Investigating $\eta\pi^-$ and $\eta'\pi^-$ Final States in the Double-Regge Region at COMPASS

IWHSS 2025

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on behalf of the COMPASS collaboration

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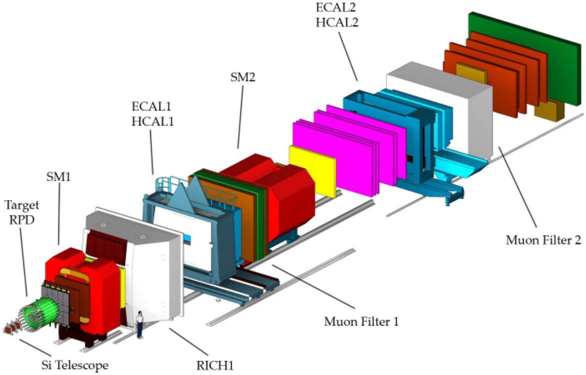
The COMPASS experiment

- **CO**mmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

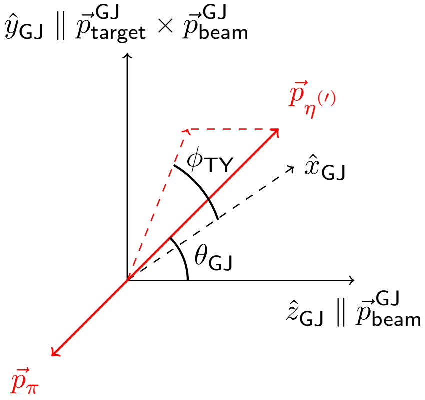


Reaction – 190 GeV beam energy

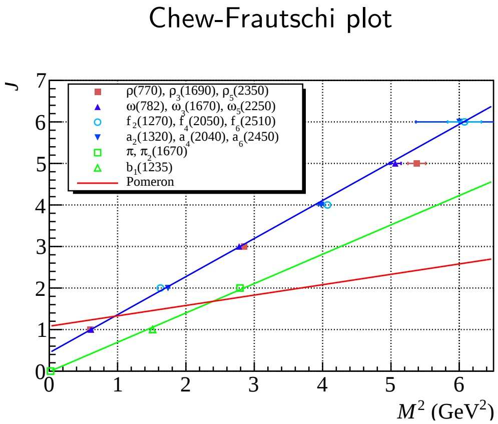
$$\underbrace{\pi^-}_{\text{beam}} + \underbrace{p}_{\text{target}} \to \eta^{(\prime)} + \pi^- + \underbrace{p}_{\text{recoil}}$$

The Gottfried-Jackson frame

- Rest frame of $\eta^{(\prime)}\pi^-$
- $\vec{p}^{\,\text{GJ}}_{\text{beam}}$ defines z-axis
- y-axis is defined by $\vec{p}^{\,\text{GJ}}_{\text{target}} \times \vec{p}^{\,\text{GJ}}_{\text{beam}}$



Regge theory

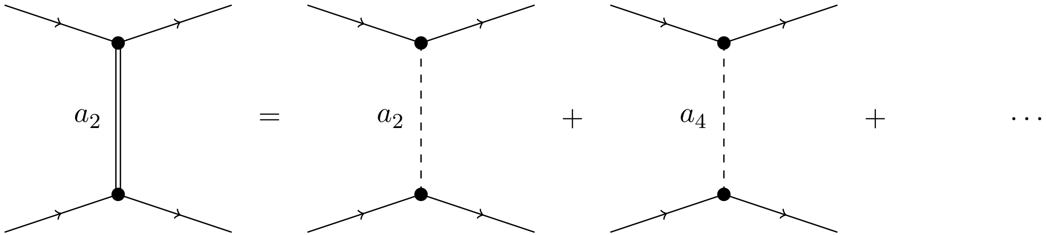


[Ketzer et al., 2020, Prog. Part. Nucl. Phys., 113]

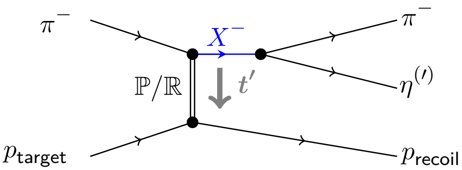
- Resonances with same isospin, intrinsic spin and parity fall on a straight line in M^2 vs J
- This resummation is called a Regge trajectory
- Pomeron: Introduced to obtain an asymptotically constant total cross section

$$\alpha_{a_2}(t) = 0.53 + 0.90t$$
$$\alpha_{f_2}(t) = 0.47 + 0.89t$$
$$\alpha_{\mathbb{P}}(t) = 1.08 + 0.25t$$

REGGE THEORY – a_2 TRAJECTORY

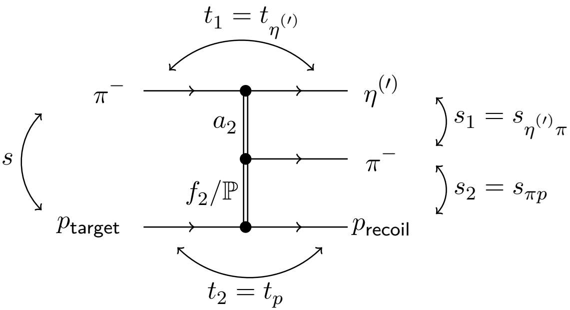


Resonance production



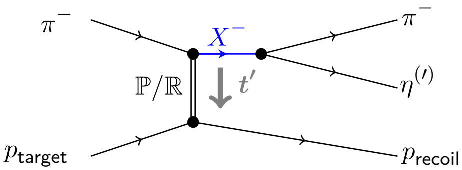
Dominating in the lower $s_{\eta^{(\prime)}\pi^-}$ region

