Single Meson Production in Proton Diffraction

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Institutsseminar Kernphysik
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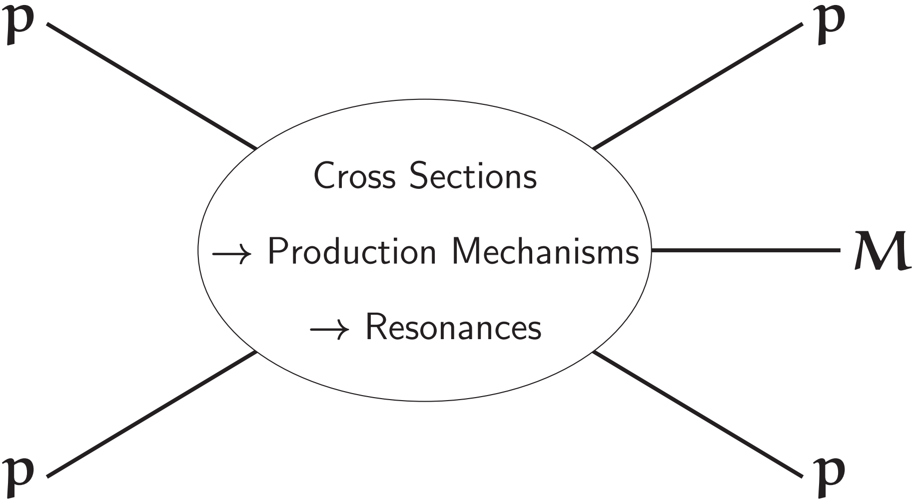
Motivation



Outline

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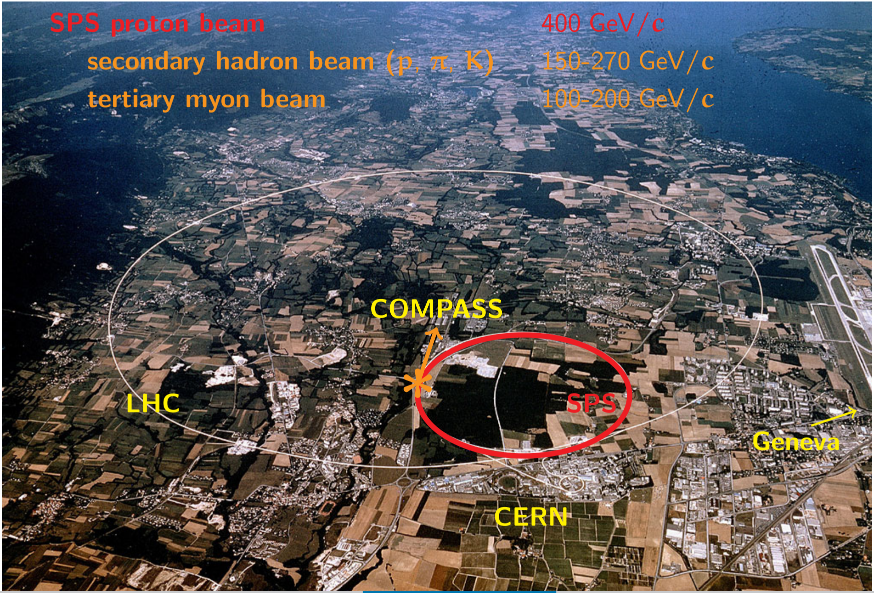
The COMPASS Experiment



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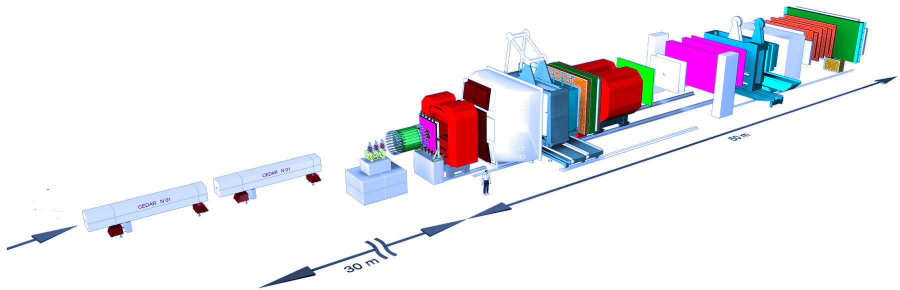
- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Two-stage spectrometer, $0.4° \leq \theta \leq 12°$



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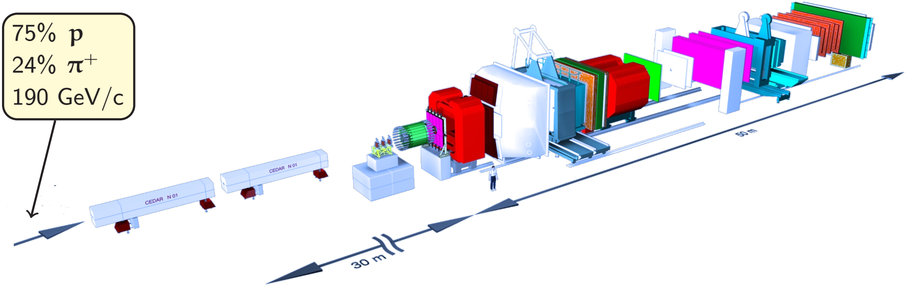

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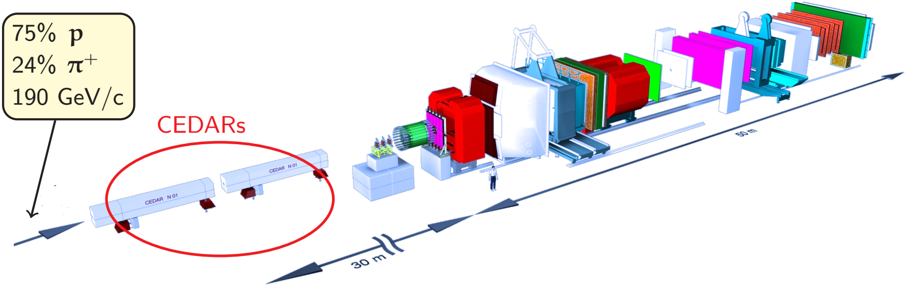

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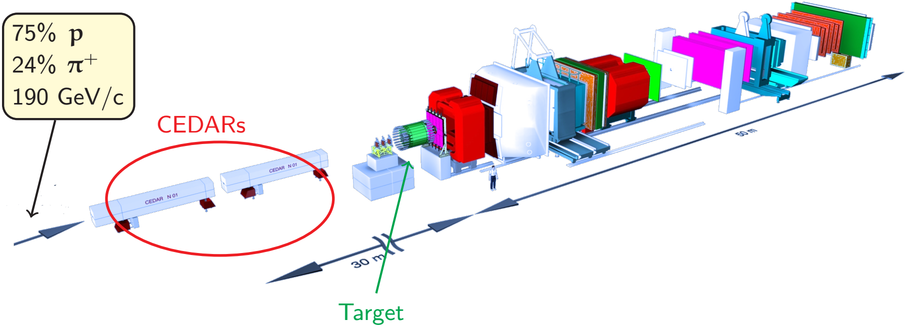

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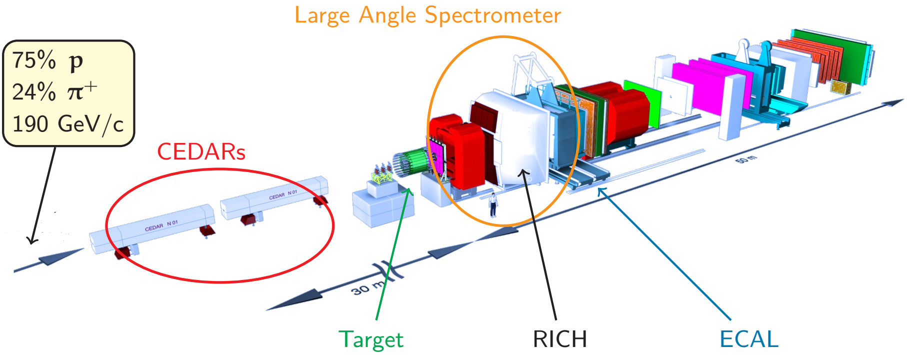

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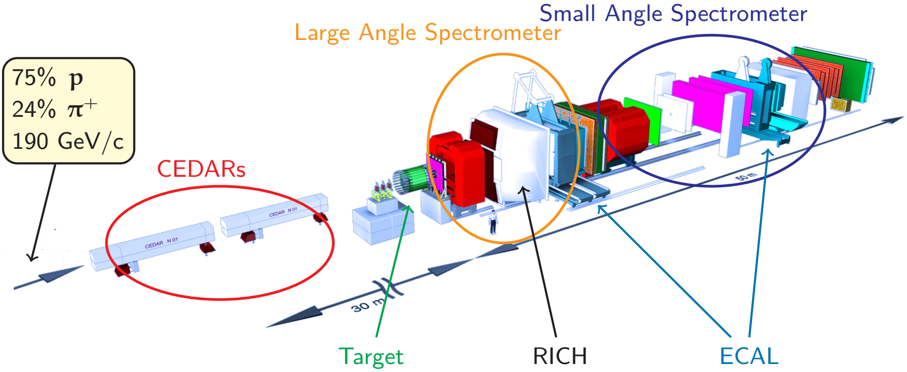

