Study of $\pi^- p \rightarrow \pi^- \eta(\eta) p$ at 190 GeV with the COMPASS experiment

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on behalf of the COMPASS collaboration

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Agenda

- Exotic $\pi(1400)$ observations.
- Lightest scalar nonet and beyond.
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• COMPASS Detector description.
• $\eta$ reconstruction.
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- Selection and preliminary statistics of $\pi^- p \rightarrow \pi^- \eta\eta p$
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• A first glimpse of $f_0(1500) \rightarrow \eta\eta$
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- PWA description and comparison with standard formalisms.
- Conclusion and outlook.
Exotic $\pi(1400)$

Seen by E852 exp. in $\pi^- p \to \eta \pi^- p$ at 18 GeV/c (publ. in 1997) and by CBAR exp. in $\bar{p}d \to \pi^- \pi^0 \eta p_{spectator}$ (publ. in 1998).
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Questioned by **Dzierba et al.** in 2003 in $\pi^- p \rightarrow \eta\pi^0 n$ at 18 GeV/c.

Confirmed again by **E852** in 2007 in $\pi^- p \rightarrow \eta\pi^0 n$ at 18 GeV/c, but with a lower mass ($M = 1257 \pm 20 \pm 25$ MeV).
Hypothetical lightest scalar nonets configurations and beyond

Hypo 1 for $0^{++}$ Nonet

Hypo 2 for $0^{++}$ Nonet

$K^*_0(1430)$ $K^{*+}_0(1430)$

$K^{*-}_0(1430)$ $\bar{K}^*_0(1430)$

$a_0^-(980)$ $a_0^+(980)$

$f_0(1370)$ $f_0(980)$

$i_z$ $S$

$K^*_0(1430)$ $K^{*+}_0(1430)$

$K^{*-}_0(1430)$ $\bar{K}^*_0(1430)$

$a_0^-(1450)$ $a_0^+(1450)$

$f_j(1710)$ $f_0(1370)$

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Hypo 5: $f_0(1370), f_0(1500), f_0(1710)$ are the result of the mixing of the glueball (and a tetraquark) with ordinary mesons.
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Mixing scheme is based mainly on the results of WA102 experiment.

COMPASS goal in centrally produced data is to confirm and improve the observation of WA102:

measure the decay branching widths in $K\bar{K}, \pi\pi, \eta\eta', 4\pi, \eta'\eta', ...$
Hypothetical lightest scalar nonets configurations and beyond

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$\pi^- p \to \pi^- \eta p$ very selective: $X \to \eta\eta$ has $I(J^{PC}) = 0(0^{++}, 2^{++}, 4^{++}, ...)$
COMPASS setup and detector description

- Two arm spectrometer
- Tracking: Straw, Drift chambers, MicroMegas, PixelGEM, Recoil Proton Detector
- Calorimetry: ECAL1 (2006), ECAL2, HCAL1, HCAL2, Sandwich Veto
- Cherenkov: CEDAR, RICH
Electromagnetic Calorimeters

**ECAL1**
- 11.1 m downstream, low energetic photon detection, $L \times H$: 3.97 × 2.86 m$^2$
- 1500 channels:
  - OLGA: 302 cells, 14.3 × 14.3 cm$^2$
  - MAINZ: 572 cells, 7.5 × 7.5 cm$^2$
  - GAMS: 608 cells, 3.8 × 3.8 cm$^2$

**ECAL2**
- 33.2 downstream, high energetic photon detection, $L \times H$: 2.45 × 1.94 m$^2$
- 3068 channels:
  - peripheral area: GAMS lead glass blocks 3.8 × 3.8 cm$^2$
  - central area: new ~ 900 radiation hard SHASHLYK modules 3.8 × 3.8 cm$^2$
- New ADC (2008) with 32 sample converters
Pre-selection of exclusive events

