Status of the CMD-3

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G-2 Theory Initiative Meeting
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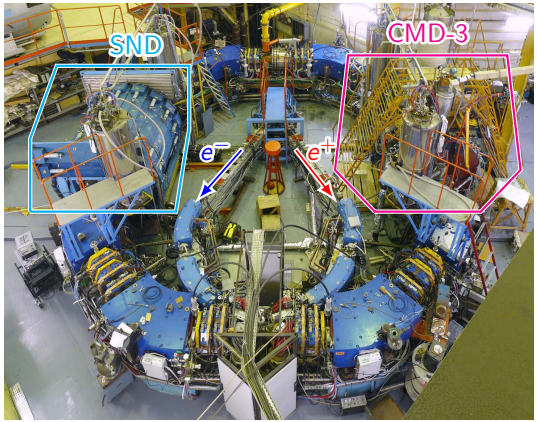
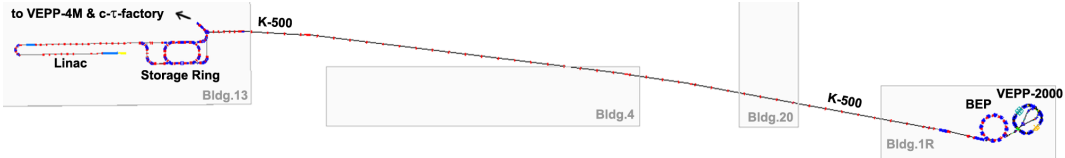
VEPP-2000

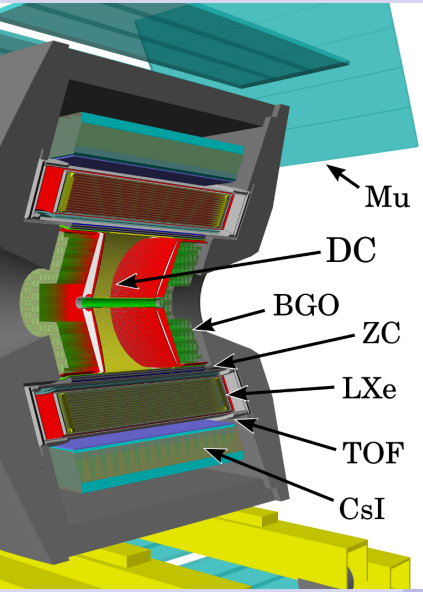
	Parameters at 1 GeV	
	Design	Achieved
Circumference	24.388 m	
Beam energy, MeV	150–1000	160–1005
N of bunches	1×1	
N of particles / bunch	1×10^{11}	0.9×10^{11}
Luminosity, $cm^{-2}s^{-1}$	1×10^{32}	0.5×10^{32}

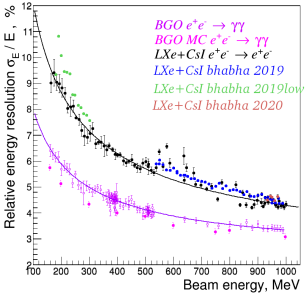
- Round beams concept
- 13 T solenoids for FF
- E_{beam} controled by Compton back scat. ($\sigma_{\sqrt{s}} = 0.1$ MeV)

