Изучение процесса электрон-позитронной аннигиляции в четыре пиона

Евгений Козырев
BINP, NSU
e.a.kozyrev@inp.nsk.su
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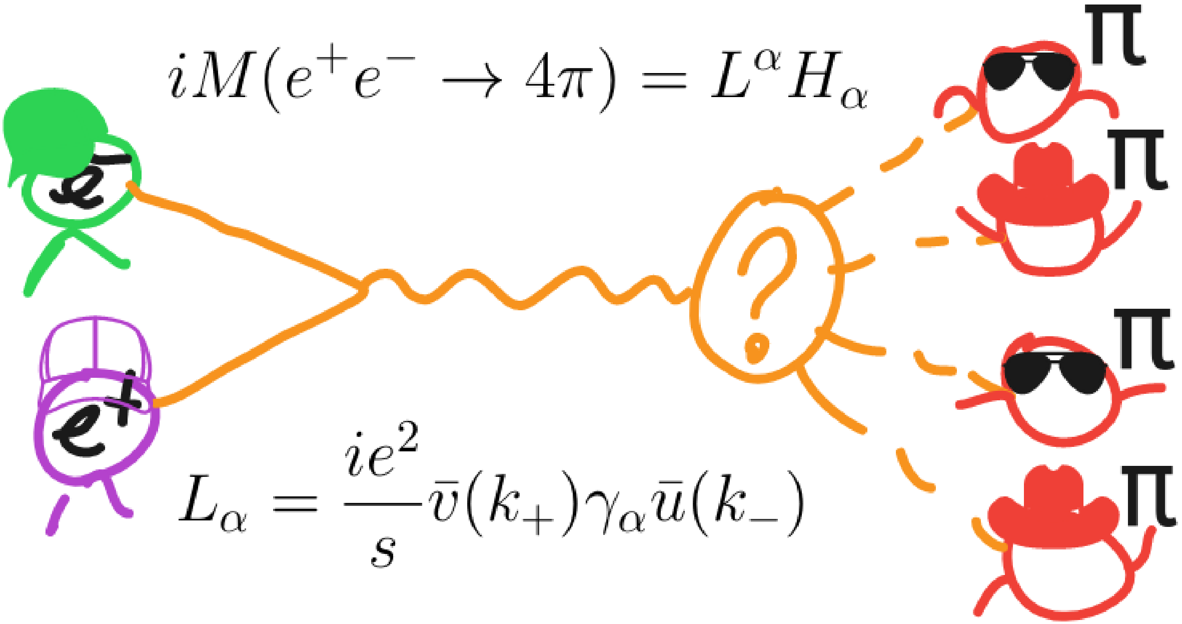
Научный руководитель
д.ф.-м.н. гл.н.с. ИЯФ СО РАН
Солодов Евгений Петрович

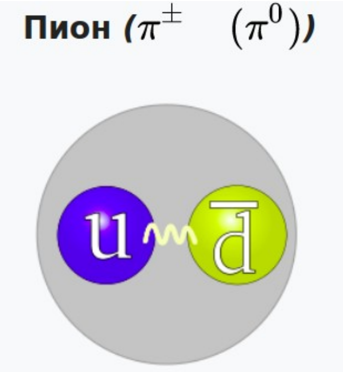
Оглавление

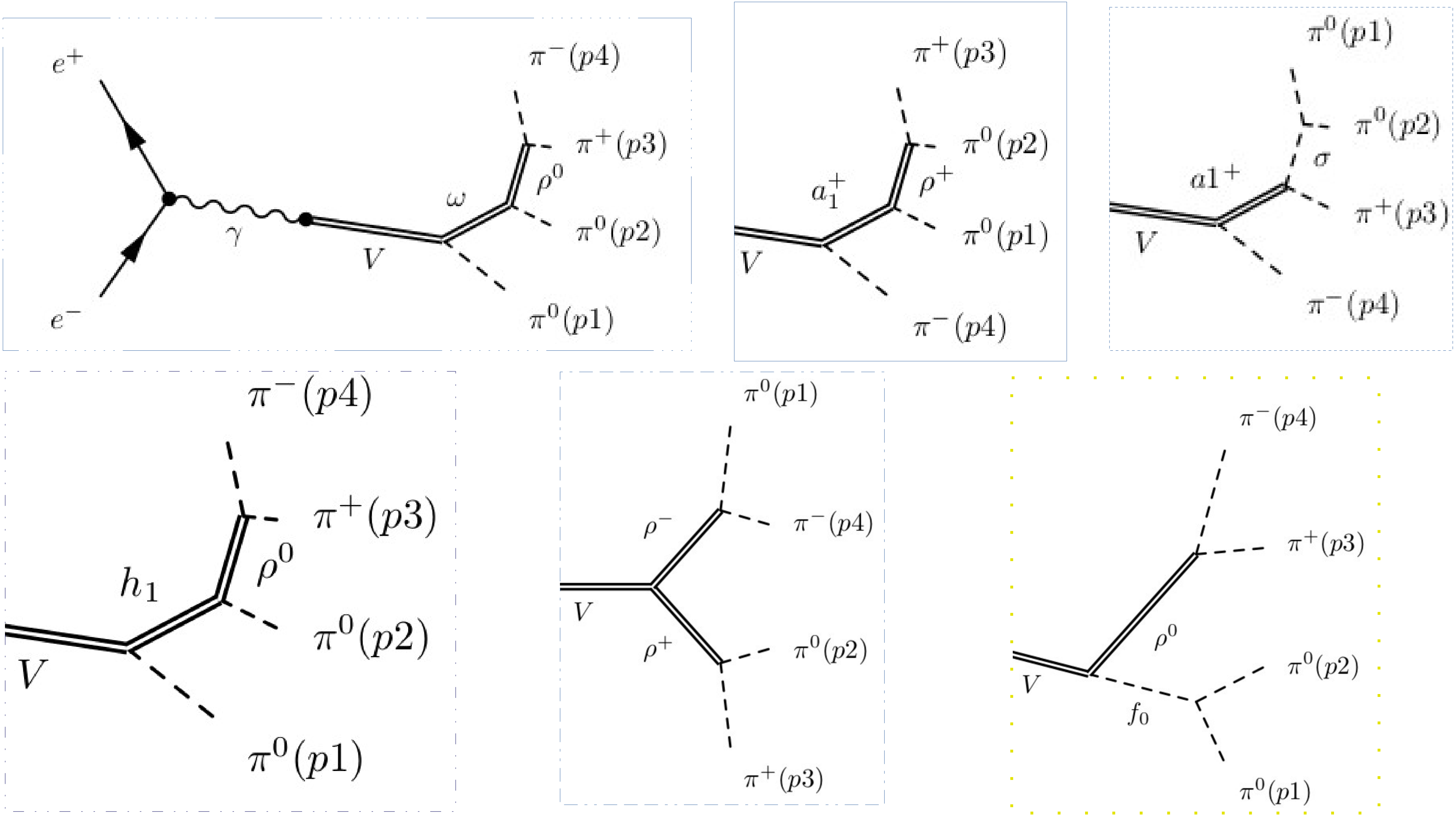
Цель работы

- **Построить модель промежуточной динамики**



- **Померить сечение**





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

Амплитудный анализ с детектором КМД-2 (5.8 pb^{-1})

- The data in the $ee \to \pi^+\pi^-2\pi^0$ (22128 events) with $\sqrt{s}$ = [1.05–1.38] GeV is used

- The **dominance of the $\omega\pi$ and $a_1\pi$** is proved

The results of a search for the admixture of other possible states

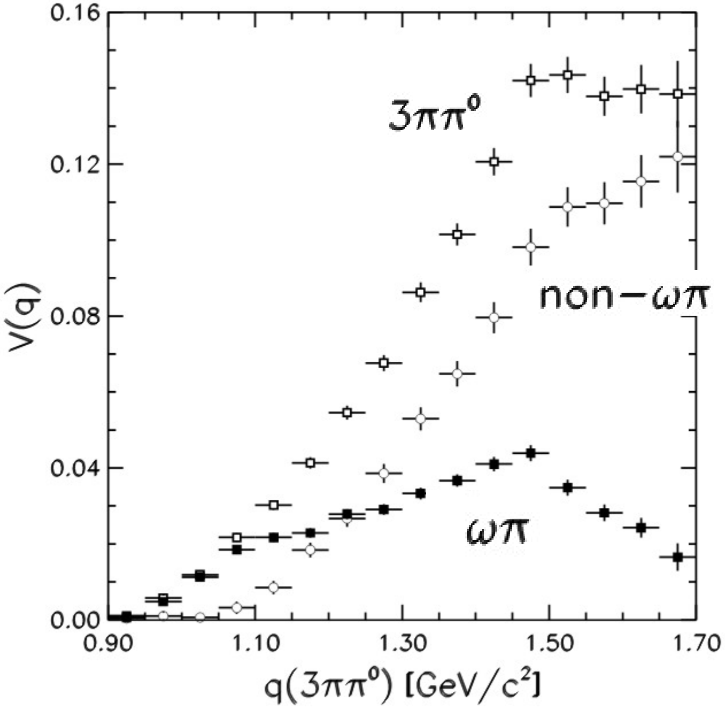
Model	L_{min}	r_X [%]	U.L. [%]
$\omega\pi^0 + a_1\pi$	1264	–	–
$\omega\pi^0 + a_1\pi + \rho\sigma$	1256	$2.1^{+1.2}_{-0.9}$	4.3
$\omega\pi^0 + a_1\pi + h_1\pi$	1263	$0.1^{+0.2}_{-0.1}$	0.4
$\omega\pi^0 + a_1\pi + a_2\pi$	1263	$0.2^{+0.4}_{-0.2}$	0.8
$\omega\pi^0 + a_1\pi + \pi'\pi$	1250	$9.5^{+3.2}_{-2.8}$	15.
$\omega\pi^0 + a_1\pi + \rho^+\rho^-$	1246	$4.7^{+2.0}_{-1.6}$	7.7

*R.R. Akhmetshin et al., Physics Letters B **466**, 392–402 (1999)*

- The data in $ee \to \pi^+\pi^-2\pi^0$ and $ee \to 2\pi^+2\pi^-$ (28552) is used for the estimation: $B(a_1\to\sigma\pi)/B(a_1\to\rho\pi) \sim 0.3$

- The measured cross section are systematically shifted from other measurement.

Амплитудный анализ процесса $\tau\to3\pi\pi^0\nu_\tau$ с детектором CLEO (1999)



Spectral functions

$$\frac{\Gamma(\tau^-\to\nu_\tau 2\pi^-\pi^+\pi^0)}{\Gamma(\tau^-\to\nu_\tau e^-\overline{\nu}_e)} = \frac{3\cos^2\theta_c}{2\pi\alpha^2 m_\tau^8}\int_0^{m_\tau^2} dQ^2 Q^2 (m_\tau^2-Q^2)^2(m_\tau^2+2Q^2) \cdot\left[\frac{1}{2}\sigma_{e^+e^-\to2\pi^-2\pi^+}(Q^2)+\sigma_{e^+e^-\to\pi^+\pi^-2\pi^0}(Q^2)\right]$$

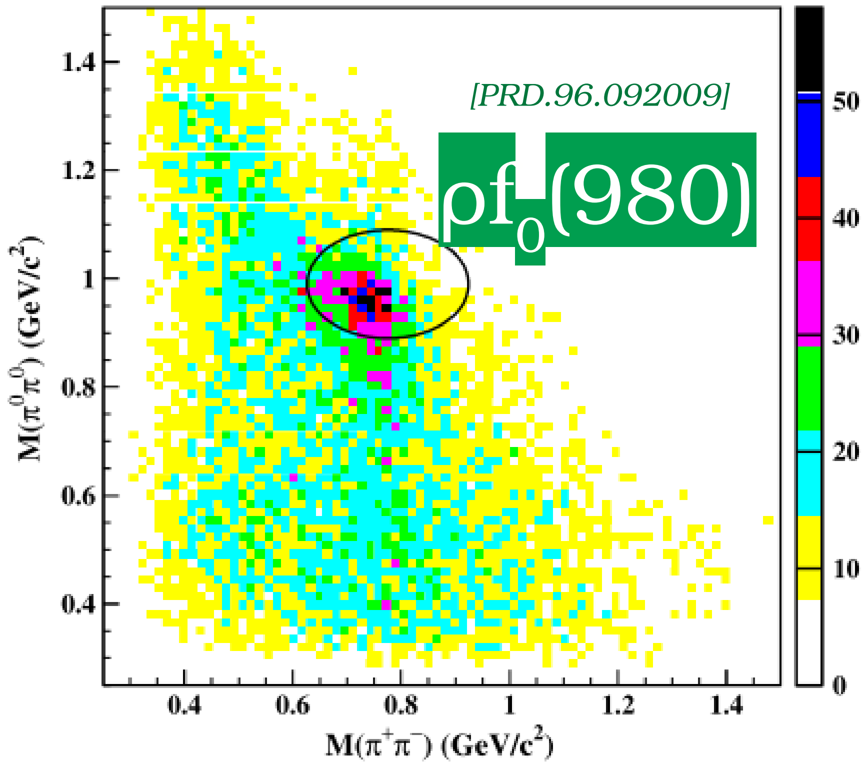
Model	Integrated amplitudes	Goodness-of-fit
Model 2	$R_{\omega\pi}=0.38\pm0.02\pm0.02$	$<5\%$
	$R_{a_1\pi}=0.43\pm0.02\pm0.02$	
Model 3	$R_{\omega\pi}=0.38\pm0.02\pm0.01$	20%
	$R_{a_1\pi}=0.49\pm0.02\pm0.02$	
	$R_{\sigma\rho}=0.01\pm0.02\pm0.01$	
	$R_{f_0\rho}=0.01\pm0.01\pm0.01$	

Fit results for various models

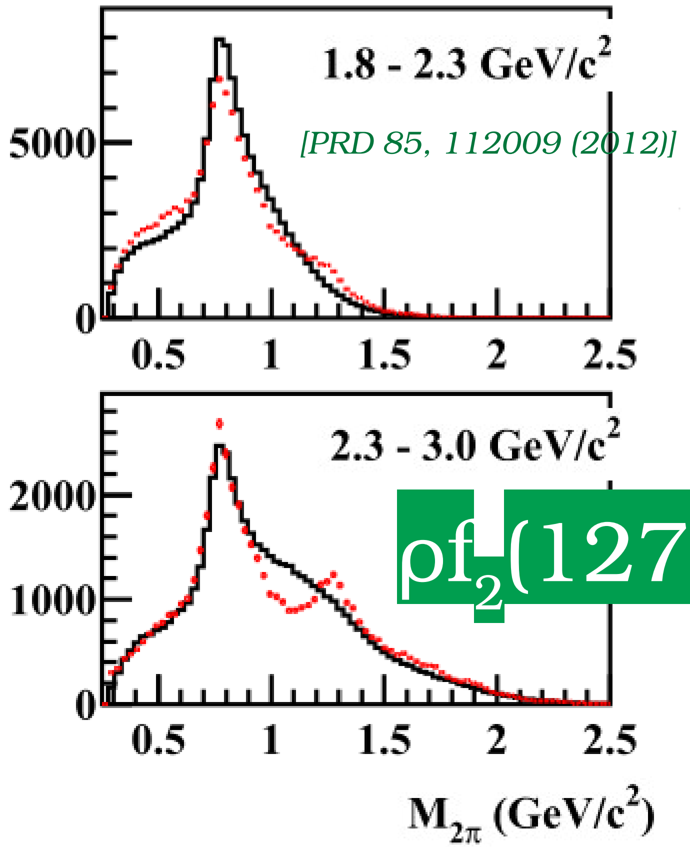
- Model with $\omega\pi$ and $a_1\pi$ and $\rho\sigma$, ρf_0 provides the best description of the data.

