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

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### R(s)



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

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### 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  $\frac{1}{2}$  particle has exactly g=2

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

 $\pi^{0}, \eta, \eta$ 



### g-2 Experiments

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

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

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

#### $a_{\mu} = 11\ 659\ 208.9(6.3)\ 10^{-10}[0.54ppm]$



 $\begin{array}{ll} \mbox{Harvard Univ.} & \mbox{One electron quantum cyclotron} \\ \mbox{The value of } a_{e} \mbox{ was used to get the best determination of} \\ \mbox{fine-structure constant } \alpha. \end{array}$ 

#### <u>R. Parker et al., Science 360 (2018) 191</u>

Recent  $\alpha_{QED}$  measurement using the recoil frequency of Cs-133 atoms with 0.20ppb gives 2.5 $\sigma$  tension with experimental ae 21 August 2019

Bennet et al., PRD 73(2006)072003



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

#### Muon g-2 theory SM



#### The lowest-order hadronic contribution

The hadronic contribution is calculated by integrating experimental cross-section  $\sigma(e+e- \rightarrow hadrons)$ .

Starting at high energy the pQCD estimation of  $\sigma(e+e- \rightarrow hadrons)$  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 The diagram to be evaluated:



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



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### SM prediction for muon g-2

DHMZ10 Standard Mode JS11 HLMNT11 Phys. Rev. D 73 FJ17 072003 (2006) DHMZ17 Experiments stat. 460 ppb **KNT18** syst. 280 ppb BNL E821 2004 3.7σ BNL (x4 accuracy) 7.0σ 160 170 180 190 200 210 220  $(a_{\mu}^{SM} \times 10^{10})$ -11659000  $\Delta$  (Exp - Theory)  $\sim 3-4 \sigma$ 

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

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#### $\alpha_{OFD}(M_Z)$ from R(s) The electromagnetic fine structure constant $\alpha_{OED}(q^2)$ 물 1.2 르 is a running parameter with momentum transfer $q^2$ Vacuum Polarization 1.15 due to Vacuum Polarization effects -effective electron charge (charge screening) 1.1 $\alpha(s) = \frac{\alpha(0)}{1 - \Lambda \alpha(s)},$ 1.05 $\Delta \alpha_{\rm had}(s) = -\frac{\alpha(0)s}{3\pi} \int_{0}^{\infty} ds' \frac{R(s')}{s'(s'-s)-i\epsilon}$ 0.95 0.9 -10 5 10 -15 -5 o √s. GeV The $\alpha_{QED}(q^2)$ at mass of Z is used in predictions (<sup>2</sup>∑<sup>2</sup> 0.033 0.032 G fitter of electroweak model. 99% CL fit contours incl. $\Delta \alpha_{-}^{(5)}$ (M<sup>2</sup>) 0.031 It is the least known EW parameter like 0.03 68%, 95%, 99% CL fit contours incl. $\Delta \alpha_{bad}^{(5)}(M_{-}^{2})$ and direct Higgs searches δG /Gμ~0.9×10<sup>-5</sup>, δM /M ~2.4×10<sup>-5</sup> 0.029 1 $\sigma$ band for $\Delta \alpha_{had}^{(5)}$ (M<sup>2</sup>) 0.028 $\Delta \alpha_{\text{QFD}}^{5\text{had}}(M_Z) = 276.11 \pm 1.11 \times 10^{-4}$ 0.027 0.026 For future ILC, CLIC, FCC-ee it should be known 99% CL fit contours excl 0.025 100 150 250 300 350 with ~ $0.5 - 0.3 \times 10^{-4}$ M<sub>u</sub> [GeV]

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Eur.Phys.J. C74 (2014) 3046

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### Current PDG $\alpha_{s}$ world average (NNLO)

Gehrm.

GFitter

CMS

Hoang 🗕 🗕

(tt cross section)

0.115

0.11



Tau decays to hadrons give the best non-lattice  $\alpha_{\rm s}$  estimation

 $\alpha_{s}(M_{z}) = 0.1196 \pm 0.0030 (\pm 2.5\%)$  $\alpha_{s}(M_{z}) = 0.1151 \pm 0.0028 (\pm 2.5\%)$ 

unweighted  $\chi^2$  average:

Z decay width

0.12

& shapes

electroweak

precision fits

hadron

collider

0.125

0.13

α<sub>s</sub>(M<sub>z</sub>)= 0.1181 ± 0.0011 (±0.9%)

#### Sum rules theory From analyticity and using Cauchy's theorem Im(s) $\frac{1}{12\pi^2 s_0} \int_0^{s_0} ds \, w(s/s_0) R(s) = -\frac{1}{2\pi i s_0} \oint dz \, w(s/s_0) \Pi(z)$ Re(s) Integrated R(s) with different weights (pinched at $s_0$ where OPE is under question, w(y)~(1-y)) data $e+e- \rightarrow hadrons$ $\tau \rightarrow v$ + hadrons cc 20 $(v_1 + a_1)(s)$ з 18 erturbative QCD (massless) 16F Parton model prediction 14 exclusive data 2 12 pQCD 1.5 BES 1 KEDR 0.5 0 1 1.5 2 2.5 s (GeV<sup>2</sup>)

 $\tau \rightarrow v + hadrons$  limited until = 1.77 GeV (V+A the QCD asymptotic behaviour is reached faster ) e+e-  $\rightarrow$  hadrons can be extended to upper s<sub>0</sub> limits

 $\begin{array}{ll} \underline{M.Davier\ et\ al.,\ arXiv:1312.1501} & \underline{D.Boito\ et\ al.,\ arXiv:1805.08176} \\ \alpha_{s}(m^{2}_{\tau}) &= \ 0.332 \pm 0.005_{exp} \pm 0.011_{theo} & \alpha_{s}(m^{2}_{\tau}) &= \ 0.301 \pm 0.017_{exp} \pm 0.007_{theo} \\ (\pm \ 0.006\ DV, higher\ order\ \pm \ 0.009\ FOPT\ vs\ CIPT) & (\pm \ 0.005\ DV\ \pm \ 0.003\ higher\ order\ s\ \pm \ 0.003\ FOPT\ vs\ CIPT) \\ \alpha_{s}(m^{2}_{z}) &= \ 0.1199 \pm 0.0015\ (\pm 1.3\%) & \alpha_{s}(m^{2}_{z}) &= \ 0.1162 \pm 0.0025\ (\pm 2.1\%) \\ e+e-:\ Limited\ by\ data,\ Difference\ between\ FO\ and\ CIPT\ ~3\ times\ smaller\ than\ in\ tau\ decays\ 10 \end{array}$ 

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### Current PDG $\alpha_{s}$ world average (NNLO)



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#### Inclusive vs exclusive measurements



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#### **R** measurements



VEPP-2000: direct exclusive measurement of  $\sigma$  (e+e-  $\rightarrow$  hadrons) Only one working these days on scanning below <2 GeV World-best luminosity below 2 GeV (except 1 GeV - where KLOE outperformed everybody)

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

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#### **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.

