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

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HADRON2019, Guilin, China
$R(s)$ 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, $\Lambda_{QCD}$; Dispersion relations → $\alpha_{QED}(M_Z)$, hyperfine muonium splitting, muon $(g-2)$. 

\[
R(s) = 3 \sum_q e_q^2 (1 + \delta_{QCD}(s)) 
\]
What is $g$ 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 $a = (g-2)/2 \sim \alpha/2\pi \sim 0.00116$.
\[ \vec{\mu} = g \frac{e}{2m} \vec{s}, \quad g = 2(1 + \alpha) \]

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

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

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

Bennet et al., PRD 73(2006)072003

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

Recent \( \alpha_{\text{QED}} \) measurement using the recoil frequency of Cs-133 atoms with 0.20ppb gives 2.5\( \sigma \) tension with experimental \( a_e \)

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

One electron quantum cyclotron

Harvard Univ.

21 August 2019
Muon $g-2$ theory SM

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

**Precisions:**
- 7 ppb
- HVP: 210 ppb
- 9 ppb
- $< 2300$ ppb
- LbL: $220$ ppb

**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; measurement of transition formfactors can help, improvement is expected from lattice calculations

**New g-2 experiments at FNAL, J-PARC:** $540 \rightarrow 140$ ppb
The hadronic contribution is calculated by integrating experimental cross-section $\sigma(e^+e^- \rightarrow \text{hadrons})$.

Starting at high energy the pQCD estimation of $\sigma(e^+e^- \rightarrow \text{hadrons})$ is used. At lower energies only the experimental data can be used.

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

$< 2 \text{GeV}$ gives 93% of the integral, $\pi^+\pi^-$ gives the main contribution (73%) to $a_\mu$.

$\begin{align*}
2 \text{Im} \langle \langle \pi^+\pi^- \rangle^2 & = \sum \int d\Phi |\langle \pi^+\pi^- \rangle^2 | \\
\langle \langle \pi^+\pi^- \rangle^2 & = \left( \frac{\alpha m_{\mu}}{3 \pi} \right)^2 \int_{s_{\text{th}}}^{\infty} \frac{1}{s^2} \tilde{K}(s) R(s) ds \\
\tilde{K}(s) & = 0.6 \div 1.0
\end{align*}$
SM prediction for muon g-2


\[ \Delta (E_{\text{xp}} - \text{Theory}) \sim 3-4 \sigma \]

\[ (a_{\mu}^{\text{SM}} \times 10^{10}) = 11659000 \]
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):
  \[
  \alpha(s) = \frac{\alpha(0)}{1 - \Delta \alpha(s)},
  \]
  \[
  \Delta \alpha_{\text{had}}(s) = -\frac{\alpha(0)s}{3\pi} \int_0^\infty ds' \frac{R(s')}{s'(s' - s) - i\epsilon}.
  \]

The $\alpha_{QED}(q^2)$ at mass of Z is used in predictions of electroweak model. It is the least known EW parameter like $\delta G/\mu\sim 0.9 \times 10^{-5}$, $\delta M_z/M_z \sim 2.4 \times 10^{-5}$. $\Delta \alpha_{QED}^{5\text{had}}(M_z) = 276.11 \pm 1.11 \times 10^{-4}$.

For future ILC, CLIC, FCC-ee it should be known with $\sim 0.5-0.3 \times 10^{-4}$. 

Current PDG $\alpha_s$ world average (NNLO)

Tau decays to hadrons give the best non-lattice $\alpha_s$ estimation

Particle Data Group '18

class averages:

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

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

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

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

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

From analyticity and using Cauchy’s theorem

\[
\frac{1}{12\pi^2s_0} \int_{0}^{s_0} ds \, w(s/s_0)R(s) = -\frac{1}{2\pi i s_0} \int \, dz \, w(s/s_0)\Pi(z) \bigg|_{z=s_0}
\]

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

\[ \tau \rightarrow \nu + { \text{hadrons}} \]

\[ e^+e^- \rightarrow { \text{hadrons}} \]

\[ \tau \rightarrow \nu + { \text{hadrons}} \text{ limited until } s = 1.77 \text{ GeV} (V+A \text{ the QCD asymptotic behaviour is reached faster}) \]

\[ e^+e^- \rightarrow { \text{hadrons}} \text{ can be extended to upper } s_0 \text{ limits} \]

