R measurement at the KEDR experiment

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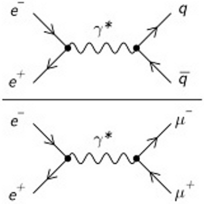
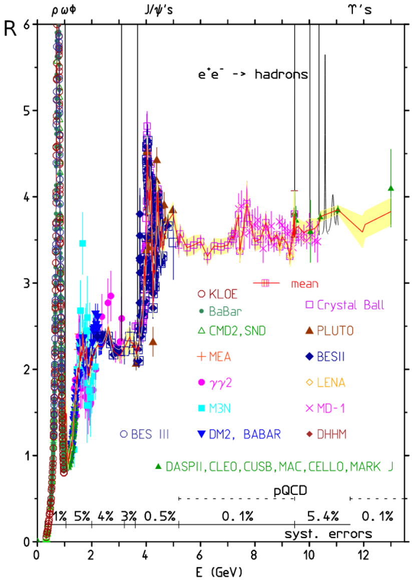
$$R = \frac{\sigma(e^-e^+ \to \text{hadrons})}{\sigma(e^-e^+ \to \mu^-\mu^+)} \approx$$



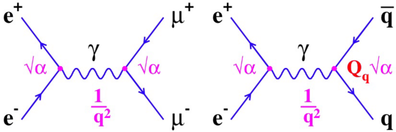


F. Jegerlehner arXiv:1511.04473

$R(s)$ is used to determine:

- $\alpha(M_Z^2)$
- $(g_\mu - 2)/2$
- $\alpha_s(s)$
- heavy quark masses

The R ratio and the vacuum polarization



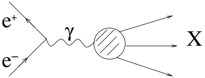
$$\sigma_0^{e^+e^-\to\mu^+\mu^-}(s) = \frac{4\pi\alpha^2}{3s}$$

It is natural to define the value R as a ratio:

$$R \stackrel{\text{def}}{\equiv} \frac{\sigma^{e^+e^-\to hadrons}(s)}{\sigma_0^{e^+e^-\to\mu^+\mu^-}(s)}$$

In first approximation:

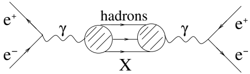
$$R(s) \simeq 3\sum Q_q^2$$



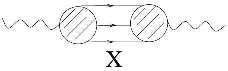
X – hadron state.

$$\sigma^{e^+e^-\to hadrons}(s) = R\sigma_0^{e^+e^-\to\mu^+\mu^-}(s)$$

The process diagram $e^+e^- \to e^+e^-$



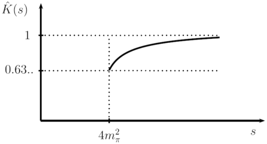
Relationship between the R ratio and the vacuum polarization

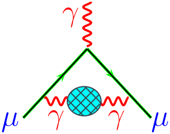


$$R = -\frac{3}{\alpha}\,\mathrm{Im}_h\,\Pi(s)$$

Contribution R in a_μ и $\alpha(M_Z^2)$

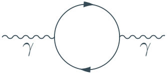
$$a_\mu^{exp} = (g_\mu - 2)/2$$



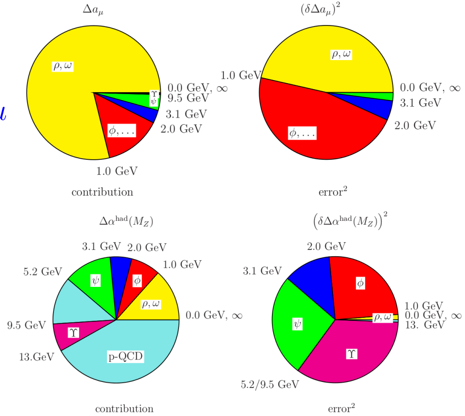


$$a_\mu^{LO\ VP} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{\hat{K}(s)R(s)}{s^2} ds$$

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

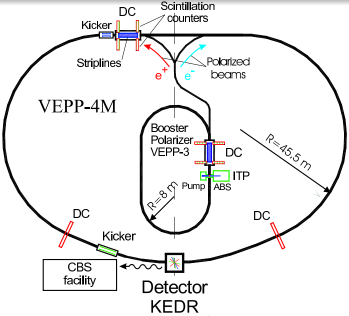
$$\Delta\alpha = \sum_f$$  $$= \Delta\alpha_{\mathrm{lep}}(s) + \Delta\alpha_{\mathrm{had}}(s)$$

$$\Delta\alpha^{(5)}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi} \mathrm{Re} \int_{4m_\pi^2}^{\infty} \frac{R(s)ds}{s(s - M_Z^2 - i\epsilon)}$$



