Central Exclusive Production of 2π and 4π systems

—an overview from an experimental physicist—

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- This talk is mostly theoretical/phenomenological in nature.
- However, this talk is given by an experimental physicist, i.e. the theory part is brief and necessarily rudimentary.
- We shall define four reference frames—necessary for 2- to 3-body processes.

Plan of Talk

- Kinematics for Central Production: Two- to Three-Body Processes

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- Conclusions and Future Prospects

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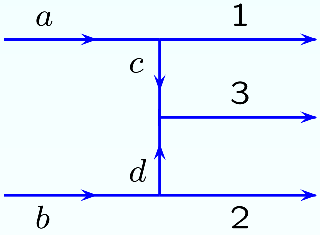

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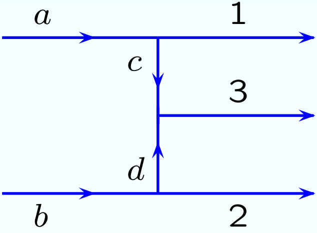

Overall CM system

$\vec{a} + \vec{b} = 0$
($\vec{a}$ along the z axis)

$\vec{p}_1 + \vec{p}_2 + \vec{p}_3 = 0$
(a plane going through the origin)

Three Euler angles needed
to define the plane.

$$d\phi_3(a+b\to 1+2+3) = \frac{4}{(4\pi)^5}\,(dR)_{\rm CM}\left(\frac{1}{4s}\right) dm_{13}^2\, dm_{23}^2$$
$$dR = d\alpha(d\cos\beta)d\gamma$$

There are four coordinate systems needed for the process $a+b\to 1+2+3$:

- The Detector system in the LAB (The first coordinate system).

$$\hat{z} = (0,0,1) \propto \text{the beam direction}$$
$$\hat{y} = (0,1,0) \propto \text{vertical in LAB}$$
$$\hat{x} = (1,0,0) = \hat{y}\times\hat{z}$$

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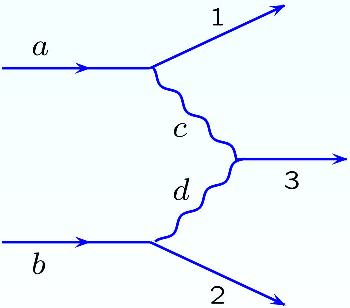
- We stay in the overall CM frame, i.e. $\vec{a}+\vec{b}=0$, $\vec{a}=-\vec{b}\propto\hat{z}$
The plane defined by $\vec{p}_1+\vec{p}_2+\vec{p}_3=0$ where (β,α) stands for the normal (defined by $\hat{y}_n\propto\vec{p}_1\times\vec{p}_2$) to the reaction plan, i.e.
$$\hat{z}_n = (-\sin\alpha, \cos\alpha, 0), \quad \text{this is the node}$$
$$\hat{y}_n = (\sin\beta\cos\alpha, \sin\beta\sin\alpha, \cos\beta)$$
$$\hat{x}_n = \hat{y}_n\times\hat{z}_n$$
The vectors $\vec{p}_i$, $(i=1,2,3)$, lie in the x_n-z_n plane.
We define $\vec{p}_1$ to be in this plane, rotating around the $\hat{y}_n$ axis by $\gamma_1=\pi/2+\gamma$ from the $\hat{z}_n$ axis. If $\gamma\simeq 0$, then we see that $\hat{z}_n\simeq\hat{z}$, which simply means that $\vec{a}$ and $\vec{p}_1$ are nearly parallel. The $\vec{p}_2$ is obtained by a similar rotation by $\gamma_2=3\pi/2-\delta+\gamma$ where $\vec{p}_1\cdot\vec{p}_2=p_1p_2\cos(\pi-\delta)$. This is the second coordinate system.