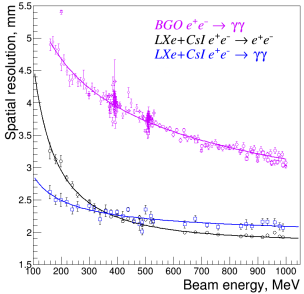




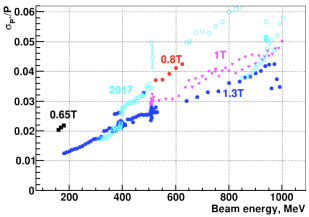
CMD-3 detector



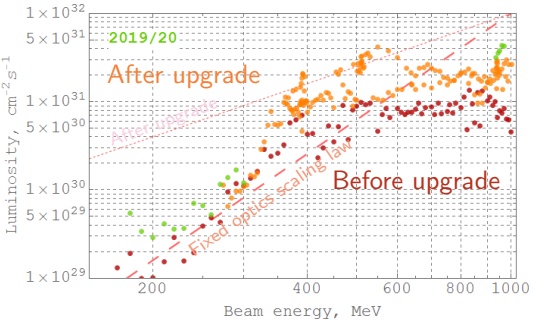


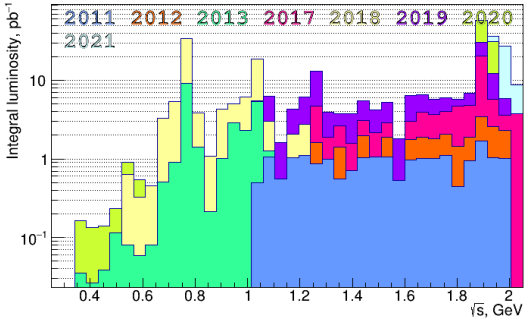


- Magnetic field 1.3 T
- Track reconstruction:
  $\sigma_{\rho\varphi} \sim 100\,\mu\text{m}$,
  $\sigma_z \sim 2$–$3\,\text{mm}$
- Combined EM-calorimeter:
  $\sigma_E \sim 3$–$10\,\%$, $\sigma_\Omega \sim 5\,\text{mrad}$



Luminosity



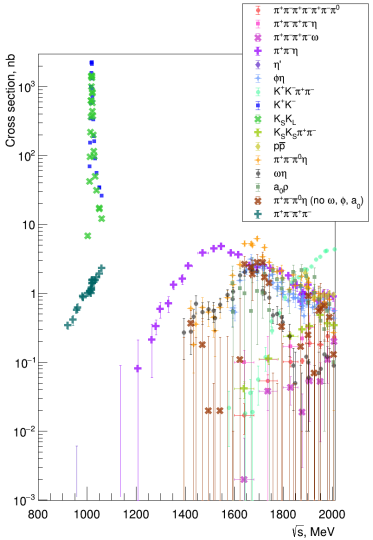


2017–2019: big improvement in luminosity, still way to go to the project parameters and collection of $1\,\text{fb}^{-1}$.
Overall collected luminosity is $0.32\,\text{fb}^{-1}$.
Measure luminosity by $e^+e^- \to e^+e^-$, $\gamma\gamma$.

$\sqrt{s}$	$< \omega$	ω	ω–ϕ	ϕ
pb^{-1}	17.5	30.4	15.5	17.4

$\sqrt{s}$	ϕ–$N\bar{N}$	$N\bar{N}$	$N\bar{N}$–D^{*0}	D^{*0}
pb^{-1}	114	14.9	93.2	8.8

Exclusive channels $e^+e^- \to$ hadrons



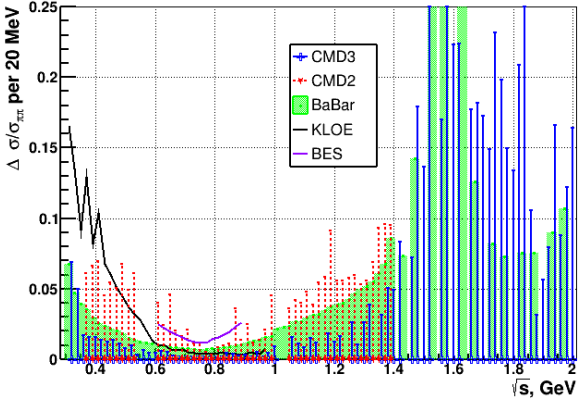
Signature	Final state (preliminary, published)
2 charged	$\pi^+\pi^-$, K^+K^-, K_SK_L, $p\bar{p}$
2 charged + γs	$\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-2\pi^0$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\eta$, $\pi^+\pi^-2\pi^0\eta$, $K^+K^-\pi^0$, $K^+K^-2\pi^0$, $K^+K^-\eta$, $K_SK_L\pi^0$, $K_SK_L\eta$
4 charged	$2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K_SK^\pm\pi^\mp$
4 charged + γs	$2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-\pi^0)$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\omega$, $2(\pi^+\pi^-)\eta$, $K^+K^-\omega$, $K_SK^\pm\pi^\mp\pi^0$
6 charged	$3(\pi^+\pi^-)$, $K_SK_S\pi^+\pi^-$
6 charged + γs	$3(\pi^+\pi^-)\pi^0$
Neutral	$\pi^0\gamma$, $2\pi^0\gamma$, $3\pi^0\gamma$, $\eta\gamma$, $\pi^0\eta\gamma$, $2\pi^0\eta\gamma$
Other	$n\bar{n}$, $\pi^0e^+e^-$, ηe^+e^-
Rare decays	η', $D^*(2007)^0$