A. Blondel и др. arXiv:1905.05078.

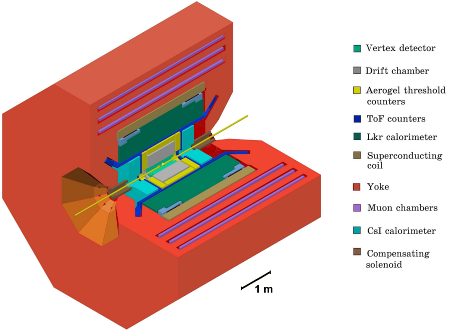
VEPP-4M and KEDR



Beam energy	$1 \div 5$ GeV
Number of bunches	2×2
Luminosity 1.8 GeV	1.5×10^{30} cm^{-2} s^{-1}

Energy measurement:

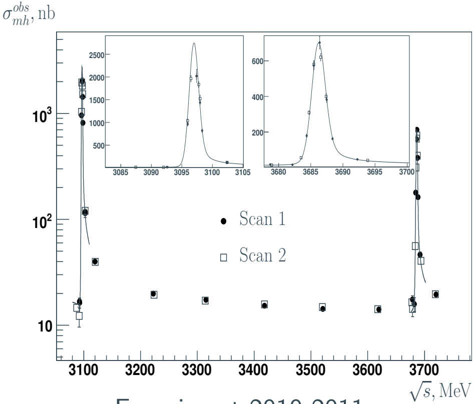
- Resonant depolarization method:
  Instant measurement accuracy ~ 1 keV
  Energy interpolation accuracy $10 \div 30$ keV
- Compton backscattering method ~ 100 keV



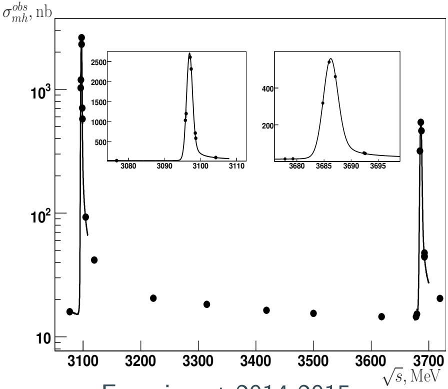
R scan	Energy range	N_{points}	$\int Ldt$ pb^{-1}
2010	1.84-3.05	13	0.66
2011 2014-2015	3.08-3.72	9	2.7
2019-2020	4.56-6.96	17	13.7

R measurement between J/ψ and $\psi(2S)$

The observed multihadron cross section as a function of the c.m. energy



Experiment 2010-2011



Experiment 2014-2015

- The c.m. energy range between 3.076 and 3.72 GeV studied
- An integrated luminosity of 2.7 pb^{-1} collected at 9 energies 3.077, 3.120,3.223, 3.315, 3.418, 3.500, 3.521, 3.618, 3.719 GeV
- $\sim (2-6)\times 10^3$ m.h. events per point, $\sim 38\times 10^3$ in total

Analysis

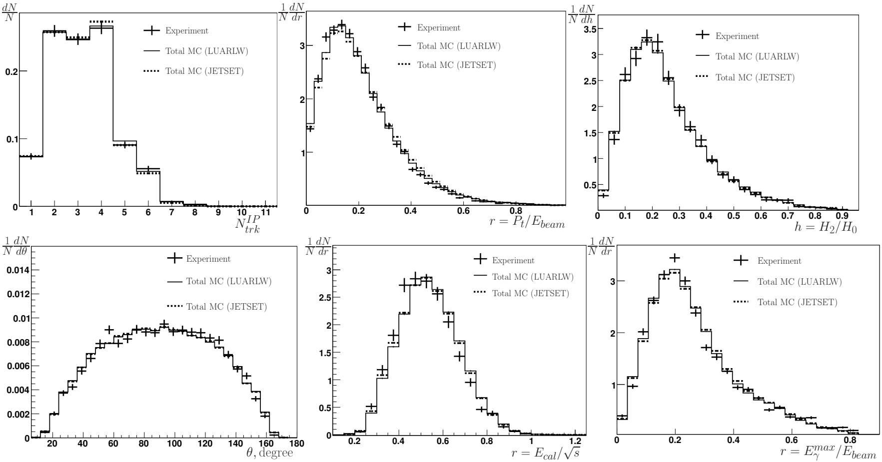
The way that we are measuring R:

$$R = \frac{\sigma_{obs}(s) - \sum \varepsilon_{\psi}^{tail}(s)\sigma_{\psi}^{tail}(s) - \sum \varepsilon_{bg}^{i}(s)\sigma_{bg}^{i}(s)}{\varepsilon(s)(1+\delta(s))\sigma_{\mu\mu}^{0}}$$

with $\sigma_{obs}(s) = \frac{N_{mh} - N_{res.bg.}}{\int \mathcal{L}dt}$ where N_{mh} represent all events pass hadronic selection criteria, $N_{res.bg.}$ – residual machine background
$\sum \varepsilon_{\psi}^{tail}(s)\sigma_{\psi}^{tail}(s)$ is contribution from J/ψ and $\psi(2S)$ resonances
$\sum \varepsilon_{bg}^{i}(s)\sigma_{bg}^{i}(s)$ is contribution from physical processes: $e^+e^- \to l^+l^-$, $\gamma\gamma$-processes.
$\varepsilon(s)$ – multihadron efficiency.

$$1+\delta(s) = \int dx \frac{1}{1-x} \frac{\mathcal{F}(s,x)}{\left|1-\tilde{\Pi}(s(1-x))\right|^2} \frac{\tilde{R}(s(1-x))\varepsilon(s(1-x))}{R(s)\varepsilon(s)}$$

$\mathcal{F}(s,x)$ – radiative correction kernel (**E.A.Kuraev, V.S.Fadin Sov.J.Nucl.Phys.41(466-472)1985**) Here $\tilde{\Pi}$ and $\tilde{R}$ does not includes J/ψ and $\psi(2S)$ resonances. **To determine the contributions of the J/ψ and $\psi(2S)$ without external data, the additional data samples of about 0.4 pb^{-1}(2010-2011) and 0.34 pb^{-1}(2014-2015) were collected in the vicinity of peak regions.**



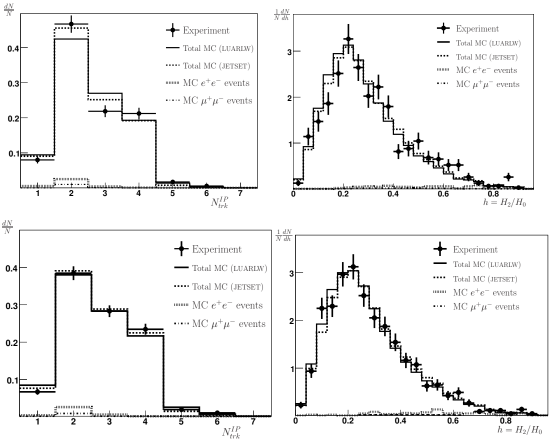
Properties of hadronic events produced in the uds continuum at 3.119 GeV (2014-2015).

Here N is the number of events, N_{trk}^{IP} is the number of tracks originated from IP, P_t is a transverse momentum of the track, H_2 and H_0 are Fox-Wolfram moments, θ is a polar angle of the track, E_{cal} is energy deposited in the calorimeter, E_γ^{max} is energy of the most energetic photon.

R for $\sqrt{s}$ = 1.84 – 3.05 GeV

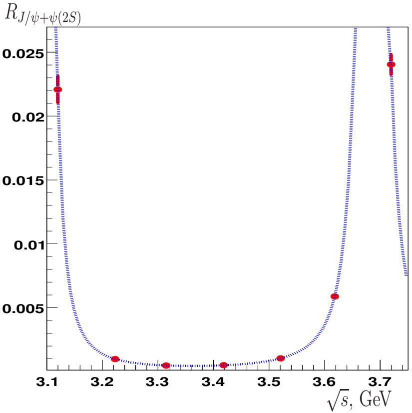
- An integrated luminosity 0.66 pb^{-1} collected at 13 equidistant points with a step $\sim$ 0.1 GeV: 1.841, 1.937 ... 3.048 GeV
- $\sim 10^3$ hadronic events per point, 14.8×10^3 events in total
- Simulation of the *uds* continuum based on the LUARLW generator, tuned JETSET alternatively used at 6 points for a cross-check.

Experimental distribution and two variants of MC simulation based on LUARLW and tuned JETSET are plotted ($\sqrt{s}$ = 1.94 GeV and $\sqrt{s}$ = 2.14 GeV).