M. Davier et al., arXiv:1312.1501

\[ \alpha_s(m_{\tau}^2) = 0.332 \pm 0.005_{\text{exp}} \pm 0.011_{\text{theo}} \]

\[ (\pm 0.006 \text{ DV, higher order } \pm 0.009 \text{ FOPT vs CIPT}) \]

\[ \alpha_s(m_{Z}^2) = 0.1199 \pm 0.0015 (\pm 1.3\%) \]

D. Boito et al., arXiv:1805.08176

\[ \alpha_s(m_{\tau}^2) = 0.301 \pm 0.017_{\text{exp}} \pm 0.007_{\text{theo}} \]

\[ (\pm 0.005 \text{ DV } \pm 0.003 \text{ higher orders } \pm 0.003 \text{ FOPT vs CIPT}) \]

\[ \alpha_s(m_{Z}^2) = 0.1162 \pm 0.0025 (\pm 2.1\%) \]

\[ e^+e^- \text{: Limited by data, Difference between FO and CIPT } \sim 3 \text{ times smaller than in tau decays} \]
Current PDG $\alpha_s$ world average (NNLO)

Particle Data Group '18

class averages:

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

$\alpha_s(M_Z) = 0.1162 \pm 0.0025$ ($\pm 2.1\%$)

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

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

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

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

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

unweighted $\chi^2$ average:

$\alpha_s(M_Z) = 0.1181 \pm 0.0011$ ($\pm 0.9\%$)

$\tau$ decays to hadrons give the best non-lattice $\alpha_s$ 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

$e^+e^- \rightarrow$ hadrons

$R$ vs $\sqrt{s}$ (GeV)

- Exclusive approach:
  - measure each final state separately
  - 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
VEPP-2000: direct exclusive measurement of $\sigma (e^+e^- \to \text{hadrons})$

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 - direct 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.

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

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
biggest Drift Chamber ever built (Ø4m)

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 GeV²

direct extraction of \( \alpha_{QED}(s) \) via e+e- → μ+μ-γ

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

From 2004 - KEDR experiment
Low luminosity, but high precision measurement of the beam energy

\[ \frac{\Delta m}{m} \sim 2 \times 10^{-6} \] (only 6 particles known better)

Best measurement of inclusive \( R(s) \), \( 2E < 3.7 \text{ GeV} \) with \( \sim 2\% \) systematic precision

Few more years to do scan above charm region
New positron source from 2016

(no luminosity limitation due to lack of e+)

Data taking was restarted by the end of 2016

<table>
<thead>
<tr>
<th>before</th>
<th>after upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁺ /sec</td>
<td>2×10⁷</td>
</tr>
<tr>
<td>e⁻ /sec</td>
<td>10⁹</td>
</tr>
</tbody>
</table>

BEP E max, MeV

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

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

Experiments with two detectors, CMD-3 and SND, started by the end of 2010
1.3 T magnetic field
Tracking: $\sigma_{R\phi} \sim 100 \mu m$, $\sigma_Z \sim 2 mm$

Combined EM calorimeter (LXe, CsI, BGO): $\sigma_E \sim 3-8\%$, 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).

$x$ study of production dynamics, ChPT

But also we do:

$x$ properties of light vector mesons, their decays,
$x$ nucleon formfactors at threshold,
$x$ two photon physics,
$x$ search of exotics,
$x$ and so on...

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

Meson parameters in PDG 2011 from CMD2 and SND

Rare decays

Results of these experiments determine the accuracy of the light vector mesons parameters.
Overview of CMD-3 data taking runs

- 1 fb$^{-1}$ project
- 0.32 - 1 GeV scan
- 1-2 GeV scan
- >1 GeV scan
- upgrade

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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 (×4 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:
\[ e^+e^- \rightarrow \eta', \text{pp, } 2(\pi^+\pi^-), \text{3}(\pi^+\pi^-), \text{3}(\pi^+\pi^-)\pi^0, \eta\pi^+\pi^-, \eta\pi^+\pi^{-}\pi^0, \eta\pi^+\pi^+\pi^- \]
\[ K^+K^- K^0\bar{K}^0, K^0\bar{K}^0, K^+\pi^-\pi^+\pi^0, K^+K^- \eta \]

