Measuring the cross sections of the processes $e^+e^- \to K_L K_S \pi^+\pi^-$, $K^+K^-\pi^+\pi^-$ with the CMD-3 detector at the VEPP-2000 electron-positron collider

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On behalv CMD-3 collaboration

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Layout of my talk

- Collider VEPP-2000, CMD-3 detector, data collection history
- Main selection criteria to extract signal events of the processes
  $e^+e^- \to K_L K_S \pi^+\pi^-$, $K^+K^-\pi^+\pi^-$
- Kinematic reconstruction and determination the number of signal events
- Cross section calculation and comparison with the results of other experiments

Motivation

- At low energies, direct measurements of hadron cross sections are necessary, since they cannot be calculated within the framework of QCD with the required accuracy
- The energy dependence of hadron cross sections is an important source of information on the mechanisms of hadronization of quarks into final particles in each individual channel
- Precision measurements of the cross section allow us to reconstruct the intermediate dynamics and improve the accuracy of calculating the hadronic contribution to the (g-2)/2 muon
- Such measurements allow us more accurate determination of resonance parameters in the energy range of the VEPP-2000 collider

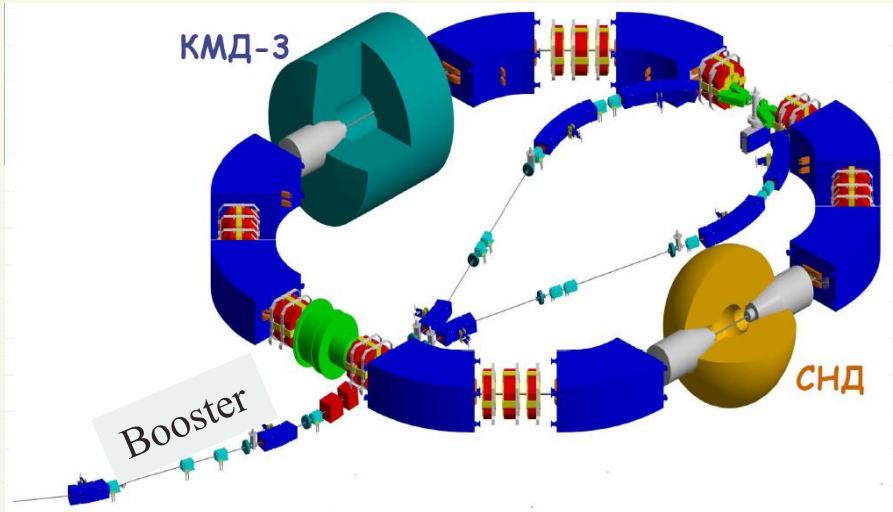
Collider VEPP-2000 (BINP, Novosibirsk)

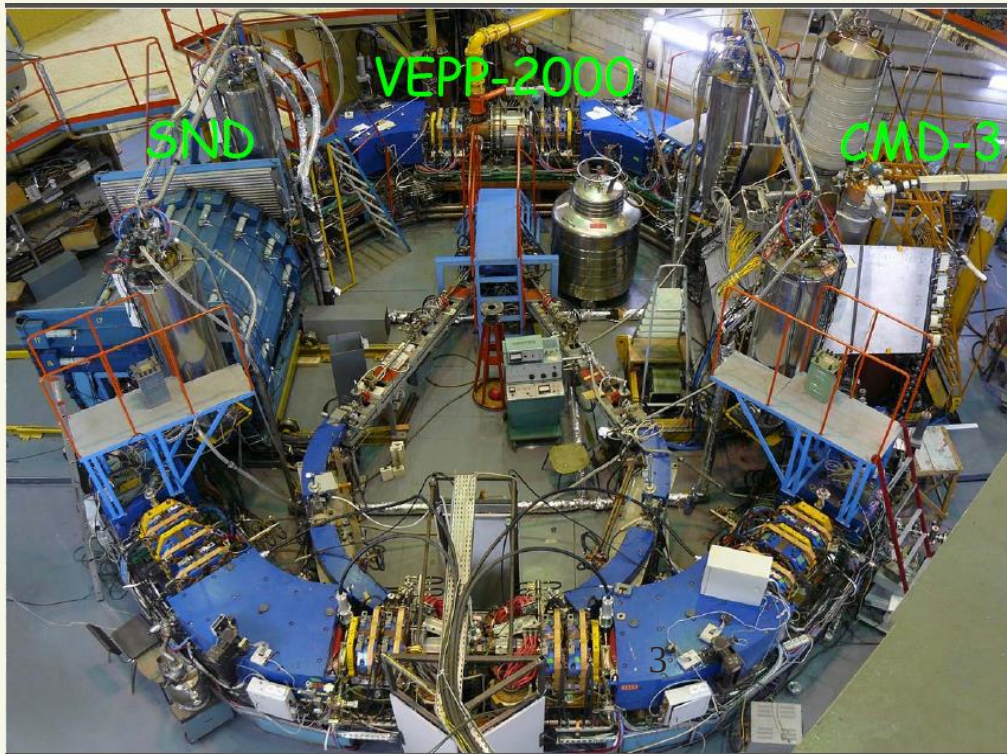
Data were collected in the energy range of 0.32 to 2.01 GeV. The beam energy was monitored by measuring energy of laser photons during their backscattering with special counter an accuracy of ~ 50 keV every 10-20 minutes

The "round beams" method was used for the first time. Focusing solenoids with a magnetic field of 13 T were installed near the beam interaction points

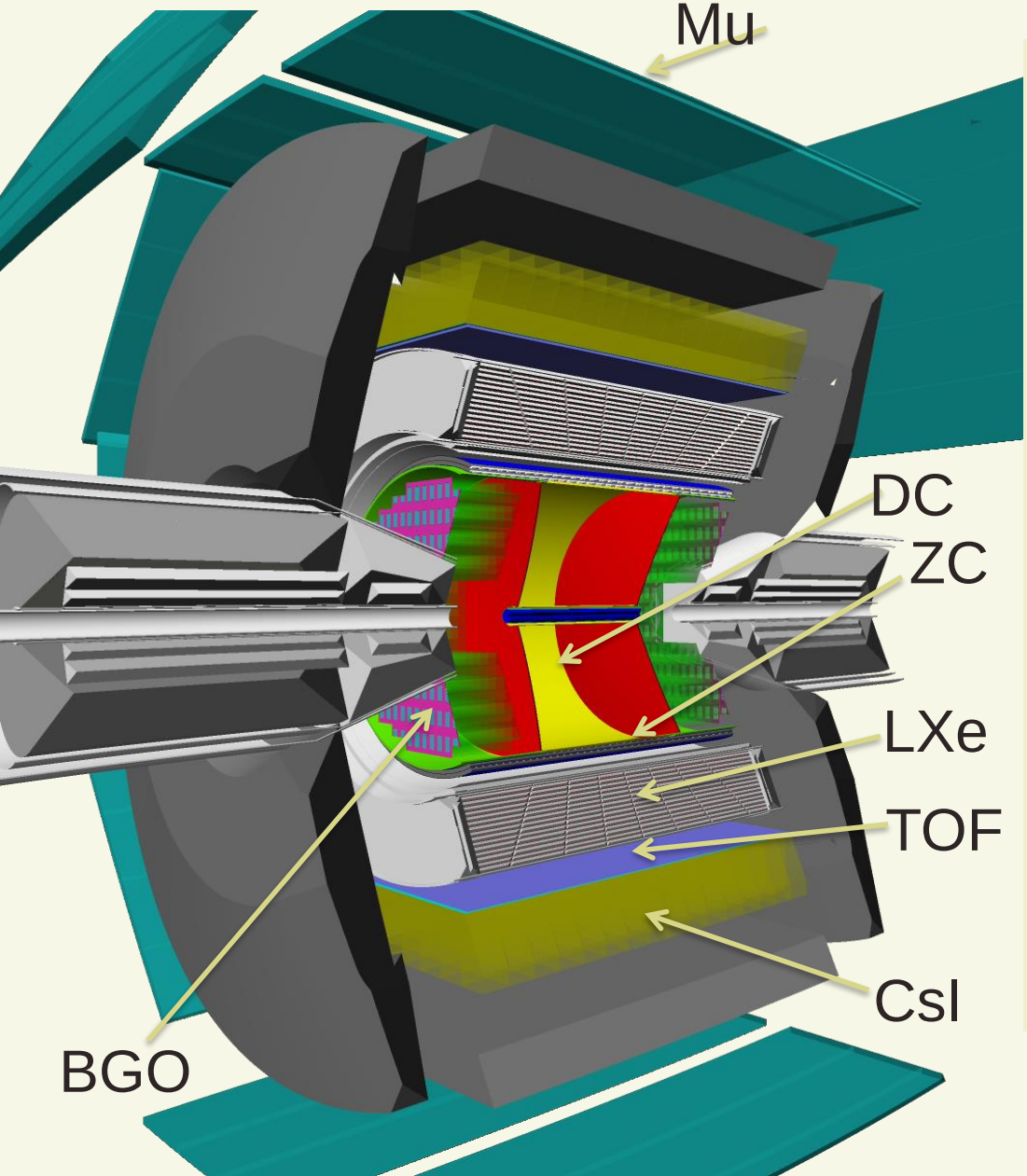
The achieved peak luminosity is ~ 8×10^{31} cm^{-2} s^{-1} (design ~ 10^{32} $cm^{-2}s^{-1}$).
A record luminosity integral of ~1000 pb^{-1} has been achieved

Two detectors CMD-3 and SND are installed opposite each other at two beam interaction points