Outline

Introduction

- 2009 data taking
- 190 GeV/c proton beam on liquid hydrogen target
- diffractive dissociation

→ no isospin exchange

- Different channels investigated:
  - $pp \rightarrow p_f \pi^0 p_{\text{recoil}}$
  - $pp \rightarrow p_f \eta p_{\text{recoil}}$
  - $pp \rightarrow p_f \omega p_{\text{recoil}}$
  - $pp \rightarrow p_f \phi p_{\text{recoil}}$

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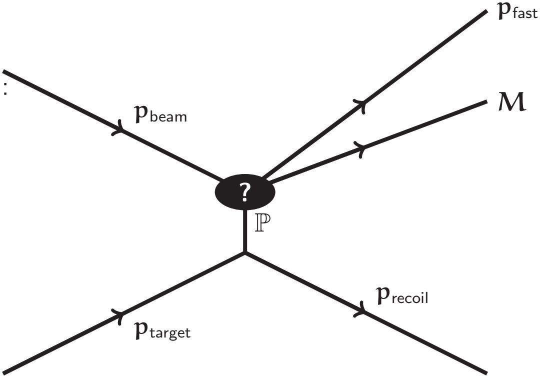

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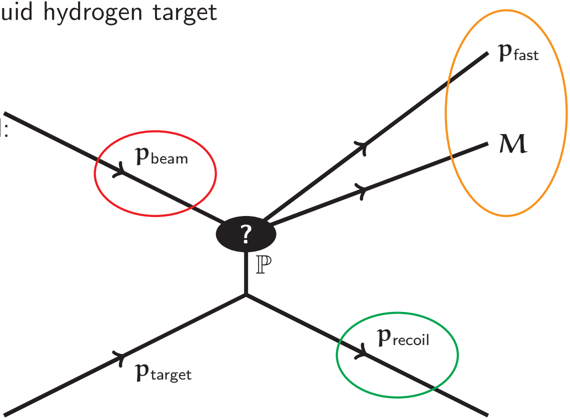


Selecting Exclusive Events

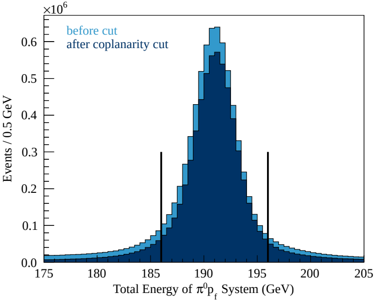
Use energy and momentum conservation to select exclusive events

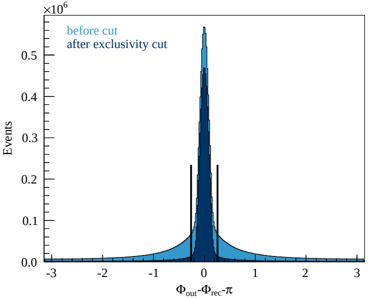
Energy conservation = Exclusivity

energy sum of outgoing particles = beam energy

Momentum conservation = Coplanarity

beam has no transverse momentum
$\rightarrow$ azimuthal angles of outgoing system and recoil proton differ by π





Event Selection

Basic Cuts

- minimum bias trigger
  - incoming beam + recoiling proton
- exactly 1 primary vertex reconstructed inside the target
- identified incoming proton
- 1 reconstructed recoil proton
- $\approx 4 \times 10^9$ events at this stage

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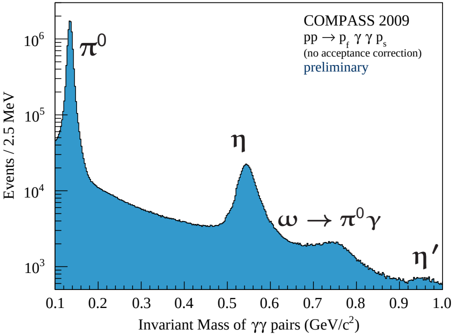
Selection of $\pi^0/\eta \to \gamma\gamma$

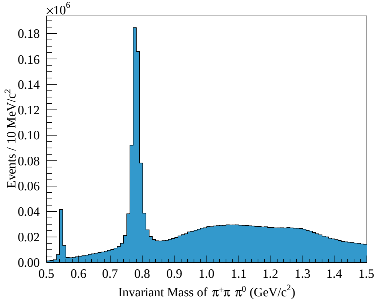
- 1 outgoing charged particle with positive charge
- 2 ECAL clusters
  - Combined to a π^0 or η
- 8.8M π^0 events, 440k η events



Event Selection

Selection of ω

- $\omega \to \pi^+\pi^-\pi^0$
- 3 outgoing charged particles with positive charge sum
- 2 ECAL clusters
  - Combined to a π^0
- positively charged particle identified as pion



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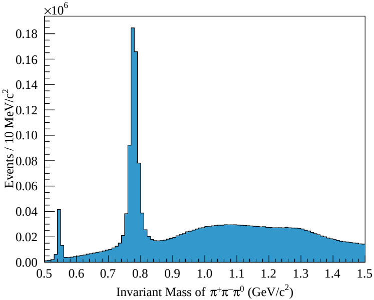
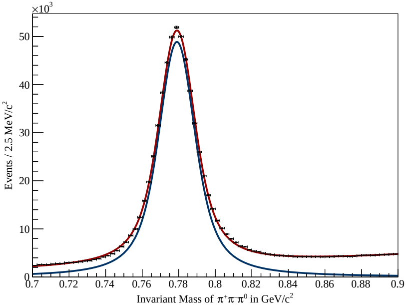
- Fit peak + background
  - peak = Breit-Wigner $*$ Gauß
  - bkg = polynomial degree 3
- 600k ω events

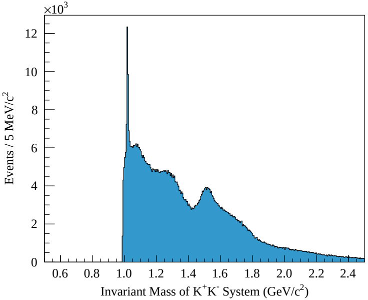




Event Selection

Selection of ϕ

- $\phi \rightarrow K^+K^-$
- 3 outgoing charged particles with positive charge sum
- positively charged particle identified as kaon

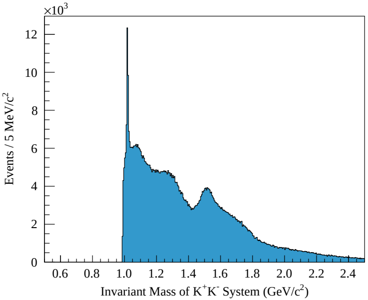


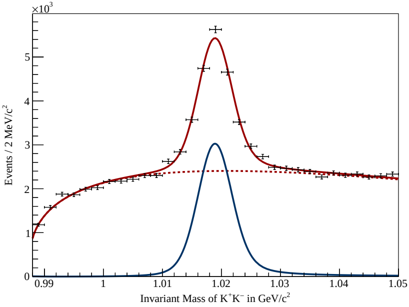
Event Selection

Selection of ϕ

- $\phi \rightarrow K^+K^-$
- 3 outgoing charged particles with positive charge sum
- positively charged particle identified as kaon

- Fit peak + background
  - peak = rel. Breit-Wigner $*$ Gauß
  - bkg = $(m_{KK} - m_{\text{thr}})^n \exp\left[-\alpha(m_{KK} - m_{\text{thr}})\right]$
- 12k ϕ events





Acceptance Correction

Determination of cross sections $\rightarrow$ Experimental acceptance needed

- Produce Monte-Carlo events of $\mathbf{pp} \rightarrow \mathbf{ppX}$
- Run detector simulation and event reconstruction
- Run reconstructed events through event selection
- Acceptance $=$ processed events / generated events
  as a function of kinematic variables
- Correct distributions event by event