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



## **KLOE ISR+ VP**

KLOE experiment (2000 - 2006,2014 - 2018) biggest Drift Chamber ever built (Ø4m)



Measurement with ISR  $e+e- \rightarrow \pi+\pi-\gamma$ 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<sup>2</sup>

direct extraction of  $\alpha_{QED}(s)$  via e+e-  $\rightarrow \mu+\mu-\gamma$ Phys. Lett. B, 767 (2017), 485

KLOE results by Dr. Xiaolin Kang: Presentation for  $\eta$  decays &  $\gamma\gamma$  physics Poster on ISR (e+e- $\rightarrow \pi + \pi - \pi 0$ )



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



Maximum c.m. energy is 2 GeV, project luminosity is L = 10<sup>32</sup> cm<sup>-2</sup>s<sup>-1</sup>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 17

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#### CMD-3 and SND





1.3 T magnetic field Tracking:  $\sigma_{R\phi} \sim 100 \ \mu m$ ,  $\sigma_{Z} \sim 2mm$ Combined EM calorimeter (LXe,CsI, BGO):  $\sigma_{E} \sim 3-8\%$ ,Tracking in LXe calorimeter 21 August 2019 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 19
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#### Physics at VEPP-2000

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

× study of production dynamics, ChPT

But also we do: \* properties of light vector mesons, their decays,

× nucleon formfactors at threshold.

accuracy of the light vector mesons parameters

- × two photon physics,
- × search of exotics,
- × and so on...

### Properties of light vector mesons in the PDG mostly comes from Novosibirsk measurements Aleson parameters in PDG 2011 from CMD2 and SND Rare decays

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$\begin{array}{c} & & & \\$	770 (MeV) .e+e- 	DOCUMENT ID           1 AKHMETSHIP           3 AKHMETSHIP           4 ACHASOV           5 AKHMETSHIP           6 ACHASOV           7 BARKOV           8 ALOISIO           8 ALOISIO	800 <u>TECW</u> 005 SND 03 KLOE 03 KLOE 02 SND 85 OLYA 5 SOLYA 03 KLOE	<u>comment</u> <u>e^+e^-</u> 1.02 <u>e^+e</u> 1.02 <u>e^+e^-</u> 1.02 <u>e^+e^-</u> 1.02 <u>e^+e^-</u>	x <sup>1</sup> = x+= = = = = = = = = = = = =	781 762 ω(782) mass w(0.05 (MeV) 782.65±0.12 OUR A 783.20=0.13±0.16 782.68±0.08±0.03 782.79±0.08±0.03 782.7±0.1±1.5	71 (MeV) EV75 VERAGE 1 18680 11200 1.2M 19500
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(750 760 760 p) (750) 0 mass     (170) 0 mass     (	770 (MeV) e+e- <u>6075</u> WERACE 0004 8004 1144 5004 5004 0.98M 1.98M 1.98M	DOCUMENT ID           DOCUMENT ID           1           AKHMUTSHIP           4           4           4           4           4           4           5           4           6	800 72200 06 SND 06 SND 03 KLOE 02 SND 85 OLYA 85 OLYA 93 KLOE 03 KLOE 03 KLOE 03 KLOE	<u>comment</u> <u>e1</u> <u>e</u> <u>e1</u> <u>e2</u> <u>e1</u> <u>e1</u> <u>e2</u> <u>e1</u> <u>e1</u> <u>e2</u> <u>e1</u> <u>e1</u> <u>e2</u> <u>e1</u> <u>e1</u> <u>e1</u> <u>e2</u> <u>e1</u> <u>e1</u> <u>e1</u> <u>e1</u> <u>e1</u> <u>e1</u> <u>e1</u> <u>e1</u>	x1 = x+= = = = = = = = = = = = = = = = = =	761 762 w(762) mass w(762) mass 982,055,012,008,4 782,79-0,013+0,16 782,79-0,08+0,09 782,79-0,08+0,09 782,7-0,1+1,5 781,96_0,01,710,08	71 (MeV) 25/75 VERAGE 1 18860 11200 122M 19500 11k 3463
(750 760 µ(770) <sup>0</sup> mass <b>VEUTRAL ONLY</b> <b>VALUE (MM)</b> 75.04 0.40 0.67 75.04 0.5 0.5 75.04 0.5 1.0.5 75.04 0.5 1.0.5 75.04 0.5 1.0.5 75.04 0.5 1.0.5 75.04 0.05 1.0.5 75.04 0.05 1.0.5 75.04 0.05 1.0.5 75.04 0.05 1.0.5 75.04 0.05 0.05 1.0.5 75.04 0.05 0.05 0.05 75.04 0.05 0.0	770 (MeV) • • • • • <u>2015</u> 900k 900k • 900k • 900k • 114k • 1.98M 1.98M 1.98M 500k	Document in         Teo           000000000000000000000000000000000000	800 722W 005 SND 006 SND 006 SND 003 KLOE 002 SND 003 KLOE 003 KLOE 003 KLOE 003 KLOE 003 KLOE	$- \frac{COMMENT}{e^+e^-}$ $= \frac{e^+e^-}{1.02 e^+e^-}$ $= \frac{1.02 e^+e^-}{1.02 e^+e^-}$ $= \frac{1.02 e^+e^-}{1.02 e^+e^-}$ $= \frac{1.02 e^+e^-}{1.02 e^+e^-}$	x1 m x+ m x+ m m <sup>0</sup> , m <sup>0</sup> , m <sup>0</sup> , m <sup>0</sup> , m <sup>0</sup>	761 782 w(762) mass w(762) ma	77 (MeV) 2075 2075 2075 2075 2075 2075 2075 2075
250 760 760 μ/270) <sup>0</sup> mass <b>VEUTRAL ONLY</b> <i>MUD</i> ( <i>MN</i> ) 75.541.633 OUR A 75.971.040 10.70 75.0 10.51 0.5 75.0 10.51 0.5 75.0 10.51 0.5 75.0 10.51 0.5 75.0 10.61 0.7 75.0 10.61 1.1 75.1 ±0.7 ±5.3	770 (MeV) • + e- <u>CVTS</u> <u>VERACE</u> 900k 900k 900k 114k 500k the following 1.98M 1.98M	Воссимент во           1         аклиметствир           43         аснаком           43         аснаком           43         аснаком           53         аснаком           63         аснаком           7         ваком           64         аснаком           7         ваком           64         аснаком           7         ваком           64         аснаком           9         аснаком           9         аснаком           14         венаком           14         венаком	800 <u>TECM</u> 005 SND 004 CMD2 003 KLOB 02 SND 03 KLOB 03 KLOB 03 KLOB 03 KLOB 03 KLOB 04 SND 04 SND 05 SND 05 SND 05 SND 05 SND 06 SND 07 SND 07 SND 07 SND 08 SND 00 SND	<u>consecutor</u> <u>e1e</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u> <u>i102</u> <u>ete</u>	x <sup>1</sup> x x+x= x+x= x0 <sup>1</sup> x+x= x0 <sup>1</sup> x+x= x0 <sup>1</sup> x,x=x= x0 <sup>1</sup> x <sup>1</sup> x	761 762 w(762) mass w(762) mass <b>100</b> <b>762.65±0.12 OUR A</b> <b>783.20-0.13±0.16</b> <b>787.70-0.18±0.10</b> <b>789.70-0.15</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.11</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.05±0.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>781.01</b> <b>78</b>	71 (MeV) 24775 248462 118680 1120 1284 19500 1124 19500 114 3463 154 2704 2704
750 760 p(770) <sup>0</sup> mass <b>VEUTRAL ONLY</b> VALUE (MAN) 76,00 1 0,00 76,00 1 0,00 76,00 1 0,00 75,00 1 0,00 75,00 1 0,00 75,00 0,00 75,00 75,00 0,00 75,000 75,0000 75,0000 75,0000 75,0000 75,0000 75,0000 75,0000 75,00000 75,00000 75,00000 75,00000000 75,0000000000000000000	770 (MoV) •••• ••• ****************************	Document         750         750           0 AKHMUTSHIP         0         0         0           1 AKHMUTSHIP         0         0         0           2 AKHMUTSHIP         0         0         0           3 AKHMUTSHIP         0         0         0           5 AKHMUTSHIP         0         0         0           6 ALDISIO         0         ACHASOV         0           7 BARKOV         0         ALDISIO         0           9 ALDISIO         0         ALDISIO         0           10 ACHASOV         1         BENAYOUN         12           2 GARDNER         12         CARDNER         12	800 7ECW 06 SND 04 CM22 03 KL0E 02 SND 85 OLYA 35 OLYA 36 KL0E 03 KL0E 03 KL0E 03 KL0E 03 KL0E 03 KL0E 03 KL0E 03 KL0E 03 KL0E 03 KL0E	$\begin{array}{c} conserved \\ c \ c \ c \ c \ c \ c \ c \ c \ c \ c$	$x^{1}\pi$ $x+\pi^{-}$ $x^{-}\pi^{-}$ $\pi^{0}$ $\pi^$	761 762 w(762) mass w(762) mass w(762) mass 76265±0.12 OUR A 762.65±0.12 OUR A 762.65±0.13 -0.08 762.79-0.08 +0.09 762.08 -0.01 +0.5 762.08 -0.13 -0.08 762.08 -0.13 -0.01 762.08 -0.03 ±0.17 762.4 =0.2 762.4 =0.5	71 (MeV) EV75 VERAGE 1 18680 11200 122M 19500 11k 3463 270k 1488 270k 1488
750 760 760 p(770) <sup>0</sup> mass <b>NEUTRAL ONLY</b> with the second seco	770 (MaV) e <sup>+</sup> e <sup>-</sup> <u>CV73</u> VCRACE 9006 8006 1.08M 1.08M 1.98M 1.98M 5006	Doctoment and         780           780         790           1 AKHMUTSHIP           AKHMUTSHIP           AKHMUTSHIP           ALDISID           CALDISID           CALDISID	500 <u>TECM</u> 005 501 005 505 5	- <u>conserv</u> - <u>e^+e^-</u> - <u>e^+e^-</u> - <u>e^+e^-</u> - <u>102 e^+e</u> - <u>e^+e^-</u> - <u>e^+e^-</u>	$x^{1}\pi^{0}$ $x^{+}\pi^{-}$ $x^{0}$ $\pi^{0}$ $\pi^{0}$ $\pi^{0}$ $\pi^{0}$ $\pi^{0}$ $x^{+}\pi^{-}$ $x^{+}\pi^{-}$ $x^{+}\pi^{-}$ $x^{+}\pi^{-}$	761 762 w(762) mass w(762) mass WL02 (hkv) 762.654-0.12 OUR A 783.30-0.13 + 0.14 787.74-0.08 + 0.09 + 0.04 782.74-0.08 + 0.09 + 0.04 782.74-0.1 + 1.5 781.05-0.13 ± 0.17 782.4 = 0.2 782.2 + 0.4 782.2 + 0.5	217 (MeV) EV75 VERAGE 1 18680 11200 11200 114 3463 156 270k 1488 7000
750 760 760 p(770) <sup>0</sup> mass <b>NEUTRAL ONLY</b> subject (MA) 775,4910,440,670 775,4910,440,670 775,4910,440,670 775,4910,440,670 775,4910,440,670 775,4910,490 775,4910,400 775,4910,400 775,490 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,590 775,5000 775,50000 775,50000 775,50000 775,50000 775,500000 775,500000 775,50000000000000000000000000000000000	770 (MoV) ••••• •••• •••• •••• •••• •••• ••••	280         780           780         780           200000000         780           200000000         780           200000000         780           200000000         780           200000000         780           2000000000         780           2000000000000         780           2000000000000000000000000000000000000	800 7200 107 106 106 106 106 106 106 106 106 107 100 107 100 100 100 100 100 100 100	$\begin{array}{c} \hline construct \\ c \downarrow c \\ c$	***** **** **** **** **** **** **** ****	761 762 w(782) mass w(782) mass (782) mass 782,55,412,00 m A 781,20-0,13-0,16 782,7-0,1 - 1,06 782,7-0,1 - 1,06 782,7-0,01 - 0,09 782,0 - 0,01 - 0,01 782,0 - 0,01 782	71 (MeV) <b>EV75</b> <b>1860</b> <b>1200</b> <b>1200</b> <b>121</b> 19500 <b>11</b> 19500 <b>11</b> 19500 <b>11</b> 14k 3463 15k 270k 14k8 7000

