Measurement of the $e^+e^- \to \pi^+\pi^-\pi^0$ process in the ω-meson energy region with the CMD-3 detector at VEPP-2000

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CMD-3 Collaboration

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TWENTY-SECOND LOMONOSOV
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ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

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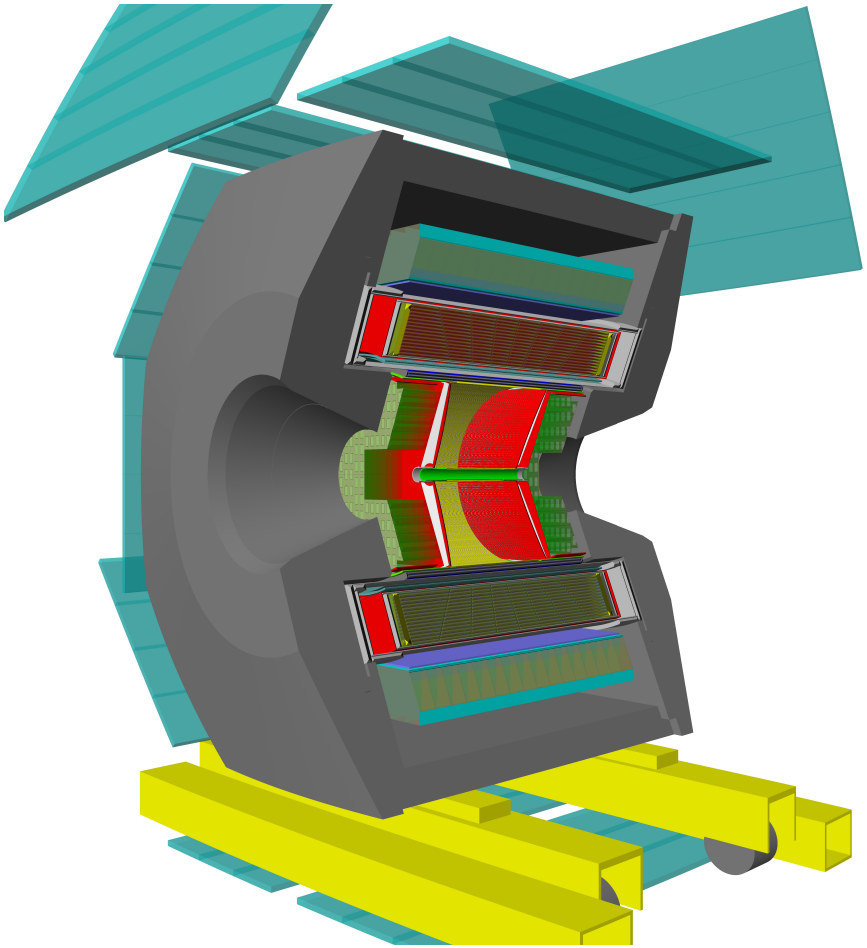
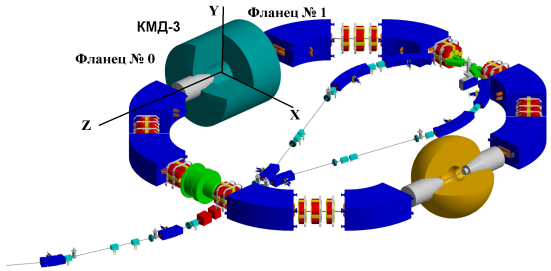
CMD-3, VEPP-2000





- VEPP-2000
- CMD-3

- $\sqrt{s} = 0.3$ - 2 GeV
- Drift chamber
  $(\sigma_{R\phi} \sim 100\mu m, \sigma_Z \sim 2.5mm)$
- Calorimeters
  - Barrel: LXe + CsI
  - Endcap: BGO
- TOF system
- Muon system
- Magnetic field 1.3 T

Study of $e^+e^- \to \pi^+\pi^-\pi^0$ process

Motivation

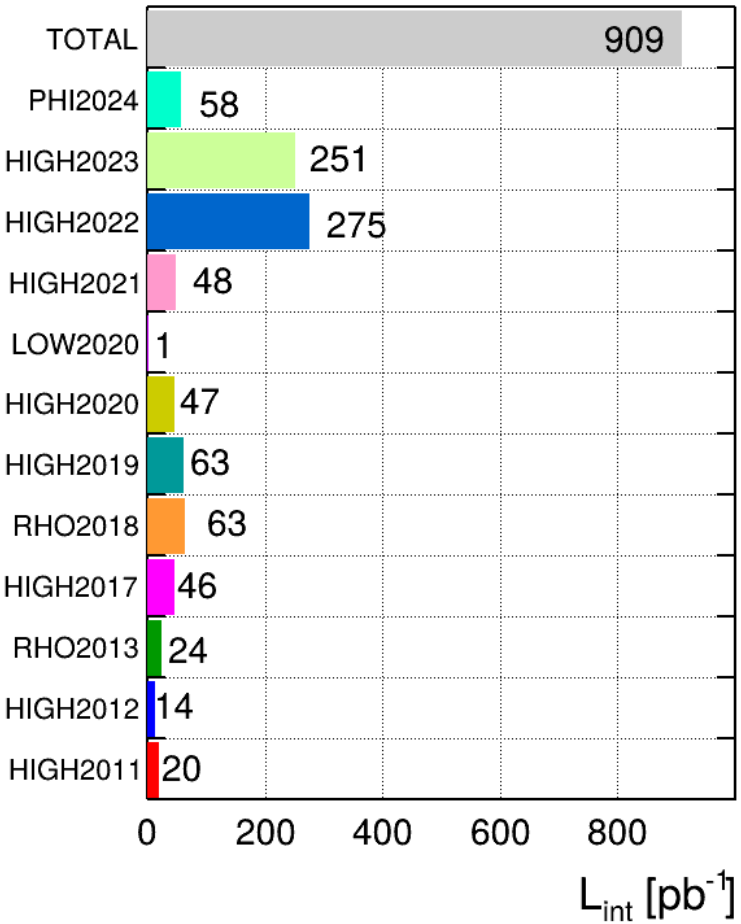
- Second largest contribution to hadronic part of $(g-2)_\mu$
- Discrepancy between CMD-2 and SND ($\sim$130 nb)
- Measurement of ω-meson parameters
- Study of dynamics (ρ-ω interference in $\pi^+\pi^-\pi^0$ channel)

Key analysis tasks

- Measurement of $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ cross section
- Determination of ω-meson parameters from cross section approximation
- Study of ρ-ω interference
- Calculation of contribution to $(g-2)_\mu$

- CMD-2
- SND

Data. Luminosity. Energy measurement

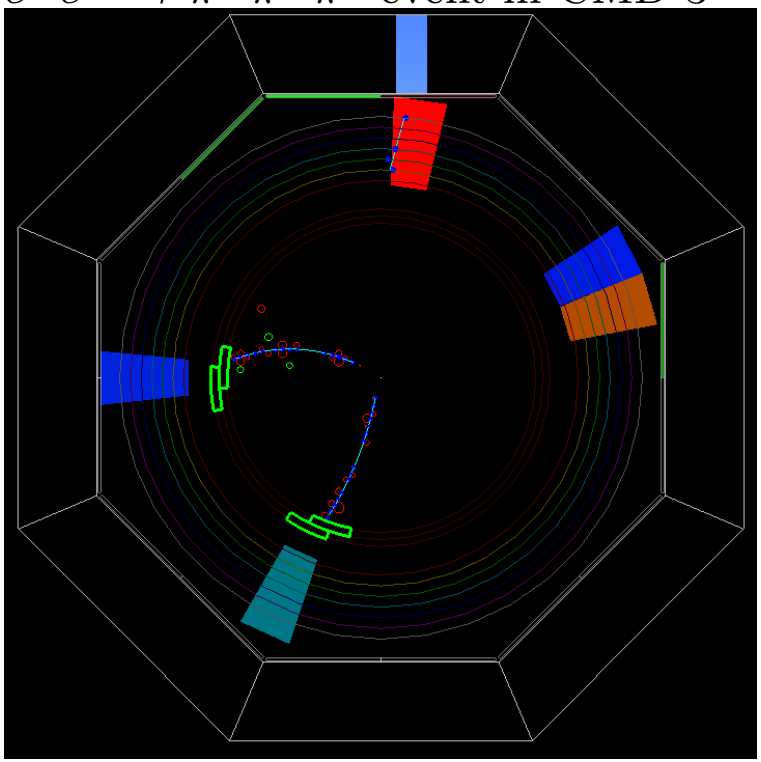


- Luminosity
- Energy measurement

- 4 scans in the energy range $\sqrt{s} = 0.65 - 0.98$ GeV
- RHO2013 (47 points) $L_{int} \sim 13$ pb^{-1}
- RHO2018 (69 points) $L_{int} \sim 34$ pb^{-1}
- Luminosity measured via $e^+e^- \to e^+e^-$ ($\Delta_{sys} \sim 1.5\%$)
- Beam energy measured by Compton backscattering ($\Delta_{sys} \sim 60$ keV)
- Beam energy spread $\sigma_E \sim 250$ keV