Results

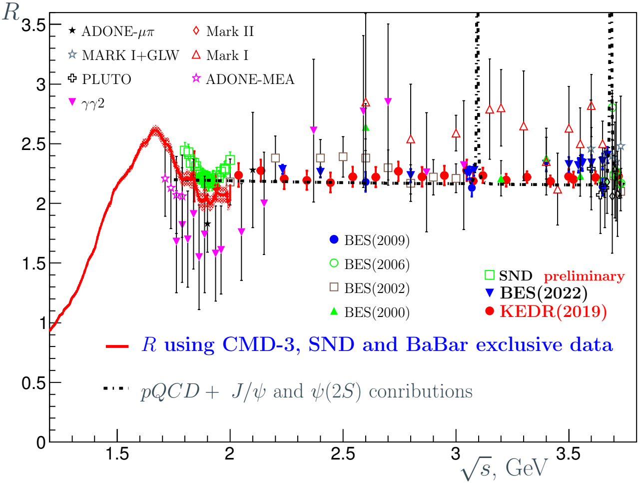
$\sqrt{s}$, GeV	$R_{uds}(s)\{R(s)\}$	$\frac{\delta R}{R}$ $(\frac{\delta R_{syst}}{R})$, %
1.841	$2.226 \pm 0.139 \pm 0.158$	9.5(7.1)
1.937	$2.141 \pm 0.081 \pm 0.073$	5.1(3.4)
2.037	$2.238 \pm 0.068 \pm 0.072$	4.4(3.2)
2.134	$2.275 \pm 0.072 \pm 0.055$	4.0(2.4)
2.239	$2.208 \pm 0.069 \pm 0.053$	3.9(2.4)
2.340	$2.194 \pm 0.064 \pm 0.048$	3.7(2.2)
2.444	$2.175 \pm 0.067 \pm 0.048$	3.8(2.2)
2.543	$2.222 \pm 0.070 \pm 0.047$	3.8(2.1)
2.645	$2.220 \pm 0.069 \pm 0.049$	3.8(2.2)
2.745	$2.269 \pm 0.065 \pm 0.050$	3.6(2.2)
2.850	$2.223 \pm 0.065 \pm 0.047$	3.6(2.1)
2.949	$2.234 \pm 0.064 \pm 0.051$	3.7(2.3)
3.048	$2.278 \pm 0.075 \pm 0.048$	3.9(2.3)
3.077	$2.188 \pm 0.056 \pm 0.042$	3.2(2.1)
3.120	$2.212\{2.235\} \pm 0.042 \pm 0.049$	2.9(2.2)
3.223	$2.194\{2.195\} \pm 0.040 \pm 0.035$	2.4(1.6)
3.315	$2.219\{2.219\} \pm 0.035 \pm 0.035$	2.2(1.6)
3.418	$2.185\{2.185\} \pm 0.032 \pm 0.035$	2.2(1.6)
3.500	$2.224\{2.224\} \pm 0.054 \pm 0.040$	3.0(1.8)
3.521	$2.200\{2.201\} \pm 0.050 \pm 0.044$	3.0(2.0)
3.618	$2.212\{2.218\} \pm 0.038 \pm 0.035$	2.3(1.6)
3.720	$2.204\{2.228\} \pm 0.039 \pm 0.042$	2.6(1.9)



Using J/ψ and $\psi(2S)$ parameters, we obtain

$$R_{uds}(s) + R_{J/\psi+\psi(2S)} \Longrightarrow R(s)$$

Comparison with others experiments



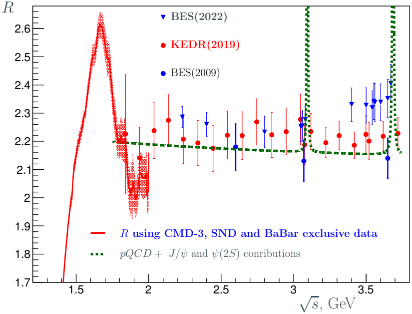
The quantity R versus the c.m. energy and the sum of the prediction of perturbative QCD and a contribution of narrow resonances.