Double-Regge exchange
Forward



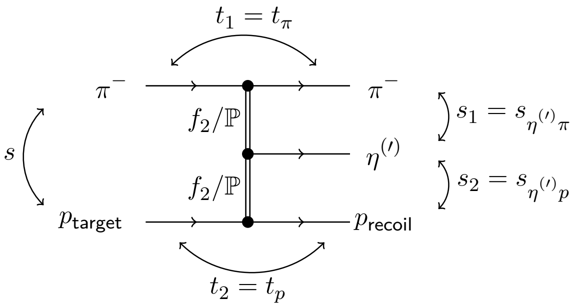
Dominating in the higher $s_{\eta^{(\prime)}\pi^-}$ region

Resonance production

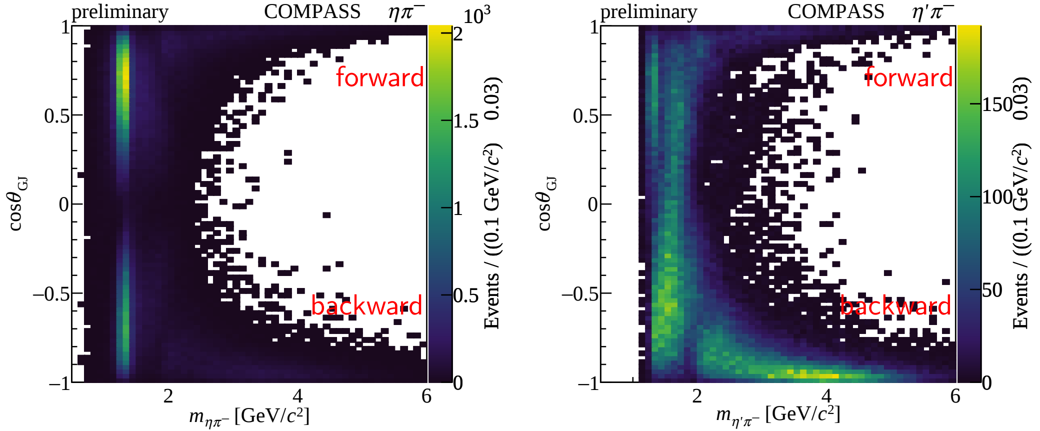


Dominating in the lower $s_{\eta^{(\prime)}\pi^-}$ region

Double-Regge exchange
Backward



Dominating in the higher $s_{\eta^{(\prime)}\pi^-}$ region


preliminary
COMPASS
$\eta\pi^-$
forward
backward
$\cos\theta_{GJ}$
$m_{\eta\pi^-}$ [GeV/c^2]
Events / ((0.1 GeV/c^2) 0.03)
10^3
preliminary
COMPASS
$\eta'\pi^-$
forward
backward
$\cos\theta_{GJ}$
$m_{\eta'\pi^-}$ [GeV/c^2]
Events / ((0.1 GeV/c^2) 0.03)

Show double-Regge behavior

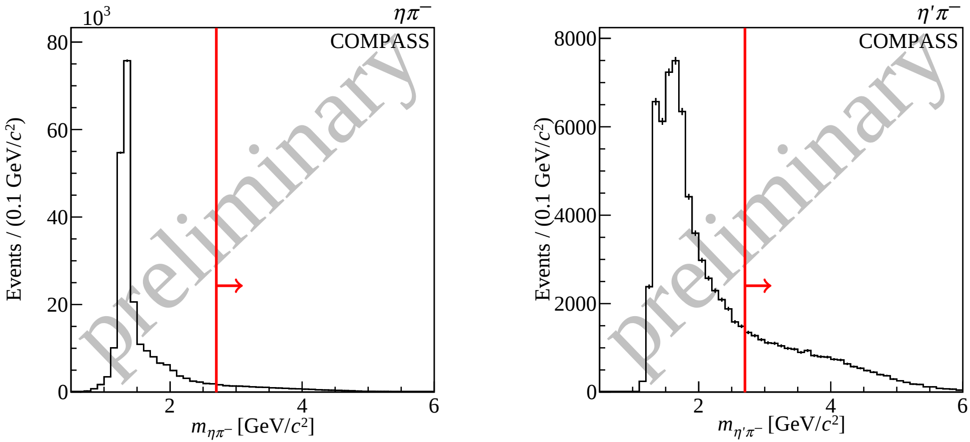
- First event based study to extract double-Regge behavior in $\eta^{(\prime)}\pi^-$
- Determine dominating exchange Reggeons
- Is bottom $\mathbb{P}$ the most dominating process?
  - In the resonance region, only $\mathbb{P}$ exchange is considered

Improve resonance-model fit

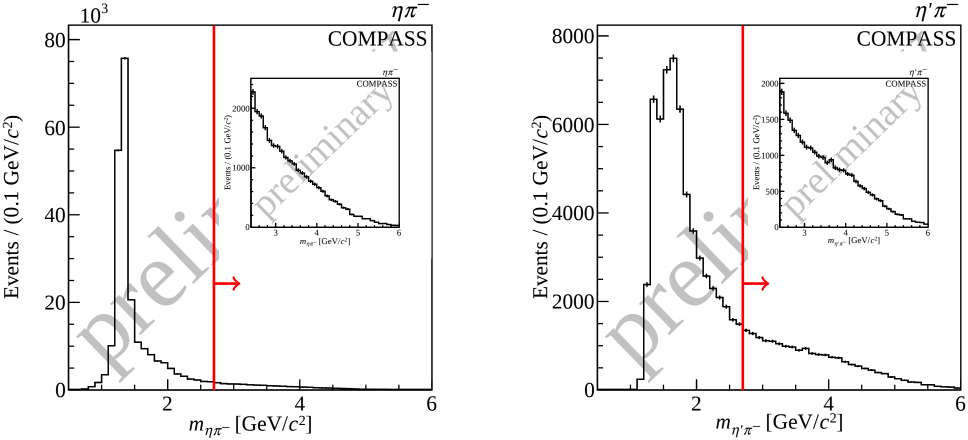
- Until now: only phenomenological background description
- Use finite energy sum rules to link resonance and double-Regge region

