Central exclusive production of mesons in proton-proton collisions

Stanisław Kalinowski, Javier Oliva del Moral

Supervisor: dr. Piotr Lebiedowicz

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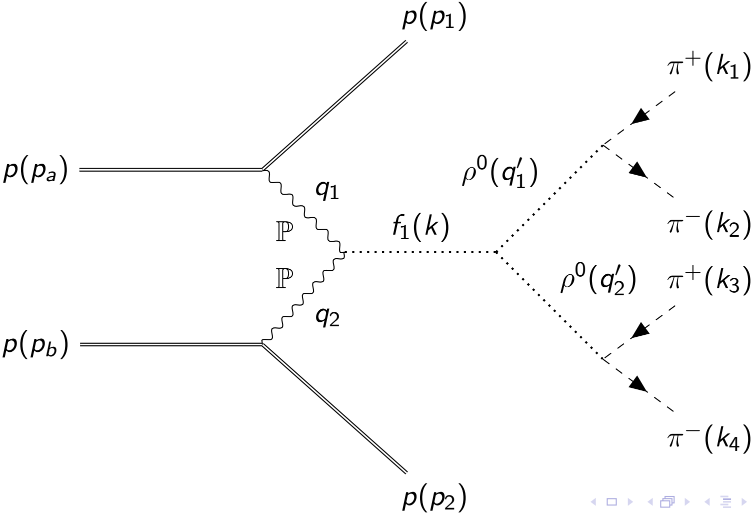
Development of the theoretical model

Diffractive production of axial-vector $f_1(1285)$ meson (with quantum numbers $I^G J^{PC} = 0^+1^{++}$) via pomeron-pomeron-fusion mechanism in proton-proton collisions. [2]



Recent ATLAS-ALFA measurement

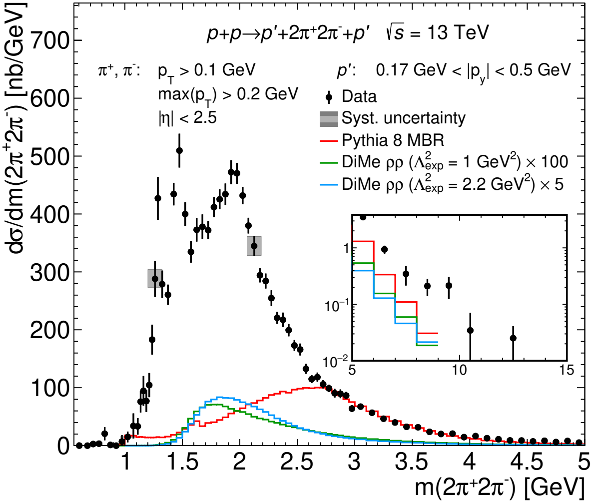


Figure: Preliminary result. Courtesy of Rafał Sikora, CERN-THESIS-2020-235

Why we are interested in it?

- What is underlying production mechanism for CEP of $f_1(1285)$ at LHC?
- What is underlying decay mechanism: $f_1(1285) \to \pi^+\pi^-\pi^+\pi^-$?
- What is the nature of the $f_1(1285)$? For instance, is it a normal $q\bar{q}$ state or $\bar{K}K^*$ molecule?

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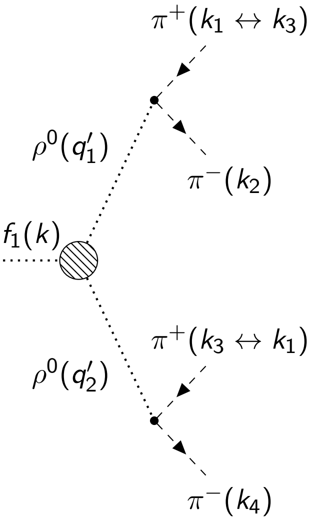
2. Theoretical formulas
   - $f_1 \to \pi^+\pi^-\pi^+\pi^-$
   - $f_1 \to \gamma\pi^+\pi^-$

