

Update on an exclusive study of $pp \rightarrow pp\eta(\rightarrow \pi^+\pi^-\pi^0)$ Unfolding

Szymon Trelński
(IFJ PAN Kraków & Ruhr-Universität Bochum)

Motivation - analysis objectives

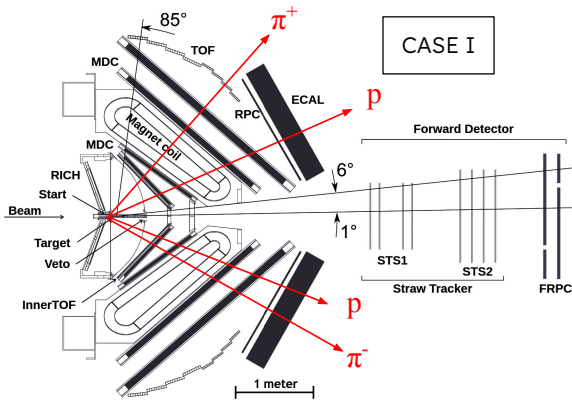
Measure total and differential cross-sections for exclusive η production:

- Study resonance contribution, excitation mechanism, FSI, ISI
- Input for heavy-ion transport models (GIBUU, SMASH, RQMD, ...)
- Test models prepared by IFJ PAS theory group - important in the context of future CBM@FAIR experiments

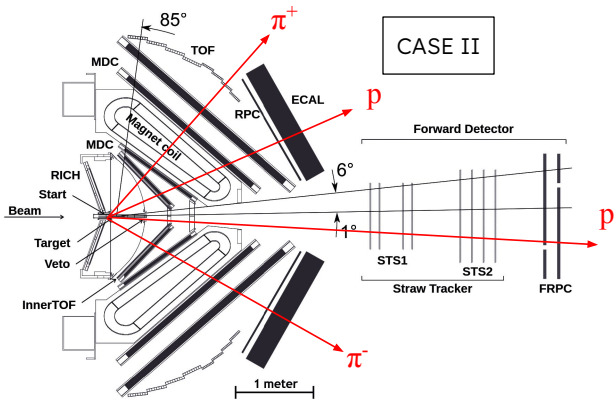
Variables of interest:

- Invariant masses
- Dalitz plot of $pp \rightarrow pp\eta$
- η production angle
- Helicity angles
- Gottfried-Jackson angles
- Momenta and transverse momenta of protons and η

Analysis overview



CASE I



CASE II

Study η production in channel:

$$pp \rightarrow pp\eta \rightarrow pp\pi^+\pi^-\pi^0$$

[Channel which offers greatest statistic]

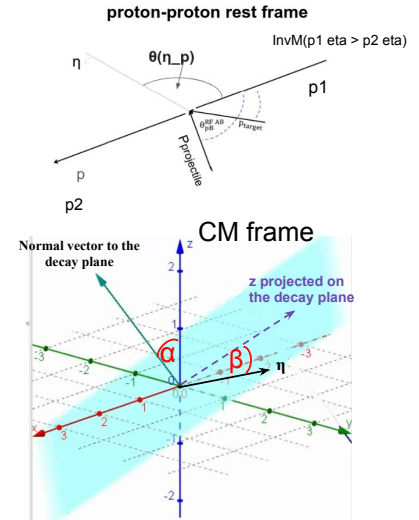
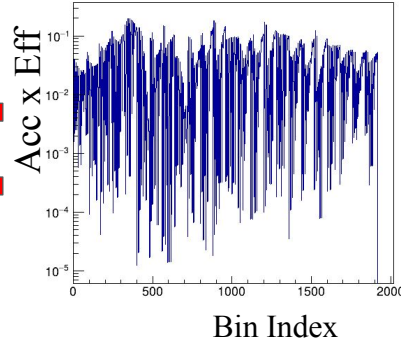
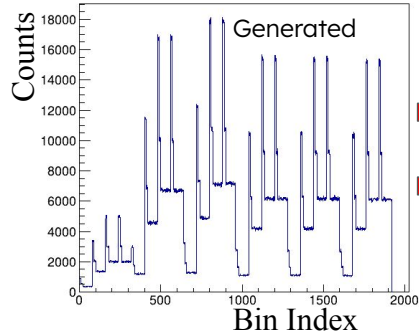
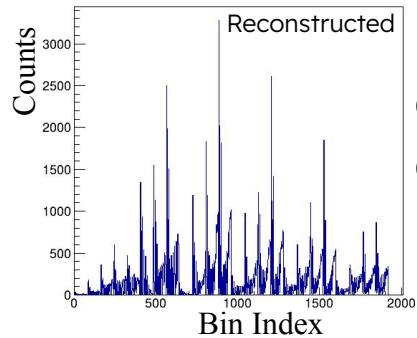
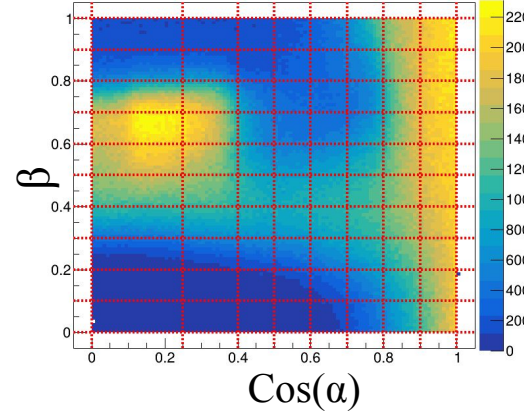
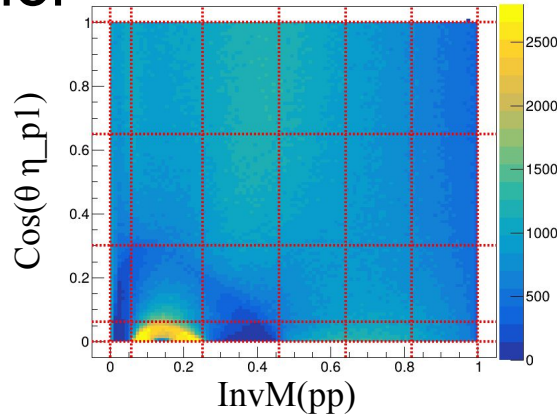
π^0 obtained from kinematic fit (missing particle constraint)

- 4-particle hypothesis: 2 protons, π^+ , π^-
- Particle identification:
 - In Magnetic spectrometer - beta vs momentum relationship
 - In Forward Detector - assumed to be protons
- Two topological cases:
 - Both protons in Magnetic Spectrometer
 - One proton in MS, one in Forward Detector **[Larger detector acceptance compared to previous HADES pp measurement]**
- Using kinematic fit with π^0 missing mass and total 4-mom conservation constraints **[Bkg suppression and improvement of mass resolution]**
- Correcting Data for detector Acceptance x Efficiency (3D matrices, SMASH-based) **[Possibility to study reaction in 4 π]**

Acc x Eff matrix preparation

- Full Phase-Space coverage (HH + HFp)
- Reasonable Acc x Eff values in bins
- 4D interpolation applied

