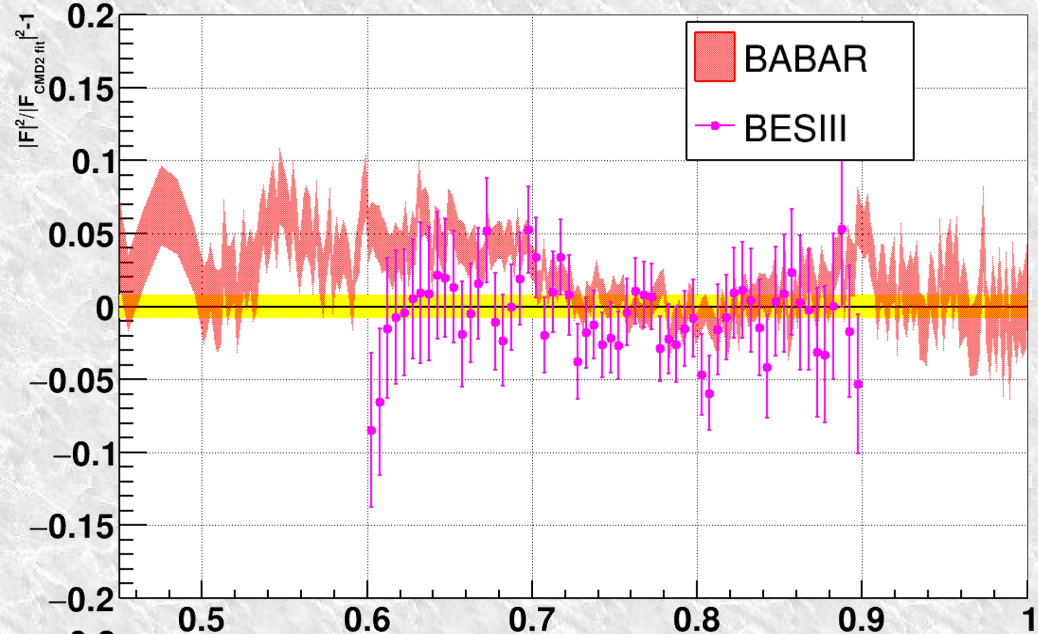
BES: 0.9%

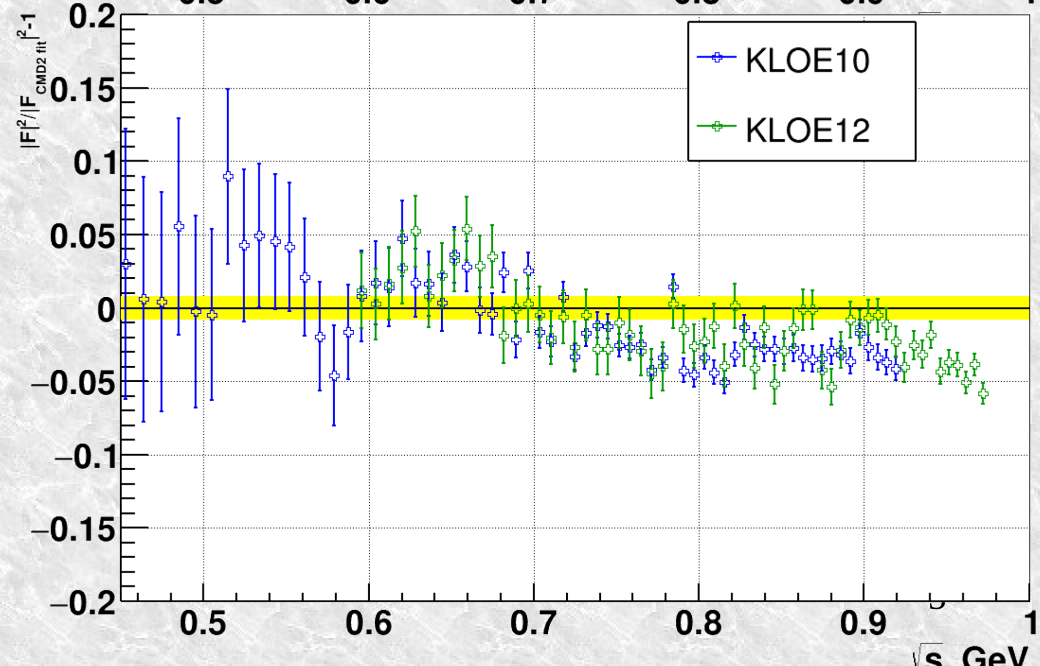
Comparison of e+ e− → π+ π− cross-section

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

Points, red band:
only statistical error



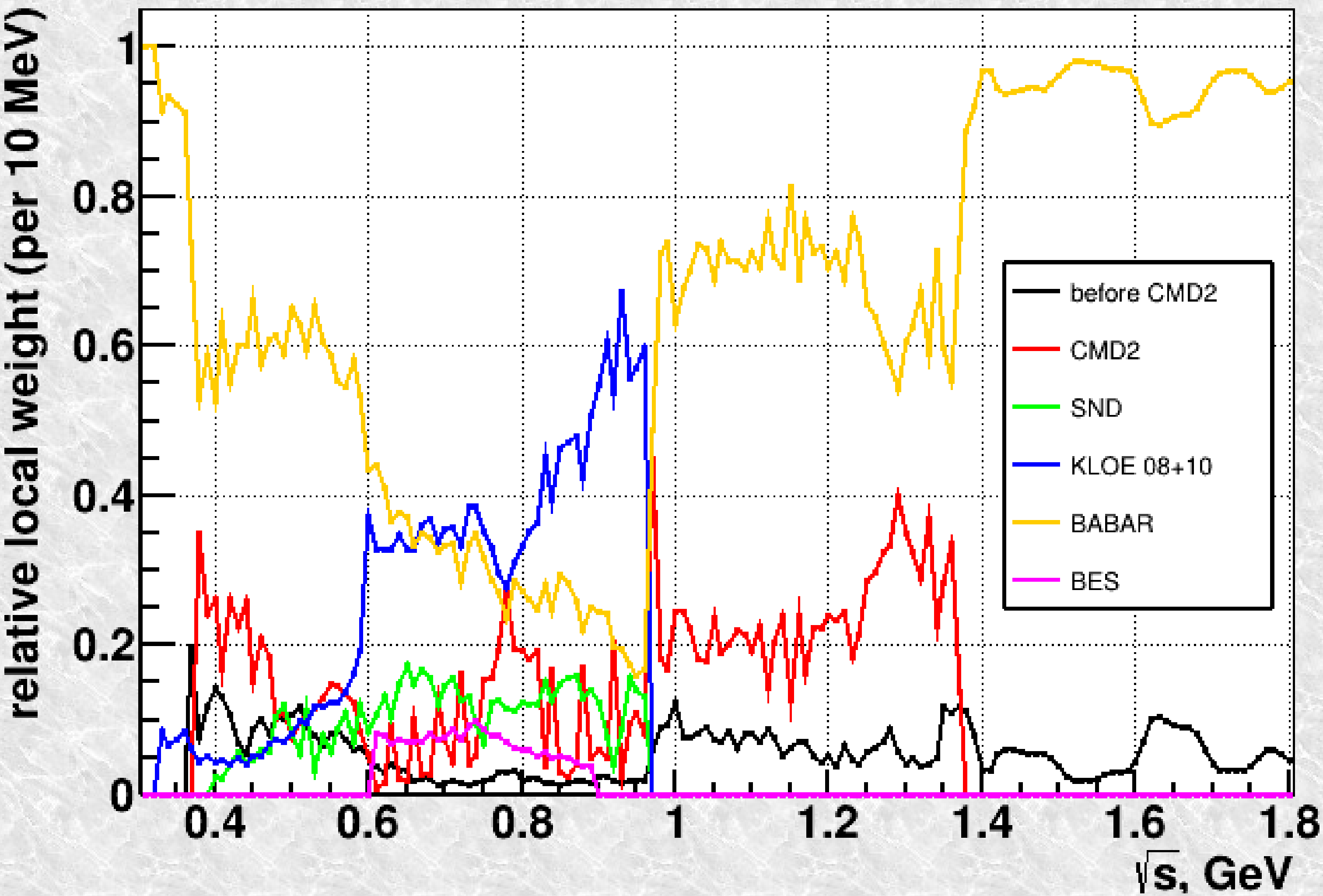




In integral, there is reasonable agreement between existing data sets
But there are local inconsistencies larger than claimed systematic errors
→ additional scale factor for error of integral value

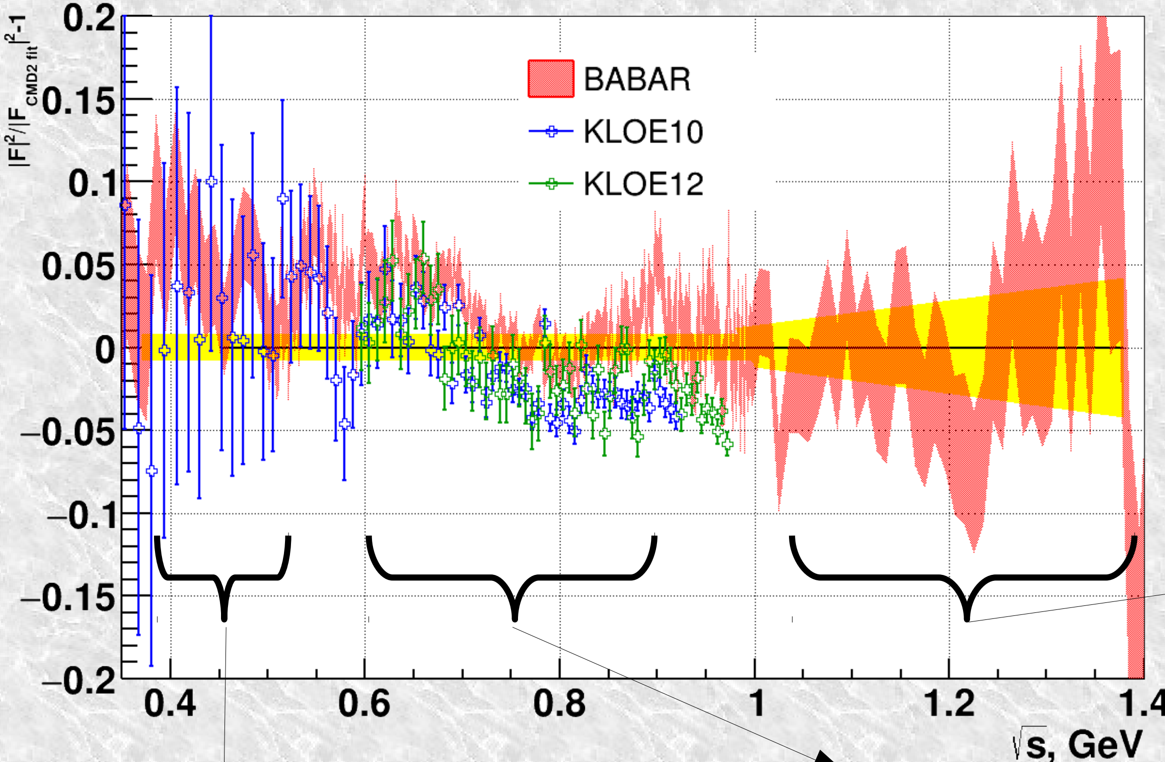
Relative local weight of different experiments in π+π-

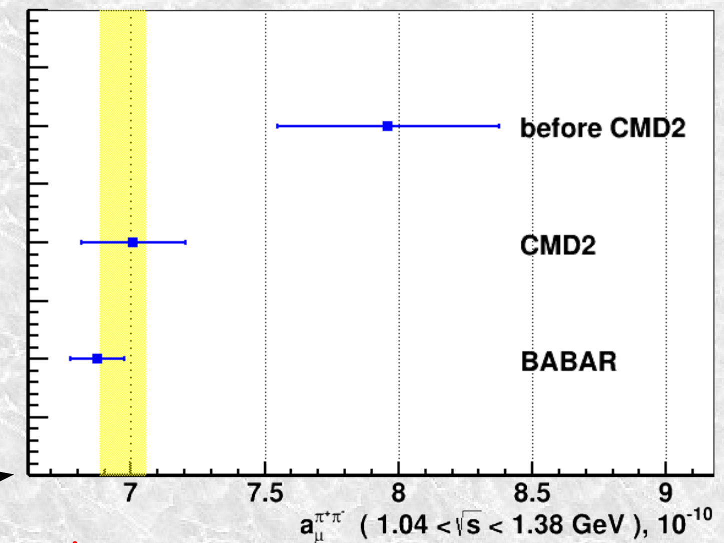
Nowadays the π+π- data is statistically dominated by ISR(KLOE, BaBar)



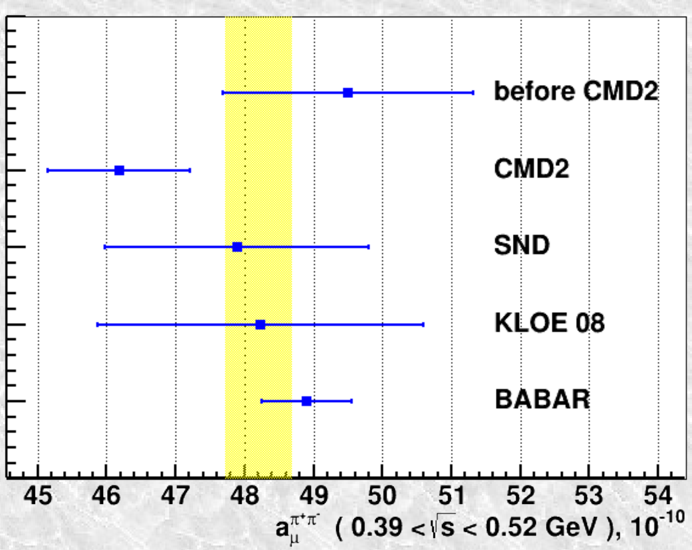
Locally precision is limited by statistic

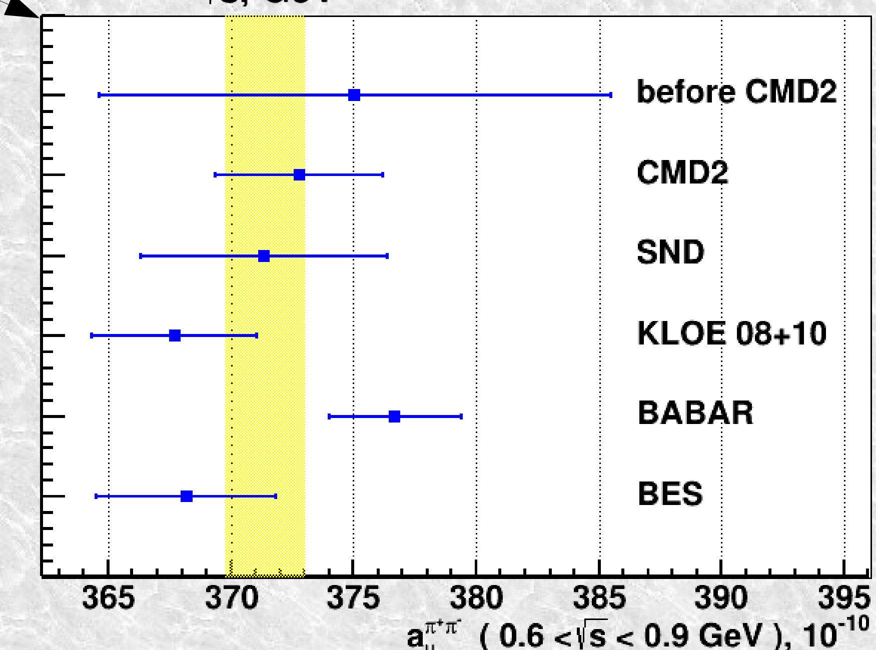
The $\pi+\ \pi-$ contribution to a_μ^{had}





In integral precision
is limited by systematics





Systematic Uncertainties (ρ-region)