*Physical Review D - Particles, Fields, Gravitation and Cosmology, **61**, 1-16 (2000).*

Наблюдение состояний ρf_0 и ρf_2 с детектором BaBar при $E_{с.м.}$ > 1.8 ГэВ

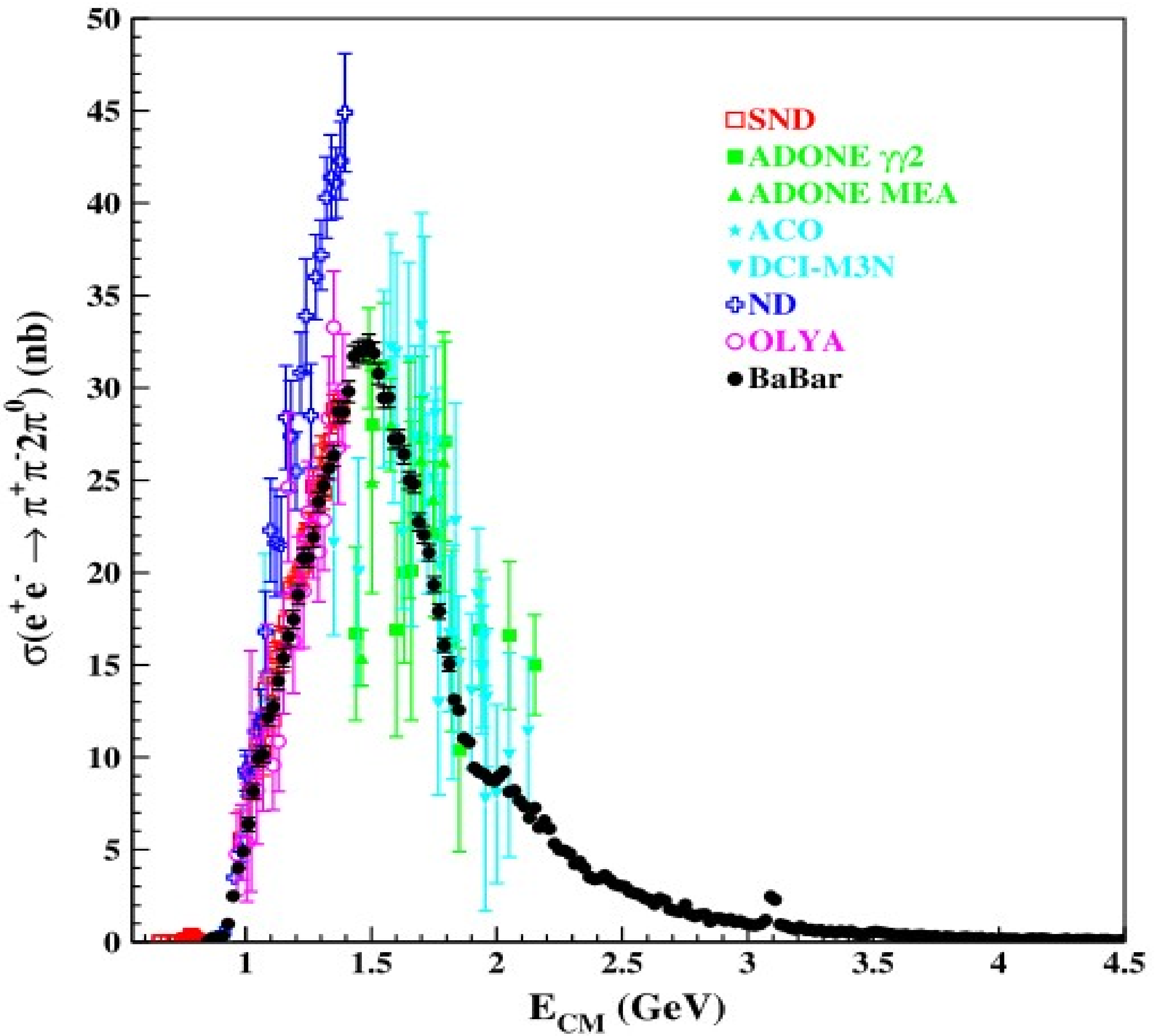


The evidence of $\rho f_0(980)$ in the process $\boldsymbol{e^+e^-\to 2\pi^0\pi^-\pi^+}$ *with BaBar*



The evidence of $\rho f_2(1270)$ in the process $\boldsymbol{e^+e^-\to 2\pi^+2\pi^-}$ *with BaBar*

Измерения $e^+e^- \to \pi^+\pi^-2\pi^0$ на других экспериментов



Общая стратегия амплитудного анализа

Signal selection
(ee → $pi^+pi^-2pi^0$)

Signal selection
(ee → $2pi^+2pi^-$)

Building of the amplitudes formalism

The definition and minimization of likelihood function (L)

Model vs Experiment comparison

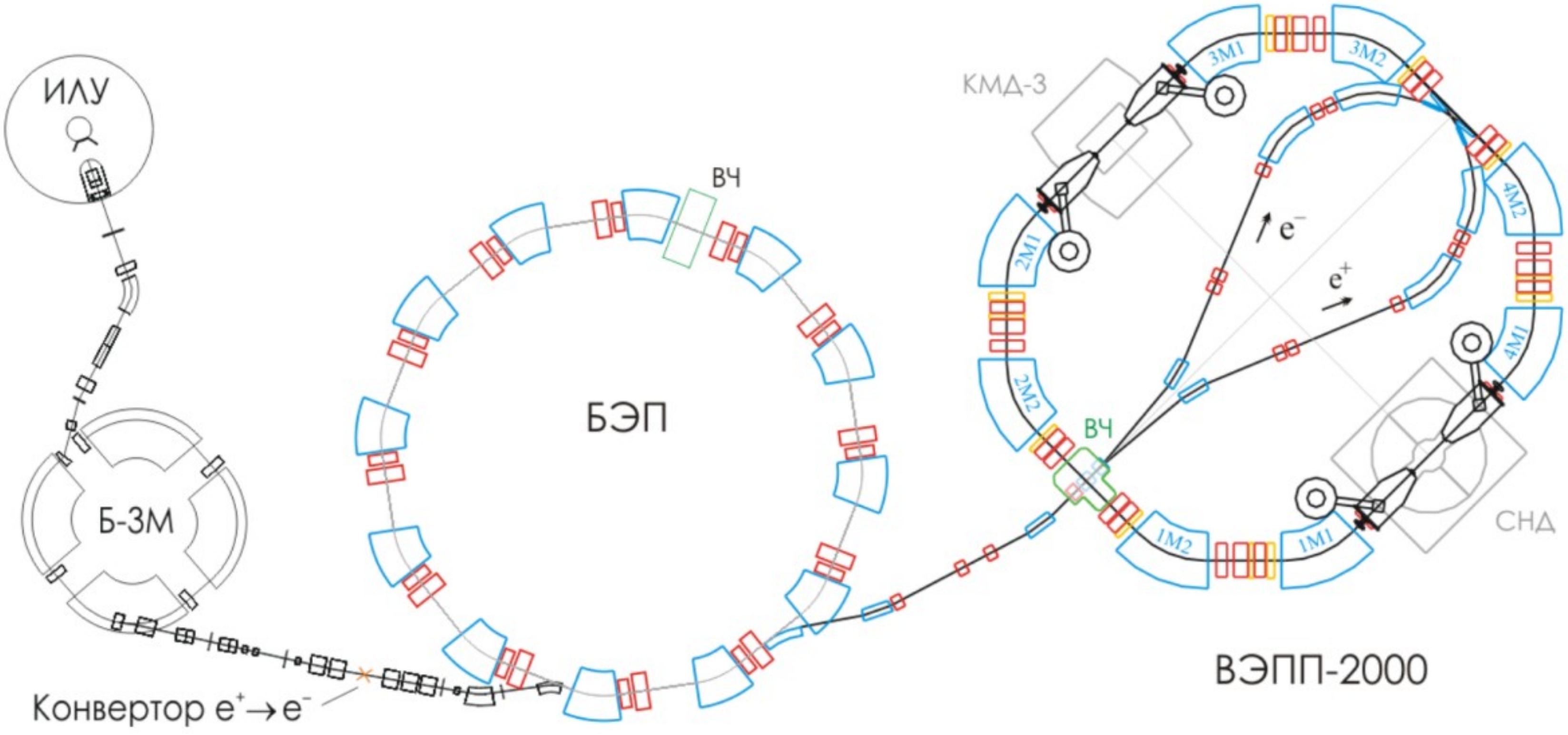
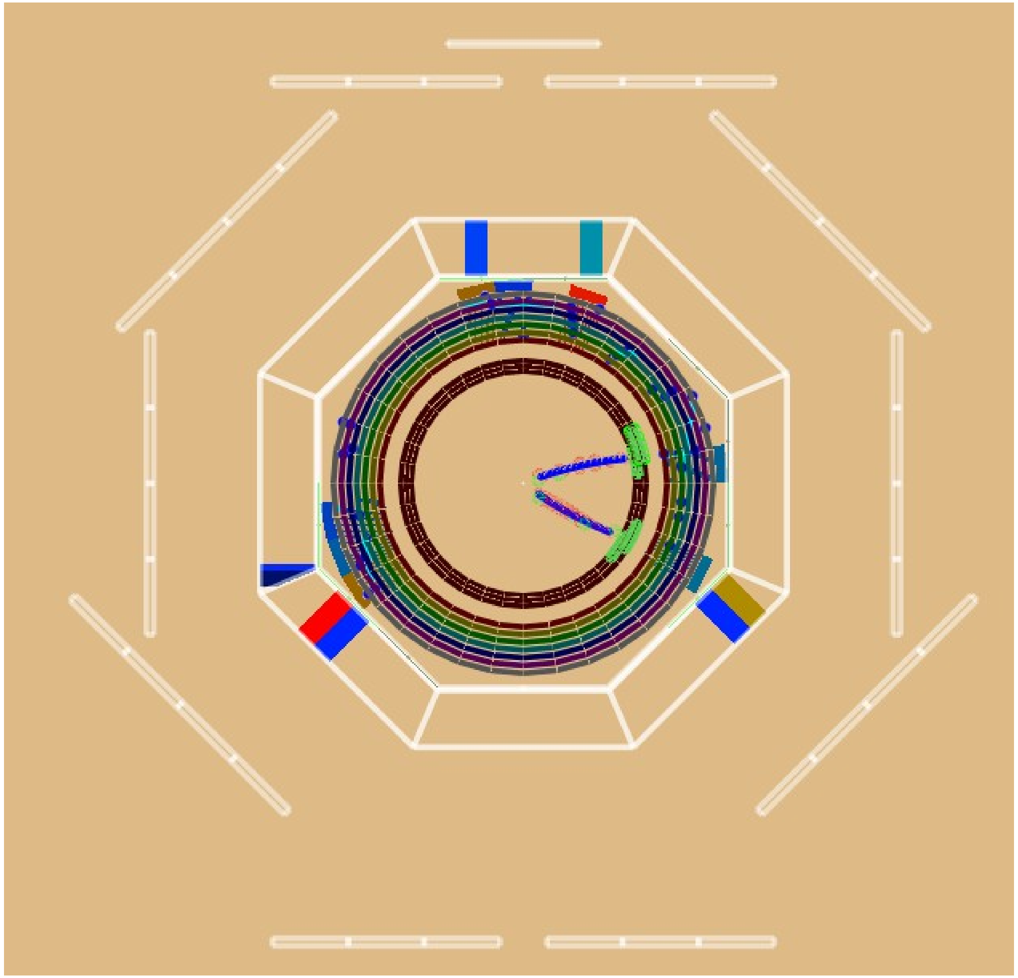


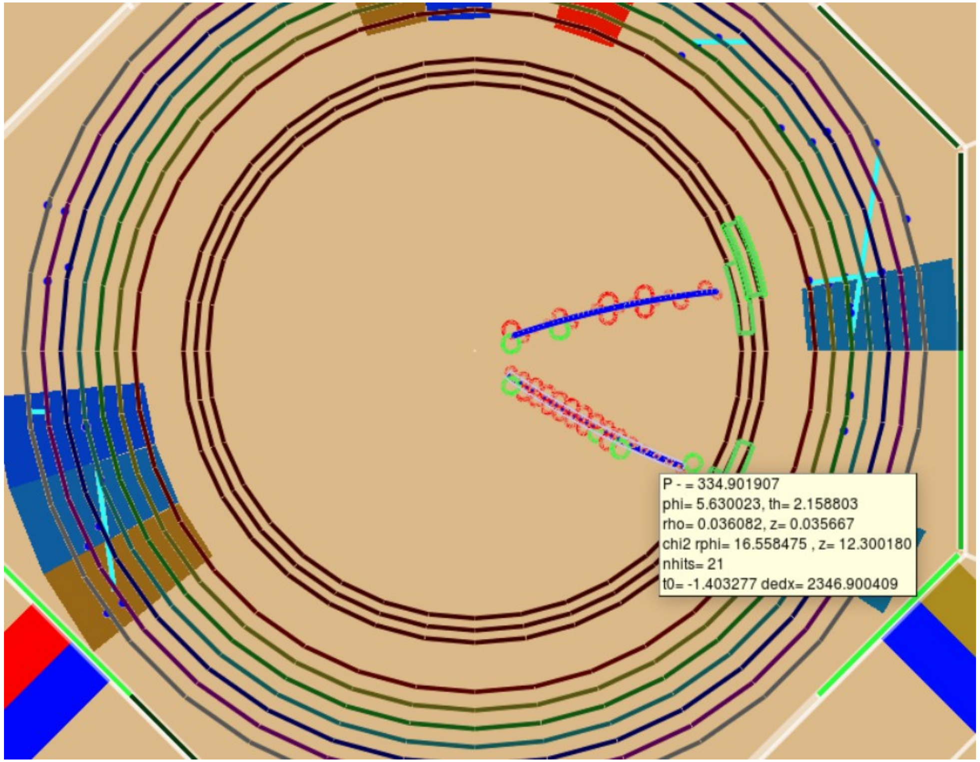
Схема ускорительного комплекса ВЭПП-2000

Сезон	Светимость, пб$^{-1}$
scan2011	20.16
scan2012	13.34

scan2012_omphi	0.68
scan2013_rho scan2013_omphi	11.59
scan2017	6.07

Отбор событий ee → $\pi^+\pi^-2\pi^0$

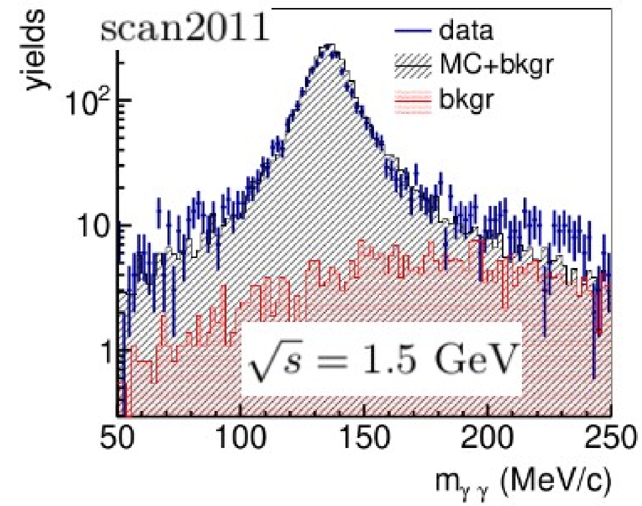


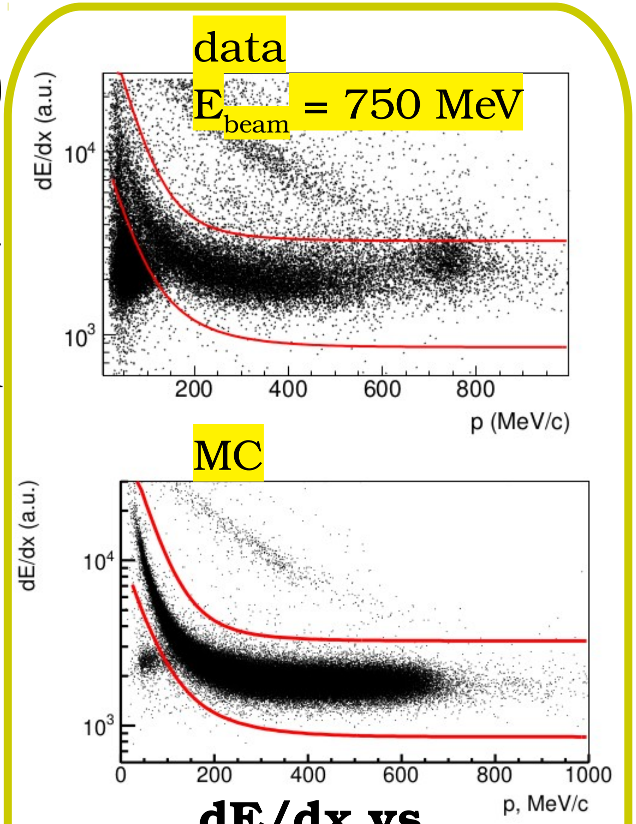


Визуализация типичного события $e^+e^-\to 2\pi^0\pi^+\pi^-$

Отбор событий
$(ee \to pi^+pi^-2pi^0)$ 64 kevents

- $0.7 < \theta_{\pi,\gamma} < \pi - 0.7$ rad
- Total (E-√s) and P < 150 MeV/(c)
- Two candidates for π^0
- 5C kinematic fit
- The invariant mass spectrum of 3rd and 4th photons is used for the estimation of the contribution of background:

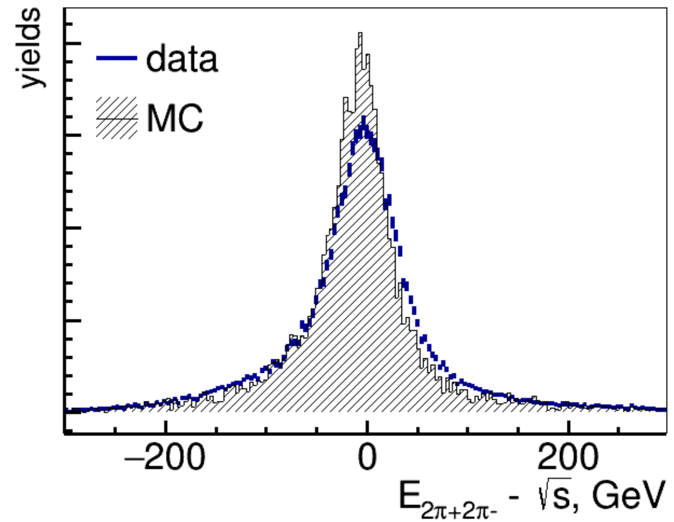




dE/dx vs momentum

Отбор событий
$(ee \to 2pi^+2pi^-)$ 72 kevents

- $0.7 < \theta_{\pi} < \pi - 0.7$ rad
- Total (E-√s) and P < 150 MeV/(c)
- 4C kinematic fit
- The spectrum of total energy of four tracks (E-√s) is used for the estimation of the contribution of background:



Функция правдоподобия

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

- $\omega[1^{--}]\pi^0[0^{-+}]$ (only $2\pi^0 2\pi^\pm$)
- $a1(1200)[1^+]\pi[0^-]$
- $\rho[1^{--}]f_0/\sigma[0^{++}]$
- $\rho f_2(1270)[2^{++}]$
- $\rho^+\rho^-$ (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 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.