SND@VEPP-2000:
\[ e^+e^- \rightarrow \eta, \eta', f1, nn, \eta\gamma, \pi^0\gamma, \pi^+\pi^-\pi^0, \omega\pi^0, \omega\eta\pi^0, \eta\pi^+\pi^-, \eta\pi^+\pi^-\pi^0, K^+K^-, K_S K_L \pi^0, K^+K^- \eta \]

Many channels is under active analysis

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

Gives main contribution to $R(s)$ at $\sqrt{s} < 1$ GeV
$e^+ e^- \rightarrow \pi^+ \pi^-$ today

Before 1985
Low statistical precision
Systematic $>10\%$
NA7 A few points with $>1-5\%$

1985 - VEPP-2M
with more detailed scan
OLYA systematic 4\%
CMD 2\%

2004 with CMD2 at VEPP-2M
was boost to systematic: 0.6\%
(near same total statistic)
The uncertainty in $a_\mu(\text{had})$ was improved by factor 3 as the result of VEPP-2M measurements

New ISR method
$e^+e^- \rightarrow \gamma + \text{hadrons}$
(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 $\sim 0.2\%$

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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 $a_\mu^{\text{had}}$ in integral precision is limited by systematics. Systematic Uncertainties (\(\rho\)-region): CMD2: 0.6-0.8\%, SND: 1.5\%, KLOE: 0.8\%, BABAR: 0.5\%, BES: 0.9\%, CLEO: 1.5\%.
**e+e- → π+π- 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:
- e/μ/π separation
- precise fiducial volume
- radiative corrections

Many systematic studies rely on high statistics

Events separation either by momentum or by energy deposition

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

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

Emission signature with 2 back-to-back charged particles

P+ x P-,  \(E_{\text{beam}}=250\) MeV

E+ x E-,  \(E_{\text{beam}}=460\) MeV
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)

At CMD-2 it was possible to make separation by momentum only $<0.52$ GeV

$|F_{\pi}|^2$ result after event separation without additional corrections

$e/\mu/\pi$ separation using energy deposition in calorimeter

$e/\mu/\pi$ separation using particles momentum

At CMD-3 it was possible to make separation by momentum only $<0.52$ GeV

$\Delta = 0.10 \pm 0.09 \%$

$N_{\mu\mu}/N_{ee}$ /QED

$N_{\mu\mu}/N_{ee}$ /QED

$\Delta = 0.10 \pm 0.09 \%$

$|F_{\pi}|^2$

$N_{\mu\mu}/N_{ee}$ /QED

$\chi^2$/ndf 34.66/34

Prob 0.4364

p0 1.002 $\pm$ 0.002379

With BESIIIcharm

$|F_{\pi}|^2$

$2\epsilon e$ GeV

$\chi^2$/ndf 66.66/58

Prob 0.2038

p0 0.000747 $\pm$ 0.000098

For CMD-3

$|F_{\pi}|^2$

$2\epsilon e$ GeV

$\chi^2$/ndf 82.12/77

Prob 0.3236

p0 -0.0002457 $\pm$ 0.0004885
## Systematic e+e- → π+π- by CMD-3

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

<table>
<thead>
<tr>
<th>× Radiative corrections</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>with current MC generators</td>
<td></td>
</tr>
<tr>
<td>0.2% - integral cross-section</td>
<td></td>
</tr>
<tr>
<td>0.0 - 0.4% - from P spectra</td>
<td></td>
</tr>
<tr>
<td>(we need theory help, NNLO generators)</td>
<td></td>
</tr>
</tbody>
</table>

| × e/μ/π separation |        |
| can be checked and combined from different methods |        |

| × Fiducial volume |        |
| controlled independently by LXe and ZC subsystems, angular distribution |        |

| × Beam Energy |        |
| measured by method of Compton back scattering of the laser photons(σ_ε < 50 keV) |        |

| × Electron bremsstrahlung loss |        |

| × Pion specific correction |        |
| decay, nuclear interaction taken from data |        |

| Many systematic studies rely on high statistics |        |
| For some sources of systematics there is clear way how to bring it down |        |