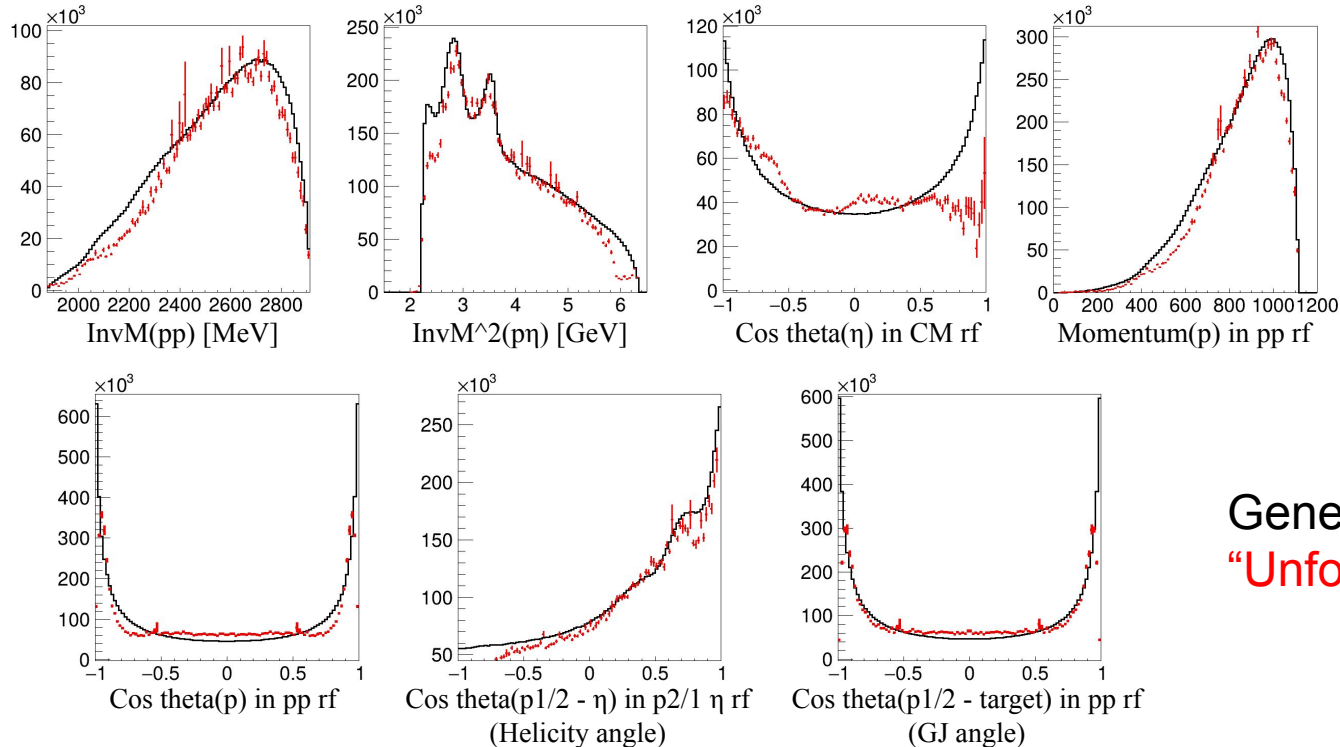
Binning:



Cross-check in simulations

PREVIOUS APPROACH 4D Phase-Space Pluto - based matrix

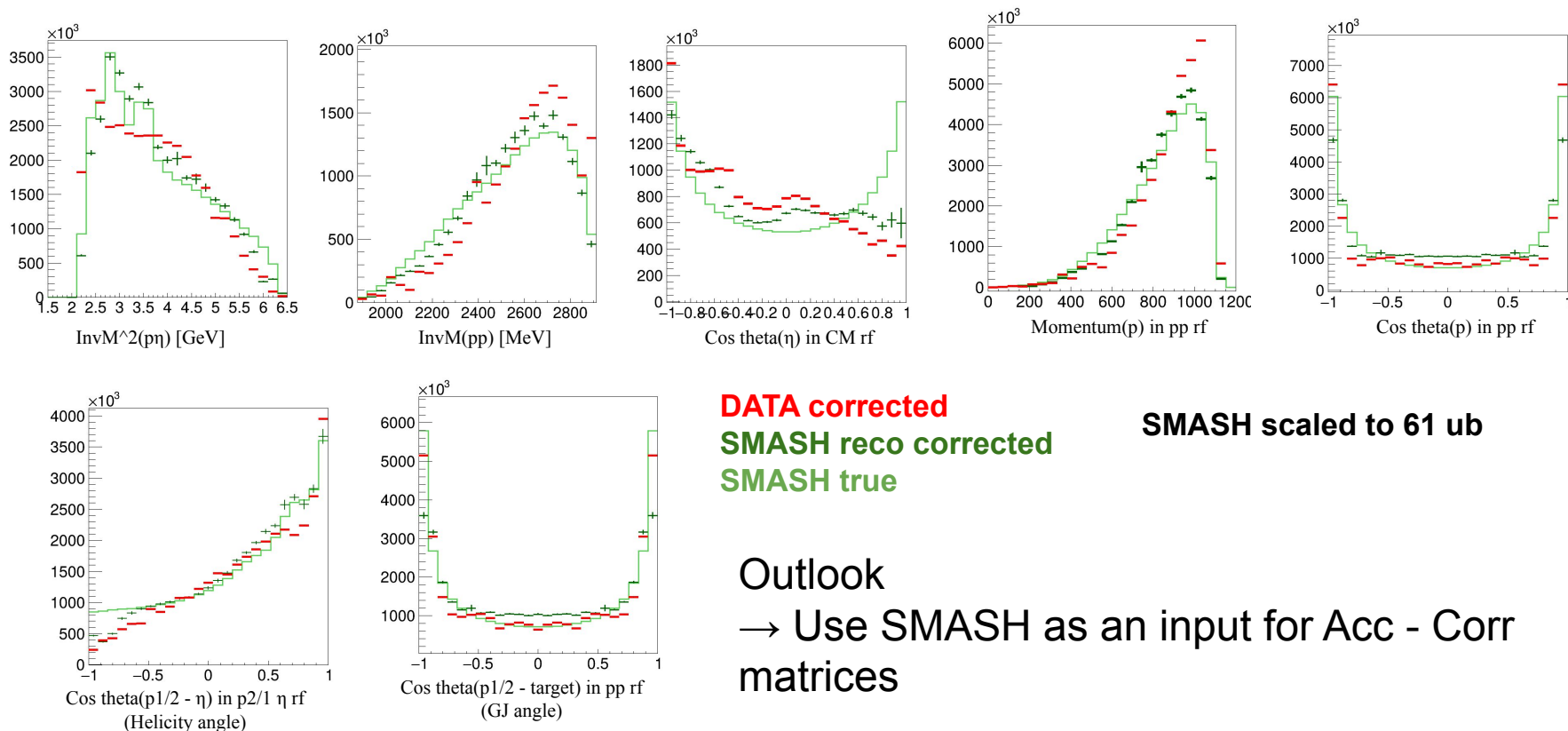
Conclusion: Only few projections properly reproduce the generator level, large systematic error (still not satisfactory)