Published, but not included in WP2020

		$\sqrt{s}$, GeV	KNT [20]	DHMZ [20]
$K_S K_S \pi^+ \pi^-$	PLB 804 (2020) 135380	1.6 – 2.0	no	no
$3(\pi^+ \pi^-)\pi^0$	PLB 792 (2019) 419-423	1.6 – 2.0	no	yes
$\eta \pi^+ \pi^-$	JHEP 01 (2020) 112	1.1 – 2.0	no	no
$K^+ K^- \eta$	PLB 798 (2019) 134946	1.59 – 2.007	no	yes

$\pi^+\pi^-$

$a_\mu^{\text{had, LO VP}} \times 10^{10}$	$\sqrt{s}$	
503.46 ± 1.91	≤ 1.937 GeV	KNT19
$507.85 \pm 0.83 \pm 3.23 \pm 0.55$	≤ 1.8 GeV	DHMZ20

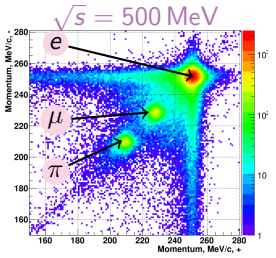


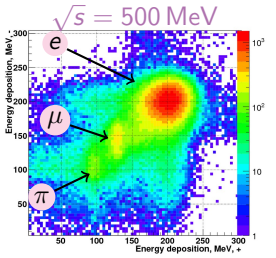
$\pi^+\pi^-$ below ϕ

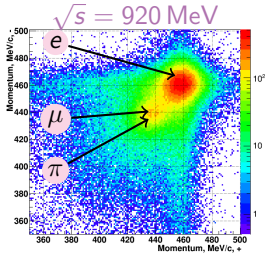
Analysis strategy

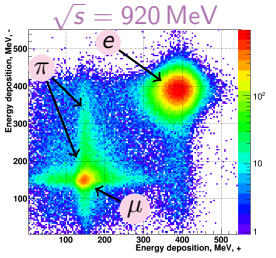
- 2 tracks with $1 \leq \theta \leq \pi - 1$
- Separation of $e/\mu/\pi$/cosmic
  - $\mu^+\mu^-$ can be fixed from QED
  - Two independent approaches:
    - Separation by vertex constrained momenta
    - Separation by energy depositions
- Binned likelihood minimisation:

$$-\ln L = -\sum_{\text{bins}} n_i \ln\Big[\sum_{\substack{X=ee,\\ \mu\mu,\,\pi\pi,\\ \text{bg}}} N_X f_X(p^+,\, p^-)\Big] + \sum_X N_X$$









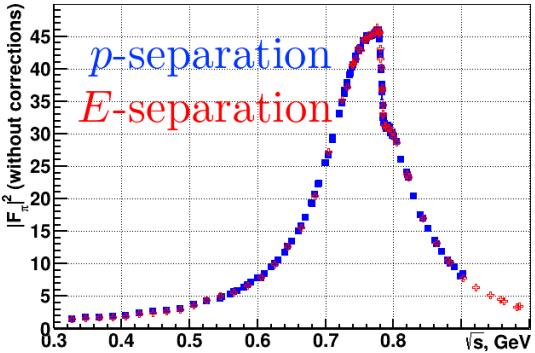
Extracting data and outlook

Separation by **momentum**

- Input:
  - Take e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ PDFs from MC generators smeared by the detector resolution.
  - Cosmic PDF from data
- 35 free parameters

Separation by **energy deposition in LXe**

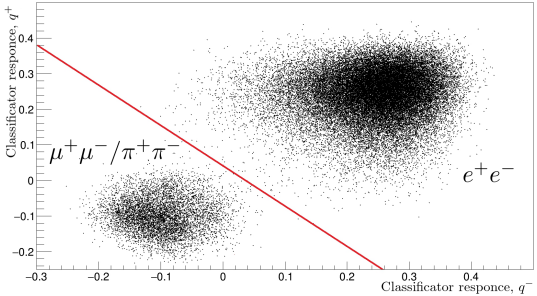
- No need for PDFs from MC
- Energy deposition includes FSR ($\Delta\Omega < 0.4$)
- Fit data by analytical functions
- 56 free parameters



The analysis on its final stages. Additional local consistency checks should be fulfilled. The aim systematic uncertainty is 0.5 %.

