Measurement of hadronic cross-sections at CMD-3

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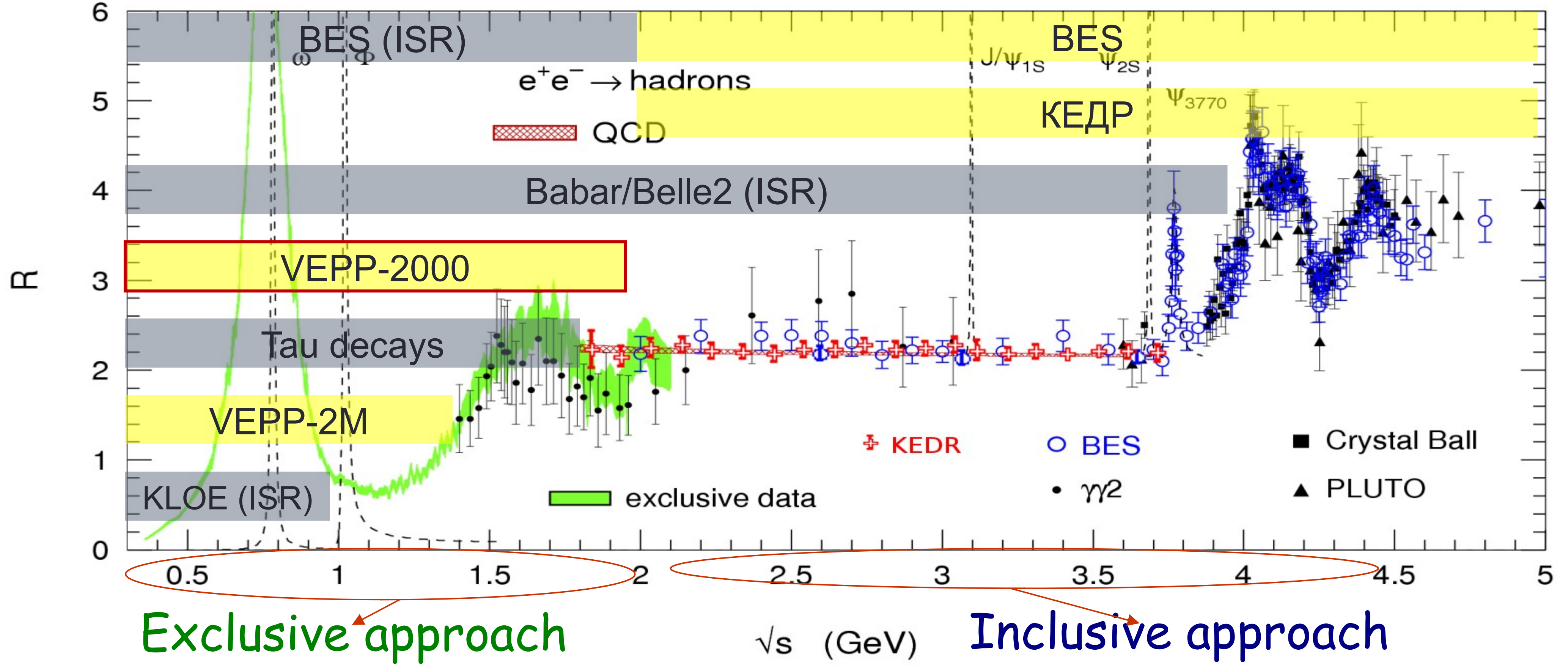
PHIPSI19, Novosibirsk

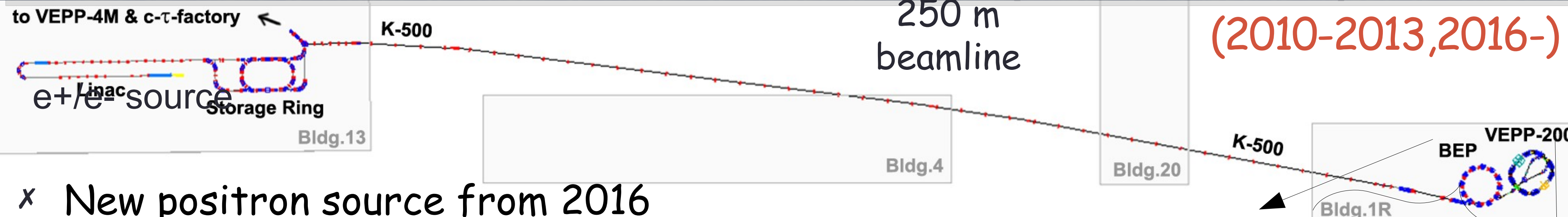
R measurements



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)

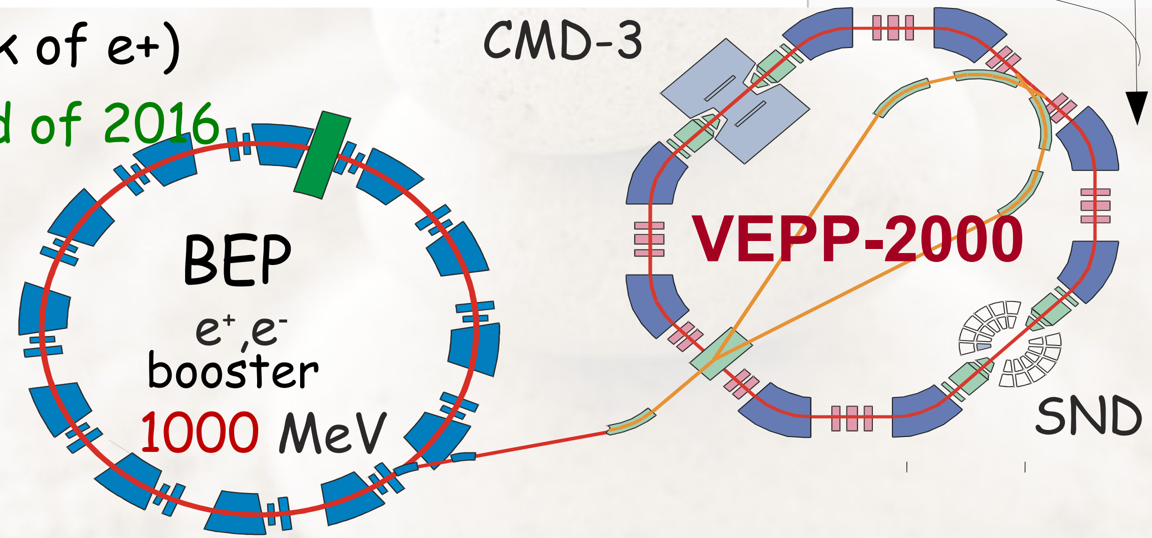


(2010-2013,2016-)

- ✗ 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 , МэВ	825	1000



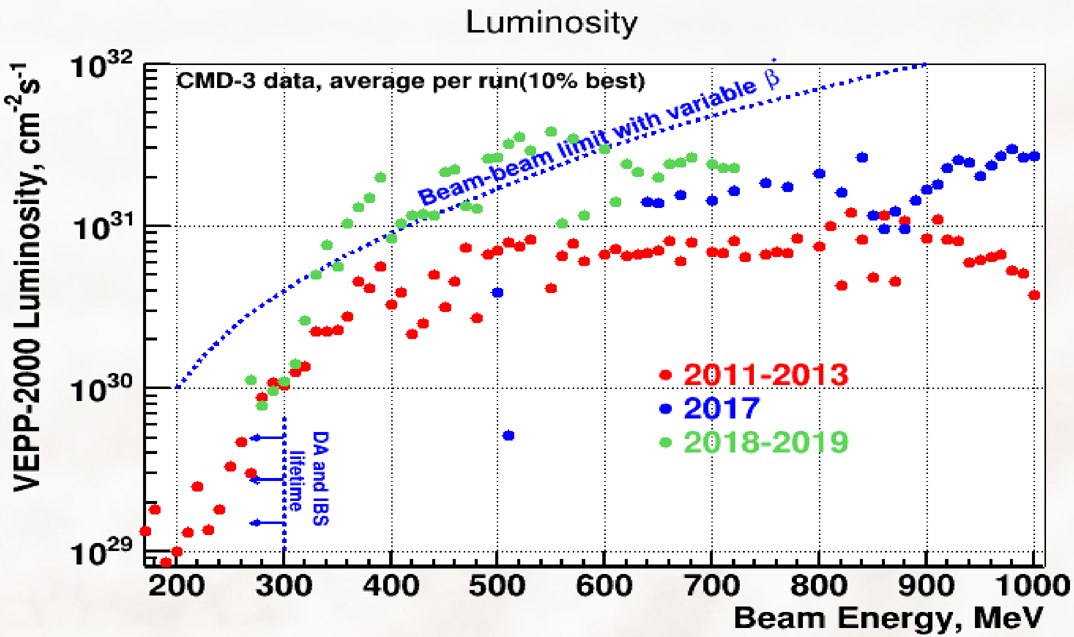
Maximum c.m. energy is 2 GeV, project luminosity is $L = 10^{32}\ cm^{-2}s^{-1}$ at 2E= 2 GeV

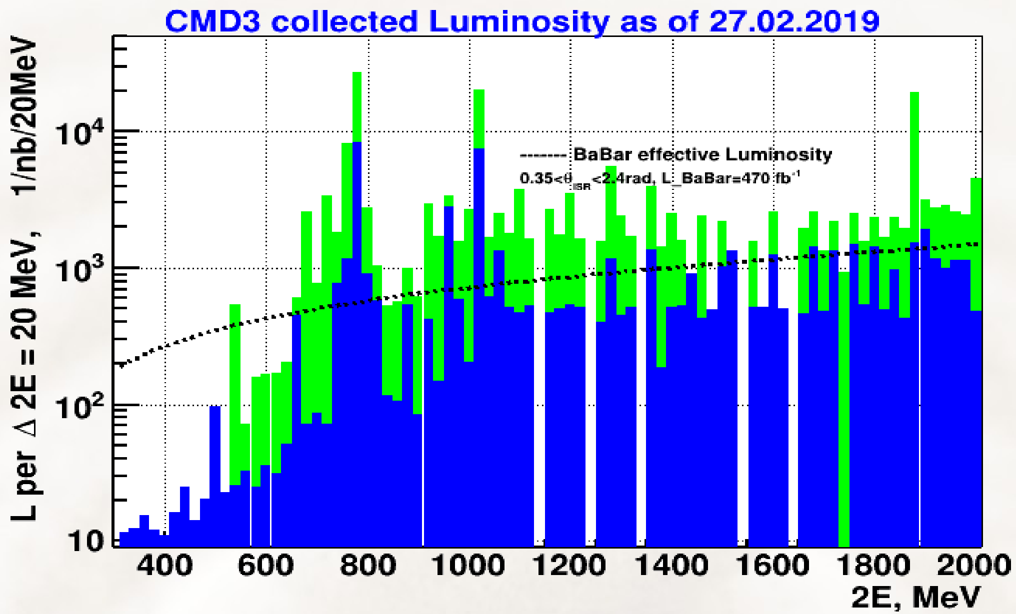
Unique optics, "round beams", allows to reach higher luminosity

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


VEPP-2000
collider ring
SND
CMD-3
6.65 m

Collected Luminosity





<u>Before VEPP-2000 upgrade (before 2013)</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

2018: "Beamshaking" technique was introduced, which suppress beam instabilities (x4 Lum)