- Trigger dedicated to diffractive and "central" reactions.
- Loop to all primary vertexes.
- Interaction in the target: \(-69 < z_{\text{vertex}} < -29\) cm and \(r_{\text{vertex}} < 1.5\) cm.
- 1 outgoing negative track with \(E_{\text{track}} < 180\) GeV.
- 2 and 4 good clusters in ECAL1 and in ECAL2 for the 2\(\gamma\) and 4\(\gamma\) channels, respectively:
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- 2 and 4 good clusters in ECAL1 and in ECAL2 for the $2\gamma$ and $4\gamma$ channels, respectively:
  - not pointed by a track.
  - noise suppression.
  - $E_{\text{clus min}} > 1$ GeV in ECAL1 and $E_{\text{clus min}} > 4$ GeV in ECAL2.
  - in time with the beam: $-3 < t_{\text{cluster}} - t_{\text{beam}} < 5$ ns.
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  - in time with the beam: $-3 < t_{\text{cluster}} - t_{\text{beam}} < 5$ ns.
- Correction of the photons momenta assuming they originate from the primary vertex.
- Correlation with RPD: $-0.3 < \phi_{\pi^- n\gamma} - \phi_p < 0.3$ rad.
- Energy balance: $180 < E_{\pi^- n\gamma} < 200$ GeV assuming the track to be a pion.
- $\pi^0, \eta \rightarrow \gamma_1 \gamma_2$: 1 combination.
  - $\pi_1^0, \eta_1 \rightarrow \gamma_i \gamma_j, \pi_2^0, \eta_2 \rightarrow \gamma_k \gamma_m$: 3 combinations.
Vertex distributions

COMPASS 2008 data
42% of 2008 DATA

π⁻ p → π⁻ p + anything

π⁻ p → π⁻ p + neutrals only

π⁻ p → π⁻ p + anything

1 outgoing track only

π⁻ p → π⁻ p + neutrals

≥ 1 outgoing tracks

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Recoil Proton Detector and exclusivity cuts

COMPASS preliminary 42% of 2008 DATA

\[ \pi^- p \rightarrow \pi^- 4\gamma p \]

COMPASS preliminary 42% of 2008 DATA

\[ \pi^- 4\gamma p \rightarrow \pi^- \eta p \]
\( \eta \) and two-body \( \eta \pi^- \) invariant masses in the \( 2\gamma \) channel

\[ m_{\gamma \gamma} \text{[GeV]} \]

- 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75
- 2000 4000 6000 8000 10000 12000 14000 16000

\[ \eta \text{-}\pi^\text{-} \text{m} \text{[GeV]} \]

- 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5
- Entries/20 [MeV]
- 0 2000 4000 6000 8000 10000

\( \eta \) mass:
- \( m_\eta = 548.7 \pm 0.1 \text{ MeV} \)
- \( \sigma = 22.5 \pm 0.1 \text{ MeV} \)

\[ \eta \pi^- \rightarrow \eta \pi^- \text{p} \]

COMPASS
- Preliminary
- 28% of 2008 DATA

\[ \pi^- \text{p} \rightarrow \pi^- \eta \text{-} \text{p} \]

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Study of \( \pi^- \text{p} \rightarrow \pi^- \eta(\eta) \text{p} \) at 190 GeV
η masses in the 4γ channel

COMPASS
42% of 2008 DATA

\( \pi^- p \rightarrow \pi^- \eta \eta p \)

\( m_\eta = 548.6 \pm 0.2 \text{ MeV} \)

\( \sigma = 23. \pm 0.2 \text{ MeV} \)
A preliminary sample of about 150K fitted $\pi^- p \rightarrow \pi^- \eta p$ events is used for the amplitude analysis.

Better statistics will be achieved with improved calorimeter calibration (2008 data) and additional LASER and LED calorimeter monitoring system (2009 DATA).
A preliminary sample of about 5K fitted $\pi^- p \to \eta\eta p$ events is used for the amplitude analysis.

