Measurements of the hadronic cross sections with the CMD-3 and SND detectors at the VEPP-2000 e+e- collider

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Motivation

Measurement of the cross section e+e- → hadrons in the low energy range is interesting for:

- measurement of parameters of light vector mesons ρ, ω, φ, ρ′, ρ″, ω′, ω″
- Test of QCD sum rules, ChPT, VDM, ... etc, search of exotics (light hybrids and glueballs)
- CVC test in comparison with spectral functions of tau decays

- measurement of R(s) :

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

it is essential for the interpretation of precision measurements of:

muon (g-2) - good test of SM

for calculation of:

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

(better precision in case of ILC physics needed)

SM prediction for muon g-2

ArXiv:1010.4180,arXiv:1105.3149

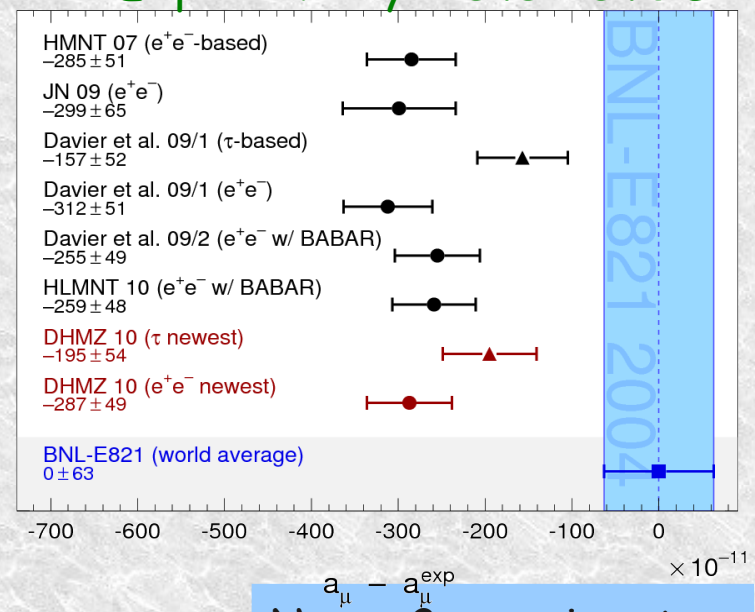
$a_\mu^{experimental} = (g-2)_\mu/2$

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

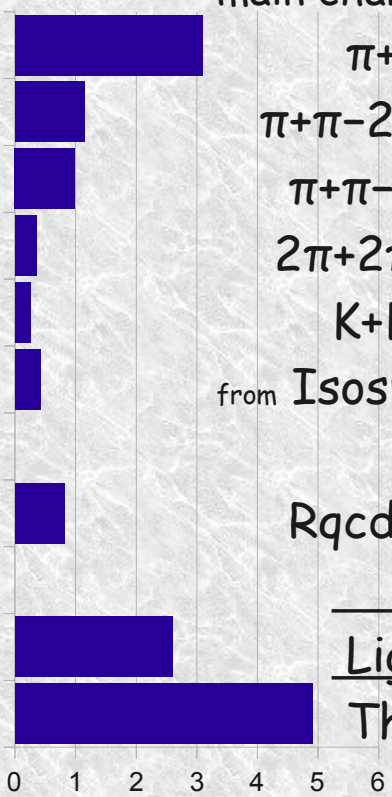
Δ Exp - Theory~ 3.3–3.6σ



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

From direct integration
Without model constraints

δa_μ



Hadronic contributions

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

main channels contribution to precision at √s<1.8 GeV

π+π−	505.65 ± 3.09	
π+π−2π0	18.62 ± 1.15	
π+π−π0	47.38 ± 0.99	(mostly from omega region)
2π+2π−	13.64 ± 0.36	(BaBar)
K+K-	22.95 ± 0.26	(BaBar)

from Isospin relations 5.98 ± 0.42 for not measured KKpi,KK2π,2π4π0,2π3π0

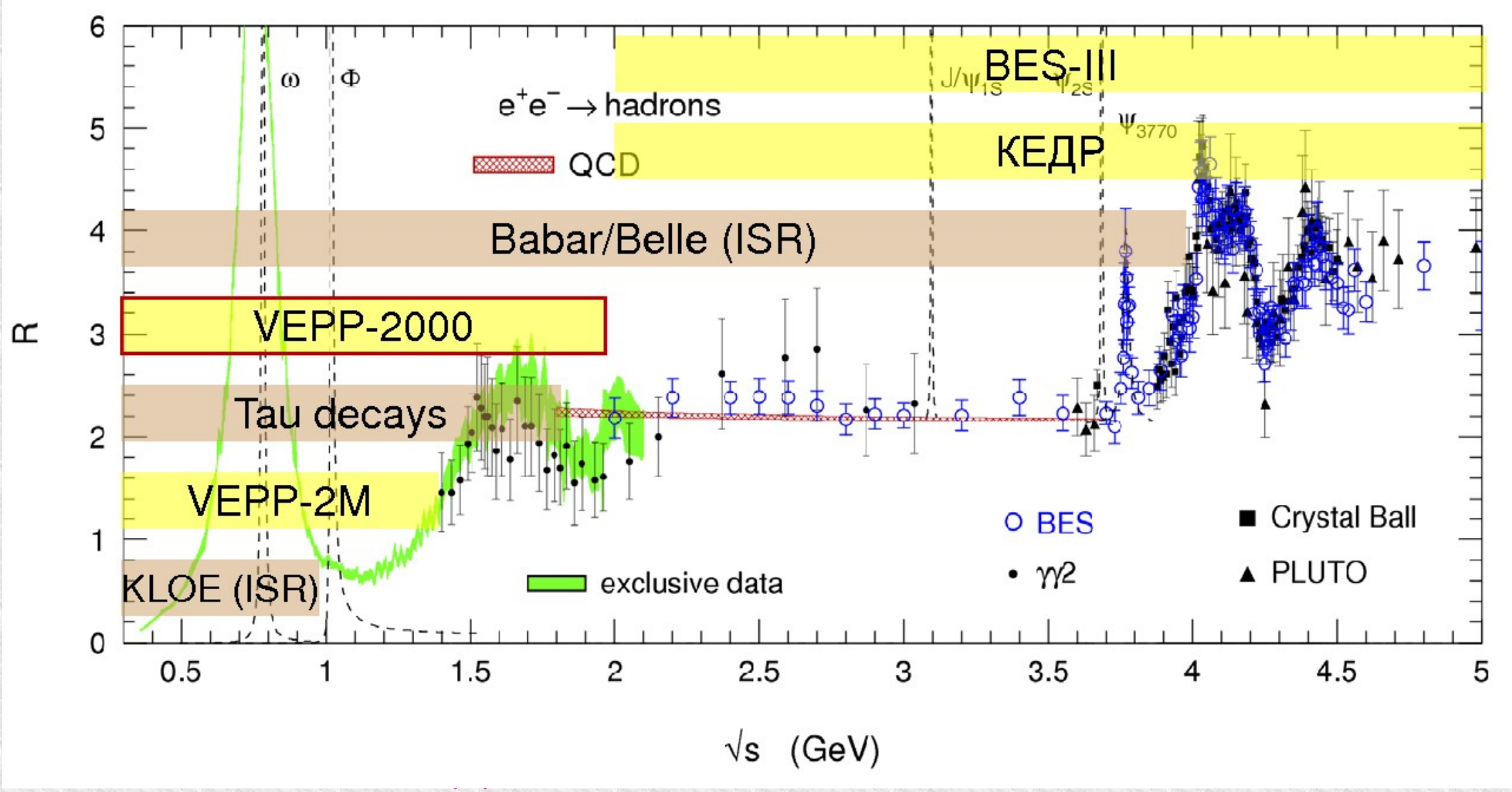
(or 12.46 ± 0.76 for √s<2 GeV) (1.5-3σ of total error - crucial in case of isospin violation)

Rqcd[2-11.09GeV] 41.19 ± 0.82

Light-by-light 10.5 ± **2.6** Prades, de Rafael & Vainshtein need more theory, probably with help of experimental Transition FormFactors

Theory TOTAL ± **4.9**

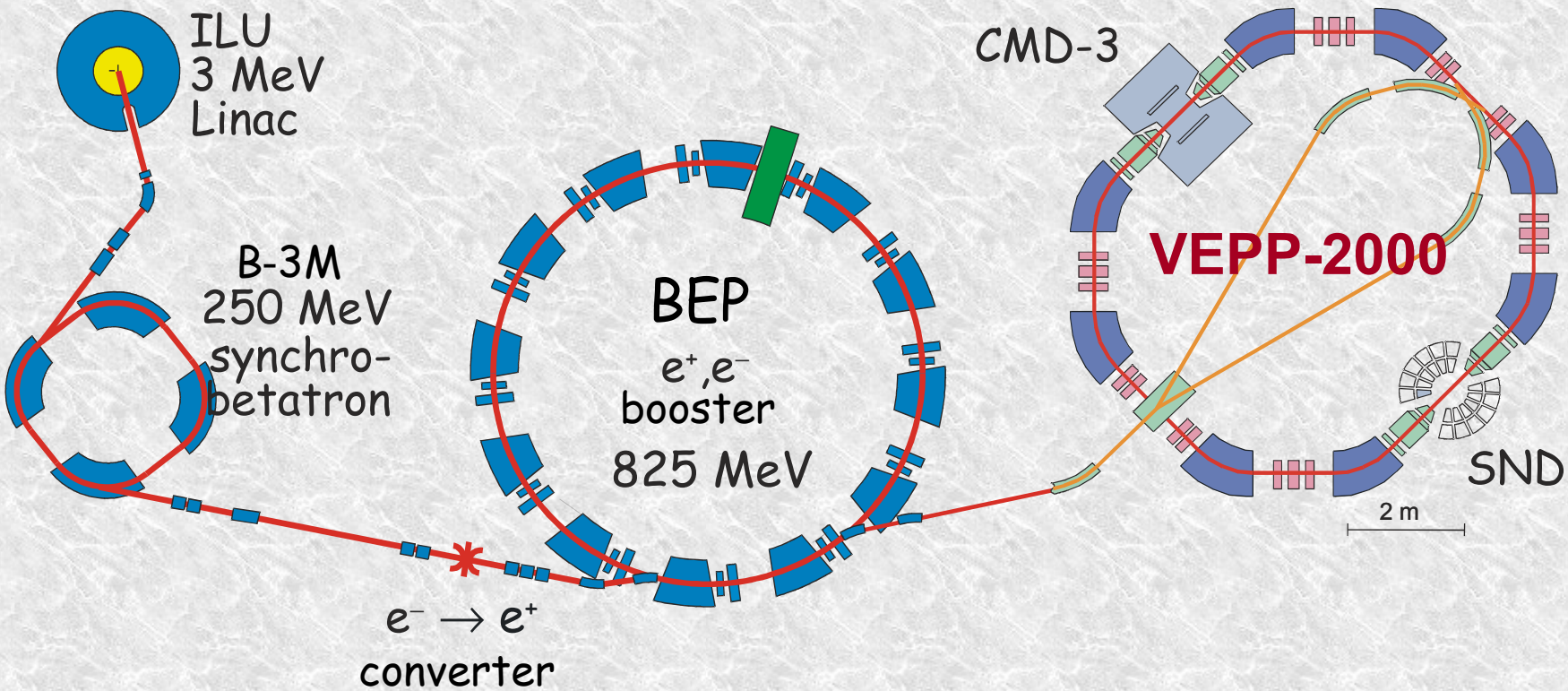
R(s) measurements at low s



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

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

VEPP-2000 storage ring



- Up to 2 GeV c.m. Energy
- VEPP-2000 uses special optics providing "round beams" give additional gain in luminosity and will provide:

$L=10^{31}\ cm^{-2}c^{-1}$, $\sqrt{s}=1.0$ GeV

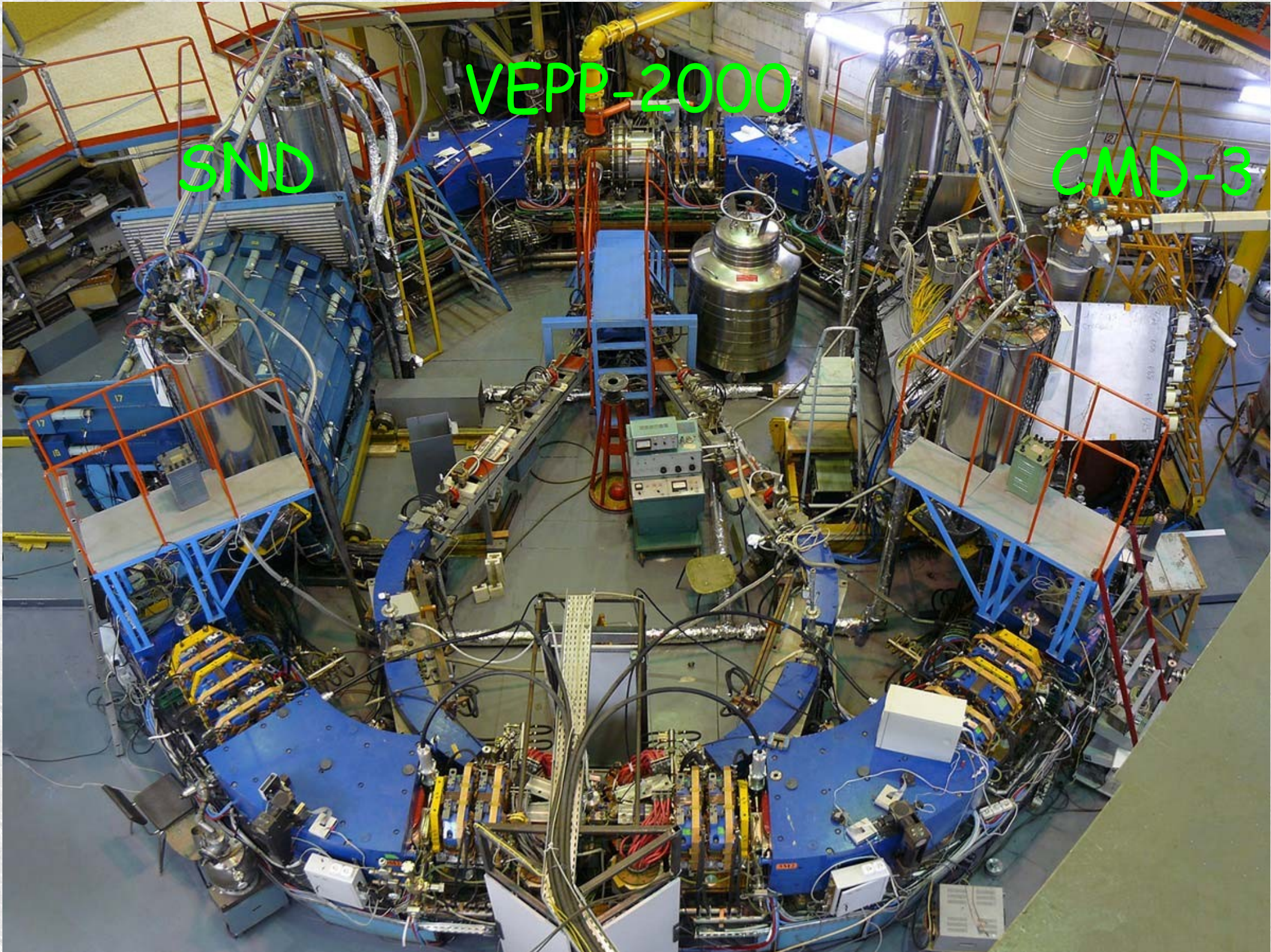
$L=10^{32}\ cm^{-2}c^{-1}$, $\sqrt{s}=2.0$ GeV

Status:

2010 – start of experiments

Plans:

$\approx 100\ pb^{-1}$ per detector per year


VEPP-2000
SND
CMD-3

CMD-3 Detector

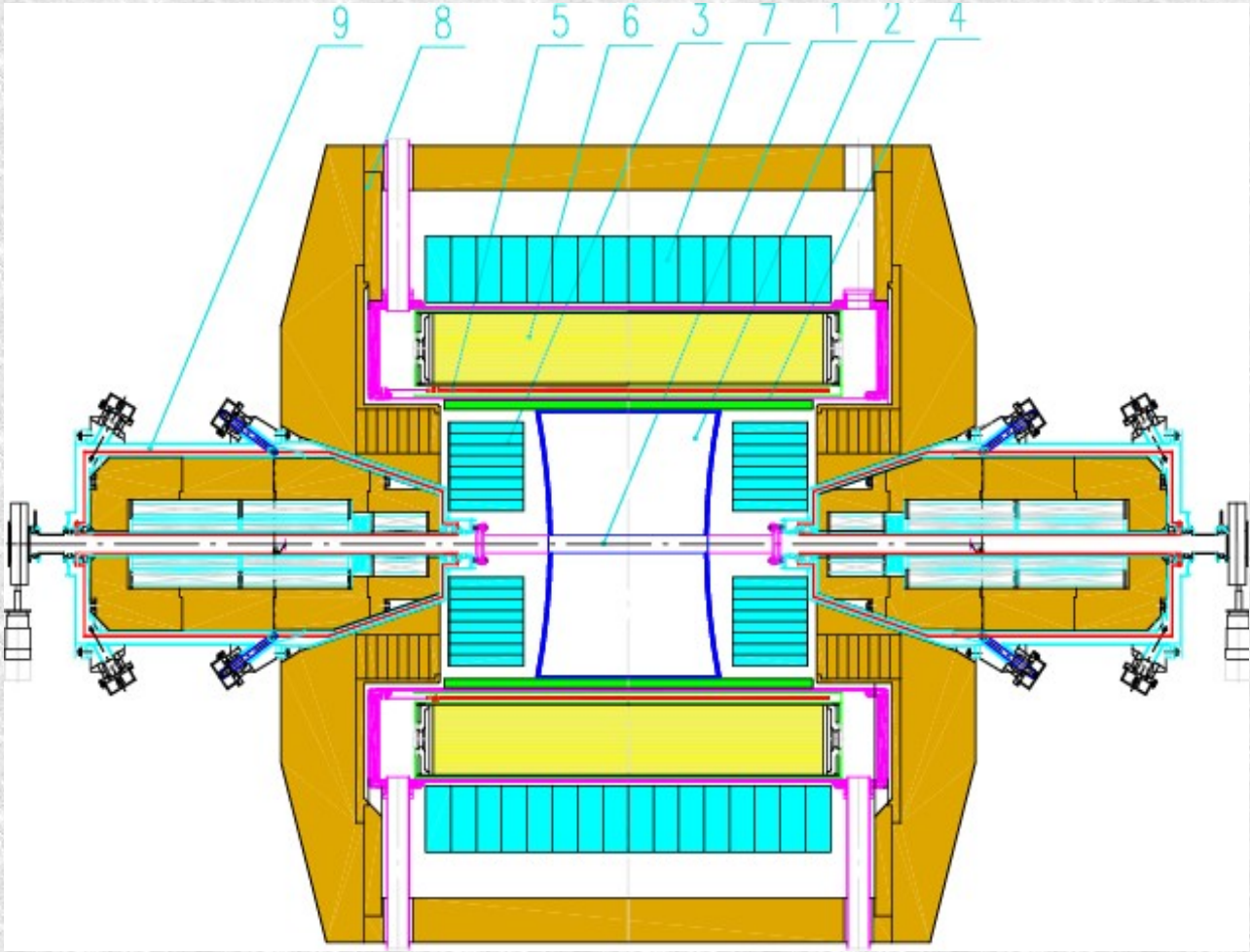
Advantages compared to previous CMD-2:

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

✗ thicker barrel calorimeter ($8X_0$->$15X_0$)
- better particle separation

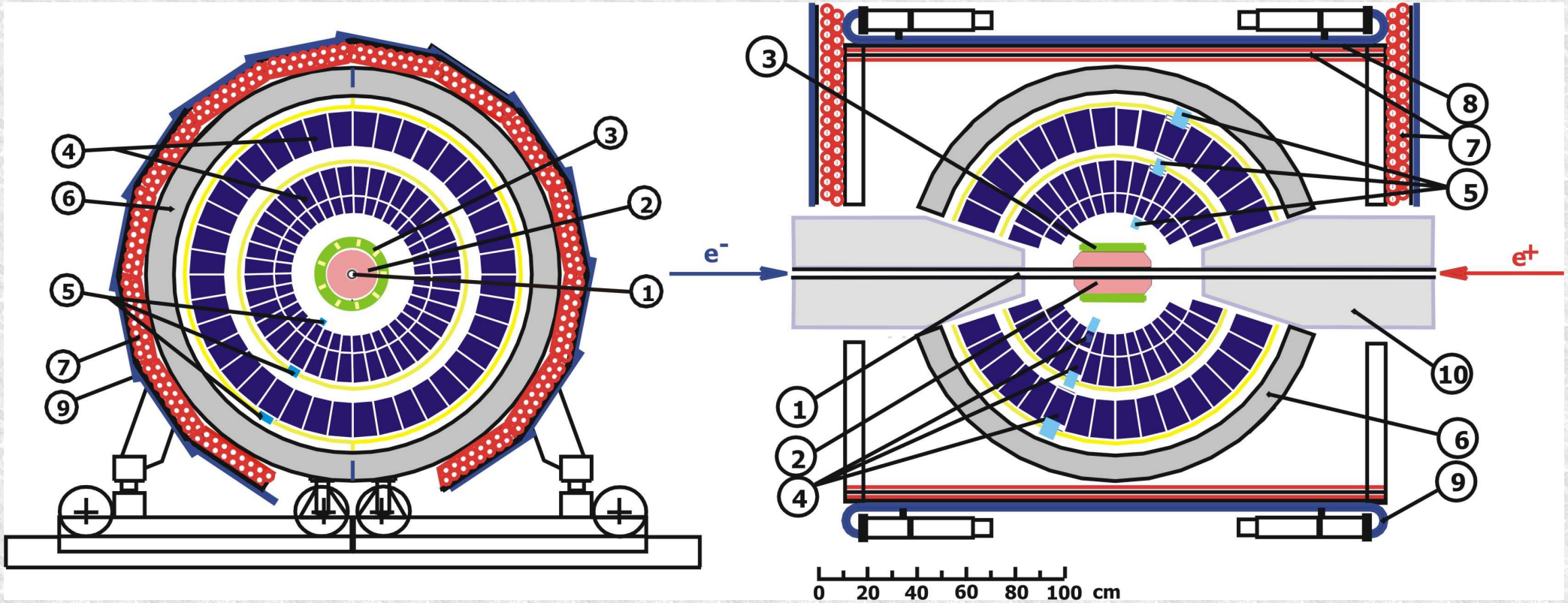
✗ LXe calorimeter
- measurement of conversion point for γ's
- shower profile

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



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

SND Detector – new version



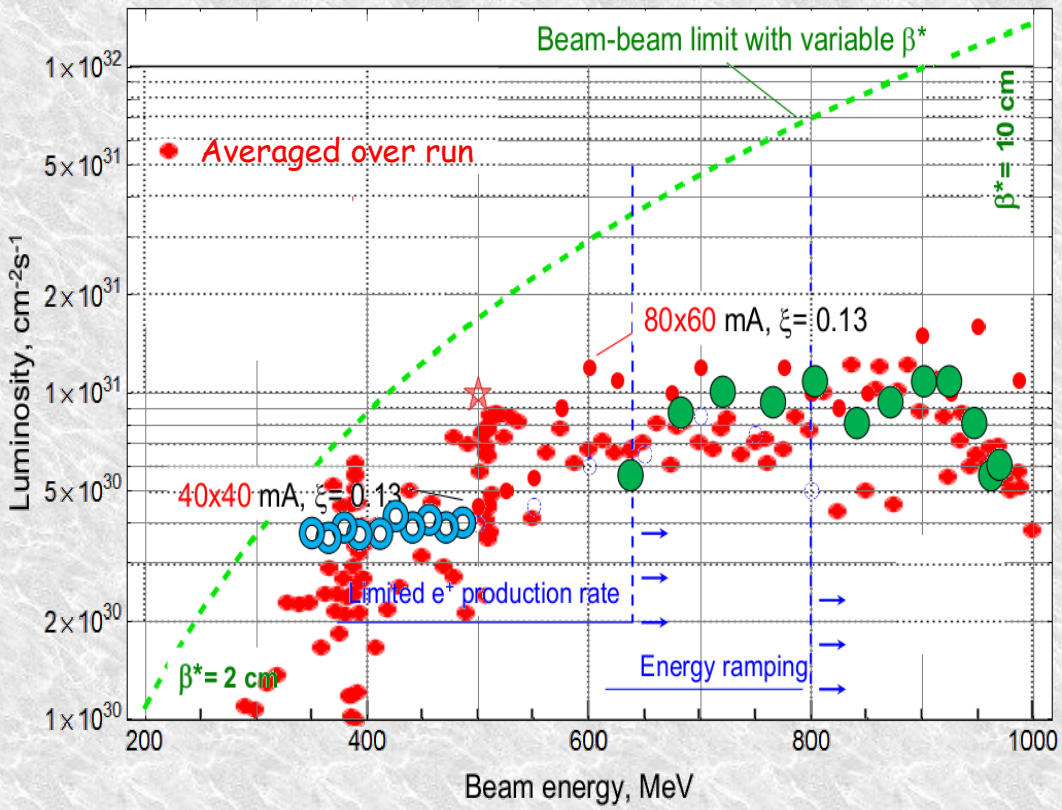
1 – beam pipe
2 – tracking system
3 – aerogel
4 – NaI(Tl) crystals
5 – phototriodes
6 – muon absorber
7–9 – muon detector
10 – focusing solenoid

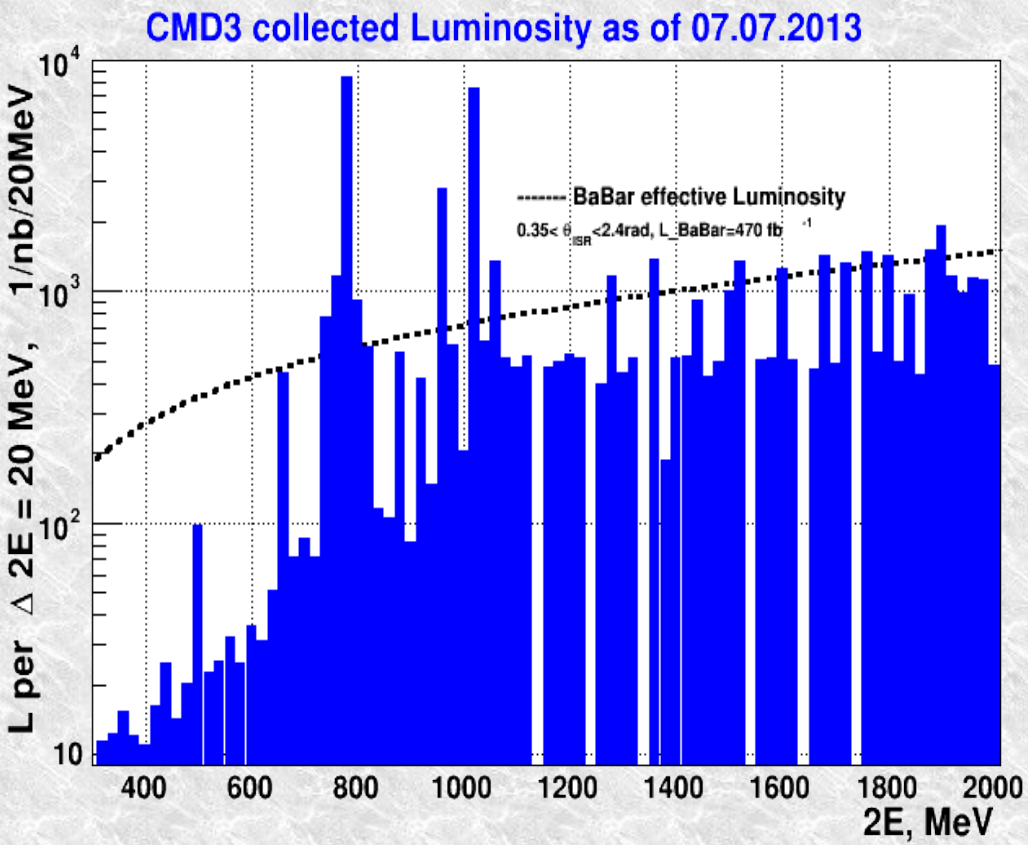
Advantages compared to previous SND:

- new system - Cherenkov counter (n=1.05, 1.13)
  - e/π separation E<450 MeV
  - π/K separation E<1 GeV
- new drift chamber
  - better tracking
  - better determination of solid angle

NIM A449 (2000) 125-139

Collected Luminosity





The 10^{31} $cm^{-2}c^{-1}$ 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 (825 MeV now), after upgrade it will gain factor x10

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

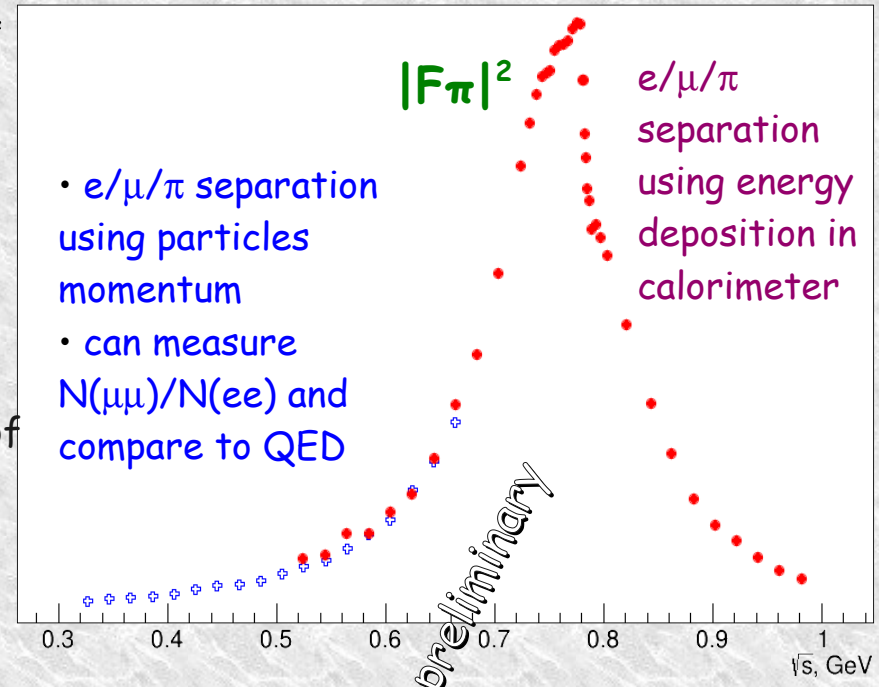
8.3 pb^{-1}	ω - region
9.4 pb^{-1}	< 1 GeV (except ω)
8.4 pb^{-1}	φ - region
34.5 pb^{-1}	> 1.04 GeV

e+e- -> π+π- by CMD3

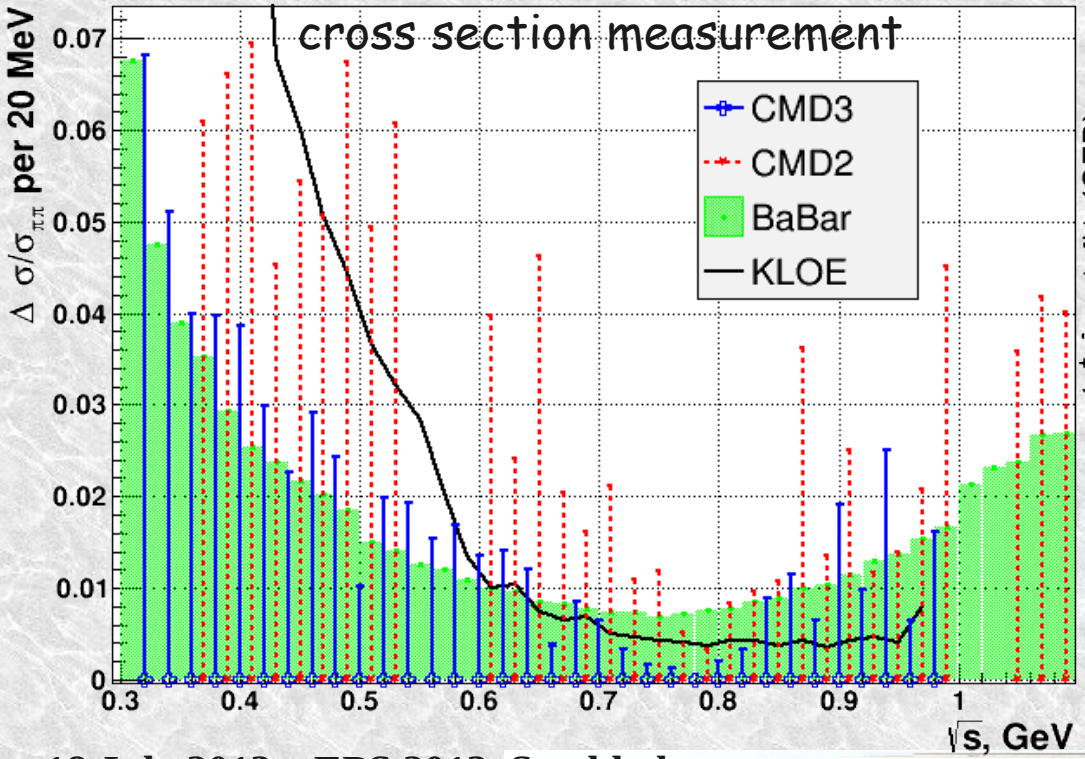
Clean collinear events (mostly without background)
Overall corrections at the level of a few percent

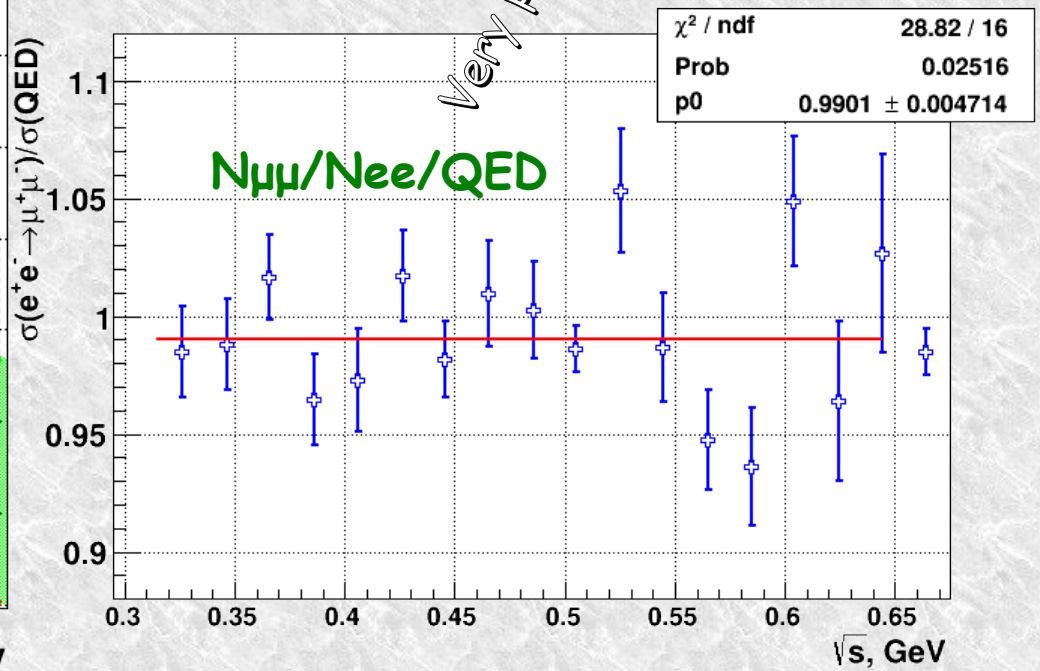
Plans to reduce systematic error from 0.6-08% -> 0.35%:

- ✗ Event Separation will be checked by different methods (0.2%)
- ✗ More proof of Radiative corrections 0.3% -> 0.1%
- ✗ Determination of fiducial volume controlled independently by LXe and ZC subsystems (0.1%)
- ✗ Beam Energy measured by method of Compton back scattering of the laser photons(σ_E< 50 keV)(0.1%)