Previous study [Eur. Phys. J. C 81, 647 (2021)]

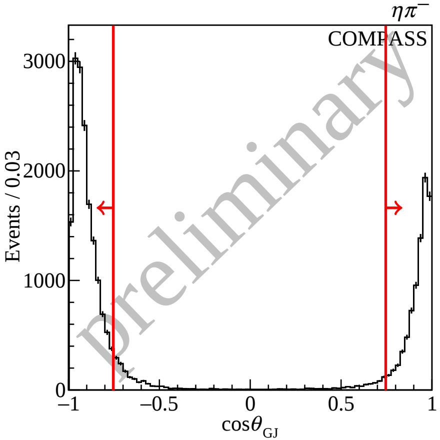
- Fit to COMPASS partial waves in the $\eta^{(\prime)}\pi^-$ final state
  - Similar model, limited mass range ($2.4\,\text{GeV}/c^2$ to $3\,\text{GeV}/c^2$), integrated over t_2

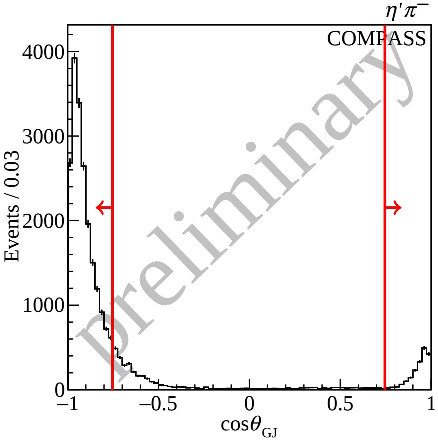

10^3
$\eta\pi^-$
COMPASS
preliminary
Events / (0.1 GeV/c^2)
80
60
40
20
0
2
4
6
$m_{\eta\pi^-}$ [GeV/c^2]
$\eta'\pi^-$
COMPASS
preliminary
Events / (0.1 GeV/c^2)
8000
6000
4000
2000
0
2
4
6
$m_{\eta'\pi^-}$ [GeV/c^2]

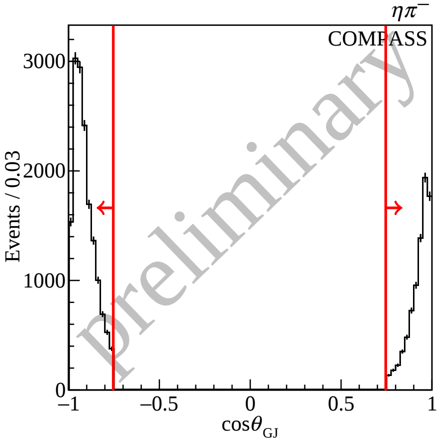
Cutting on the double-Regge kinematics



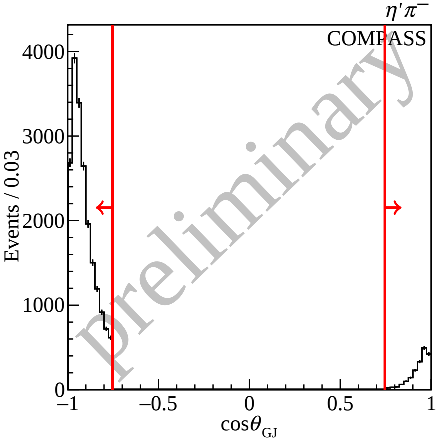
Cutting on the double-Regge kinematics







Removes 13% of the events



Removes 8% of the events

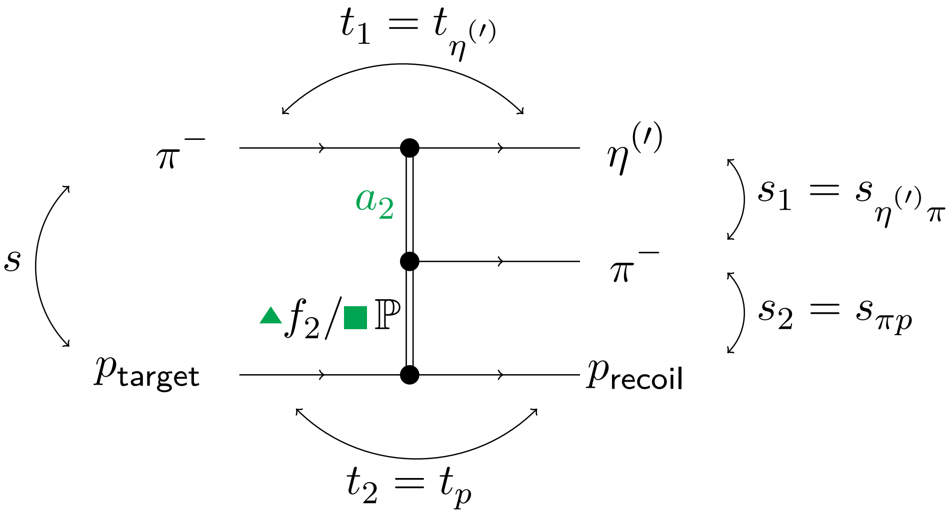
Main features, inspired by [Eur. Phys. J. C 81, 647 (2021)]