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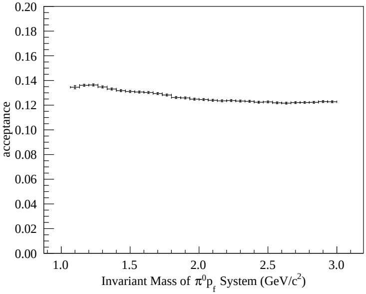
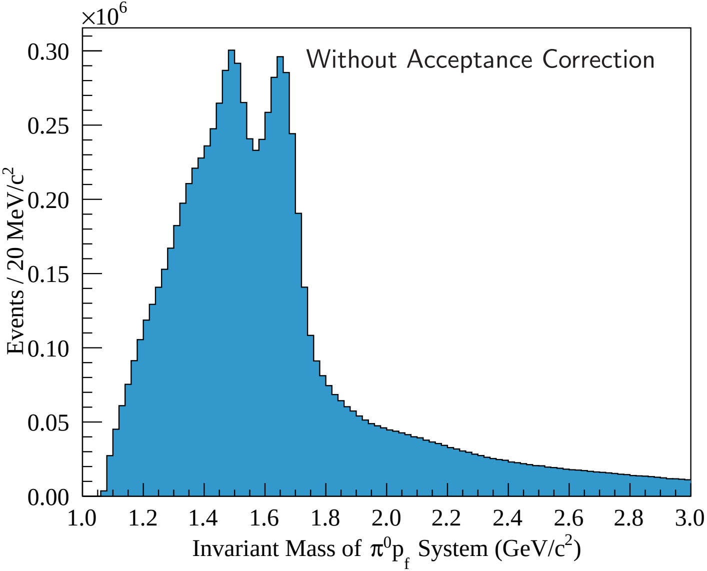


Example:

- Acceptance as a function of $\mathbf{M_{p\pi^0}}$
- Smooth, no complicated structures
- $\approx$ 13%

Final Goal: Understand $p\pi^0$ Mass Spectrum



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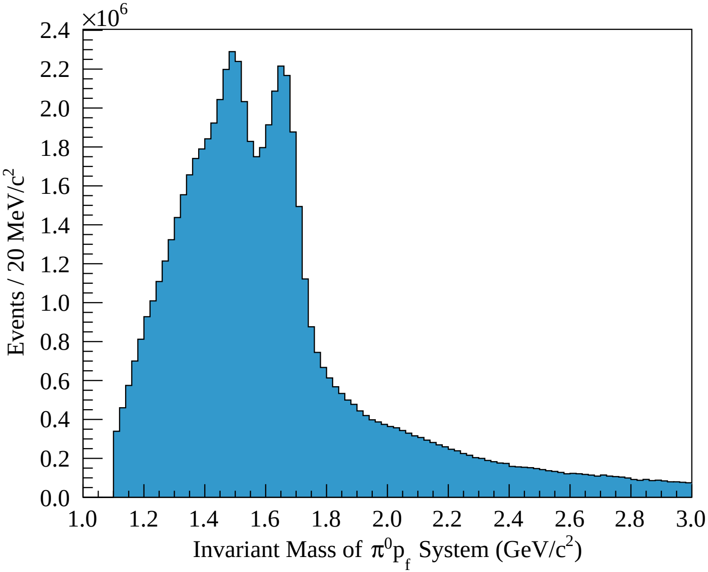

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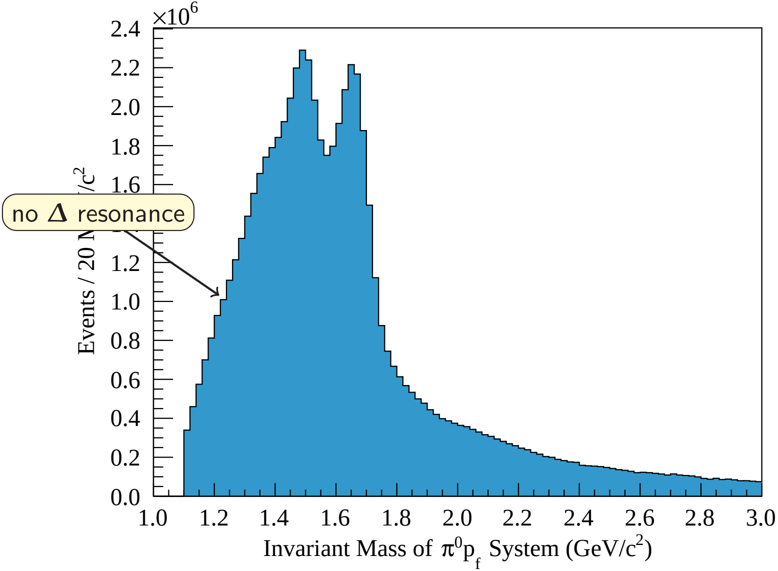

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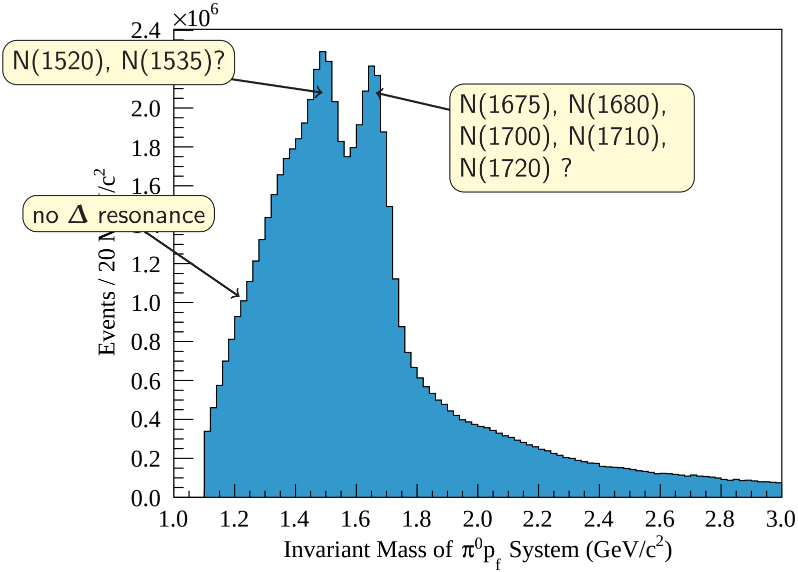

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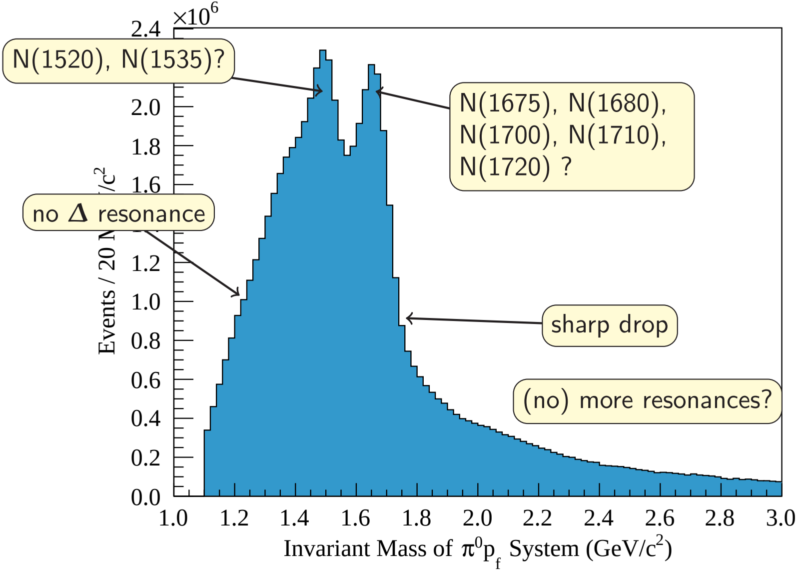
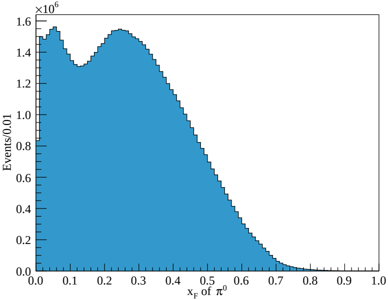


Kinematic Variables – Feynman Variable x_F

$$x_F = \frac{2p_L(M)}{\sqrt{s}} \approx \left(\frac{p_z(M)}{p_z(\text{beam})}\right)_{\text{CMS}}$$

longitudinal momentum relative to the beam in centre-of-mass system

$-1 < x_F < 1$, negative values outside of COMPASS acceptance



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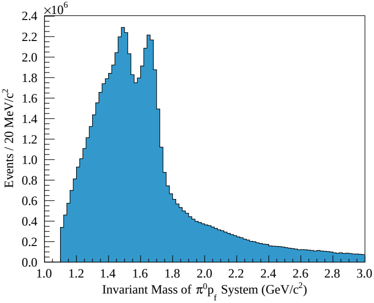
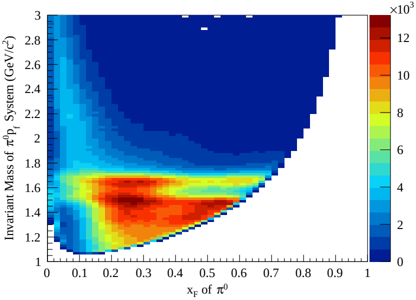
$-1 < x_F < 1$, negative values outside of COMPASS acceptance
connection to production mechanisms





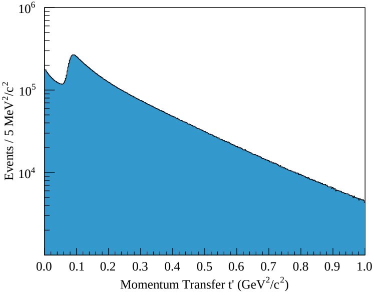
Kinematic Variables – Momentum Transfer t'