w meson	φ Λ
AVI-METSHIN 06 CM22 ADD-METSHIN 06 CM22 ADD-METSHIN 06 CM22 ADD-METSHIN 06 CM22 ADD-METSHIN 06 CM22 AVIENT 05 SPEC AVIENT 05 SPEC SPECIAL AVIENT 05 CM24 AVIENT 05 CM	
	ø(1020) width (MeV)
MASS	ML0E (MAV) EV75 DOCU 1019.455±0.020 OUR AVERACE Extended 1019.30 ±0.02 ±0.10 105k AKMI
ID TECN COMMENT	1019.52 ±0.05 ±0.05 17.4k AKH
cale factor of 1.9. See the ideogram below.	1019.483+0.011+0.025 272k 1 AKH
aning the course of the course	1019.42 ±0.05 19008 * ACTS
SHINOM CMD2 $e^+e^- \rightarrow \pi^+\pi^-\pi^0$	1010.40 _0.04 _0.01 _031 _AKH
035 RVUE 0.44-2.00 e e	1019.36 0.12 3 ACH/
ER 95 SPEC 1.33 pd <sup>3</sup> Heω 94c CBAR 0.0 pp ωηπ <sup>0</sup> 94c CBAR 0.0 pp ωηπ <sup>0</sup>	1019.51 -0.07 +0.10 11169 AKH1 1019.51 =0.4 BAR
933 CBAR 0.0 pp → wa0x0	1019.42 ±0.06 55600 AKH
UER 93 ASTE $\overline{p}p \rightarrow 2\pi^+ 2\pi^- \pi^0$	1019.7 TU.5 2012 DAVE
(E 833 OLYA $e^+e^ \pi^+\pi^-\pi^0$	1019.7 ±0.1 ±0.1 9079 ALBF
76 CNTR π p → ωn	1019.3 ±0.1 1500 AREP
	1019.67 -0.17 25080 <sup>5</sup> PELL
	1019.52 ±0.13 3681 BUKI
IDTH	¢(1020