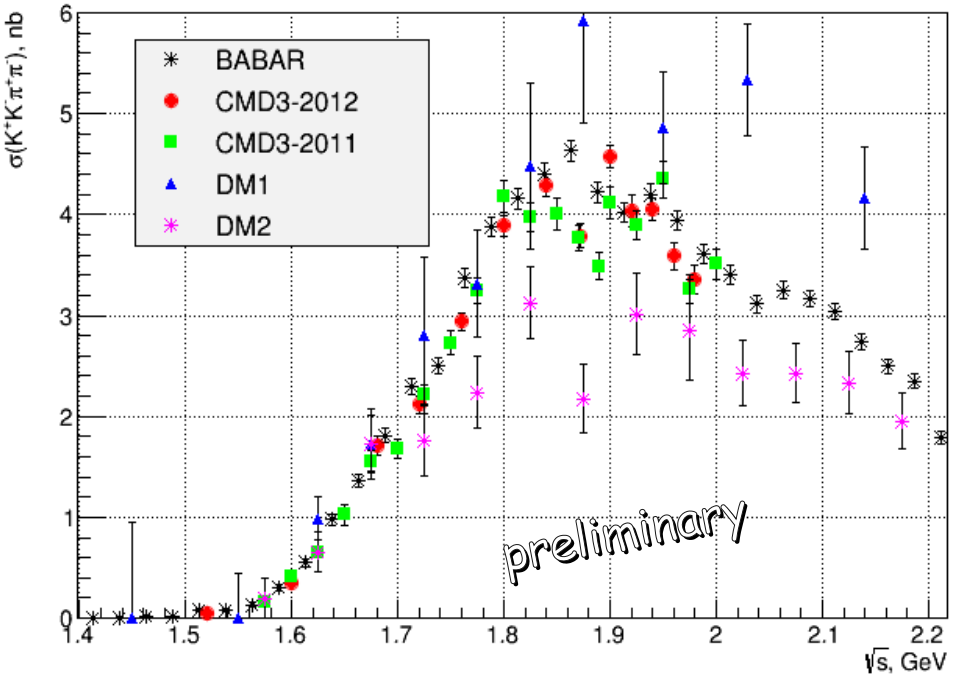


Statistical precision of cross section measurement



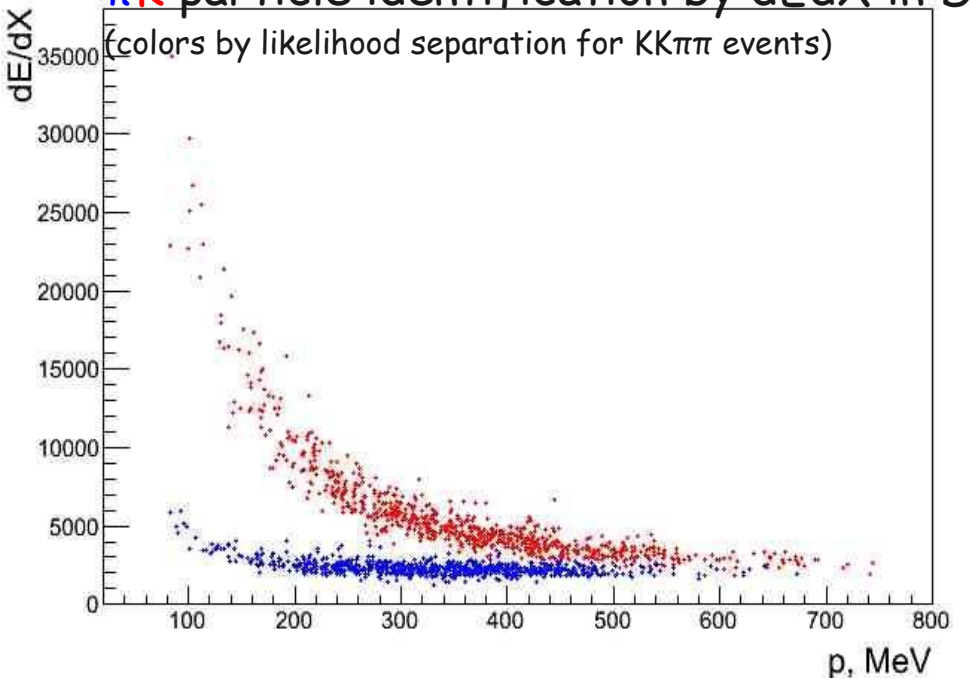


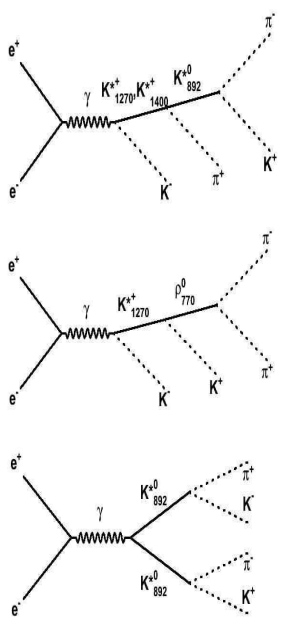
e+e- -> K+K-π+π- by CMD3



πK particle identification by dEdX in DC

(colors by likelihood separation for KKππ events)





Seen rich dynamics, many intermediate states:

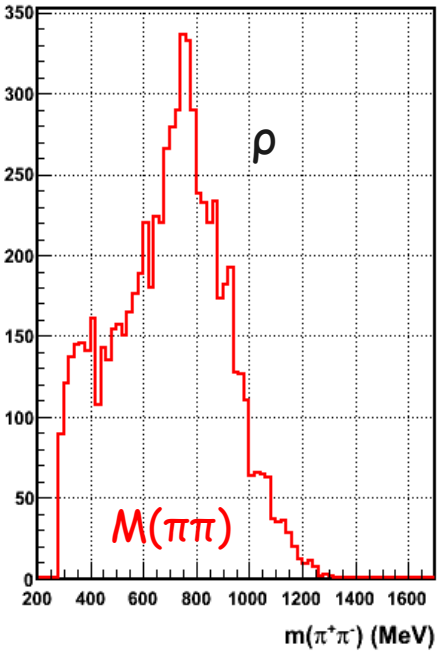
K*(1270)K->K*(892)Kπ

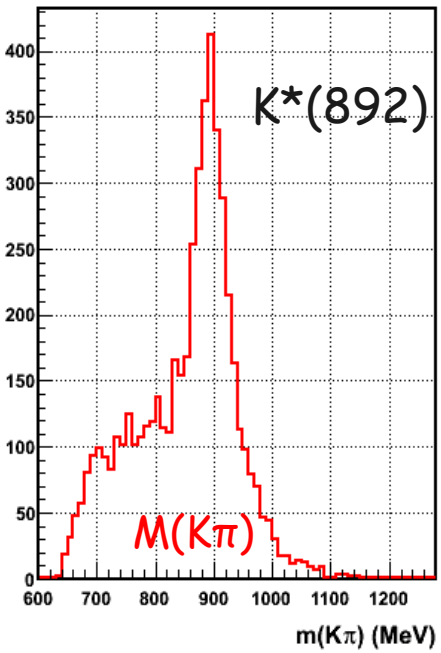
K*(1400)K->K*(892)Kπ

K*(1270)K->ρKK

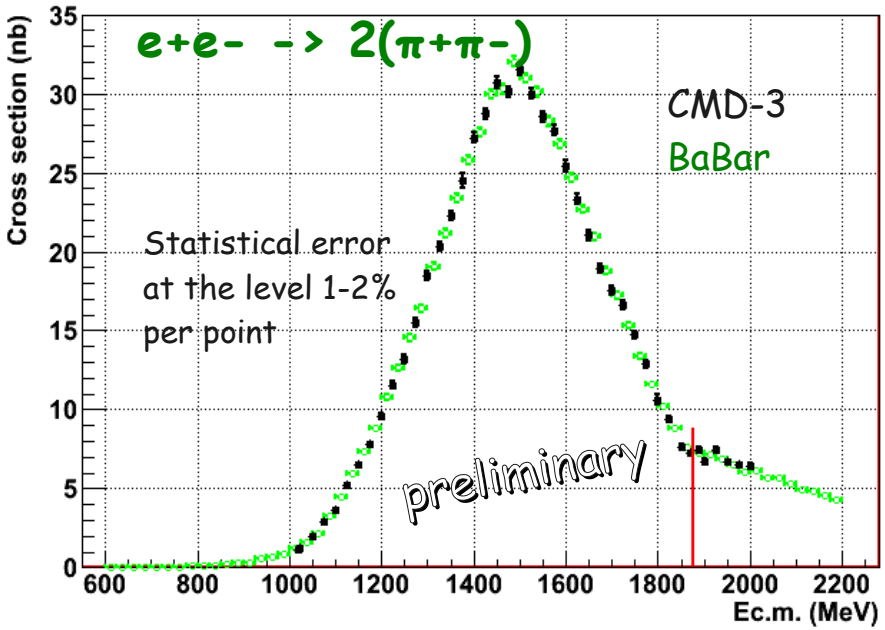
K*(892)K*(892), φππ

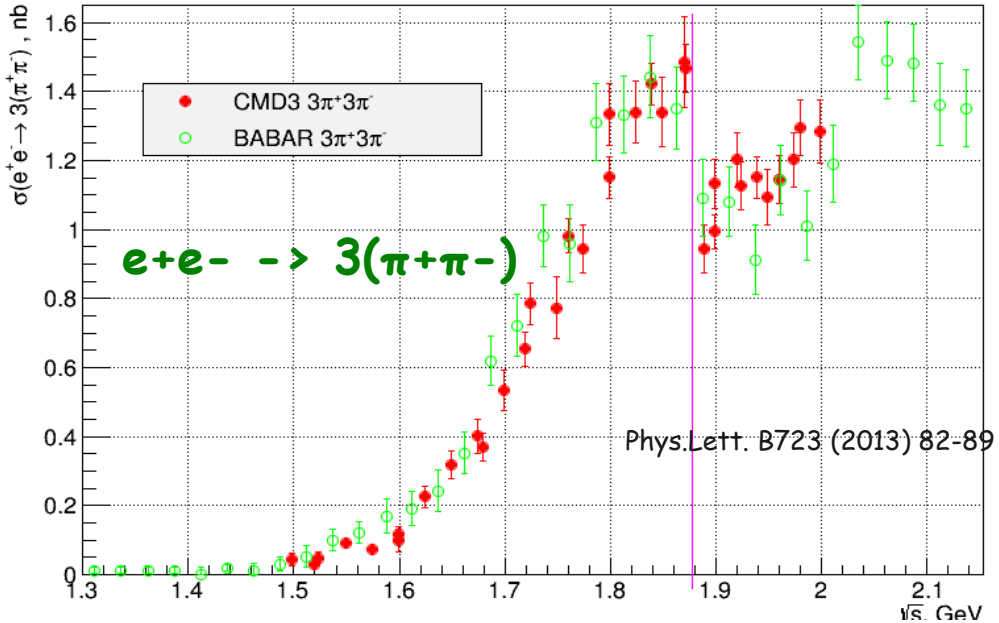
For $(g-2)_\mu$, $\alpha_{QED}(M_Z)$ need to be measured also all possible KKπ KKππ, with K – also neutral





e+e- -> multi pions with CMD3





One of the dominated systematic source is model uncertainty

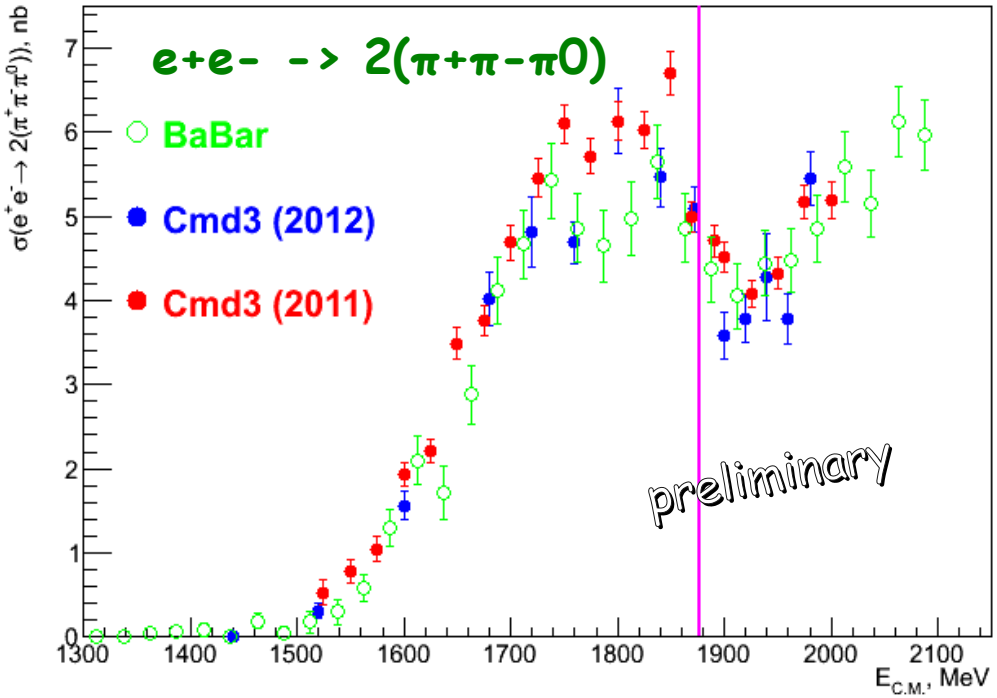
High statistic will allow much better dynamics study

3(π+π-) main production channel by ρ(770) + 4π in phase space or f_0

Seen change of dynamics in 1.7-1.9 GeV range

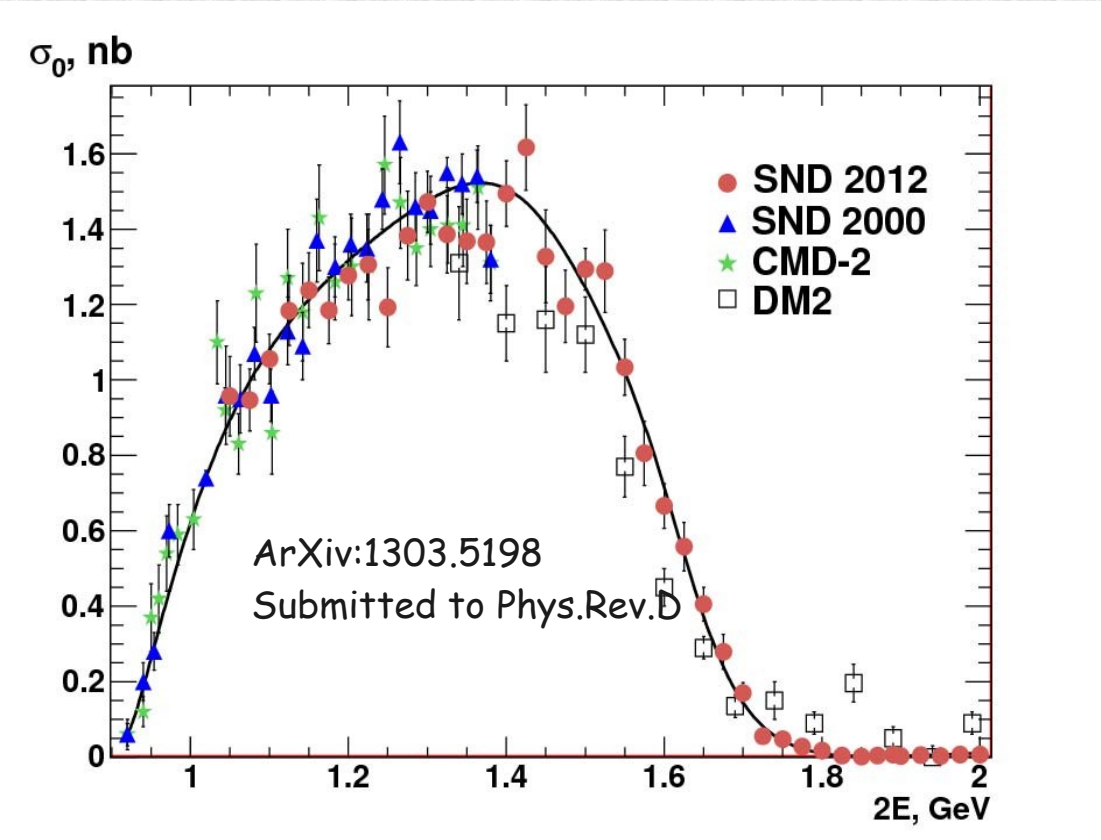
Interesting feature: sharp dip at $p\bar{p}$ threshold

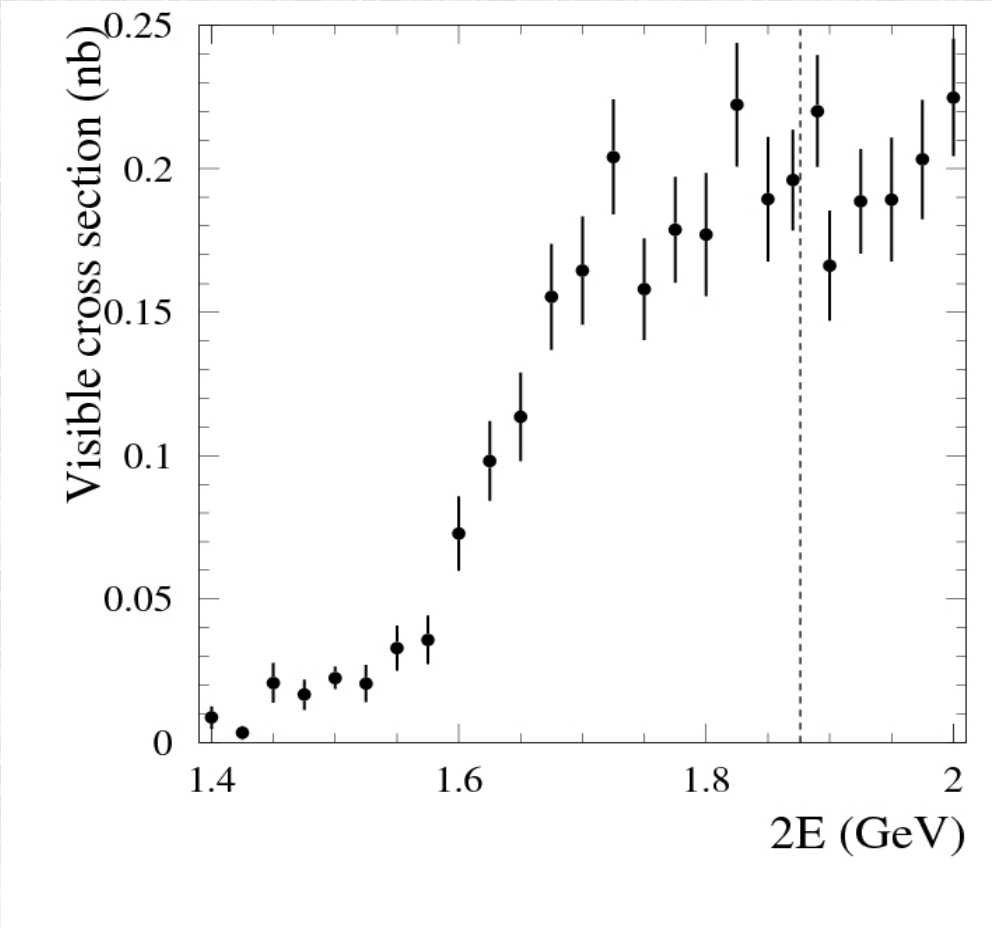
(dip in sum of 6π roughly as $p\bar{p}$+$n\bar{n}$ cross section)