Event selection criteria

Characteristic signature of $e^+e^- \to \pi^+\pi^-\pi^0$ event in CMD-3



"Good" track:

- $N_{\text{hits}} > 10$
- $1 < \theta < \pi - 1$ rad
- $\rho < 0.2$ cm
- $|z| < 10$ cm
- $\mathrm{d}E/\mathrm{d}x < 5000$
- $0.2 < P/E_{\text{beam}} < 0.8$

General criteria:

- $N_{\text{good tr}} = 2$
- $Q_1 + Q_2 = 0$
- $N_{\text{good }\gamma} \geq 2$
- $0.25 < |\Delta\phi| < \pi - 0.25$
- $0.4 < (P_1 + P_2)/2E_{\text{beam}} < 0.75$

"Good" photon:

- $E_\gamma > 50$ MeV
- $0.84 < \theta_\gamma < \pi - 0.84$ rad

Kinematic fit:

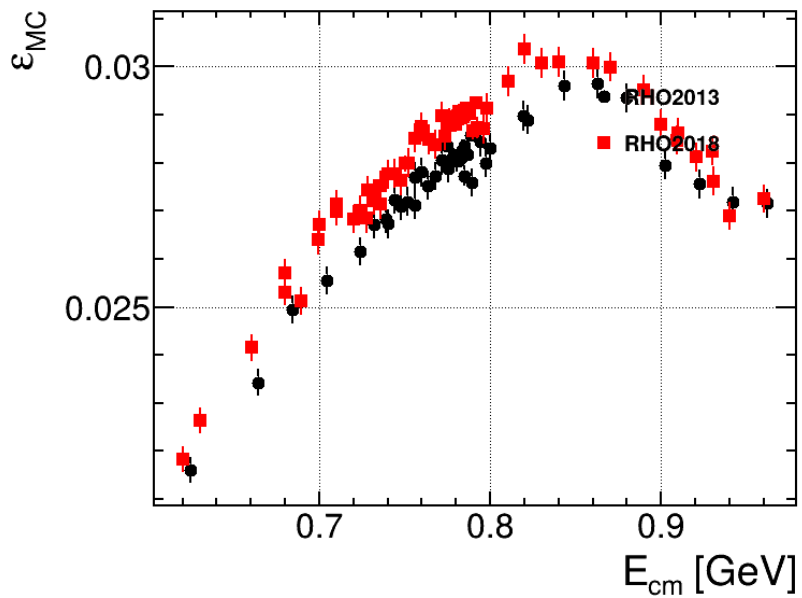
- $\chi^2_{\pi\pi\gamma} > 40$
- $\chi^2_{ee\gamma} > 200$
- $\chi^2_{\mu\mu\gamma} > 100$

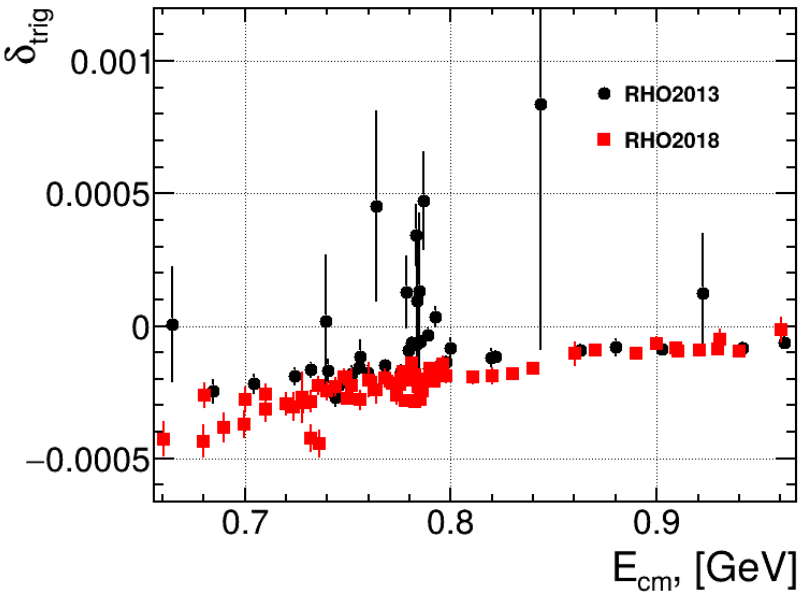
Main background processes:

- $\pi^+\pi^-\gamma$
- $e^+e^-\gamma$
- $\mu^+\mu^-\gamma$

- KinFit

Efficiency. Trigger efficiency correction





Simulation

- $\rho\pi$ mechanism for 3π production
- ISR accounted for

Definitions:

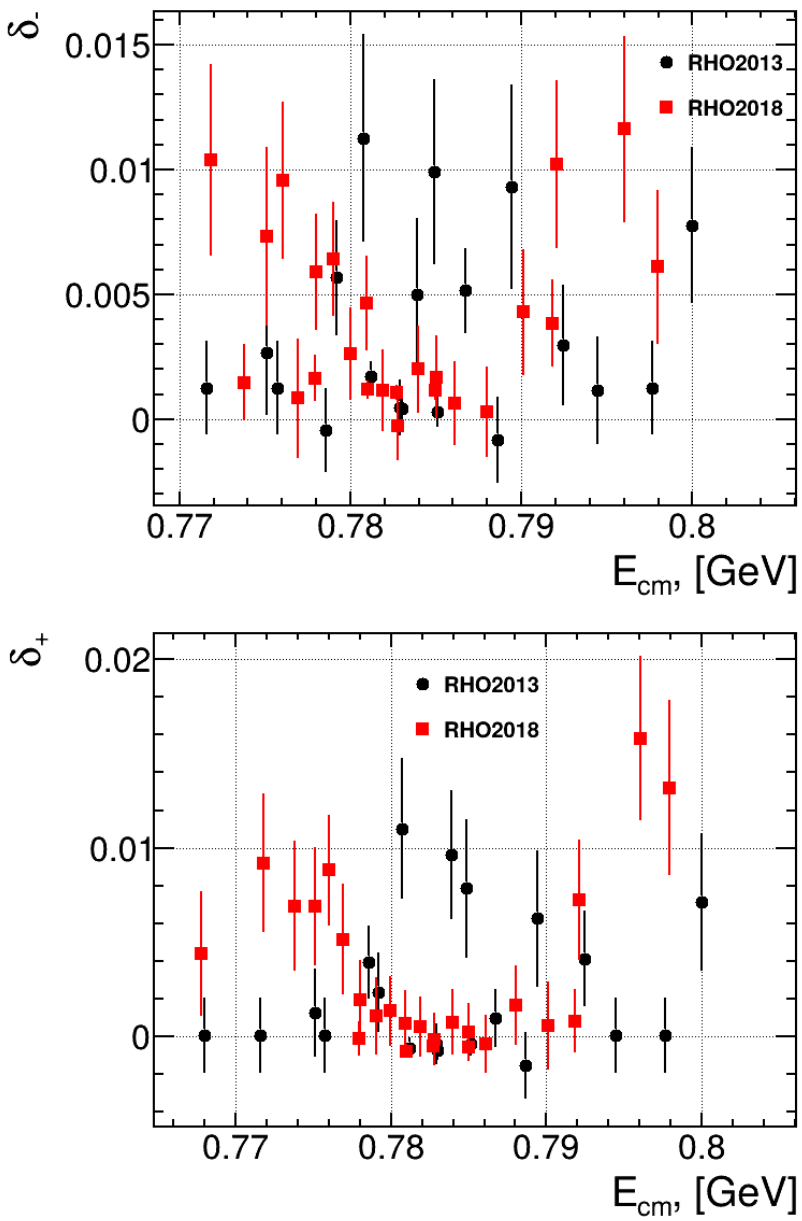
- $\varepsilon_{MC} = \frac{N_{sel}^{MC}}{N_{tot}^{MC}}$, $\sim 3\%$ due to π^0
- $\delta_{\text{trig}} = 1 - \frac{\varepsilon_{\text{trig}}^{exp}}{\varepsilon_{\text{trig}}^{MC}}$

$$\varepsilon_{\text{trig}} = 1 - (1 - \varepsilon_{\text{ch}})(1 - \varepsilon_{\text{neut}})$$

$$\varepsilon_{\text{neut}} = \frac{N_{\text{both}}}{N_{\text{ch}} + N_{\text{both}}}$$