CMD2: 0.6-0.8%

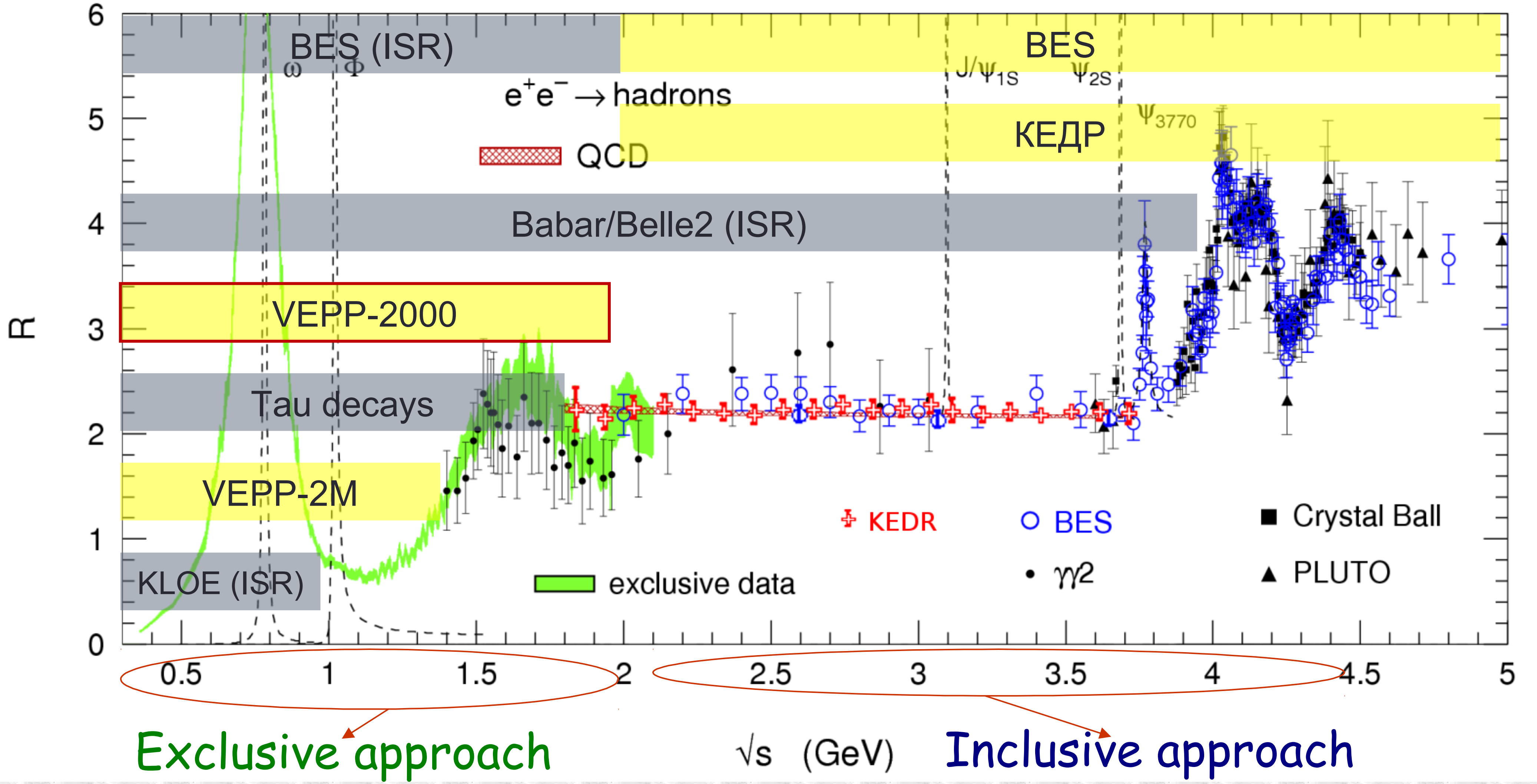
SND: 1.5%

KLOE: 0.8%

BABAR :0.5%

BES: 0.9%

R measurements



VEPP-2000: direct exclusive measurement of σ (e+e- → hadrons)
Only one working this days on scanning below <2 GeV
World-best luminosity below 2 GeV (1 GeV excluded – where KLOE outperfom everybody)

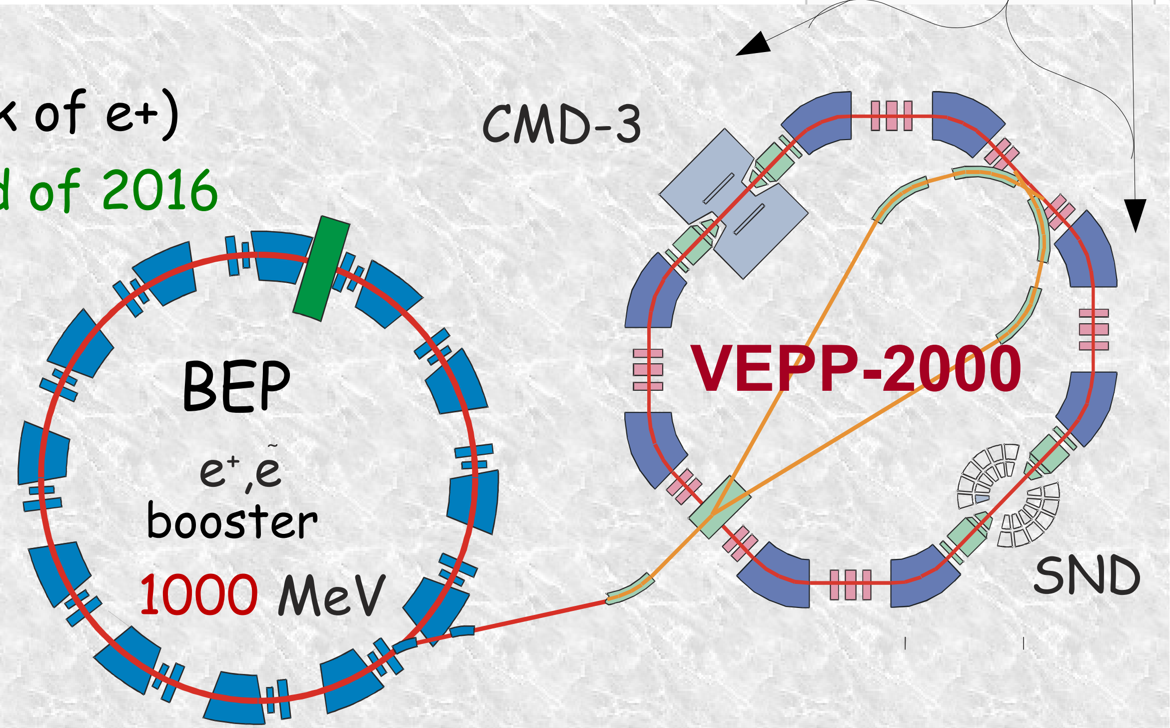
BESIII, KEDR – direst scan from 2 GeV to 5 GeV

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

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

Data taking was restarted by the end of 2016

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

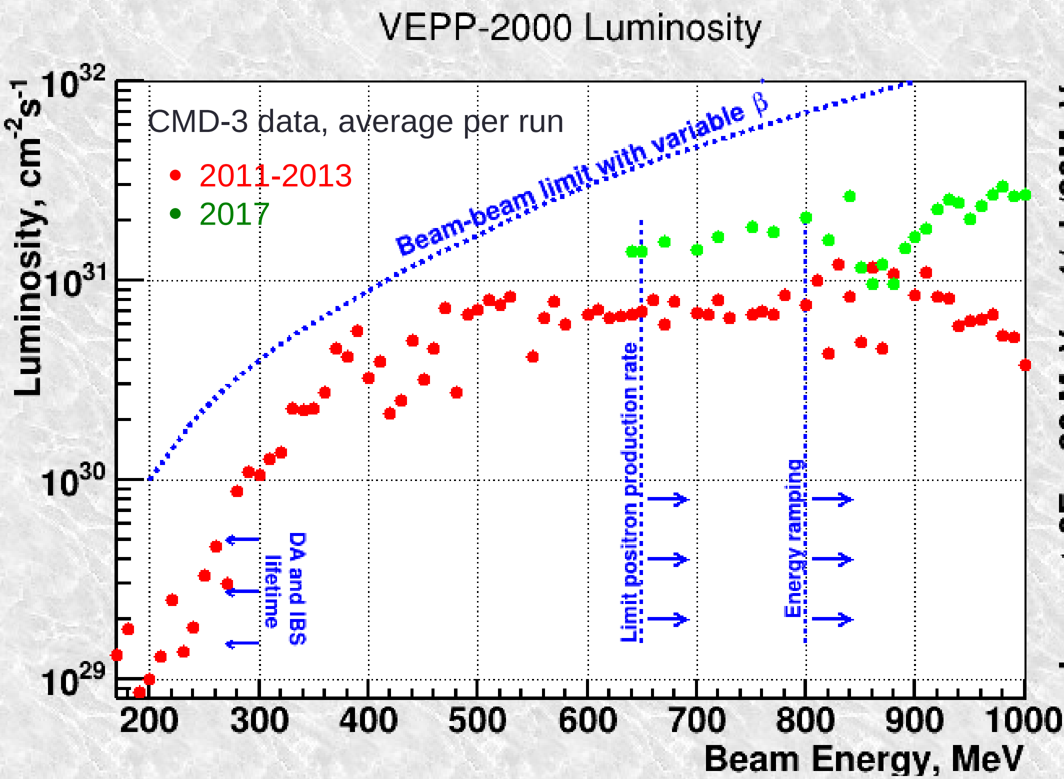


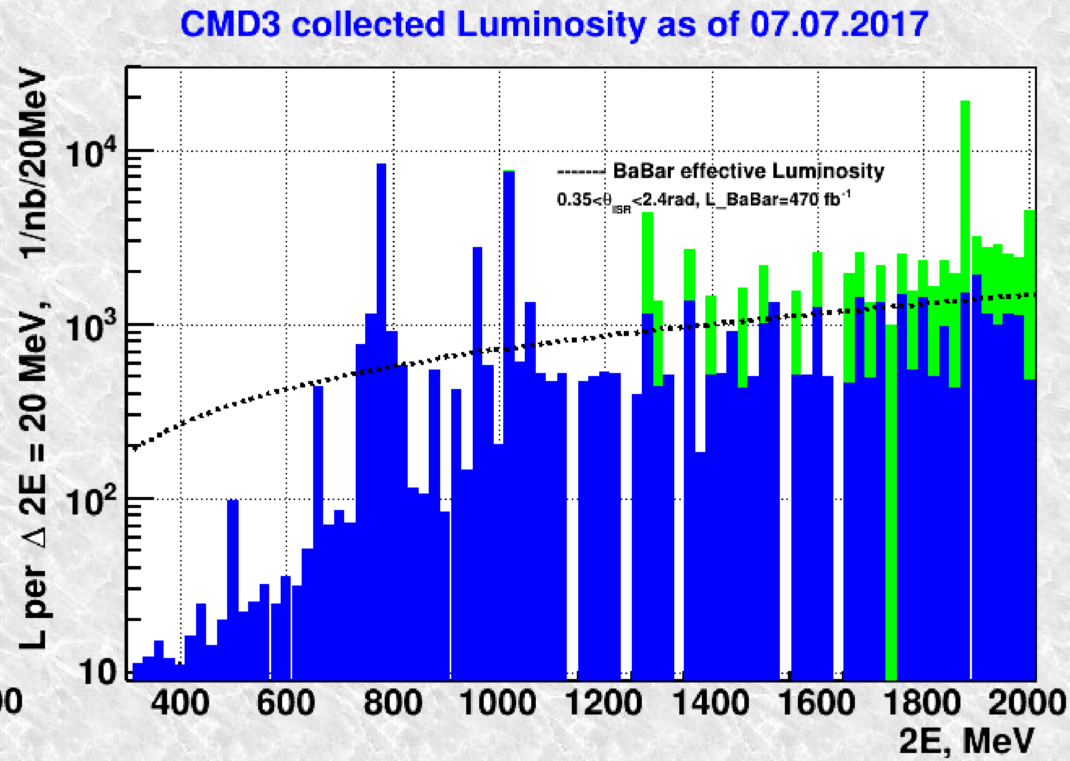
Maximum c.m. energy is 2 GeV, project luminosity is $L = 10^{32}\ cm^{-2}s^{-1}$ at 2E= 2 GeV

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

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

Collected Luminosity





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

The luminosity at high energy was limited by a deficit of positrons and limited energy of the booster