$\pi^+\pi^-$ above ϕ

- 2 opposite central tracks
- Suppress K^+K^-
  - $p_{\min} = \begin{matrix} 1.1\sqrt{E^2 - {M_K}^2} & E < 1.58 M_K \\ 0.84E & E \geq 1.58 M_K \end{matrix} < p < 1.2E$
- Use BDT and NN to separate $e|(\mu,\, \pi)$, $K|\pi$ and $\mu|\pi$.
- Iterative calculation of $|F_\pi|$.
  $N_{\pi\pi} = N_{low} - N_{cosm} - N_{ee}\frac{\sigma_{\mu\mu}}{\sigma_{ee}}$
  $\left|F_\pi^{i+1}\right|^2 = \frac{N_{\pi\pi}}{N_{ee}} \times \frac{\sigma_{ee}}{\sigma_{\pi\pi}} \times \left|F_\pi^{i}\right|^2$

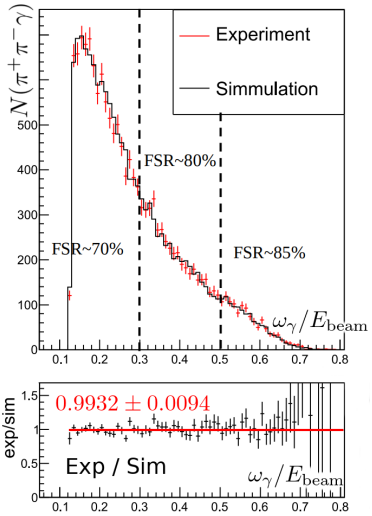


$\pi^+\pi^-\gamma$

- Measure $e^+e^- \to \pi^+\pi^-\gamma$
- Check the correctness of the point-like π assumption for the rad. corr. in MCGPJ (FSR)

- Dataset: $\sqrt{s} \in 660-785$ MeV, 8.4 pb^{-1}
- 2 central tracks with + 1 γ
- FSR $\sim 80\,\%$, ISR $\sim 20\,\%$
- Background: $e^+e^- \to e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\pi^+\pi^-\pi^0$

- $\pi^\pm$ point-likeness assumption negligiably contributes to $\sigma(e^+e^- \to \pi^+\pi^-)$



$\pi^+\pi^-\pi^0$ at ω

$a_\mu^{\text{had, LO VP}} \times 10^{10}$	$\sqrt{s}$	
46.73 ± 0.94	$\leq 1.937\,\text{GeV}$	KNT19
$46.21 \pm 0.40 \pm 1.10 \pm 0.86$	$\leq 1.8\,\text{GeV}$	DHMZ20

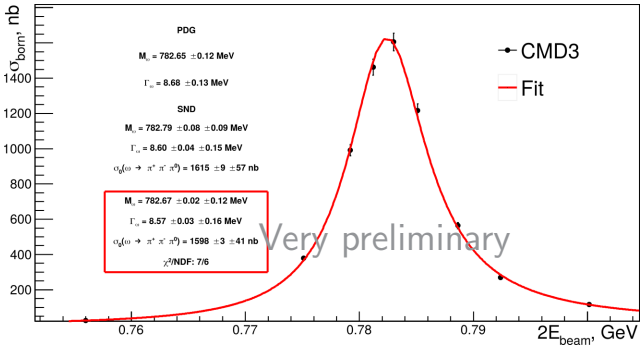
$\pi^+\pi^-\pi^0$ at ω

Status:

- Look for π^0 in $M_{\text{miss}}(\pi^+\pi^-)$
- e^+e^-, $\mu^+\mu^-$ and $\pi^+\pi^-$ background is fixed from MC.
- Statistic 2013 ($7.8\,\text{pb}^{-1}$)
- Systematic uncertainty $\sim 3.1\,\%$

Further steps:

- Add 2018 data ($30\,\text{pb}^{-1}$)
- Search for ρ–ω interference
- Analysis with $\pi^0 \to \gamma\gamma$



$\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^0\pi^0$

	$a_\mu^{\text{had, LO VP}} \times 10^{10}$	$\sqrt{s}$	
$\pi^+\pi^-\pi^+\pi^-$	14.87 ± 0.20	≤ 1.937 GeV	KNT19
	$13.68 \pm 0.03 \pm 0.27 \pm 0.14$	≤ 1.8 GeV	DHMZ20
$\pi^+\pi^-\pi^0\pi^0$	19.39 ± 0.78	≤ 1.937 GeV	KNT19
	$18.03 \pm 0.06 \pm 0.48 \pm 0.26$	≤ 1.8 GeV	DHMZ20