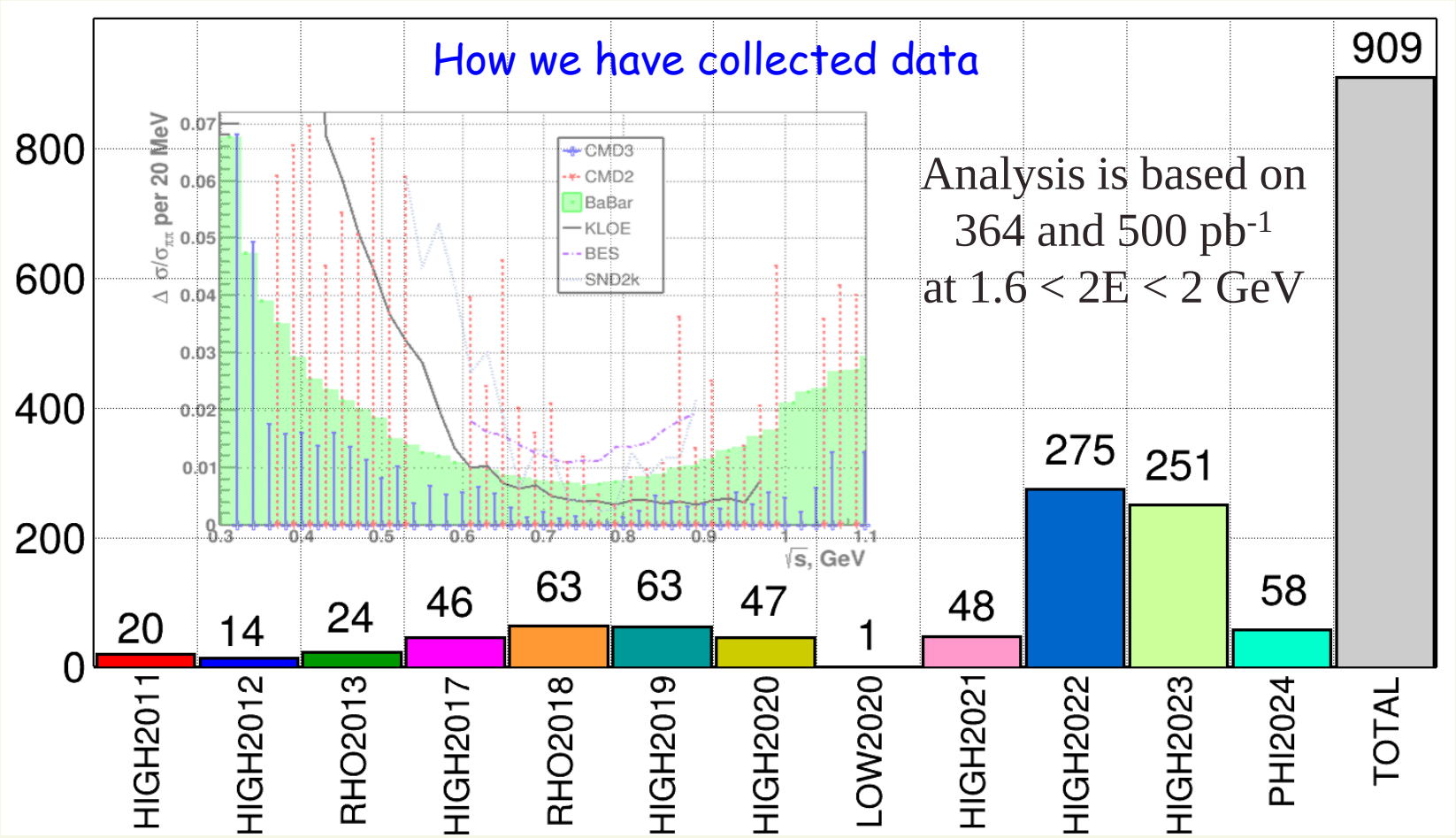
CMD-3 DETECTOR



- DC – 1218 hexagonal cells with sensitive wires, W-Re alloy, 15 μ in diameter, spatial resolution ~ $\sigma_{R\varphi}$ ~ 100 μm, σ_Z ~ 2.5mm
  σP/P ~ √0.62+(4.4*p[GeV])2 ,%
- Z-chamber – start FLT, precise z-coordinate ~ 500 μ (detector acceptance)
- LXe calorimeter thickness 5,1X_0, 196 towers & 1286 strips. Spatial resolution 1 – 2 mm, for photon point conversion
  σE /E ~ 0.034/ √E [GeV] ⊕ 0.020 - barrel
  σE /E ~ 0.024/√E [GeV] ⊕ 0.023– endcap
- Calorimeter with CsI crystals (~3,5 t), 8 octants, number of crystals - 1152, ~8X_0
- TOF – 16 counters, time resolution ~ 0.5 ns mainly for anti neutron detection
- MR system – 8 octants (cosmic veto, ~ 1ns) particle ID
- Magnetic field is about 1.3 T

CMD-3: data taking history

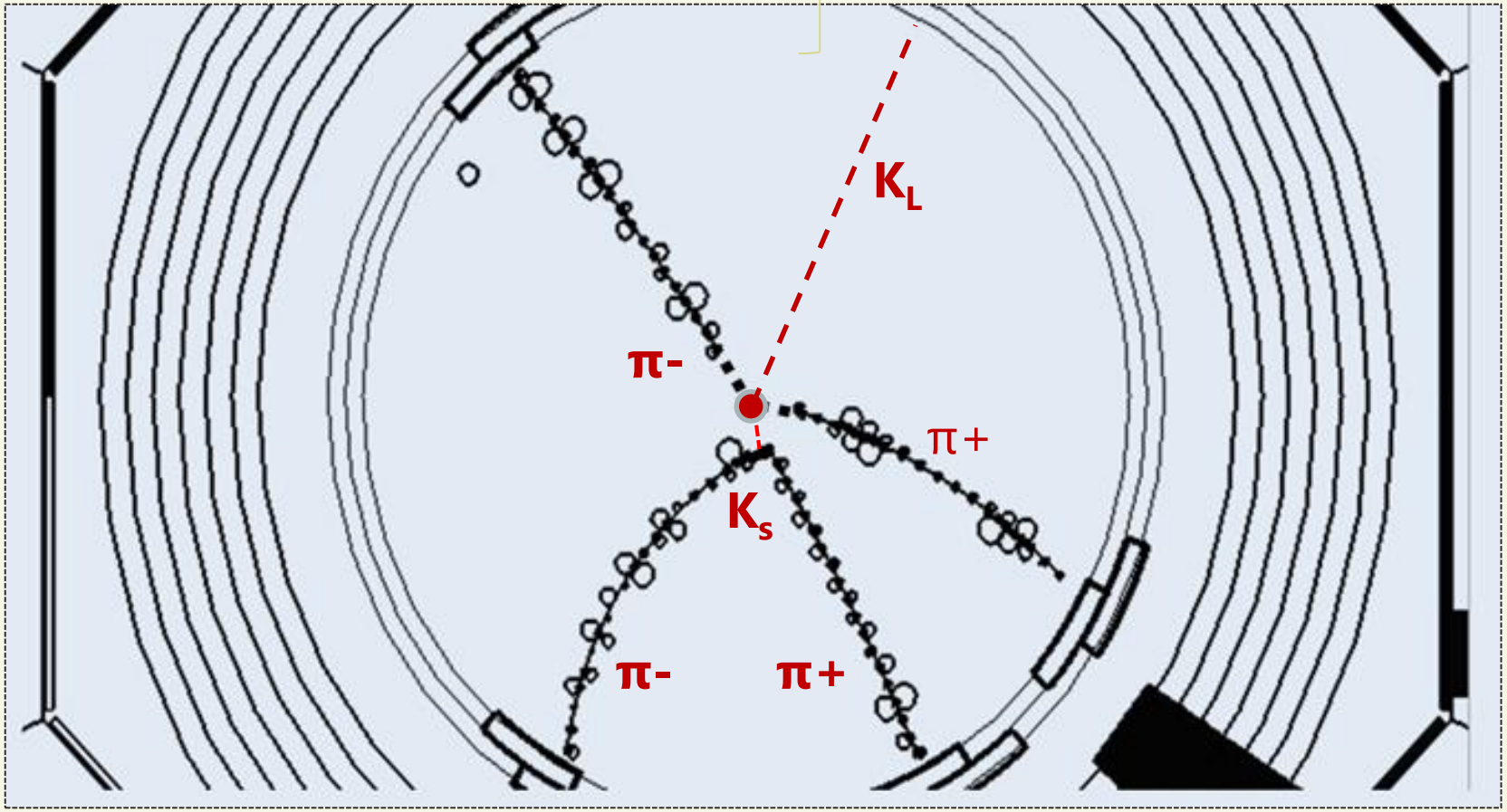
- Before upgrade (2011-2013) luminosity at high energies was limited by deficit of positrons and limited energy of the booster
- 2017: new injection complex and booster gave a big improvement in luminosity
- 2018: “Beamshaking” technique was introduced too at low energies, which suppressed beam instabilities that increased luminosity by a factor of 4



How event e+e-⟶ $K_L K_S \pi^+\pi^-$ looks on CMD-3 display

2020	**1.4K**
2021	**1.1K**
2022	**3.2K**

Number of selected events in different energy scans



● - Beam axis

--------- - Decay length of K_L, Ks

Some kinematic criteria of the events selection with 4 good tracks

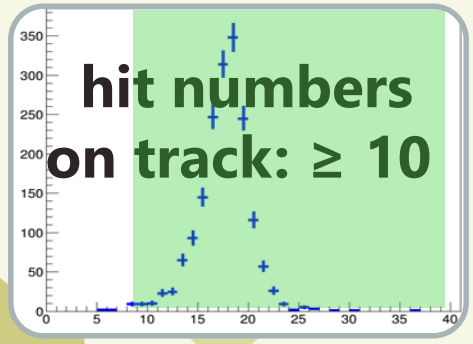
One Ks

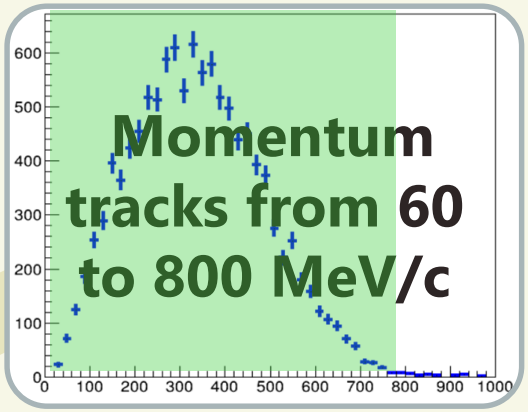
4 and more good tracks

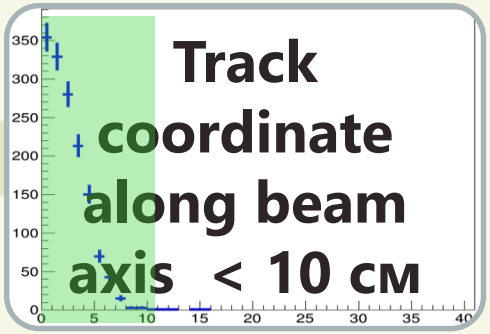
2 and more tracks coming from IP

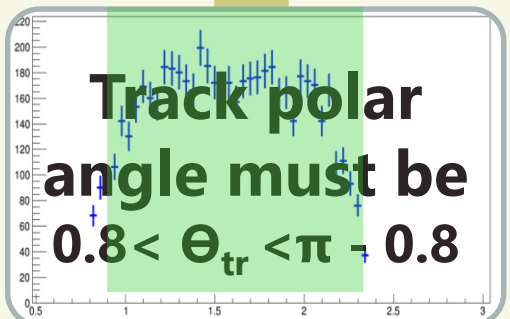
Total charge = 0

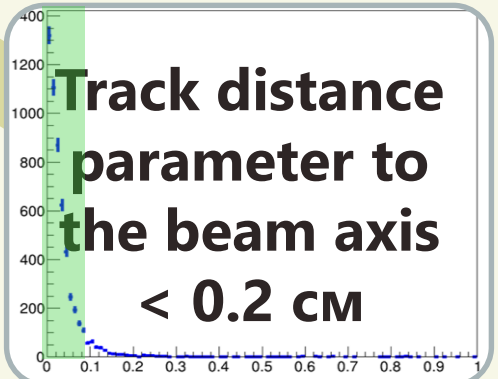
Tracks



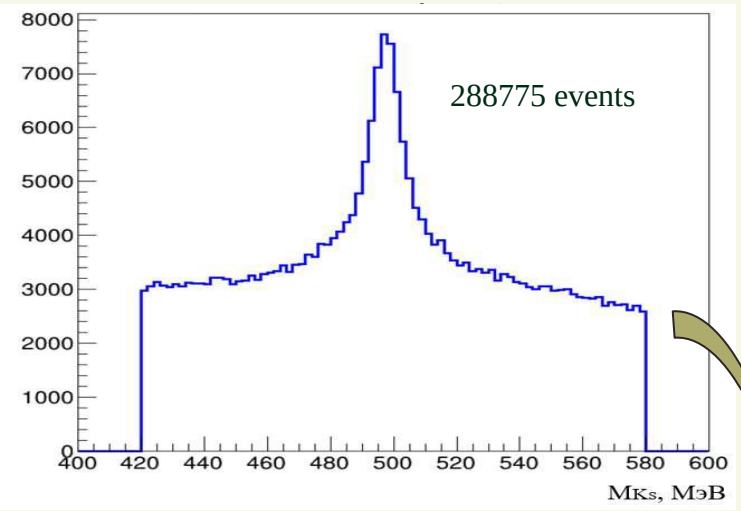






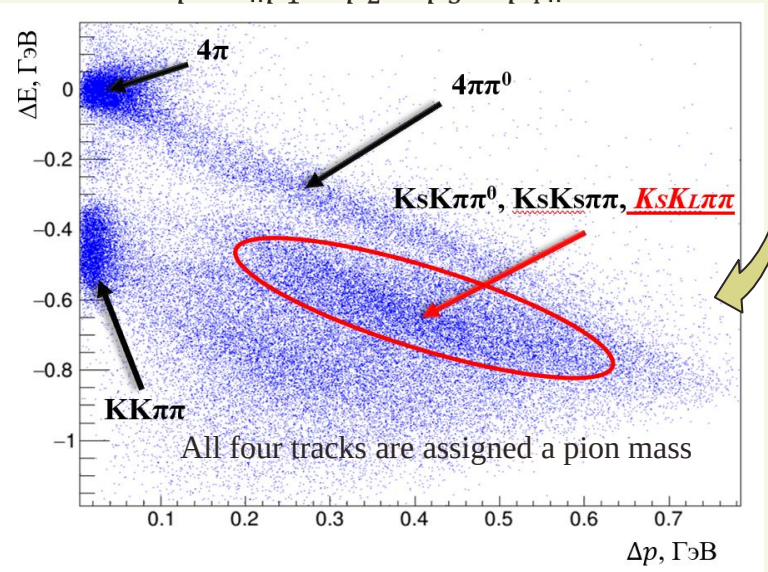


Distribution of events depending on the invariant mass of two tracks sorted out
(to look for Ks candidates)
Only those pairs of tracks are selected that have a vertex that is separated from the beam axis by



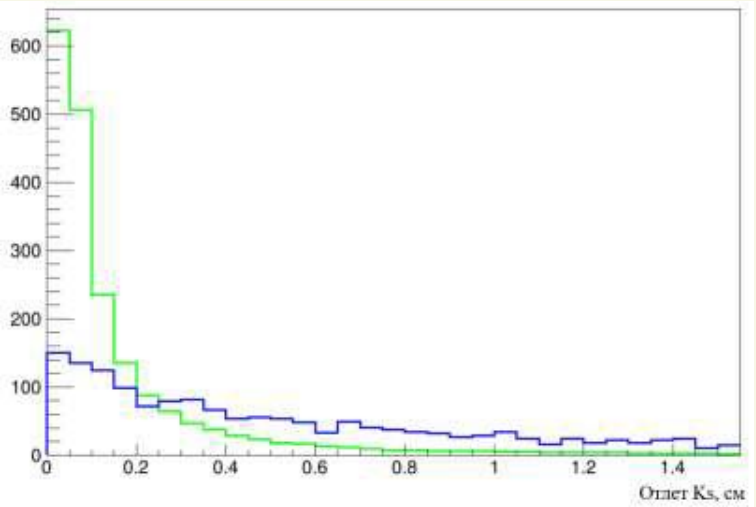
$$\Delta E = E_1 + E_2 + E_3 + E_4 - 2E_{beam}$$

$$\Delta p = \|\vec{p}_1 + \vec{p}_2 + \vec{p}_3 + \vec{p}_4\|$$

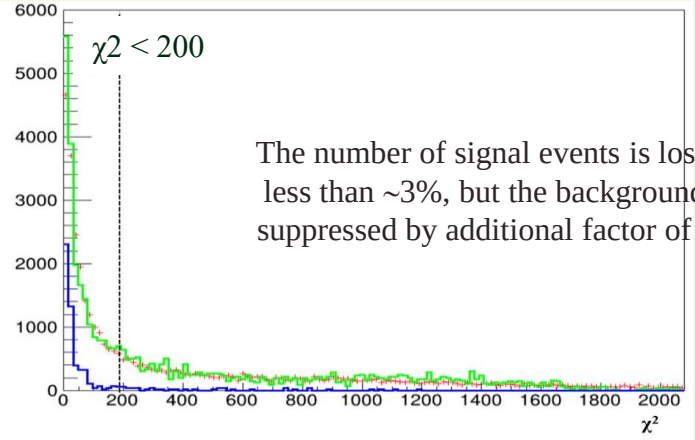


Distribution of events depending on the distance of the decay vertex of two tracks (Ks candidates) to the beam axis.

Signal events are shown in blue, 4π events in green (one of the main physical background)

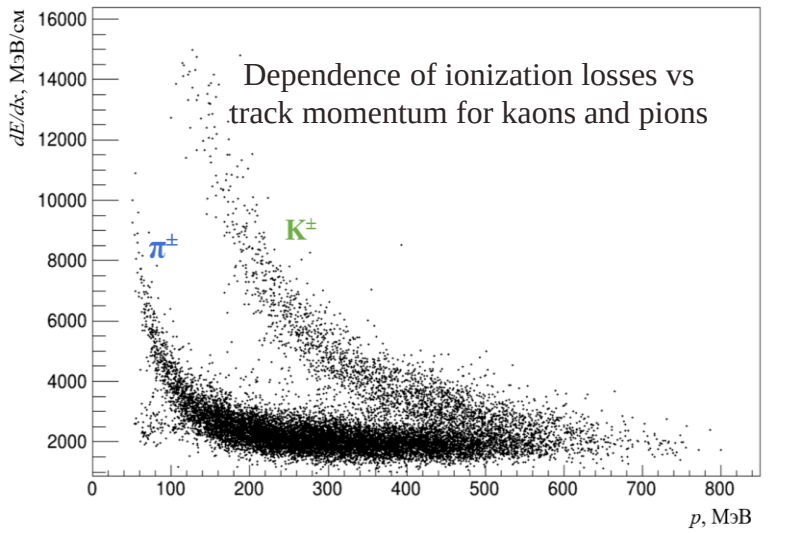


Kinematic reconstruction is carried out in three hypotheses (signal and two background 4ππ° и $K_SK\pi\pi°$)



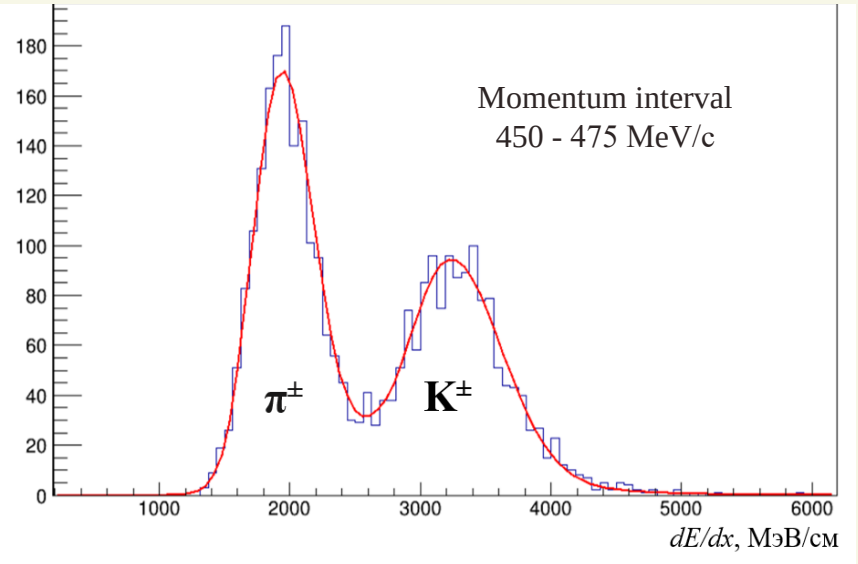
χ2 distribution for kinematic reconstruction in the signal hypothesis. Blue color – modeling of signal events, green – modeling of background, red – experiment.

To suppress events with charged kaons, the K/π separation technique is used, based on measuring ionization losses in DC



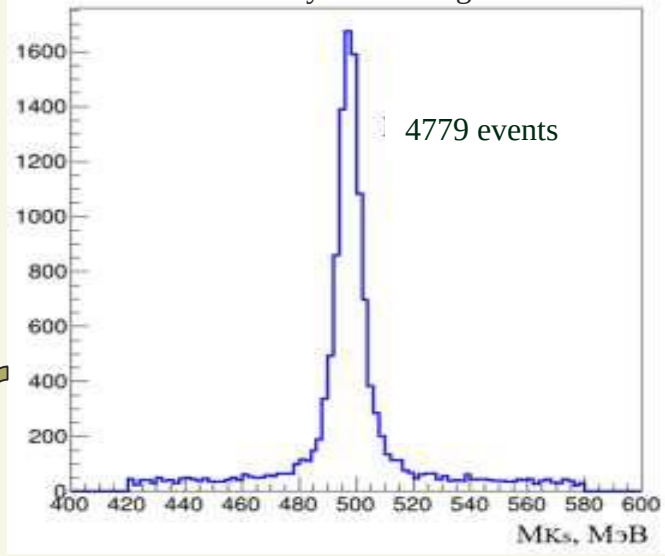
Each PDF function is the sum of a normal and log-normal distribution.

$$L_{\pi\pi\pi\pi} = \ln \frac{\prod f_\pi^i(p,dE/dx)}{\prod [\, f_\pi^i(p,dE/dx) + f_K^i(p,dE/dx)\,]}$$

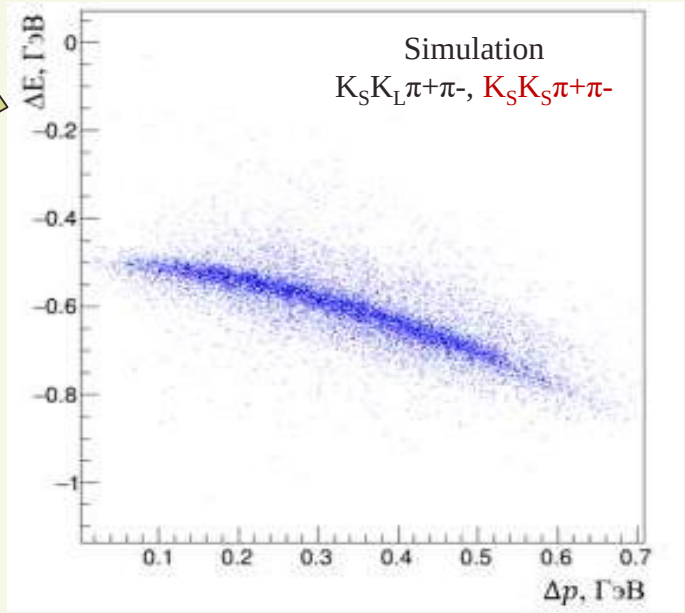


Square of the invariant mass of a pair of tracks from candidate on event decays to K_S

Only those pairs of tracks are selected that have a vertex that is separated from the beam axis by distances greater than 2 mm.



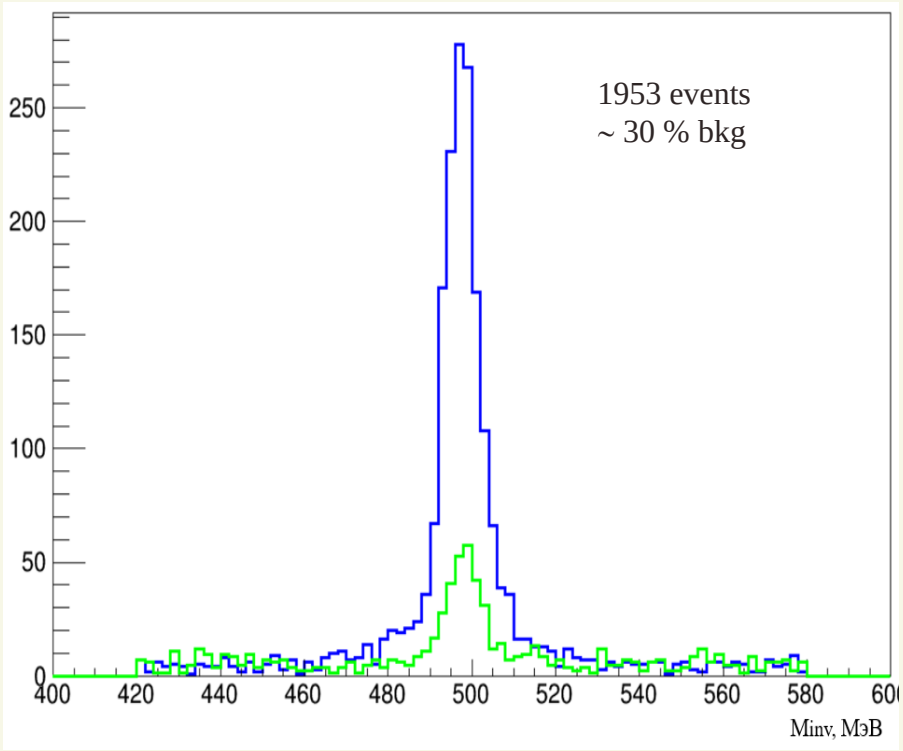
The distribution of these events after all selection cuts on plot ΔE:Δp



Invariant mass of candidates for Ks mesons

Blue - experimental data for 2020

Green – background simulation ($K_SK_S\pi+\pi-$)



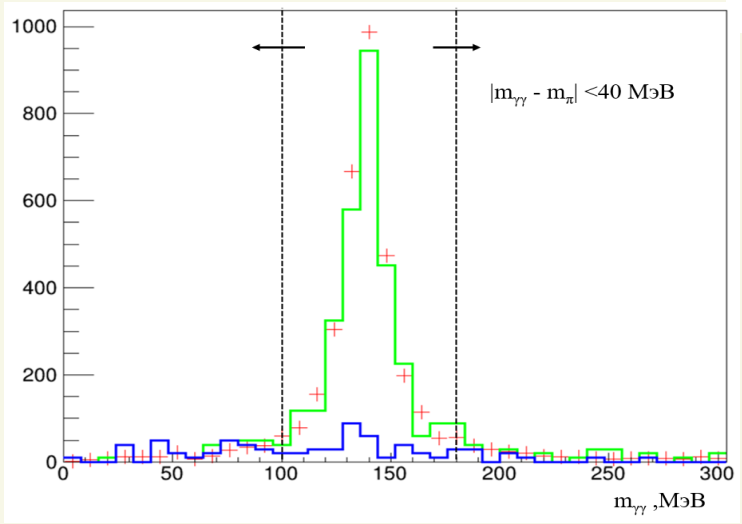
Since π^0 decays into two photons with a probability of 44%, a distribution of the invariant mass of a pair of photons was constructed to suppress the events of this process, as well as other processes with π^0 in the final state. Photon pairs were selected whose invariant mass lies in the range of ± 40 MeV from the mass of a neutral pion

Invariant mass of photon pairs $|m\gamma\gamma - m\pi| < 40$ MeV.

Red crosses - experiment

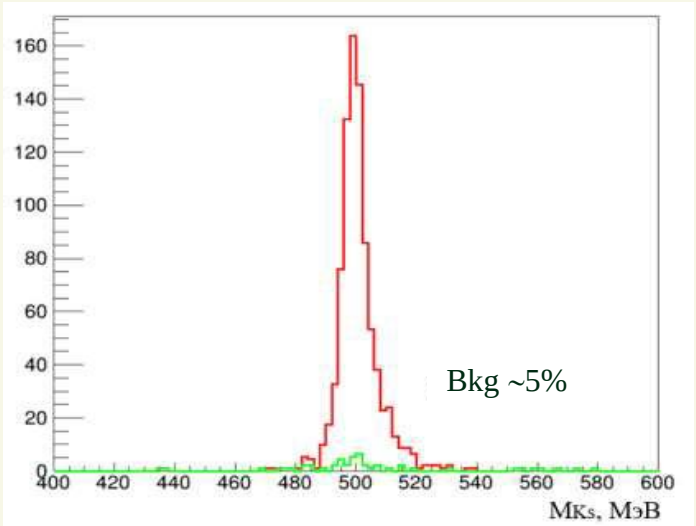
Green - full simulation of all background processes

Blue - simulation of signal events only

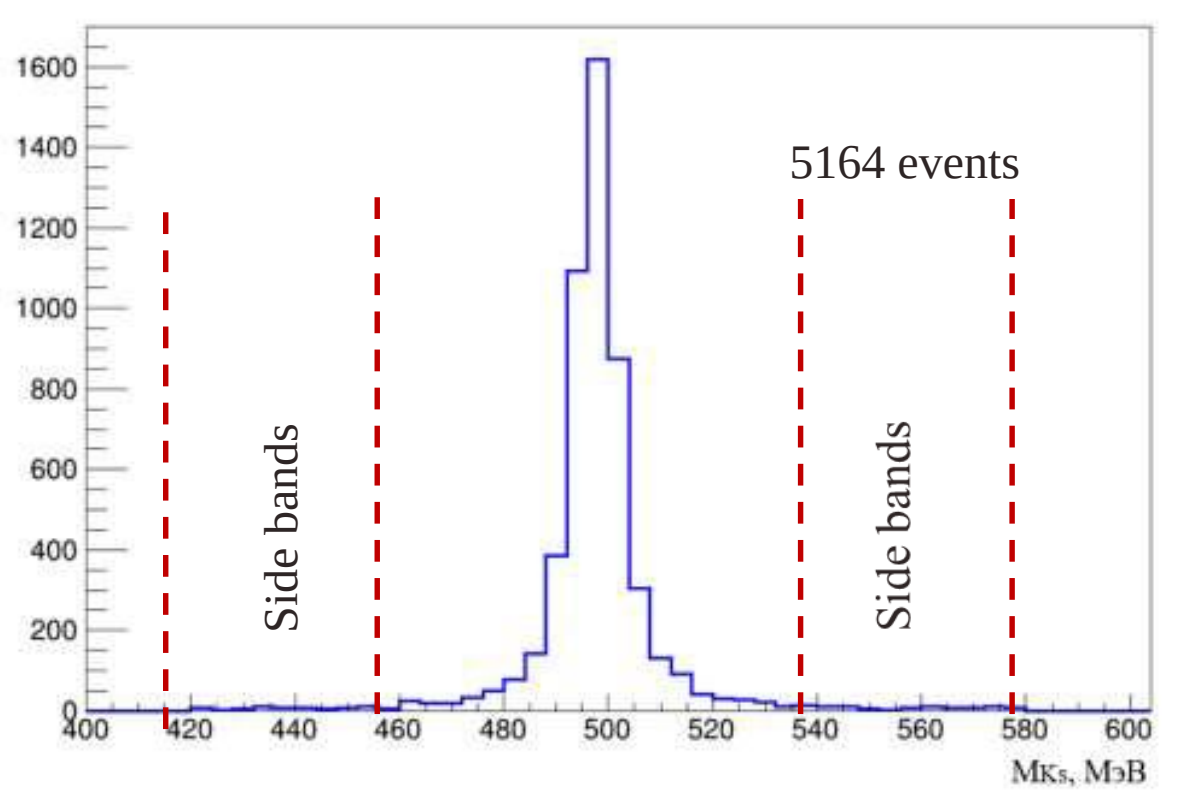


Red color – full simulation of all physical processes by a multi- hadron generator with signal events

Green – simulation of the physical background $K_SK_S\pi+\pi-$ ($K_S \rightarrow 2\pi^\circ$) with cut $|m\gamma\gamma - m\pi| < 40$ MeV



Final distribution of events for the invariant mass of the Ks meson for all seasons after applying all criteria for selecting signal events

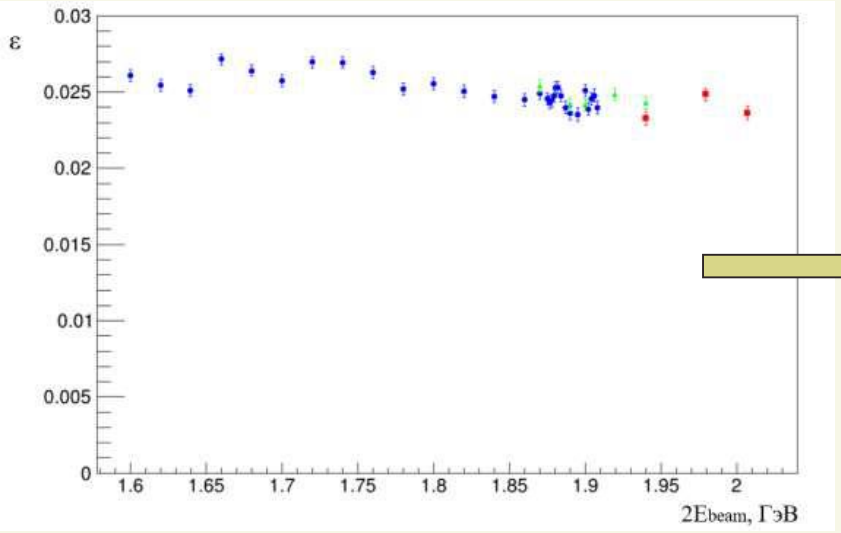


To determine the background, the "side-band" method was used, which amounted to ~ 3% (153 events)

Simulation - peak in the signal region from the process $e^+e^- \rightarrow K_S K_S \pi^+\pi^-$ is 5% (~248) events

The total number of events with background subtraction was found to be 4763±72

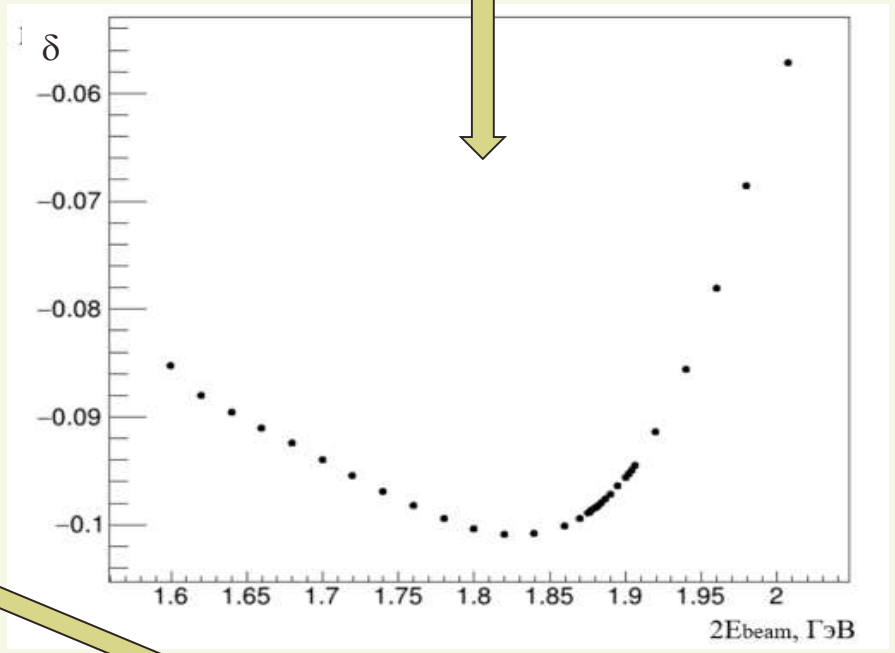
Detection efficiency
phase space



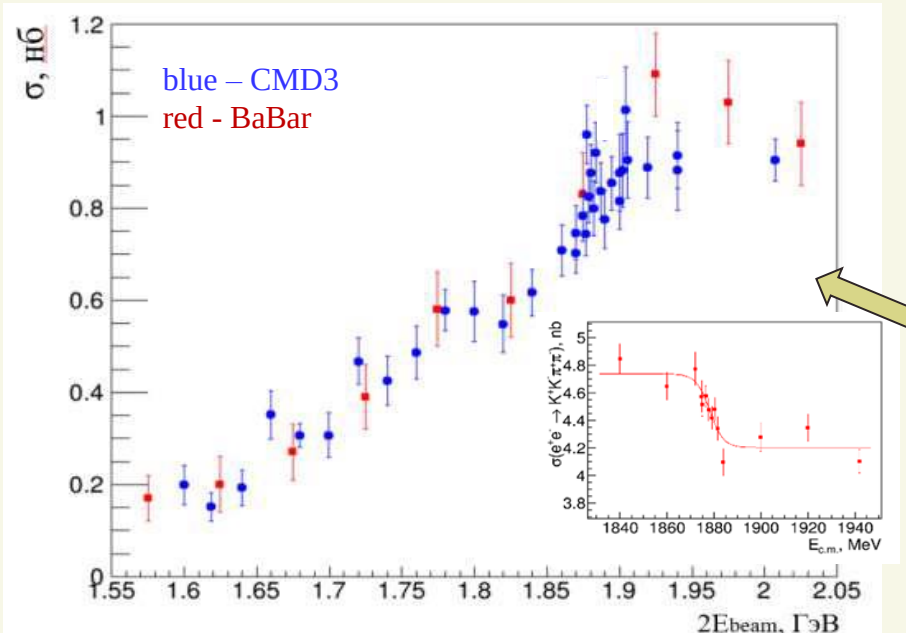
$$\sigma_{visible} = \frac{N_{signal}}{L*\epsilon}$$

RC $(1 + \delta)$ has been calculated by iteration method. About 3 – 5 step is enough to get accuracy ~ 1%.

$$\sigma_{born} = \sigma_{vis} / (1 + \delta)$$



Cross section of the process
$e^+e^- \rightarrow K_S K_L \pi^+\pi^-$

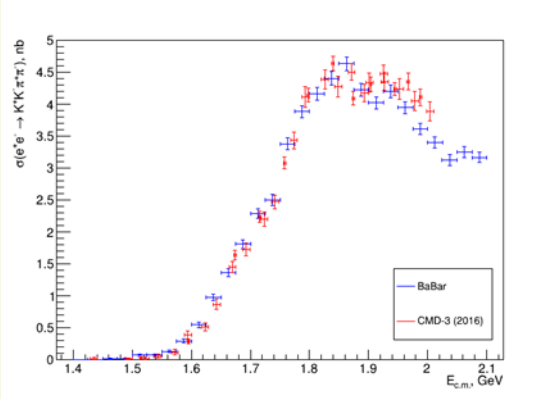


$$\sigma_{visible}(s) = \int_0^{\varepsilon} dx\, \sigma_{born}\big(s(1-x)\big) F(x,s)$$

Cross sections of the process $K+\ K-\ \pi+\ \pi-$

Motivation

- Cross section measurement of the process $e^+e^- \to K^+K^-\pi^+\pi^-$ with high statistic with respect to previous experiments
- Study intermediate states such as $K^*(892)^0K\pi, \phi(1020)f_0(980), \rho(770)KK, K_1(1270, 1400)K$



- BaBar, 2012: 1.4 – 5 GeV, 454 fb^{-1}, ~84000 events, ISR-method was used
- CMD-3, 2016: 1.4 – 2 GeV 23 pb^{-1}, ~10 000 events, energy scan

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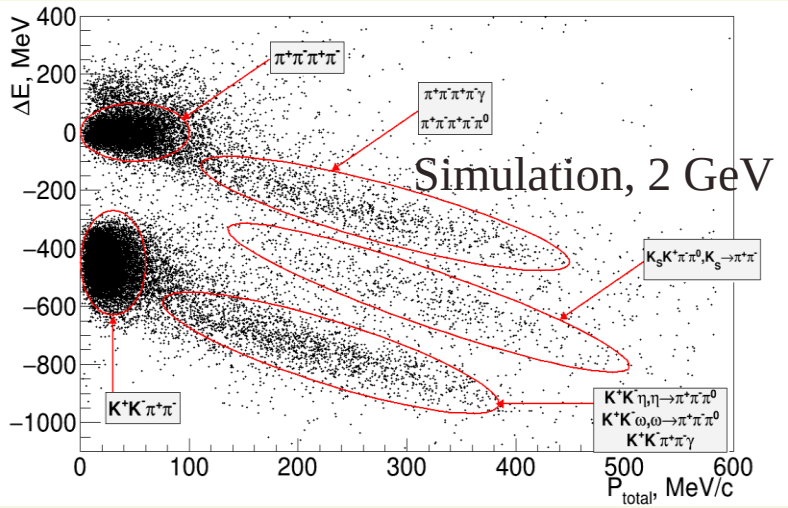
Track selection criteria and dataset

- ✓ 4 “хороших” трека в дрейфовой камере (ДК):
- Число сработавших проволочек на треке в ДК ≥ 9
- координаты точки вылета: |z| < 10 см, |ρ| < 0.4 см
- полярный угол вылета: 0.9 рад < θ < (π – 0.9) рад
- реконструированный импульс: p > 50 МэВ/с
- Полный заряд системы 4-х треков равен 0

- HIGH 2019, 40.0 пб$^{-1}$, 1.4-1.975 ГэВ
- HIGH 2020, 47.3 пб$^{-1}$, 1.87-1.94 ГэВ
- HIGH 2021, 47.1 пб$^{-1}$, 1.94-2.007 ГэВ
- NNBAR 2022, 280.3 пб$^{-1}$, 1.58-1.908 ГэВ
- HIGH 2023, 86.3 пб$^{-1}$, 1.4-1.58 ГэВ

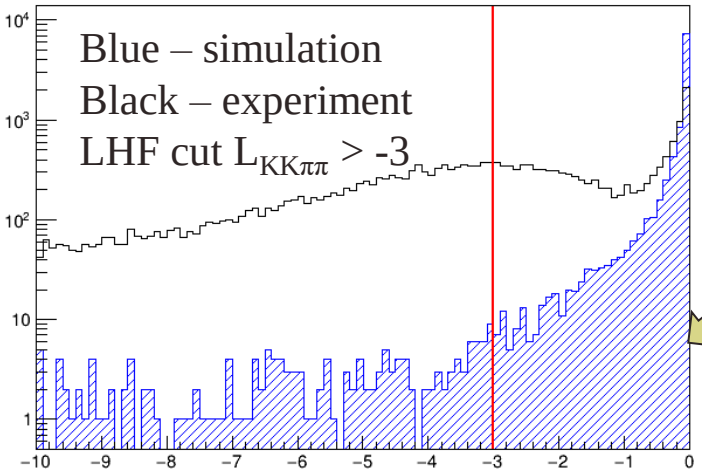
In total 500.0 pb^{-1}

Plot: ΔE vs P_{total}

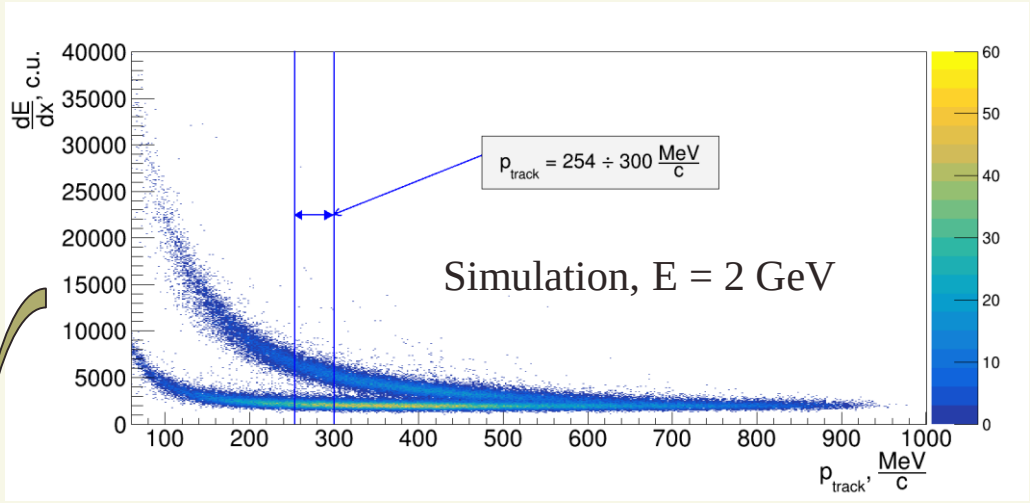


$$\Delta E = \sum_{i=1}^{4} E_{\pi}^{i} - E_{c.m.},\ E_{\pi}^{i} = \sqrt{(p^i)^2 + m_{\pi}^2}$$

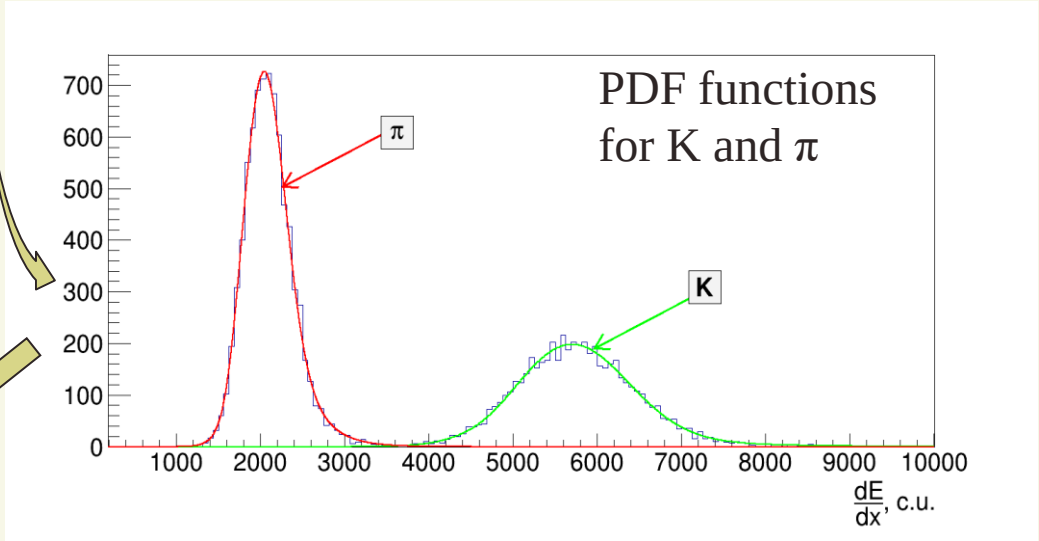
$$P_{total} = \left| \sum_{i=1}^{4} \vec{p^i} \right|$$



K/π-separation



254 MeV/c < p_{track} < 300 MeV/c



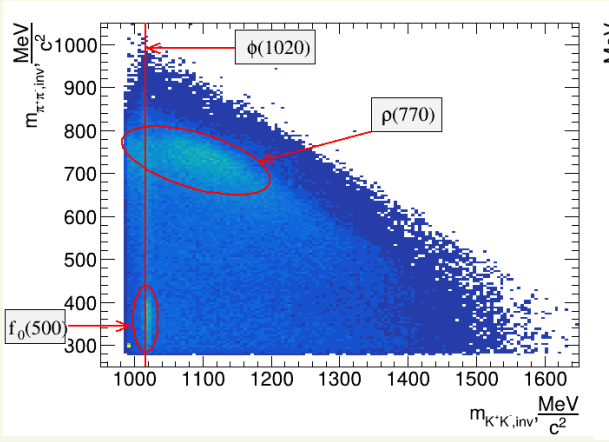
$$f_{K,\pi}(p, \frac{dE}{dx}) = A \cdot N_{K,\pi}(p, \frac{dE}{dx}) + B \cdot LogN_{k,\pi}(p, \frac{dE}{dx})$$

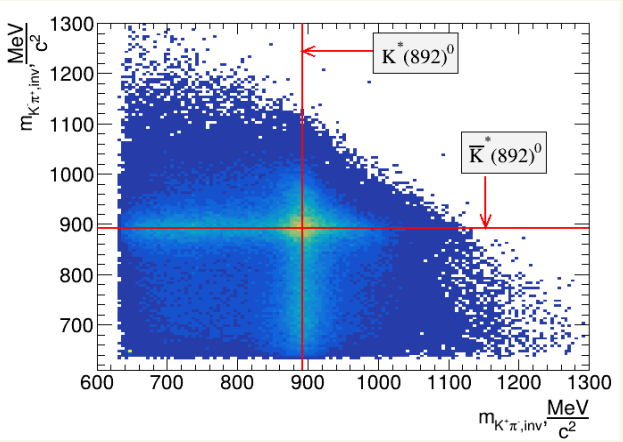
What we realy see

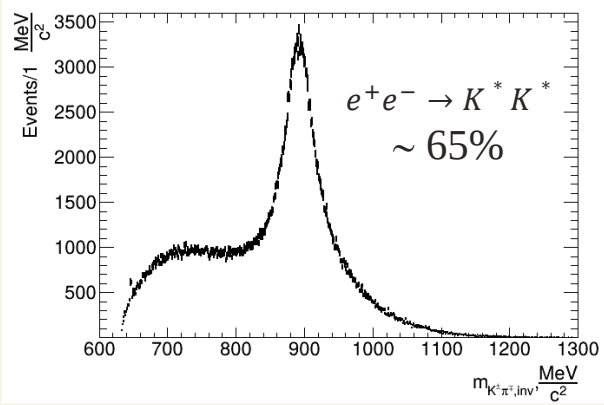
All intermediate states were included in simulation to calculate detection efficiency

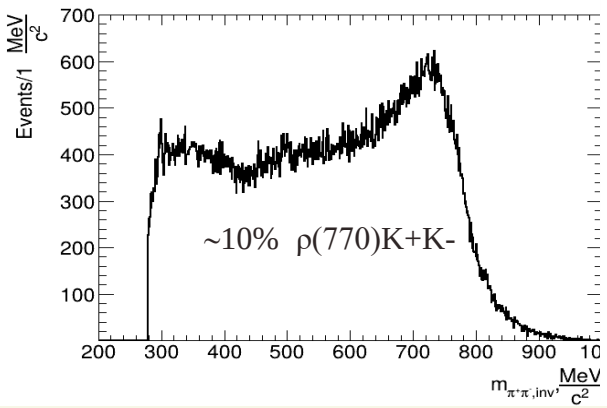
$$e^+e^- \to K^+K^-\pi^+\pi^-:$$

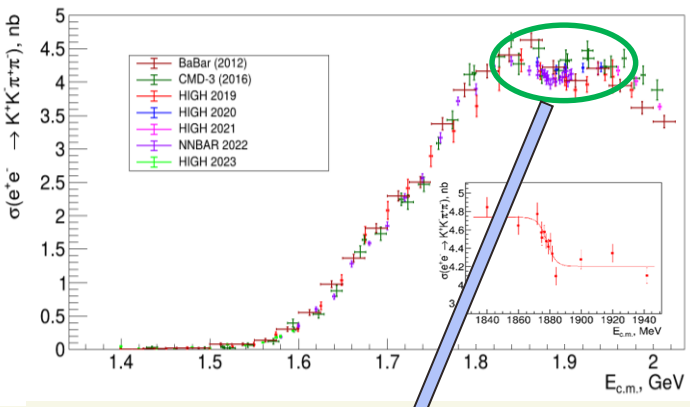
$$e^+e^- \to K_1(1270,1400)K \to K^*(892)^0 K\pi$$
$$e^+e^- \to K_1(1270,1400)K \to \rho(770)^0 K K$$
$$e^+e^- \to \rho(770)^0 K K$$
$$e^+e^- \to \phi(1020) f_0(980)$$
$$e^+e^- \to \phi(1020) f_0(500)$$

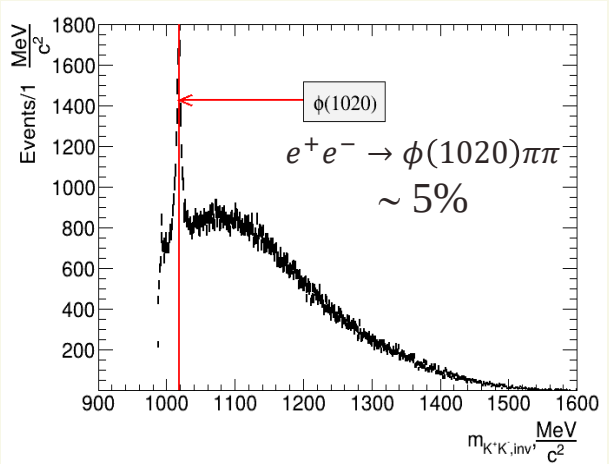


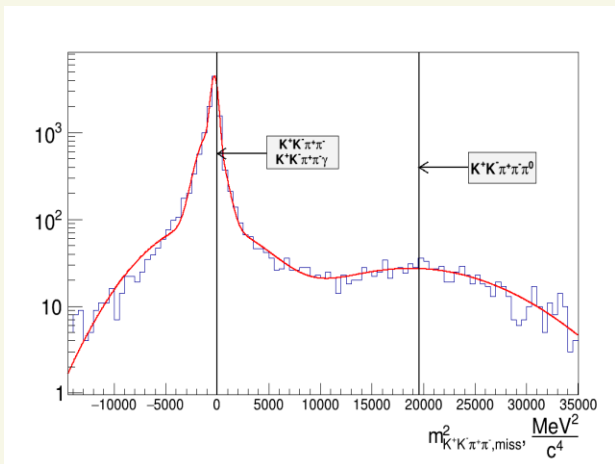


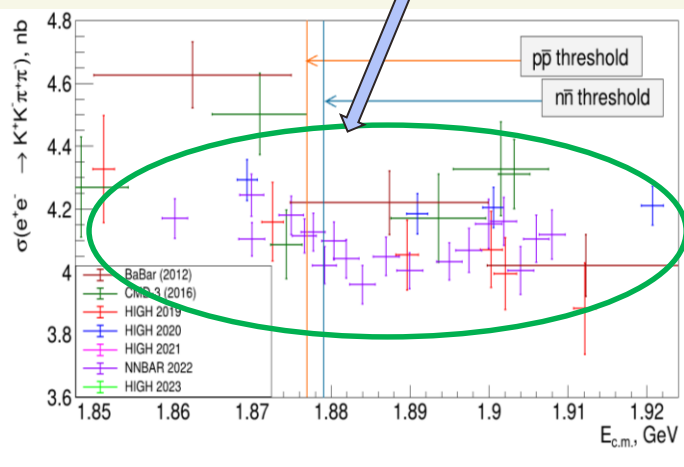












Summary and nearest Outlook

- In the energy region of the VEPP-2000 electron-positron collider, preliminary results were obtained measuring the cross sections of the processes $e^+e^- \to K_L K_S \pi^+\pi^-$, $K^+K^-\pi^+\pi^-$ with CMD-3 detector.

- The analysis is based on statistics collected in all seasons, which amounted to ~ 500 pb^{-1}.
- In the most stringent criteria for selecting signal events for analysis, there were about 5,000 events left for the first process and about 230,000 for the second.
- It is necessary to develop additional criteria to suppress events of the process

  $e^+e^- \to K_S K_S \pi^+\pi^-$
- There were included three main intermediate states that determine the dynamics of the production this $K^+K^-\pi^+\pi^-$ final state:

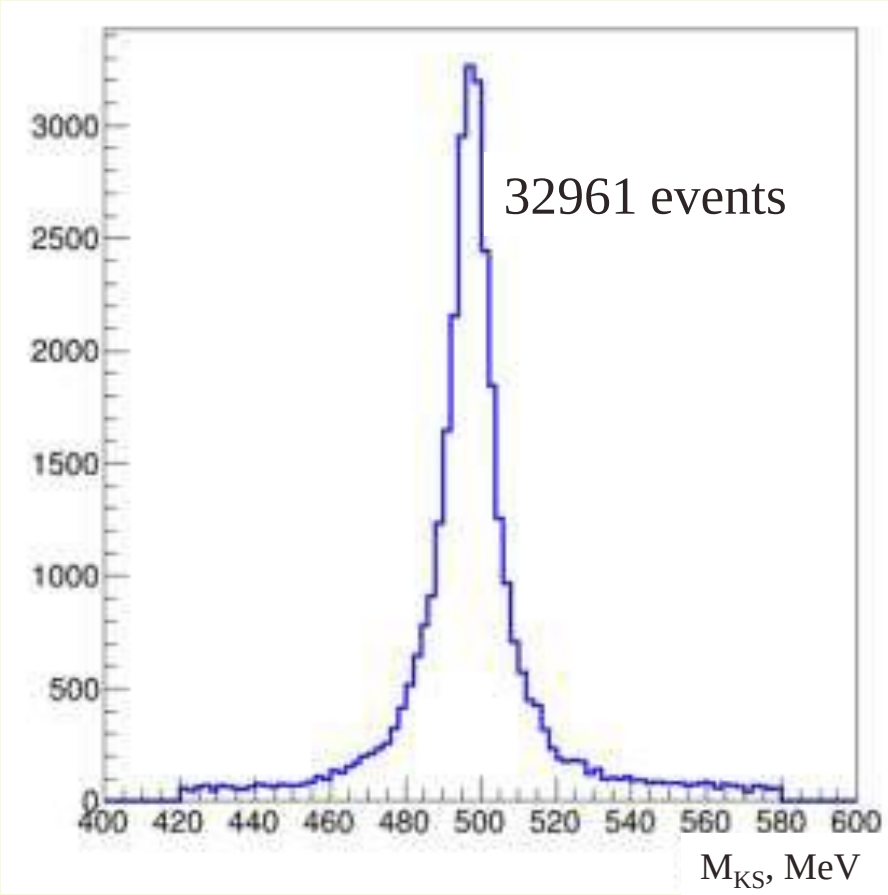
  $e^+e^- \to \phi(1020)\pi^+\pi^-$ (ρ, $f_0(980) \to \pi^+\pi^-$),

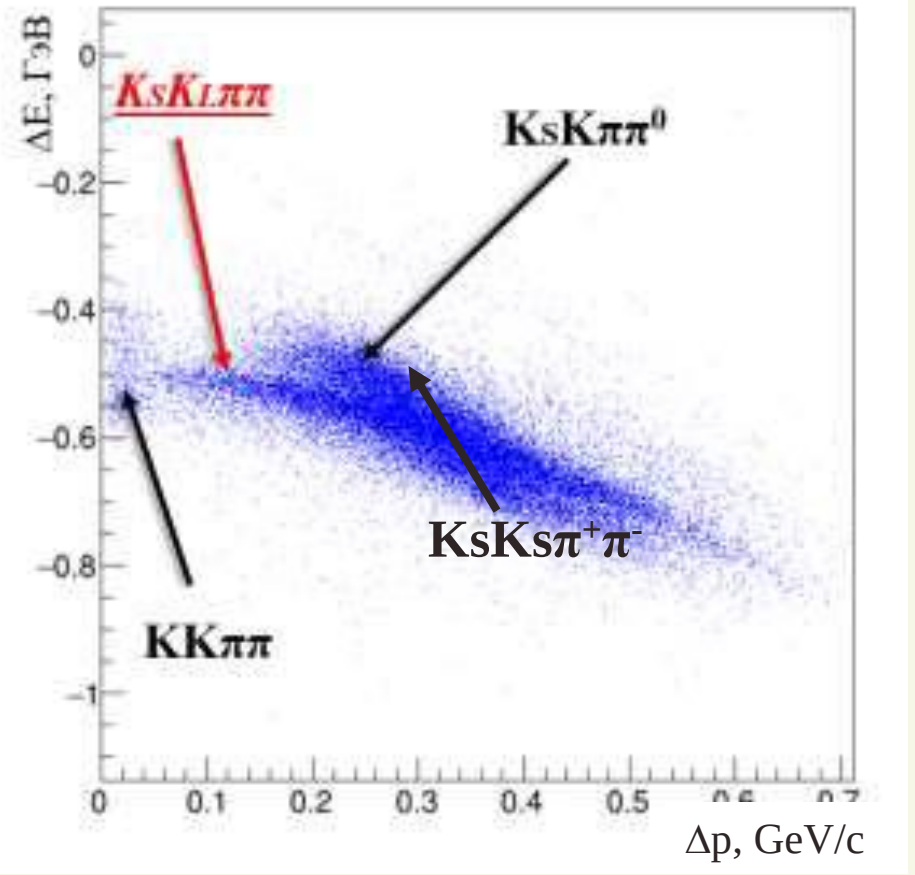
  $e^+e^- \to K^{*+}(892)K^{*-}(892)$, $K^{*\pm}(892)K_2^{*\mp}(1420)$.
- The current systematic error in measuring the cross section depends on the energy and is estimated as 10 %.

THANKS

Left plot - event distribution as a function of invariant mass of a pair of tracks for Ks meson candidates after applying all previous selection criteria and $\chi 2$ cuts

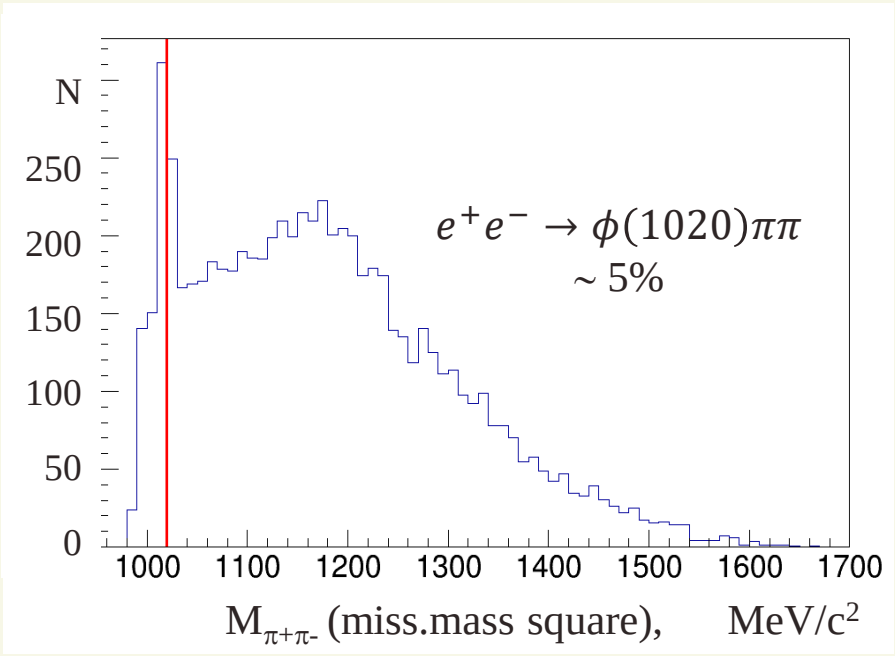
The background substrate has been reduced by almost 10 times





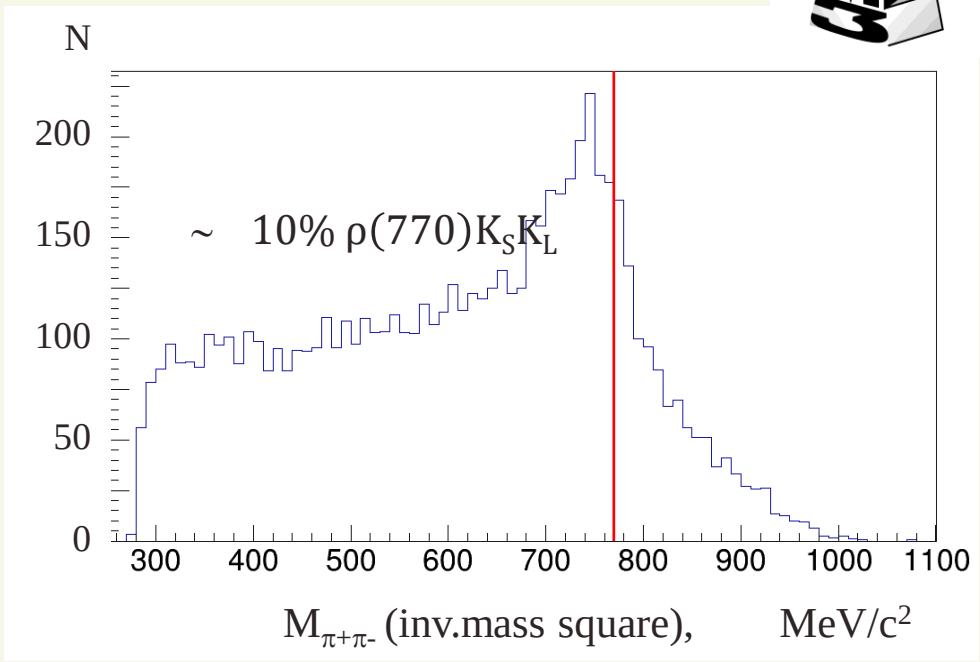
Right plot - the distribution of these events on the ΔE:Δp diagram. There are some part events with charged kaons

Distribution of events depending on the square of the missing mass π+π-
Data 2022



$M_{\pi+\pi-}$ (miss.mass square), MeV/c^2

Distribution of events depending on the square of the missing mass $\pi^+\pi^-$.
Data 2022.



$M_{\pi+\pi-}$ (inv.mass square), MeV/c^2

Two dimentionial plot invariant mass
$K_S\pi^{\pm}$ vs $K_L\pi^{\mp}$