<u>After upgrade</u>

2017: big improvement in luminosity at high energy, still way to go

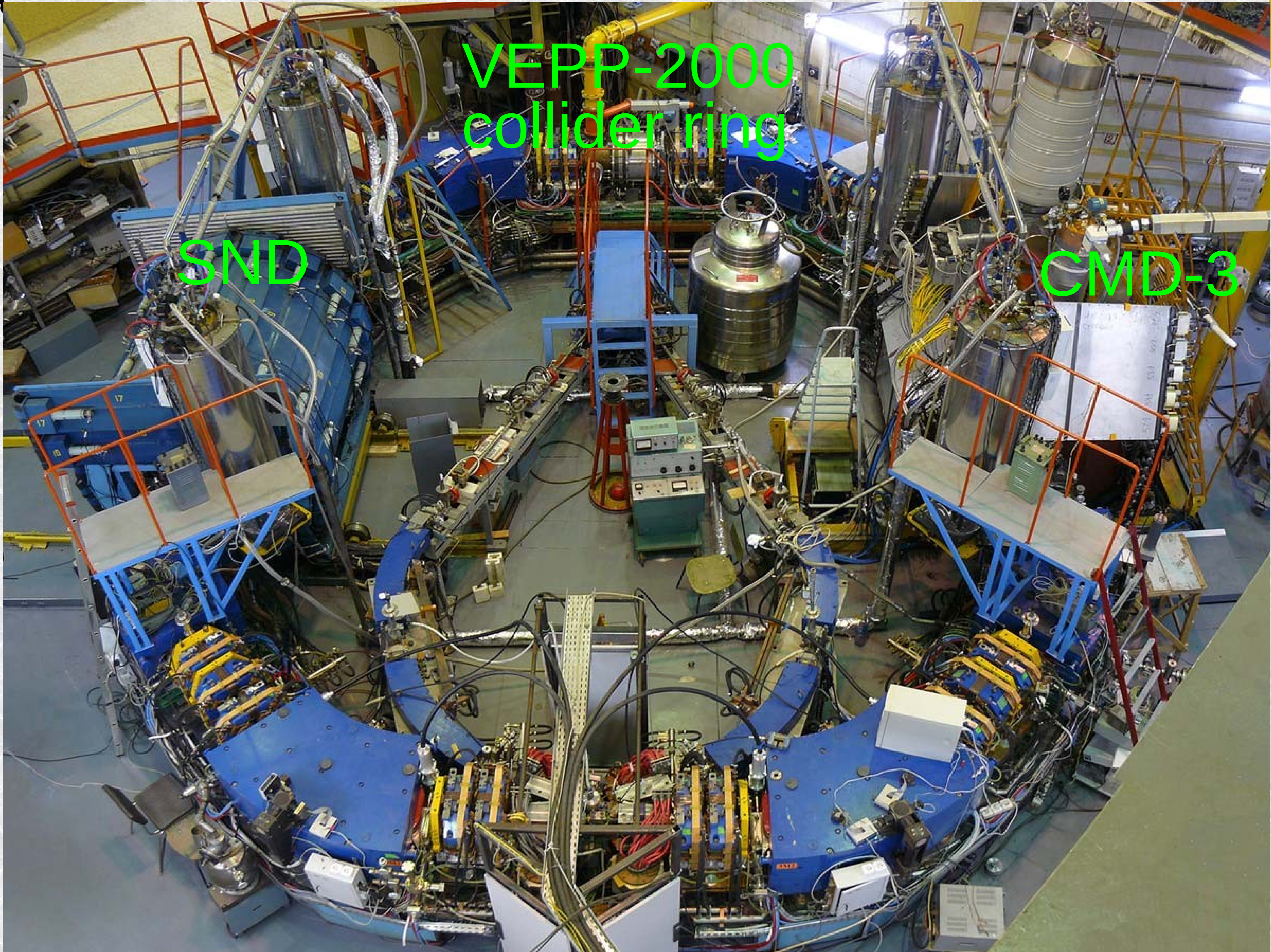
<u>Collected during 12.2010-07.2013</u>

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

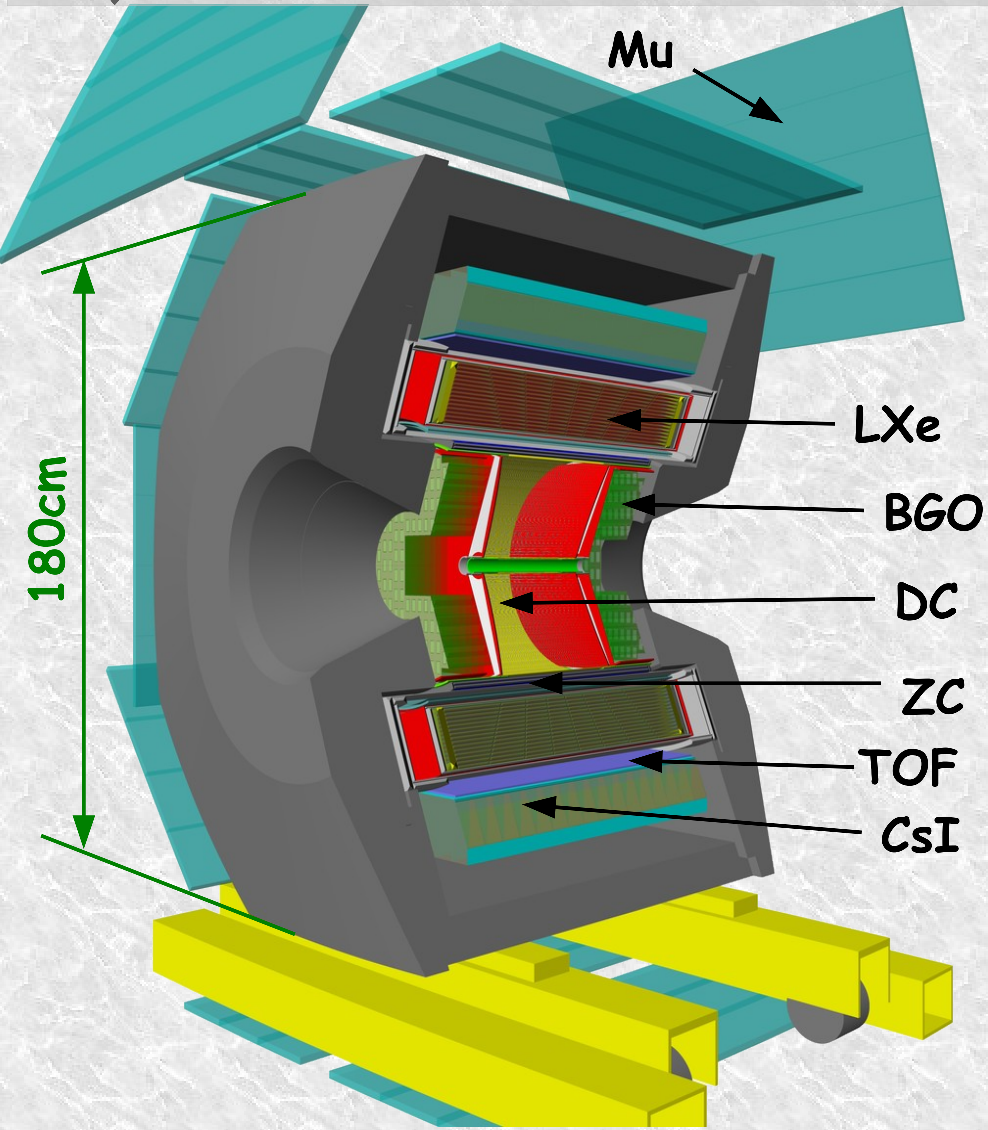
8.3 pb^{-1}	ω - region
9.4 pb^{-1}	< 1 GeV (except ω)
8.4 pb^{-1}	φ - region
34.5 pb^{-1}	> 1.04 GeV

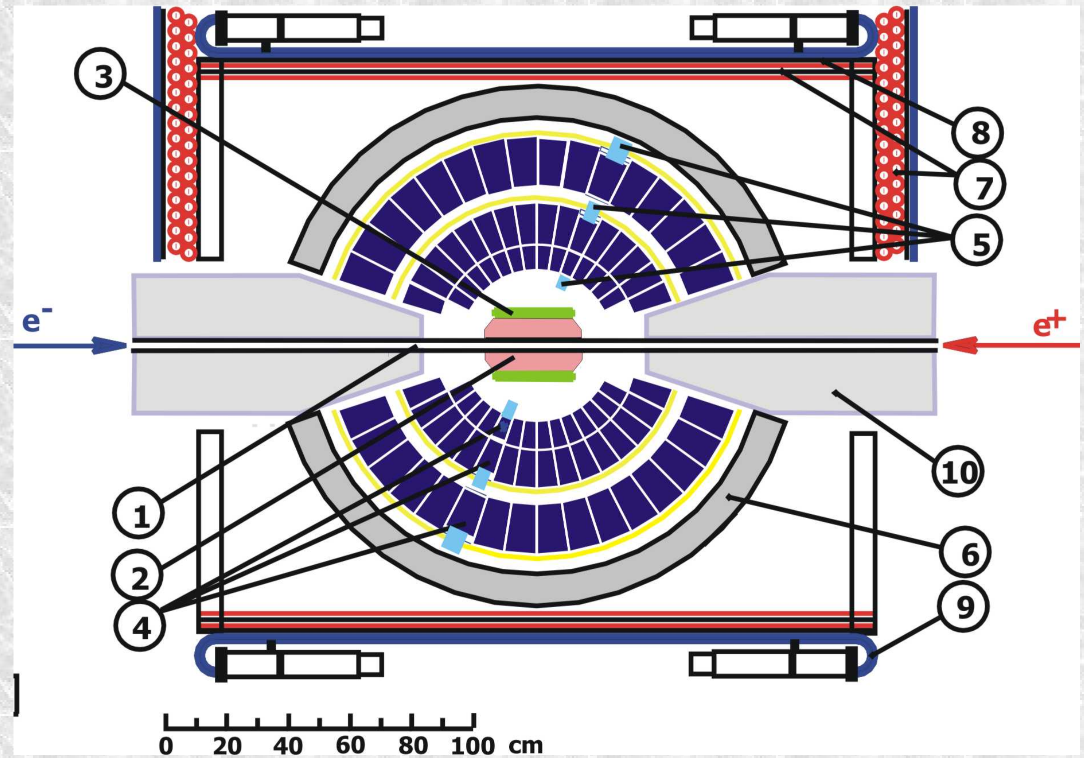
<u>2017 season</u>

53.4 pb^{-1} > 1.3 GeV


VEPP-2000
collider ring
SND
CMD-3

CMD-3 and SND





1.3 T magnetic field

Tracking: $\sigma_{R\varphi}$ ~ 100 μm, σ_Z ~ 2mm

Combined EM calorimeter (LXe,CsI, BGO):

σ_E ~ 3-8%,Tracking in LXe calorimeter

1 – beam pipe, 2 – tracking system, 3 – aerogel Cherenkov counter , 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – iron muon absorber, 7–9 – muon detector

In 1996-2000 SND collected data at VEPP-2M

Recently measured cross sections

e^+e^- scan

- ✓ KEDR@VEPP-4M:
  inclusive R measurement at <3.72 GeV
- ✓ SND@VEPP-2M:
  $e^+e^- \to \pi^0\gamma$
- ✓ SND@VEPP-2000:
  $e^+e^- \to n\bar{n}$, $\eta\gamma$, $\omega\pi^0$, $\eta\pi^+\pi^-$, $\pi^+\pi^-\pi^0$,
  $\omega\eta$, $\omega\eta\pi^0$, K^+K^-
- ✓ CMD-3@VEPP-2000:
  $e^+e^- \to p\bar{p}$, $3(\pi^+\pi^-)$, $2(\pi^+\pi^-)$, $\omega\eta$, $\omega\pi^+\pi^-\pi^0$,
  $K^+K^-\pi^+\pi^-$, K^+K^-, K_SK_L,

e+e- -> π+π- by CMD3

Very simple, but the most challenging channel due to high precision requirement.

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

Crucial pieces of analysis:

- ✗ e/μ/π separation
- ✗ precise fiducial volume
- ✗ radiative corrections

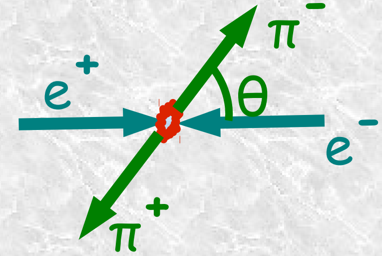
Many systematic studies rely on high statistics

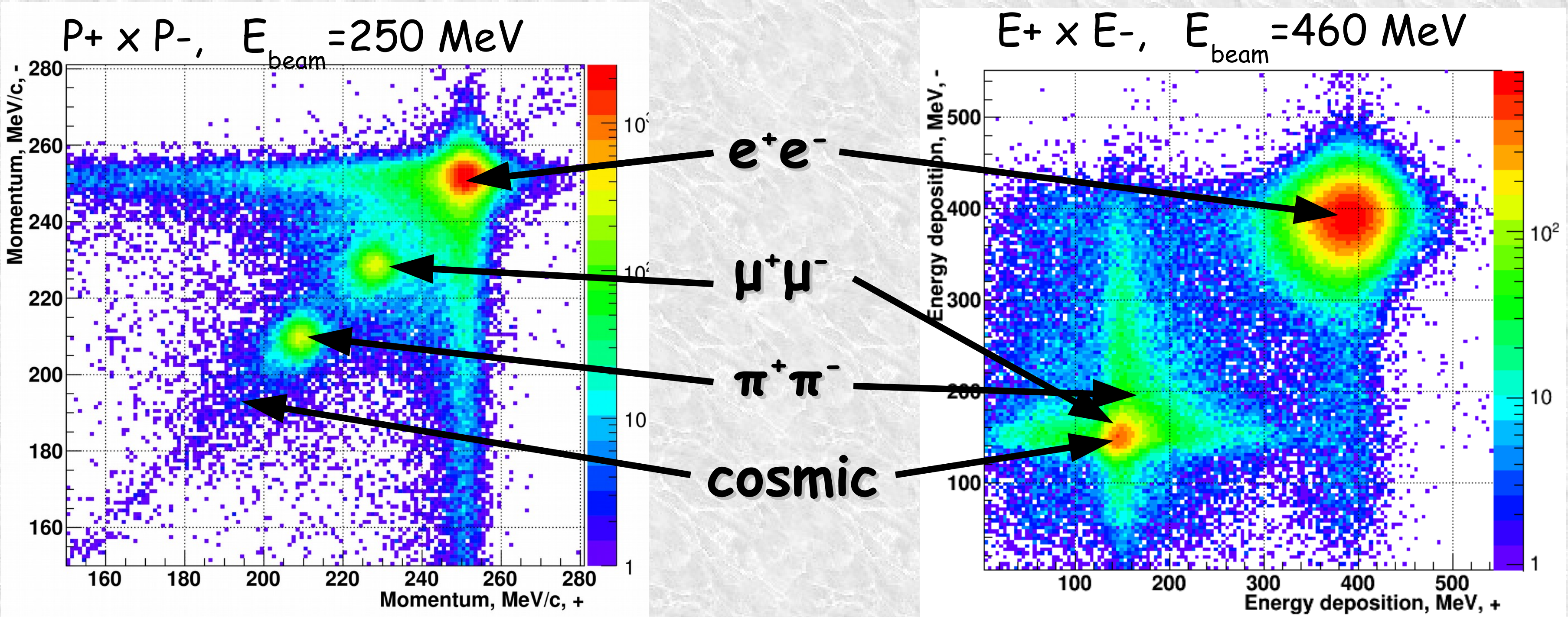
events separation either by momentum or by energy deposition

Momentums works better at low energy < 0.8 GeV

Energy deposition > 0.6 GeV

Simple event signature with 2 back-to-back charged particles

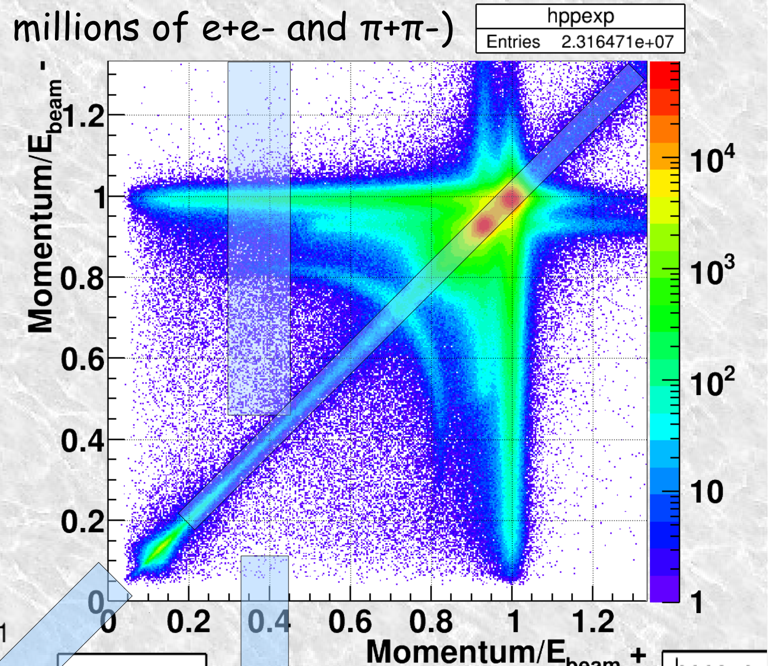




MC generator, MCGPJ

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

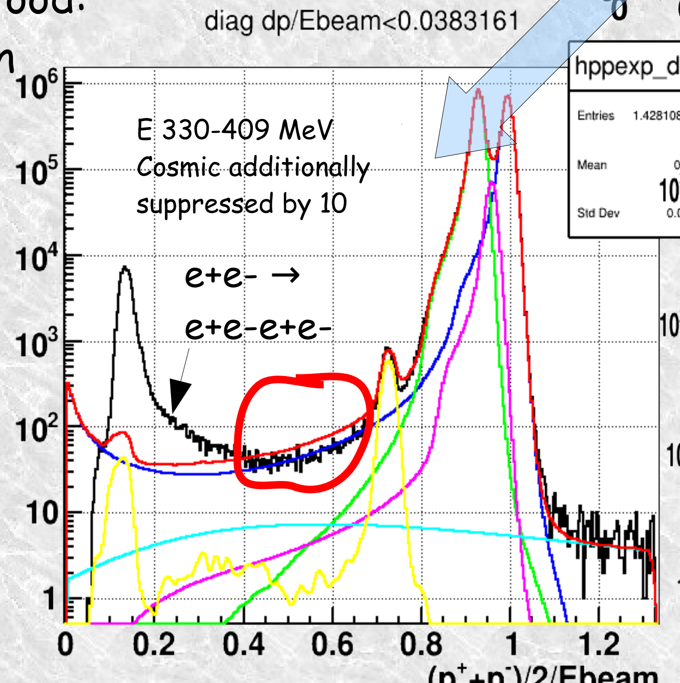
All events from RHO2013 scan
(~ 10 millions of e+e- and π+π-)

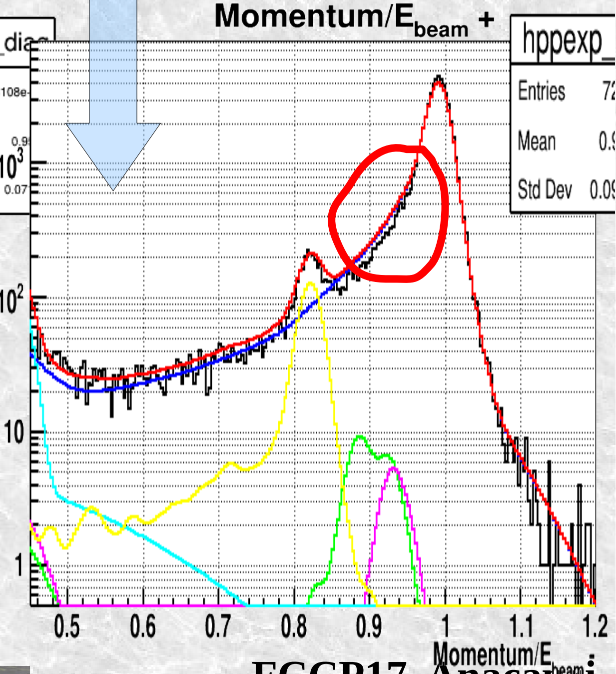


Several MC generators available with 0.1-0.5% precision.
<u>MCGPJ generator (0.2%)</u> is used by Novosibirsk group:
1 real γ + γ jets along all particles (with collinear Structures function)

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:
also important γ jets angular distribution