With many neutral pions by SND

SND have advantages in neutral modes





e+e−→ ωπ0 → π0π0γ

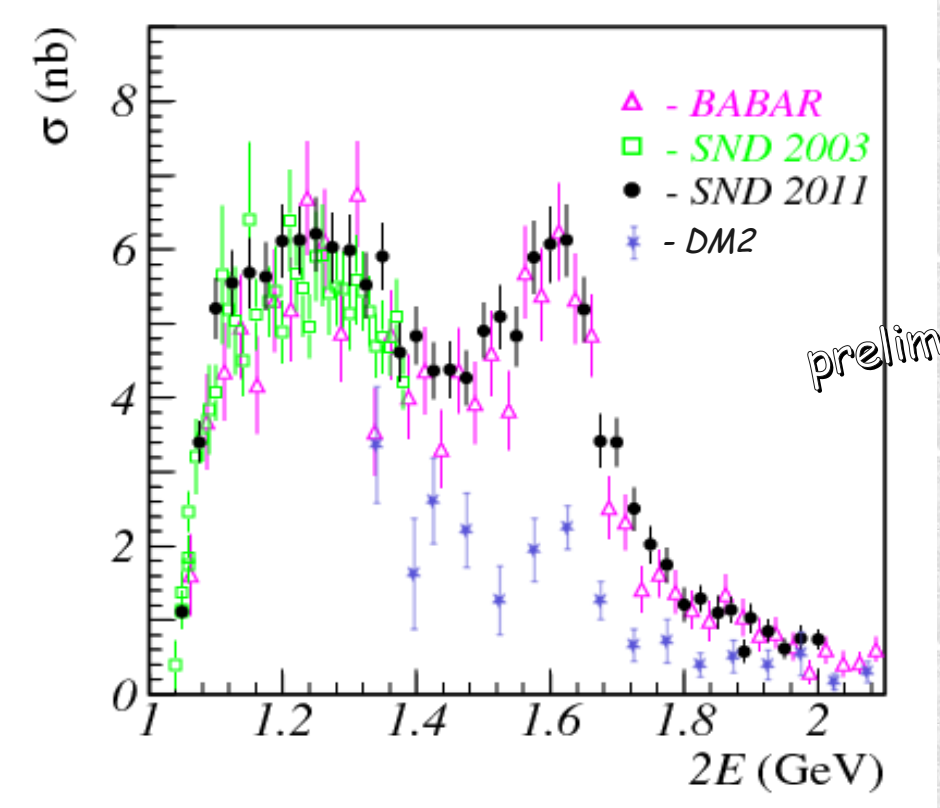
First published data by new SND

e+e−→ π+π−π0π0π0π0 → π+π− 8γ

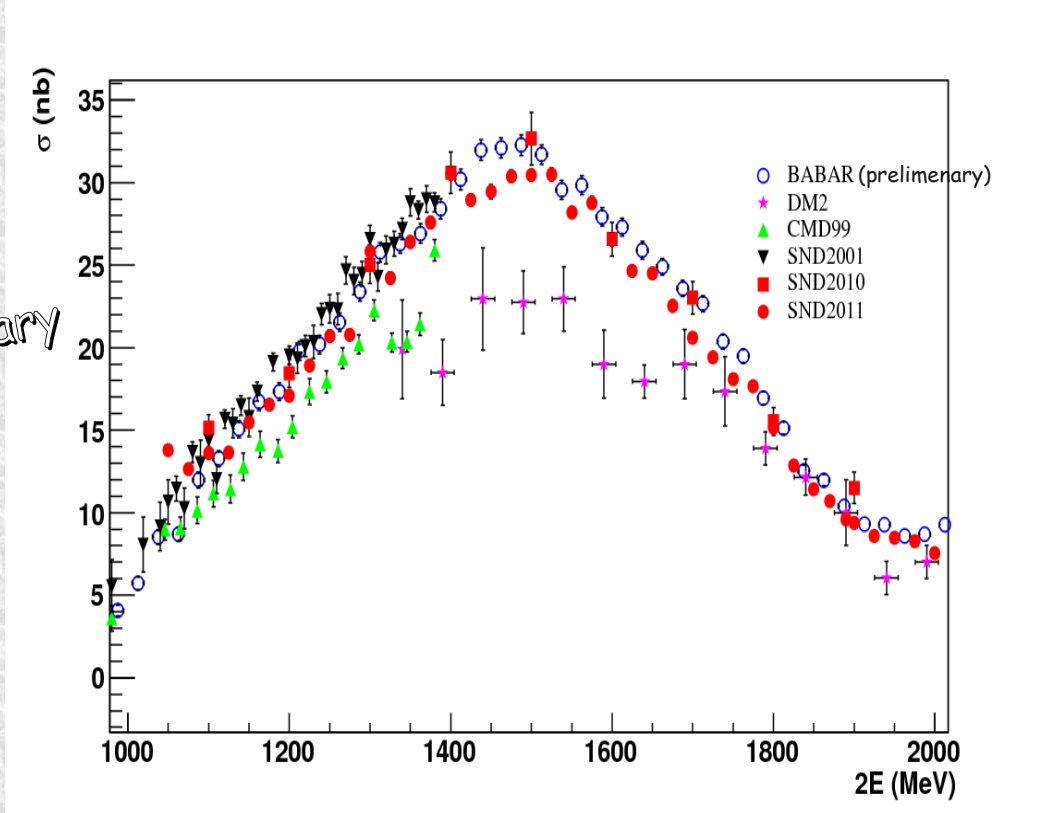
Not measured before

(in R(s) taken by Isospin relations)

3π, 4π by SND



preliminary



e+e- → π+π-π0

Need to be measured also in ω-region, now we have plenty of statistics for it

CMD2 has publication(2000) with good systematic(1.3%), but low statistics,

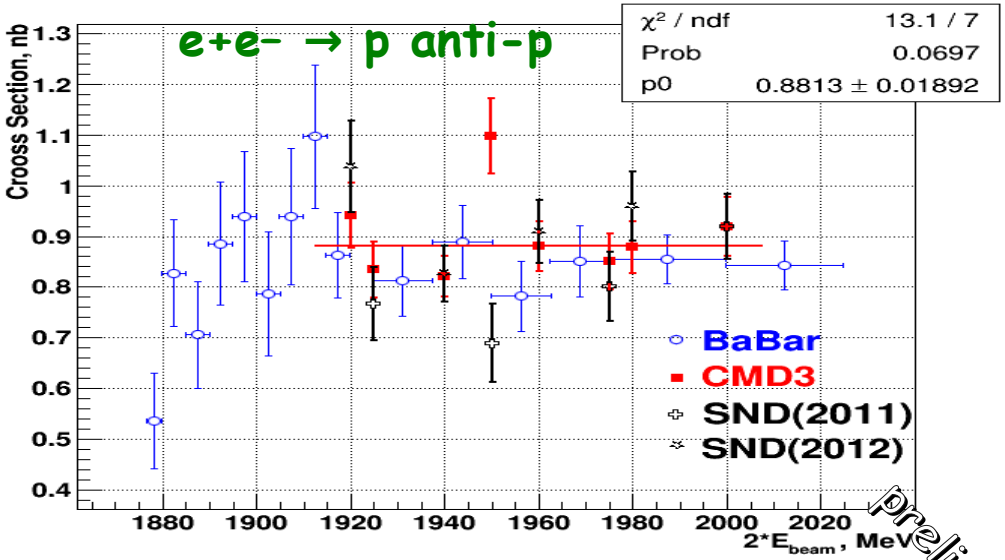
SND have good statistics but lower systematics(3.4%)

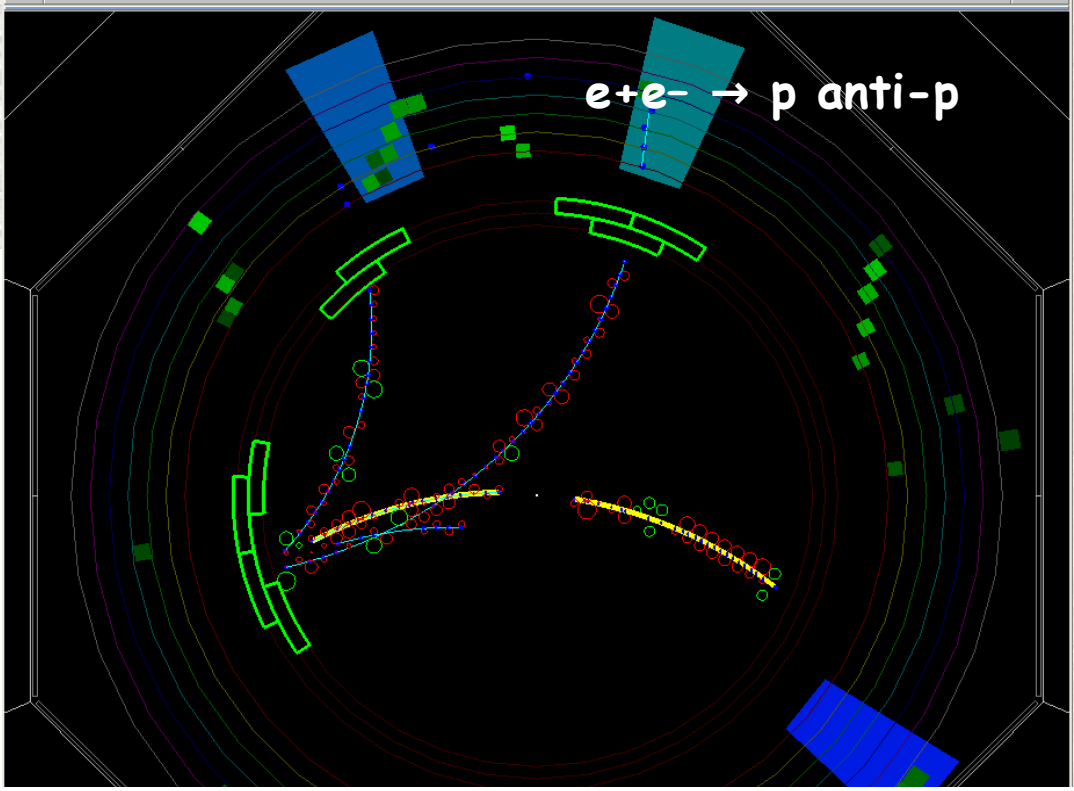
e+e-→ π+π-π0π0

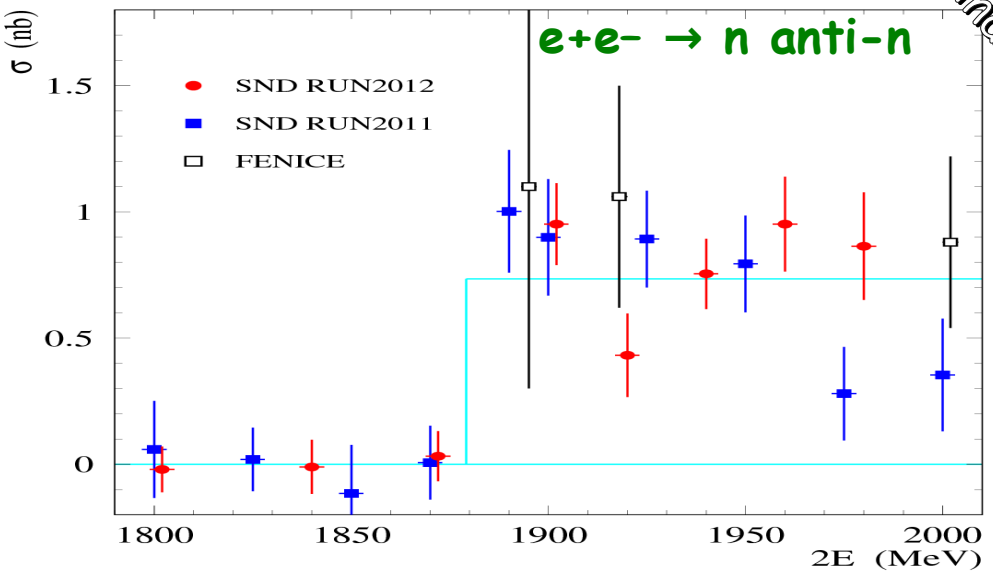
Worse known cross-section above phi For >1.4 GeV a this moment the only published data from >30 year old experiments from Orsay DCI and ADONE

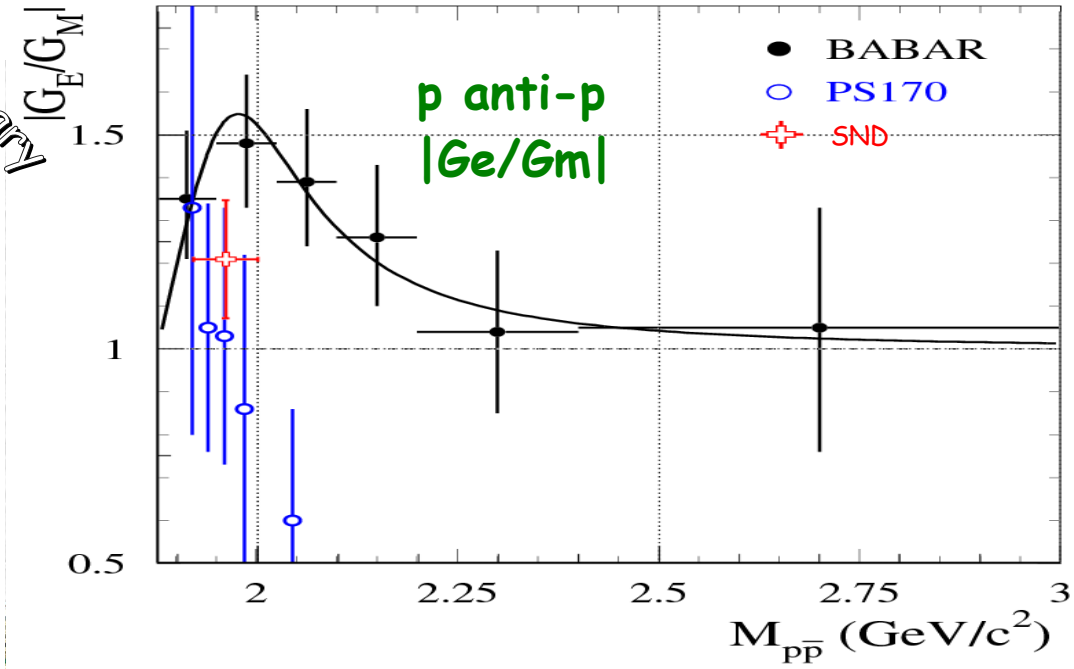
2 nucleons at threshold

We are able to measure nucleon formfactor at threshold.
With more statistics we want to distinguish electrical and magnetic part by |Ge/Gm|









Conclusion

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

x We have upgraded detectors CMD-3 and SND, with much better performance and monitoring of different detector subsystems

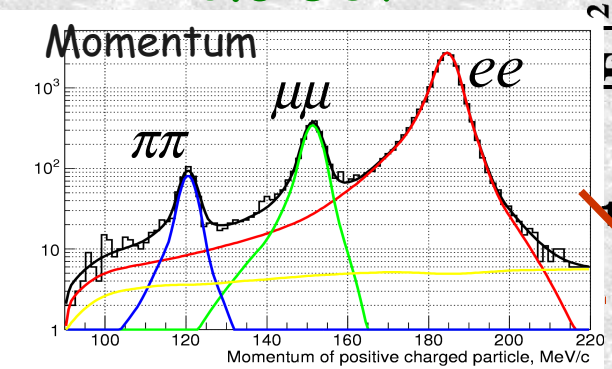
x Data analysis is in progress, the already collected data have same or better statistical precision on cross sections than previous experiments.