Kinematics



Diagrams for the decay $f_1 \to \pi^+\pi^-\pi^+\pi^-$ via $\rho^0\rho^0$. Shown is diagram (1). Diagram (2) is obtained by the replacements of momenta as indicated.

$$q_1' = k_1 + k_2, \quad q_2' = k_3 + k_4,$$

$$q_1'' = k_3 + k_2, \quad q_2'' = k_1 + k_4,$$

$$k = q_1' + q_2' = q_1'' + q_2'' = k_1 + k_2 + k_3 + k_4$$

Amplitude 1/3

The amplitude for the $1 \to 4$ decay is obtained as a sum from the diagram (1) where the ρ^0 mesons carry the momenta q_1' and q_2' and (2) where their momenta are q_1'' and q_2''.

$$\langle \pi^+(k_1), \pi^-(k_2), \pi^+(k_3), \pi^-(k_4) | \mathcal{T} | f_1(k, \epsilon) \rangle \equiv \mathcal{T}^{(\rho\rho)}$$

,

$$\mathcal{T}^{(\rho\rho)} = \mathcal{T}^{(1)} + \mathcal{T}^{(2)},$$

$$\mathcal{T}^{(1)} = (-i) i\Gamma^{(\rho\rho f_1)}_{\mu\nu\alpha}(-q'_1, -q'_2) i\Delta^{(\rho)\mu\sigma}(q_1') i\Delta^{(\rho)\nu\rho}(q'_2)$$

$$\times i\Gamma^{(\rho\pi\pi)}_{\sigma}(k_1, k_2) i\Gamma^{(\rho\pi\pi)}_{\rho}(k_3, k_4) \epsilon^{(f_1)\alpha},$$

$$T^{(2)} = T^{(1)}|_{k_1 \to k_3, q_1' \to q''_1, q'_2 \to q''_2}$$

Amplitude 2/3

The $\rho^0\pi^+\pi^-$ vertex is [4]:

$$i\Gamma_\sigma^{(\rho\pi\pi)}(k_1, k_2) = -\frac{1}{2} g_{\rho\pi\pi}(k_1 - k_2)_\sigma$$

$$g_{\rho\pi\pi} = 11.51 \pm 0.07$$

The ρ^0 propagator is [4]:

$$i\Delta_{\mu\nu}^{(\rho^0)}(q) = i(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2 + i\epsilon})\Delta_T^{(\rho^0)}(q^2) - i\frac{q_\mu q_\nu}{q^2 + i\epsilon}\Delta_L^{(\rho^0)}(q^2)$$

The $\rho\rho f_1$ vertex satisfies the following relations:

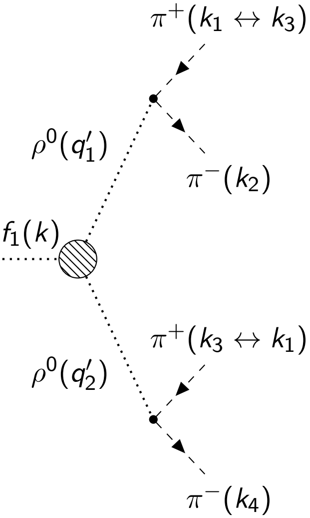
$$\Gamma_{\mu\nu\alpha}^{(\rho\rho f_1)}(q_1, q_2) = \Gamma_{\nu\mu\alpha}^{(\rho\rho f_1)}(q_2, q_1)$$

$$\Gamma_{\mu\nu\alpha}^{(\rho\rho f_1)}(q_1, q_2) q_1^\mu = 0$$

$$\Gamma_{\mu\nu\alpha}^{(\rho\rho f_1)}(q_1, q_2) q_2^\nu = 0$$

$$\Gamma_{\mu\nu\alpha}^{(\rho\rho f_1)}(q_1, q_2)(q_1 + q_2)^\alpha = 0$$

Amplitude 3/3



Then the amplitude for this process is given by

$$T^{(\rho\rho)} = T_{fi}^{(1)} + T_{fi}^{(2)}$$

Where:

$$T_{fi}^{(1)} = \frac{1}{2} g_{\rho\pi\pi}(k_1 - k_2)^{\mu} \Delta_T^{(\rho)}(q_1'^2)$$

$$\times \frac{1}{2} g_{\rho\pi\pi}(k_3 - k_4)^{\nu} \Delta_T^{(\rho)}(q_2'^2)$$

$$\times \Gamma_{\mu\nu\alpha}^{(\rho\rho f_1)}(-q_1', -q_2')|_{bare} F(q'^2_1, q'^2_2, m_{f_1}^2) \epsilon^{(f1)\alpha}$$

$$T_{fi}^{(2)} = T_{fi}^{(1)}|_{k_1 \leftrightarrow k_3, q_1' \to q_1'', q_2' \to q_2''}$$

Polarisation

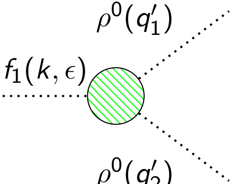
$f_1(\epsilon)$

The polarisation of f_1 meson is [7]:

$$\epsilon^{M=\pm 1} = \mp \frac{1}{\sqrt{2}}(e_1 \pm i e_2),$$

$$\epsilon^{M=0} = e_3$$

Vertex



$$i\Gamma^{(\rho\rho f_1)}_{\mu\nu\alpha}(-q_1',-q_2')|_{bare}=$$

$$\frac{2g_{f_1\rho\rho}}{M_0^4}[(q_1-q_2)^\rho(q_1-q_2)^\sigma\varepsilon_{\lambda\sigma\alpha\beta}k^\beta$$

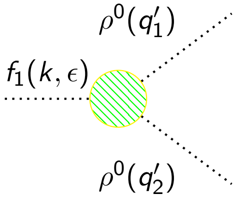
$$\times(q_{1\kappa}\delta^\lambda_\mu - q_1^\lambda g_{\kappa\mu})(q_2^\kappa g_{\rho\nu} - q_{2\rho}\delta^\kappa_\nu)$$

$$+(q_1\leftrightarrow q_2, \mu\leftrightarrow\nu)];$$

$$M_0 = 1 GeV$$

$$g_{f_1\rho\rho} = to \quad determine$$

Form factor [8]

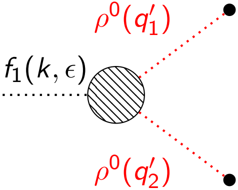


$$F(m_\rho^2, m_\rho^2, m_{f_1}^2) = 1$$

$$F({q'}_1^2, {q'}_2^2, m_\rho^2) = \frac{\Lambda^4}{\Lambda^4 + ({q'}_1^2 - m_\rho^2)^2} \frac{\Lambda^4}{\Lambda^4 + ({q'}_2^2 - m_\rho^2)^2}$$

where Λ should be adjusted to experimental data

Breit-Wigner transverse propagator



$$\Delta_T^{(\rho)}(q_1'^2) = \frac{1}{q_1'^2 - m_\rho^2 + i m_\rho \Gamma_\rho}$$

$$\Delta_T^{(\rho)}(q_2'^2) = \frac{1}{q_2'^2 - m_\rho^2 + i m_\rho \Gamma_\rho}$$

$$\Gamma_{\rho[PDG]} = 0.148\ GeV$$

Improvement of propagator

We can improve our results, if we include more precise propagator[9]:

$$\Delta_T^{(\rho)}(s) = \frac{1}{s - m_\rho^2 + B_{\rho\rho}(s)}$$

Where

$$B_{\rho\rho}(s) = g_{\rho\pi\pi}^2 s[R(s, m_\pi^2) - R(m_\rho^2, m_\pi^2) + \frac{1}{2}(R(s, m_K^2)$$

$$-R(m_\rho^2, m_K^2))] + ig_{\rho\pi\pi}^2[I(s, m_\pi^2) + \frac{1}{2}I(s, m_K^2)]$$