Momentum transfer t:

$$t = -(p_{p\pi^0} - p_{\text{beam}})^2$$

Subtract minimal required momentum transfer t_{min} to produce final state:

$$t_{\text{min}} = \frac{(M_{p\pi^0}^2 - m_p^2)^2}{4p_{\text{beam}}^2}$$



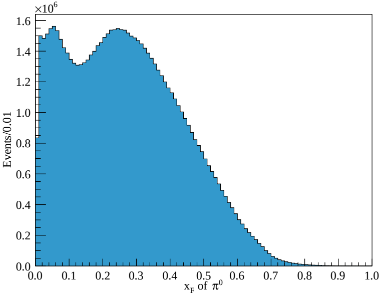
Outline

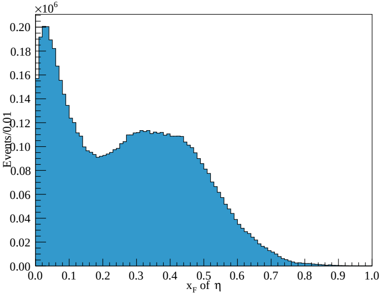
Comparison of π^0 and η production

- Corrected for acceptance
- Corrected for branching fractions

$$\pi^0 \to \gamma\gamma \qquad \text{BR} = 98.823(34)\%$$
$$\eta \to \gamma\gamma \qquad \text{BR} = 39.31(20)\%\,.$$

- Compare in bins of $x_F(M)$ and momentum transfer t'





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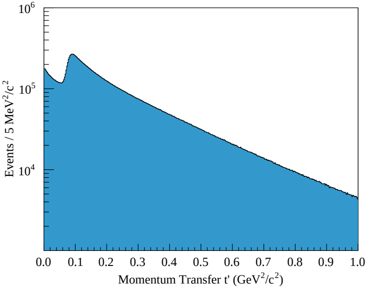
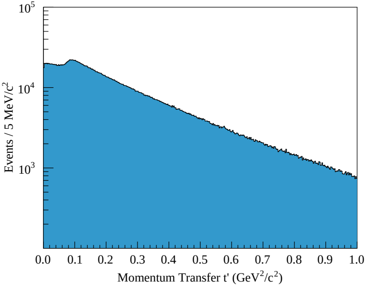
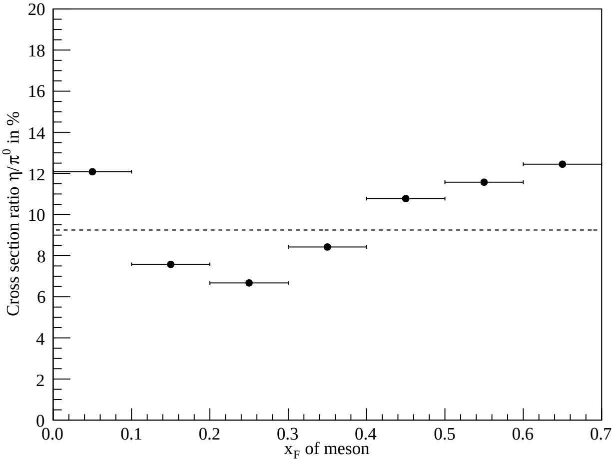




Ratio in Bins of x_F



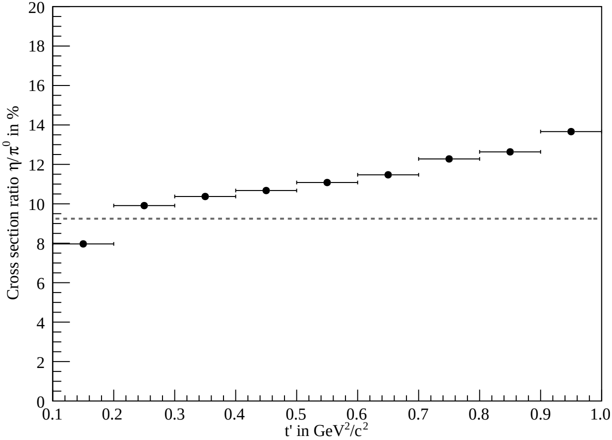
Ratio depends strongly on x_F, probably connected to resonances
Average value: $\sigma(\eta)/\sigma(\pi^0)$ = 9.245(4)%

Comparison

Ratio η/π^0 has be determined before:

1. WA102 [PLB 427 (1998) 398-402]
   $0.0 < x_F < 0.1$ @ 450 GeV/c: $(7.3 \pm 0.5)\%$
   COMPASS: $(12.08 \pm 0.02)\%$
   disagreement, some cuts unclear
2. NA12/2 [Z.Phys., C43:541, 1989]
   $\pi^- p$ with $0.05 < x_F < 0.20$ @ 300 GeV/c: $(8.3 \pm 1.4)\%$
   COMPASS: $(8.66 \pm 0.02)\%$
   good agreement

Ratio in Bins of t'

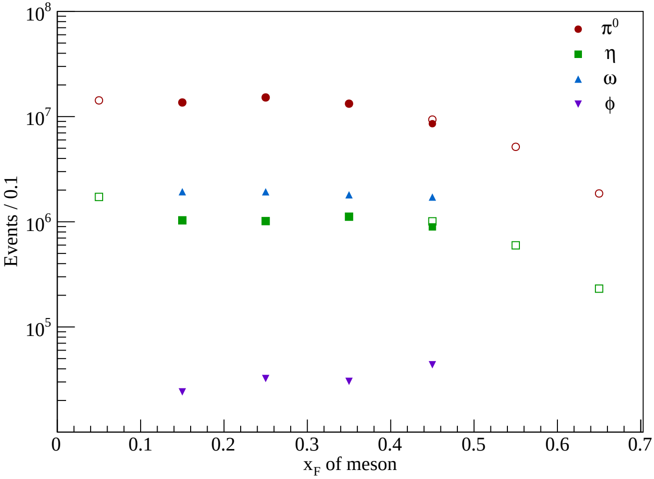


Ratio rises with t'

Average value ($\sigma(\eta)/\sigma(\pi^0) = 9.245(4)\%$) dominated by first bin

Comparison with Vector Mesons

Comparison as a function of $x_F(M)$ with $0.5 < x_F(p) < 0.9$ for ω and ϕ



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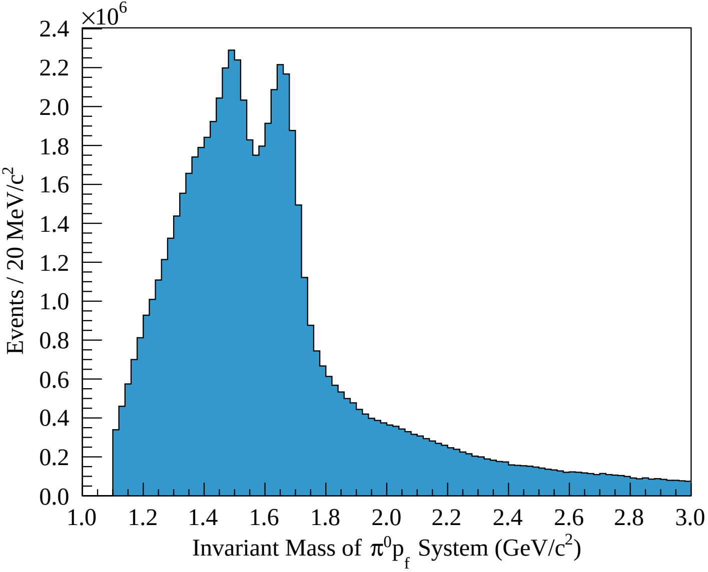

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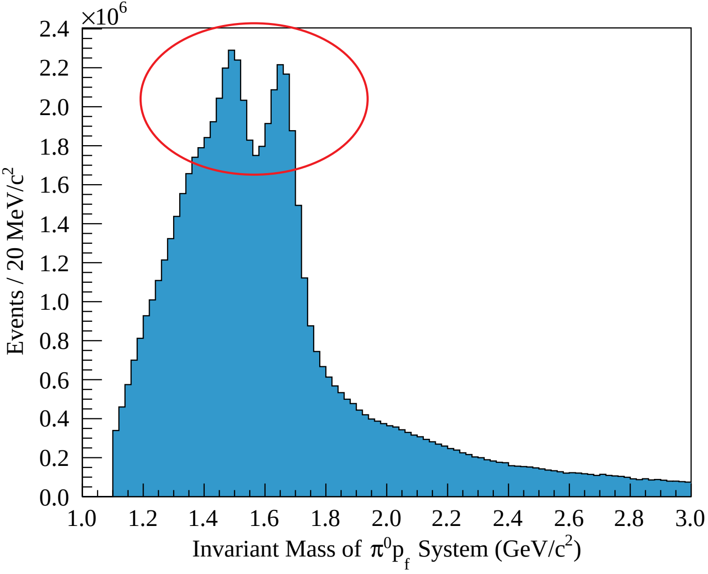
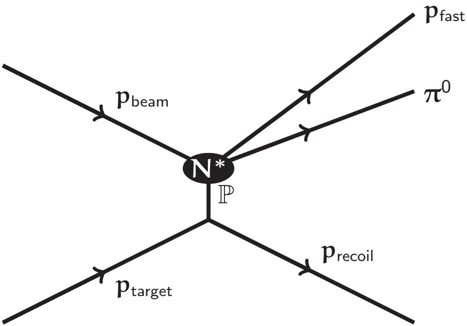