21 August 2019
e+e- → π+π- @ SND

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 (%)

<table>
<thead>
<tr>
<th>Source</th>
<th>&lt; 0.6 GeV</th>
<th>0.6 - 0.9 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Selection criteria</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>e/π separation</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Nucl. interaction</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Theory</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.9</strong></td>
<td><strong>0.8</strong></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>SND @ 2000</th>
<th>VEPP-2M</th>
<th>SND @ 2000</th>
<th>VEPP-2M</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_\rho), MeV</td>
<td>775.4±0.5±0.4</td>
<td>775.6±0.4±0.5</td>
<td>775.3±0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Gamma_\rho), MeV</td>
<td>145.7±0.7±1.0</td>
<td>146.1±0.8±1.5</td>
<td>147.8±0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(B_{\rho e e} \times 10^5)</td>
<td>4.89±0.2±0.4</td>
<td>4.88±0.2±0.6</td>
<td>4.72±0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(B_{\omega \pi \nu})</td>
<td>1.77±0.08±0.02</td>
<td>1.66±0.08±0.05</td>
<td>1.53±0.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$e^+e^- \rightarrow \pi^+\pi^- @ SND$

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

| $\alpha_\mu(\pi^+\pi^-) \times 10^{10}$ |  
|--------------------------------------|---|
| 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 $\sim$1% of R(s) at 2 GeV

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

- The intermediate states are $\omega\eta$, $\phi\eta$, $\alpha_0\rho$ and structureless $\pi^+\pi^-\pi^0$
- The known before $\omega\eta$ and $\phi\eta$ contributions explain about $\sim$50% of the cross section below 1.8 GeV.
- Above 1.8 GeV the dominant reaction mechanism is $\alpha_0\rho$

Not accounted part before is about $\sim$ 3-5% of R(s)

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

- The dominant mechanism is $\omega_0(980)$
- Before was partially accounted by "isospin relation":
  \[
  \sigma(\eta\pi^+\pi^-2\pi^0) = \sigma(\eta2\pi^-2\pi^+)
  \]

The cross section is about 2.5 nb $\sim$ 5% of R(s)
Production of $e^+e^- \rightarrow \pi^+\pi^-2\pi^0$, $2(\pi^+\pi^-)$ can be via many intermediate states:

- $\omega[1^{--}]\pi^0[0^{++}]$
- $a_1(1200)[1^+]\pi[0^-]$
- $\rho[1^{--}]f_0/\sigma[0^{++}]$
- $\rho f_2(1270)[2^{++}]$
- $\rho^+\rho^-$
- $a_2(1320)[2^{++}]\pi$
- $h_1(1170)[1^{+-}]\pi^0$
- $\pi'(1300)(0^{--})\pi$

Detail amplitude analysis was performed.
Multihadrons production at NN

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

Seen many dip structures in multihadron production

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

$$e^+e^- \rightarrow 3(\pi^+\pi^-)$$

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

BESII - most detailed 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

$R_{KEDR} = 2.23 \pm 0.05$ $2.204 \pm 0.030$

consistent with $R_{pQCD} = 2.18 \pm 0.02$ $2.16 \pm 0.01$

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)

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

Two projects is under consideration

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

SCTF in Novosibirsk

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

STCF in China

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

see talk after on future facilities by Prof. S. Eidelman
Future low energy e+e- machines (mumutron)

Can be as an accelerator technology testbench for SCTauF

1st stage:
Observation & study of dimuonium - $\mu\mu$ bound state
$\sqrt{s} = 212$ MeV
$L \sim 8 \times 10^{31} \text{ 1/cm}^2\text{s}$

2nd stage with reversed beams and dedicated detector:

Rho-factory

- 15° crossing angle
- $\sqrt{s} = 0.55$-0.96 GeV
- $L \sim 0.6$-$1. \times 10^{33} \text{ 1/cm}^2\text{s}$
• Precise low-energy $e^+e^-$ hadronic cross section data is used in many applications of accurate SM predictions such as $a_\mu^{\text{had,LO-VP}}, \alpha_{\text{QED}}(M_Z)$, ....