- Intensity per event k: $I_k(\vec{c}, \vec{b}; \tau_k) = \left|\sum_{i=1}^{6} c_i A_i(\vec{b}; \tau_k)\right|^2$
- General amplitude structure: $A_i(\vec{b}; \tau_k) = e^{b_{i,1} t_1} e^{b_{i,2} t_2} T(\alpha_1(t_1), \alpha_2(t_2), s_1, s_2)$
- $T(\alpha_1(t_1), \alpha_2(t_2), s_1, s_2)$ is taken from Shimada [Nucl. Phys. B 142 (1978)]
- Form factors $e^{b_{i,1} t_1} e^{b_{i,2} t_2}$ added to capture t dependence from top / bottom vertex
- Real valued strength parameters $(\vec{c})$, to be determined
- Slope parameters of the form factors $(\vec{b})$, to be determined
- We describe the full dataset at once $\rightarrow$ global fit

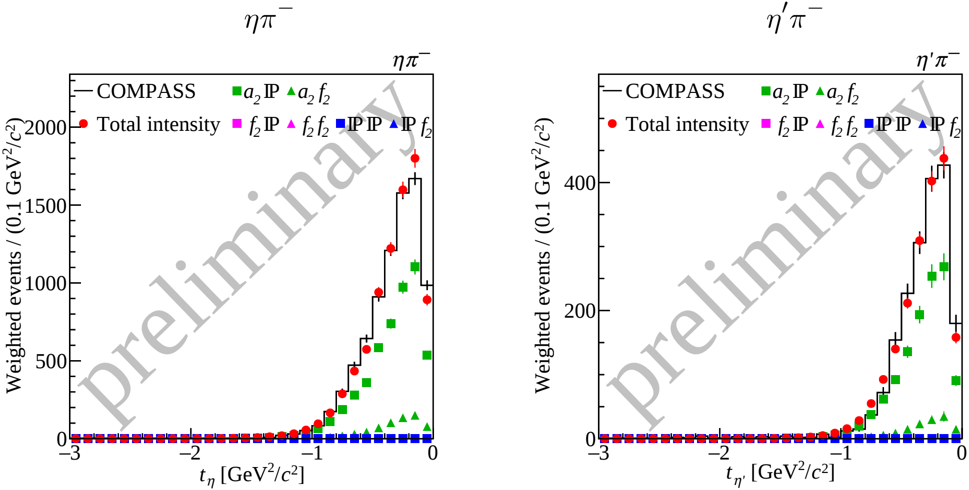
Test of the Shimada model

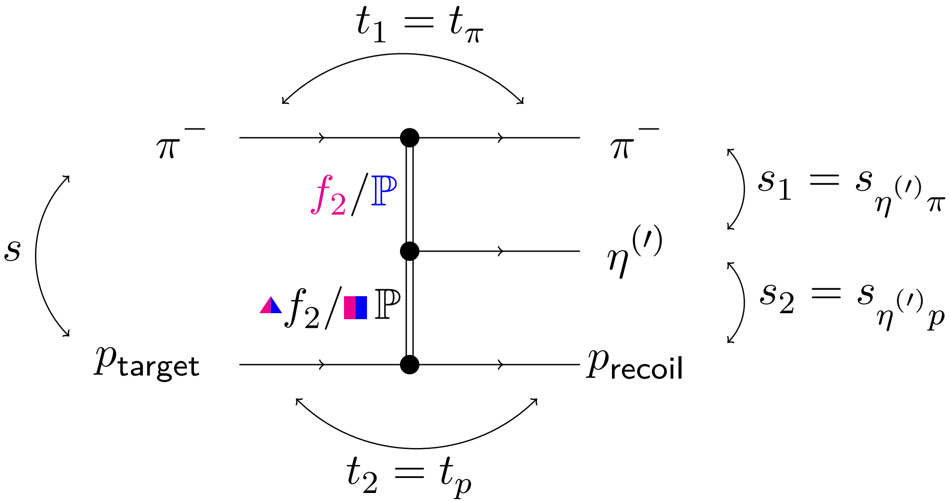
- Shimada model predicts s_1 dependence
- Fit in bins of $m_{\eta^{(\prime)}\pi^-} = \sqrt{s_1}$ with fixed $(\vec{b})$. Ideally, $(\vec{c})$ is const.

Forward diagrams in the $\eta^{(\prime)}\pi^-$ final state



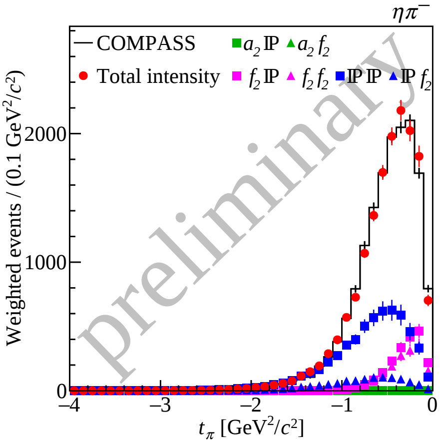
Pomeron dominance in the forward region



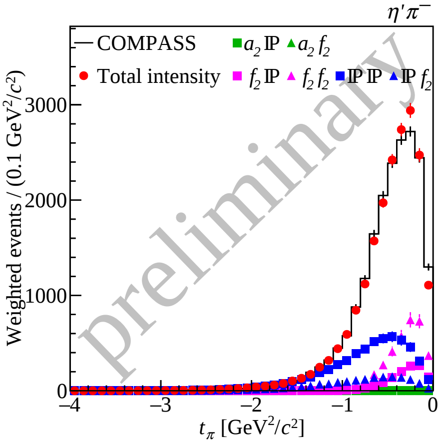


$t_1 = t_\pi$
π^-
π^-
$f_2/\mathbb{P}$
$s_1 = s_{\eta^{(\prime)}\pi}$
s
$\eta^{(\prime)}$
$f_2/\mathbb{P}$
$s_2 = s_{\eta^{(\prime)}p}$
p_{target}
p_{recoil}
$t_2 = t_p$