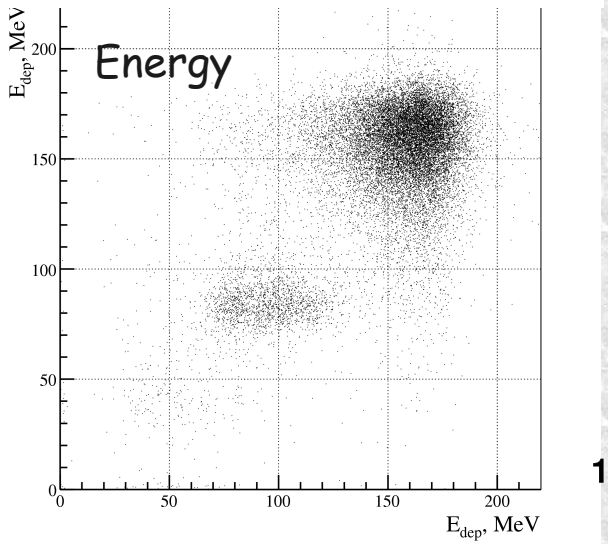
x First publications on data analysis appeared (6π, ωπ0)

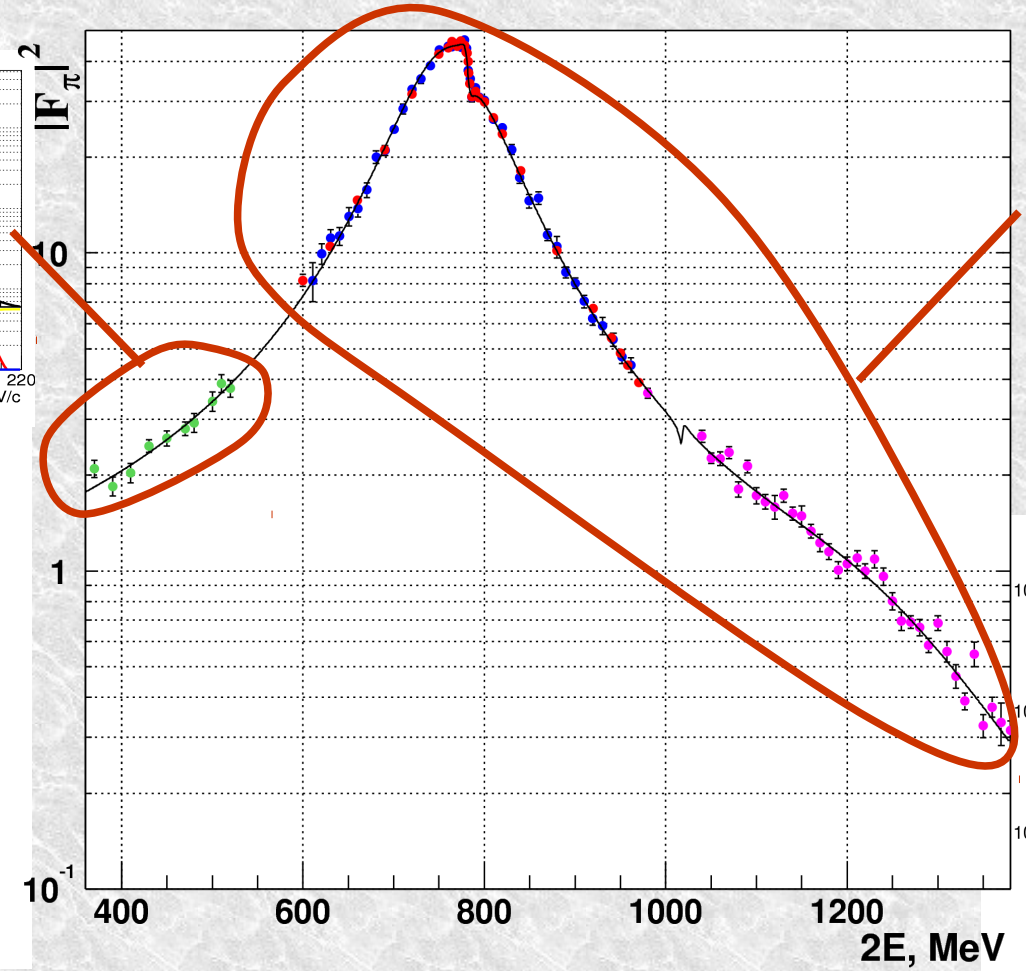
x During upcoming shutdown for about 1.5 year new positron injection complex to increase luminosity by factor x10 up to 10**32 cm-2s-1 on 2E=2 GeV will be commissioned

Pion formfactor : Event separation (CMD-2)

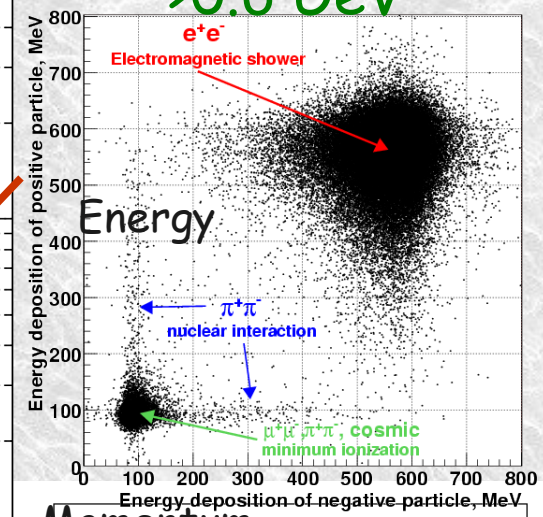
<0.6 GeV

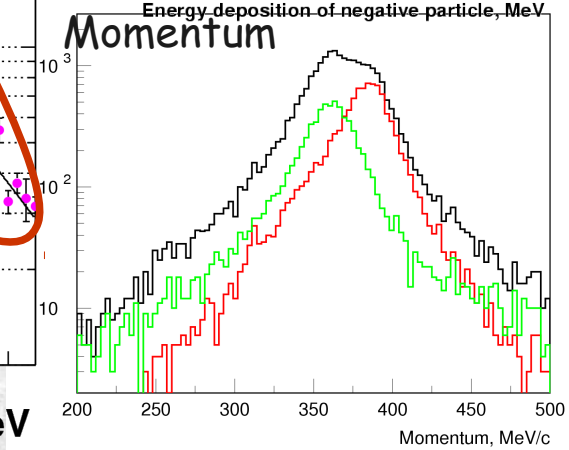






>0.6 GeV





- e/μ/π separation using particles momentum
- can measure N(μμ)/N(ee) and compare to QED

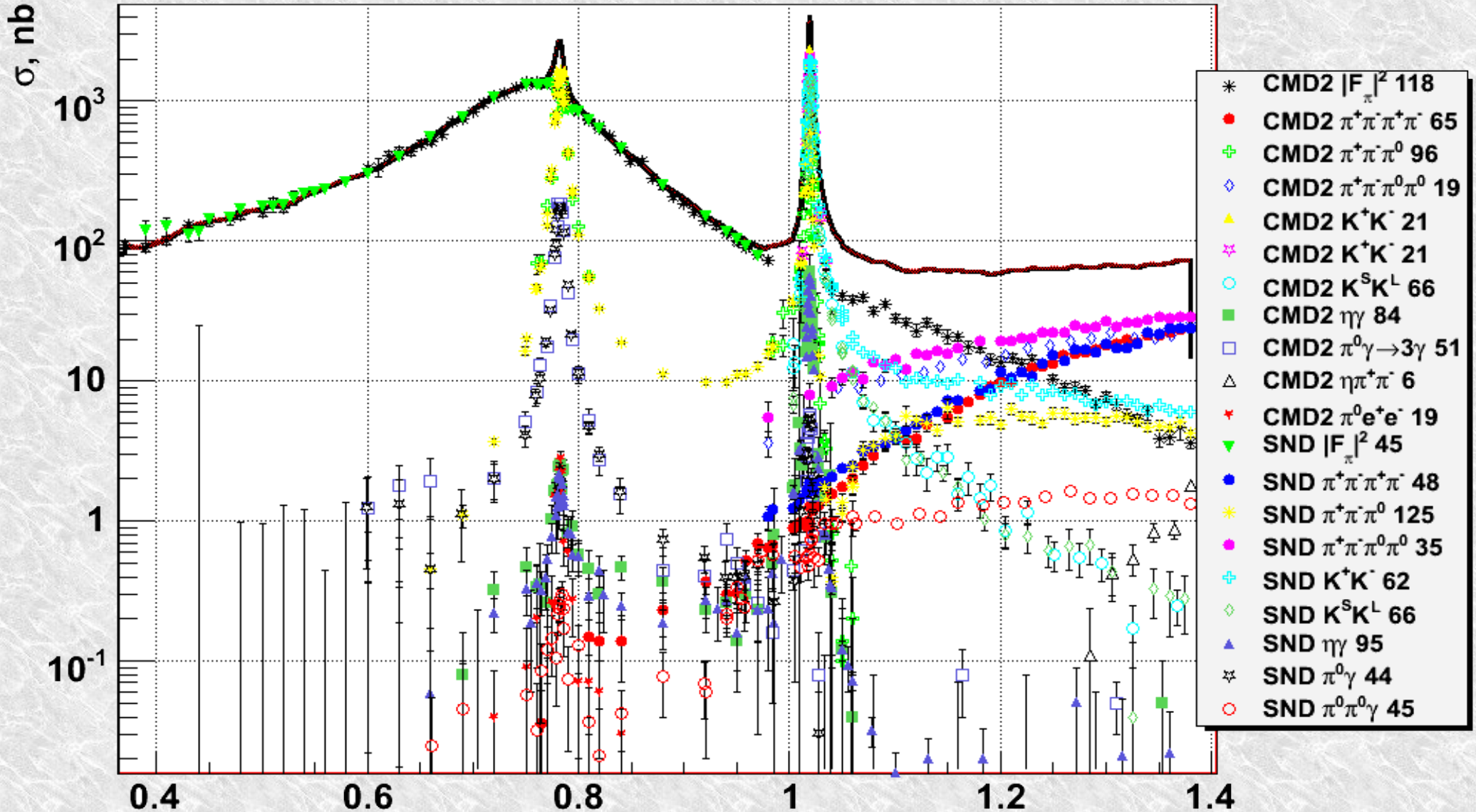
Likelihood minimization:

$$\mathscr{L} = -\sum_{\text{events}} \ln\left(\sum_{\text{type}} N_{\text{type}} \cdot f_{\text{type}}\left(E^+, E^-\right)\right) + \sum_{\text{type}} N_{\text{type}}$$

$$\text{type} = e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \text{cosmic}$$

- e/μ/π separation using energy deposition
- N(μμ)/N(ee) is fixed according to QED

Inclusive Hadronic Cross-Sections with CMD2&SND

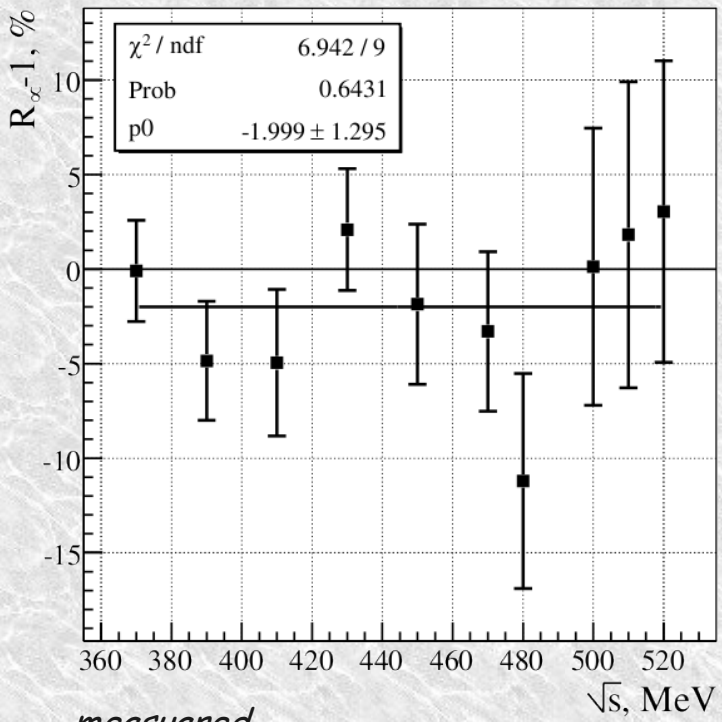


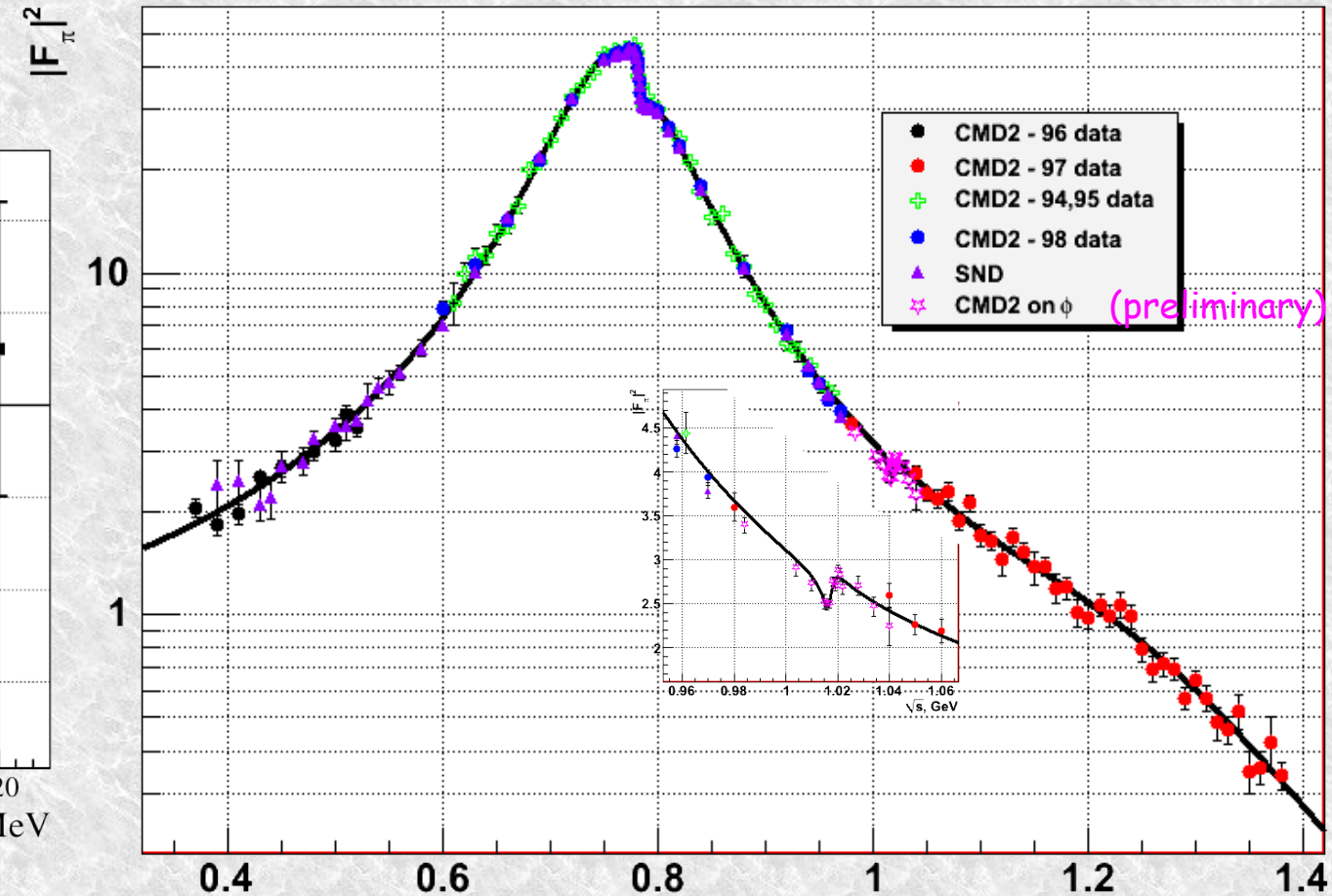
Combined precision of R(s) from CMD2&SND

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

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

Pion formfactor





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

Systematic error

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

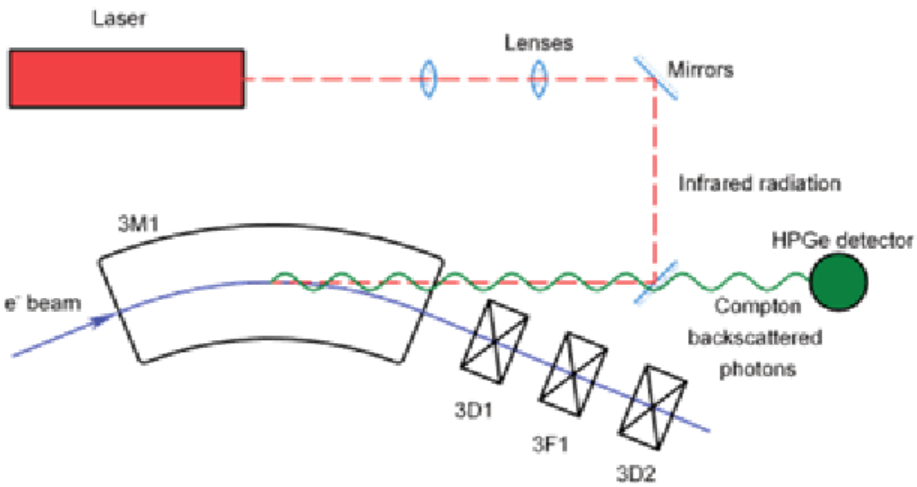
SND: 3.2% | 1.3%

R measurement: systematic errors

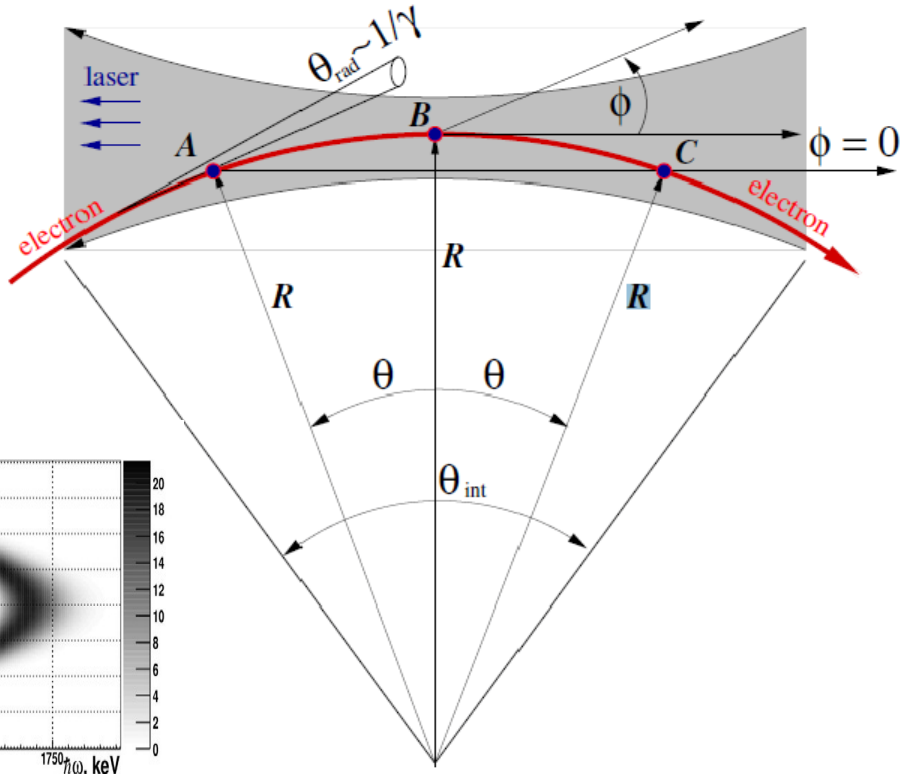
What systematic error can be achieved for R measurement at CMD-3?