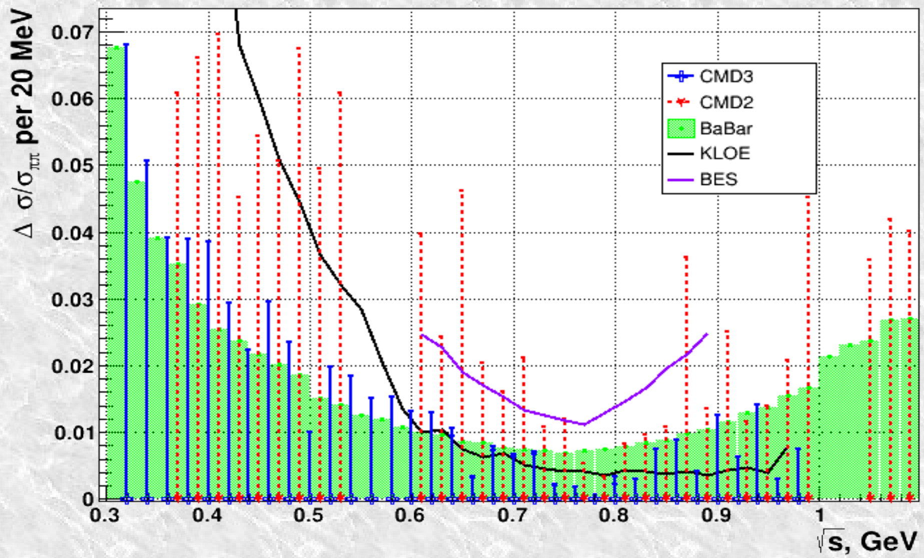


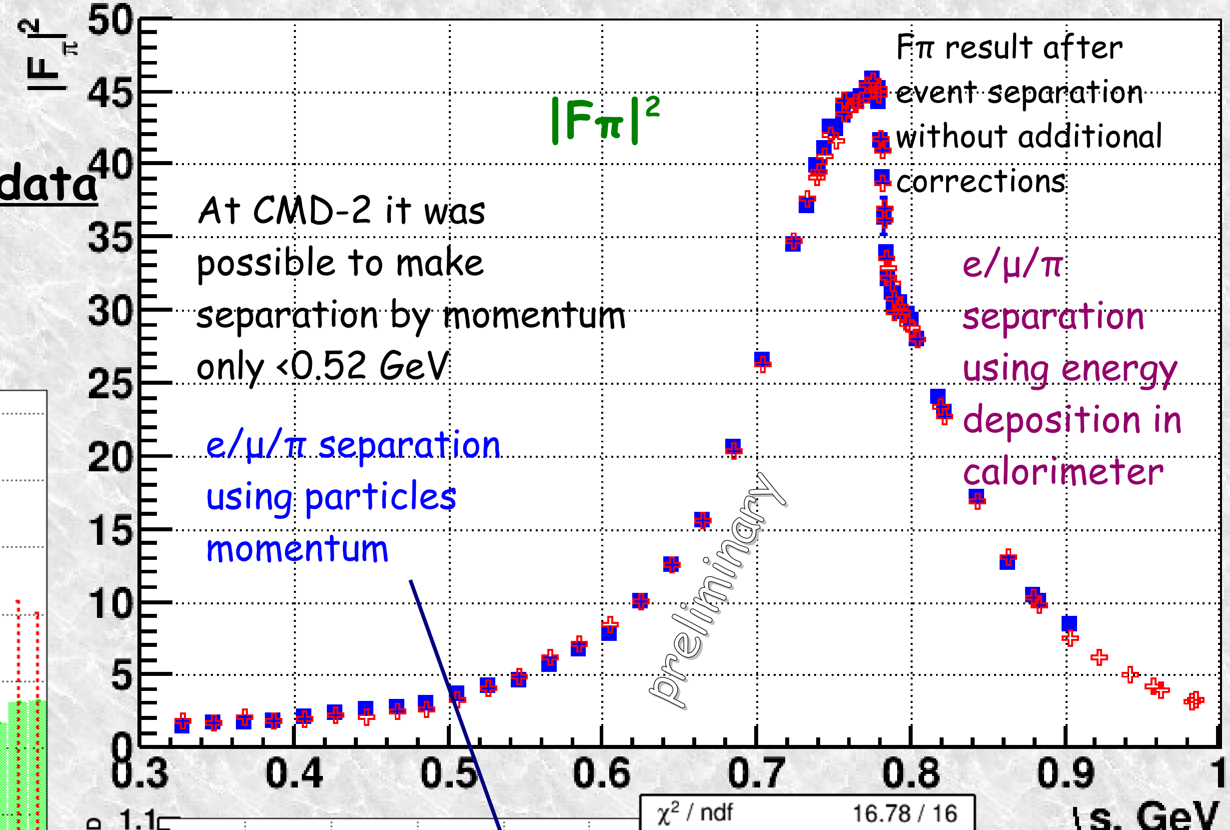
Several steps for upgrading MCGPJ
were done.
But still some question under inspection

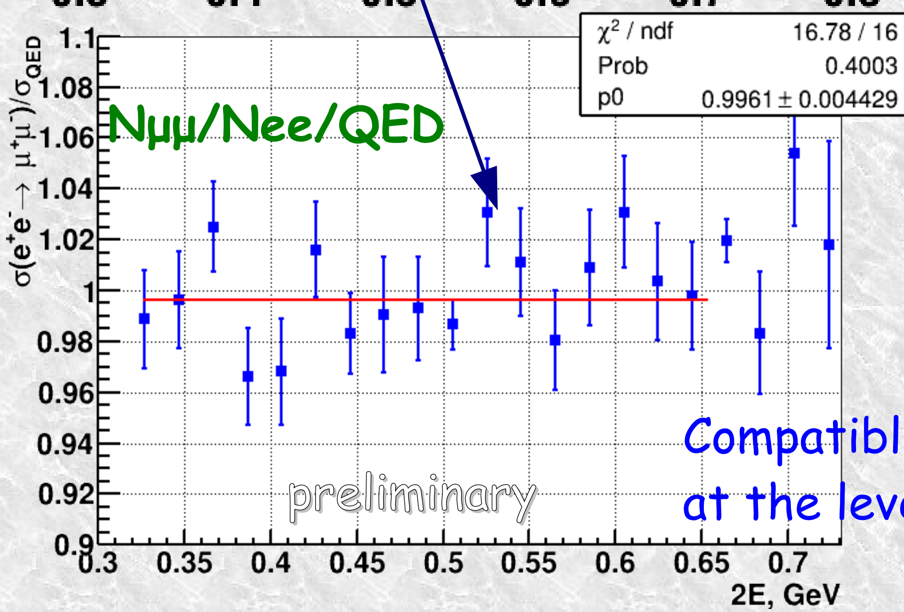
<u>Exact e+e-→e+e-(γγ) NNLO generator</u>
<u>will help to solve all our doubts</u>
<u>(and to go below <0.1% precision)</u>

e+e- -> π+π- by CMD-3

Statistical precision of
cross section measurement for **2013 data**
is at the same level
or better than other experiments







Compatible with QED
at the level of 0.5 %

Systematic e+e- -> π+π- by CMD3

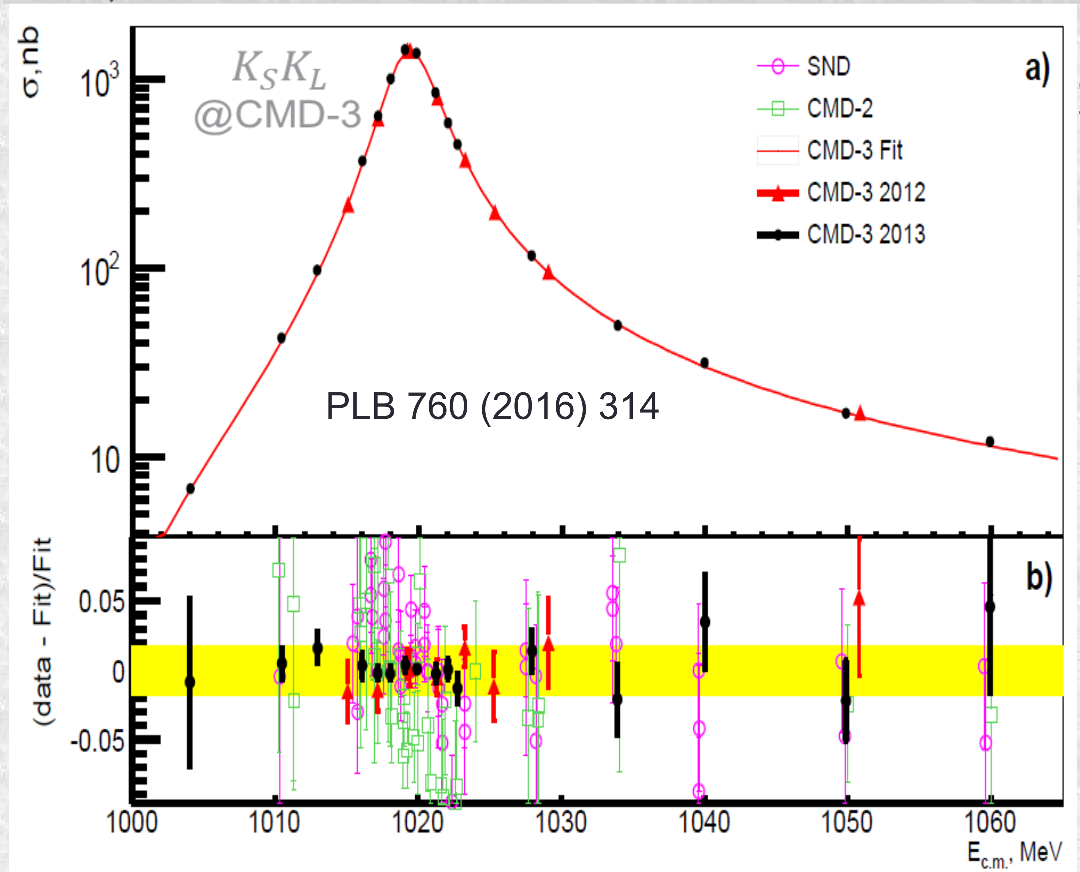
Our goals are to reach systematic level up to 0.35%:	status
✗ Radiative corrections - 0.2%	with current MCGPJ 0.2% - integral cross-section 0.0 – 0.4% - from P spectra
✗ e/μ/π separation – 0.2% can be checked and combined from different methods	~ 0.1 – 0.5% by momentum ~ 1.5% by energy
✗ Fiducial volume – 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

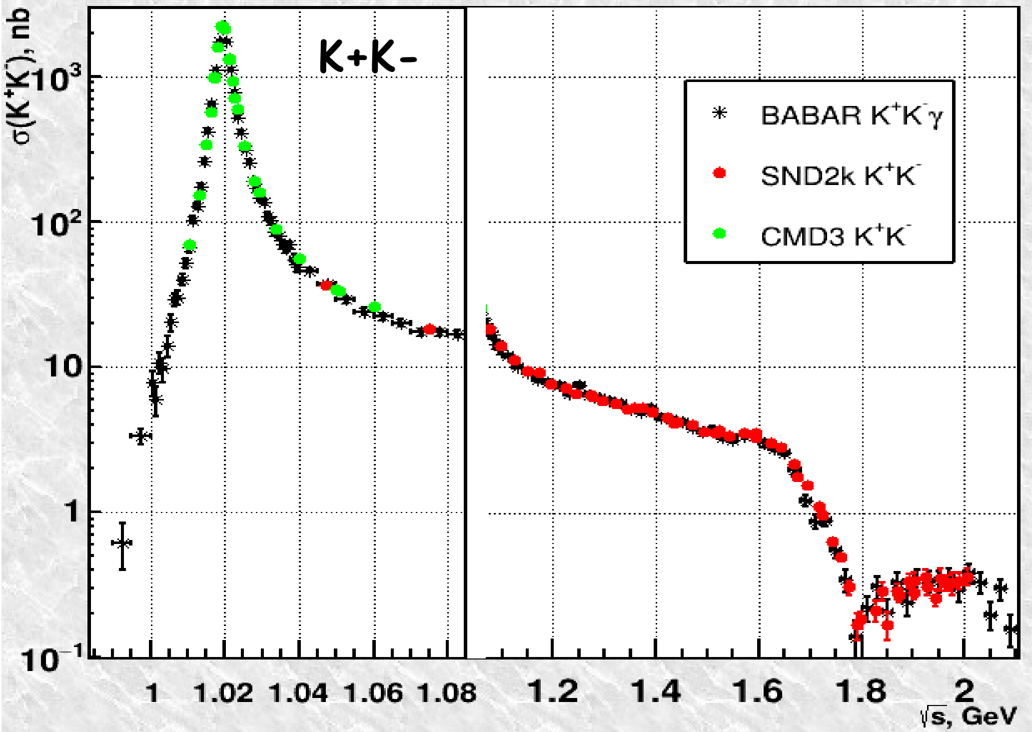
Many systematic studies rely on high statistics

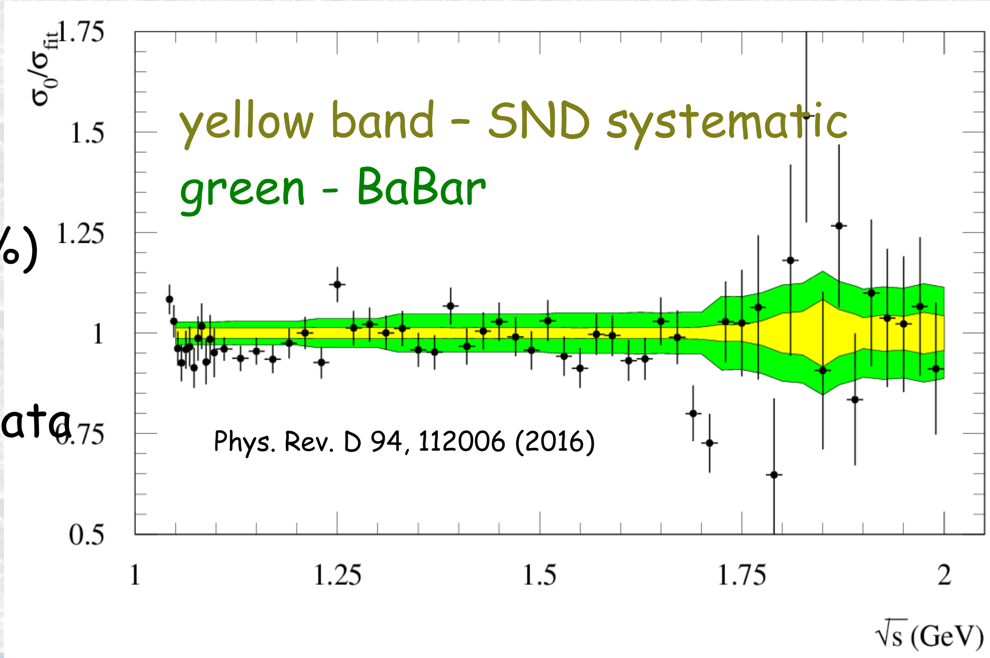
For most sources of systematics there is clear way how to bring it down

For 2013 data we aim at sub-% accuracy

e+e- -> KK̄



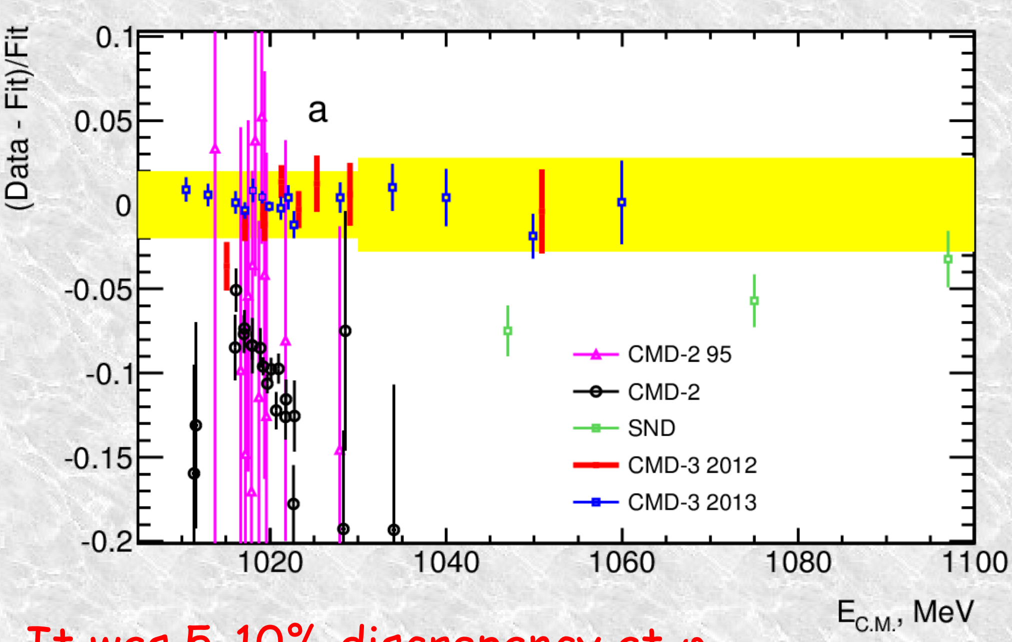


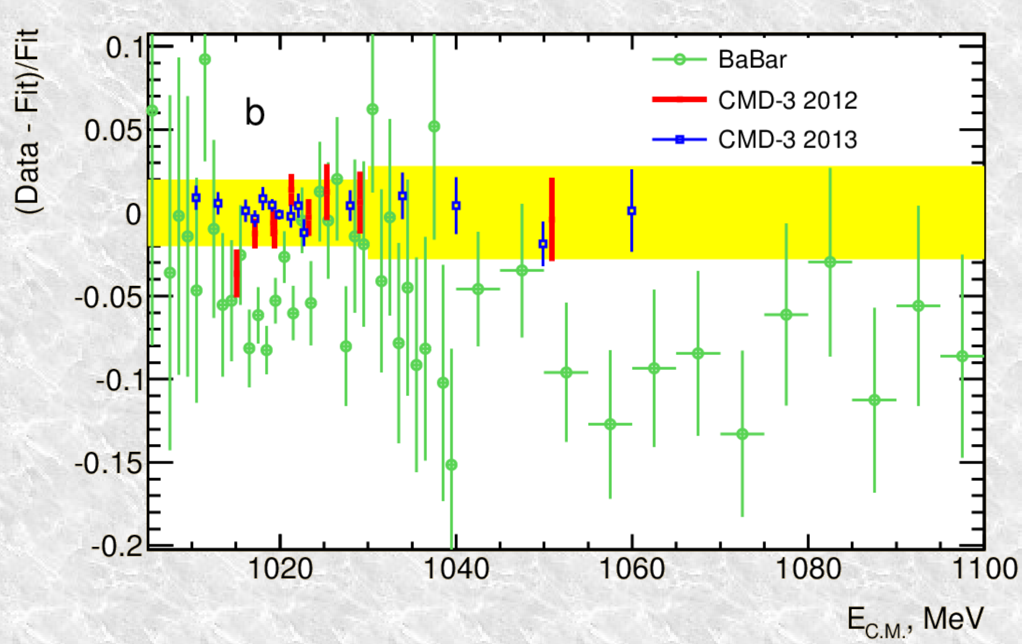


CMD3: KsKl at φ - Best systematic precision (1.8%)
CMD3: K+K- is under internal review (syst 2%)

The SND measurement agrees with the BABAR data and has comparable or better accuracy.