Функция правдоподобия

The likelihood for model under test is

$$L = -\log \prod_{i=signal}^{pi^+pi^-2pi^0} \frac{I(\Omega_i)}{\int \varepsilon I(\Omega) d\Omega} - \log \prod_{i=signal}^{2pi^+2pi^-} \frac{I(\Omega_i)}{\int \varepsilon I(\Omega) d\Omega}$$

The limited acceptance and efficiency of the detector is taken into account by summing only over simulated events that pass the reconstruction and analysis cuts.

$$\int \varepsilon I(\Omega) d\Omega = \frac{1}{N_{MC}^{gen}} \sum_{rec}^{phase\ space\ MC} |V_\alpha A_\alpha(\Omega)|^2$$

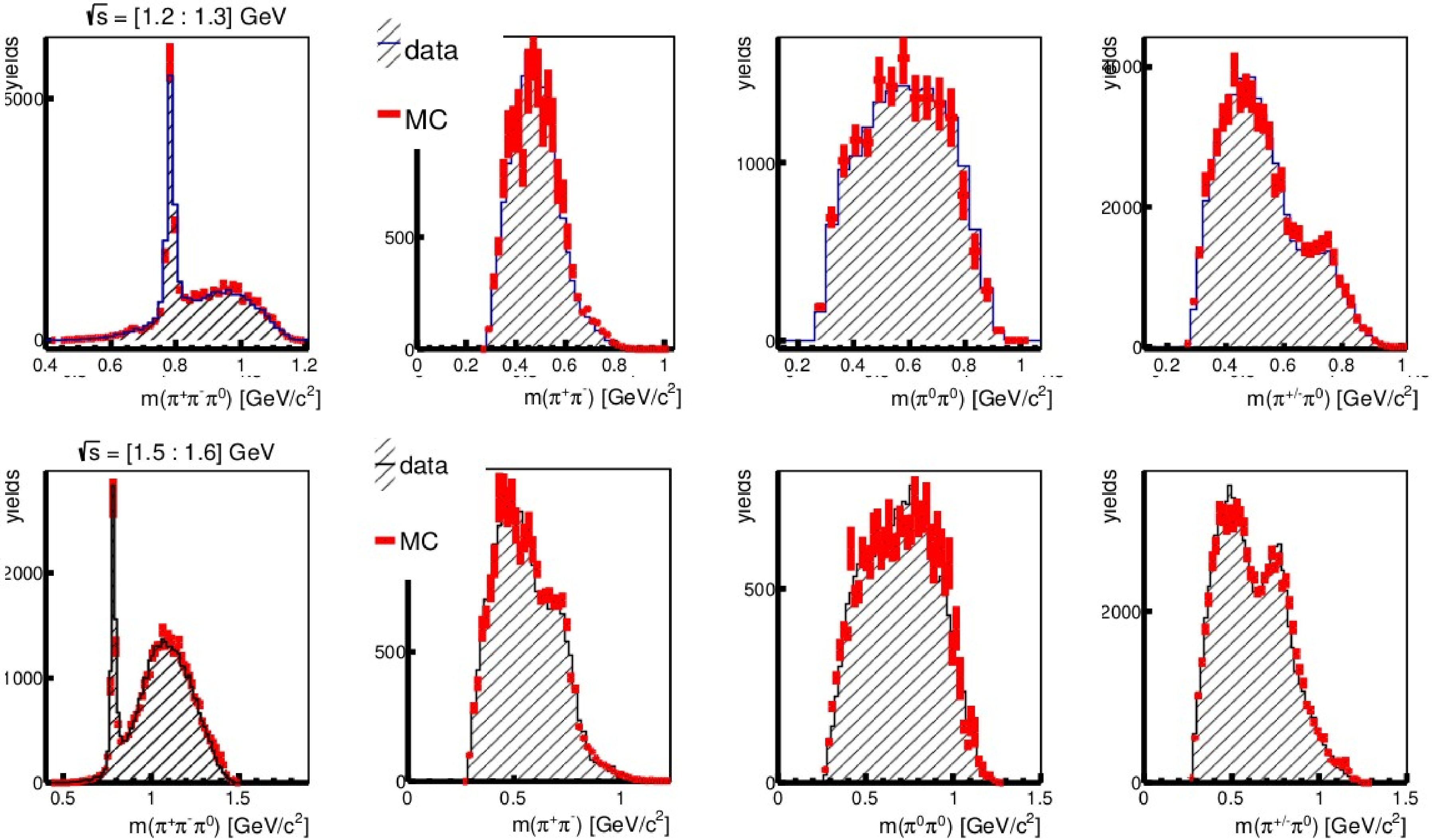
- An amplitude is normalized to 1: $\int |A_\alpha(\Omega)|^2 d\Omega = 1$;
- The $\omega\pi^0$ amplitude is clearly seen at all energies, so $A_{\omega\pi^0}$ fixes at 1;

Функция правдоподобия

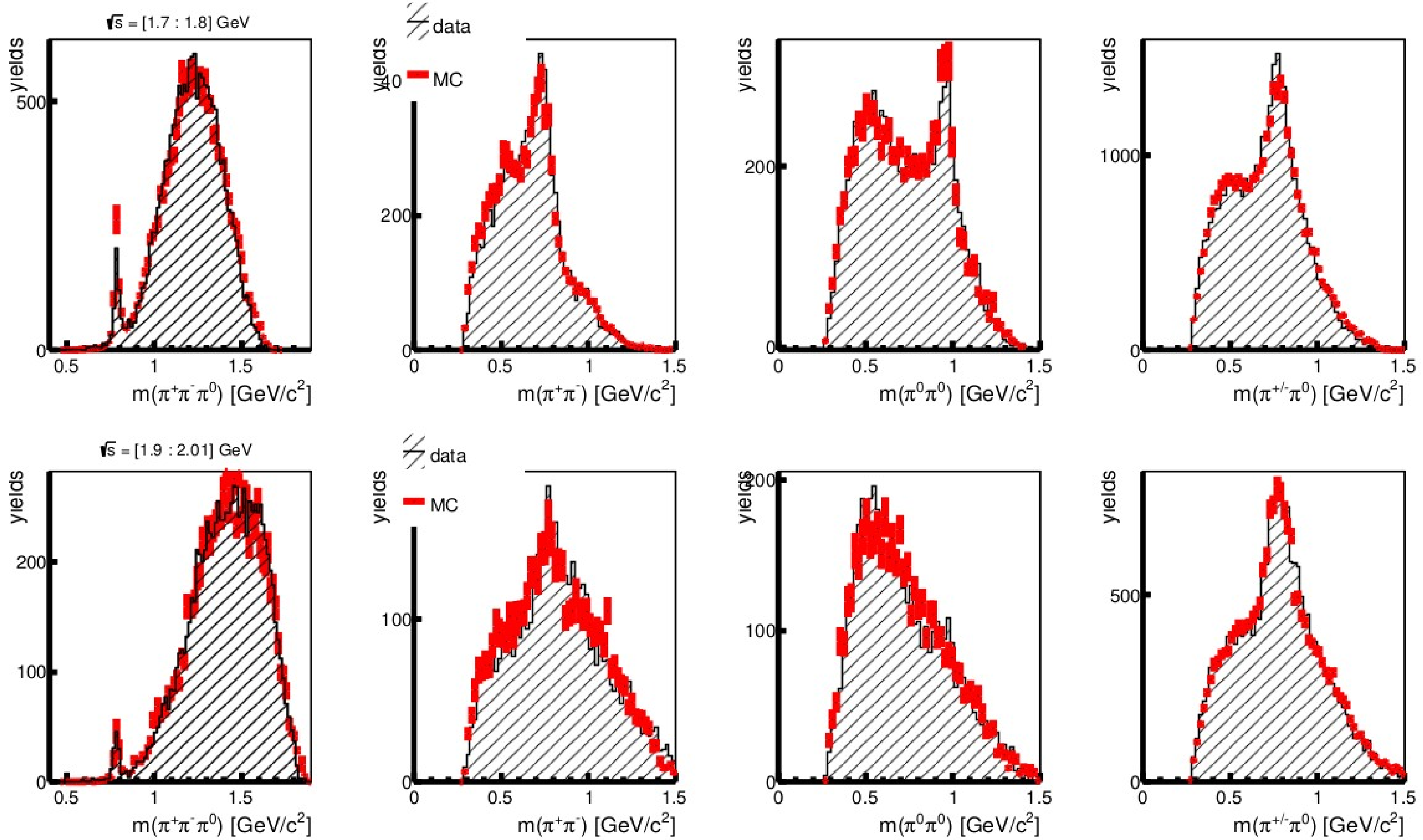
- The amplitudes is symmetric (anti-symmetric) with respect to the interchange of the momenta of neutral (charged) mesons according to Bose symmetry and C-parity conservation.
- $$L(\omega\rho\pi) = g_{\omega\rho\pi} \cdot \epsilon_{\mu\nu\rho\sigma} \cdot \delta^{ab} \cdot \omega_\mu \cdot d_\nu \pi^{\star a} \cdot (d_\rho \rho_\sigma^{\star b} - d_\sigma \rho_\rho^{\star b}),$$
$$L(a_1\rho\pi) = g_{a_1\rho\pi} \cdot \epsilon^{abc} \cdot a_{1\mu}^a \cdot d_\nu \pi^{\star b} \cdot (d_\mu \rho_\nu^{\star c} - d_\nu \rho_\mu^{\star c}),$$
$$L(a_1\sigma\pi) = g_{a_1\sigma\pi} \cdot \delta^{ab} \cdot (d_\mu a_{1\nu}^a - d_\nu a_{1\mu}^a) \cdot d_\mu \phi^\star(\sigma) \cdot d_\nu \phi^{\star b}(\pi),$$
$$L(\rho'\rho f_0) = g_{\rho'\rho f_0} \cdot \delta^{ab} \cdot (d_\mu \rho_\nu'^a - d_\nu \rho_\mu'^a)(d_\mu \rho_\nu^{\star b} - d_\nu \rho_\mu^{\star b}) \cdot \phi_{f0}^\star;$$
$$L(\rho'\rho^+\rho^-) = g_{\rho'\rho^+\rho^-} \cdot \epsilon^{abc}(d_\mu \rho_\nu'^a - d_\nu \rho_\mu'^a) \cdot (d_\alpha \rho_\nu^{\star b} - d_\nu \rho_\alpha^{\star b}) \cdot (d_\mu \rho_\alpha^{\star c} - d_\alpha \rho_\mu^{\star c}).$$
$$L(\rho' h_1 \pi^0) = g_{\rho' h_1 \pi^0} \cdot \delta^{ab}(d_\mu \rho_\nu'^a - d_\nu \rho_\mu'^a) \cdot (d_\mu h_{1\nu}^{\star b} - d_\nu h_{1\mu}^{\star b})\phi_\pi^\star,$$

- Masses and central values of widths of resonances are fixed according to PDG.
- Flatté distribution is used for the propagator of $f_0(980)$.