2	$1.8 \pm 0.9 \pm 0.3$	153	AKHMETS	HIN OD	CMD2	0.6-0.97 0 0
X CMD2 00	We do not use	the following	data for avera	ages, fits	, limits,	etc. • • •
04 CMD2 0.2 01E SND 1.8	<20 90		KURDADZ	E 88	OLYA	$a^+a^{\pi^+\pi^-}\pi^+\pi^-$
12 AEMS 31 OLYA 30 DM1 78C OLYA	$\Gamma(\pi^0 \gamma) / \Gamma_{\text{total}}$ VALUE (with 10 <sup>-4</sup> ) ••• We do not use t	EV75 he following	DOCUMENT I	v prs. fits.	TECN	COMMENT
74 CNTR 71 OSPK	5.21 + 1.28 + 0.39	1868518,1	<sup>19</sup> AKHMETSI	HIN 05	CMD2	0.60-1.38 + -
6.8	s.22   1.17   0.75	3650619,1	ACHASOV	03	SND	0.60-0.07 ++ ++
dence Level = 0.120)	5.8 11.7	10	21 BENAYOUN	96	RVUE	0.54 J.04 el e
	7.9 1 2.0	1		89	ND	ele , x <sup>0</sup> y
	$\Gamma(\pi^0 e^+ e^-)/\Gamma_{total}$					
A REAL PROPERTY OF THE REAL PR	MALUE (units 10 %) CL16	DOCU	MENT ID	TECN	COMMO	INT .
COMMENT	<1.2 90	ACH	ASOV 08	SND	0.36-0	197 el e - #0
1D2 0.98-1.05 e <sup>+</sup> <sub>0</sub> e <sup>-</sup> -	<1.6	AKH	METSHIN 05A	CMD2	0.72-0	84 c+c-
$102 * 1^{6} = \kappa_L^0 \kappa_S^0$	Γ(ηe <sup>1</sup> e )/Γ <sub>total</sub>		DOCUMENT	10	TECN	COMMENT
D +	<0.7	ive following	AKHMETS	ges, fics. HIN 05A	CMD2	0.72-0.84 e <sup>+</sup> e
$102 e^+e^- \rightarrow \pi^+\pi^- \ge 2$	$\Gamma(\pi^0\pi^0\gamma)/\Gamma_{total}$					
102 et et - et at	(4.5+0.8) OUR FIT	EVTS	DOCUMENT	0	TECN	COMMENT
D2 e1 e hadrons	$5.2 \frac{1}{-1.3} + 0.6$	190 1	22 AKHMETSI	IIN 04B	CMD2	0.6-0.97 e+e-
MS 11.8 polar. pp	$1.1 \pm 1.0 \pm 0.3$	295 L	<sup>23</sup> ACHASOV	027	SND	0.36-0.97 + + +
UE	• • • We do not use t	he following	data for avera	ges, fits,	limits, c	atc. • • •
YA elle - hadrons	$4.8 \pm 3.4 \pm 0.5$	63 L	24 ACHASOV	00G	SND	e'e , =0=0
COMMENT		0	o me	sor	۱	
4. See the ideogram below.	$\Gamma(\pi^0 \alpha)/\Gamma_{max}$					
	VALUE (units 10 2) EV	is not	CUMPNET D)	TICK	CDMA	N NT
e e nyhe	the second se				-	