- Comparable amount of data is available in $\pi^- p$ and in $pp$ at 190 GeV in the 2009 run.
- Better statistics will be achieved with improved calorimeter calibration (2008 data) and additional LASER and LED calorimeter monitoring system (2009 DATA).
- The statistics will be further increased by using the mixed decay mode of one of both $\eta$s in $\pi^+\pi^-\pi^0$. 

### Preliminary statistics of $\pi^- p \to \pi^- \eta\eta p$

<table>
<thead>
<tr>
<th>Condition</th>
<th>2008 Data (42%)</th>
<th>2009 Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of processed data</td>
<td>100.00%</td>
<td>73.78%</td>
</tr>
<tr>
<td>DT0 trigger</td>
<td></td>
<td>72.49%</td>
</tr>
<tr>
<td>Majority $&lt;6$ for CEDAR1 and CEDAR2</td>
<td></td>
<td>66.91%</td>
</tr>
<tr>
<td>Primary vertex $&lt;69 &lt; z_{\text{vertex}} &lt; -29$ cm</td>
<td></td>
<td>54.81%</td>
</tr>
<tr>
<td>$r_{\text{vertex}} &lt; 1.5$ cm</td>
<td></td>
<td>53.36%</td>
</tr>
<tr>
<td>1 negative track</td>
<td></td>
<td>4.94%</td>
</tr>
<tr>
<td>4 good clusters</td>
<td></td>
<td>0.61%</td>
</tr>
<tr>
<td>$-0.3 &lt; \phi_{\pi^-4\gamma} - \phi_p &lt; 0.3$</td>
<td></td>
<td>0.21%</td>
</tr>
<tr>
<td>Exclusivity ($180 &lt; E_{\pi^-4\gamma} &lt; 200$ GeV)</td>
<td></td>
<td>0.10%</td>
</tr>
</tbody>
</table>

\[
\sqrt{(m_{\gamma_1\gamma_2} - m_{\pi^0})^2 + (m_{\gamma_3\gamma_4} - m_{\pi^0})^2} < 25 \text{ MeV} \quad 69.78\% \text{ of excl. events}
\]

\[
2\pi^0 \text{ 2C CL > 10\% (}\pi^0\text{ mass)} \quad 27.39\% \text{ of excl. events}
\]

\[
\sqrt{(m_{\gamma_1\gamma_2} - m_{\eta})^2 + (m_{\gamma_3\gamma_4} - m_{\eta})^2} < 25 \text{ MeV} \quad 0.17\% \text{ of excl. events}
\]

\[
2\eta \text{ 2C CL > 10\% (}\eta\text{ mass)} \quad 0.13\% \text{ of excl. events}
\]
Two and three-body inv. masses in the $4\gamma$ channel

- $\pi^0(1800)$, $\pi_2(1880)$
- $f_0(1500)$
- $a_1(980)$, $a_2^*(1320)$
Production mechanisms

At 190 GeV incoming beam energy two compelling mechanisms for the production process of a state X are possible:

- as a product of the decay of a diffractively produced state Y: \( \pi^- p \rightarrow Y p, Y \rightarrow \pi^- X, X \rightarrow \eta \eta \)
- centrally produced via Double Pomeron Exchange: \( \pi^- p \rightarrow \pi^-_{fast} X p, X \rightarrow \eta \eta \)

\( x_f \) and rapidities overlap: both processes have to be fitted simultaneously!
Amplitude Ansatz for the decay process

- Amplitude (isobar model):
  \[ A_f^J = G_A e^{i\delta_A} F_J(q) \]
  \[ Y_f^J(\alpha, \beta) \]
  \[ m_0^2 - s - i m_0 \Gamma(m) \]

- Blatt-Weisskopf barrier factors
- Angular part: spherical harmonics, decay angles \( \alpha, \beta \) after "Wick rotations" (no D-functions needed).
- Relativistic Breit Wigner

\[ \Gamma(m) = \Gamma_0 \left( \frac{m_0}{m}, \frac{q}{q_0}, \frac{F_J^2(q)}{F_J^2(q_0)} \right) \]

\[ w(m, m_0, m_1) = \sum_\lambda \left[ |A_{XJ}^J(m, m_0)|^2 + |A_{YJ'}^J(m, m_1)|^2 + 2 c_\lambda \Re(A_{XJ}^J(m, m_0) A_{YJ'}^J(m, m_1)) \right] \]
Amplitude Ansatz for the decay process