<u>Collected since 12.2010</u>

<u>L ~ 200 pb^{-1} per detector</u>

<u>2011-2013 seasons:</u>

17.7 pb^{-1} < 1 GeV

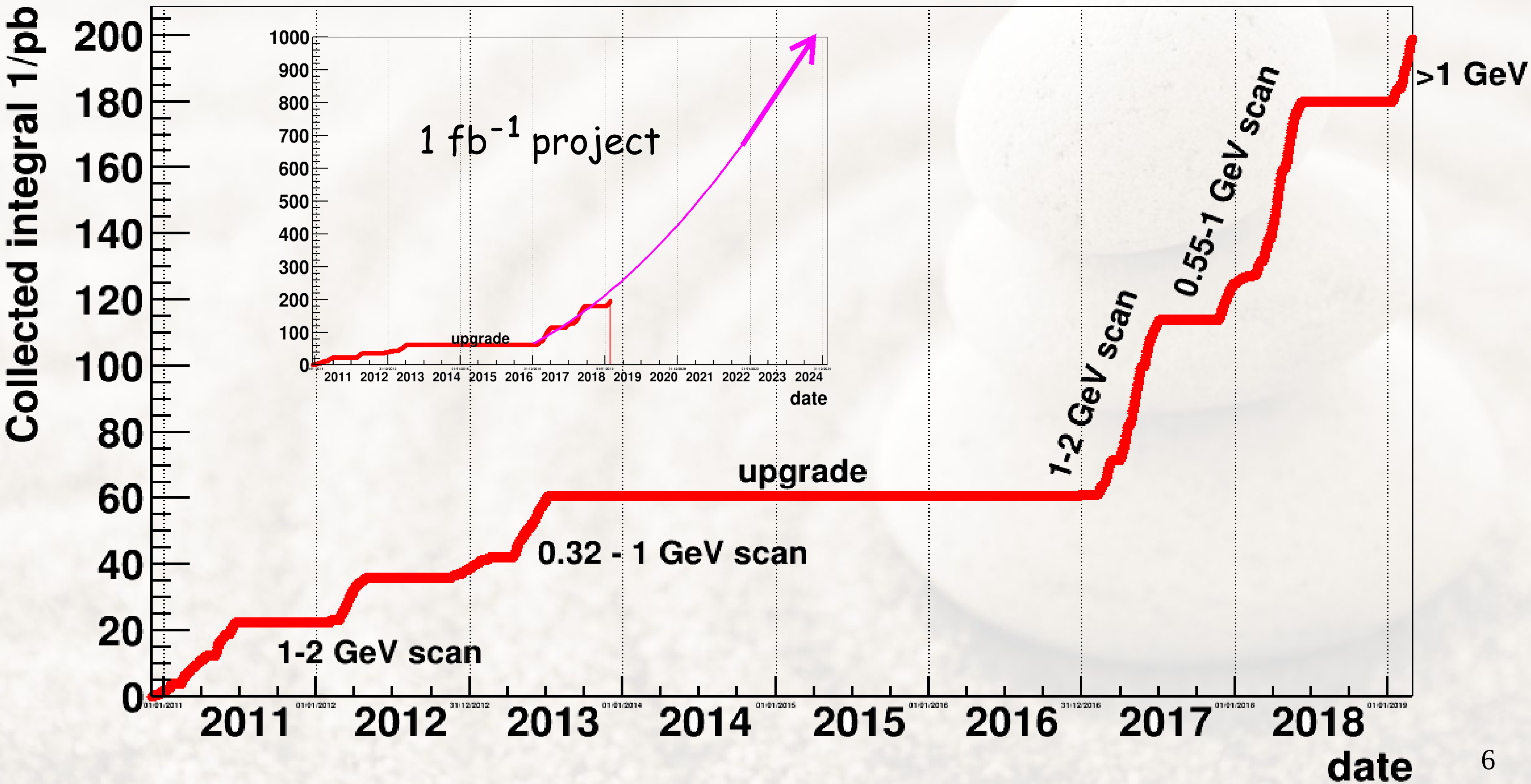
42.9 pb^{-1} > 1. GeV

<u>2017-2019 seasons:</u>

45.4 pb^{-1} < 1 GeV

86.8 pb^{-1} > 1. GeV

Overview of CMD-3 data taking runs



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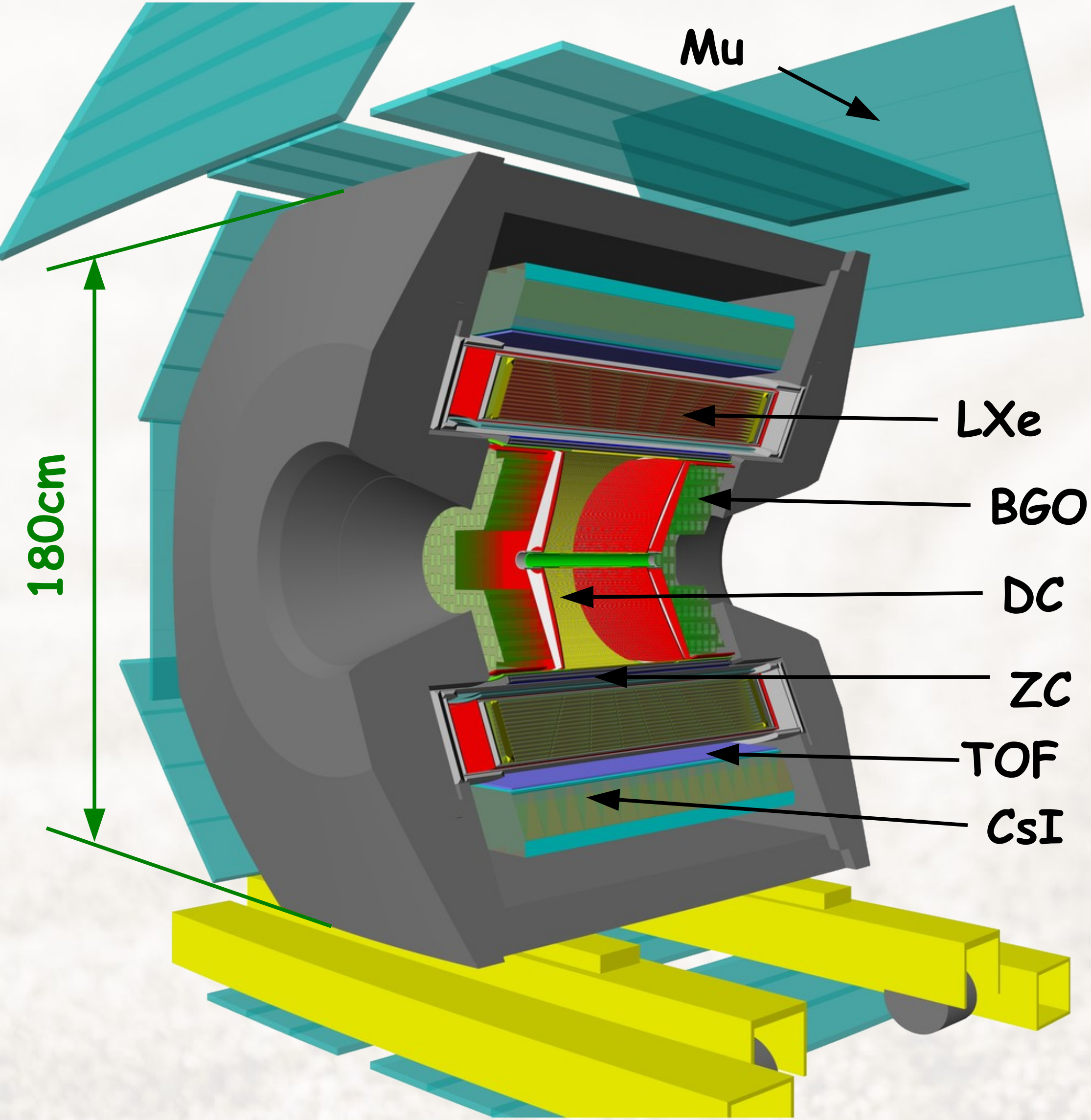
CMD-3 detector



Tracking:

- ✗ Drift Chamber in 1.3 T magnetic field

  $\sigma_{R\varphi} \sim 100\ \mu m$, $\sigma_Z \sim 2.5mm$

  $\sigma_p/P \sim \sqrt{0.6^2 + (4.4*p[GeV])^2}$,%

Calorimetry:

- ✗ Combined EM calorimeter (LXe,CsI, BGO)

  13.4 X_0 in barrel part

  $\sigma_E\ /E \sim 0.034/\sqrt{E\ [GeV]} \oplus 0.020$ - barrel

  $\sigma_E\ /E \sim 0.024/\sqrt{E\ [GeV]} \oplus 0.023$ - endcap

- ✗ LXe calorimeter with 7 ionization layers with strip readout

  ~2mm measurement of conversion point,
  tracking capability,
  shower profile (from 7 layers + CsI)

PID:

- ✗ TOF system (σ_T < 1nsec)

  particle id mainly for p, n

- ✗ Muon system

measured cross sections by CMD-3

✔ Published (or submitted):

- $e^+e^- \to p\bar{p}$, — Phys.Lett. B759 (2016) 634-640
- $e^+e^- \to \eta'$ — Phys.Lett. B740 (2015) 273-277
- $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$, — Phys.Lett. B768 (2017) 345-350; Phys.Lett. B723 (2013) 82-89
- $\omega\eta$, $\eta\pi^+\pi^-\pi^0$, — Phys.Lett. B773 (2017) 150-158
- $3(\pi^+\pi^-)\pi^0$, — arXiv:1902.06449, submitted to PLB
- K^+K^-, K_SK_L, — Phys.Lett. B760 (2016) 314-319; Phys.Lett. B779 (2018) 64-71
- $K^+K^-\pi^+\pi^-$ — Phys.Lett. B756 (2016) 153-160

✗ Near finished result:

- $e^+e^- \to D_0^*$
- $K^+K^-\eta$, $K^+K^-\omega$
- $\omega\pi^+\pi^-$, $\eta\pi^+\pi^-$

Under active analysis:

- $e^+e^- \to \pi^+\pi^-$,
- $e^+e^- \to \pi^+\pi^-\gamma$,
- $\eta\gamma$, $\pi^0\gamma$,
- $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)$,
- $2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-\pi^0)$
- K^+K^-, K_SK_L – at higher energies
- $K^+K^-\pi^0$, $K_SK_L\pi^0$, $K_SK_L\eta^0$,
- $n\bar{n}$, $\pi^0e^+e^-$, ηe^+e^-

Analysis of mostly each channel takes full person-years:
higher systematic requirement → more effects → more years

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) -> ~0.4-0.5% (CMD3)

Crucial pieces of analysis:

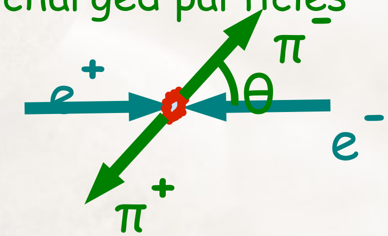
- ✗ e/μ/π separation
- ✗ precise fiducial volume
- ✗ radiative corrections

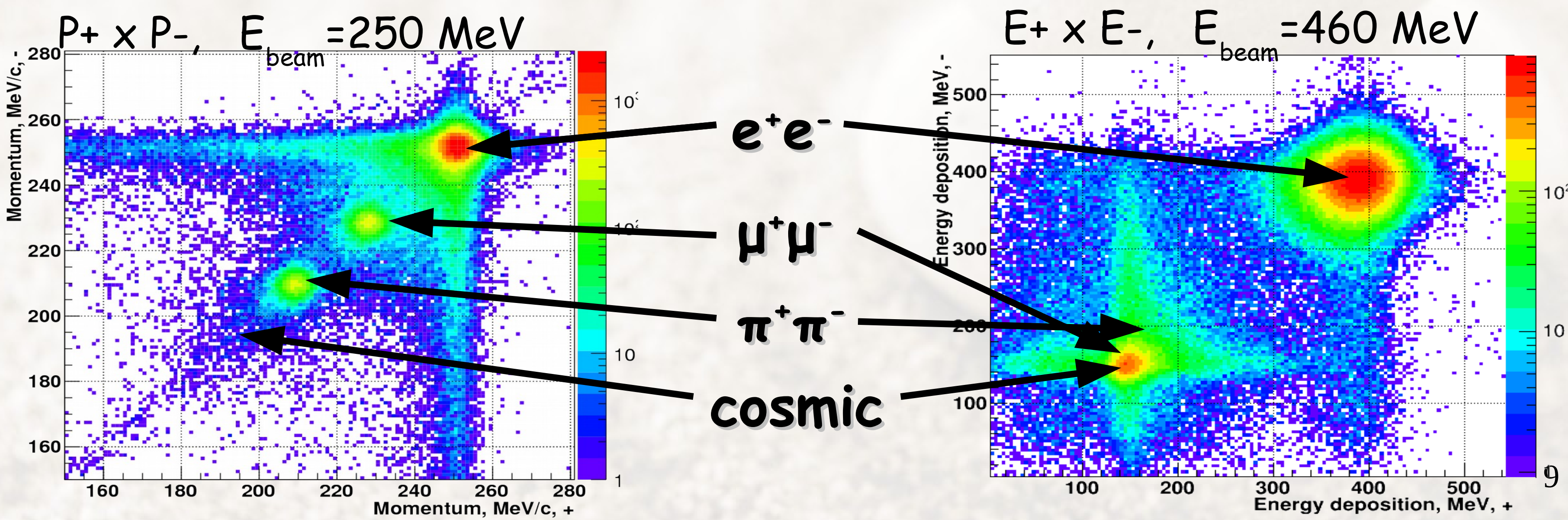
Many systematic studies rely on high statistics

events separation either by momentum or by energy deposition

Momentums works better at low energy < 0.8 GeV
Energy deposition > 0.6 GeV

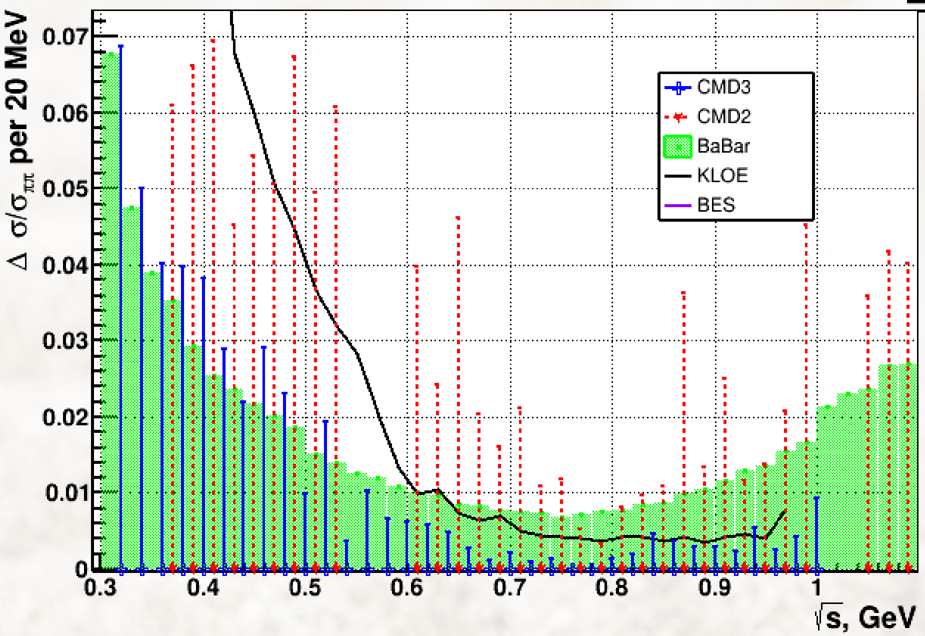
Simple event signature with 2 back-to-back charged particles

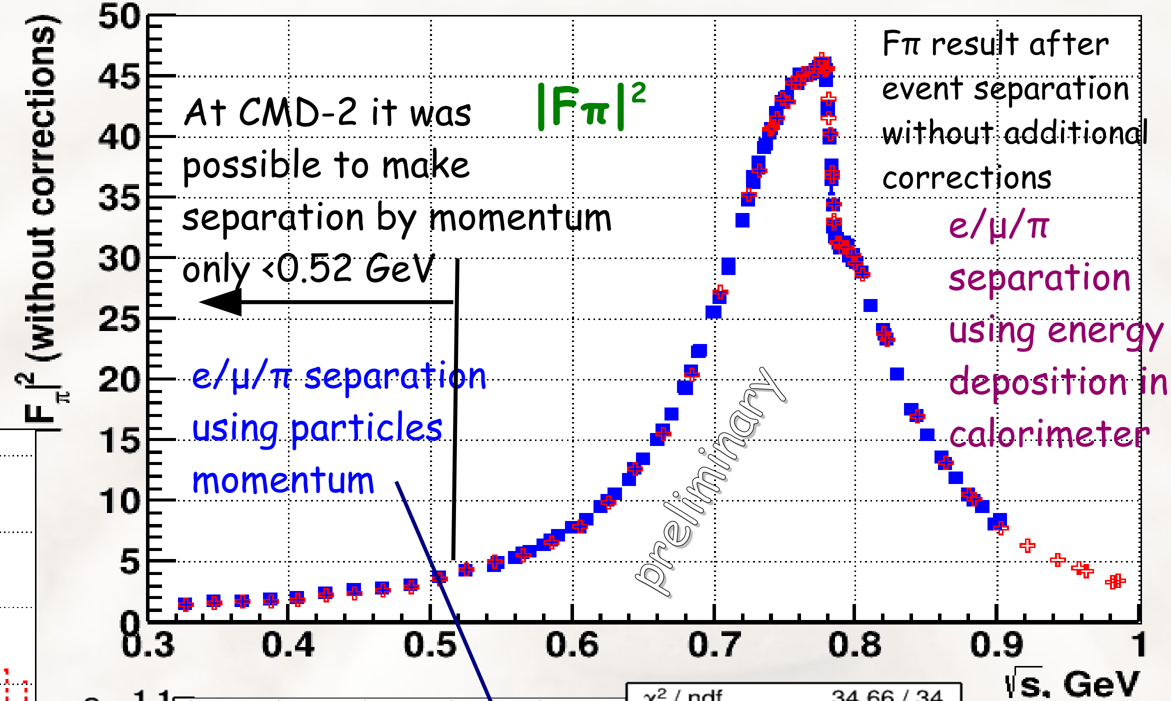


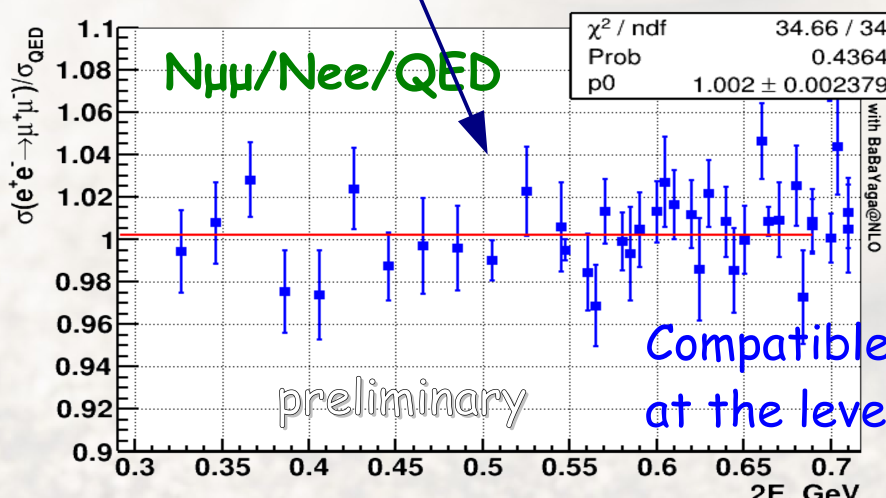


e+e- -> π+π- by CMD-3

Statistical precision of cross section measurement for 2013+2018 data a few times better than any other experiments