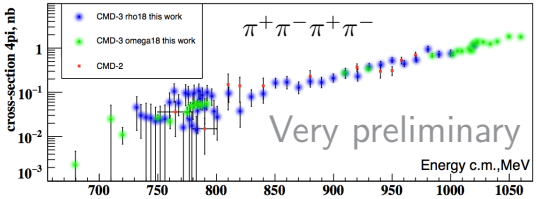
$\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^0\pi^0$

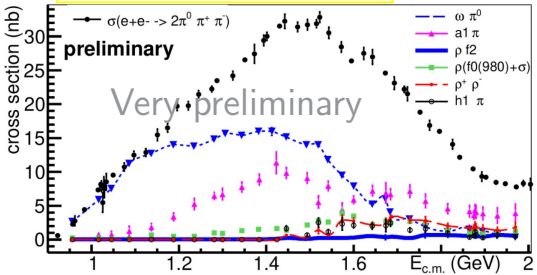
$4\pi^\pm$ for $\sqrt{s} < 1.06\,\text{GeV}$:

- Events:
  - 4 pion tracks
  - $-20\,\text{MeV} < E_{\text{sys}} - \sqrt{s} < 30\,\text{MeV}$
  - $|\vec{p}_{\text{sys}}| < 100\,\text{MeV}/c$
- Background: $\pi^+\pi^-(\pi^0 \to e^+e^-\gamma)$, $e^+e^-e^+e^-$, $e^+e^-\gamma$

$4\pi^\pm$ and $2\pi^\pm 2\pi^0$ for $\sqrt{s} > 0.95\,\text{GeV}$:

- Events:
  - Find $\pi^+\pi^-\pi^\pm$ or $\pi^+\pi^-\pi^0$
  - Look for last $\pi^\mp$ or π^0
- Amplitude analysis:
  - $\omega\pi^0$, $a_1\pi$, $\rho f_0/\sigma$, ρf_2, $\rho^+\rho^-$, $a_2\pi$, $h_1\pi^0$ and $\pi'\pi$



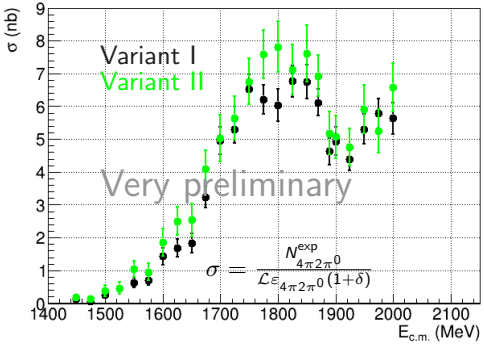


$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$

$a_\mu^{\text{had, LO VP}} \times 10^{10}$	$\sqrt{s}$		
no η	1.35 ± 0.17	≤ 1.937 GeV	KNT19
	$0.71 \pm 0.06 \pm 0.07 \pm 0.14$	≤ 1.8 GeV	DHMZ20

Status:

- Events:
  - 4 tracks + 2 π^0 $\rightarrow$ 5C fit
  - 4 tracks + 1 π^0 $\rightarrow$ 1C fit
  - 3 tracks + 2 π^0 (lost in DC or out of DC) $\rightarrow$ 2C fit
- Background: $2(\pi^+\pi^-)$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\pi^0$, $3(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$
- Simulation: $e^+e^- \rightarrow \omega 3\pi$, $\rho 4\pi$, $\omega\eta$, $a_o\rho$
- 2 methods of π^0s reconstruct:
  1. Constrained KF with all γ permutation
  2. Combine γs with $(m_{\text{inv}}(\gamma_1, \gamma_2) - m_{\pi^0})^2 + (m_{\text{inv}}(\gamma_3, \gamma_4) - m_{\pi^0})^2) \rightarrow$ min $\rightarrow$ 5C KF $\rightarrow$ cut on χ^2
- Find the number of π^0 in $m_{\text{inv}}(\gamma, \gamma)$