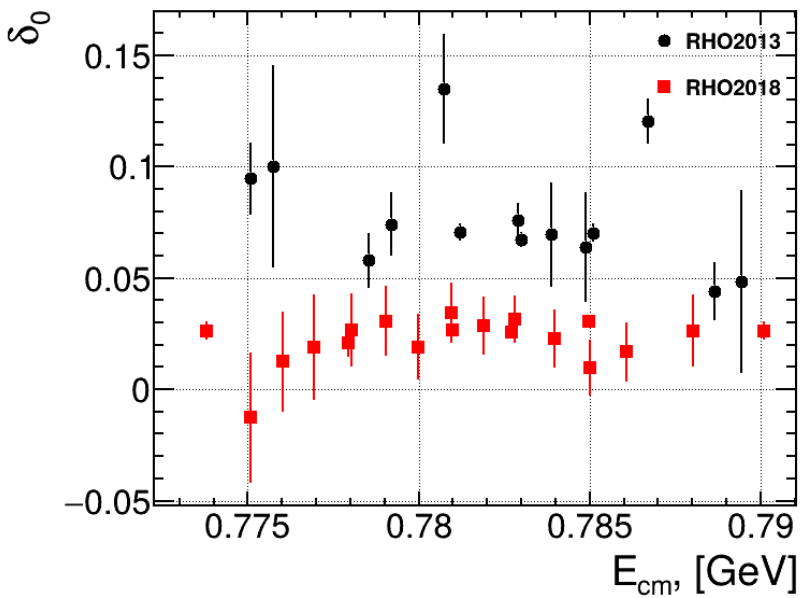
$$\varepsilon_{\text{ch}} = \frac{N_{\text{both}}}{N_{\text{neut}} + N_{\text{both}}}$$

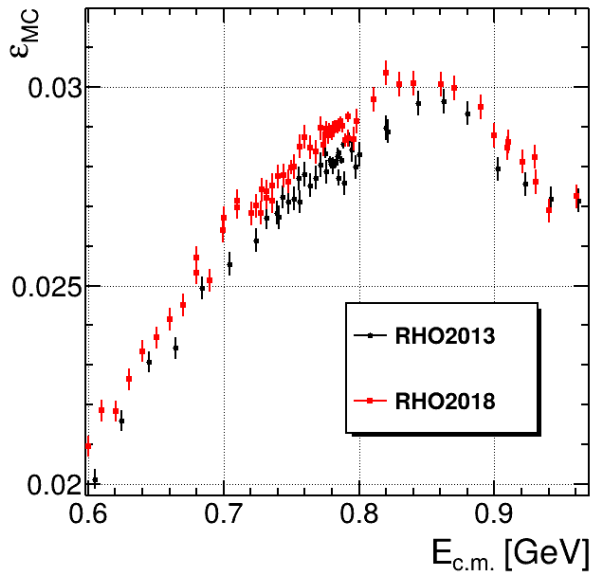
Track reconstruction corrections



- Two event classes (N_{2tr,π^0} and $N_{2tr+1tr,\pi^0}$) selected with tighter π^0 criteria
- $120 < M_{\gamma\gamma} < 150$ MeV
- For integral correction per point, $\delta_{\pm} = 1 - \frac{\varepsilon_{\pm}^{exp}}{\varepsilon_{\pm}^{MC}}$ distribution was folded with angular distribution of events
- For points with insufficient statistics, weighted average over the season was taken
- At peak $< 0.5\%$ per track (RHO2018)

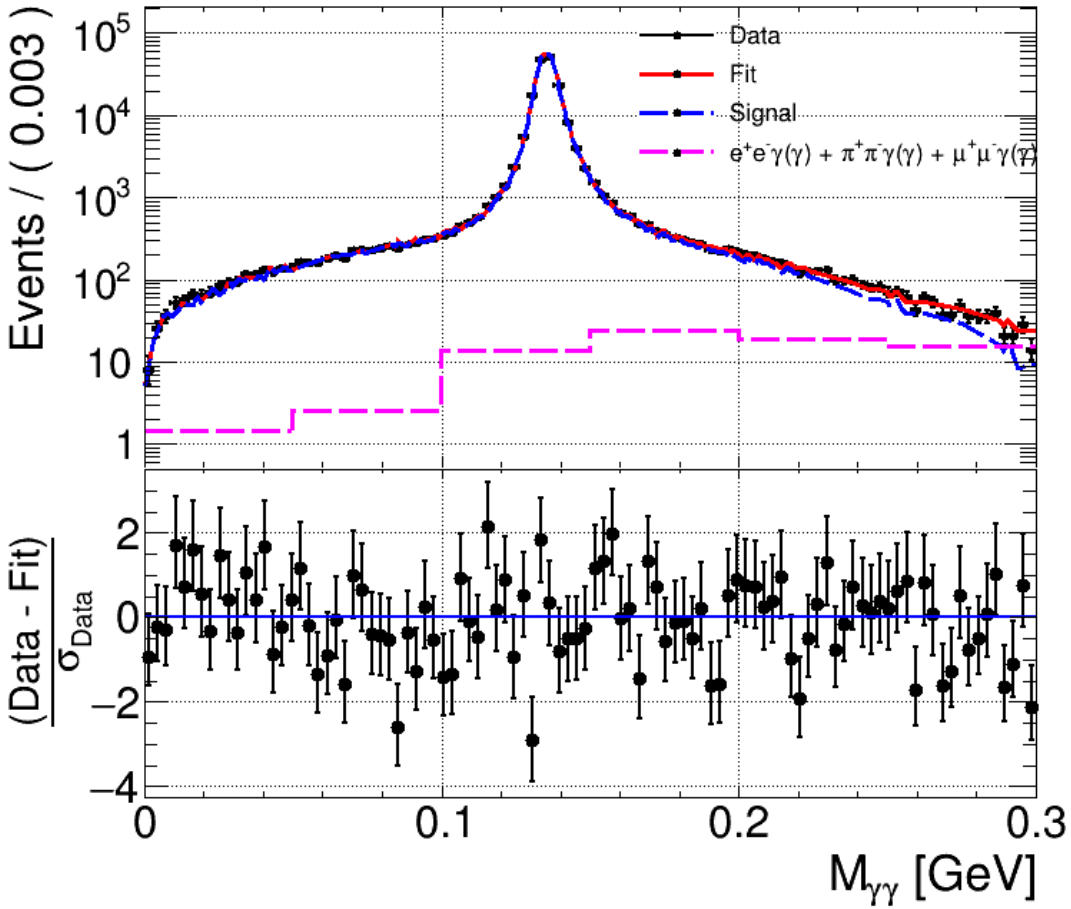
π^0 reconstruction corrections





- Two event classes (N_{2tr,π^0} and N_{2tr}) selected with tighter M_{miss} criteria
- $40 < M_{miss} < 180$ MeV
- For integral correction per point, $\delta_0 = 1 - \frac{\varepsilon_0^{exp}}{\varepsilon_0^{MC}}$ distribution was folded with momentum distribution of lost π^0
- For points with insufficient statistics, weighted average over the season was taken
- RHO2018 $\sim 2.5\%$
- RHO2013 $\sim 7.5\%$

Event counting. Visible cross section calculation.

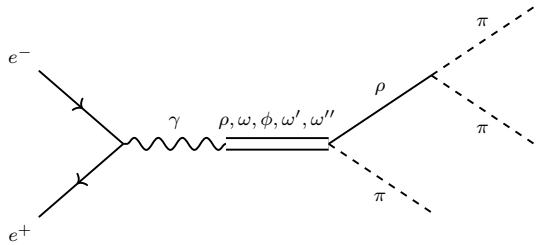


- Fit to invariant mass distribution of photon pair with smallest $\chi^2_{\pi^+\pi^-\pi^0}$ in signal hypothesis
- $Sig(MC + res) + Bkg(MC + uniform)$
- RHO2018
- $E_{beam} = 391.5$ MeV
- $L_{int} \sim 5$ pb^{-1}
- $N_{sig} \sim 200k$ $N_{bkg} \sim 1k$

$$\sigma_{\text{vis}} = \frac{N_{sig}}{\varepsilon_{MC} L (1-\delta_+)(1-\delta_-)(1-\delta_0)(1-\delta_{trig})}$$

Visible cross section approximation

$$\sigma_{\text{vis}} = \frac{1}{\sqrt{2\pi\sigma_E^2}} \int \exp\left(\frac{(\sqrt{s'}-\sqrt{s})^2}{2\sigma_E^2}\right) \times \int_0^{1-s_{th}/s'} F(x,s')\sigma_{\text{born}}(s'(1-x))dx\, d(\sqrt{s'})$$



