Measurement of hadronic cross-sections at low energy e+e- colliders

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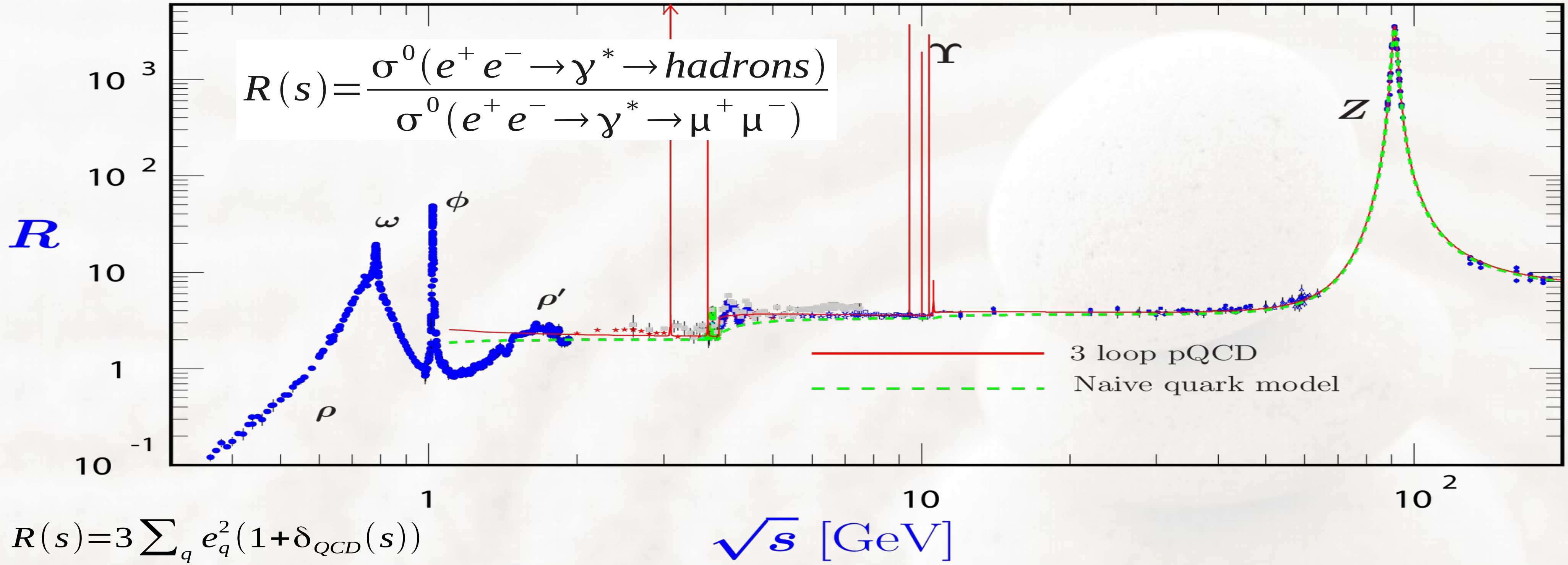
HADRON2019, Guilin, China

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;

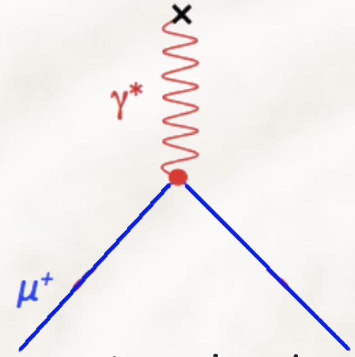
QCD sum rules → quark masses,quark and gluon condensates, Λ_{QCD}

Dispersion relations → $\alpha_{QED}(M_Z)$, hyperfine muonium splitting, muon (g-2)

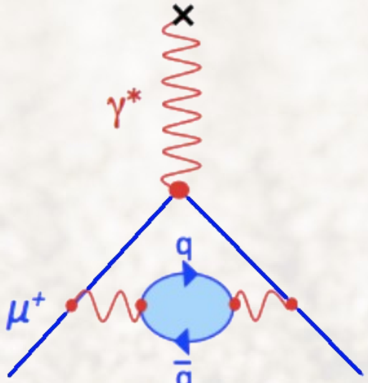
What is g-2 and how it connect to R(s)

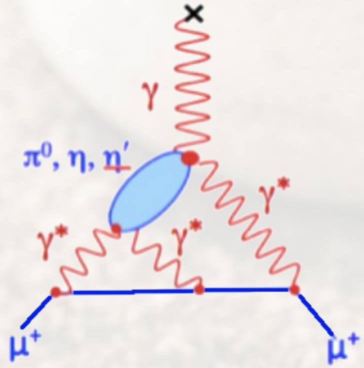
The magnetic moment of the particle relates spins to its angular momentum via the gyromagnetic ratio, g: $\vec{\mu} = g \frac{e}{2m} \vec{s}$

In Dirac theory, point-like, spin ½ particle has exactly g=2



Quantum loop effects via vacuum fluctuations lead a calculable deviation:
the anomalous magnetic moment a = (g-2)/2 ~ $\alpha/2\pi$ ~ 0.00116





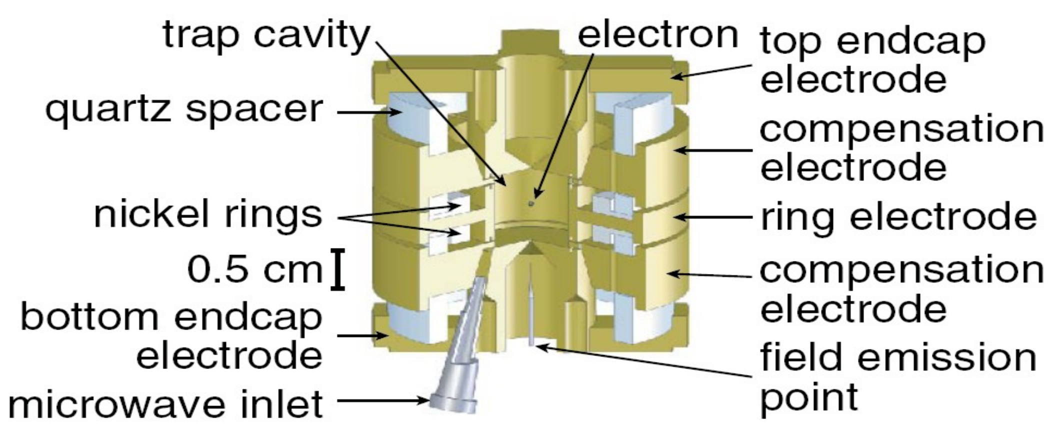
g-2 Experiments

$$\vec{\mu} = g\frac{e}{2m}\vec{s}, g = 2(1+a)$$

a_e = 11 596 521.8073 (0.0028) 10^{-10}[0.24ppb]

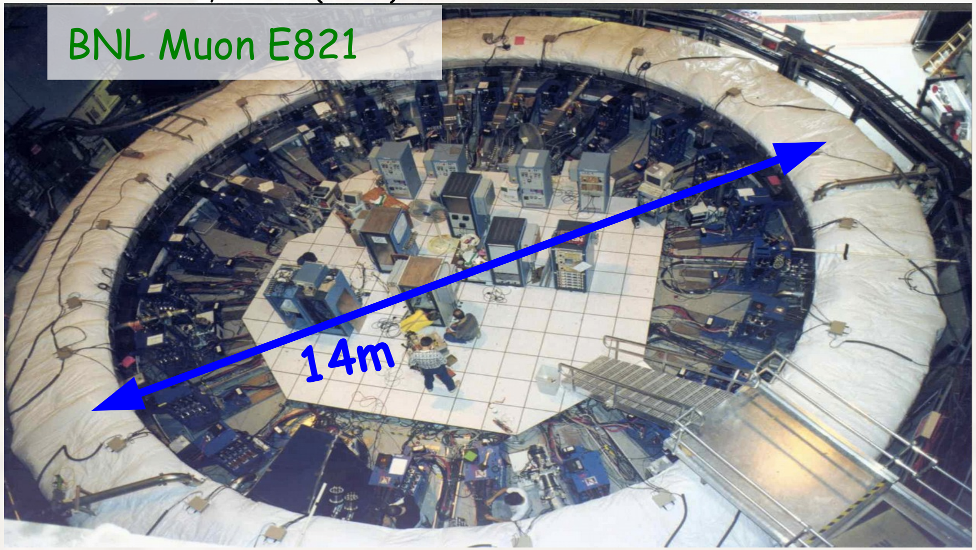
a_μ = 11 659 208.9(6.3) 10^{-10}[0.54ppm]

Hanneke, Fogwell, Gabrielse, PRL 100(2008)120801



Harvard Univ. One electron quantum cyclotron

Bennet et al., PRD 73(2006)072003



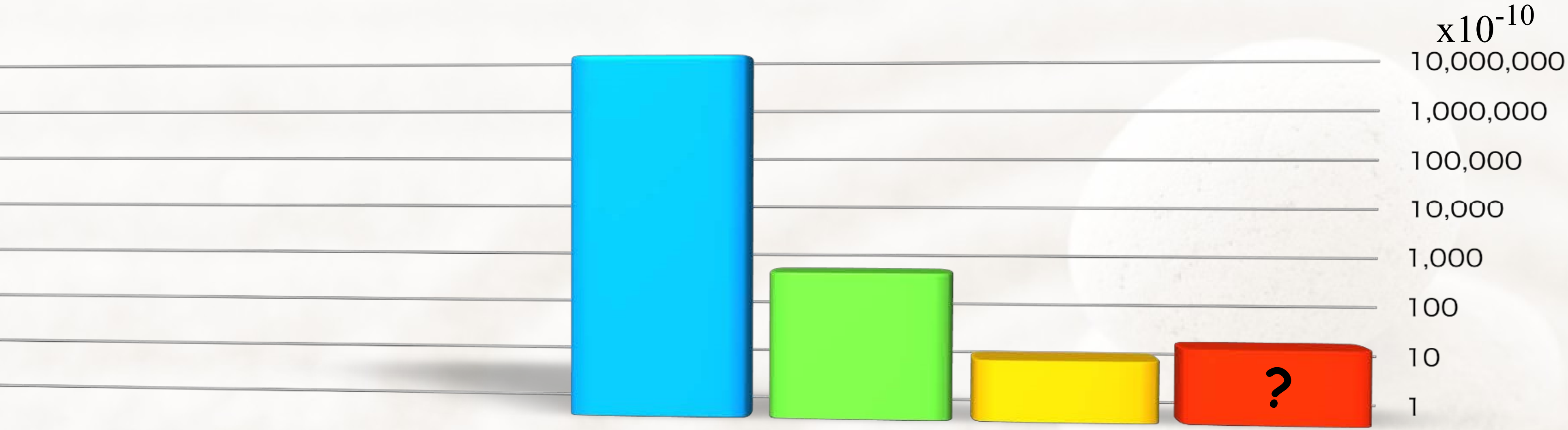
The value of a_e was used to get the best determination of fine-structure constant α.

R. Parker et al., Science 360 (2018) 191

Recent α_{QED} measurement using the recoil frequency of Cs-133 atoms with 0.20ppb gives 2.5σ tension with experimental a_e

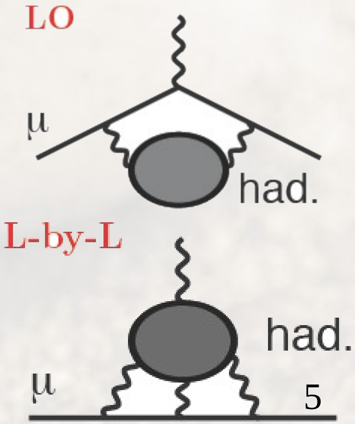
Muon (g-2) is 40,000 times more sensitive to non-QED fields than electron (g-2) ~ $(m_\mu/m_e)^2$, providing more sensitive probe for New Physics.

Muon g-2 theory SM



$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

Precisions: 7 ppb HVP: 210ppb 9ppb < 2300ppb
+ LbL: 220ppb



QED: Kinoshita et al., 2012: up to 5 loops (12672 diagrams), EW: 2 loop

Hadronic: HVP: the value is based on the hadronic cross-section e+e- data;

LBL: model-dependent calculations; mesuarement of transition formfactors can help, improvement is expected from lattice calculations

New g-2 experiments at FNAL, J-PARC: 540 → 140 ppb

The lowest-order hadronic contribution

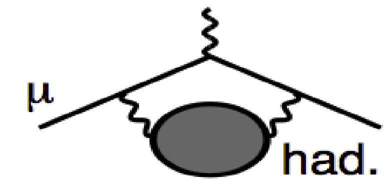
The hadronic contribution is calculated by integrating experimental cross-section σ(e+e- → hadrons).

Starting at high energy the pQCD estimation of σ(e+e- → hadrons) is used. At lower energies only the experimental data can be used.

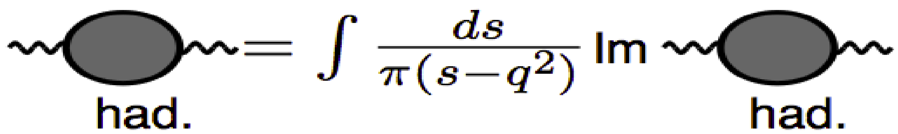
Weighting function ~ $1/s^2$, therefore lower energies contribute the most:

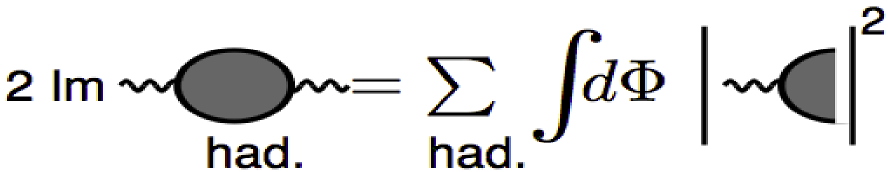
<2GeV gives 93% of the integral,
$\pi^+\pi^-$ gives the main contribution (73%) to a_μ

The diagram to be evaluated:



pQCD not useful. Use the dispersion relation and the optical theorem.



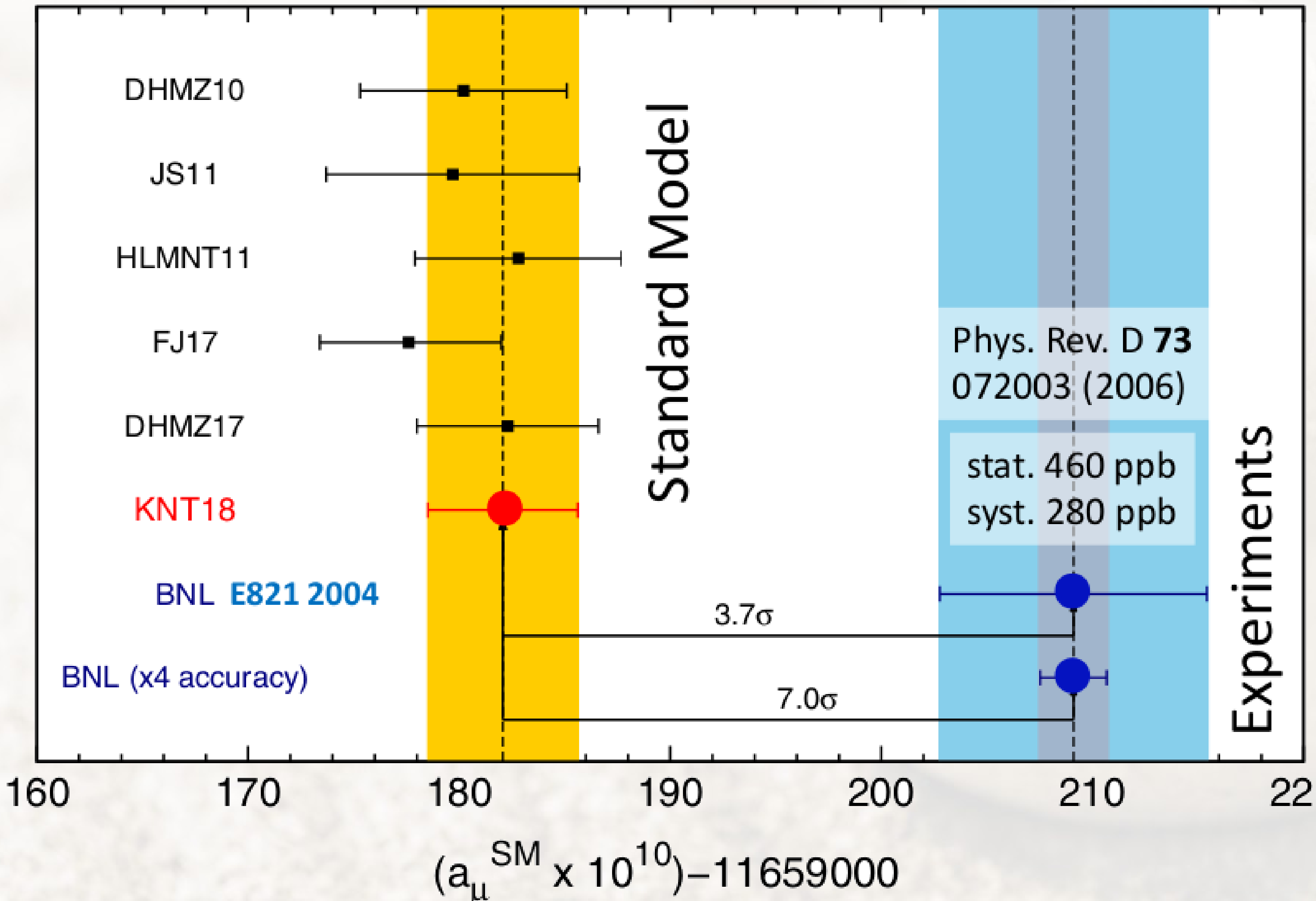


$$a_\mu^{had,\,LO} = \left(\frac{\alpha\, m_\mu}{3\,\pi}\right)^2 \int_{s_{th}}^{\infty} \frac{1}{s^2}\, \tilde{K}(s)\, R(s)\, ds$$

$$\tilde{K}(s) = 0.6 \div 1.0$$

SM prediction for muon g-2

A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D 97, 114025 (2018)



Δ (Exp - Theory) ~ 3-4 σ

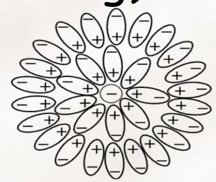
$\alpha_{QED}(M_Z)$ from R(s)

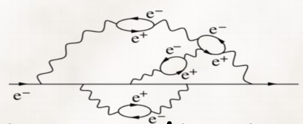
The electromagnetic fine structure constant $\alpha_{QED}(q^2)$ is a running parameter with momentum transfer q^2 due to Vacuum Polarization effects

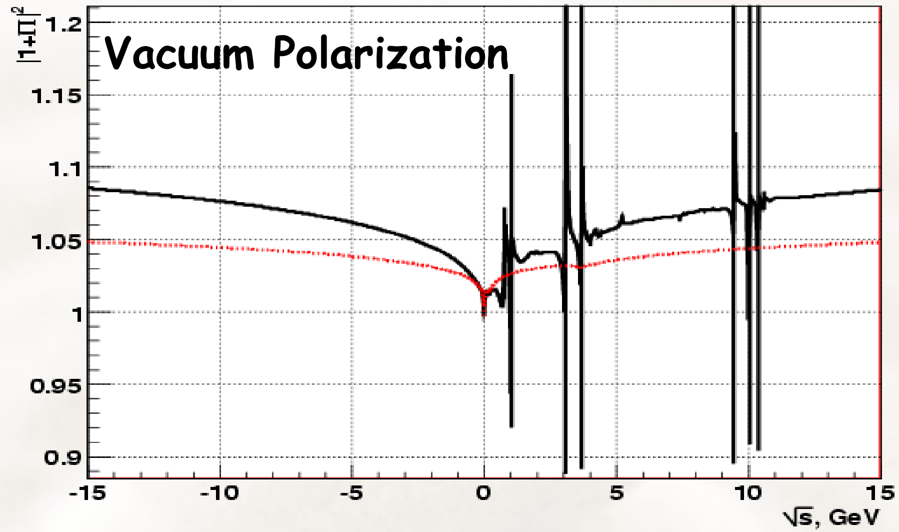
-effective electron charge (charge screening)

$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)},$$

$$\Delta\alpha_{had}(s) = -\frac{\alpha(0)s}{3\pi}\int_0^\infty ds' \frac{R(s')}{s'(s'-s)-i\epsilon}$$







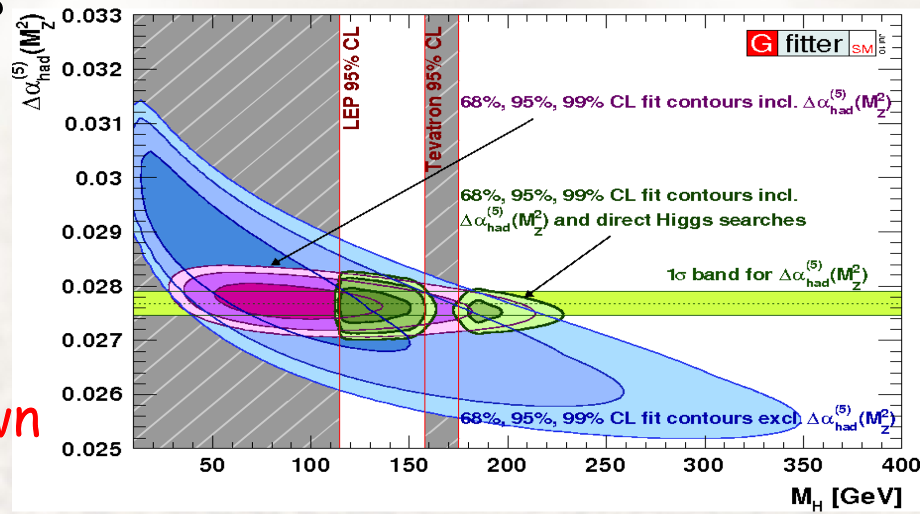
The $\alpha_{QED}(q^2)$ at mass of Z is used in predictions of electroweak model.

It is the least known EW parameter like

$\delta G_\mu/G\mu \sim 0.9\times10^{-5}$, $\delta M_z/M_z \sim 2.4\times10^{-5}$

$\Delta\alpha_{QED}^{5had}(M_Z) \quad = 276.11 \pm 1.11 \times 10^{-4}$

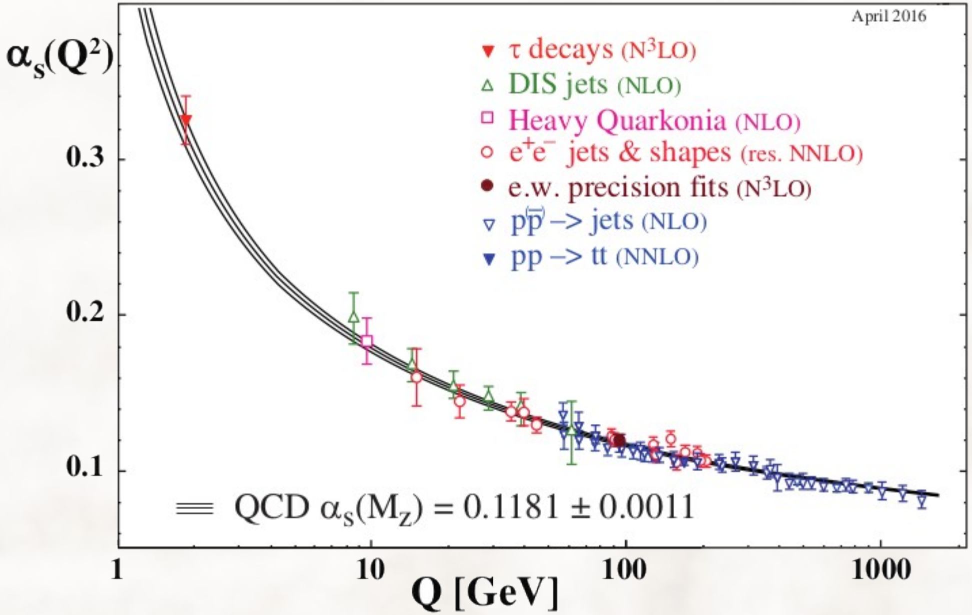
For future ILC, CLIC, FCC-ee it should be known with ~ 0.5-0.3 × 10^{-4}

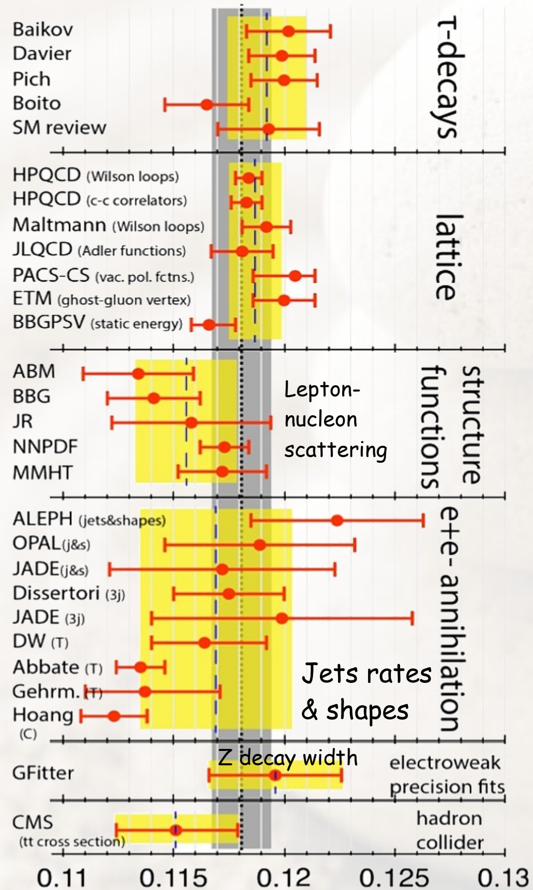


Eur.Phys.J. C74 (2014) 3046

Current PDG α_s world average (NNLO)

Particle Data Group '18





class averages:

$\alpha_s(M_Z)$ = 0.1192 ± 0.0018 (±1.5%)

$\alpha_s(M_Z)$ = 0.1184 ± 0.0012 (±1.0%)

$\alpha_s(M_Z)$ = 0.1156 ± 0.0021 (±1.8%)

$\alpha_s(M_Z)$ = 0.1169 ± 0.0034 (±2.9%)

$\alpha_s(M_Z)$ = 0.1196 ± 0.0030 (±2.5%)

$\alpha_s(M_Z)$ = 0.1151 ± 0.0028 (±2.5%)

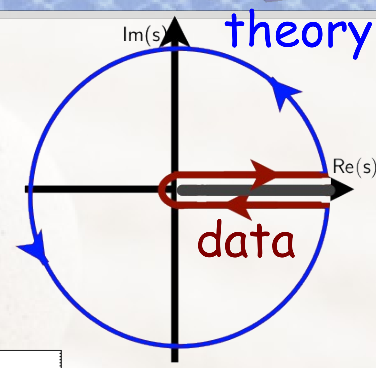
unweighted χ^2 average: $\alpha_s(M_Z)$ = 0.1181 ± 0.0011 (±0.9%)

Tau decays to hadrons give the best non-lattice α_s estimation

Sum rules

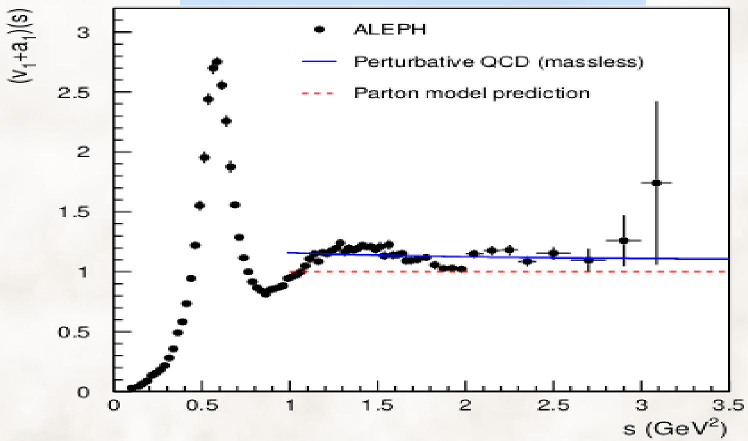
From analyticity and using Cauchy's theorem

$$\frac{1}{12\pi^2 s_0}\int_0^{s_0} ds\, w(s/s_0)R(s) = -\frac{1}{2\pi i s_0}\oint_{|z|=s_0} dz\, w(s/s_0)\Pi(z)$$