- **Amplitude (isobar model):**
  \[ A_f^A = G_\lambda e^{i\delta_\lambda} F_J(q) \yn Y_J^\lambda(\alpha,\beta) \yn m_0^2 - s - im_0 \Gamma(m) \]

- **Blatt-Weisskopf barrier factors**
  - Angular part: spherical harmonics, decay angles \( \alpha, \beta \) after "Wick rotations" (no D-functions needed).
  - Relativistic Breit Wigner

- Mass of the two-body system
- Break-up momentum
- Intensity with two resonances with masses \( m_0 \) and \( m_1 \), spin \( J \) and \( J' \):
  \[ w(m,m_0,m_1) = \sum_\lambda \left[ |A_{XJ}^\lambda(m,m_0)|^2 + |A_{YJ'}^\lambda(m,m_1)|^2 + 2 \Re(A_{XJ}^\lambda(m,m_0)A_{YJ'}^\lambda(m,m_1)) \right] \]

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- Amplitude (isobar model):
  \[ A_J^\lambda = G_\lambda e^{i\delta_\lambda} F_J(q) \]
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  \[ m_0^2 - s - im_0\Gamma(m) \]

- Blatt-Weisskopf barrier factors

- Angular part: spherical harmonics, decay angles \( \alpha,\beta \) after "Wick rotations" (no D-functions needed).

- Relativistic Breit Wigner

\[ w(m,m_0,m_1) = \sum_{J} |A_J^X(m,m_0)|^2 + |A_{J'}^X(m,m_1)|^2 + 2 \text{Re}(A_J^X(m,m_0)A_{J'}^X(m,m_1)) \]
Amplitude Ansatz for the decay process

- Amplitude (isobar model):
  \[ A^\lambda J^f = G^\lambda e^{i\delta^\lambda} F_f(q) Y^\lambda_J(\alpha, \beta) \]
  \[ m^2_0 - s - i m_0 \Gamma(m) \]

- Blatt-Weisskopf barrier factors

- Angular part: spherical harmonics, decay angles \( \alpha, \beta \) after "Wick rotations" (no D-functions needed).

- Relativistic Breit Wigner

- Resonance mass dependent width
  \[ \Gamma(m) = \Gamma_0 \left( \frac{m_0}{m} \right)^2 \frac{q}{q_0} \left( \frac{F^2_f(q)}{F^2_f(q_0)} \right) \]

- Mass of the two-body system

- Break-up momentum

- Intensity with two resonances with masses \( m_0 \) and \( m_1 \), spin \( J \) and \( J' \):
  \[ w(m, m_0, m_1) = \sum_{\lambda} \left[ |A^\lambda_{XJ} (m, m_0)|^2 + |A^\lambda_{YJ'} (m, m_1)|^2 + 2 c_\lambda \Re(A^\lambda_{XJ} (m, m_0) A^\lambda_{YJ'} (m, m_1)) \right] \]
Amplitude Ansatz for the decay process

- Amplitude (isobar model):
  \[ A^4_J = G_\lambda e^{i\delta_\lambda} F_J(q) \]
  \[ Y^\lambda_J(\alpha, \beta) \]
  \[ m_0^2 - s - im_0 \Gamma(m) \]

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- Resonance mass dependent width

\[ \Gamma(m) = \Gamma_0 \left( \frac{m_0}{m} \frac{q}{q_0} \frac{F^2_J(q)}{F^2_J(q_0)} \right) \]