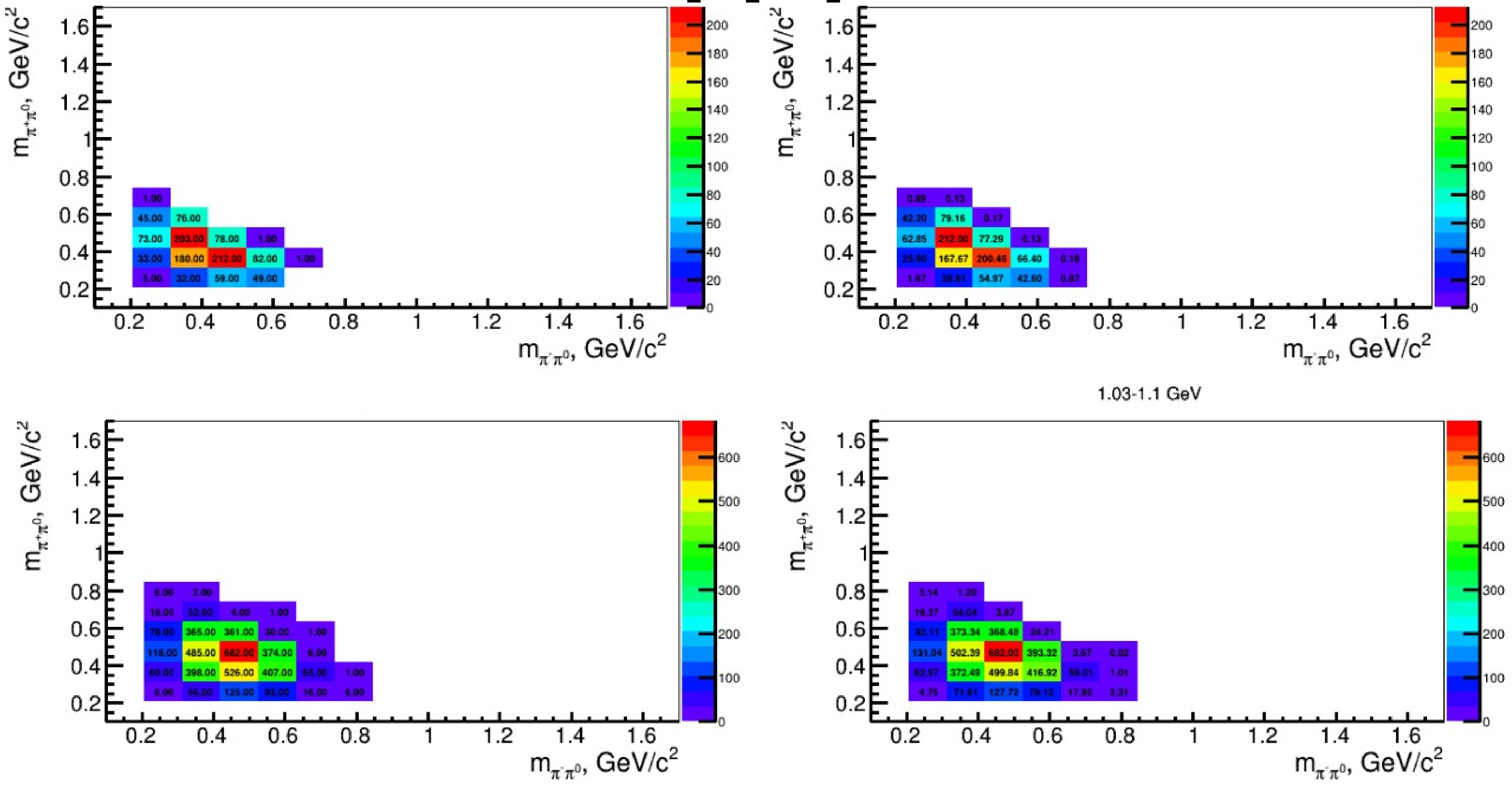
$(ee \rightarrow pi^+pi^-2pi^0)$



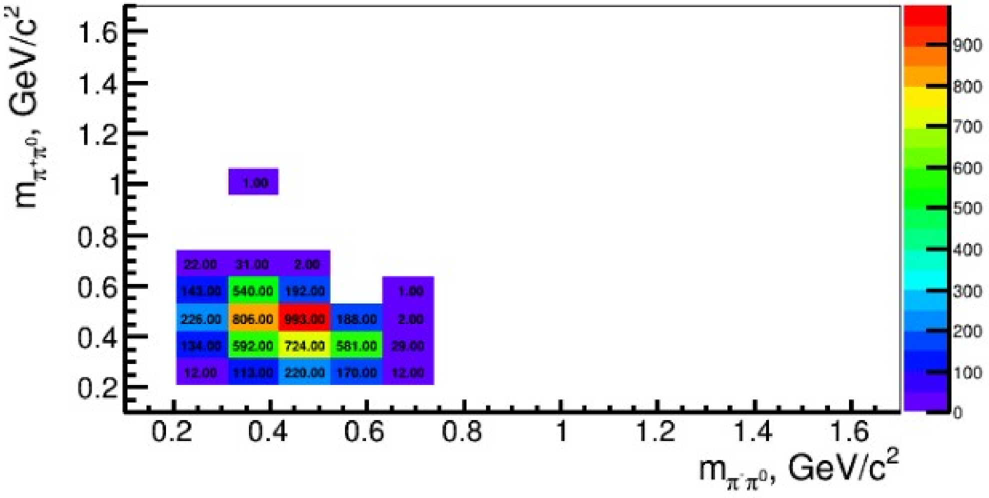
$(ee \rightarrow pi^{+}pi^{-}2pi^{0})$



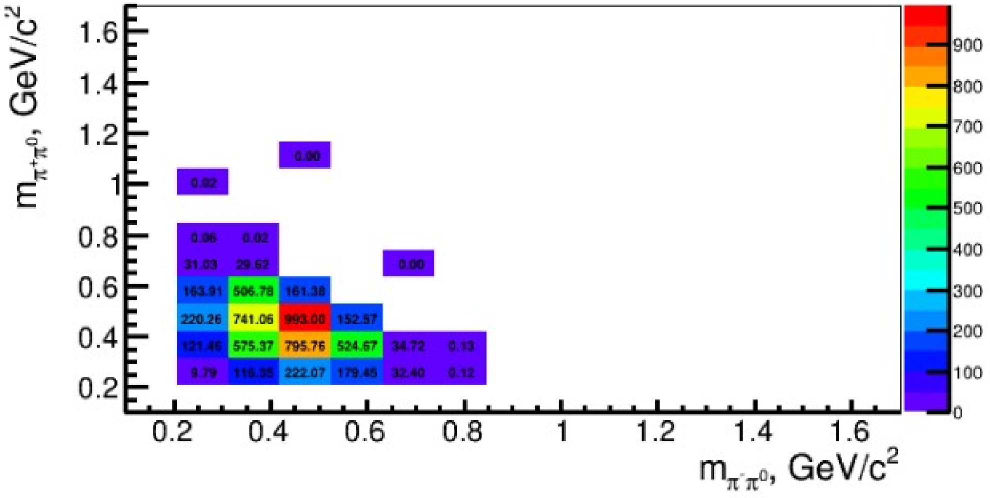
$(ee \to pi^+pi^-2pi^0)$

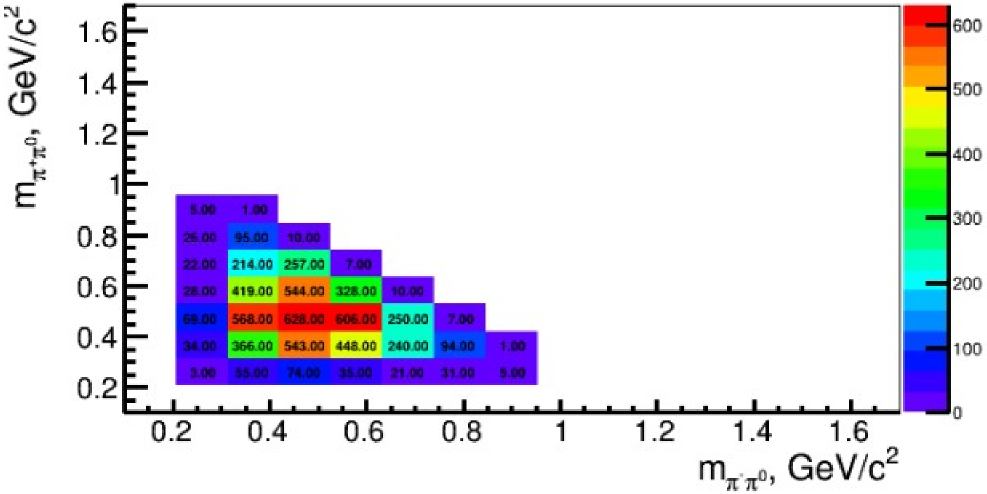


$(ee \to \pi^+\pi^-2\pi^0)$

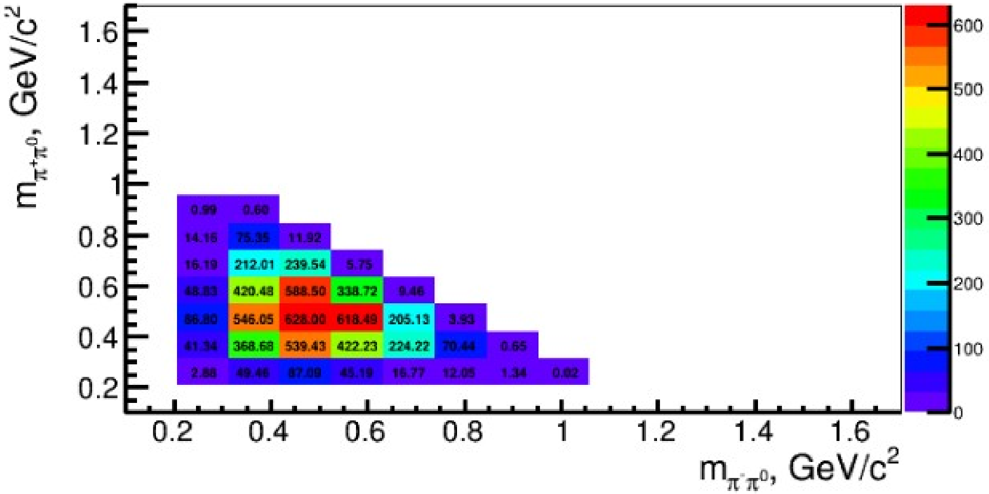


1-1.03 GeV

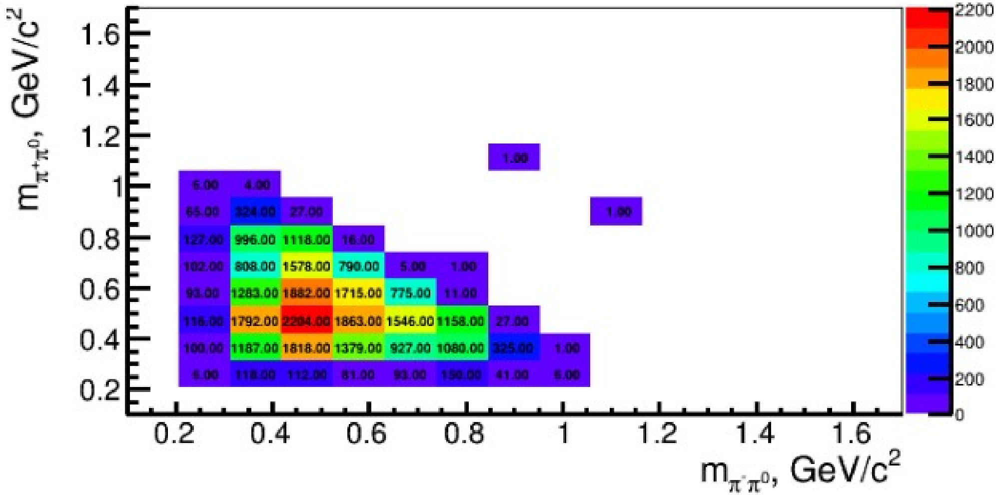




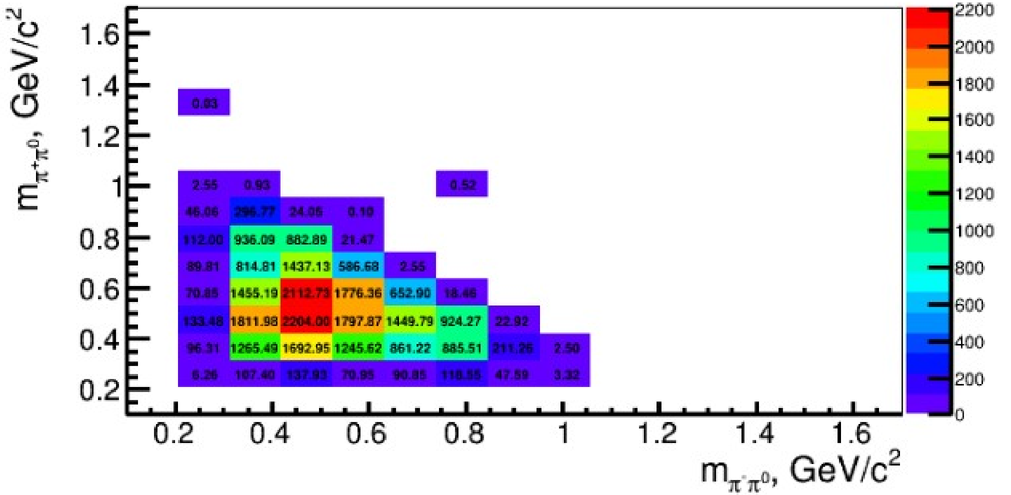
1.1-1.2 GeV

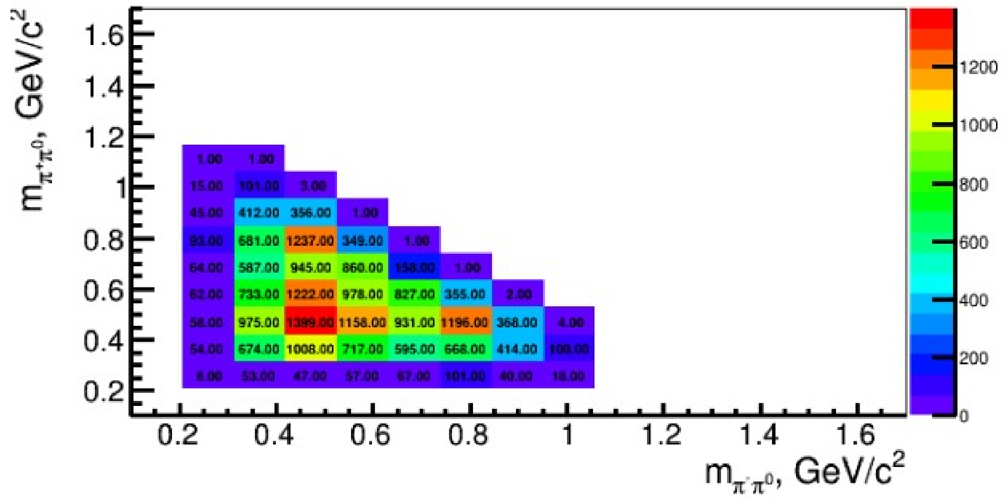


$(ee \rightarrow pi^+pi^-2pi^0)$

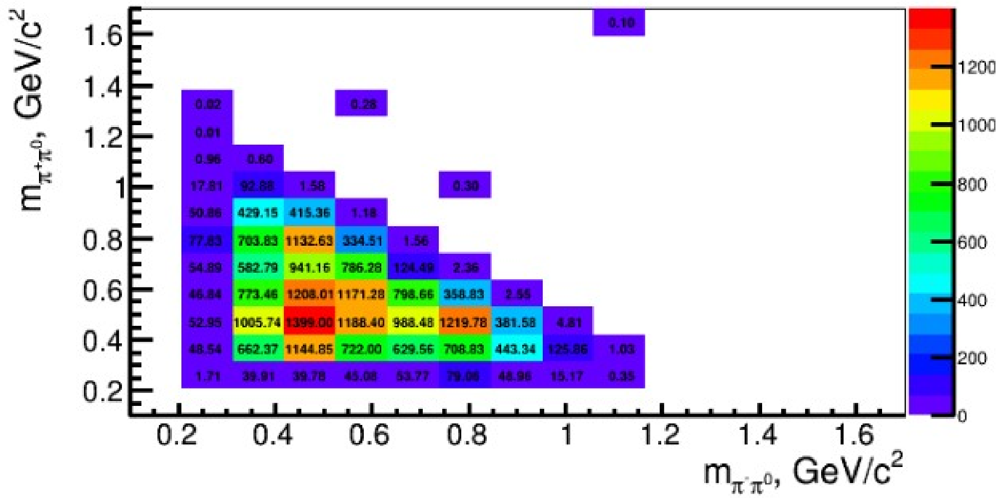


1.2-1.3 GeV

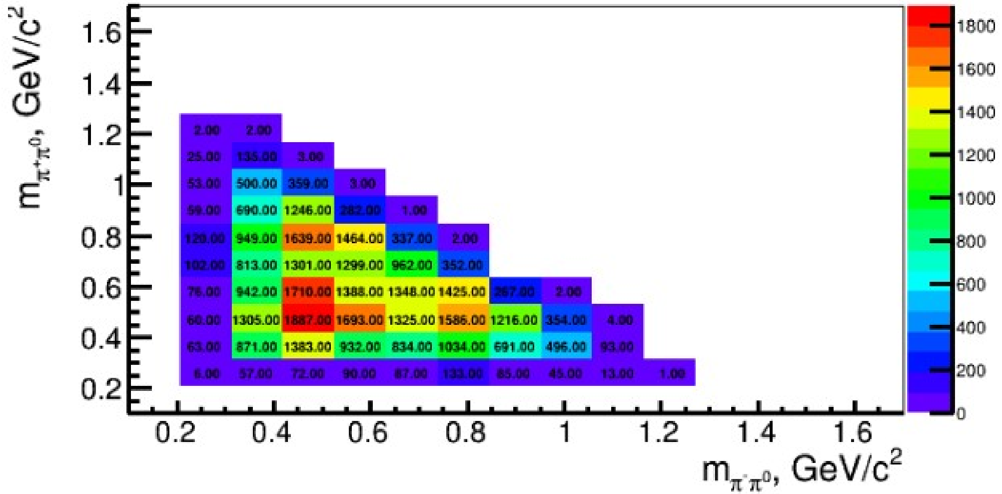




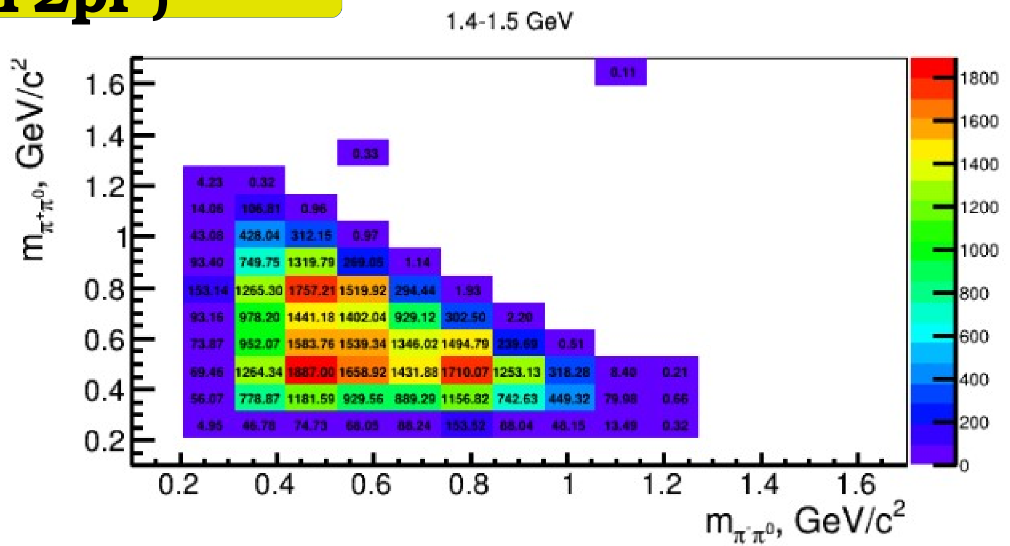
1.3-1.4 GeV



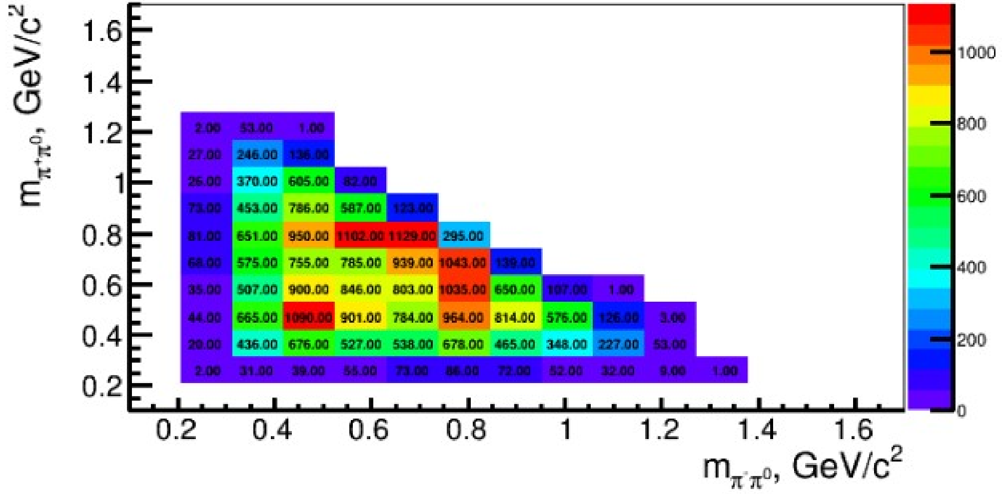
(ee → $\pi^+\pi^-2\pi^0$)



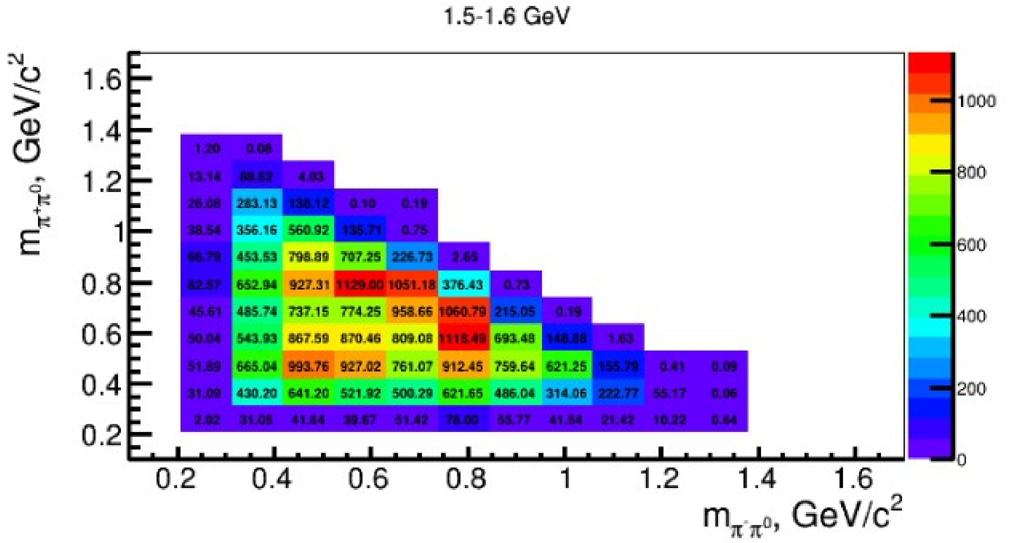
$m_{\pi^+\pi^0}$, GeV/c^2
$m_{\pi^-\pi^0}$, GeV/c^2