 $\Gamma(-0, e^+, e^-)/\Gamma_-$ 

		Γ(ηe+e-)	//T <sub>total</sub>					
	1	VAL LIF (units 1	0 4)	EVIS	DOCUMEN	IT ID	1	FCN
		(1.15 : 0.10)	OUR AV	ERACE				
	100	110+010+ 114+010+	0.12	213	2 AKUMET	TSUIN 0	10 5	MD
	Fe/F	1.3 70.9	.0.00	7	GOLUBE	V 8	5 N	ID.
TECN COMMENT	. 6/.	1.0 -0.6		,	002002			
SND 0.36_0.07 et at0		Γ(ργ)/Γte	cz %	DOCUMN	VT #2	nen	COM	Ment
CMD2 0.72-0.84 c+c-	100	< 0.12	90	71 AKHME	TSHINGOR	CMD2	0+0	
$s \rightarrow z_0 s s$	201	• • • We de	o not use	the following	data for av	erages. r	its, in	mits.
	Г3/Г	5 7	00	AKHME	TSHIN 076	CMD2	0 * 0	
		<200	84	LINDSE	Y 66	HBC	2.1-3	2.7 A
TECN COMMENT		$\Gamma(\pi^+\pi^-\alpha)$	/E					
1.2		VALUE CONTRACT	-1	an Date	DOCUM	ICNT ID		70
of 1.3. See the ideogram (	below.	0.41+0	12+0.04	30175	72 AKUL	AUTSIA	a no	Ch
1D2 e+e	100	• • • We do	not use t	he following	data for ave	rages. It	ts, hrr	nits.
ID 1.1-1.38 e	1.1	< 0.3		00	73 AKHN	AETSHI	97C	Ch
A c+c x+n-	794	<600		90	KALB	FLEISCH	175	HB
e+e + =-		~ 70		00	COSH	(E	74	05
1 e - m1 m		<400		00	LINDS	SEY	65	HE
0.36-0.97 + +		3.21+0.03 2.90 + 0.21 +	0.18		74 AMBR	OSINO	07 99c	CM
	Γ14/Γ	$\Gamma(\pi^0\pi^0\gamma)/$	<b>F</b> total					
		WALVE farits 30	-11	CIAL CUTS				<u></u>
CMD2 0.6-0.97 e+e=	2	(1.07+-0.06)	OUR AVE	RAGE	pocul	alari ap		
CN COMMENT MD2 0.6 0.97 e <sup>+</sup> e <sup>-</sup> ηπ <sup>0</sup> γ	•	(1.07+-0.06) 1.07 +0.01 -0.03	OUR AVE	RAGE	84 AMB	ROSINO	07	к
CN COMMENT AD2 0.6 0.97 e <sup>+</sup> e <sup>-</sup> η= <sup>0</sup> γ	•	$(1.07 \pm 0.06)$ $1.07 \pm 0.01$ -0.03 $1.08 \pm 0.17$	OUR AVE +0.06 -0.05 ±0.09	268	84 AMBF AKHM	ROSINO	07 990	KL CN
см соммемл MD2 0.6-0.97 с+ с- туж <sup>0</sup> у		(1.07+0.06) 1.07 +0.01 -0.03 1.08 ±0.17 • • We do	OUR AVE +0.06 ±0.09 not use th	268 te following o	84 AMBF AKHN Jata for aver	ROSINO METSHI roges. fit	07 990 5. lim	KL CN
7 COMMENT 32 0.6 0.97 c <sup>+</sup> c <sup>-</sup> η# <sup>0</sup> γ	,	(1.07 + 0.06) 1.07 + 0.01 - 0.03 1.08 ± 0.17 • • We do 1.09 = 0.02 1.08 ± 0.093	OUR AVE +0.06 ±0.09 not use ti ±0.05	268 te following o 2429 419	84 AMBF AKHN Jata for aver ALOIS 78.85 ACHA	AETSHI Inges fit	07 N 99C s. lim 02D	KL CN its. +
теси соммент СМD2 0.6 0.97 с+с- 17***	, Г <sub>б</sub> /Г	(1.07+0.06) 1.07 +0.01 -0.03 1.08 ±0.17 • • We do 1.09 =0.03 1.158 + 0.093 <10	OUR AVE + 0.06 = 0.05 ± 0.09 not use th ± 0.05 1 0.052	268 te following o 2438 419 90	84 AMBF AKHIN data for aver ALOIS 78,85 ACHA DRUZ	ROSINO METSHII roges, fit EIO SOV THININ	07 N 99c s. lim 020 00H 87	KL CN its. e SN NE
т соммант 22 0.6 0.97 с+с- ул <sup>2</sup> 0 у ТСN соммант ND с <sup>1</sup> с т 7	, Г <sub>б</sub> /Г	(1.07 + 0.06) 1.07 + 0.01 -0.03 $1.08 \pm 0.17$ $\cdot \cdot We do$ $1.09 \pm 0.03$ < 10 $\Gamma(\pi^+\pi^-\pi)$	OUR AVE +0.06 -0.05 ±0.09 not use ti ±0.05 10.052	268 e following o 2400 410 90	84 AMBF AKHM Jata for aver ALOIS 78,85 ACHA DRU2	ALETSHI METSHI Toges fit EIO SOV THININ	07 N 99C s. lim 920 00H 87	KL CN its. 4 SN NE
е соммент 20.6.6.037 с+с= 19.6.2 ТСN СОММЕНТ ИП = 1 = 75 20.02 с <sup>1</sup> с - х	, Ге/Г	$ \begin{array}{l} (1.07 \pm 0.01) \\ 1.07 \pm 0.01 \\ -0.03 \\ 1.08 \pm 0.17 \\ \cdot \bullet & \text{We do} \\ 1.09 \pm 0.03 \\ < 10 \\ \hline \Gamma(\pi^+\pi^-\pi) \\ \text{VALUE (units)} \end{array} $	OUR AVE +0.06 =0.05 $\pm 0.05$ $\pm 0.05$ 1 0.052 $(+\pi^{-})/[$ $10^{-6})$ (1)	268 se following o 2432 410 90 total 5_EVTS	84 AMBF AKHM Jata for aver ALOIS 78,85 ACHA DRU2 DRU2		07 N 99C s. lim 92C 00H 87	KL CA its. 4 91 NE
сонмант 20.6.0.97 с+с= 200 сонмент ГСN сонмент MD2 с!с х 0 с+с= х	Γ <mark>6/Γ</mark>	$\begin{array}{c} (1.07 + 0.06) \\ 1.07 + 0.253 \\ -0.533 \\ -0.533 \\ 1.08 \pm 0.17 \\ \bullet & We \ do \\ 1.09 \pm 0.02 \\ \bullet \\ 1.158 \\ 0.093 \\ < 10 \\ \hline \Gamma(\pi^+\pi^-\pi \\ \underline{WALUE \ (units)} \\ \bullet & \bullet \ We \ do \\ \hline \end{array}$	OUR AVE +0.06 =0.05 =0.05 =0.05 =0.052 (0.052) (0.052) (0.052) (0.052) (0.052) (0.052)	268 e following o 2432 419 90 total 5. <u>EVTS</u> the following	84 AMBF 84 AMBF AKHB Jata for aver ALOIS 78,85 ACHA DRU2 <u>Document</u> data for aver	ROSINO METSHII rages. fit 10 SOV CHININ ID erages. fit	07 N 99c s. lim 920 00H 87 	KL CN KL SN NL
$\frac{1}{2} \frac{1}{2} \frac{1}$	Γ <sub>6</sub> /Γ	(1.07+0.06) 1.07 +0.01 1.07 +0.01 1.08 +0.17 : • • We do 1.09 =0.02 : 1.158 +0.093 <10 <b>Г</b> ( <b>π</b> + <b>π</b> - <b>π</b> <u>VALUE (onits</u> ) • • We do 3.03±1.74± < 8/0	OUR AVE +0.06 = 0.09 not use th = 0.05 1 0.052 $(+\pi^{-})/1$ $10^{-6}$ CU o not use = 2.14 on	268           te following of 2433           410           90           total           5         EVTS           the following 3285	<sup>84</sup> AMBF AKH ata for aver ALOIS 78,85 ACHA DRU2 DOCUMENT data for aver AKHMETS CORDIER	ROSINO METSHII ages. fit 10 SOV THININ 10 erages. fit HIN 000 70	07 N 99c s. lim 020 00H 87 	KL CN iits. e SN NI NI NI
ECN СОВИДАУ! MD2 0.6.6 ут.+ с+ ут.9 у+ с+ ут.9 у+ с+ ут.9 у+ с+ П ТССИ СОМИДИТ 1.2. СМП2 + 1 = − 75 СМП2 + 1 = − 75 СМП2 + 1 = − 75 ОСП2 + 2 + с - 55 ОСП2 + 2 + с - 55 ОСП2 + 2 + с - 15 уС0	г <mark>6/Г</mark>	(1.07+0.06) 1.07 +0.01 1.07 +0.01 1.08 ±0.17 ••• We do 1.09 ±0.02 1.158 0.093 <10 <b>Г(7+π-π</b> <u>VALUE (ories</u> •• We do 3.03±1.74± < \$70	OUR AVI + 0.06 ± 0.09 not use tl ± 0.05 1 0.052 $(+\pi^{-})/I$ $10^{-6}$ Cl 0 not use 2.14 90	268 2432 410 90 total 5 <i>EVTS</i> the following 3285	<sup>84</sup> AMBF AKHM data for aver ALOIS 78.85 ACHA DRUZ DRUZ DOCUMENT data for aver AKHMETS CORDIER	ROSINO METSHII ages. fit iIO SOV THININ ID erages. fit HIN 000 70	07 N 99c s. lim 026 00H 87 	KL CN its. e SN NI NI NI NI NI NI NI NI NI NI NI NI NI
