R Measurements at Low Energy

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Outline

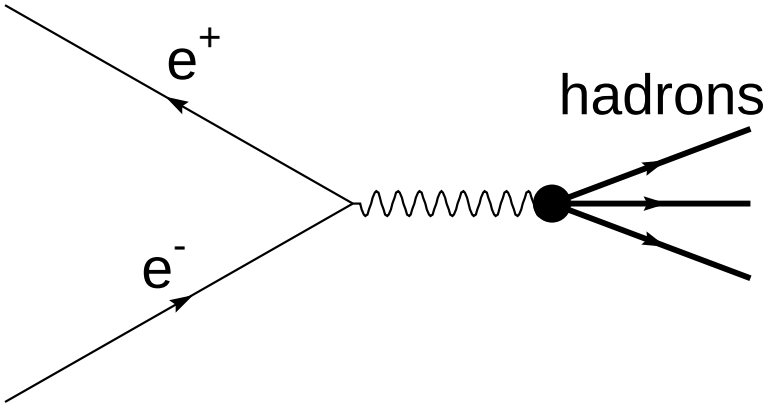
1. General
2. $\sqrt{s} < 2$ GeV
3. $\sqrt{s} > 2$ GeV
4. Conclusions

Why Measure R at Low Energy?

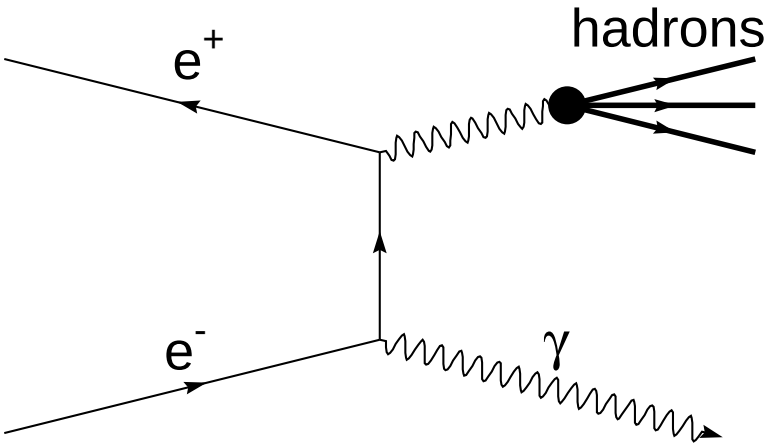
Precise measurement of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ allows a study of u, d, s interactions with numerous applications:

- Light vectors (ρ, ω, ϕ) and their excitations
- A search for and studies of regular and exotic mesons with various quantum numbers in $e^+e^- \to$ hadrons
- Muon anomalous magnetic moment $(g_\mu - 2)/2$
- Running fine structure constant $\alpha(M_Z^2)$
- QCD parameters (α_s, quark masses, gluon condensates) and sum rules
- Tests of CVC (Conserved Vector Current)-based relations between $\sigma_{I=1}(e^+e^- \to \text{hadrons})$ and corresponding τ lepton decays

Scan and ISR



Scan



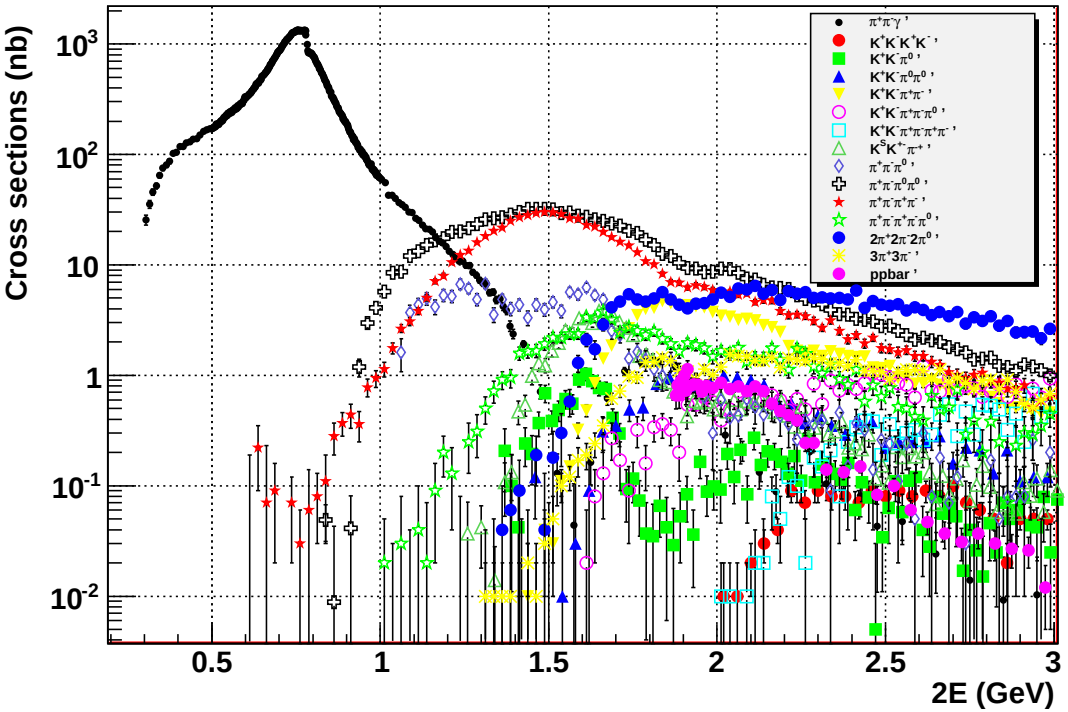
ISR

Scan can provide larger data samples

ISR benefits from the same systematics and flat acceptance,

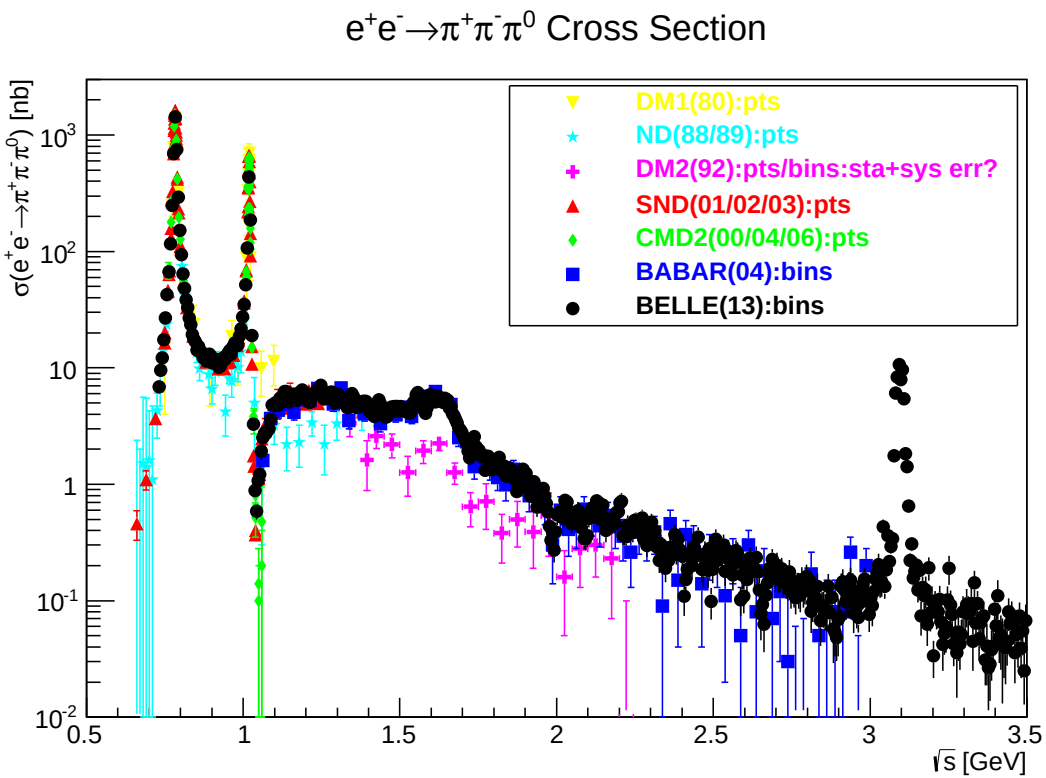
but may suffer from more complicated radiative effects

Current Status of Exclusive Measurements



Impressive achievements of CMD-2, SND (scan at $\sqrt{s} < 1.4$ GeV) and KLOE (ISR at $\sqrt{s} < 1.0$ GeV) and BaBar (ISR at $\sqrt{s} < 3.0$ GeV), Belle may contribute as well to ISR measurements