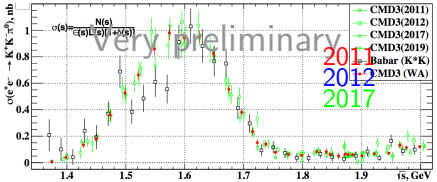


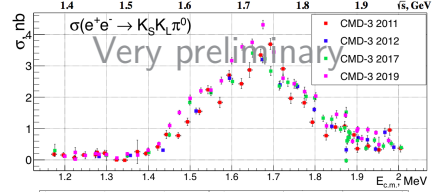
$KK\pi$

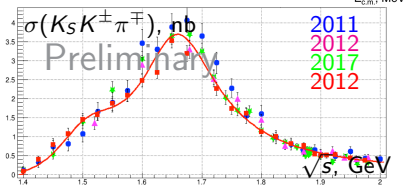
$a_\mu^{\text{had, LO VP}} \times 10^{10}$	$\sqrt{s}$	
2.71 ± 0.12	$\leq 1.937\,\text{GeV}$	KNT19
$2.45 \pm 0.05 \pm 0.10 \pm 0.06$	$\leq 1.8\,\text{GeV}$	DHMZ20

$KK\pi$

- $K^+K^-\pi^0$
  - 2 tracks + 2γs w/ $p_{\rm sys} < 160\,{\rm MeV}/c$ & $|E_{\rm sys} - \sqrt{s}| < 180\,{\rm MeV}$
  - 4C KF + BDT to suppress BG
  - Find π^0 in $m_{\rm inv}(\gamma\gamma)$
  - Also extract $\sigma(e^+e^- \to \phi\pi^0)$
- $K_SK_L\pi^0$
  - 2 tracks + 2γs w/ $\rho_{K_S} > 2\,{\rm mm}$
  - 4C KF + side bands
  - Find π^0 in $m_{\rm inv}(\gamma\gamma)$
- $K_SK^\pm\pi^\mp$
  - 4 tracks w/ $\rho_{K_S} > 2\,{\rm mm}$
  - 4C KF: $K_SK^\pm\pi^\mp$, $2(\pi^+\pi^-)$
  - Find K_S in $m_{\rm inv}(\pi^+\pi^-)$
  - Dynamics: $e^+e^- \to (\rho', \rho'', \phi') \to K^*K$
  - Systematic uncertainty $\sim 5\,\%$







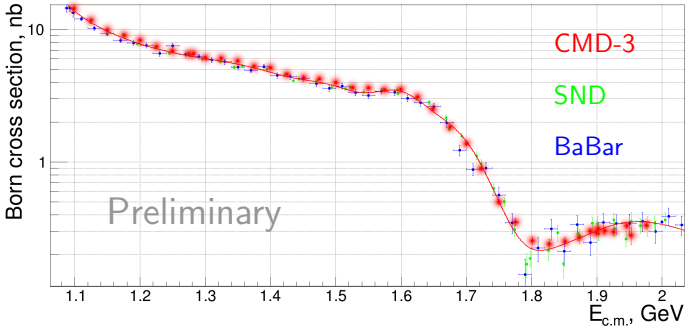
K^+K^- above ϕ

$a_\mu^{\text{had, LO VP}} \times 10^{10}$	$\sqrt{s}$	
23.03 ± 0.22	$\leq 1.937\,\text{GeV}$	KNT19
$23.08 \pm 0.20 \pm 0.33 \pm 0.21$	$\leq 1.8\,\text{GeV}$	DHMZ20

K^+K^- above ϕ

Status:

- 2 tracks
  - Collenearity suppress ISR
- Work with $\Delta E = \sqrt{m_K^2 + p_+^2} + \sqrt{m_K^2 + p_-^2 + |\vec{p}_+ + \vec{p}_-|} - \sqrt{s}$
- Background: e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, cosmic and multihadron proc's
- Statistic: 2019 ($7.8\,\text{pb}^{-1}$)



Further steps:

- Add 2011, 2012, 2017 and 2020
- Investigate MCGPJ
- Track and trigger efficiencies corrections
- Rad. corr. with full error matrix

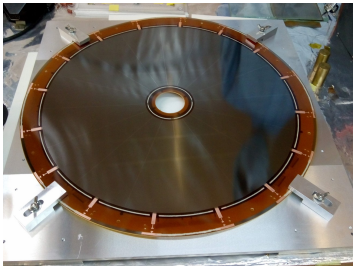
Summary

- CMD-3 has collected $320\,\text{pb}^{-1}$ in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0\,\text{GeV}$, available at VEPP-2000, with the goal to collect $\sim 1\,\text{fb}^{-1}$ in total.
- Data analysis of exclusive modes of $e^+e^- \to$ hadrons is in progress. Many results have been published.
- Detector upgrade: end-cap coordinate system installation in summer of 2023, next is a new Z-chamber.