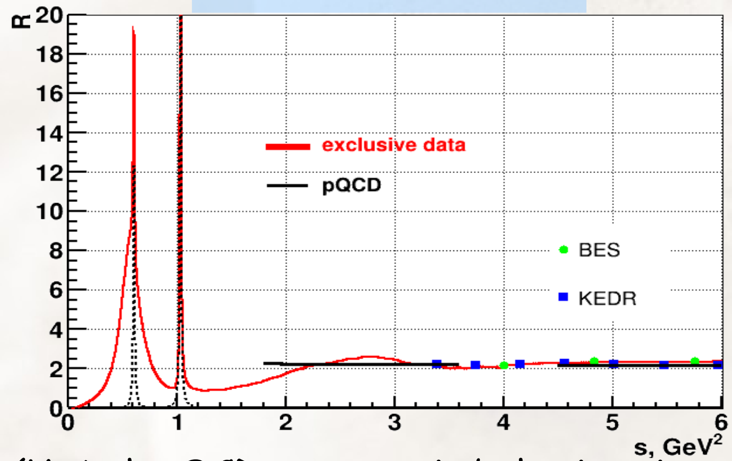


Integrated R(s) with different weights (pinched at s_0 where OPE is under question, w(y)~(1-y))

$\tau \to \nu$ + hadrons



e+e- → hadrons



$\tau \to \nu$ + hadrons limited until = 1.77 GeV (V+A the QCD asymptotic behaviour is reached faster)

e+e- → hadrons can be extended to upper s_0 limits

M.Davier et al., arXiv:1312.1501

$\alpha_s(m^2_\tau)$ = 0.332 ± 0.005_{exp} ± 0.011_{theo}

(± 0.006 DV,higher order ± 0.009 FOPT vs CIPT)

$\alpha_s(m^2_Z)$ = 0.1199 ± 0.0015 (±1.3%)

D.Boito et al. , arXiv:1805.08176

$\alpha_s(m^2_\tau)$ = 0.301 ± 0.017_{exp} ± 0.007_{theo}

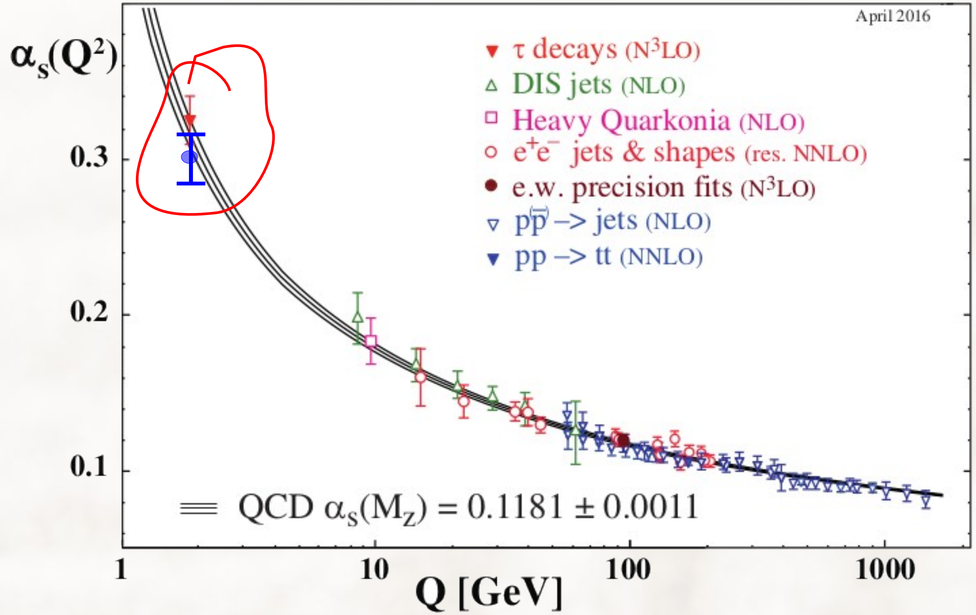
(± 0.005 DV ± 0.003 higher orders ± 0.003 FOPT vs CIPT)

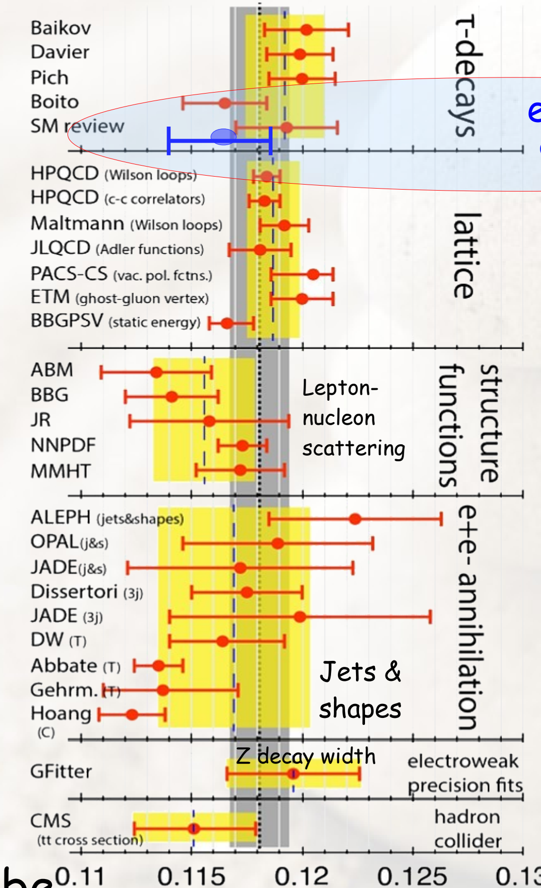
$\alpha_s(m^2_Z)$ = 0.1162 ± 0.0025 (±2.1%)

e+e-: Limited by data, Difference between FO and CIPT ~3 times smaller than in tau decays

Current PDG α_s world average (NNLO)

Particle Data Group '18





class averages:

$\alpha_s(M_Z) = 0.1192 \pm 0.0018$ (±1.5%)

e+e- → hadrons $\alpha_s(M_Z) = 0.1162 \pm 0.0025$ **(±2.1%)**

$\alpha_s(M_Z) = 0.1184 \pm 0.0012$ (±1.0%)

$\alpha_s(M_Z) = 0.1156 \pm 0.0021$ (±1.8%)

$\alpha_s(M_Z) = 0.1169 \pm 0.0034$ (±2.9%)

$\alpha_s(M_Z) = 0.1196 \pm 0.0030$ (±2.5%)

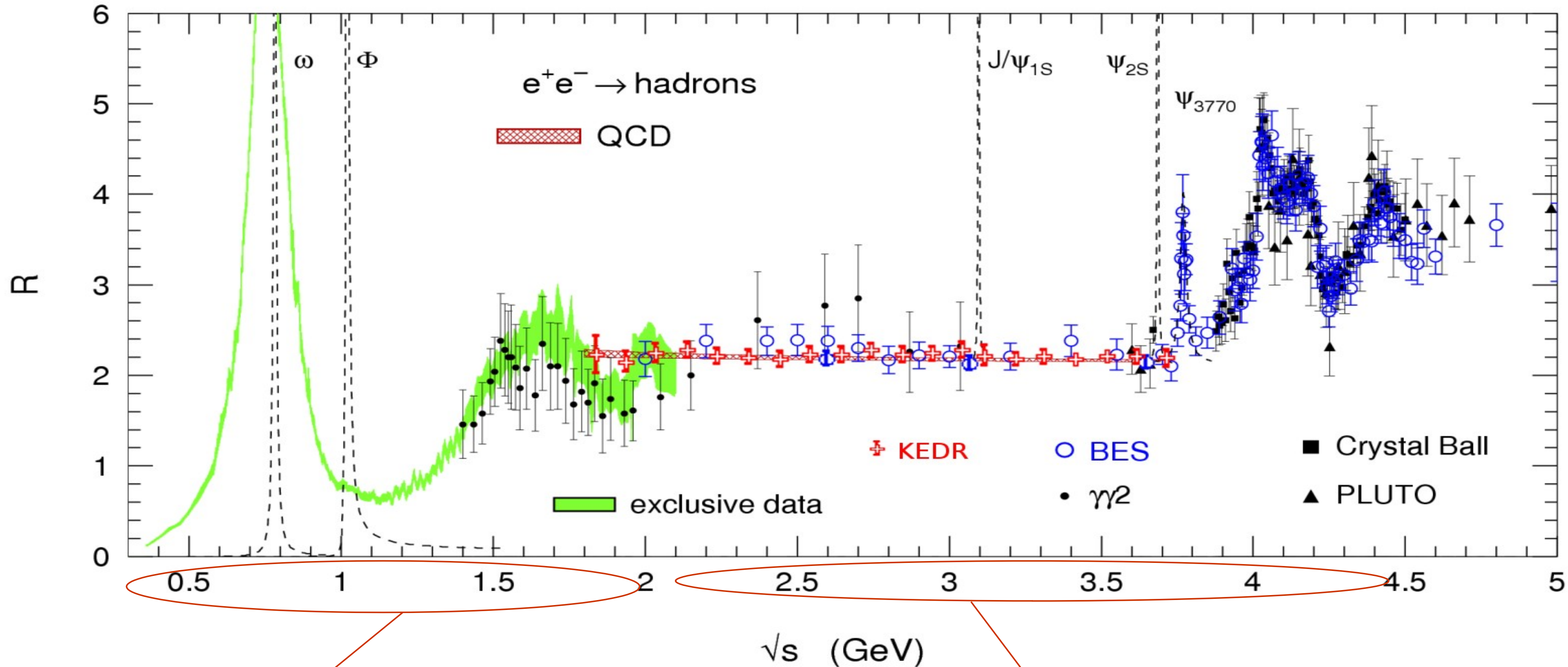
$\alpha_s(M_Z) = 0.1151 \pm 0.0028$ (±2.5%)

unweighted χ^2 average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (±0.9%)

Tau decays to hadrons give the best non-lattice α_s estimation

In future jump in precision (<0.2%) can be obtained from W,Z decays with huge statistic (x10^4-10^5 LEP) at FCC-ee

Inclusive vs exclusive measurements



Exclusive approach:

✗ measure each final state separately and calculate the sum
VEPP-2M, VEPP-2000, Babar, KLOE

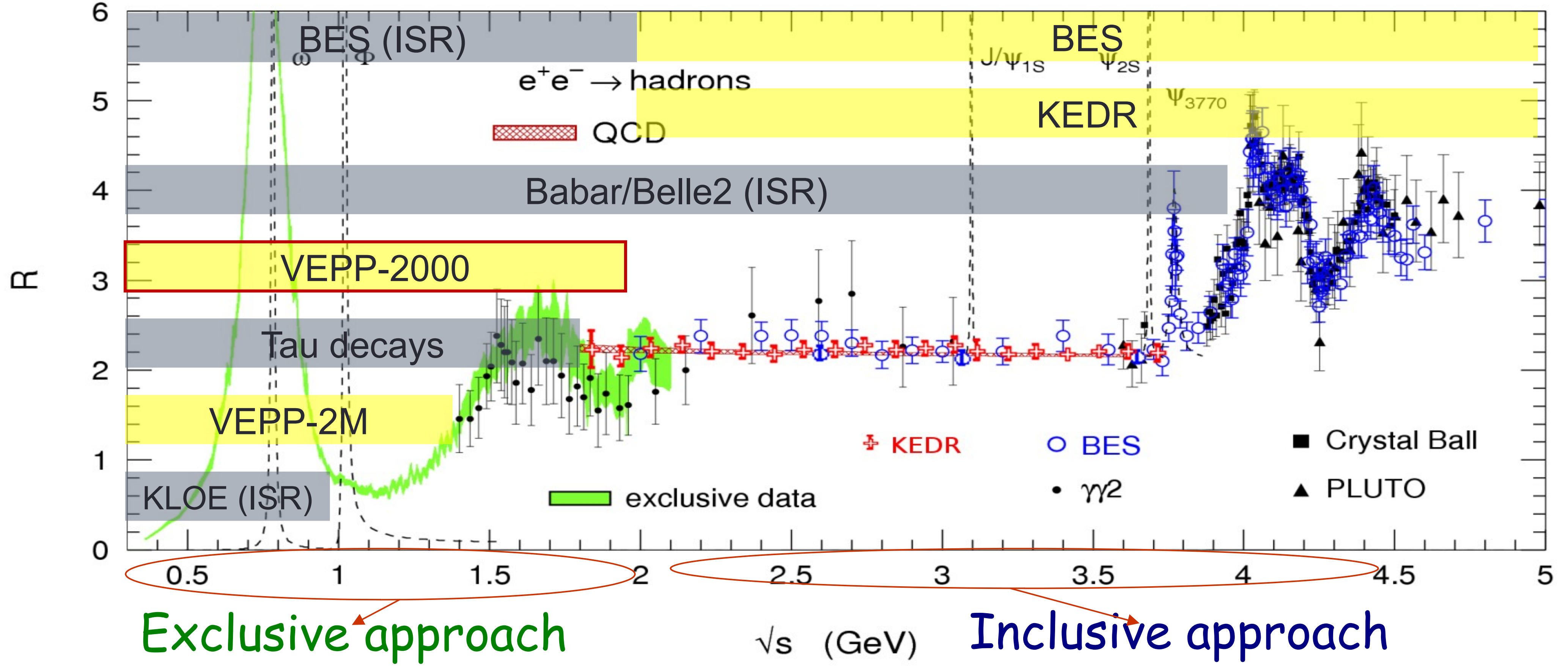
✗ gives better precision

Inclusive approach:

✗ select events with any hadron(s) in the final state
BES, KEDR, etc

✗ possible because of many modes and high track multiplicity

R measurements



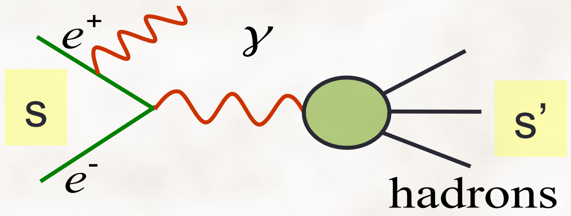
VEPP-2000: direct exclusive measurement of σ (e+e- → hadrons)
Only one working these days on scanning below <2 GeV
World-best luminosity below 2 GeV (except 1 GeV – where KLOE outperfomed everybody)

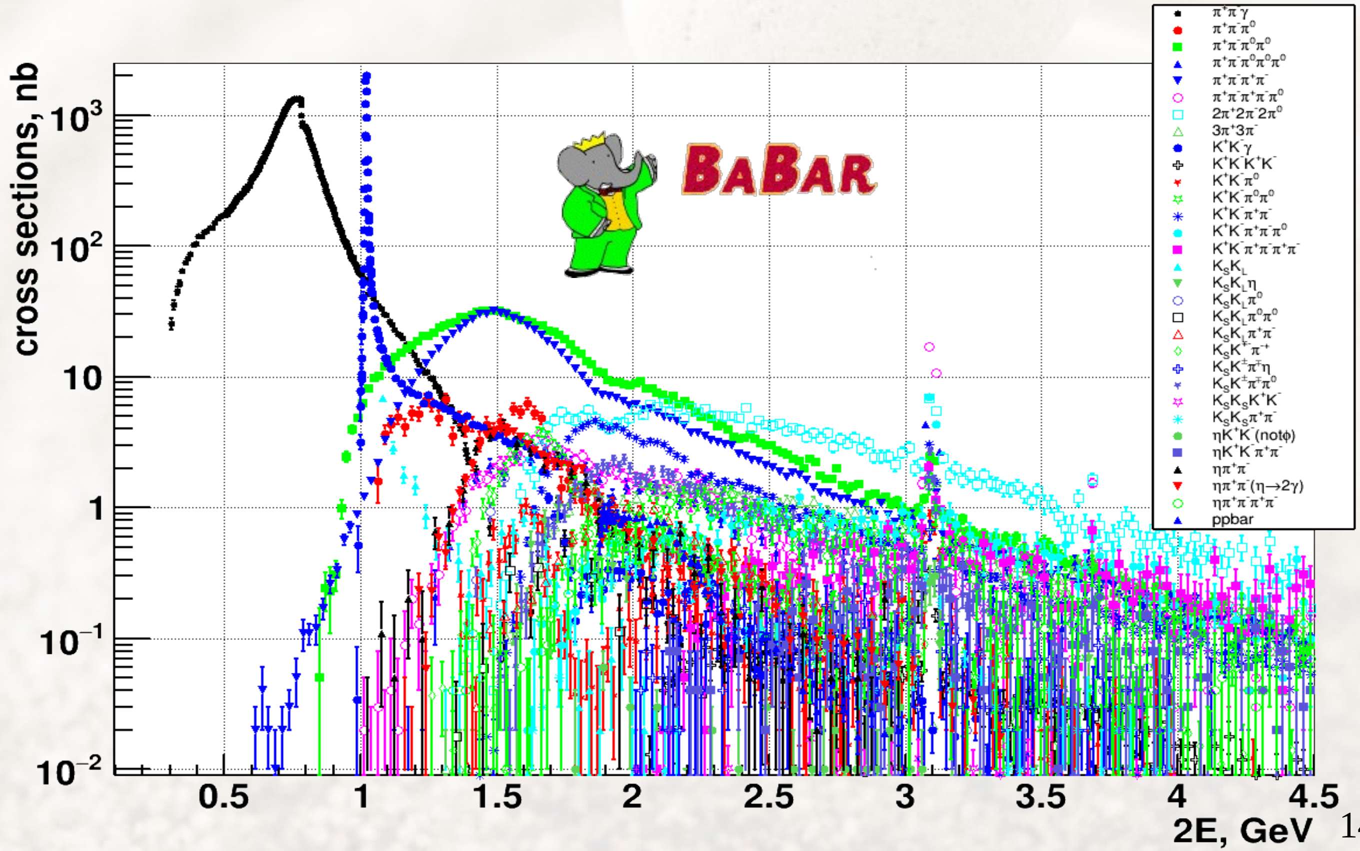
BESIII, KEDR – direst scan from 2 GeV to 5 GeV

ISR approach

Additional approach to measurement of the hadronic cross-sections was fully developed over last decades: ISR (Initial State Radiation), advanced by BaBar and KLOE.

$$d\sigma(e^+e^- \to \text{hadrons} + \gamma) = H(Q^2,\theta_\gamma) \times d\sigma(e^+e^- \to \text{hadrons})$$





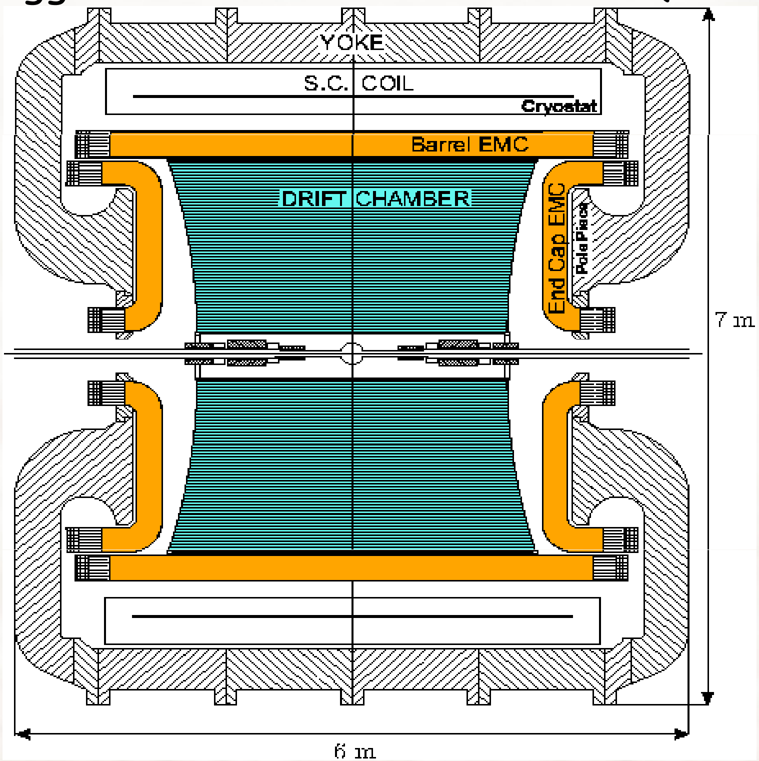
Main idea: cross-section is measured in the wide energy range, using events with hard photon, emitted by initial particles.

KLOE ISR+ VP

KLOE experiment

(2000 – 2006,2014 – 2018)

biggest Drift Chamber ever built (Ø4m)



KLOE results by Dr. Xiaolin Kang:
KLOE results by Dr. Xiaolin Kang:
Presentation for η decays & γγ physics
Presentation for η decays & γγ physics
Poster on ISR (e+e-→π+π-π0)
Poster on ISR (e+e-→π+π-π0)

Measurement with ISR

e+e- → π+π-γ

JHEP 1803 (2018) 173

3 analyses:

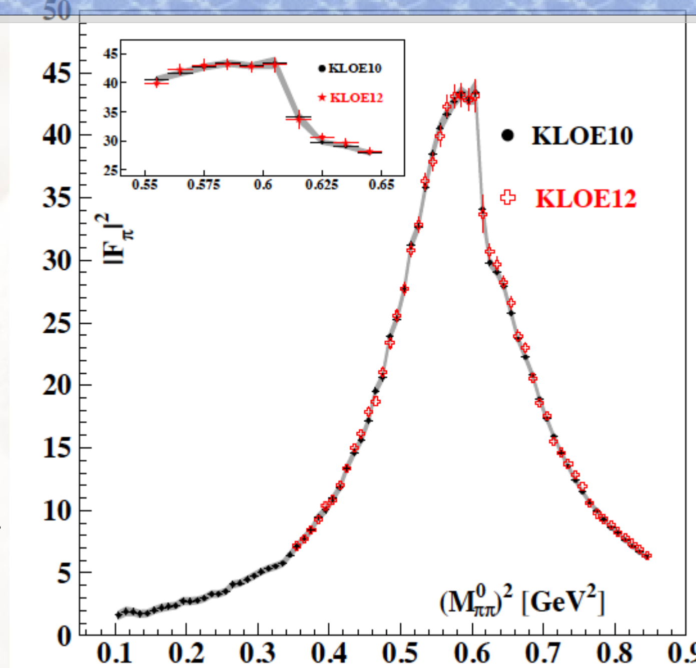
with ISR photon on small angles/ large angle/ using radiator function from ISR μ+μ-

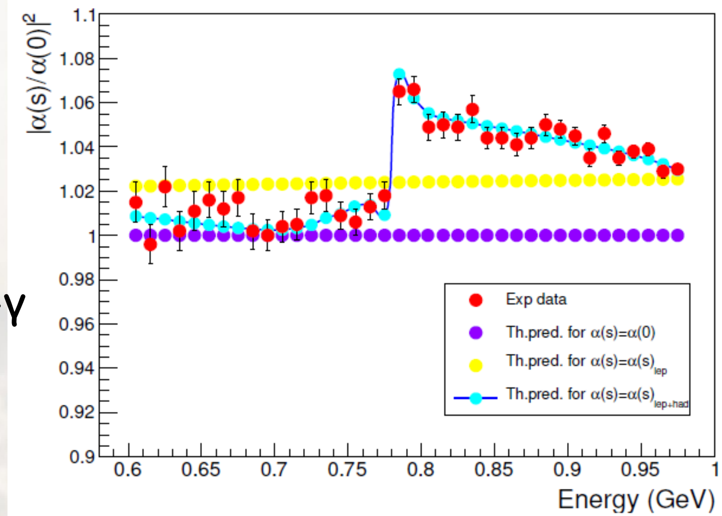
Best over experiments local precision at $s=0.5-0.85\ GeV^2$

direct extraction of

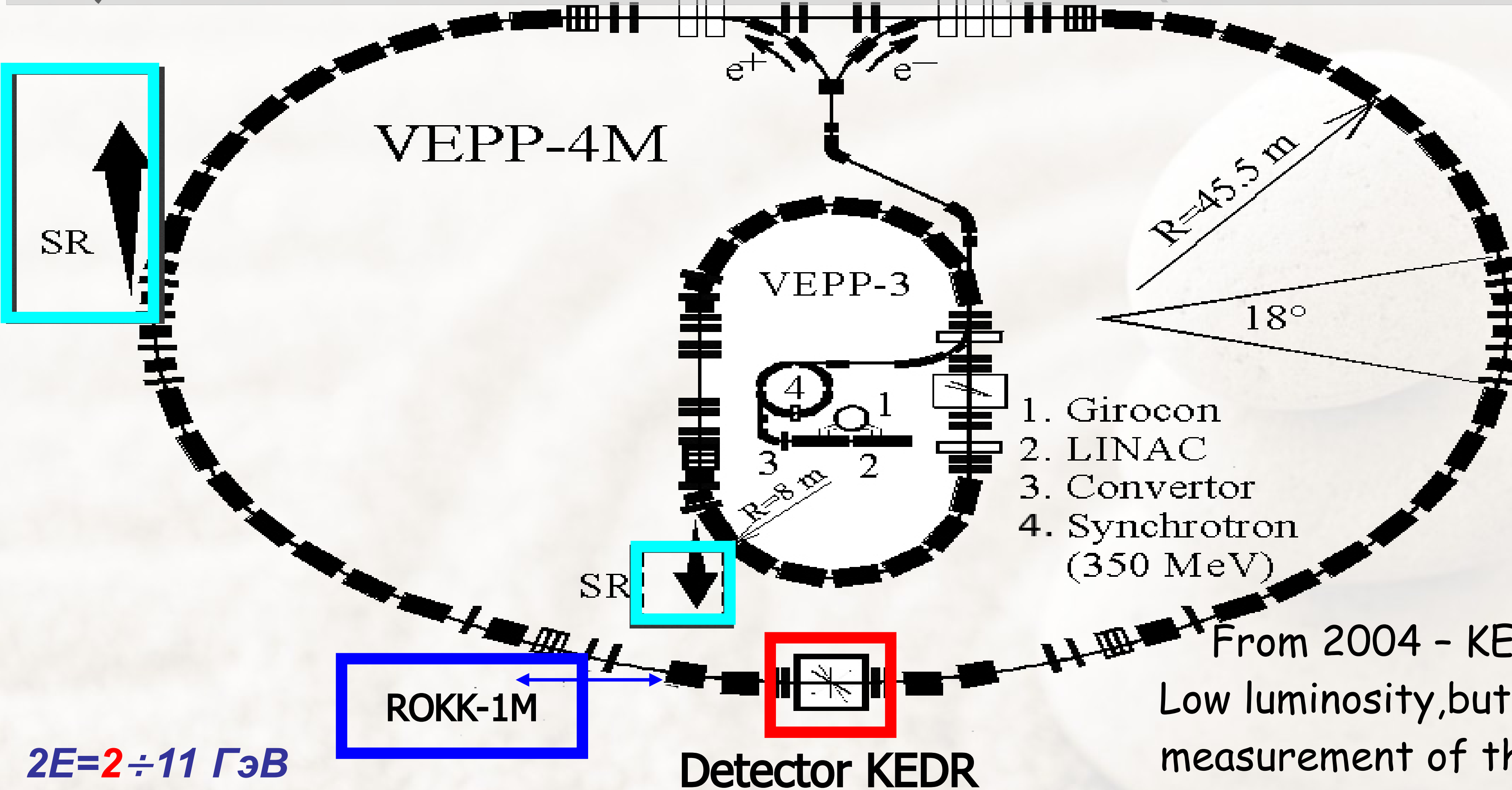
$\alpha_{QED}(s)$ via e+e- → μ+μ-γ

Phys. Lett. B, 767 (2017), 485





VEPP-4M Collider Complex (1994- 202?)