Ansatz for PWA

Full process is complicated



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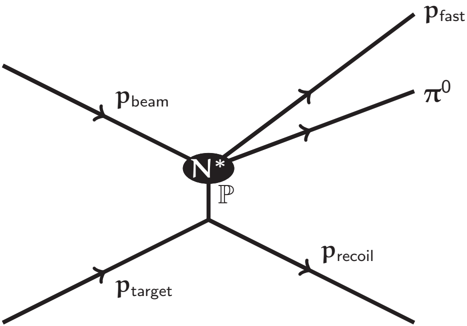


Ansatz for PWA

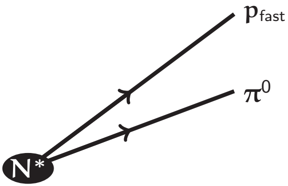
Full process is complicated

$\Longrightarrow$ Use a simple ansatz

- ignore production of resonances
- simple two-body decay $\mathbf{N^* \to p\pi^0}$
- 3 kinematic variables

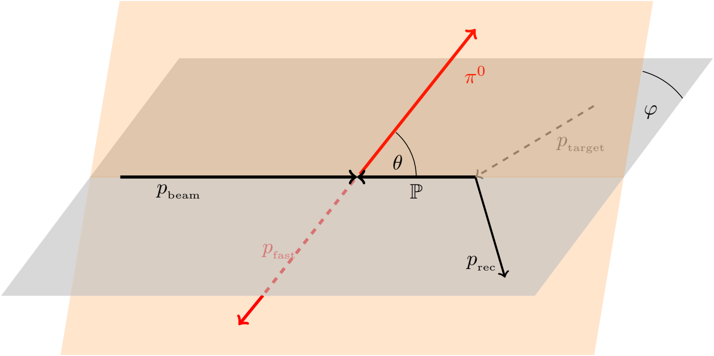
$\rightarrow$ $\mathbf{M_{p\pi^0}}$ and two angles

- no angular dependence of background



Gottfried-Jackson Frame

- z-axis = beam direction
- x-axis = direction of $\mathbf{p}\boldsymbol{\pi}^0$
- boost into $\mathbf{p}\boldsymbol{\pi}^0$ rest frame



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- Intensity ($\propto$ cross section):

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- Decay amplitude:

$$A^{\epsilon,\lambda}_{J^{\mathcal{P}}}(\theta, \varphi; m_X) = \sqrt{2L+1}\left(L0, \tfrac{1}{2}\lambda \middle| JM\right) D^{J,\epsilon}_{M\lambda}{}^{*}(\varphi, \theta, 0) F_L(q)$$

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- Parity: $\mathcal{P}(X) = \mathcal{P}(p) \cdot \mathcal{P}(\pi^0) \cdot (-1)^L = (+1) \cdot (-1) \cdot (-1)^L = (-1)^{L+1}$

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- Parity: $\mathcal{P}(X) = \mathcal{P}(p) \cdot \mathcal{P}(\pi^0) \cdot (-1)^L = (+1) \cdot (-1) \cdot (-1)^L = (-1)^{L+1}$
- Angular functions with reflectivity ϵ:

$$D^{J,\epsilon}_{M\lambda}(\varphi, \theta, 0) = \frac{1}{\sqrt{2}} \left[D^J_{M\lambda}(\varphi, \theta, 0) - \epsilon \cdot \mathcal{P} \cdot (-1)^{J-M} D^J_{-M\lambda}(\varphi, \theta, 0) \right], \quad \epsilon = \pm i$$

Ansatz for PWA

- Resonance with $J^{\mathcal{P}}$ decays into π^0 and proton with helicity λ
- Intensity ($\propto$ cross section):

$$\mathcal{I}(m_X) = \sum_{\epsilon,\lambda} \left| \sum_{J^{\mathcal{P}}} T^{\epsilon}_{J^{\mathcal{P}}} A^{\epsilon,\lambda}_{J^{\mathcal{P}}}(\theta, \varphi; m_X) \right|^2$$

- Resonance shape: $T^{\epsilon}_{J^{\mathcal{P}}} \in \mathbb{C}$
- Decay amplitude:

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- Blatt-Weisskopf barrier factor (angular momentum barrier)

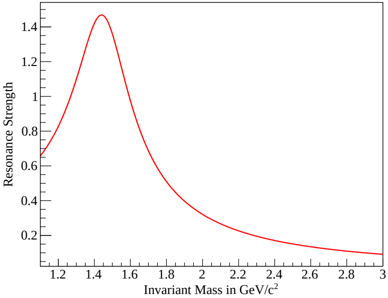
Test on Pseudo Data

- Model for $T_{J^{\mathcal{P}}}$ of shape and phases of the resonances

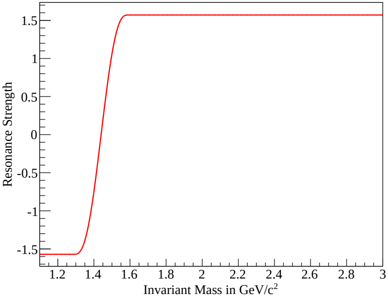
Test on Pseudo Data

- Model for $\mathbf{T}_{\mathbf{J}^{\mathcal{P}}}$ of shape and phases of the resonances

Strength = rel. BW



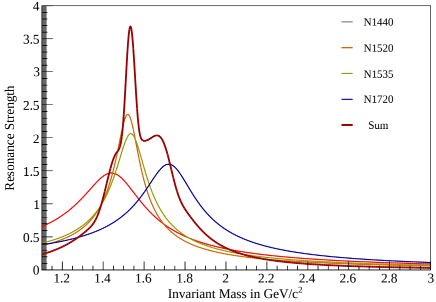
Smooth phase shift

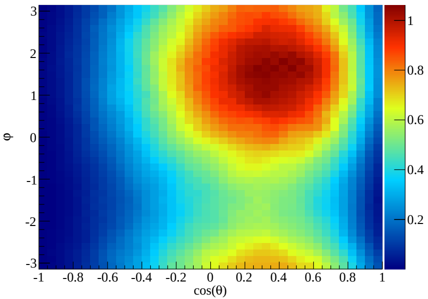


Test on Pseudo Data

- Sample angular distributions in 76 mass bins of 25 MeV
- 40×40 bins in $\cos(\theta)$ and ϕ
- Gaussian smearing:

$$\mathbf{N_i} = \text{RandGauss}(\mathbf{N_i}, \sqrt{\mathbf{N_i}})$$





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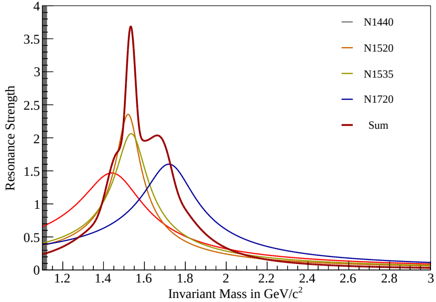
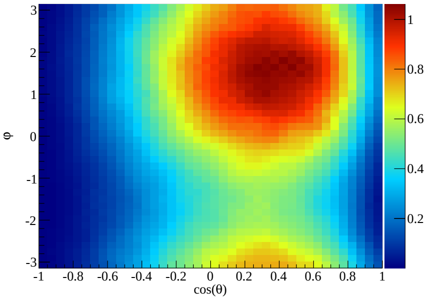
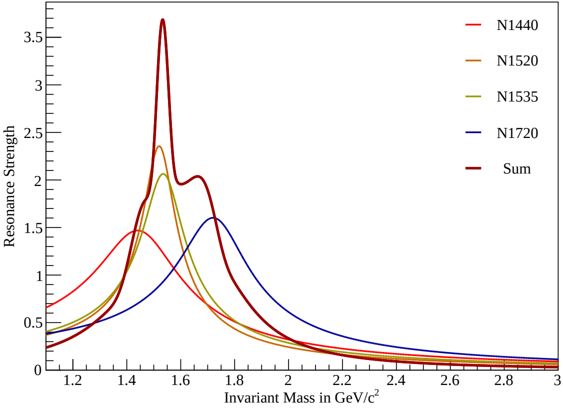




Example Result I

- 4 resonances up to $J = \frac{3}{2}$
- fit angular distributions in 76 bins to get $T_{J^{\mathcal{P}}}$
- take fit with best χ^2 out of 20 attempts



