BINP-IHEP Seminar

"Tau and QCD physics at present and future electron-positron colliders"

December 16–18, 2019

Study of electron-positron annihilation to hadrons with CMD-3 at VEPP-2000

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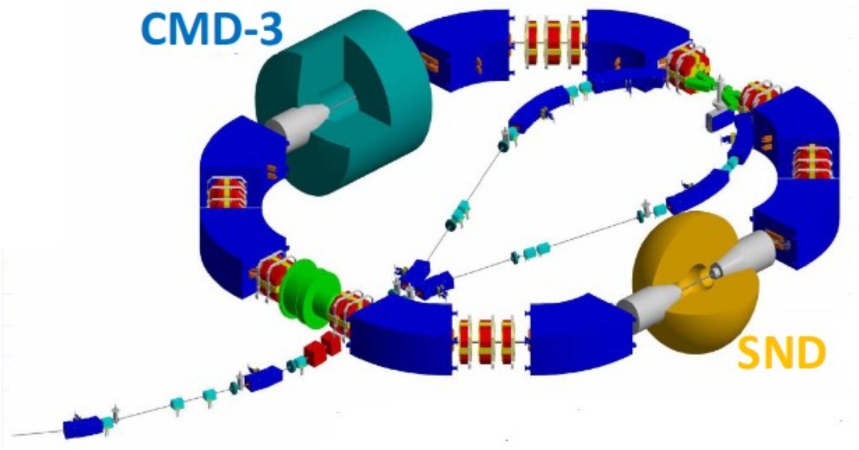
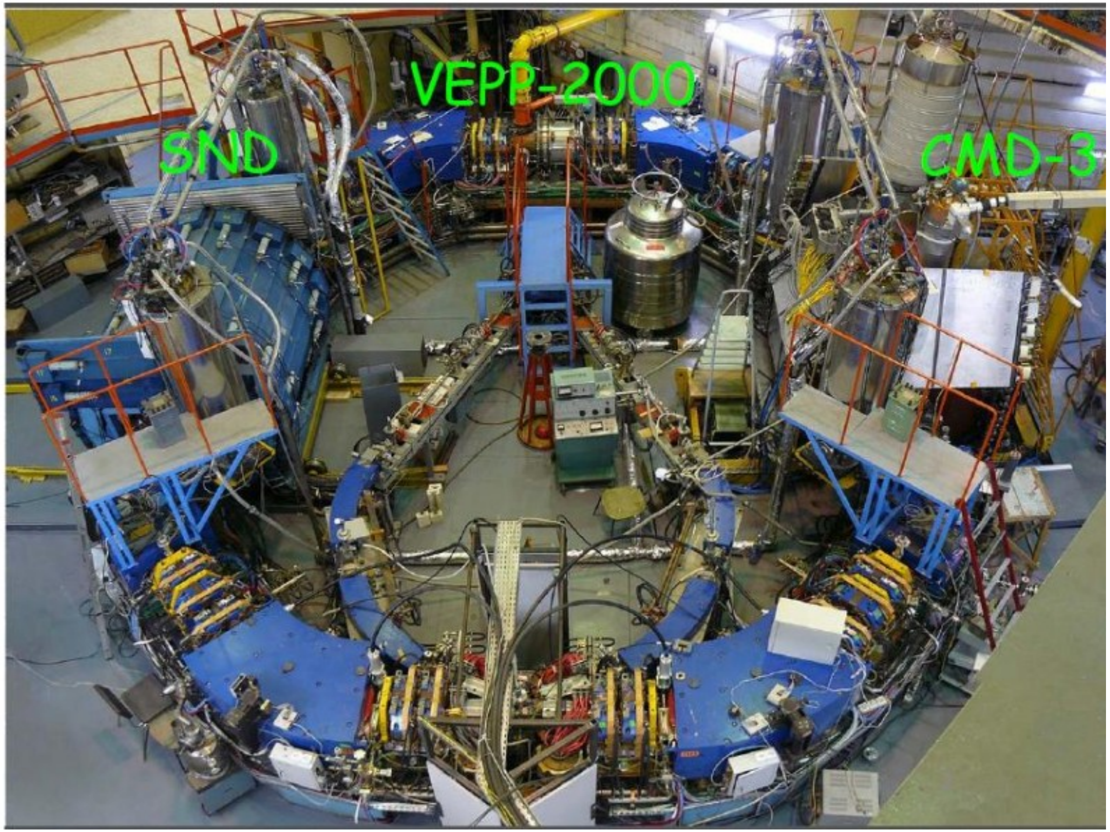
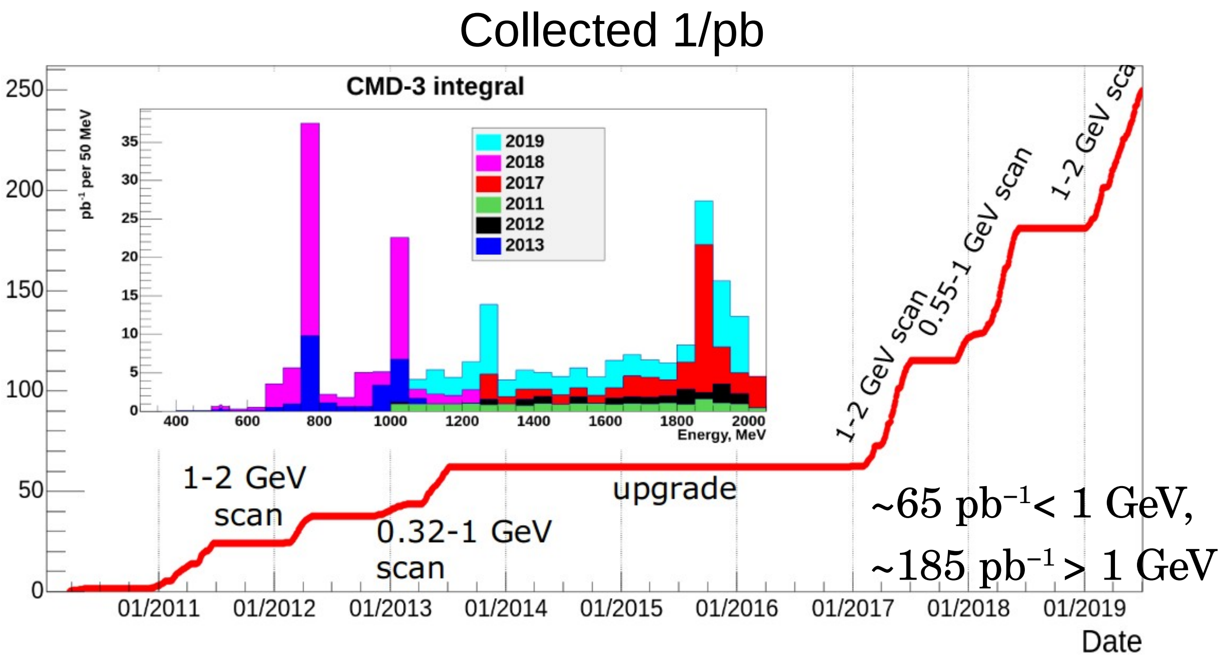
VEPP-2000

- VEPP-2000 (Novosibirsk, Russia) scans the $\sqrt{s}$ in the range from 0.32 to 2.01 GeV
- Beam energy is monitored by the Compton backscattering laser light system with ~50 keV precision
- Uses "round beams" technique (focusing solenoids)
- Maximum luminosity achieved - $4 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- CMD-3 and SND detectors placed at two beam interaction points





CMD-3 detector & physics program



° Precise measurement of $\boldsymbol{R=\sigma(e+e-\to hadrons)/\sigma(e+e-\to\mu+\mu-)}$ to achieve <1% systematic for major channels

° Study of the exclusive hadronic channels of $e+e-$ annihilation, test of the isotopic relations

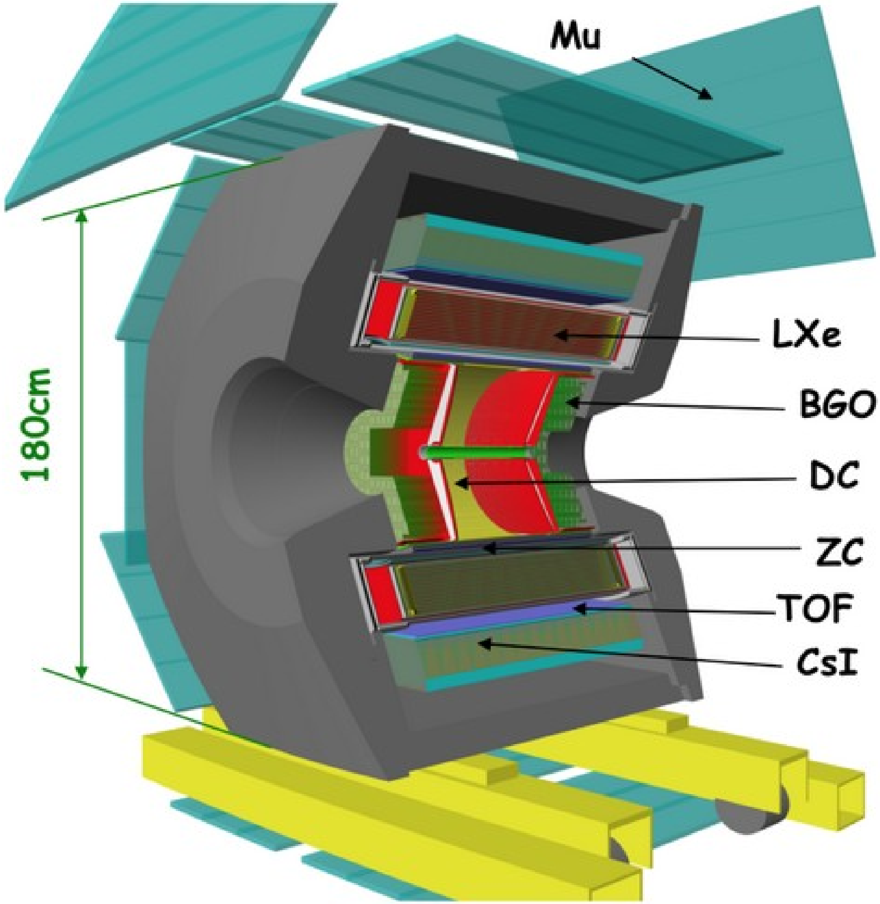
° Study of the "excited" vector mesons: ϱ', ϱ'', ω', ϕ'…

° Study of GE/GM for nucleons and behavior of hadronic cross sections near nucleon-antinucleon threshold

° CVC tests: comparison of isovector part of $\sigma(e+e-\to hadrons)$ with $\tau-$decays spectra

° Two-photon physics (e.g. η' production)

Detector CMD-3



Tracking:

- Drift Chamber in 1.3 T magnetic field

  $\sigma_{R\phi} \sim 100\ \mu m$, $\sigma_Z \sim 2.5mm$

  $\sigma_p/P \sim \sqrt{0.6^2+(4.4*p[GeV])^2}$,%

Calorimetry:

- Combined EM calorimeter (LXe,CsI, BGO) 13.4 X_0 in barrel part

  $\sigma_E /E \sim 0.034/ \sqrt{E\ [GeV]} \oplus 0.020$ - barrel

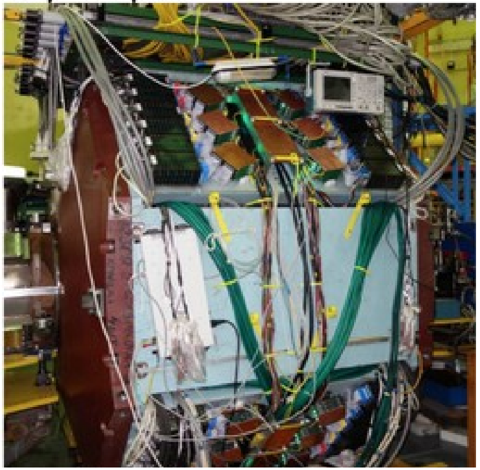
  $\sigma_E /E \sim 0.024/ \sqrt{E\ [GeV]} \oplus 0.023$ - endcap
- LXe calorimeter with 7 ionization layers with strip readout

  ~2mm measurement of conversion point,
  tracking capability,
  shower profile (from 7 layers + CsI)

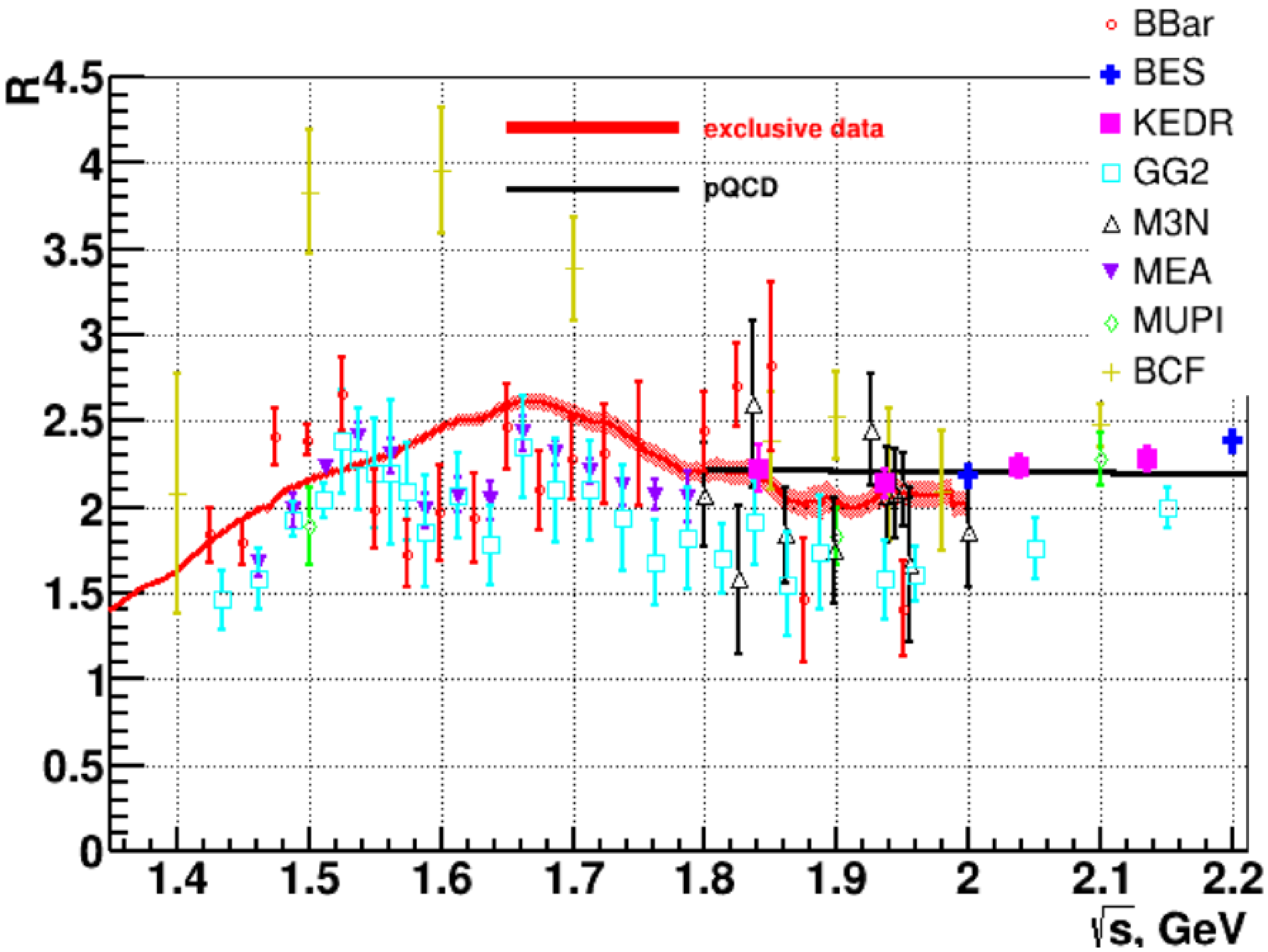
PID:

- TOF system (σ_T < 1nsec)

  particle id mainly for p, n
- Muon system



CMD-3 Motivation



- Indication:
  The sum of exclusive measurements disagree with pQCD as well as with inclusive data
- More presice data is needed
- There is still unmeasured exclusive processes

Exclusive channels of $e^+e^- \to hadons$

Event signature	Final state (published/submitted, in progress)
2 charged	$\pi^+\pi^-$ K^+K^- K_SK_L pp $\pi^+\pi^-\gamma$
2 charged +γ's	$\pi^+\pi^-\pi^0$ $\pi^+\pi^-2\pi^0$ $\pi^+\pi^-3\pi^0$ $\pi^+\pi^-4\pi^0$ $\pi^+\pi^-\eta$ $\pi^+\pi^-\pi^0\eta$ $\pi^+\pi^-2\pi^0\eta$ $K^+K^-\pi^0$ $K^+K^-2\pi^0$ $K^+K^-\eta$ $K_SK_L\pi^0$ $K_SK_L\eta$ $\eta'(958)$
4 charged	$2\pi^+2\pi^-$ $K^+K^-\pi^+\pi^-$ $K_SK^\pm\pi^\mp$
4 charged +γ's	$2\pi^+2\pi^-\pi^0$ $2\pi^+2\pi^-2\pi^0$ $\pi^+\pi^-\eta$ $\pi^+\pi^-\omega$ $2\pi^+2\pi^-\eta$ $K^+K^-\omega$ $K_SK^\pm\pi^\mp\pi^0$ $D^{*0}(2007)$
6 charged	$3\pi^+3\pi^-$ $K_SK_S\pi^+\pi^-$
6 charged +γ's	$3\pi^+3\pi^-\pi^0$
Fully neutral	$\pi^0\gamma$ $2\pi^0\gamma$ $3\pi^0\gamma$ $\eta\gamma$ $\pi^0\eta\gamma$ $2\pi^0\eta\gamma$
Other	nn $\pi^0e^+e^-$ ηe^+e^-

Published/submitted results:

$3\pi^+3\pi^-$: PLB 723 (2013) 82-89

η': PLB 740 (2015) 273-277

ppbar: PLB 759 (2016) 634-640

$K^+K^-\pi^+\pi^-$: PLB 756 (2016)

K^+K^-(at $\phi(1020)$): PLB 760 (2016) 314-319

$2\pi^+2\pi^-$ (near $\phi(1020)$):PLB 768 (2017) 345-350

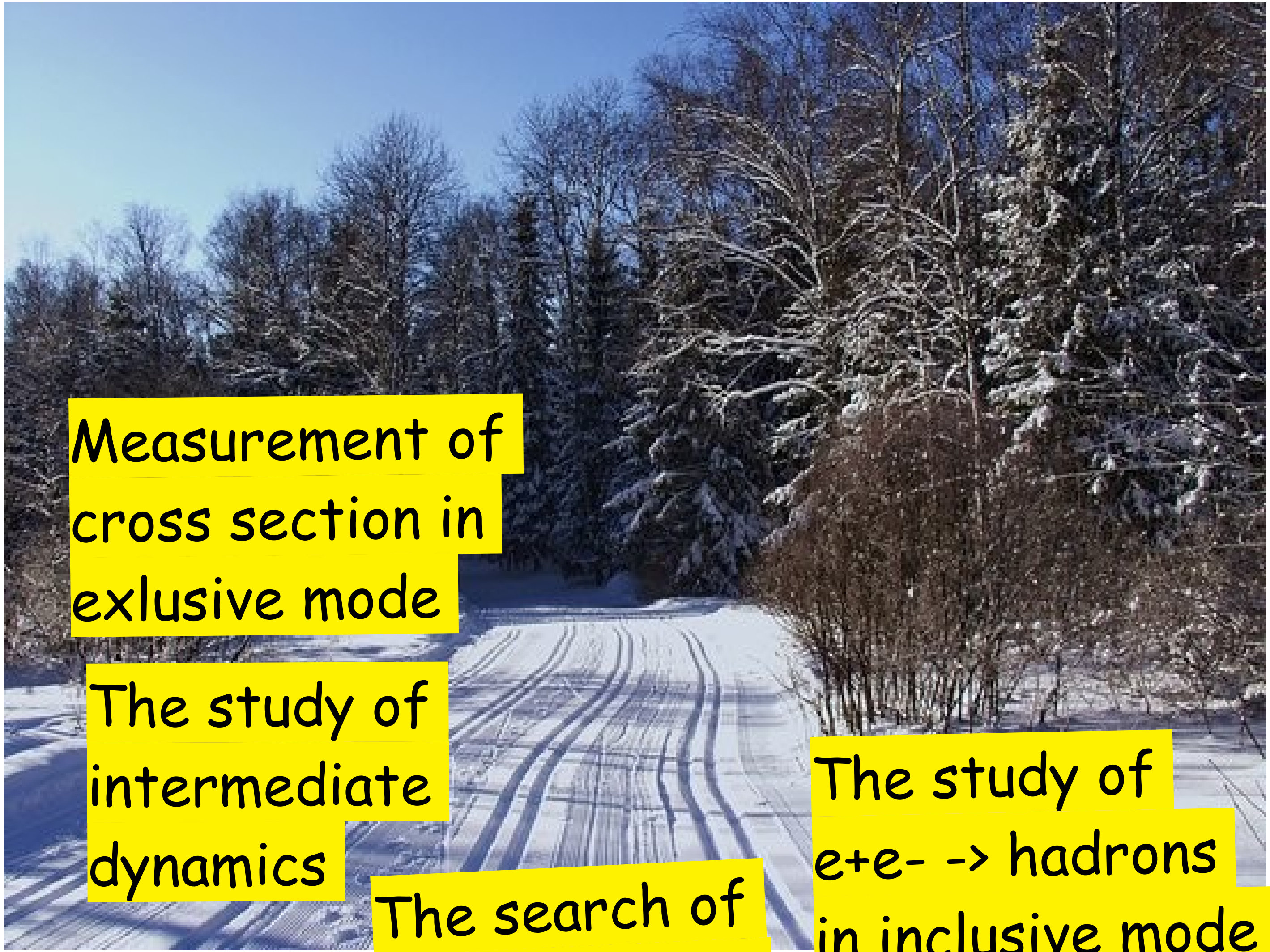
$\omega\eta$, $\eta\pi^+\pi^-\pi^0$: PLB 773 (2017)

$KSKL$ (at $\phi(1020)$): PLB 779 (2018) 64-71

$3\pi^+3\pi^-\pi^0$: PLB 792 (2019)

$K^+K^-\eta$: PLB 798, (2019)134946

Observation of a fine structure …: PLB-D-19-00534R1

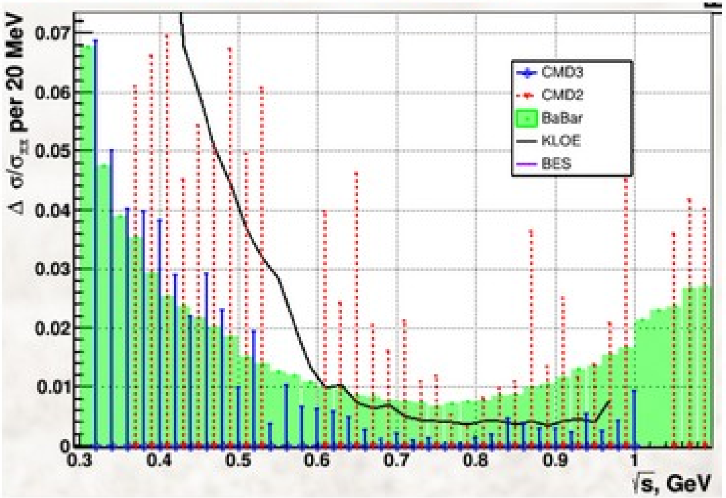

Measurement of cross section in exlusive mode
The study of intermediate dynamics
The search of rare processes
The study of e+e- -> hadrons in inclusive mode

The search of rare processes, like, $e^+e^- \to \eta'(950)$, $f_1(1285)$, $D^{*0}(2007)$

$e^+e^- \to \pi^+\pi^-$: pion formfactor measurement

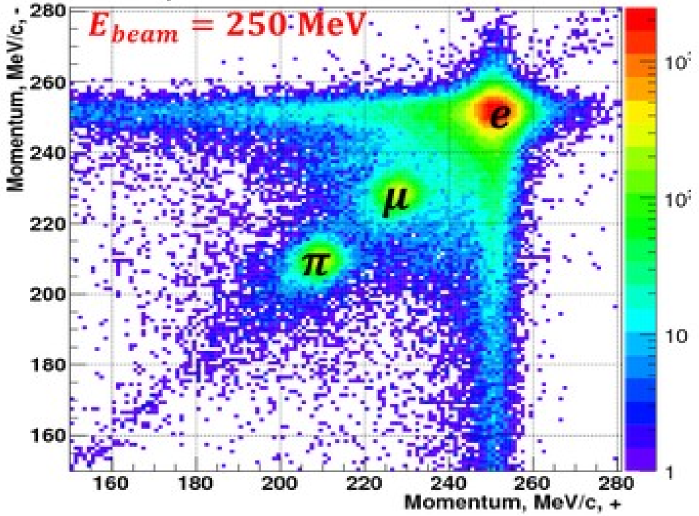
- It is a main contributor to the $a^{\mathrm{had,LO}}_{\mu}$ (~73%)
- The CMD-3's goal it to measure the $|F_\pi|^2$ with 0.4-0.5% systematics uncertainty
- CMD-3's 2013 & 2018 statistics for $\pi^+\pi^-$ a few times larger than in other experiments
- To control systematics, two independent approaches for determination of the number of $\pi^+\pi^-$ events are used:

momentum-based and energy deposition-based

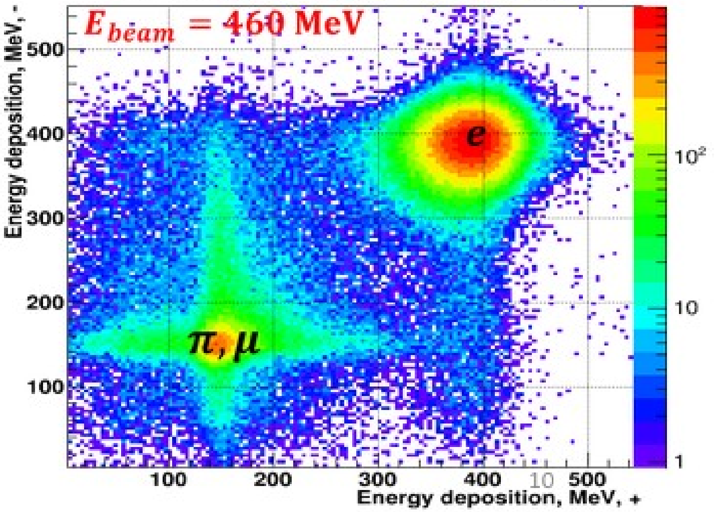


- Momentum-based approach works better at low c.m. energies (<0.8 GeV), energy-based – at large energies (>0.6 GeV). Using both methods in the middle allows to control systematics
- In both cases 2D-likelihood function is constructed, its minimization gives $N_{\pi\pi}/N_{ee}$

1) momentum-based

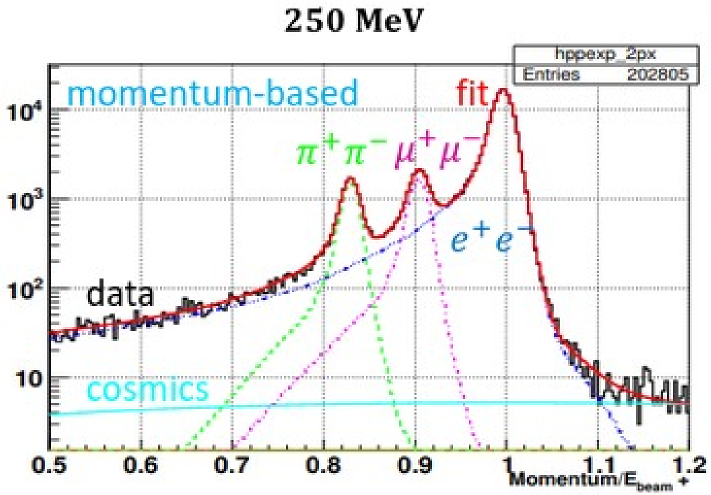


2) energy deposition-based



$e^+e^- \to \pi^+\pi^-$: pion formfactor measurement

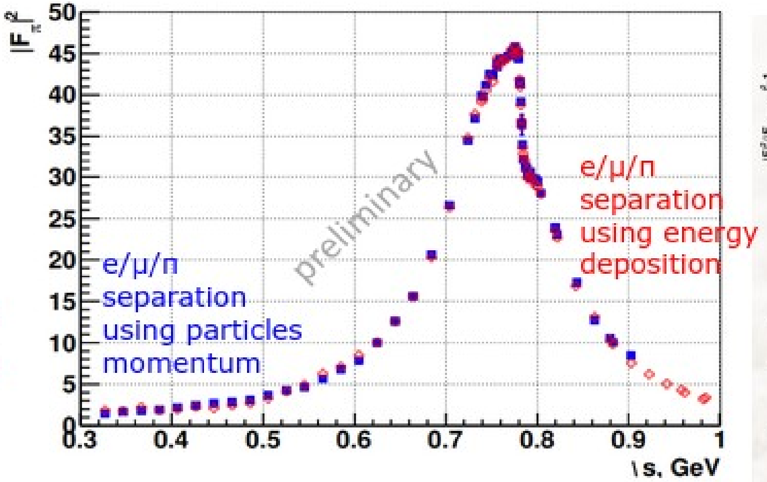
- The projection of the fitting functions after minimization:



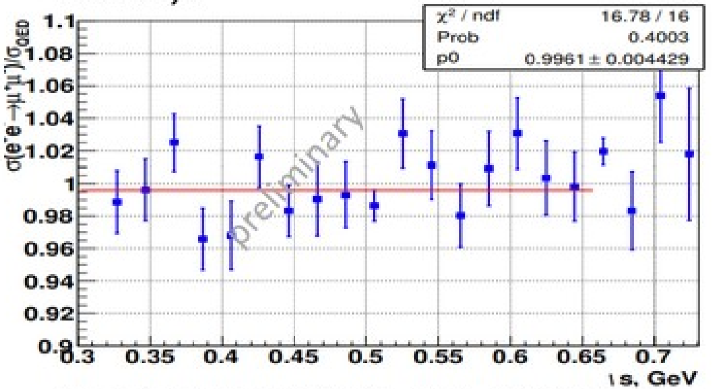
The list of sources of systematics:

- Radiative corrections
- $e/\mu/\pi$ separation
- Uncertainty of fiducial volume
- Beam energy
- Electron bremsstrahlung loss
- Pion specific corrections

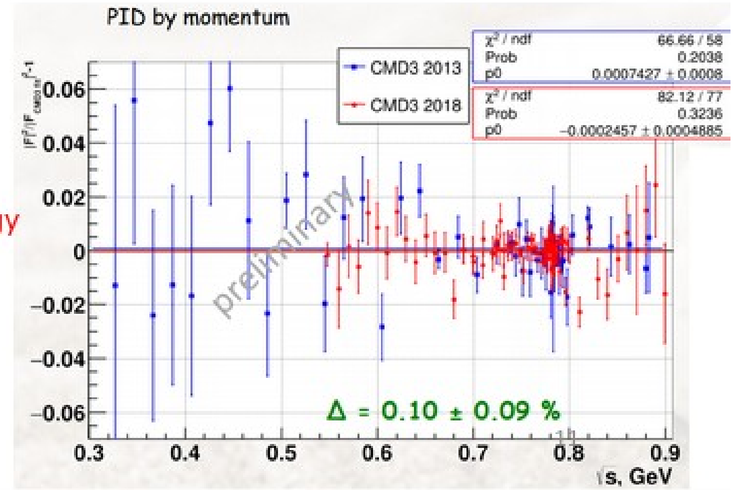
- Currently the systematics is estimated to be 0.6-0.9% (momentum-based)



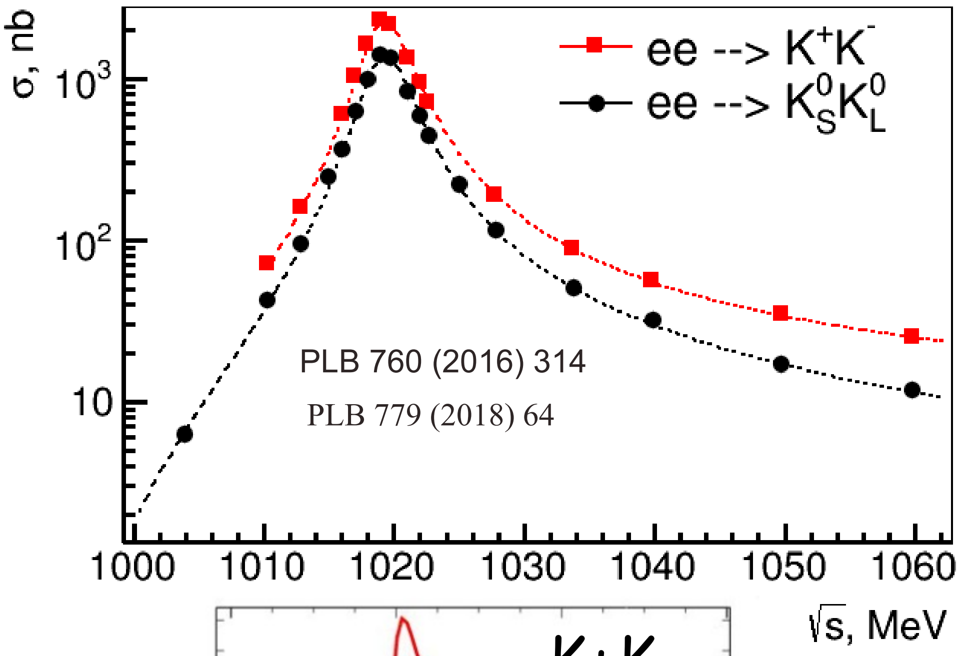
- Additional test – $\sigma(e^+e^- \to \mu^+\mu^-)$ measurement (compatible with QED at ~0.25%):

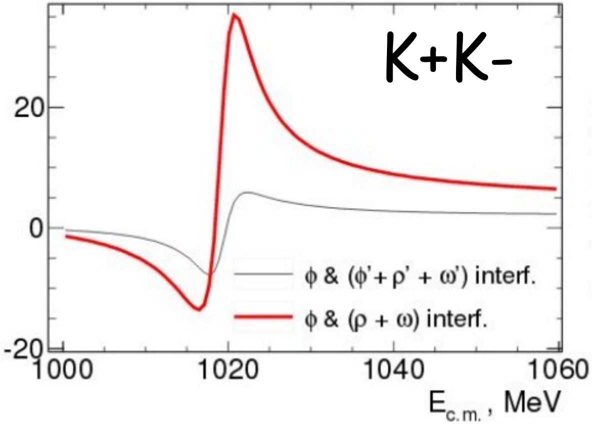


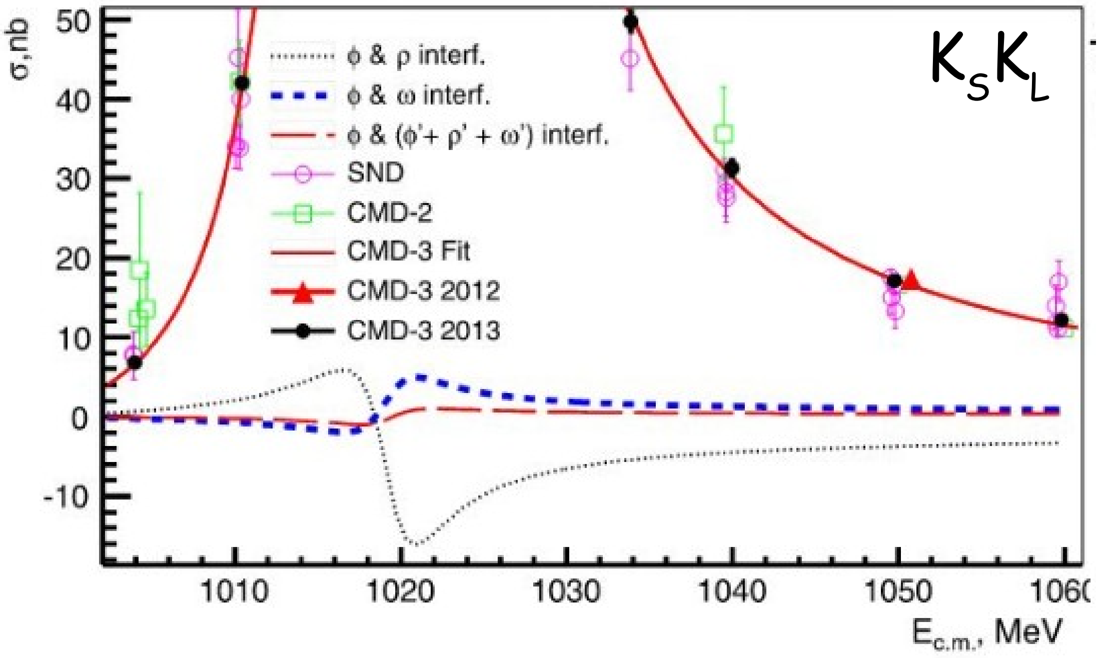
- The results of 2013 and 2018 are consistent within ~0.1%:



$e^+e^- \to$ K antiK







$$m_\phi = 1019.464 \pm 0.061 \text{ MeV}/c^2$$

$$\Gamma_\phi = 4.250 \pm 0.015 \text{ MeV}$$

$$\Gamma_{\phi\to ee} B_{\phi\to K^+K^-} = 0.671 \pm 0.020 \text{ keV}$$

$$\Gamma_{\phi\to ee} B_{\phi\to K_S^0 K_L^0} = 0.428 \pm 0.009 \text{ keV}$$

$$R_{c/n} = \sigma_{e^+e^- \to K^+K^-} \times \frac{p^3_{K^0}(s)}{p^3_{K^\pm}(s)} \times \frac{1}{Z(s)} - \delta_{K^0_S K^0_L} \times \sigma_{e^+e^- \to K^0_S K^0_L}$$

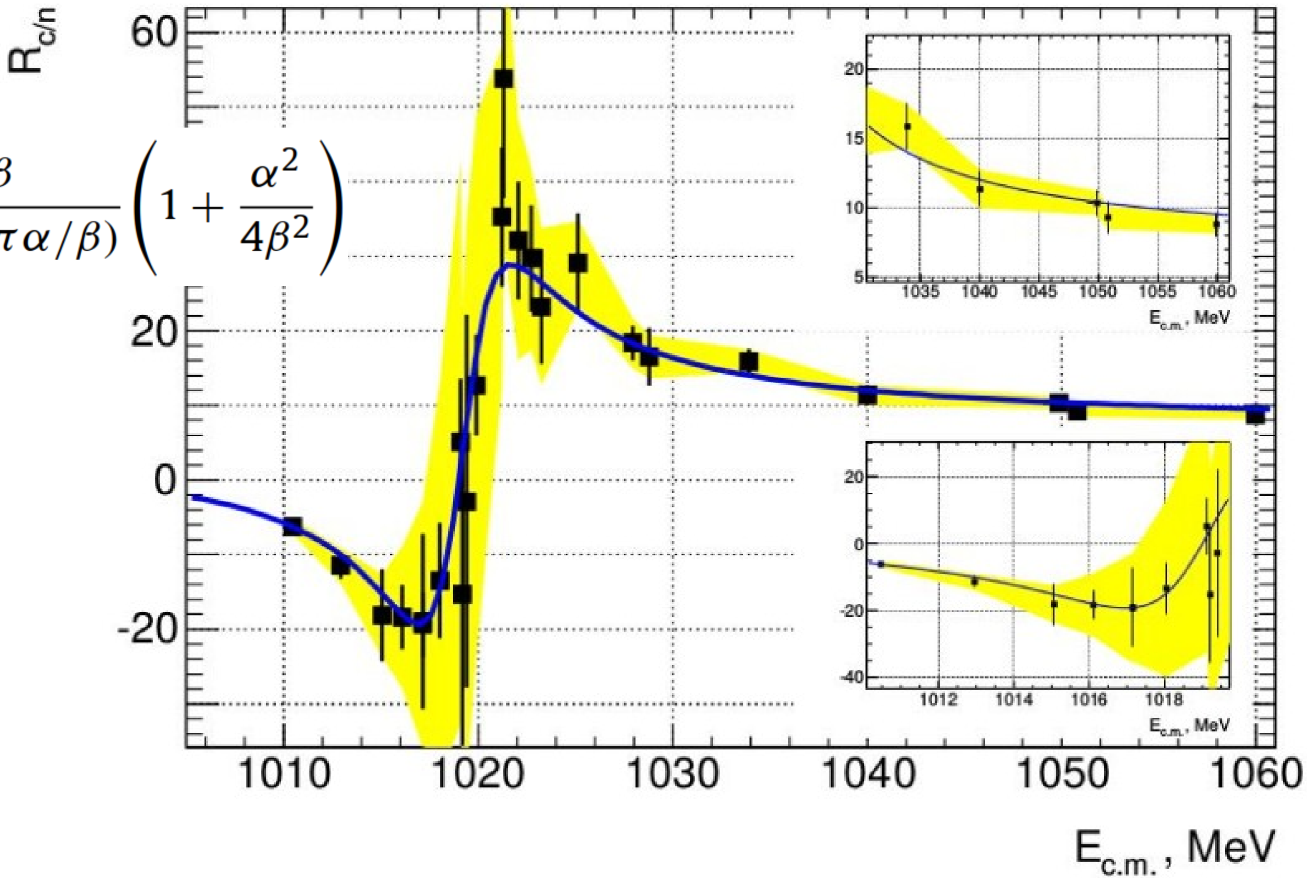
$$r_{\rho/\omega} = 0.91 \pm 0.04$$

$$\delta_{K^0_S K^0_L} = 0.989 \pm 0.003$$

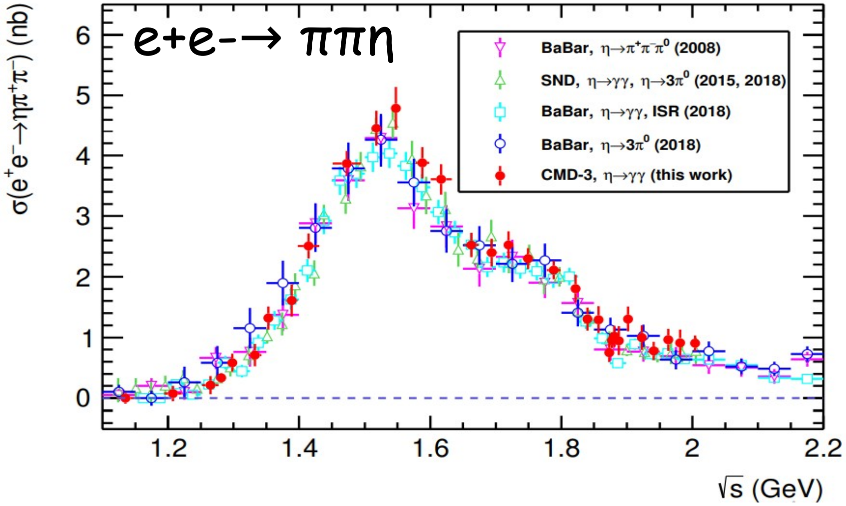
$$\chi^2/ndf = 10/22$$

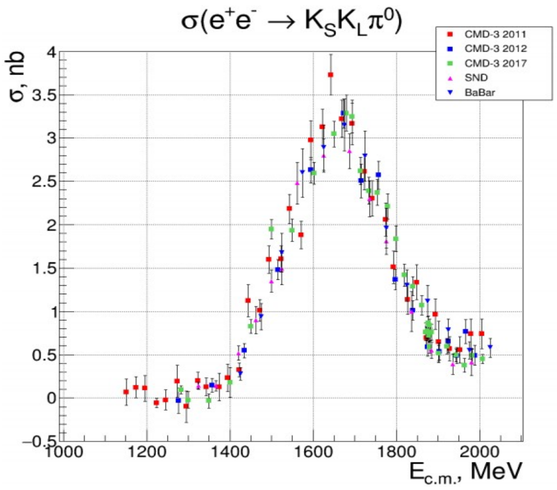
Two floating parameters

$$Z(s) = \frac{\pi\alpha/\beta}{1 - exp(-\pi\alpha/\beta)}\left(1 + \frac{\alpha^2}{4\beta^2}\right)$$

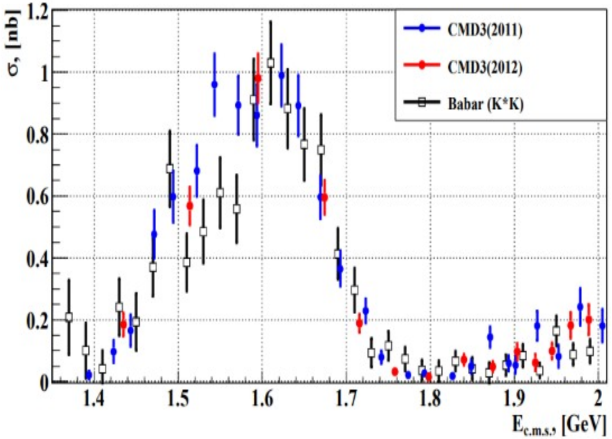


Other processes

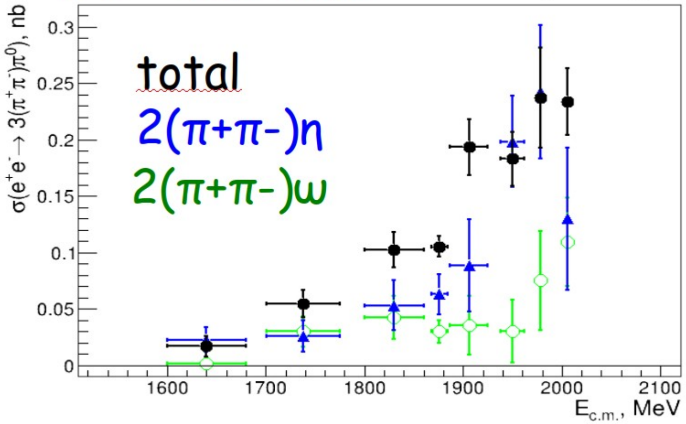




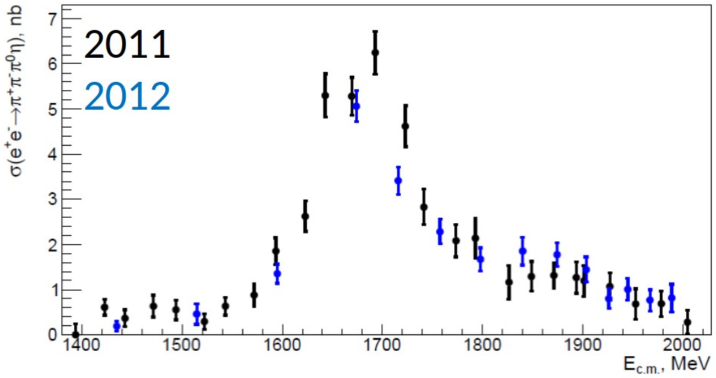
- Study of $e^+e^- \to K^+K^-\pi^0$:

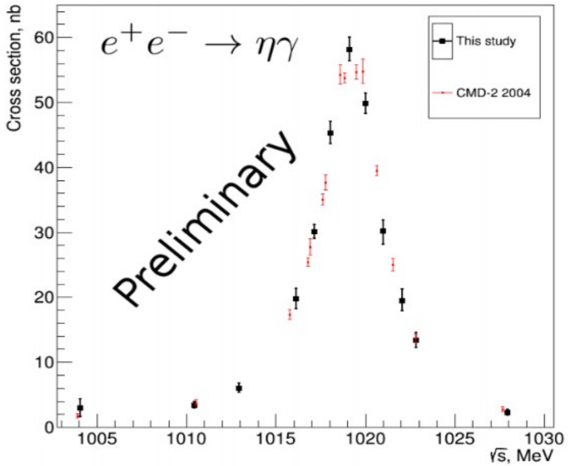


- $e^+e^- \to 3(\pi^+\pi^-)\pi^0$: PLB 792 (2019), 419-423



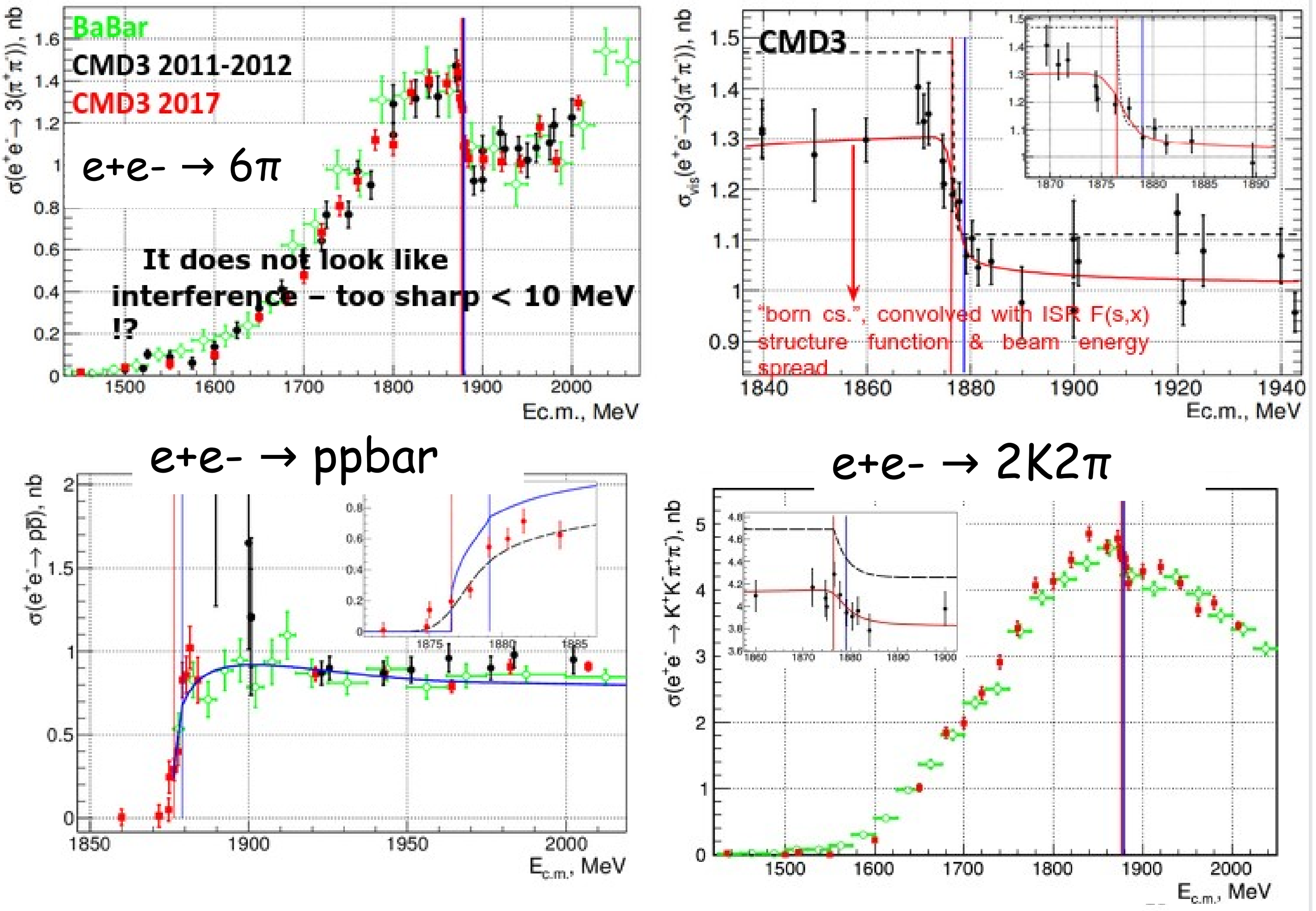
- $e^+e^- \to \pi^+\pi^-\pi^0\eta$: PLB 773 (2017) 150-158





Multihadron production @ $N\bar{N}$ threshold

- In 2017 we did the detailed scan of $N\bar{N}$ threshold region with the step 0.8 MeV (~beam energy spread)
- Several dip structures with ~ 1 MeV width are seen in multihadron production! (see details in PLB 794 (2019) 64-68)
- Effect can be described via optical nucleon-antinucleon potentials ("Milstein-Salnikov" parametrization, see Nuc. Phys. A 977 (2018) 60-68)



Results of the fit to the exponentially rising function. Only statistical uncertainties are shown.

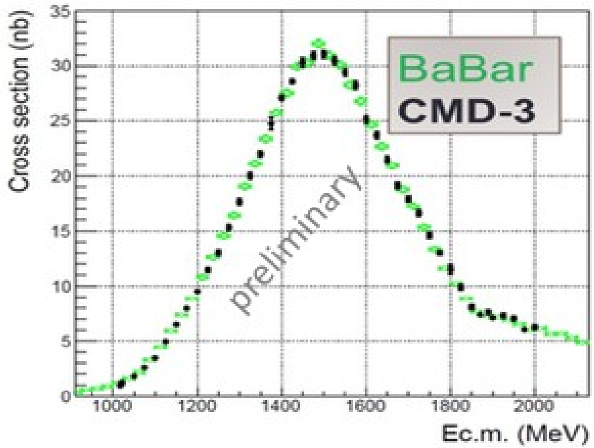
Reac.	A, nb	B, nb	E_{thr}, MeV	σ_{thr}, MeV	χ^2/ndf
$p\bar{p}$	0 – fxd	0.91±0.02	1877.1±0.2	0.18±0.27	29/26
$p\bar{p}$	0 – fxd	0.91±0.02	1876.54-fxd	0.76±0.28	31/27
6π	1.55±0.02	–0.42±0.03	1875.8±0.2	0.18±0.67	17/20
6π	1.54±0.02	–0.41±0.03	1876.54–fxd	0.0±2.5	18/21
2K2π	4.69±0.08	–0.44±0.12	1878.8±0.2	0.35±2.69	7/10
2K2π	4.70±0.08	–0.45±0.12	1876.54–fxd	2.36±2.01	8/11

$$\sigma_{\mathrm{Born}}(\mathrm{E}_{\mathrm{c.m.}}) = \mathrm{A} + \mathrm{B}\left[1 - \exp\left(-\frac{(\mathrm{E}_{\mathrm{c.m.}} - \mathrm{E}_{\mathrm{thr}})}{\sigma_{\mathrm{thr}}}\right)\right]$$

Multihadron production @ $N\bar{N}$ threshold

- Hovewer, some questions still remain: why no "dip" structure in $e^+e^- \to 2\pi^+2\pi^-$, $\pi^+\pi^-4\pi^0$?

$e^+e^- \to 2(\pi^+\pi^-)$



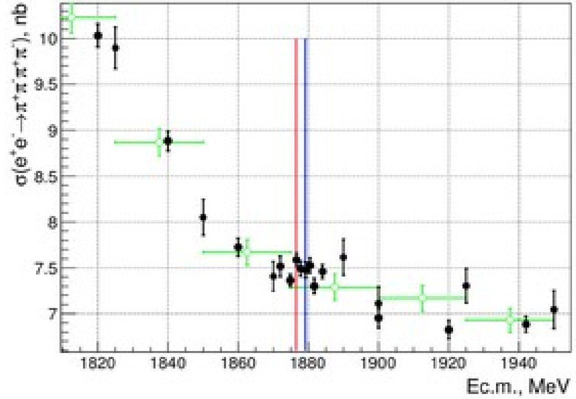
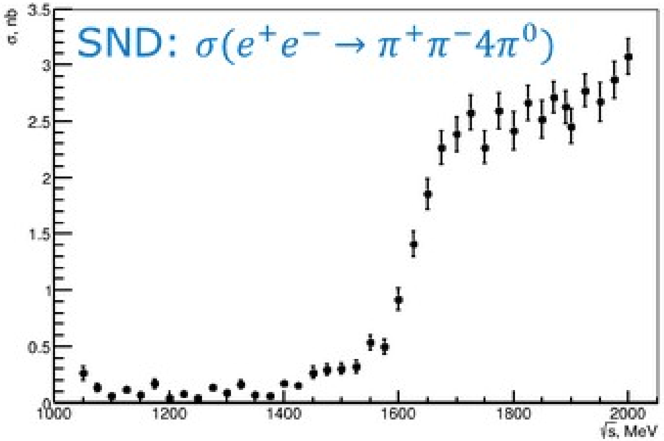
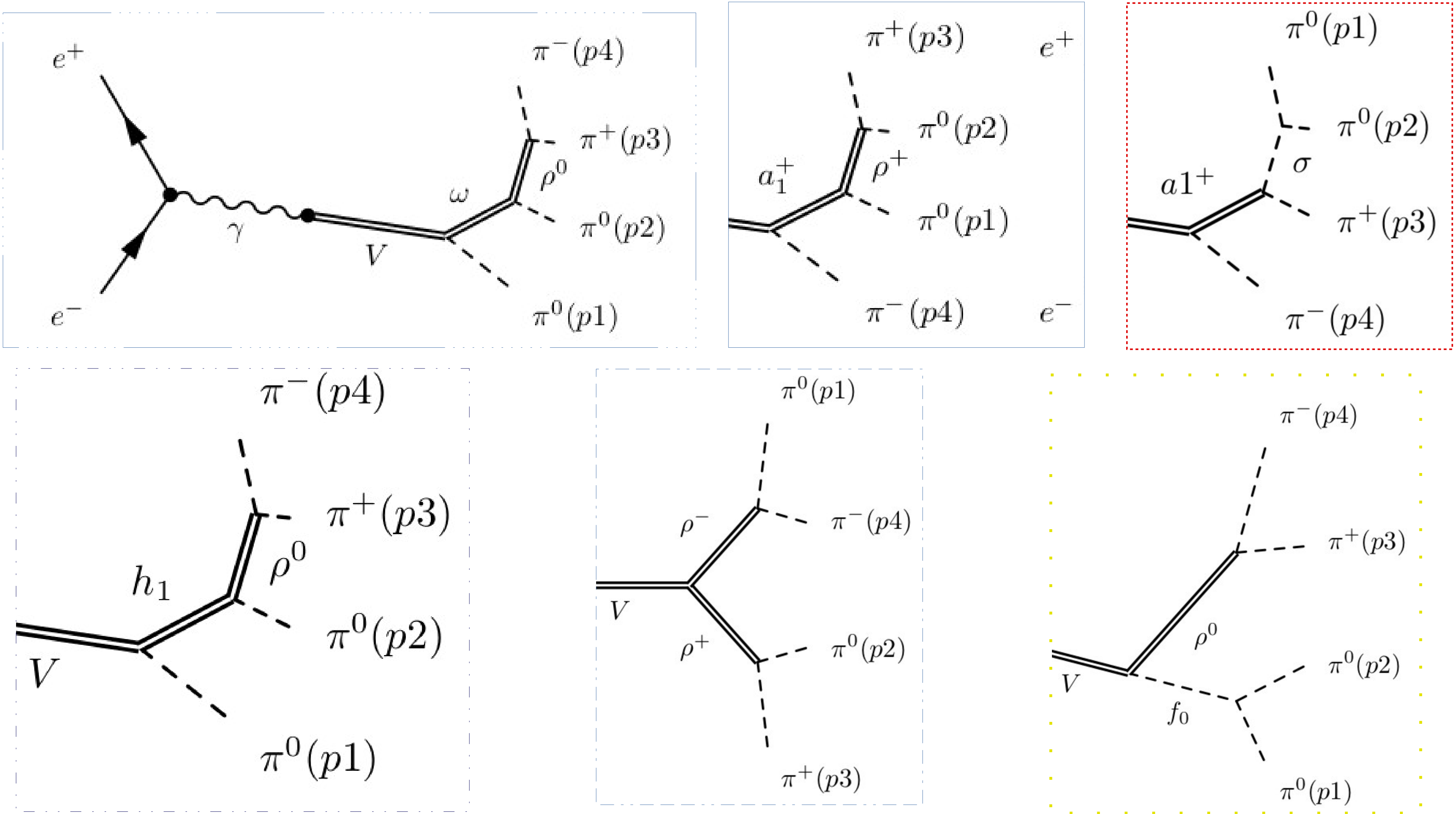


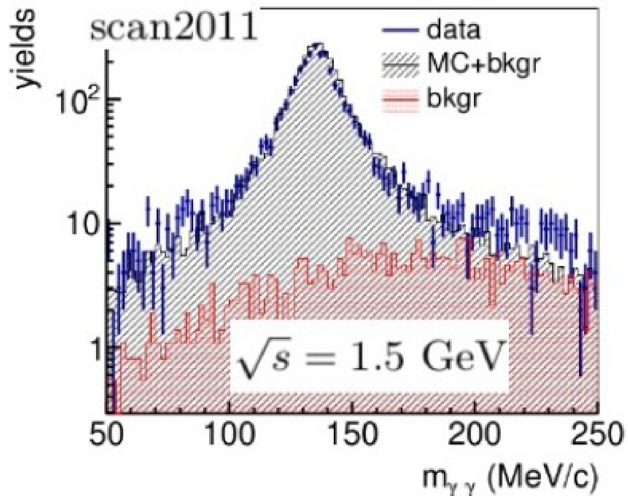
Figure 4: The $e^+e^- \to 2(\pi^+\pi^-)$ cross section measured with the CMD-3 detector. Lines show the $p\bar{p}$ and $n\bar{n}$ thresholds.

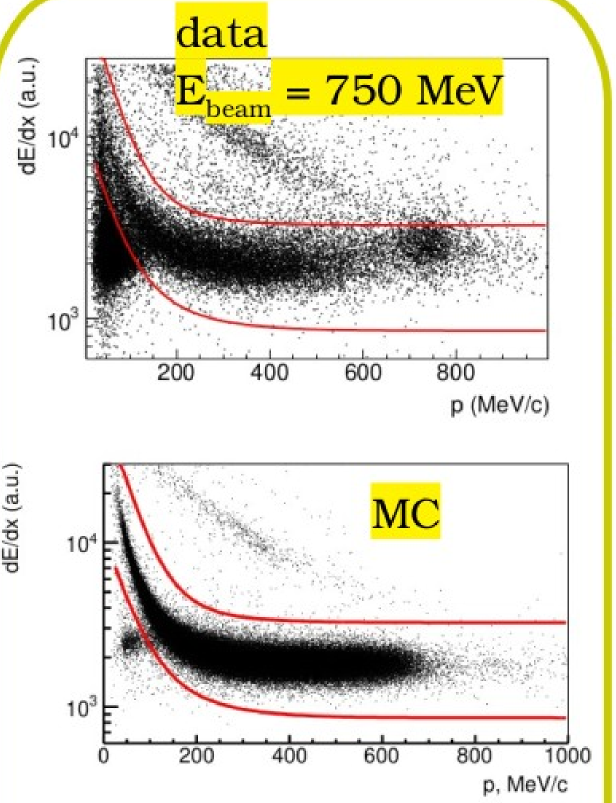



e^+
e^-
γ
V
ω
ρ^0
$\pi^-(p4)$
$\pi^+(p3)$
$\pi^0(p2)$
$\pi^0(p1)$
$\pi^+(p3)$
e^+
a_1^+
ρ^+
$\pi^0(p2)$
$\pi^0(p1)$
$\pi^-(p4)$
e^-
$\pi^0(p1)$
$\pi^0(p2)$
σ
$a1^+$
$\pi^+(p3)$
$\pi^-(p4)$
$\pi^-(p4)$
$\pi^+(p3)$
h_1
ρ^0
$\pi^0(p2)$
V
$\pi^0(p1)$
$\pi^0(p1)$
ρ^-
$\pi^-(p4)$
V
ρ^+
$\pi^0(p2)$
$\pi^+(p3)$
$\pi^-(p4)$
$\pi^+(p3)$
ρ^0
$\pi^0(p2)$
V
f_0
$\pi^0(p1)$

Event selection ($ee \to \pi^+\pi^- 2\pi^0$) 43 kevents

- $0.75 < \theta_{\pi,\gamma} < \pi - 0.75$ rad
- Total $E-\sqrt{s}|$ and $P < 150$ MeV/(c)
- Two candidates for π^0
- 6C kinematic fit
- The invariant mass spectrum of 3rd and 4th photons is used for the estimation of the contribution of background:

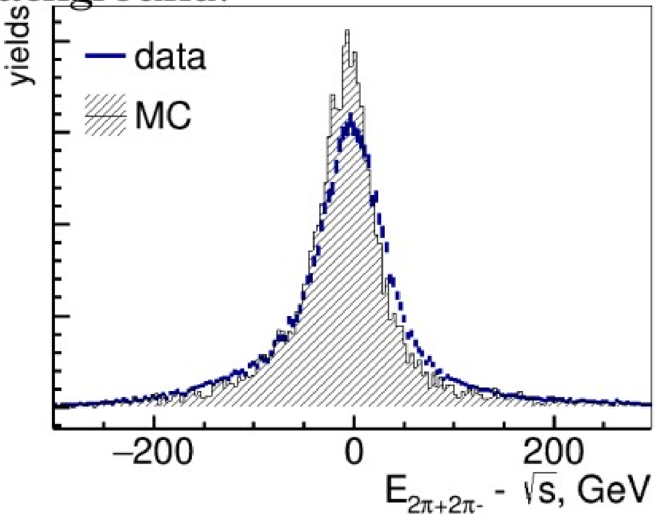




dE/dx vs momentum

Event selection ($ee \to 2\pi^+ 2\pi^-$) 83 kevents

- $0.75 < \theta_{\pi} < \pi - 0.75$ rad
- |Total E|-$\sqrt{s}$) and $P < 150$ MeV/(c)
- 4C kinematic fit
- The spectrum of total energy of four tracks ($E-\sqrt{s}$) is used for the estimation of the contribution of background:



Amplitude analysis

The production of 4π system can proceed via a list of intermediate states:

- $\omega[1^{--}]\pi^0[0^{-+}]$ (only $2\pi^0 2\pi^\pm$)
- $a1(1260)[1^+]\pi[0^-]$
- $\rho[1^{--}]f_0/\sigma[0^{++}]$
- $\rho f_2(1270)[2^{++}]$
- $\rho^+\rho^-$ (only $2\pi^0 2\pi^\pm$)
- $a_2(1320)[2^{++}]\pi$
- $h_1(1170)[1^{+-}]\pi^0$ (only $2\pi^0 2\pi^\pm$)
- $\pi'(1300)(0^{-+})\pi$

The likelihood for model under test is

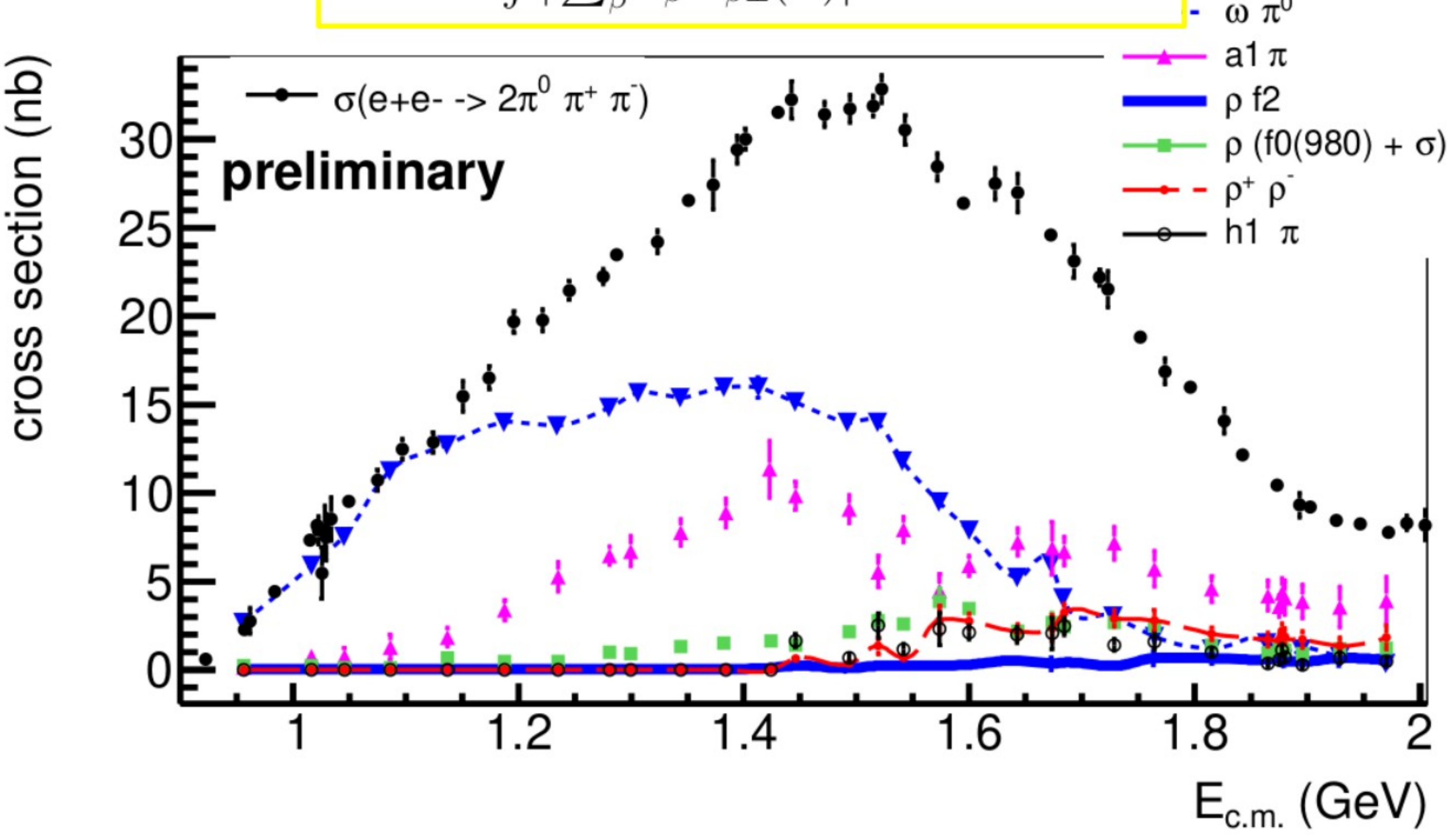
$$L = -\ln\prod_{\mathrm{i}} \frac{|\sum_\alpha \mathbf{V}_\alpha \mathrm{A}^0_\alpha(\Omega_\mathrm{i})|^2}{\frac{1}{\mathrm{N}^{\mathrm{gen}}_{\mathrm{MC}}}\sum_\mathrm{k}|\sum_\alpha \mathbf{V}_\alpha \mathrm{A}^0_\alpha(\Omega_\mathrm{k})|^2} - \ln\prod_{\mathrm{j}} \frac{|\sum_\alpha \mathbf{V}_\alpha \mathrm{A}^\pm_\alpha(\Omega_\mathrm{j})|^2}{\frac{1}{\mathrm{N}^{\mathrm{gen}}_{\mathrm{MC}}}\sum_\mathrm{k}|\sum_\alpha \mathbf{V}_\alpha \mathrm{A}^\pm_\alpha(\Omega_\mathrm{k})|^2},$$

The relative number of events I at a particular point Ω in phase space can be represented as

$$I(\Omega) = |V_\alpha A_\alpha(\Omega)|^2$$

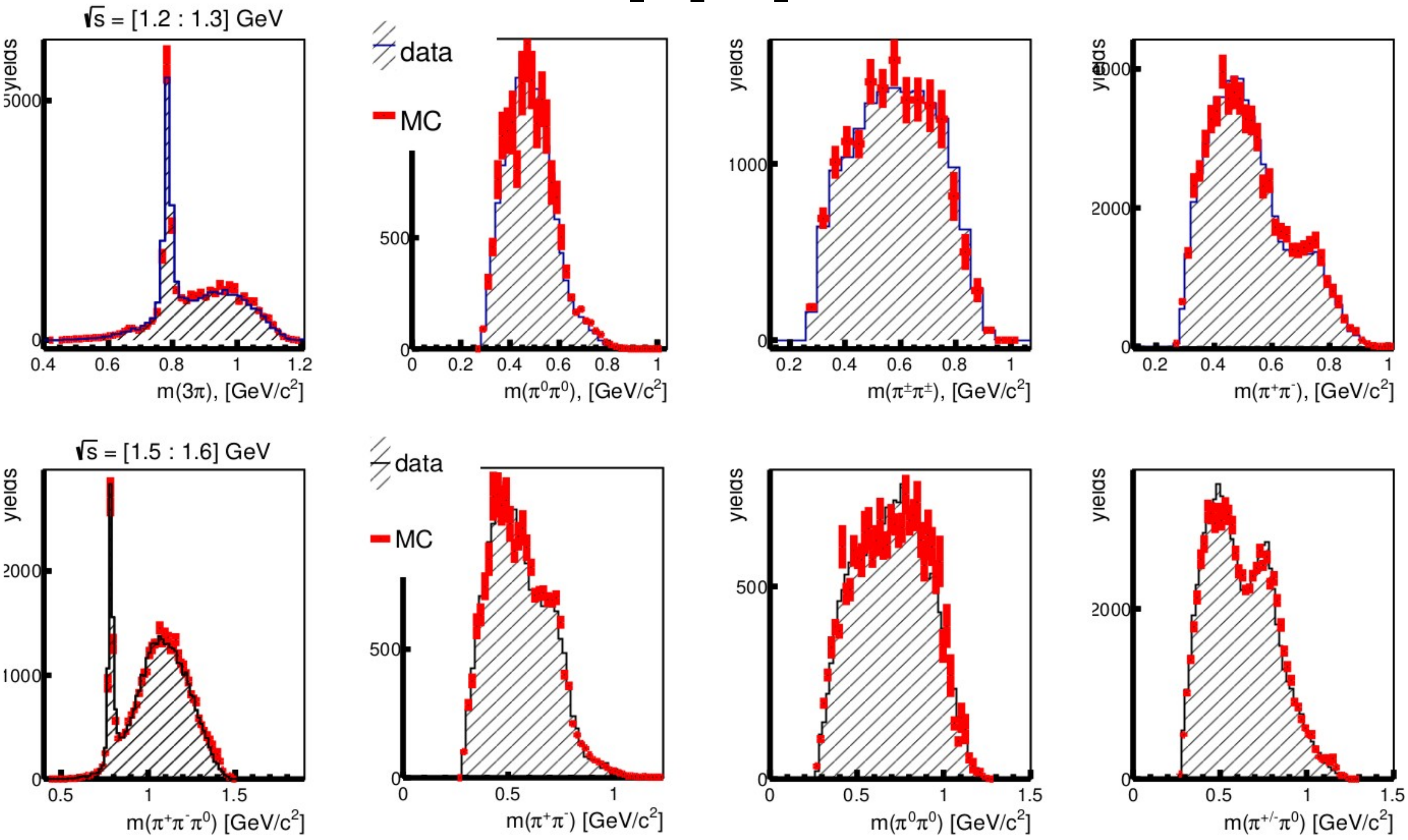
where the sum runs over all intermediate states, V_α - the complex production amplitude (the free parameter) and $A_\alpha(\Omega)$ - the amplitude at a particular point in phase space.

$$R_i(s) = \frac{\int |V_i \cdot \mathbf{H}_{i\perp}(\Omega)|^2 d\Phi}{\int |\sum_\beta V_\beta \mathbf{H}_{\beta\perp}(\Omega)|^2 d\Phi} \cdot \sigma_{2\pi^0\pi^+\pi^-}(s)$$



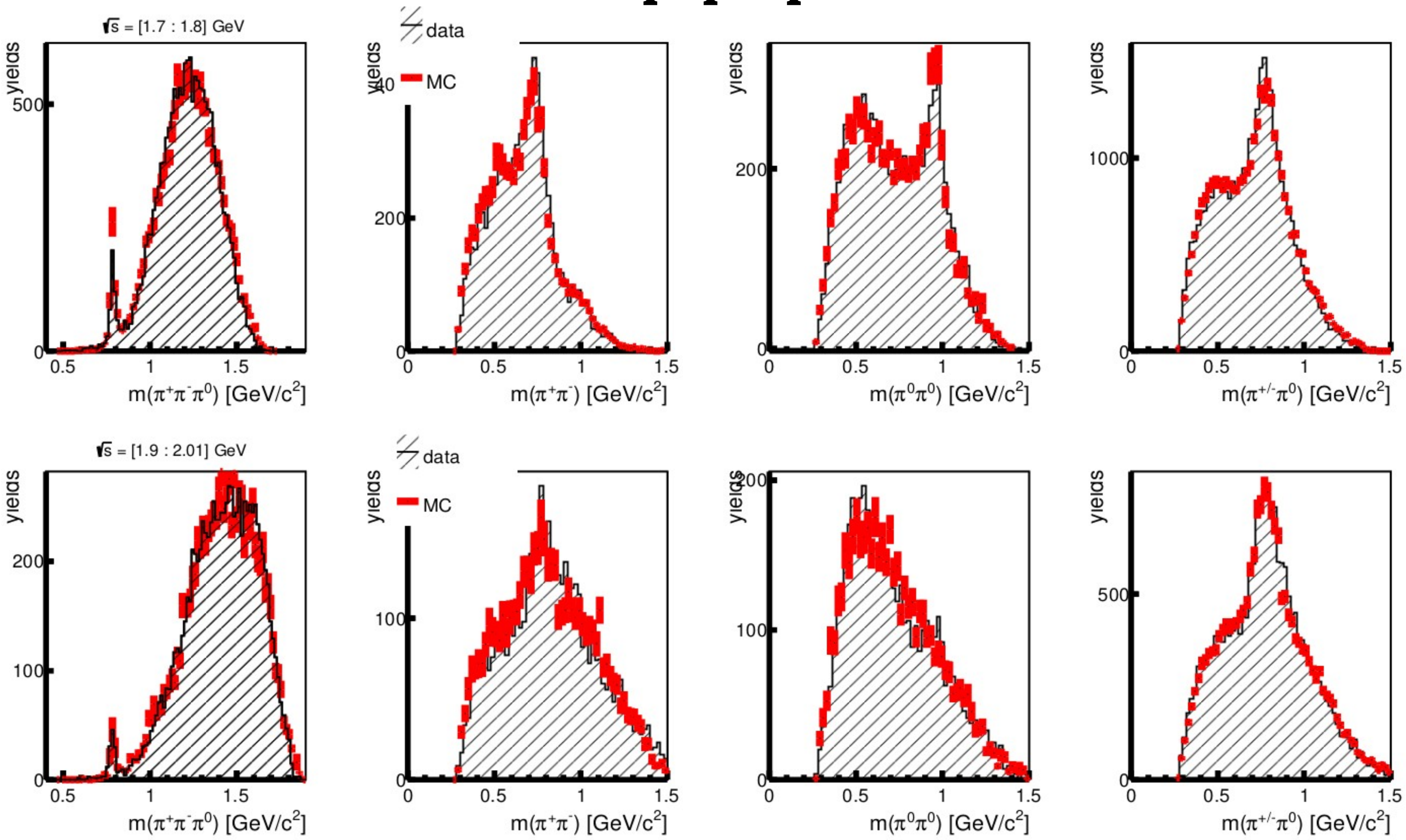
Obtained amplitudes can be used for the prediction of $W \to 4\pi$, ex., $\tau \to \omega\pi^-$, $\tau \to a_1(1260)\pi$, $\tau \to \rho^-[\sigma(500) + f_0(980)]$, $\tau \to \rho^- f_2(1270)$, $\tau \to \rho^-\rho^0$, $\tau \to h_1(1170)\pi^0$

ee → pi$^+$pi$^-$2pi^0



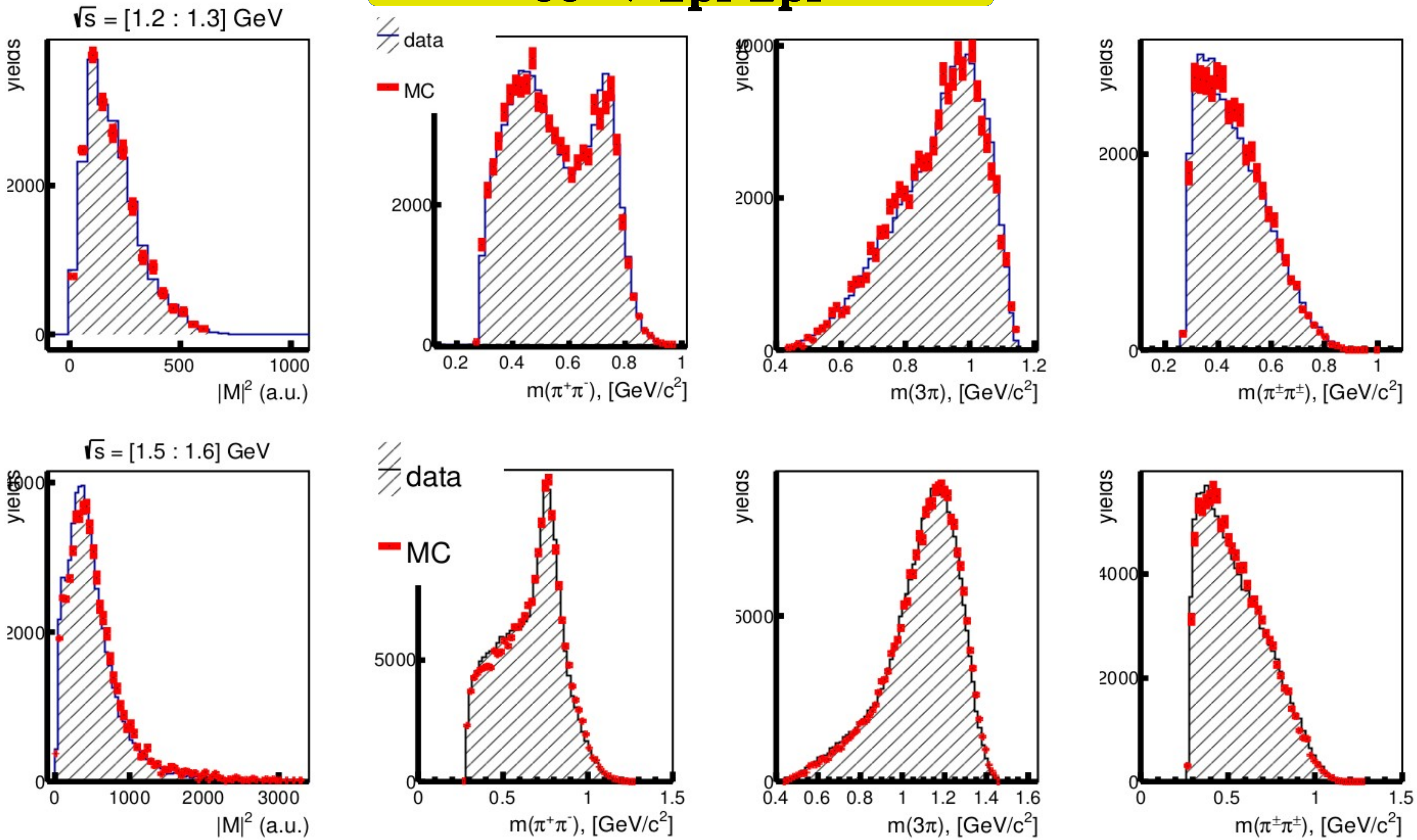
$\sqrt{s}$ = [1.2 : 1.3] GeV
yields
m(3π), [GeV/c²]
data
MC
m(π⁰π⁰), [GeV/c²]
m(π±π±), [GeV/c²]
m(π⁺π⁻), [GeV/c²]
$\sqrt{s}$ = [1.5 : 1.6] GeV
m(π⁺π⁻π⁰) [GeV/c²]
m(π⁺π⁻) [GeV/c²]
m(π⁰π⁰) [GeV/c²]
m(π⁺/⁻π⁰) [GeV/c²]

ee → pi$^+$pi$^-$2pi^0



$\sqrt{s}$ = [1.7 : 1.8] GeV
data
MC
yields
m($\pi^+\pi^-\pi^0$) [GeV/c^2]
m($\pi^+\pi^-$) [GeV/c^2]
m($\pi^0\pi^0$) [GeV/c^2]
m($\pi^{+/-}\pi^0$) [GeV/c^2]
$\sqrt{s}$ = [1.9 : 2.01] GeV

ee → 2pi⁺2pi⁻



√s = [1.2 : 1.3] GeV
yields
|M|^2 (a.u.)
data
MC
m(π⁺π⁻), [GeV/c²]
m(3π), [GeV/c²]
m(π±π±), [GeV/c²]
√s = [1.5 : 1.6] GeV

There are three different options to study dynamics (measure cross section) at BESIII

1. Using ISR events in data sets at charmonium and other resonances
2. Using data from R-scans
3. Huge BESIII data at, ex., J/ψ allows to study the dynamics of J/ψ decays into hadrons as well as continuum dynamics

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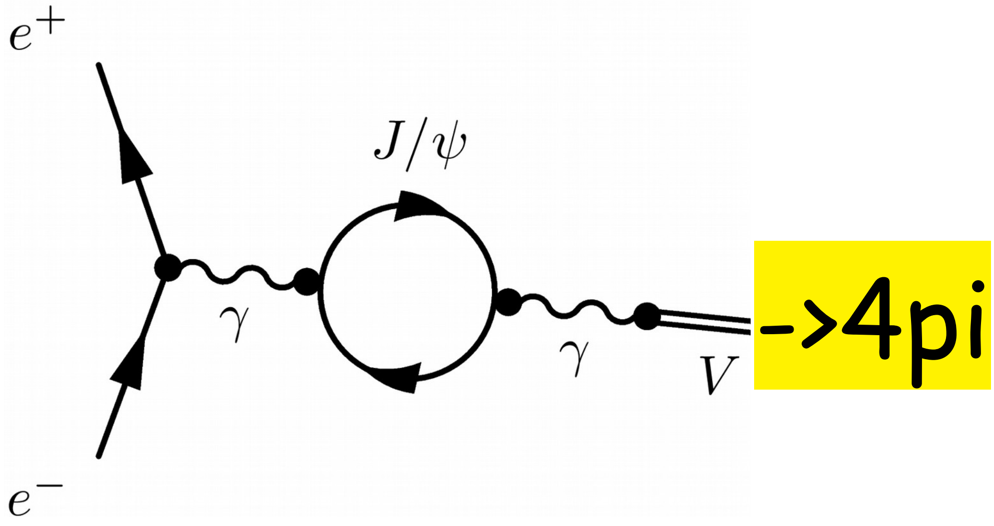
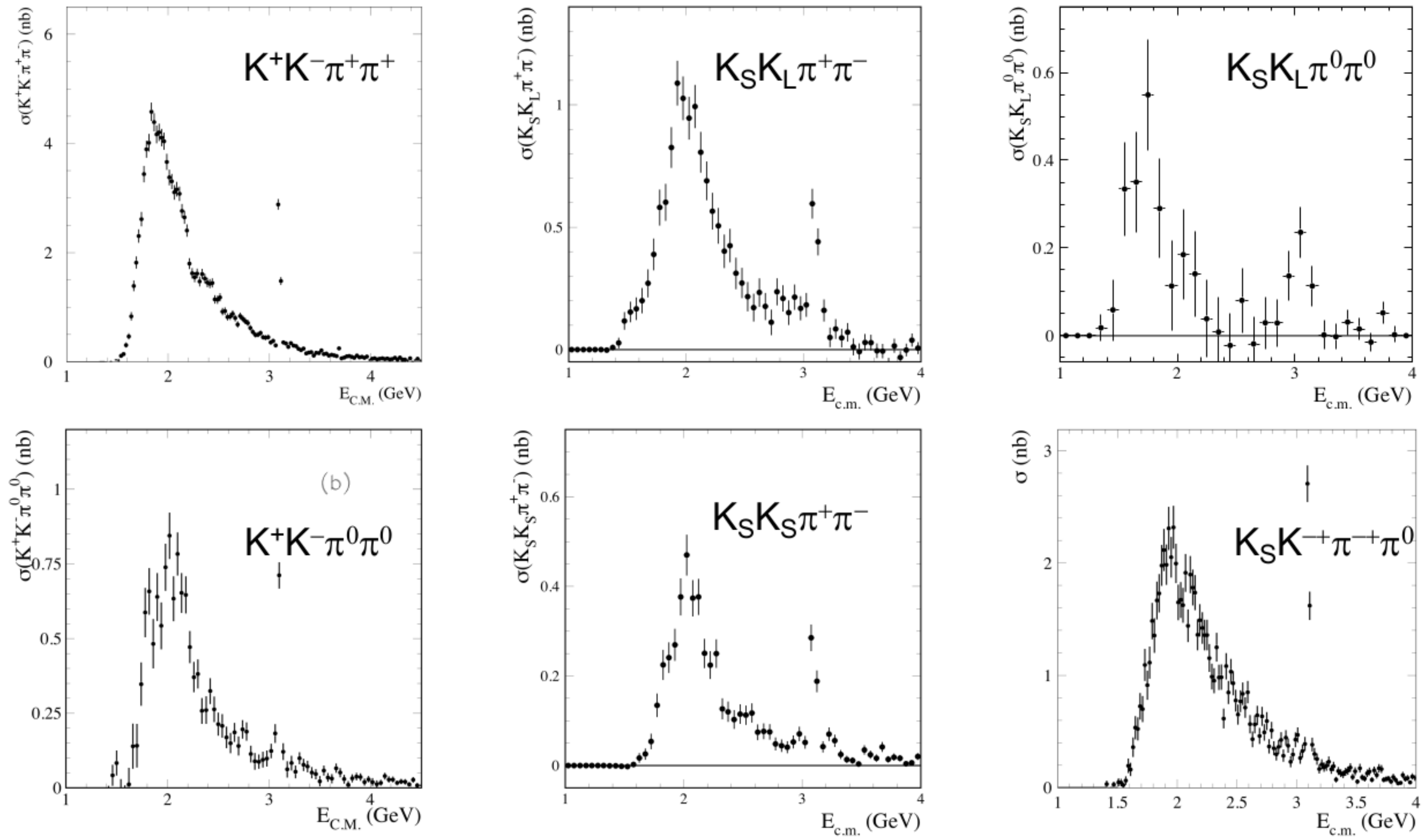


$B(J/\psi \to \pi^+\pi^- 2\pi^0) \sim 5 \times 10^{-3}$

$10 \times 10^9 \times B(J/\psi \to \pi^+\pi^- 2\pi^0) = 5 \times 10^6$

All possible KKππ combinations are measured – BaBar data



Contribution to $(g\text{-}2)_\mu$: (10^{-10} units)

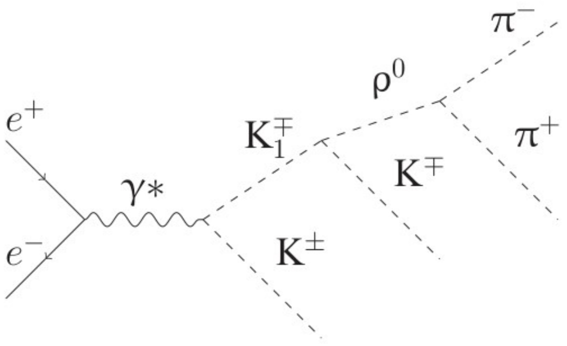
BaBar data only !

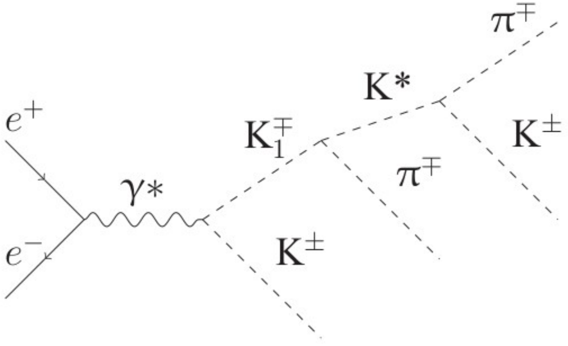
using iso-spin $1.35 \pm 0.09 \pm 0.38 \pm 0.03$ direct 2.41 ± 0.11 √s < 2.0 GeV

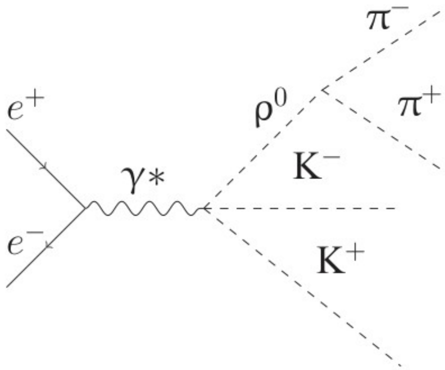
$$\sigma(K\bar{K}\pi\pi) = 9[\sigma(K^+K^-2\pi^0) - \sigma(\phi 2\pi^0)] + \frac{9}{4}\sigma(K^{\star 0}K^{\pm}\pi^{\mp}) + \frac{3}{2}\sigma(\phi\pi^+\pi^-) + 4\sigma(K^+K^-\rho^0).$$

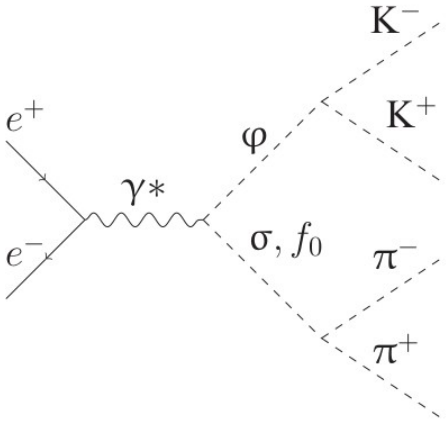
Eur.Phys.J.C71:1515,2011

The most important diagrams for the analysis of $e^+e^- \to K^+K^-\pi^+\pi^-$



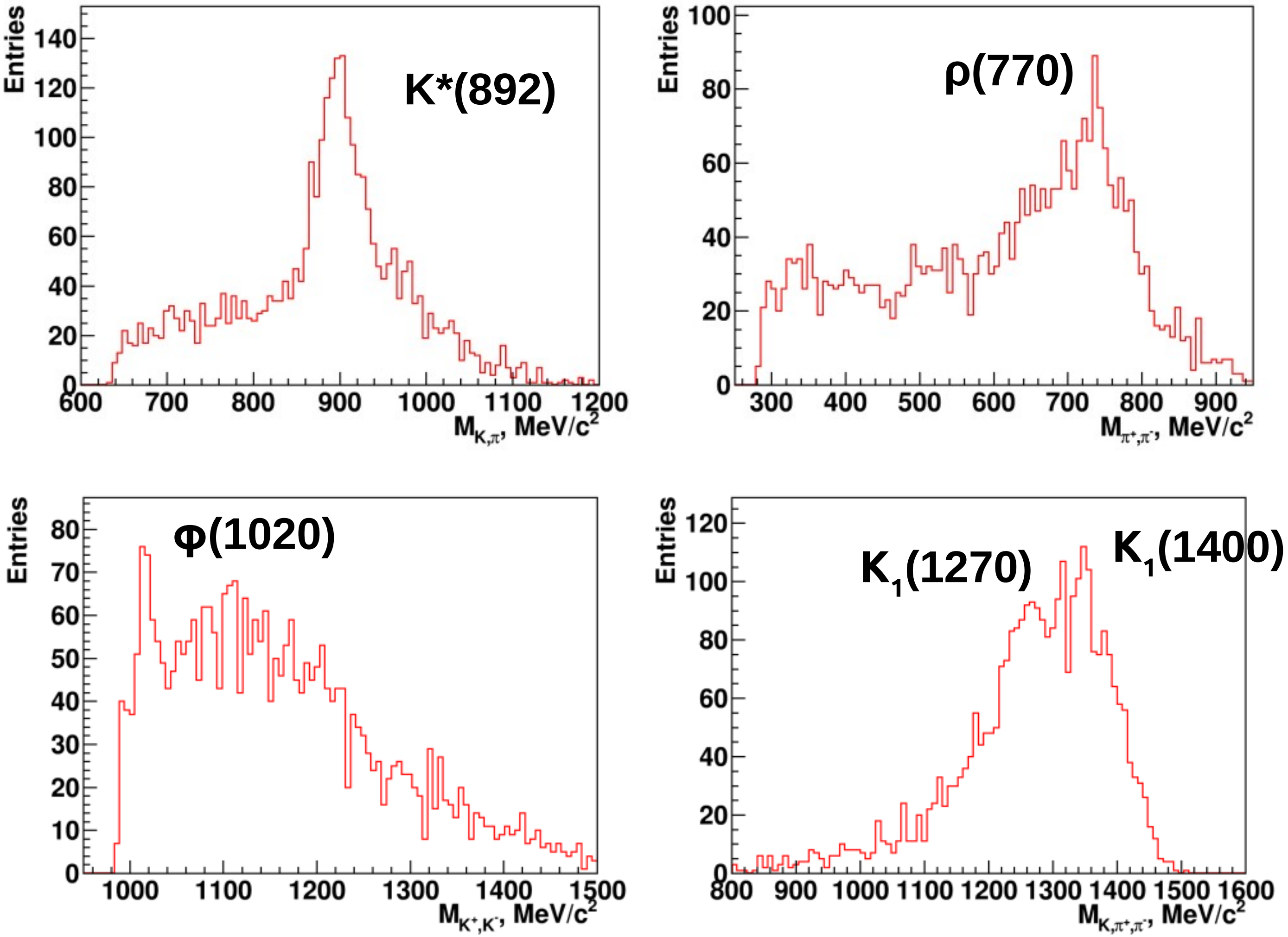




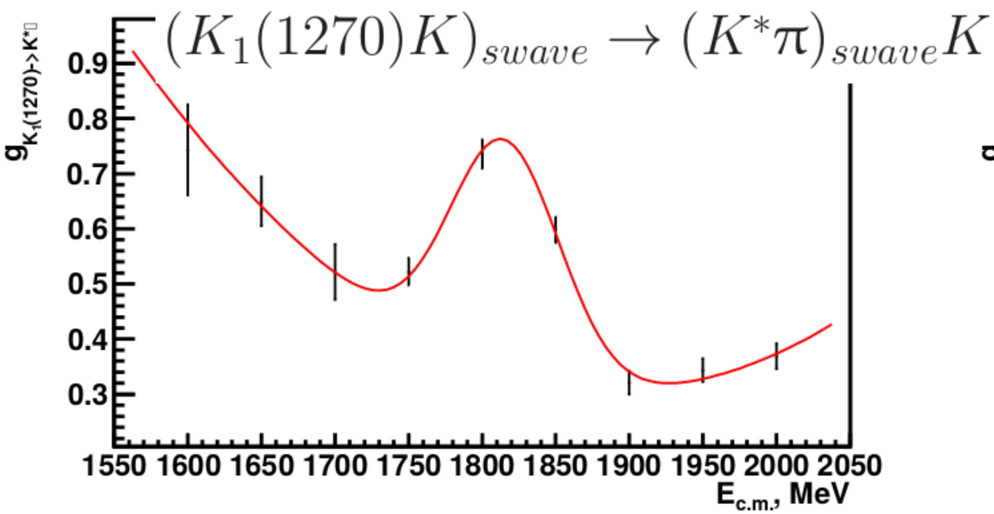


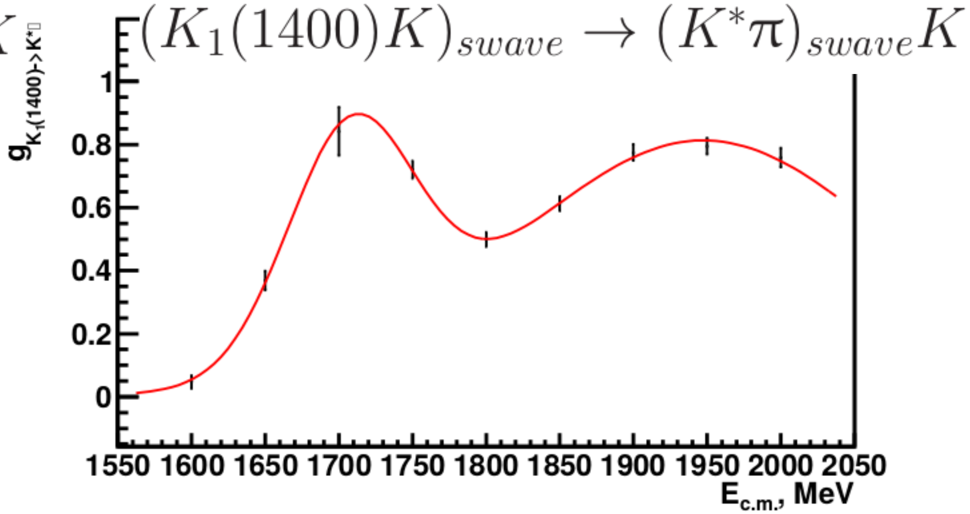
- $e^+e^- \to (K_1(1270)K)_{swave} \to (K^*\pi)_{swave}K \to K\pi\pi K$
- $e^+e^- \to (K_1(1400)K)_{swave} \to (K^*\pi)_{swave}K \to K\pi\pi K$
- $e^+e^- \to (K_1(1270)K)_{swave} \to (\rho K)_{swave}K \to \pi\pi KK$
- $e^+e^- \to f_0\varphi \to \pi\pi KK$
- $e^+e^- \to \sigma\varphi \to \pi\pi KK$
- $e^+e^- \to \rho(KK)_{swave}$

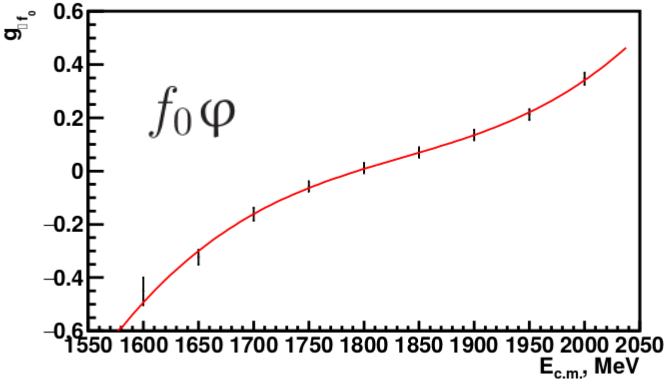
Invariant mass spectra for $e^+e^- \to K^+K^-\pi^+\pi^-$ (10 kevents)

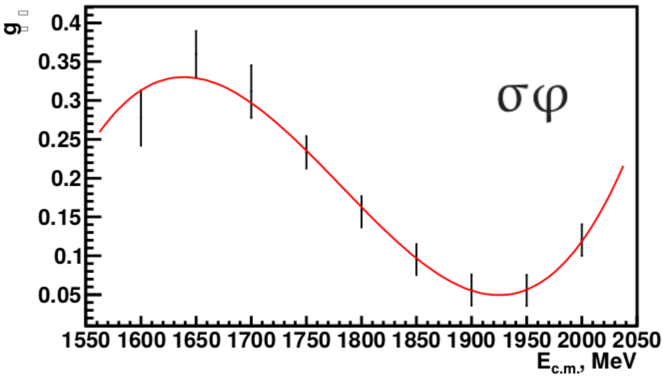


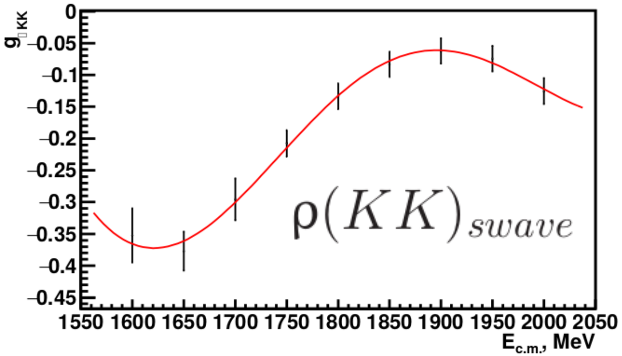
The constant of the amplitudes relatively to e+e- → $(K_1(1270)K)_{swave} \to (\rho K)_{swave} K \to KK\pi\pi$







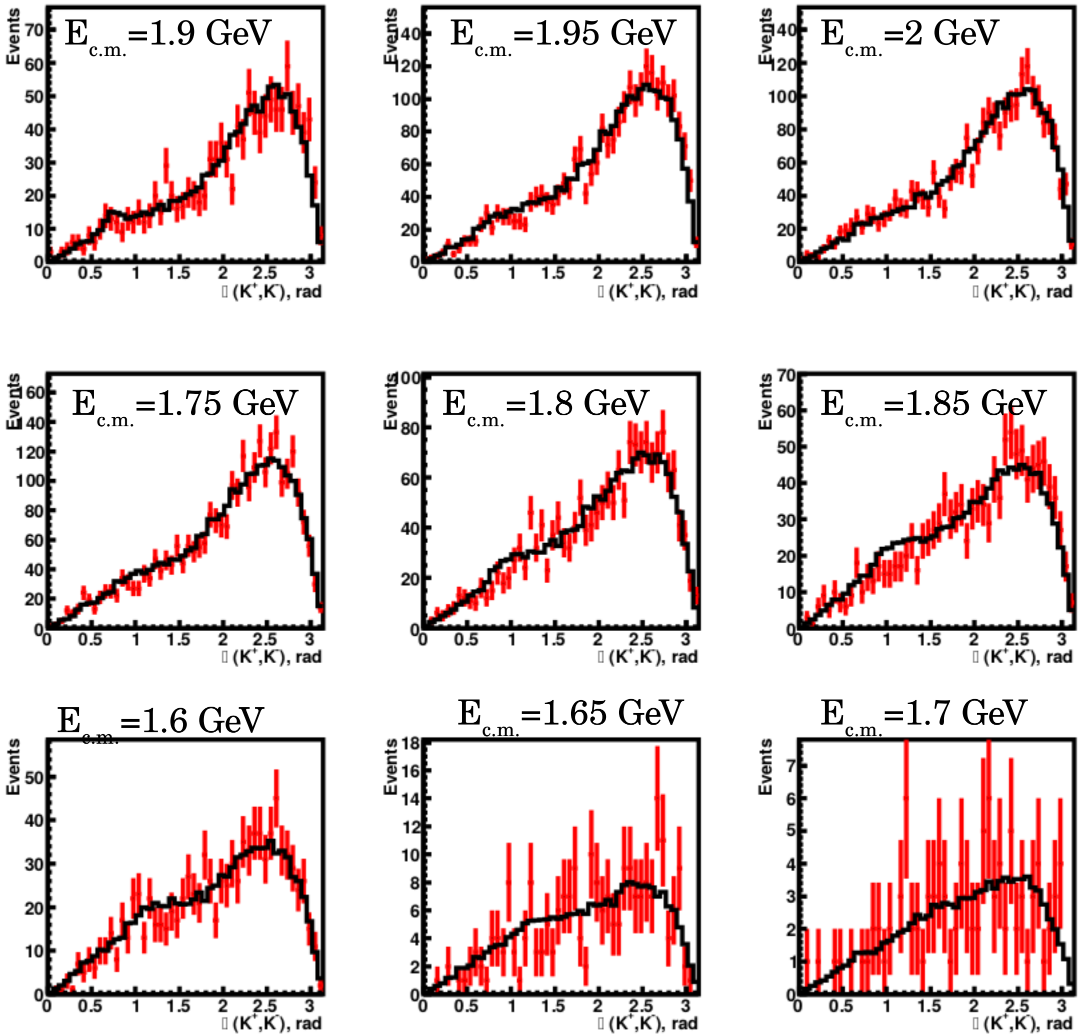




The angle between kaons

EXP

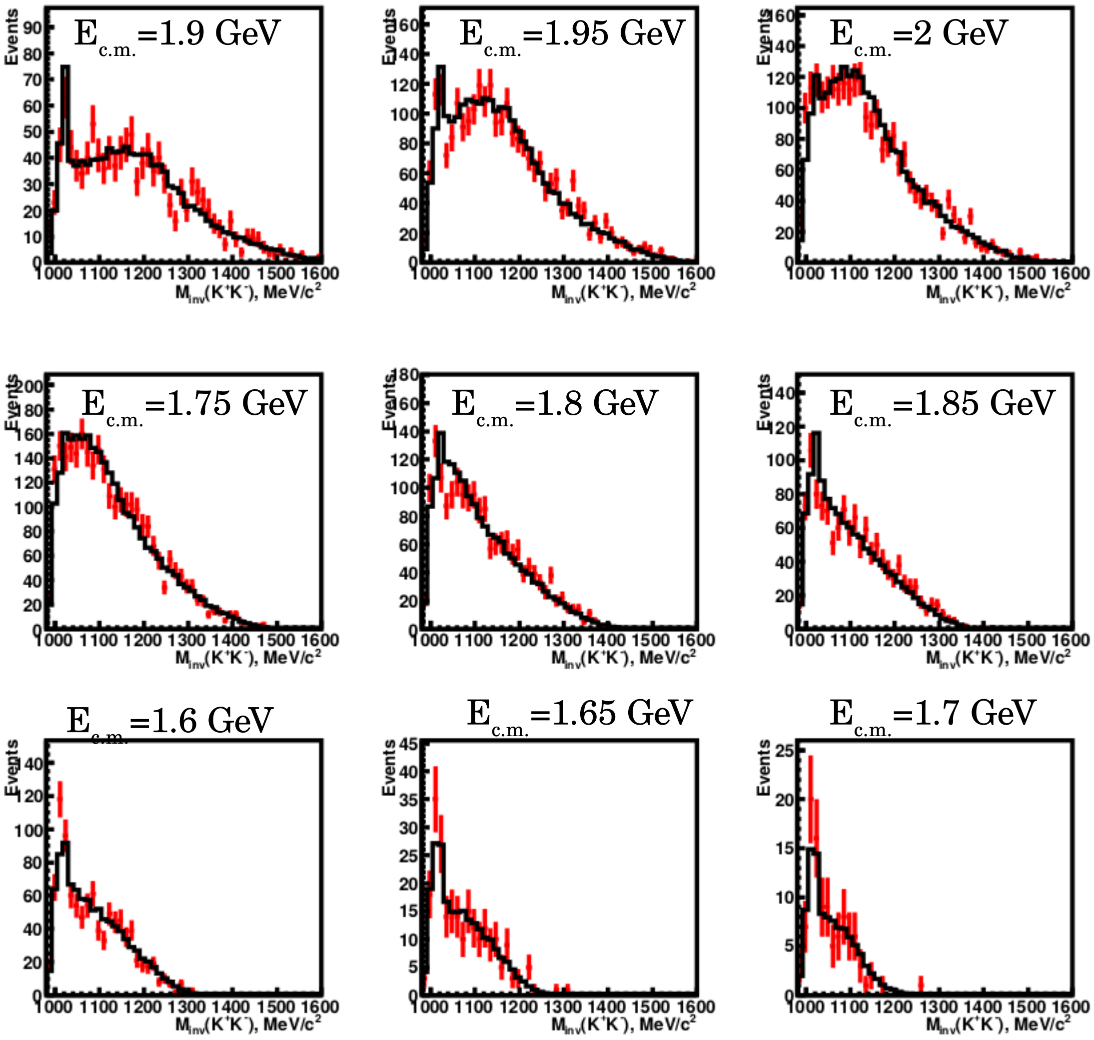
MC



Invariant mass of K+K-

EXP

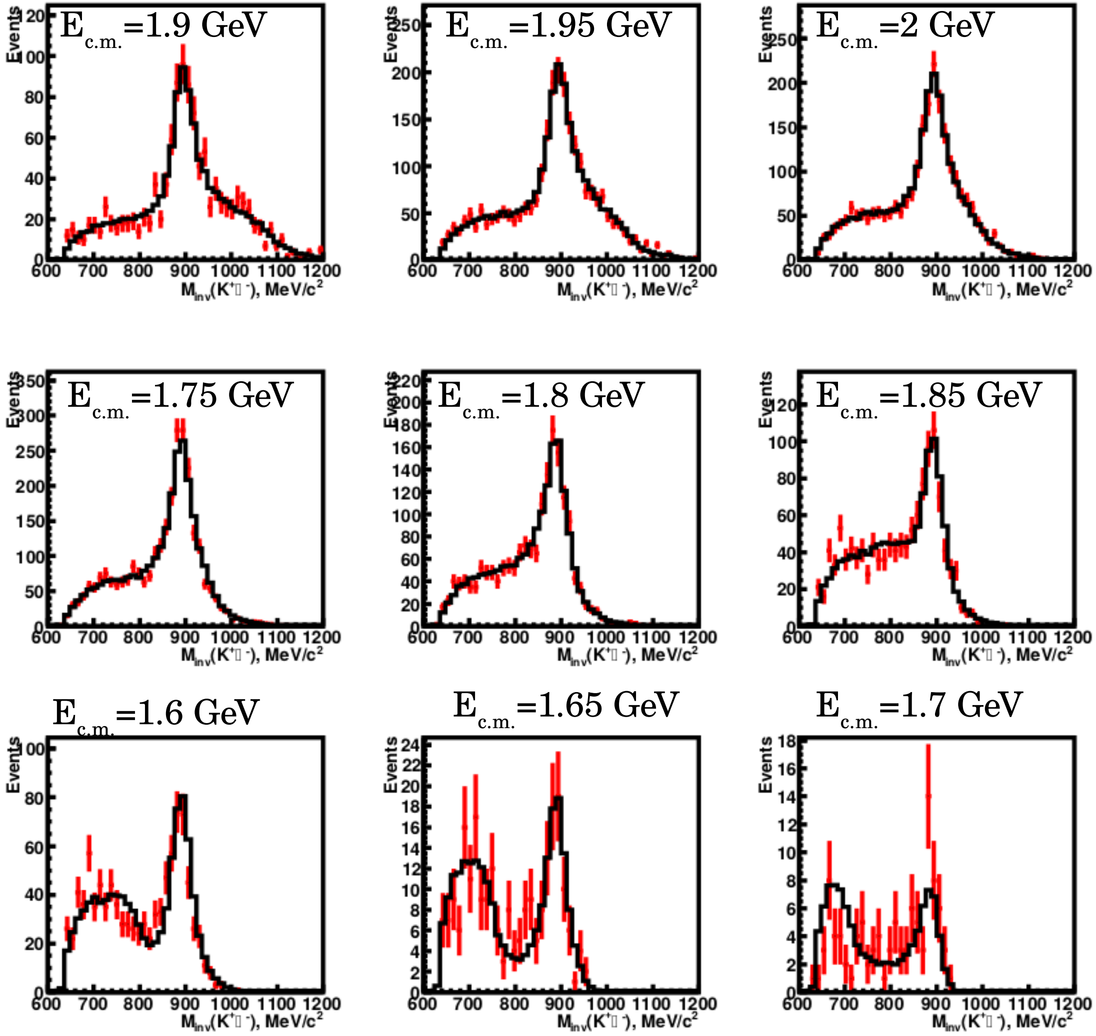
MC



Invariant mass of πK

EXP

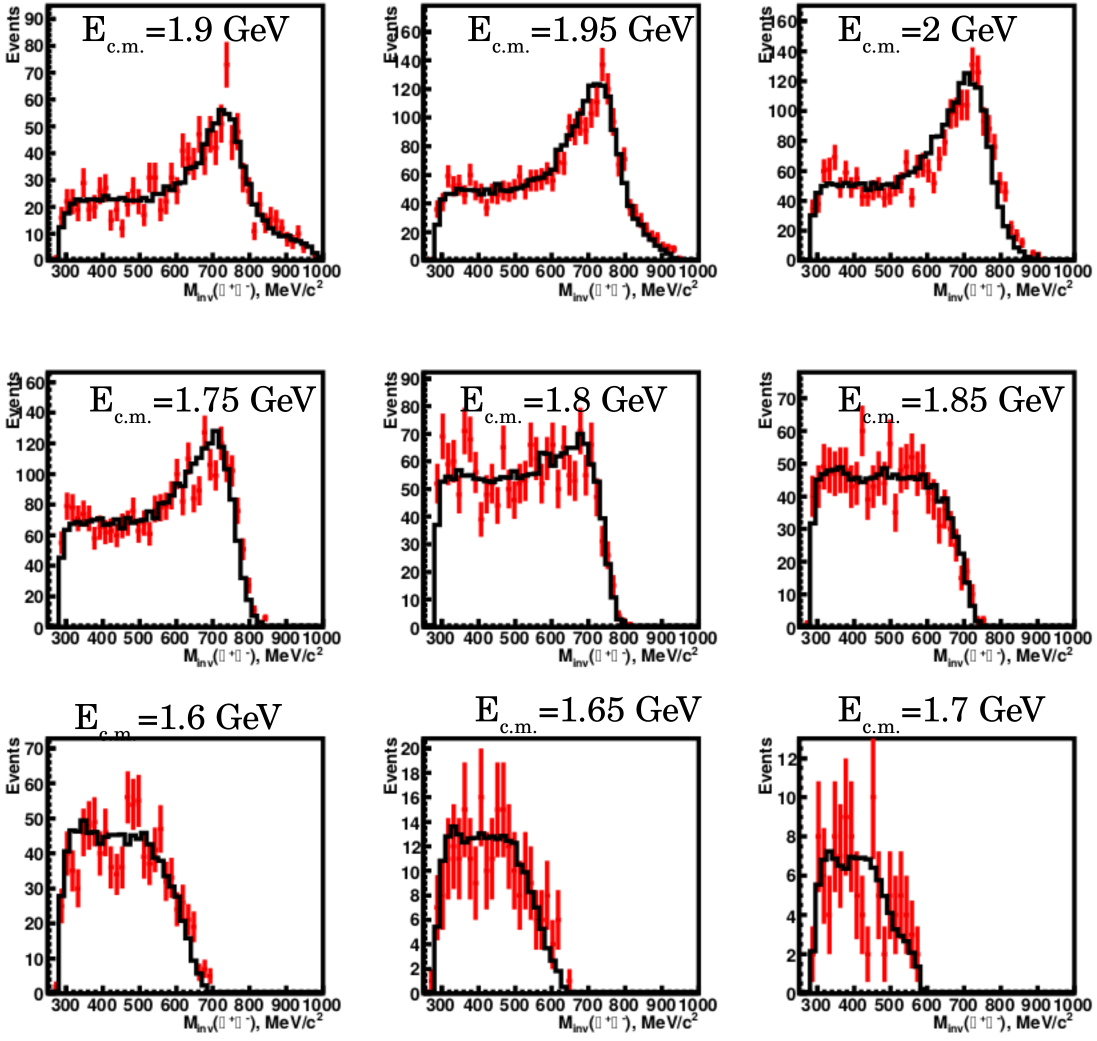
MC



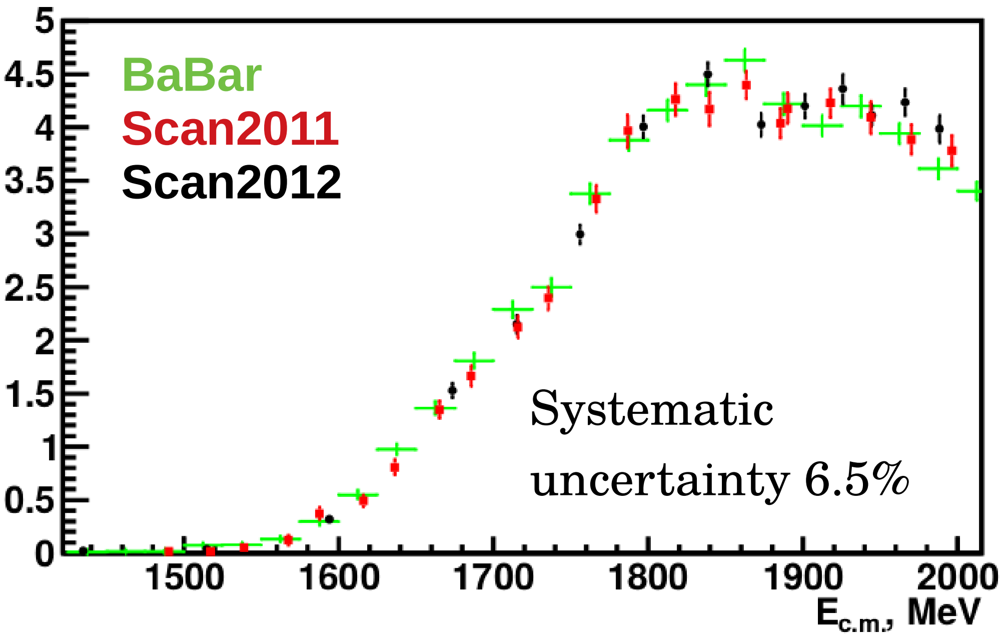
Invariant mass of 2π

EXP

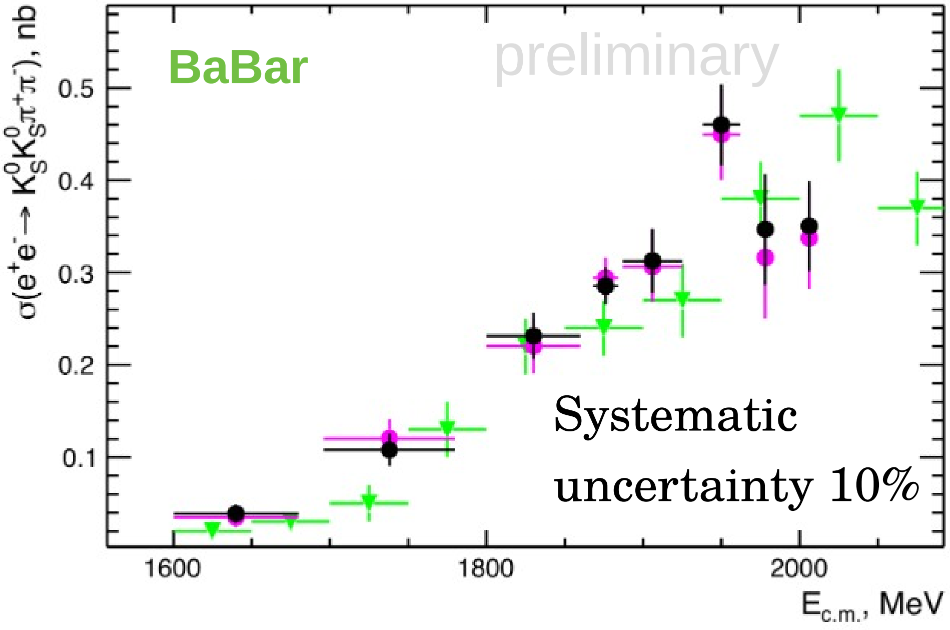
MC



Cross section of $e^+e^- \to K^+K^-\pi^+\pi^-$



Cross section of $e^+e^- \to K_SK_S\pi^+\pi^-$



This reaction is dominated by $K^{*+}(892)K^{*-}(892)$ production

- Simultaneous analysis of all $e+e- \to KK\pi\pi$ channels is required for comprehensive meson spectroscopy and the test of isospin relations

Summary

- CMD-3 has taken ~250 pb^{-1} of data in the whole energy range GeV and is going to take ~1 fb^{-1} in the next ~5 years.

- Many analyses have been published. Many others are in progress.

- The dominance of the channels $\omega\pi$ and $a_1\pi$ below 2 GeV is confirmed in the $e^+e^-\to 4\pi$.
- The perspectives of the analysis of $e+e-\to KK\pi\pi$ is shown
- It looks that the production of two ground-state vectors ($\rho^-\rho^+$, K*(890)barK*(890)) is suppressed relatively to the emission of pseudoscalar ($\omega\pi$, $a_1\pi$, K_1K).
- If you are interesting in the analysing of the CMD-3 data you are more than welcome.
- BES-III and CMD-3 physics programs are strongly overlapping. We can be useful to each other.