New systems

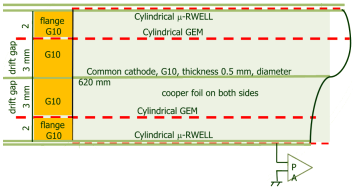
Z-discs

- 2 layers of μRWELL
- $\sigma_r \sim 0.6\,\text{mm}$ & $\sigma_{r\varphi} \sim 1.2\,\text{mm}$
- First disc is ready
- Read-out electronics under test.
- Installation 2023–2024



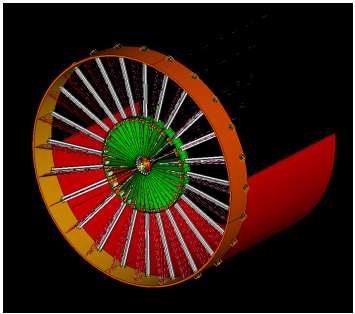
Z-chamber

- 2 layers of cyl. μRWELL
- Conceptual design is ready
- Strip pitch 1.5 mm
- $\sigma_z \sim 0.4\,\text{mm}$

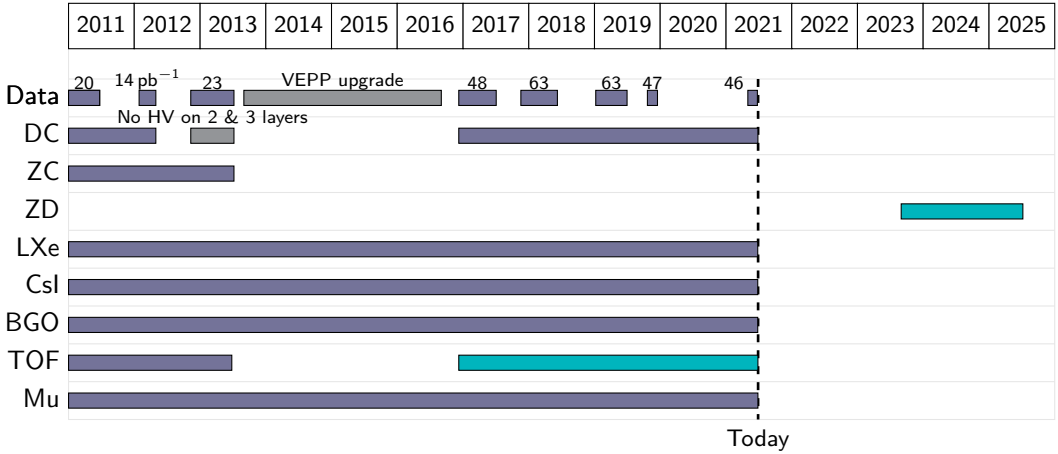


DC chamber

- INFN design mechanics inspired by MEG
- BINP develop ASIC for cluster counting and wires
- Work on the prototype probably start in 2022-2023



CMD-3 systems



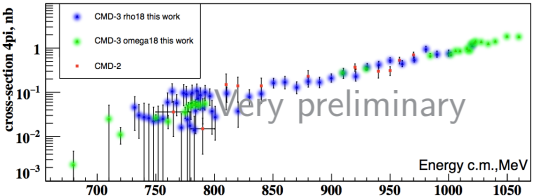
$\pi^+\pi^-\pi^+\pi^-$

Status:

- Events:
  - 4 pion tracks
  - $-20\,\text{MeV} < E_{\text{sys}} - \sqrt{s} < 30\,\text{MeV}$
  - $|\vec{p}_{\text{sys}}| < 100\,\text{MeV}/c$
- Background: $\pi^+\pi^-(\pi^0 \to e^+e^-\gamma)$, $e^+e^-e^+e^-$, $e^+e^-\gamma$

Plan:

- Systematics study
- Process dynamics



$\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^0\pi^0$

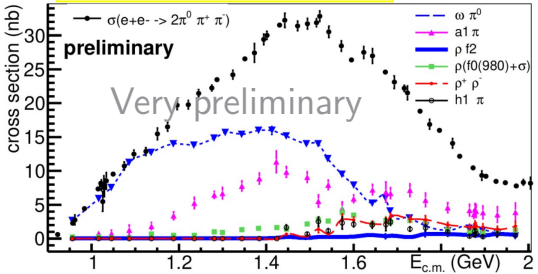
Status:

- Events:
  - Find $\pi^+\pi^-\pi^\pm$ or $\pi^+\pi^-\pi^0$
  - Look for last $\pi^\mp$ or π^0
- Amplitude analysis:
  - $\omega\pi^0$, $a_1\pi$, $\rho f_0/\sigma$, ρf_2, $\rho^+\rho^-$, $a_2\pi$, $h_1\pi^0$ and $\pi'\pi$