Generator
"Unfolded" Reco

Results for data

PREVIOUS APPROACH 4D Phase-Space Pluto - based matrix



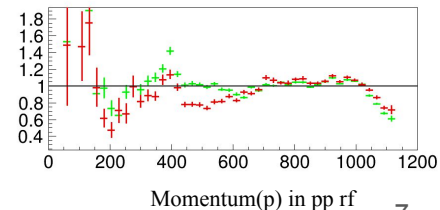
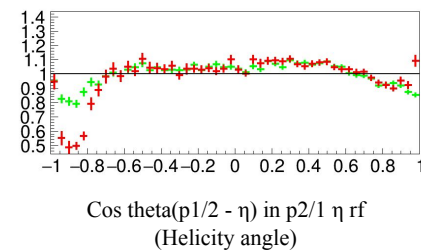
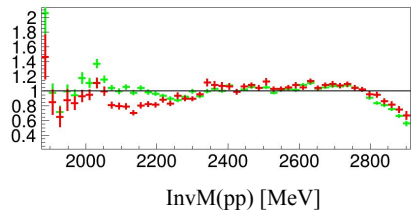
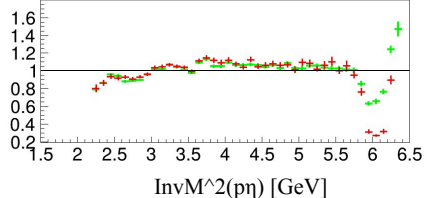
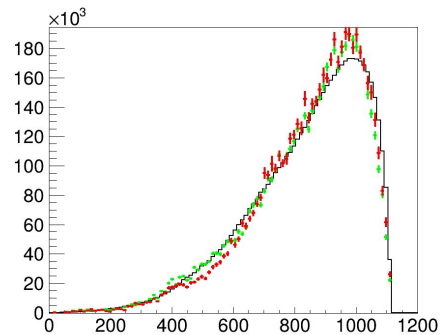
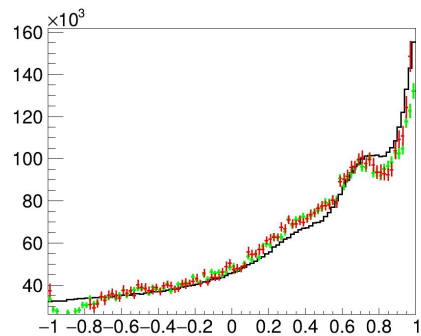
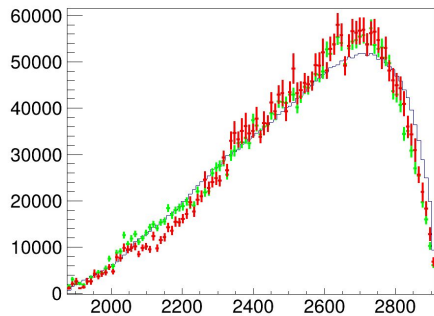
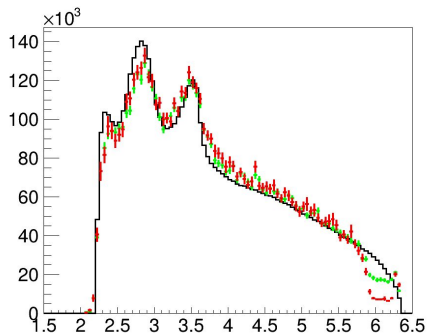
SMASH cross-check

New Approach Two 3D SMASH-based matrices

SMASH gen

Data corrected with **matrix 1**

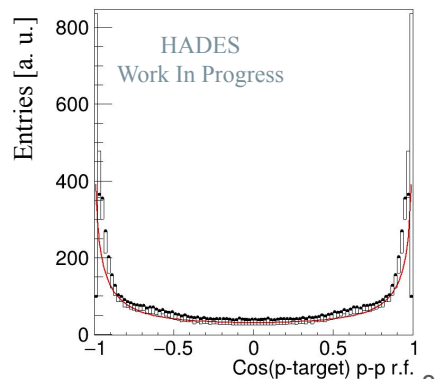
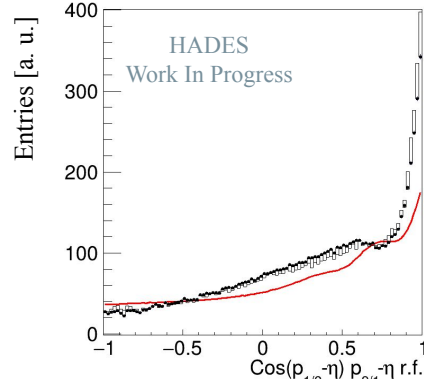
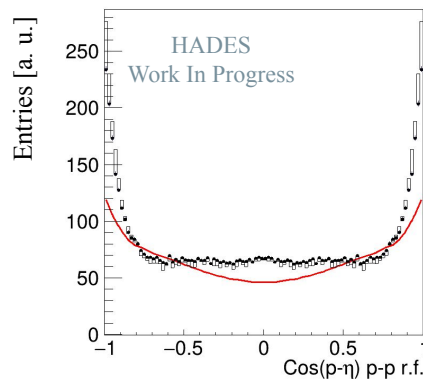
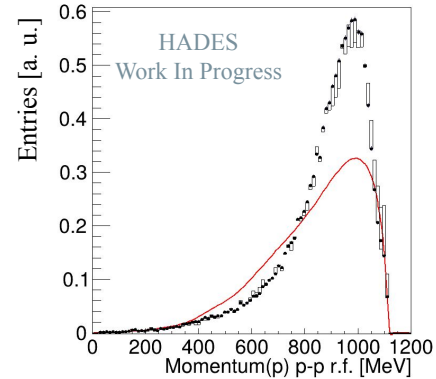
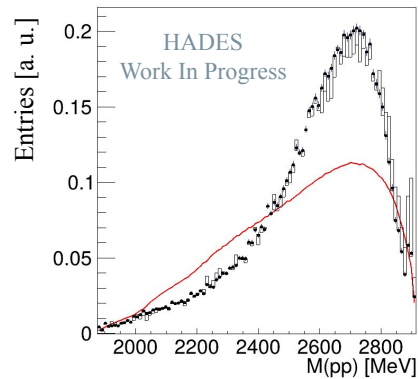
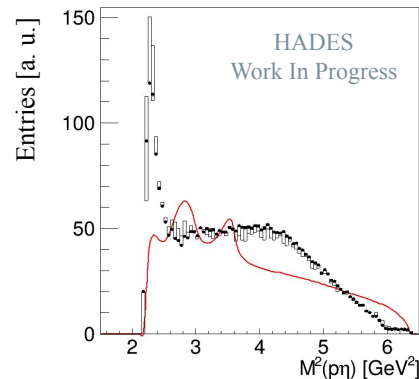
Data corrected with **matrix 2**



Data - SMASH comparison

SMASH description is too simplified, it significantly underestimates the N(1535) contribution, further deviations seen in other distributions.

New Approach Two 3D SMASH-based matrices



Effective Lagrangian models

P. Lebiedowcz [Phys. Rev. C **112**, 015201 (2025)]

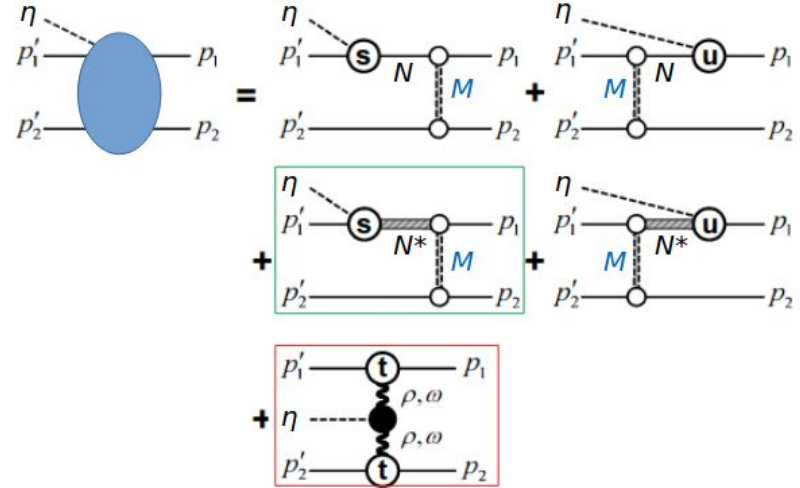
Three models developed by IFJ theory group:

- Effective lagrangian approach
- Production via N(1535), N(1655), N(1710) and N(1880), VV-fusion
- Coherent sum of all contributions

➤ **Model 1** - ρ meson exchange only, pseudoscalar couplings for all N^*
 $[\sigma_{\text{total}} = 141.0 \mu\text{b}]$

➤ **Model 2** - ρ meson exchange only, pseudoscalar couplings for N(1535), N(1650), pseudovector couplings for N(1710), N(1880)
 $[\sigma_{\text{total}} = 119.9 \mu\text{b}]$

➤ **Model 3** - ρ , π^0 and η mesons exchange, pseudoscalar couplings for all N^*
 $[\sigma_{\text{total}} = 81.4 \mu\text{b}]$

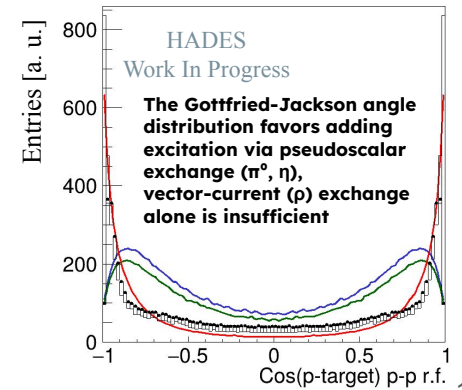
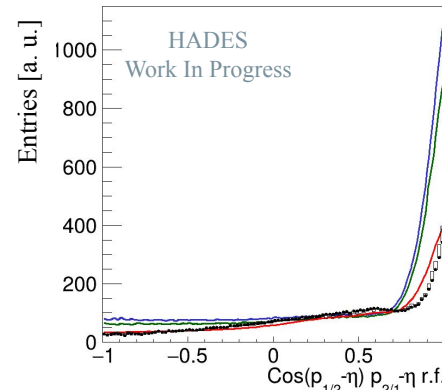
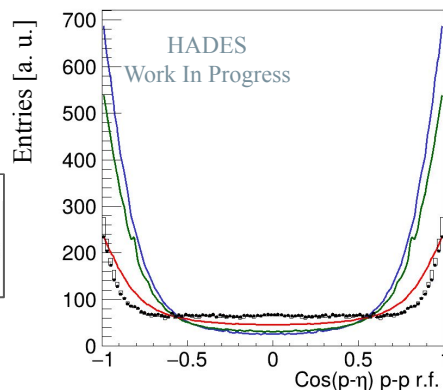
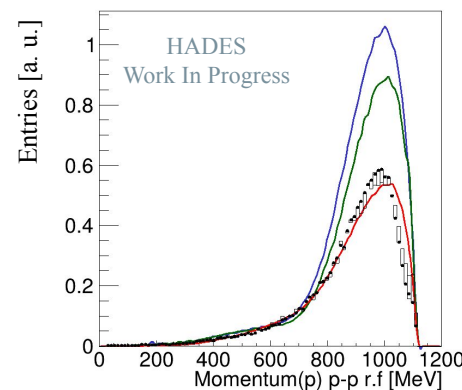
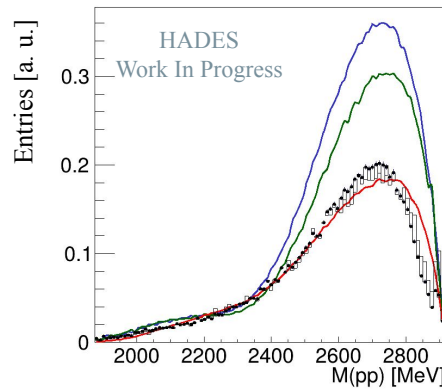
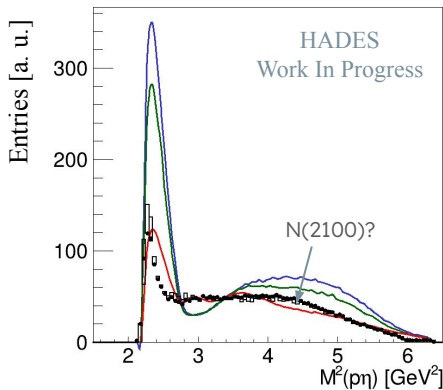


Data - Effective Lagrangian models comparison

New Approach Two 3D SMASH-based matrices

Data clearly favor Model 3, both for the total cross-section and the differential distributions.

Adding N(2100) may further improve agreement with the data.



—•—	Data	σ_{total}
—	Model 1	$\sigma_{\text{total}} = 141.0 \mu\text{b}$
—	Model 2	$\sigma_{\text{total}} = 119.9 \mu\text{b}$
—	Model 3	$\sigma_{\text{total}} = 81.4 \mu\text{b}$

Summary

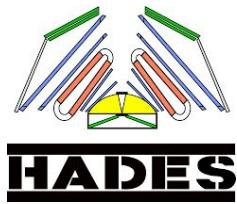
- Ongoing analysis favors Model 3: η production proceeds via an excitation mechanism that requires pseudoscalar meson exchange (π^0 , η), not just vector (ρ) exchange.
- Data may indicate the need for an including N(2100) contribution.
- SMASH provides a too simplified description of exclusive η production
- Models 1 and 2 (ρ -exchange only) fail to describe the data, demonstrating that vector-current exchange alone is not a sufficient description of the reaction.

&

Outlook

- Determine total cross-section with systematic error estimation
- Study Dalitz plots of $pp \rightarrow pp\eta$ for deeper insight into baryonic resonance contributions.
- Study polar angle, momenta, and transverse momenta of the proton and η for further insight into the excitation mechanism.

BACKUP



Study of exclusive η meson production in proton-proton collisions with HADES

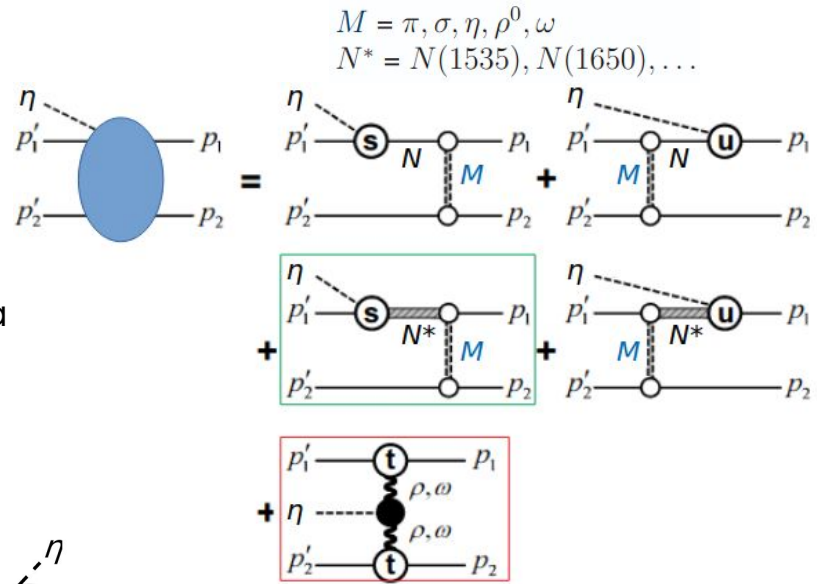
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Outline