φ → K+K- comparison between experiments





It was 5-10% discrepancy at φ

Between CMD-2 (2.2% systematic)

SND at VEPP-2M (7.1%)

with BaBar data (0.72%)

CMD2 underestimated trigger inefficiency for slow K+K-

New CMD-3 cross-section is above CMD-2 and BaBar,

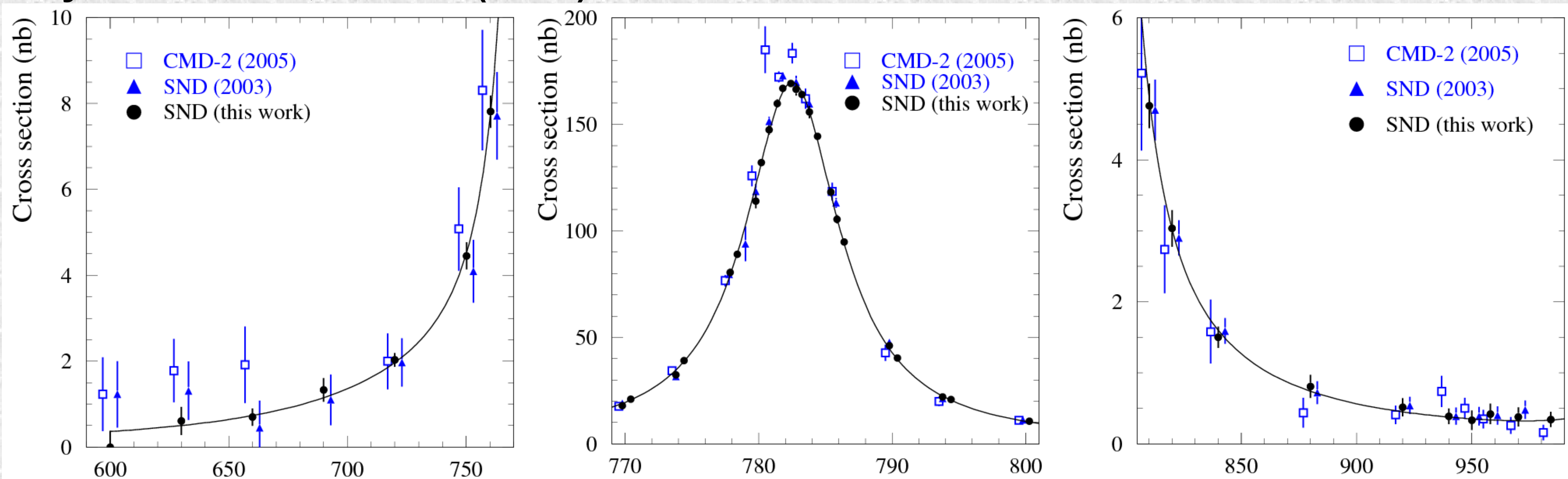
but it is in consistency with isospin symmetry:

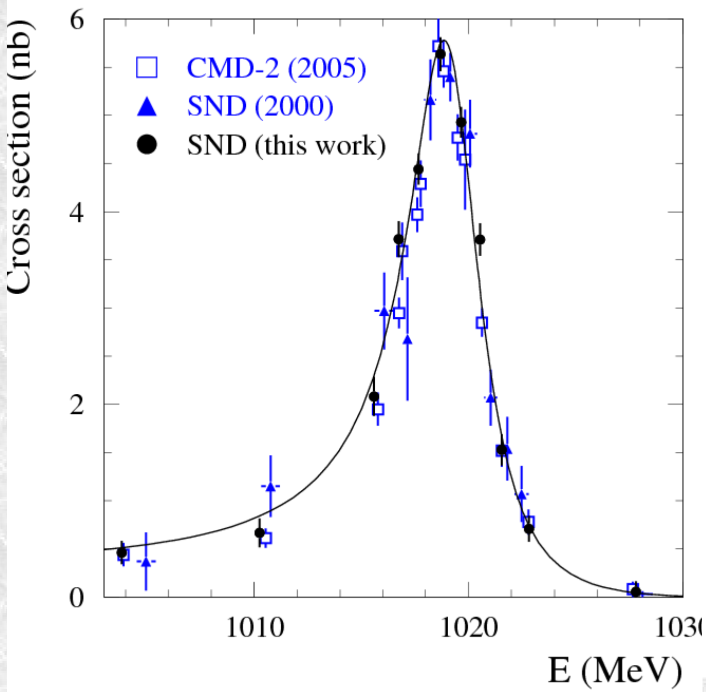
$$R = \frac{g_{\phi K+K-}}{g_{\phi K_S K_L}\sqrt{Z(m_\phi)}} = 0.990 \pm 0.017$$

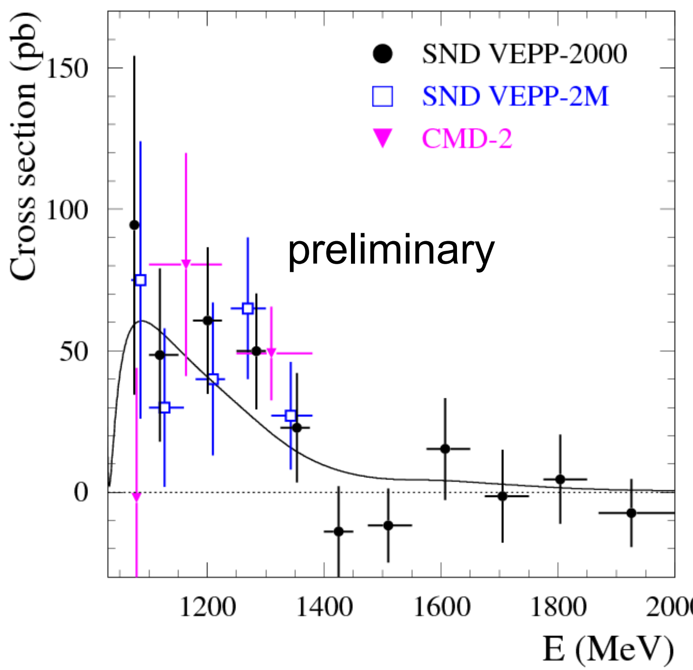
- $R_{SND} = 0.92 \pm 0.03 (2.6\sigma)$
- $R_{CMD-2} = 0.943 \pm 0.013 (4.4\sigma)$
- $R_{BaBar} = 0.972 \pm 0.017 (1.5\sigma)$

$e^+e^- \to \pi^0\gamma$ @ SND, VEPP-2M

Phys. Rev. D 93, 092001 (2016)







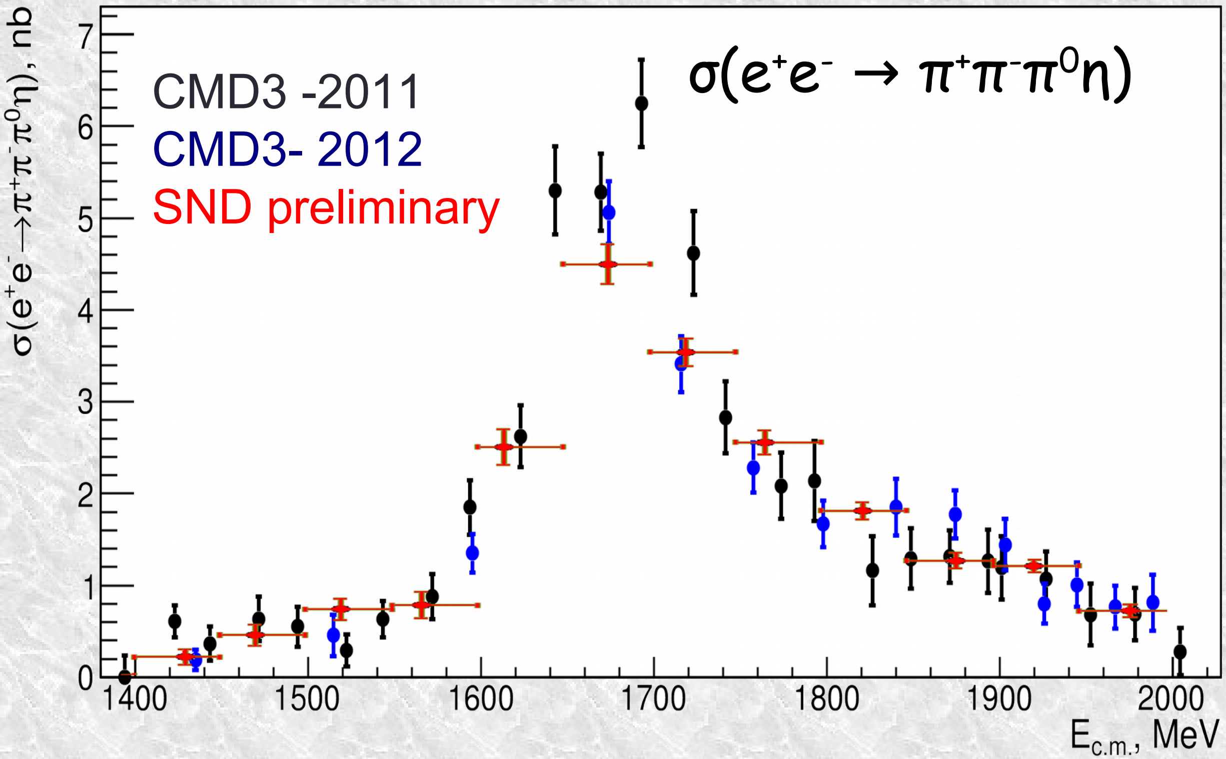
- ✗ Full VEPP-2M statistic (x4 to previous publication)
- ✗ The most precise measurement of this cross section
- ✗ Systematic uncertainty at the ω peak is 1.4% (1.2% from luminosity and 0.6% due to selection criteria)

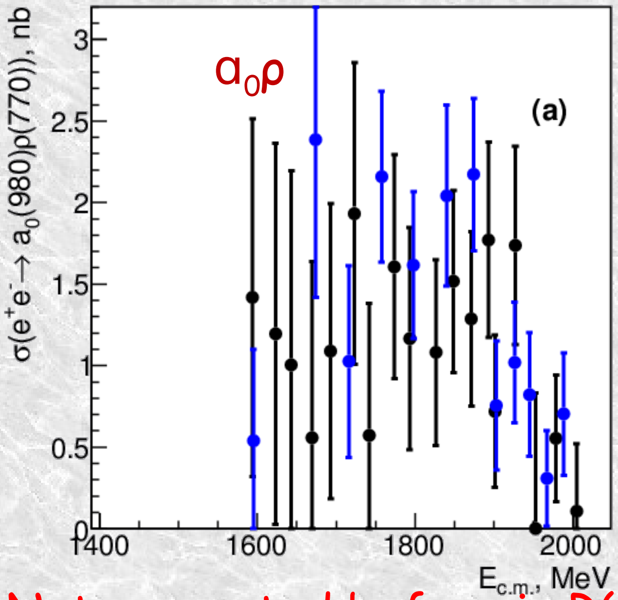
$e^+e^- \to \pi^+\pi^-\pi^0\eta$ @ CMD-3, SND

First measurement of total $e^+e^- \to \pi^+\pi^-\pi^0\eta$ cross section.

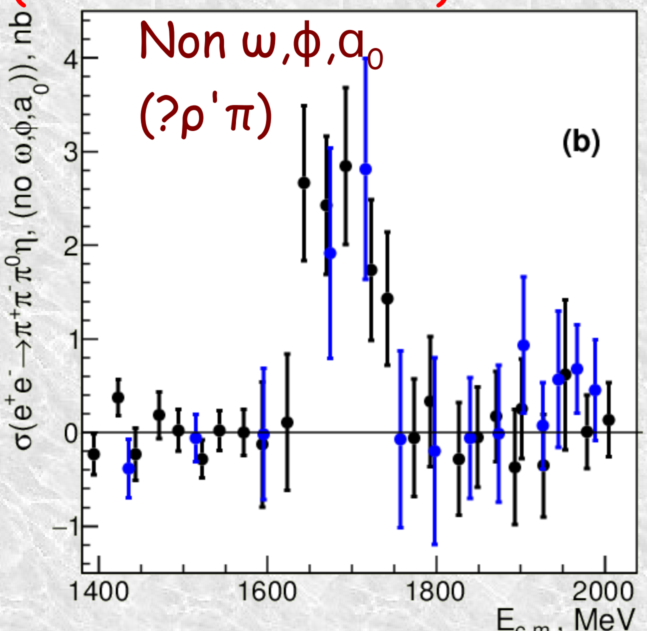
Systematic error is 11%.

Phys.Lett. B773 (2017) 150-158,arXiv:1706.06267v3





Not accounted before in R(s) (3-5% contribution)



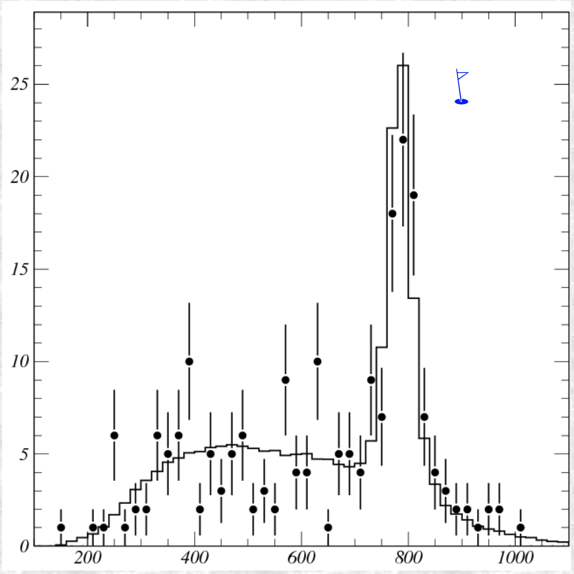
- The intermediate states are $\omega\eta$, $\phi\eta$, $a_0\rho$ and structureless $\pi^+\pi^-\pi^0$
- The known $\omega\eta$ and $\phi\eta$ contributions explain about ~50% of the cross section below 1.8 GeV.
- Above 1.8 GeV the dominant reaction mechanism is $a_0\rho$

$e^+e^- \to \omega\pi^0\eta$ @ SND

Phys. Rev. D 94,032010 (2016)