2E=2÷11 ГэВ

L=2x10**30 см-2с-1

L= 8x10**31 см-2с-1

From 2004 – KEDR experiment

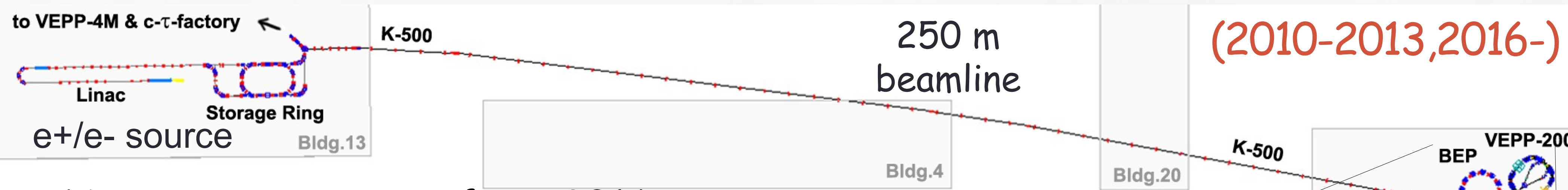
Low luminosity,but high precision measurement of the beam energy

J/ψ δm/m ~ 2e^{-6} (only 6 particles known better)

Best measurement of inclusive R(s), 2E<3.7 GeV with ~2% systematic precision

Few more years to do scan above charm region

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

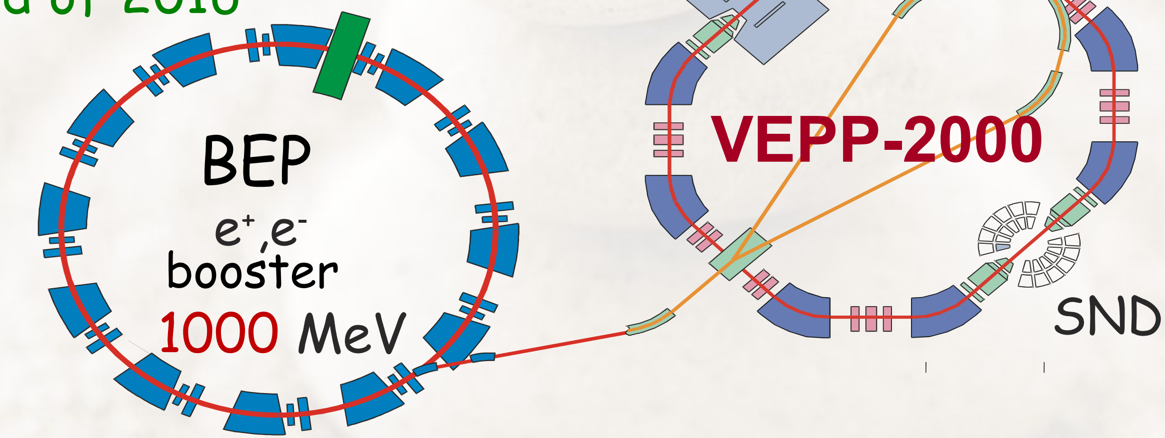


✗ New positron source from 2016

(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



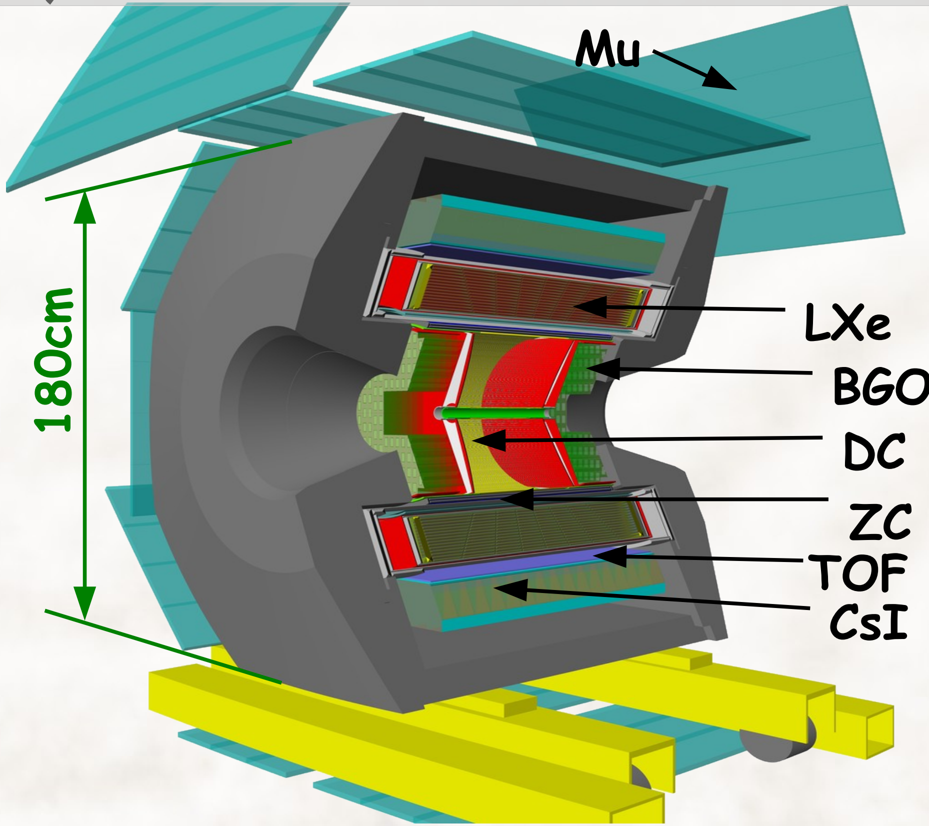
Maximum c.m. energy is 2 GeV, project luminosity is $L = 10^{32}$ $cm^{-2}s^{-1}$at 2E= 2 GeV

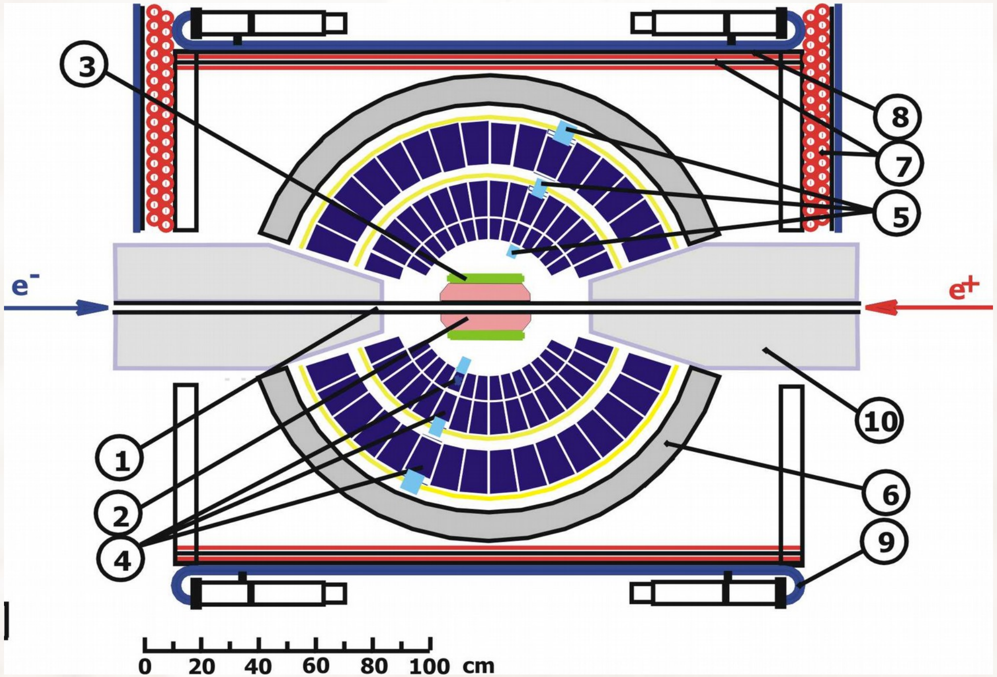
Unique optics, "round beams", allows to reach higher luminosity

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


VEPP-2000
collider ring
SND
CMD-3
6.65 m

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

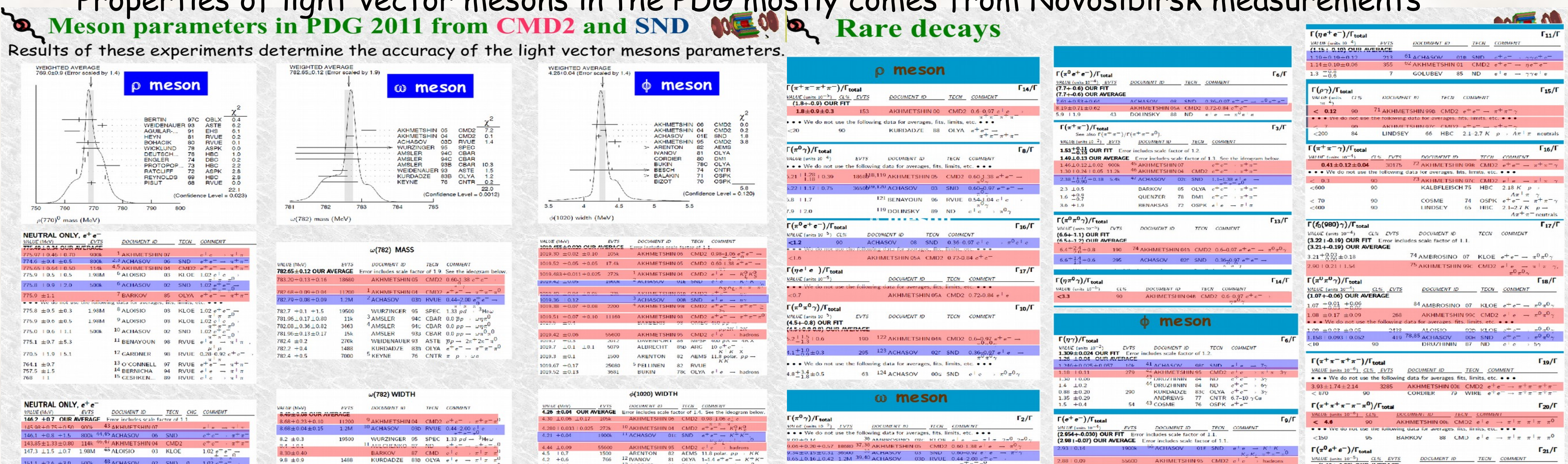
Physics at VEPP-2000

We are doing not only precise measurement of total R(s) = hadron production cross-section at low energies (by sum of exclusive channels).

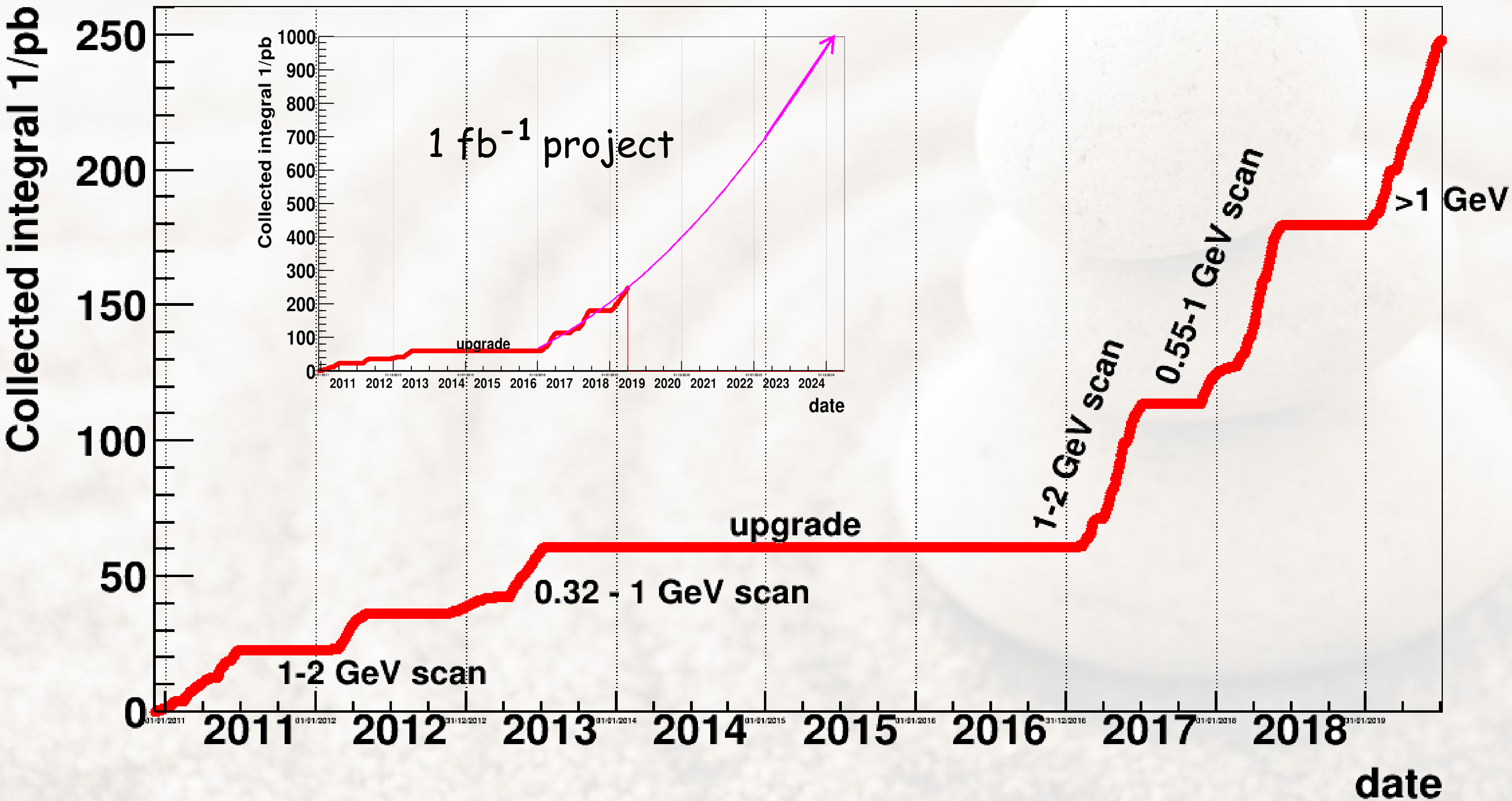
But also we do:

- ✗ study of production dynamics, ChPT
- ✗ properties of light vector mesons, their decays,
- ✗ nucleon formfactors at threshold,
- ✗ two photon physics,
- ✗ search of exotics,
- ✗ and so on…

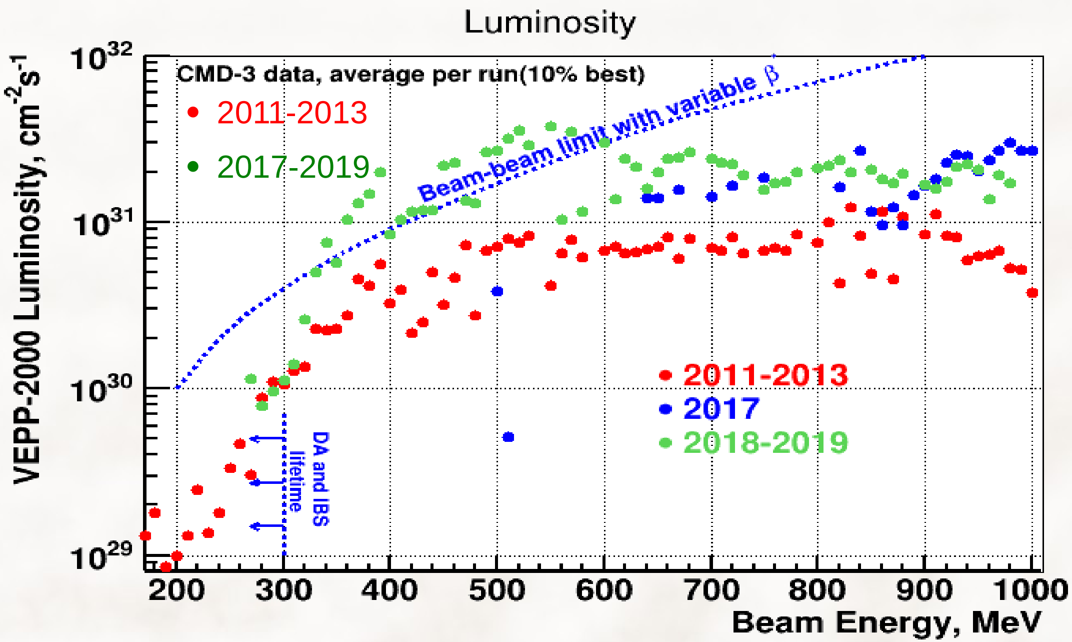
Properties of light vector mesons in the PDG mostly comes from Novosibirsk measurements

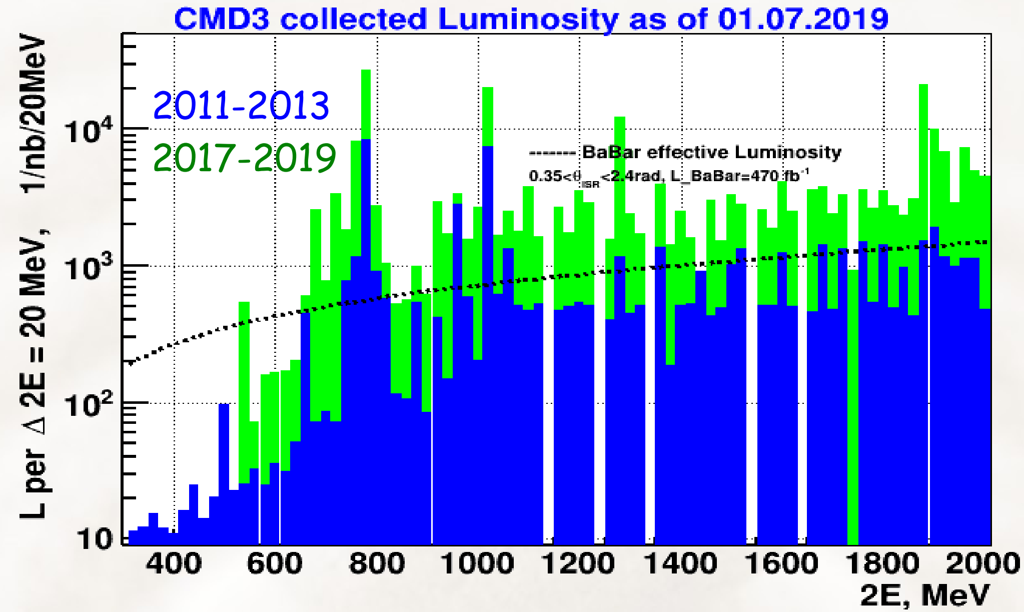


Overview of CMD-3 data taking runs



Collected Luminosity





Before VEPP-2000 upgrade (before 2013)

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

After upgrade

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

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

Collected since 12.2010

L ~ 250 pb^{-1} per detector

2011-2013 seasons:

17.8 pb^{-1} < 1 GeV

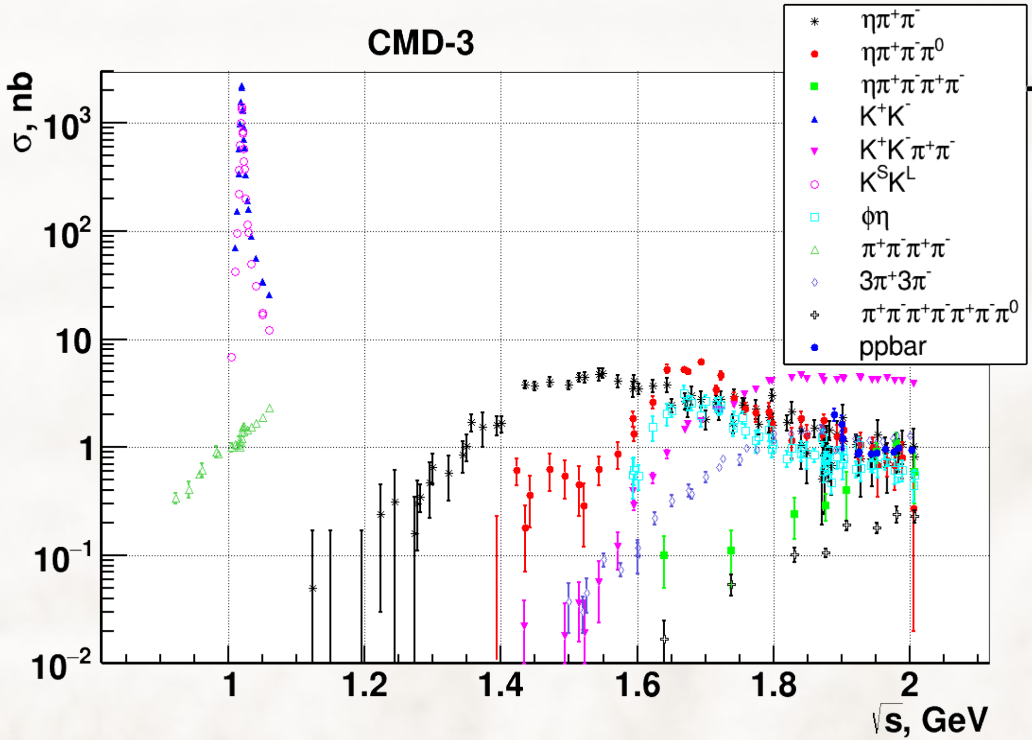
42.8 pb^{-1} > 1. GeV

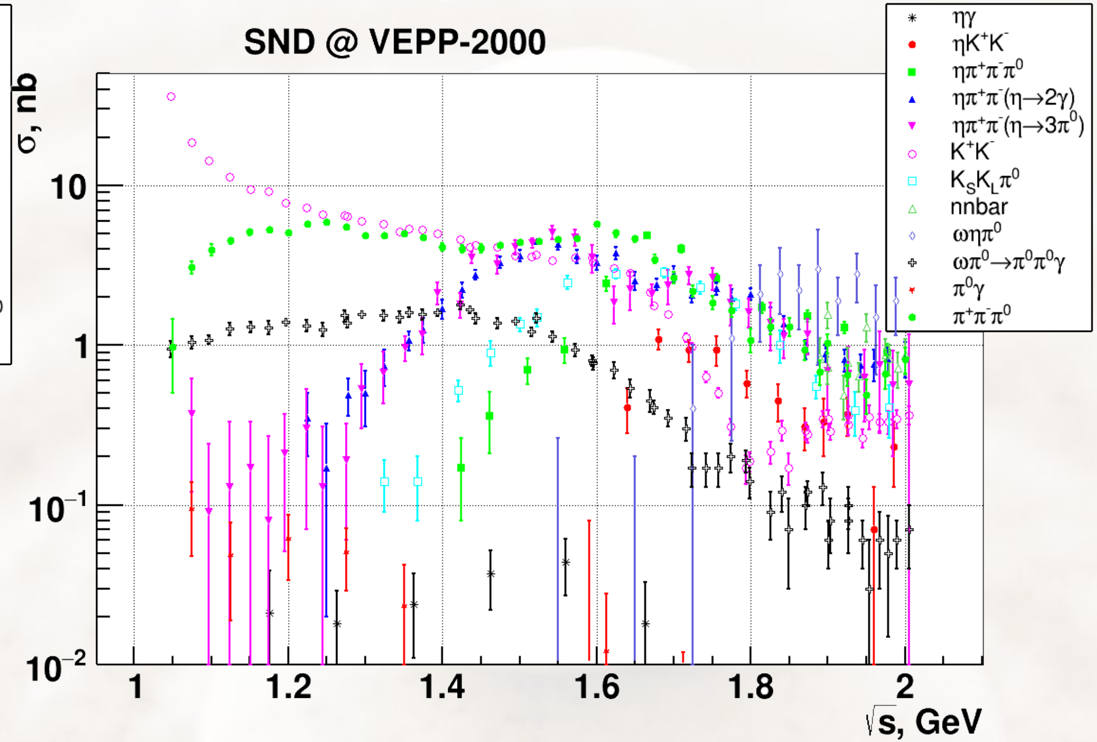
2017-2019 seasons:

45.4 pb^{-1} < 1 GeV

141.8 pb^{-1} > 1. GeV

CMD-3 & SND published



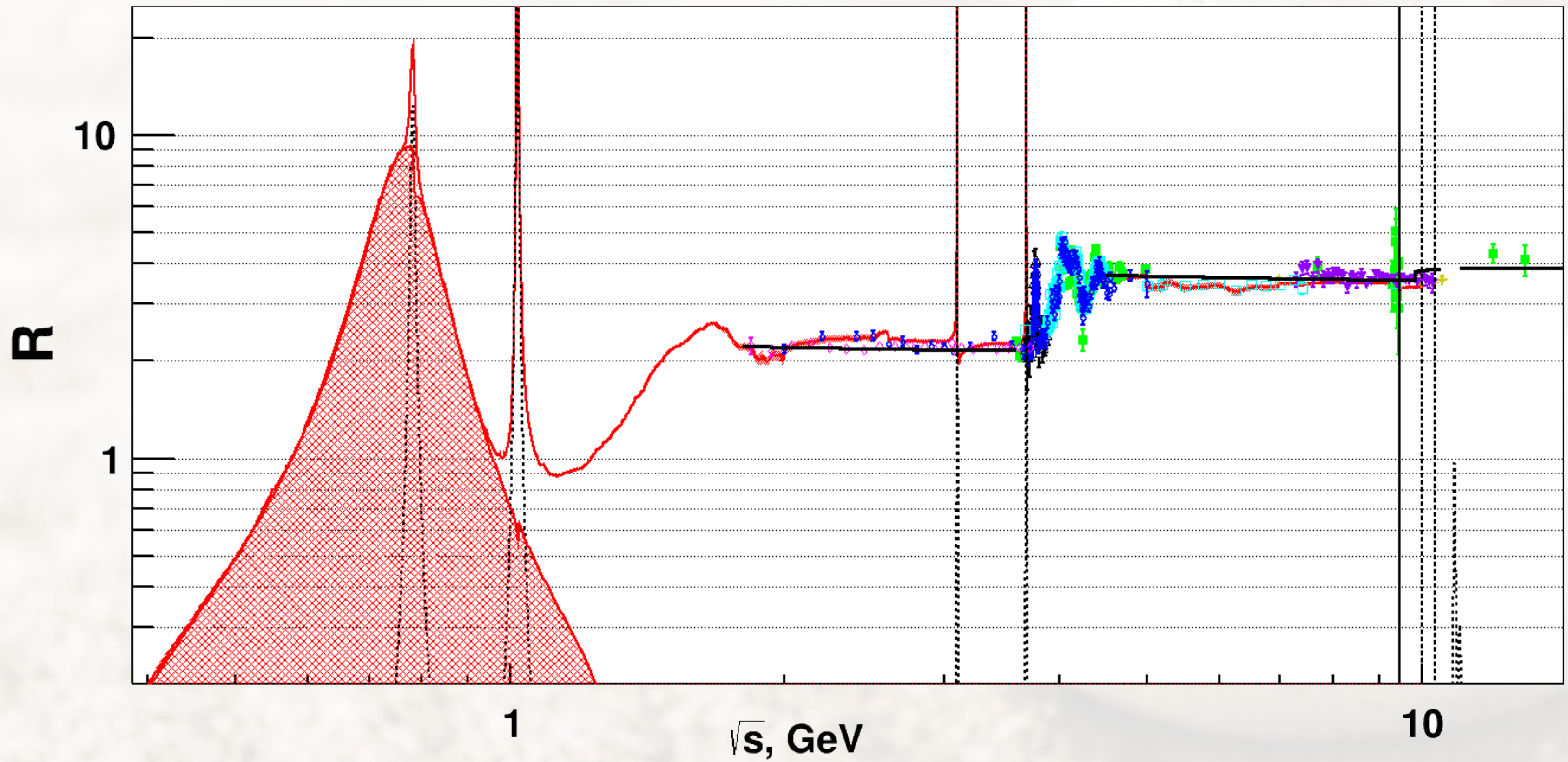


- CMD-3@VEPP-2000: $e^+e^- \to$ η', $p\bar{p}$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$, $3(\pi^+\pi^-)\pi^0$, $\eta\pi^+\pi^-$, $\eta\pi^+\pi^-\pi^0$, $\eta\pi^+\pi^-\pi^+\pi^-$, K^+K^-, K_SK_L, $K^+K^-\pi^+\pi^-$, $K^+K^-\eta$
- SND@VEPP-2000: $e^+e^- \to \eta$, η', f1, $n\bar{n}$, $\eta\gamma$, $\pi^0\gamma$, $\pi^+\pi^-\pi^0$, $\omega\pi^0$, $\omega\eta\pi^0$, $\eta\pi^+\pi^-$, $\eta\pi^+\pi^-\pi^0$, K^+K^-, $K_SK_L\pi^0$, $K^+K^-\eta$