• VEPP-2000 is only one working this days on direct scanning below $<2$ GeV for measurement of exclusive $\sigma(e^+e^- \rightarrow \text{hadrons})$

• 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
Published (or submitted):

\[ e^+e^- \rightarrow pp, \]
\[ e^+e^- \rightarrow \eta', \]
\[ 2(\pi^+\pi^-), 3(\pi^+\pi^-), \]
\[ \omega \eta, \eta \pi^+\pi^-\pi^0, \eta \pi^+\pi^- \]
\[ 3(\pi^+\pi^-)\pi^0, \]
\[ K^+K^-, K_SK_L, \]
\[ K^+K^-\pi^+\pi^- \]
\[ K^+K^-\eta \]

Under active analysis:

\[ e^+e^- \rightarrow \pi^+\pi^-, \]
\[ e^+e^- \rightarrow \pi^+\pi^-\gamma, \]
\[ \eta\gamma, \pi^0\gamma, \]
\[ \pi^+\pi^-\pi^0\pi^0, 2(\pi^+\pi^-), \]
\[ 2(\pi^+\pi^-)\pi^0, 2(\pi^+\pi^-\pi^0) \]
\[ K^+K^-, K_SK_L - \text{at higher energies} \]
\[ K^+K^-\pi^0, K_SK_L\pi^0, K_SK_L\eta^0, \]
\[ n\bar{n}, \pi^0e^+e^-, \eta e^+e^- \]

Near finished result:

\[ e^+e^- \rightarrow D_0^* \]
\[ K^+K^-\omega, \omega\pi^+\pi^- \]

Analysis of mostly each channel takes full person-years:

higher systematic requirement \rightarrow more effects \rightarrow more years
SND@VEPP-2000 summary of results, (journal articles)

Published:
1. \(e^+e^- \rightarrow \pi^0\pi^0\gamma\), Ph.Rev.D, (2013,2016)
2. \(e^+e^- \rightarrow nn\), Phys.Rev.D,(2014)
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. \(e^+e^- \rightarrow \pi^+\pi^0\), JETP,(2015)
7. \(e^+e^- \rightarrow \eta\), 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. \(e^+e^- \rightarrow K_SK_L\pi^0\), 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)

In analysis:
1. \(e^+e^- \rightarrow \pi^+\pi^-\),
2. \(e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\),
3. \(e^+e^- \rightarrow K^+K^-\pi^0\),
4. \(e^+e^- \rightarrow \omega\pi^0\pi^0\),
5. \(e^+e^- \rightarrow 6\pi\)

.....
Hadron production in QCD

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

Using Operator Product Expansion (OPE)

\[
\delta_{\text{QCD}}(Q) = \sum_{n=1}^{\infty} c_n \left( \frac{\alpha_s(Q)}{\pi} \right)^n + \frac{C_4}{Q^4} + \frac{C_6}{Q^6} + ... + \Delta_{\text{DV}}(Q)
\]

- Quark, gluon condensates
- Duality Violations factor (quarks \(\leftrightarrow\) hadrons)

How well non-perturbative part can be controlled?
Its contribution decreases with higher energies...
To extract $\alpha_s$ directly from $R(s)$ with competitive precision $\delta\alpha/\alpha_s(m_Z) \sim 1%$:  

5th $\alpha_s$ order calculation should be done, and $R(s)$ measured with ~0.1-0.2%.
First time measurement of total cross-section

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

$\sim 1\%$ of $R(s)$ at 2 GeV

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.


The intermediate states are $\omega\eta$, $\phi\eta$, $\alpha_0\rho$ and structureless $\pi^+\pi^-\pi^0$.

The known before $\omega\eta$ and $\phi\eta$ contributions explain about ~50% of the cross section below 1.8 GeV.

Above 1.8 GeV the dominant reaction mechanism is $\alpha_0\rho$.