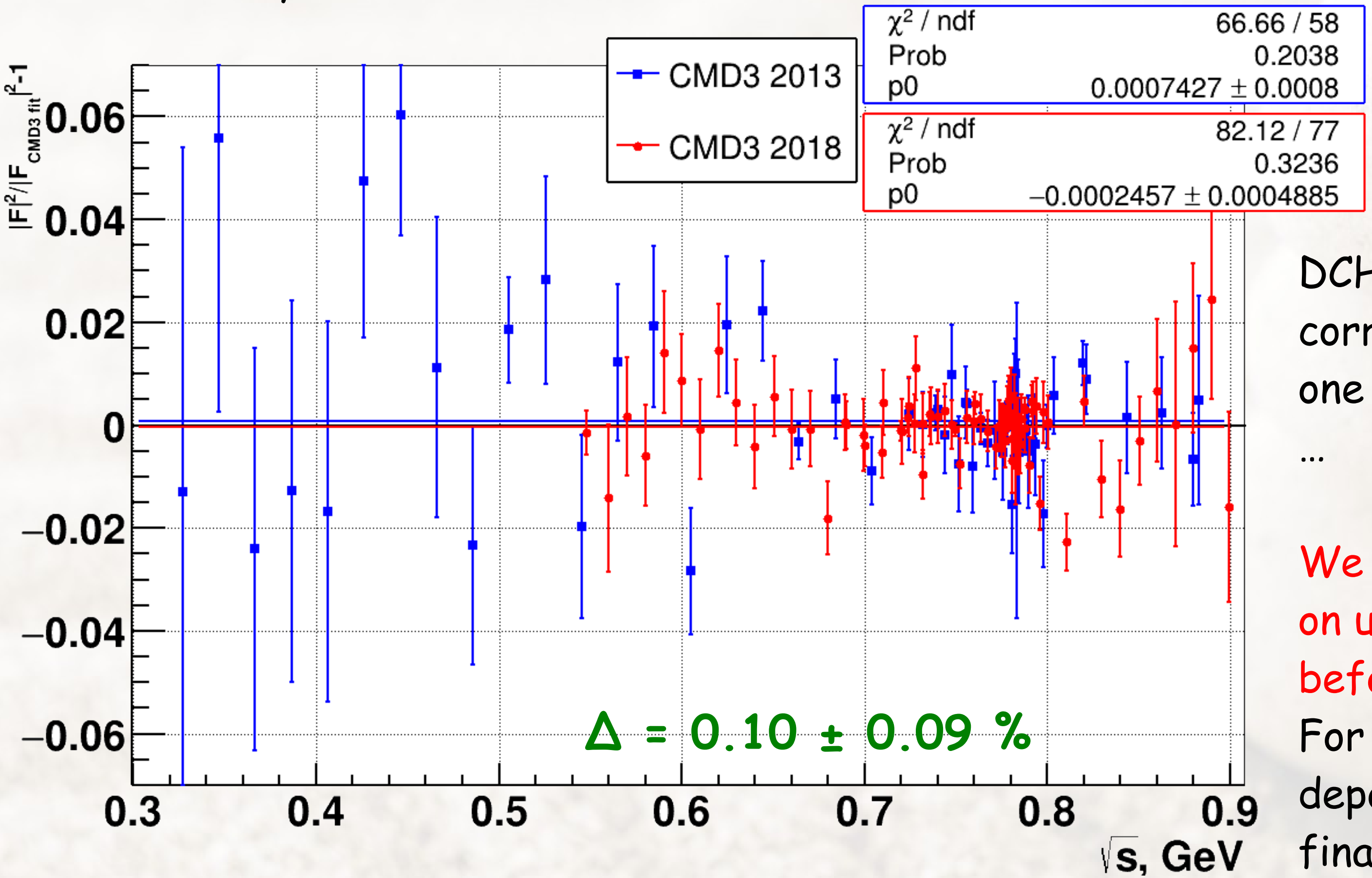




Compatible with QED at the level of 0.25 %

$|F_\pi|^2$ 2013 vs 2018 scans

PID by momentum



Event separation using momentum consistent within ~ 0.1% between seasons

DCH was in different conditions:
correlated noise
one HV layer off in 2013
...

We should finalize analysis based on using energy deposition, before opening box.

For 1st paper: using only full energy deposition in calorimeter

final paper: exploiting info on shower profile + polar angle distribution

Systematic e+e- -> π+π- by CMD3

Our goals are to reach systematic level ~0.4-0.5%:

	status
✗ Radiative corrections	with current MC generators 0.2% - integral cross-section 0.0 – 0.4% - from P spectra (we need theory help, NNLO generators)
✗ e/μ/π separation can be checked and combined from different methods	~ 0.6 - 0.2 (at ρ) – 1.0(at 0.9 GeV) % by momentum ~ 1 % by energy – still work in progress...
✗ Fiducial volume controlled independently by LXe and ZC subsystems, angular distribution	0.2%
✗ Beam Energy measured by method of Compton back scattering of the laser photons(σ_E< 50 keV)	0.1%
✗ Electron bremsstrahlung loss	0.05%
✗ Pion specific correction decay, nuclear interaction taken from data	~ 0.1 % nuclear interaction 0.6-0.3% pion decay

at ρ-peak by P : 0.6%

at few lowest points : 0.9%

Many systematic studies rely on high statistics

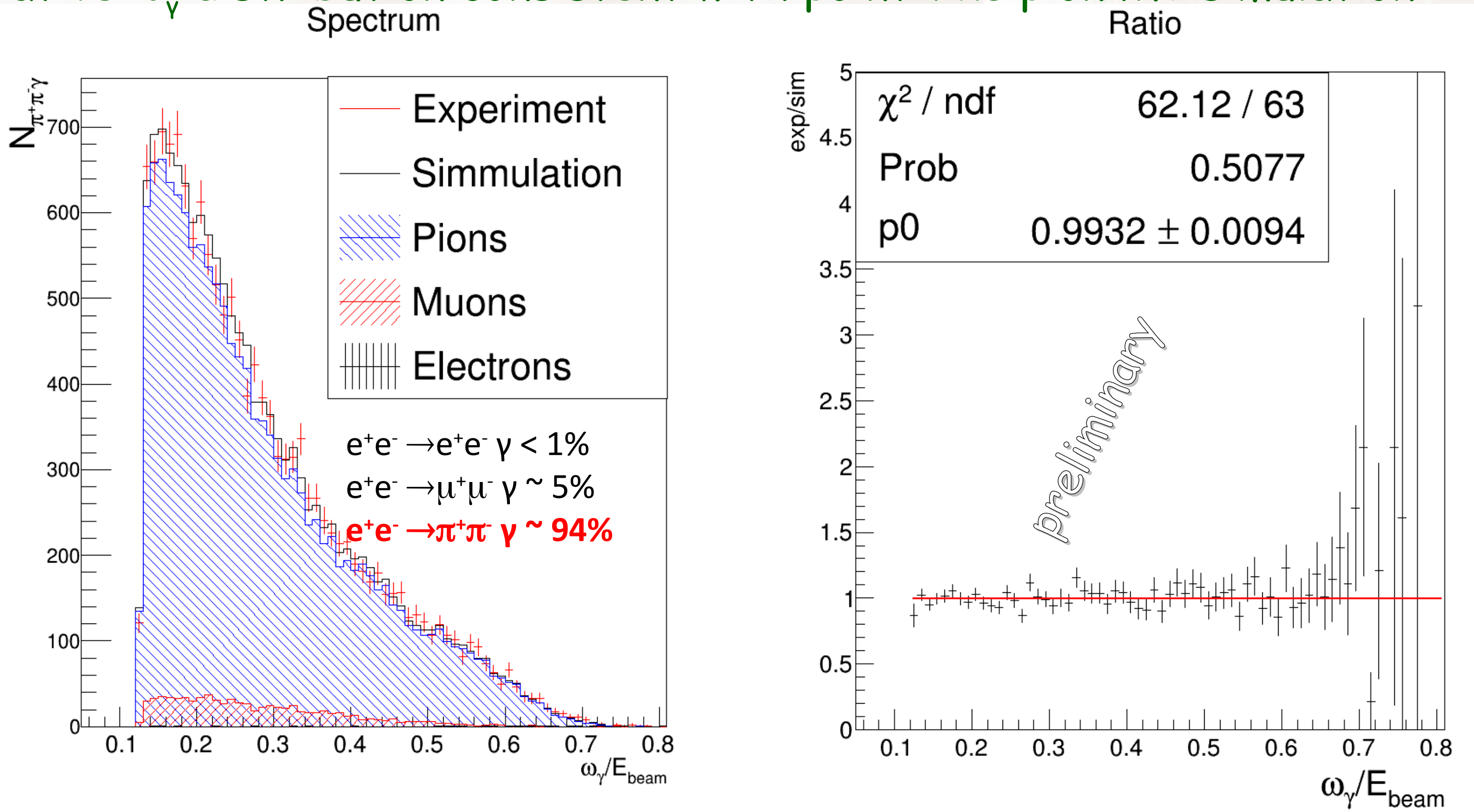
For some sources of systematics there is clear way how to bring it down

e+e- -> π+π-γ

By selection non-collinear 2 tracks events,
+suppression of bhabha by energy deposition
It can be selected π+π-γ events with detected photon

See poster by S.Tolmachev

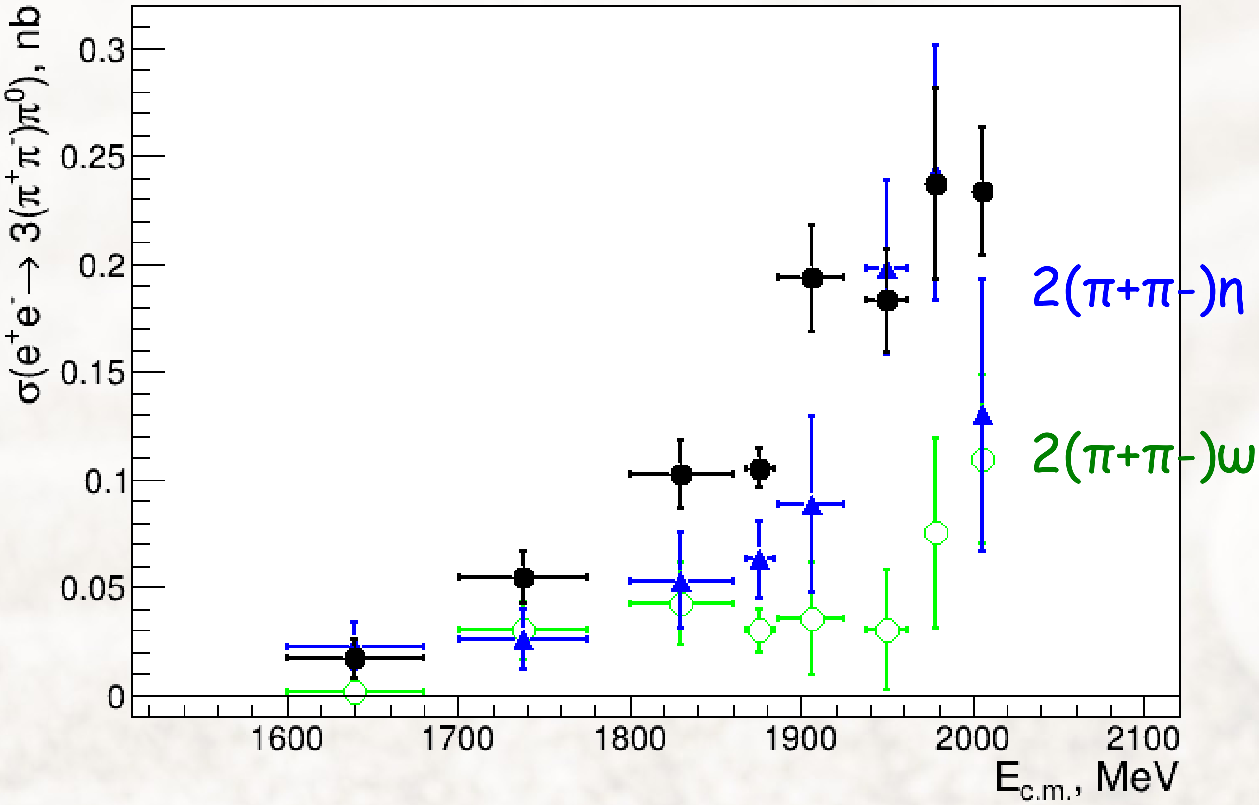
Radiative ω_γ distribution consistent with point-like pion MC simulation

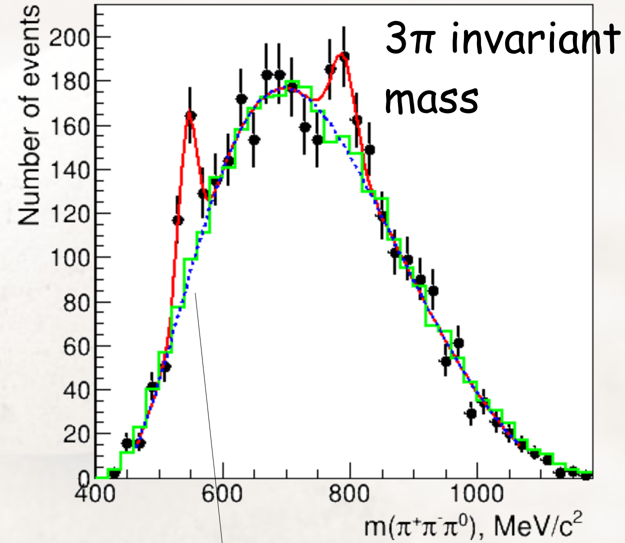


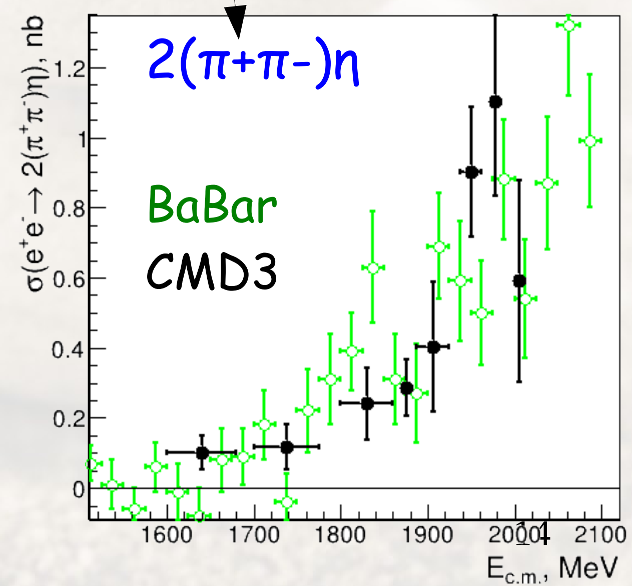
$e^+e^- \to 3(\pi^+\pi^-)\pi^0$

First time measurement of total cross-section

$4\pi\eta, 4\pi\omega$ dominated







~1% of R(s) at 2 GeV

ArXiv:1902.06449
Submitted to Phys.Letters B

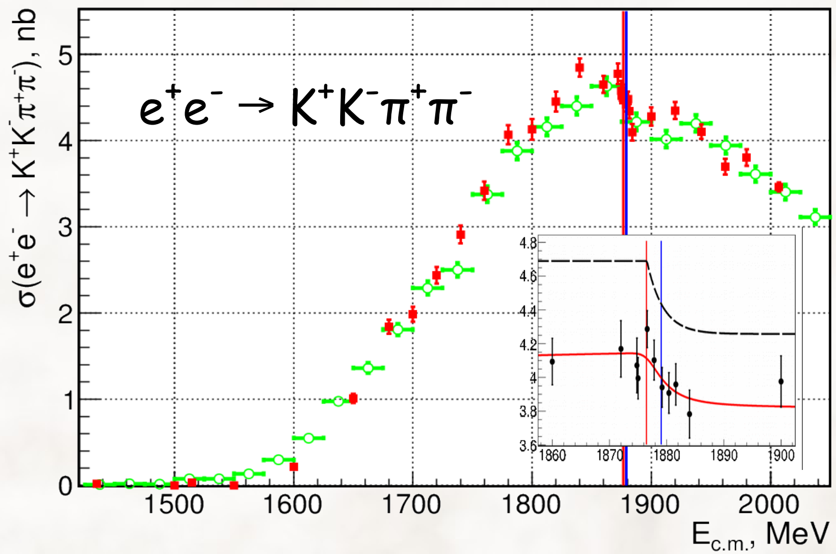
Multihadrons production at NN

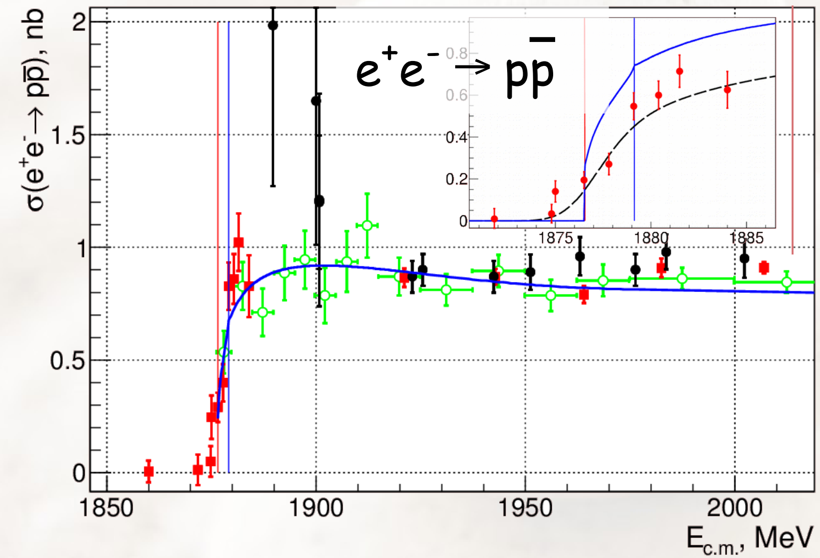
We did detail scan of $N\bar{N}$ threshold region