SND talk at Tuesday by L.Kardapoltsev

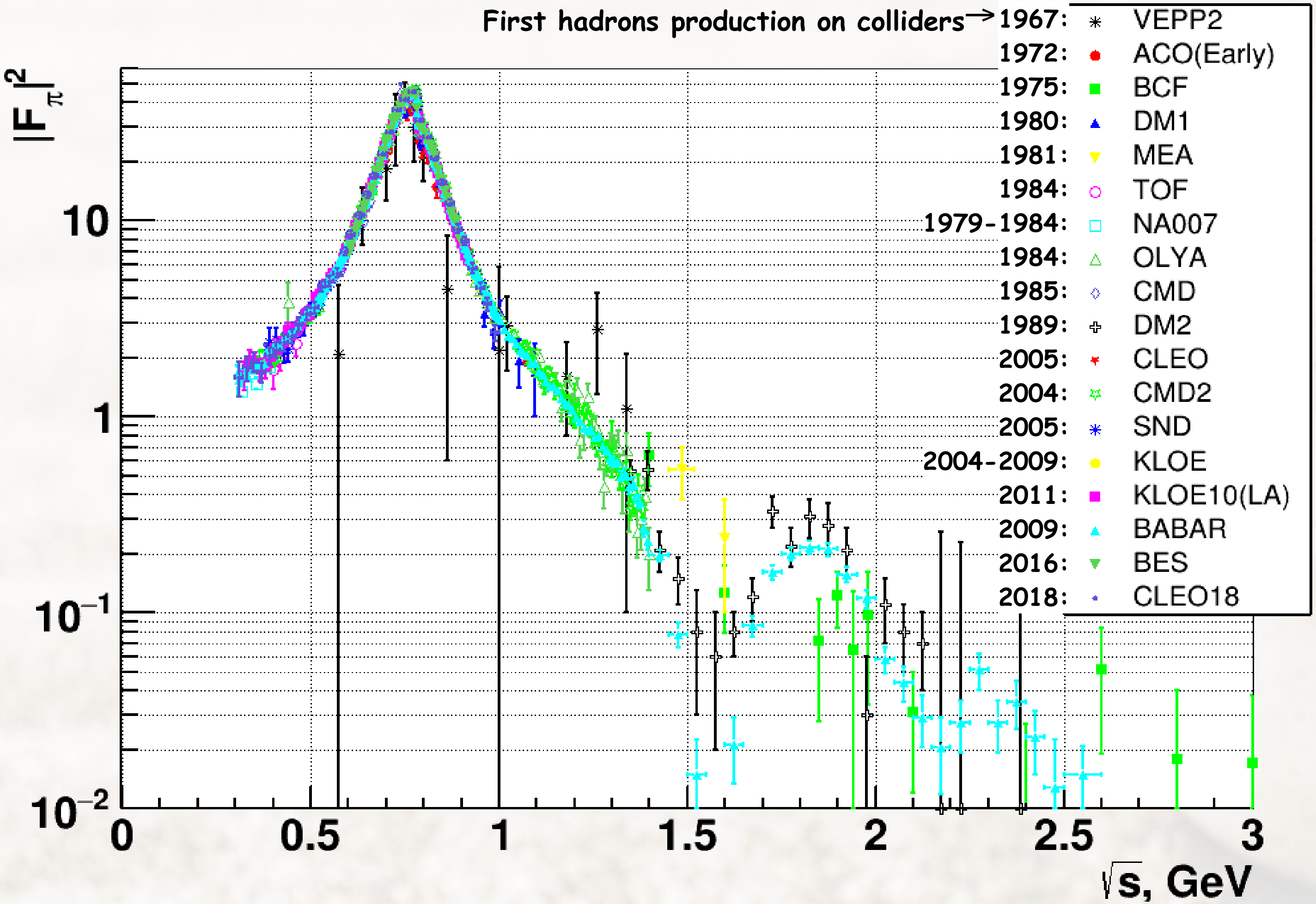
<u>Many channels is under active analysis</u>

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



Gives main contribution to R(s) at $\sqrt{s} < 1$ GeV

e+ e− → π+ π− today



<u>Before 1985</u>

Low statistical precision

Systematic >10%

NA7 A few points with >1-5%

<u>1985 - VEPP-2M</u>

with more detailed scan

OLYA systematic 4%

CMD 2%

<u>2004 with CMD2 at VEPP-2M</u>

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

<u>New ISR method</u>

e+e- → γ + hadrons

(limited only by systematic):

KLOE: 0.8%

BaBar: 0.5%

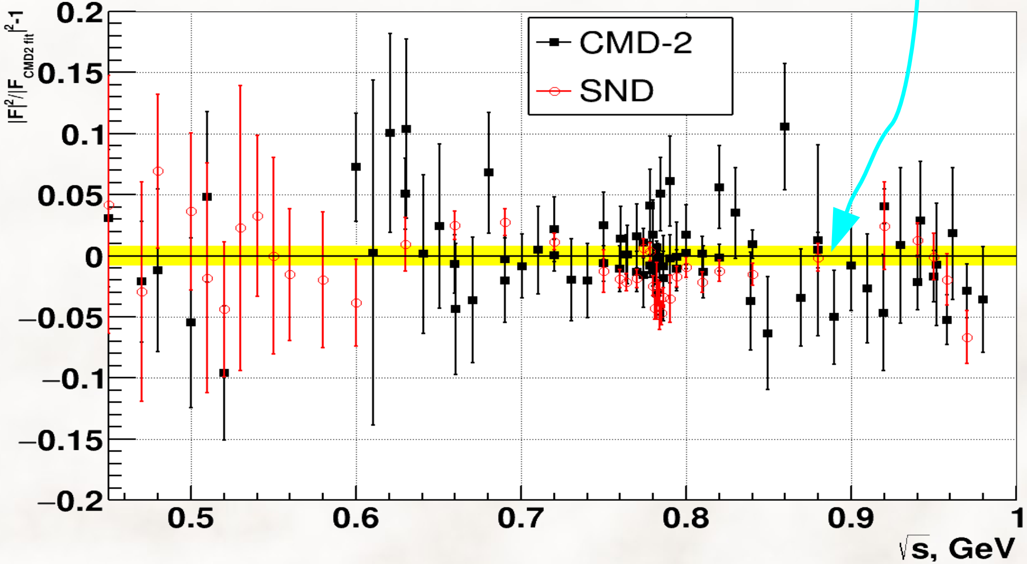
BES: 0.9%

CLEO: 1.5%

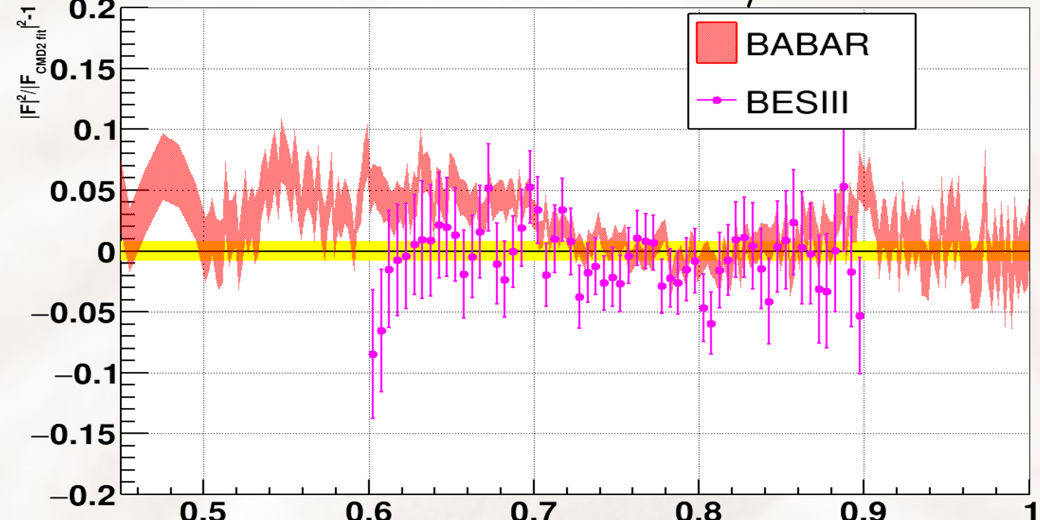
New g-2 experiments and future e+e- as ILC, FCC-ee require average precision ~0.2%

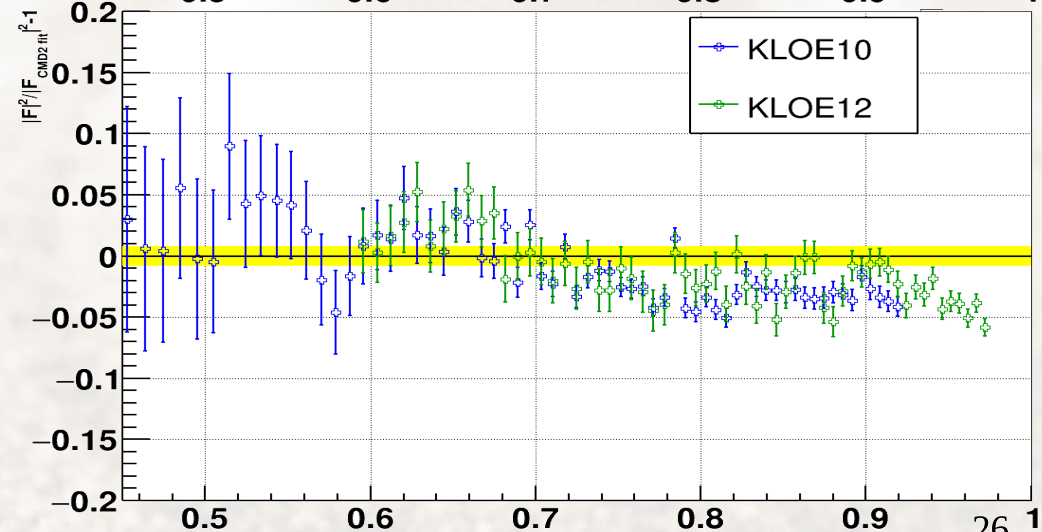
Comparison of e+ e− → π+ π− cross-section

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



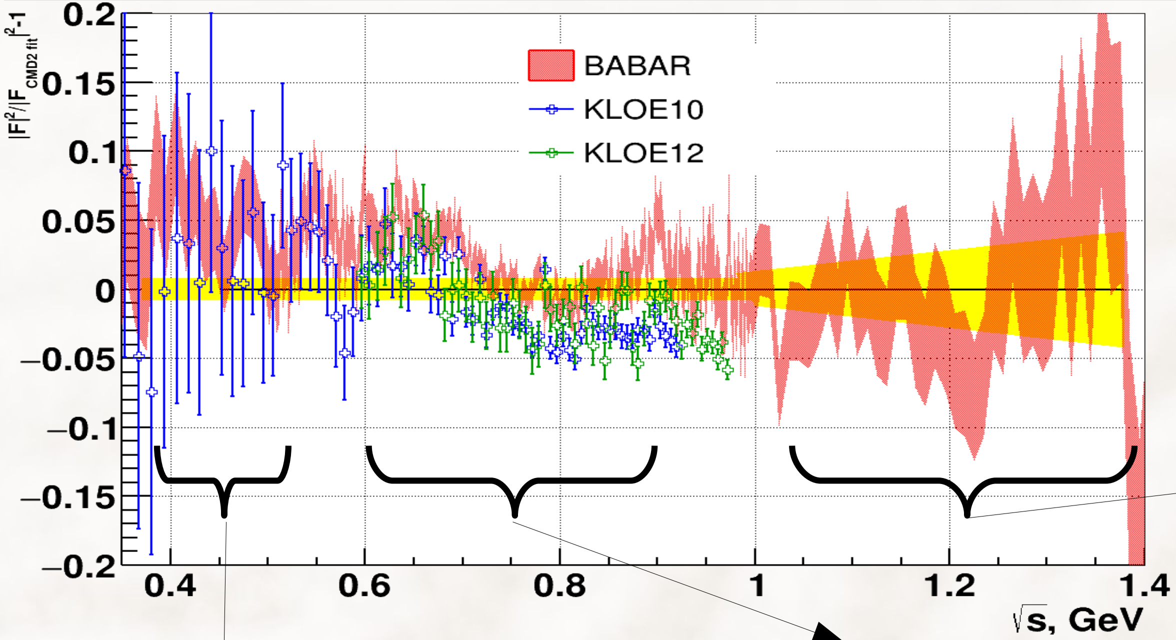
Points, red band: only statistical error

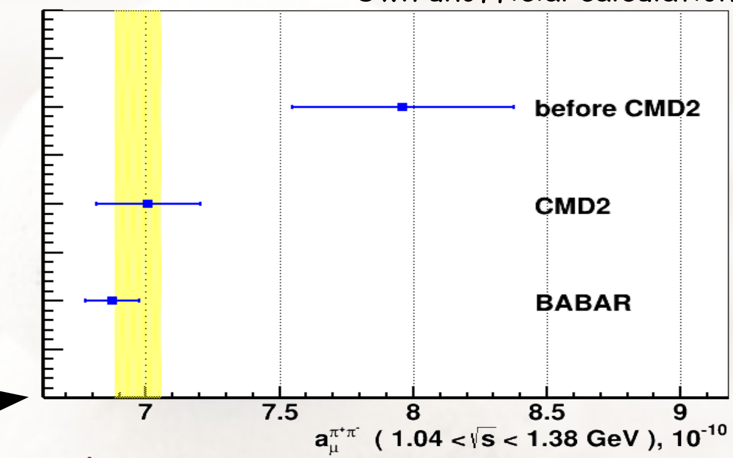




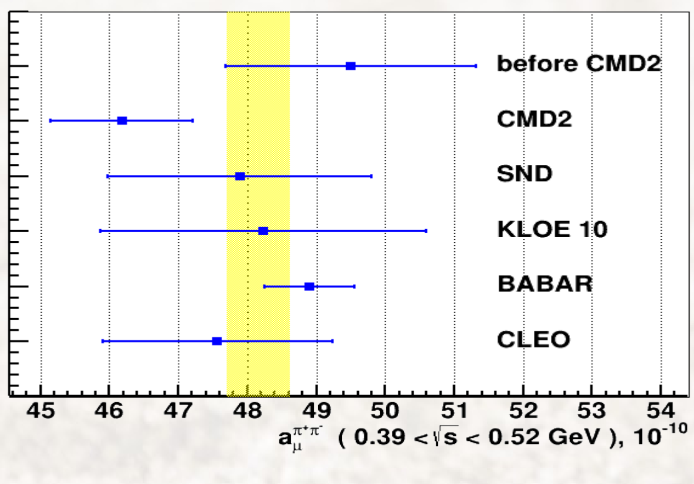
In integral, there is reasonable agreement between existing data sets
But there are local inconsistencies larger than claimed systematic errors
→ additional scale factor for error of integral value

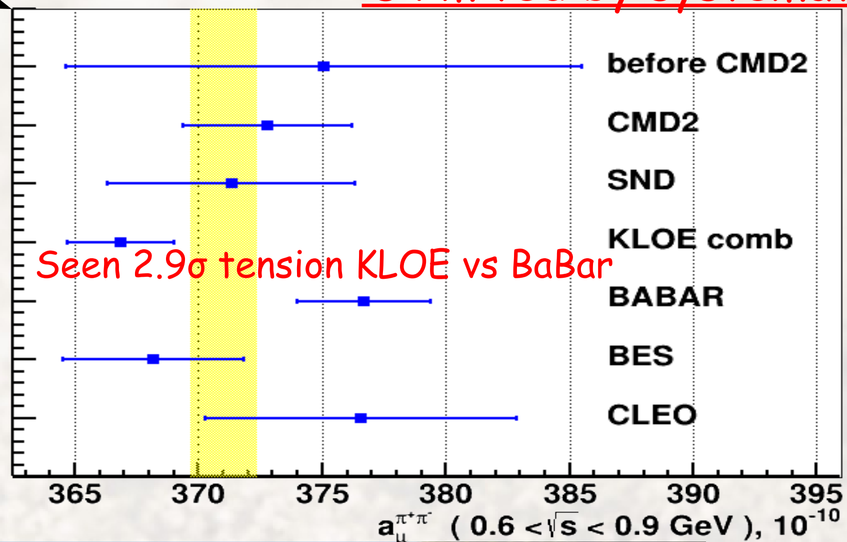
The $\pi + \pi -$ contribution to a_μ^{had}





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%
CLEO: 1.5%

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% (CMD-3)

Crucial pieces of analysis:

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

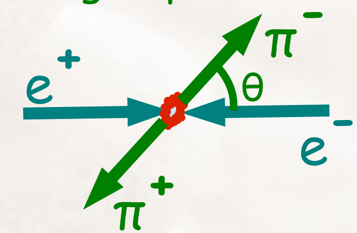
<u>Many systematic studies rely on high statistics</u>

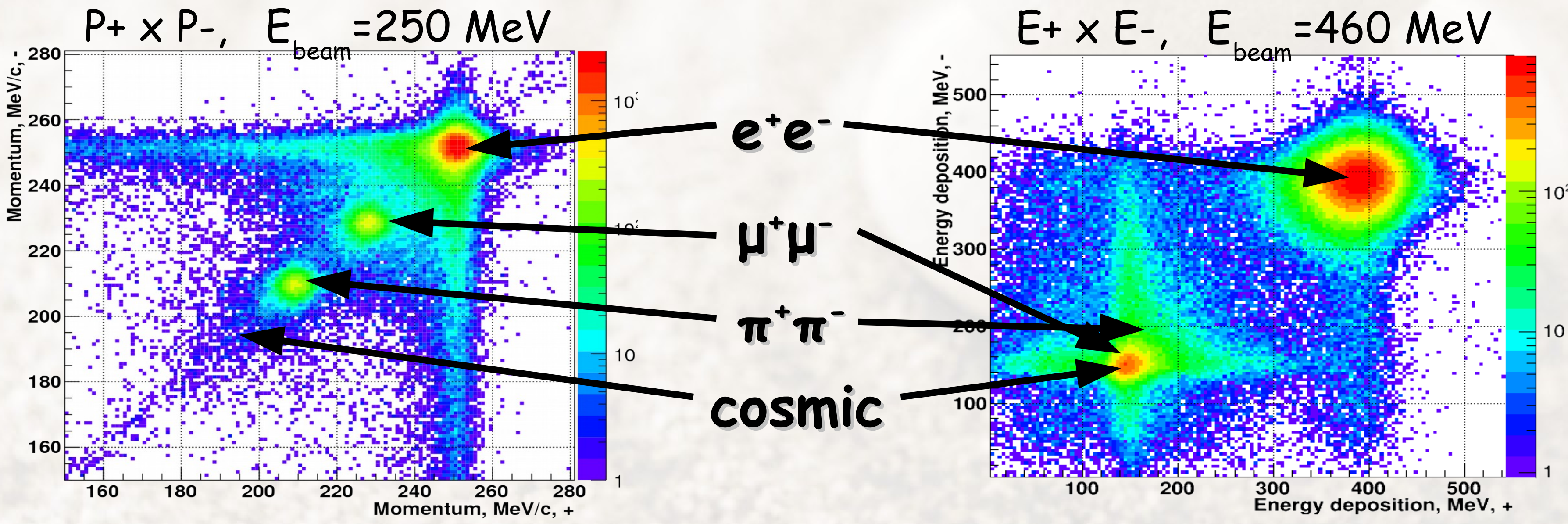
events separation either by momentum or by energy deposition

Momentums works better at low energy < 0.8 GeV

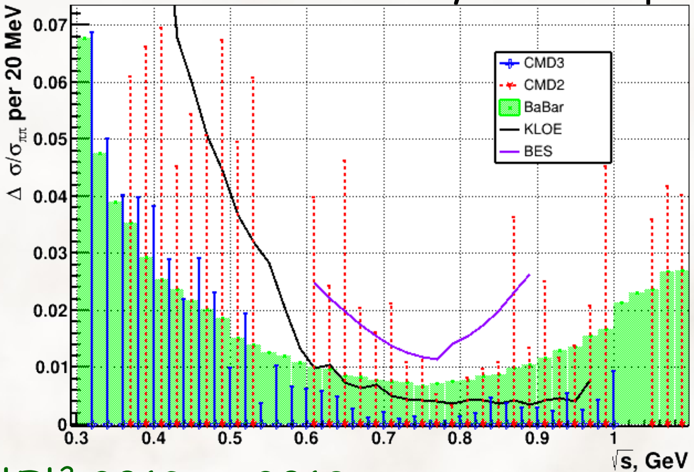
Energy deposition > 0.6 GeV

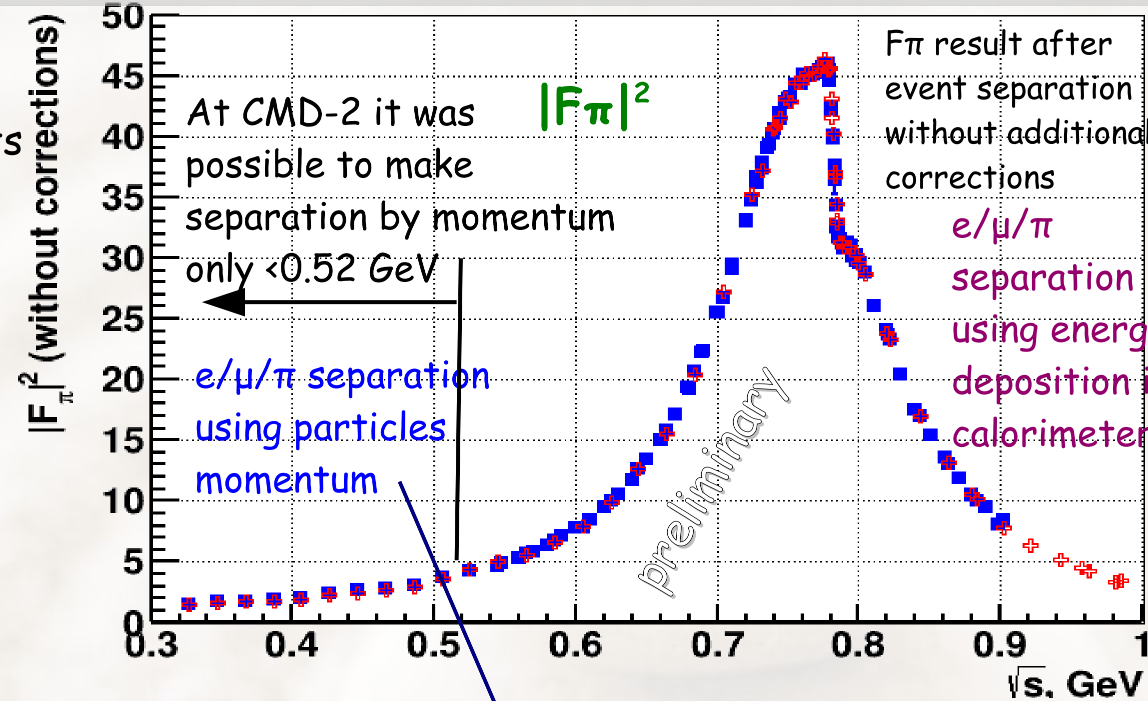
Simple event signature with 2 back-to-back charged particles





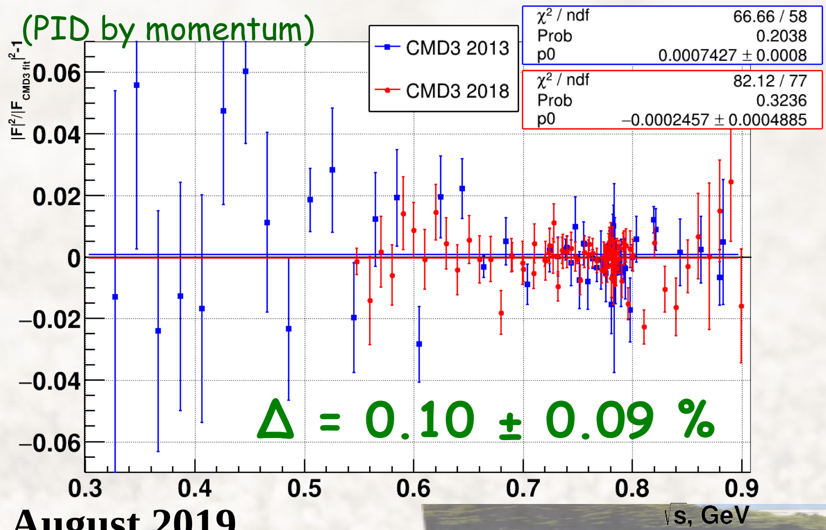
Statistical precision of cross section measurement for 2013+2018 data a few times better than any other experiments

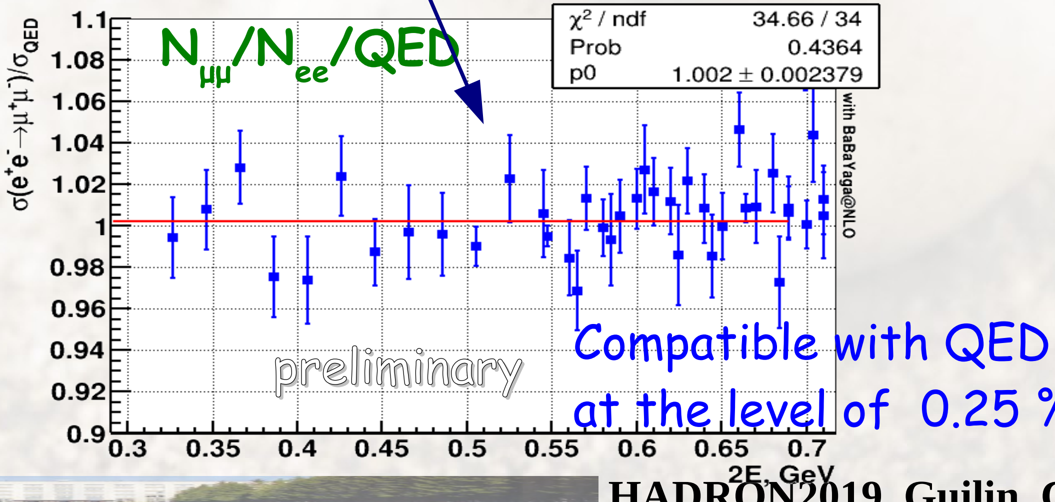




$|F|^2$ 2013 vs 2018 scans

(PID by momentum)