- Mass of the two-body system
- Break-up momentum

\[ w(m, m_0, m_1) = \sum_\lambda \left( |A^4_{\lambda J}(m, m_0)|^2 + |A^4_{\lambda J'}(m, m_1)|^2 + 2 \Re(A^4_{\lambda J}(m, m_0)A^4_{\lambda J'}^*(m, m_1)) \right) \]
Amplitude Ansatz for the decay process

- Amplitude (isobar model):
  \[ A^λ_J = G^λ e^{iδ^λ} F^J(q) \]
  \[ Y^λ_J(α,β) \]
  \[ m_0^2 - s - im_0Γ(m) \]

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- Angular part: spherical harmonics, decay angles \( α, β \) after "Wick rotations" (no D-functions needed).
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- Resonance mass dependent width
  \[ Γ(m) = Γ_0 \left( \frac{m_0}{m} \frac{q}{q_0} \frac{F^2_0(q)}{F^2_0(q_0)} \right) \]

- Mass of the two-body system
- Break-up momentum

\[ w(m, m_0, m_1) = \sum_4 \left[ |A^4_J(m, m_0)|^2 + |A^4_J(m, m_1)|^2 + 2 |A^4_J(m, m_0)A^4_J(m, m_1)| \right] \]
Amplitude Ansatz for the decay process

- Amplitude (isobar model):

\[ A_f^J = G_\lambda e^{i\delta_\lambda} F_J(q) \]

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\[ w(m, m_0, m_1) = \sum_\lambda |A_{X_f}^J(m, m_0)|^2 + |A_{Y_J'}^J(m, m_1)|^2 + 2 |\Re(A_{X_f}^J(m, m_0)A_{Y_J'}^J(m, m_1))| \]
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Intensity with two resonances with masses \( m_0 \) and \( m_1 \), spin \( J \) and \( J' \):
\[
  w(m, m_0, m_1) = \sum_\lambda |A^\lambda_X_f (m, m_0)|^2 + |A^\lambda_{Y_f'} (m, m_1)|^2 + 2 c_\lambda \Re(A^\lambda_X_f (m, m_0) A^{\dagger}_{Y_{f'}'} (m, m_1))
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- Relativistic Breit Wigner

- Resonance mass dependent width

\[ \Gamma(m) = \Gamma_0 \left( \frac{m_0}{m} \right) Q \left( \frac{q}{q_0} \right) \frac{F_J^2(q)}{F_J^2(q_0)} \]

- Mass of the two-body system

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\[ w(m, m_0, m_1) = \sum_\lambda \left| A_j^{\lambda, (m, m_0)} \right|^2 + \left| A_{J'}^{\lambda, (m, m_1)} \right|^2 + 2 c_\lambda \Re(A_j^{\lambda, (m, m_0)}A_{J'}^{\lambda, (m, m_1)}) \]

\( c_\lambda \) spin component along \( z \), \(-1 \leq c_\lambda \leq 1 \) degree of coherence.

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  \[ A^J_{\lambda} = G_\lambda e^{i\delta_\lambda} F_J(q) Y^\lambda_J(\alpha, \beta) \]

- Blatt-Weisskopf barrier factors
- Angular part: spherical harmonics, decay angles $\alpha, \beta$ after "Wick rotations" (no D-functions needed).
- Relativistic Breit Wigner
- Resonance mass dependent width

\[ \Gamma(m) = \Gamma_0 \left( \frac{m^2}{m_0^2} - s - i m_0 \Gamma(m) \right) \]

- Mass of the two-body system
- Break-up momentum

- Intensity with two resonances with masses $m_0$ and $m_1$, spin $J$ and $J'$:
  \[ w(m, m_0, m_1) = \sum_\lambda |A^J_{XJ}(m, m_0)|^2 + |A^J_{YJ'}(m, m_1)|^2 + 2 c_\lambda \Re(A^J_{XJ}(m, m_0)A^{J*}_{YJ'}(m, m_1)) \]