1.4-1.5 GeV
$m_{\pi^+\pi^0}$, GeV/c^2
$m_{\pi^-\pi^0}$, GeV/c^2

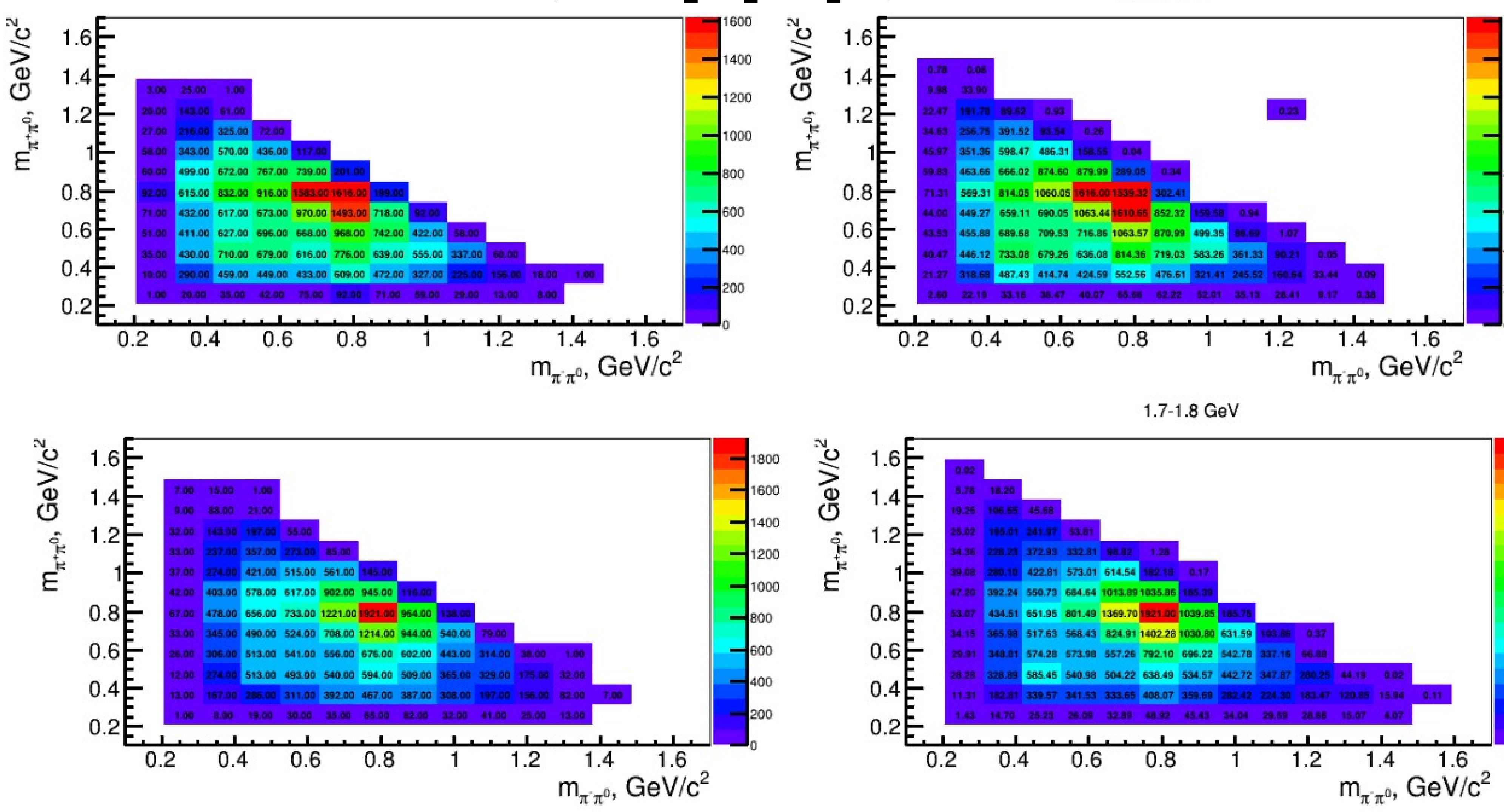


$m_{\pi^+\pi^0}$, GeV/c^2
$m_{\pi^-\pi^0}$, GeV/c^2

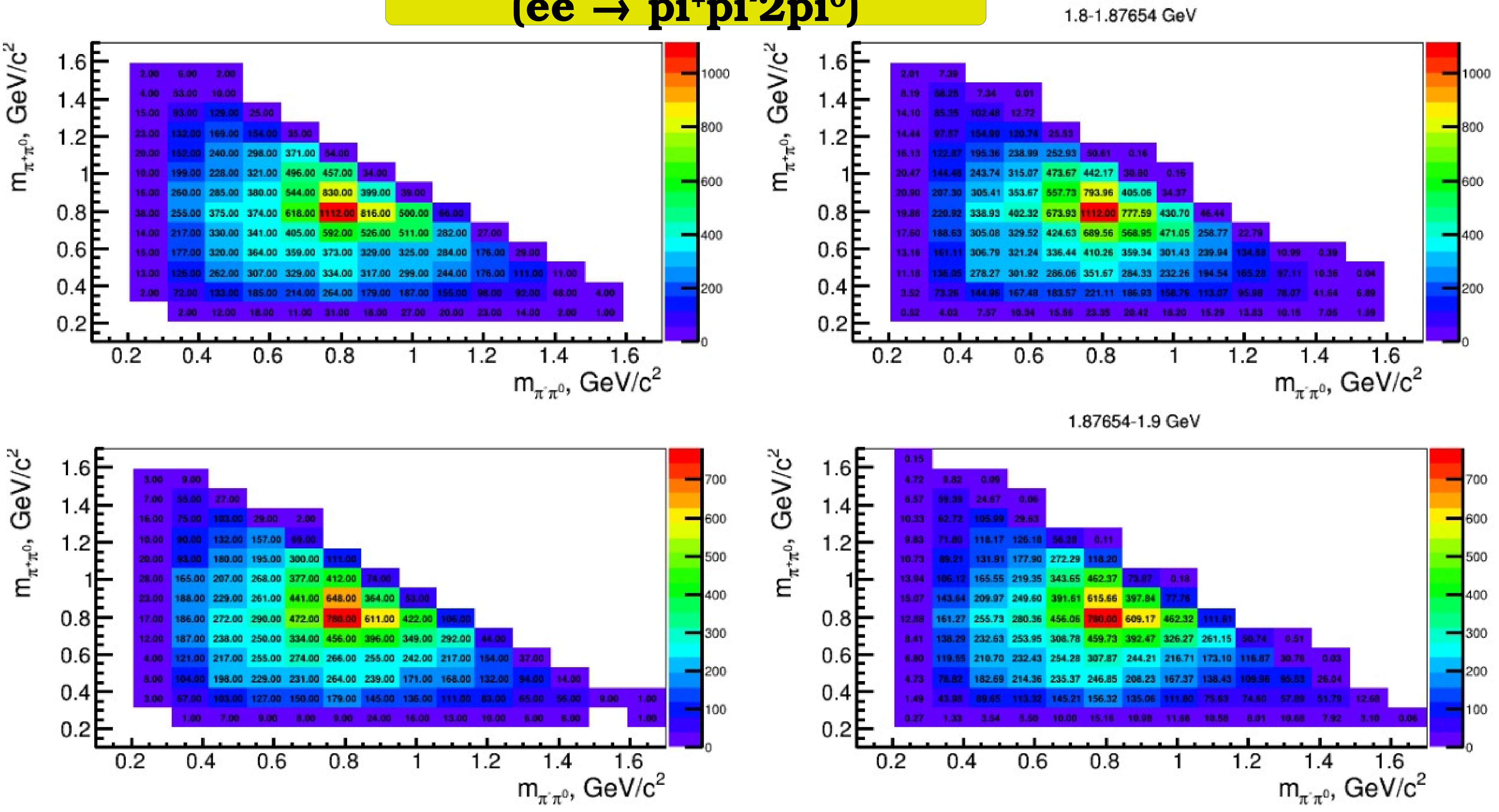


1.5-1.6 GeV
$m_{\pi^+\pi^0}$, GeV/c^2
$m_{\pi^-\pi^0}$, GeV/c^2

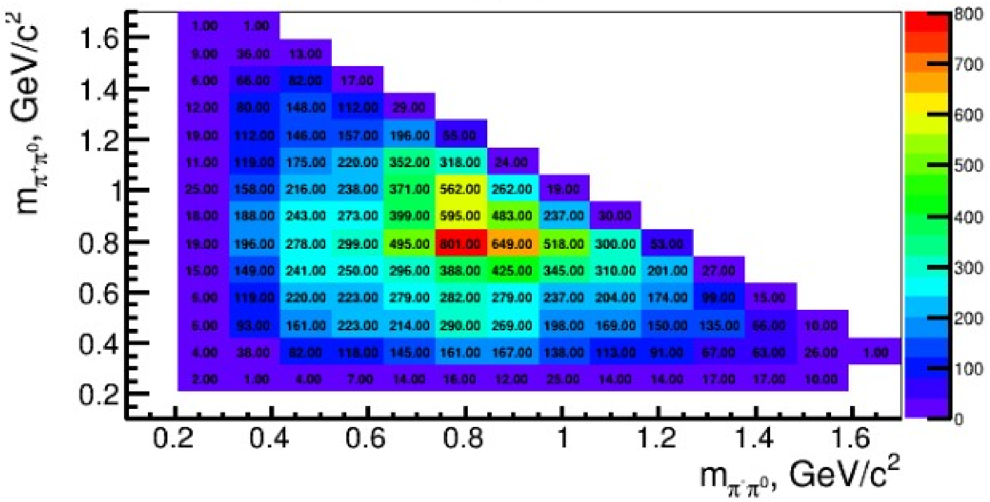
$(ee \rightarrow \pi^+\pi^-2\pi^0)$



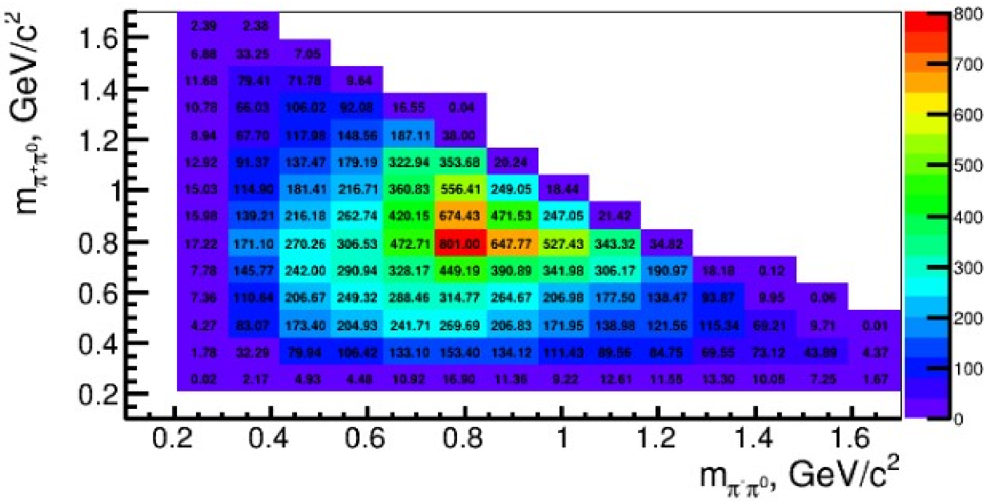
$(ee \rightarrow pi^+pi^-2pi^0)$



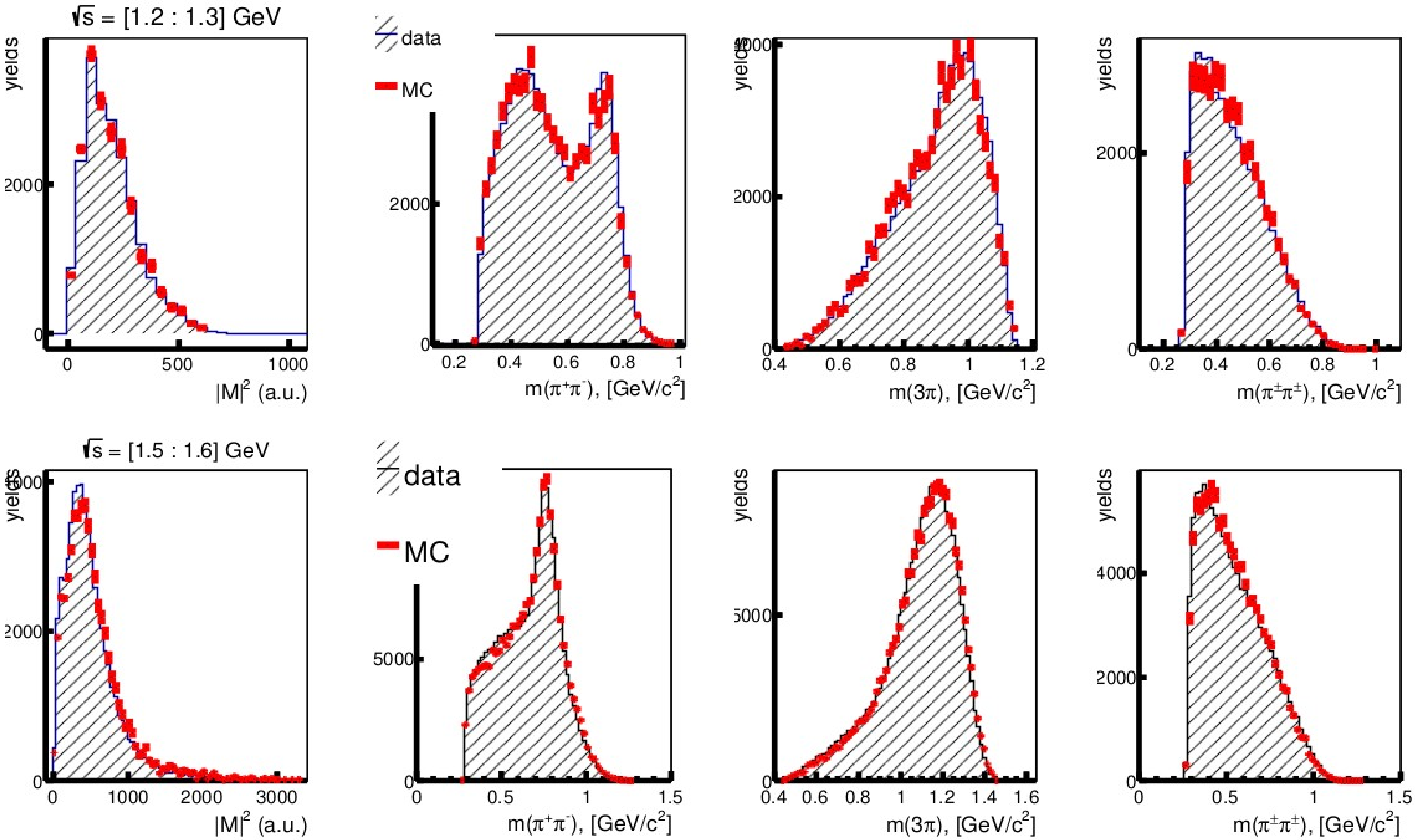
(ee → pi$^+$pi$^-$2pi^0)