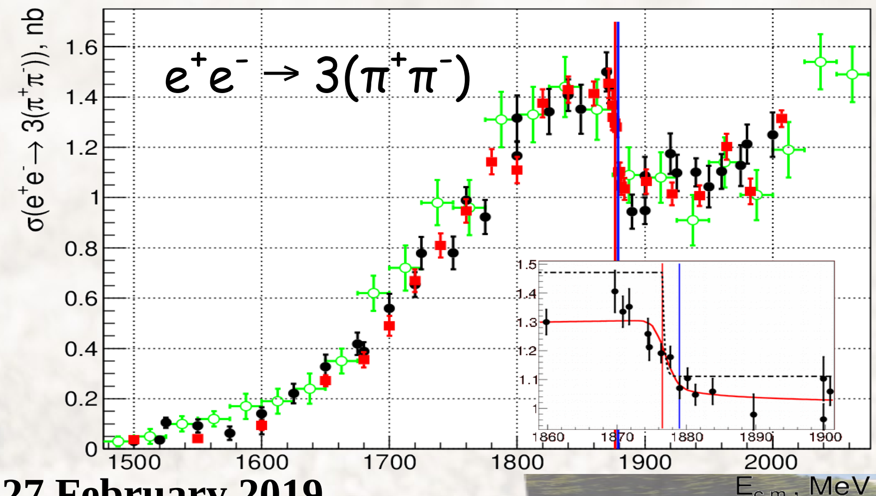
Seen many dip structures in multihadron production

See talk on Thursday by E.Solodov

arXiv:1808.00145







Can be described via optical nucleon-antinucleon potentials (most advanced "Milstein-Salnikov" parametrization)

Some questions still opened, for example:

Why no structure in e+e- → 2(π+π-),

but KK2pi effect is stronger

than expected as seen in $p\bar{p}$ anihilation

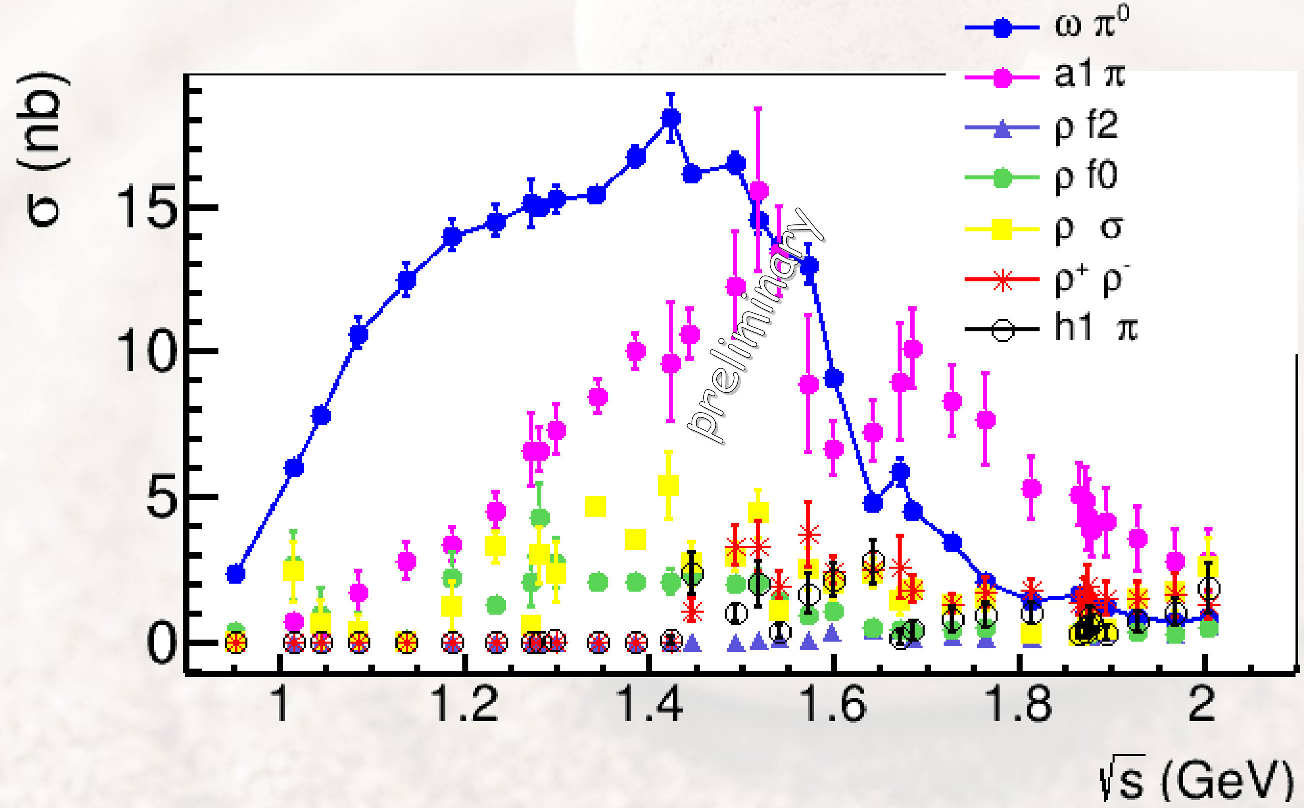
Dynamics in 4π

See talk on Friday by E.Kozyrev

Production of e+e- → $\pi^+\pi^-2\pi^0$, $2(\pi^+\pi^-)$ can be via many intermediate states:

- $\omega[1^{--}]\pi^0[0^{-+}]$
- $a1(1200)[1^+]\pi[0^-]$
- $\rho[1^{--}]f_0/\sigma[0^{++}]$
- $\rho f_2(1270)[2^{++}]$
- $\rho^+\rho^-$
- $a_2(1320)[2^{++}]\pi$
- $h_1(1170)[1^{+-}]\pi^0$
- $\pi'(1300)(0^{-+})\pi$

Detail amplitude analysis was performed



Search for e +e − → D0*

<u>**We are trying to probe also charm-physics**</u>

See poster by D.Shemyakin

motivation

A. Khodjamirian et al, JHEP11(2015)142 :

SM: Br(D^* → e^+e^-) >= $5. \times 10^{-19}$

New Physics with Z' : Br(D^* → e^+e^-) < 2.5×10^{-11}

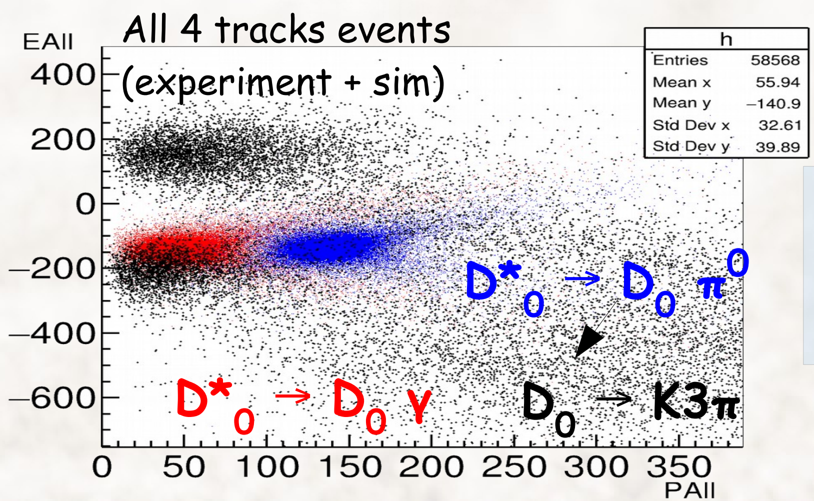
They did estimation

for e+e- collider with $\int L = 1fb^{-1}$: Br(D^* → e^+e^-) > 4×10^{-13}

But, they didn't take into account 10^2 - 10^4 factor: detection efficiency and beam energy spread

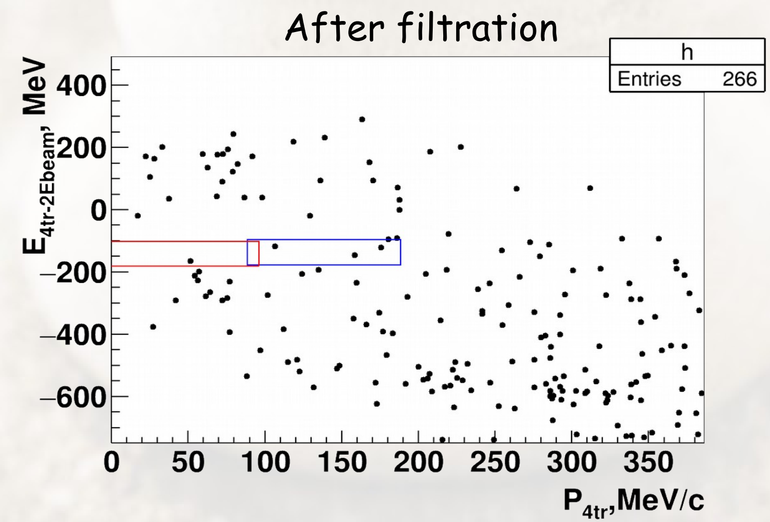
<u>VEPP-2000 was able to jump above 2 GeV design machine limit:</u>

<u>At 2017 scan: E=2007 МэВ, L=3.4 пb^{-1}</u>



Likelihood of K3π (dE/dX,p)
Ks filtration

1./500 bg suppression

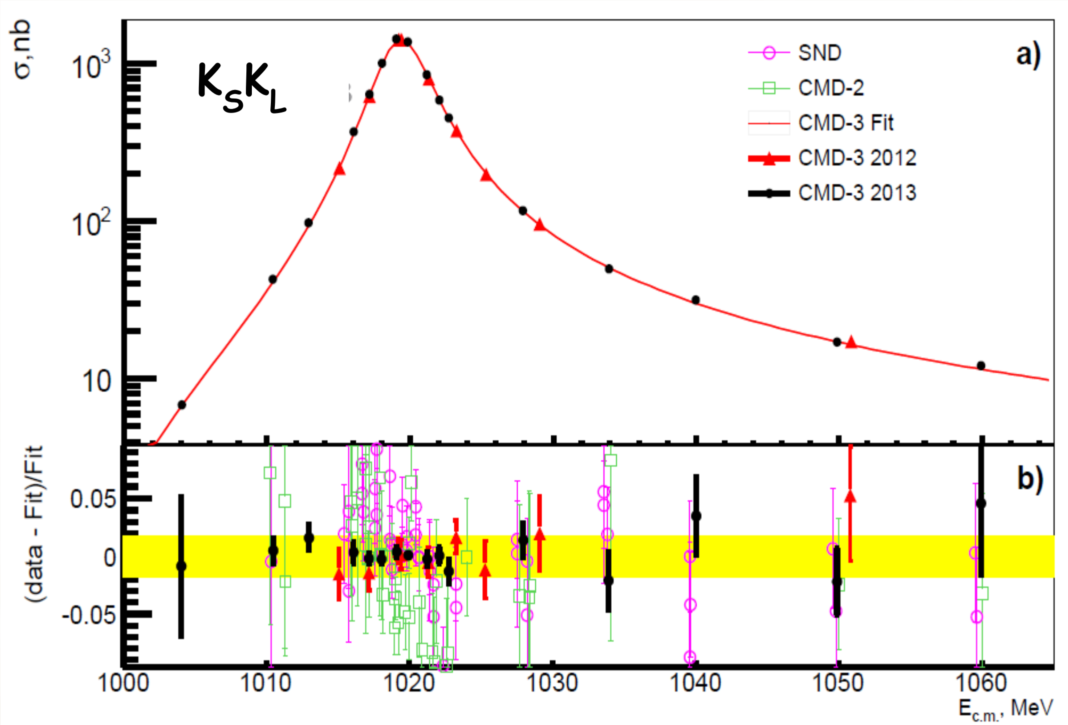


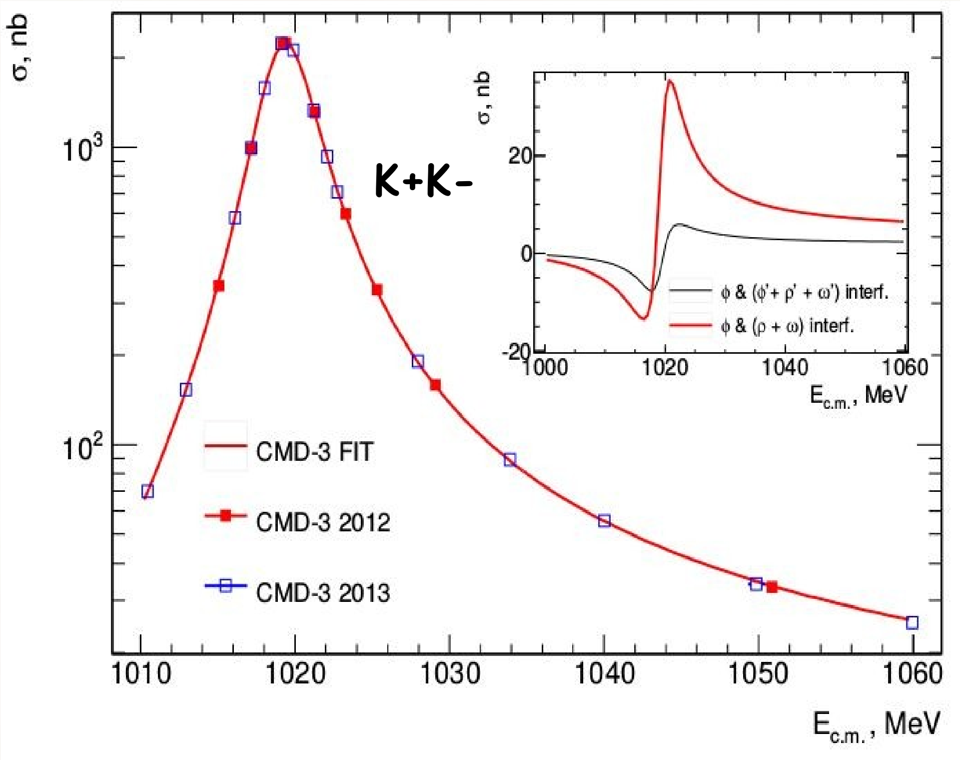
$D^*_0 \to D_0 \gamma$: Br(D^*→ee) < $5.2 \cdot 10^{-6}$

$D^*_0 \to D_0 \pi^0$: Br(D^*→ee) < $1.7 \cdot 10^{-6}$

First time UL measurement

e+e- -> K$\bar{K}$

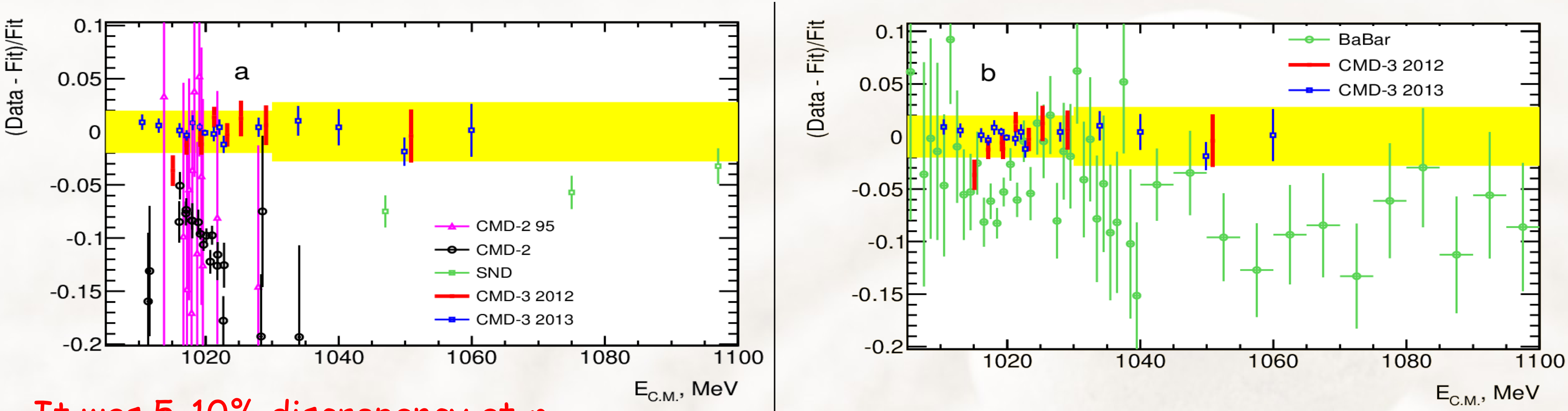




CMD3: KsKl at φ - Best systematic precision 1.8% Phys.Lett. B760 (2016) 314

K+K- - syst 2% Phys.Lett. B779 (2018) 64-71

φ → K+K- comparison between experiments



<u>It was 5-10% discrepancy at φ</u>

Between CMD-2 (2.2% systematic) CMD2 underestimated trigger inefficiency for slow K+K-