Production Amplitudes

Production Amplitudes



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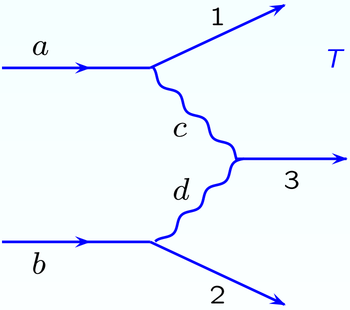


$$T \propto A(a \to 1 + c) * A(b \to 2 + d)$$
$$A(c + d \to 3) * A(3 \to 4 + 5 + 6 + \cdots)$$

$A(a \to 1 + c)$ in the a rest frame

$A(b \to 2 + d)$ in the b rest frame

$A(c + d \to 3)$ in the 3 rest frame

$A(3 \to 4 + \cdots)$ in the 3 rest frame

Decay Amplitudes

Let the particle $3(X^0)$ be in the state of $|jm\rangle$
and let it decay into two particles

$$|jm\rangle \to |s_4\,\lambda_4\rangle + |s_5\,\lambda_5\rangle$$

(particles 4 and 5 are new— introduced to indicate decay products)

$$A(j \to s_4 + s_5) = \langle (4+5)|\mathcal{M}_d|jm\rangle \propto \boxed{{}^jF^{s_4\,s_5}_{\lambda_4\,\lambda_5}\; D^{j\,*}_{m,(\lambda_4-\lambda_5)}(\phi_4, \theta_4, 0)}$$

$${}^jF^{s_4\,s_5}_{-\lambda_4\,-\lambda_5} = \nu_j \nu_4 \nu_5\; {}^jF^{s_4\,s_5}_{\lambda_4\,\lambda_5}$$

where ν_j is the 'naturality' of the particle j

$$\nu_j = \eta(-)^j \quad \text{for} \quad \text{bosons} \qquad = \eta(-)^{j-1/2} \quad \text{for} \quad \text{fermions}$$

where η is the intrinsic parity. Similarly for s_4 and s_5.

Pomerons

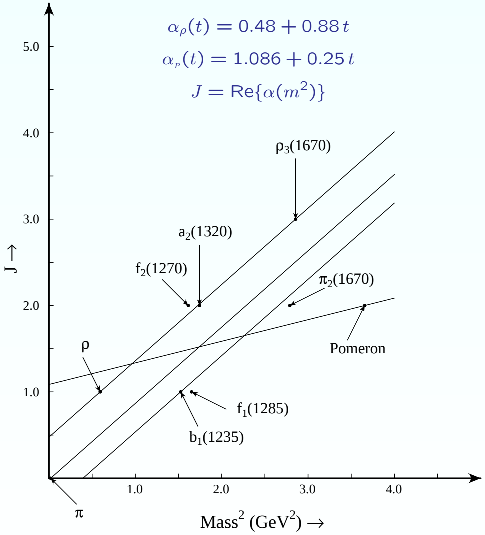
Pomerons

Regge Trajectories

$$\alpha_\rho(t) = 0.48 + 0.88\,t$$

$$\alpha_{_P}(t) = 1.086 + 0.25\,t$$

$$J = \mathrm{Re}\{\alpha(m^2)\}$$



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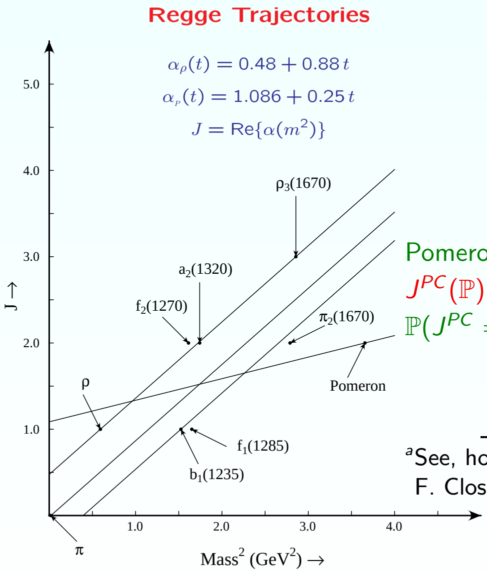

Pomeron comes with an even signature[a].

$J^{PC}(\mathbb{P}) = 2^{++},\ 4^{++},\ 6^{++}, \cdots$

$\mathbb{P}(J^{PC} = 2^{++})$ at mass $= 1.91$ GeV.