Systematic e+e- → π+π- by CMD-3

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%

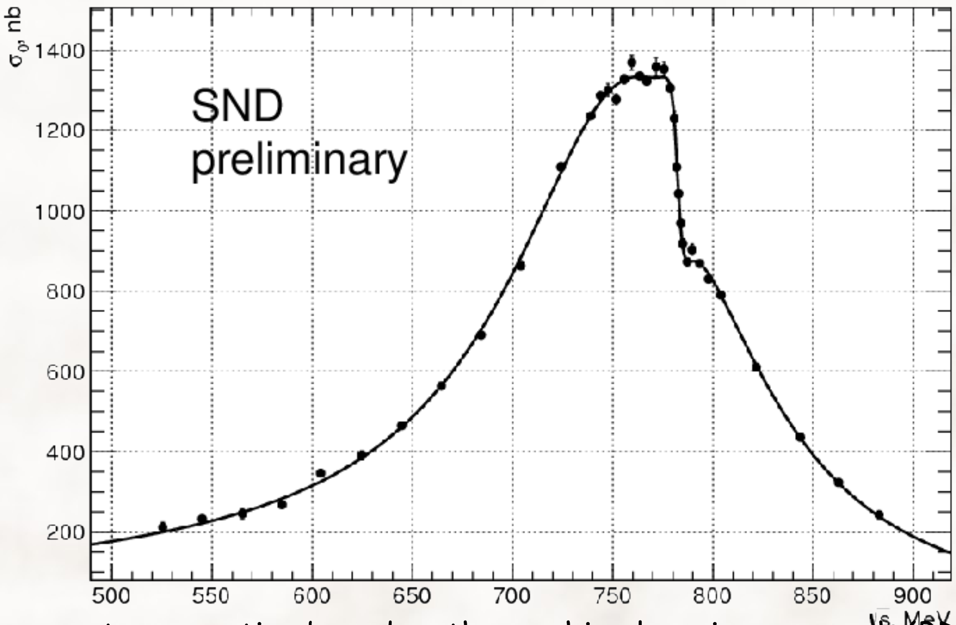
at few lowest points : 0.9%

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- @ SND

slides from V.Druzhinin @ EPS HEP 2019



The events separation based on the machine learning approach (BDT) using information on shower profile from 3-layers of calorimeter

Systematic uncertainty on the cross section (%)

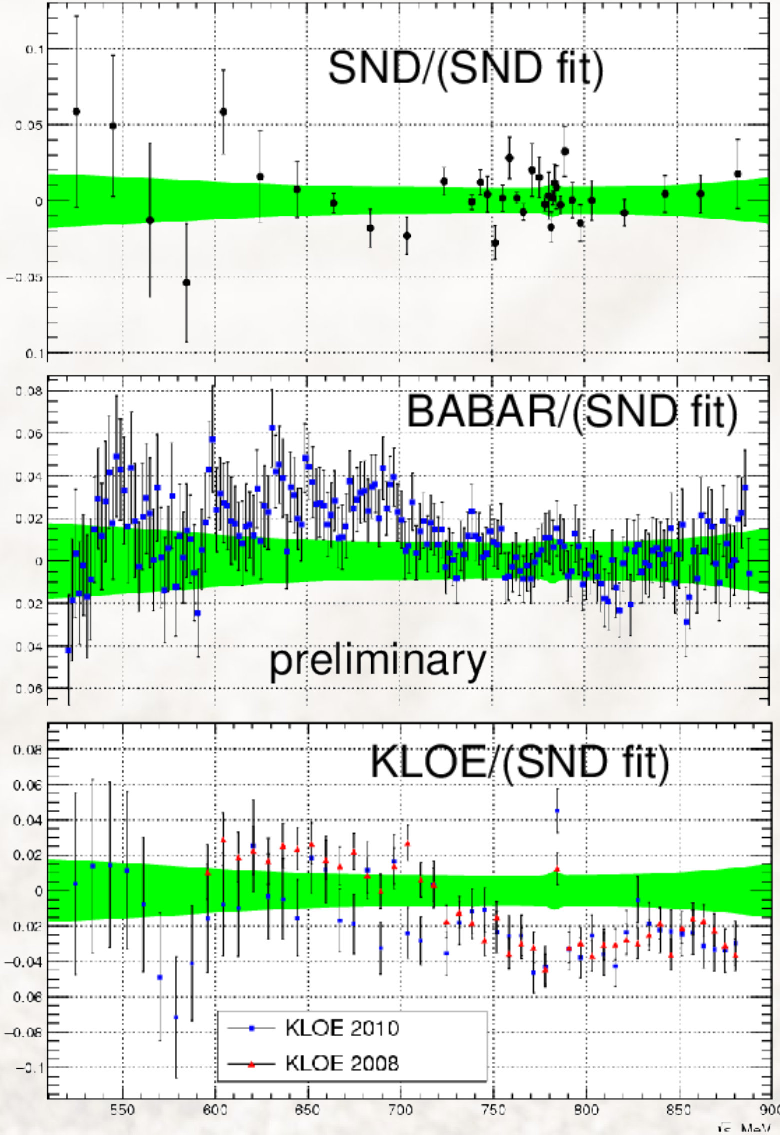
Source	< 0.6 GeV	0.6 - 0.9 GeV
Trigger	0.5	0.5
Selection criteria	0.6	0.6
e/π separation	0.5	0.1
Nucl. interaction	0.2	0.2
Theory	0.2	0.2
Total	**0.9**	**0.8**

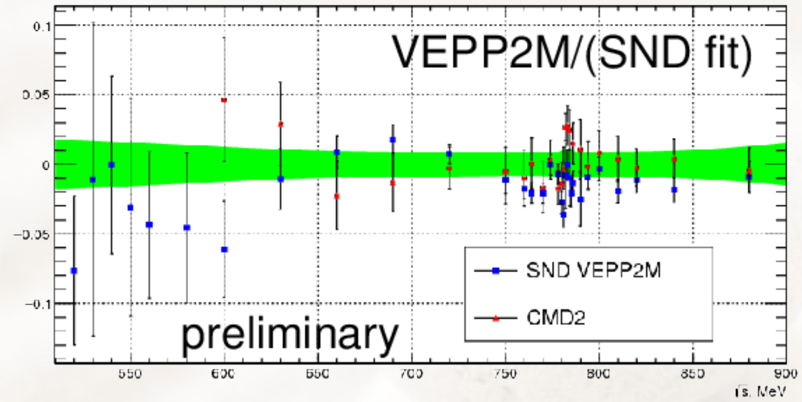
	SND @ VEPP-2000	SND @ VEPP-2M	PDG
M_ρ, MeV	775.4±0.5±0.4	775.6±0.4±0.5	775.3±0.3
Γ_ρ, MeV	145.7±0.7±1.0	146.1±0.8±1.5	147.8±0.9
$B_{\rho ee}\times10^5$	4.89±0.2±0.4	4.88±0.2±0.6	4.72±0.5
$B_{\omega\pi\pi}$, %	1.77±0.08±0.02	1.66±0.08±0.05	1.53±0.06

The analysis is based on 4.7 pb^{-1} data recorded in 2013, ~1/10 full SND data set.

e+e- → π+π- @ SND

slides from V.Druzhinin @ EPS HEP 2019



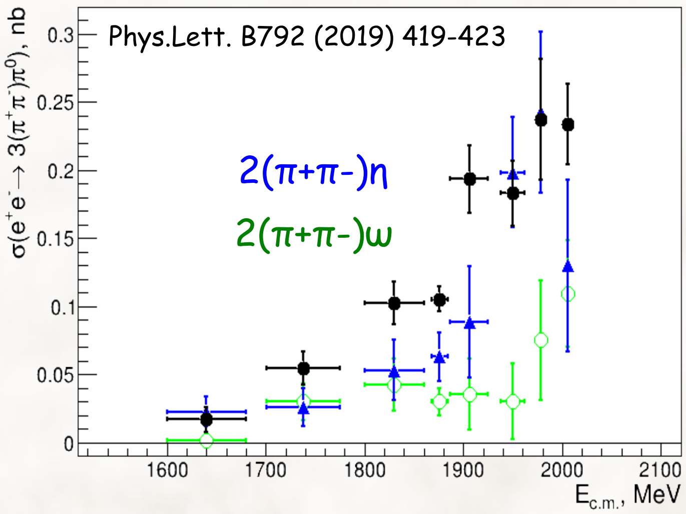


$$0.53 < \sqrt{s} < 0.88 \text{ GeV}$$

	$a_\mu(\pi^+\pi^-) \times 10^{10}$
SND & VEPP-2000	$411.8 \pm 1.0 \pm 3.7$
SND & VEPP-2M	$408.9 \pm 1.3 \pm 5.3$
BABAR	$414.9 \pm 0.3 \pm 2.1$

First time measurements

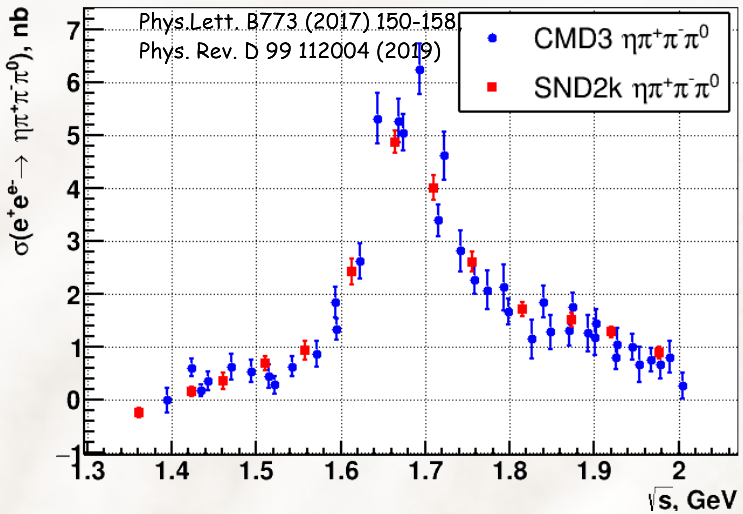
$e^+e^- \to 3(\pi^+\pi^-)\pi^0$ @ CMD-3



- The dominant mechanisms are $4\pi\eta$, $4\pi\omega$
- The known before is $4\pi\eta$

The cross section is about 0.25 nb ~1% of R(s) at 2 GeV

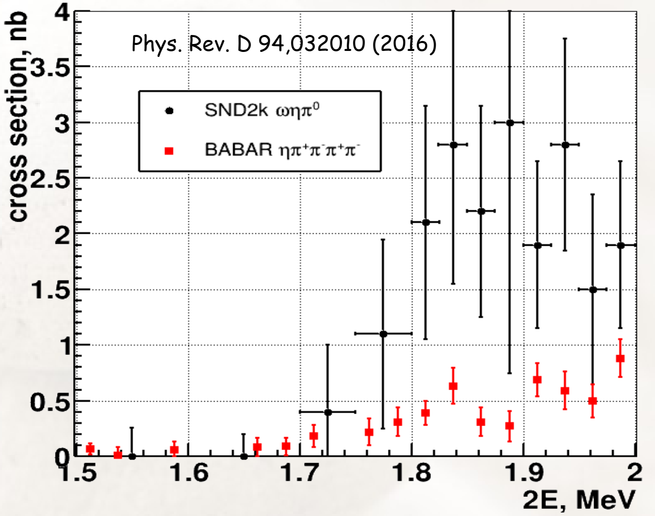
$e^+e^- \to \pi^+\pi^-\pi^0\eta$ @ CMD-3, SND



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

Not accounted part before is about ~ 3-5% of R(s)

$e^+e^- \to \omega\eta\pi^0$ (7γ mode) @ SND



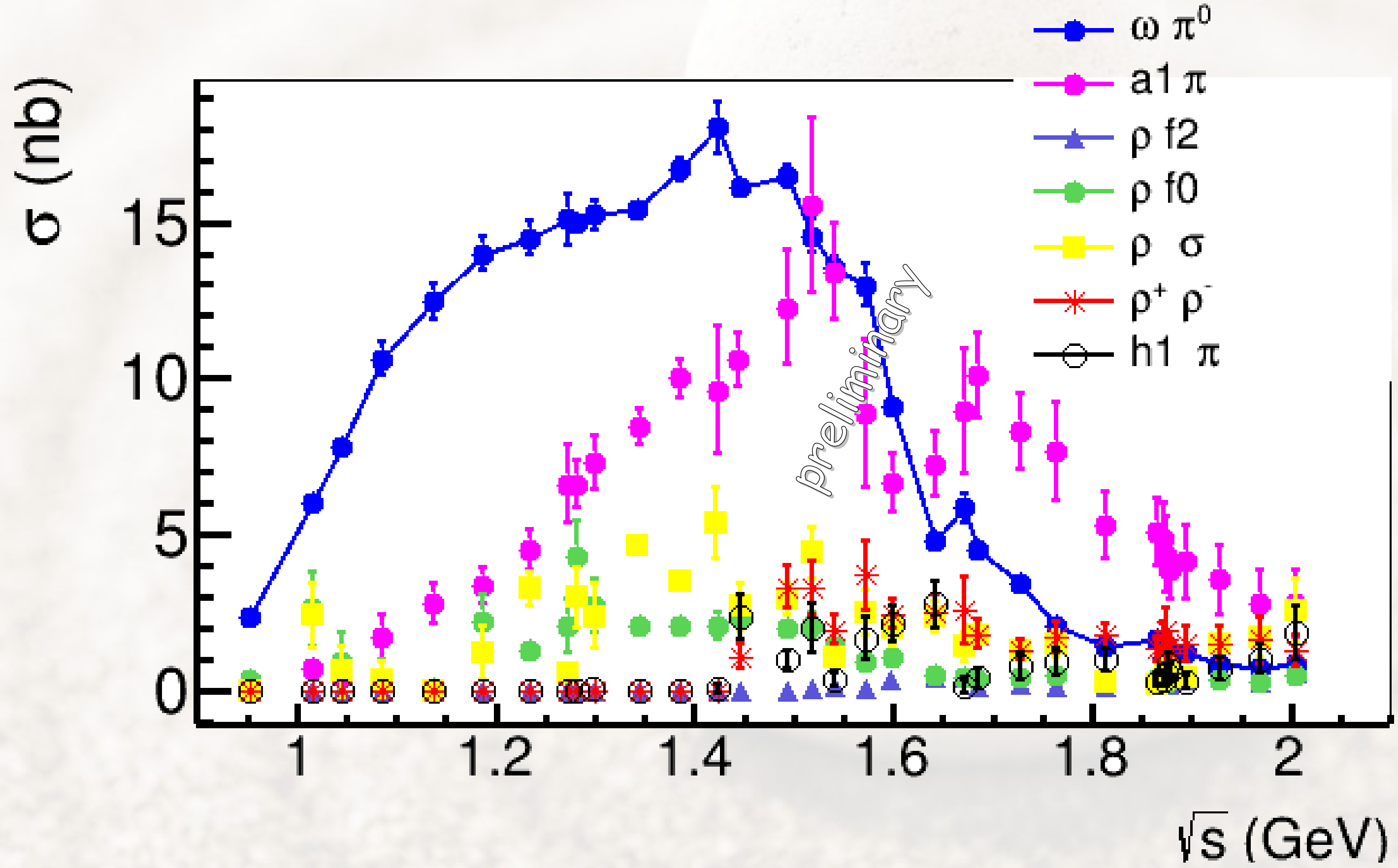
- The dominant mechanism is $\omega a_0(980)$
- Before was partially accounted by "isospin relation": $\sigma(\eta\pi^+\pi^-2\pi^0)=\sigma(\eta 2\pi^+2\pi^-)$

The cross section is about 2.5 nb ~ 5% of R(s)

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

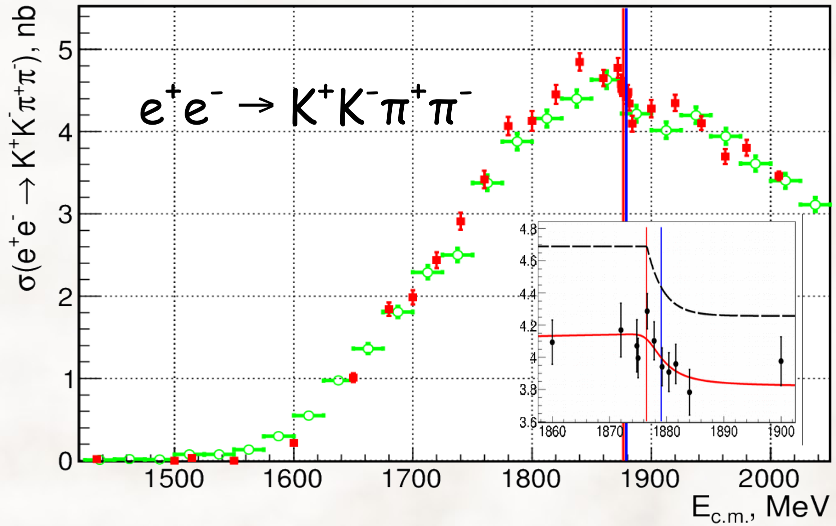


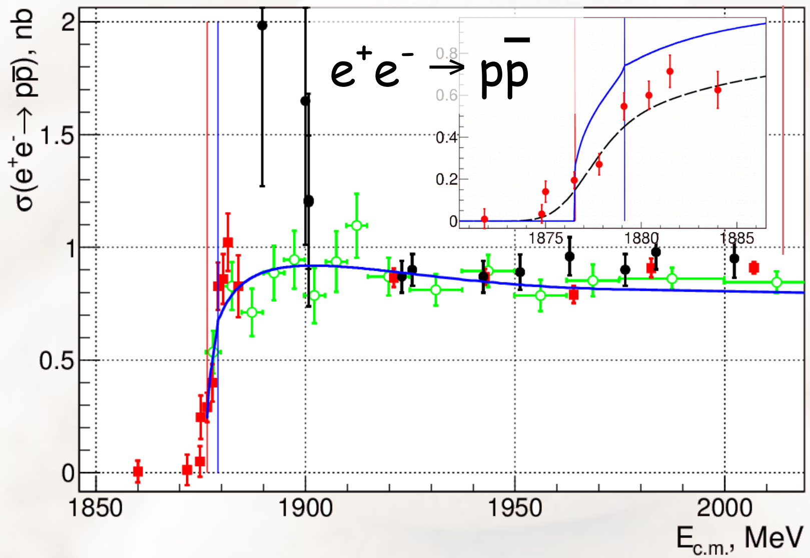
Multihadrons production at NN

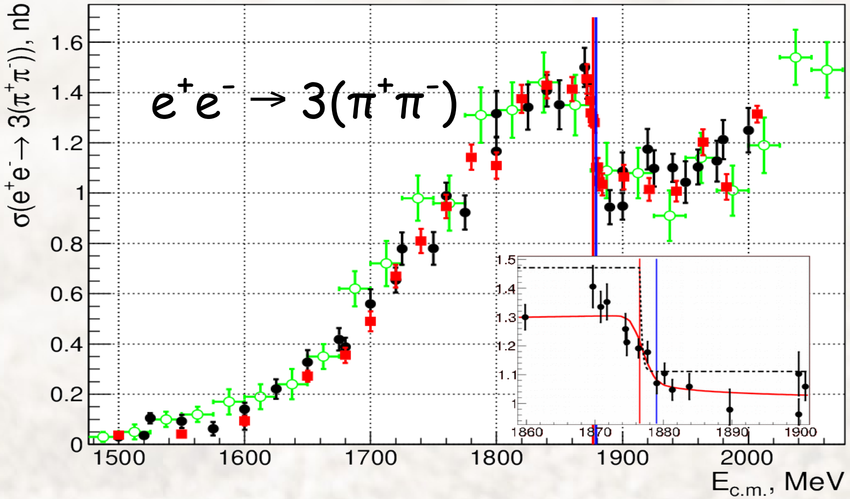
We did detail scan of $N\bar{N}$ threshold region

Seen many dip structures in multihadron production

Phys.Lett. B794 (2019) 64







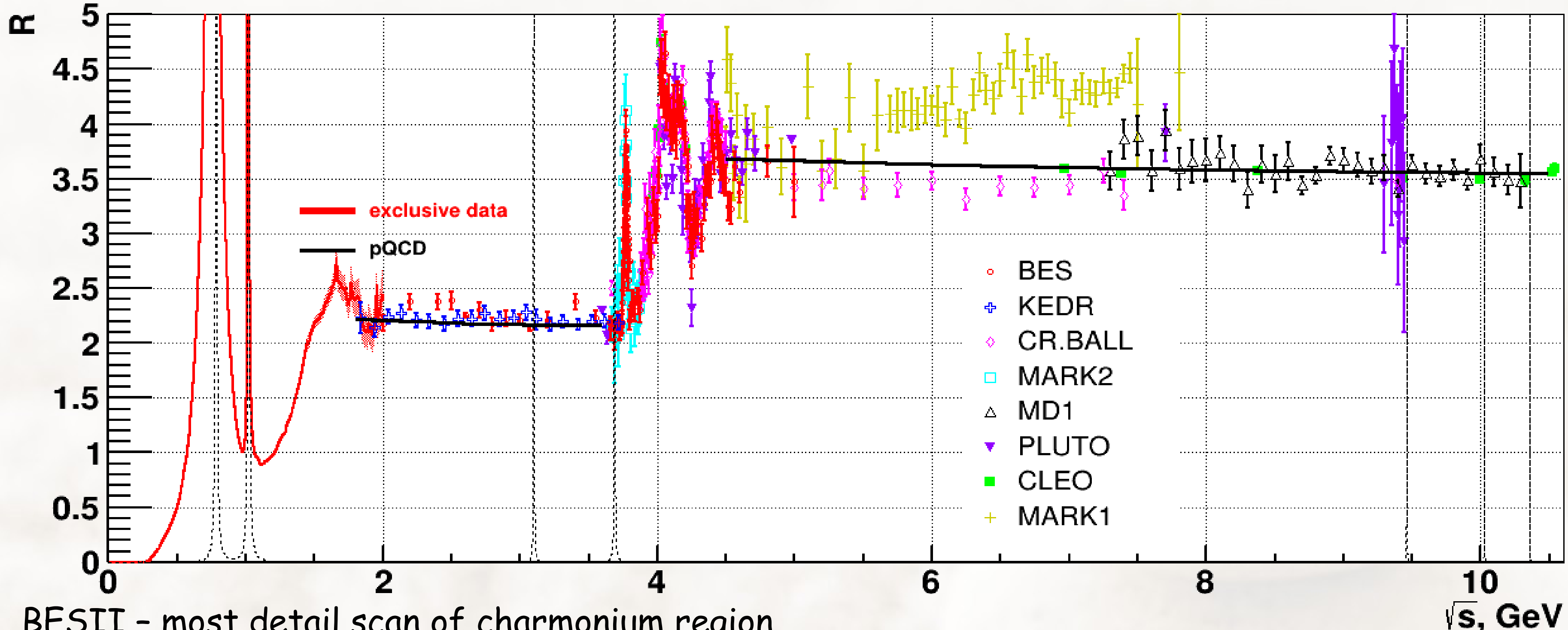
Can be described via optical nucleon-antinucleon potentials (most advanced "Milstein-Salnikov" parametrization)

Some questions still opened, for example:

Why no structure in e+e- → 2(π+π-),

KK2π effect is stronger than expected from $p\bar{p}$ anihilation

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

$\sqrt{s}$ =	1.84 – 3.05 GeV	3.08 – 3.72 GeV
R_{KEDR} =	2.23 ± 0.05	2.204 ± 0.030
consistent with R_{pQCD}=	2.18 ± 0.02	2.16 ± 0.01

Phys.Lett. B770 (2017) 174-181
Phys.Lett. B788 (2019) 42-51

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})

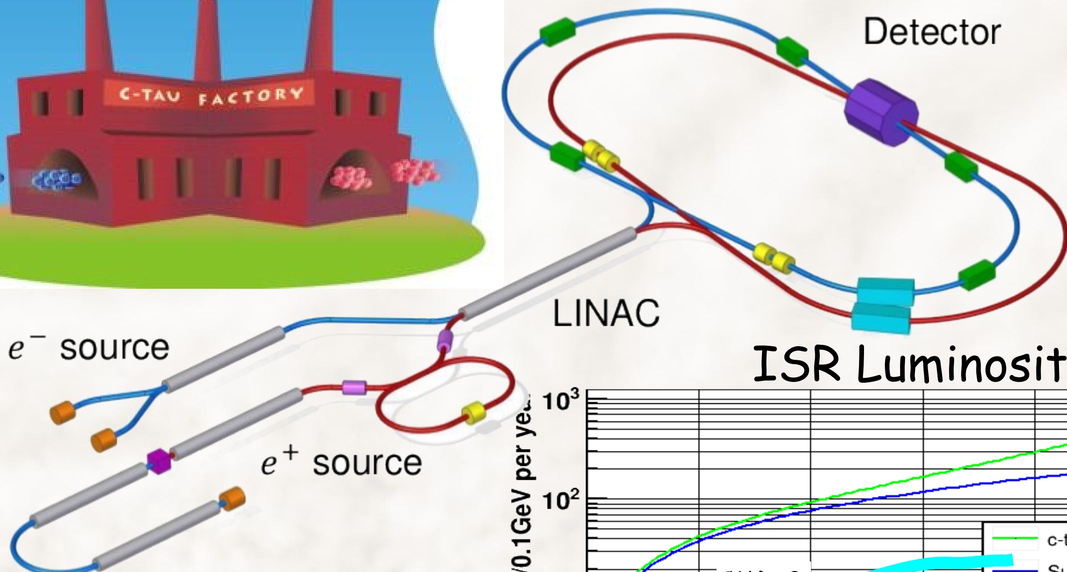
KEDR – did 2 scans of 2E=4.5 - 7 GeV (plans to collect more & few points @10 GeV)

Future low energy e+e- machines(super c-tau factories)

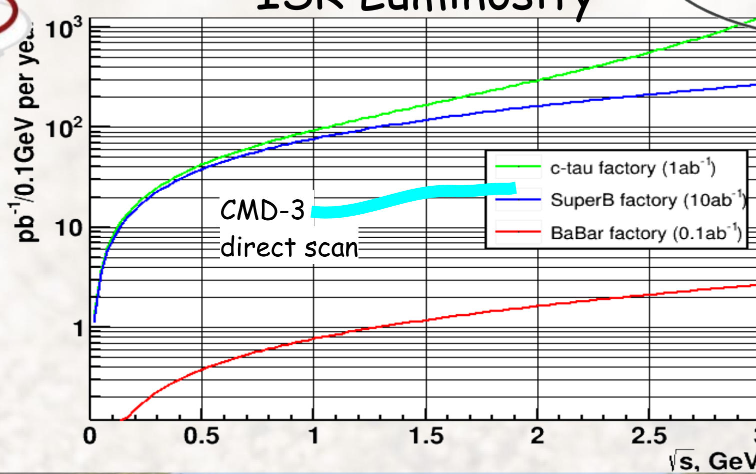
Two projects is under consideration

- e+e– collider, 2E = 2 ÷ 7 GeV
- Study of charmed hadrons and τ
- 10^{35} 1/cm^{2}s luminosity with Crab-waist collisions
- Polarized e- beam