$\eta\pi^-$

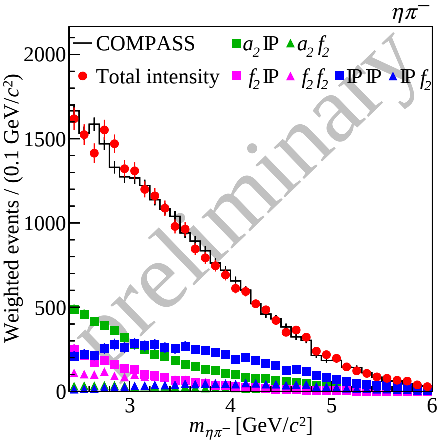

ηπ⁻
— COMPASS
Total intensity
a_2 IP
$a_2 f_2$
f_2 IP
$f_2 f_2$
IP IP
IP f_2
preliminary
Weighted events / (0.1 GeV²/c²)
t_π [GeV²/c²]

$\eta'\pi^-$

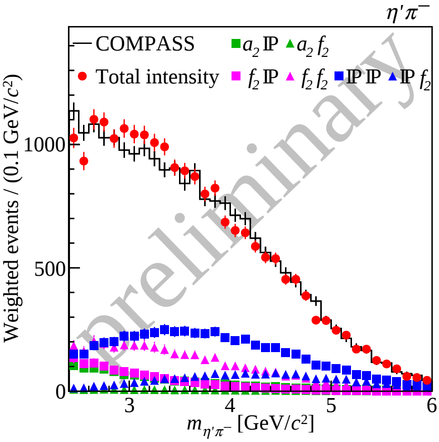

η'π⁻
— COMPASS
Total intensity
a_2 IP
$a_2 f_2$
f_2 IP
$f_2 f_2$
IP IP
IP f_2
preliminary
Weighted events / (0.1 GeV²/c²)
t_π [GeV²/c²]

Relative strength of all amplitudes

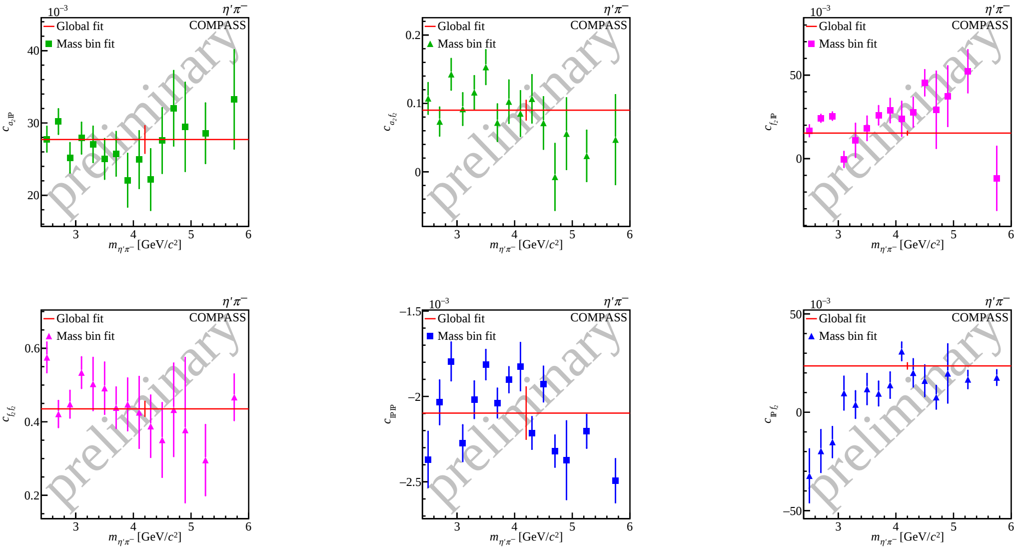
$\eta\pi^-$



$\eta'\pi^-$



Mass dependence of $\vec{c}$ in $\eta'\pi^-$



Summary

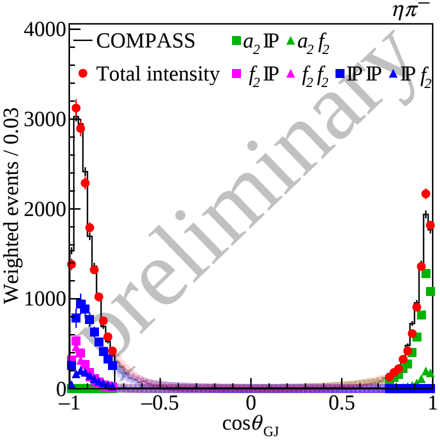
- We are able to describe our high-precision data with only 13 free parameters
  - Two forward and four backward amplitudes
  - Seven form factors
- No need for daughter trajectories
- Forward region: very dominant bottom $\mathbb{P}$
- Backward region:
  - Dominating bottom $\mathbb{P}$ in $\eta\pi^-$
  - Similar strength of bottom $\mathbb{P}$ and f_2 amplitudes for $\eta'\pi^-$
- Accurate description of the t dependence
- $m_{\eta^{(\prime)}\pi^-}$ dependence is captured well by the model