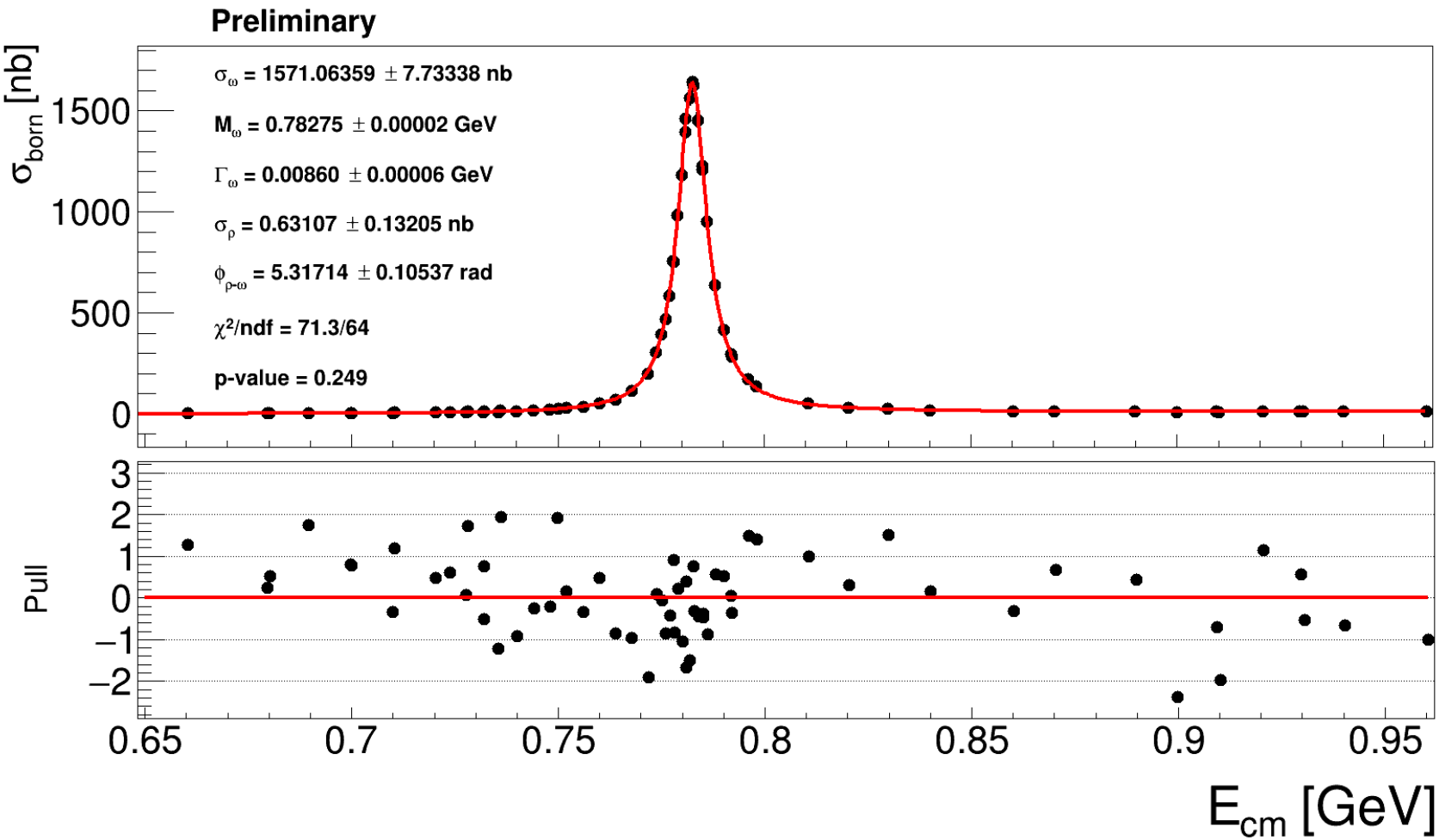
$$\sigma(s)_{\text{born}} = \frac{F_{3\pi}^{\rho\pi}(s)}{s^{3/2}} \left| \sum_{V=\ \rho,\omega,\phi,\omega',\omega''} e^{i\phi_{\omega V}} \sqrt{\frac{\sigma_0(V\to 3\pi)M_V}{F_{3\pi}^{\rho\pi}(M_V^2)}} \frac{\Gamma_V M_V^2}{D_V(s)} \right|^2$$

$$F_{3\pi}^{\rho\pi}(s) = \frac{(4\pi\alpha)^2\sqrt{s}}{12\pi} \int \left[\vec{P}_+ \times \vec{P}_-\right]_\perp^2 \left| \sum_{i=\ 0,+,-} \frac{g_{\rho^i\pi\pi}}{D_{\rho^i}(P_{\rho^i}^2)} \right|^2 d\Phi_{3\pi}$$

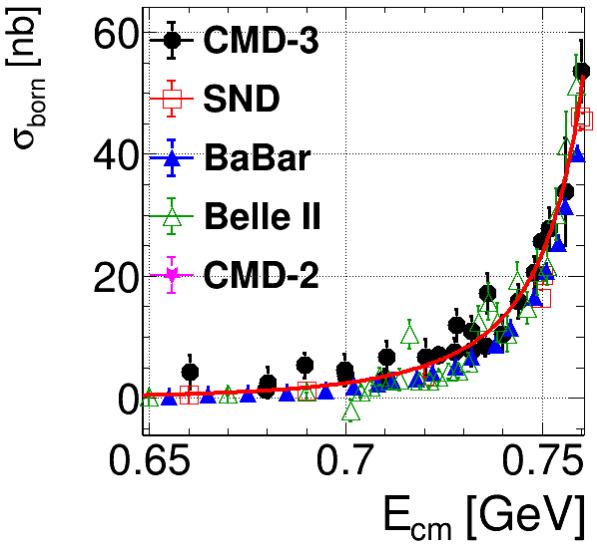
- V - vector meson
- $\phi_{\omega V}$ - relative mixing phase of vector mesons
- $F_{3\pi}^{\rho\pi}(s)$ - phase space in $\rho\pi$ mechanism
- $M_\omega, \Gamma_\omega, \sigma_0(\omega \to 3\pi), \sigma_0(\rho \to 3\pi), \phi_{\omega\rho}$ - free parameters
- $\phi_{\omega\phi} = 162°$ (SND)

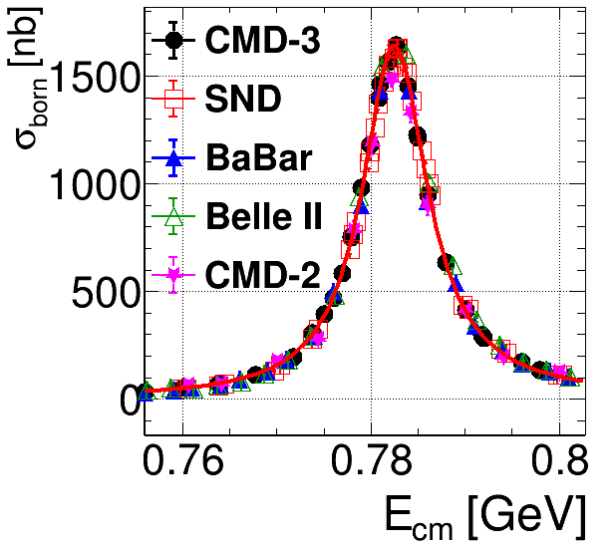
- Isrsolver
- SND

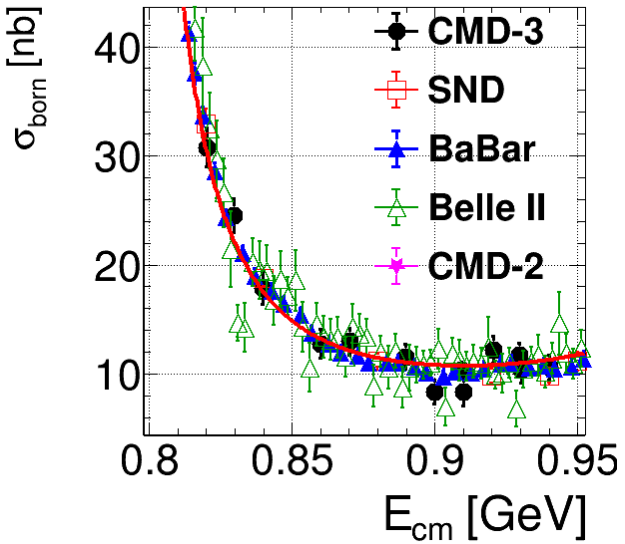
Cross section approximation. Comparison with other experiments.



Comparison with other experiments.