1.9-2.01 GeV

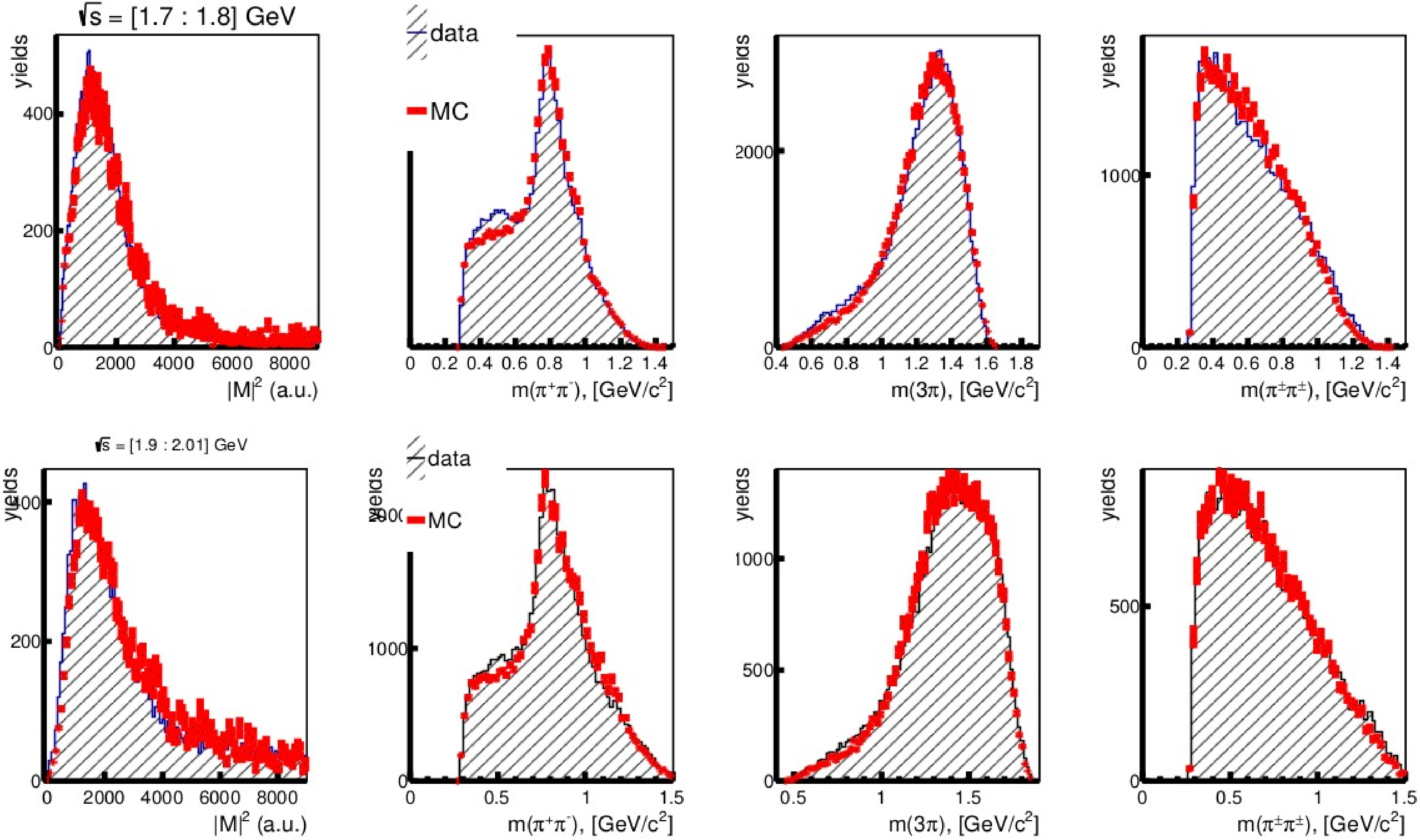


$(ee \to 2pi^{+}2pi^{-})$



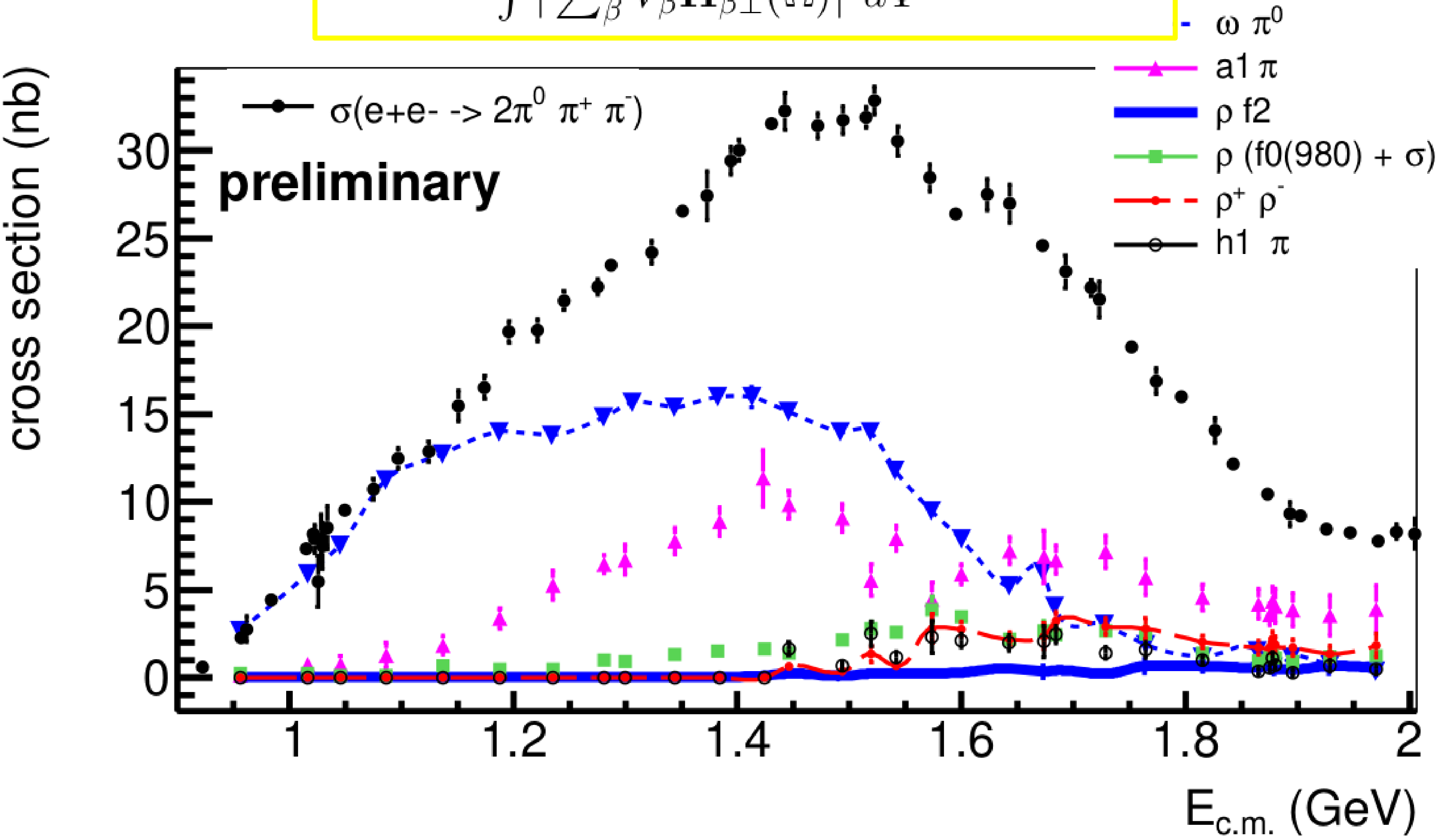
√s = [1.2 : 1.3] GeV
yields
2000
0
0
500
1000
|M|² (a.u.)
data
MC
2000
0
0.2
0.4
0.6
0.8
1
m(π⁺π⁻), [GeV/c²]
yields
4000
2000
0
0.4
0.6
0.8
1
1.2
m(3π), [GeV/c²]
yields
2000
0
0.2
0.4
0.6
0.8
1
m(π±π±), [GeV/c²]
√s = [1.5 : 1.6] GeV
yields
2000
0
0
1000
2000
3000
|M|² (a.u.)
data
MC
5000
0
0
0.5
1
1.5
m(π⁺π⁻), [GeV/c²]
yields
5000
0
0.4
0.6
0.8
1
1.2
1.4
1.6
m(3π), [GeV/c²]
yields
4000
2000
0
0
0.5
1
1.5
m(π±π±), [GeV/c²]

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

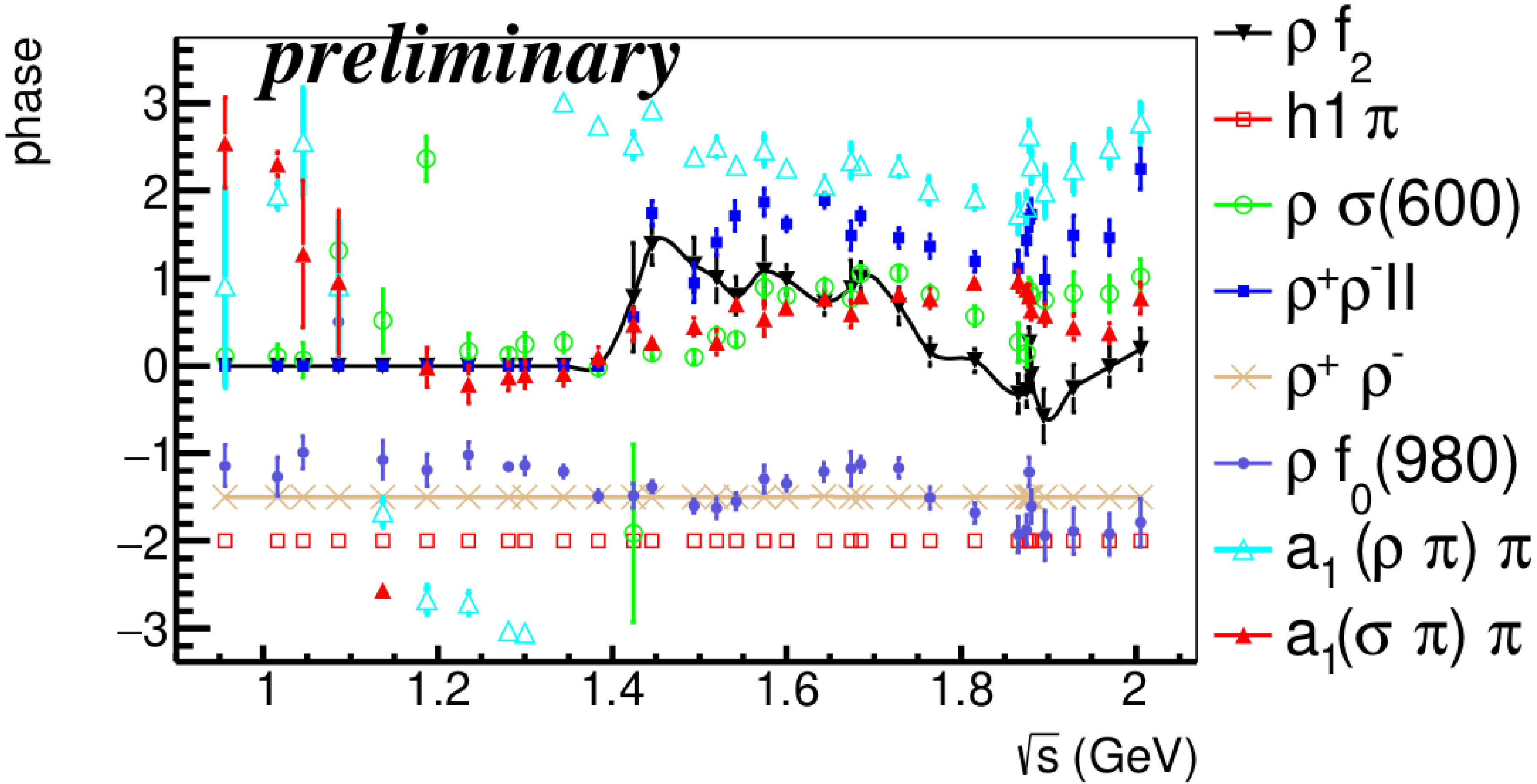


$\sqrt{s}$ = [1.7 : 1.8] GeV
yields
data
MC
|M|^2 (a.u.)
m($\pi^+\pi^-$), [GeV/c^2]
m(3π), [GeV/c^2]
m($\pi^\pm\pi^\pm$), [GeV/c^2]
$\sqrt{s}$ = [1.9 : 2.01] GeV

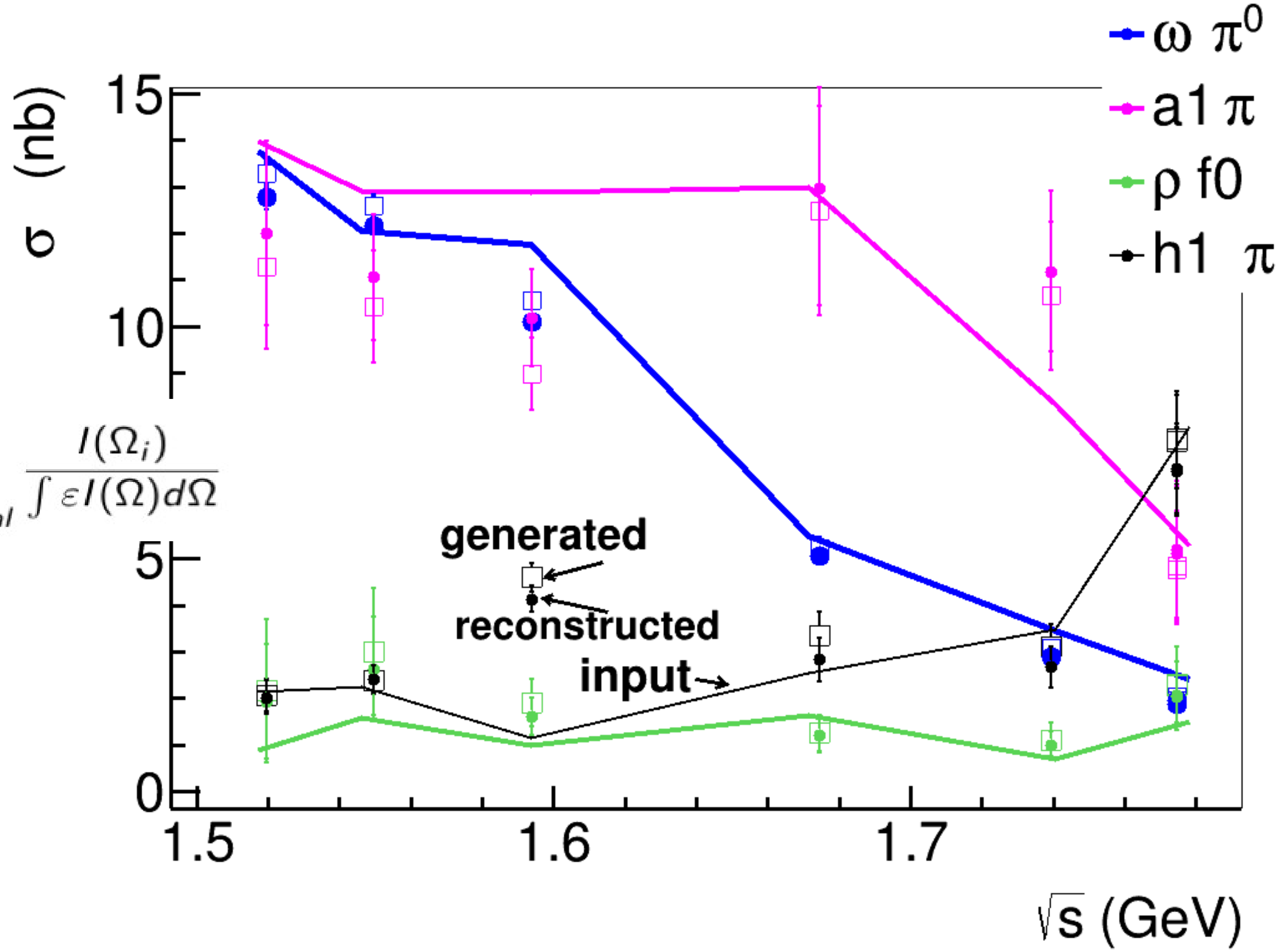
$$R_i(s) = \frac{\int |V_i \cdot \mathbf{H}_{i\perp}(\Omega)|^2 d\Phi}{\int |\sum_\beta V_\beta \mathbf{H}_{\beta\perp}(\Omega)|^2 d\Phi} \cdot \sigma_{2\pi^0\pi^+\pi^-}(s)$$



Значения фаз различных компонент матричного элемента

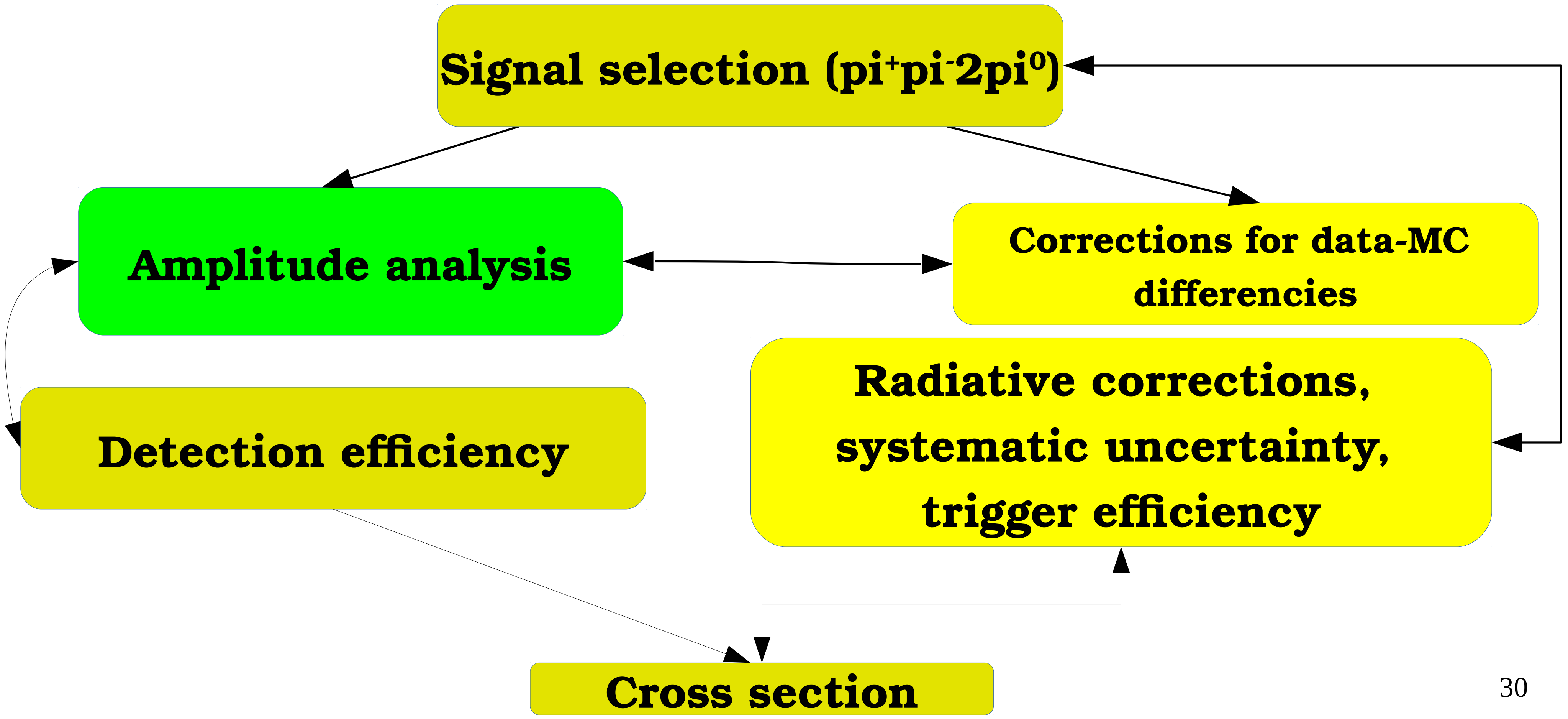


$$L = -log \prod_{i=signal} \frac{I(\Omega_i)}{\int \varepsilon I(\Omega) d\Omega}$$



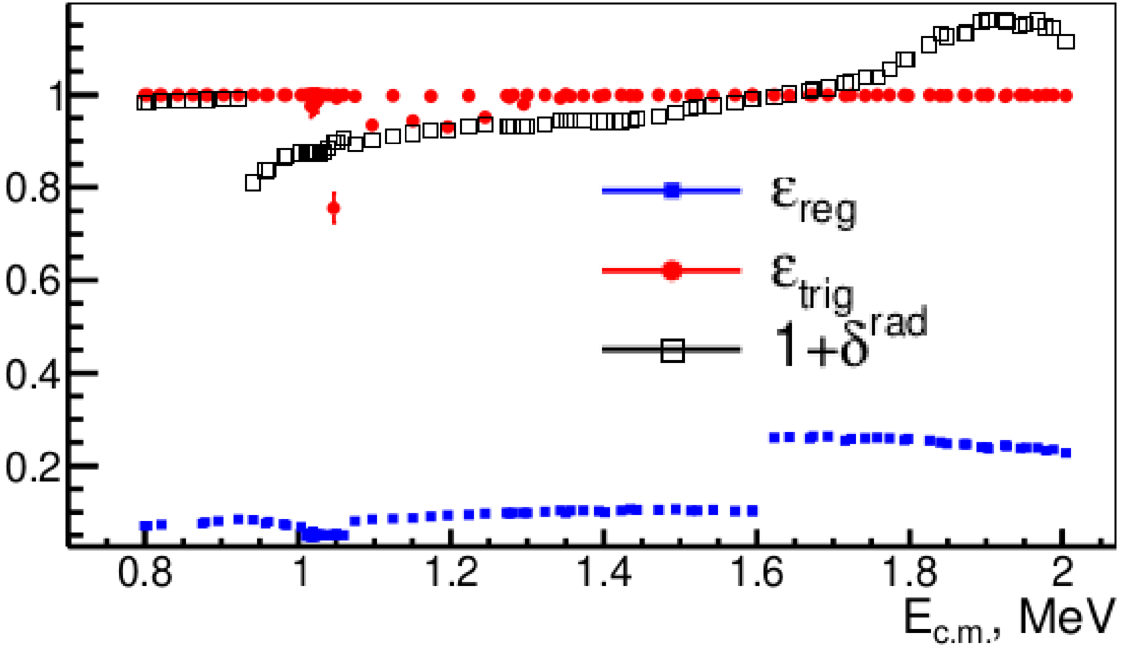
- **Ошибка методики ~ 3-7%**

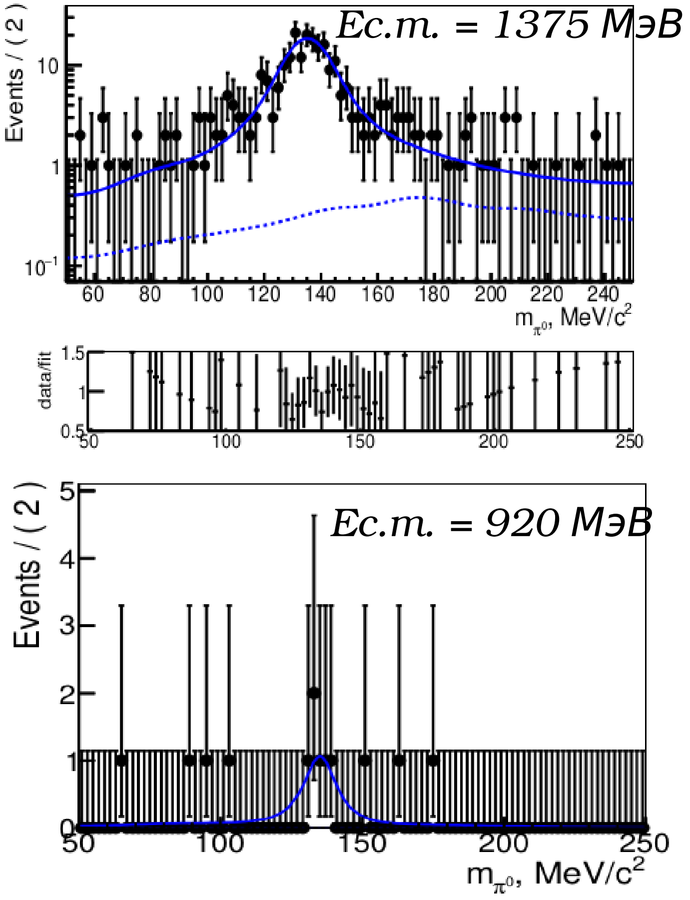
Общая стратегия измерения сечения



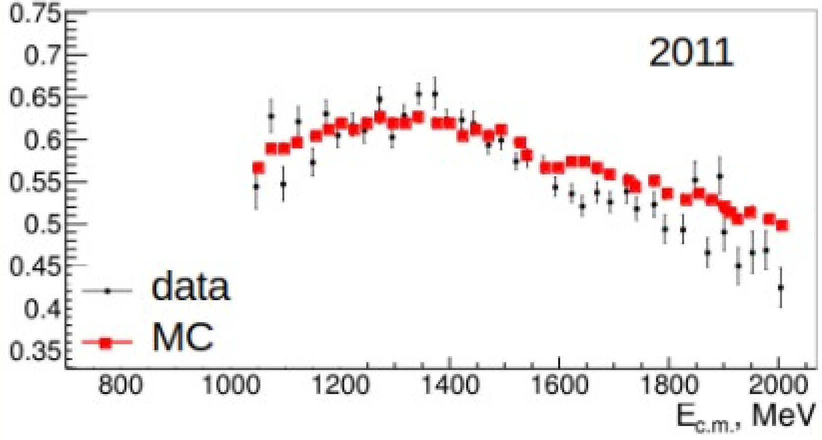
$$\sigma^{Born} = \frac{N_{exp}}{\epsilon_{reg}\epsilon_{trig}L(1+\delta^{rad.})},$$