Outlook

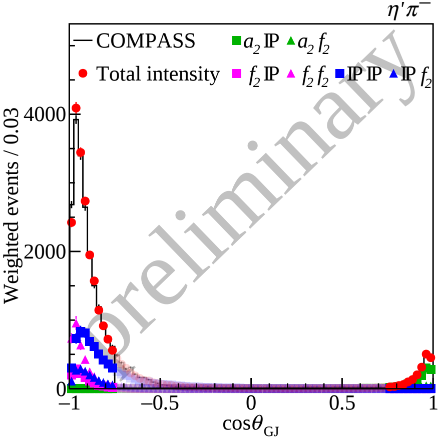
- Systematic studies
  - Vary trajectory parameters
  - Vary start of $m_{\eta^{(\prime)}\pi^-}$
- Use finite energy sum rules to link the double-Regge amplitude to the low mass region
  - Needs input from theory
- Publication in preparation

Backup

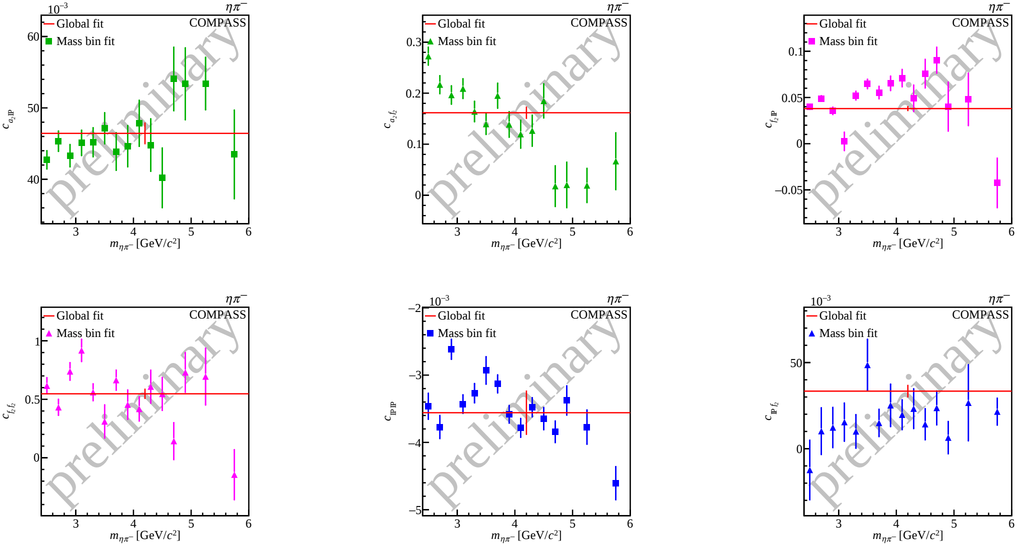
$\eta\pi^-$


ηπ⁻
COMPASS
Total intensity
a₂ IP
a₂ f₂
f₂ IP
f₂ f₂
IP IP
IP f₂
preliminary
Weighted events / 0.03
0
1000
2000
3000
4000
−1
−0.5
0
0.5
1
cosθ_GJ

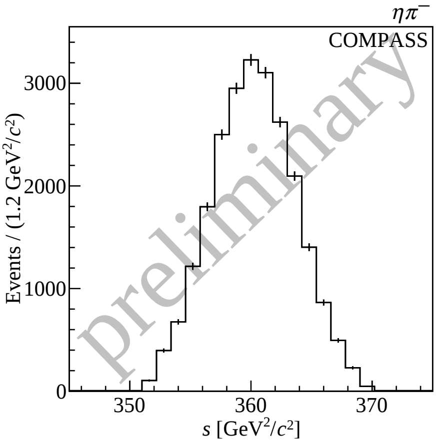
$\eta'\pi^-$


η'π⁻
COMPASS
Total intensity
a₂ IP
a₂ f₂
f₂ IP
f₂ f₂
IP IP
IP f₂
preliminary
Weighted events / 0.03
0
2000
4000
−1
−0.5
0
0.5
1
cosθ_GJ

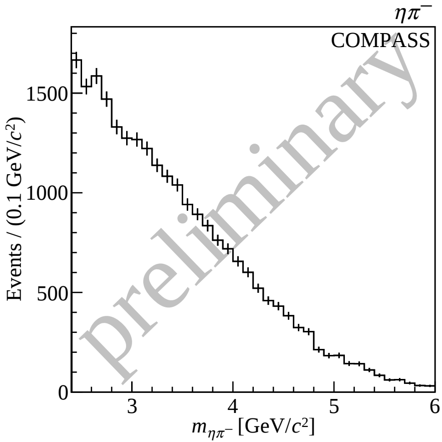
Mass dependence of $\vec{c}$ in $\eta\pi^-$