$$R(s, m^2) = \frac{s}{192\pi^2} V.P \int_{4m^2}^{\infty} \frac{ds'}{s'(s' - s)}(1 - \frac{4m^2}{s'})^{3/2}$$

$$I(s, m^2) = \frac{1}{192\pi} s(1 - \frac{4m^2}{s})^{3/2}\theta(s - 4m^2)$$

Decay rate

Once we obtain the amplitude for the decay, we can calculate the decay rate:

$$\Gamma(f_1 \to \pi^+\pi^-\pi^+\pi^-) = \frac{1}{2m_{f_1}}\frac{1}{2!2!}\int \prod_{j=1}^{4}[\frac{d^3 k_j}{(2\pi)^3 2k_j^0}](2\pi)^4$$
$$\delta^{(4)}(k_1 + k_2 + k_3 + k_4 - k)|\mathcal{T}^{(\rho\rho)}|^2$$

To calculate it, we use DECAY generator[6].

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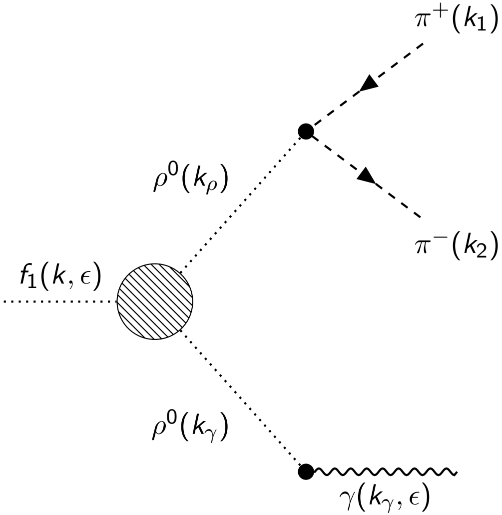
1->3 Decay process



Amplitude

Amplitude for the reaction $f_1 \to \pi^+\pi^-\gamma$ is given by[8]:

$$M_{\lambda_{f_1} \to \pi^+\pi^-\lambda_\gamma} = $$
$$-\frac{e}{\gamma_{\rho[VMD]}}\frac{g_{\rho\pi\pi}}{2}(k_1 - k_2)^\mu \Delta_T^{(\rho)}(k_\rho^2)(\epsilon^{(\gamma)\nu}(\lambda_\gamma)^* \Gamma_{\mu\nu\alpha}^{(\rho\rho f_1)}(-k_\rho, -k_\gamma)$$
$$\times \epsilon^{(f_1)\alpha}(\lambda_{f_1}) F(k_\rho^2, k_\gamma^2, m_{f_1}^2)$$

The factor e/γ_ρ comes from the $\rho \to \gamma$ transition vertex (VMD model)
Photon polarisation vector: $\epsilon_{\pm 1}^{(\gamma)} = \mp\frac{1}{\sqrt{2}}(e_1 \pm ie_2)$,
Form factor for this process can be rewritten as:

$$F(k_\rho^2, k_\gamma^2, m_{f_1}^2) = F(k_\rho^2, 0, m_{f_1}^2) = F(k_\rho^2)F(0)$$

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Obtained Results

Coupling constant $g_{\rho\rho f_1}$ obtained during the $1 \rightarrow 4$ decay is presented in table below with different Λ values.

$$\Gamma_{exp}((f_1(1285) \rightarrow \pi^+\pi^-\pi^+\pi^-) = \mathcal{BR}(f_1(1285) \rightarrow \pi^+\pi^-\pi^+\pi^-)\Gamma_{f_1}$$

Where: $\Gamma_{f_1[PDG]} = (22.7 \pm 1.1)MeV$
$\mathcal{BR}_{PDG}(f_1(1285) \rightarrow \pi^+\pi^-\pi^+\pi^-) = (10.9 \pm 0.6)\%$