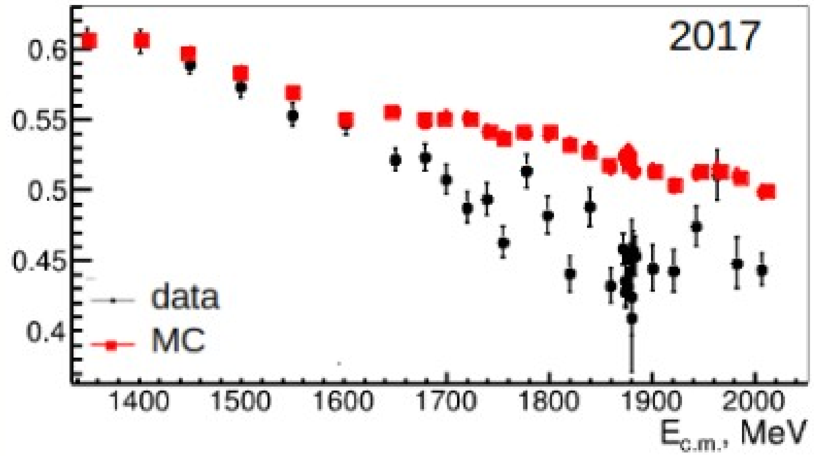
$$1+\delta^{rad}(s) = \frac{\int F(x,s)\sigma^{Born}(s(1-x))dx}{\sigma^{Born}(s)},$$



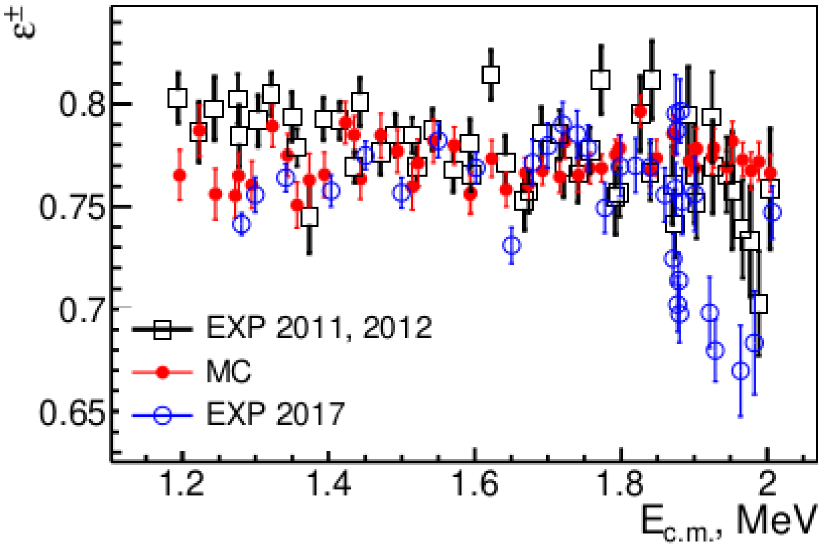


Пример аппроксимации спектра инвариантной массы 3-го и 4-го фотонов





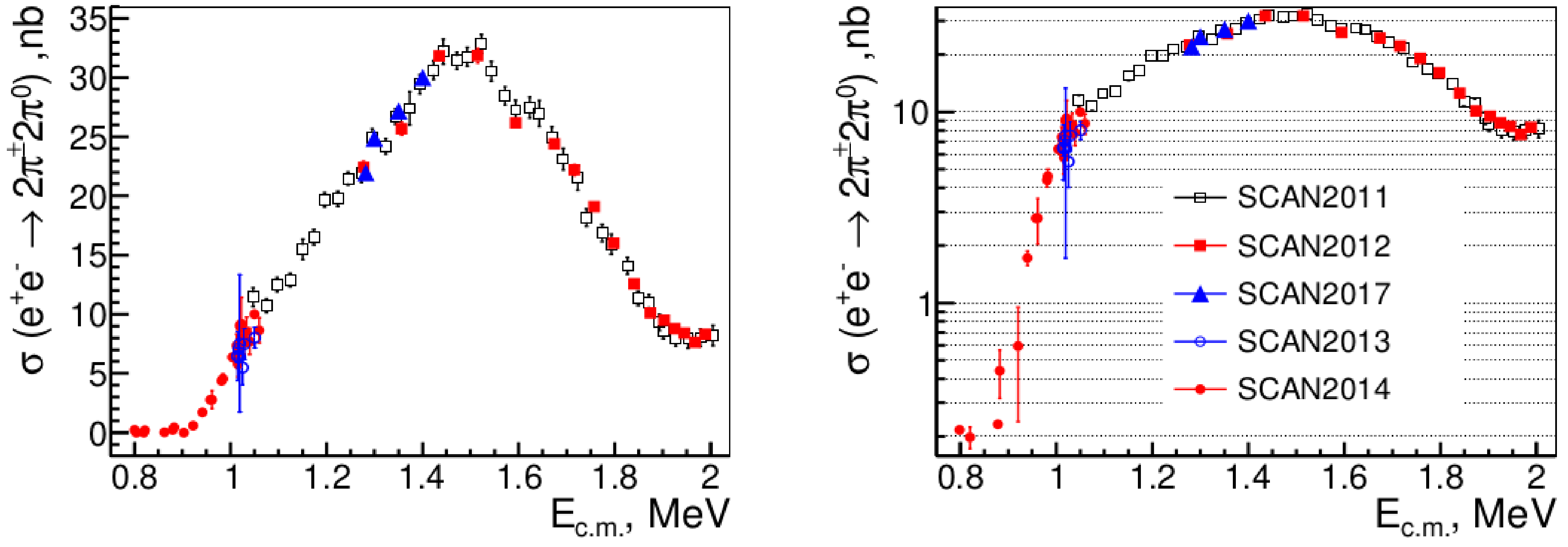
Эффективность реконструкции нейтральных пионов



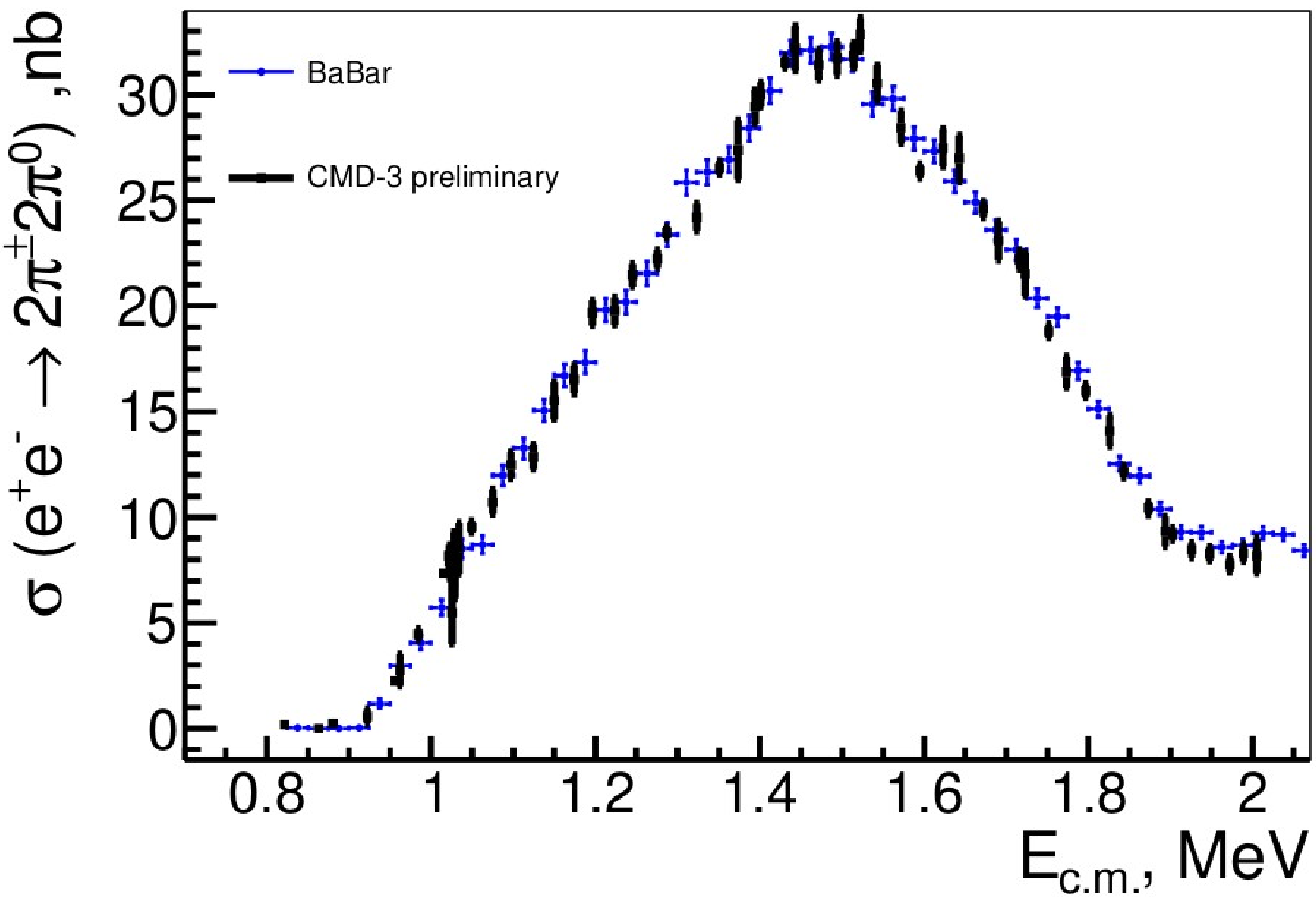
Эффективность реконструкции заряженных пионов

Источник ошибки	$E_{c.m.} < 1.06$ ГэВ (%)	$1.06 < E_{c.m.} < 1.6$ ГэВ (%)	$1.6 < E_{c.m.}$ ГэВ (%)
Вычитание фона	3	1	4
Модельная ошибка	0.5	0.8	0.8
Условия отбора	4	4	2
Реконструкция заряженных пионов	2	2	2
Реконструкция нейтральных пионов	8	8	8
Эффективность триггера	0.3	0.3	0.3
Радиационная поправка	1.5	0.9	0.9
Светимость	1.0	1.0	1.0
Total	10	9	10

Источники систематической ошибки в сечении процесса $e^+e^- \to 2\pi^0\pi^+\pi^-$



Зависимость полученных значений сечений $e^+e^- \to 2\pi^0\pi^+\pi^-$ энергии для разных сезонов набора данных.



Сравнение полученных усредненных значений сечений $e^+e^- \to 2\pi^0\pi^+\pi^-$ от энергии с результатом на детекторе BaBar.

Заключение

- Выполнено предварительное изучение промежуточной динамики процесса $e^+e^-\to 4\pi$ в диапазоне энергий $\sqrt{s}$ = [0.95–2.01] ГэВ

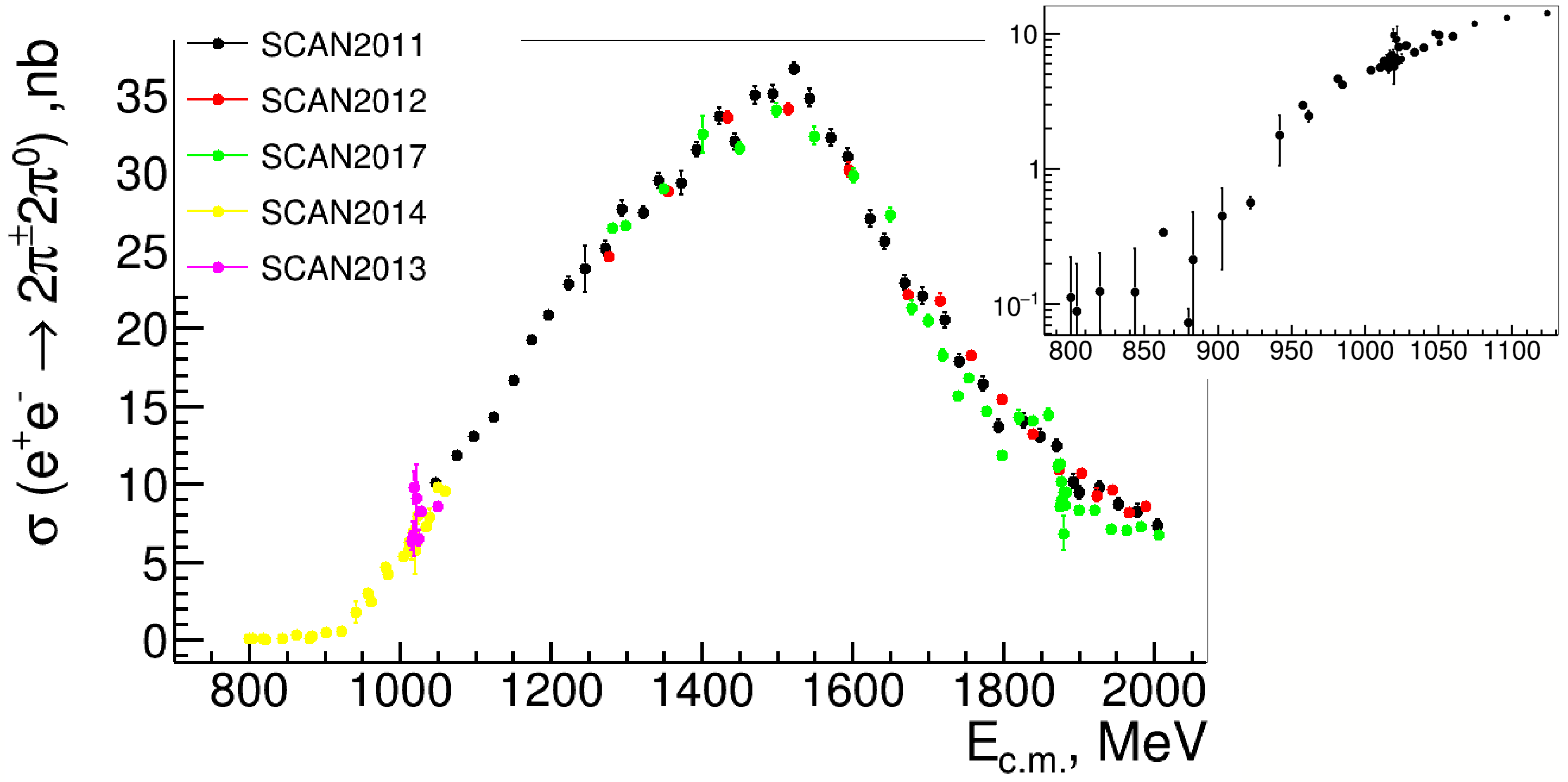
- Подтверждена доминантность амплитуд $\boldsymbol{\omega\pi}$ и $\boldsymbol{a_1\pi}$ при $\sqrt{s} < 2$ ГэВ

- Канал $\omega\pi$ является доминирующим в процессе $e^+e^- \to \pi^+\pi^-2\pi^0$ при $\sqrt{s} < 1.5$ ГэВ

- Определены вклады амплитуд $\rho\sigma$, ρf_0, $\rho^-\rho^+$, ρf_2, $h_1\pi$

- Измерено сечение процесса $e^+e^-\to 2\pi^0\pi^+\pi^-$ с систематической точностью около 10% в области энергий $E = 0.8 \div 2$ ГэВ.