- $\lambda$ spin component along $z$, $-1 \leq c_\lambda \leq 1$ degree of coherence
Minimization of total intensity of the negative log-likelihood:

\[-\ln \mathcal{L} = \left( - \sum_{j=1}^{N} \ln w_j \right) + N \ln \left( \sum_{i=1}^{M} w_i \right)\]
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  \(M\): number of MC events
  Well established resonance parameters fixed at PDG values.
  \(G_\lambda, \delta_\lambda, c_\lambda\): free parameters of the fit
  With this definition, and for a fixed set of parameters, a reduction of \(\ln L\) by 0.5 is statistically significant and corresponds to one standard deviation in mass and width optimizations.
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Disadvantages:

- Computing limitations (presently fast convergence only for < 100K events).
- Additional mass and width scans for all possible spin combination of all unknown resonances needed.
Conclusion and outlook

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- The rest of 2008 and all of the 2009 data will added to the final sample.
Simulation of the production of a diffractive $X$ in $\pi^- p \rightarrow X p$ with $X \rightarrow \pi^- \eta$

- $M_X$ uniformly from $m_\pi + m_\eta$ to 3.5 GeV
- $t_X$ as $e^{-bt}$ with $b = 6 \text{ GeV}^{-2}$ with $0 < t < 1 \text{ GeV}^2$. To take into account a resonance dependent production mechanism the shape of the $t$-distribution will be optimized from the data in different mass ranges around the resonance masses.
- $\phi_X(\phi_p)$ uniformly from 0 to $2\pi$

$$1 - x_X = \frac{M_X^2 - m_{\pi^-}^2}{s}$$

$$p_{T,X}^2 = -t_X$$
Simulation of the production of a central $X$ in $\pi^- p \rightarrow X p$ with $X \rightarrow \eta \eta$

- $M_X$ uniformly from $2m_\eta$ to 3.5 GeV
- $t_X$ as $e^{-bt}$ with an average $b = 6$ GeV$^{-2}$ with $0 < t < 1$ GeV$^2$. The optimization of a resonance dependent $t$-distribution will be obtained from the data.
- Flat rapidity distribution $-1 < y(X) < 1$
- $\phi_X(\phi_p)$ uniformly from 0 to $2\pi$

\[ M_X^2 = -x_{P_1} x_{P_2} s \]

$x_{P_2} = 1 - x_\pi$ on the $\pi$ side, $x_{P_1} = x_p - 1$ on the $p$ side

In the center of mass

\[ x_p + x_\pi + x_X = 0 \]

\[ x_X = M_T \frac{e^y - e^{-y}}{\sqrt{s}} = \frac{2M_T \sinh y_{cm}}{\sqrt{s}} \]

Solution:

\[ x_{P_1} = \frac{M_T}{\sqrt{s}} \left[ \pm \sqrt{\left( \frac{M_X}{M_T} \right)^2 + (\sinh y)^2 + \sinh y} \right] . \]
**Definition of angles for a diffractive $X$ in $\pi^- p \rightarrow \pi^- X p$, $X \rightarrow \pi^- \eta p$:**

- The $z$ axis is defined in the $\pi p$ c.m. frame. The $x, y$ axes are defined by the angle formed by the production plane and the decay plane.

- The Wick rotation by angles $-\phi$ and $\theta$ to the direction of flight of the diffractive $X$ are followed by a Lorentz boost to the its rest frame ($x', y', z'$) and by another rotation by $-\theta$ and $-\phi$ so that the direction of the new reference frame $x'', y'', z''$ correspond to one of $x, y, z$.

- $\alpha, \beta$ define the direction of one $\eta$ in the rest frame of $X$ after the Wick rotations. The effect of the Lorentz boost is to leave the $\eta$ with final momenta different from those in the overall $\pi p$ rest frame.

**The angles $\alpha, \beta$ obtained in this reference frame after Wick rotations enter in the decay amplitude definition:**

$$ A_j^\lambda = G_\lambda e^{i\delta_\lambda} F_j(q) \frac{Y_j^\lambda(\alpha, \beta)}{m_0^2 - s - im_0 \Gamma(m)} $$