SND at VEPP-2M (7.1%)

with BaBar data (0.72%)

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

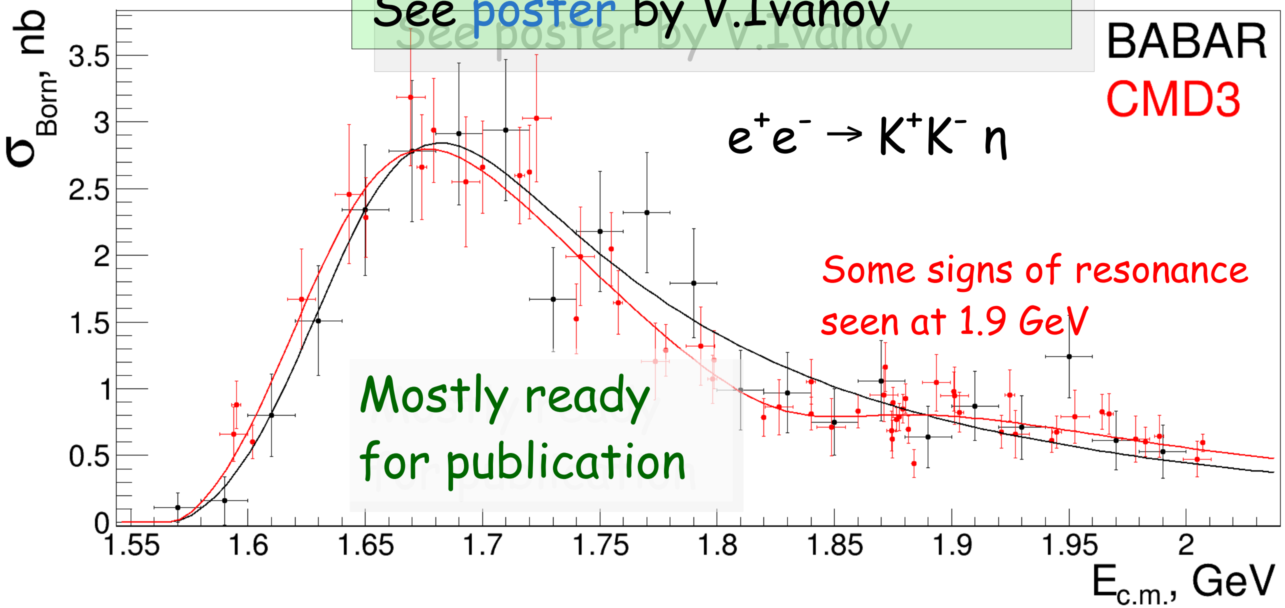
but it is in consistency with isospin symmetry:

$$R=\frac{g_{\phi K+K-}}{g_{\phi K_S K_L}\sqrt{Z(m_\phi)}}=0.990\pm0.017$$

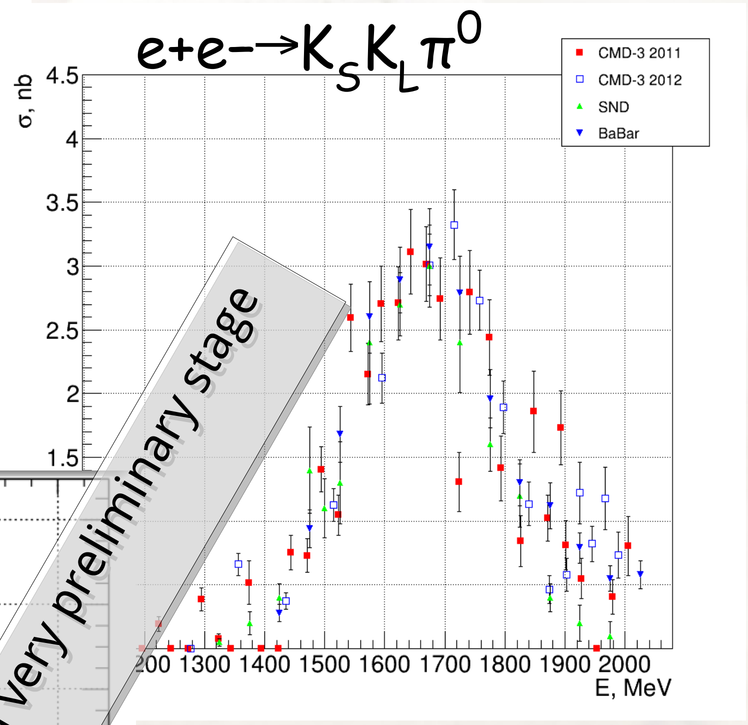
- $R_{SND} = 0.92 \pm 0.03 (2.6\sigma)$
- $R_{CMD-2} = 0.943 \pm 0.013 (4.4\sigma)$
- $R_{BaBar} = 0.972 \pm 0.017 (1.5\sigma)$

KKpi KKeta

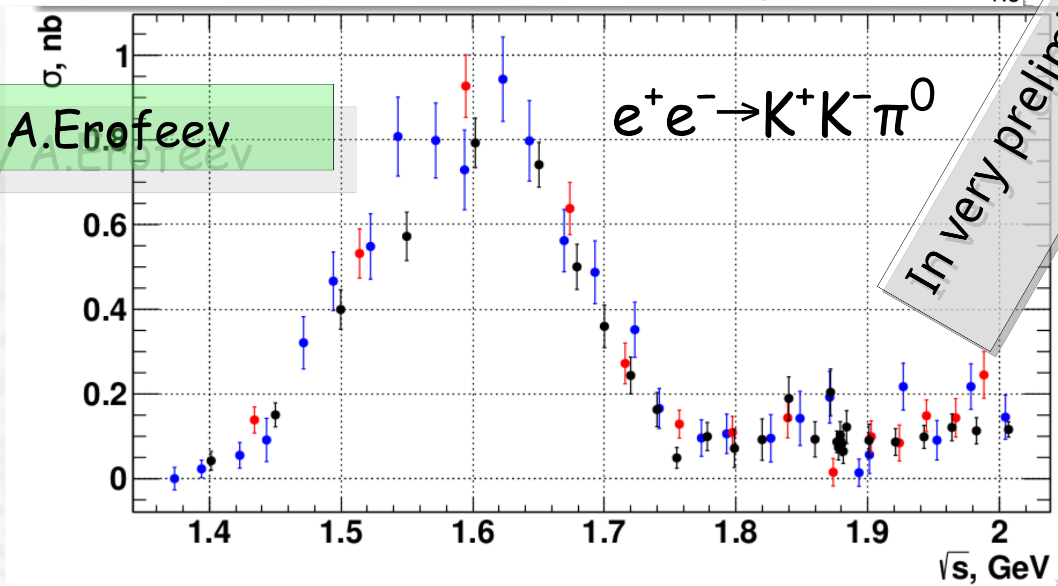
See poster by V.Ivanov



See poster by S.Semenov



See poster by A.Erofeev



Conclusion

- Precise low-energy e^+e^- hadronic cross section data are needed to obtain an accurate SM prediction for $a_\mu^{had,LO-VP}$, $\alpha_{QED}(M_Z)$

- 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.
- 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

- Several previously unmeasured processes contributed to the total hadronic cross section ($e^+e^- \to \eta\pi^+\pi^-\pi^0$, $3(\pi^+\pi^-)\pi^0$) below 2 GeV have been studied.
- We have goal to collect O(1) 1/fb in 5 years,

  which should provide new precise results on the hadron production

Talks and poster from CMD3 at PhiPsi19

An amplitude analysis of the e+e–→4π reaction	Mr. Evgeny KOZYREV
The NNbar and multihadron production at the threshold at VEPP2000	Prof. Evgeny SOLODOV
Identification of the e+e-→n anti-n events in CMD-3 detector	Mr. Artem AMIRKHANOV
Luminosity measurement with the CMD-3 detector	Artem RYZHENENKOV
STUDY OF PRODUCTION OF FOUR CHARGED PIONS WITH CMD-3 DETECTOR AT VEPP-2000 COLLIDER	Mr. Alexandr KOROBOV
Search for the process e+e- -->D*0(2007) with the CMD-3 detector	Mr. Dmitry SHEMYAKIN
Study of the e+e– → π+π–γ process at the CMD - 3	Sergey TOLMACHEV
Study of the process $e^+e^- \to K^+K^-\pi^0$ with the CMD-3 detector	Mr. Andrei EROFEEV
Study of the process $e^+e^-{\to}K^+K^-\eta$ with the CMD-3 detector at VEPP-2000 collider	Mr. Vyacheslav IVANOV
Study of the process e+e- to KS KL pi0 up to 2 GeV with CMD-3 detector	Mr. Semenov ALEKSANDR

Exclusive channels under analysis

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

- ✔ 2 charged

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

- ✔ 2 charged + γ 's

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

- ✔ 4 charged

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

- ✔ 4 charged + γ's

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

- ✔ 6 charged

  e+e- → $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$

- ✔ γ 's only

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

- ✔ other

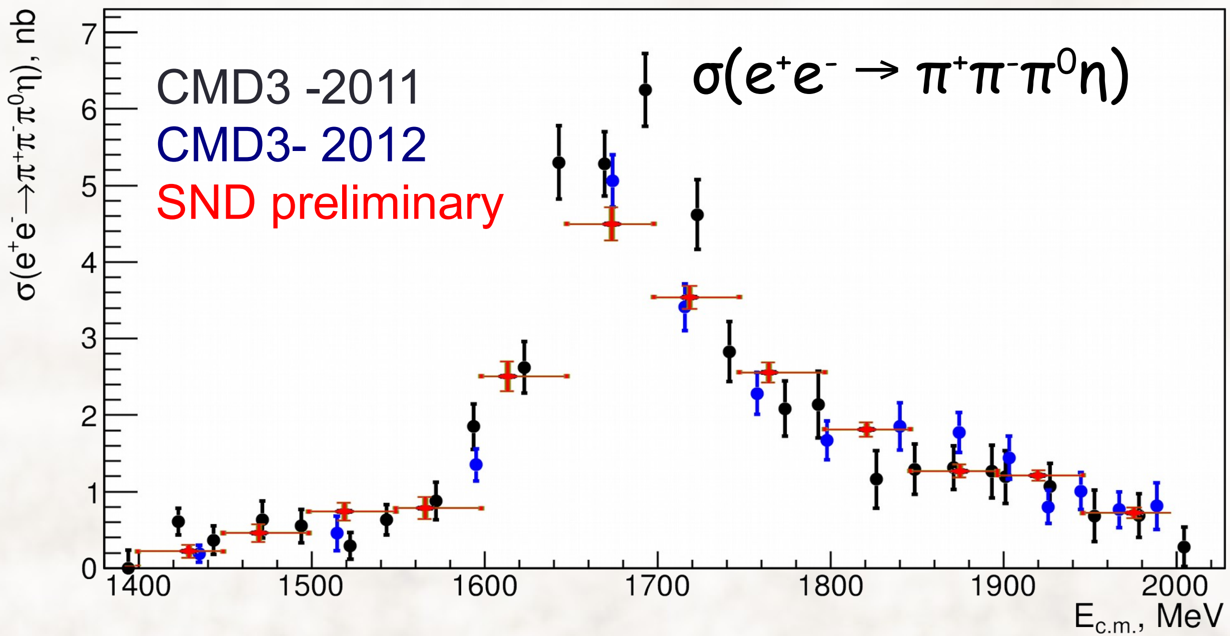
  e+e- → $n\bar{n}$, π^0e+e-, ηe+e-

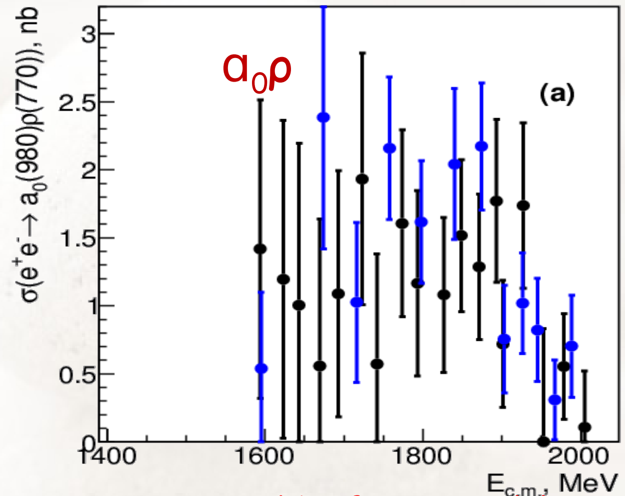
$e^+e^- \to \pi^+\pi^-\pi^0\eta$

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

Systematic error is 11%.

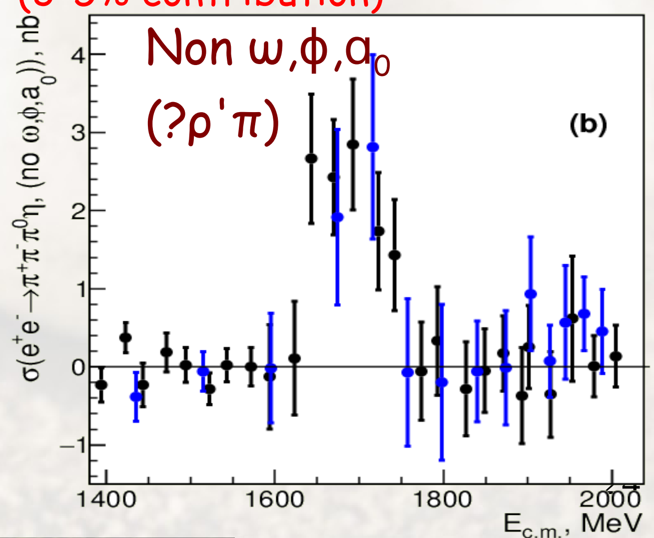
Phys.Lett. B773 (2017) 150-158,arXiv:1706.06267v3





Not accounted before in R(s)