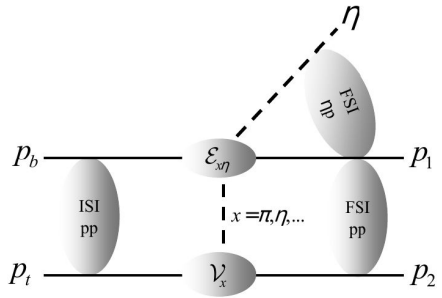
1. Motivation
2. HADES detector
3. Analysis procedure overview
4. Data - SMASH comparison
5. Data - Eff. Lagr. models comparison

Description of the η production in pp collisions

- Effective Lagrangian approach
- Exchange of mesons ($\pi, \rho, \omega, \sigma, \eta$)
- Intermediate baryon resonances (e.g. $N(1535)$)
- Coupling constants and form factors fitted to data or derived from other models
- Interference effects: coherent sum of amplitudes - can enhance or suppress contributions
- Initial/Final State Interactions impact



[Phys. Rev. C 112, 015201 (2025)]



[Phys. Scr. 73 663 (2006)]

Motivation - analysis objectives

Measure total and differential cross-sections for exclusive η production:

- Study resonance contribution, excitation mechanism, FSI, ISI
- Input for heavy-ion transport models (GIBUU, SMASH, RQMD, ...)
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Variables of interest:

- Invariant masses
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Previous measurements

Some Most recent measurements:

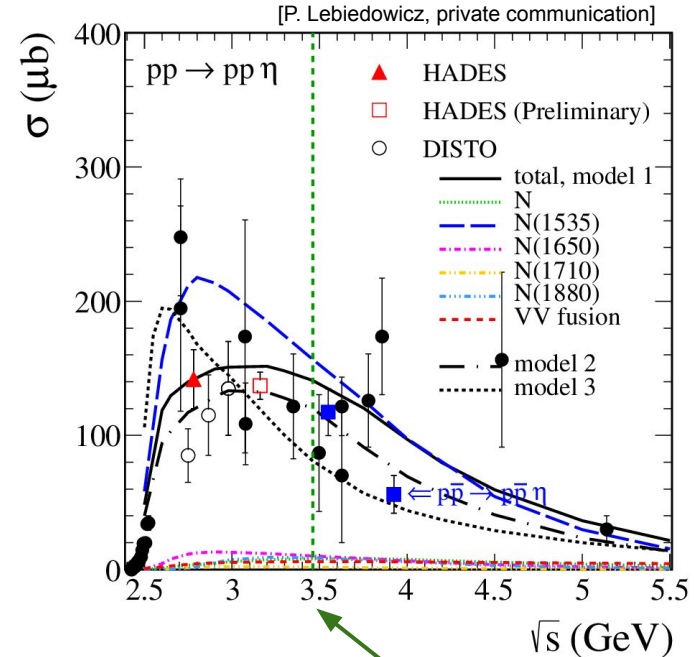
- WASA@COSY (1.4, 2.0 GeV)
- DISTO Collaboration (2.115, 2.5, 2.85 GeV)
- HADES Collaboration (2.2, 3.5 GeV)

Close to threshold:

- ❑ FSI/ISI needed to take into account
- ❑ very important role played by baryonic resonances, mostly N(1535)
- ❑ Depending on model: ρ , ω , η , σ , exchanges, destructive ρ/π interference
→ **Excitation mechanism is still open question**

Higher energies (>20 GeV):

- ❑ pomeron-pomeron exchange
- ❑ reggeon exchange
- ❑ diffraction processes



This measurement: 4.5 GeV ($\sqrt{s} = 3.46$ GeV)

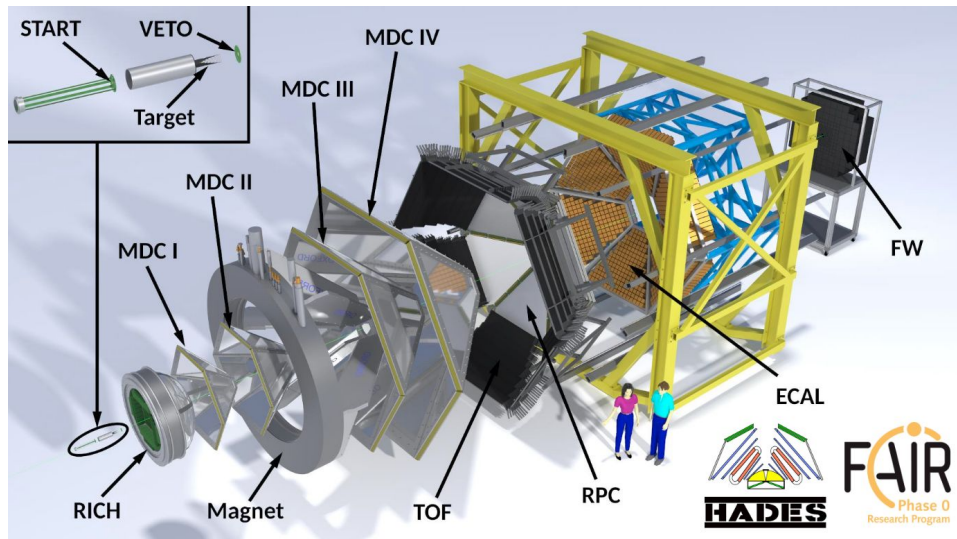
→ far from threshold, probes a kinematic region that has been poorly studied so far - important for testing theoretical models

HADES Detector

High Acceptance Di-Electron Spectrometer

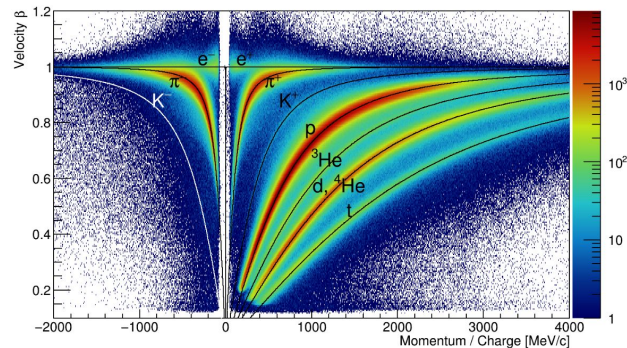
Fixed-target experiment at the SIS18 (GSI), utilizing π , p, d, and heavy-ion beams

- **Large acceptance:** $\phi \in [0^\circ, 360^\circ]$ and $\theta \in [0.5^\circ, 7^\circ] \cup [18^\circ, 85^\circ]$
- **Start + RPC/TOF** - velocity measurement
- **RICH** - lepton identification (e^\pm)
- **MDC + Magnet** - momentum determination
- **ECAL** - e^\pm and γ energy measurement