7 photon final state

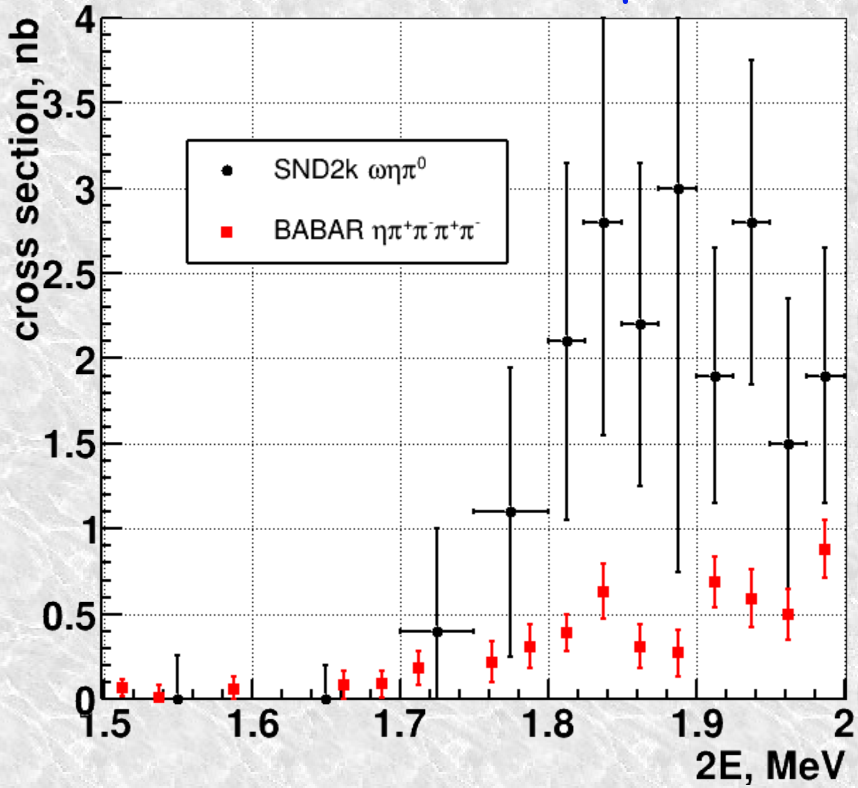
$e^+e^- \to \pi^0\pi^0\eta\gamma \to 7\gamma$



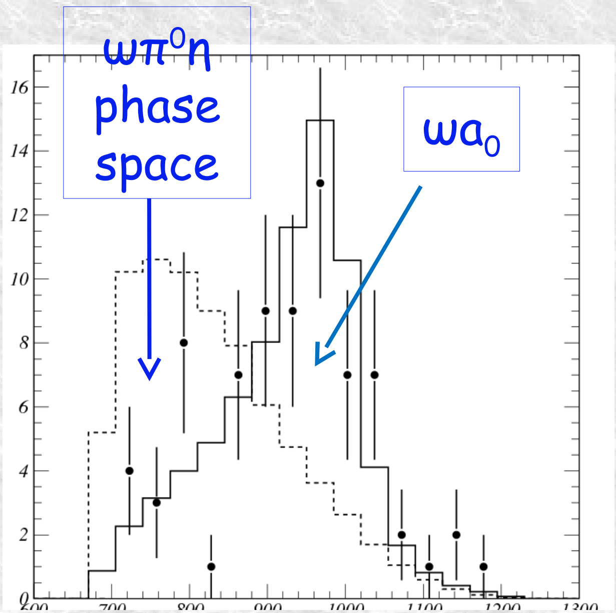
$\pi^0\gamma$ mass

Total cross section

$e^+e^- \to \omega\pi^0\eta$



a_0 dominance



$\pi^0\eta$ mass

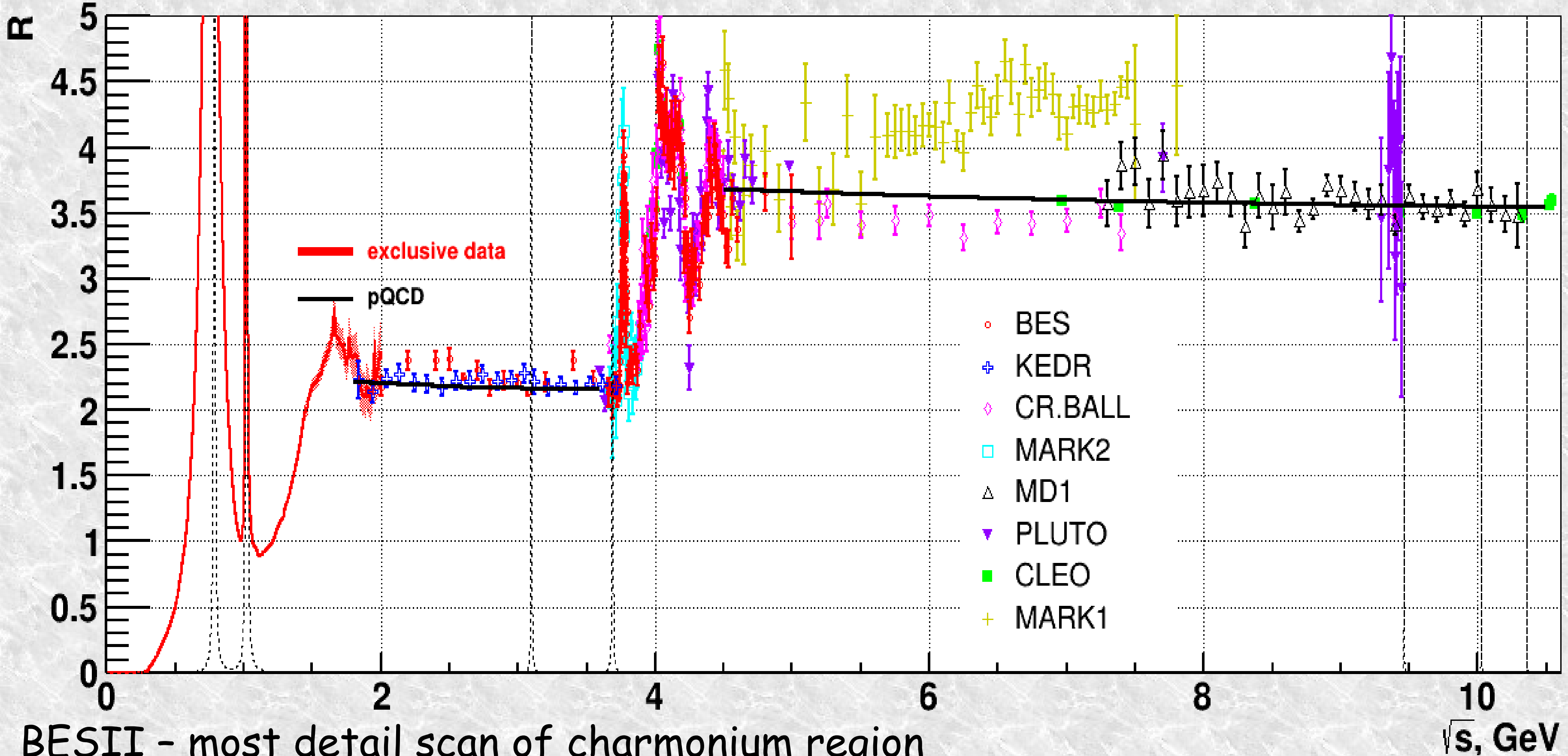
First measurement of the $e^+e^- \to \omega\pi^0\eta$ cross section.

The dominant mechanism is $\omega a_0(980)$.

The cross section is about 2.5 nb, 5% of the total hadronic cross section

before was partially accounted by "isospin relation" $\sigma(\eta\pi^+\pi^-2\pi^0)=\sigma(\eta 2\pi^+2\pi^-)$

Inclusive R(s) at √s > 2 GeV



BESII – most detail scan of charmonium region

KEDR – best systematic precision(up to 2%) at $\sqrt{s} < 3.7$ GeV

$R_{KEDR} = 2.23 \pm 0.05$ Phys.Lett. B770 (2017) 174-181

consistent with $R_{pQCD} = 2.18 \pm 0.02$

Expected in future:

BESIII – already did R(s)-scan during 2012- 2015 years at $2. < \sqrt{s} < 4.6$ GeV (125 points, 1.3 fb^{-1})

KEDR – plans to do scan of 2E=4.5-8 (10) GeV

Conclusion

- ✗ Precise low-energy e^+e^- hadronic cross section data are needed to obtain an accurate SM prediction for $a_\mu^{had,LO-VP}$
- ✗ **Direct scan experiments provides this σ (e+e- → hadrons) measurements with independent systematic sources (very different from ISR method)**
- ✗ Several previously unmeasured processes contributed to the total hadronic cross section ($e^+e^- \to \omega\pi^0\eta$, $\eta\pi^+\pi^-\pi^0$) below 2 GeV have been studied.

- ✗ New precise results are expected from CMD-3, SND, KEDR, BESIII

- ✗ VEPP-2000 is only one working this days on direct scanning below <2 GeV for measurement of exclusive σ (e+e- → hadrons)
- ✗ In 2013-2016 the VEPP-2000 collider and the detectors have been upgraded. The data taking was resumed in 2017. Additional scan of $\sqrt{s}$ < 1 GeV is planned in 2017-2018
- ✗ The VEPP-2000 results will help to reduce error of the hadronic contribution and it is independent cross-check of ISR data, future Lattice, space-like measurements

Exclusive channels under analysis

At VEPP-2000 we do exclusive measurement of σ (e+e- → hadrons).

- 2 charged

  $e^+e^- \to \pi^+\pi^-, K^+K^-, K_SK_L, p\bar{p}$

- 2 charged + γ 's

  $e^+e^- \to \pi^+\pi^-\pi^0, \pi^+\pi^-\eta, K^+K^-\pi^0, K^+K^-\eta, K_SK_L\pi^0, \pi^+\pi^-\pi^0\eta,$

  $\pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0\pi, \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0,$

- 4 charged

  $e^+e^- \to \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K_SK^*$

- 4 charged + γ's

  $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0, \pi^+\pi^-\eta, \pi^+\pi^-\pi^0\eta, \pi^+\pi^-\omega, \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0, K^+K^-\eta, K^+K^-\omega,$

- 6 charged

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

- γ 's only

  $e^+e^- \to \pi^0\gamma, \eta\gamma, \pi^0\pi^0\gamma, \pi^0\eta\gamma, \pi^0\pi^0\pi^0\gamma, \pi^0\pi^0\eta\gamma,$

- other

  $e^+e^- \to n\bar{n}, \pi^0e^+e^-, \eta e^+e^-$

Analysis of mostly each channel takes own person-years:
lower systematic needed → more effects → more years

SM prediction for muon g-2

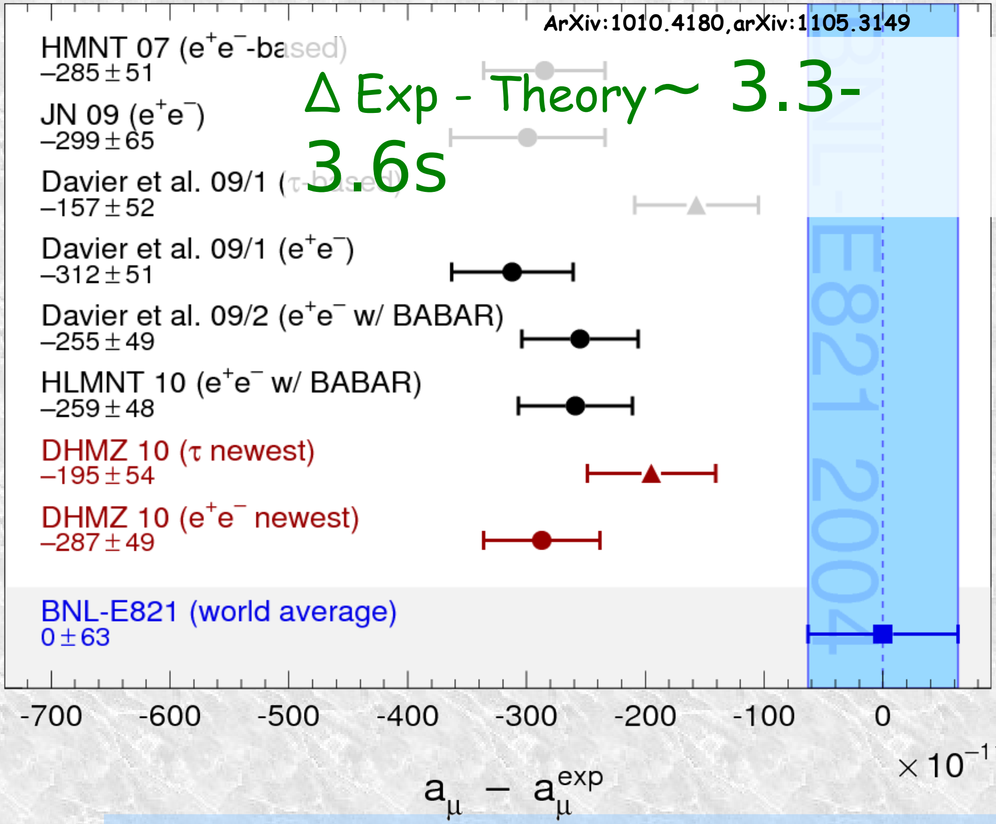
Experimental world average

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 ~ 3.3-3.6s

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)
.....		

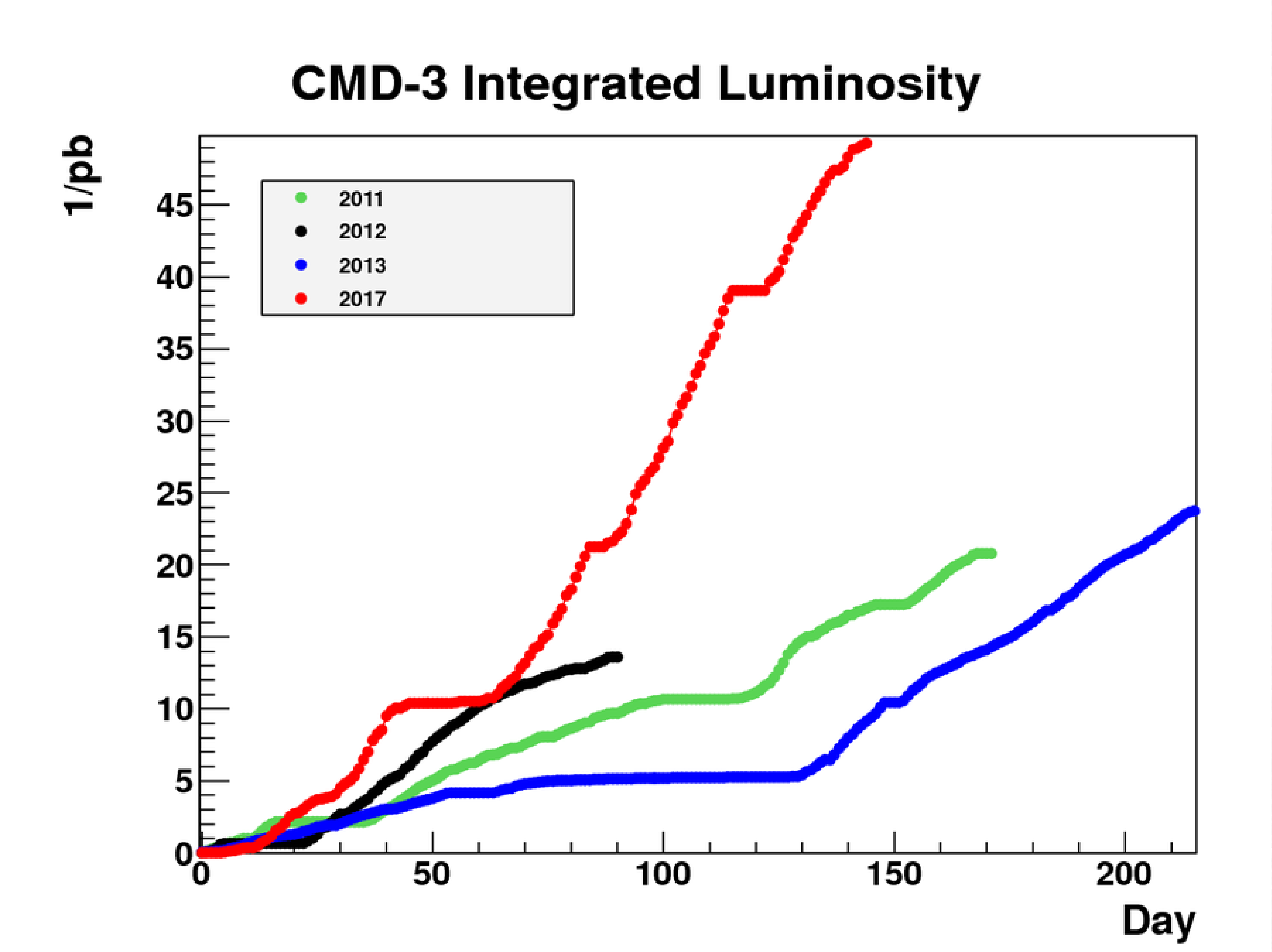
New g-2 experiments at FNAL and J-PARC have plans to reduce error to **1.5×10^{-10}**

Light-by-light 10.5 ± 2.6 need more theory input, with help of experimental transition form factors

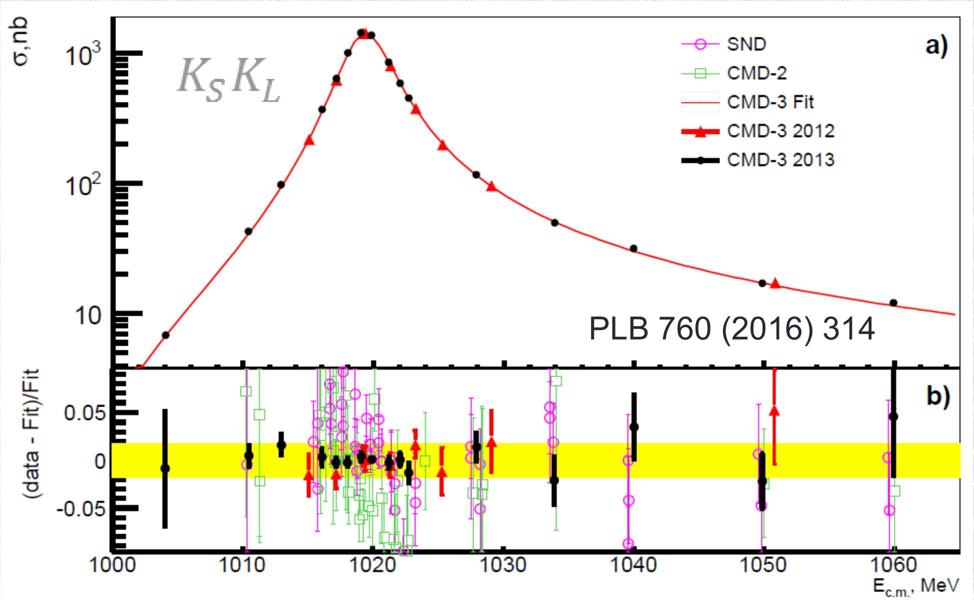
The value and the error of the hadronic contribution to muon (g-2) are dominated by low energy R(s) (<2GeV gives 93% of the value).