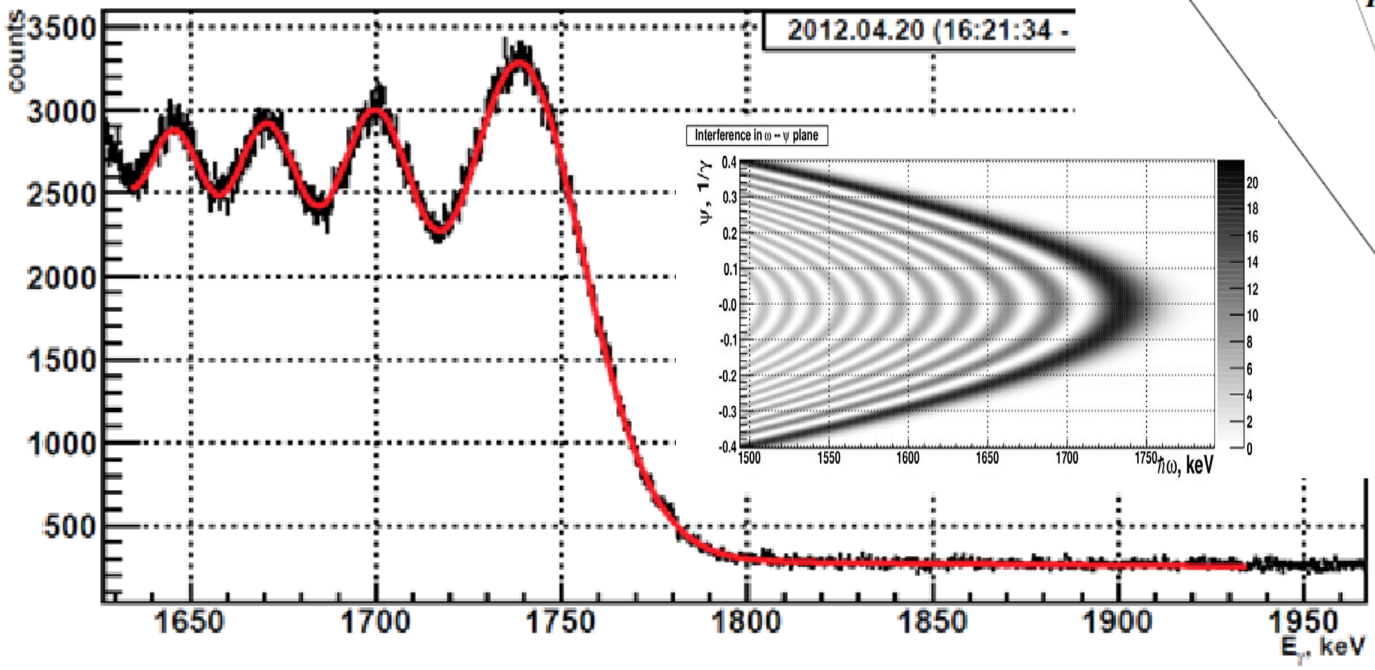
Source of error	CMD2, 2pi $\sqrt{s}$<1 GeV	SND, 2pi $\sqrt{s}$<1 GeV	CMD2,4pi $\sqrt{s}$>1.1 GeV	CMD3, 2pi $\sqrt{s}$<1 GeV	CMD3,4pi $\sqrt{s}$>1.1 GeV
Event separation	0.2-0.4%	0.5%	2% (cuts)	0.2%	1% (cuts)
Fiducial volume	0.2%	0.8%	3% (model)	0.2%	2% (model)
Energy calibration	0.1-0.3%	0.3%	1%	0.1%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

Energy measurement by Compton back scattering



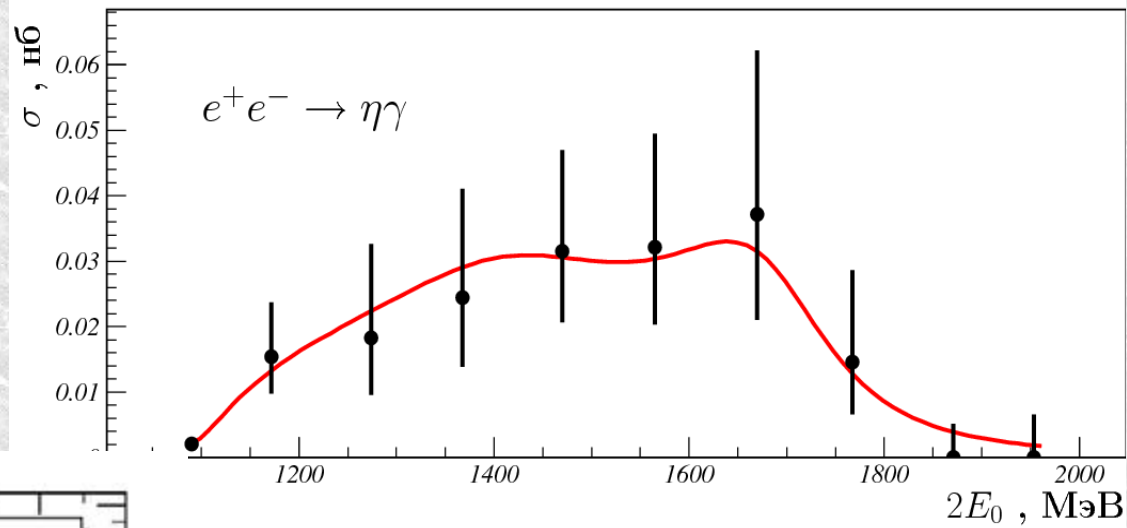
Излучение из точек A и C под углом φ = 0 интерферирует



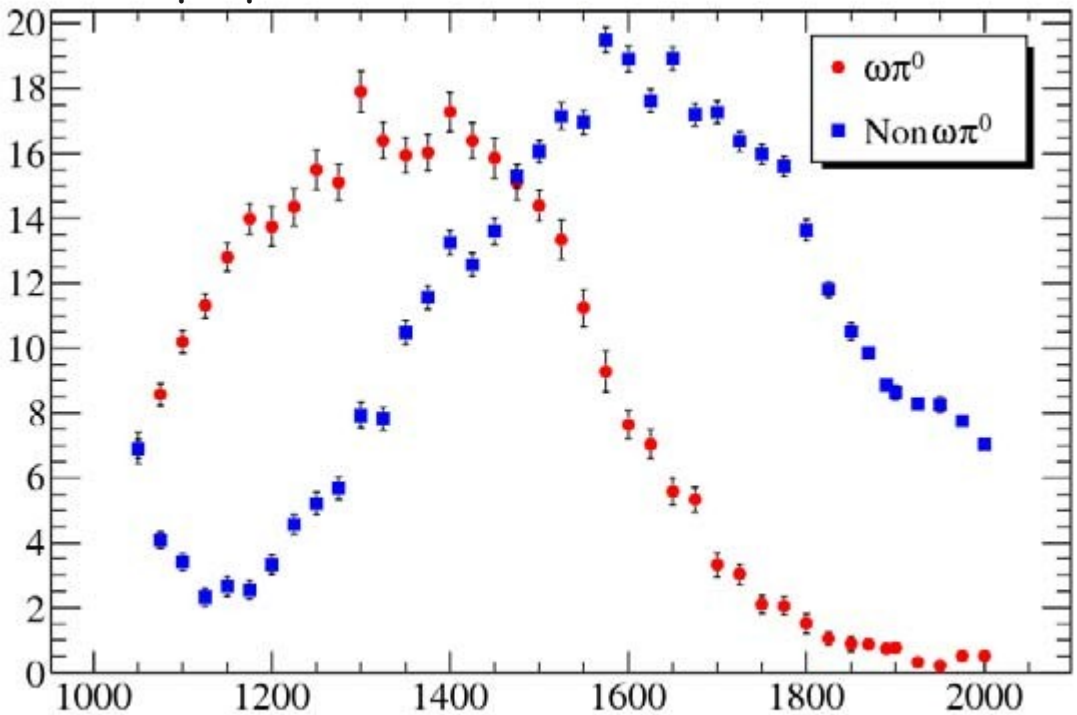


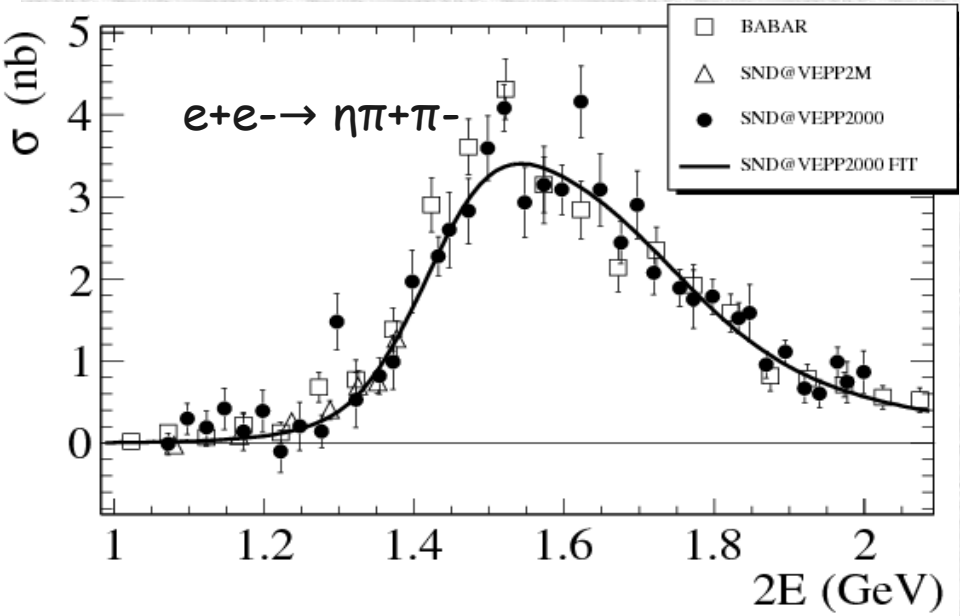
E = 993.662 ± 0.016 МэВ

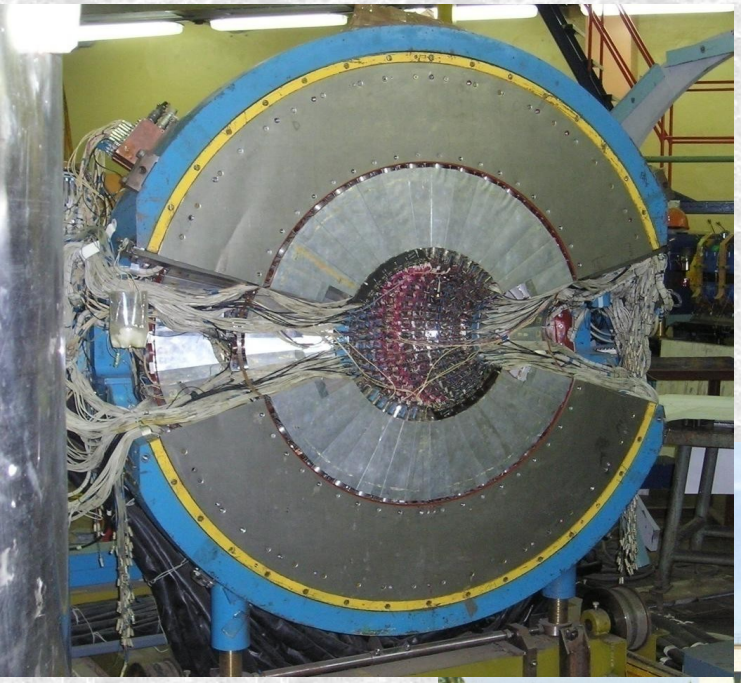
M.N. Achasov et al. arXiv:1211.0103v1 [physics.acc-ph] 1 Nov 2012

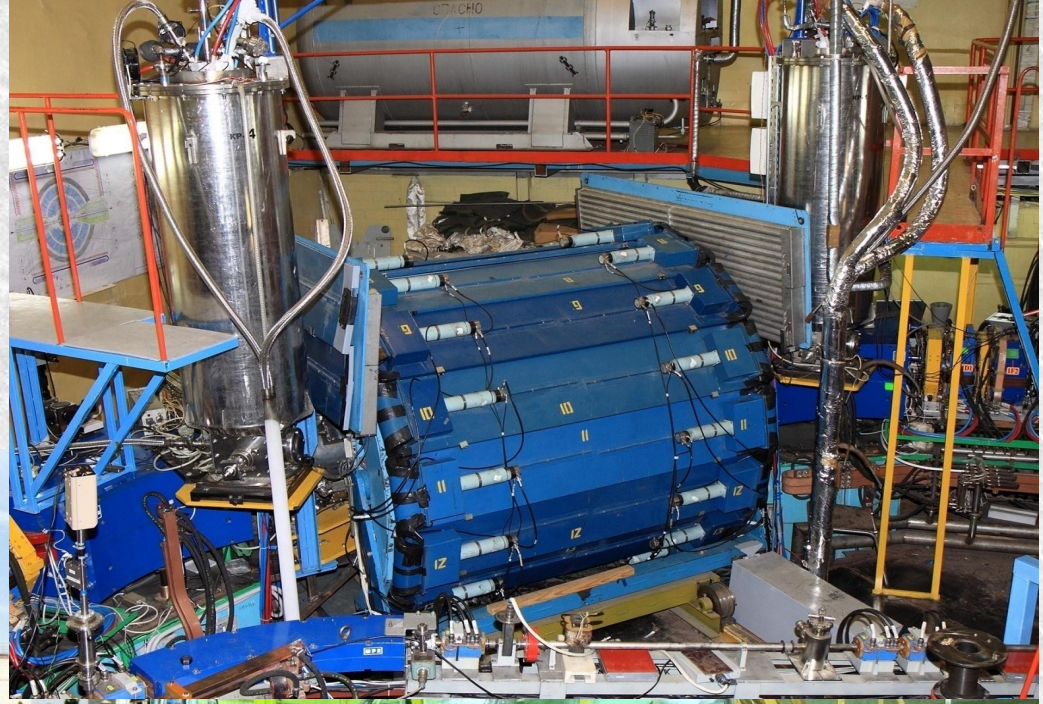

$e^+e^- \to \eta\gamma$
σ , нб
0.06
0.05
0.04
0.03
0.02
0.01
1200
1400
1600
1800
2000
$2E_0$, МэВ

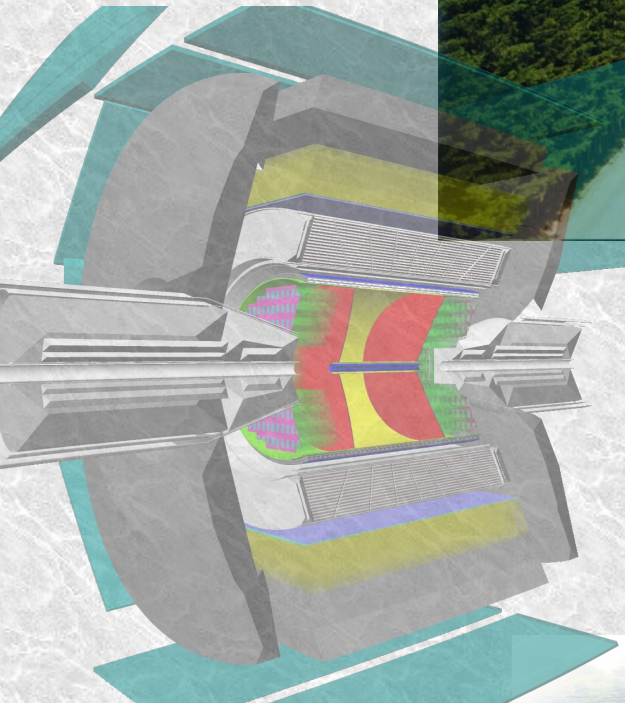
2pi2pi0

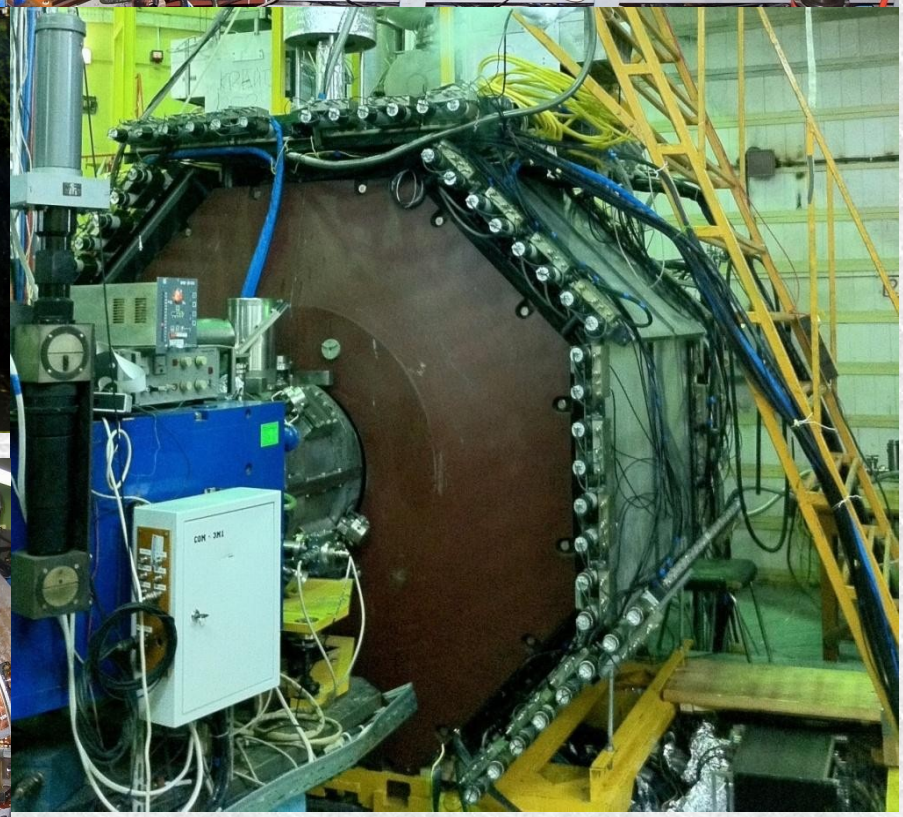

$\omega\pi^0$
Non$\omega\pi^0$
20
18
16
14
12
10
8
6
4
2
0
1000
1200
1400
1600
1800
2000

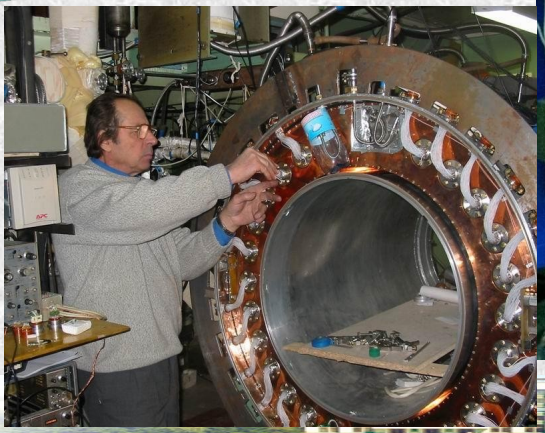

e+e-→ ηπ+π-
BABAR
SND@VEPP2M
SND@VEPP2000
SND@VEPP2000 FIT
σ (nb)
5
4
3
2
1
0
1
1.2
1.4
1.6
1.8
2
2E (GeV)



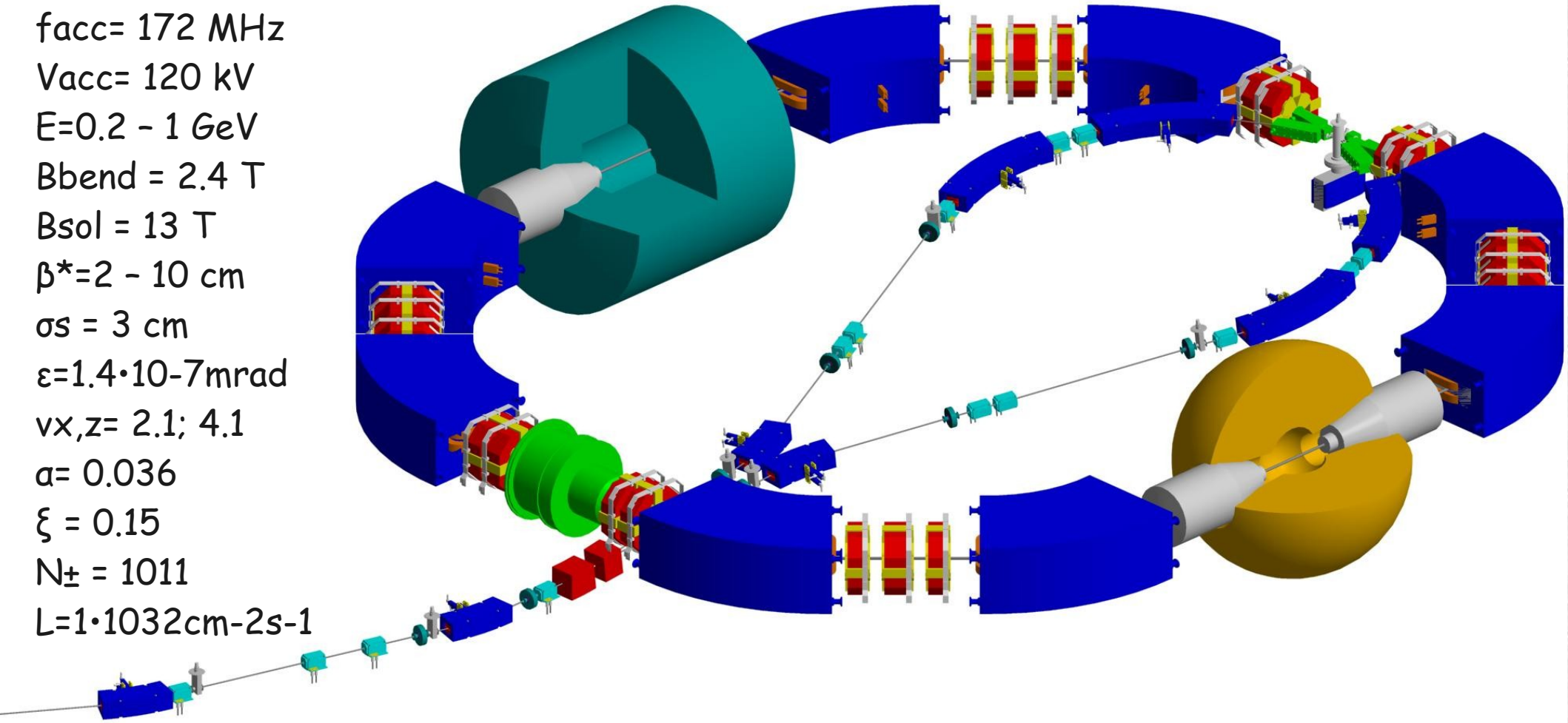


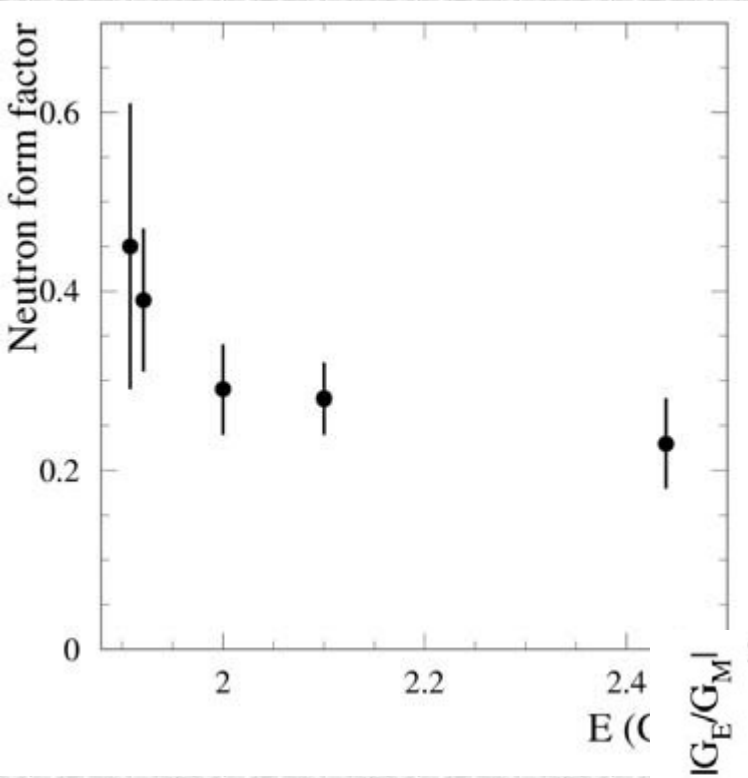


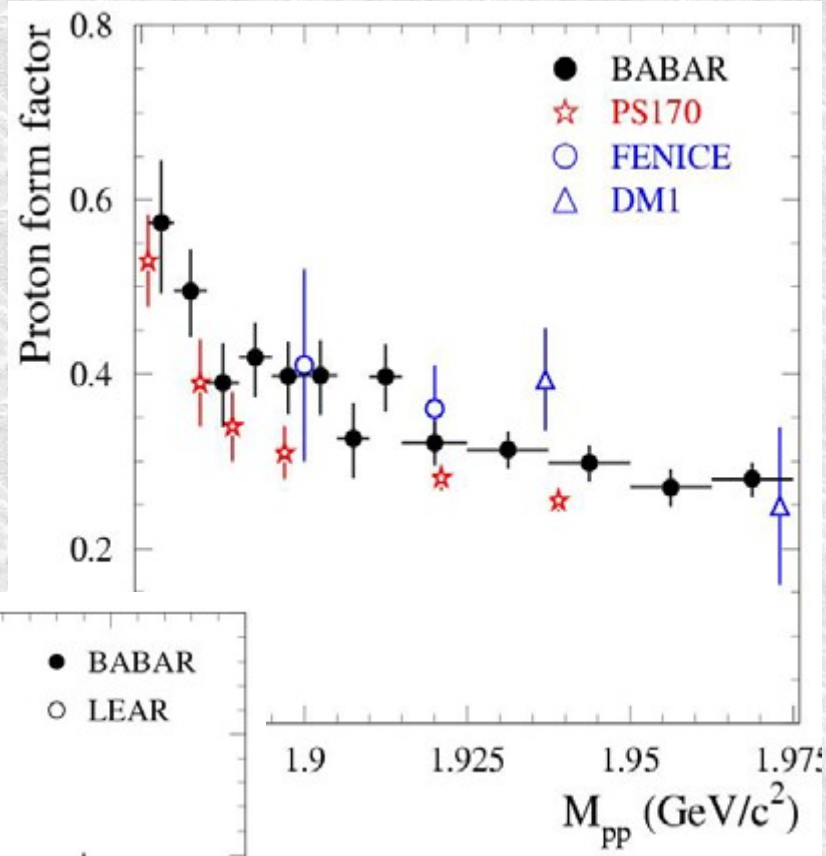


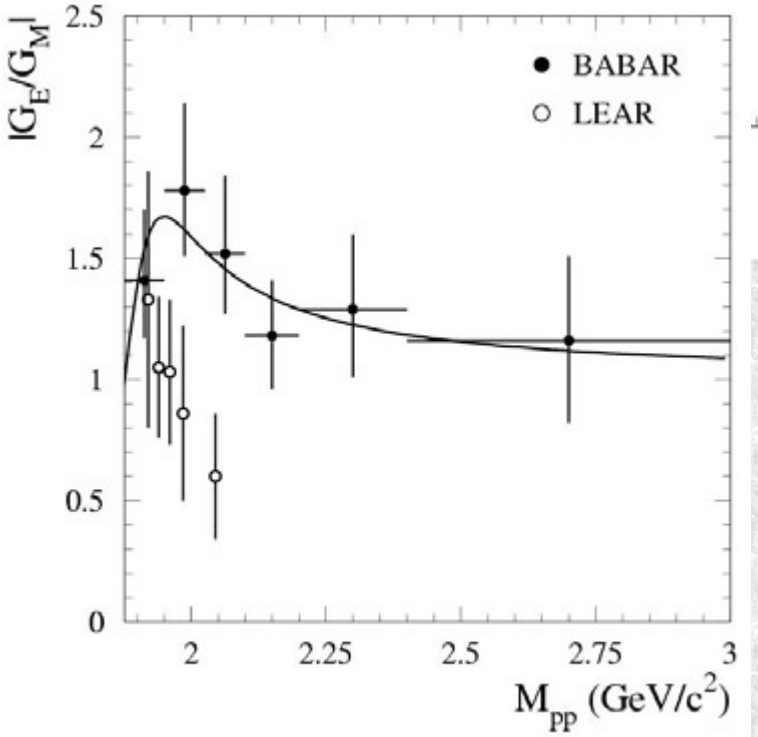


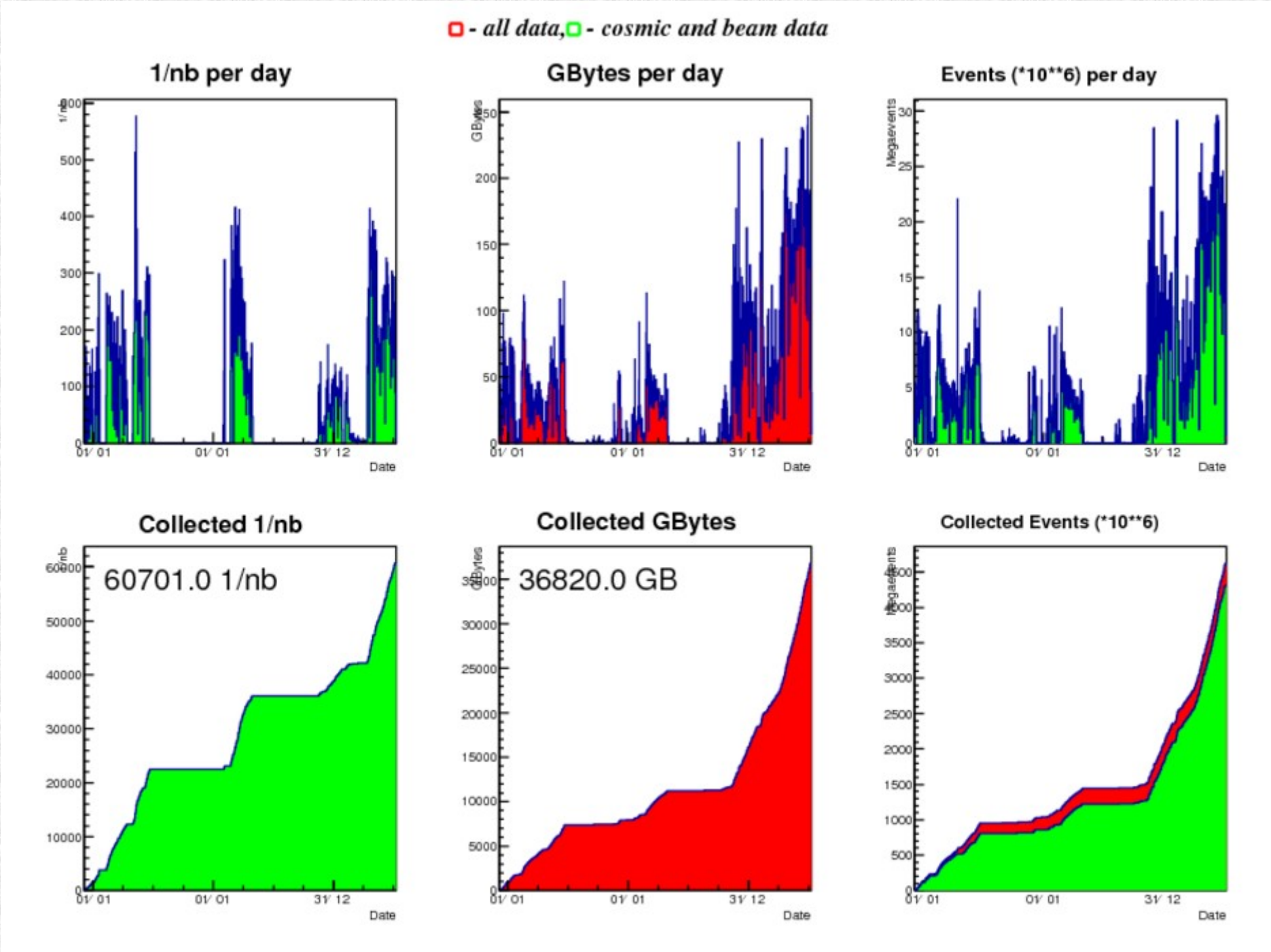
L = 24.39 m
facc= 172 MHz
Vacc= 120 kV
E=0.2 – 1 GeV
Bbend = 2.4 T
Bsol = 13 T
β*=2 – 10 cm
σs = 3 cm
ε=1.4•10-7mrad
vx,z= 2.1; 4.1
α= 0.036
ξ = 0.15
N± = 1011
L=1•1032cm-2s-1

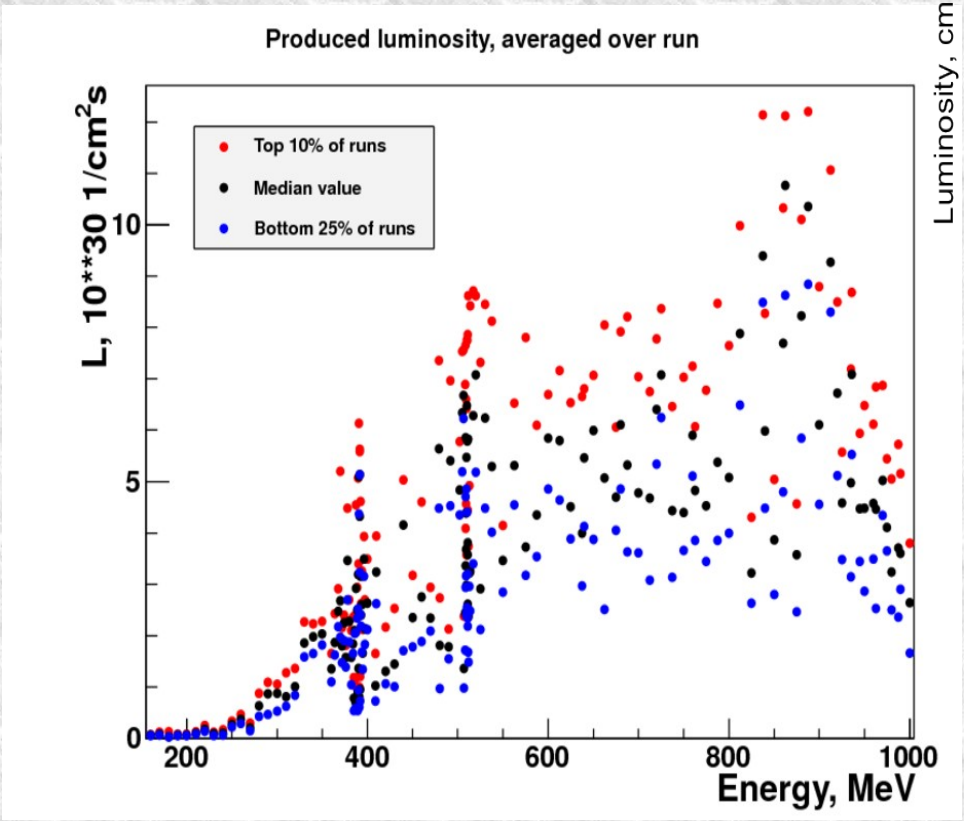


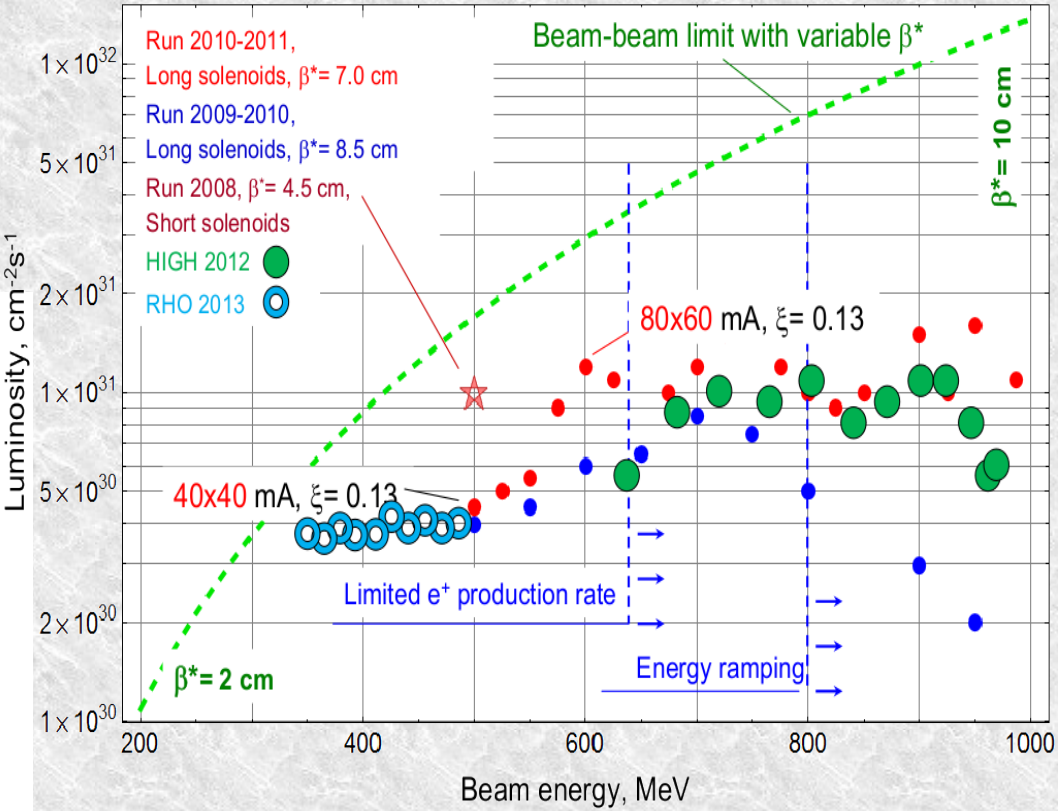

Neutron form factor
0.6
0.4
0.2
0
2
2.2
2.4
E (


Proton form factor
0.8
0.6
0.4
0.2
BABAR
PS170
FENICE
DM1
1.9
1.925
1.95
1.975
M_{pp} (GeV/c^2)