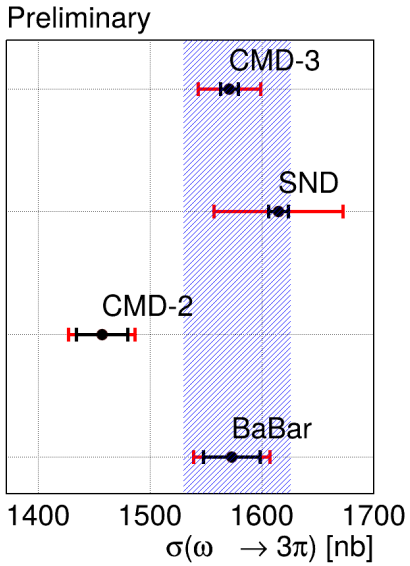


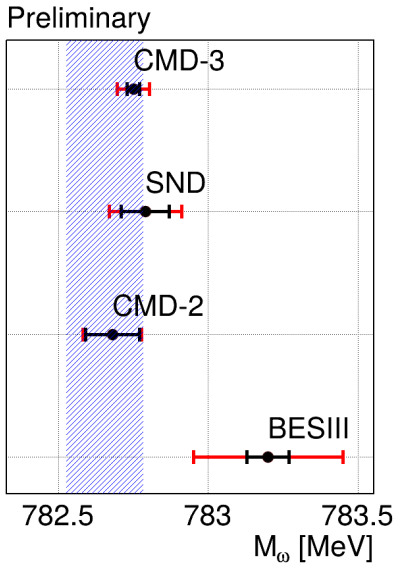


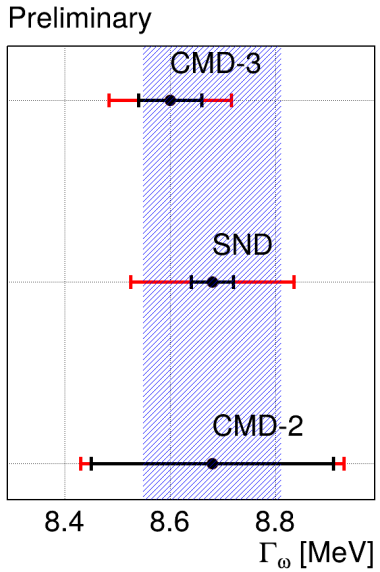


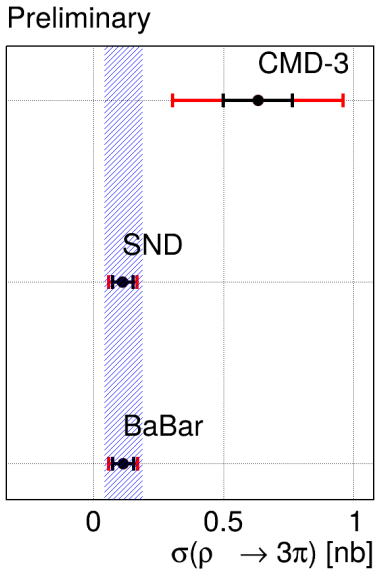
- BaBar
- Belle II
- SND
- CMD-2

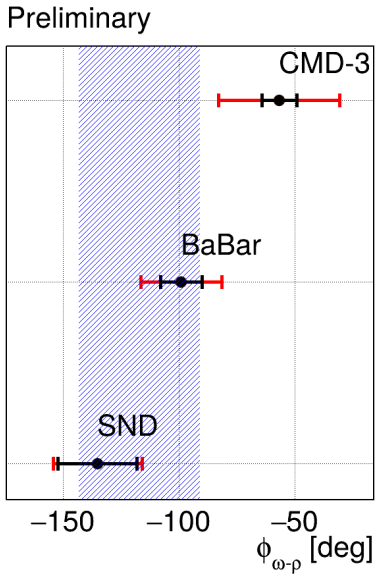
Approximation parameters. Comparison with other experiments.











- Black line - statistical error
- Red line - total error
- Agreement of ω-meson parameters

Systematic uncertainties

Source	**Contribution (%)**	**Estimation method**
Luminosity	1.5	Difference between $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$
π^0 reconstruction	0.5	Comparison with cross section without π^0 reconstruction
Selection criteria	0.5	Variation of selection criteria
Background subtraction	0.3	Different event counting procedures
ISR in MC	0.3	Different cross-sections
Energy spread	0.3	Calculation of radiative correction without taking account for beam energy spread
Track reconstruction	0.2	Calculation in different selection criteria
Trigger efficiency	<0.1	–
Total systematic uncertainty of cross section: 1.8%		

Systematic uncertainties for Γ_ω, $\sigma(\rho \to 3\pi)$ and $\phi_{\omega-\rho}$ were estimated from parameter spread in different independent datasets.

Contribution to $a_\mu^{had,LO}$.

$$a_\mu^{had,3\pi} = \frac{1}{4\pi^3}\int_{s_{\min}}^{s_{\max}} \sigma_{\text{born}}^{3\pi}(s)|1-\Pi(s)|^2 \cdot K(s)\,ds$$

$\sigma_{\text{born}}^{3\pi}(s)$ – Born cross section function after approximation of experimental data

$a_\mu^{had,3\pi}$ in range $0.62 < \sqrt{s} < 1.1\ GeV/c^2$

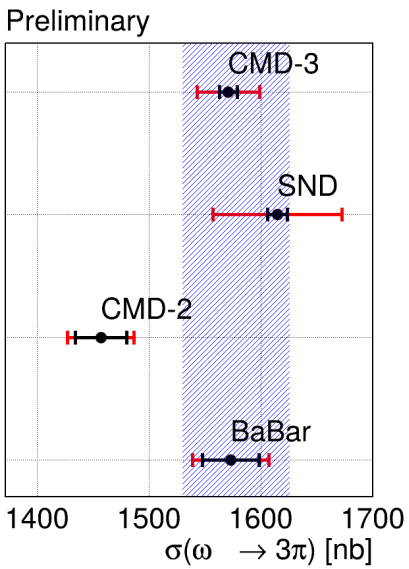
- **CMD-3** $(44.3 \pm 0.2 \pm 0.8) \times 10^{10}$ **(Function) [Preliminary]**
- BaBar $(42.91 \pm 0.14 \pm 0.55 \pm 0.09) \times 10^{10}$ $(\Delta = (1.4 \pm 1) \times 10^{10}$

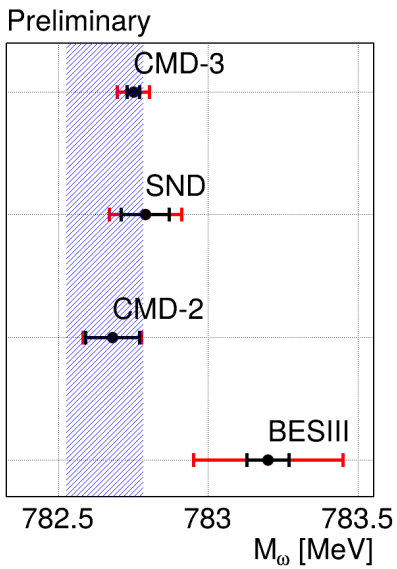
$a_\mu^{had,3\pi}$ in range $0.65 < \sqrt{s} < 0.98\ GeV/c^2$

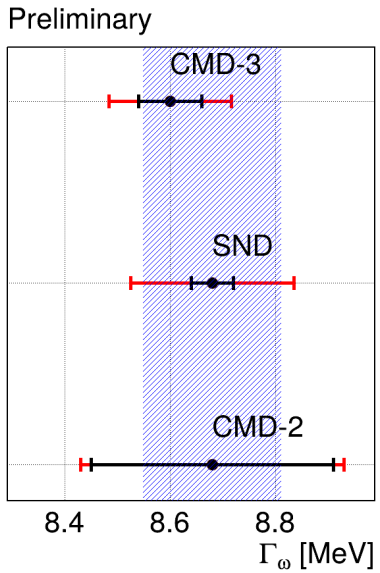
- **CMD-3** $(38.0 \pm 0.2 \pm 0.8) \times 10^{10}$ **(Function) [Preliminary]**
- **CMD-3** $(38.2 \pm 0.2 \pm 0.8) \times 10^{10}$ **(Linear approximation,** $\Delta = (0.2 \pm 1.2) \times 10^{10}$**)**

- Vacuum polarization operator

Conclusion





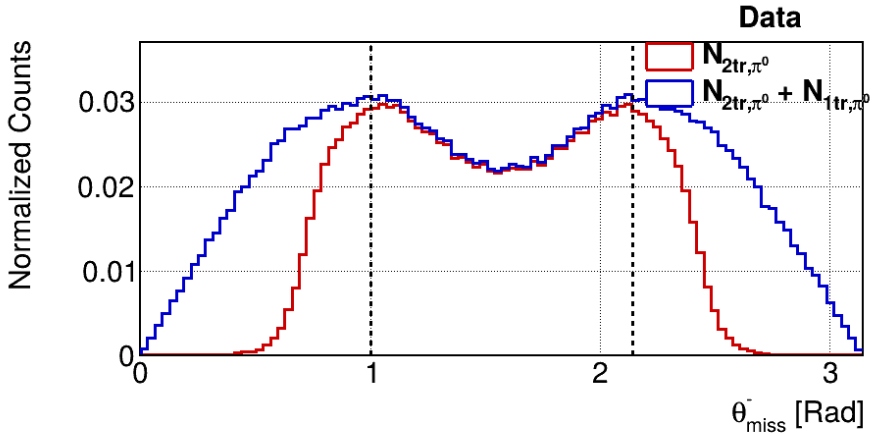


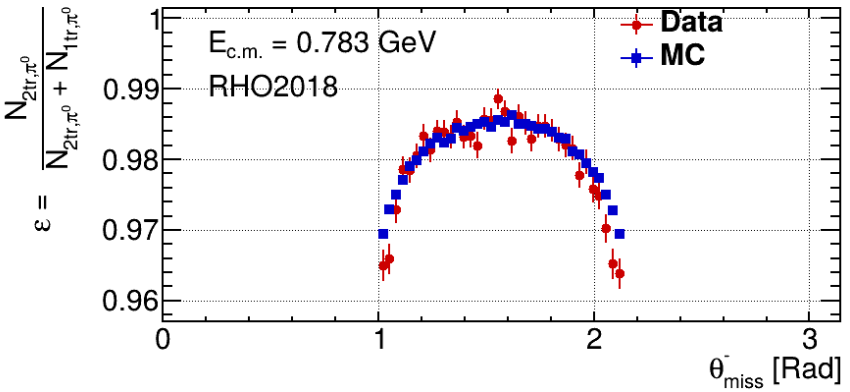
- Preliminary measurements of the 3π cross section with CMD-3 detector at VEPP-2000 ($\Delta_{stat} \sim 0.5\%$, $\Delta_{sys} \sim 1.8\%$)
- Determining ω-meson (in agreement with other measurements) and $\rho - \omega$-interference parameters
- Calculation of contribution to $a_\mu^{had,3\pi}$
- The work was supported by grants: the Russian Science Foundation No 23-42-10025; the Belarusian Republican Foundation for Basic Research No. F23RSF-118.