[a] See, however, a paper by F. Close and A. Kirk, PLB **397**, 333 (1997).

$$|\ell\, S\, JM\rangle = \sum_{m_1\, m_2} (s_1 m_1\, s_2 m_2|S m_s)\,(S m_s\, \ell\, m|JM) \times \int \mathrm{d}\vec{k}\; Y^\ell_m(\vec{k})\; |\mathbb{G},\, +\vec{k},\, s_1 m_1\rangle |\mathbb{P},\, -\vec{k},\, s_2 m_2\rangle$$

so that

$$2|\ell\, S\, JM\rangle\Big|_{\mathrm{symm}} = \sum_{m_1\, m_2} (s_1 m_1\, s_2 m_2|S m_s)\,(S m_s\, \ell\, m|JM) \times \int \mathrm{d}\vec{k}\; Y^\ell_m(\vec{k})\; |\mathbb{G}, +\vec{k},\, s_1 m_1\rangle |\mathbb{P}, -\vec{k},\, s_2 m_2\rangle + \sum_{m_1\, m_2} (s_2 m_2\, s_1 m_1|S m_s)\,(S m_s\, \ell\, m|JM) \times \int \mathrm{d}\vec{k}\; Y^\ell_m(\vec{k})\; |\mathbb{P}, +\vec{k},\, s_2 m_2\rangle |\mathbb{G}, -\vec{k},\, s_1 m_1\rangle$$

The result:

$$s_1 + s_2 + S + \ell = \text{even} \quad \longrightarrow \quad (\mathbb{P}+\mathbb{P}) \oplus (\mathbb{P}+\mathbb{P});\ \boxed{S + \ell = \text{even}}$$

$$(\gamma+\mathbb{P}) \oplus (\mathbb{P}+\gamma);\ \boxed{S + \ell = \text{odd}}$$

Exotic(non-$q\bar{q}$) $J^{PC} = 0^{--},\ 0^{+-},\ 1^{-+},\ 2^{+-},\ 3^{-+},\ 4^{+-},\ 5^{-+}$

Likely J^{PC} states allowed are:

$(\mathbb{P}+\mathbb{P}) \oplus (\mathbb{P}+\mathbb{P})$; $S+\ell = \text{even}$ $\longrightarrow$

$$I^G = 0^+, \quad S = 0,1,2,3,4; \quad \vec{J} = \vec{S} + \vec{\ell}$$

$$J^{PC}(\ell = 0; S = 0,2,4) \longrightarrow 0^{++}, 2^{++}, 4^{++}$$

$$(\ell = 1; S = 1,3) \longrightarrow 0^{-+}, 1^{-+}, 2^{-+}, 3^{-+}, 4^{-+}$$

$$(\ell = 2; S = 0,2,4) \longrightarrow 0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}, 5^{++}, 6^{++}$$

$(\gamma+\mathbb{P}) \oplus (\mathbb{P}+\gamma)$; $S+\ell = \text{odd}$ $\longrightarrow$

$$I^G = (0^-, 1^+),\ S = 1,2,3; \quad \vec{J} = \vec{S} + \vec{\ell}$$

$$J^{PC}(\ell = 0; S = 1,3) \longrightarrow 1^{+-}, 3^{+-}$$

$$(\ell = 1; S = 2) \longrightarrow 1^{--}, 2^{--}, 3^{--}$$

$$(\ell = 2; S = 1,3) \longrightarrow 1^{+-}, 2^{+-}, 3^{+-}, 4^{+-}, 5^{+-}$$

Three Processes for Central Production of $\pi\pi$: $\boxed{I + \ell = \text{even}}$

- $\mathbb{P}(2^{++}) + \mathbb{P}(2^{++}) \to \pi\pi(I^G = 0^+;\ J^{PC} = 0^{++},\ 2^{++},\ 4^{++}, \cdots)$
  Two Natural-parity exchanges $\to \pi\pi$ ($\ell = 0,\ 2,\ 4$)
  Dominant Process: $S + D$ waves

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  P-wave dominant

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  P-wave dominant
- $b_1(1235)(1^{+-}) + \mathbb{P}(2^{++}) \to \pi\pi(I^G = 1^+;\ \ J^{PC} = 1^{--},\ 3^{--},\ 5^{--}, \cdots)$
  Unnatural-parity and Natural-parity exchanges $\to \pi\pi$ ($\ell = 1,\ 3,\ 5$)
  P-wave dominant

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  Mass $\simeq$ 0.8 GeV or higher