Not accounted before in $R(s)$ (3-5% contribution)
First measurement of the $e^+e^- \rightarrow \omega\eta\pi^0$ 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 $e^+e^- \rightarrow \pi^+\pi^-4\pi^0$ (where no data exist) with $N\gamma > 8$ in FS is also underway.
CMD-3: KsKl at $\phi$ - 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.
It was 5-10% discrepancy at $\phi$

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:

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

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

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

$$R_{BaBar} = 0.972 \pm 0.017 (1.5\sigma)$$
$e^+e^- \rightarrow K^+K^- \eta$

Some signs of resonance seen at 1.9 GeV

$e^+e^- \rightarrow K_S K_L \pi^0$

In very preliminary stage
$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^- \ @ \phi(1020)$

PLB 768 (2017) 345-350

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

\[ B(\phi \rightarrow 2(\pi^+\pi^-)) = (6.5 \pm 2.7 \pm 1.6) \times 10^{-6} \]
Published results from 2011-2013: CMD-3

- $K_SK_L$
- $3(\pi^+\pi^-)$
- $K^+K^-\pi^+\pi^-$

# Graphs

- **Graph a):**
  - Title: $K_SK_L$
  - Data points and fits for SND, CMD-2, CMD-3 Fit, CMD-3 2012, CMD-3 2013
  - Source: PLB 760 (2016) 314

- **Graph b):**
  - Title: $\sigma_{ee\rightarrow 3(\pi^+\pi^-)}$ nb
  - Data points and fits
  - Source: PLB 723 (2013) 62

- **Graph c):**
  - Title: Cross section
  - Data points for $p\bar{p}$, CMD-3, BaBar
  - Source: PLB 759 (2016) 634

- **Graph d):**
  - Title: $\sigma_{ee\rightarrow K^+K^-\pi^+\pi^-}$ nb
  - Data points
  - Source: PLB 756 (2016) 153
Published results from 2011-2013: SND

- PRD 91 (2015) 052013
- JETP 121 (2015) 27
- PRD 90 (2014) 112007
- arXiv:1607.00371
- PRD 90 (2014) 032002
- arXiv:1606.06481

Graphs showing
- $\omega \pi^0 (7\gamma)$
- $\omega \eta$
- $\eta \gamma (7\gamma)$
- $\eta \eta$

Cross-sections and energies plotted for different reactions.
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(π⁺π⁻) are mainly produced through ρ(770) + 4π (in phase space or f₀).

Seen change of dynamics in 1.7-1.9 GeV range
Interesting feature: sharp dip at p̅p threshold (dip in sum of 6π roughly as pp+n̅n cross section)
Nowadays the $\pi^+\pi^-$ data is statistically dominated by ISR (KLOE, BaBar).

Locally precision is limited by statistic.
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. **MCGPJ generator (0.2%)** 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

**Exact e+e-→e+e-(γγ) NNLO generator** will help to solve all our doubts (and to go below <0.1% precision)
50 years of hadron production at colliders

**1 September 1967**

Start of $e^+e^- \rightarrow$ 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
### Colliders History

<table>
<thead>
<tr>
<th>Year</th>
<th>Collider</th>
<th>Location</th>
<th>Country</th>
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<td>AdA</td>
<td>Frascati</td>
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<td>1965</td>
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<td>2018</td>
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**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 ~ $10^{25} \text{cm}^{-2} \text{s}^{-1}$

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

$L ~ 10^{28} \text{cm}^{-2} \text{s}^{-1}$
SM prediction for muon g-2

Experimental world average
$$a_\mu = 11\,659\,208.9 \pm 6.3 \times 10^{-10}$$

Theoretical prediction
$$\delta a_\mu = \pm 3.6 \times 10^{-10} \quad \text{(KNT 18)}$$

Hadronic content of $a_\mu$ calculated
From measured cross-section by dispersion integral
$$\text{LO hadronic } 693.27 \pm 2.46 \times 10^{-10}$$

main channels contribution to precision at $\sqrt{s} < 1.937$ GeV
$$\pi^+\pi^- \quad 502.97 \pm 1.97$$
$$\pi^+\pi^-\pi^0 \quad 47.79 \pm 0.89 \quad \text{(mostly from omega region)}$$
$$\pi^+\pi^-2\pi^0 \quad 19.39 \pm 0.78$$
$$K+K^- \quad 23.03 \pm 0.22$$

Inclusive ($\sqrt{s} > 1.937$ GeV) 43.67 $\pm$ 0.67

| Light-by-light | $9.8 \pm 2.6$ need more theory input, with help of experimental transition form factors |

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

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