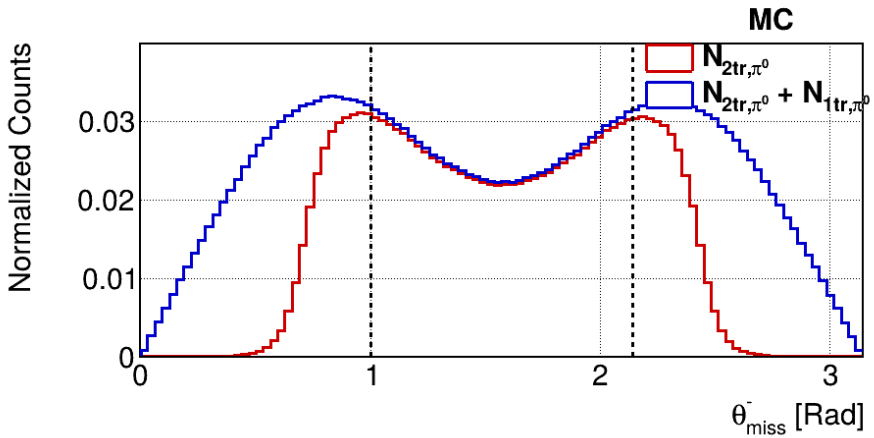
Backslides. Track reconstruction corrections (Calculation)

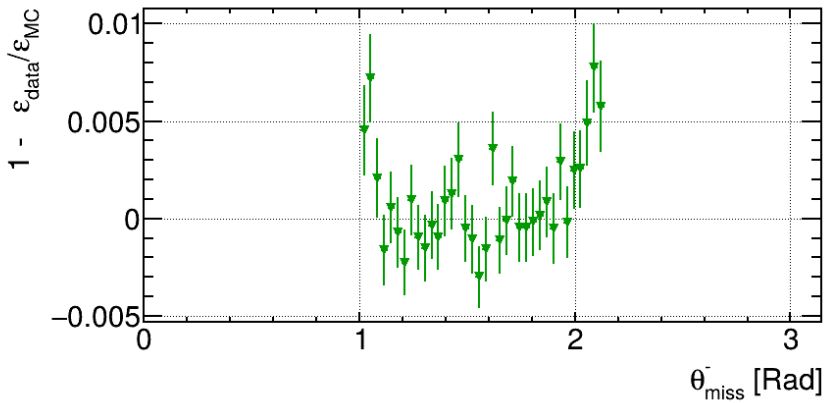
Two event classes (N_{2tr,π^0} and $N_{2tr+1tr,\pi^0}$) selected with tighter π^0 criteria

- $120 < M_{\gamma\gamma} < 150$ MeV





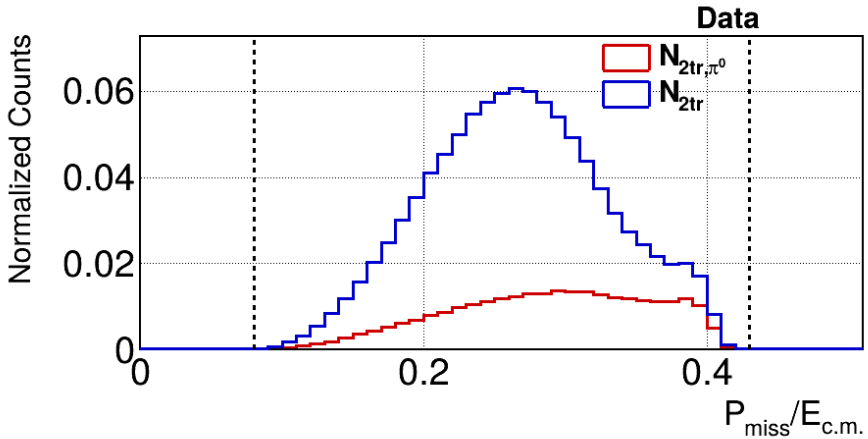


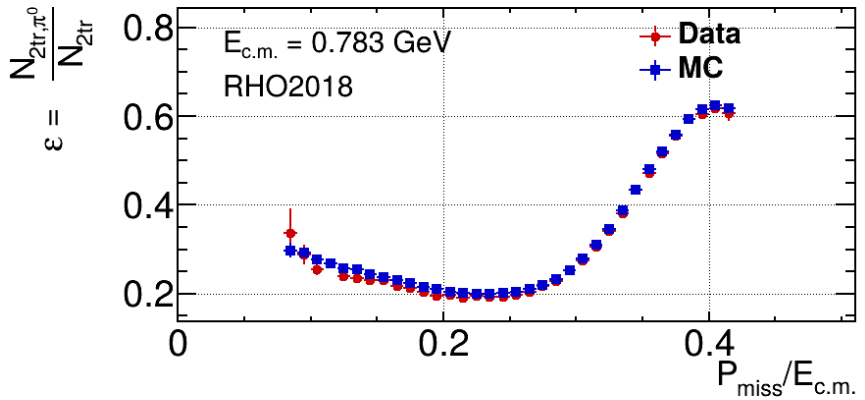


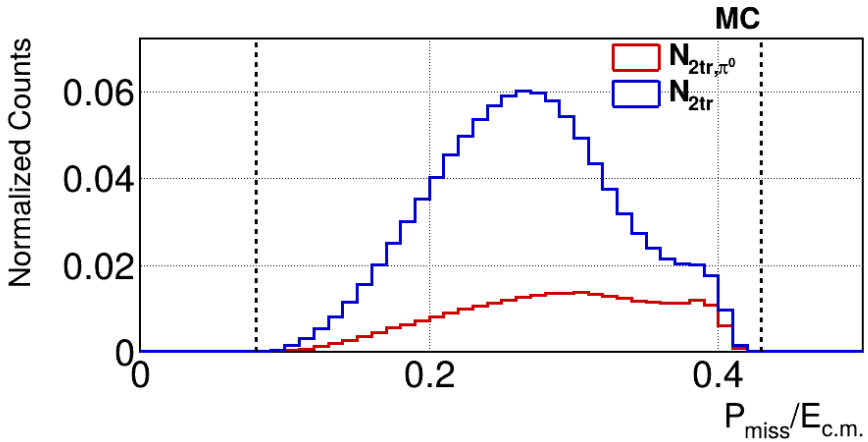
Backslides. π^0 reconstruction corrections (calculation)

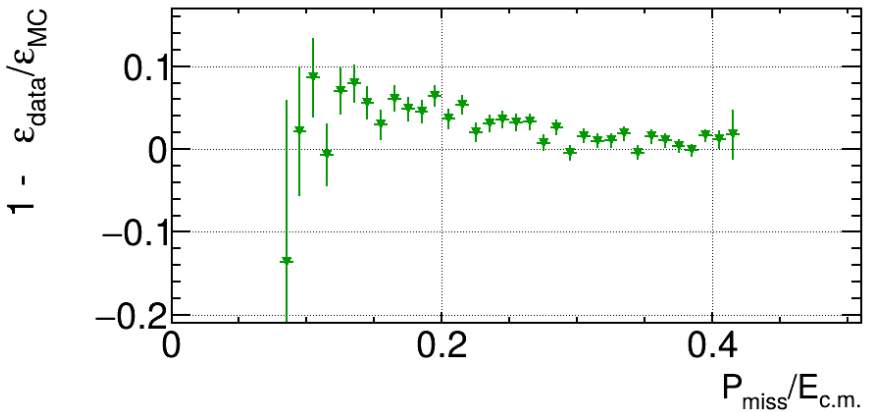
Two event classes (N_{2tr,π^0} and N_{2tr}) selected with tighter M_{miss} criteria