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- ϕ+Pomeron$\rightarrow K\bar{K}$ or $K\bar{K} + 2\pi$ all with $I^G = 0^-$
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- Υ+Pomeron→ $B\bar{B}$ or $\Upsilon + 2\pi$ all with $I^G = 0^-$
  $b\bar{b}$ bound systems—bottomonia
  Mass $\simeq$ 9.5 GeV or higher

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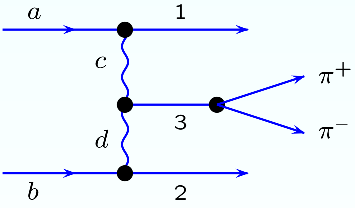
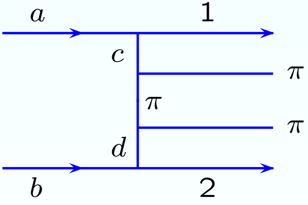
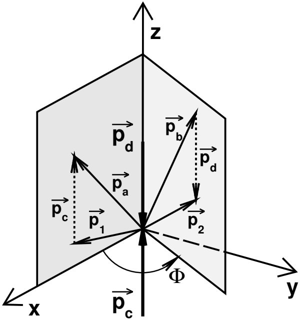


2π Resonace



2π Continuum

$a + b \to 1 + 3 + 2$ in the 3RF



$$p_a = p_1 + p_c, \quad p_b = p_2 + p_d$$

$$p_c + p_d = p_3$$

$$\vec{p}_c + \vec{p}_d = \vec{p}_3 = 0$$

$$\hat{z}_m \propto \vec{p}_c \text{ and } -\hat{z}_m \propto \vec{p}_d$$

$\vec{p}_a$ and $\vec{p}_1$ in the x_m-z_m plane by defintion. So we must have

$$\hat{y}_m \propto \vec{z}_m \times \vec{p}_a \quad \text{and} \quad \hat{x}_m = \hat{y}_m \times \hat{z}_m$$

The plane formed by $\vec{p}_b$ and $\vec{p}_2$ is denoted by the plane rotated by Φ around the z_m-axis.

This completes the construction of the third coordinate system.

Amplitudes for $a + b \to 1 + 3 + 2$

The reaction

$$a \to 1 + c, \quad b \to 2 + d, \quad c + d \to 3$$

The corresponding amplitudes

$$A = \sum_{i\,j} A(a \to 1 + c_i) * \Delta(c_i) * A(b \to 2 + d_j) * \Delta(d_j) \\ * A(c_j + d_j \to 3)$$

where

$$\{i, j\} = \{\text{Pomeron+Pomeron},\ \text{photon+Pomeron},\ \text{Pomeron+photon}\}$$

This completes the construction of all the relevant ampltidues in the problem.

Conclusions:

- The reaction

$$a + b \to 1 + 3 + 2 \qquad 3 \to 4 + 6 + \cdots$$
$$a \to 1 + c \quad b \to 2 + d \quad c + d \to 3$$

is a 2- to 3-body process, if and only if the Regge domain formula holds

$$\boxed{s_{13}\, s_{23} \simeq s\, w_3^2}, \quad \text{transverse mass:} \quad w_3^2 = m_3^2 + \boldsymbol{\kappa}_3^2$$

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- The reaction requires three different rest frames (RF's):
  (a) The detector frame: $\boxed{\{\hat{x}, \hat{y}, \hat{z}\}}$
  (b) The overall CM system where the normal $\hat{y} \propto \vec{p}_1 \times \vec{p}_2$
  the plane $\vec{p}_1 + \vec{p}_2 + \vec{p}_3 = 0$ lies the x-z plane: $\boxed{\{\hat{x}_n, \hat{y}_n, \hat{z}_n\}}$
  The Euler angles $R = (\alpha, \beta, \gamma)$ are used to transform from the frame (a) to the frame (b).
  (c) In the 3RF, $\hat{z}_m \propto \vec{c}$, $\hat{y}_m \propto \vec{a} \times \vec{p}_1$ $\hat{x}_m = \hat{y}_m \times \hat{z}_m$: $\boxed{\{\hat{x}_m, \hat{y}_m, \hat{z}_m\}}$
  $\vec{a}$ and $\vec{p}_1$ lies in the x_m-z_m plane; the plane formed by $\vec{b}$ and $\vec{p}_2$ rotated by angle Φ around the $\hat{z}_m$ axis.