EXY COMMANY MD2 0.6.07 c+c- y= <sup>0</sup> y= T TECN COMMENT .2. CMD2 c <sup>1</sup> c - 70 CMD2 c <sup>1</sup> c - 30 ND c <sup>1</sup> y - 10 CMTR 67-10 yCu	F6/F	$ \begin{array}{c} (1.07+-0.06) \\ 1.07 & \pm 0.01 \\ 1.07 & \pm 0.03 \\ 1.08 & \pm 0.17 \\ \cdot \cdot & We \ do \\ 1.09 & \pm 0.17 \\ \cdot & We \ do \\ 1.09 & \pm 0.02 \\ \cdot & We \ do \\ 1.09 & \pm 0.02 \\ \cdot & We \ do \\ 1.09 & \pm 0.02 \\ \cdot & We \ do \\ 1.09 & \pm 0.02 \\ \cdot & We \ do \\ 1.09 & \pm 0.02 \\ \cdot & We \ do \\ 1.09 & \pm 0.02 \\ \cdot & We \ do \\ 0.03 \pm 1.74 \\ \cdot & \times $	OUR AVE +0.06 $\pm 0.09$ not use th $\pm 0.05$ $+ \pi^{-})/1$ $10^{-6}$ (21) $10^{-6}$ (21) 0 not use $-\pi^{-}\pi^{0}$	268 2432 410 90 total <i>EVTS</i> the following 3285	BOCUMENT AKHM ALOIS 78.85 ACHA DRUZ DRUZ DRUZ DRUZ CORDIER	ROSINO METSHII Dages, fit BO ISOV THININ ID Frages, fit HIN 000 79	07 N 99C S. lim 020 00H 87 57 57 57 57 57 57 57 57 57 57 57 57 57	KL CN its. 4 SN NE NE NE NE
СК СОМИНУИ 102 0.6.9.97 «+ «- ту»", 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	Γ6/Γ	$(1.07+0.06) \\ 1.07 + 0.01 \\ 1.07 + 0.01 \\ 1.08 + 0.03 \\ 1.08 \pm 0.17 \\ 1.08 \pm 0.17 \\ 1.08 \pm 0.17 \\ 1.08 \pm 0.17 \\ 1.08 \pm 0.03 \\ 1.09 \pm 0.02 \\ $	OUR AVE $\pm 0.06$ $\pm 0.09$ not use th $\pm 0.05$ $\pm 0.05$ $\pm 0.05$ $\pm 0.052$ $\pm 0.$	268           268           te following of 2433           419           90           total           5           3285           0// Ftotal           5	84 AMBF AKHM Jata for aver BR-85 ACHA DRU2 DRU2 DRU2 DRU2 DRU2 DRU2 DRU2 DRU2	ROSINO METSHII Doges fit DO SOV THININ ID Frages fit HIN 000 70 16	07 N 99c s. lim 026 00H 87 ts, lim c.M WIF	KL CN KL SN NI NI NI NI NI COM
К. СОМАНУТ 102 0.0 0.97 «+ «= 100° 7 «+ «= 100° 7 «+ «= 100° 7 «+ «= 2. СМП2 « 1 «= — 75 СМП2 « 1 « 1 «= — 75 СМП2 « 1 « 1 « 1 « 1 « 1 « 1 « 1 « 1 « 1 «	Г6/Г Г0/Г	$\begin{array}{c} (1.07+0.06)\\ 1.07+0.01\\ -0.03\\$	OUR AVE + 0.06 = 0.09 not use tl = 0.05 1 0.052 + $\pi^{-}$ )/I 10.652 + $\pi^{-}$ )/I - $\pi^{-}\pi^{0}$ 10.052	RAGE         268           1000000000000000000000000000000000000	BOCUMENT 84 AMBE ALOIS 78.85 ACITA DRUZ DOCUMENT data for ave AKHMETS CONDIER UMENT ID HIMETSHIN	ID I	07 N 99c s. lim 02b 00H 87 . <u>TEO</u> ts, lim VIF CM	KL CN its. e SN NE mits. ED2 RE
СОВАЦКУТ 20.6.0027 ст. с 20.7 ст. с 20.7 ст. с 20.7 ст. с 20.7 ст 20.7 ст 2	F6/F	(1.07 + 0.06) 1.07 - 0.21 1.08 = 0.17 $\cdot \cdot We do 1.09 = 0.02\cdot 1.09 = 0.02\cdot 1.09 = 0.02\cdot 1.158 = 0.0933< 10\Gamma(\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi$	OUR AVE +0.06 =0.00 ±0.09 not use tl =0.05 10.052 $(+\pi^{-})/[1-6]$ :2.14 00 $(-\pi^{-}\pi^{0})$ (d) 00 not use (c) not use	RAGE         268           c following c         2432           410         90           total         5           c fV/Ts         5           MALTS         AK           the following c         3285	BOCH 84 AMBF AKHI Jata for over ALOIS 78,85 ACHI 18,85 ACHI 18,85 ACHI 19,85 000 10,0000 10,000 10,000 10,000 10,000 10,0000 10,000 10,000 10,	ID SOV	07 N 99c s. lim 02b 00H 87 . <u>TEG</u> ts, lin CM WIF CM	KL CA KL SN NI NI NI NI NI NI NI NI NI NI NI NI NI
ранцалт тработ тработ созвании созвани созвани созвани созвании созвании созвании соз	Г6/Г Г9/Г	$\begin{array}{c} (1.07+0.06)\\ (1.07+0.06)\\ 1.07 = 0.013\\ 1.08 = 0.17\\\\\\\\\\\\\\\\ $	OUR AVE $\pm 0.06$ $\pm 0.09$ not use th $\pm 0.05$ $\pm 0.05$ $\pm 0.05$ $\pm 0.052$ $\pm 0.$	RAGE         268           2492         2492           90         410           90         5           600xing 410         3285           0/Footal         5           5         480           10         480           10         480           10         480	BAMBE AMBE ALOS BASS ACIA BRUZ DOCUMENT data for ave ACIA DRUZ DOCUMENT data for ave AKHMETS HIMETSHIN data for ave MMETSHIN data for ave	ROSINO AETSHII Tages fit SOV THININ ID Frages fit HIN O2E 79 100E CP Frages fit 88 CP	07 N 99c s. lim 02b 00H 87 . <u>TEG</u> 00H 87	KL CA KL SN NI NI NI NI RE COM e <sup>1</sup> e
$\begin{array}{c} \text{Tree conserved} \\ \text{CADD: } & \text{de } \log_{2} \sigma_{1}^{-1} \sigma_{1}^{-1} \\ \text{de } \log_{2} \sigma_{1}^{-1} \sigma_{1}^{-1} \\ \text{Tree conserved} \\ \text{for } \sigma_{1}^{-1} \sigma_{1}^{-1} \sigma_{2}^{-1} \\ \text{for } \sigma_{1}^{-1} \sigma_{1}^{-1} \\ \text{for } \sigma_{1}$	Γ <sub>6</sub> /Γ Γ <sub>9</sub> /Γ + - 0	$\begin{array}{c} (1.07+0.06)\\ (1.07-0.01)\\ 1.07&-0.01\\ 1.08&-0.17\\ \bullet\bullet\bullet We \ do\\ 1.09&-0.02\\ \bullet\\ \bullet\\ 1.09&-0.02\\ \bullet\\ 1.168&-0.008\\ \bullet\\ 1.168&-0.008\\ \bullet\\ 0.03\pm1.74\pm\\ \bullet& We \ do\\ 0.03\pm1.74\pm\\ \bullet& We \ do\\ 0.03\pm1.74\pm\\ \bullet& We \ do\\ 0.05\pm1.74\pm\\ \bullet& We \ do\\ 0.150\\ \Gamma(\pi^0e^+e^-) \end{array}$	OUR AVE + 0.05 $\pm 0.09$ $\pm 0.09$ $\pm 0.05$ $\pm 0.05$ $\pm 0.052$ $\pm 0.0$	RAGE 268 e following c 2422 410 90 total <u>5 £V75</u> the following 3285 //Footal <u>5 £K75</u> AK HA	84 AMBF AKHN Jata for aver ALOIS 78,85 ACHA DRU/ DOCUMENT data for aver AKHMETS CONDIER MINETSHIN UMENT ID HIMETSHIN UMENT ID HIMETSHIN UMENT ID	ROSINO AETSHII rages fit SOV THININ ID srages fit HIN O2 70 16 1001 Cf srages fit 88 Cf	07 N 990 5. lim 020 000 87 87 87 5. lim 87 000 40 40 0, lim 920 000 40 920 920 920 920 920 920 920 920 920 92	KL CN NE NE NE NE E2 RE COM e <sup>1</sup> e