- $40 < M_{miss} < 180$ MeV

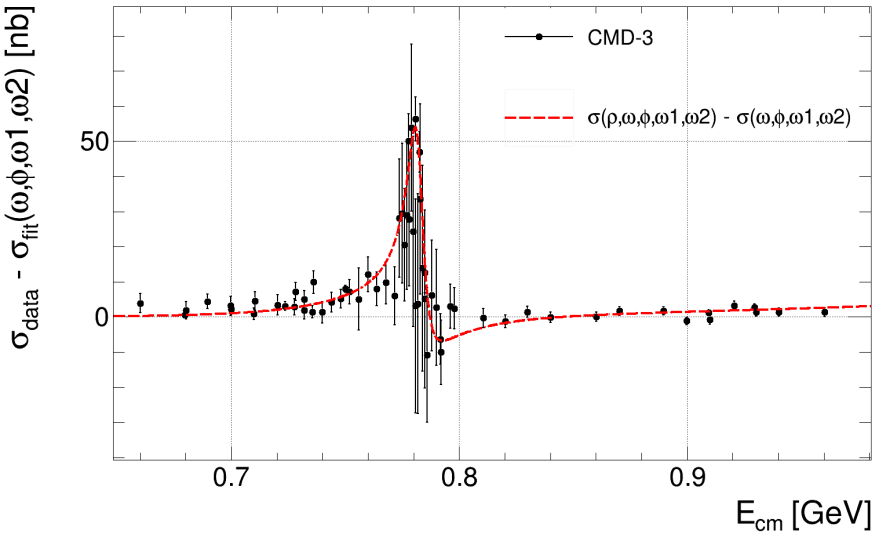


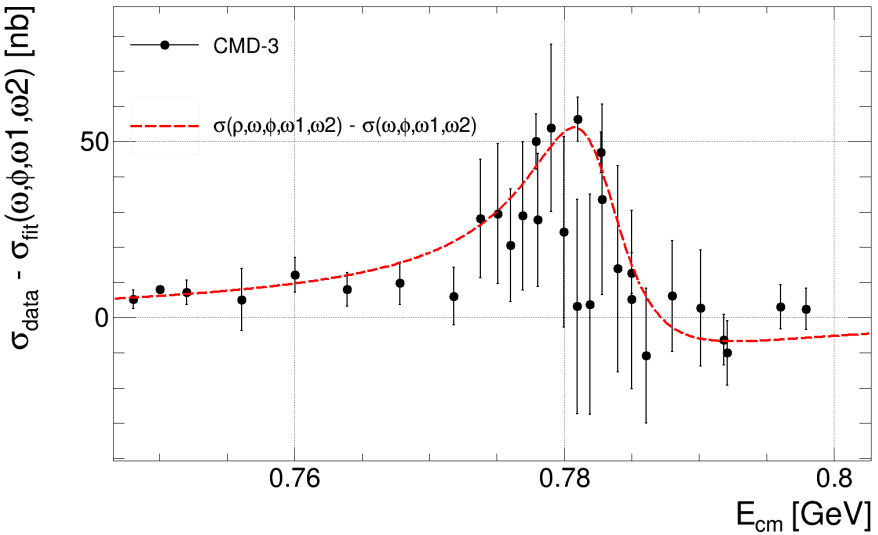




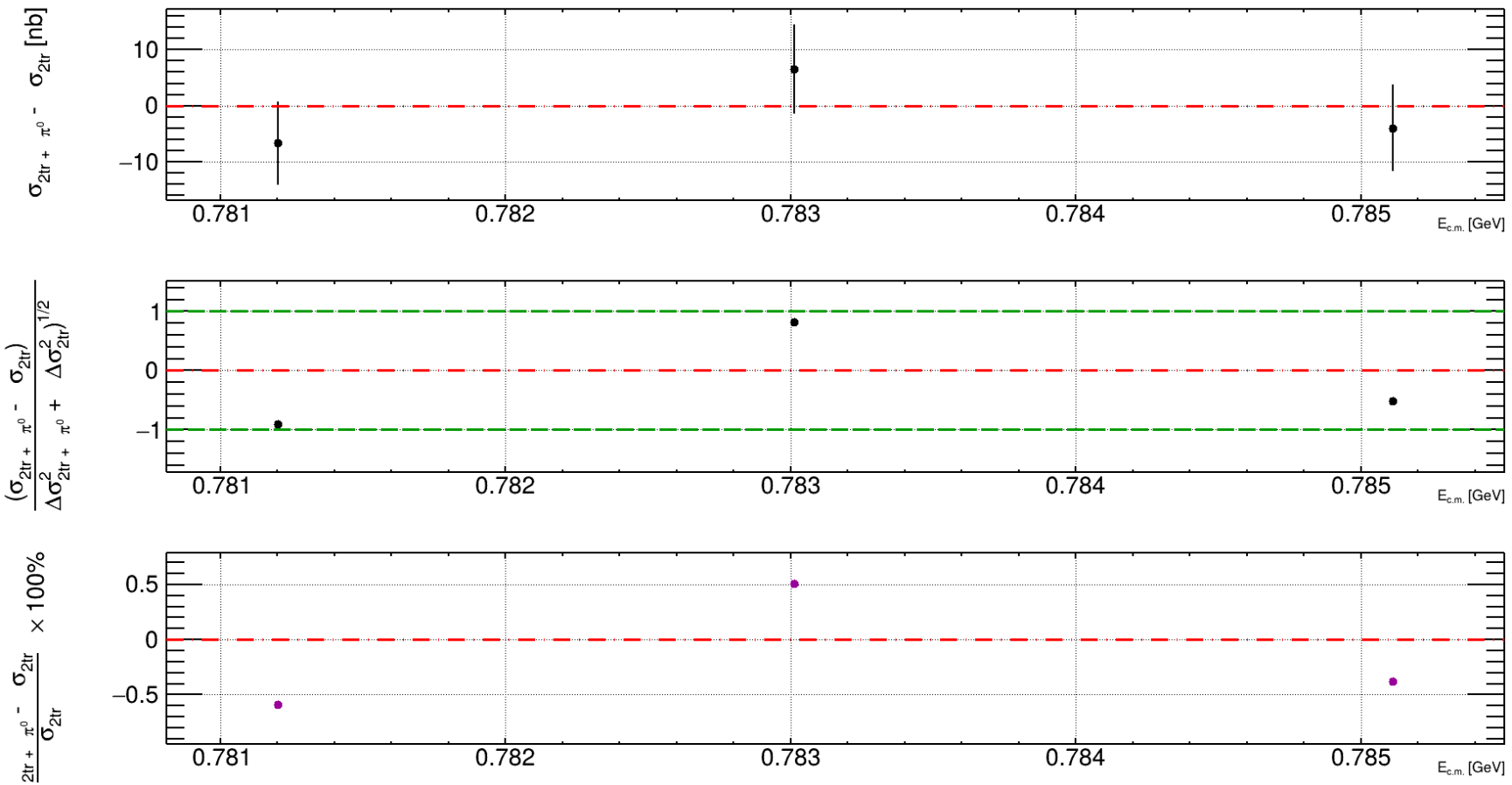


Backslides. ρ contribution subtraction

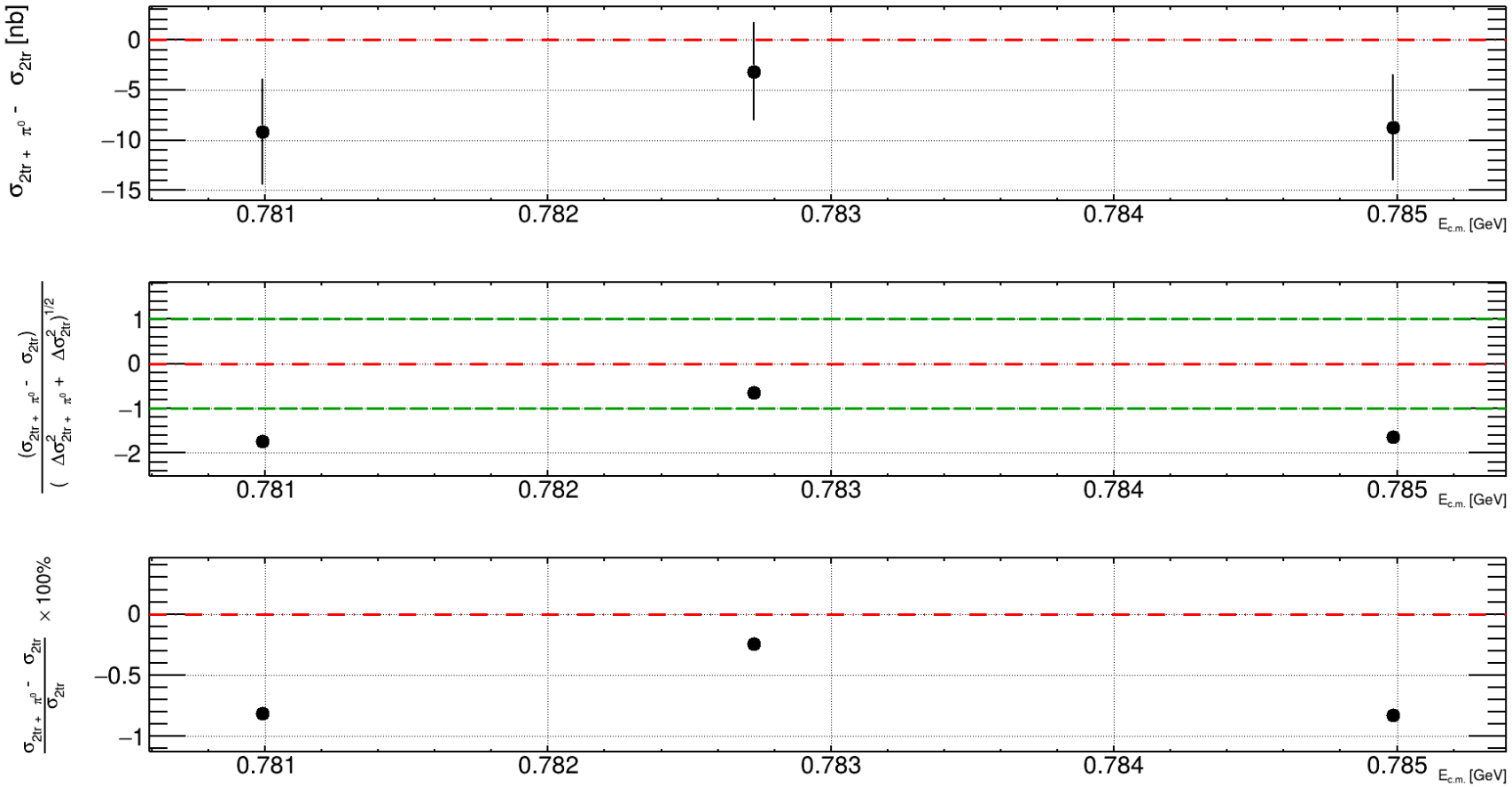




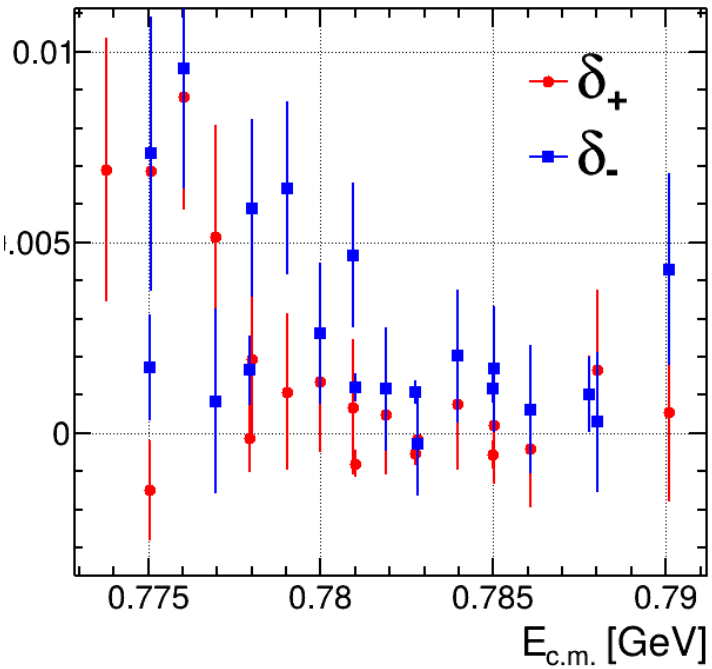
Backslides. Systematics. Cross section comparison (RHO2013)



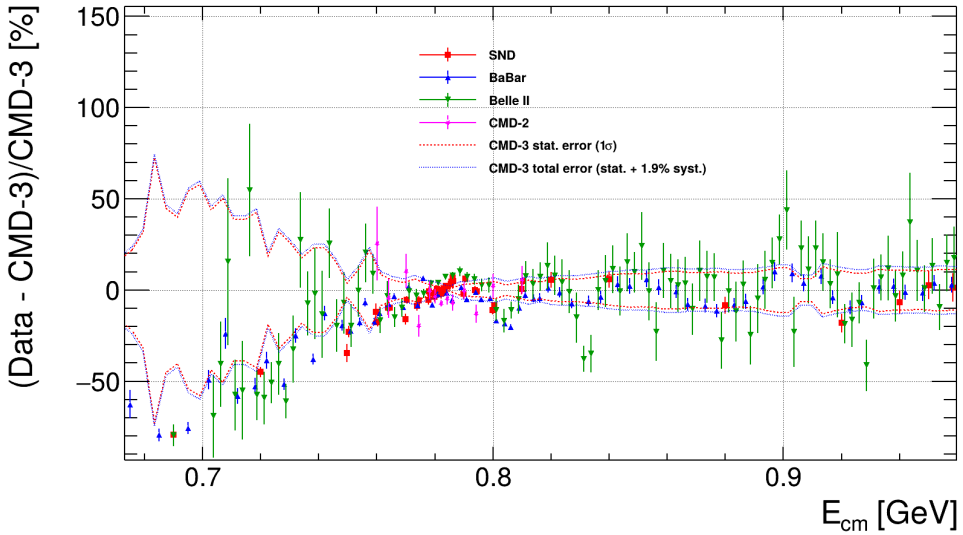