1.84-3.08 GeV $\overline{R}^{KEDR}_{\mathrm{uds}} = 2.213 \pm 0.013 \pm 0.037$ $(R^{\mathrm{pQCD}}_{\mathrm{uds}} = 2.17 \pm 0.02)$

3.11-3.72 GeV $\overline{R}^{KEDR}_{\mathrm{uds}} = 2.205 \pm 0.014 \pm 0.026$ $(R^{\mathrm{pQCD}}_{\mathrm{uds}} = 2.16 \pm 0.01)$

Comparison KEDR and BESIII results

Energy	$\overline{R}^{BES2022}$	$\overline{R}^{KEDR}$	$\frac{\overline{R}^{BES2022} - \overline{R}^{KEDR}}{total\ error}$
1.84-3.08 GeV	$2.265 \pm 0.003 \pm 0.019$	$2.213 \pm 0.013 \pm 0.037$	1.2
3.11-3.72 GeV	$2.330 \pm 0.003 \pm 0.020$	$2.211 \pm 0.014 \pm 0.026$	3.3

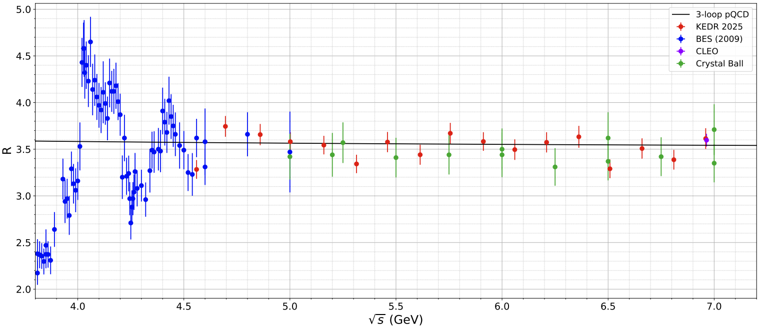


In the BES-III paper (Phys. Rev. Lett. 128, 062004 (2022)) is noted that the uncertainties of some sources are correlated between energy points. Assuming that this correlation is equal to the minimum total systematic uncertainty of these sources ($\sim 1.5\%$), one can obtain.

Energy	$\overline{R}^{BES2022}$	$\frac{\overline{R}^{BES2022} - \overline{R}^{KEDR}}{total\ error}$
1.84-3.08 GeV	$2.273 \pm 0.004 \pm 0.036$	1.1
3.11-3.72 GeV	$2.338 \pm 0.004 \pm 0.056$	2.0

R measurement at KEDR between 4.56 and 6.96 GeV

- An integrated luminosity 13.7 pb^{-1} collected at 17 equidistant energy points.



The quantity R versus the c.m. energy. Preliminary results of the KEDR experiment are presented. Estimated total uncertainty is about 3% (systematic uncertainty is 2.4%).

4.56-6.96 GeV $\overline{R}^{KEDR}_{preliminary} = 3.51 \pm 0.02 \pm 0.05$, $R^{\mathrm{pQCD}} = 3.56 \pm 0.02$

Summary

- KEDR measured the R values at 22 center-of-mass energies between 1.84 and 3.72 GeV.

  In the energy range between 1.84 and 3.05 GeV the achieved accuracy is about or better than 3.9% at most of the energy points with a systematic uncertainty less than 2.4%. For the energies above J/ψ resonance the total error is about or better than 2.6% and a systematic uncertainty of about 1.9%.

  V. V. Anashin et al., Phys.Lett. B 770C, 174-181, 2017.[arXiv:1610.02827]
  V. V. Anashin et al., Phys.Lett. B 753, 533-541, 2016.[arXiv:1510.02667]
  V. V. Anashin et al., Phys.Lett. B 788, 42-51, 2019.[arXiv:1805.06235]

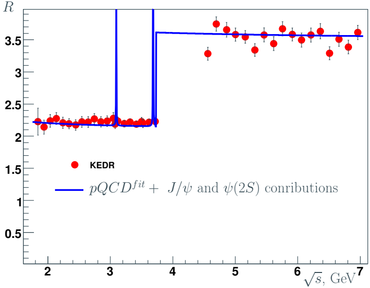
- Preliminary results of the R measurement between 4.56 and 6.96 GeV were obtained in the KEDR experiment. Estimated systematic uncertainty is about 2.4% and total is about 3%.

  Phys. of Part. and Nuclei Lett. **22**, 137-141,2025

Thank you for your time and attention!