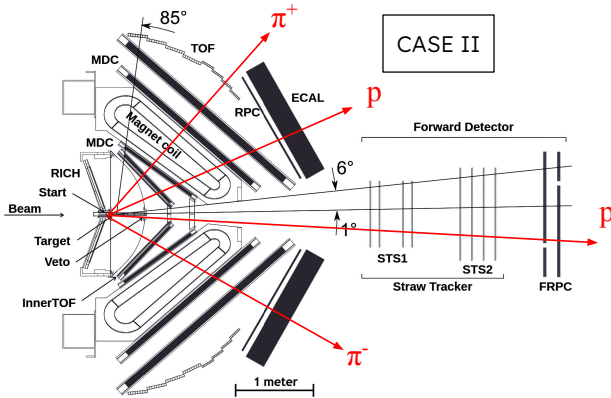
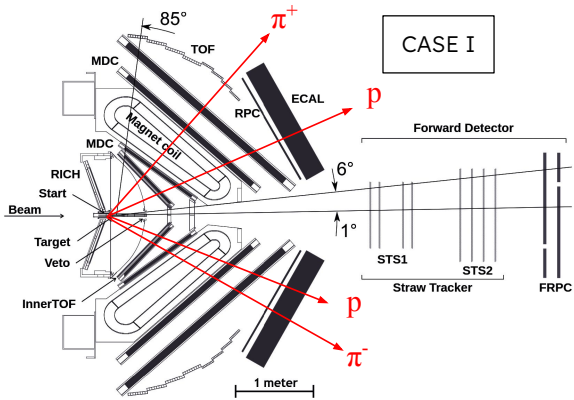


P+p 2022 run:

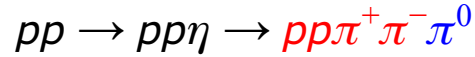
- Beam kinetic energy = 4.5 GeV ($\sqrt{s} = 3.46$ GeV)
- Luminosity = 5.66 pb^{-1}
- Forward Detector added



Analysis overview



Study η production in channel:



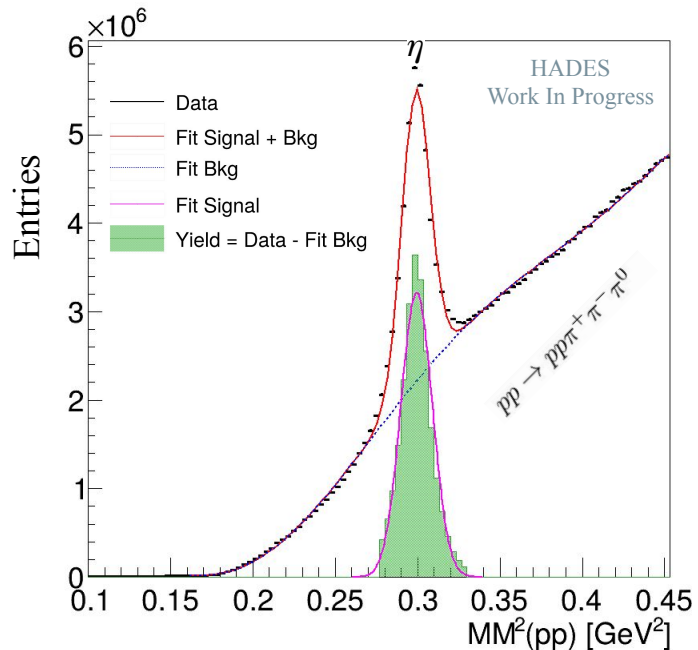
[Channel which offers greatest statistic]

π^0 obtained from kinematic fit (missing particle constraint)

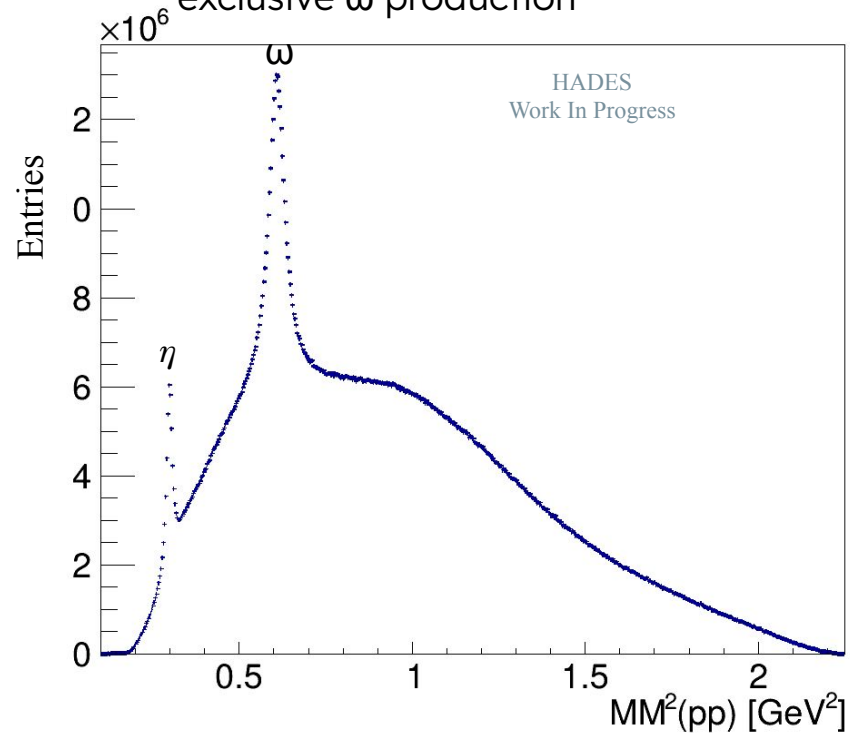
- 4-particle hypothesis: 2 protons, π^+ , π^-
- Particle identification:
 - In Magnetic spectrometer - beta vs momentum relationship
 - In Forward Detector - assumed to be protons
- Two topological cases:
 - Both protons in Magnetic Spectrometer
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- Using kinematic fit with π^0 missing mass and total 4-mom conservation constraints **[Bkg suppression and improvement of mass resolution]**
- Correcting Data for detector Acceptance x Efficiency (3D matrices, SMASH-based) **[Possibility to study reaction in 4 π]**

Total cross-section determination

A pol5 (background) + Gaussian (signal) function is fitted to the data corrected for acc x eff



(Outlook) The analysis procedure also provides a good opportunity to study exclusive ω production



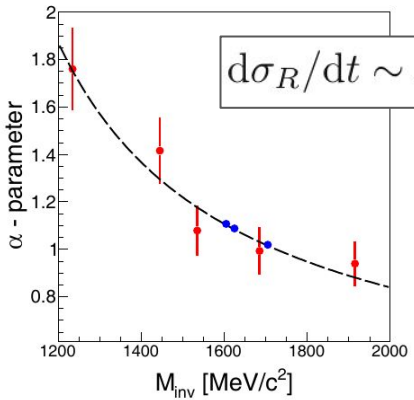
Simulation reference: SMASH

Relativistic hadronic transport model

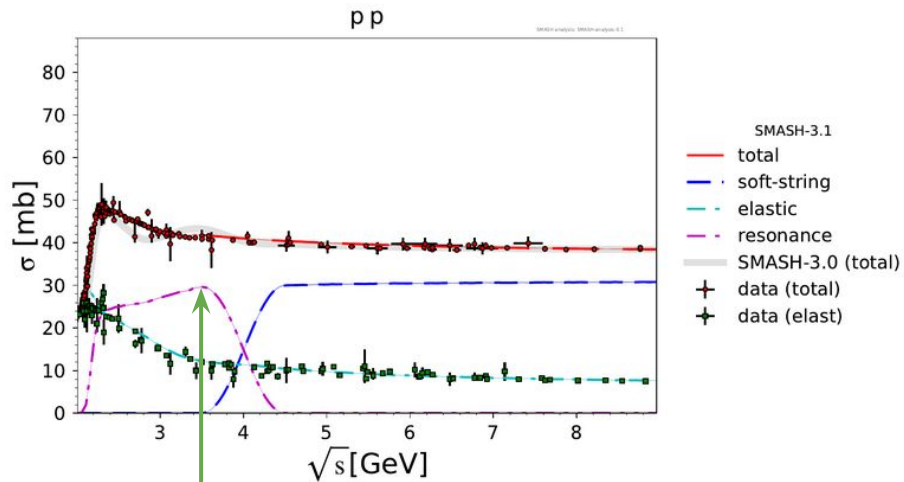
(Phys.Rev.C 94 (2016) 5, 054905)

In context of eta production in pp at 3.5 GeV:

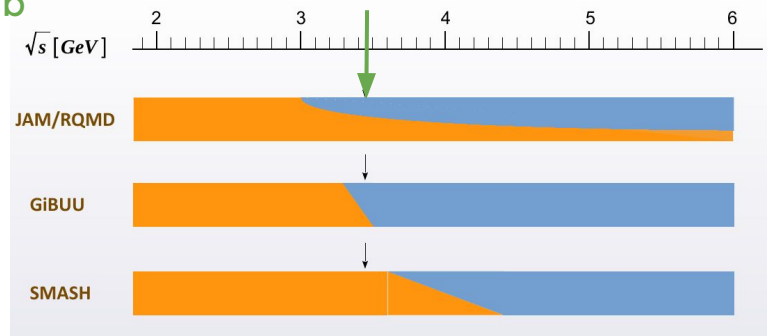
- Production always via baryon resonances
 $pp \rightarrow pN^* \rightarrow pp\eta \rightarrow pp\pi^+\pi^-\pi^0$
- N^* incoherent sum
- Parametrization of angular distribution
 production of N^* obtain from experimental
 measurements (Eur. Phys. J. A (2014) 50: 82)



Particle	J^P	N_η	DECAY MODES	
			Fraction (Γ_i/Γ)	N_η
$N(1535)$	$1/2^-$	****	30-55 %	
$N(1650)$	$1/2^-$	****	15-35 %	
$N(1710)$	$1/2^+$	***	10-50 %	
$N(1895)$	$1/2^-$	****	15-45 %	
$N(2060)$	$5/2^-$	*		
$N(2100)$	$1/2^+$	*		



$\sqrt{s} = 3.46 \text{ GeV (4.5 GeV)}$ $\sigma_{\text{total pp inelastic}} = 30 \text{ mb}$



Hadron **String**

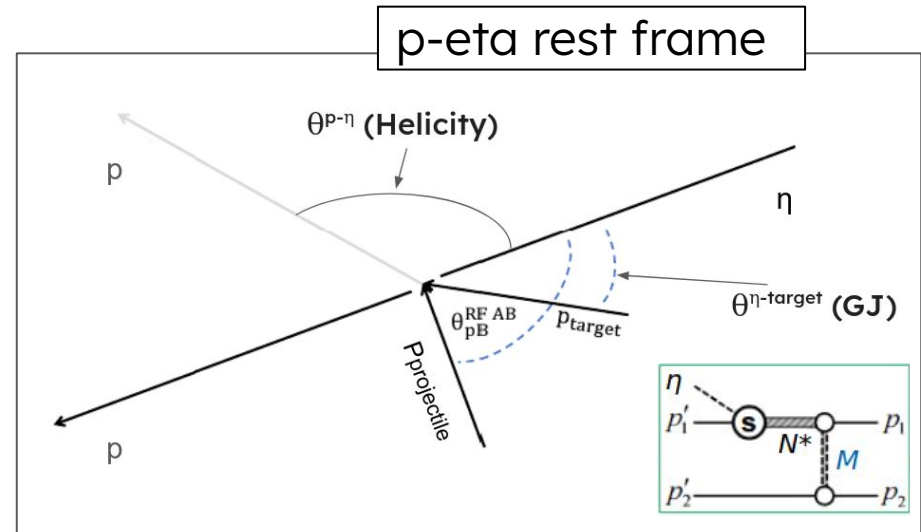
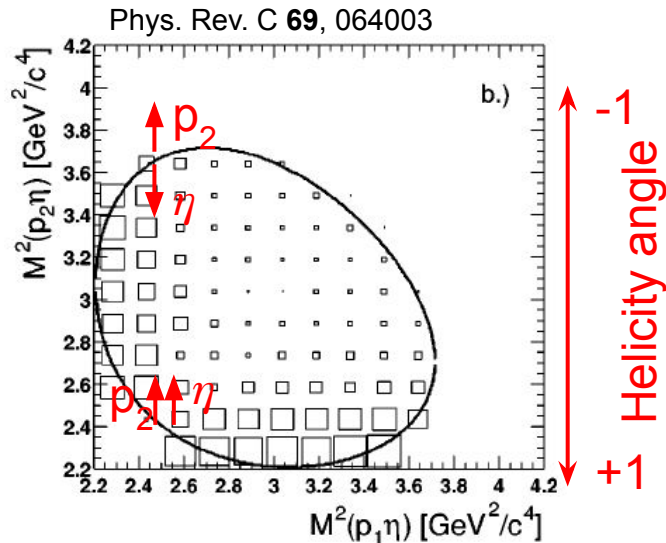
Significant uncertainty of BR, $\sigma(pp \rightarrow pN^*)$, α parameter

Observables sensitive to production mechanism

Gottfried-Jackson angles - connect entrance and exit channels, sensitive to 2-body scattering (to the spin and parity of baryon resonances)

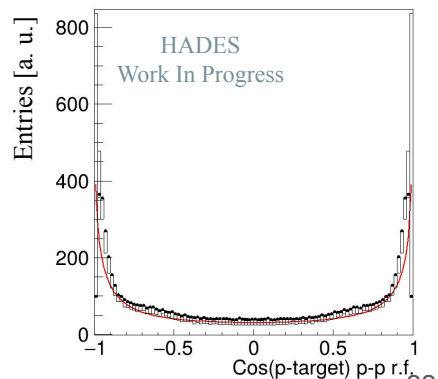
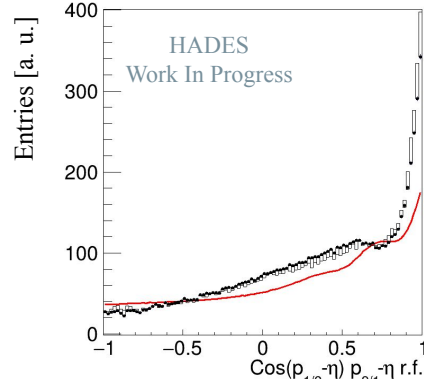
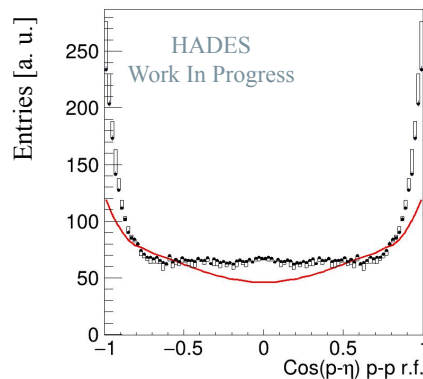
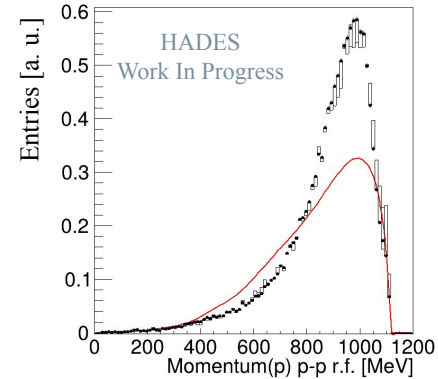
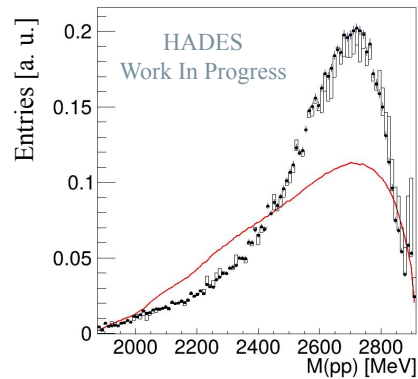
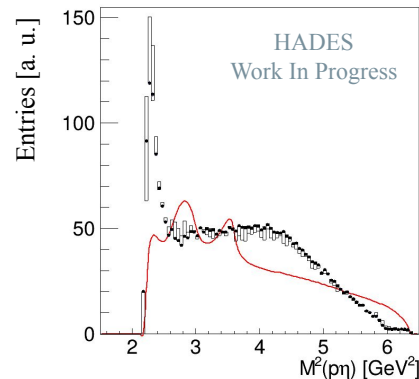
Helicity angles - quantify relations within the exit channel, special projection of Dalitz plot:

- uniformly populated Dalitz plot \rightarrow isotropic helicity angle distribution
- physical, kinematical effects modifying Dalitz plot \rightarrow anisotropic helicity angle distribution



Data - SMASH comparison

SMASH description is too simplified, it significantly underestimates the $N(1535)$ contribution, further deviations seen in other distributions.



Effective Lagrangian models

P. Lebedowicz [Phys. Rev. C **112**, 015201 (2025)]

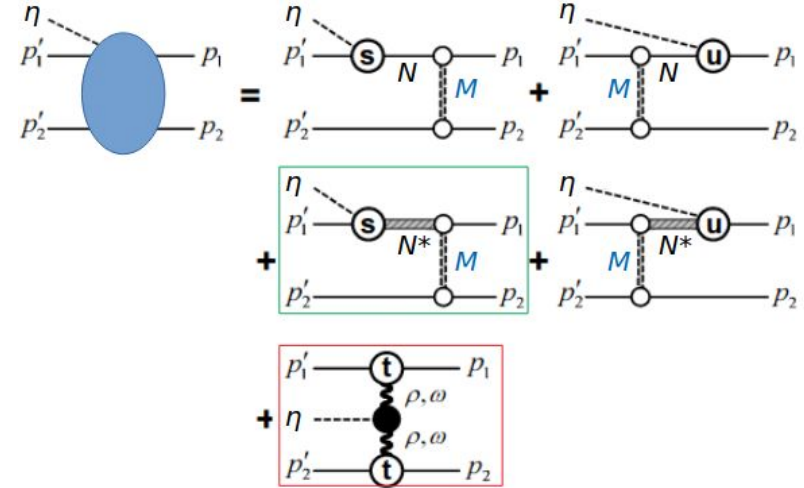
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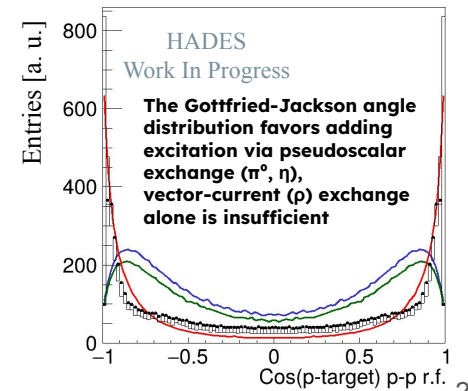
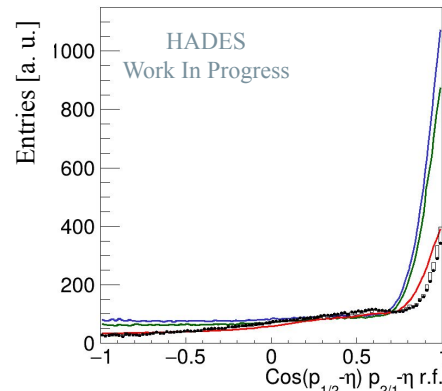
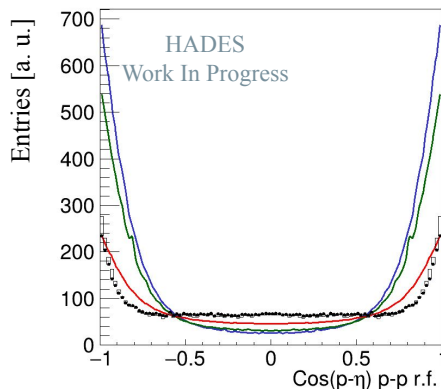
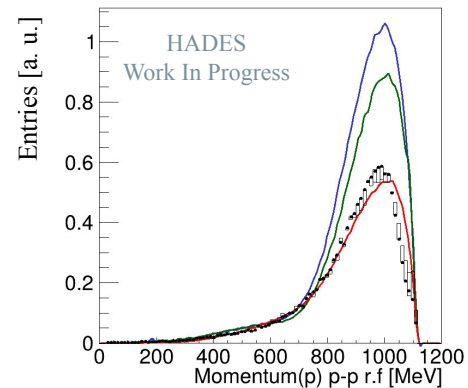
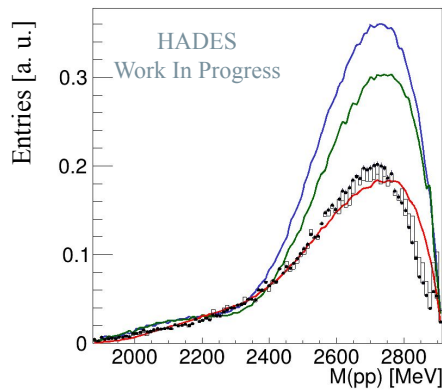
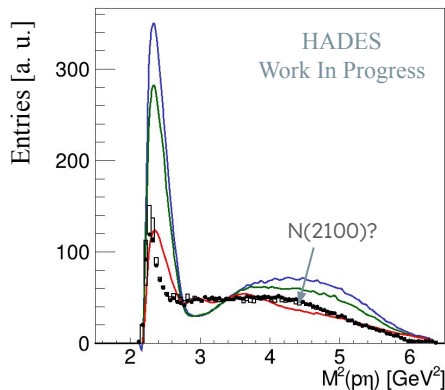


Data - Effective Lagrangian models comparison

—•—	Data	σ_{total}
—	Model 1	$\sigma_{\text{total}} = 141.0 \mu\text{b}$
—	Model 2	$\sigma_{\text{total}} = 119.9 \mu\text{b}$
—	Model 3	$\sigma_{\text{total}} = 81.4 \mu\text{b}$

Data clearly favor Model 3, both for the total cross-section and the differential distributions.

Adding N(2100) may further improve agreement with the data.



Summary

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Outlook

- Ongoing analysis favors Model 3: η production proceeds via an excitation mechanism that requires pseudoscalar meson exchange (π^0 , η), not just vector (ρ) exchange.
- Data may indicate the need for an including N(2100) contribution.
- SMASH provides a too simplified description of exclusive η production
- Models 1 and 2 (ρ -exchange only) fail to describe the data, demonstrating that vector-current exchange alone is not a sufficient description of the reaction.

- Determine total cross-section with systematic error estimation
- Study Dalitz plots of $pp \rightarrow pp\eta$ for deeper insight into baryonic resonance contributions.
- Study polar angle, momenta, and transverse momenta of the proton and η for further insight into the excitation mechanism.

BACKUP