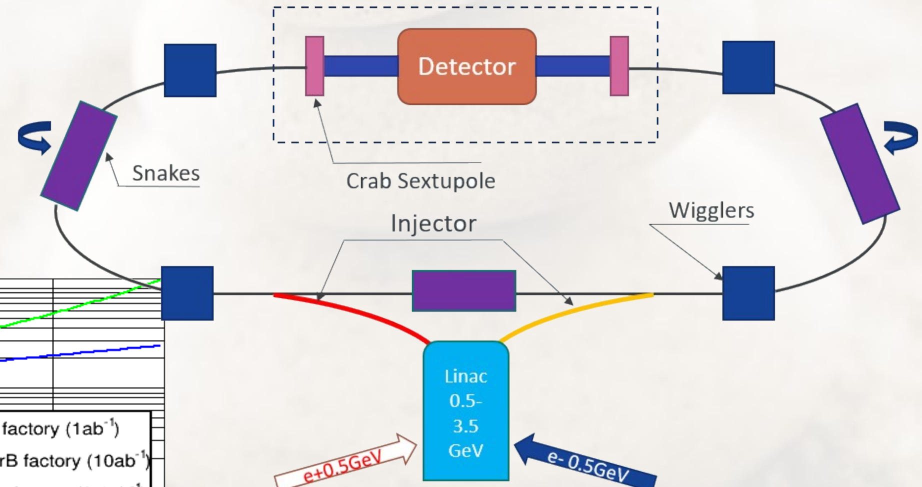
SCTF in Novosibirsk



ISR Luminosity

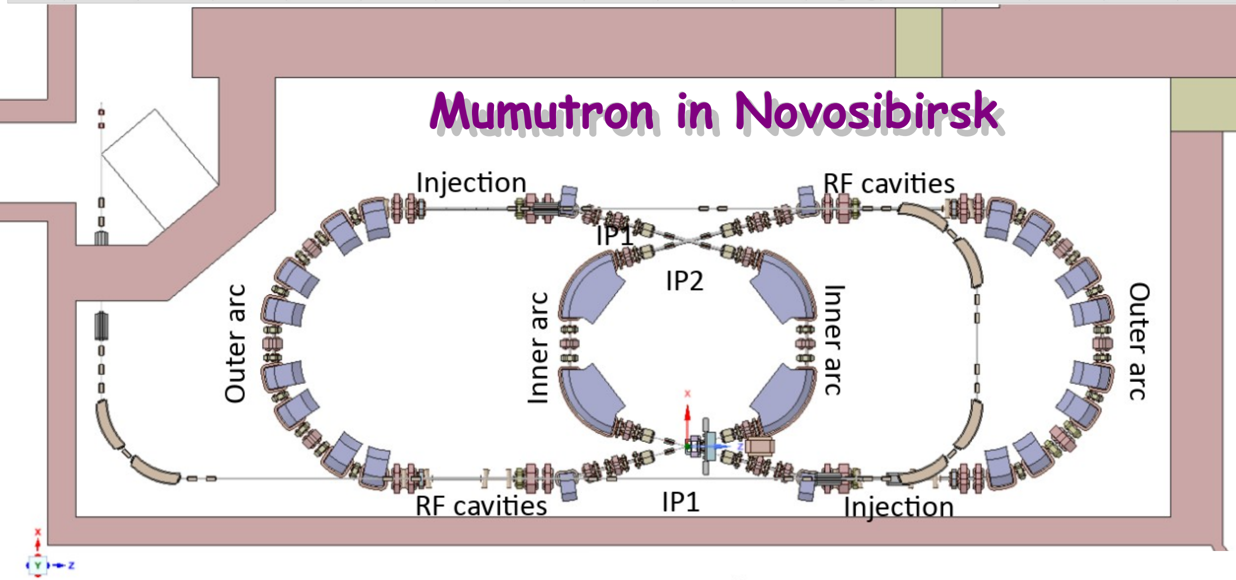


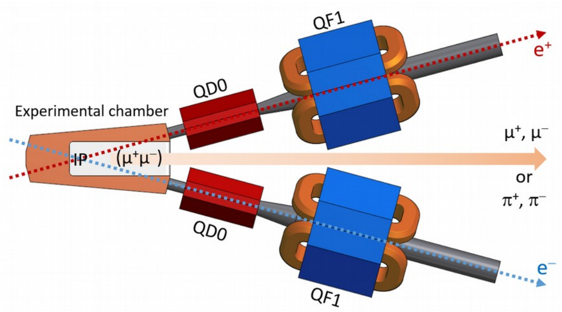
STCF in China

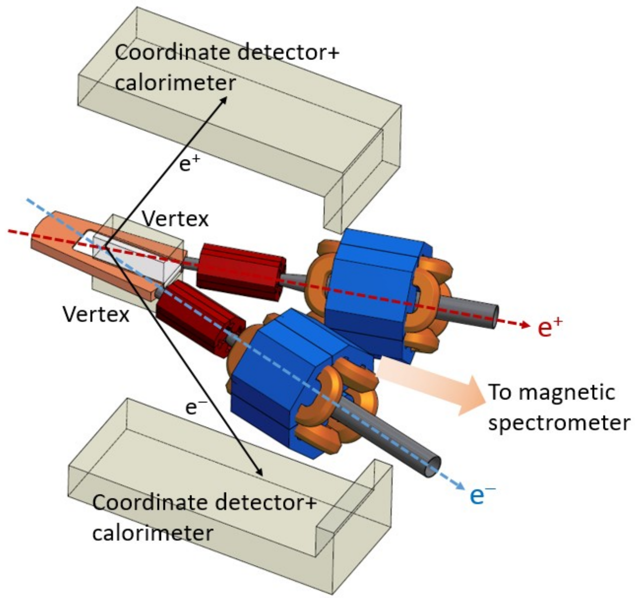


see talk after
on future facilities
by Prof. S.Eidelman

Future low energy e+e- machines(mumutron)







project is under consideration

Can be as an accelerator technology testbench for SCTauF

1st stage :

Observation & study of dimuonium - μμ bound state

$\sqrt{s}$ = 212 MeV

L ~ 8×10^{31} 1/cm^{2}s

2nd stage with reversed beams and dedicated detector:

Rho-factory

- 15° crossing angle
- $\sqrt{s}$ = 0.55-0.96 GeV
- L ~ 0.6-1. × 10^{33} 1/cm^{2}s

Conclusion

✗ Precise low-energy e^+e^- hadronic cross section data is used in many applications of accurate SM predictions such as $a_\mu^{had,LO-VP}$, $\alpha_{QED}(M_Z)$, ...

✗ VEPP-2000 is only one working this days on direct scanning below <2 GeV for measurement of exclusive σ (e+e- → hadrons)

✗ The VEPP-2000 results will help to reduce error of the hadronic contribution to $(g-2)_\mu$, etc and it is important independent cross-check of ISR data, future Lattice, space-like measurements

✗ Several previously unmeasured processes contributed to the total hadronic cross section ($e^+e^- \to \eta\pi^+\pi^-\pi^0$, $3(\pi^+\pi^-)\pi^0$,$\omega\eta\pi^0$) below 2 GeV have been studied.

✗ We have goal to collect O(1) 1/fb in 5 years,

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

✗ Belle2 and possible SuperC-Tau factories can provide even more data with ISR

backups

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

$\omega\eta$, $\eta\pi^+\pi^-\pi^0$, $\eta\pi^+\pi^-$ Phys.Lett. B773 (2017) 150-158; arXiv:1907.08002, subm. JHEP

$3(\pi^+\pi^-)\pi^0$, Phys.Lett. B792 (2019) 419-423

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

$K^+K^-\eta$ arXiv:1906.08006, subm. PLB

✗ Near finished result:

$e^+e^- \to D_0^*$

$K^+K^-\omega$, $\omega\pi^+\pi^-$

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

SND@VEPP-2000 summary of results, (journal articles)

Published:

1. $e^+e^- \to \pi^0\pi^0\gamma$, Ph.Rev.D, (2013,2016)
2. $e^+e^- \to nn$, Phys.Rev.D,(2014)
3. $e^+e^- \to \eta\gamma$, Phys.Rev.D,(2014)
4. $e^+e^- \to \eta'$, Phys.Rev.D,(2015)
5. $e^+e^- \to \eta\pi^+\pi^-$, Phys.Rev.D,(2015,2018)
6. $e^+e^- \to \pi^+\pi^-\pi^0$, JETP,(2015)
7. $e^+e^- \to \eta$, Phys.Rev. D,(2018)
8. $e^+e^- \to K^+K^-$, Phys.Rev.D,(2016)
9. $e^+e^- \to \omega\eta\pi^0$, Phys.Rev.D,(2016)
10. $e^+e^- \to \pi^0\gamma$, Phys.Rev.D,(2018)
11. $e^+e^- \to K_SK_L\pi^0$, Phys.Rev.D(2018)
12. $e^+e^- \to \eta K^+K^-$, Phys.Atom.Nucl.(2018)
13. $e^+e^- \to \eta\pi^0\pi^+\pi^-$, Phys.Rev.D(2019)
14. $e^+e^- \to f1(1285)$, submitted(2019)

In analysis:

1. $e^+e^- \to \pi^+\pi^-$,
2. $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$,
3. $e^+e^- \to K^+K^-\pi^0$,
4. $e^+e^- \to \omega\pi^0\pi^0$,
5. $e^+e^- \to 6\pi$

…..

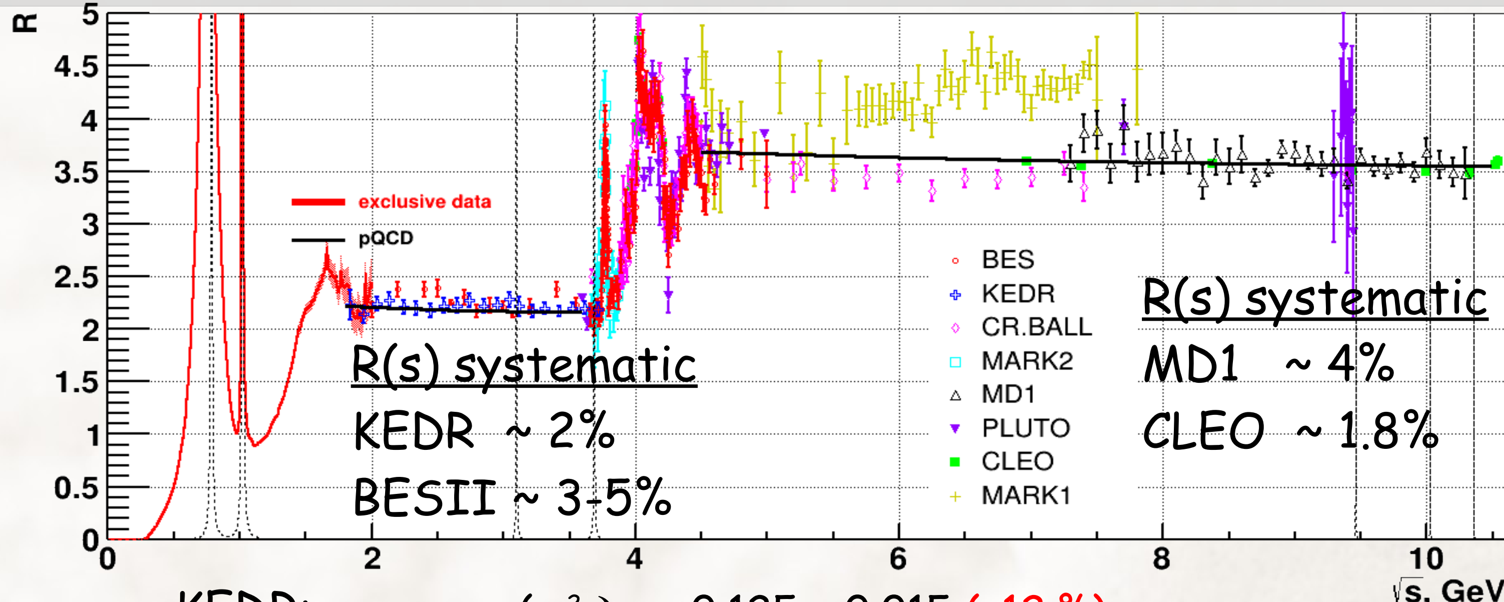
Hadron production in QCD

$$\frac{\sigma\left(e^+ e^- \rightarrow \text{hadrons}\right)}{\sigma\left(e^+ e^- \rightarrow \mu^+ \mu^-\right)} \equiv R(Q) = R_{EW}(Q)\left(1+\delta_{QCD}(Q)\right), \quad R(Q) = 12\pi\, \Im\, \Pi(Q)$$

$$\delta_{QCD}(Q) = \overbrace{\underbrace{\sum_{n=1}^{\infty} c_n \left(\frac{\alpha_s(Q)}{\pi}\right)^n}_{\text{pQCD – known until 5-loop}} + \underbrace{\overbrace{\frac{C_4}{Q^4} + \frac{C_6}{Q^6} + \ldots}^{\text{non pertubative}}}_{\text{Quark, gluon condensates}} + \underbrace{\Delta_{DV}(Q)}_{\text{Duality Violations factor (quarks} \Leftrightarrow \text{hadrons)}}}^{\text{Using Operator Product Expansion (OPE)}}$$

How well non-perturbative part can be controlled?
Its contribution decreases with higher energies...

α_s from R(s)

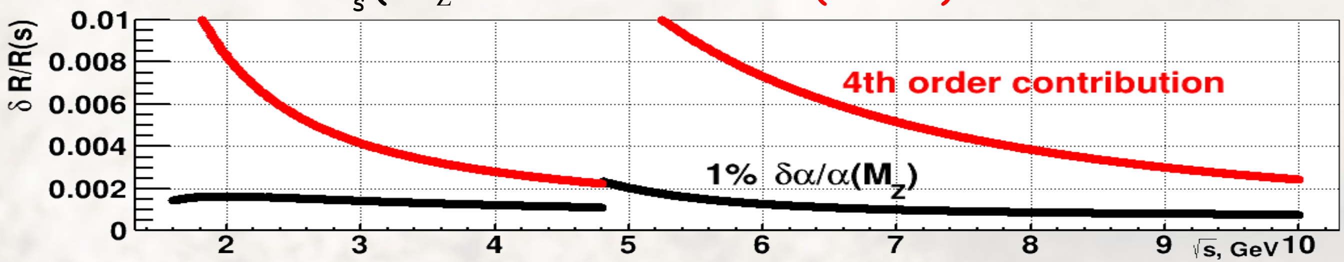


KEDR: $\alpha_s(m^2_Z) = 0.125 \pm 0.015$ (±12.%) arXiv:1805.06235

BESII+MD1: $\alpha_s(m^2_Z) = 0.124 \pm 0.014$ (±11.%) arXiv:hep-ph/0109084

CLEO: $\alpha_s(m^2_Z) = 0.110 \pm 0.017$ (±15.%) arXiv:0707.2589

δR(s) from pQCD:



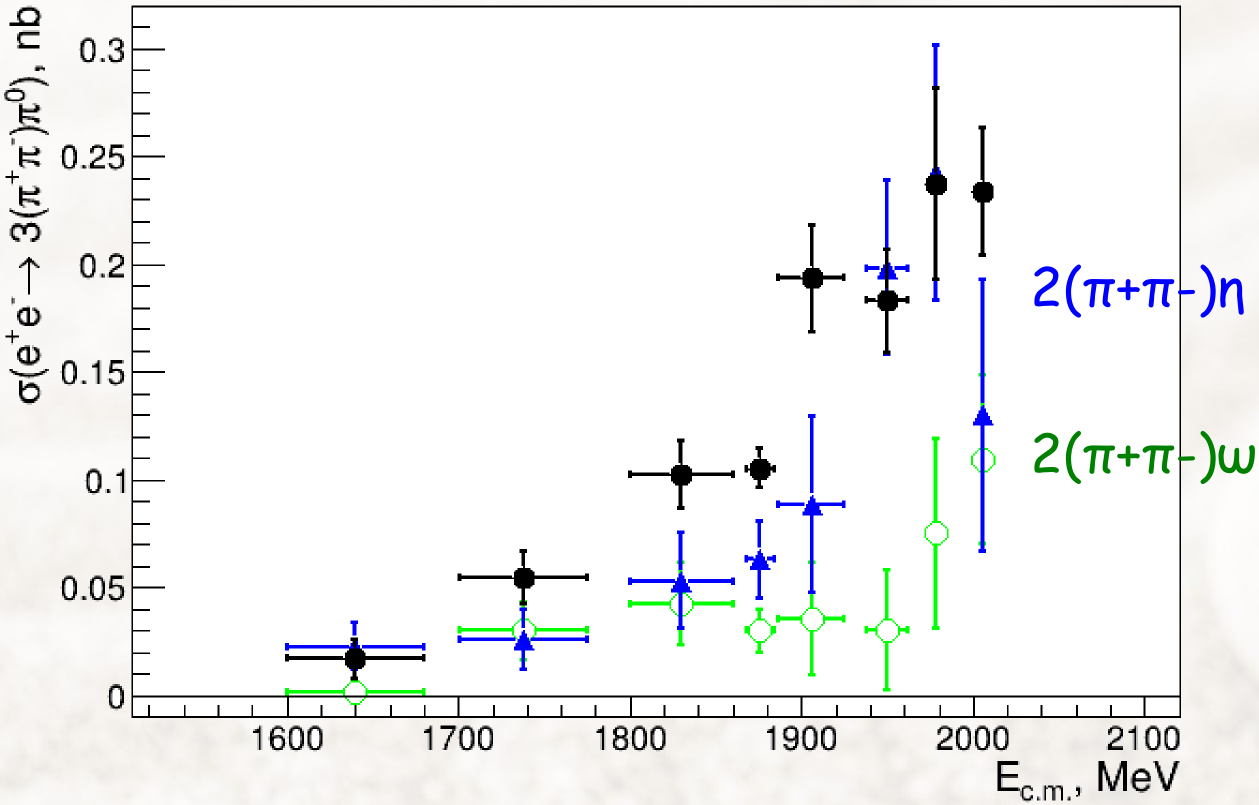
To extract α_s directly from R(s) with competitive precision $\delta\alpha/\alpha_s(m_Z) \sim 1\%$:

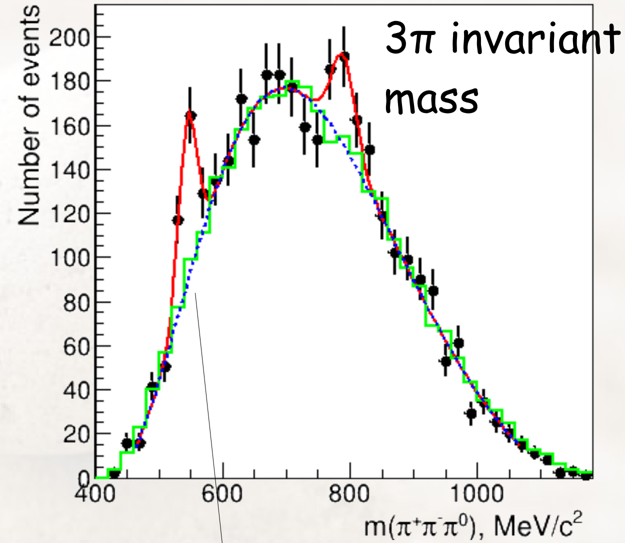
5^{th} α_s order calculation should be done, and R(s) measured with ~0.1-0.2%

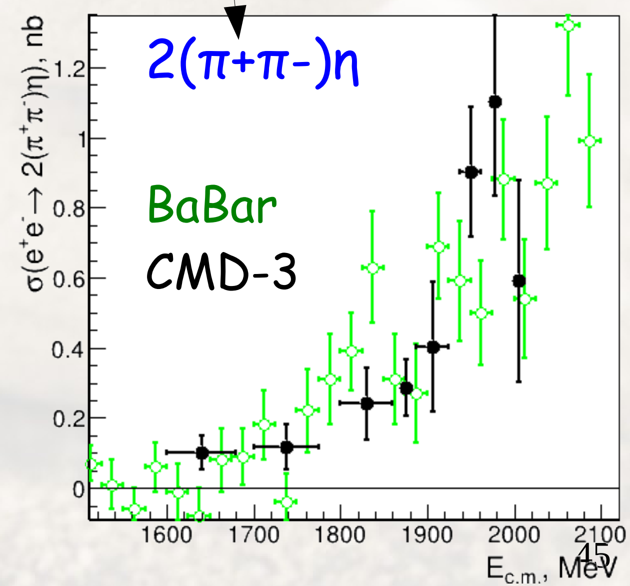
e+e- → 3(π+π-)π0 @ CMD-3

First time measurement of total cross-section

4πη,4πω dominated







~1% of R(s) at 2 GeV

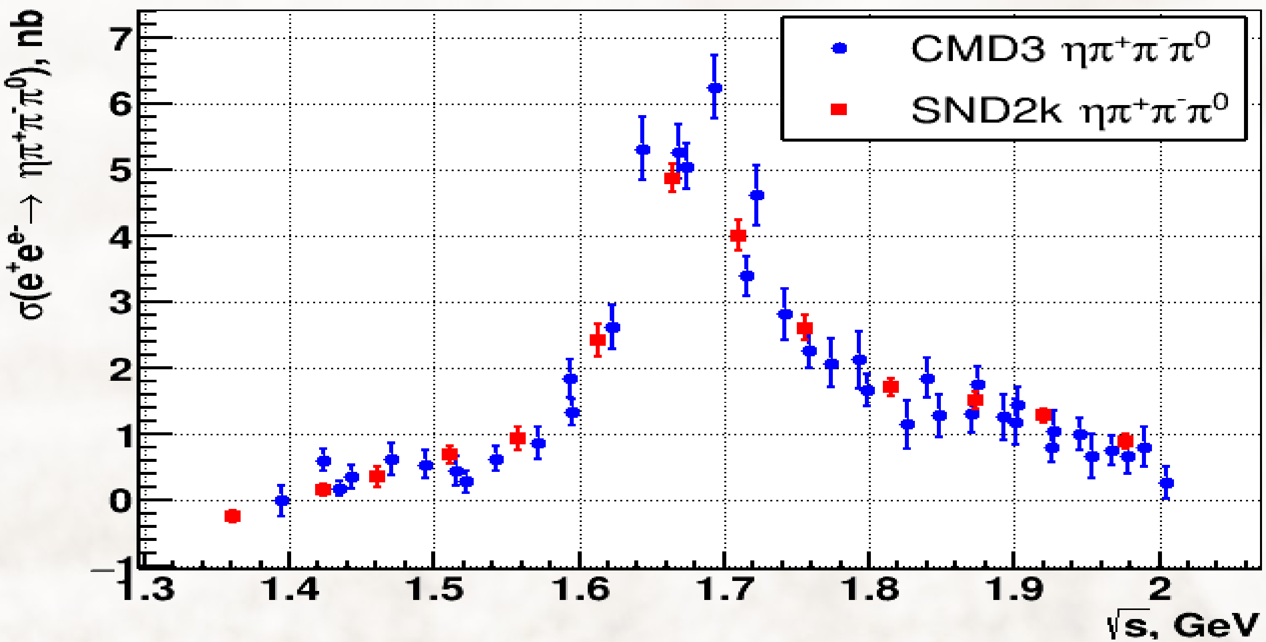
Phys.Lett. B792 (2019) 419-423

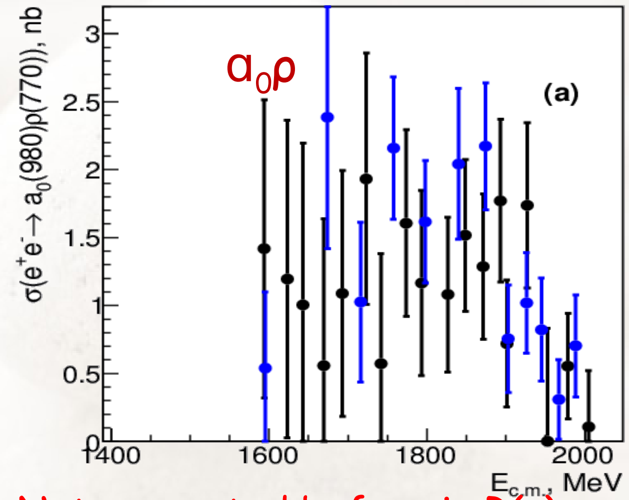
$e^+e^- \to \pi^+\pi^-\pi^0\eta$ @ CMD-3, SND

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

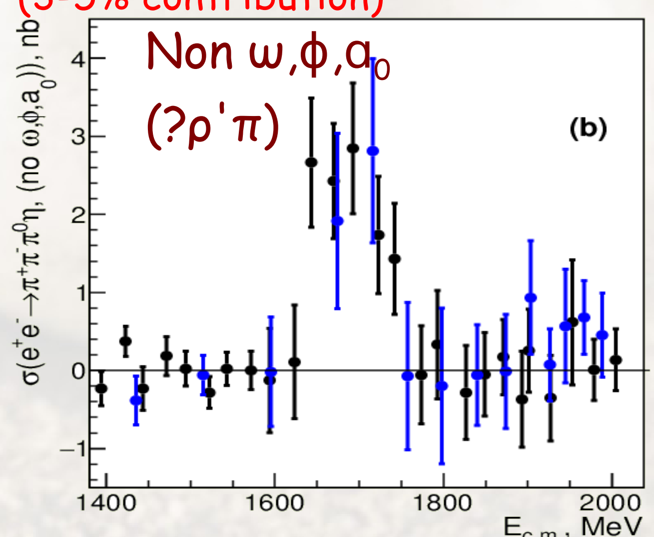
Systematic error is 11% for CMD-3, 7-11% for SND .

Phys.Lett. B773 (2017) 150-158, Phys. Rev. D 99 112004 (2019)





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

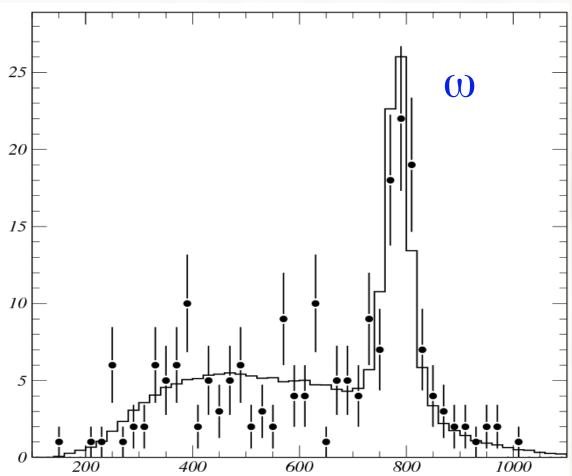


- The intermediate states are $\omega\eta$, $\varphi\eta$, $a_0\rho$ and structureless $\pi^+\pi^-\pi^0$
- The known before $\omega\eta$ and $\varphi\eta$ contributions explain about ~50% of the cross section below 1.8 GeV.
- Above 1.8 GeV the dominant reaction mechanism is $a_0\rho$

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

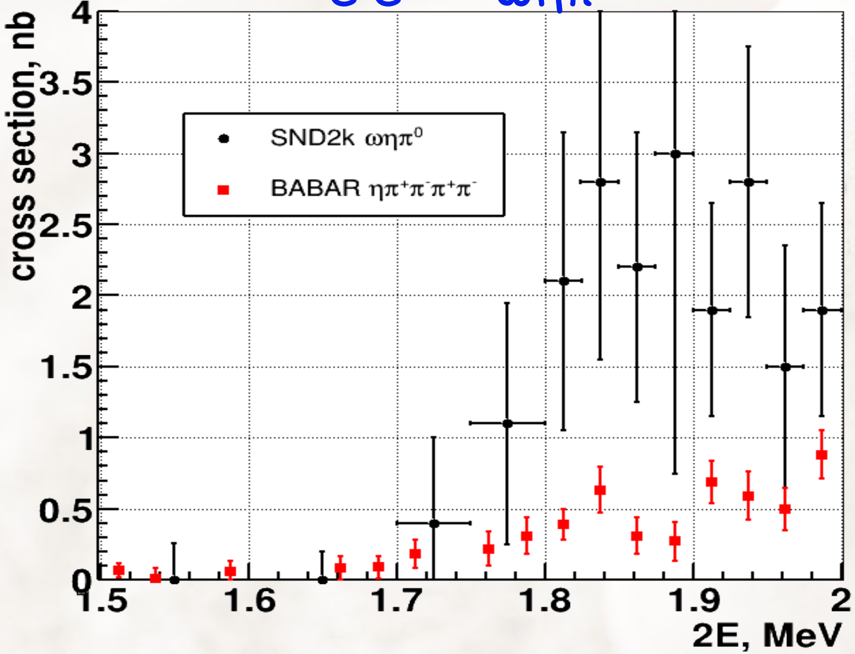
Phys. Rev. D 94,032010 (2016)

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

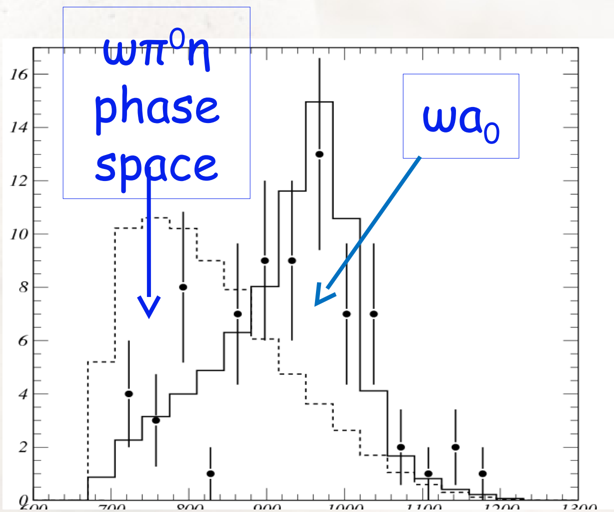


$\pi^0\gamma$ mass

Total cross section
$e^+e^- \to \omega\eta\pi^0$



a_0 dominance



$\pi^0\eta$ mass

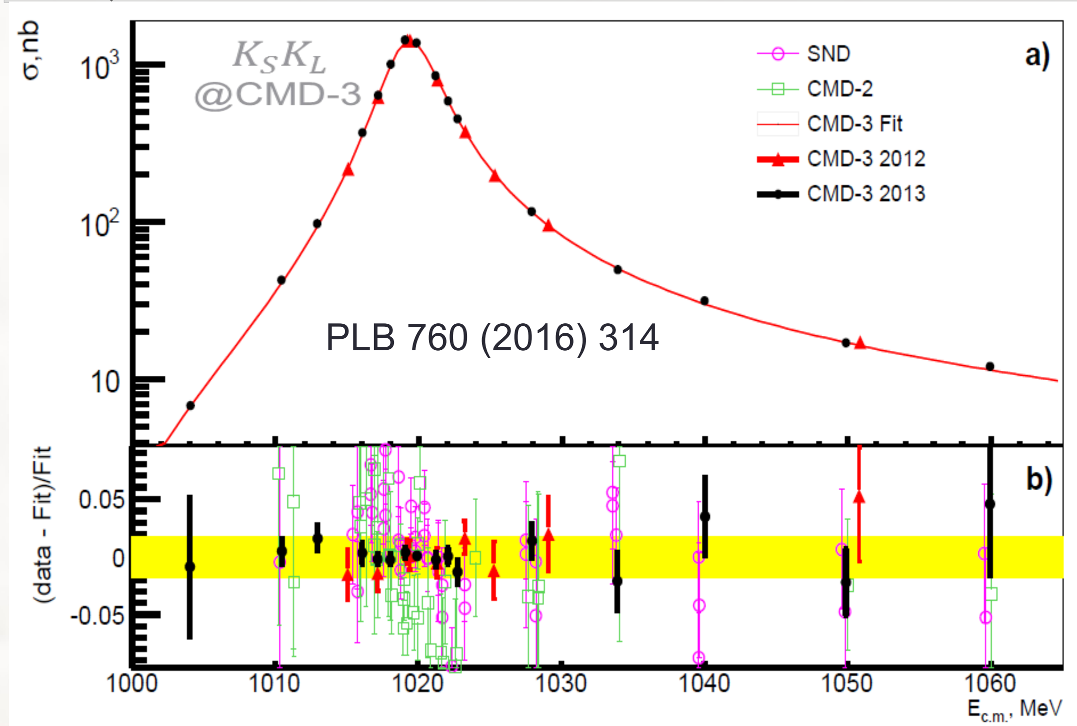
First measurement of the $e^+e^- \to \omega\eta\pi^0$ cross section.