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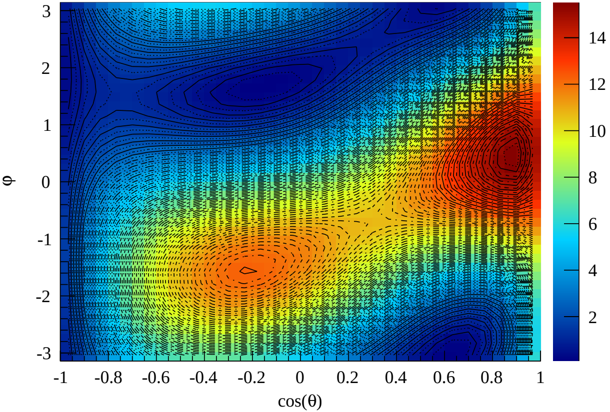

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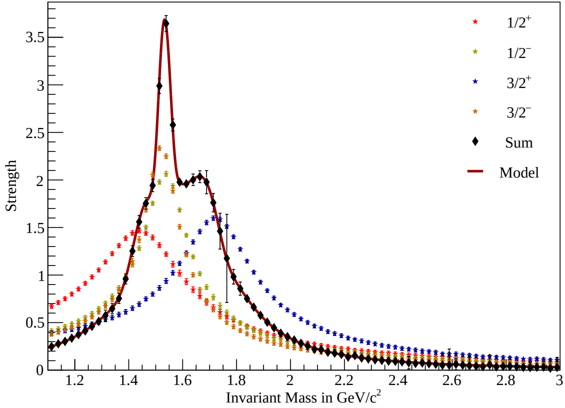

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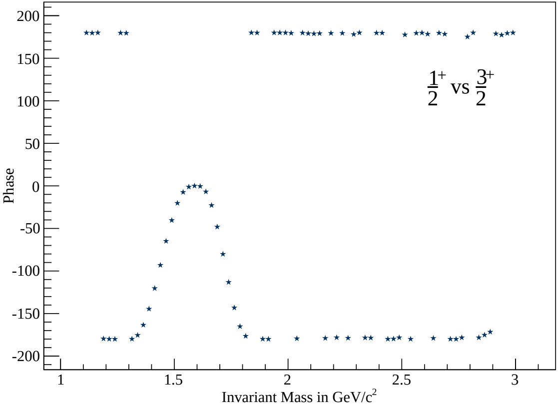

Fit Attempt on Real Data

- same fit program as in the tests
- allow resonances up to $\mathbf{J} = \frac{9}{2}$
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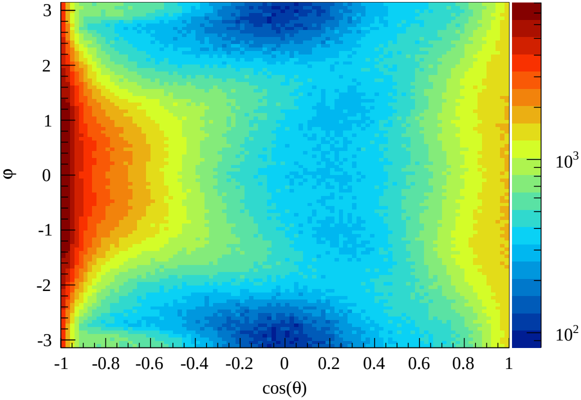

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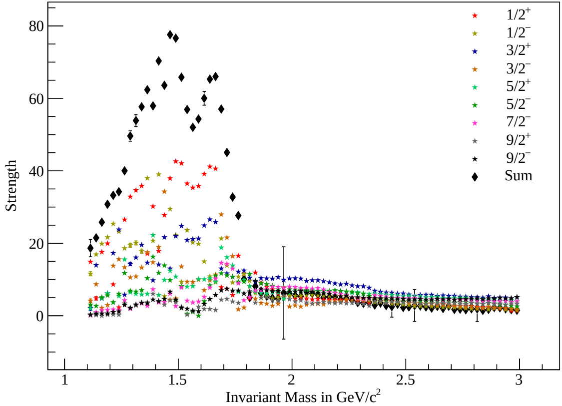

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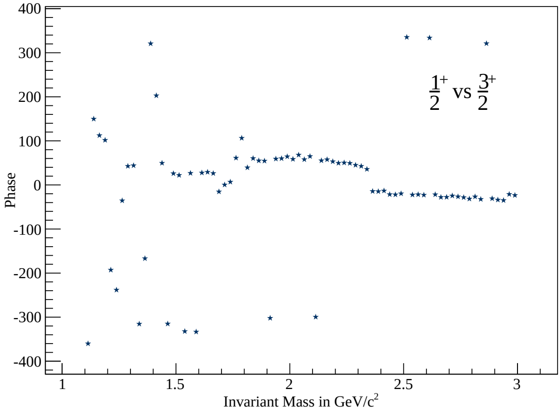

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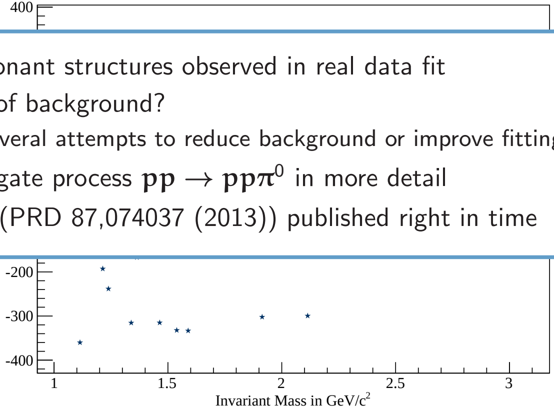


- no resonant structures observed in real data fit
- effect of background?
  - several attempts to reduce background or improve fitting

→ investigate process $\mathbf{pp} \to \mathbf{pp}\pi^0$ in more detail

- Paper (PRD 87,074037 (2013)) published right in time

Outline

The COMPASS Experiment

Event Selection for $\mathbf{pp} \to \mathbf{pp}M$

Cross Section Ratios for Meson Production

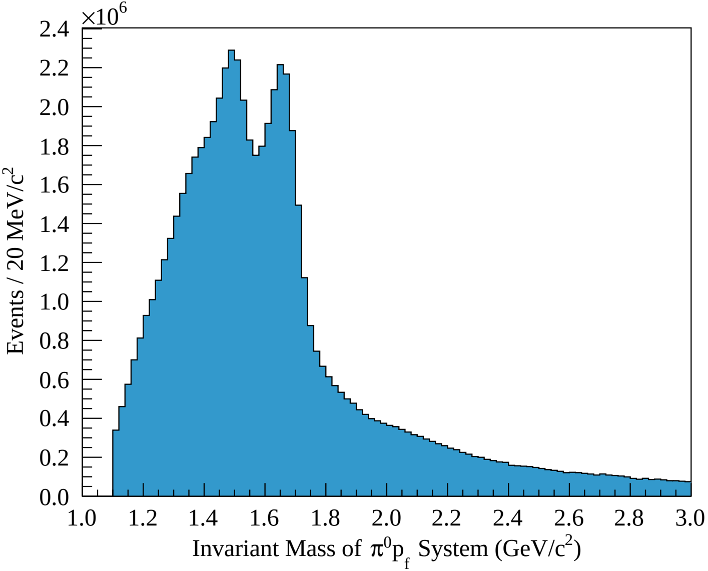
Partial Wave Analysis for $\mathbf{pp} \to \mathbf{pp}\boldsymbol{\pi}^0$ I

Production Mechanisms in $\mathbf{pp} \to \mathbf{pp}\boldsymbol{\pi}^0$

Partial Wave Analysis for $\mathbf{pp} \to \mathbf{pp}\boldsymbol{\pi}^0$ II

Conclusion and Outlook

Goal: Understand $\mathbf{p}\boldsymbol{\pi}^0$ Mass Spectrum



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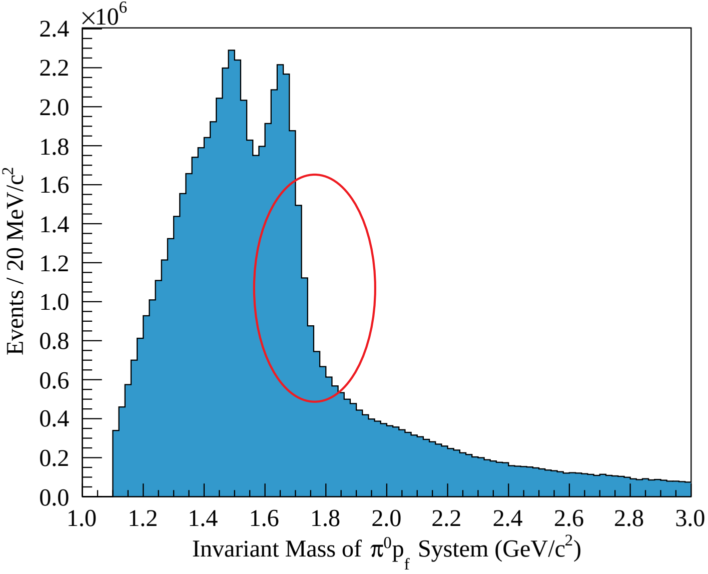
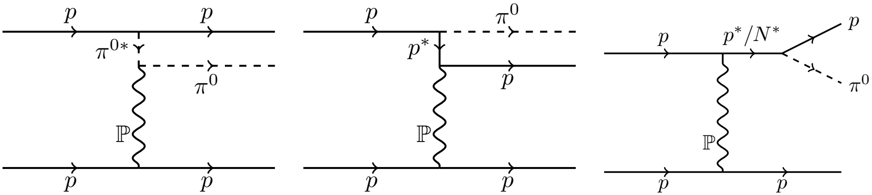


