Study of the processes $e^+e^- \to K\bar{K}(n)\pi$ with the CMD-3 detector at VEPP-2000 collider

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Outline

1. VEPP-2000 collider and CMD-3 detector

2. $e^+e^- \to K\bar{K}(n)\pi$ processes: charged kaons/pions identification

3. $e^+e^- \to K\bar{K}(n)\pi$ processes

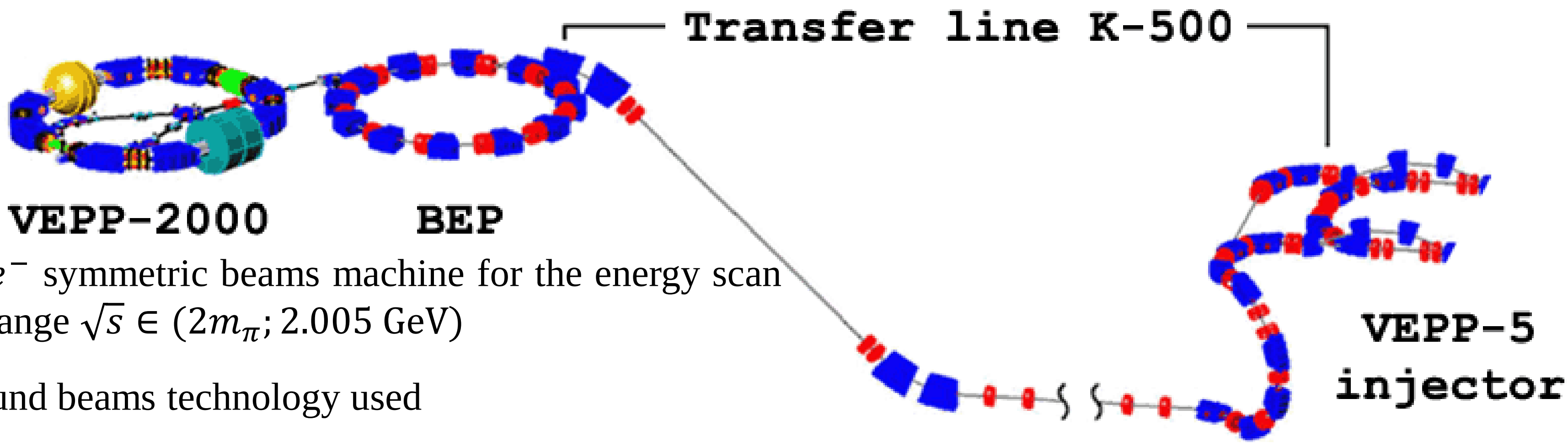
   3.1 $K^+K^-\pi^+\pi^-$ final state

   3.2 $e^+e^- \to K^+K^-\eta$ and $K^+K^-\omega(782)$ processes

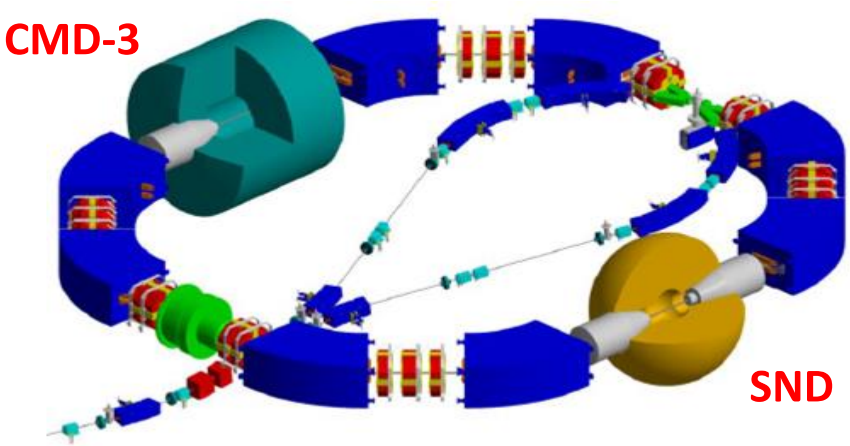
   3.3 $K^+K^-\pi^0$ final state

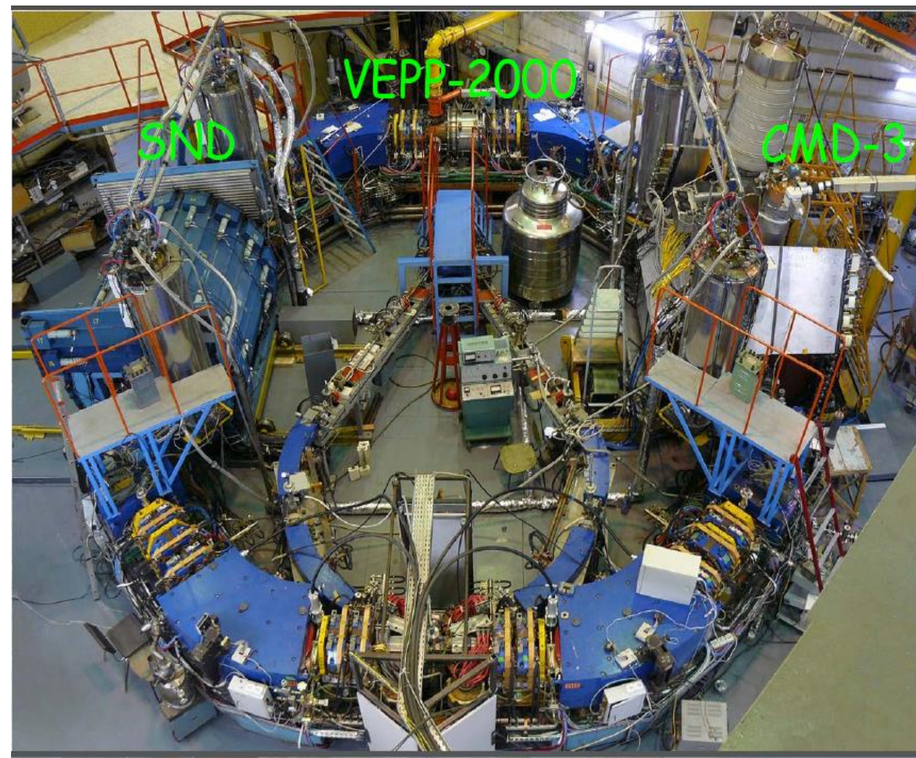
4. Plans & Conclusion

1. VEPP-2000 collider & CMD-3 detector

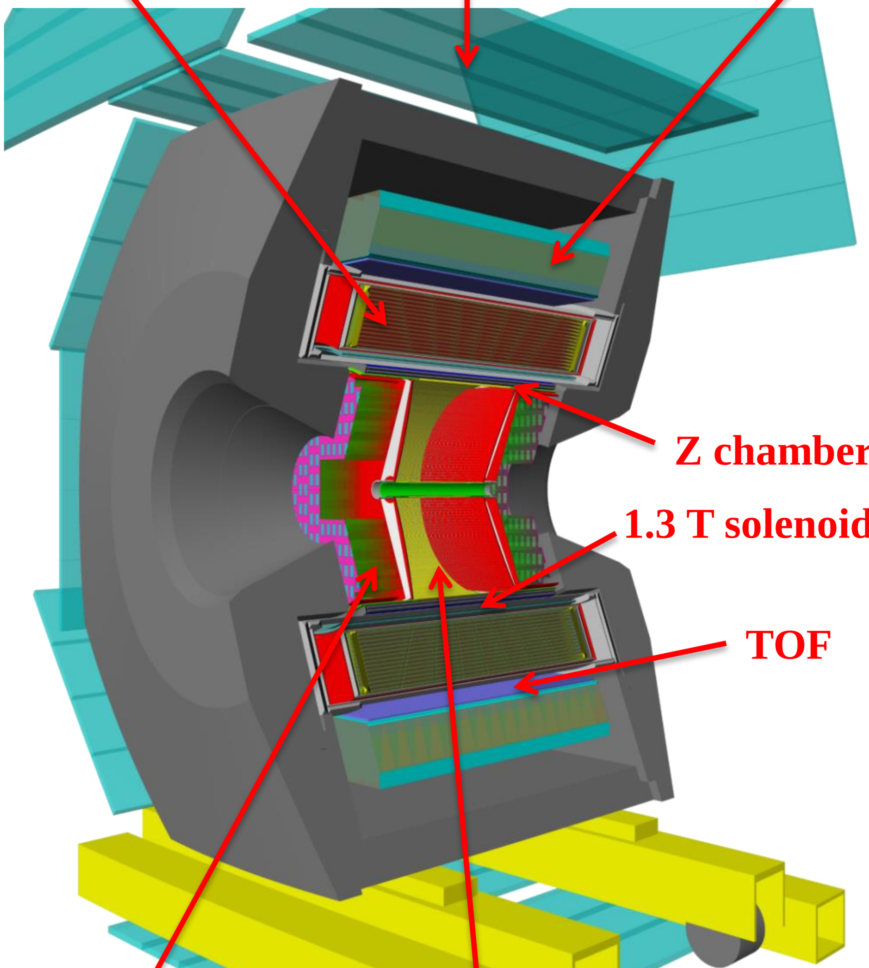


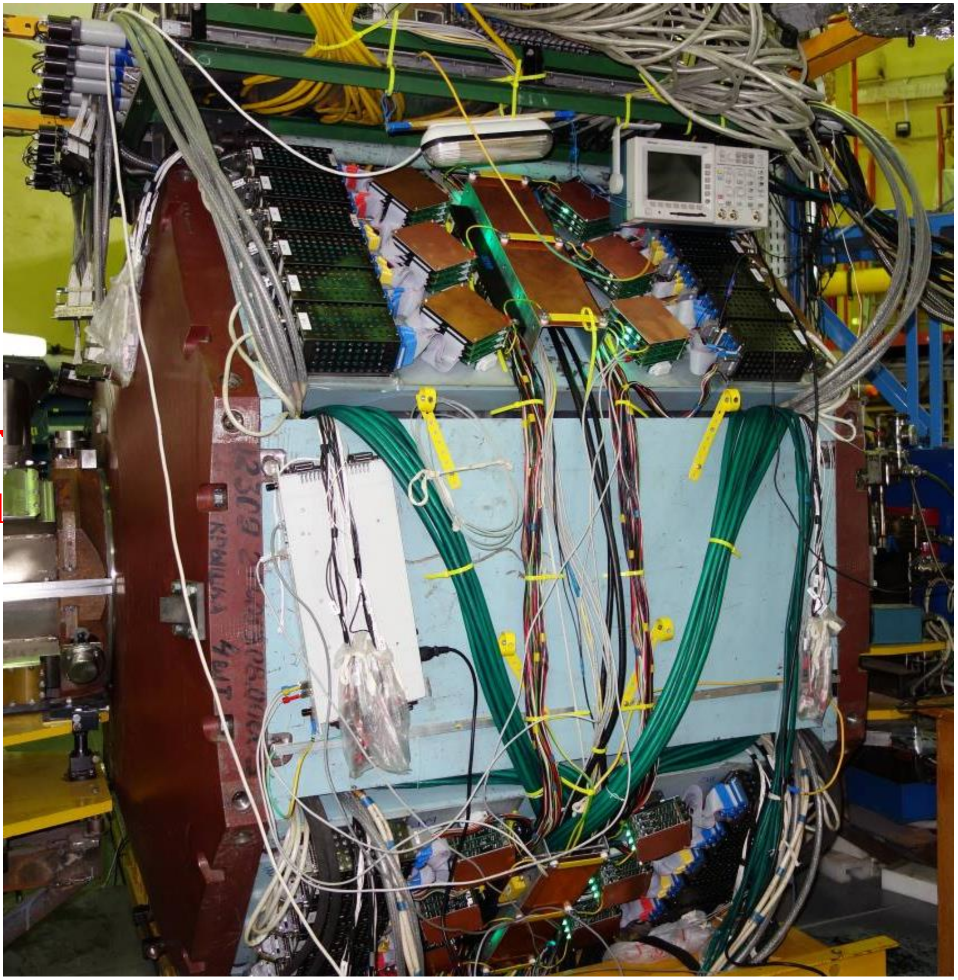
- e^+e^- symmetric beams machine for the energy scan in range $\sqrt{s} \in (2m_\pi; 2.005 \text{ GeV})$
- Round beams technology used
- The maximum luminosity is $10^{32}\ \text{cm}^{-2}\text{s}^{-1}$ at 2.0 GeV
- Compton backscattering beam energy measurement ($\pm$60 keV precision)
- ~ 120 pb^{-1} is collected by each detector, the goal is to collect ~1 fb^{-1} in ~5 years





CMD-3 detector





Physics program of CMD-3

- $(g_\mu - 2)$ puzzle: precise measurement of $R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$ - the goal is to achieve <1% systematic for major channels
- Study of exclusive hadronic channels of e^+e^- annihilation, test of isotopic relations
- Study of the “excited” vector mesons: $\rho', \rho'', \omega', \phi'$ ...
- CVC tests: comparison of isovector part of $\sigma(e^+e^- \to hadrons)$ with τ −decay spectra
- Study of $\mathrm{G_E}/\mathrm{G_M}$ for nucleons near threshold
- Diphoton physics (e.g. η' production)

CMD-3 data analysis status

$e^+e^- \to \pi^+\pi^-$		$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$	ϕ
$e^+e^- \to K^+K^-$	ϕ	$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$	ϕ
$e^+e^- \to K_SK_L$	ϕ	$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$	
$e^+e^- \to \eta\gamma, \pi^0\gamma$, 3γ		$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	
$e^+e^- \to K^+K^-\pi^0$		$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	
$e^+e^- \to K^+K^-(\eta, \omega)$		$e^+e^- \to p\bar{p}$	
$e^+e^- \to K_SK^*$		$e^+e^- \to n\bar{n}$	
$e^+e^- \to \pi^+\pi^-\pi^0$		$e^+e^- \to \eta'(958)$	
$e^+e^- \to \pi^+\pi^-\eta$		$e^+e^- \to K_SK_L\eta, \pi^0$	
$e^+e^- \to \pi^+\pi^-\gamma$		$e^+e^- \to \eta\gamma$, η–> 3π	
Dark photon search		$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$	
$e^+e^- \to K^+K^-\pi^+\pi^-$		**Conversion decays** $e^+e^- \to e^+e^-\pi^0, e^+e^-\eta$	

- Final results are published

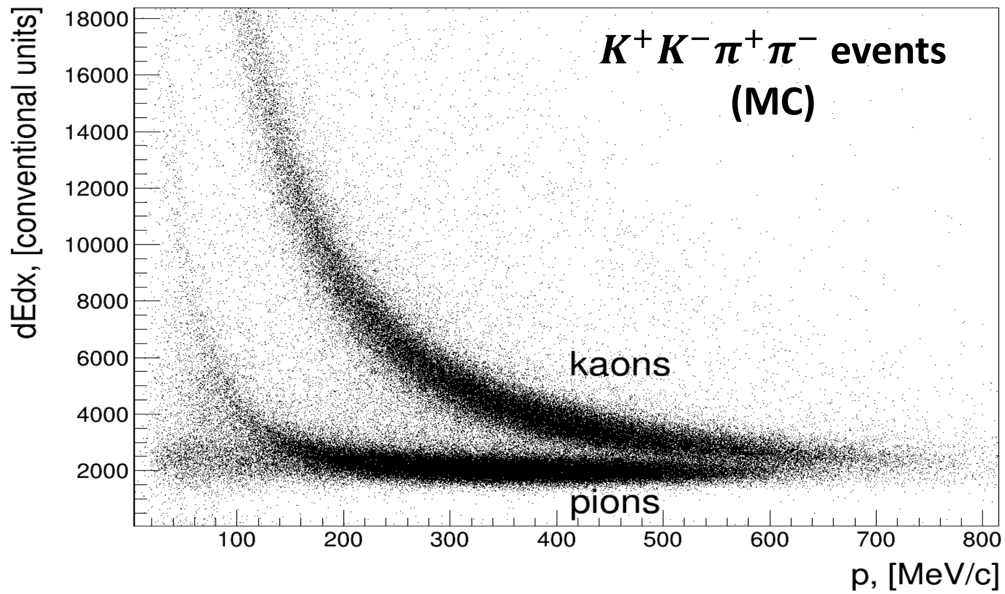
- Preliminary results reported at conferences

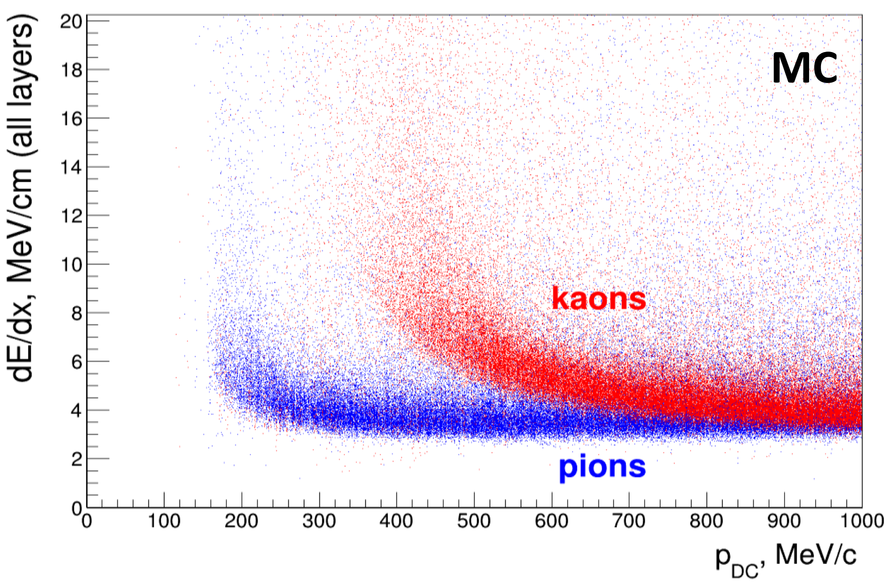
- Is being studied, not reported

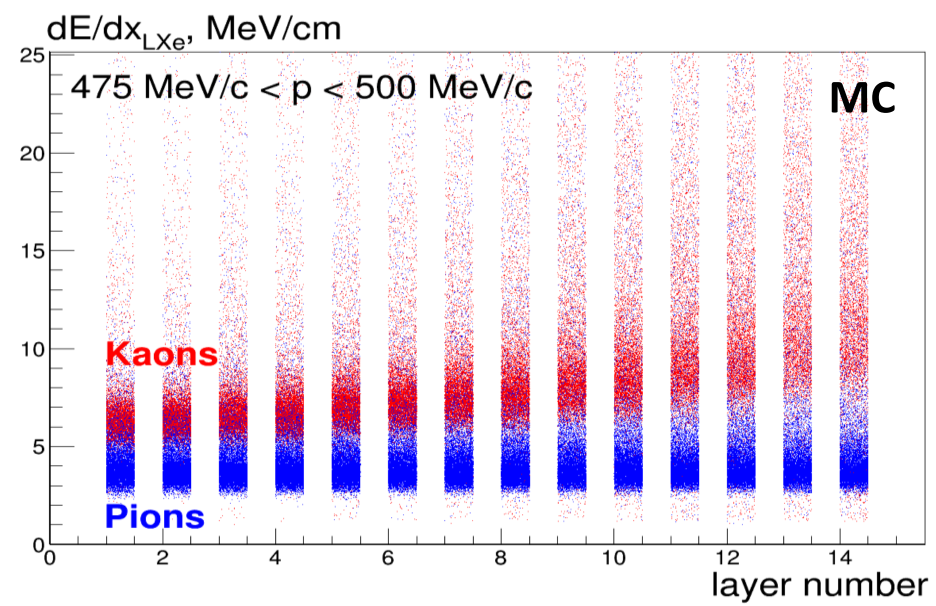
+ also
$K^+K^-2\pi^0$,
$K_SK^\pm\pi^\mp\pi^0$ **etc.**

2. $e^+e^- \rightarrow K\bar{K}(n)\pi$ processes: kaon/pion separation

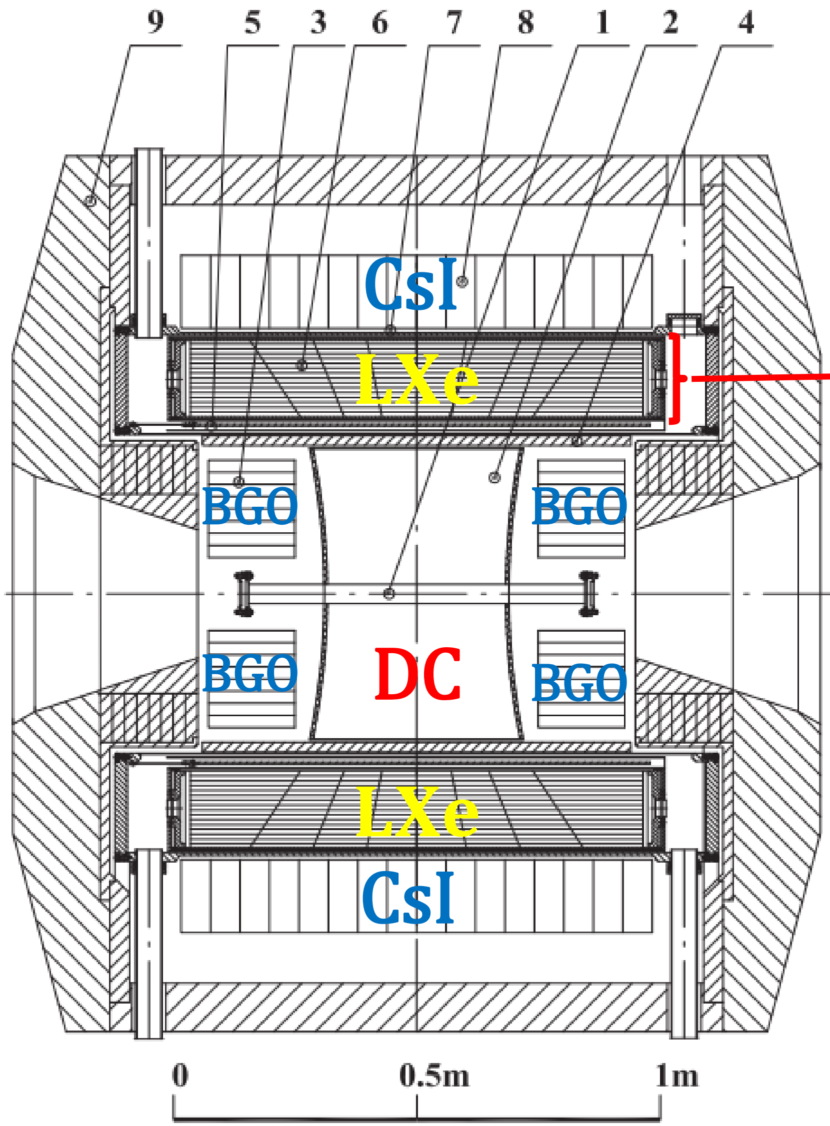
- K/π separation is the starting point and key issue for such processes
- We use the dE/dx in drift chamber (DC), but for single kaons and pions it works reliably only up to $p <$ 450 MeV/c
- For the final states K^+K^-, $K^+K^-\pi^0$, $K^+K^-2\pi^0$ the use of dE/dx_{DC} is insufficient
- We are developing the PID procedure with the use of dE/dx_{LXe} in 14 layer LXe-calorimeter

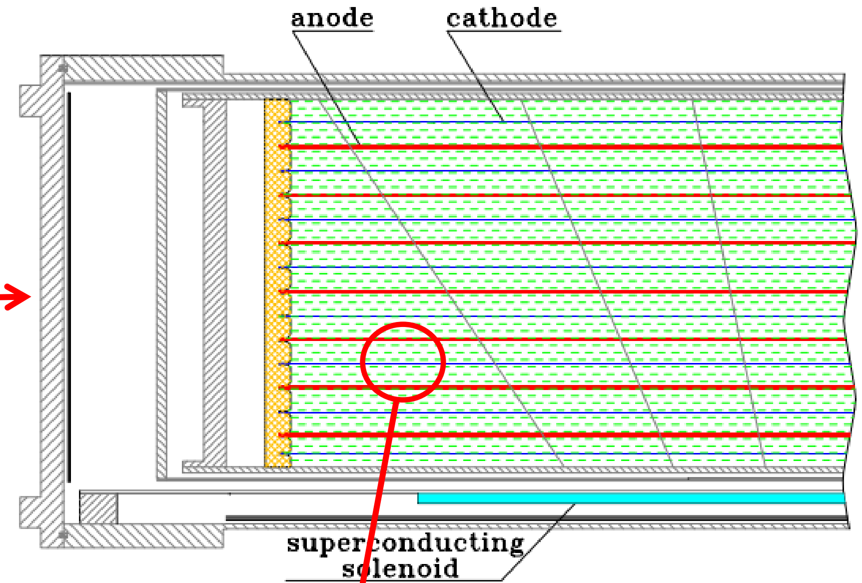






LXe-calorimeter of CMD-3





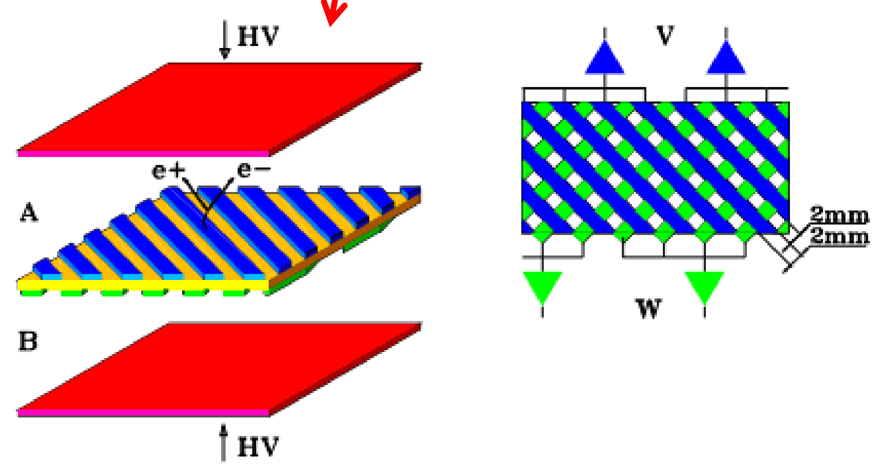


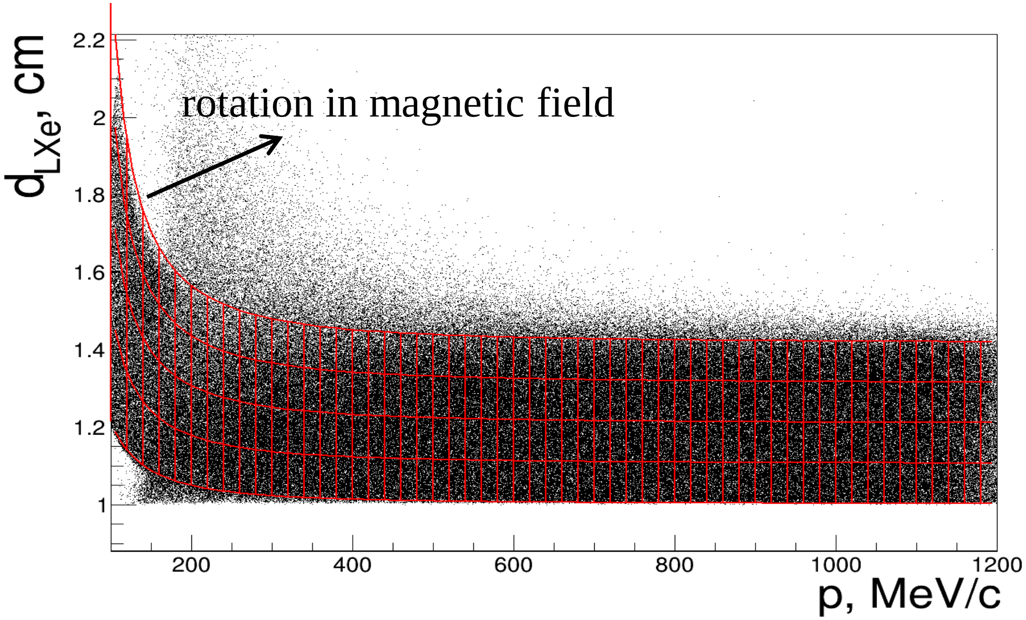
Fig. 1. 1 – beam pipe, 2 – drift chamber, 3 – BGO electromagnetic calorimeter, 4 – Z-chamber, 5 – SC solenoid ($0.13X_0$, 13 kGs), 6 – LXe electromagnetic calorimeter (the segmentation with "towers" specially shown), 7 – TOF system, 8 – CsI electromagnetic calorimeter, 9 – Yoke.

The PID with LXe

- For each DC-track we calculate the 10 values of the responses of the boosted decision trees (BDT) classifiers, trained for the separation of particular pair of charged particles in particular ranges of momenta and path length in LXe-layer (2200 classifiers in total):

	$e^{\pm}$	$\mu^{\pm}$	$\pi^{\pm}$	$K^{\pm}$
$\mu^{\pm}$	$Response_{ij}(\mu^{\pm}/e^{\pm})$	-	-	-
$\pi^{\pm}$	$Response_{ij}(\pi^{\pm}/e^{\pm})$	$Response_{ij}(\pi^{\pm}/\mu^{\pm})$	-	-
$K^{\pm}$	$Response_{ij}(K^{\pm}/e^{\pm})$	$Response_{ij}(K^{\pm}/\mu^{\pm})$	$Response_{ij}(K^{\pm}/\pi^{\pm})$	-
$p^{\pm}$	$Response_{ij}(p^{\pm}/e^{\pm})$	$Response_{ij}(p^{\pm}/\mu^{\pm})$	$Response_{ij}(p^{\pm}/\pi^{\pm})$	$Response_{ij}(p^{\pm}/K^{\pm})$

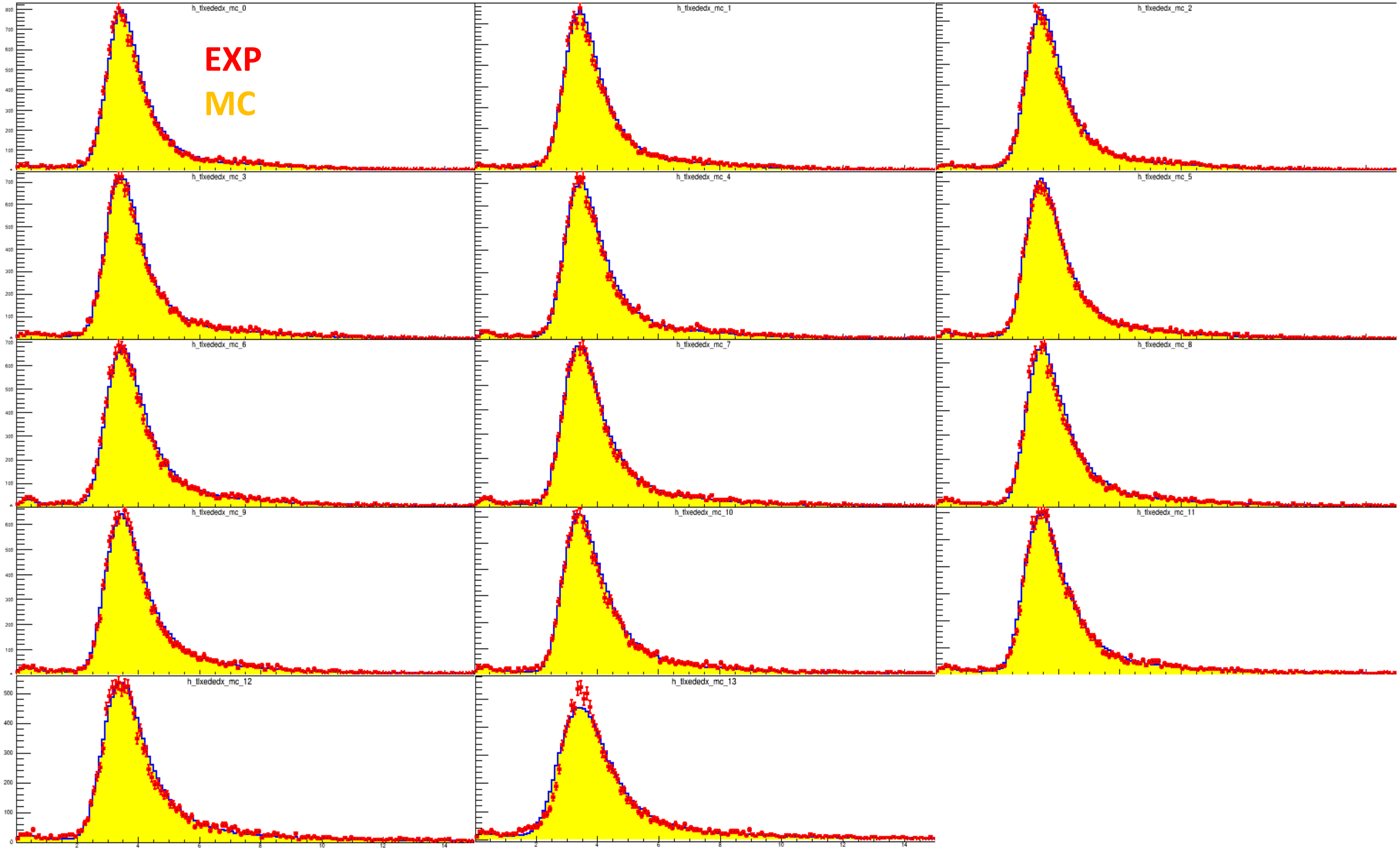
- The training samples: MC for $K^{\pm}$, MC & experimental events for others
- Input variables: dE/dx_{DC}, 14 values of dE/dx_{LXe}
- Sophisticated detector response simulation is required: determination of the layers transparency coefficients, correlative and anticorrelative redistribution of induced charge between upper and lower strips etc., “geometric effect”, recombination etc.



- Main problem: bad simulation of π^{-}, K^{-} interactions with nuclei (the PID only for π^{+}, K^{+} will be used at first)

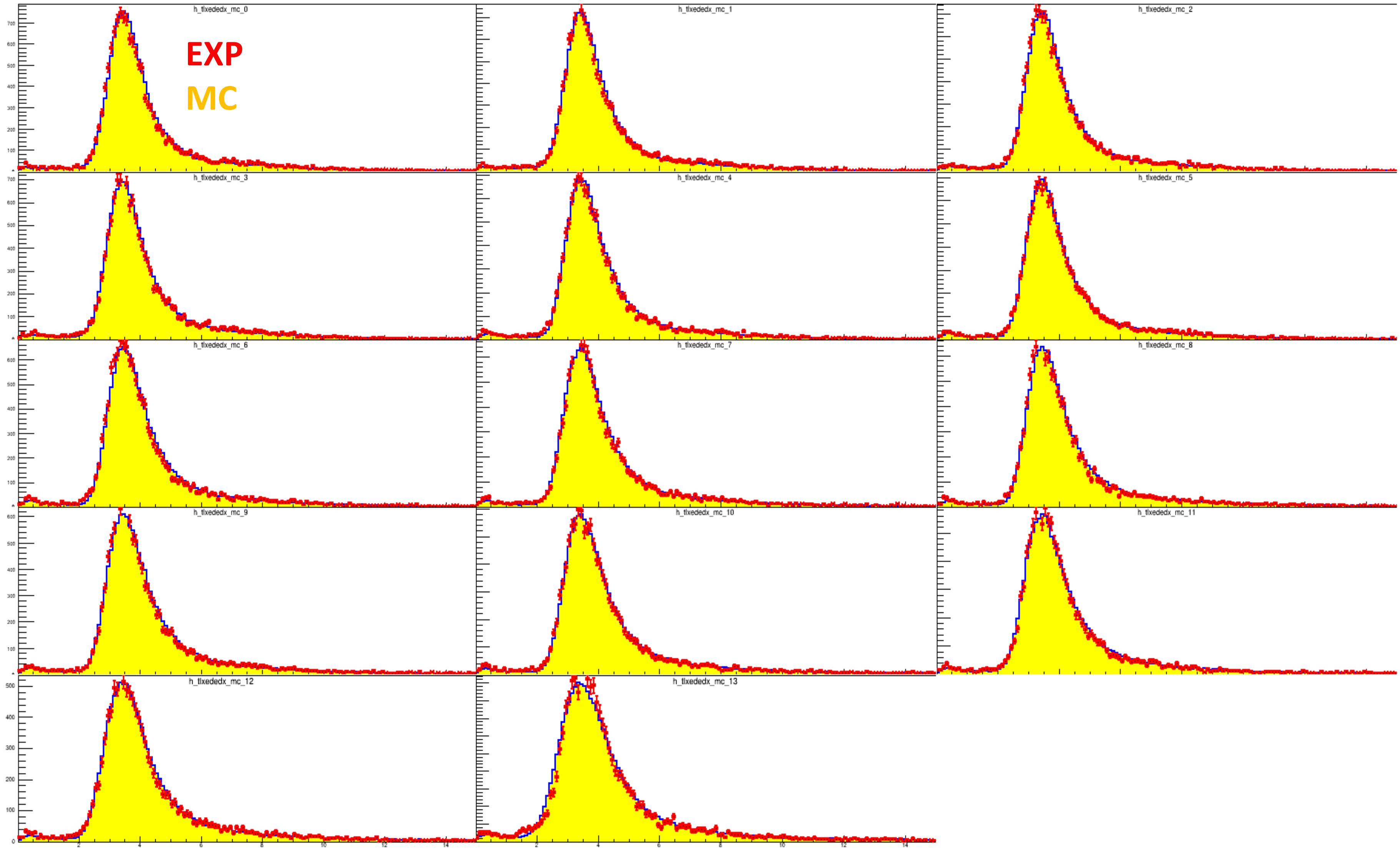
dE/dx_{LXe} in 14 layers: MC/exp comparison for π^+

- π^+ sample is selected from $2\pi^+2\pi^-$ events, $\sqrt{s} \in (1.6\ \text{GeV}; 2\ \text{GeV})$

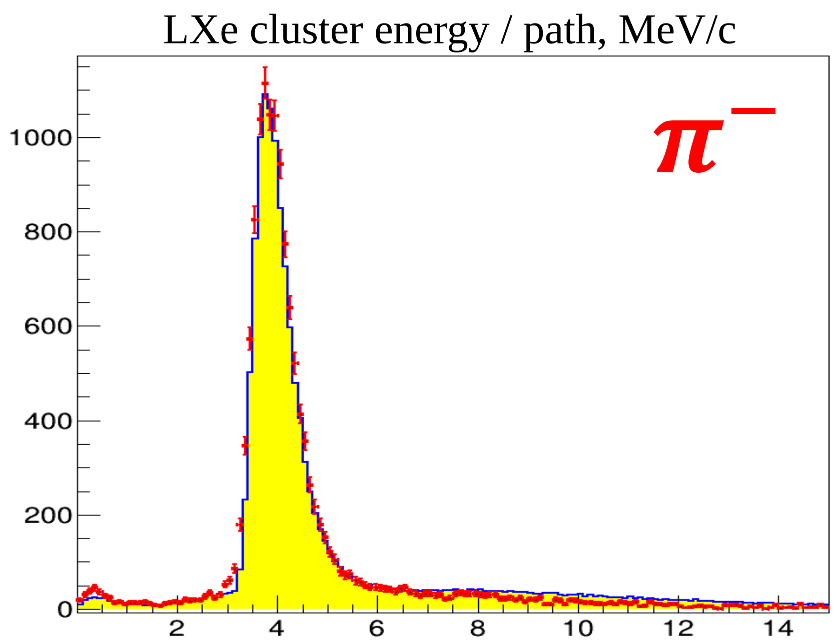


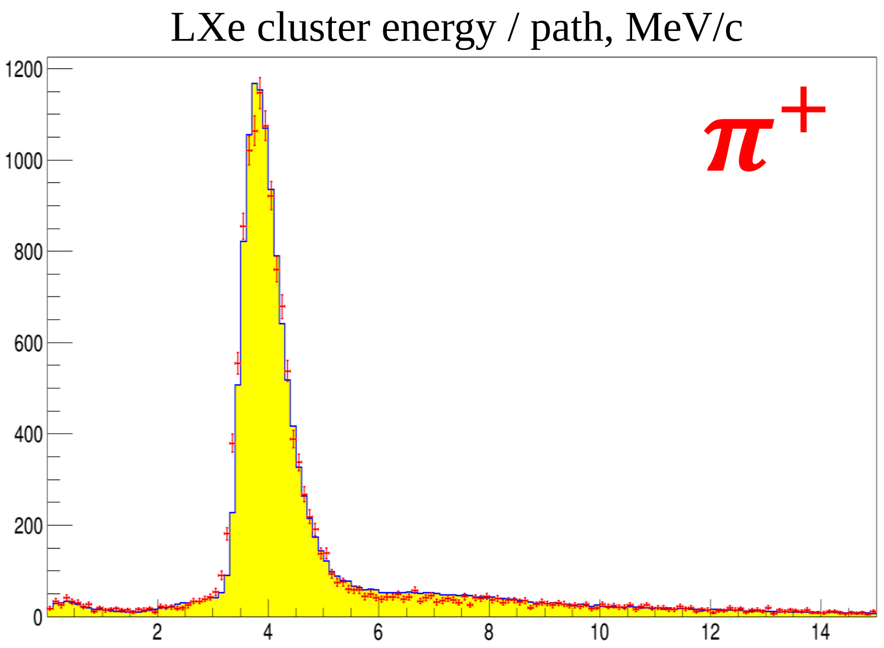
dE/dx_{LXe} in 14 layers: MC/exp comparison for π^-

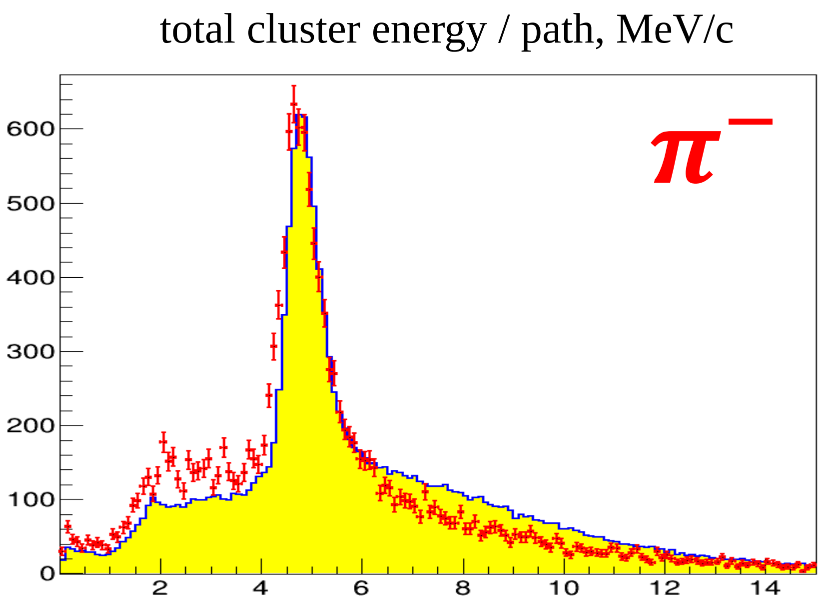
- π^- sample is selected from $2\pi^+2\pi^-$ events, $\sqrt{s} \in (1.6\ \text{GeV}; 2\ \text{GeV})$

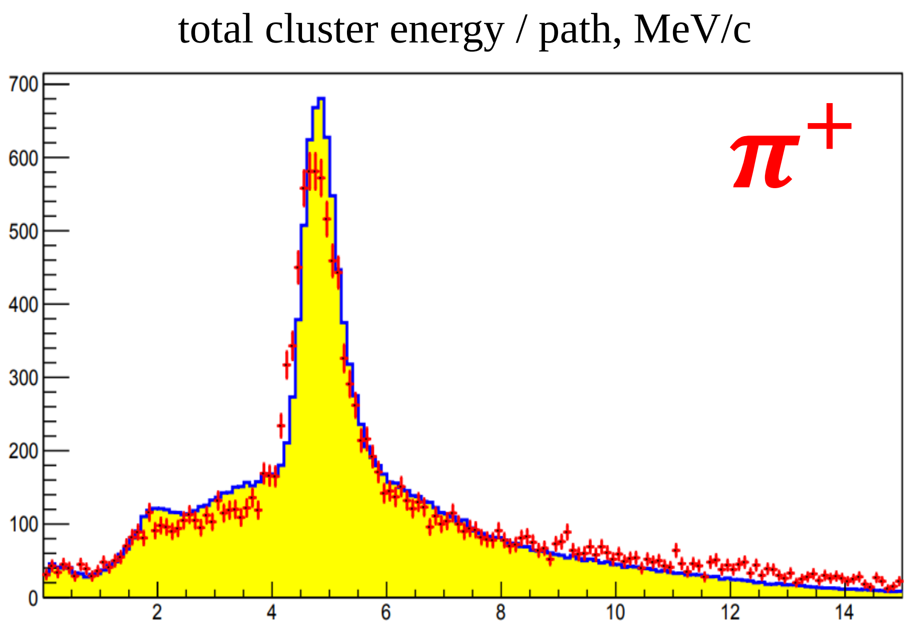


MC/exp comparison for π^- & π^+



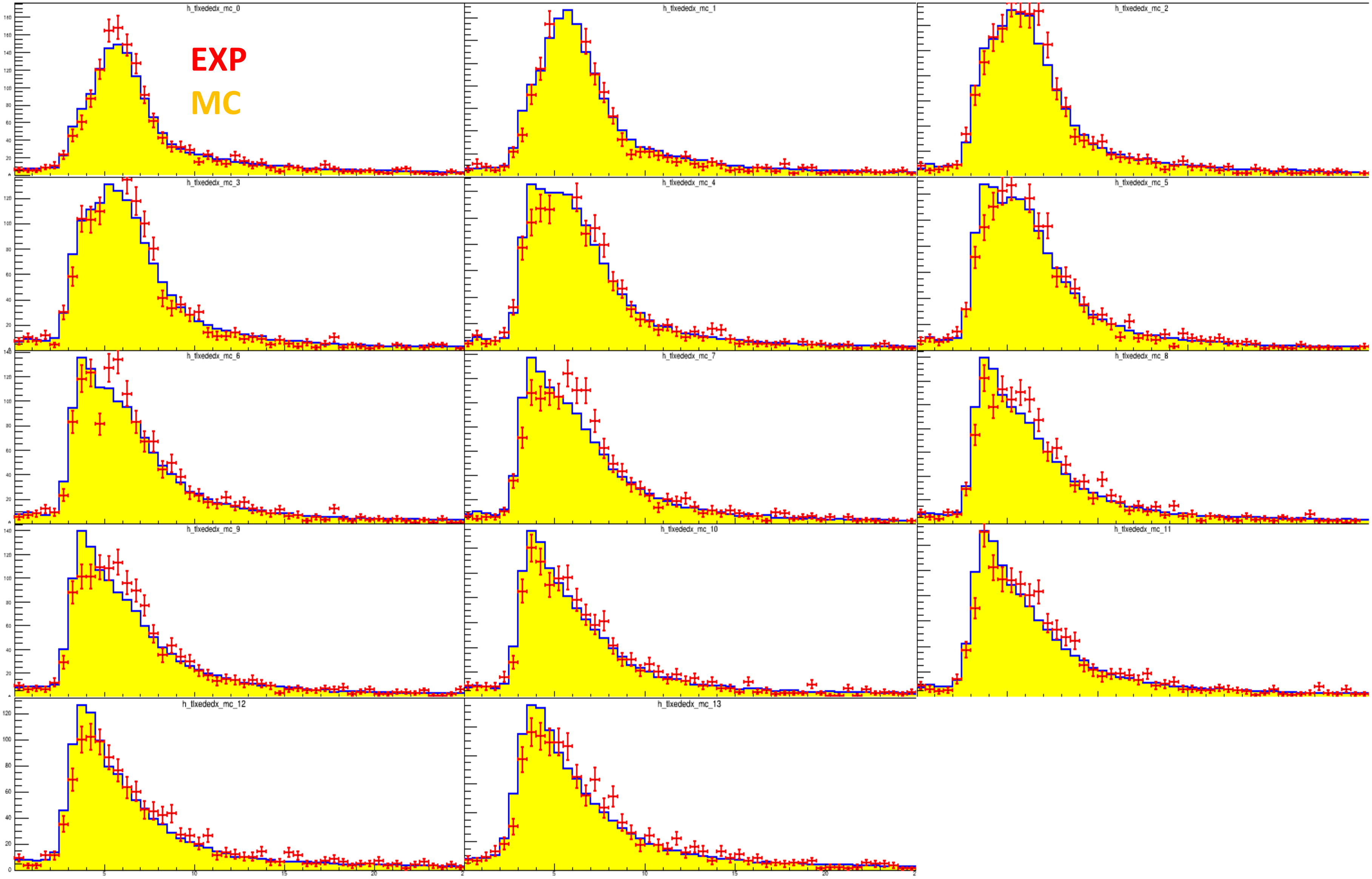






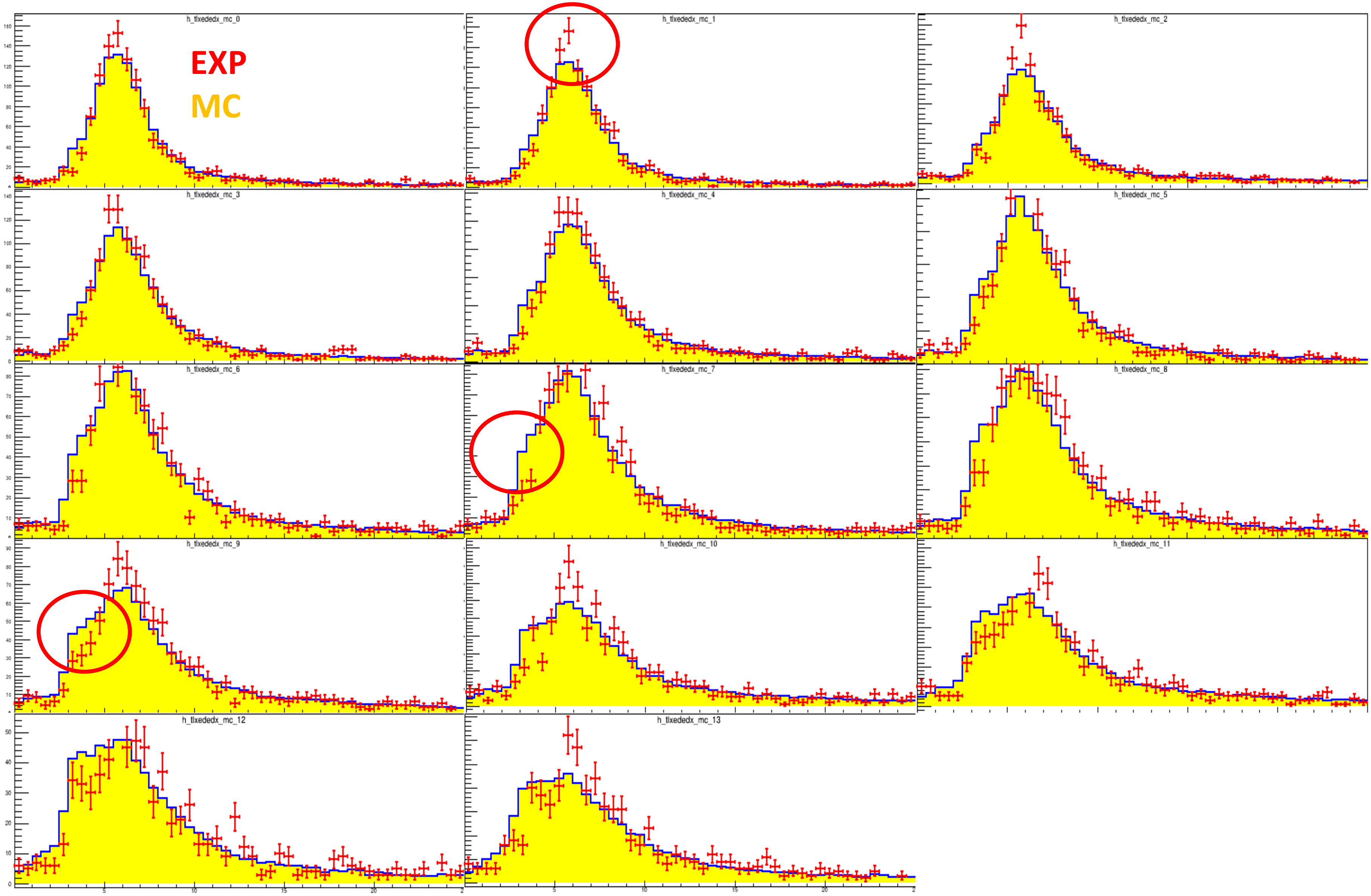
dE/dx_{LXe} in 14 layers: MC/exp comparison for K^+

- K^+ sample is selected from $K^+K^-\pi^+\pi^-$ events, $\sqrt{s} \in (1.6\text{ GeV}; 2\text{ GeV})$

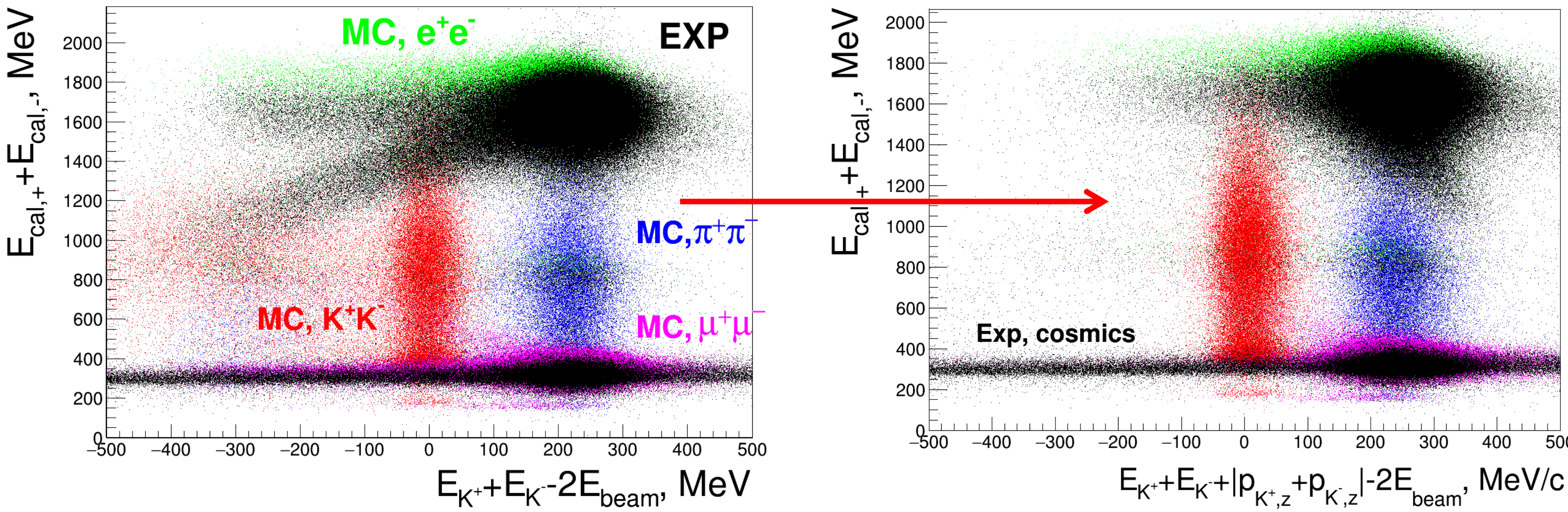


dE/dx_{LXe} in 14 layers: MC/exp comparison for K^-

- K^- sample is selected from $K^+K^-\pi^+\pi^-$ events, $\sqrt{s} \in (1.6\ \text{GeV}; 2\ \text{GeV})$

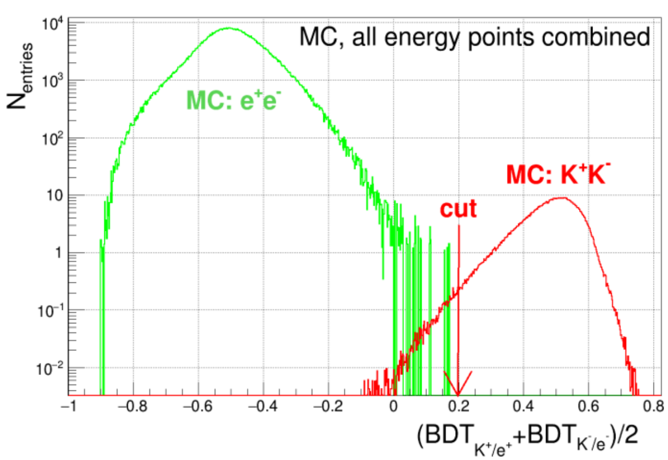


Example: selection of $e^+e^- \to K^+K^-(\gamma)$ at $\sqrt{s} > 1.8$ GeV

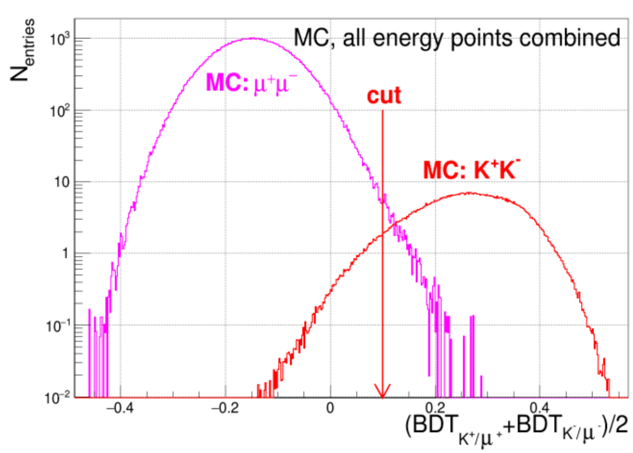


- Background suppression via cuts on BDT responses:

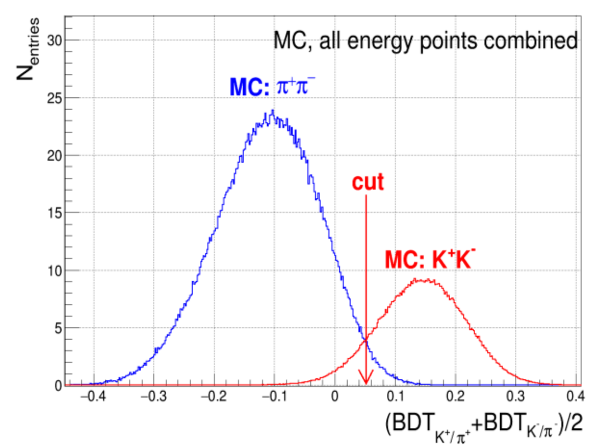
electrons



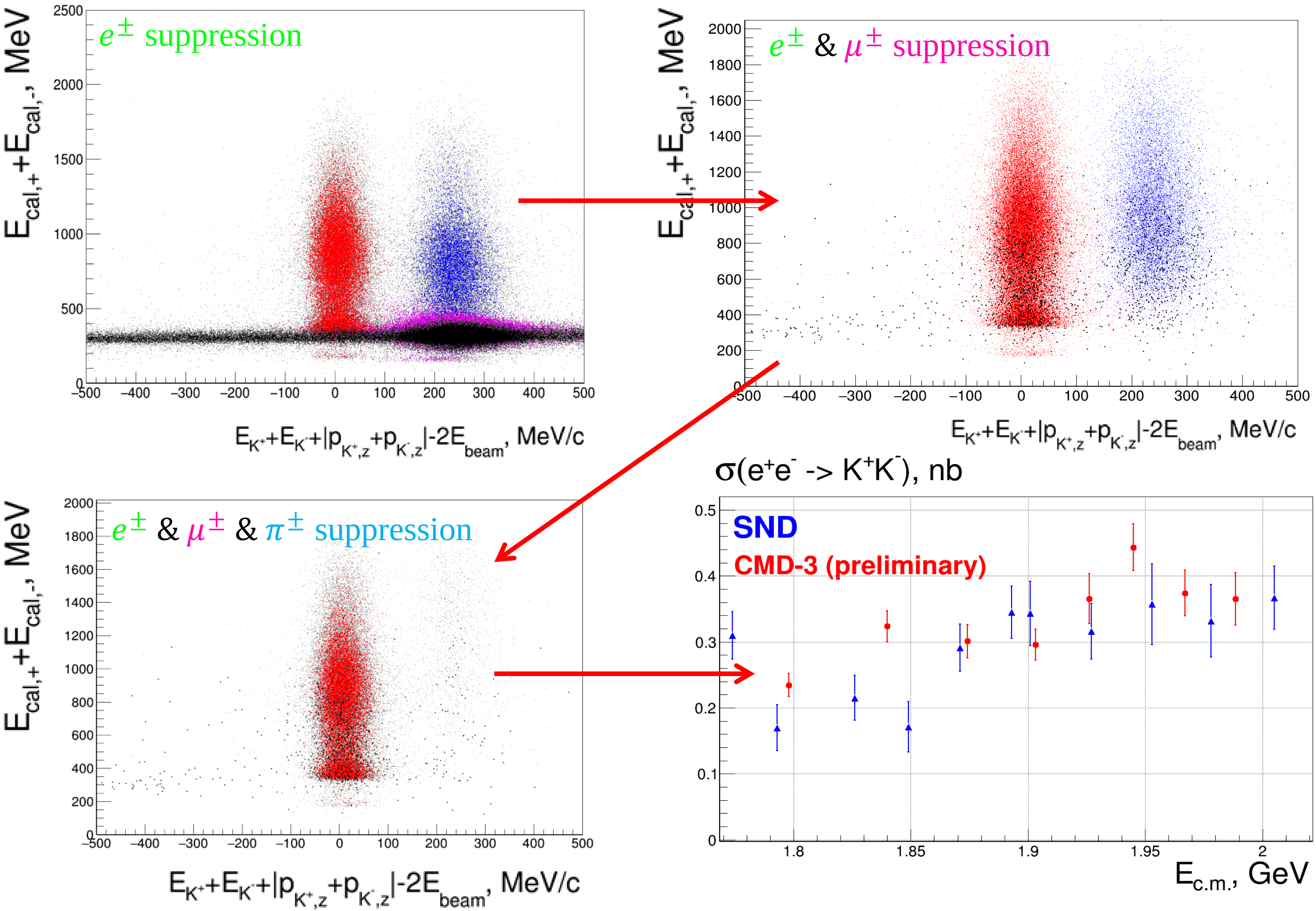
muons



pions



Example: selection of $e^+e^- \to K^+K^-(\gamma)$ at $\sqrt{s} > 1.8$ GeV

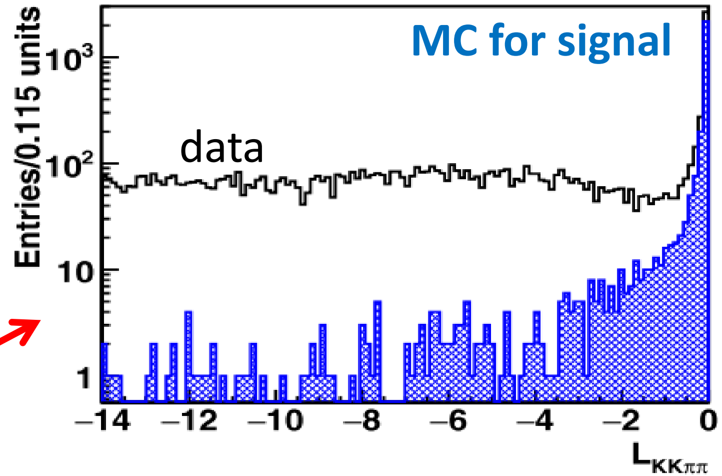


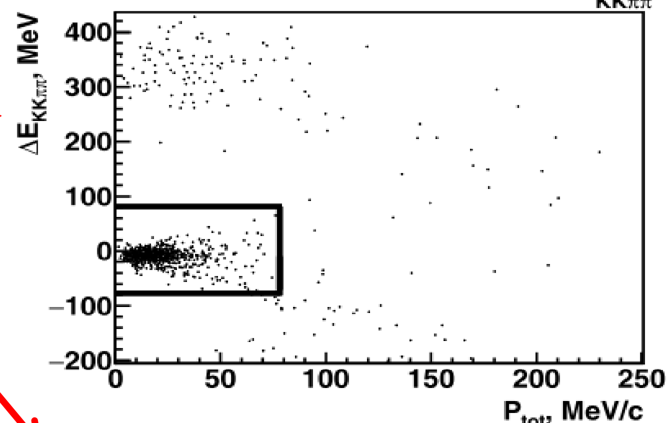
3.1 Study of $e^+e^- \to K^+K^-\pi^+\pi^-$ process

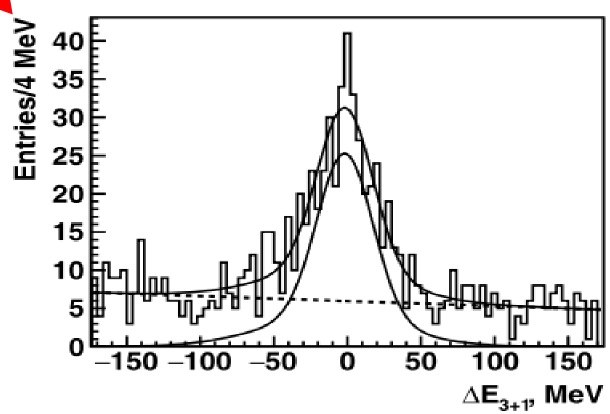
- 2011-2012 energy scan, 23 pb^{-1}
- Event selection: 4 or 3 tracks
- Kaon/pion separation using log-likelihood function based on dE/dx_{DC}:

$$L_{KK\pi\pi} = \ln\left(\frac{\prod f^i_\alpha(p, dE/dx_{DC})}{\prod[f^i_\pi(p, dE/dx_{DC}) + f^i_K(p, dE/dx_{DC})]}\right)$$

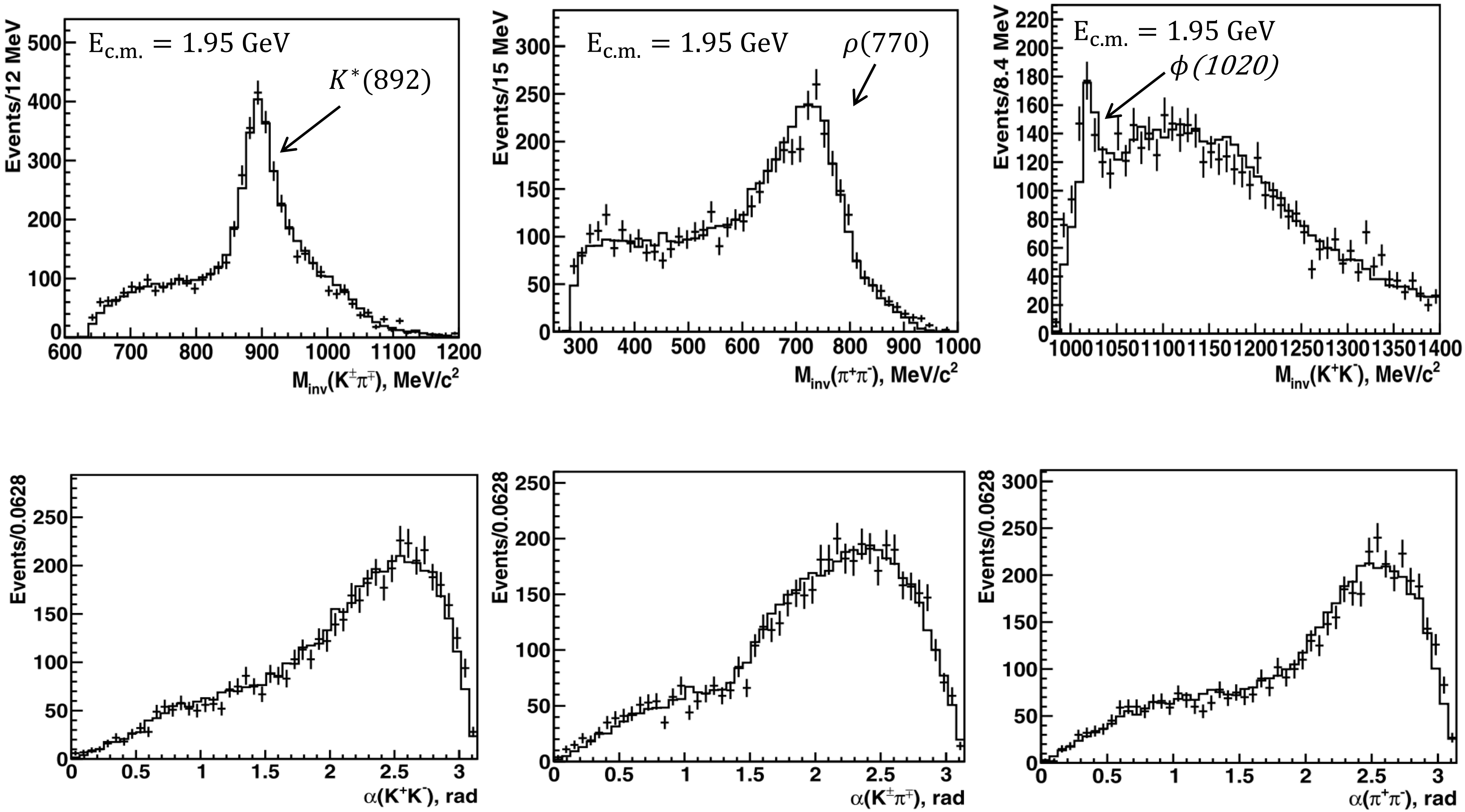
- 4-tracks events: signal events selection using energy-momentum conservation
- 3-tracks events: signal/background separation by fitting energy disbalance distribution
- => ~24k of signal events selected
- The major intermediate states were found to be
  - $f_0(500)\phi$ & $f_0(980)\phi$
  - $\rho(770)(KK)_{S-wave}$
  - $(K_1(1270)K)_{S-wave} \to (K^*(892)\pi)_{S-wave}K$
  - $(K_1(1400)K)_{S-wave} \to (K^*(892)\pi)_{S-wave}K$
  - $(K_1(1400)K)_{S-wave} \to (\rho(770)K)_{S-wave}K$
- Their relative amplitudes were found from the unbinned fit of the data (relative phases were fixed at 0)





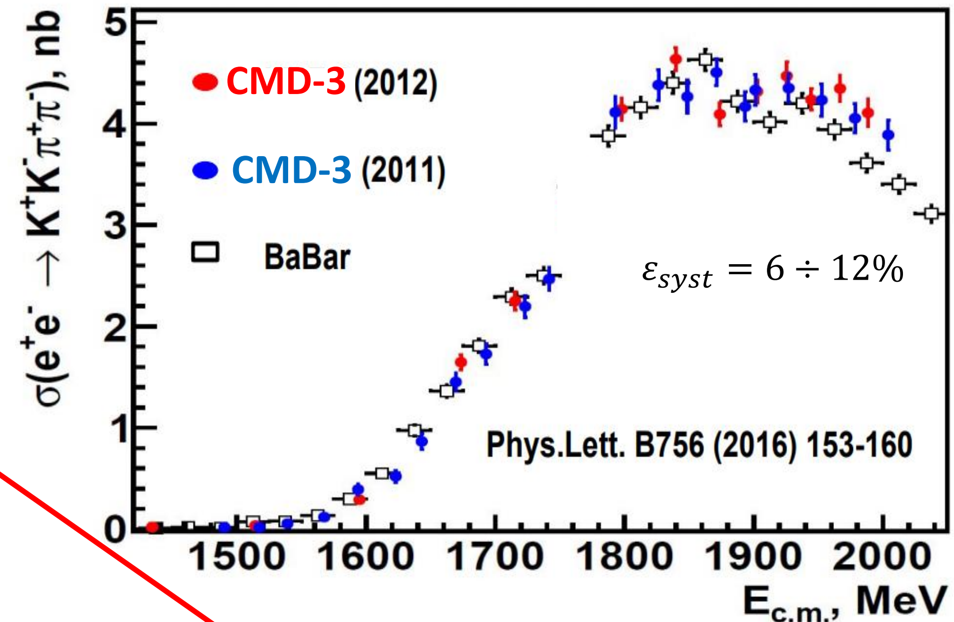


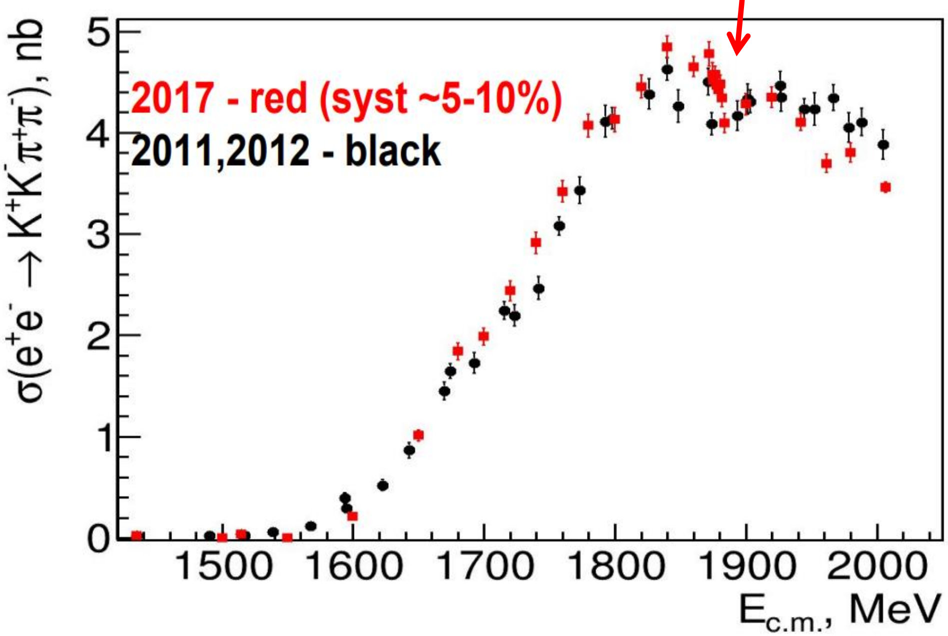
Study of the dynamics of $K^+K^-\pi^+\pi^-$ production

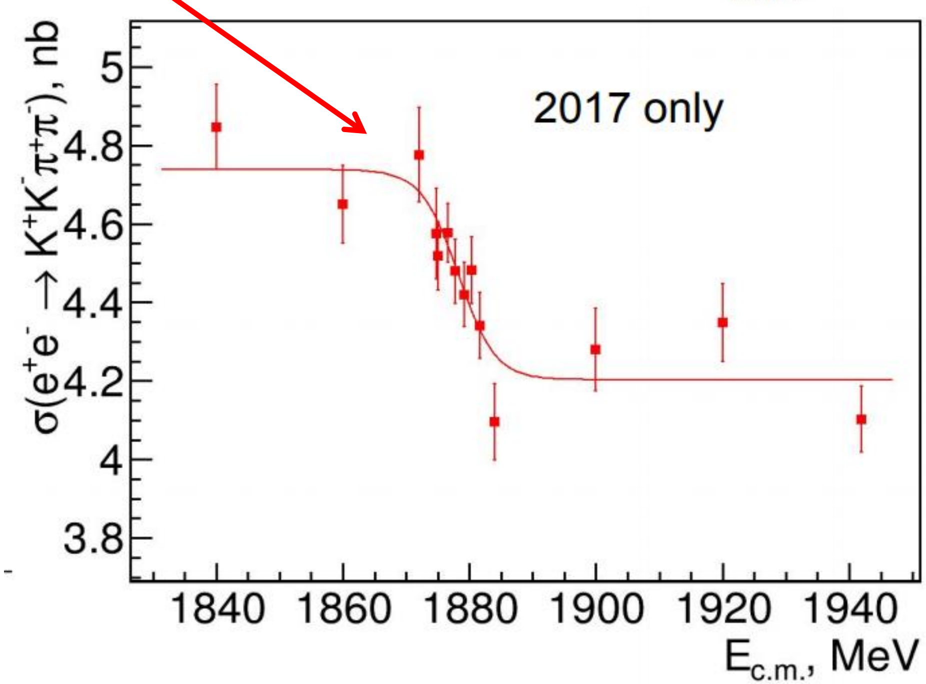


Cross section of the $e^+e^- \to K^+K^-\pi^+\pi^-$ process

- The results for 2011-2012 scan were published, but new 2017 scan with ~60 pb^{-1} of integrated luminosity provided ~3 times more signal events
- First look: we see a systematic drop near $p\bar{p}$ threshold
- But the result is too preliminary to make any statement

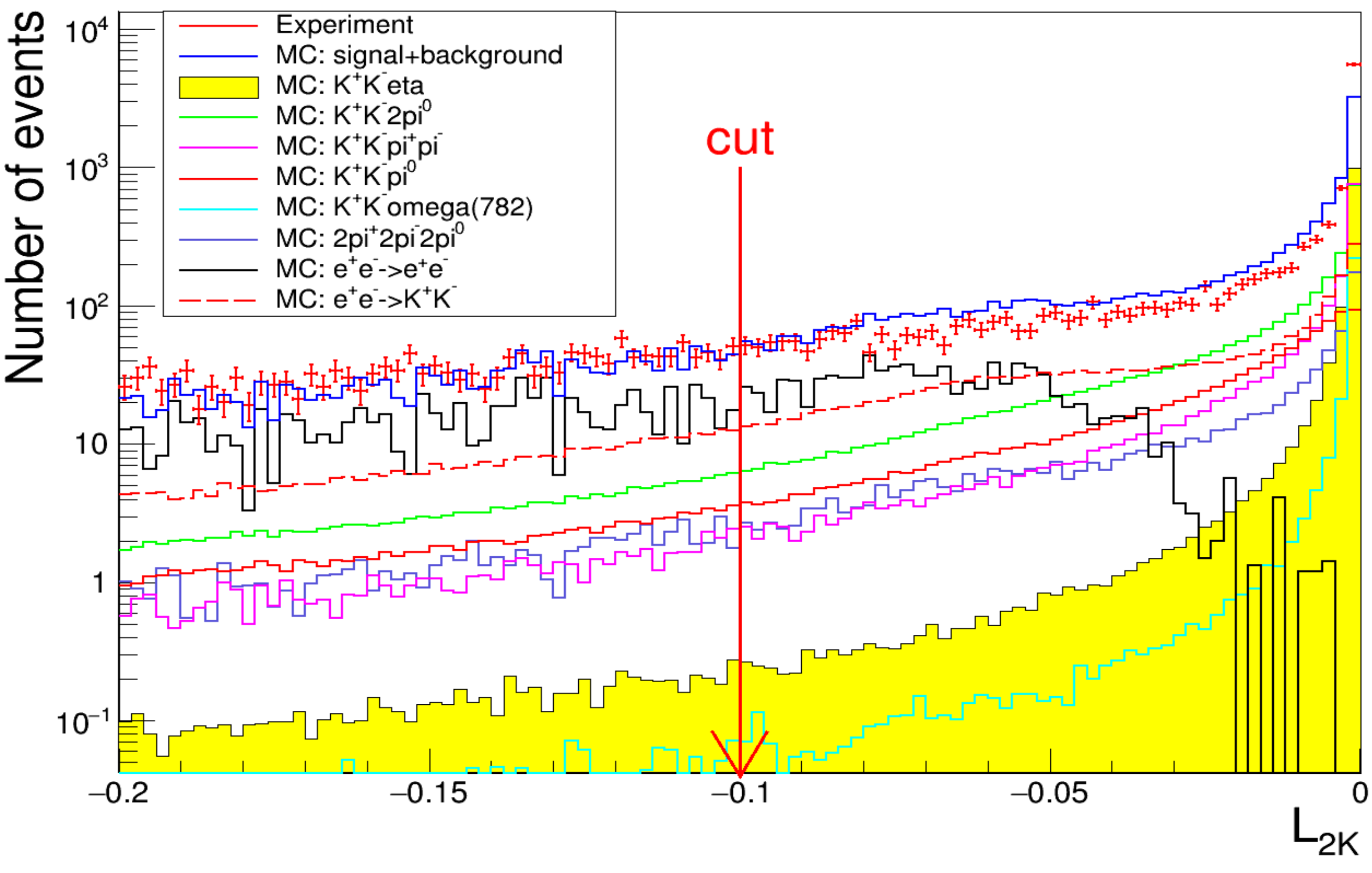






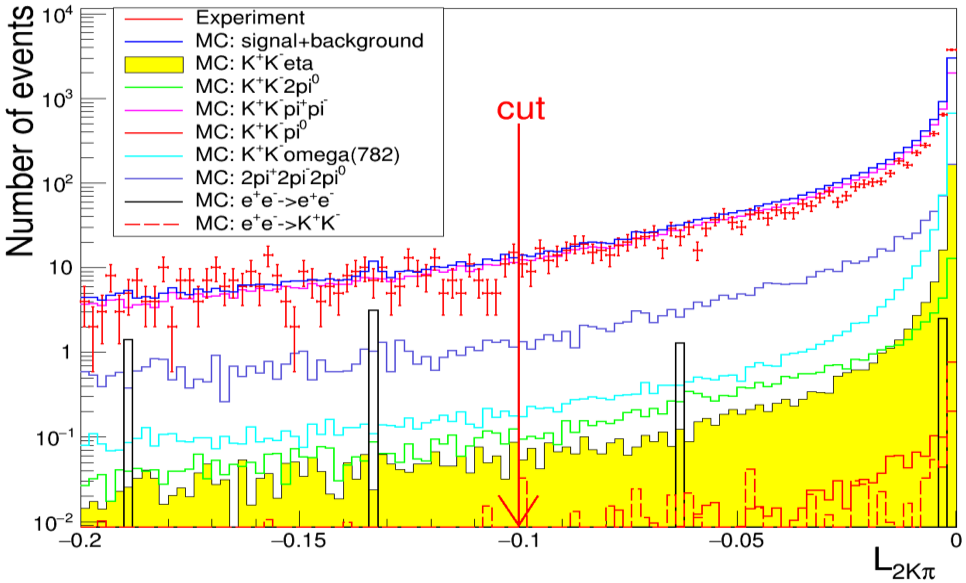
3.2 Study of $e^+e^- \to K^+K^-\eta$ & $K^+K^-\omega(782)$ processes

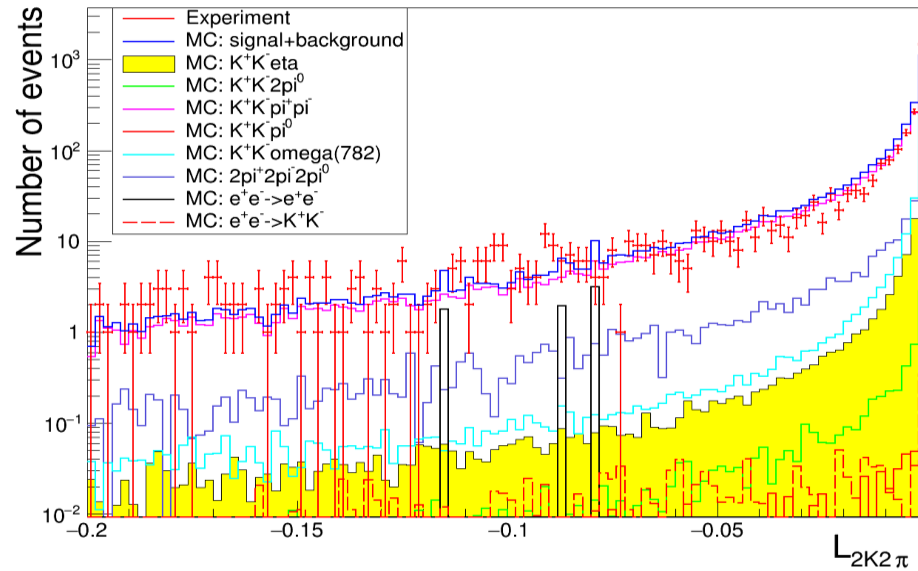
- η and $\omega(782)$ are treated as the recoil particles
- Only $\phi\eta$ intermediate state is seen in $K^+K^-\eta$
- Event classes with 2, 3 and 4 tracks are considered. K/π separation is performed using log-likelihood function. For instance, in 2-track class the distribution is:



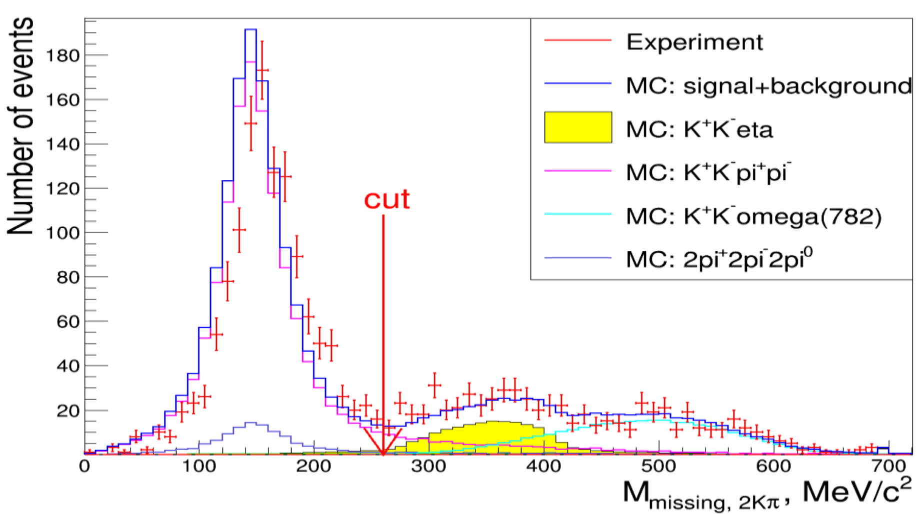
Study of $e^+e^- \to K^+K^-\eta$ & $K^+K^-\omega(782)$ processes

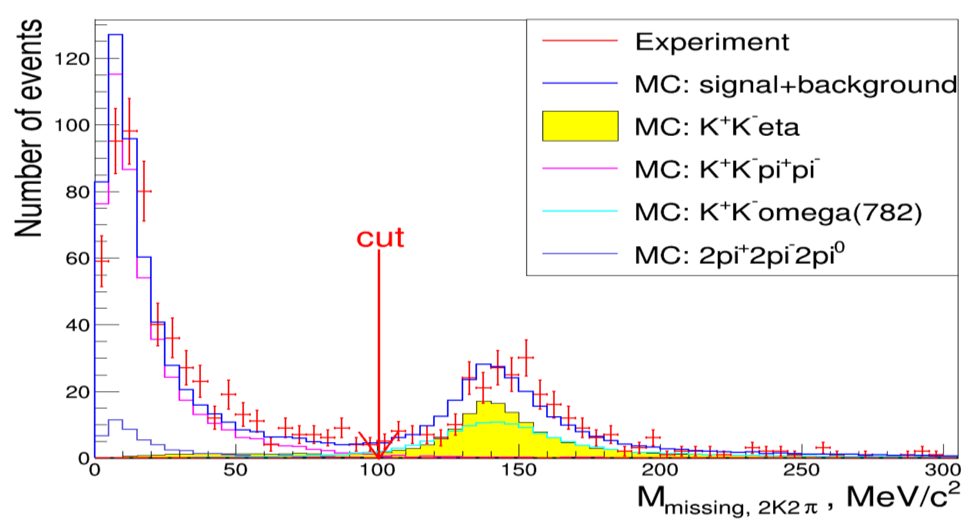
- $K^+K^-\pi^+\pi^-$ is the major background in 3- and 4-track classes:





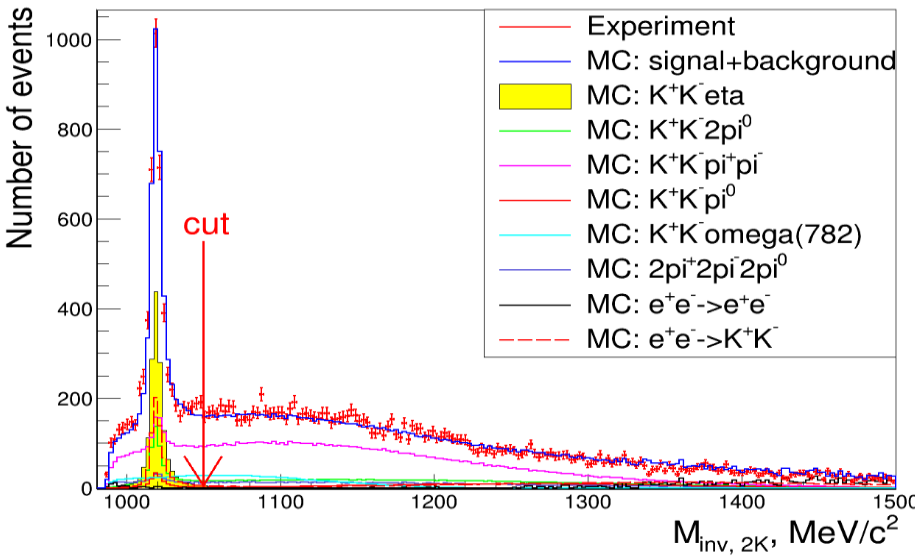
- But it can be suppressed by the cuts on $2K\pi$ and $2K2\pi$ missing masses:

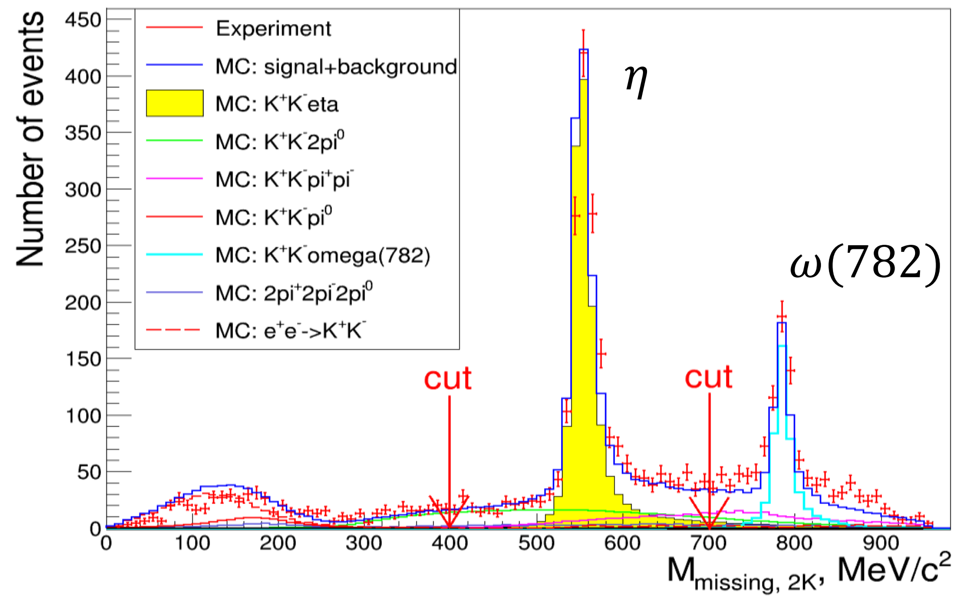




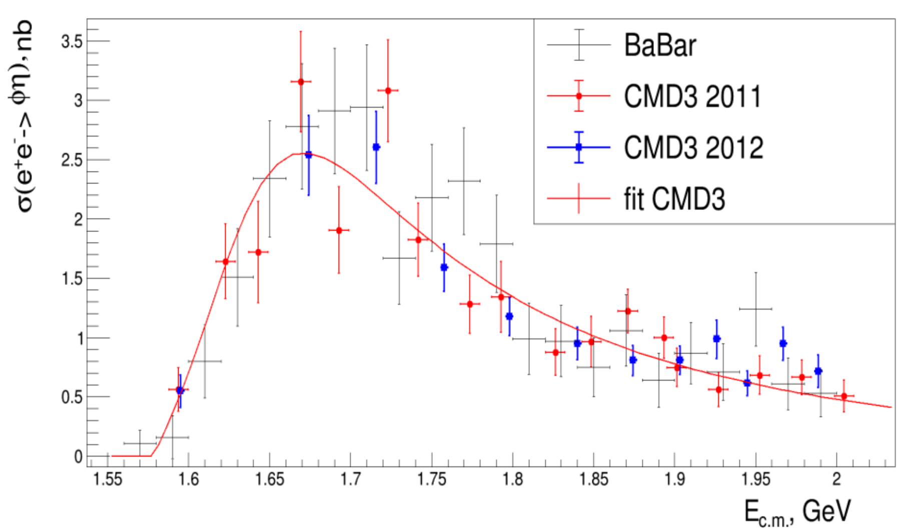
Study of $e^+e^- \to K^+K^-\eta$ & $K^+K^-\omega(782)$ processes

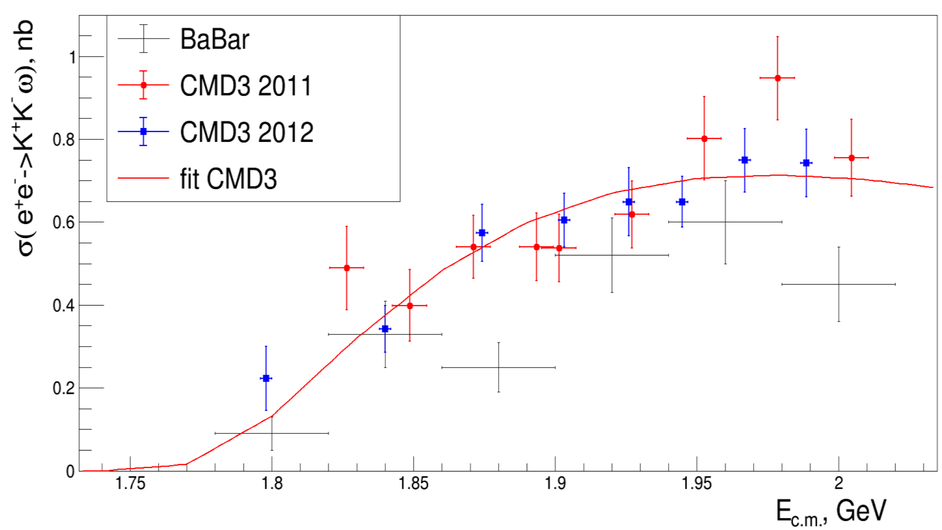
- $\phi\eta$ selection:





- Signal/background separation for both processes is performed by fitting of $m_{miss,2K}$ distribution





$e^+e^- \to \phi\eta$ cross section fitting

- Fitting of the $e^+e^- \to \phi\eta$ cross section is the one of the best way for $\phi(1680)$ parameters extraction
- Cross section of $e^+e^- \to \phi\eta$ is parametrized by quasi-two body formula

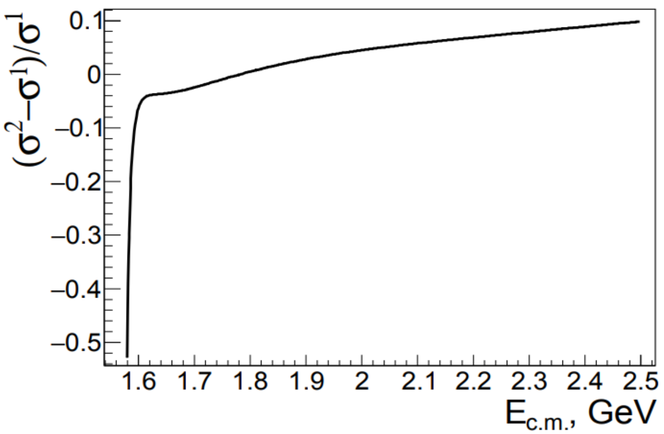
$$\sigma^{(1)}_{\phi\eta}(s) = 12\pi \frac{|\vec{p}_\phi(\sqrt{s})|^3}{s^{3/2}} F(s)$$ or, more precisely, as three-body expression

$$\sigma^{(2)}_{\phi\eta}(s) = \frac{27\Gamma_\phi m_\phi^2}{\pi^2 |\vec{p}_K(m_\phi)|^3 s} F(s) \cdot \int |\vec{p}_{K+} \times \vec{p}_{K-}|^2 sin^2(\theta_{\text{normal}}) |D_\phi(p_\phi^2)|^2 d\Phi_{K+K-\eta}(\sqrt{s})$$

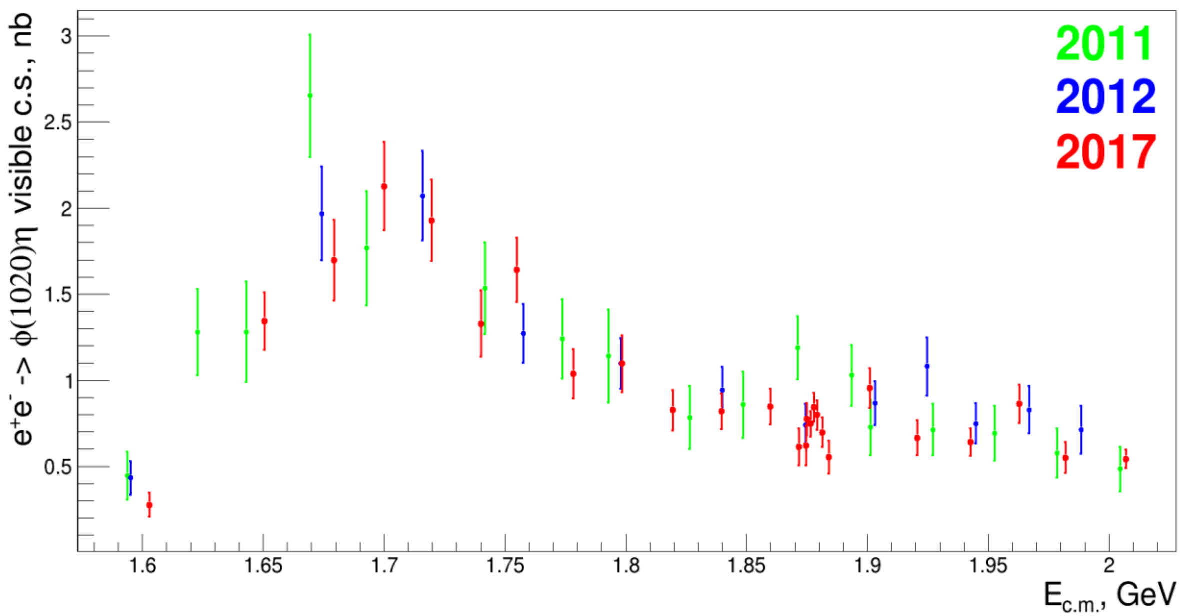
with $$F(s) = \left| A_{\text{non}-\phi'}(s) e^{i\Psi} + \sqrt{\frac{(\Gamma^{\phi'}_{ee}\mathcal{B}(\phi' \to \phi\eta))\Gamma_{\phi'} m^3_{\phi'}}{|\vec{p}_\phi(m_{\phi'})|^3}} D_{\phi'}(s) \right|^2$$

Table 2: The ϕ' parameters obtained from the fit.

Parameter	Value
χ^2/n.d.f	46.3/33≈1.4
$\Gamma^{\phi'}_{ee}\mathcal{B}(\phi' \to \phi\eta)$, eV	$163 \pm 37_{\text{stat}} \pm 6_{\text{mod}}$
$m_{\phi'}$, MeV	$1690 \pm 12_{\text{stat}} \pm 3_{\text{mod}}$
$\Gamma_{\phi'}$, MeV	$327 \pm 88_{\text{stat}} \pm 14_{\text{mod}}$



- New data of 2017 scan is being analyzed and new $\phi(1680)$ - dedicated scans are planned for near future => we are at good disposition to perform the most precise study of ϕ'



$e^+e^- \to K^+K^-\omega(782)$ cross section fitting

$$\sigma_{K^+K^-\omega}(s) = \frac{9(\Gamma_{ee}^{\phi'} g^2_{\phi' K^+K^-\omega}) m^3_{\phi'} \Gamma_\omega}{(2\pi)^5 m_\omega C_{\omega\to 3\pi} s^2} |D_{\phi'}(s)|^2 \cdot \int |D_\omega|^2 |D_{\rho^0} + D_{\rho^+} + D_{\rho^-}|^2 (|J_x|^2 + |J_y|^2) d\Phi_{K^+K^-\pi^+\pi^-\pi^0}(\sqrt{s})$$

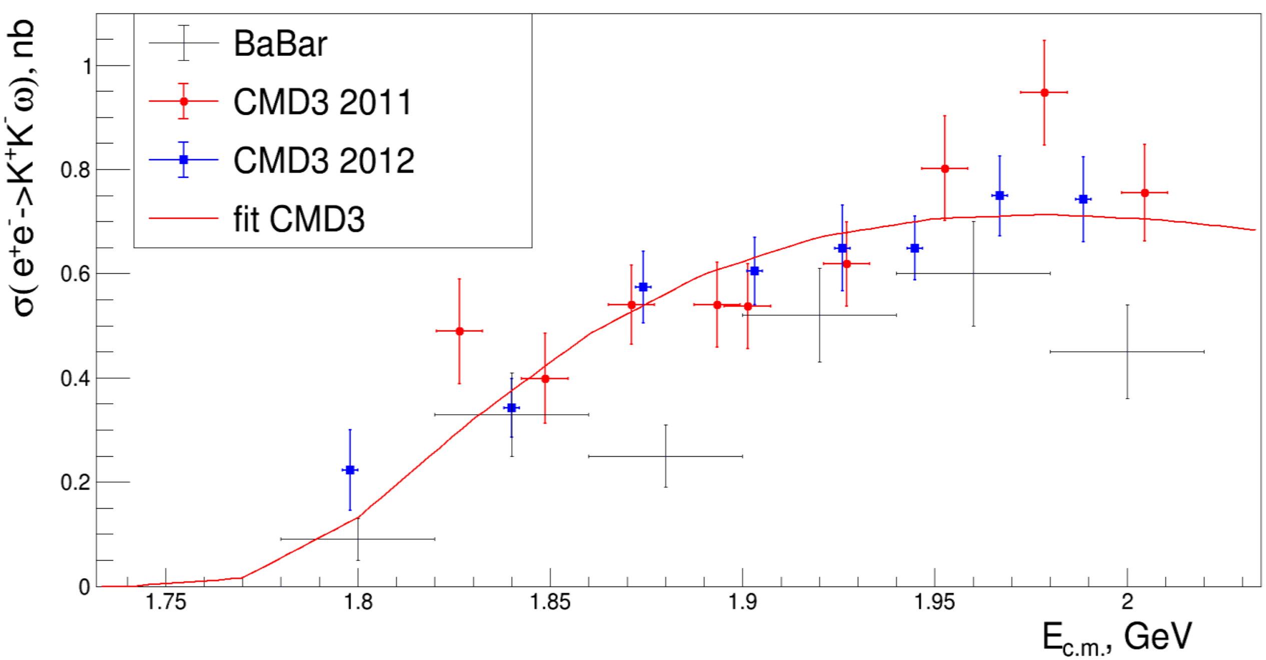
where

$$C_{\omega\to 3\pi} = \int |[\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}] D_{\rho^0} + [\vec{p}_{\pi^0} \times \vec{p}_{\pi^-}] D_{\rho^-} + [\vec{p}_{\pi^+} \times \vec{p}_{\pi^0}] D_{\rho^+}|^2 d\Phi_{\pi^+\pi^-\pi^0}(m_\omega)$$

and the components of hadronic current $J_{x,y}$ are

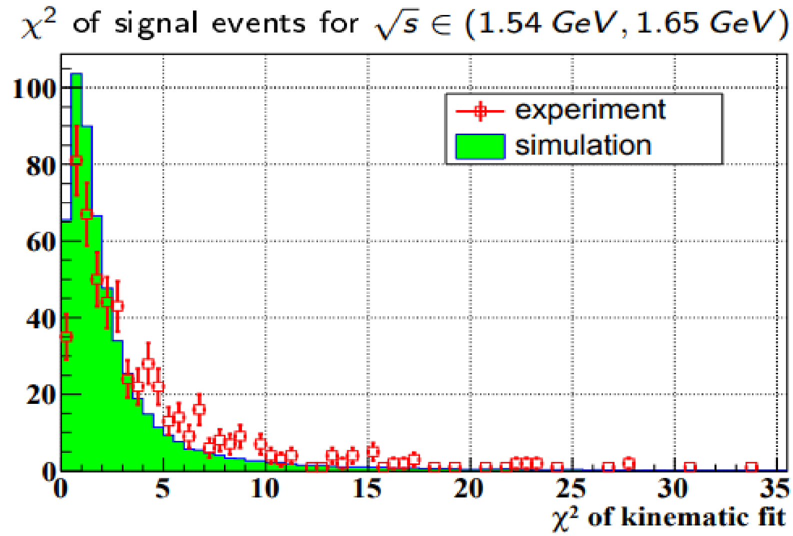
$$J_x = \epsilon_{\pi^0}(p^y_{\pi^+} p^z_{\pi^-} - p^y_{\pi^-} p^z_{\pi^+}) + \epsilon_{\pi^+}(p^y_{\pi^-} p^z_{\pi^0} - p^y_{\pi^0} p^z_{\pi^-}) + \epsilon_{\pi^-}(p^y_{\pi^0} p^z_{\pi^+} - p^y_{\pi^+} p^z_{\pi^0})$$

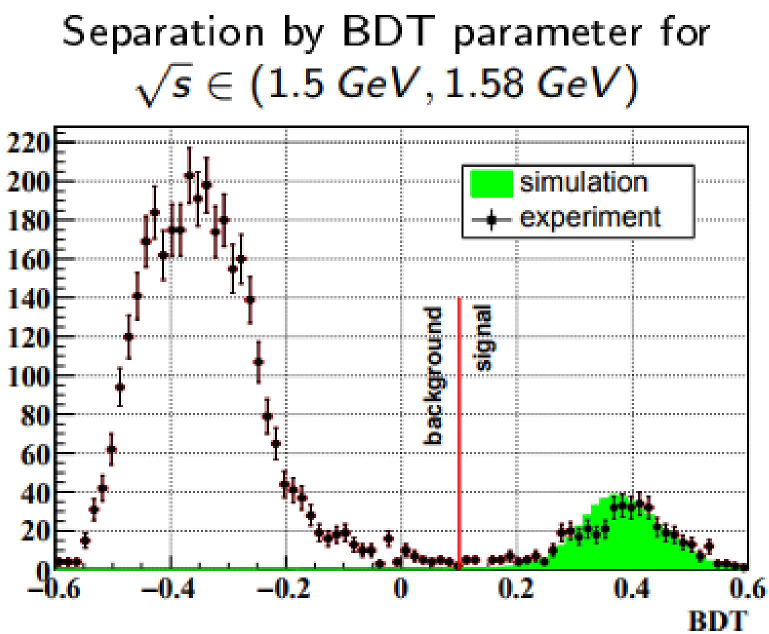
$$J_y = \epsilon_{\pi^0}(p^x_{\pi^-} p^z_{\pi^+} - p^z_{\pi^-} p^x_{\pi^+}) + \epsilon_{\pi^+}(p^x_{\pi^0} p^z_{\pi^-} - p^z_{\pi^0} p^x_{\pi^-}) + \epsilon_{\pi^-}(p^x_{\pi^+} p^z_{\pi^0} - p^x_{\pi^0} p^z_{\pi^+})$$

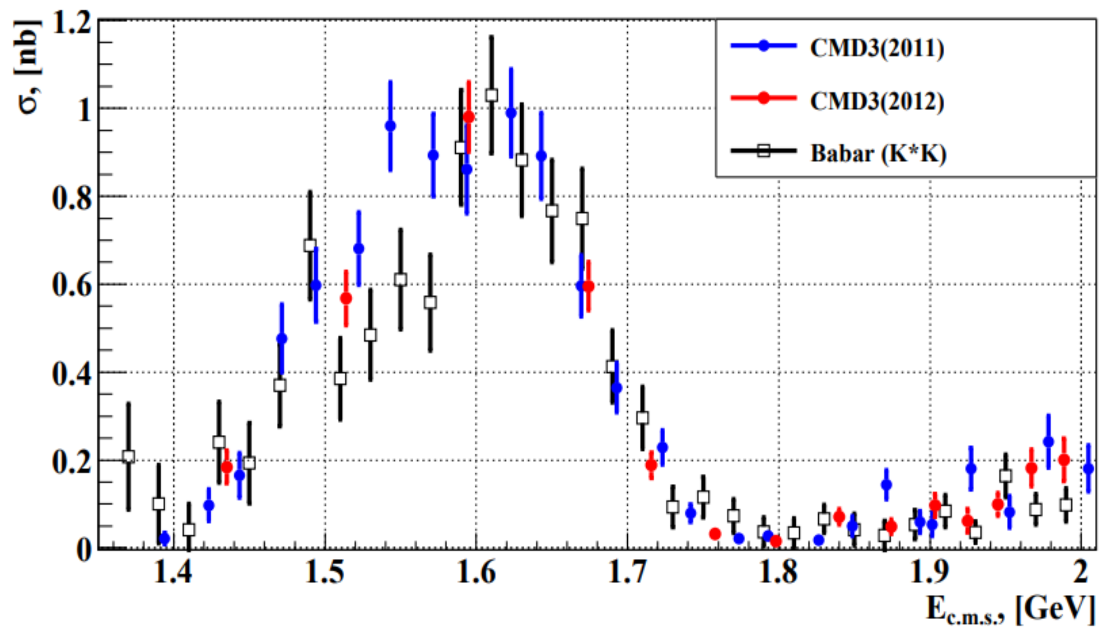


3.3 $K^+K^-\pi^0$ final state

- Events selection: 2 tracks, >= 2 photons
- 4C kinematic fit with all the photon pairs (energy-momentum conservation required), $\chi^2 < 35$
- The main backgrounds: $K^+K^-\gamma$, $K^+K^-2\pi^0$, $K^\pm K_{S,L}\pi^\mp$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-2\pi^0$
- The background suppression is performed by the training of BDT classifier. The input variables are: 1) dE/dx_{DC}, 2) momenta and angles of charged particles & photons 3) $m^2{}_{miss,2K}$







Conclusion & Plans

- CMD-3 collaboration is progressing in datataking and data analysis for the $e^+e^- \to K\overline{K}(n)\pi$ processes
- K/π separation is the starting point and key issue for such processes => the charged PID procedure using dE/dx_{LXe} is being developed
- $e^+e^- \to K\overline{K}(n)\pi$ processes has reach dynamics, provide a case for isotopic relations test and, especially, for $\phi(1680)$ parameters measurement

Thank you for attention!