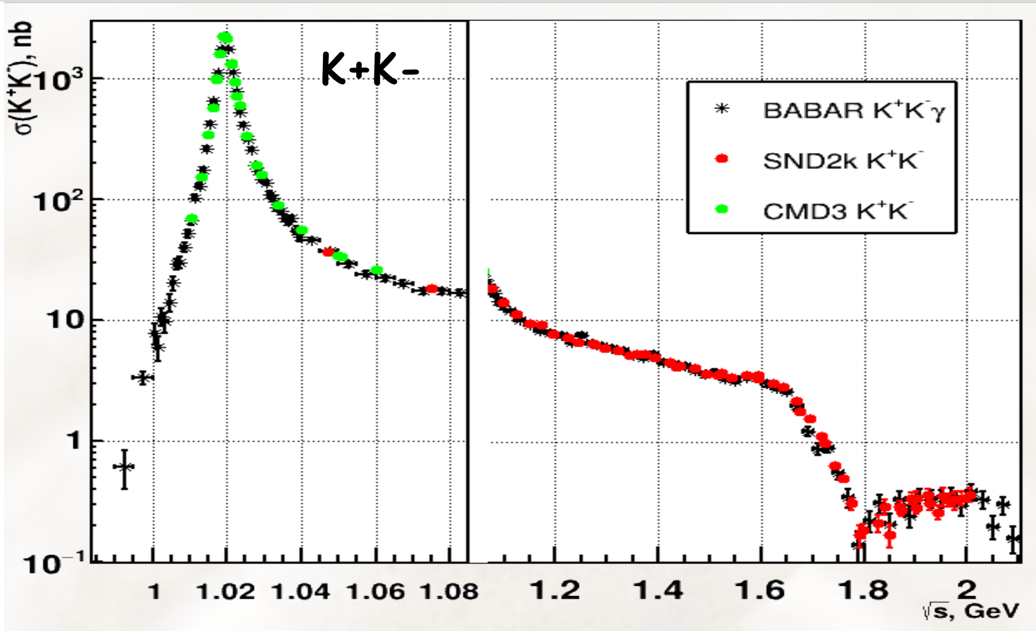
The dominant mechanism is $\omega a_0(980)$.

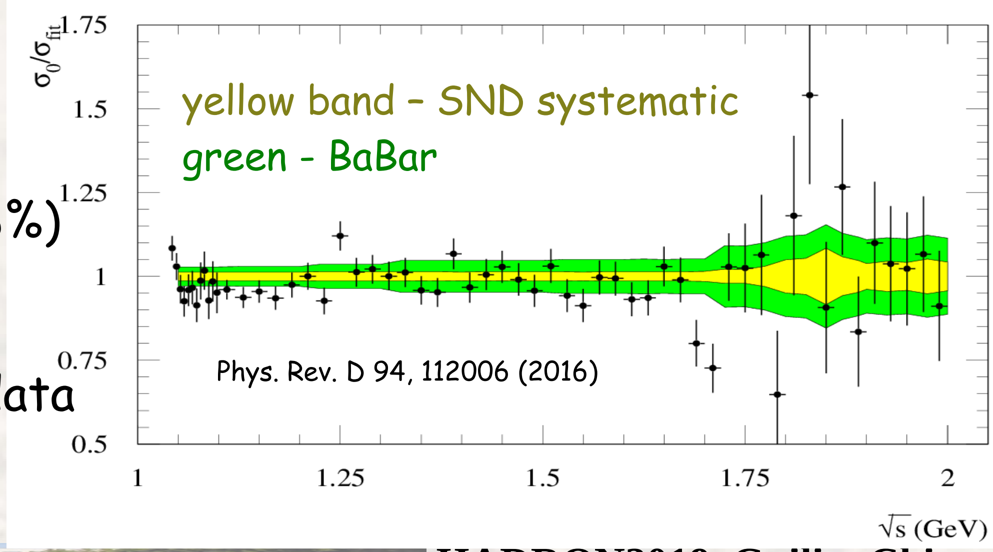
The cross section is about 2.5 nb, 5% of the total hadronic cross section
before was partially accounted by “isospin relation” $\sigma(\eta\pi^+\pi^-2\pi^0)=\sigma(\eta2\pi^+2\pi^-)$

Analysis of $e^+e^- \to \pi^+\pi^-4\pi^0$ (where no data exist) with $N\gamma>8$ in FS is also underway

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



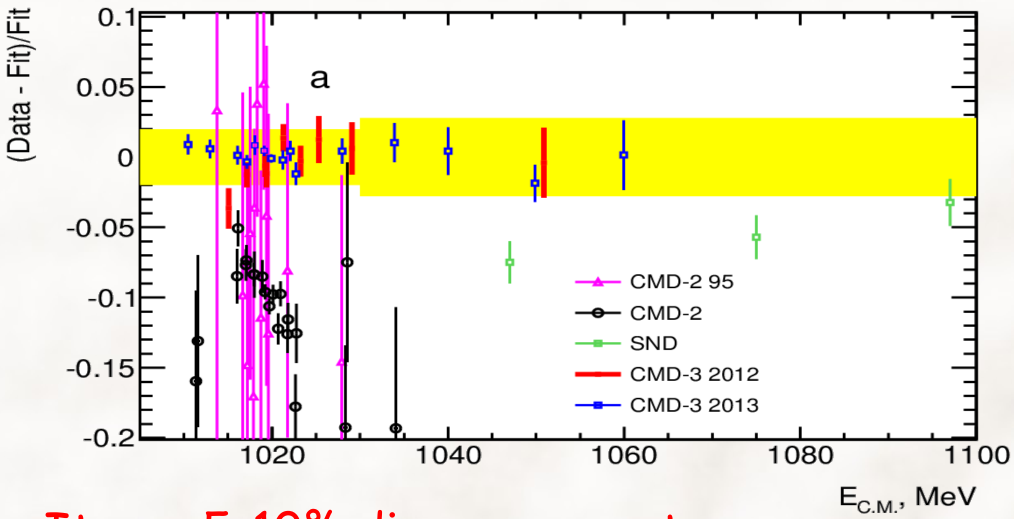


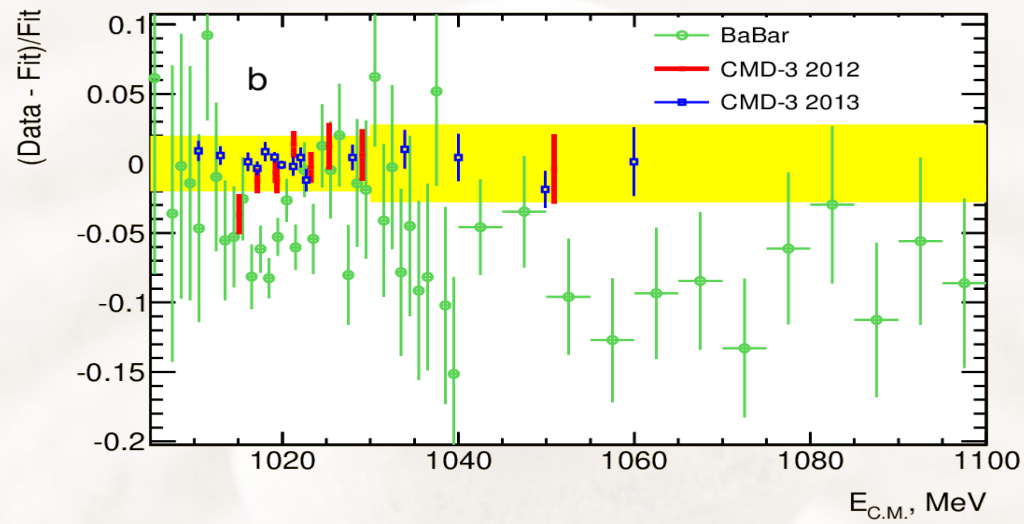


CMD-3: KsKl at φ - Best systematic precision (1.8%)
CMD-3: K+K- is under internal review (syst 2%)

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) CMD2 underestimated trigger inefficiency for slow K+K-

SND at VEPP-2M (7.1%)

with BaBar data (0.72%)

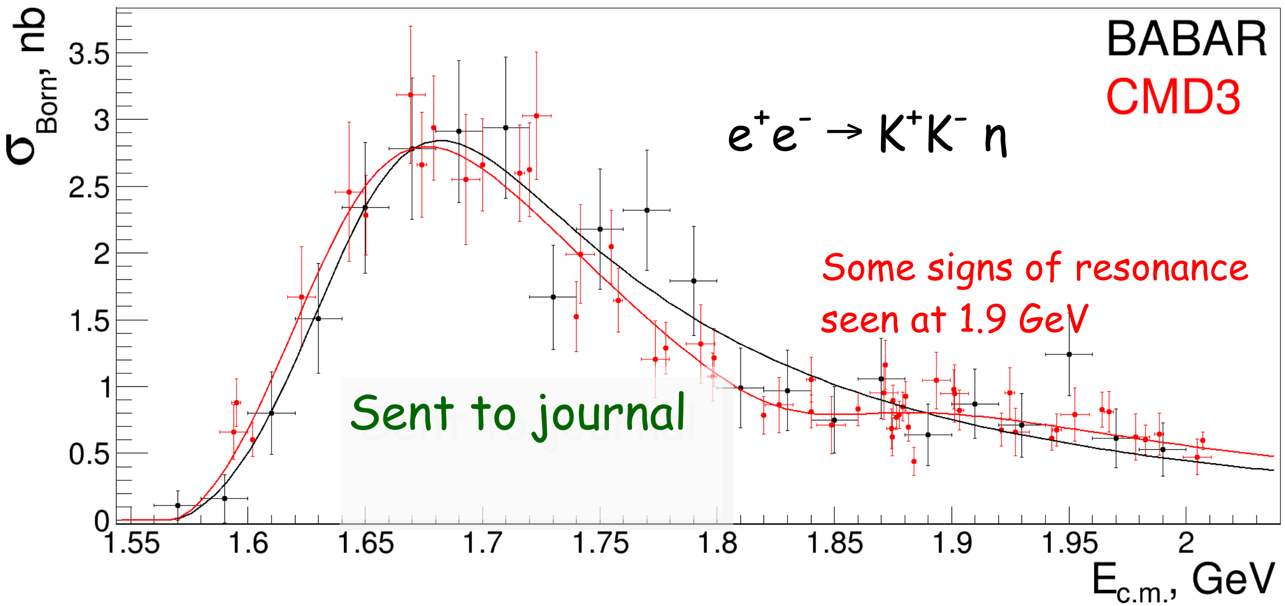
New CMD-3 cross-section is above CMD-2 and BaBar,

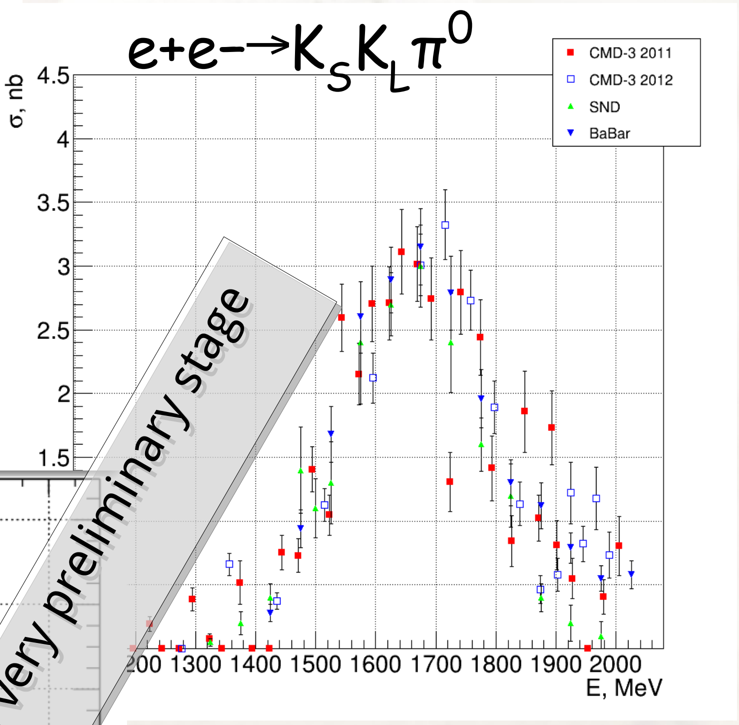
but it is in consistency with isospin symmetry:

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

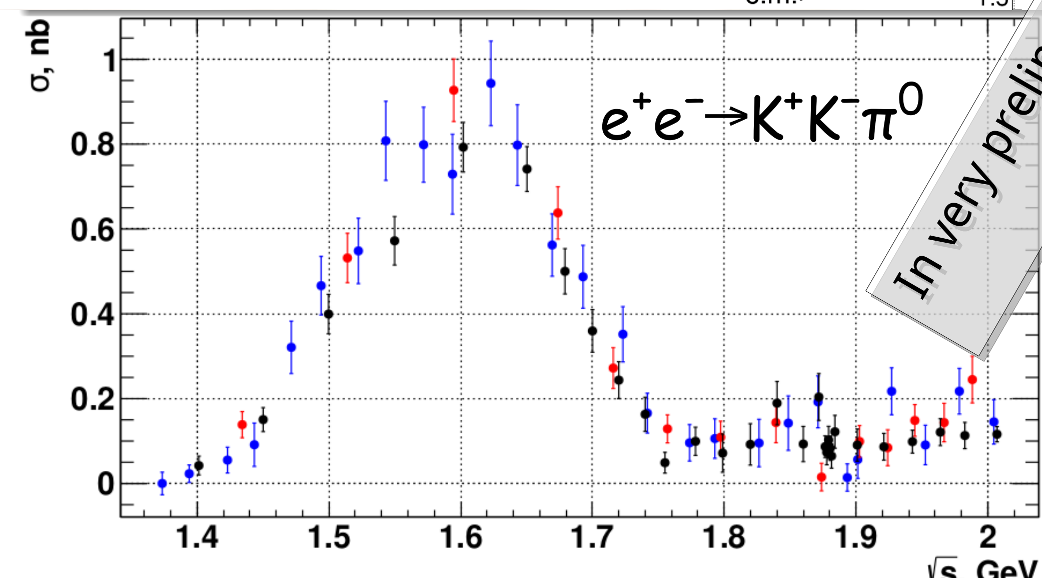
- $R_{SND} = 0.92 \pm 0.03 (2.6\sigma)$
- $R_{CMD-2} = 0.943 \pm 0.013 (4.4\sigma)$
- $R_{BaBar} = 0.972 \pm 0.017 (1.5\sigma)$

KKpi KKeta





In very preliminary stage

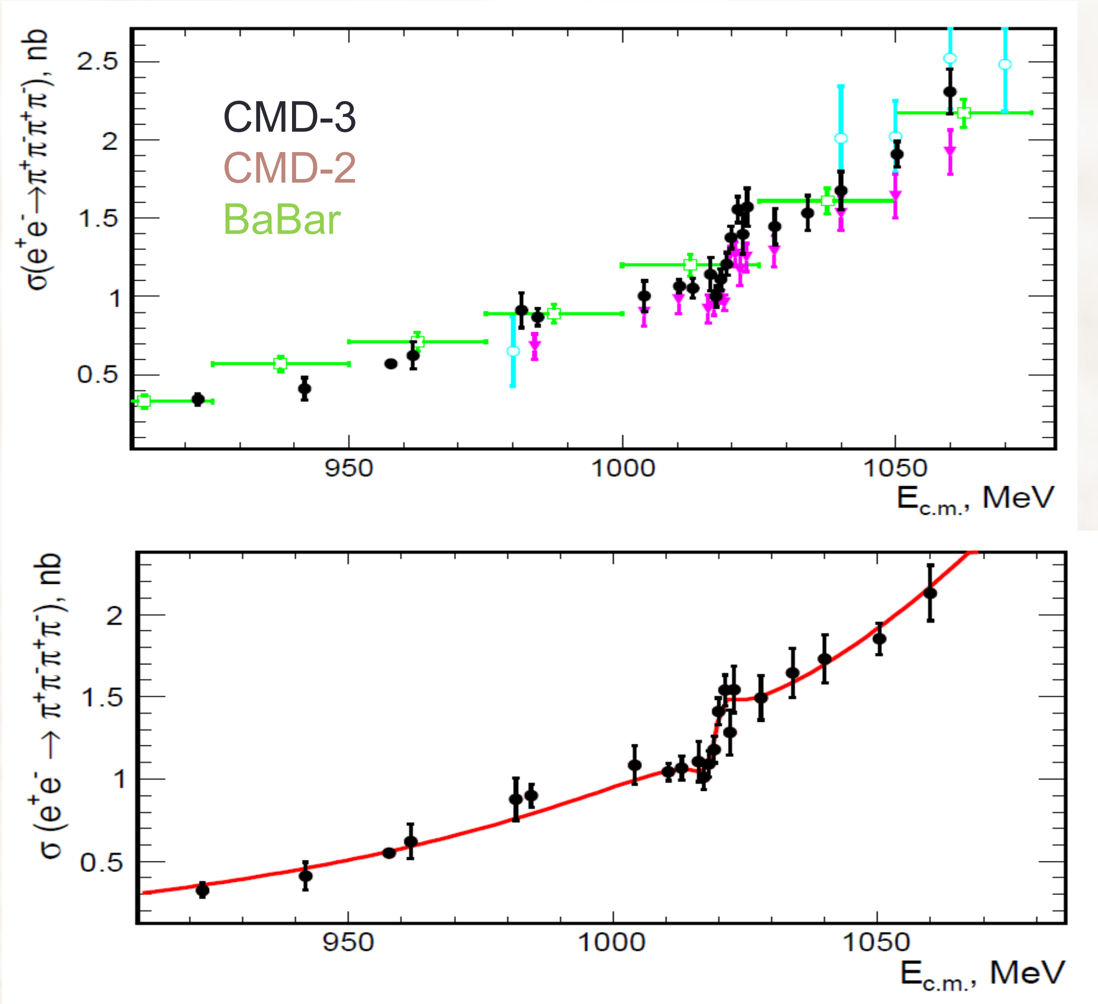


e+e- → π+π-π+π- @φ(1020)

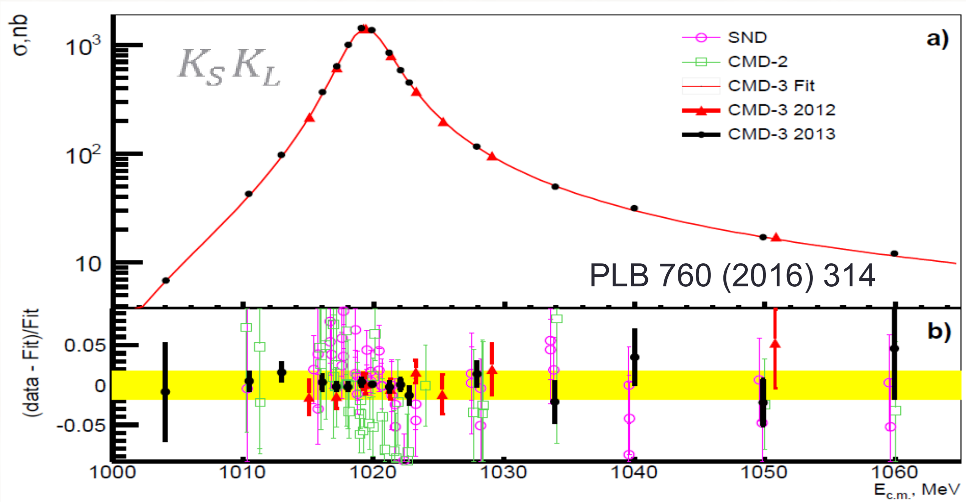
PLB 768 (2017) 345-350

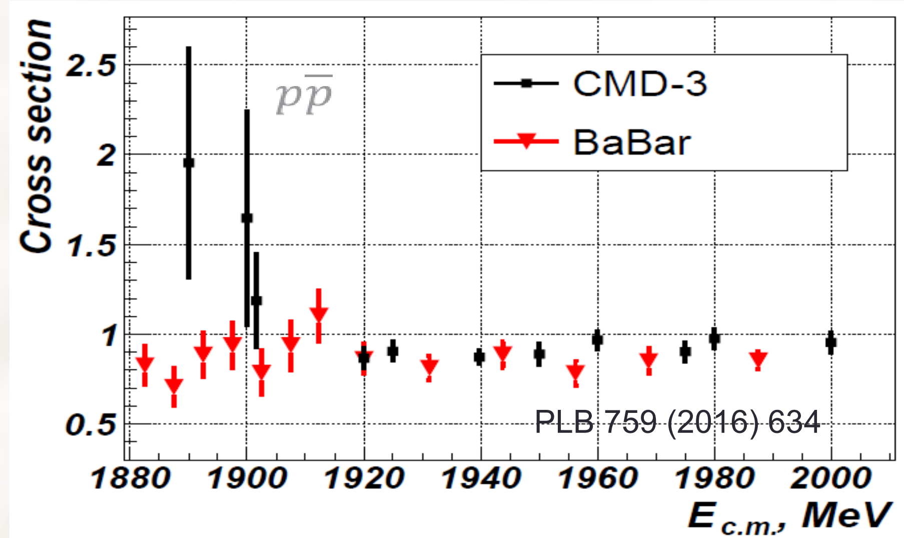
2011-2013 data, 10 1/pb
systematic error 3.5%

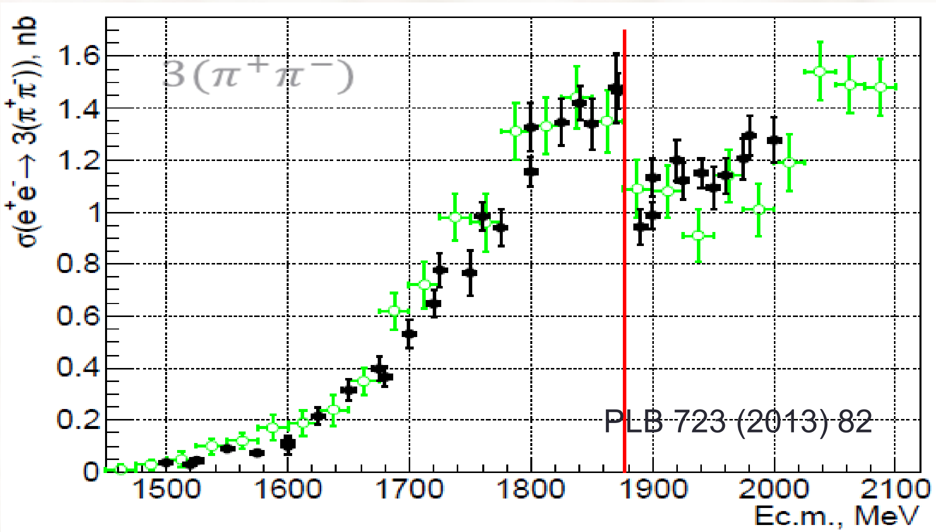
$$B\left(\varphi \to 2(\pi^+\pi^-)\right) = (6.5 \pm 2.7 \pm 1.6) \times 10^{-6}$$