#### **Overview of CMD-3 data taking runs**



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#### **Collected Luminosity**



### CMD-3 & SND published





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

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

#### $e + e \rightarrow \pi + \pi - today$



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CLEO: 1.5%

#### Comparison of $e + e \rightarrow \pi + \pi - cross$ -section

0.2 -- CMD-2 SND 0 0.05 0 -0.05 -0.1 -0.15 -0.2 0.5 0.6 0.7 0.8 0.9 √s. GeV

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



#### The $\pi$ + $\pi$ - contribution to $a_{\mu}^{had}$



#### $e+e- \rightarrow \pi+\pi-$ by CMD-3

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: Simple event signature

- ×  $e/\mu/\pi$  separation
- × precise fiducial volume
- × radiative corrections

<u>Many systematic studies</u> <u>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



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with 2 back-to-back

charged particles

#### $e+e- \rightarrow \pi+\pi-$ by CMD-3



#### Systematic e+e- $\rightarrow \pi + \pi$ - by CMD-3

Our goals are to reach systematic level ~0.4-0.5%:	<u>status</u>
* 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/ $\mu/\pi$ separation	$\sim 0.6 - 0.2$ (at $\rho$ ) - 1.0(at 0.9 GeV) % by momentum
can be checked and combined from different methods	~ 1 % by energy - still work in progress
<ul> <li>Fiducial volume controlled independently by LXe and ZC subsystems, angular distribution</li> </ul>	0.2%
<ul> <li>* Beam Energy measured by method of Compton back scattering of the laser photons(σ<sub>E</sub>&lt; 50 keV)</li> </ul>	0.1%
* Electron bremsstrahlung loss	0.05%
* Pion specific correction	~ 0.1 % nuclear interaction
decay, nuclear interaction taken from data	0.6-0.3% pion decay
at p-peak by	P : 0.6%
at few lowes	t points : 0.9%
Many systematic studies rely on high statistics	

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

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#### $e+e- \rightarrow \pi+\pi-@$ 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

		SND @ VEPP- 2000	SND @ VEPP- 2M	PDG
	Μ <sub>ρ</sub> , MeV	775.4±0.5±0.4	775.6±0.4±0.5	775.3±0.3
	$Γ_{ m  ho}$ , MeV	145.7±0.7±1.0	$146.1 \pm 0.8 \pm 1.5$	147.8±0.9
	$B_{ m pee}  imes 10^5$	4.89±0.2±0.4	4.88±0.2±0.6	4.72±0.5
	Β <sub>ωππ</sub> , %	1.77±0.08±0.02	$1.66 \pm 0.08 \pm 0.05$	1.53±0.06
21 A	August 2019	Carlos Carlos		

#### 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
$e/\pi$ separation	0.5	0.1
Nucl. interaction	0.2	0.2
Theory	0.2	0.2
Total	0.9	0.8

The analysis is based on 4.7 pb<sup>-1</sup> data recorded in 2013, ~1/10 full SND data set.

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#### $e+e- \rightarrow \pi+\pi-@$ SND



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

	$a_{\mu}(\pi^+\pi^-) imes 10^{10}$
SND & VEPP-2000	$411.8\pm1.0\pm3.7$
SND & VEPP-2M	$408.9 \pm 1.3 \pm 5.3$
BABAR	$414.9\pm0.3\pm2.1$

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#### First time measurements



- $\times$  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

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

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

- The dominant mechanism is wa<sub>0</sub>(980)
- × Before was partially accounted by "isospin relation": σ(ηπ<sup>+</sup>π<sup>-</sup>2π<sup>0</sup>)=σ(η2π<sup>+</sup>2π<sup>-</sup>)

The cross section is about 2.5 nb ~ 5% of R(s) 33 HADRON2019, Guilin, China

### Dynamics in $4\pi$

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

Detail amplitude analysis was performed



•  $\pi'(1300)(0^{-+})\pi$ 

•  $h_1(1170)[1^{+-}]\pi^0$ 

•  $\rho^+ \rho^-$ 

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#### Multihadrons production at NN

We did detail scan of NN 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-  $\rightarrow 2(\pi + \pi -)$ , KK2 $\pi$  effect is stronger than expected from pp anihilation

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Inclusive R(s) at  $\sqrt{s} > 2$  GeV



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



### Future low energy e+e- machines(mumutron)



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#### project is under consideration

Can be as an accelerator technology testbench for SCTauF  $1^{st}$  stage : Observation & study of dimuonium -  $\mu\mu$  bound state  $\int s = 212 \text{ MeV}$  $L \sim 8 \times 10^{31} \text{ 1/cm}^2 \text{s}$  $2^{nd}$  stage with reversed beams and dedicated detector:

#### **Rho-factory**

- 15° crossing angle
- √s = 0.55-0.96 GeV
- L ~ 0.6-1. x 10<sup>33</sup> 1/cm<sup>2</sup>s

### Conclusion

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

\* VEPP-2000 is only one working this days on direct scanning below <2 GeV for measurement of exclusive  $\sigma$  (e+e-  $\rightarrow$  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 ( $e^+e^- \rightarrow \eta \pi^+\pi^-\pi^0$ ,  $3(\pi^+\pi^-)\pi^0$ ,  $\omega\eta\pi^0$ ) 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

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## measured cross sections by CMD-3

#### Published (or submitted):

 $e+e- \rightarrow pp$ ,

 $2(\pi^{+}\pi^{-}), 3(\pi^{+}\pi^{-}),$ 

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

e⁺e⁻ → n'

 $3(\pi^{+}\pi^{-})\pi^{0}$ 

 $K^+K^-$ ,  $K_SK_L$ ,

 $K^+K^-\pi^+\pi^-$ 

K<sup>+</sup>K<sup>-</sup>n

Phys.Lett. B759 (2016) 634-640

Phys.Lett. B740 (2015) 273-277

Phys.Lett. B768 (2017) 345-350 Phys.Lett. B723 (2013) 82-89 Phys.Lett. B773 (2017) 150-158 arXiv:1907.08002, subm. JHEP Phys.Lett. B792 (2019) 419-423

Phys.Lett. B760 (2016) 314-319 Phys.Lett. B779 (2018) 64-71

Phys.Lett. B756 (2016) 153-160

arXiv:1906.08006, subm. PLB

#### Under active analysis:

```
e^+e^- \rightarrow \pi^+\pi^-,
e^+e^- \rightarrow \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_{S}K_{I}\pi^{0}, K_{S}K_{I}\eta^{0},
nn, \pi^0 e^+ e^-, \eta e^+ e^-
```