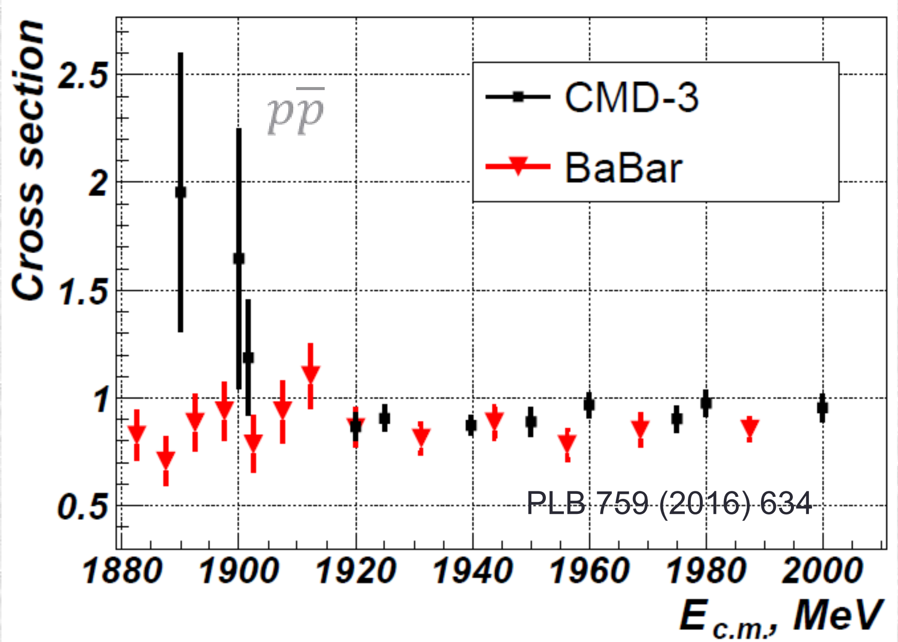
$\pi^+\pi^-$ gives the main contribution (73%) to a_μ

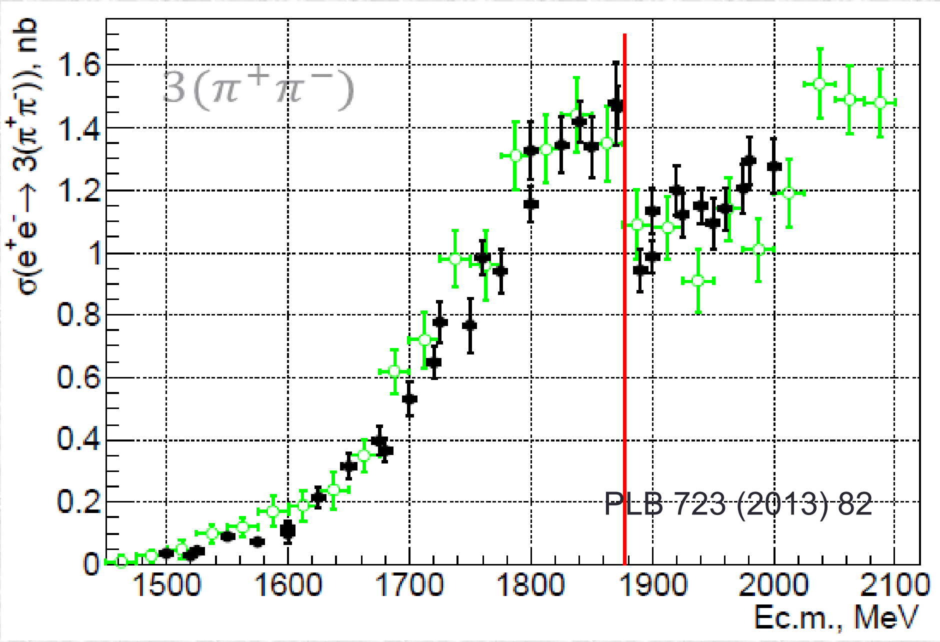
Overview of CMD-3 data taking runs

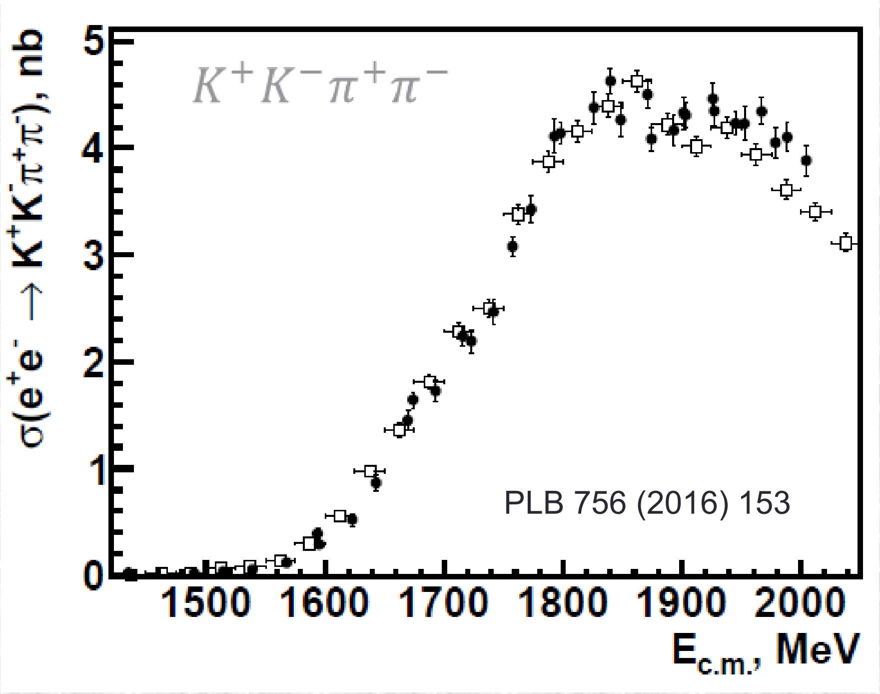


Published results from 2011-2013: CMD-3

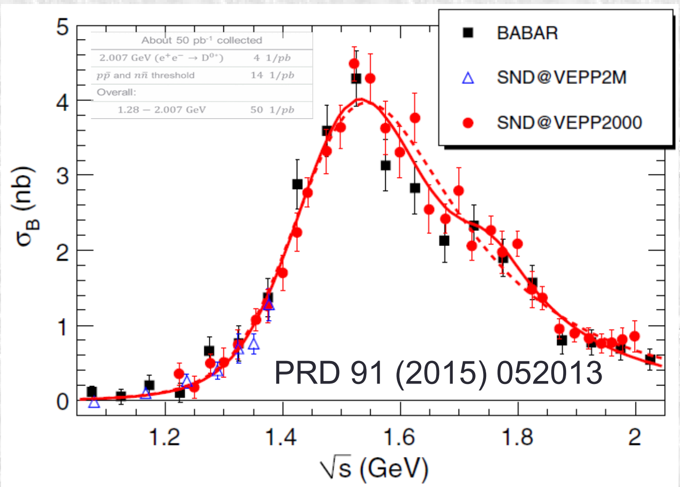


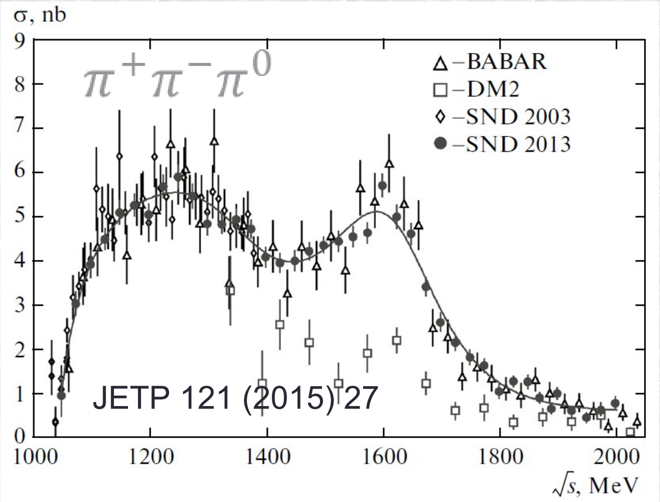


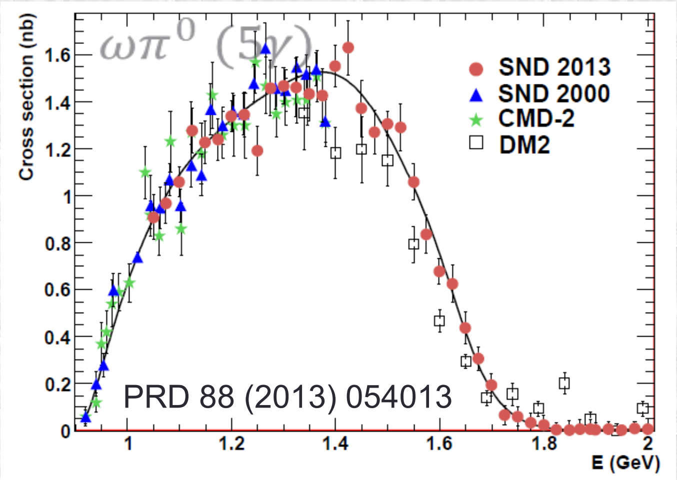


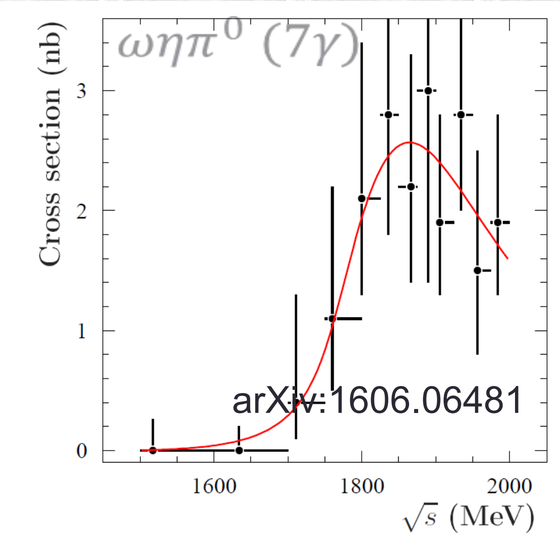


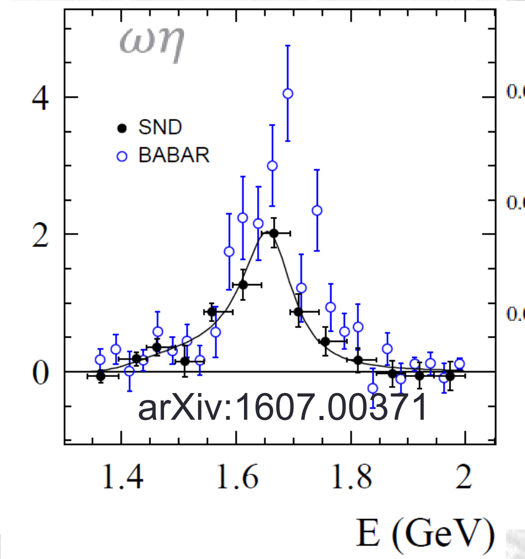
Published results from 2011-2013: SND

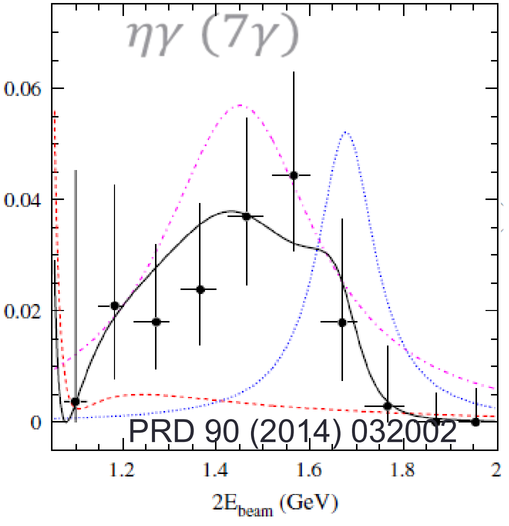


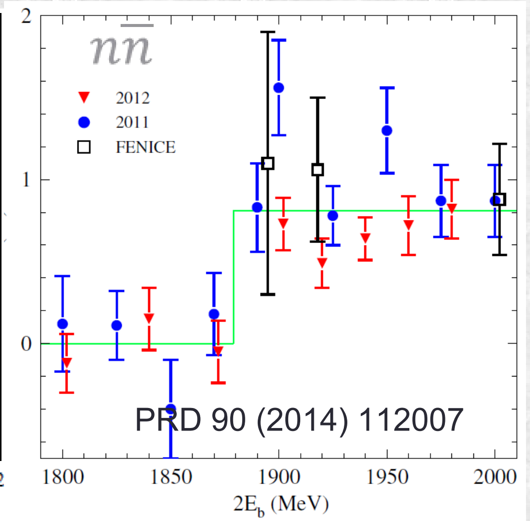












e+e- → π+π-π+π- @φ(1020)

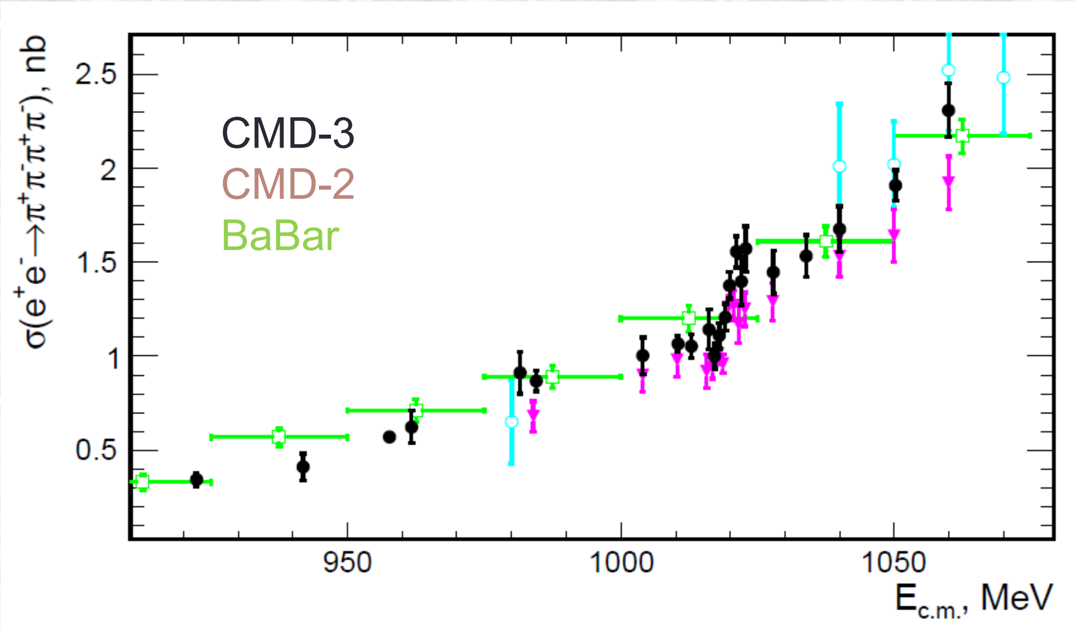
PLB 768 (2017) 345-350

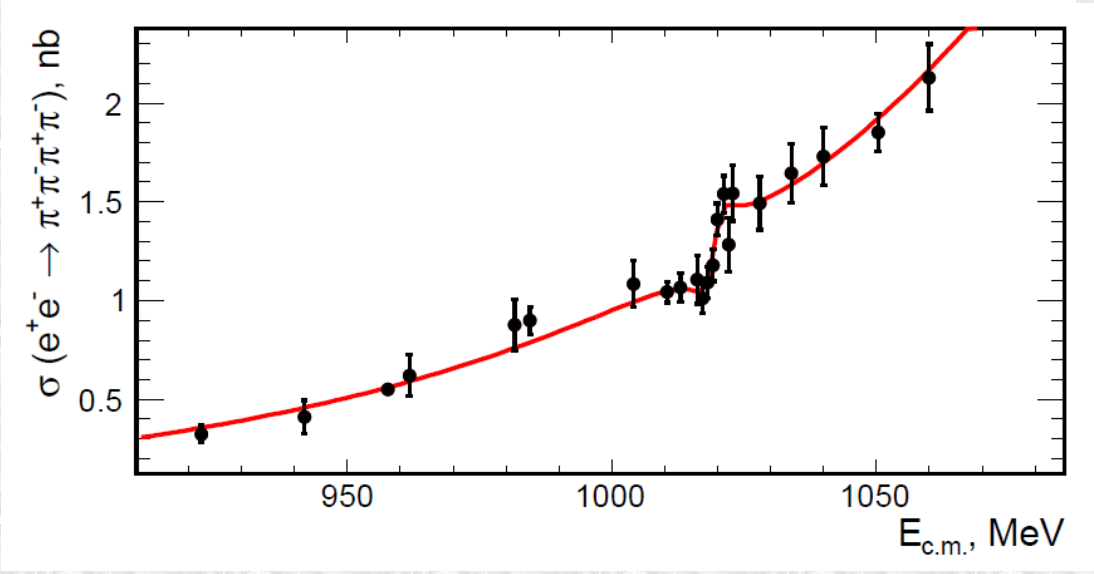
2011-2013 data, 10 1/pb
systematic error 3.5%