Backslides. Systematics. Cross section comparison (RHO2018)

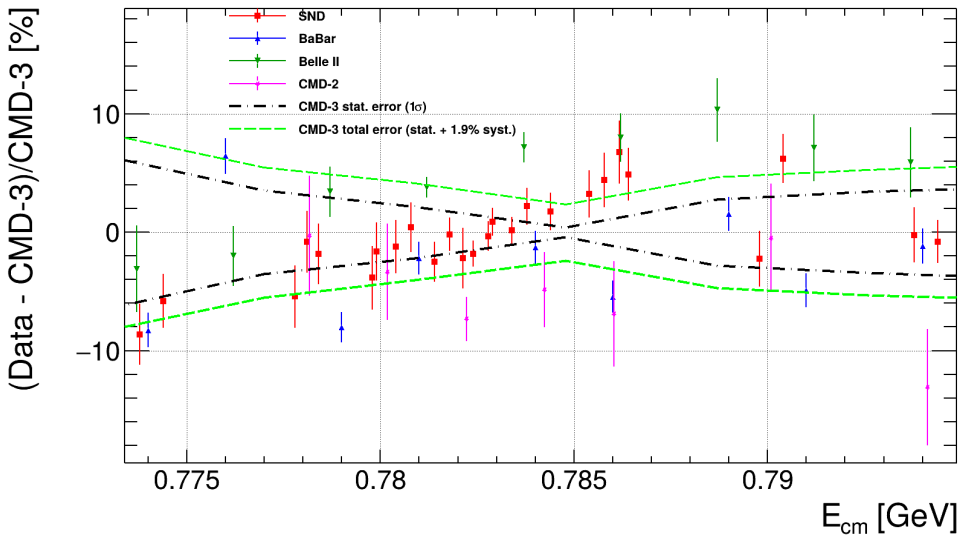


Backslides. Track reconstruction correction. π^+ vs π^- comparison (RHO2018)

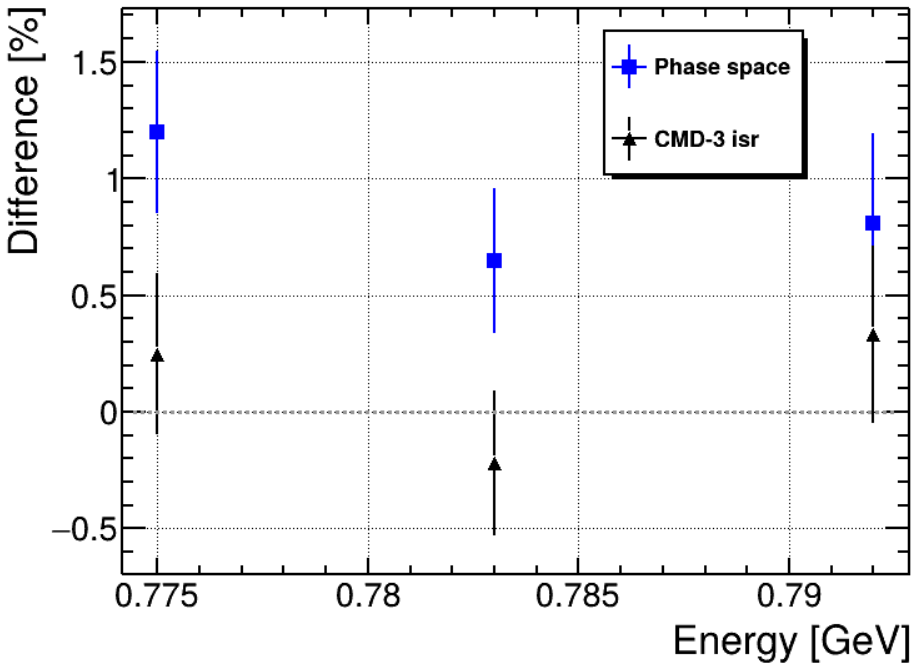


Backslides. BCS comparison (RHO2018)





Backslides. Efficiency systematics. ISR in MC. Model/



Backslides. Approximation parameters comparison in different CMD-3 scans