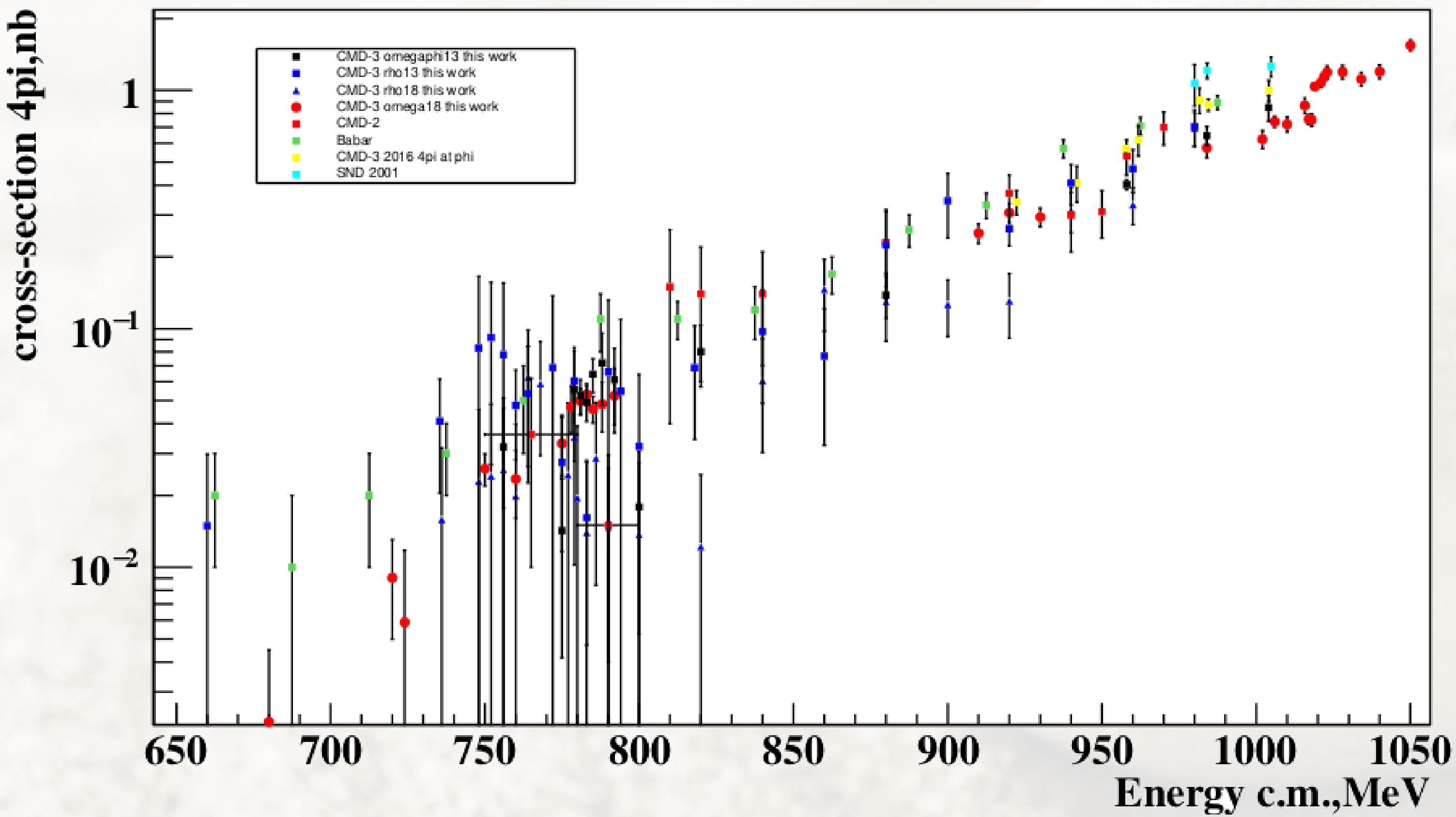
(3-5% contribution)



- 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 $a_0\rho$

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

See poster by A.Korobov



SM prediction for muon g-2

Experimental world average

a_μ = 11 659 208.9 ± 6.3 x 10^{-10}

Theoretical prediction

δa_μ = ± 3.6 x 10^{-10} (KNT 18)

Hadronic content of a_μ calculated

From measured cross-section by dispersion integral

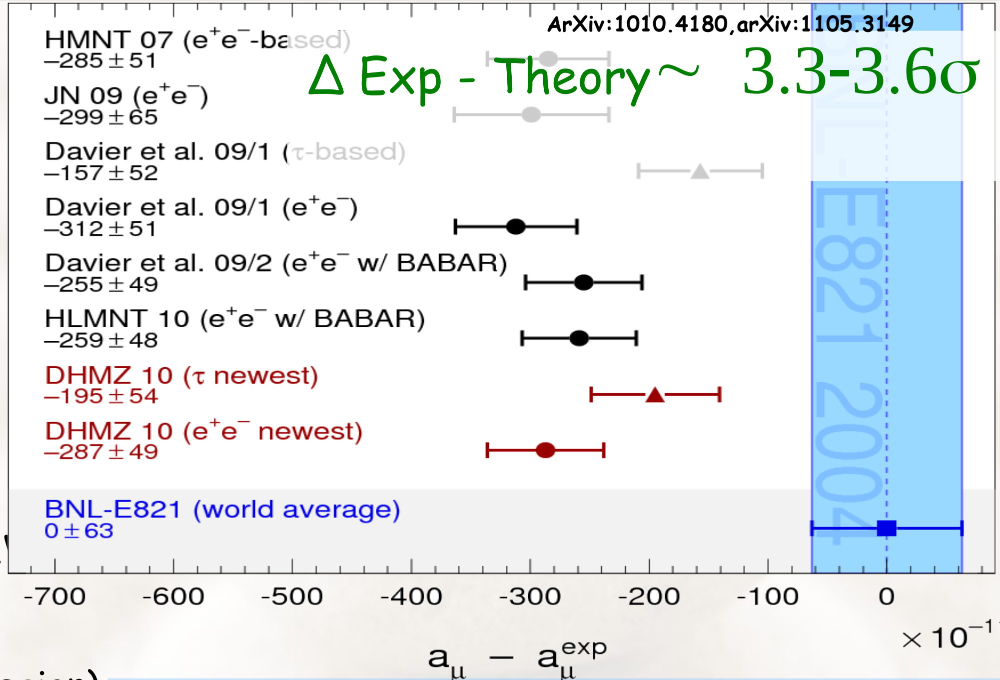
LO hadronic 693.27 ±2.46 x 10^{-10} KNT 18

main channels contribution to precision at √s<1.937 GeV

$\pi^+\pi^-$	502.97 ± 1.97
$\pi^+\pi^-\pi^0$	47.79 ± 0.89 (mostly from omega region)
$\pi^+\pi^-2\pi^0$	19.39 ± 0.78
K+K-	23.03 ± 0.22
.....	
Inclusive(√s<1.937 GeV)	43.67 ± 0.67

Light-by-light 9.8 ± 2.6 need more theory input, with help of experimental transition form factors

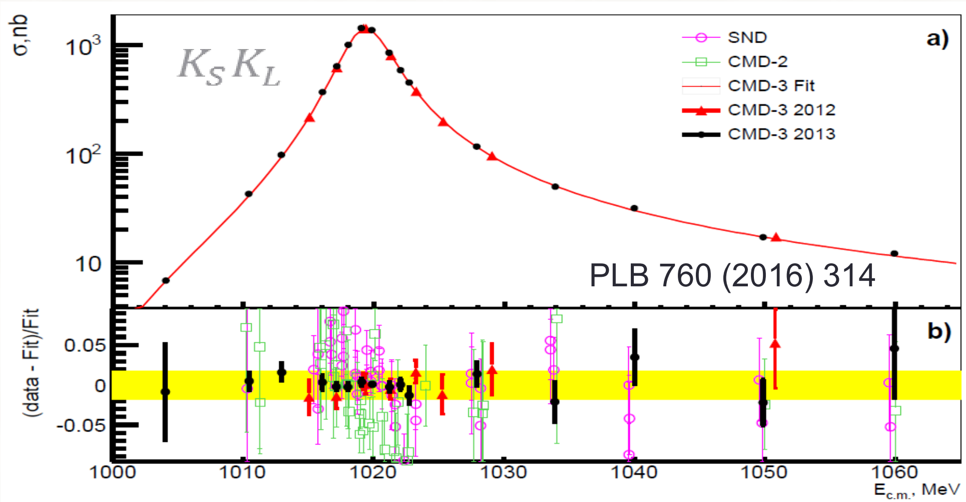
Δ Exp - Theory ~ 3.3-3.6σ

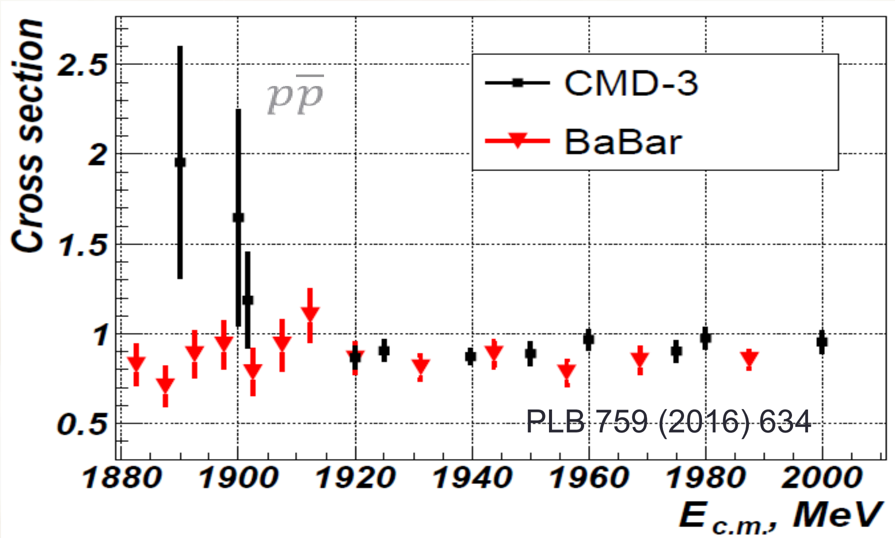


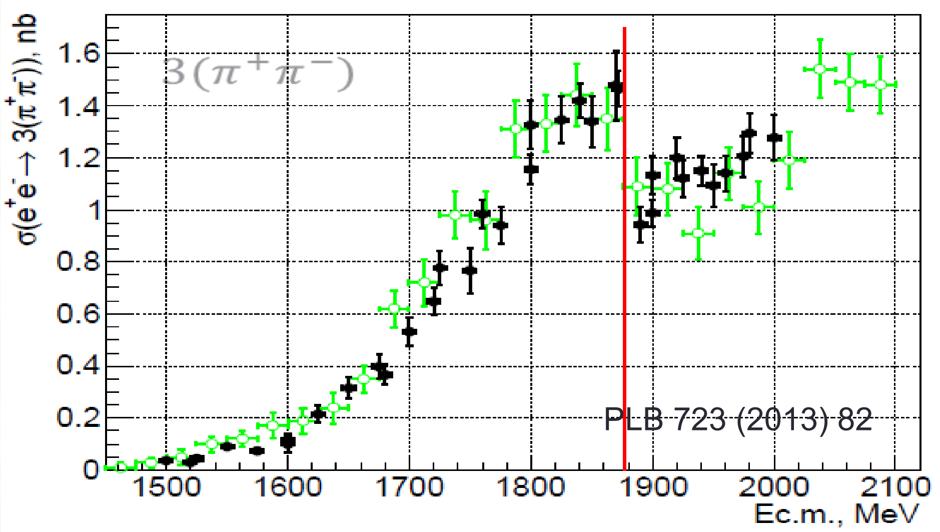
New g-2 experiments at FNAL and J-PARC have plans to reduce error to **1.5x10^{-10}**

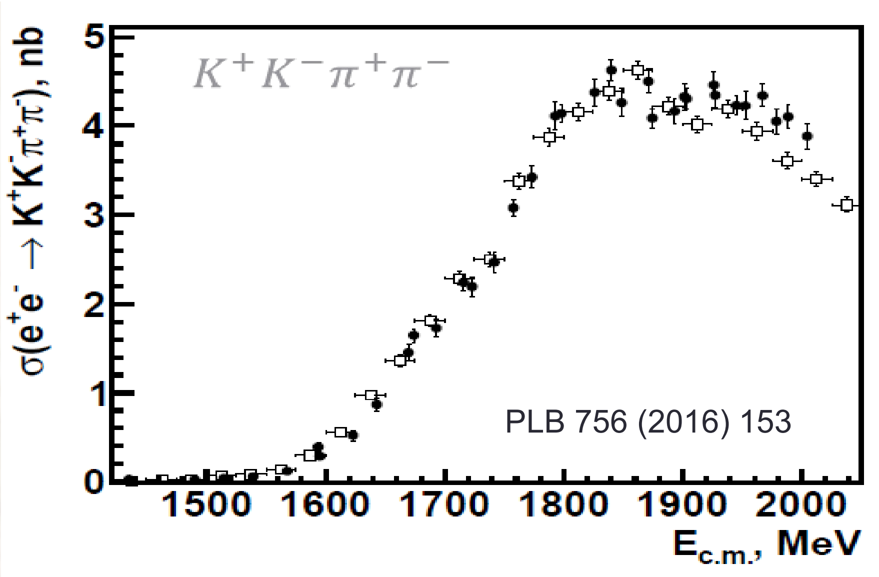
The value and the error of the hadronic contribution to muon (g-2) are dominated by low energy R(s) (<2GeV gives 93% of the value). $\pi^+\pi^-$ gives the main contribution (73%) to a_μ

Published results from 2011-2013: CMD-3







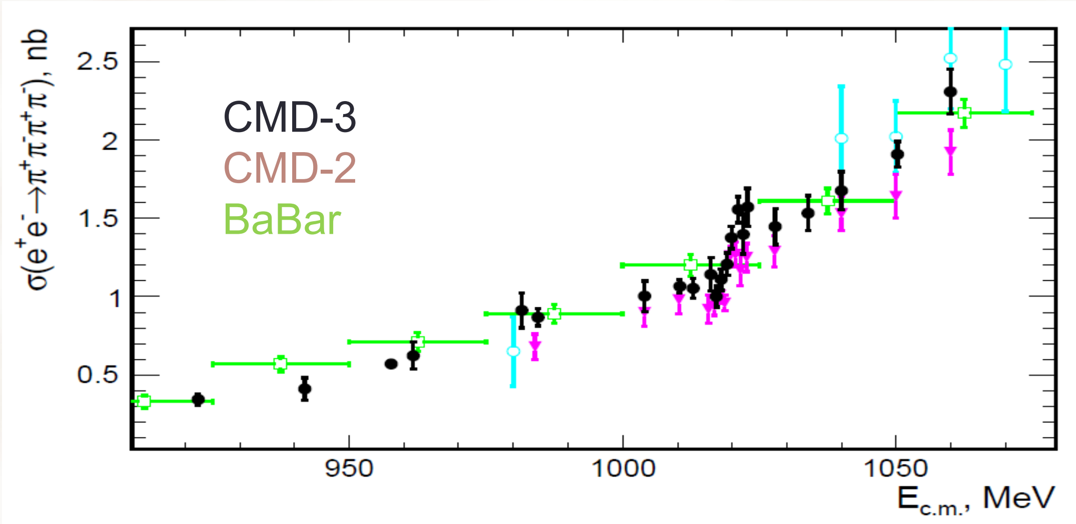


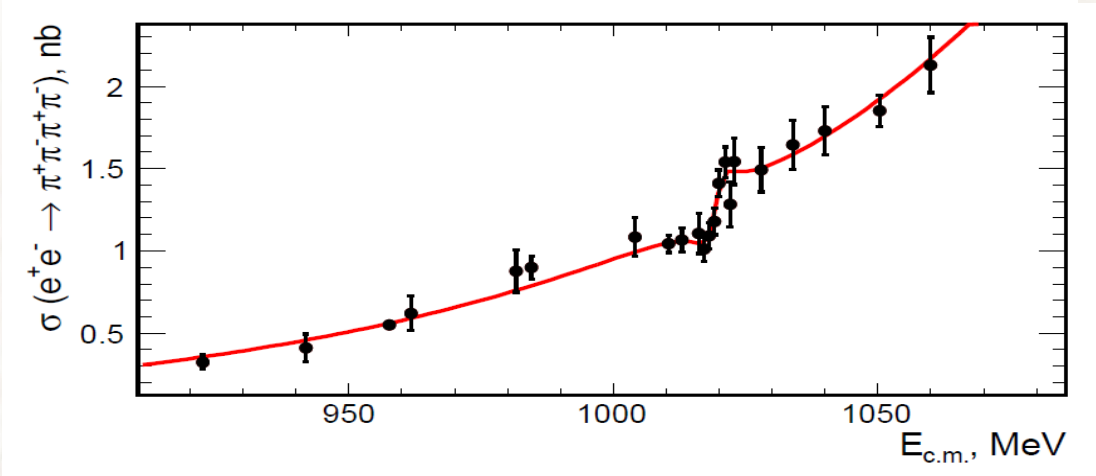
e+e- → π+π-π+π- @φ(1020)