$\Lambda[GeV]$	$\lvert g_{\rho\rho f_1}\rvert$ [Breit-Wigner]	$\lvert g_{\rho\rho f_1}[9]\rvert$
2.0	39.948256	31.985195
1.5	40.829340	32.785636
1.0	46.861702	37.546476
0.8	57.968411	46.475260
0.65	83.560864	66.586887

Which is not the value which we expected. This indicates that there might be other processes e.g. $f_1 \rightarrow a_1(1260)^{\pm}\pi^{\mp} \rightarrow (\rho^0\pi^{\pm})\pi^{\mp} \rightarrow 2\pi^{\pm}2\pi^{\mp}$

Coupling constant from $f_1 \to \gamma\rho^0$

Decay width and branching ratio we use it the calculations are(CLAS data[3])[8]:

$$\Gamma_{exp}(f_1(1285) \to \gamma\rho^0) = \mathcal{BR}_{[CLAS]}(f_1(1285) \to \gamma\rho^0)\Gamma_{f_{1[CLAS]}}$$
$$\Gamma_{exp}(f_1(1285) \to \gamma\rho^0) = \mathcal{BR}_{[PDG]}(f_1(1285) \to \gamma\rho^0)\Gamma_{f_{1[PDG]}}$$
$$\text{BR}_{[CLAS]} = (2.5^{+0.7}_{-0.8})\%$$
$$\Gamma_{exp[CLAS]} = (453 \pm 177)keV$$
$$\text{BR}_{[PDG]} = (6.1 \pm 1.0)\%$$
$$\Gamma_{exp[PDG]} = (1384.7^{+305.1}_{-283.1})keV$$

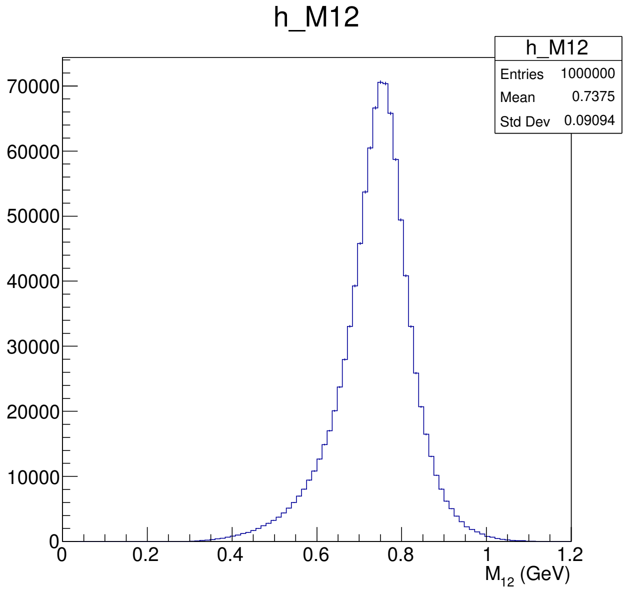
	$\lvert g_{\rho\rho f_1}\rvert$	
$\Lambda[GeV]$	CLAS	PDG
2.0	6.2929619	10.918275
1.5	6.6371057	11.515364
1.0	8.540408	14.817589
0.8	12.079842	20.9585
0.65	20.216926	35.076322

Coupling constant from $f_1 \to \gamma\rho^0$

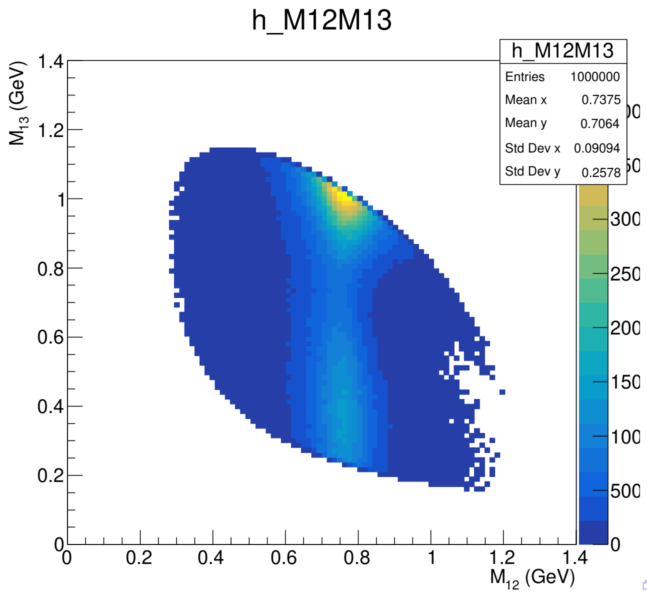
Results are consistent with the values from literature[8] given in the table below:

	$\lvert g_{\rho\rho f_1} \rvert$	
$\Lambda[GeV]$	CLAS	PDG
2.0	6.27	10.97
1.5	6.59	11.52
1.0	8.49	14.85
0.8	12.00	20.98
0.65	20.03	35.02