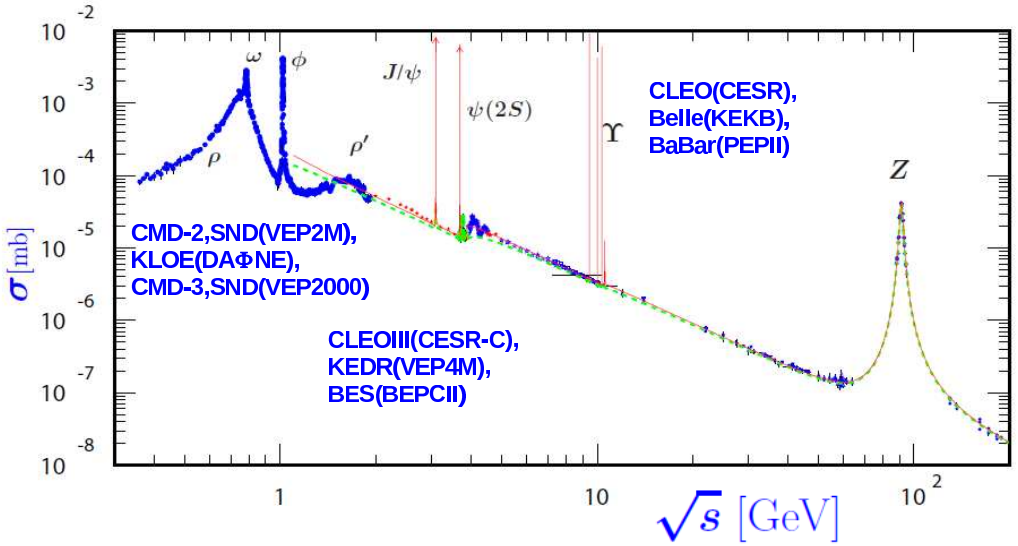
ISR Study of $e^+e^- \to \pi^+\pi^-\pi^0$ at Belle



78.5×10^3 events at $0.73 < \sqrt{s} < 3.5$ GeV

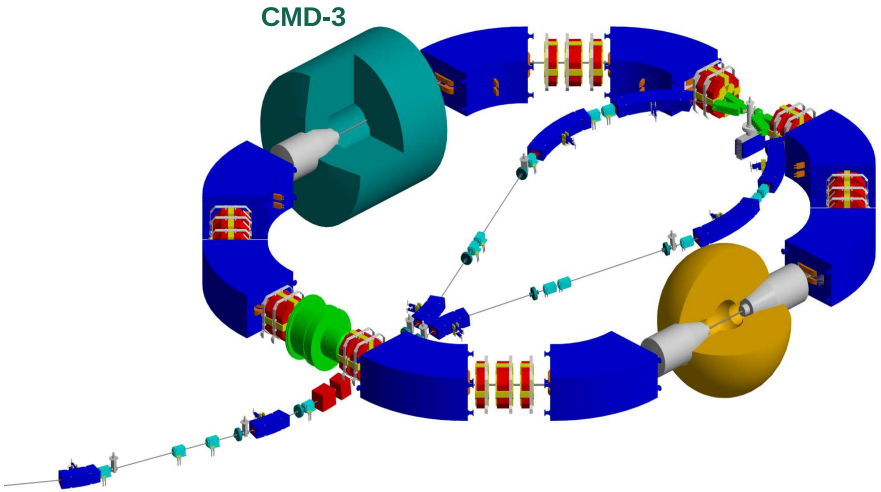
from a 526.6 fb^{-1} data sample with a goal of 5% systematic error

Current Status of Inclusive R Measurements



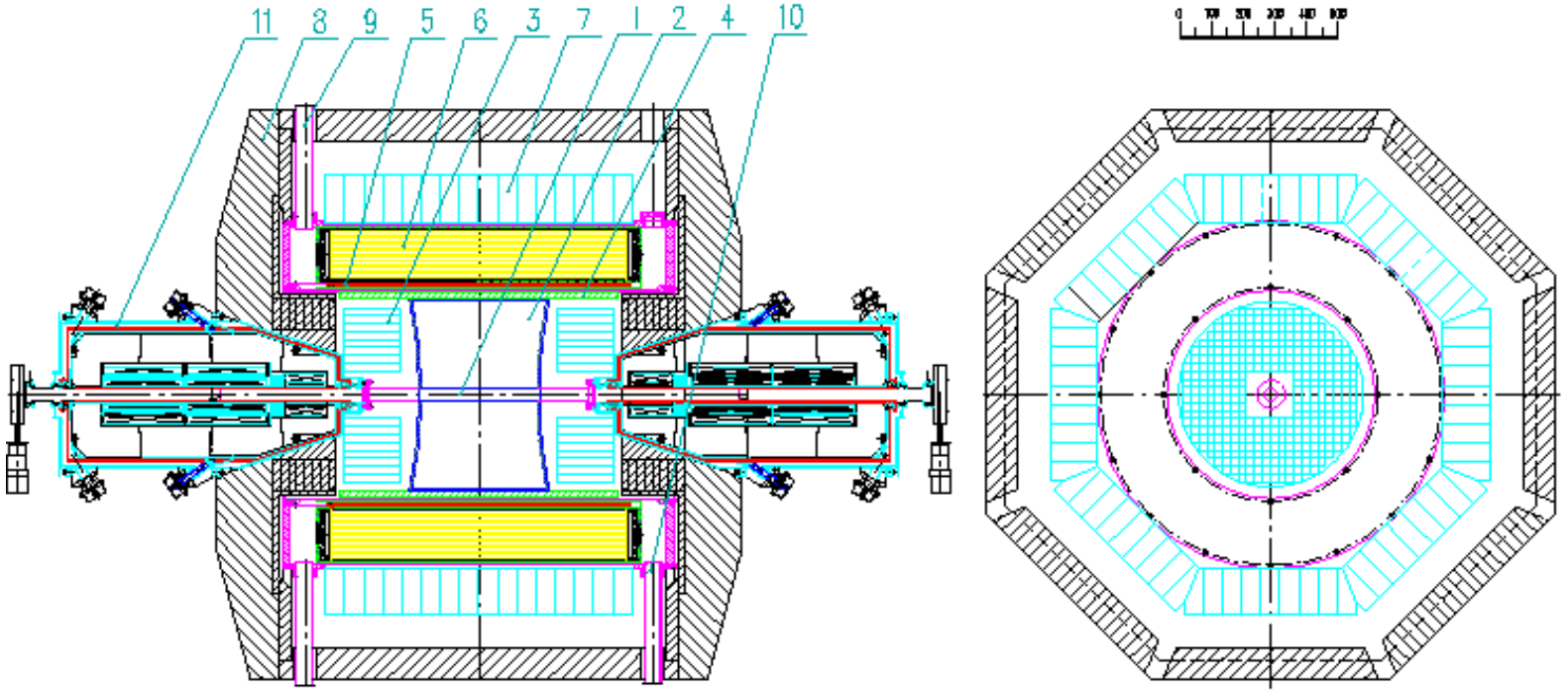
Existing accuracy is not sufficient and should be improved

VEPP-2000



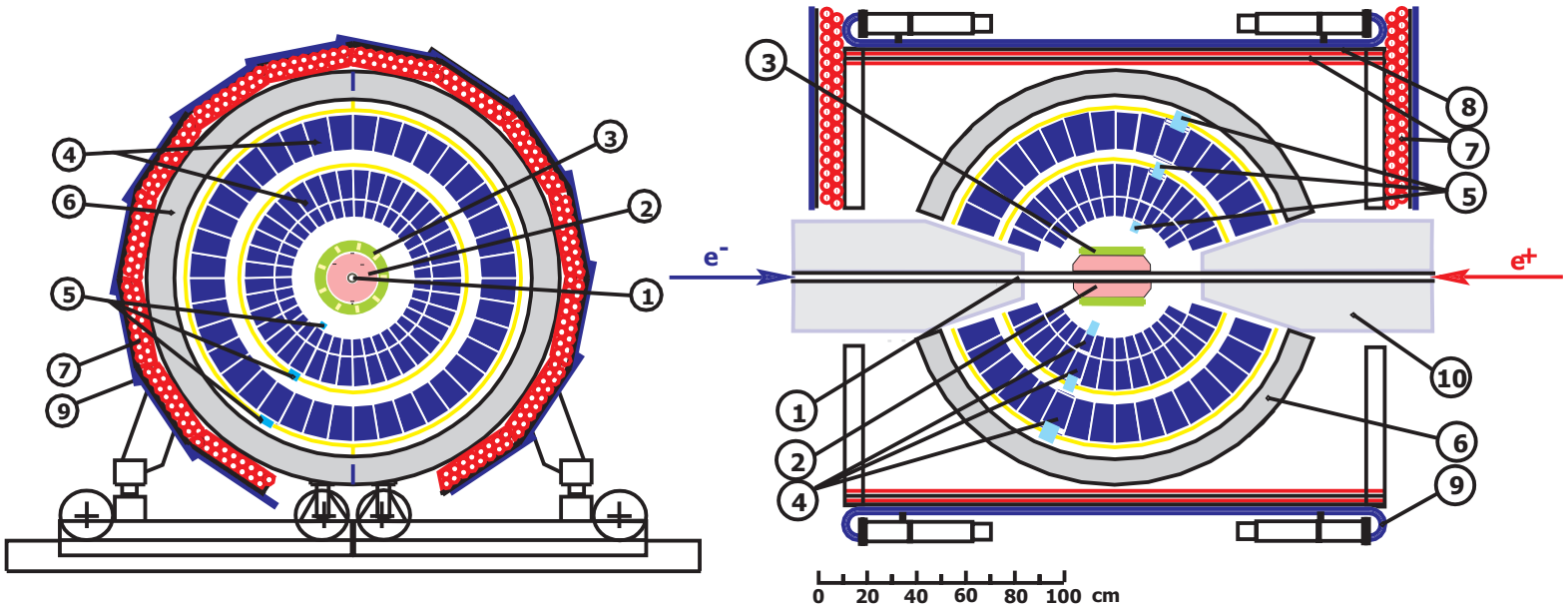
$$2m_\pi < \sqrt{s} < 2 \text{ GeV}, \mathcal{L} = 10^{32}\text{cm}^{-2}\text{s}^{-1}$$

CMD-3



General-purpose magnetic (1.3T) detector with 3 e/m calorimeters (LXe, CsI, BGO)

SND

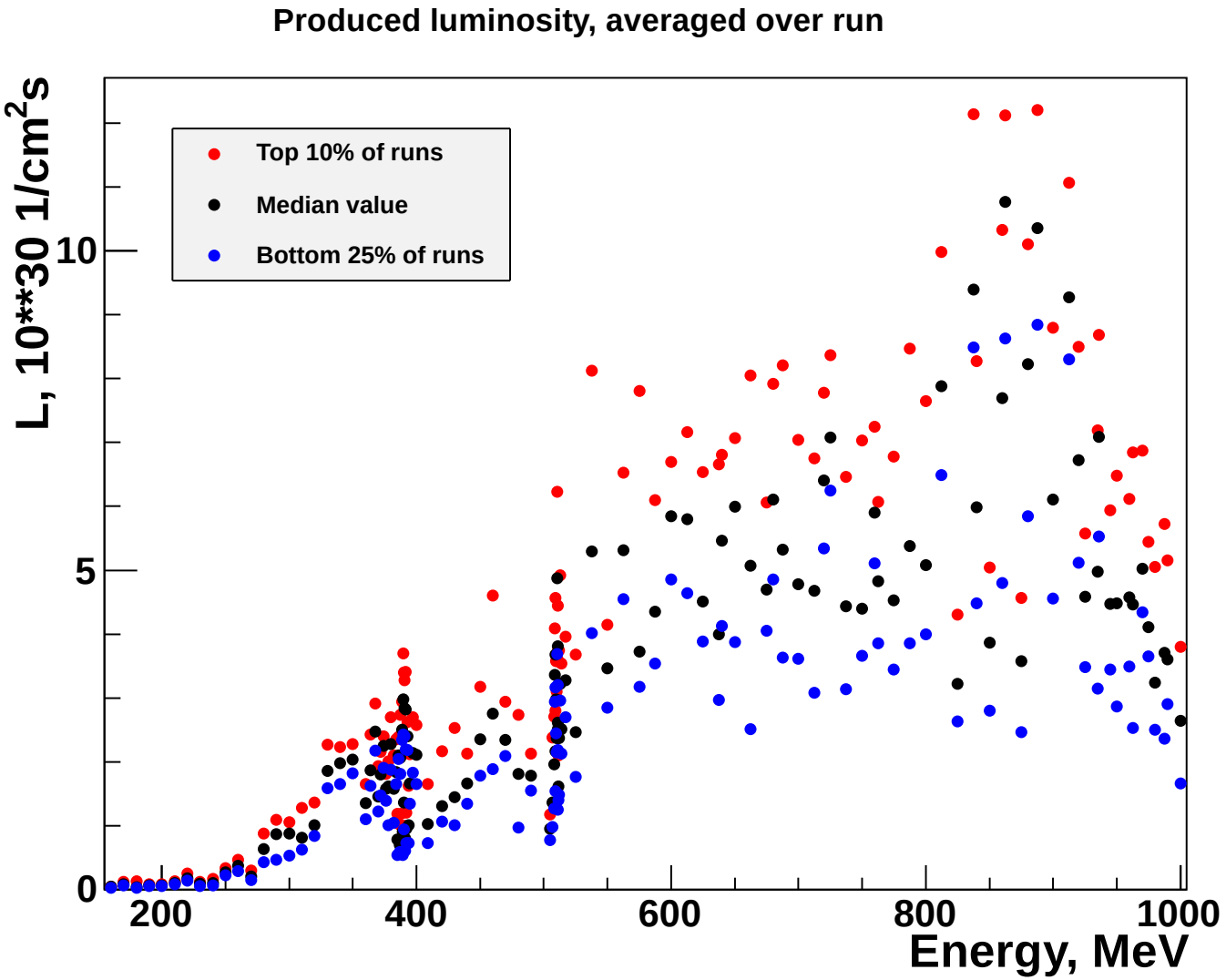


High-resolution NaI calorimeter with excellent tracking and PID

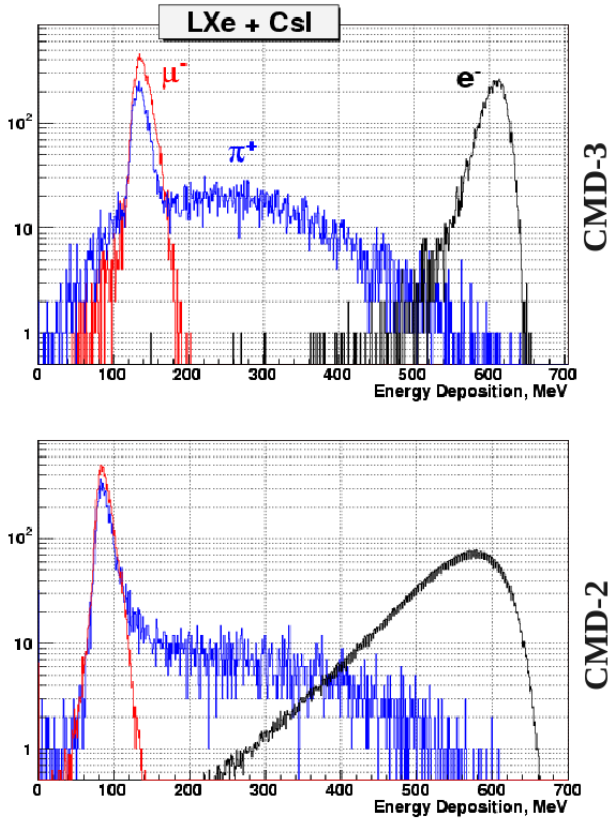
Data Taking at VEPP-2000

- Since 2010, when data taking started, until 2012 CMD-3 collected:
  3.1 pb^{-1} at the ϕ, 33 pb^{-1} from ϕ to 2 GeV, 5.2 pb^{-1} below the ϕ
- The maximum luminosity is $2 \cdot 10^{31}$ $\text{cm}^{-1}\text{s}^{-1}$ at 1.7-1.8 GeV,
  falling much slower with decreasing energy than before the round beams
- At high energies lumi is limited by a deficit of positrons and
  maximum energy of the booster (900 MeV now)
- In 2013 we reached 2×160 MeV, the smallest $\sqrt{s}$ ever,
  scanned the ϕ (6.2 pb^{-1} at 16 points between 1.004 and 1.06 GeV),
  now scanning the ρ, ω (plan 8.8 pb^{-1} at 11 points from 0.74 to 0.82 GeV)
- A long shutdown for 1-1.5 years to increase the booster energy to 1 GeV
  and commission the new injection complex to reach 10^{32} $\text{cm}^{-1}\text{s}^{-1}$

Luminosity vs. Energy

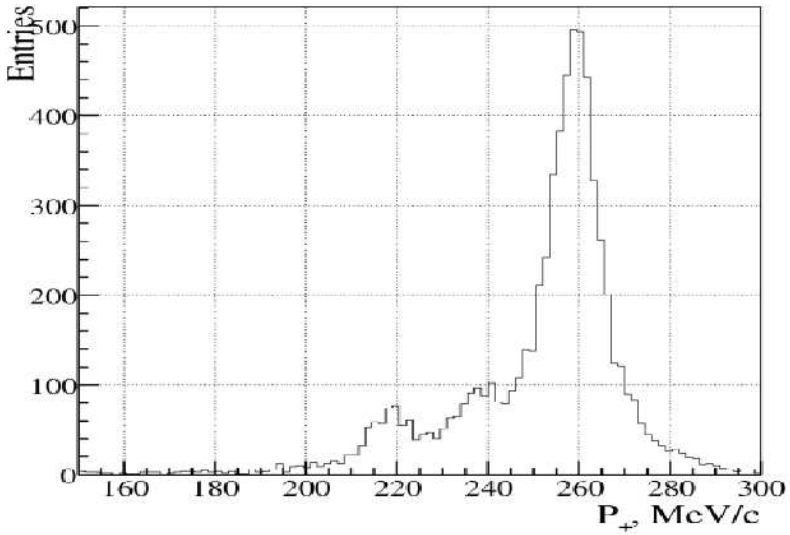


CMD-3 vs. CMD-2: PID With Calorimeters

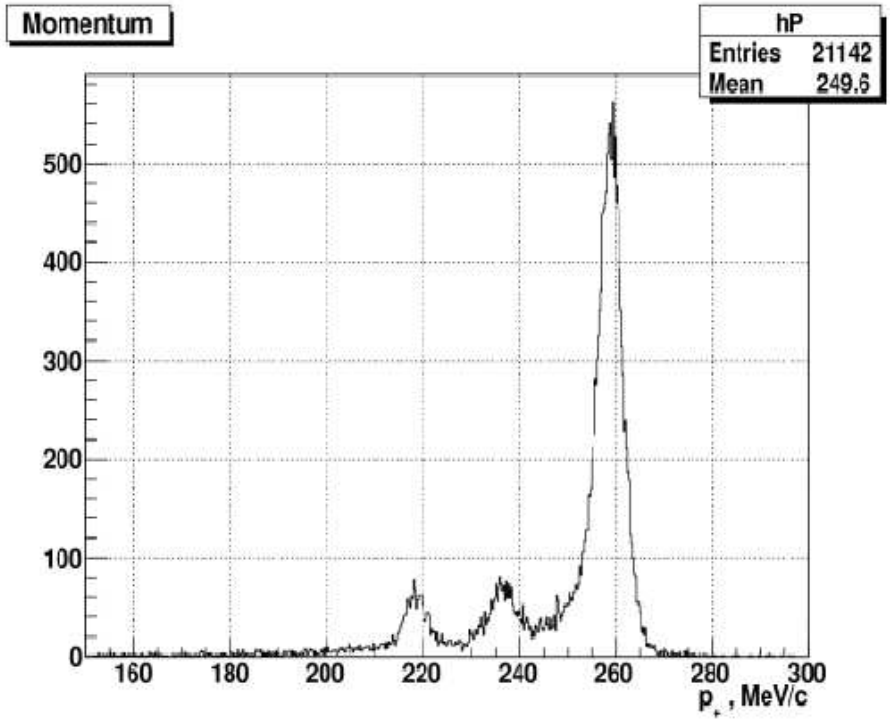


Better π/e and π/μ separation due to higher thickness

CMD-3 vs. CMD-2: PID with Tracking



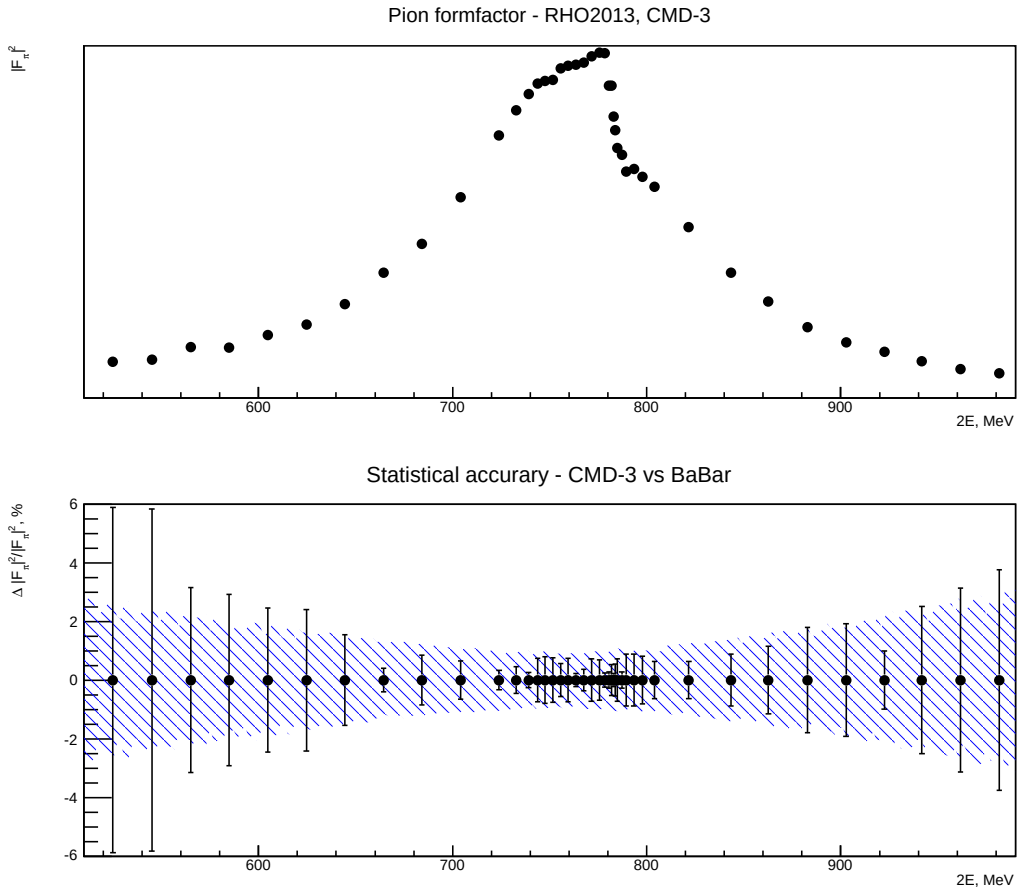
CMD-2



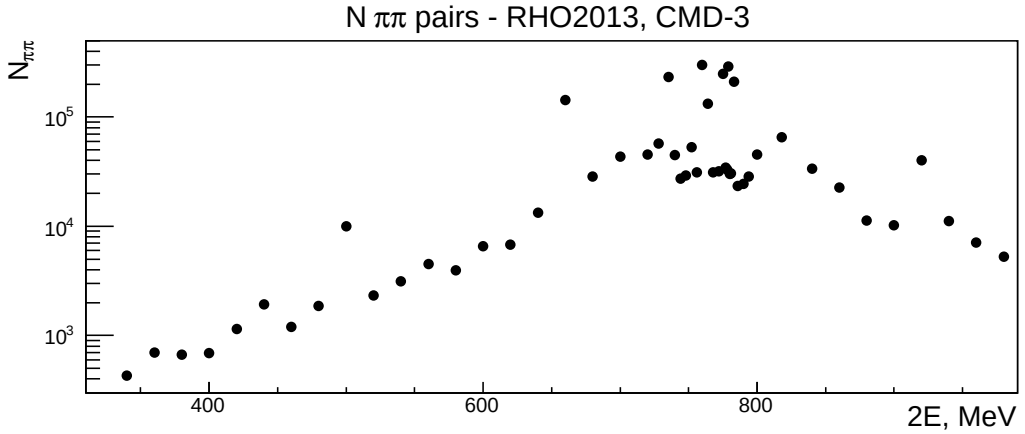
CMD-3

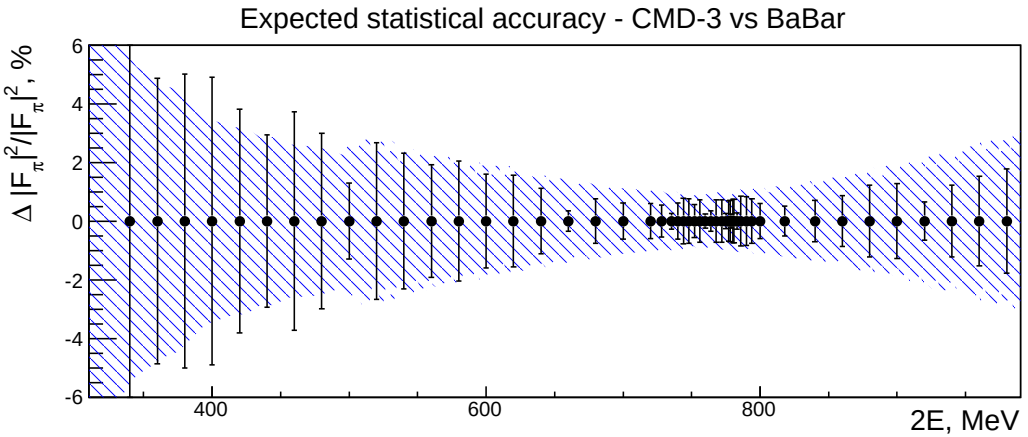
Better PID at $\sqrt{s}$=0.52 GeV due to higher B and better σ_p

Pion Form Factor – I

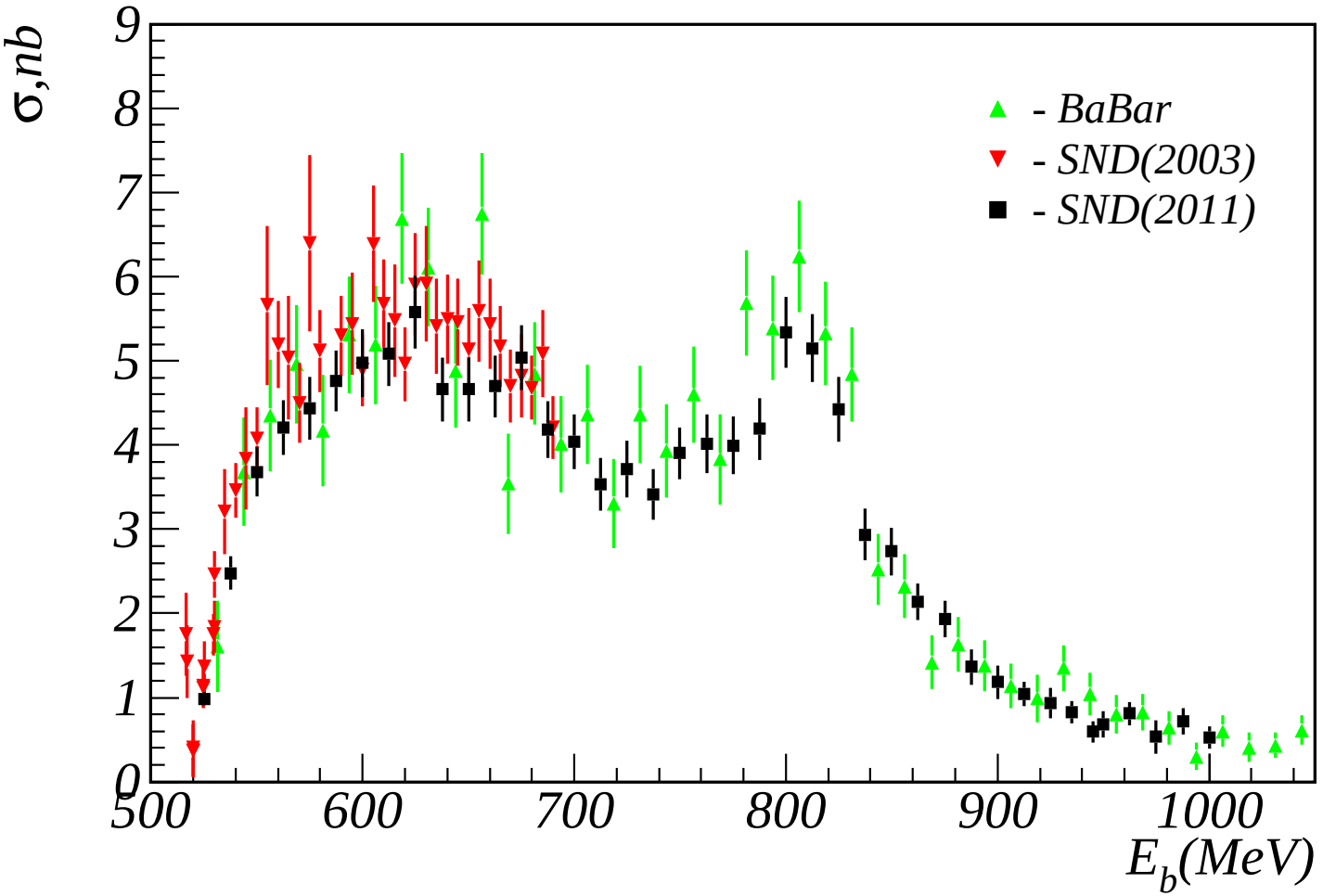


Pion Form Factor – II

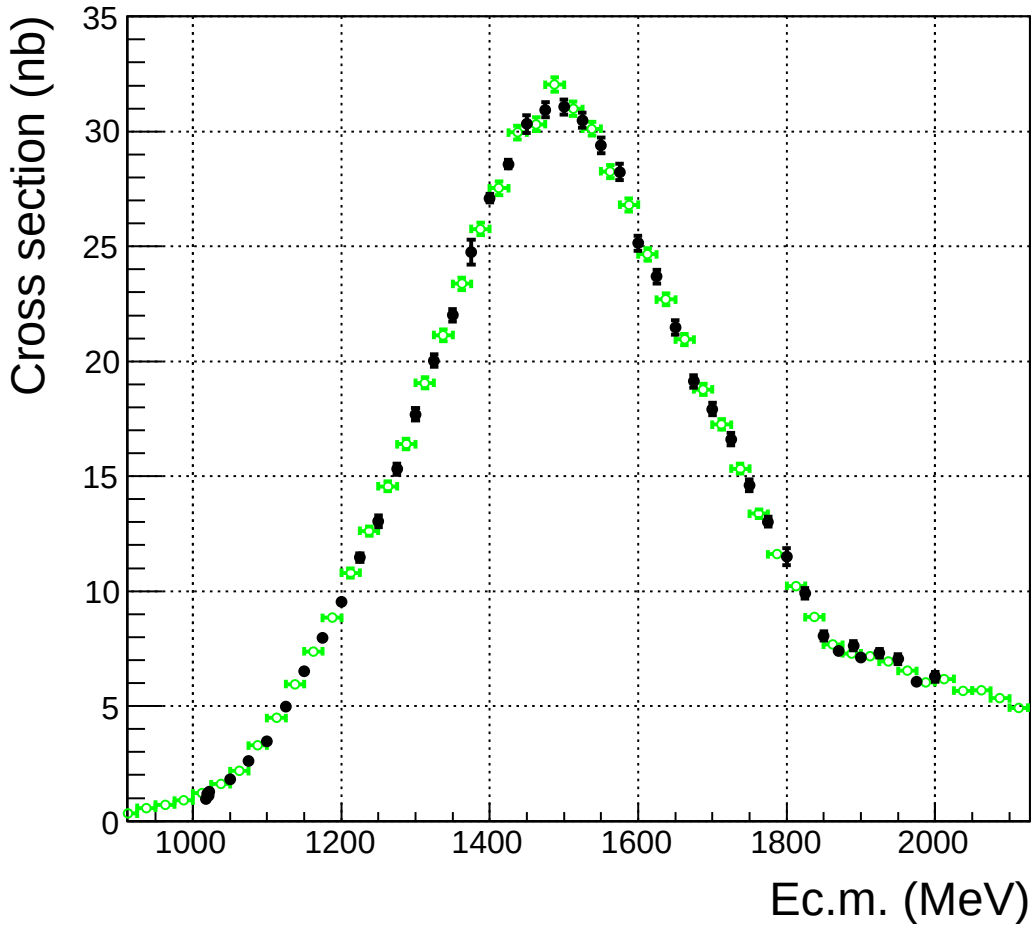




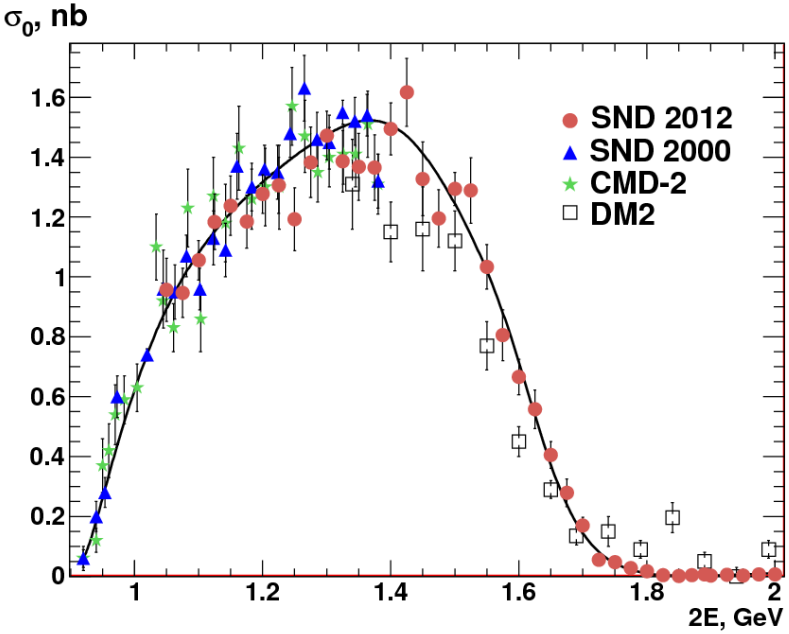
$e^+e^- \to \pi^+\pi^-\pi^0$ at SND

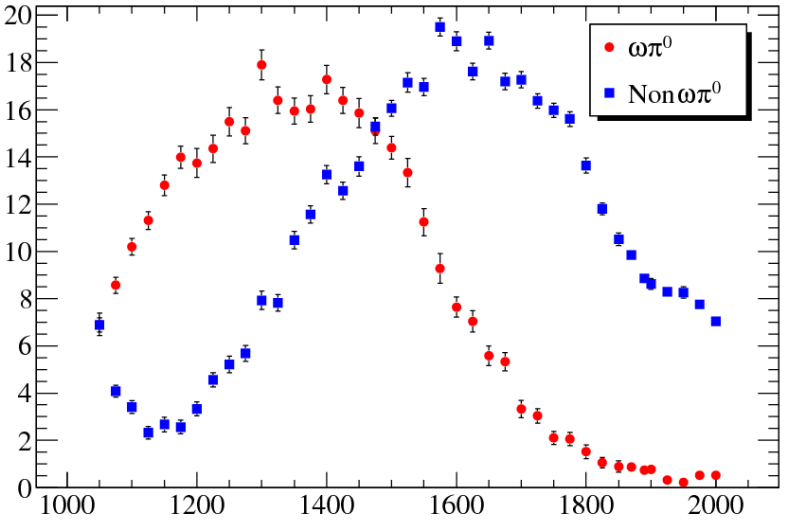


$e^+e^- \to 2\pi^+2\pi^-$ at CMD-3



$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ at SND





$e^+e^- \to 3\pi^+3\pi^-$ – I

- The very first physical publication of CMD-3 on $e^+e^- \to 3\pi^+3\pi^-$ in arxiv:1302.0053, PLB
- A scan from 1500 to 2000 MeV with a $\sqrt{s} = 25$ MeV step and a finer scan of the near-$N\bar{N}$ threshold used, $\int Ldt$ =22 pb^{-1}
- About 8k five- and six-track events selected (5069 and 2887 events, respectively)
- Very few candidates below 1.5 GeV

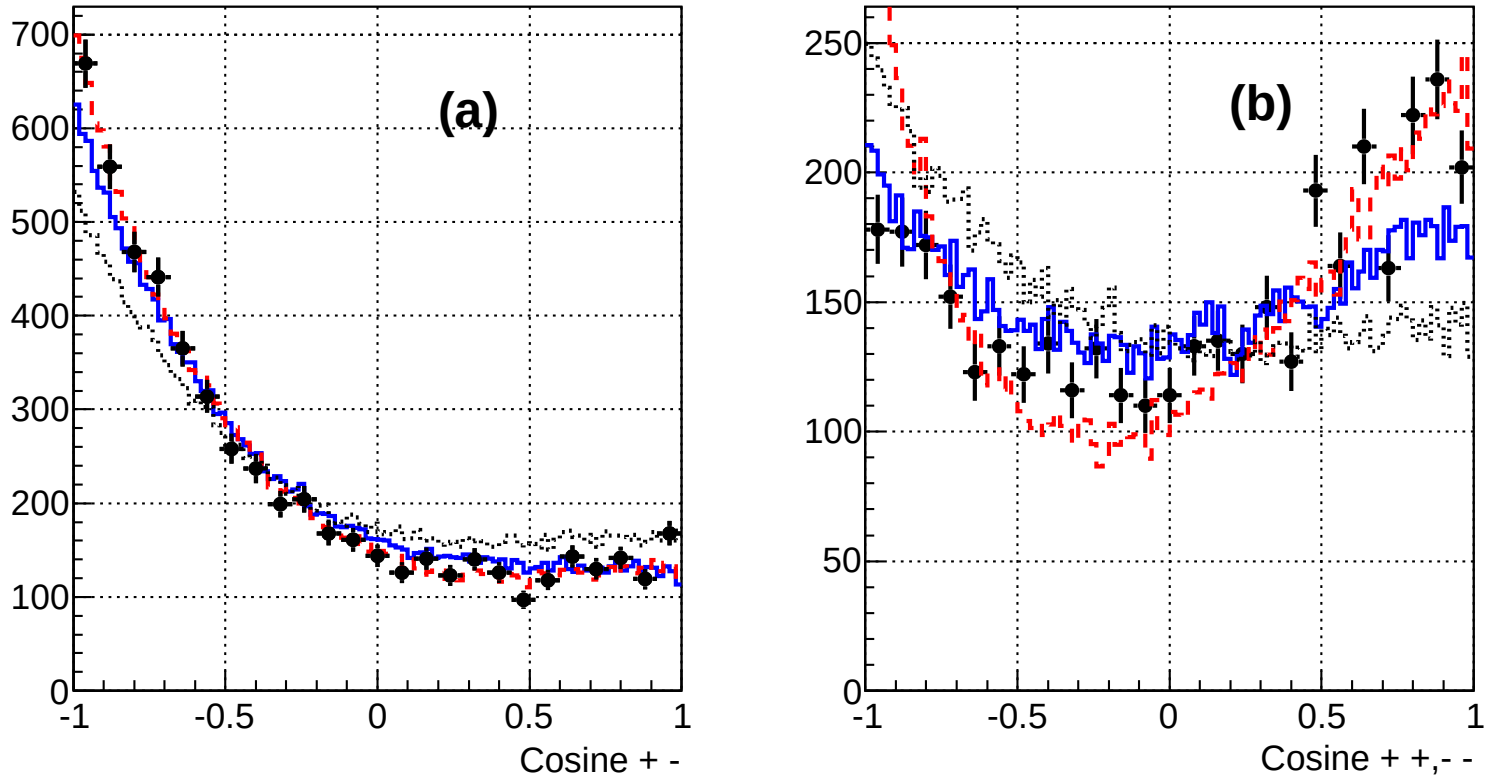
$e^+e^- \to 3\pi^+3\pi^-$ – II

We study dynamics, pure phase space doesn't work,
three models with $J^{PC} = 1^{--}$, each with one ρ^0/event:

- $\rho(1450)(\pi^+\pi^-)_{\rm S-wave} \to a_1(1260)^{\pm}\pi^{\mp}\pi^+\pi^- \to \rho^0 2(\pi^+\pi^-) \to 3(\pi^+\pi^-)$
- $\rho(770)(2\pi^+2\pi^-)_{\rm S-wave} \to 3(\pi^+\pi^-)$
  3 options for $2\pi^+2\pi^-$: phase space, $f_0(1370)$, $f_0(1500)$
- $\rho(770)f_2(1270) \to 3(\pi^+\pi^-)$

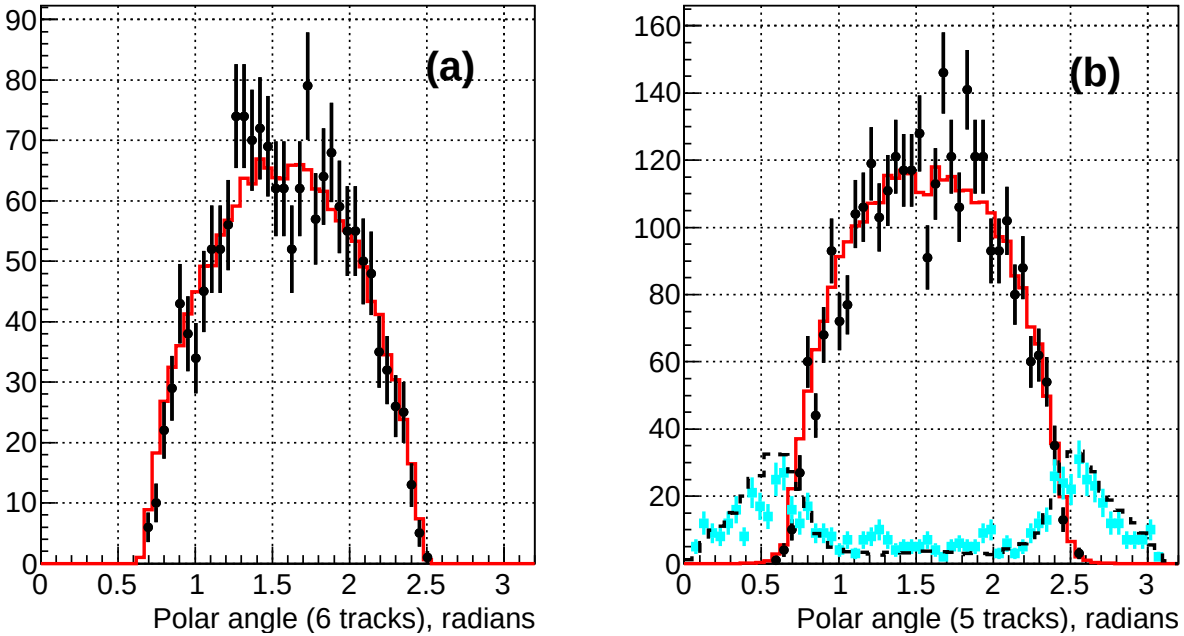
The best description is with one $\rho(770)$ and 4 pions in S-wave

$e^+e^- \to 3\pi^+3\pi^- - \mathrm{III}$



Cosines of the angle between two pions:
(a) opposite-sign charge, (b) same-sign charge

$e^+e^- \to 3\pi^+3\pi^- - \mathrm{IV}$



Polar angle distribution;

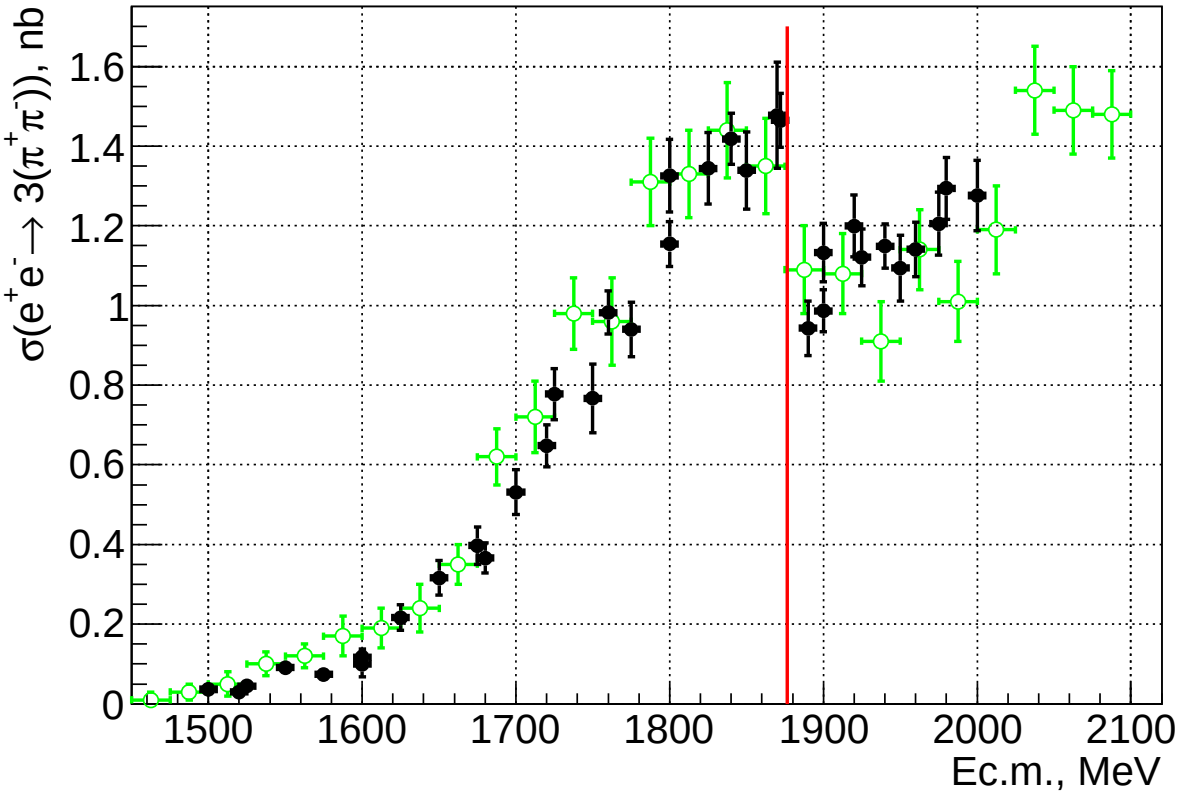
(a) – 6 tracks, (b) – 5 tracks, squares – a missing track

$e^+e^- \to 3\pi^+3\pi^- - \mathrm{V}$

Systematic uncertainties for $\sigma(e^+e^- \to 3\pi^+3\pi^-)$

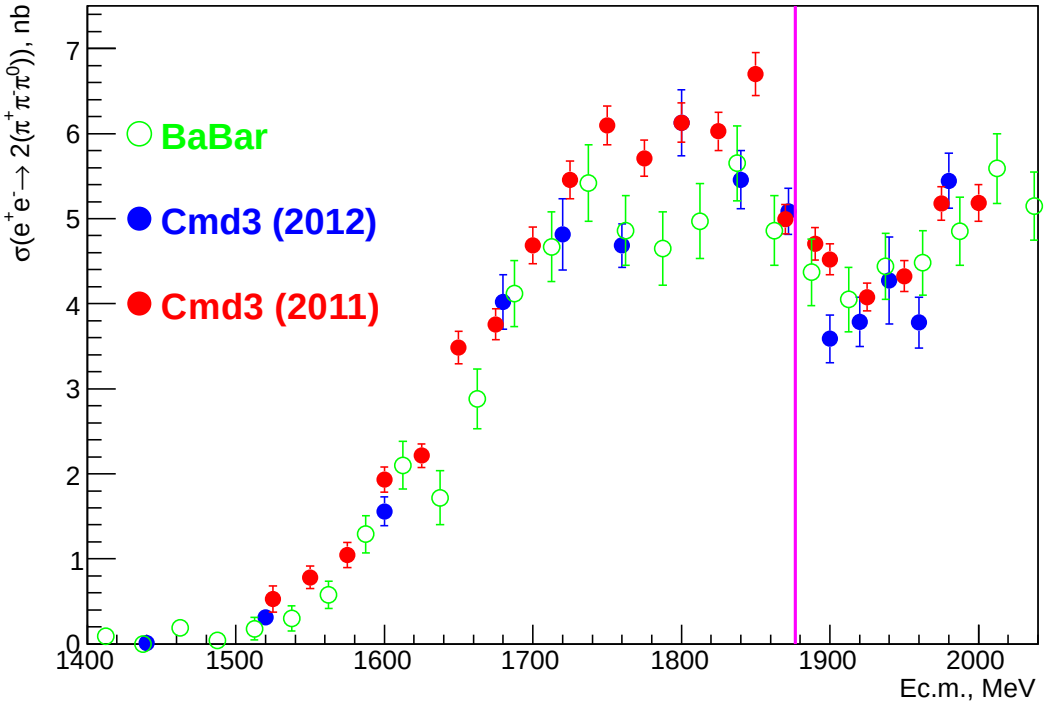
Source	$\mathrm{Error_{CMD}}$, %	$\mathrm{Error_{BABAR}}$, %
Model	4	3
Selection	3	$2 \bigoplus 3$
Lumi	2	3
Background (6 tr.)	1	3
Background (5 tr.)	3	-
$\Delta\sqrt{s}/\sqrt{s}(\sim 5 \cdot 10^{-3})$	1	-
Rad. corr.	1	1
Total	6	6

$e^+e^- \to 3\pi^+3\pi^-$ – VI



The dip structure near $N\bar{N}$ threshold is confirmed

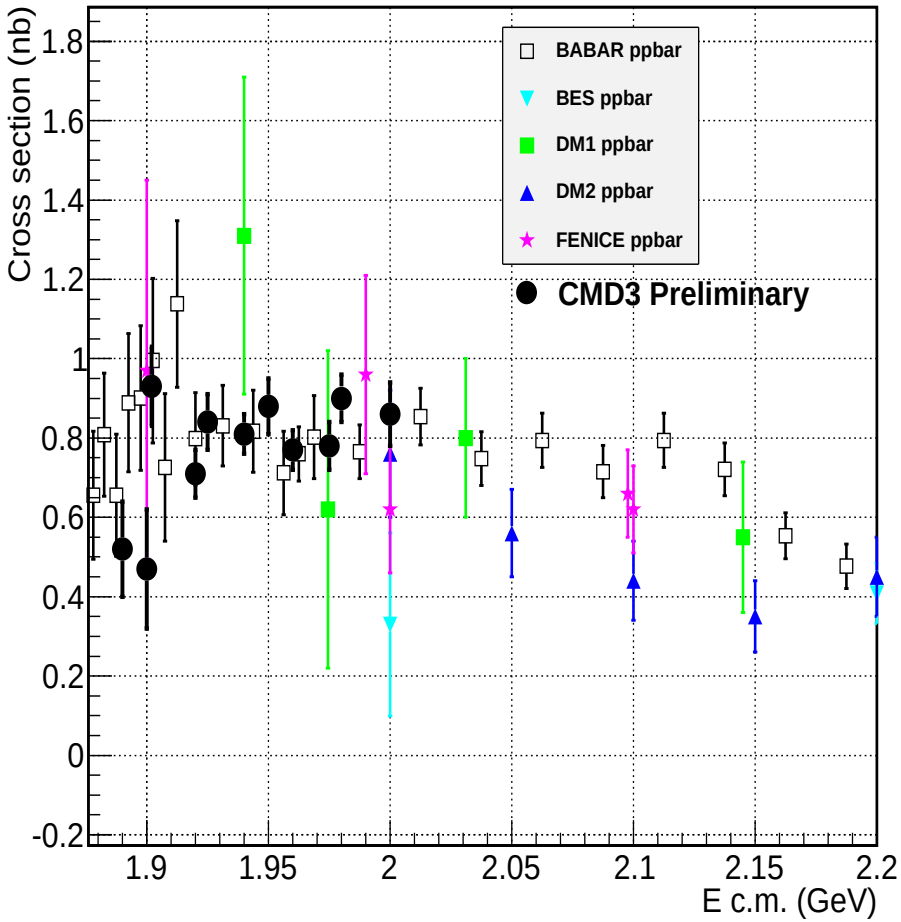
$$e^+e^- \to 2\pi^+2\pi^-2\pi^0$$

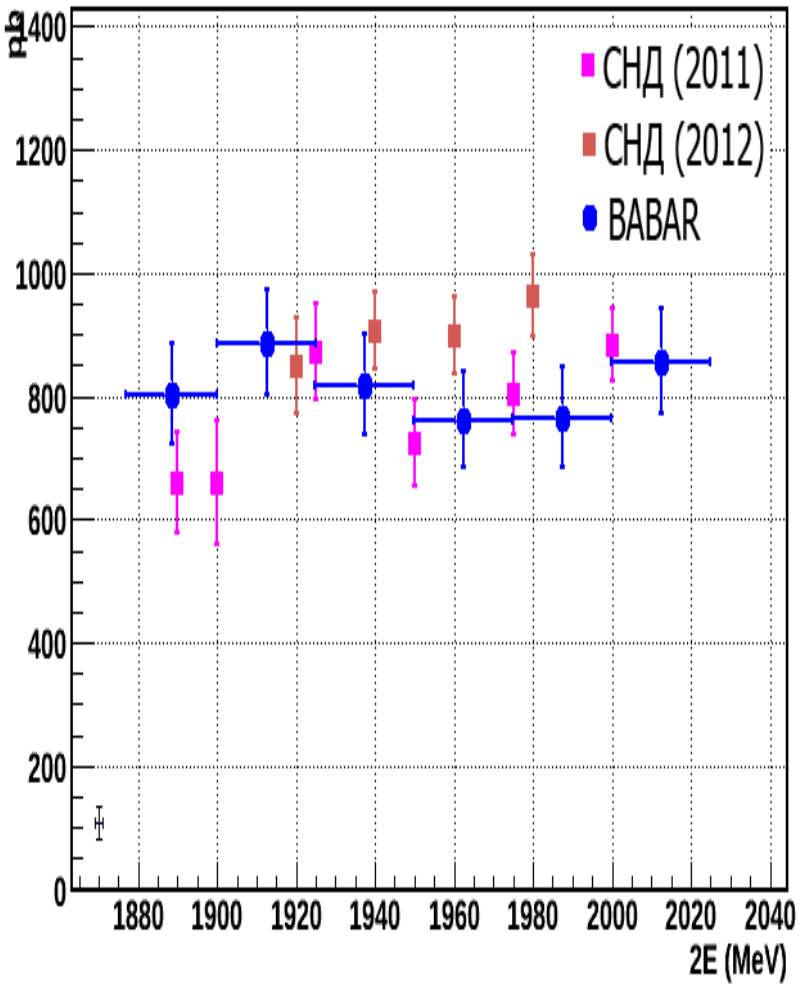


2011 – all reconstructed or a $\pi^\pm$ or π^0 lost, 2012 – all reconstructed

The dip structure near $N\bar{N}$ threshold also seen

$p\bar{p}$ Production at VEPP-2000





R_{uds} at KEDR

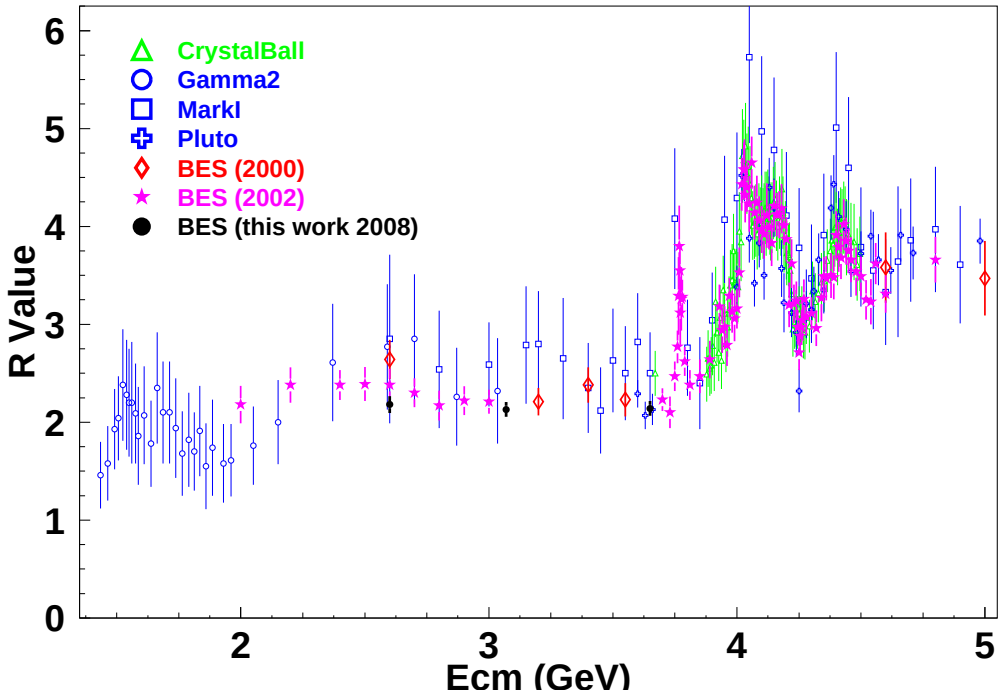
R measurements on existing or future data, the accuracy goal 4%:

- In 2009-2010 a search for narrow resonances was performed at KEDR, V. Anashin et al., PLB 703 (2011) 543, 300 nb^{-1} collected between 1.85 and 3.1 GeV with a step of $2\sigma_W \sim 1.4 - 1.9$ GeV
- From J/ψ to $\psi(2S)$

$\sqrt{s}$, MeV	$\int Ldt$, nb^{-1}	$N_{\rm ev}$, 10^3	$\sqrt{s}$, MeV	$\int Ldt$, nb^{-1}	$N_{\rm ev}$, 10^3
3090.0	53.7	0.78	3418.3	170.3	2.47
3119.9	127.1	4.74	3520.8	173.6	2.39
3223.0	153.0	2.69	3618.2	123.4	1.63
3314.7	153.0	2.43	3719.5	195.7	3.57

- There are still plans to run at higher energy, from 4 GeV to 6 GeV?

R Measurement Below 5 GeV



Dominated by BES: stat. errors (3-5)%, syst. errors (5-8)%

J.Z. Bai et al., Phys.Rev.Lett. 84 (2000) 594, Phys.Rev.Lett. 88 (2002) 101802;

M. Ablikim et al., Phys.Rev.Lett. 97 (2006) 262001, Phys.Lett. B677 (2009) 239

Plans for R measurement at BES

Three phases foreseen:

Phase 1

R in the range 2-4.5 GeV, $\sim 10^4$ events per scan point,
3% systematic accuracy to improve $\alpha_{\rm QED}(m_Z^2)$ by a factor of 2

Phase 2

R in the range 2-3 GeV, high statistics ($> 10^5$ events per scan point)
to improve nucleon $|G_E|/|G_M|$ ratio, nucleon form factors

Phase 3

Fine binning R ratio in charmonium region
for charmonium spectroscopy

Phase 1: Mini R Scan (2012)

- BESIII collected data at 2.23,2.4,2.8 and 3.4 GeV during June 8-16, 2012
- Total integrated luminosity $\sim 12\text{pb}^{-1}$
- Useful information for machine at low energy
- The data being used for generator tuning
- Necessary to establish analysis chain
- Baryon form factors, studies of fragmentation functions in progress

Conclusions

- CMD-3 and SND at VEPP-2000 will provide high accuracy, comparable or better than ISR measurements, the tentative goals are 0.5% for $\pi^+\pi^-$ and 3% for multibody modes
- Below 2 GeV progress (a factor of 2-3) expected in exclusive σ's due to scans in Novosibirsk and ISR from KLOE, BaBar, Belle, BES3 and Belle2
- Above 2 GeV R measurements with 3-4% accuracy at BES3 and KEDR
- More precise measurements of Γ_{ee} for the narrow ψ and Υ at KEDR and Belle
- Various high-statistics experiments with different approaches will substantially improve the accuracy of vacuum polarization calculations for $(g_\mu - 2)/2$, $\alpha(M_Z^2)$, quark masses etc.