BACKUP SLIDES

An application of the $R(s)$



$$R_{uds}(s) \simeq \left(3\sum Q_q^2\right) \times \left(1 + \frac{\alpha_s}{\pi} + \frac{\alpha_s^2}{\pi^2} \times \left(\frac{365}{24} - 9\zeta_3 - \frac{11}{4}\right)\right)$$

where ζ is the Euler-Riemann zeta function (K.G. Chetyrkin, A.L. Kataev, F.V. Tkachov Phys. Lett.B 85,277-279,1979.)

$$\alpha_s(s) = \frac{1}{b_0 t}\left(1 - \frac{b_1 l}{b_0^2 t} + \frac{b_1(l^2 - l - 1) + b_0 b_2}{b_0^4 t^2}\right)$$

with $t = \ln\frac{s}{\Lambda^2}$, $l = \ln t$ parametrized in terms of the QCD scale parameter Λ and coefficients b_0, b_1, b_3 (can be found in PDG).

To determine Λ, we minimise the χ^2 function

$$\chi^2 = \sum_i \sum_j \left(R_{uds}^{meas}(s_i) - R_{uds}^{calc}(s_i)\right) C_{ij}^{-1} \left(R_{uds}^{meas}(s_j) - R_{uds}^{calc}(s_j)\right),$$

The obtained value of $\Lambda = 0.37 \pm 0.05$ GeV corresponds to $\alpha_s(m_\tau) = 0.33 \pm 0.03$.

This is consistent with obtained in semileptonic τ decays $\alpha_s(m_\tau) = 0.31 \pm 0.01$

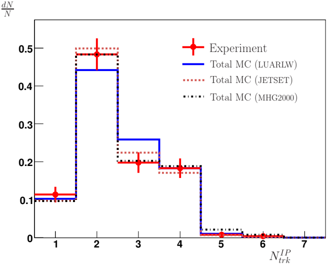
Systematic uncertainties

Source	Syst. uncertainty, %			
	Scan. 2010	Scan 1 and 2 2011	Scan 2014-2015	Corr.
Luminosity	1.2	1.1	0.9	0.4
Rad. corr.	$0.5 \div 2.0$	$0.4 \div 0.6$	$0.5 \div 0.8$	$0.2 \div 0.4$
Sim. uds continuum	$1.2 \div 6.6$	$1.3 \div 2.0$	1.1	0.9
Track reconstruction	0.5	0.5	0.4	–
J/ψ	–	$0.1 \div 2.7$	$0.1 \div 1.8$	
$\psi(2S)$ (at 3.72 GeV)	–	1.4	1.1	–
l^+l^-	$0.3 \div 0.6$	$0.1 \div 0.2$	$0.3 \div 0.4$	$0.1 \div 0.2$
e^+e^-X	0.2	$0.1 \div 0.2$	0.1	0.1
Trigger	0.3	0.2	0.2	0.2
Nuclear int.	0.4	0.2	0.2	0.2
Beam background	$0.4 \div 0.9$	$0.5 \div 1.1$	$0.4 \div 0.8$	–
Selection criteria	0.7	0.6	0.6	–
Square sum.	$2.1 \div 7.1$	$2.1 \div 3.6$ (corr. $1.8 \div 2.5$)	$1.9 \div 2.7$	1.1

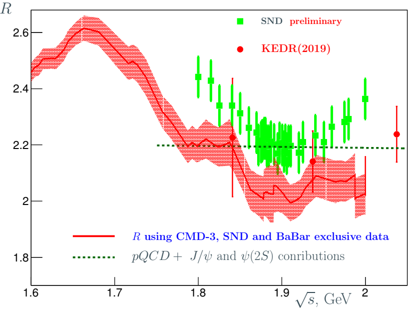
R scan 2019-2020

Source	Syst. uncertainty, %
Luminosity	1.2
Simulation	1.4
Track reconstruction	0.7
Nuclear interaction	0.6
Radiative correction	0.3
Beam background	0.2
Trigger	0.1
Cuts variation	1.1
Total	2.4

Detection efficiency uncertainty in the energy range $\sqrt{s} = 1.84 \div 3.05$ GeV



- Used two essentially different MC generators (LUARLW/JETSET)
- We validated our estimate of the systematic uncertainty related to simulation of the *uds* continuum using an unfolding method
- The estimate at the most problematic energy point 1.84 GeV was additionally verified using the exclusive generator MHG2000.



Detection efficiency uncertainties obtained by different methods

Energy, MeV	$\delta\epsilon/\epsilon$		
	LUARLW JETSET	Unfolding method	LUARLW MHG2000
1841.0	6.6%	3.6%	3.8%
$1937.0 \div 2135.7$	2.5%	1.9%	–
$2135.7 \div 3048.1$	1.2%	0.5%	–