- Double-Pomeron process:
  Ground state are $f_0(500)$, $f_2(1275)$ and $f_4(2050)$.
  Exotic mesons are possible $I^G(J^{PC}) = 0^+(1^{-+}),\ 0^+(3^{-+})\ldots$

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- Photon-Pomeron process:
  Ground state are $h_1(1170)$ and $b_1(1235)$.
  The Regge recurrence NOT observed.
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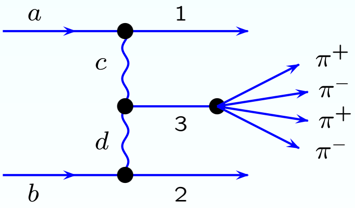
- ALICE can produced very exciting new results on mesons— in the next few years
- We need a new PhD candiate to work on the 4π channel

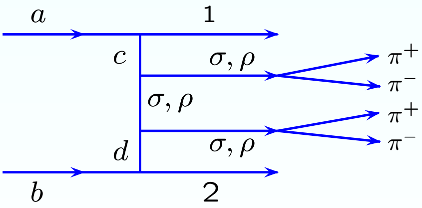
- 4π production via $\sigma\sigma$ and $\rho\rho$ intermediate states:

Exclusive diffractive production of $\pi^+\pi^-\pi^+\pi^-$
via the intermediate $\sigma\sigma$ and $\rho\rho$ intermediate states
in proton-proton collisions within tensor Pomeron approach

Piotr Lebiedowicz, Otto Nachtmann and Antoni Szczurek
Phy. Rev. **D94**, 034017(2016)



4π Resonace



4π Continuum

Distribution with an arbitrary degree of coherence

For both 2π and 4π final states, Write

$$I(\tau) = \sum_{\text{external spins}} \left| r_0\, A_{\rm Res}(\tau) + r\{\exp\phi\} A_{\rm Con}(\tau) \right|^2$$

where τ is the phase-space variable for the production of the 2π and 4π final states and $r_0(0 \to 1)$, $r\,(-\infty \to +\infty)$ and $\phi\,(0 \to 2\pi)$ are real. *We further assume that r_0, r and ϕ are real and independent of τ, i.e. they are taken to be constants in the problem.* We see that

$$I(\tau) = r_0^2 \left| A_{\rm Res}(\tau) \right|^2 + r^2 \left| \{\exp\phi\} A_{\rm Con}(\tau) \right|^2 + 2 r_0\, r\, \Re\left\{ A^*_{\rm Res}(\tau) \{\exp\phi\} A_{\rm Con}(\tau) \right\}$$

where $(r_0,\, r_1) = (1, 0)$ and $r = \phi = 0$ for the Resonance term only and $(r_0,\, r_1) = (0, 1)$ and $\phi = 0$ for the Continuum term only.

The Collins-Soper Reference Frame

Angular distribution of dileptons in high-energy hadron collisions,

J. C. Collins and D. E. Soper
Phys. Rev. **D16**, 2219 (1977)

Let $\hat{e}_i$, $(i = 1, 2, 3)$ be the unit vectors which define the reference frame. Then we have, in the 3RF,

Note that $\angle(\hat{p}_a \cdot \hat{e}_3) = \angle(-\hat{p}_b \cdot \hat{e}_3)$ so that the vector $\hat{e}_3$ bisects the two vectors $\hat{p}_a$ and $-\hat{p}_b$. And $\hat{e}_2$ is the unit vector normal to the plane formed by $\hat{p}_a$ and $-\hat{p}_b$. And $\hat{e}_2$ lies in the plane formed by $\hat{p}_a$ and $-\hat{p}_b$. This is the fourth reference frame.