PLB 768 (2017) 345-350

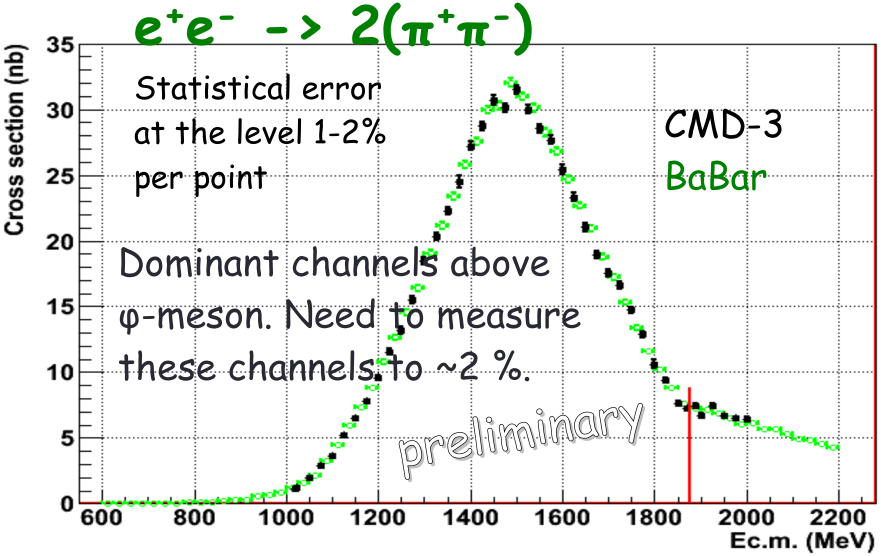
2011-2013 data, 10 1/pb
systematic error 3.5%

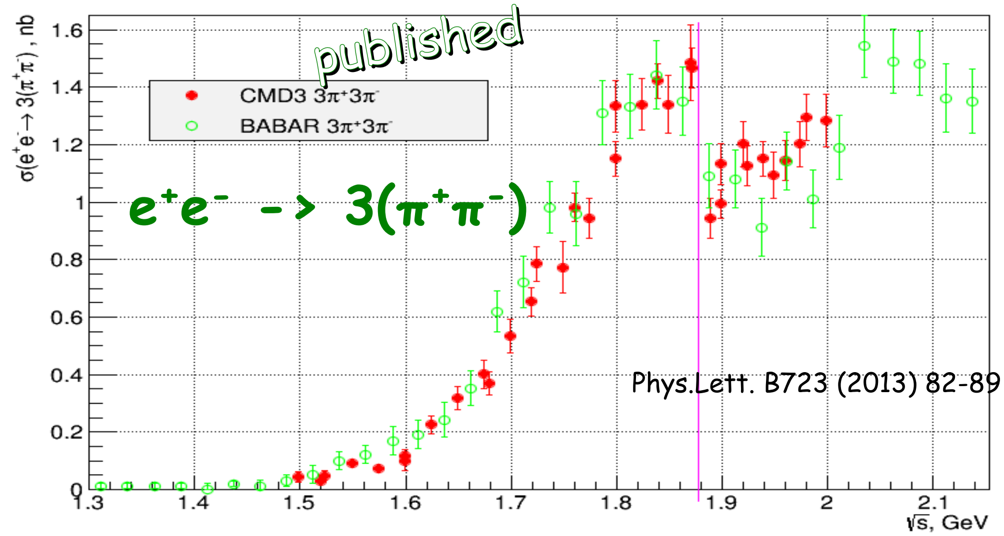
$$B(\varphi \to 2(\pi^+\pi^-)) = (6.5 \pm 2.7 \pm 1.6) \times 10^{-6}$$

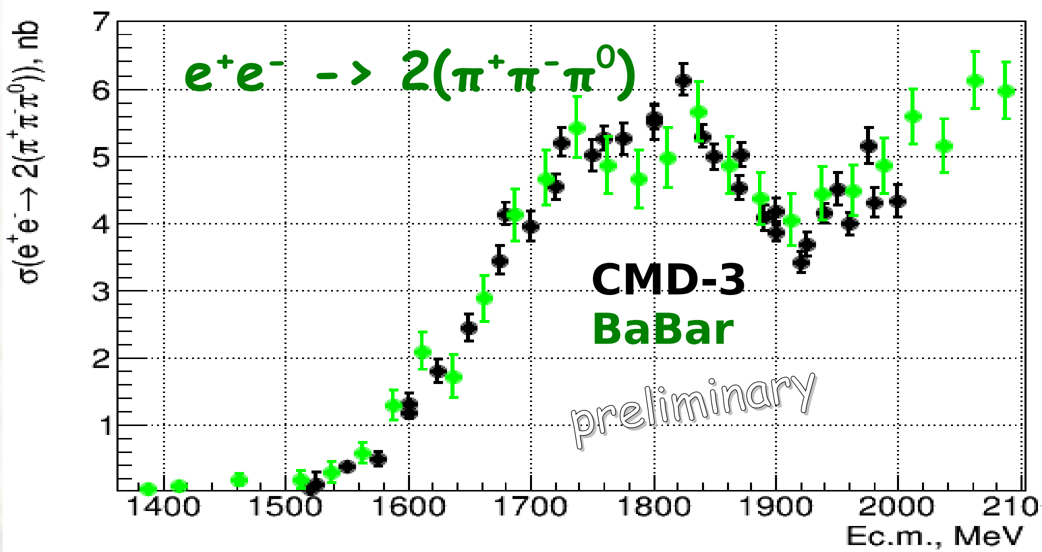




e+e- -> many pions with CMD-3







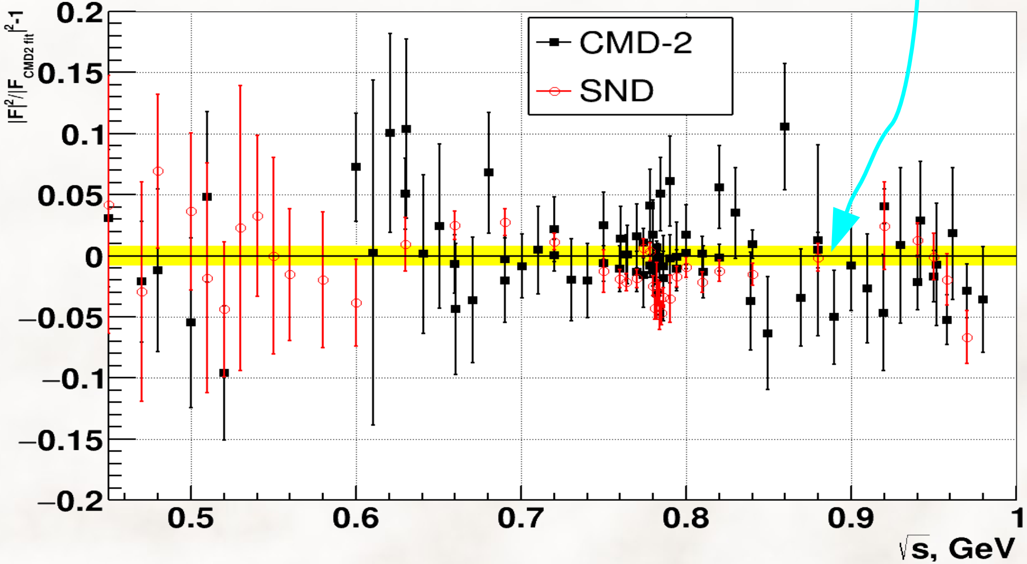
The dominated source of systematic error is model uncertainty(evaluation of the detector acceptance)
High statistics allows for more accurate study of the intermediate dynamics.

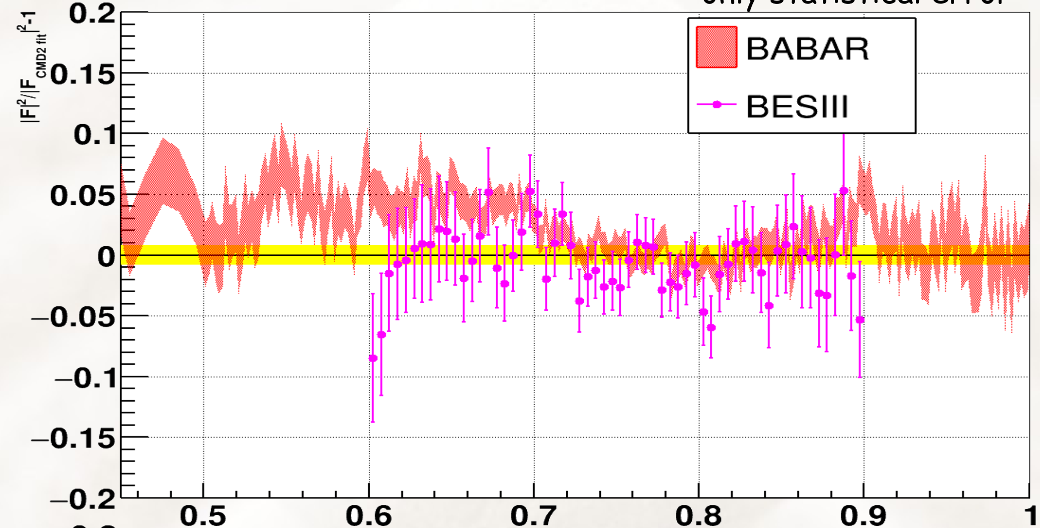
$3(\pi^+\pi^-)$ are mainly produced through $\rho(770)$ + 4π (in phase space or f_0)
Seen change of dynamics in 1.7-1.9 GeV range
Interesting feature: sharp dip at $p\bar{p}$ threshold
(dip in sum of 6π roughly as $p\bar{p}+n\bar{n}$ cross section)

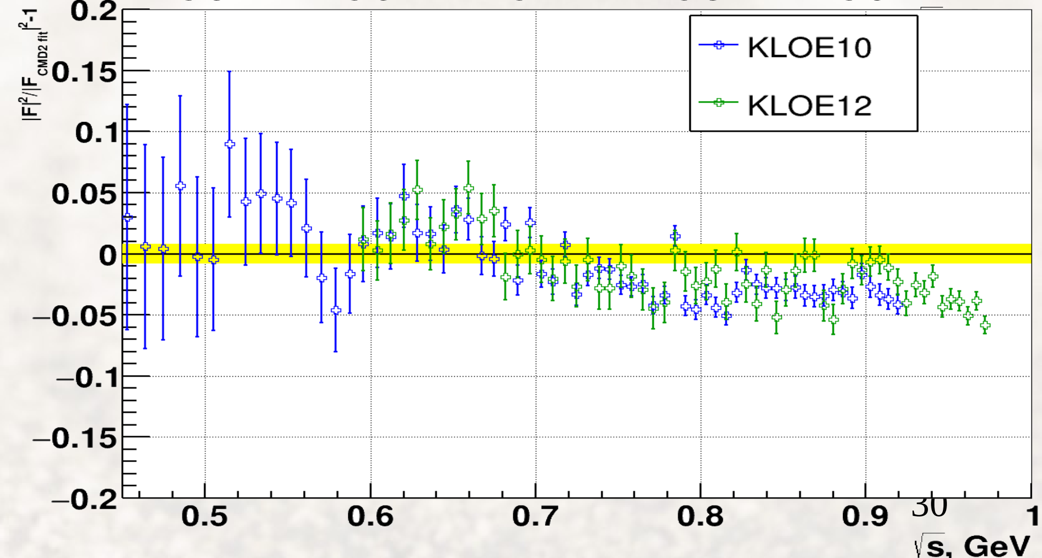
Comparison of e+ e− → π+ π− cross-section

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

Points, red band: only statistical error







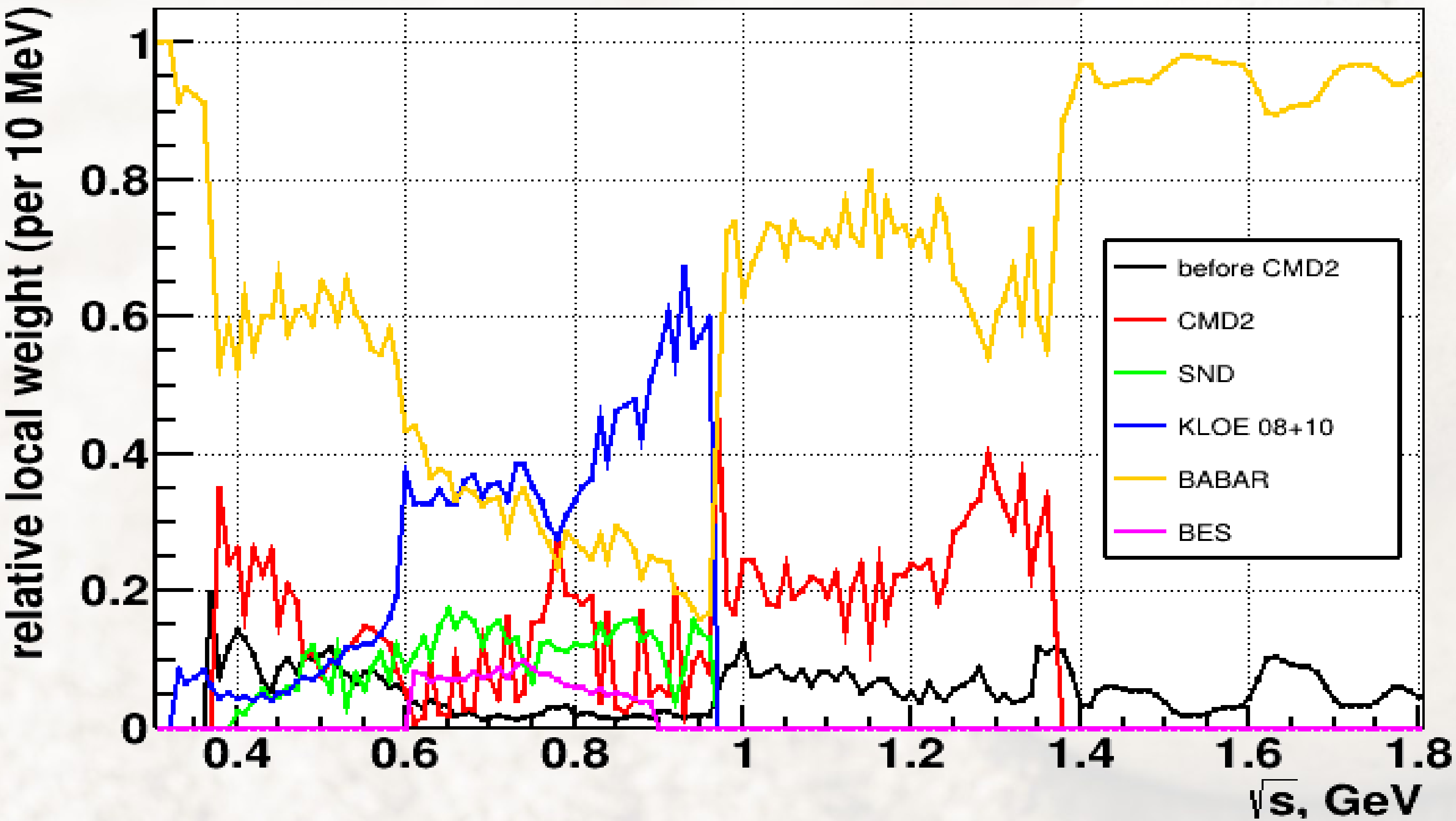
In integral, there is reasonable agreement between existing data sets