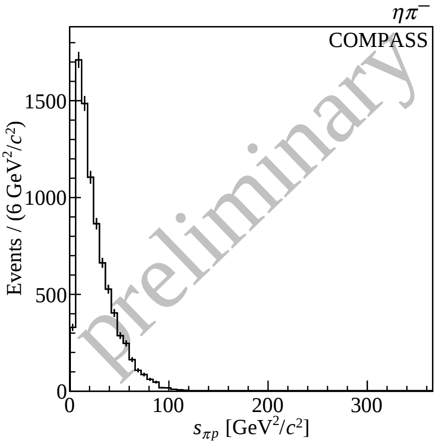
s



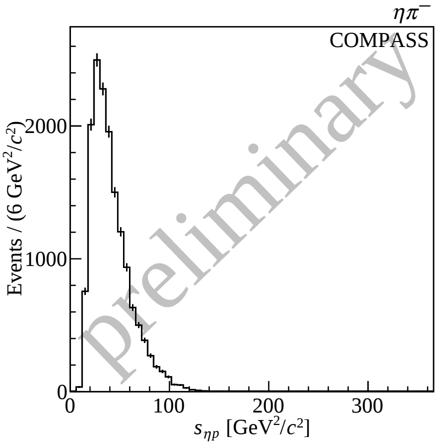
$m_{\eta^{(\prime)}\pi^-} = \sqrt{s_1}$



s_2 forward

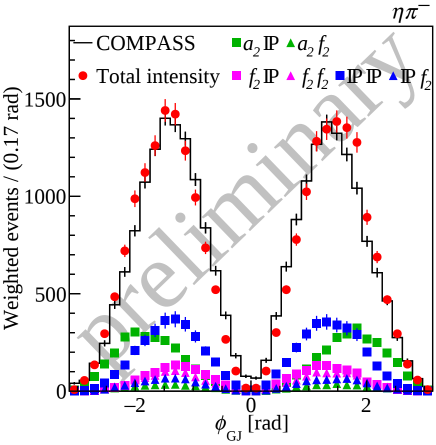


s_2 backward

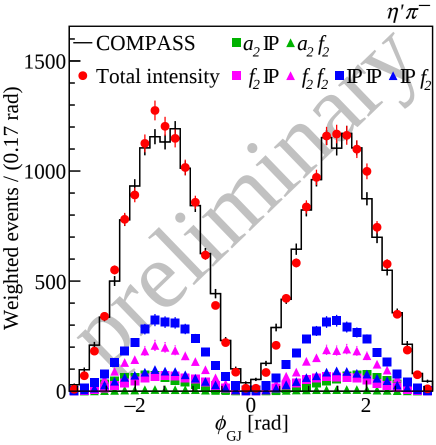


Accepted MC, weighted with the fitted intensity

$\eta\pi^-$

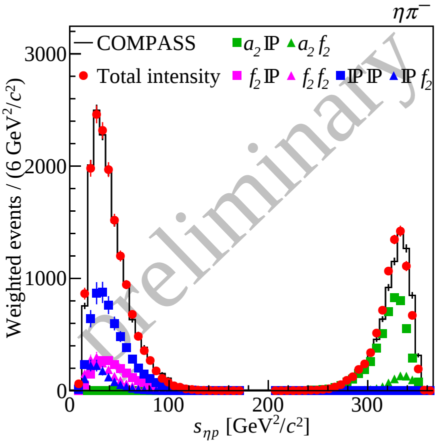


$\eta'\pi^-$

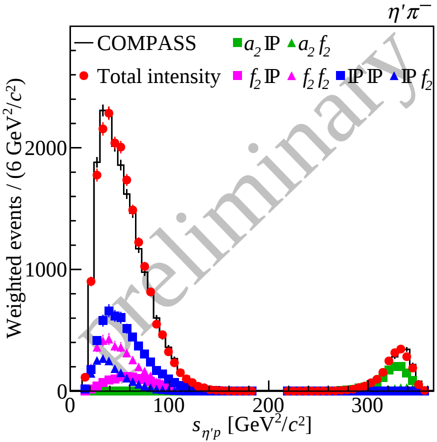


Accepted MC, weighted with the fitted intensity

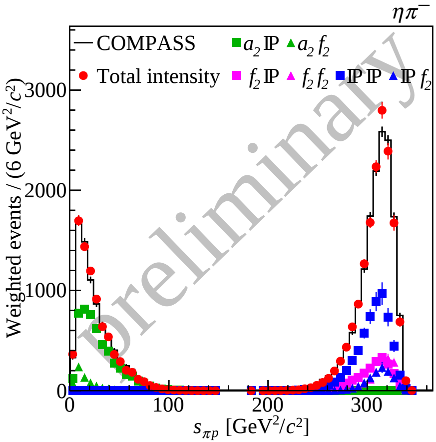
$\eta\pi^-$



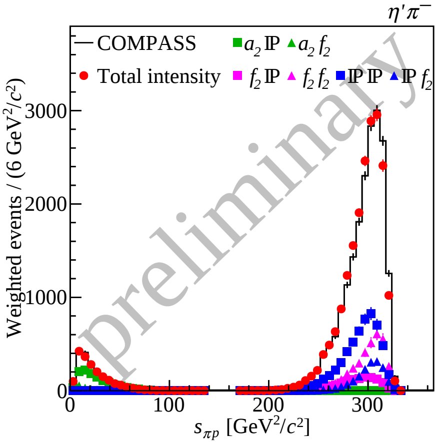
$\eta'\pi^-$



$\eta\pi^-$

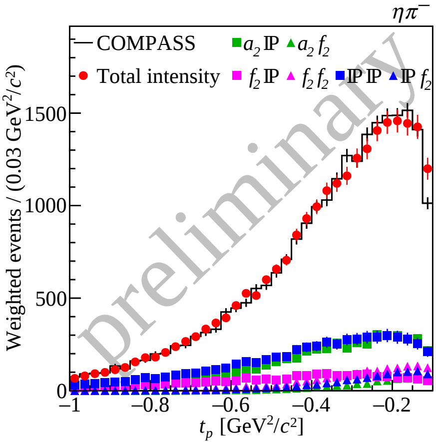

ηπ⁻
COMPASS
Total intensity
a₂ IP
a₂ f₂
f₂ IP
f₂ f₂
IP IP
IP f₂
preliminary
Weighted events / (6 GeV²/c²)
3000
2000
1000
0
100
200
300
s_πp [GeV²/c²]

$\eta'\pi^-$

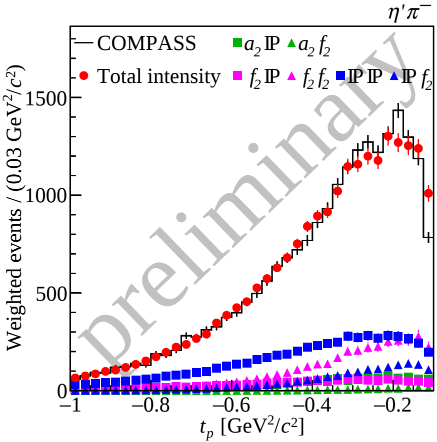

η'π⁻
COMPASS
Total intensity
a₂ IP
a₂ f₂
f₂ IP
f₂ f₂
IP IP
IP f₂
preliminary
Weighted events / (6 GeV²/c²)
3000
2000
1000
0
100
200
300
s_πp [GeV²/c²]