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$$\hat{e}_1 = \frac{\hat{p}_a + \hat{p}_b}{|\hat{p}_a + \hat{p}_b|}$$

$$\hat{e}_2 = \frac{\hat{p}_a \times \hat{p}_b}{|\hat{p}_a \times \hat{p}_b|}$$

$$\hat{e}_3 = \frac{\hat{p}_a - \hat{p}_b}{|\hat{p}_a - \hat{p}_b|}$$

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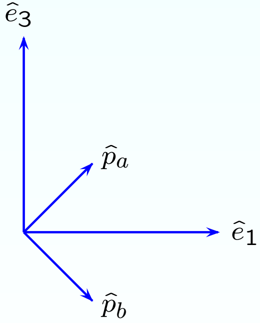

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$\pi + \pi^-$ continuum

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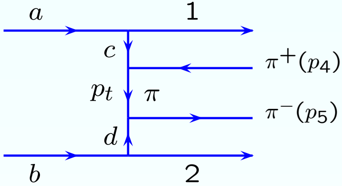
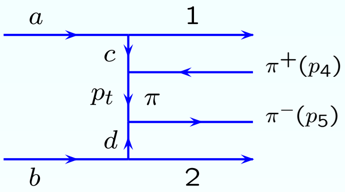
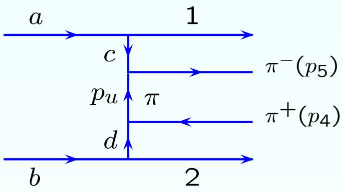


$$p_c = p_1 - p_a$$
$$= p_t - p_4$$
$$p_d = p_2 - p_b$$
$$= p_5 - p_t$$

$\pi + \pi^-$ continuum

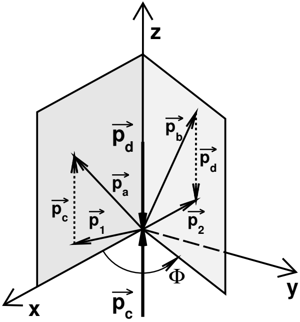




$$\begin{aligned} p_c &= p_1 - p_a \\ &= p_t - p_4 \\ p_d &= p_2 - p_b \\ &= p_5 - p_t \end{aligned}$$

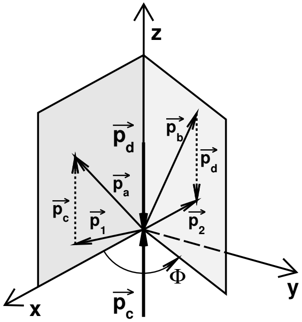
$$\begin{aligned} p_c &= p_1 - p_a \\ &= p_5 - p_u \\ p_d &= p_2 - p_b \\ &= p_u - p_4 \end{aligned}$$

The Last Slide



The ‘correct’ reference frame for a study of particle 3.

The Last Slide



The ‘correct’ reference frame for a study of particle 3.

Thank you for your attention

$\pi^+\pi^-$ continuum

The propagator for a tensor Pomeron

$$i\,\Delta^{(\mathbb{P})}_{\mu\nu,\kappa\lambda}(s,t) = \frac{1}{4s}\left(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\mu\kappa} - \frac{1}{2}g_{\mu\lambda}g_{\kappa\lambda}\right)(-i\,s\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}$$

where $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}\,t = 1.0808 + 0.25\,t$.

We obtain, for the reaction $\lambda_a\lambda_b \to \lambda_1\lambda_2\ \pi^+\pi^-$,

with $e\cdot f = e^{\mu} f_{\mu} = e^{\mu} g_{\mu\nu} f^{\nu} = e_{\nu} f^{\nu}$,

$$\mathcal{M}(\mathbb{P}\mathbb{P} \to \pi^+\pi^-\text{continuum}) =$$

$$(p_1 - p_a)\cdot(p_t - p_4) \times (p_2 - p_b)\cdot(p_5 - p_t)\ \delta_{\lambda_1\lambda_a}\delta_{\lambda_2\lambda_b}$$

$$\times\left(\frac{1}{4s_{14}}\right)(-i\,s_{14}\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t_c)-1} \times \left(\frac{1}{4s_{25}}\right)(-i\,s_{25}\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t_d)-1}$$

$$\mathcal{M}(\mathbb{P}\mathbb{P} \to \pi^-\pi^+\text{continuum}) =$$

$$(p_1 - p_a)\cdot(p_5 - p_u) \times (p_2 - p_b)\cdot(p_u - p_4)\ \delta_{\lambda_1\lambda_a}\delta_{\lambda_2\lambda_b}$$

$$\times\left(\frac{1}{4s_{15}}\right)(-i\,s_{15}\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t_c)-1} \times \left(\frac{1}{4s_{24}}\right)(-i\,s_{24}\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t_d)-1}$$