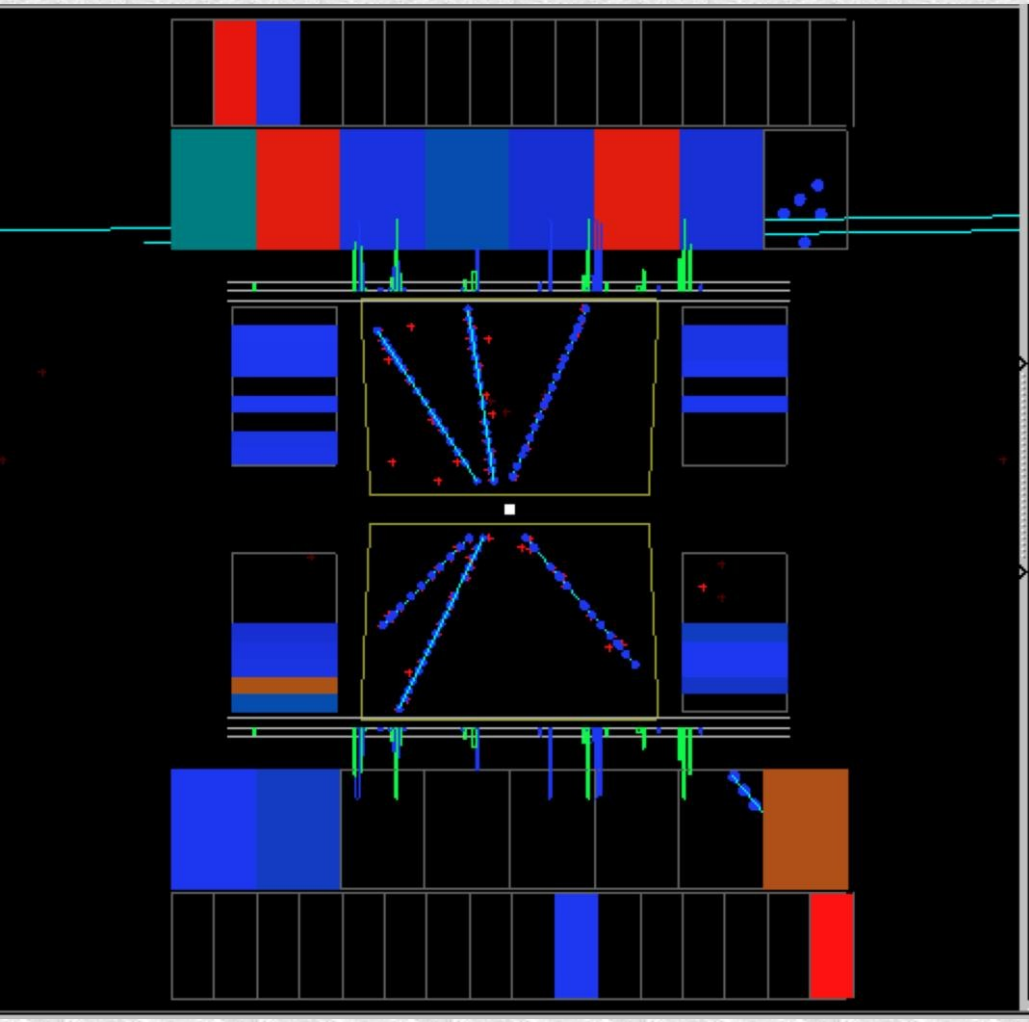

$|G_E/G_M|$
2.5
2
1.5
1
0.5
0
BABAR
LEAR
2
2.25
2.5
2.75
3
M_{pp} (GeV/c^2)

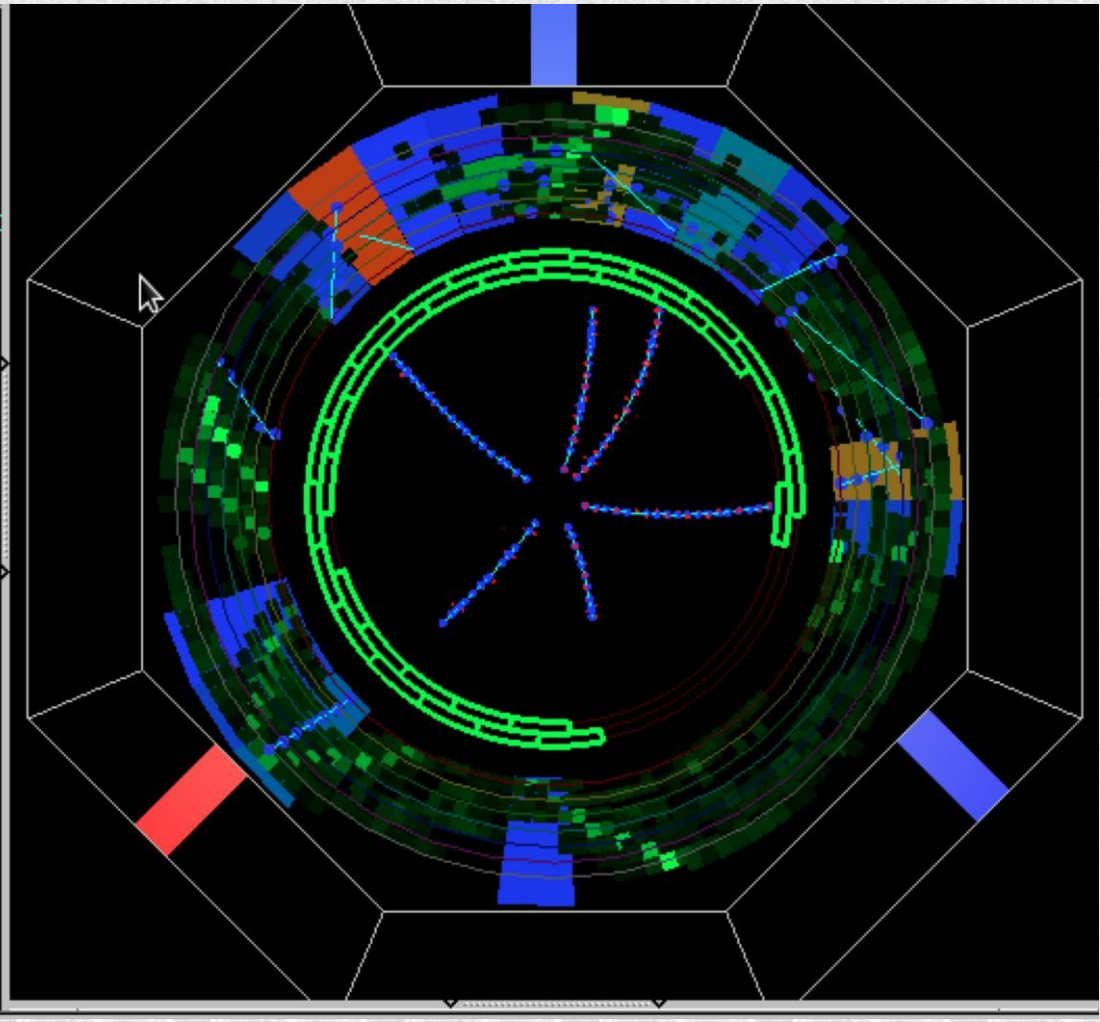

- all data, - cosmic and beam data
1/nb per day
GBytes per day
Events (*10**6) per day
Collected 1/nb
60701.0 1/nb
Collected GBytes
36820.0 GB
Collected Events (*10**6)
Date

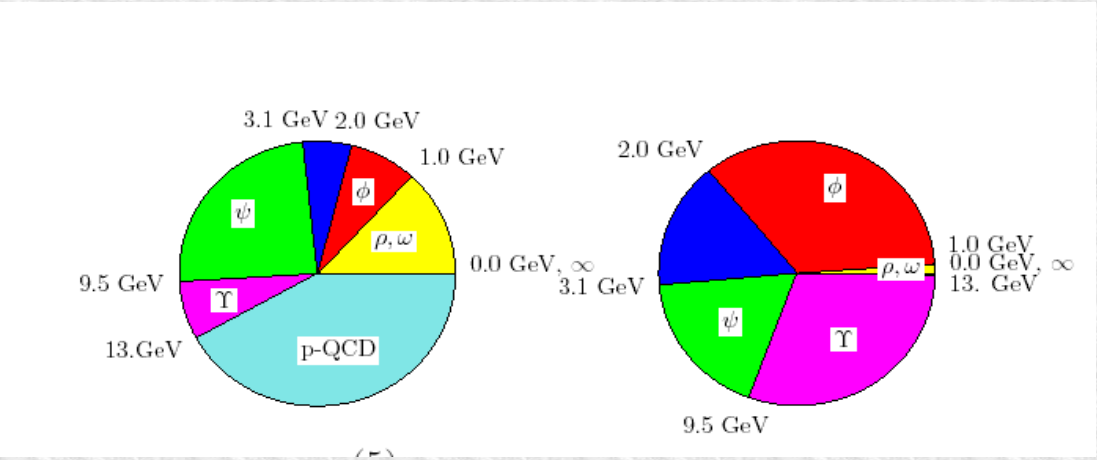

Produced luminosity, averaged over run
Top 10% of runs
Median value
Bottom 25% of runs
L, 10**30 1/cm²s
Energy, MeV


Run 2010-2011,
Long solenoids, β*= 7.0 cm
Run 2009-2010,
Long solenoids, β*= 8.5 cm
Run 2008, β*= 4.5 cm,
Short solenoids
HIGH 2012
RHO 2013
Beam-beam limit with variable β*
β*= 10 cm
80x60 mA, ξ= 0.13
40x40 mA, ξ= 0.13
Limited e⁺ production rate
Energy ramping
β*= 2 cm
Luminosity, cm⁻²s⁻¹
Beam energy, MeV

π+π-π+π-π+π-







$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$$

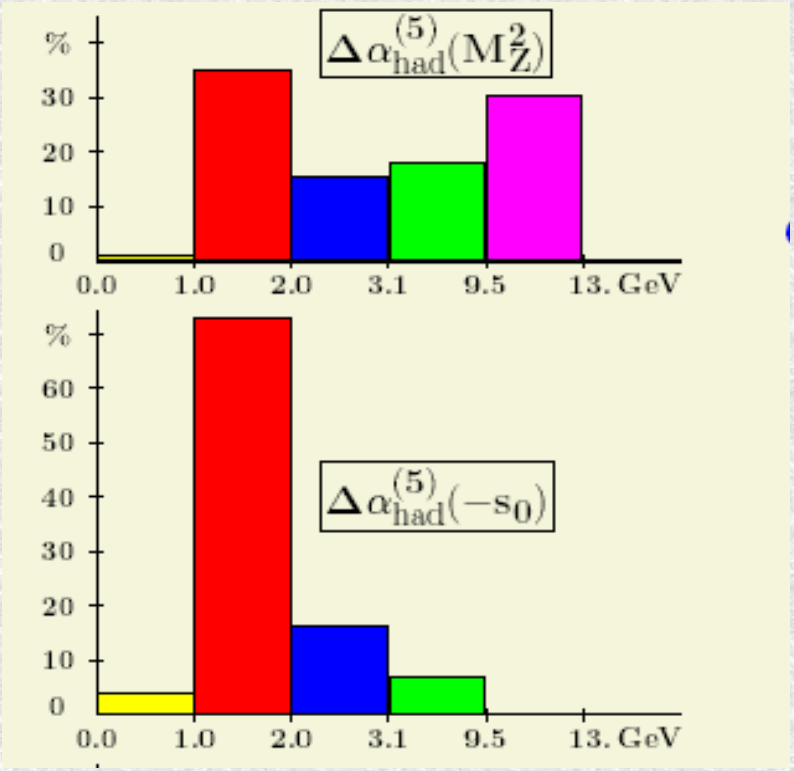
$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$$

FJ08

δa(MZ)/a(MZ)~2x10-4 → 5x10-5

Requirement from ILC (4x improvement) !

Direct integration of energy points



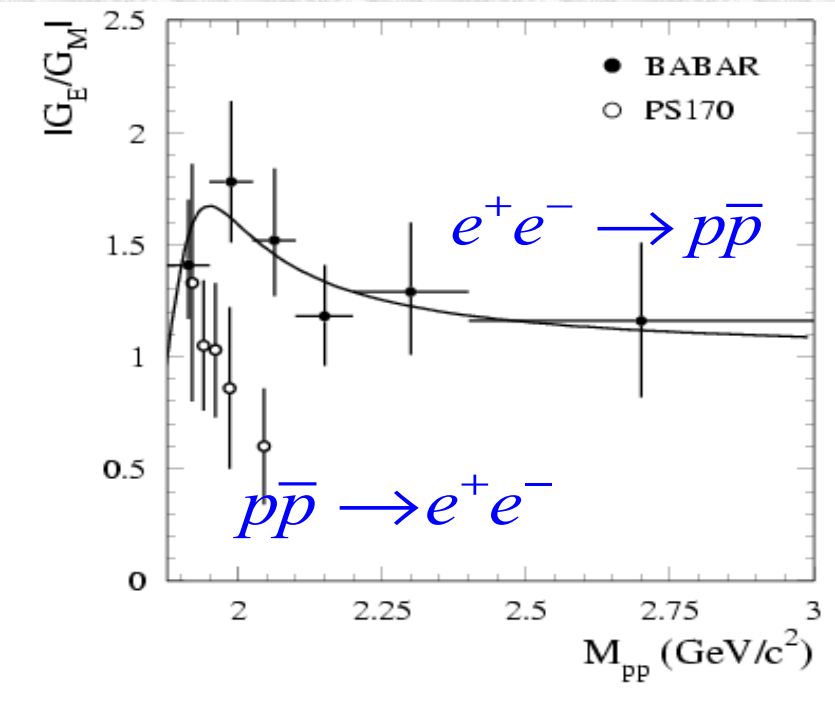
Use of Adler function
(It allows to use safely pQCD down to 2.5 GeV)

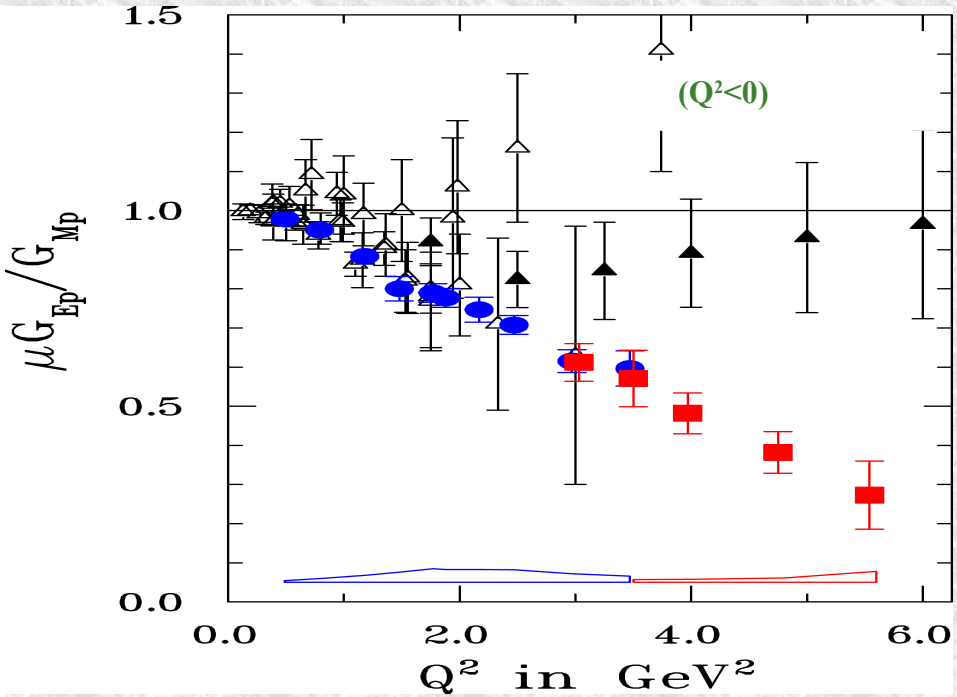
2 nucleons on threshold

e+e- → p anti-p

Spacelike region

$e^- p \longrightarrow e^- p$





pQCD prediction

GpE(q2)/GpM(q2)(|q2|→∞)→-1

Radiative corrections of polarization technique

<<Radiative corrections in Rosenbluth method