Plan:

- Agrement between different seasons
- ε_{det}(sim. model)
- Systematics study
- Process dynamics

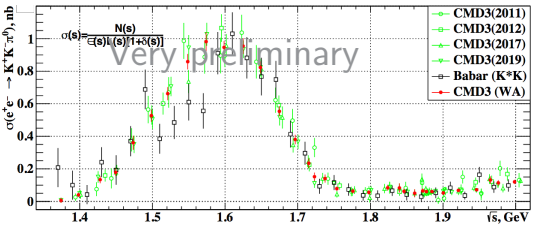
$$R_i(s) = \frac{\int |V_i \cdot \mathbf{H}_{i\perp}(\Omega)|^2 d\Phi}{\int |\sum_\beta V_\beta \mathbf{H}_{\beta\perp}(\Omega)|^2 d\Phi} \cdot \sigma_{2\pi^0\pi^+\pi^-}(s)$$



$K^+K^-\pi^0$

Status:

- Events:
  - 2 tracks + $\geq$ photons
  - $p_{\text{sys}} < 160\,\text{MeV}/c$
  - $|E_{\text{sys}} - \sqrt{s}| < 180\,\text{MeV}$
- 4C KF
- Background: $\pi^+\pi^-\pi^0\pi^0$, $K_S K\pi$, $K_L K\pi$, $K^+K^-\pi^0\pi^0$, $K^+K^-\gamma$
- BDT to suppress background
- Find the number of π^0 in $m_{\text{inv}}(\gamma,\,\gamma)$
- Also extract $e^+e^- \to \phi\pi^0 \to K^+K^-\pi^0$ cross section



Plans:

- Improve situation with dE/dx by DC
- Cross section approximation
- Background study
- Systematics study

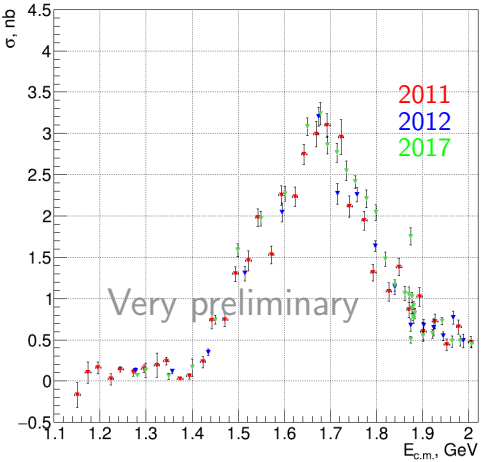
$K_S K_L \pi^0$

Status:

- Events:
  - 2 tracks
  - ρ_{K_S} vertex > 2 mm
  - $N_\gamma \geq 2$
- 4C KF
- Background: $K_S K_L(\gamma)$, $\pi^+\pi^-\pi^0\pi^0$, $K_S K_L \pi^0 \pi^0$
- Find the number of π^0 in $m_{\text{inv}}(\gamma, \gamma)$

Plans:

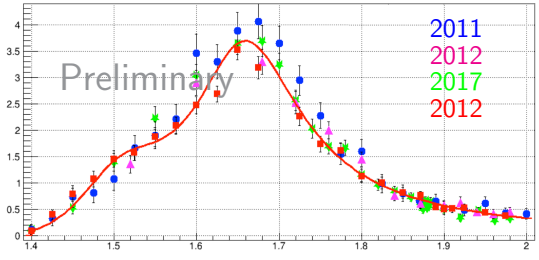
- Suppress $K_S K_L \pi^0 \pi^0$ background
- New simulation models
- Systematic study
- Process dynamics



$K_S K^{\pm}\pi^{\mp}$

Status:

- Events:
  - 4 tracks
  - ρ_{K_S} vertex $> 2\,\text{mm}$
- KF: $K_S K^{\pm}\pi^{\mp}$ and $\pi^+\pi^-\pi^+\pi^-$
- Select the spot at $(E_{\text{sys}}, p_{\text{sys}})$
- Background: $\pi^+\pi^-\pi^+\pi^-$
- Find the number of K_S in $m_{\text{inv}}(\pi^+\pi^-)$
- Dynamics: $e^+e^- \to (\rho', \rho'', \phi') \to K^*K$
- Systematic errors $\sim 5\,\%$



Plans:

- Finalise analysis