K<sup>+</sup>K<sup>-</sup>ω, ωπ<sup>+</sup>π<sup>-</sup>

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

\* Near finished result:

Analysis of mostly each channel takes full person-years: higher systematic requirement → more effects → more years HADRON2019, Guilin, China





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

#### Published:

1.e+e-  $\rightarrow \pi^0 \pi^0 \gamma$ , 2. e+e- → nn. 3.  $e+e- \rightarrow \eta \gamma$ , Phys.Rev.D,(2014) 4.  $e+e- \rightarrow \eta'$ , Phys.Rev.D,(2015) 5.  $e+e- \rightarrow \eta \pi^+ \pi^-$ , Phys.Rev.D,(2015,2018) 6.  $e+e- \rightarrow \pi^{+}\pi^{-}\pi^{0}$ , JETP,(2015) 7. e+e- → η, Phys.Rev. D,(2018) 8.  $e+e- \rightarrow K^+K^-$ , Phys.Rev.D,(2016) 9. e+e-  $\rightarrow \omega \eta \pi^0$ , Phys.Rev.D,(2016) 10.  $e+e- \rightarrow \pi^0 \gamma$ , Phys.Rev.D,(2018) 11. e+e-  $\rightarrow$  K<sub>s</sub>K<sub>1</sub> $\pi^0$ , Phys.Rev.D(2018) 12.  $e+e- \rightarrow \eta K^+K^-$ , Phys.Atom.Nucl.(2018) 13. e+e-  $\rightarrow \eta \pi^0 \pi^+ \pi^-$ , Phys.Rev.D(2019) 14.  $e+e- \rightarrow f1(1285)$ , submitted(2019)

Ph.Rev.D, (2013,2016) Phys.Rev.D,(2014)

1. e+e-  $\rightarrow \pi^+\pi^-$ . 2. e+e-  $\rightarrow \pi^+\pi^-\pi^0\pi^0$ , 3. e+e-  $\rightarrow$  K<sup>+</sup>K<sup>-</sup> $\pi^0$ , 4. e+e-  $\rightarrow \omega \pi^0 \pi^0$ . 5.  $e+e- \rightarrow 6\pi$ 

In analysis:

Hadron production in QCD

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

Using Operator Product Expansion (OPE)

+

pQCD - known until 5-loop

$$\delta_{\text{QCD}} \left( \mathbf{Q} \right) = \sum_{n=1}^{\infty} c_n \left( \frac{\alpha_s \left( \mathbf{Q} \right)}{\pi} \right)^n$$

$$\frac{C_4}{Q^4} + \frac{C_6}{Q^6} +$$

+... +  $\Delta_{\mathrm{DV}}(\mathbf{Q})$ 

Quark, gluon condensates Duality Violations factor (quarks  $\Leftrightarrow$  hadrons )

How well non-perturbative part can be controlled? Its contribution decreases with higher energies...  $\alpha_{s}$  from R(s)



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# e+e- → 3(π+π-)π0 @ CMD-3



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

First measurement of total  $e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta$  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)





**\*** The intermediate states are  $w\eta$ ,  $\phi\eta$ ,  $a_0\rho$  and structureless  $\pi^+\pi^-\pi^0$ 

- ★ The known before wn and φn contributions explain about ~50% of the cross section below 1.8 GeV.
- **\*** Above 1.8 GeV the dominant reaction mechanism is  $a_0p$

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

Phys. Rev. D 94,032010 (2016)



First measurement of the  $e^+e^- \rightarrow w\eta\pi^0$  cross section. The dominant mechanism is  $wa_0(980)$ .

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  $e^+e^- \rightarrow \pi^+\pi^-4\pi^0$  (where no data exist) with Ny>8 in FS is also underway 47 21 August 2019 HADRON2019, Guilin, China e+e- -> KK



#### $\phi \rightarrow K+K$ - comparison between experiments



New CMD-3 cross-section is above CMD-2 and BaBar, but it is in consistency with isospin symmetry:

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

•  $R_{SND} = 0.92 \pm 0.03(2.6\sigma)$ 

• 
$$R_{CMD-2} = 0.943 \pm 0.013(4.4\sigma)$$

• 
$$R_{BaBar} = 0.972 \pm 0.017(1.5\sigma)$$

21 August 2019

### KKpi KKeta



#### $e+e- \rightarrow \pi+\pi-\pi+\pi-@\phi(1020)$

PLB 768 (2017) 345-350

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

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



21 August 2019

## Published results from 2011-2013: CMD-3



HADRON2019, Guilin, China

### Published results from 2011-2013: SND





#### HADRON2019, Guilin, China

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#### 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 pp threshold (dip in sum of  $6\pi$  roughly as pp+nn cross section)



Relative local weight of different experiments in  $\pi$ + $\pi$ -

Nowadays the  $\pi+\pi$ - data is statistically dominated by ISR(KLOE, BaBar)



Locally precision is limited by statistic

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### MC generator, MCGPJ



#### 50 years of hadron production at colliders

Volume 25B, number 6

PHYSICS LETTERS

2 October 1967

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

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

Received 1 September 1967

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

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When experiments with electron-positron col-COL liding beams were planned [1, 2] investigation of ter the process ide of

 $e^{-} + e^{+} \rightarrow \pi^{-} + \pi^{+}$  $e^- + e^+ \rightarrow K^- + K^+$ 

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

#### 1 September 1967

Start of  $e+e- \rightarrow hadrons$  measurements

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



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  $90^{\circ}$  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	КЕКВ	Tsukuba	Japan
1999	PEP-II	Stanford	USA
2001	RHIC	Brookhaven	USA
2008	BEPCII	Beijing	China
2009	LHC	CERN	Switzerland
2010	VEPP-2000	Novosibirsk	Russia.
Physics	+ SuperKEKB	Tsukuba	Japan
1 Aug	ust 2019		

<u>1961: AdA</u> 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<sup>25</sup>cm<sup>-2</sup>s <sup>-1</sup>

SLAC & Novosibirsk VEP-1 works independently

<u>1965:</u> First physics at collision with e-escattering

(QED radiative effects confirmed)

<u>1967: VEPP-2</u> First e+e-  $\rightarrow$  hadron production L ~ 10<sup>28</sup> cm<sup>-2</sup>s<sup>-1</sup>

### SM prediction for muon g-2



### $|F_{\pi}|^2$ 2013 vs 2018 scans

PID by momentum  $\chi^2$  / ndf 66.66 / 58 Prob 0.2038 |F<sup>|<sup>2</sup>/|F<sub>cMD3 fil</sub><sup>2</sup>-1 90'0</sup> -- CMD3 2013 p0  $0.0007427 \pm 0.0008$  $\chi^2$  / ndf 82.12 / 77 CMD3 2018 Prob 0.3236 p0  $-0.0002457 \pm 0.0004885$ 0.02 0 ... -0.02-0.04 $\Delta = 0.10 \pm 0.09 \%$ -0.060.3 0.4 0.5 0.6 0.7 0.8 0.9 vs. GeV

21 August 2019

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 1<sup>st</sup> paper: using only full energy deposition in calorimeter final paper: exploiting info on shower profile + polar angle distribution 60