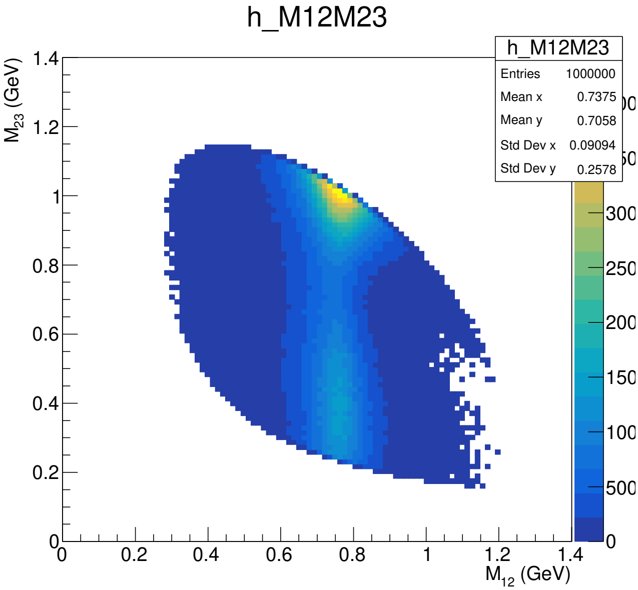
Invariant Masses in 1→3 decay



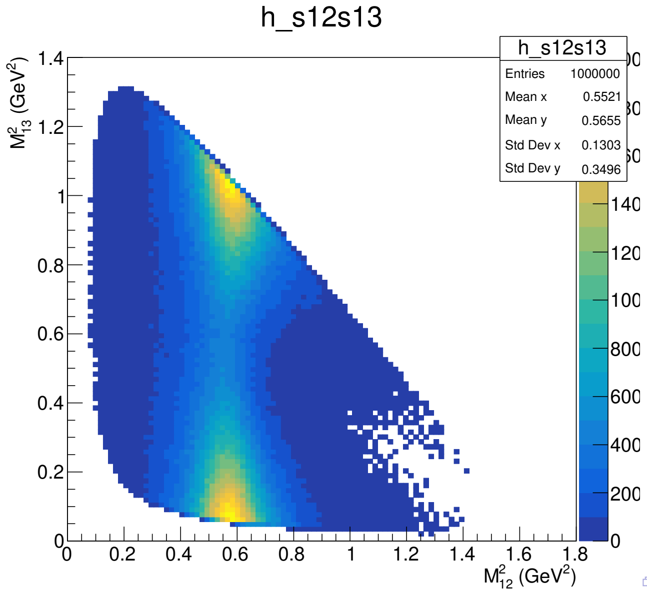
Invariant Masses in 1→3 decay



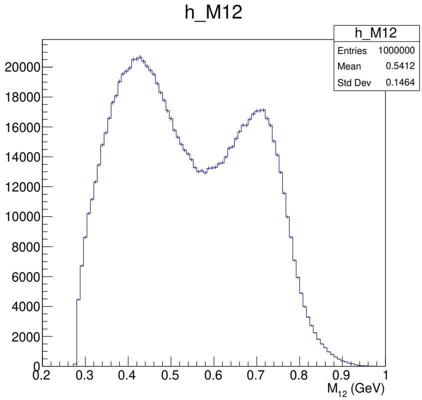
Invariant Masses in 1→3 decay

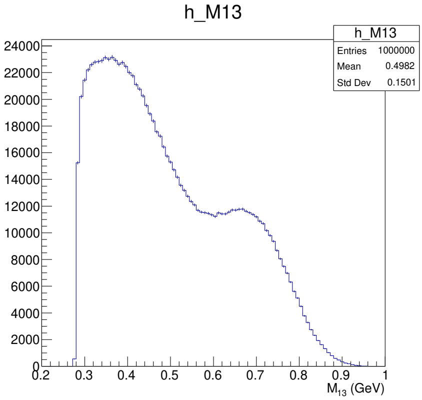


Dalitz plot

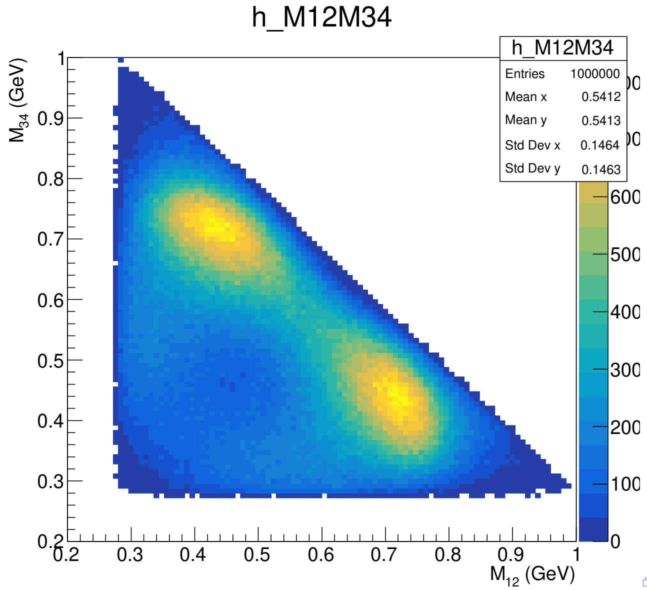

h_s12s13
h_s12s13
Entries 1000000
Mean x 0.5521
Mean y 0.5655
Std Dev x 0.1303
Std Dev y 0.3496
M^2_{13} (GeV^2)
M^2_{12} (GeV^2)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
200
400
600
800
100
120
140