PLB 768 (2017) 345-350

2011-2013 data, 10 1/pb
systematic error 3.5%

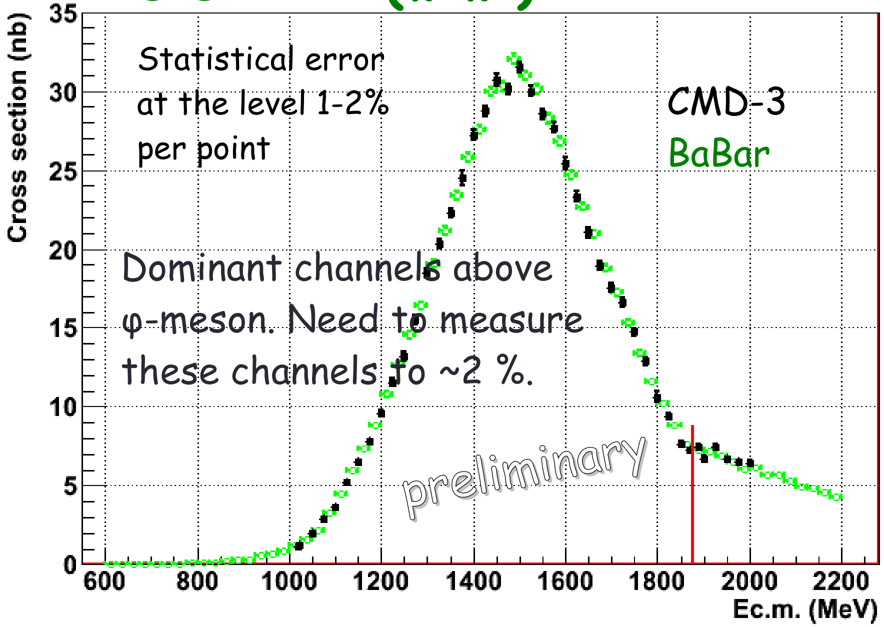
$$B\left(\varphi \to 2(\pi^+\pi^-)\right) =$$
$$(6.5 \pm 2.7 \pm 1.6) \times 10^{-6}$$

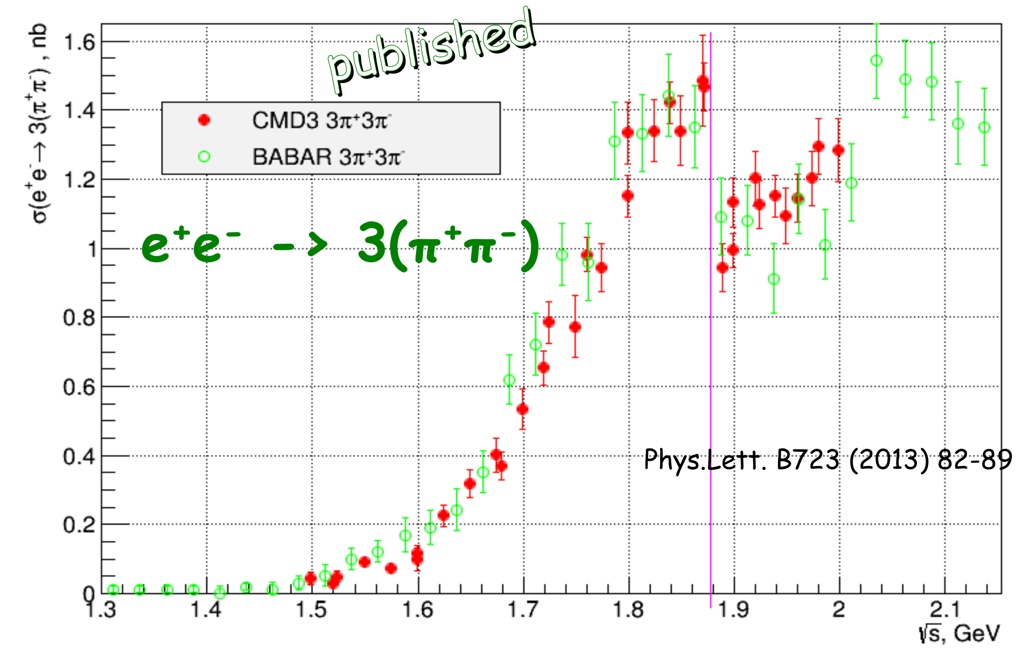


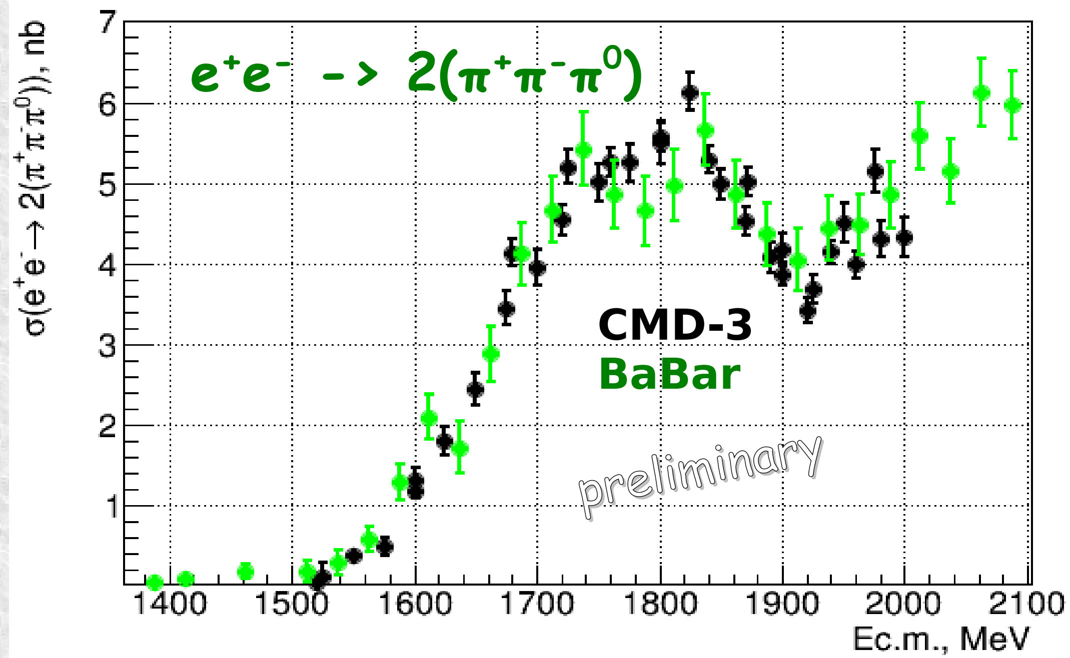


e+e- -> many pions with CMD-3

$e^+e^- \to 2(\pi^+\pi^-)$







The dominated source of systematic error is model uncertainty(evaluation of the detector acceptance)

High statistics allows for more accurate study of the intermediate dynamics.

$3(\pi^+\pi^-)$ are mainly produced through $\rho(770)$ + 4π (in phase space or f_0)

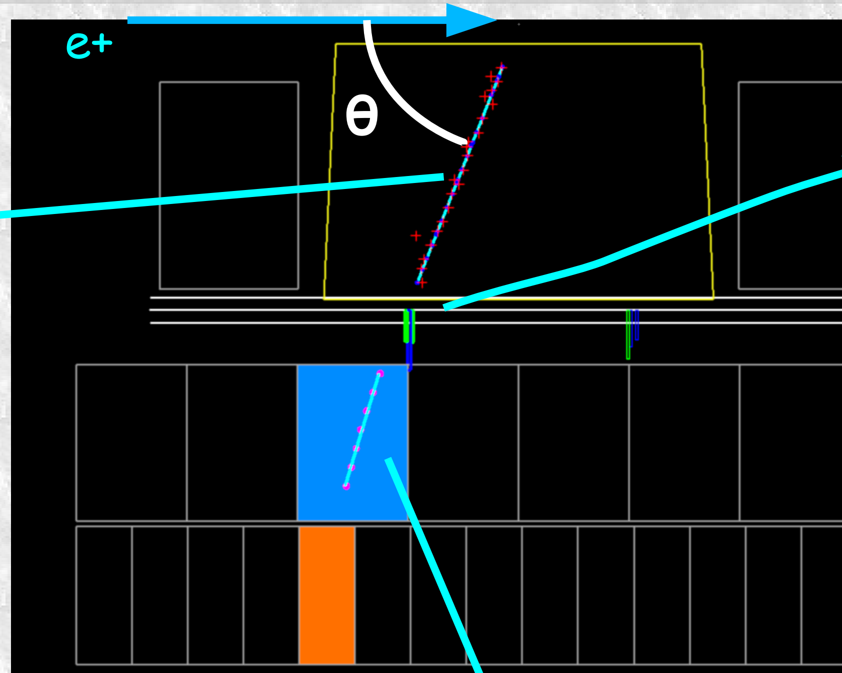
Seen change of dynamics in 1.7-1.9 GeV range

Interesting feature: sharp dip at $p\bar{p}$ threshold

(dip in sum of 6π roughly as $p\bar{p}+n\bar{n}$ cross section)

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)



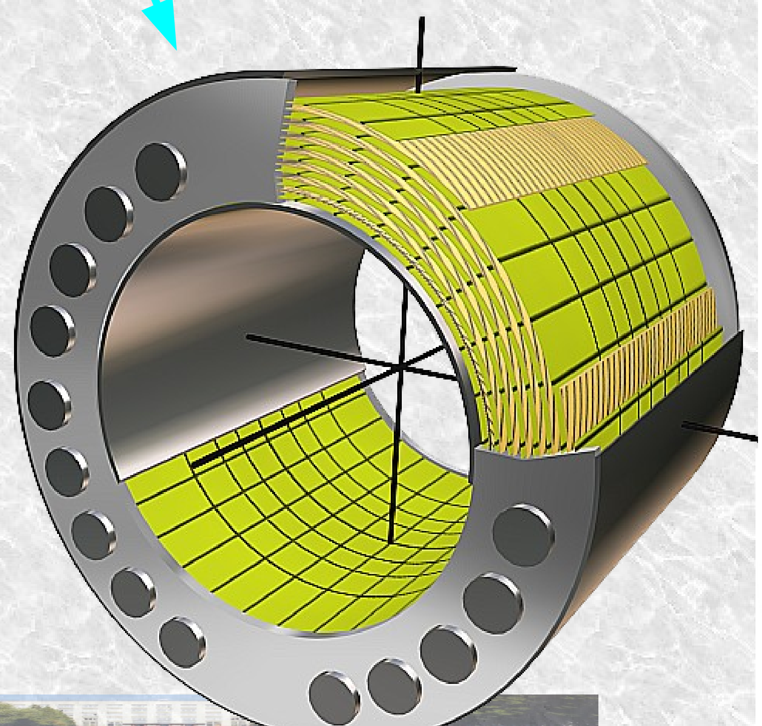
ZC chamber
multiwire chamber
with 2 layers and with strip
readout along Z coordinate

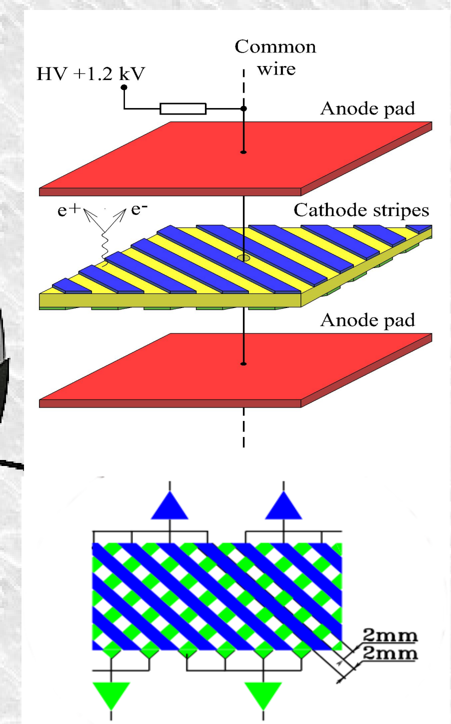
strip size: 6mm
Z coordinate resolution ~
0.7 mm (for θ_{track} ~ 1 rad)

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

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

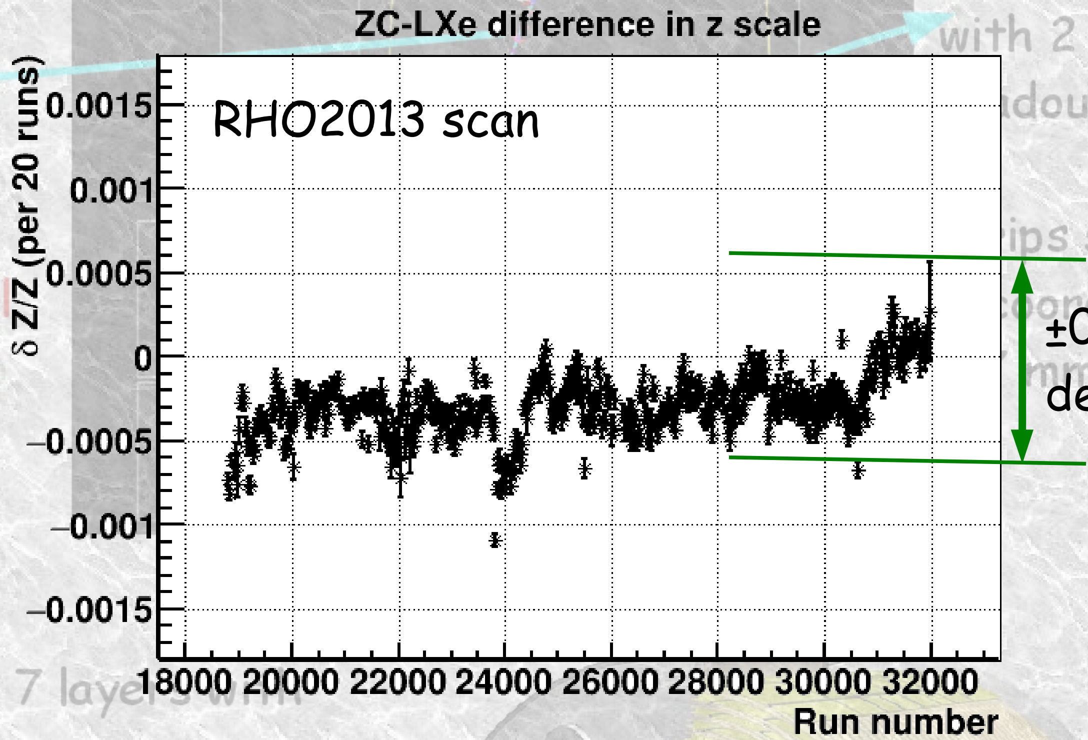
Both subsystem
with strip precision < 100 μm
give <0.1% in Luminosity determination





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