back-up

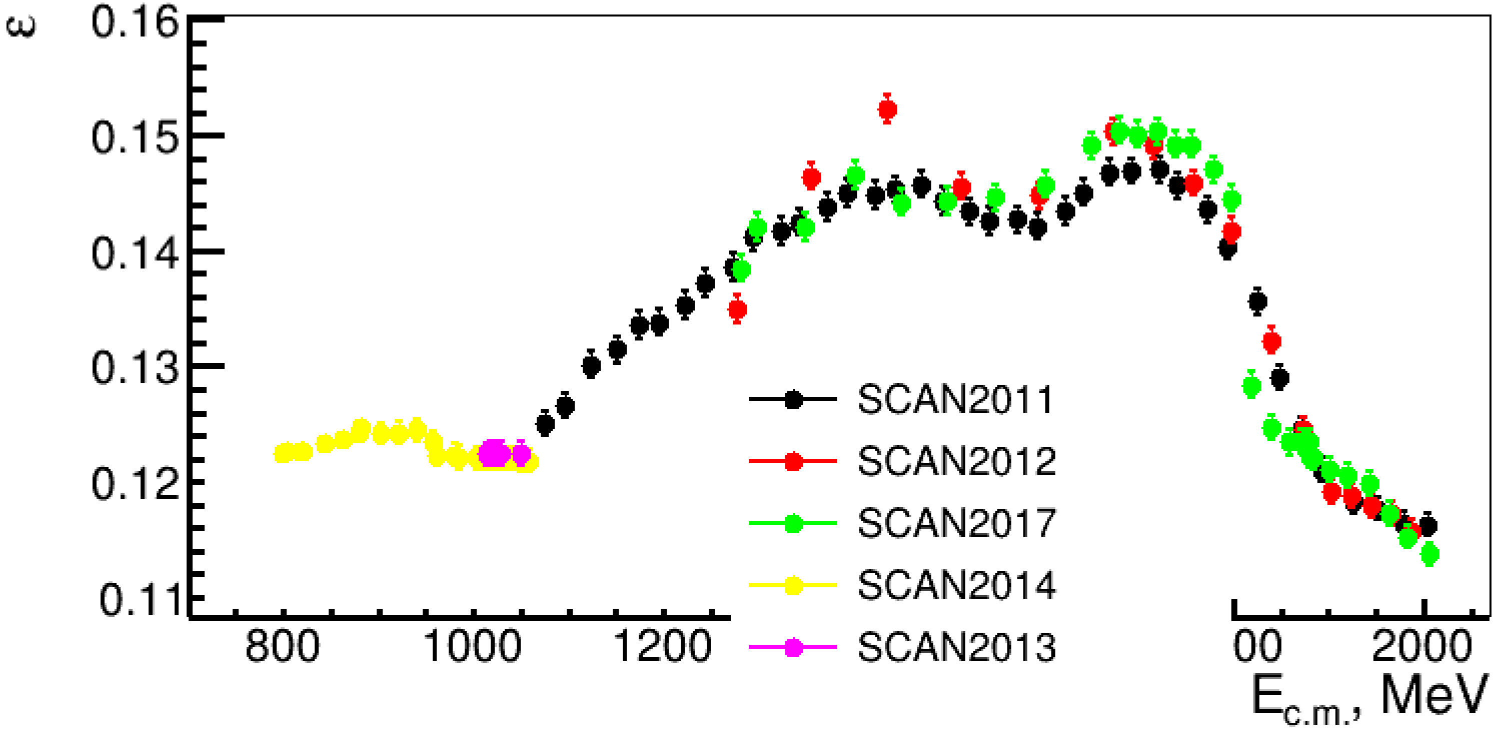


The cross-section of $e^+e^- \rightarrow 2\pi^0\pi^+\pi^-$ vs $E_{c.m.}$ for different scans

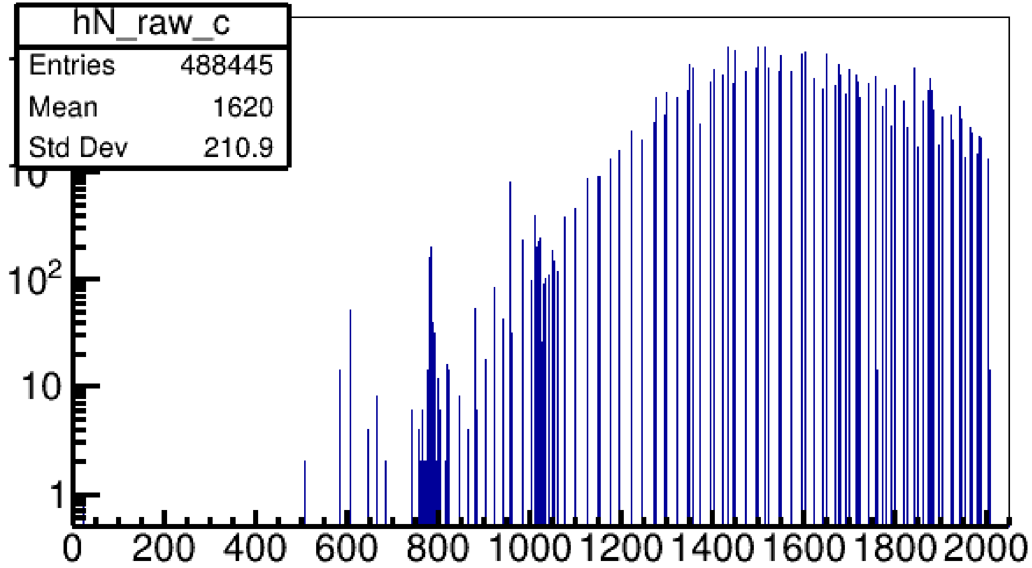
Soon we will publish the cross section of the cross section

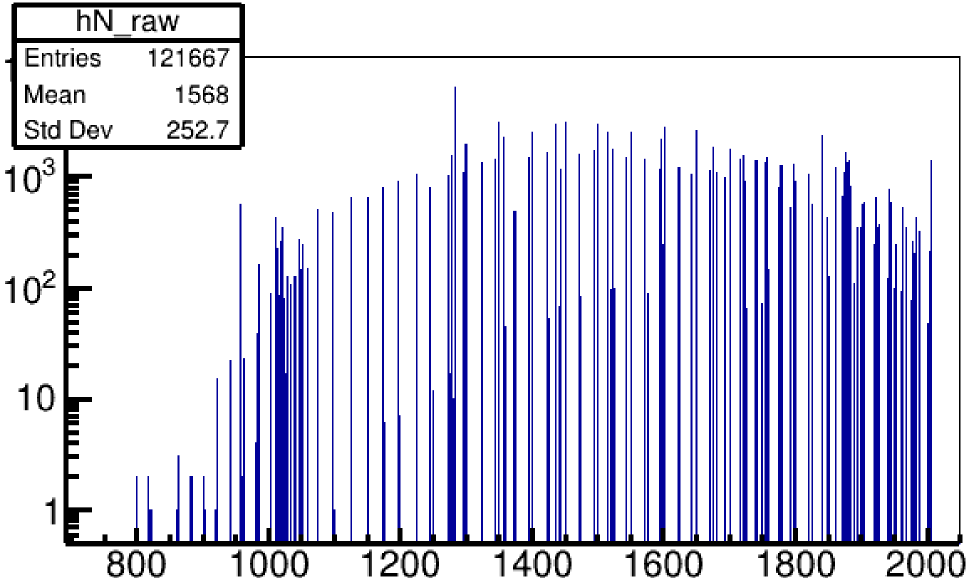
$$\varepsilon_{4\pi} = \frac{\Sigma_{det}^{ph.sp.}(|M(p_{\pi^0},p_{\pi^0},p_{\pi^+},p_{\pi^-})|^2)}{\Sigma_{gen}^{ph.sp.}(|M(p_{\pi^0},p_{\pi^0},p_{\pi^+},p_{\pi^-})|^2)}$$

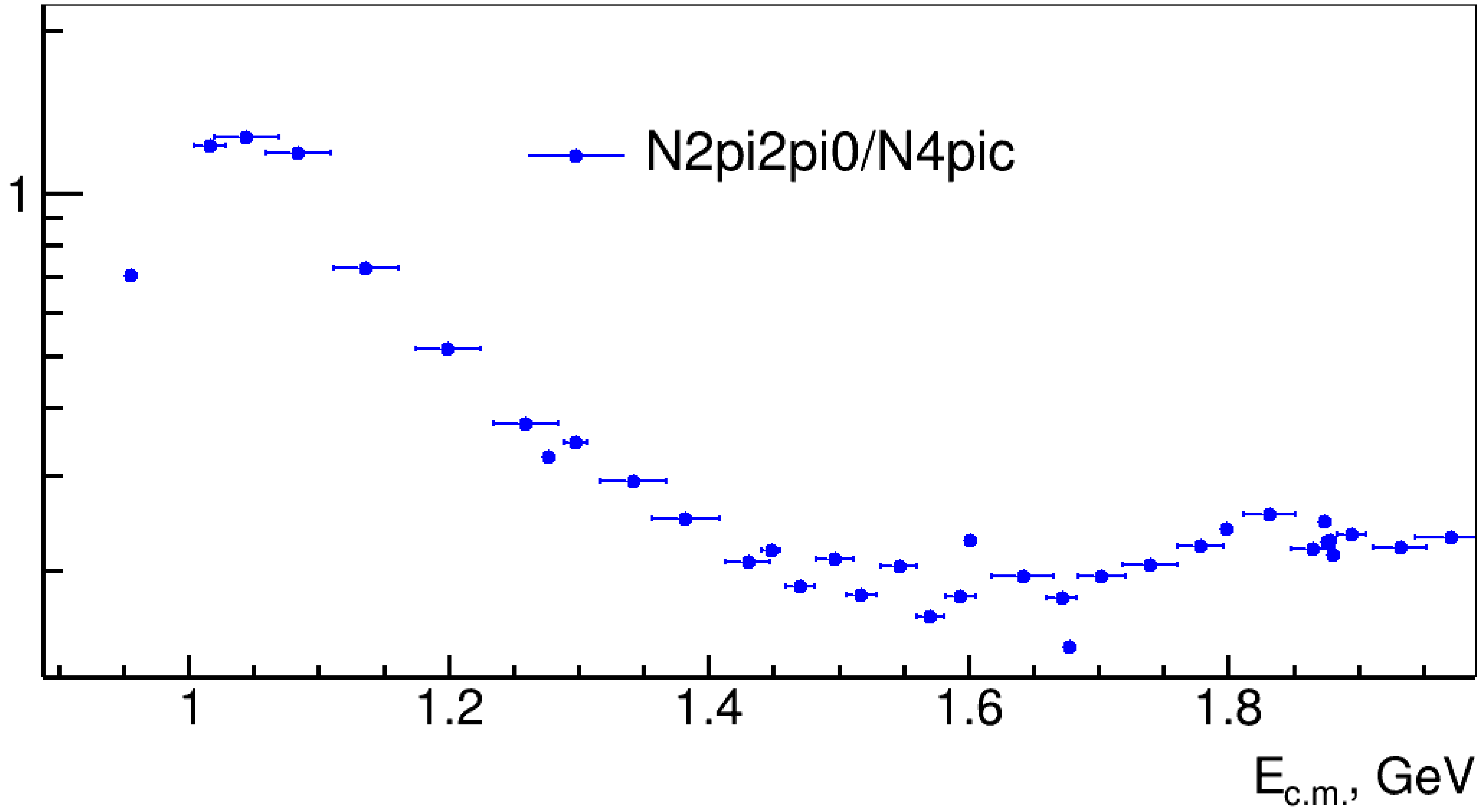
The max energy of simulated ISR is 0.2 Gev.

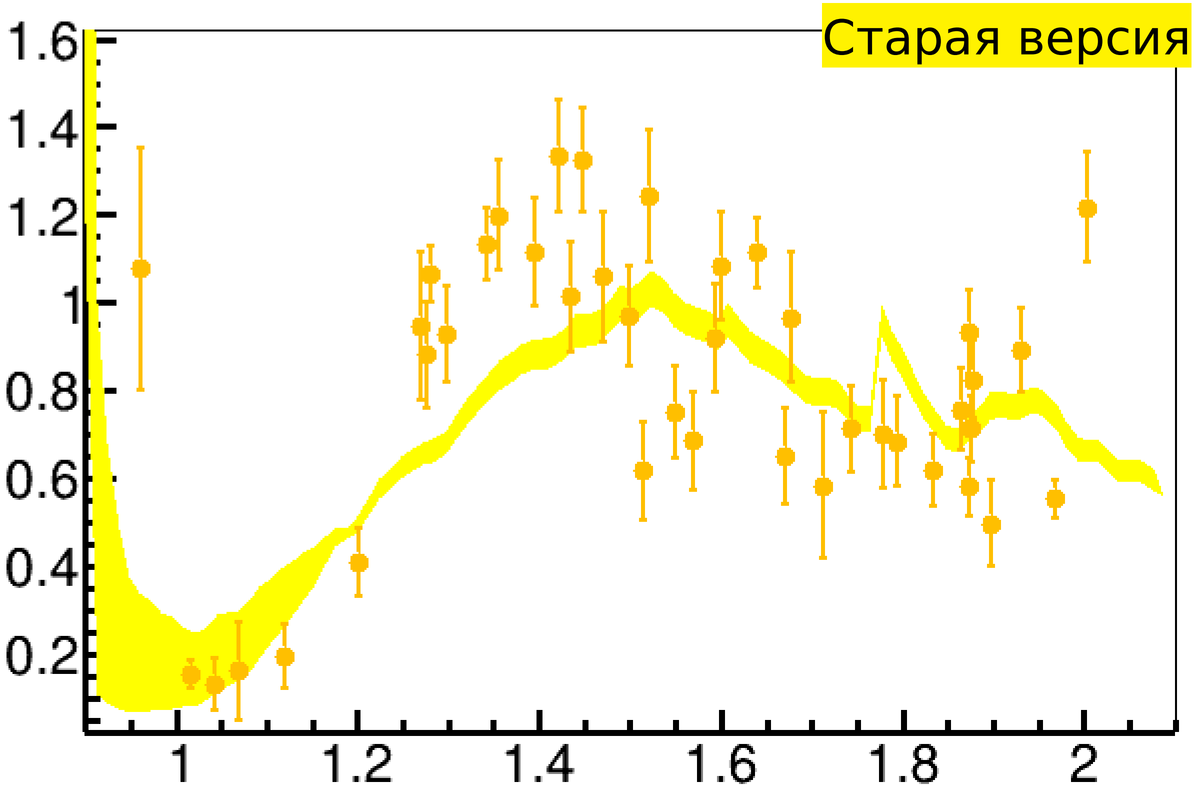


Detection efficiency vs. c.m. energy.

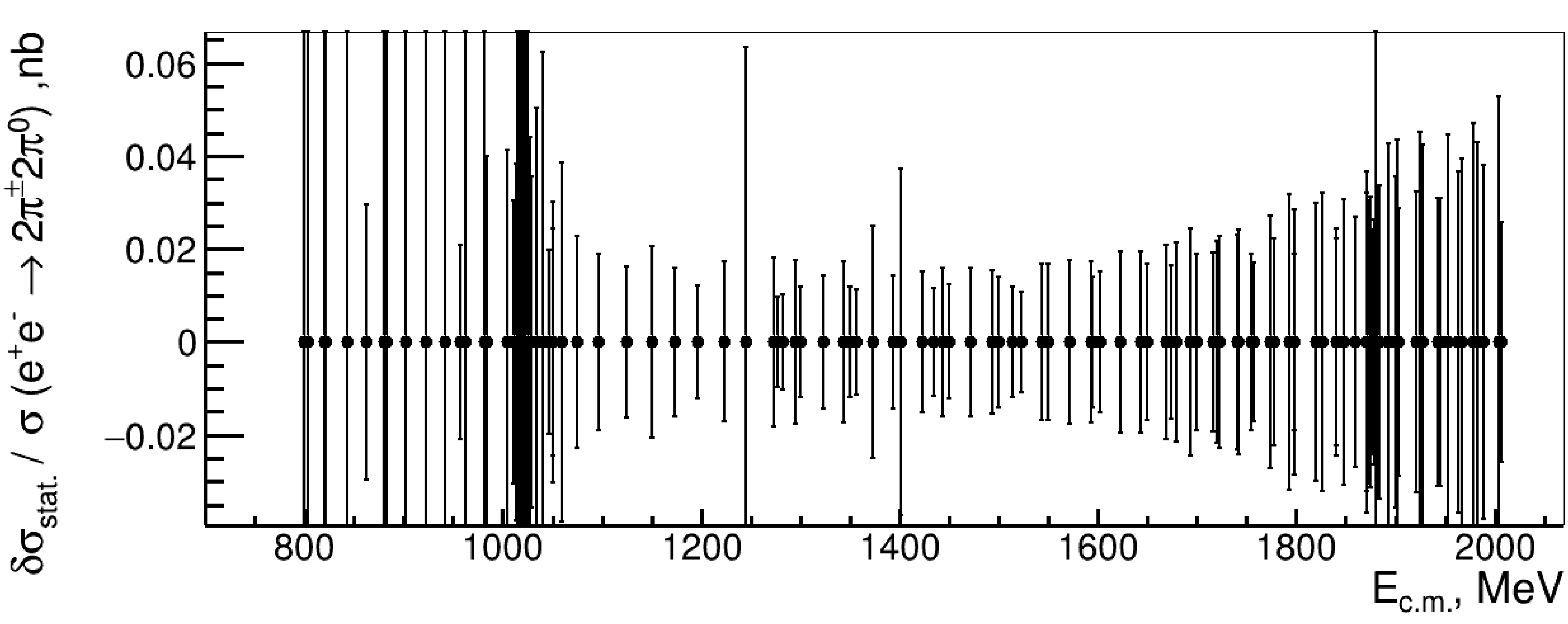

hN_raw_c
Entries 488445
Mean 1620
Std Dev 210.9
10^2
10
1
0
200
400
600
800
1000
1200
1400
1600
1800
2000


hN_raw
Entries 121667
Mean 1568
Std Dev 252.7
10^3
10^2
10
1
800
1000
1200
1400
1600
1800
2000


N2pi2pi0/N4pic
1
1
1.2
1.4
1.6
1.8
$E_{c.m.}$, GeV



Отношение сечений e+e- \to 2pi+2pi- к e+e- \to pi+pi-2pi0.
Закрашенная область — эксперимент (из др. работ).
Точки с ошибками — результат амплитудного анализа (из данной работы).



Statistical precision is about 2-3% in average