Production Mechanisms in $\mathbf{pp \to pp\pi^0}$

Main process: diffractive bremsstrahlung (Drell-Hiida-Deck)

- pion rescattering (central production)
- proton exchange
- direct production (+ resonances)



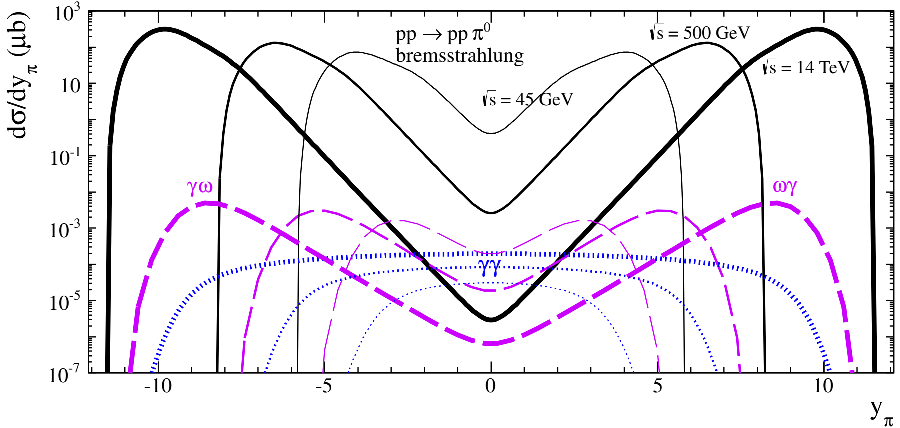
Further processes:

- $\gamma\gamma$ fusion
- $\gamma\omega^*$ fusion
- odderon exchange

Production Mechanisms in $pp \to pp\pi^0$

Differential cross section over rapidity of the pion

$$y_\pi = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$



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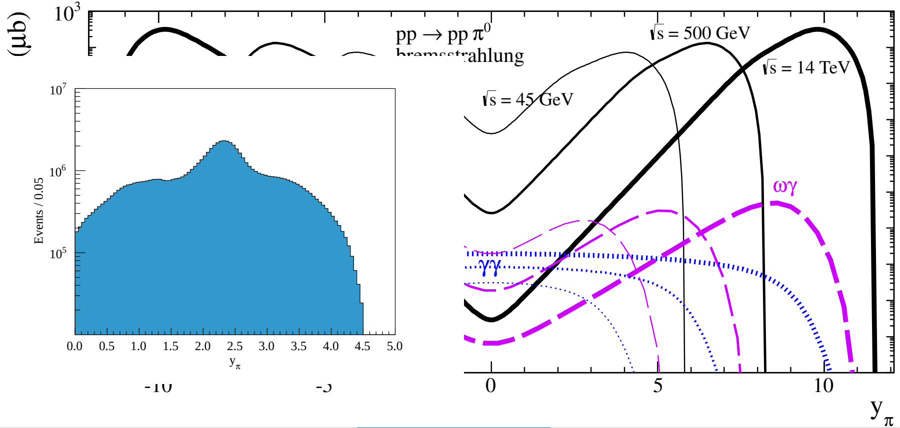

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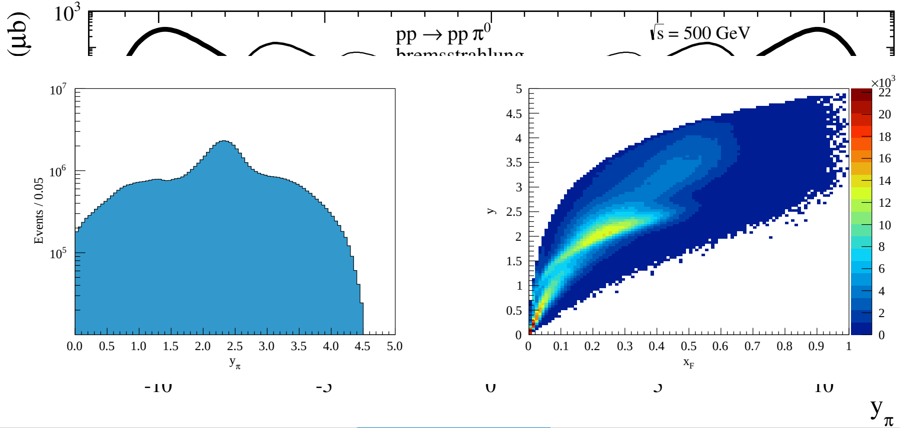
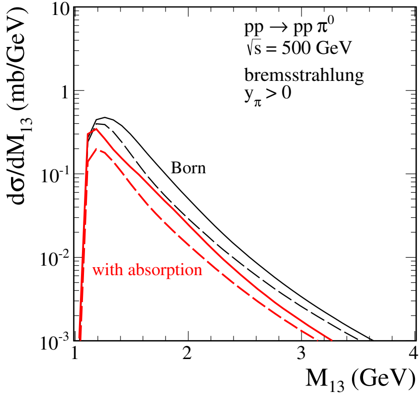
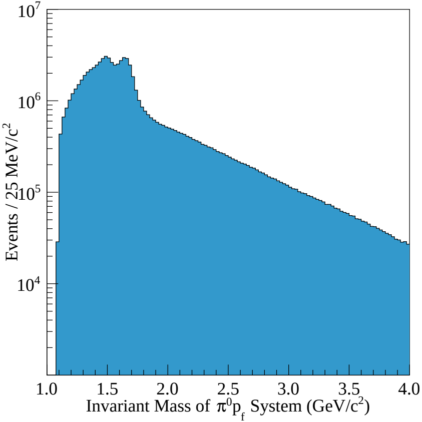


Comparison of Calculation and Data

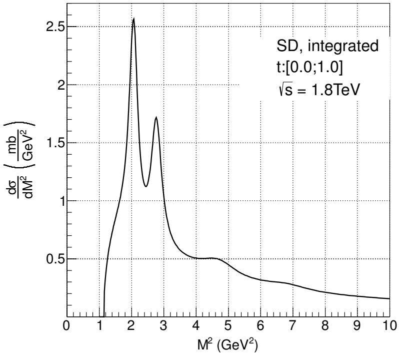


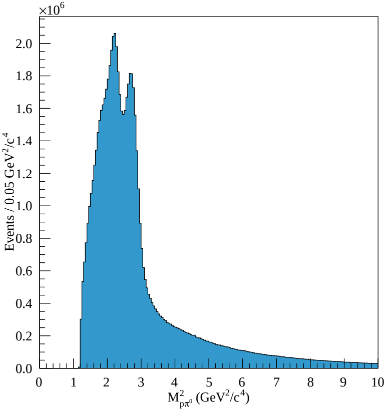


- exponential decline predicted by theory calculation
- resonances on top of background
  - → not included in calculation

Resonances in Theory Calculation

- calculation of resonances (N1440, N1680, N2220, N2700) based on LHC data
- shape of mass spectrum similar to data

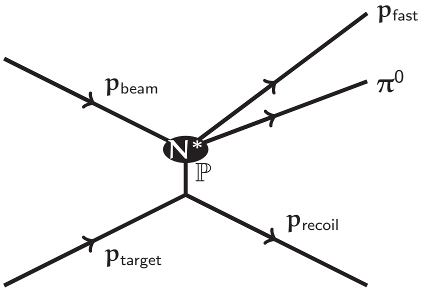




[Phys.Atom.Nucl. 77(12):1463-1474, 2014, hep-ph/1211.5841]

Outline

Basic Ideas of the Model



- Model full process
  - Pomeron exchange between protons
  - Formation of resonance
  - Decay of resonance

$\longrightarrow$ 5 kinematic variables

- Complicated model $\rightarrow$ unbinned maximum likelihood
- Acceptance $\rightarrow$ extended likelihood formalism

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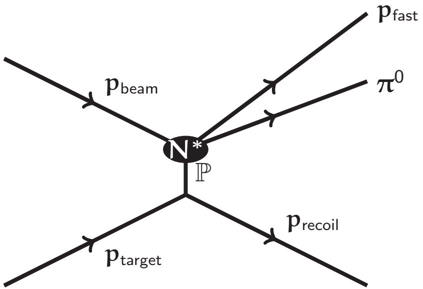

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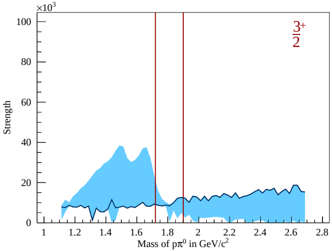