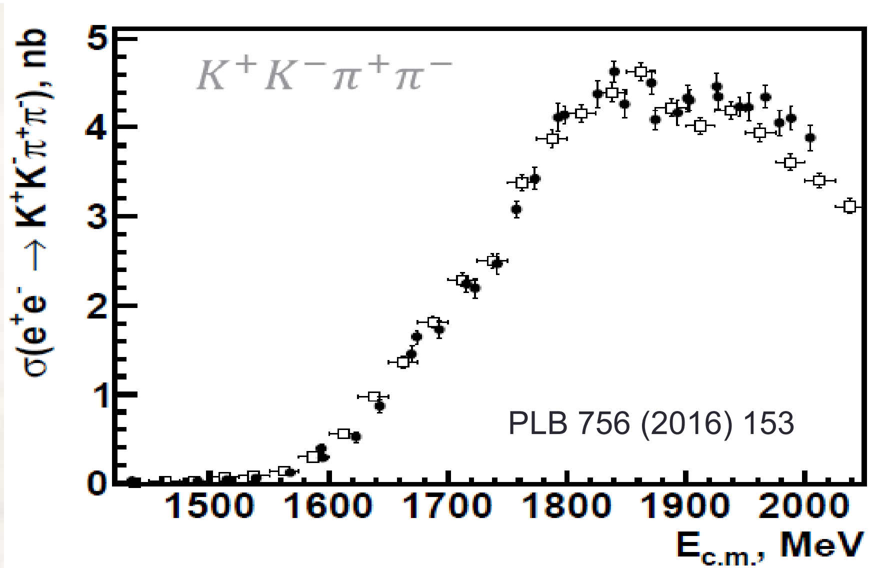


Published results from 2011-2013: CMD-3

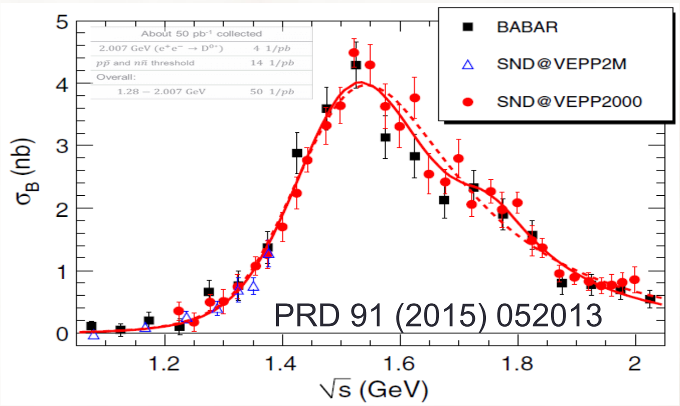


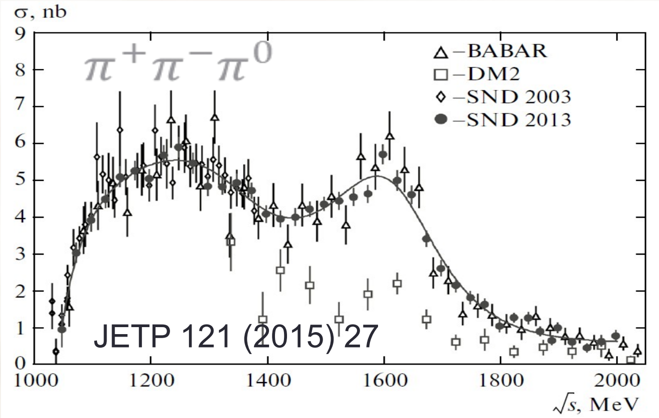


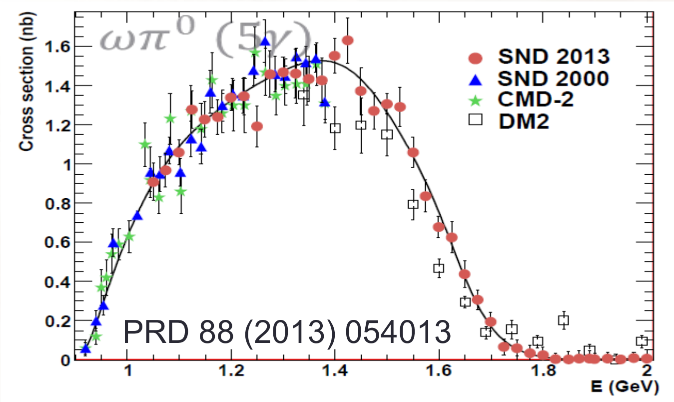


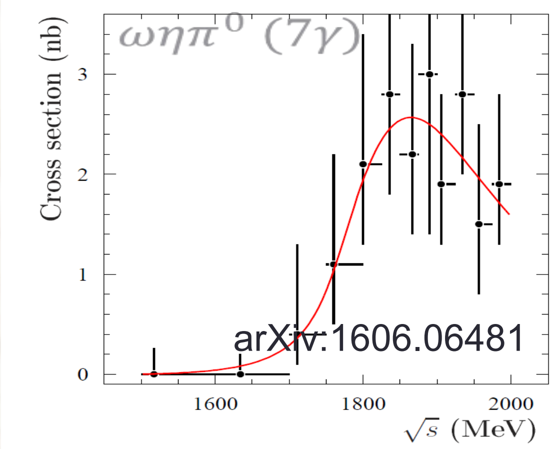


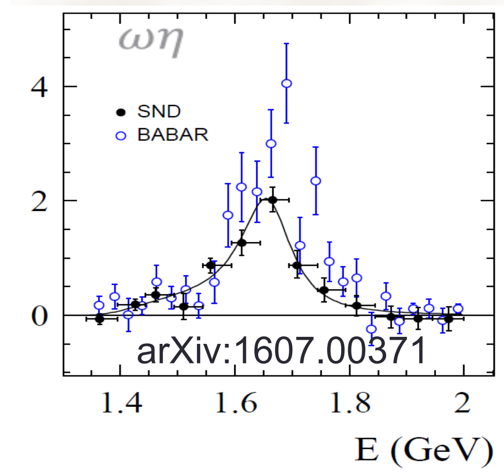
Published results from 2011-2013: SND

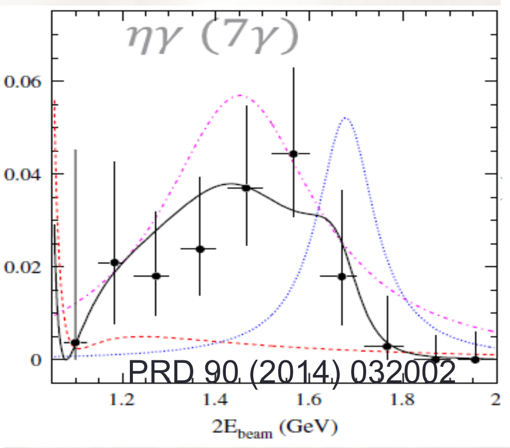


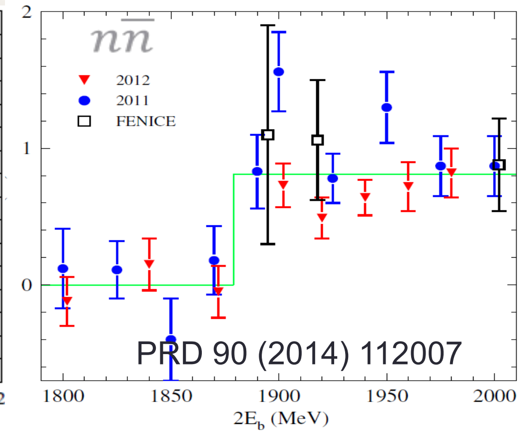




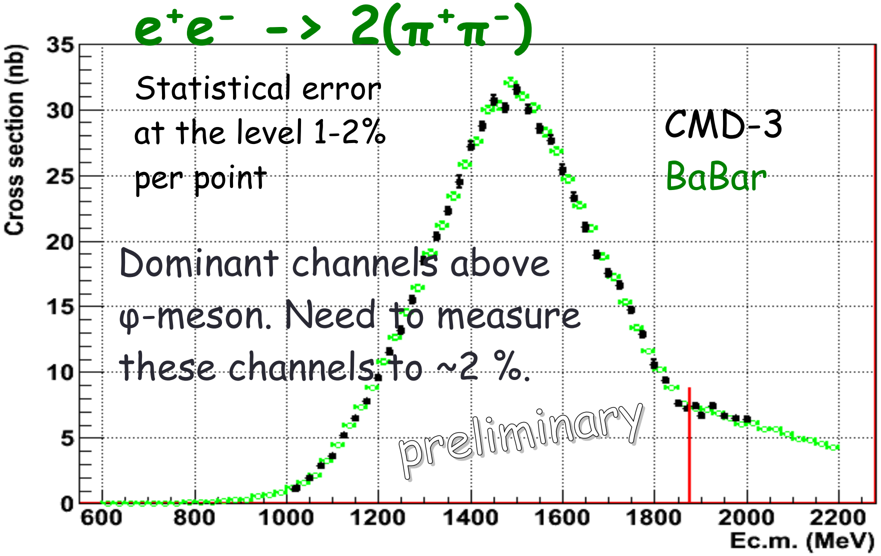


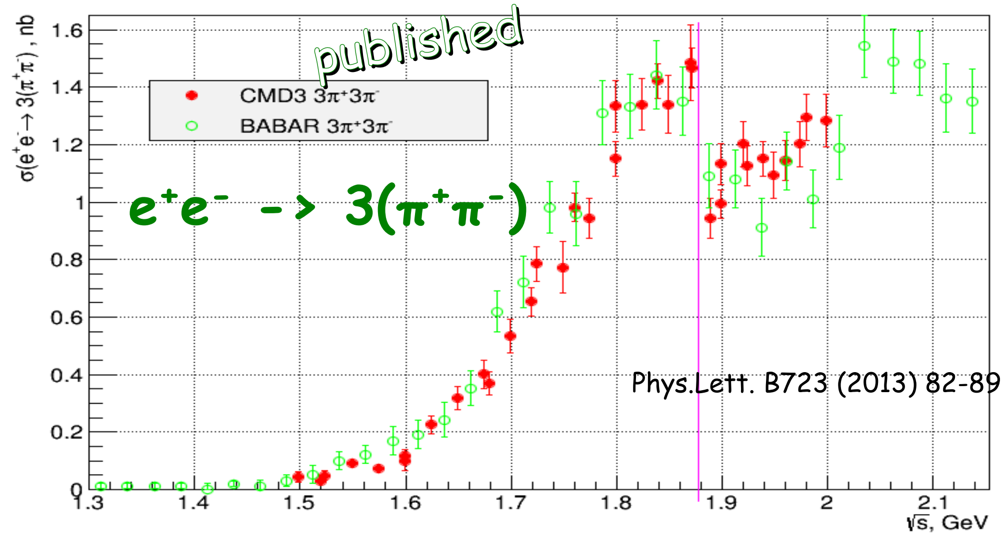






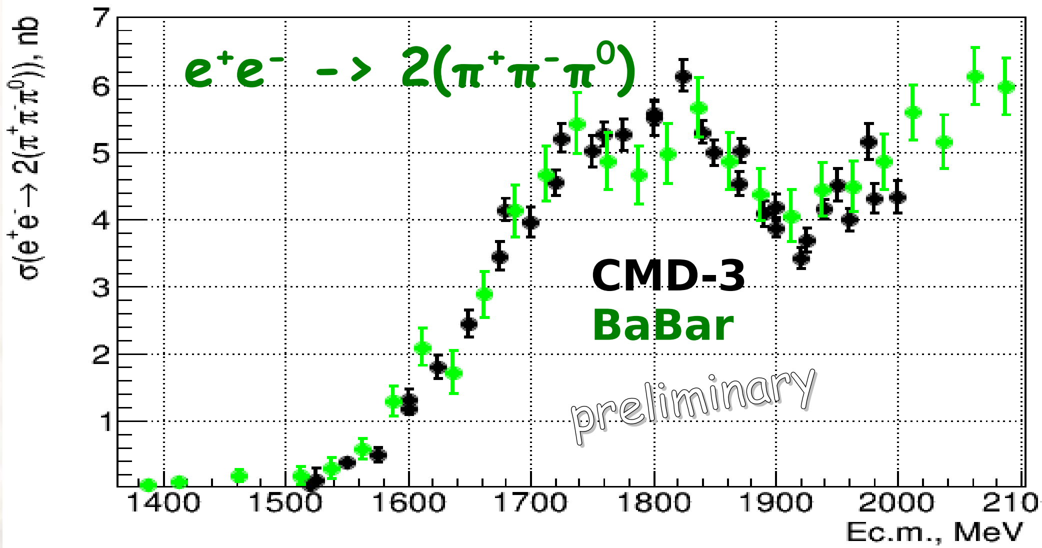
e+e- -> many pions with CMD-3





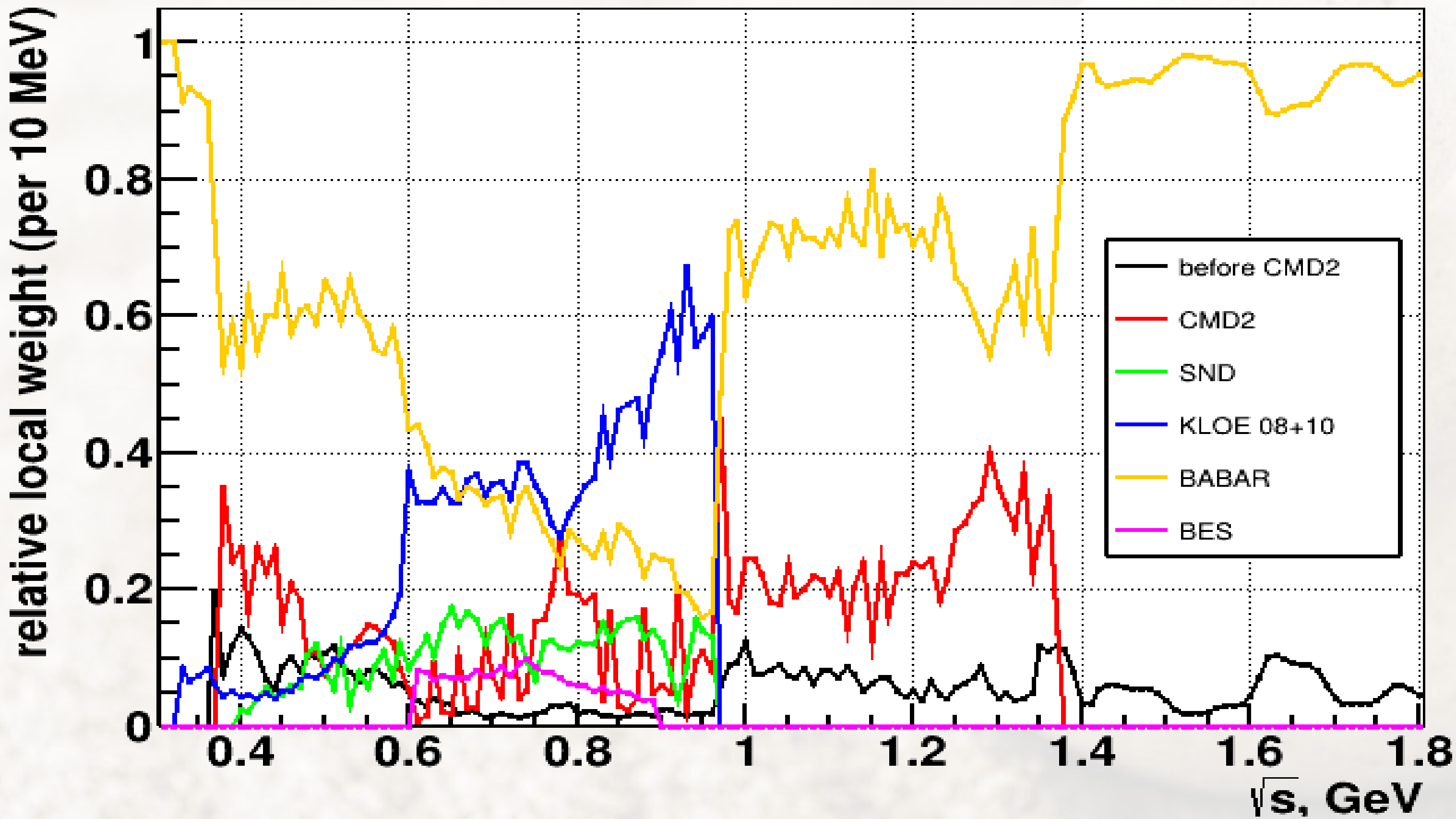
The dominated source of systematic error is model uncertainty(evaluation of the detector acceptance)
High statistics allows for more accurate study of the intermediate dynamics.

$3(\pi^+\pi^-)$ are mainly produced through $\rho(770) + 4\pi$ (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)



Relative local weight of different experiments in π+π-

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

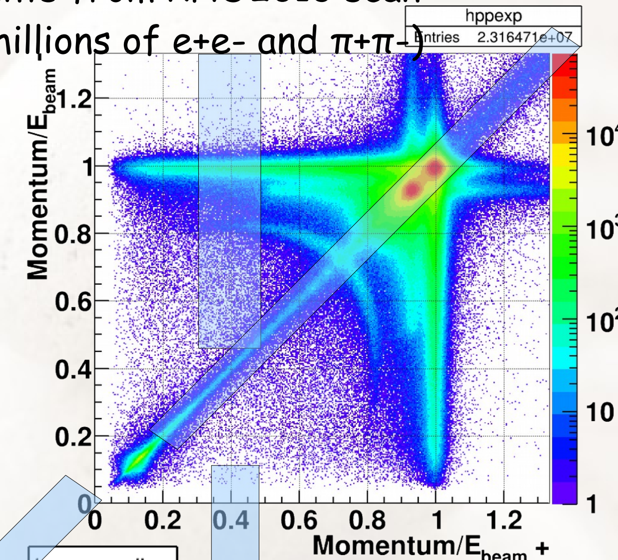


Locally precision is limited by statistic

MC generator, MCGPJ

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

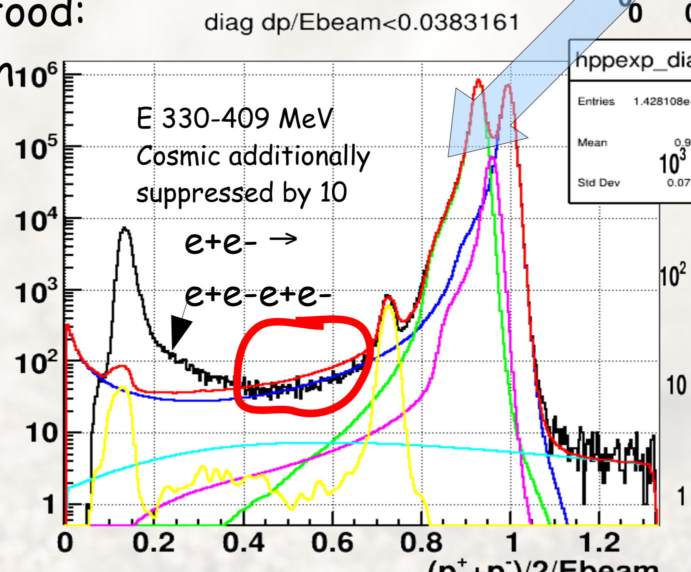
All events from RHO2013 scan
(~ 10 millions of e+e- and π+π-)

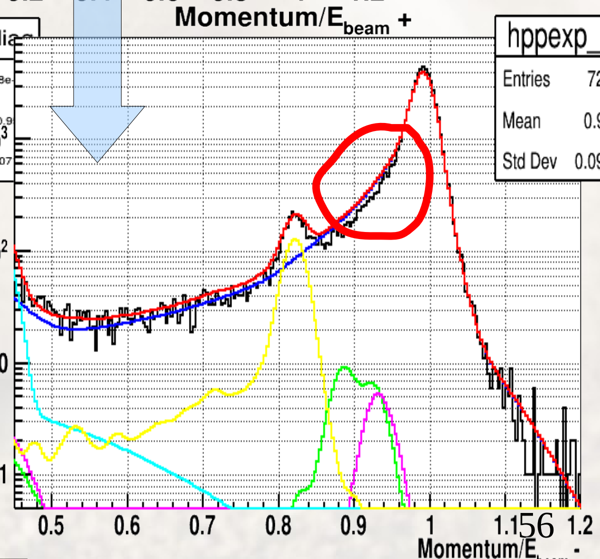


Several MC generators available with 0.1-0.5% precision.
<u>MCGPJ generator (0.2%)</u> is used by Novosibirsk group:
1 real γ + γ jets along all particles (with collinear Structures function)

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>

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

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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

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

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

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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

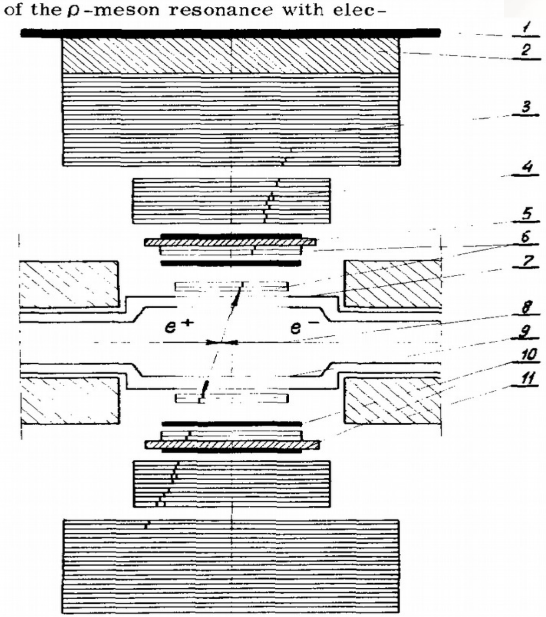


Fig. 1. Spark chambers system:
1) Anticoincidence scintillation counter
2) Lead absorber 20 cm thick
3) "Range" spark chamber
4) "Shower" spark chamber
5) Duraluminium absorber 2 cm thick
6) Thin-plate spark chambers

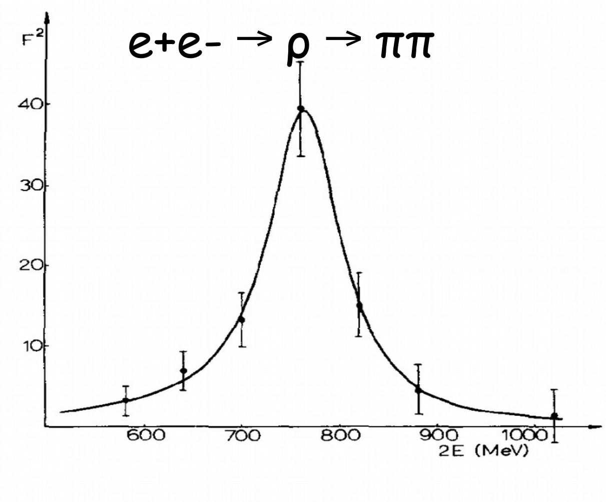


Fig. 2. Experimental values of F^2 (E) approximated by the Breit-Wigner formula.

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.

Colliders History

1961	AdA	Frascati	Italy
1965	Princeton-Stanford(e-e-)	Stanford	USA
1965	VEP-1(e-e-)	Novosibirsk	USSR
1966	VEPP-2	Novosibirsk	USSR
1967	ACO	Orsay	France
1969	ADONE	Frascat	Italy
1971	CEA	Cambridge	USA
1972	SPEAR	Stanford	USA
1974	DORIS	Hamburg	German
1974	VEPP-2M	Novosibirsk	USSR
1976	DCI	Orsay	France
1977	VEPP-3	Novosibirsk	USSR
1978	VEPP-4	Novosibirsk	USSR
1978	PETRA	Hamburg	Germany
1979	CESR	Cornell	USA
1980	PEP	Stanford	USA
1981	Sp-pbarS	CERN	Switzerland
1982	p-pbar	Fermilab	USA
1987	TEVATRON	Fermilab	USA
1989	SLC	Stanford	USA
1989	BEPC	Beijing	China
1989	LEP	CERN	Switzerland
1992	HERA	Hamburg	Germany
1994	VEPP-4M	Novosibirsk	Russia
1999	DAFNE	Frascati	Italy
1999	KEKB	Tsukuba	Japan
1999	PEP-II	Stanford	USA
2001	RHIC	Brookhaven	USA
2008	BEPCII	Beijing	China
2009	LHC	CERN	Switzerland
2010	VEPP-2000	Novosibirsk	Russia.
2018	SuperKEKB	Tsukuba	Japan

(Physics start date)

1961: AdA was the first matter antimatter storage ring with a single magnet (weak focusing) in which e+/e- were stored at 250 MeV

Touschek effect (1963); first e+e– interactions recorded – limited by luminosity ~ $10^{25}cm^{-2}s^{-1}$

SLAC & Novosibirsk VEP-1 works independently

1965: First physics at collision with e-e- scattering

(QED radiative effects confirmed)

1967: VEPP-2 First e+e- → hadron production

$L \sim 10^{28}cm^{-2}s^{-1}$

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

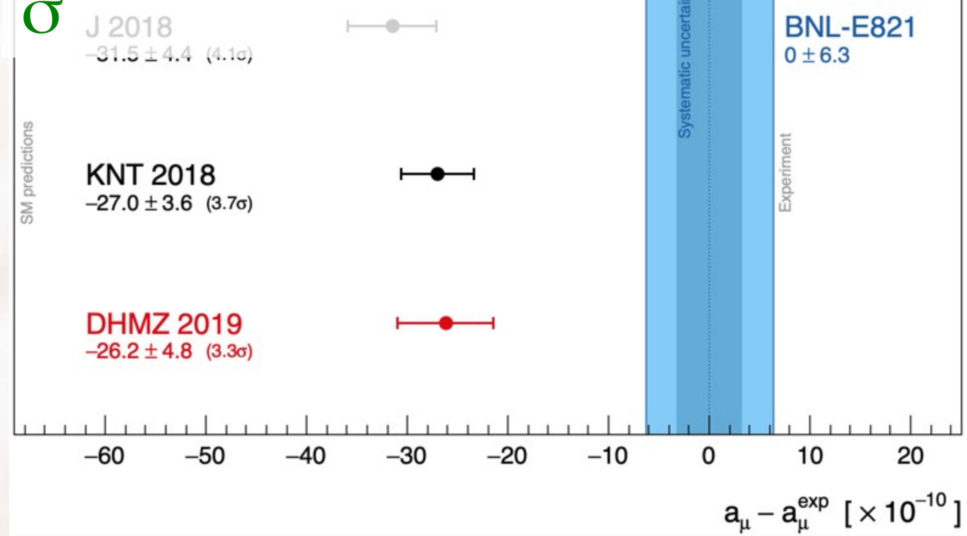
main channels contribution to precision at √s<1.937 GeV

$\pi^+\pi^-$	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- 4 σ

ArXiv:1802.02995, arXiv:1908.00921

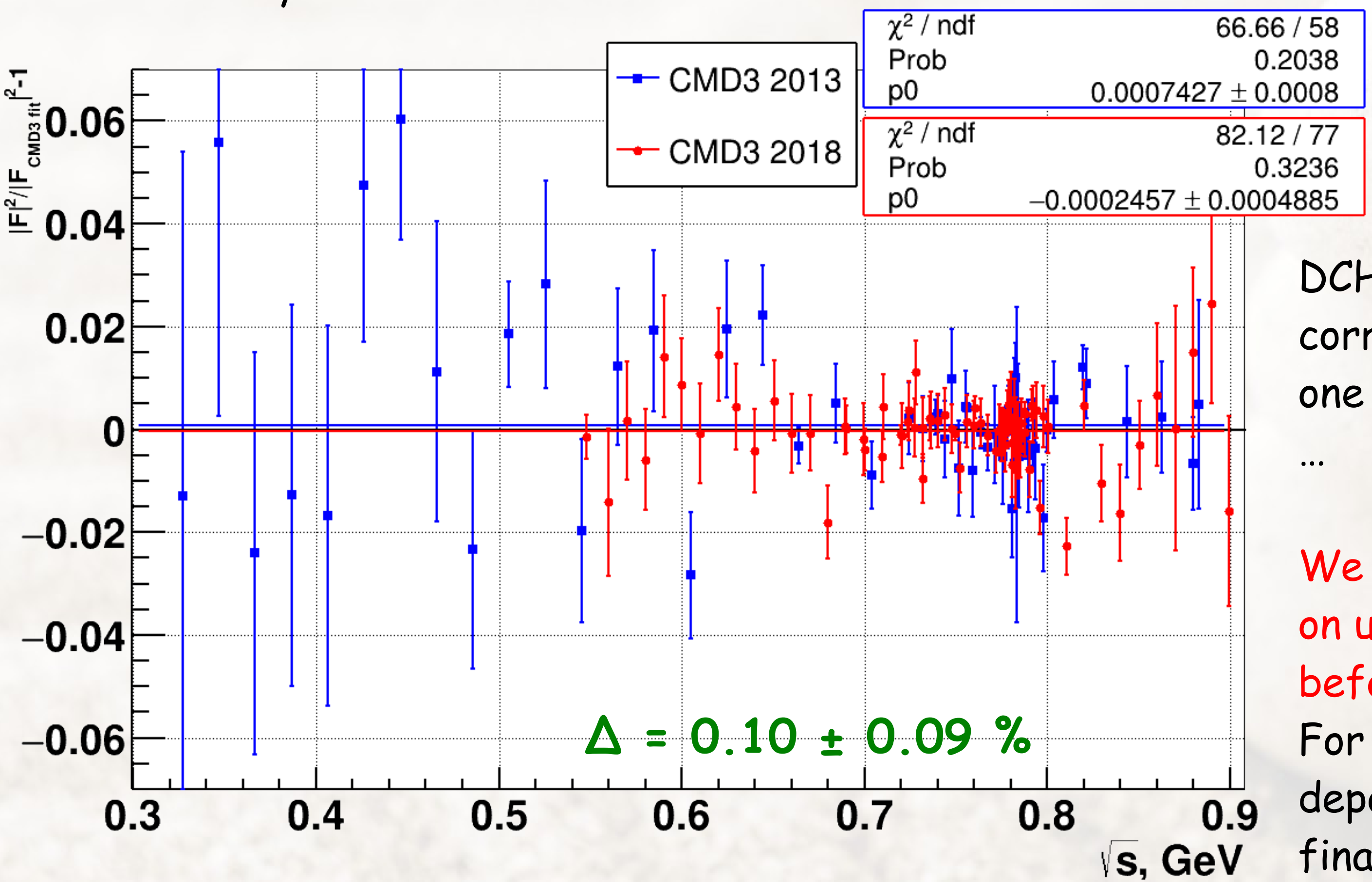


New g-2 experiments at FNAL and J-PARC have plans to reduce error to **1.5x10^{-10}**

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

$|F_\pi|^2$ 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