Accepted MC, weighted with the fitted intensity

$\eta\pi^-$

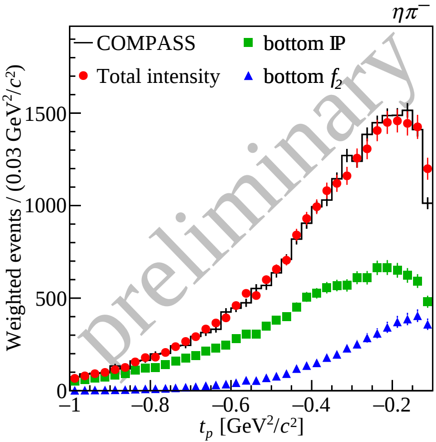


$\eta'\pi^-$

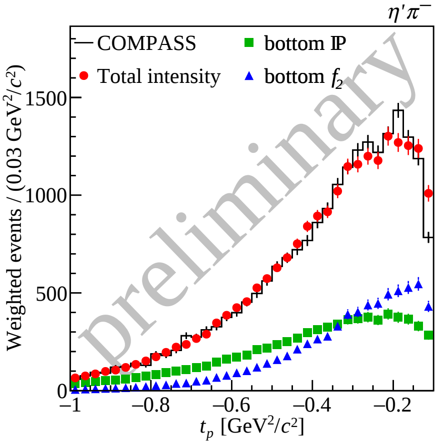


Accepted MC, weighted with the fitted intensity

$\eta\pi^-$

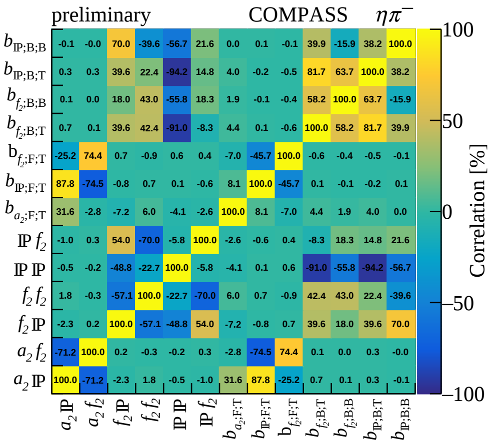


$\eta'\pi^-$

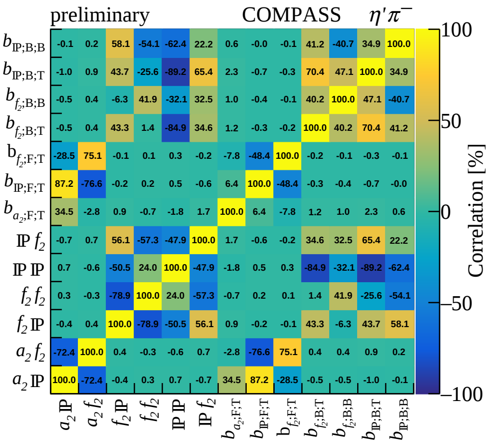


Correlation matrix for the global minimum

$\eta\pi^-$



$\eta'\pi^-$



Fitting the extended negative log likelihood

$$-\ln \mathcal{L}_{\text{ext}}(\vec{c}, \vec{b}) = \underbrace{\sum_{k=1}^{N_{\text{acc}}} \left| \sum_{i=1}^{6} c_i A_i(\vec{b}, \tau_k) \right|^2}_{\text{acceptance}} - \underbrace{\sum_{k=1}^{N_{\text{m}}} \ln \left| \sum_{i=1}^{6} c_i A_i(\vec{b}, \tau_k) \right|^2}_{\text{COMPASS data}}$$

Different studies

a) Fit the full data set $\rightarrow$ determine strength ($\vec{c}$) and slope ($\vec{b}$) parameters

b) Fit in bins of $m_{\eta^{(\prime)}\pi^-}$, while fixing ($\vec{b}$) from a) $\rightarrow$ determine ($\vec{c}$) per bin

Presentation of the results

- Weight kinematics of Monte Carlo accepted events with fitted intensity $w_k = \left|\sum_{i=1}^{6} c_i A_i(\vec{b}, \tau_k)\right|^2$ (• full intensity); $w_k^i = \left|c_i A_i(\vec{b}, \tau_k)\right|^2$ (single intensity)
- Full intensity should follow COMPASS data for that kinematics

The Shimada model

$$T(\alpha_1, \alpha_2; s_1, s_2) = K\Gamma(1-\alpha_1)\,\Gamma(1-\alpha_2)\frac{(\alpha' s_1)^{\alpha_1}(\alpha' s_2)^{\alpha_2}}{\alpha' s} \times \left[\frac{\xi_1 \xi_{21}}{\kappa^{\alpha_1}} V(\alpha_1, \alpha_2, \kappa) + \frac{\xi_2 \xi_{12}}{\kappa^{\alpha_2}} V(\alpha_2, \alpha_1, \kappa)\right]$$

- K: kinematic factor, unique per event, depends on $\cos\theta_{\mathsf{GJ}}$, etc.
- ξ removes poles for positive integer values of the trajectories α_1 and α_2
- V describes Reggeon-Reggeon coupling
- Correct Regge behavior is captured with s^{α} terms

Further motivation for the $\cos\theta_{GJ}$ cut