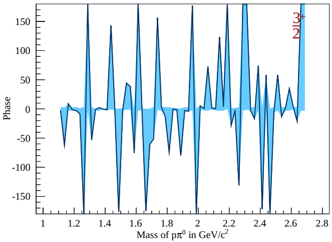

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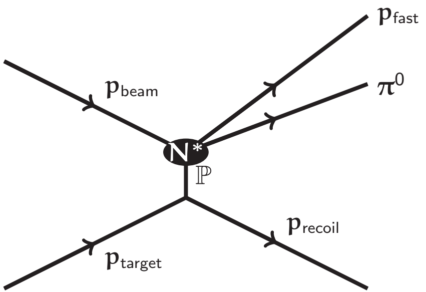

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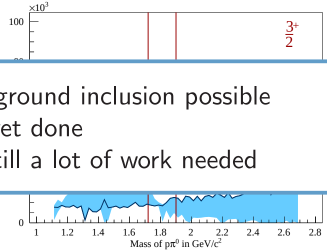
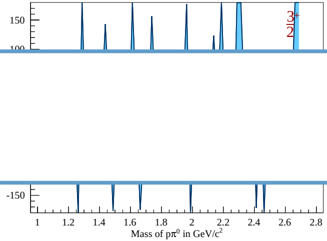




background inclusion possible
not yet done
→ still a lot of work needed

Outline

Conclusion and Outlook

- COMPASS has large datasets single meson production in $\mathbf{pp}$ scattering
- different channels accessible
- cross section ratios determined as a function of x_F and t'

→ agreement with previous results

- shape of $p\pi^0$ invariant mass spectrum understood qualitatively
- simple partial wave analysis ansatz not possible

→ partial wave analysis model developed for full process

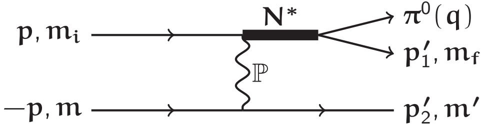
- background parametrisation not yet included
- details in my thesis (submitted today)

Thank you for your attention!

New Model

proton-proton scattering in CMS

$$p(E, \vec{p}) + p(E, -\vec{p}) \longrightarrow p(E_1', \vec{p}_1') + p(E_2', \vec{p}_2') + \pi^0(\omega_\pi, \vec{q}_\pi)$$



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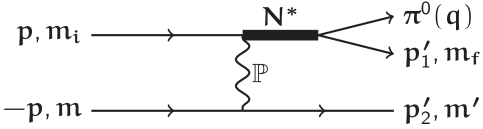

5 independent kinematic variables:

- invariant mass $\omega_{\pi p}$ of pion and fast proton p_1'
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- direction of pion in the GJ-frame $\rightarrow \Omega_\pi^* = (\theta_\pi^*, \varphi_\pi^*)$

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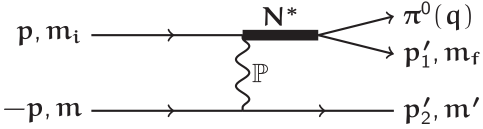

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cross section:

$$\frac{d\sigma}{d\omega_{\pi p}\, d\Omega\, d\Omega_\pi^*} = \frac{1}{(2\pi)^5} \frac{2M_N^4 p_2' q}{E^2 p} \sum_{S_i, M_i, S_f, M_f} |T_{S_i, M_i, S_f, M_f}|^2$$

with total initial/final spin
$S_{i,f} = 0, 1$ and $M_{i,f} = -S_{i,f}, \ldots, S_{i,f}$

Amplitude

$$T_{S_i,M_i,S_f,M_f}(\vec{p},-\vec{p},\vec{p}_1',\vec{p}_2') = \sum_{N^*(J^{\mathcal{P}})} \sum_{m_i,m_f,m,m',m_\pi,m_{\mathbb{P}},M_J}$$

$$\left(\frac{1}{2}m_i,\frac{1}{2}m\middle|S_iM_i\right)\left(\frac{1}{2}m_f,\frac{1}{2}m'\middle|S_fM_f\right)\left(\frac{1}{2}m_i,L_{\mathbb{P}}m_{\mathbb{P}}\middle|JM_J\right)\left(\frac{1}{2}m_f,L_\pi m_\pi\middle|JM_J\right)$$

$$\frac{f_{\mathbb{P}NN^*}f_{\mathbb{P}NN}}{M_\pi^{L_\pi+L_{\mathbb{P}}}} \times F(\omega_{\pi p})f_{\pi NN^*}G_{N^*}(\omega_{\pi p}) \times G_{\mathbb{P}}(t) \times (-1)^{m_{\mathbb{P}}} P^{[L_{\mathbb{P}}]}_{-m_{\mathbb{P}}} q^{[L_\pi]}_{m_\pi}$$

Clebsch-Gordan coefficients for single spin couplings

pomeron couplings to pp and pN^*, unknown constants

resonance shape in $p\pi$-mass $\rightarrow$ free parameters

pomeron propagator

angular dependence

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Background not yet included in model

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---

vertex form factor $F(\omega_{\pi p}) = \frac{\Lambda^4}{\Lambda^4-(\omega_{\pi p}^2-M_{N^*}^2)^2}$ with $\Lambda = 1.3$ GeV

πNN^* coupling constant $f_{\pi NN^*}$ (free parameter)

resonance propagator $G_{N^*}(\omega_{\pi p}) = \frac{1}{\omega_{\pi p}-M_{N^*}+\frac{i}{2}\Gamma_{N^*}(\omega_{\pi p})}$

$N^* \to \pi N$ partial width $\Gamma_{N^*}(\omega_{\pi p}) = \frac{f_{\pi NN^*}^2}{4\pi}\frac{F^2(\omega_{\pi p})}{\omega_{\pi p}}\frac{2M_N}{M_\pi^{2L_\pi}}\frac{L_\pi!}{(2L_\pi+1)!!}q^{2L_\pi+1}$

Amplitude

$$T_{S_i,M_i,S_f,M_f}(\vec{p},-\vec{p},\vec{p}'_1,\vec{p}'_2) = \sum_{N^*(J^{\mathcal{P}})} \sum_{m_i,m_f,m,m',m_\pi,m_{\mathbb{P}},M_J}$$

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---

pomeron propagator parameterised through Regge trajectory:

$$G_{\mathbb{P}}(t) = \left(\frac{s}{s_0}\right)^{\alpha(t)-1}\frac{\pi\alpha'}{\sin\left(\pi\alpha(t)\right)}\frac{e^{-i\pi\alpha(t)}}{\Gamma\left(\alpha(t)\right)}$$

with

$$s_0 = 1\text{ GeV}$$

$$s = 2\sqrt{\vec{p}'^2_1 + M_N^2} \quad t = (E(N^*) - E)^2 - (\overrightarrow{N^*} - \vec{p})^2$$

$$\alpha(t) = \alpha_0 + \alpha' t, \quad \alpha_0 = 1.08,\ \alpha' = 0.25$$

Amplitude

$$T_{S_i,M_i,S_f,M_f}(\vec{p},-\vec{p},\vec{p}_1',\vec{p}_2') = \sum_{N^*(J^{\mathcal{P}})} \sum_{m_i,m_f,m,m',m_\pi,m_{\mathbb{P}},M_J}$$

$$\left(\frac{1}{2}m_i,\frac{1}{2}m\middle|S_iM_i\right)\left(\frac{1}{2}m_f,\frac{1}{2}m'\middle|S_fM_f\right)\left(\frac{1}{2}m_i,L_{\mathbb{P}}m_{\mathbb{P}}\middle|JM_J\right)\left(\frac{1}{2}m_f,L_\pi m_\pi\middle|JM_J\right)$$

$$\frac{f_{\mathbb{P}NN^*}f_{\mathbb{P}NN}}{M_\pi^{L_\pi+L_{\mathbb{P}}}} \times F(\omega_{\pi p})f_{\pi NN^*}G_{N^*}(\omega_{\pi p}) \times G_{\mathbb{P}}(t) \times (-1)^{m_{\mathbb{P}}} P^{[L_{\mathbb{P}}]}_{-m_{\mathbb{P}}} q^{[L_\pi]}_{m_\pi}$$

Angular dependence for momentum $\vec{Q} = (Q, \theta_Q, \varphi_Q)$:

$$Q^{[L]}_M = \sqrt{\frac{4\pi L!}{(2L+1)!!}}Q^L Y_{LM}(\theta_Q,\varphi_Q)$$

$\vec{P}$ is the relative momentum of pomeron und beam:

$$\vec{P} = \frac{\vec{p}_{\mathbb{P}}E - \vec{p}E_{\mathbb{P}}}{E + E_{\mathbb{P}}}$$

$$\vec{p}_{\mathbb{P}} = \overrightarrow{N^*} - \vec{p} \quad E_{\mathbb{P}} = E(N^*) - E$$