Invariant Masses in 1→4 decay

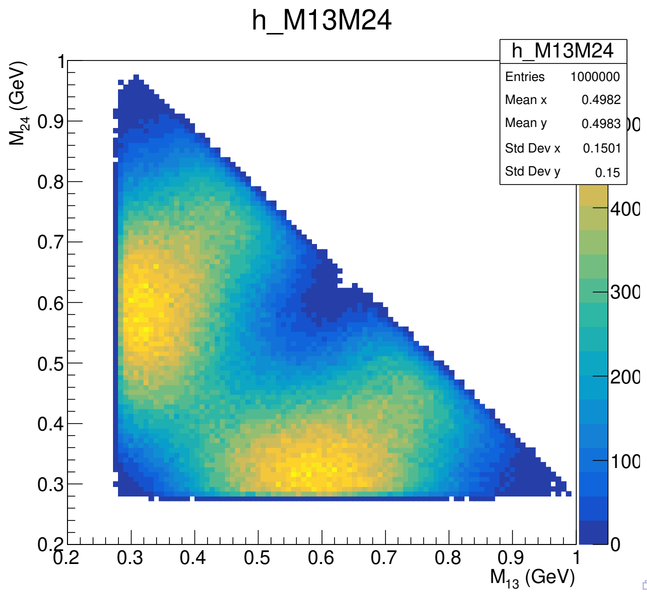




2-D Invariant Mass Distribution for 1→4 decay



2-D Invariant Mass Distribution for 1→4 decay



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Conclusions

- The $g_{\rho\rho f_1}$ coupling constant obtained during the considered $1 \to 4$ decay via intermediate $\rho^0\rho^0$ mesons doesn't match the predicted value, which should be ≈ 10 ($f_1 \to \pi^+\pi^-\gamma$).
- Value we got during our calculations, ≈ 30 suggests that there are more processes that haven't been included. There might be needed further work to explain this difference.
- The coupling constant obtained during the ($f_1 \to \pi^+\pi^-\gamma$) decay is in agreement with predictions[8].

Outlook for further work

- Theoretical studies of the CEP reactions, e.g $pp \to pp\pi^+\pi^-\pi^+\pi^-$ including both resonances and continuum contributions within the tensor pomeron approach using dedicated MC generators for exclusive processes such as GenEx[5], GenExLight[1] and DECAY[6].

Thank you for your attention!

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References

R. A. Kycia et al. "The Adaptive Monte Carlo Toolbox for Phase Space Integration and Generation". In: *Communications in Computational Physics* 25.5 (2019), pp. 1547–1563. ISSN: 1991-7120. DOI: https://doi.org/10.4208/cicp.OA-2018-0028. URL: http://global-sci.org/intro/article_detail/cicp/12961.html.

Arthur Bolz et al. "Photoproduction of $\pi^+ \pi^-$ pairs in a model with tensor-pomeron and vector-odderon exchange". In: *JHEP* 01 (2015), p. 151. DOI: 10.1007/JHEP01(2015)151. arXiv: 1409.8483 [hep-ph].

R. Dickson et al. "Photoproduction of thef1(1285)meson". In: *Physical Review C* 93.6 (June 2016). ISSN: 2469-9993. DOI: 10.1103/physrevc.93.065202. URL: http://dx.doi.org/10.1103/PhysRevC.93.065202.

Carlo Ewerz, Markos Maniatis, and Otto Nachtmann. "A model for soft high-energy scattering: Tensor pomeron and vector odderon". In: *Annals of Physics* 342 (Mar. 2014), pp. 31–77. ISSN: 0003-4916. DOI: 10.1016/j.aop.2013.12.001. URL: http://dx.doi.org/10.1016/j.aop.2013.12.001.

"GenEx: A Simple Generator Structure for Exclusive Processes in High Energy Collisions". In: *Communications in Computational Physics* 24.3 (2018), pp. 860–884. ISSN: 1991-7120. DOI: https://doi.org/10.4208/cicp.OA-2017-0105. URL: http://global-sci.org/intro/article_detail/cicp/12284.html.

R. A. Kycia, P. Lebiedowicz, and A. Szczurek. *Decay: A Monte Carlo library for the decay of a particle with ROOT compatibility*. 2020. arXiv: 2011.14750 [hep-ph].

Piotr Lebiedowicz et al. “Central exclusive diffractive production of axial-vector f1(1285) and f1(1420) mesons in proton-proton collisions”. In: *Physical Review D* 102.11 (Dec. 2020). ISSN: 2470-0029. DOI: 10.1103/physrevd.102.114003. URL: http://dx.doi.org/10.1103/PhysRevD.102.114003.

Piotr Lebiedowicz et al. “Exclusive $f_1(1285)$ meson production for energy ranges available at the GSI-FAIR with HADES and PANDA”. In: (May 2021). arXiv: 2105.07192 [hep-ph].

D. Melikhov et al. “Masses and couplings of vector mesonsfrom the pion electromagnetic, weak, and $\pi\gamma$ transition form factors”. In: *The European Physical Journal C* 34.3 (May 2004), pp. 345–360. ISSN: 1434-6052. DOI: 10.1140/epjc/s2004-01726-4. URL: http://dx.doi.org/10.1140/epjc/s2004-01726-4.