But there are local inconsistencies larger than claimed systematic errors

→ additional scale factor for error of integral value

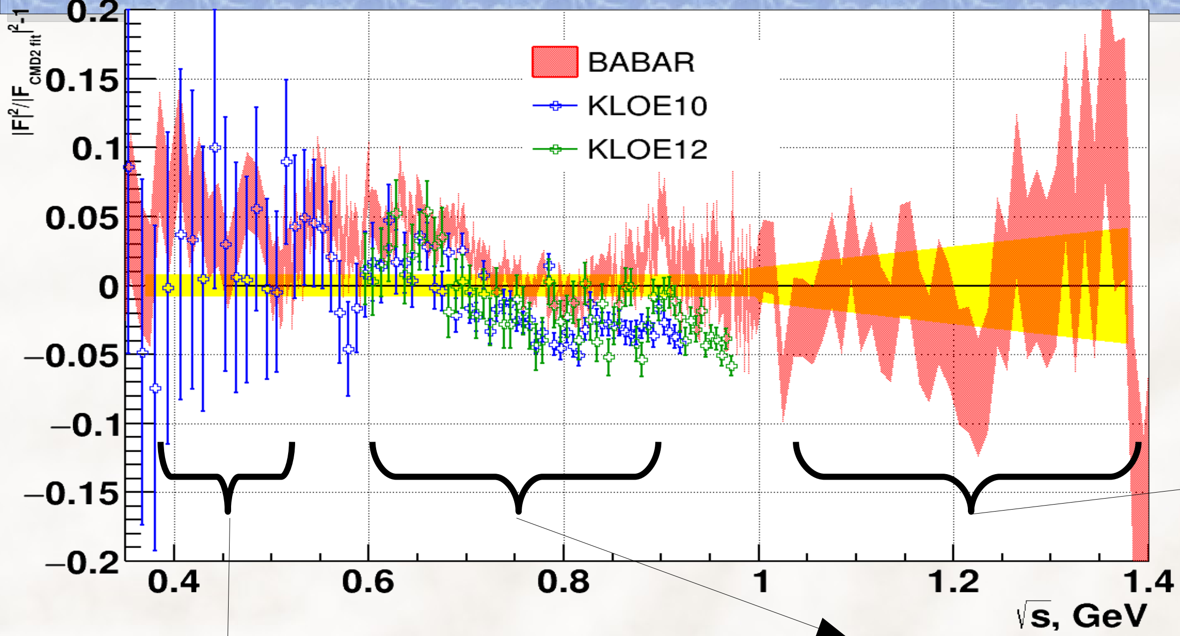
Relative local weight of different experiments in π+π-

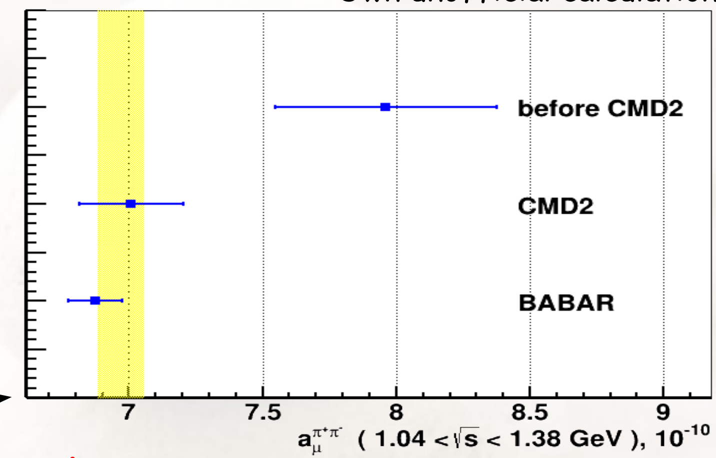
Nowadays the π+π- data is statistically dominated by ISR(KLOE, BaBar)



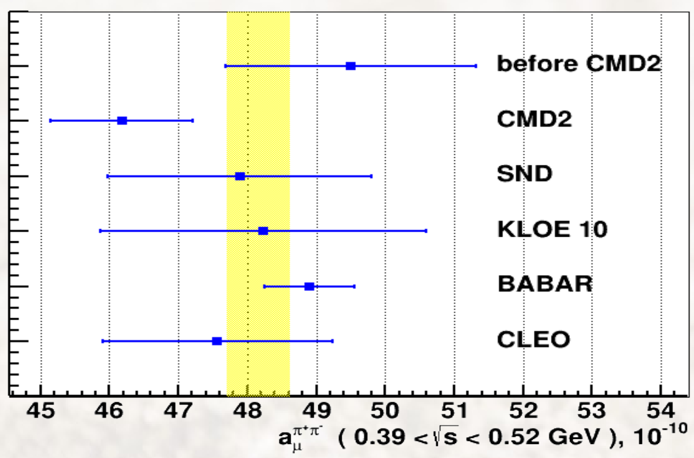
Locally precision is limited by statistic

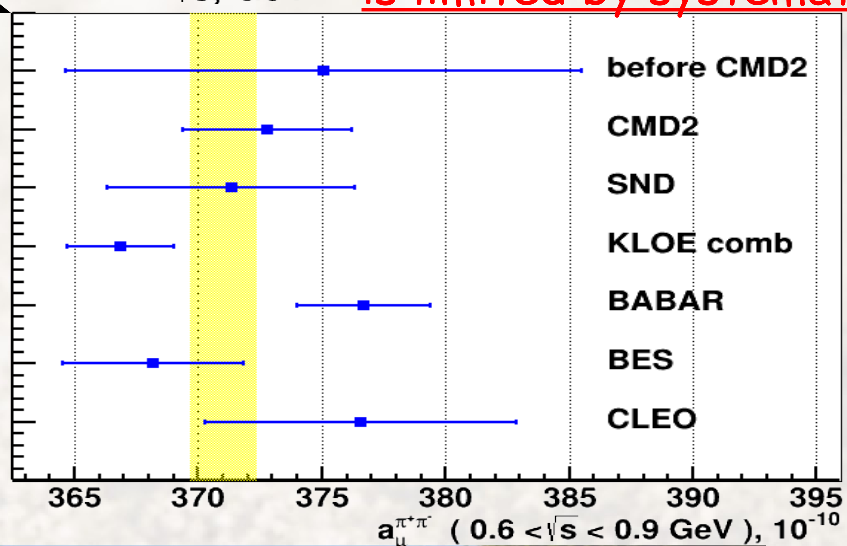
The π+ π− contribution to a_μ^{had}





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%
CLEO: 1.5%

MC generator, MCGPJ

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

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

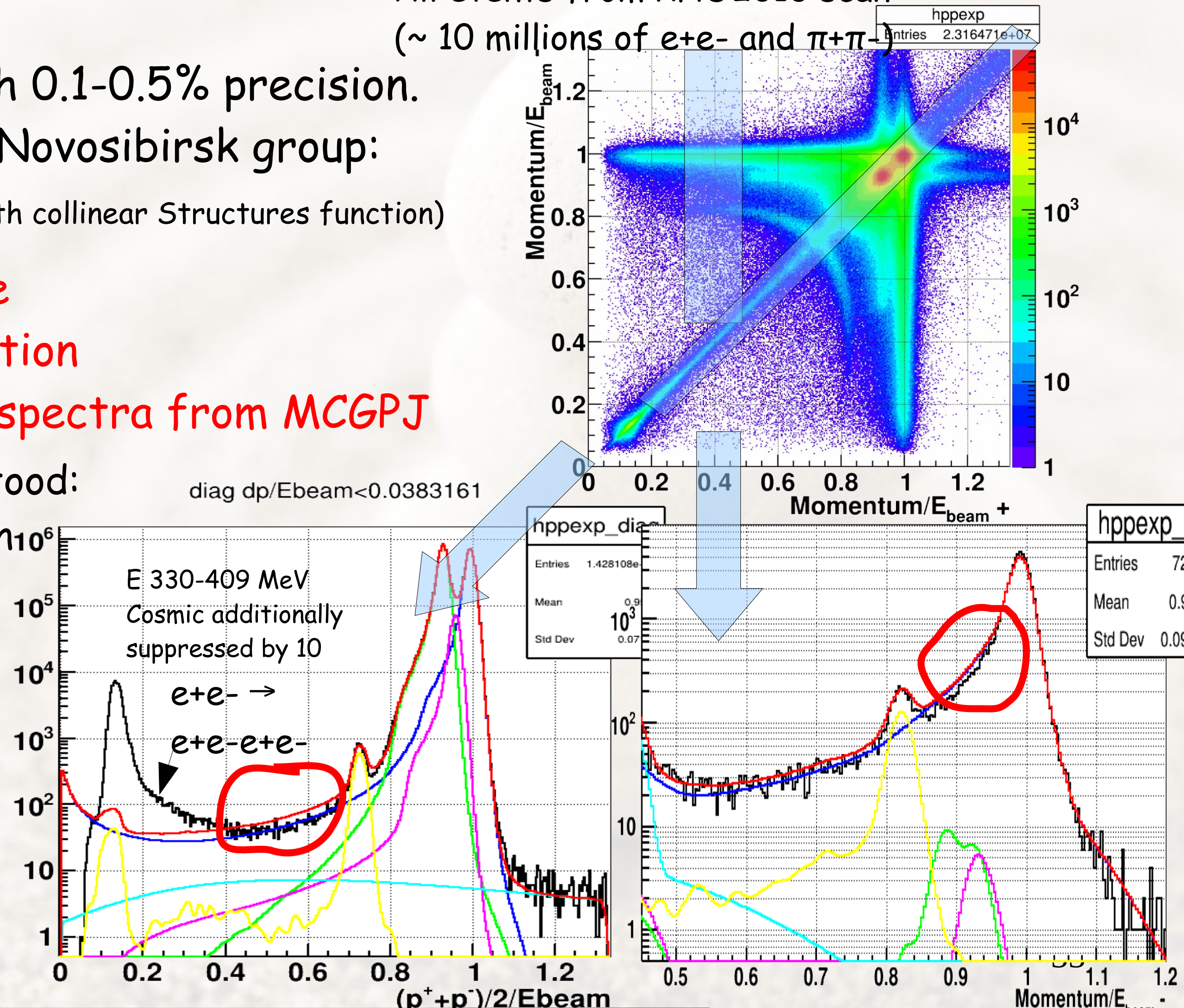
The source of the discrepancy is understood:
also important γ jets angular distribution

Several steps for upgrading MCGPJ
were done.

But still some question under inspection

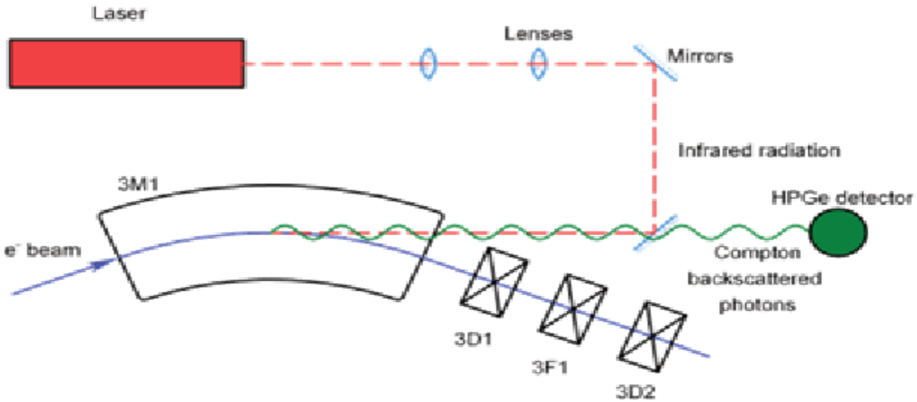
<u>Exact e+e-→e+e-(γγ) NNLO generator</u>
<u>will help to solve all our doubts</u>
<u>(and to go below <0.1% precision)</u>

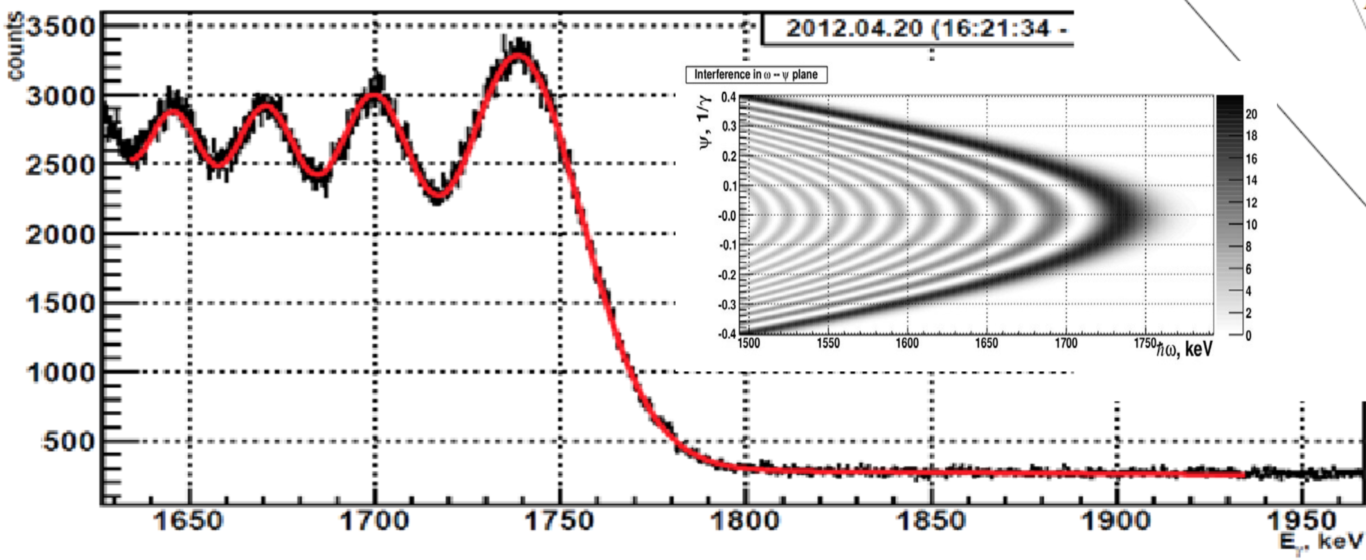
All events from RHO2013 scan
(~ 10 millions of e+e- and π+π-)



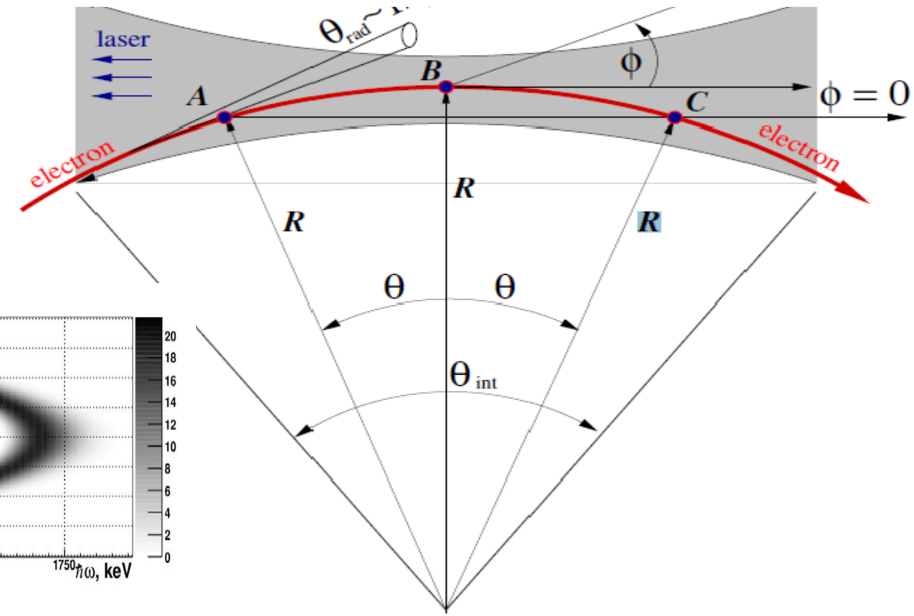
Energy measurement by Compton back scattering

Starting from 2012, energy is monitored continuously using compton backscattering





Interference of photons from A and B

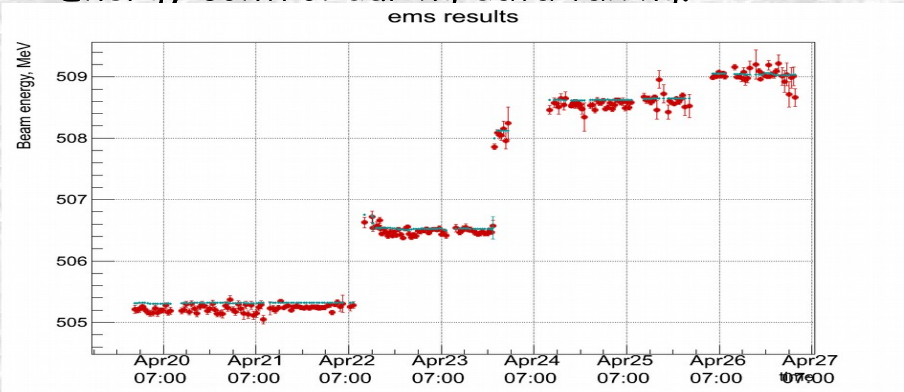


E = 993.662 ± 0.016 МэВ

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 δE/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 δE/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 δE/E < 10^{-5}
  - Very high accuracy.
  - Special configuration of VEPP-2000: "warm" optics without CMD-3 field.

Methods comparison: