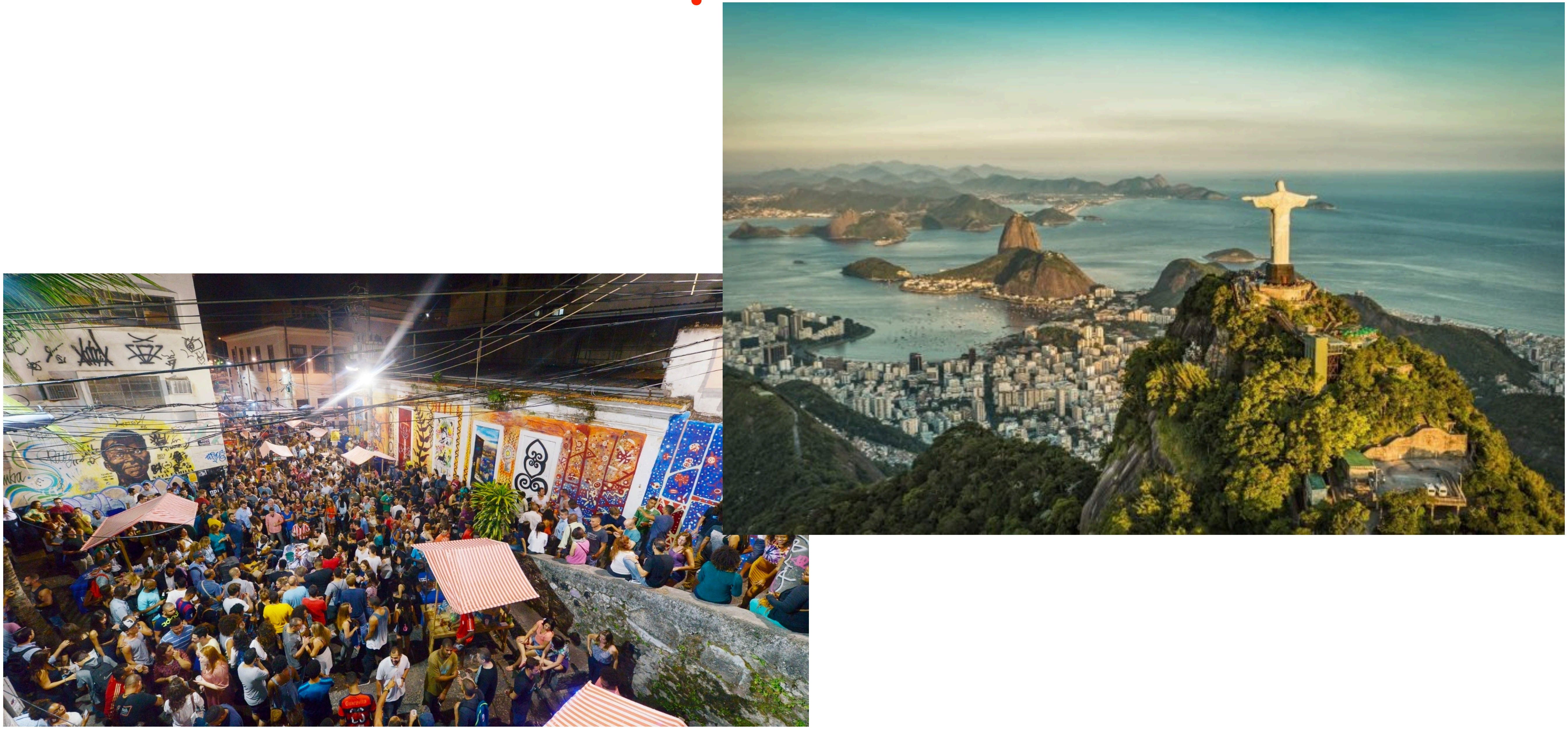
SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL
FROM QUARKS AND GLUONS TO HADRONS AND NUCLEI

PRISMA

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Recent developments with MAID



Misha Gorshteyn

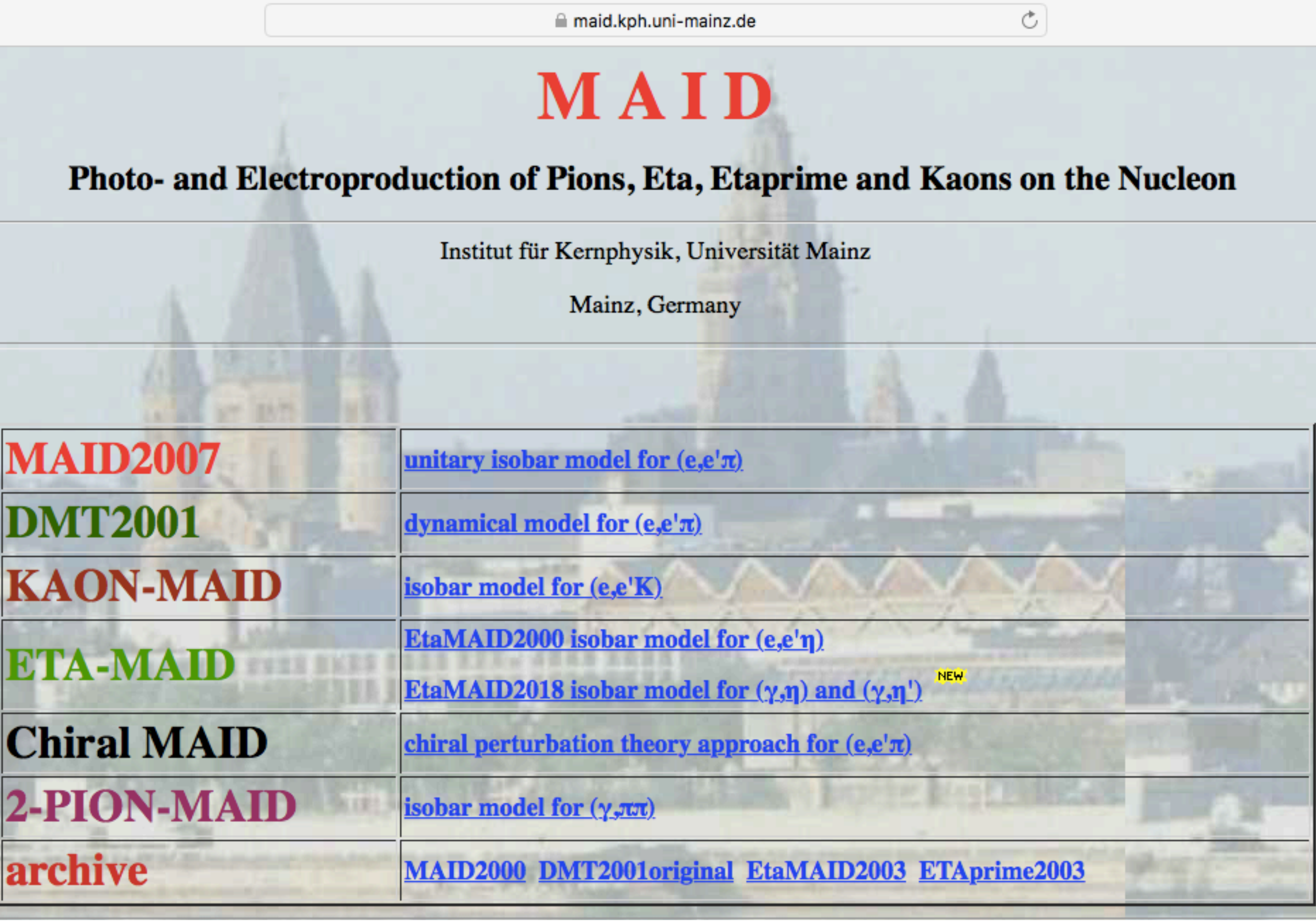
PWA/ATHOS 2019, CBPF Rio De Janeiro, Brazil, Septemer2-6, 2019

OUTLINE

Unitary isobar model MAID 1998-2019
  - New EtaMAID2018
  - Analyticity + crossing with fixed-t DR

Under development:
  - Duality (Resonance-Regge) on PW level?
  - Electroweak MAID

Summary



maid.kph.uni-mainz.de

M A I D

Photo- and Electroproduction of Pions, Eta, Etaprime and Kaons on the Nucleon

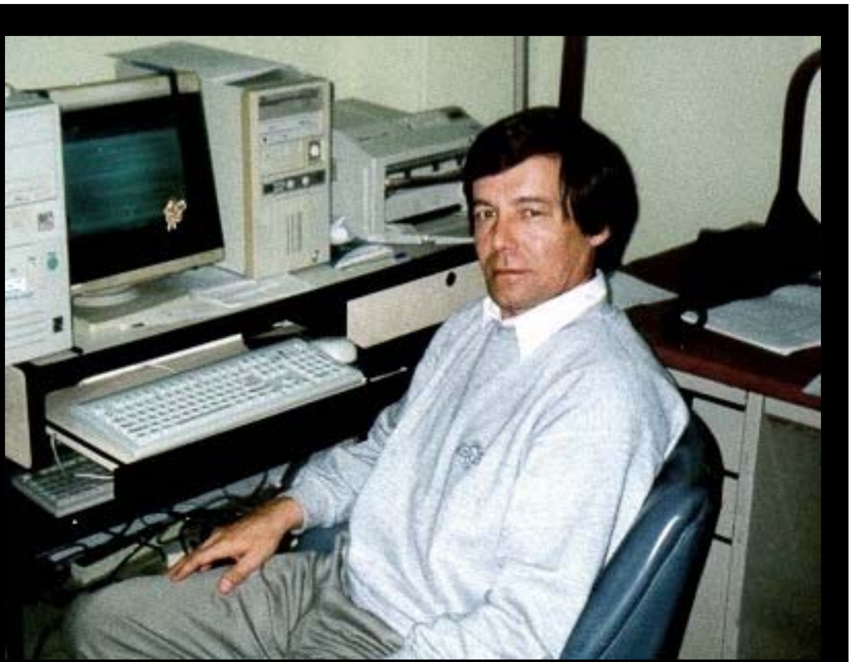
Institut für Kernphysik, Universität Mainz

Mainz, Germany

MAID2007	unitary isobar model for (e,e'π)
DMT2001	dynamical model for (e,e'π)
KAON-MAID	isobar model for (e,e'K)
ETA-MAID	EtaMAID2000 isobar model for (e,e'η) EtaMAID2018 isobar model for (γ,η) and (γ,η') NEW
Chiral MAID	chiral perturbation theory approach for (e,e'π)
2-PION-MAID	isobar model for (γ,ππ)
archive	MAID2000 DMT2001original EtaMAID2003 ETAprime2003

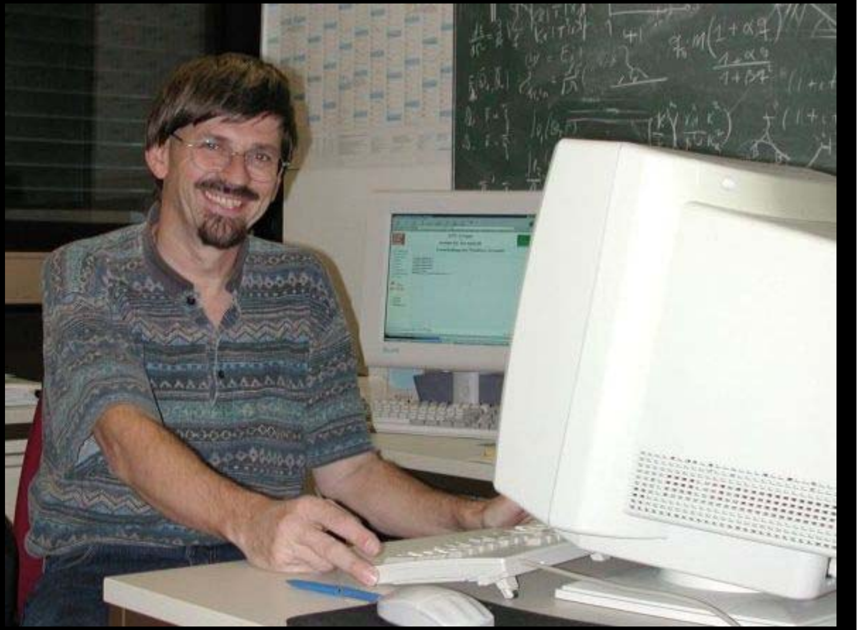
In memory of Sabit Kamalov

Dieter Drechsel



Sabit Kamalov

Olaf Hanstein



Lothar Tiator

Brief history: 1998 MAID98 - (γ,π) and (e,e’π)

2007 MAID2007 - latest update on (e,e’π)

2000 KaonMAID isobar model for (e,e’K)Λ,Σ

2001 DMT2001 - dynamical model for (e,e’π)

2001 EtaMAID2001 - isobar model for (γ,η) and (e,e’η)

2003 Reggeized EtaMAID

2007 2-PionMAID2007 - isobar model for (γ,ππ)

2012 Chiral MAID2012 - (e,e’π) at threshold in rel. ChPT

since 2013 Mainz-Tuzla-Zagreb - SE + fixed-t analyticity, L+P, …

Alfred Svarç’s talk

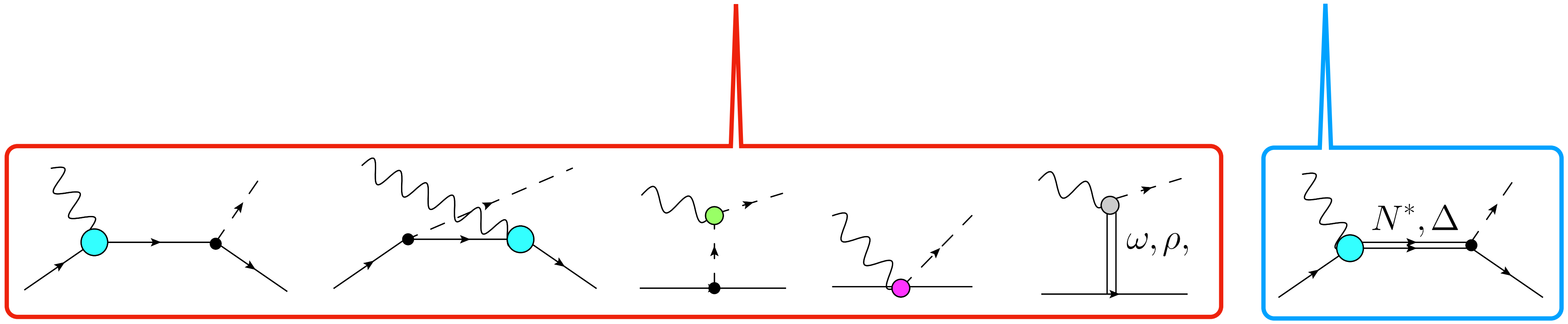
2018 EtaMAID2018 - reggeized isobar model for (γ,η(η’))

This talk

Mainz-Tuzla-Zagreb collaboration:
Victor Kashevarov, Kirill Nikonov, Michael Ostrick, Lothar Tiator, MG (Mainz);
Mirza Hadžimehmedović, Rifat Omerović, Hedim Osmanović, Jugoslav Stahov (Tuzla);
Alfred Svarc (Zagreb)

MAID model

Unitary isobar model $t^{\alpha}_{\gamma,\pi}(W,Q^2) = t^{bg,\alpha}_{\gamma,\pi}(W,Q^2)(1+it^{\alpha}_{\pi N}(W)) + t^{R,\alpha}_{\gamma,\pi}(W,Q^2)e^{i\phi_R(W,Q^2)}$



Tree-level background potential: Born + t-exchanges + Resonances

FSI: full amplitude acquires the strong phase of the pi-N amplitude $t^{\alpha}_{\pi N}$

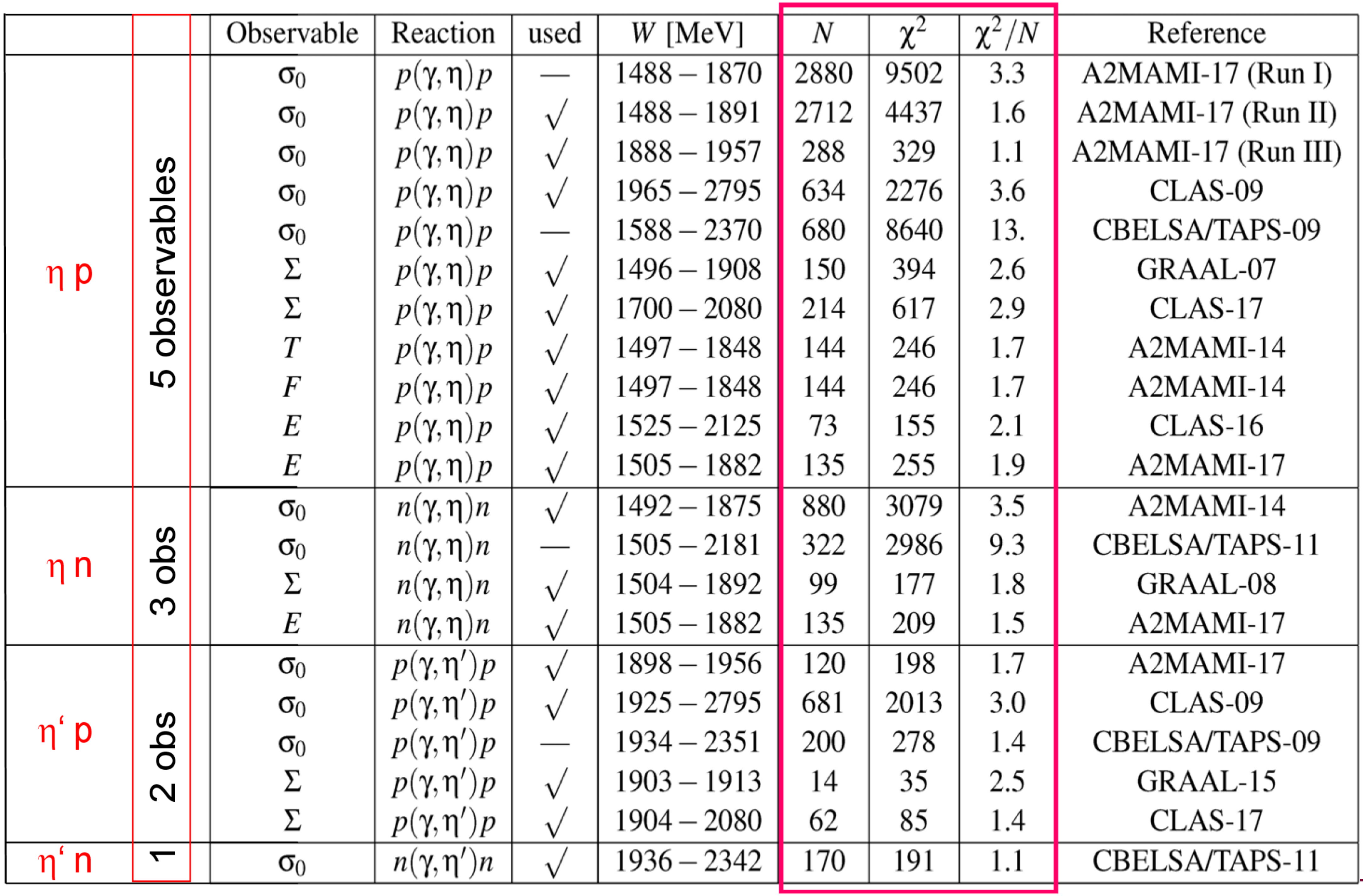
Resonances: Breit-Wigner with energy-dependent width
direct channel only (1 resonance - 1 partial wave)

$$t^{R,\alpha}_{\pi N}(W,Q^2) = A^{R}_{\alpha}(Q^2)\frac{f_{\gamma N}(W)\Gamma_{tot}(W)M_R f_{\pi N}(W)}{M_R^2 - W^2 - iM_R\Gamma_{tot}(W)}$$

Phenomenological FF's $A^{R}_{\alpha}(Q^2) = A^{R}_{\alpha}(0)(1 + a_1Q^2 + a_2Q^4 + a_3Q^6 + a_4Q^8)e^{-b_1Q^2}$

A wealth of new high quality data —> need a new EtaMAID.

total number of data points: 10,700 - our overall χ^2/data in the fit is 2.46

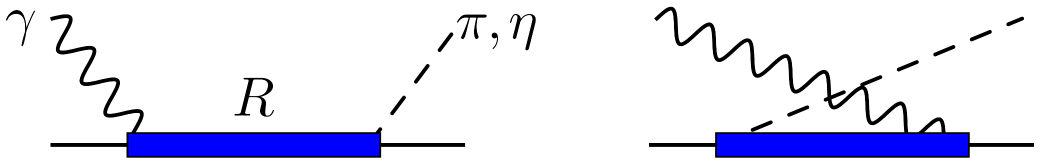


		Observable	Reaction	used	W [MeV]	N	χ^2	χ^2/N	Reference
η p	5 observables	σ_0	$p(\gamma,\eta)p$	—	1488 – 1870	2880	9502	3.3	A2MAMI-17 (Run I)
		σ_0	$p(\gamma,\eta)p$	√	1488 – 1891	2712	4437	1.6	A2MAMI-17 (Run II)
		σ_0	$p(\gamma,\eta)p$	√	1888 – 1957	288	329	1.1	A2MAMI-17 (Run III)
		σ_0	$p(\gamma,\eta)p$	√	1965 – 2795	634	2276	3.6	CLAS-09
		σ_0	$p(\gamma,\eta)p$	—	1588 – 2370	680	8640	13.	CBELSA/TAPS-09
		Σ	$p(\gamma,\eta)p$	√	1496 – 1908	150	394	2.6	GRAAL-07
		Σ	$p(\gamma,\eta)p$	√	1700 – 2080	214	617	2.9	CLAS-17
		T	$p(\gamma,\eta)p$	√	1497 – 1848	144	246	1.7	A2MAMI-14
		F	$p(\gamma,\eta)p$	√	1497 – 1848	144	246	1.7	A2MAMI-14
		E	$p(\gamma,\eta)p$	√	1525 – 2125	73	155	2.1	CLAS-16
		E	$p(\gamma,\eta)p$	√	1505 – 1882	135	255	1.9	A2MAMI-17
η n	3 obs	σ_0	$n(\gamma,\eta)n$	√	1492 – 1875	880	3079	3.5	A2MAMI-14
		σ_0	$n(\gamma,\eta)n$	—	1505 – 2181	322	2986	9.3	CBELSA/TAPS-11
		Σ	$n(\gamma,\eta)n$	√	1504 – 1892	99	177	1.8	GRAAL-08
		E	$n(\gamma,\eta)n$	√	1505 – 1882	135	209	1.5	A2MAMI-17
η‘ p	2 obs	σ_0	$p(\gamma,\eta')p$	√	1898 – 1956	120	198	1.7	A2MAMI-17
		σ_0	$p(\gamma,\eta')p$	√	1925 – 2795	681	2013	3.0	CLAS-09
		σ_0	$p(\gamma,\eta')p$	—	1934 – 2351	200	278	1.4	CBELSA/TAPS-09
		Σ	$p(\gamma,\eta')p$	√	1903 – 1913	14	35	2.5	GRAAL-15
		Σ	$p(\gamma,\eta')p$	√	1904 – 2080	62	85	1.4	CLAS-17
η‘ n	1	σ_0	$n(\gamma,\eta')n$	√	1936 – 2342	170	191	1.1	CBELSA/TAPS-11

Unlike for pion production, eta (especially eta’) threshold is close to high energy regime where resonances + LE background is not the most natural language

QCD and QED are gauge field theories ->
amplitudes for processes with e.-m. and strong interaction
possess symmetries, analyticity, unitarity

CP conservation -> crossing symmetry
resonance in crossed channel required



Crossing destroys the simple picture 1 resonance -> 1 partial wave

$$A_{\text{direct}} \sim \frac{1}{W^2 - M_R^2} \to A_{\text{crossed}} \sim \frac{1}{u(W,\theta) - M_R^2}$$

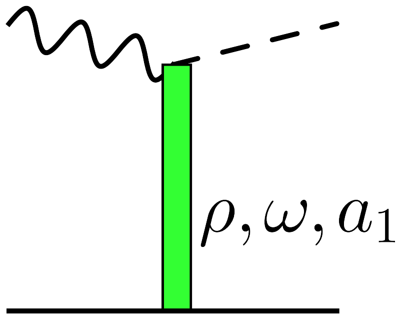
Angle-dependent crossed term -> all partial waves
(only one will be resonant; will give background in others)

At HE - u-channel Born becomes increasingly (unphysically) important

At HE also t-channel spin-1 meson exchanges rise with energy
This unphysical behavior is usually suppressed by W-dep. form factors
- but the correct solution is known - Regge theory

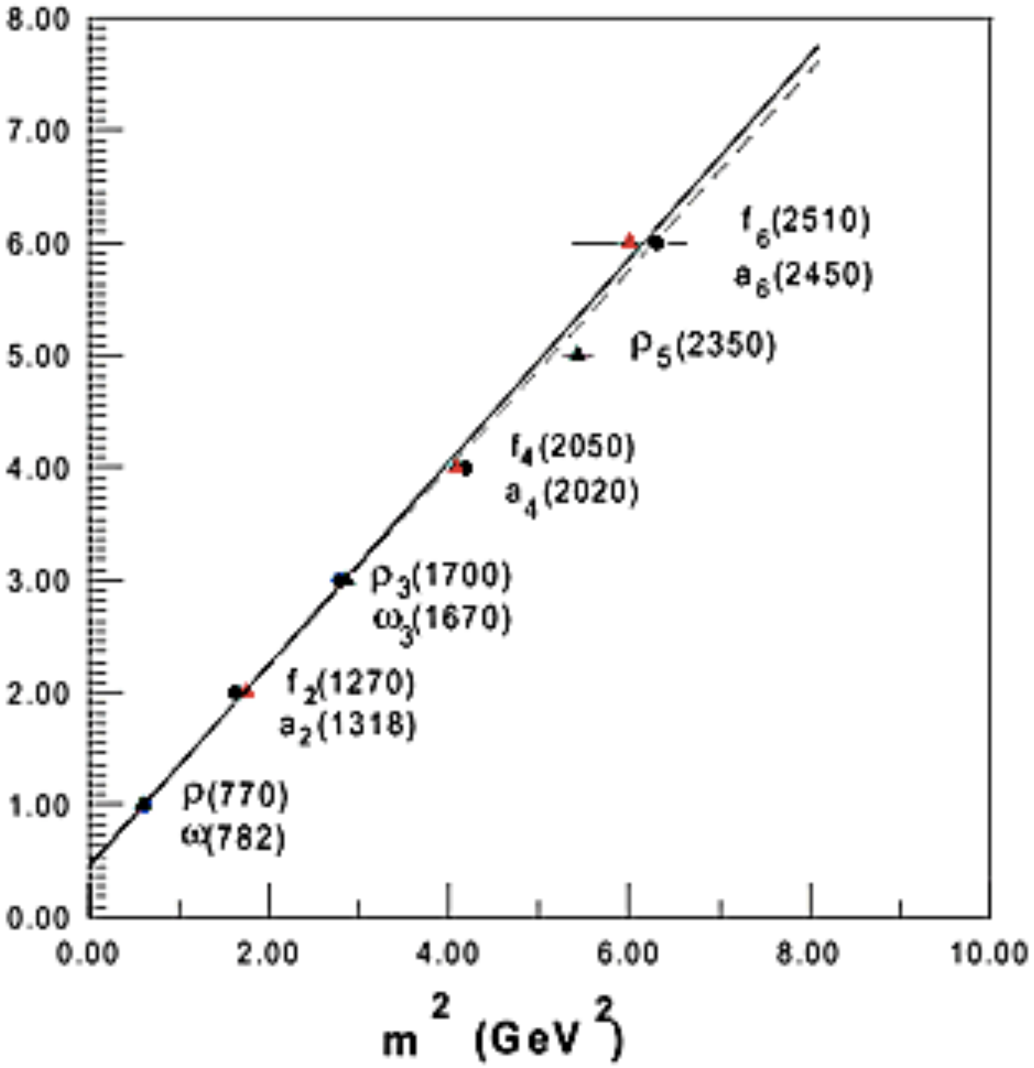
CQM and LQCD predict essentially infinite number of states

Empirical observation: above W=2.5 GeV s-channel resonances
stop being the most prominent feature of the cross section
High energies - dominated by t(u)-channel exchanges
- smooth W-dependence, strongly peaked at forward(backward) angles



Regge - exchange a tower of states
Spectrum: $J = J_0 + \boldsymbol{\alpha}' (M_J^2 - M_0^2)$
One coupling per trajectory

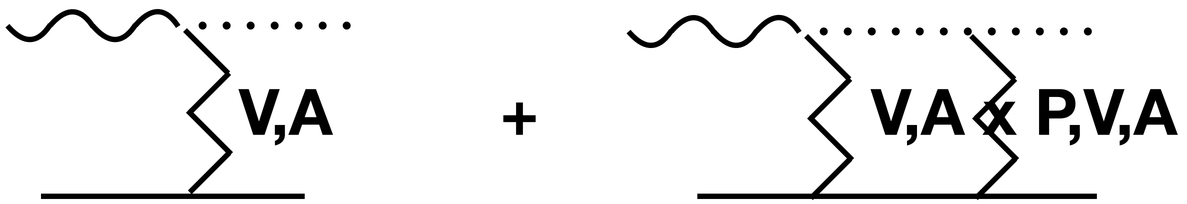
$$\sum_{\mathrm{Res}_t}^{\infty} A^t(s,t,u) \sim s^{\alpha(t)}$$



Regge fit of 3-8 GeV data for eta photoproduction

Regge poles + Regge cuts (final state interaction)

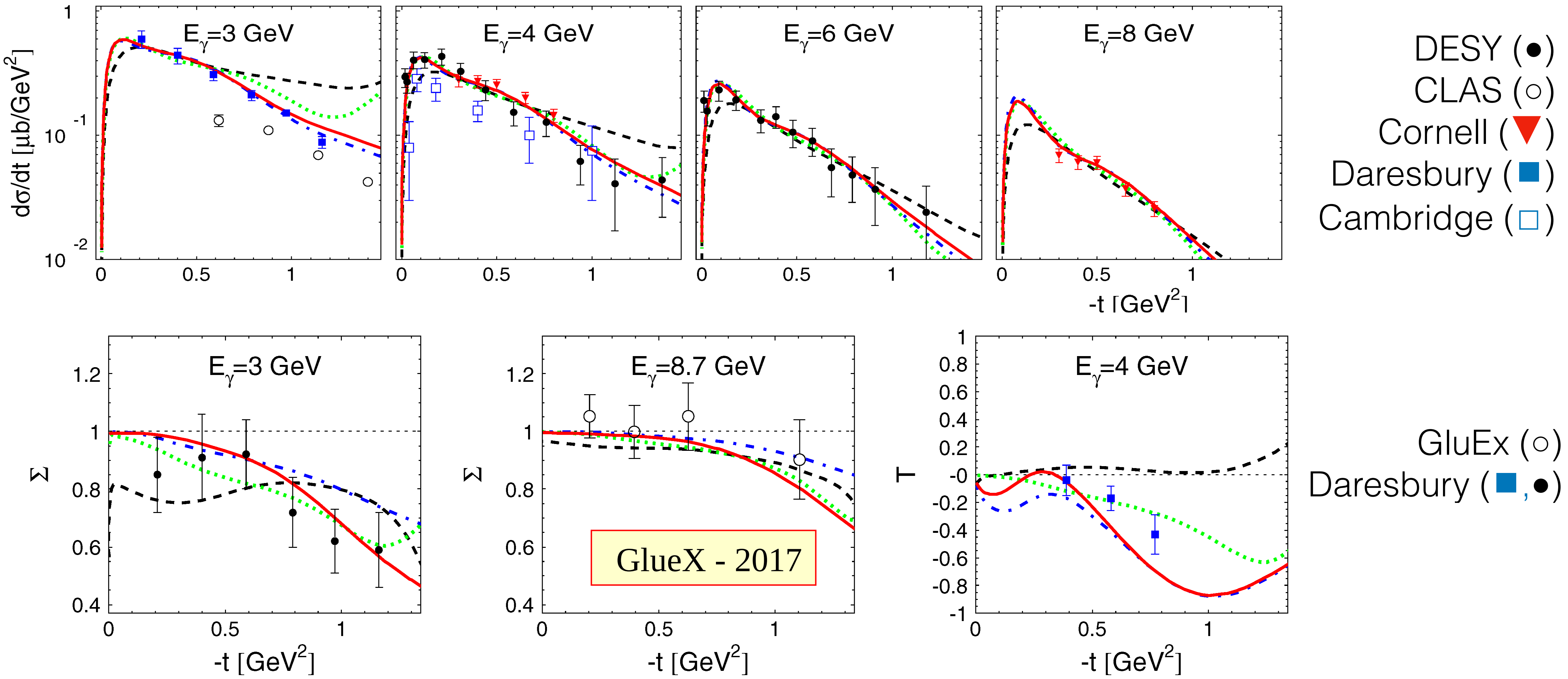
Alessandro's talk yesterday: Regge poles only



Diff. cross sections and polarisation observables for γp → ηp at high energies

comparison with different Regge models

our favoured Regge-cut model



V. L. Kashevarov, M. Ostrick, L. Tiator , Phys. Rev. C**96** (2017) 045207

To combine Regge description with the isobar model - need to answer the question:
How meson Regge exchanges relate to baryon resonances?

Duality: a full theory knows all its states and their properties

Algebraic models (van Hove, Veneziano) - duality is trivial:
spectra and couplings are exactly known

$$A(s,t,u) = \sum_{\mathrm{Res}_s}^{\infty} A^s(s,t,u) = \sum_{\mathrm{Res}_t}^{\infty} A^t(s,t,u)$$

The infinite sum over t-channel residua can be performed = Regge

Exploit duality for extracting few low-lying resonances

Remove part of the strength of Regge in the resonance region
to leave space for resonances

$$A(s,t,u) = \sum_{\mathrm{Res}_s=1}^{N} A^{\mathrm{Res}}(s,t,u) + \sum_{\mathrm{Res}_t}^{\infty} A^t(s,t,u) - \sum_{\mathrm{Res}_s=1}^{N} A^{\mathrm{Res}}(s,t,u)$$

$$\approx \sum_{\mathrm{Res}_s=1}^{N} A^{\mathrm{Res}}(s,t,u) + DF(W) \times A^{\mathrm{Regge}}(s,t,u)$$

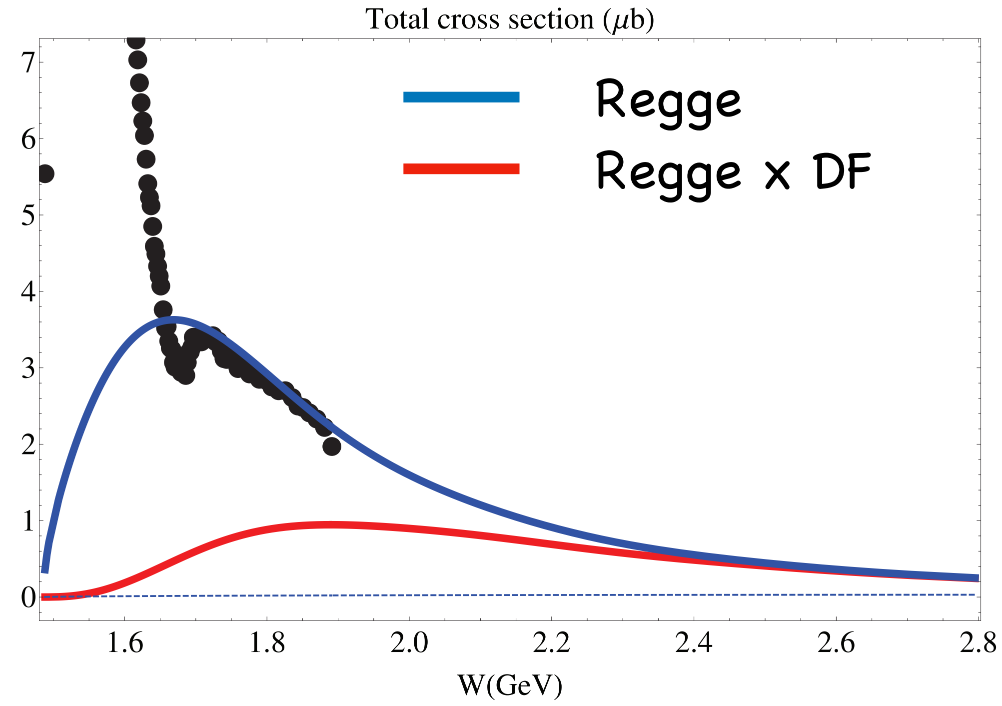
Damping factor removes double counting:
DF(W) -> 0 at threshold;
DF(W) -> 1 at high energy

DF - guessed or fitted

$$DF(W) = 1 - e^{-\frac{W^2 - W_{thr}^2}{\Lambda^2}}$$

Effect of the damping factor

Total CS (γ,η)



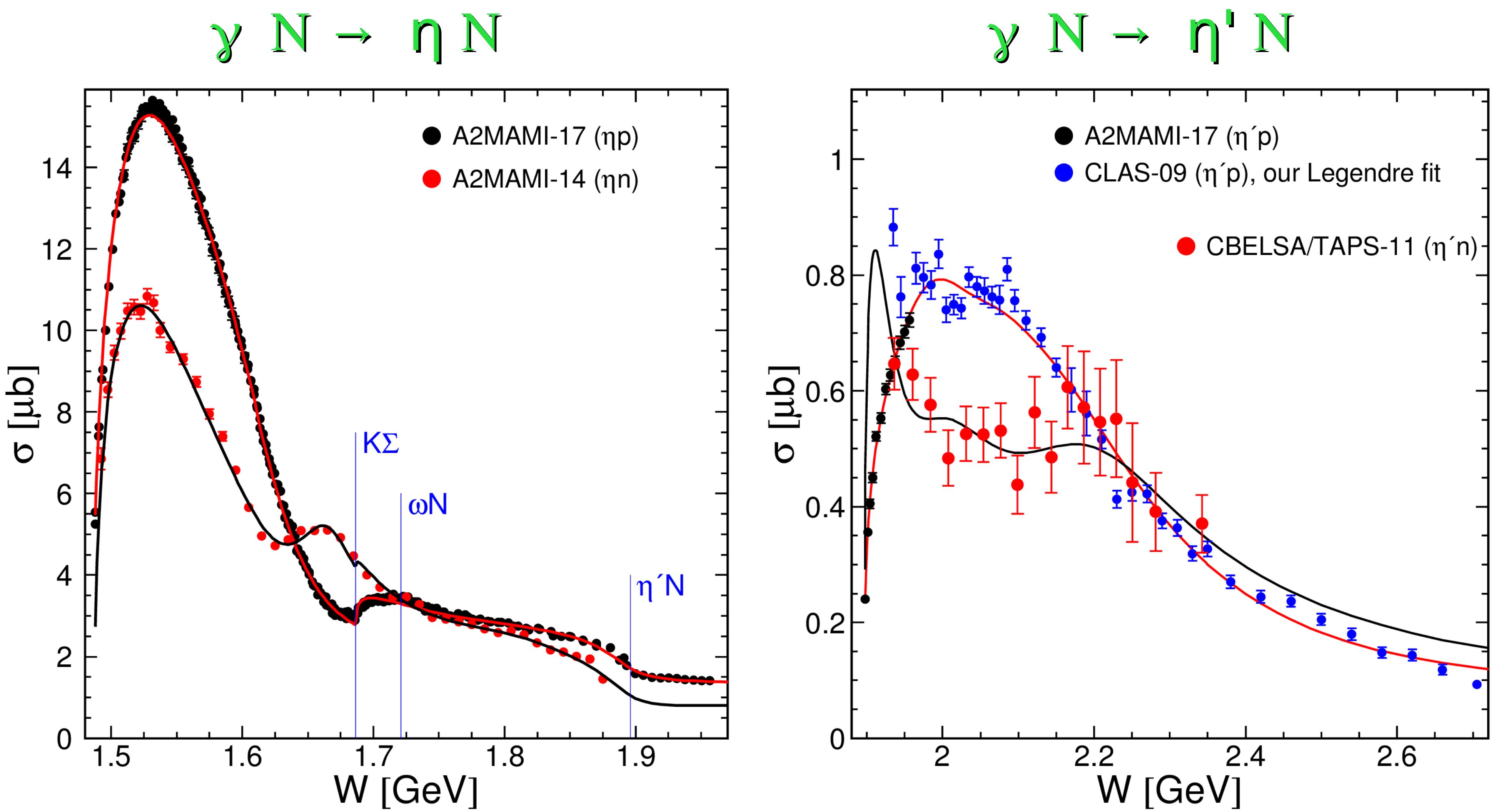
EtaMAID Ansatz:

$$T_{\gamma,\eta}(W,\theta) = T^{\mathrm{Born}}_{\gamma,\eta}(W,\theta) + T^{\mathrm{Regge}}_{\gamma,\eta}(W,\theta) \times F_d(W) + \sum_{\alpha=J,l} P_\alpha(\cos\theta)\, t^{\alpha,\,Res_j}_{\gamma,\eta}(W) \times e^{i\Phi_j}$$

phenomenological phase
taken as a free parameter

21 N* resonances included in the ηp, ηn channels
12 N* resonances included in the η’p, η'n channels

Description of total CS


γ N → η N

γ N → η' N

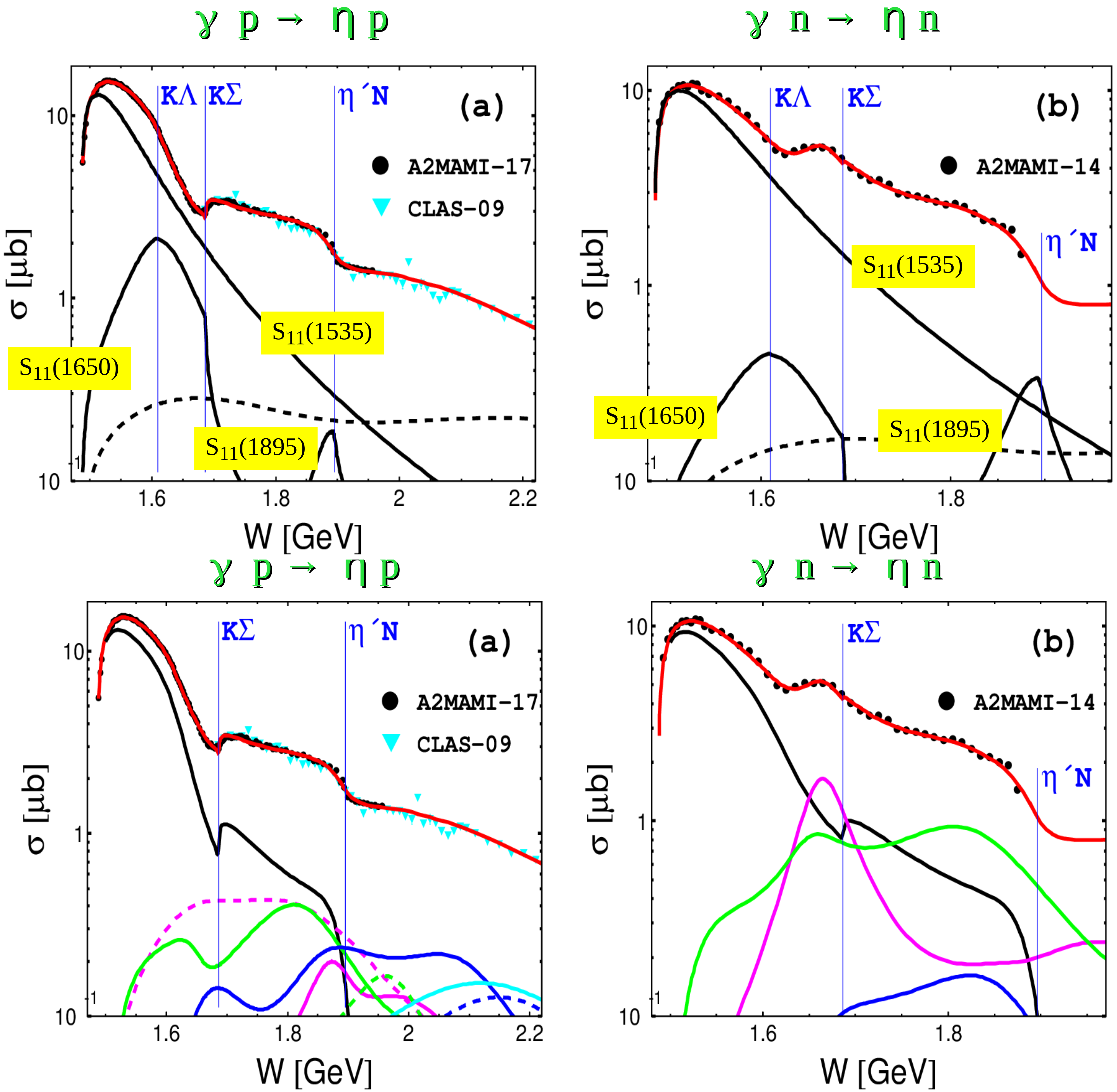
Lines: full solution for γp (red) and γn (black) channels.

γ p → η p: χ^2 = 238.6/125 ≈ 1.91;
γ n → η n: χ^2 = 120.6/44 ≈ 2.74;

γ p → η´ p: χ^2 = 9.46/12 ≈ 0.79 (A2MAMI)
γ n → η´ n: χ^2 = 10.9/17 ≈ 0.64

Total CS for γN —> ηN:

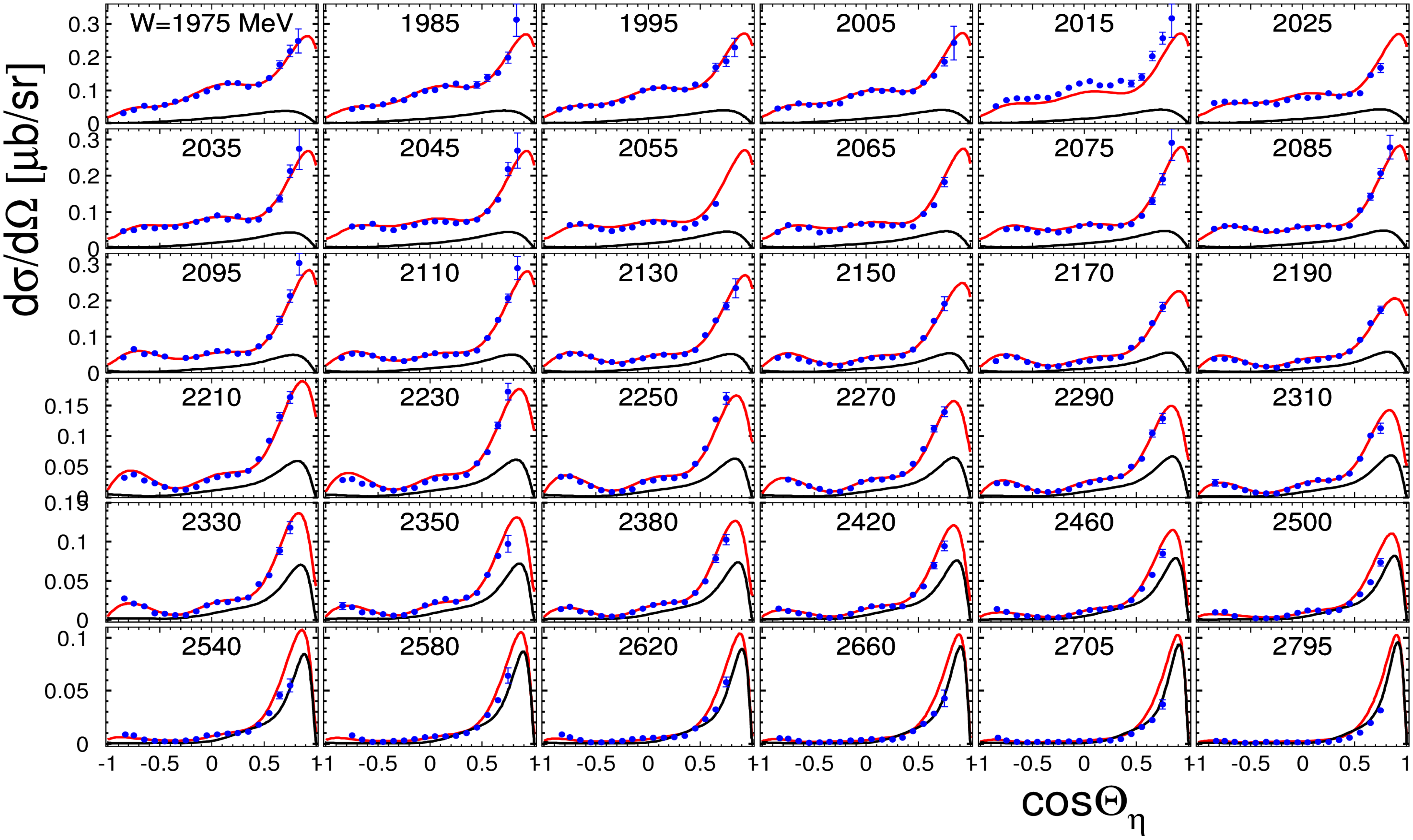
Contribution of partial waves



S_{11} – black solid;
P_{11} – magenta solid; P_{13} – magenta dashed
D_{13} – green solid; D_{15} – green dashed
F_{15} – blue solid; F_{17} – blue dashed
G_{17} – cyan solid

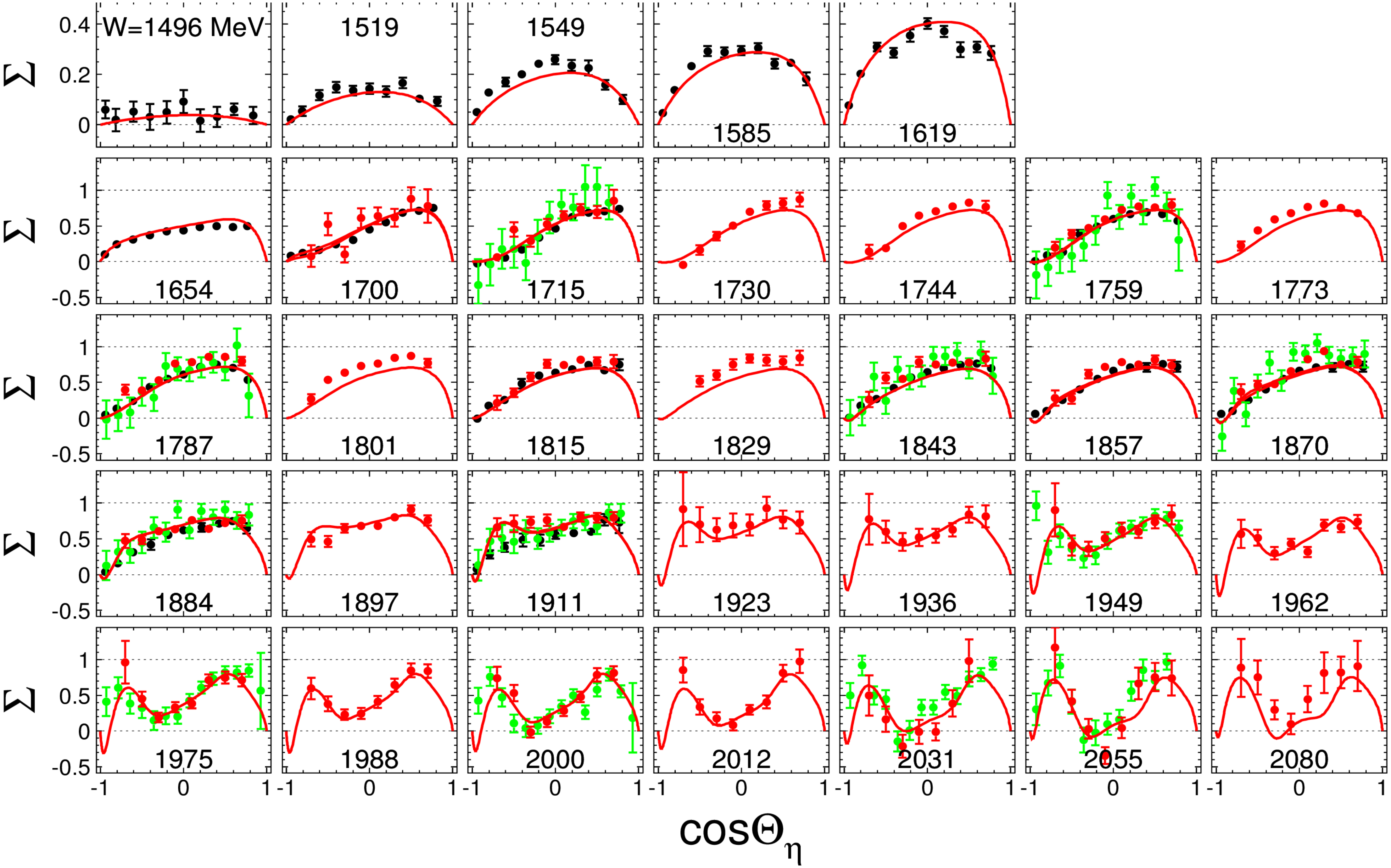
Angular distributions: γp —> ηp

CLAS ●; Regge + Born — ; Total —



$\chi^2 = 2265/634 \approx 3.57$

Beam asymmetry Σ: $\gamma p \longrightarrow \eta p$



Data: black – GRAAL-07; red – CLAS-17; green – CBELSA/TAPS preliminary

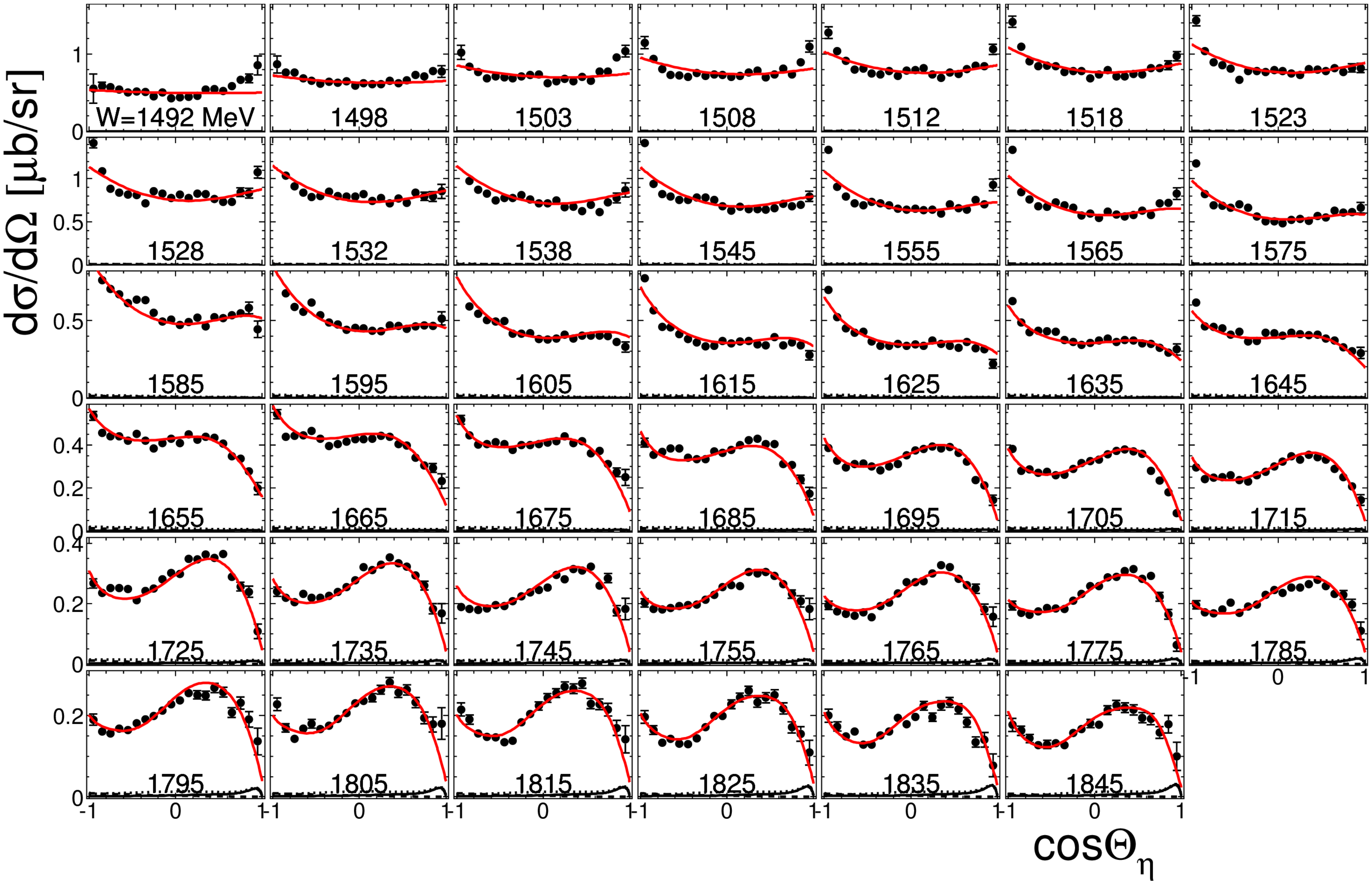
$X^2 = 531.8/150 \approx 3.55$

$X^2 = 694.1/214 \approx 3.24$

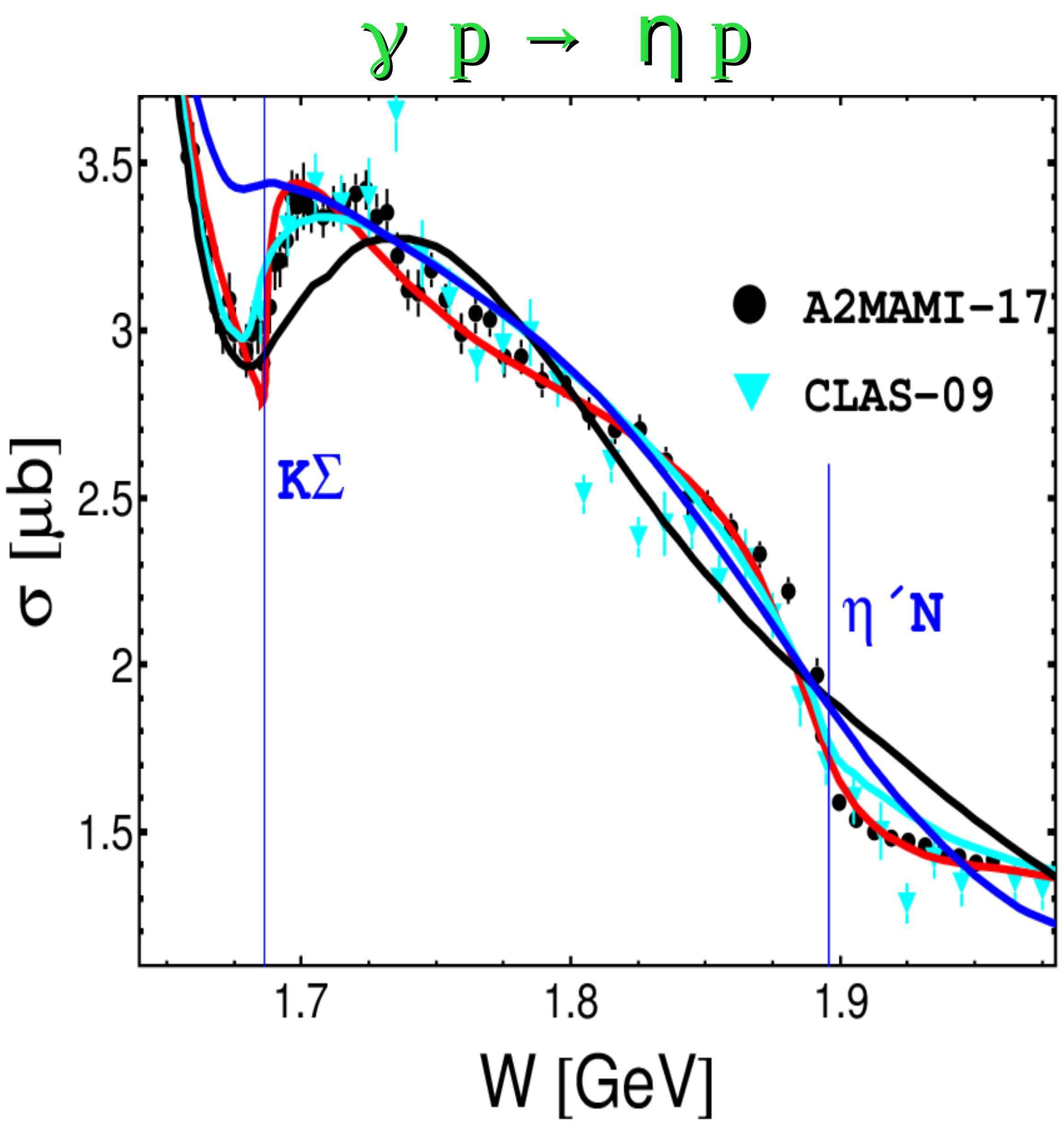
$X^2 = 309.5/156 \approx 1.98$

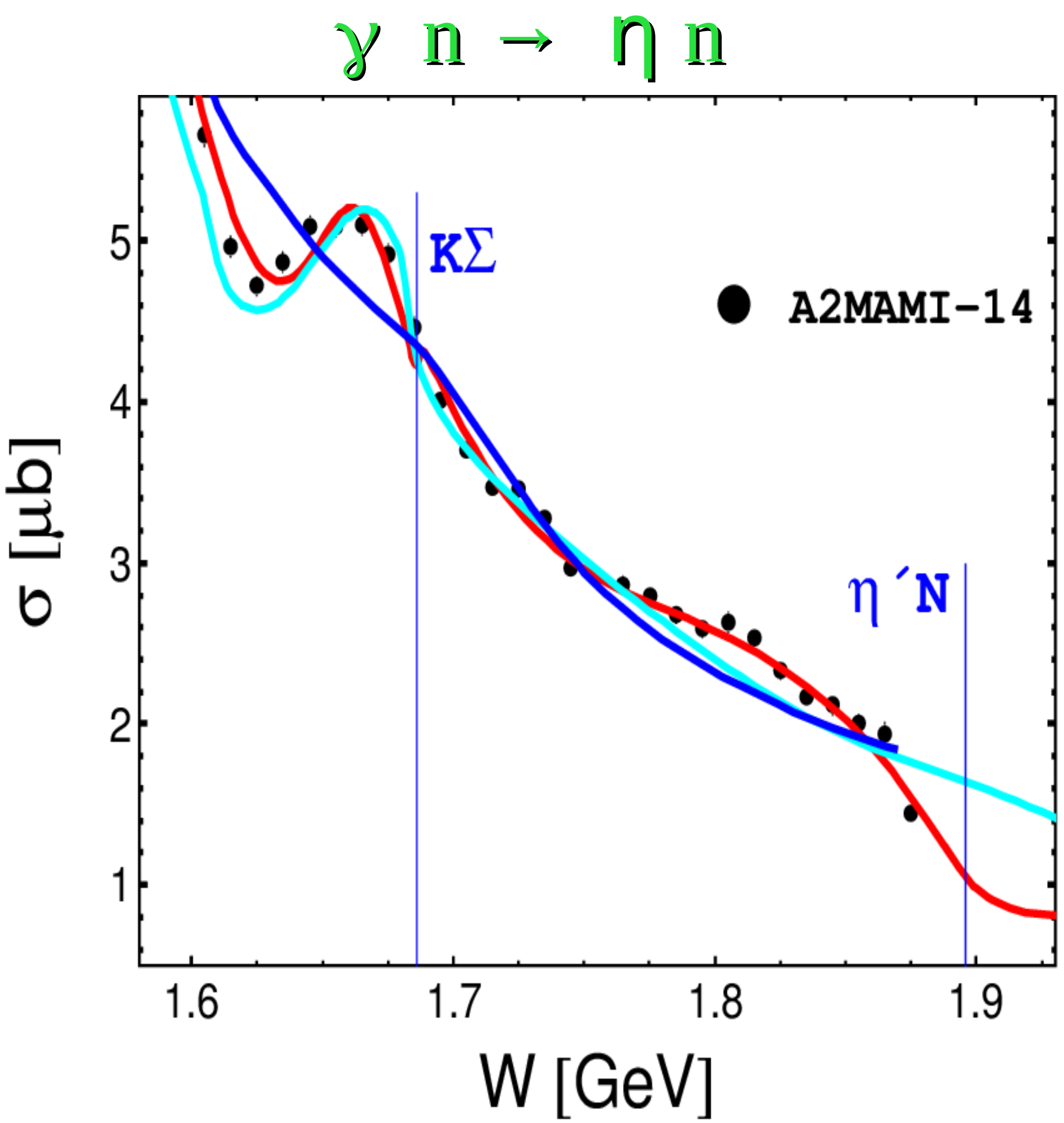
Angular distributions: γn —> ηn

A2/MAMI ●; Regge + Born —; Total —



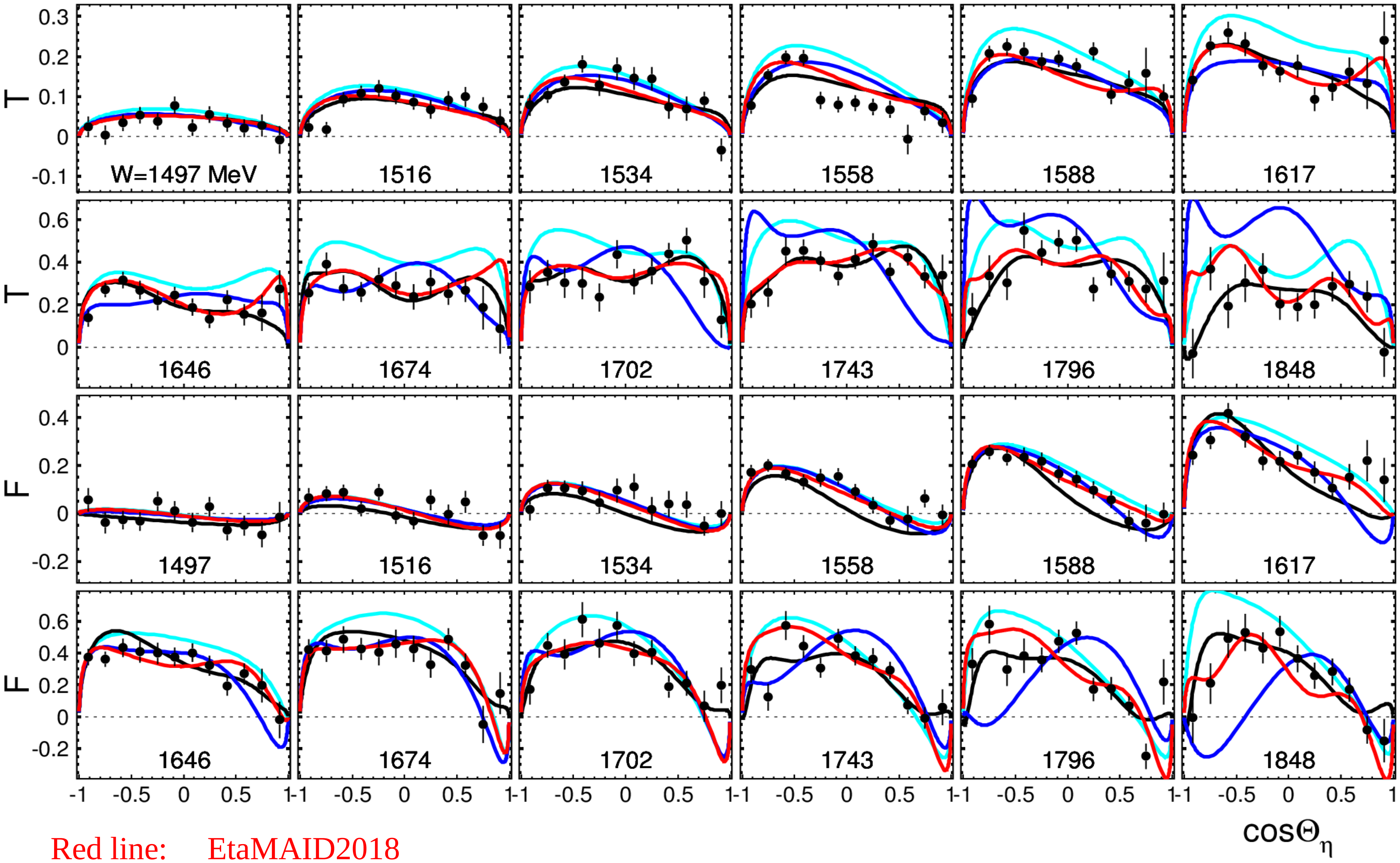
Comparison to other PWA for γN —> ηN: total cross section





Red line: EtaMAID2018
Cyan line: BnGa
Blue line: KSU
Black line: JüBo

Comparison to other PWA for $\gamma p \longrightarrow \eta p$: polarization observables T,F

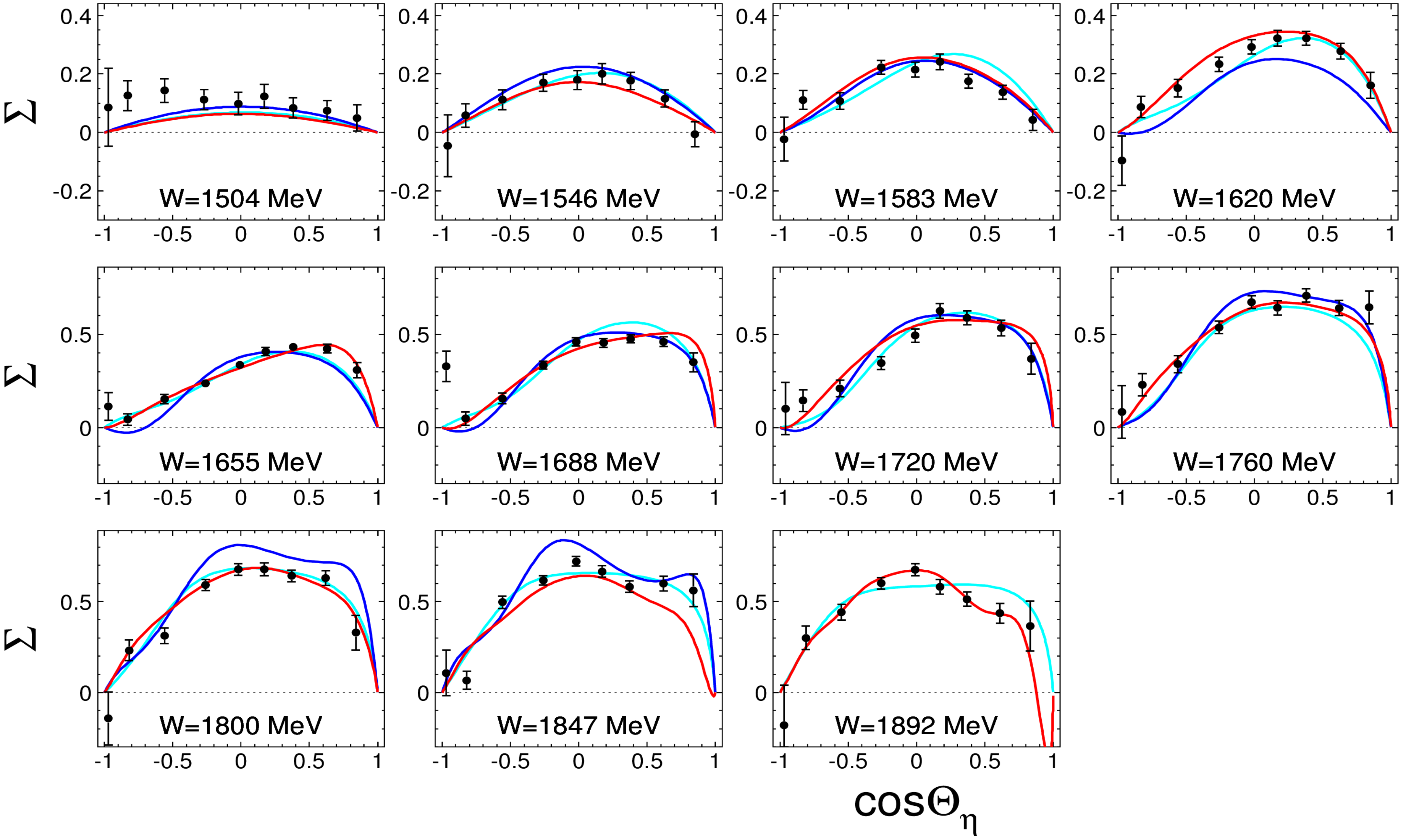


Red line: EtaMAID2018
Cyan line: BnGa
Blue line: KSU
Black line: JüBo

Data: A2MAMI-14

T: $\chi^2 = 255.3/144 \approx 1.77$; F: $\chi^2 = 253.3/144 \approx 1.76$

Comparison to other PWA for $\gamma n \longrightarrow \eta n$: polarization observable Σ



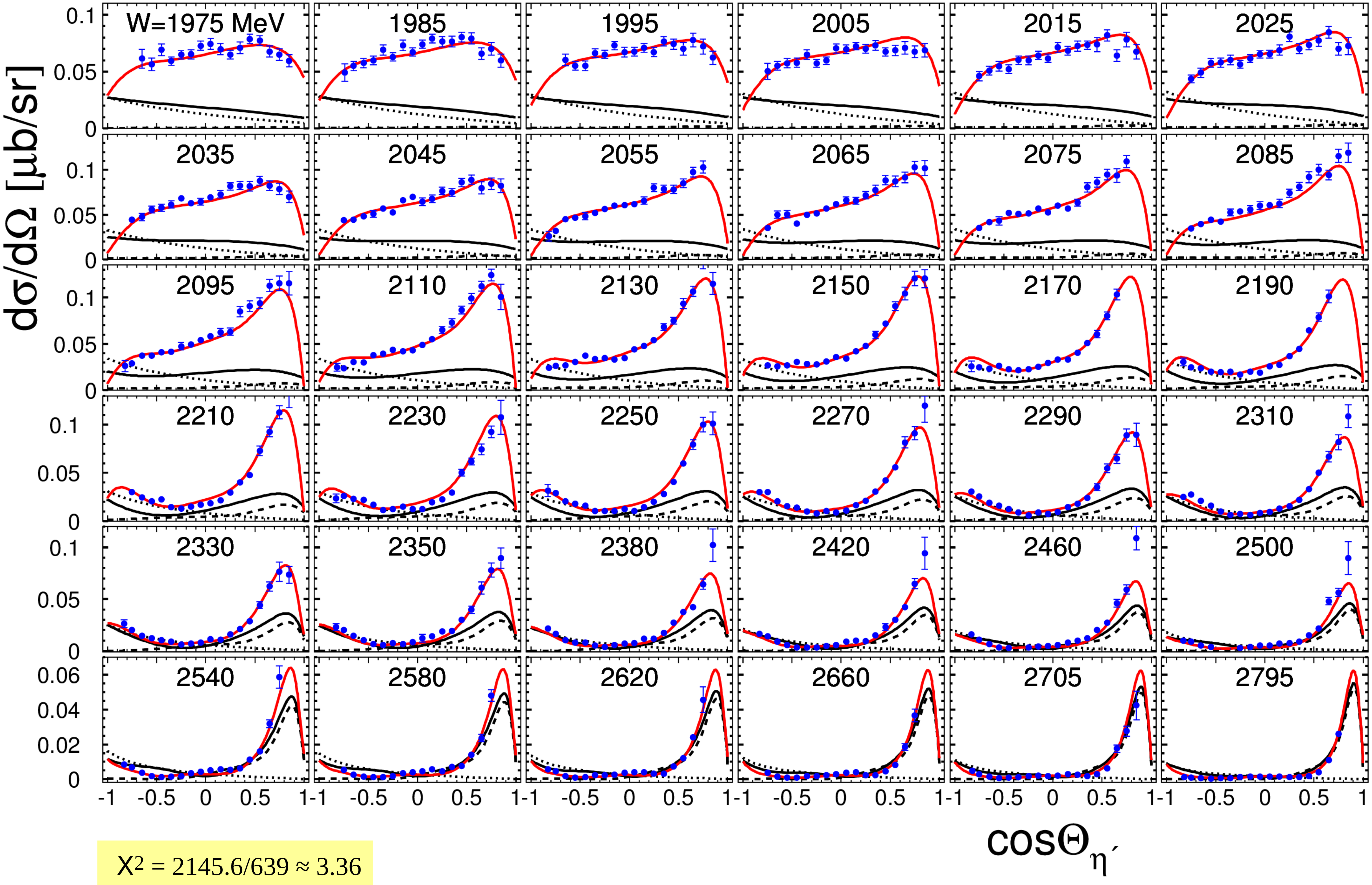
Red line:	EtaMAID2018
Cyan line:	BnGa
Blue line:	KSU

$X^2 = 238.5/99 \approx 2.41$

Data: GRAAL-08

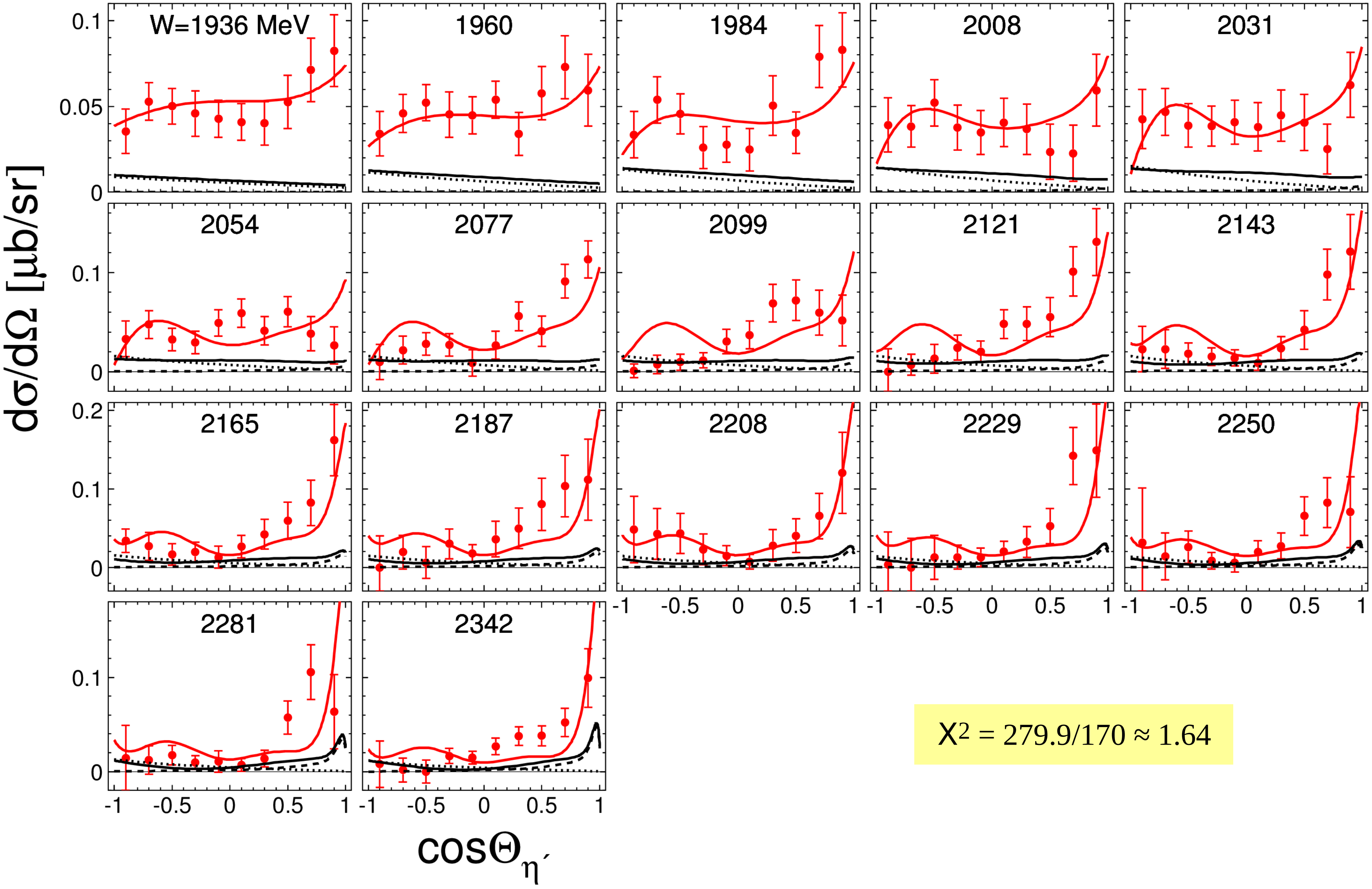
Angular distributions: $\gamma p \longrightarrow \eta' p$

CLAS ●; Regge + Born ▬ ; Total ▬



$\chi^2 = 2145.6/639 \approx 3.36$

Angular distributions: γn —> η’n   CBELSA/TAPS-11 ●; Regge + Born — ; Total —



X^2 = 279.9/170 ≈ 1.64

Bottomline: good description of all available data in 4 channels (ηp, ηn, η’p, η’n)
The resonance region model is smoothly matched to Regge by construction

Next step: implement crossing, analyticity and unitarity

Fixed-t dispersion relation $$\mathrm{Re}A_i^I(\nu,t) = A_i^{I,pole}(\nu,t) + \frac{1}{\pi}\mathscr{P}\int_{\nu_{thr}}^{\infty} d\nu' \left[\frac{1}{\nu'-\nu} + \frac{\xi_i^I}{\nu'+\nu}\right] \mathrm{Im}A_i^I(\nu',t)$$

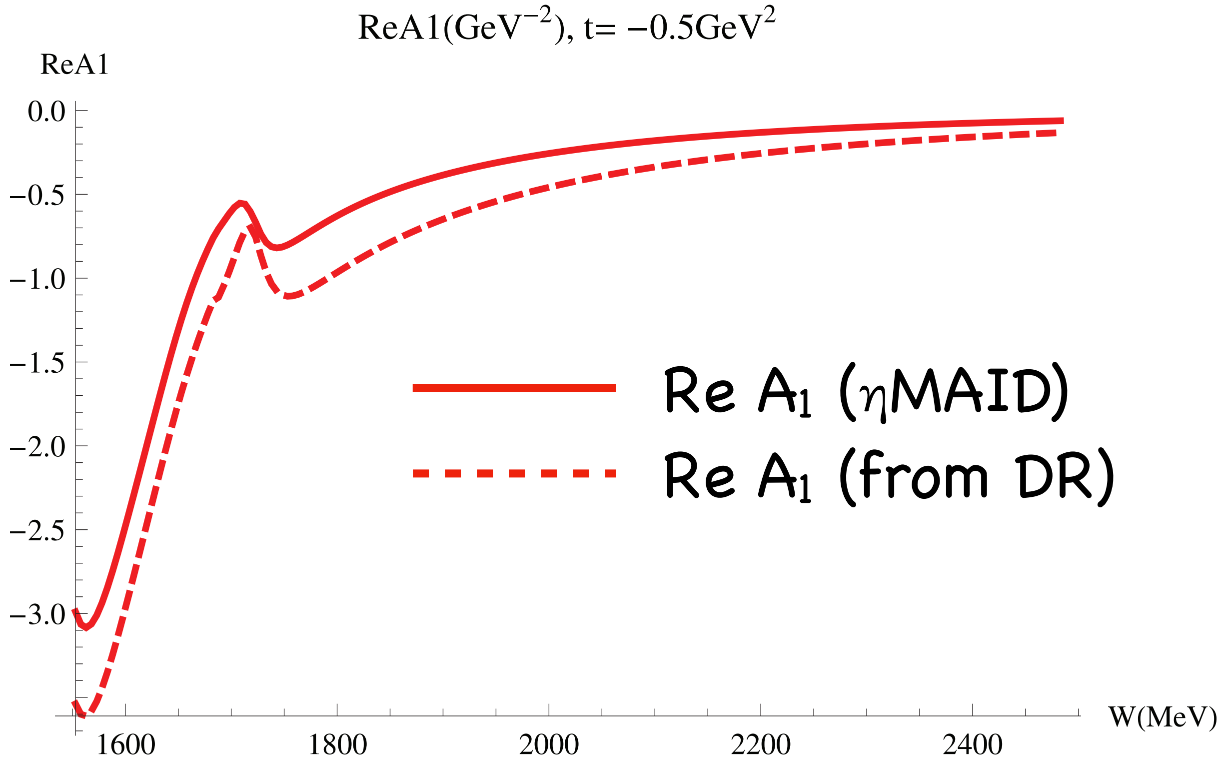
Eta photoproduction with fixed-t dispersion relations:

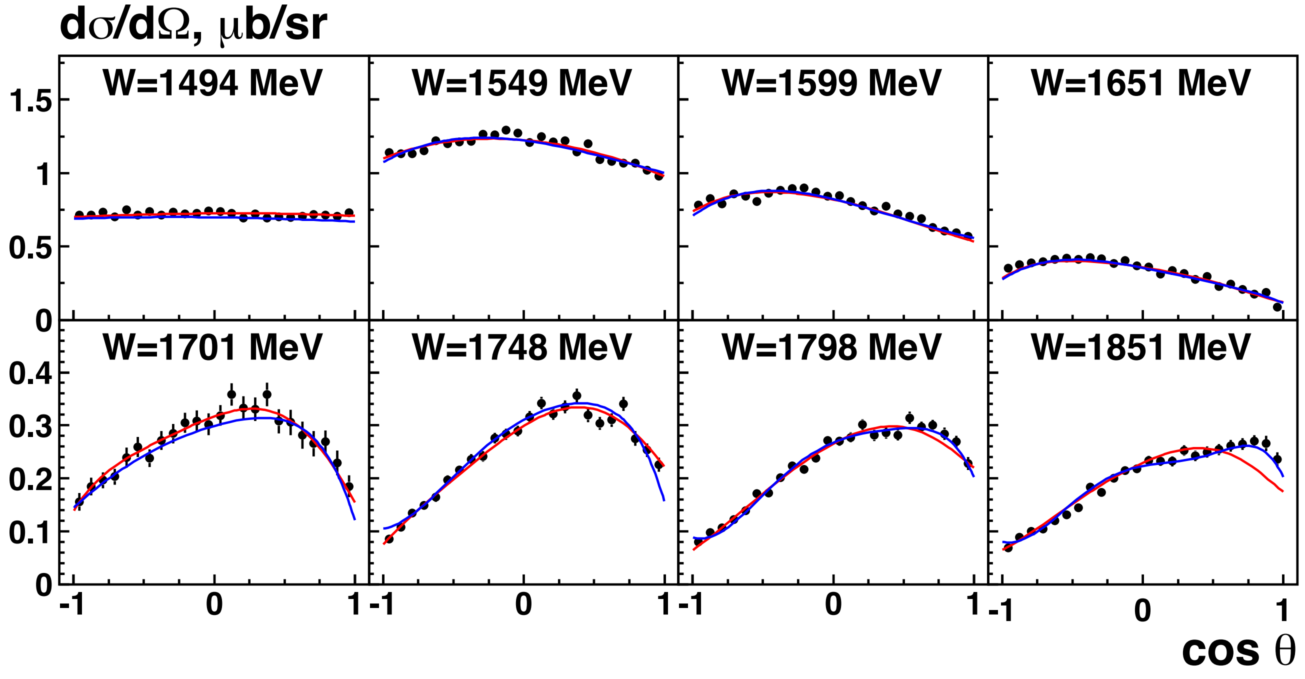
1. Isobar model fit: Born + Regge x DF + Resonances
2. Obtain Re, Im parts of the amplitudes
3. Use Im part in a dispersion relation
4. Obtain Re part
5. Reiterate

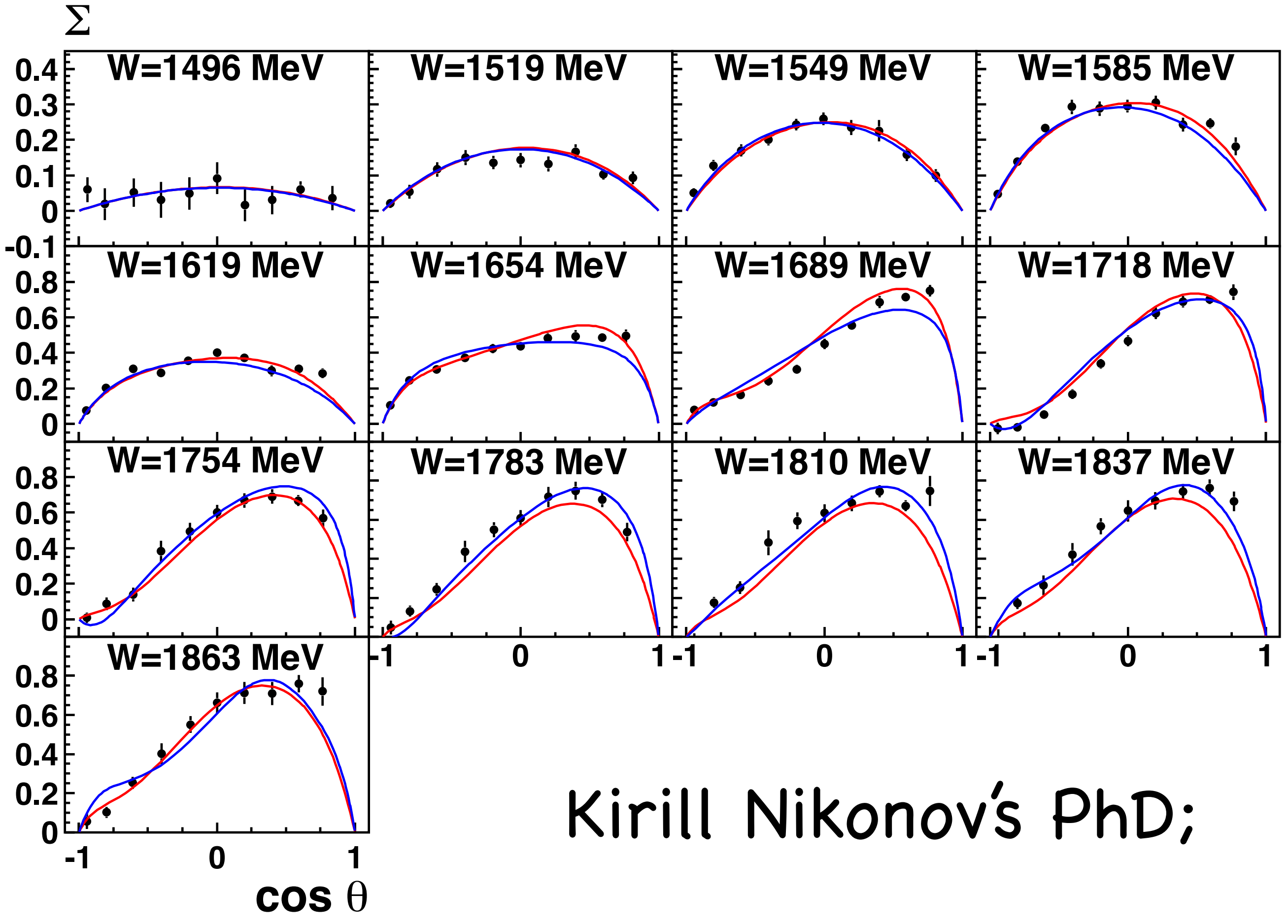
Fit: DR vs. Isobar model

$\chi^2_{IB}/N_{dof} = 1.61$ $\chi^2_{DR}/N_{dof} = 1.61$

$\gamma p \to \eta p$	Observable	χ^2_{IB}	χ^2_{DR}	Number of points
MAMI	$d\sigma/d\Omega$	3448	3388	2544
A2 MAMI	T	456	423	144
A2 MAMI	F	318	426	144
GRAAL	Σ	323	353	130
CLAS	E	38	31	42
DESY,Wilson,Daresbury,CEA	$d\sigma/d\Omega$	11	13	52
Daresbury	Σ	7	13	12
Daresbury	T	1	2	3







Kirill Nikonov's PhD;

Previous DR analysis: Aznauryan, PRC 2003 - limited energy range, only Born background; new data since

Application to pion production?

Similar in spirit - but need to include Watson’s theorem

Strong rescattering in each partial wave:
phase of γN->πN amplitude equals that of πN->πN amplitude

Now multipole decomposition is needed for the full amplitude,
not only resonance part

Multipole decomposition of Regge amplitude (vector meson exchange)

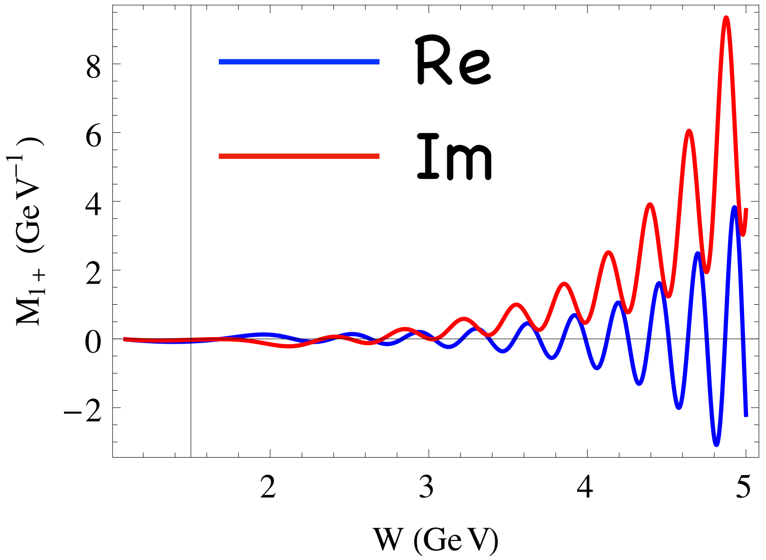
$$R_i^I(\nu,t) = \beta_i^I(t)\frac{\pi\alpha'}{2}\frac{e^{-i\pi\alpha(t)}\mp 1}{\sin(\pi\alpha(t))\Gamma(\alpha(t))}\left(\frac{\nu}{\nu_0}\right)^{\alpha(t)-1}$$

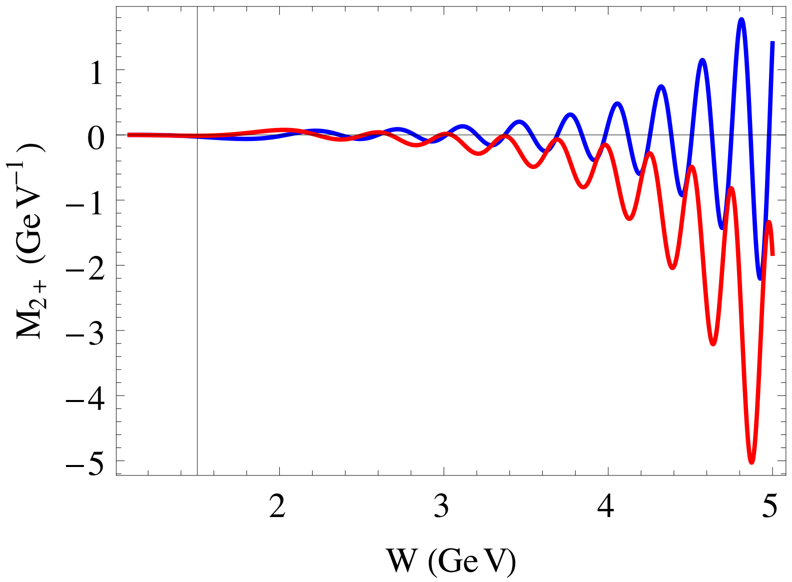
Sine: puts physical meson poles for t > 0 at α = 1,3,… (or 2,4,…)
Γ-fn: removes unphysical poles for t < 0 at α = -1,-3,… (or -2,-4,…)

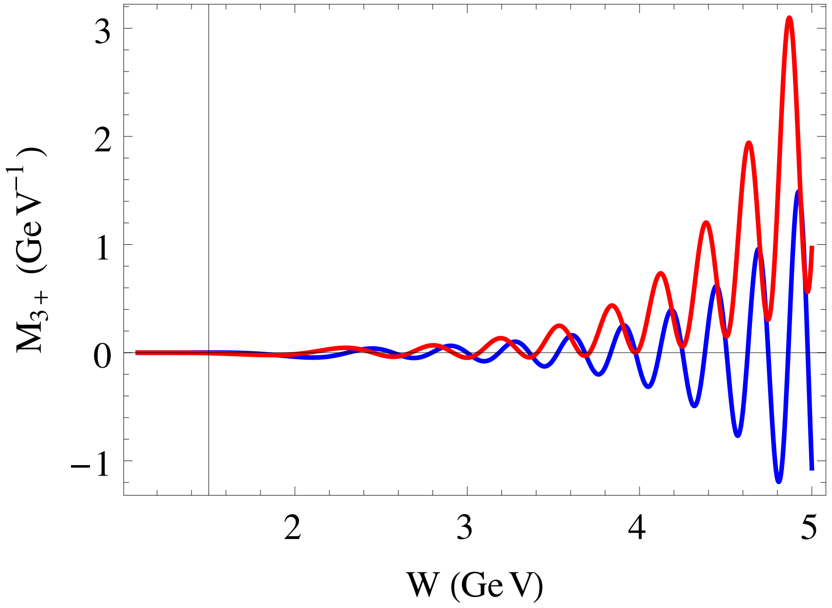
Match your favorite low-energy multipoles onto Regge multipoles above resonance region

What is the dependence on the matching point?

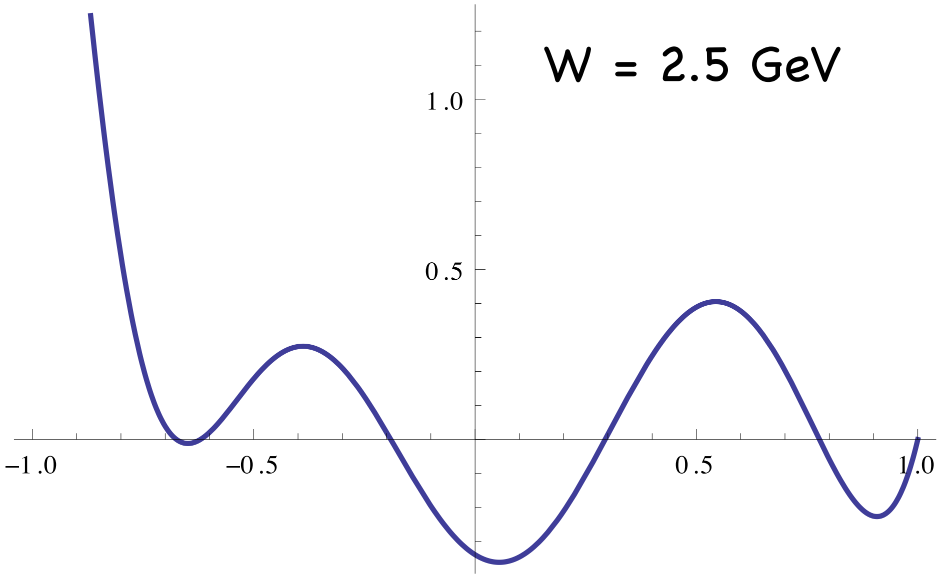
Example: ρ-exchange in π^+n channel
Vector coupling to the nucleon; M_{l+} multipoles







Oscillations observed: no reasonable matching possible!



What's the reason for these oscillations?
Integrand of R -> M_{1+} conversion
Strong backward peak, oscillations between
But one expects t-channel Regge exchanges
to dominate forward angles

Two reasons: ν decreases for -t>> and $\nu^{-|\alpha|}$ grows
Oscillations: 1/Γ[α(t)] for large negative t
Γ fn. removes unphysical poles at t = -1, -3, …

$$R_i^I(\nu,t) = \beta_i^I(t)\frac{\pi\alpha'}{2}\frac{e^{-i\pi\alpha(t)}\mp 1}{\sin(\pi\alpha(t))\Gamma(\alpha(t))}\left(\frac{\nu}{\nu_0}\right)^{\alpha(t)-1}$$

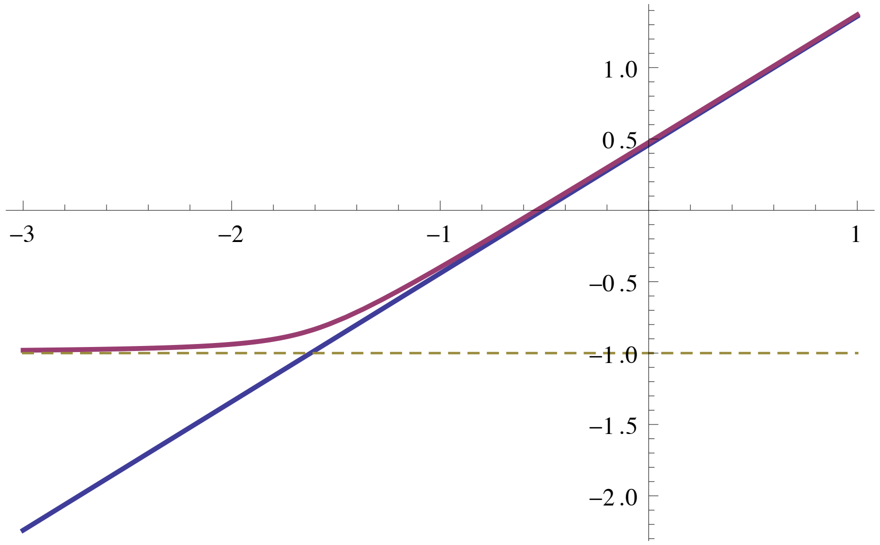
Saturated Regge trajectory

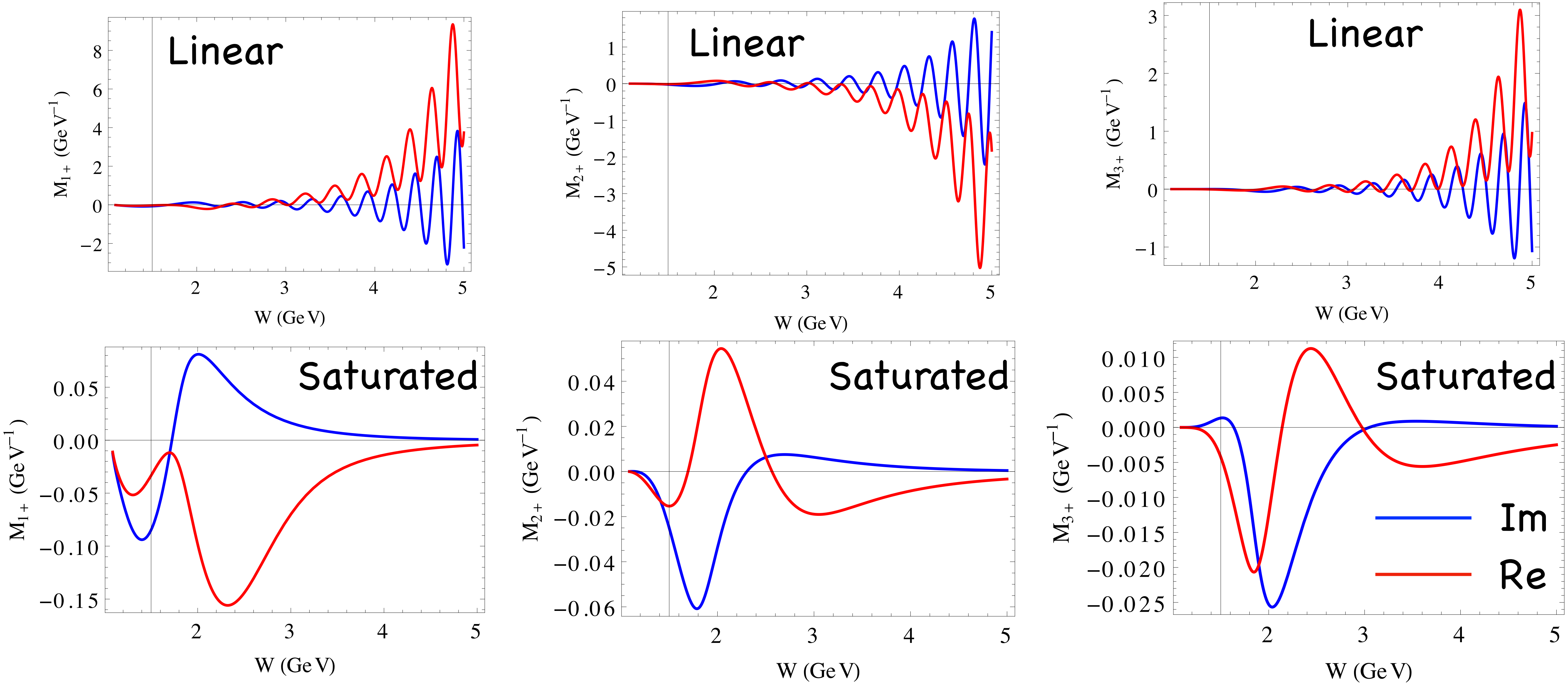
e.g., Collins, Kearney, Z. Phys. `84
“Regge theory and QCD in large-angle scattering

α(t) - linear at positive t (Frautschi plot, meson poles)
- at large |t|~s: pQCD quark exchange - expect 1/t (1/s)

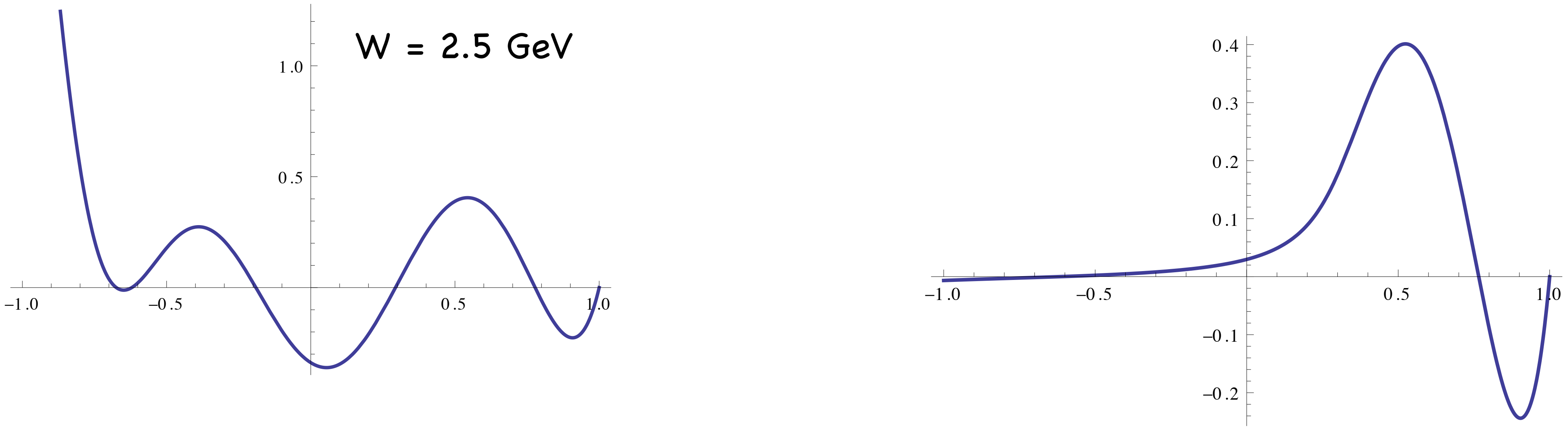
$$\tilde{\alpha}(t) = \frac{\alpha(t) - 1}{2} + \frac{1}{2}\sqrt{(\alpha(t)+1)^2 + 4\lambda^2}$$

Transition: λ



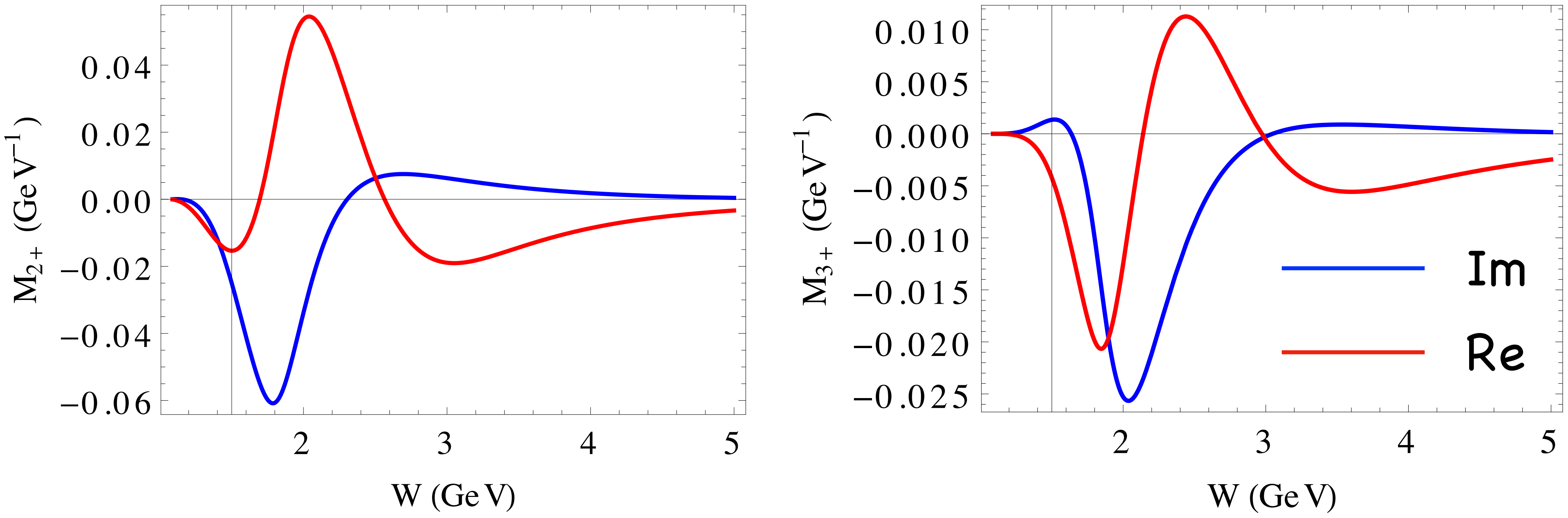


Saturated Regge trajectory
Eliminates backward structure and unphysical oscillations



Regge amplitude generates resonance-like structures (“Schmid loops”)

Schmid, PRL ’68 “Direct-channel resonances from Regge-pole exchange”



Full HE fit with saturated Regge trajectories

WORK IN PROGRESS

Match low MAID multipoles from the resonance fit onto Regge multipoles

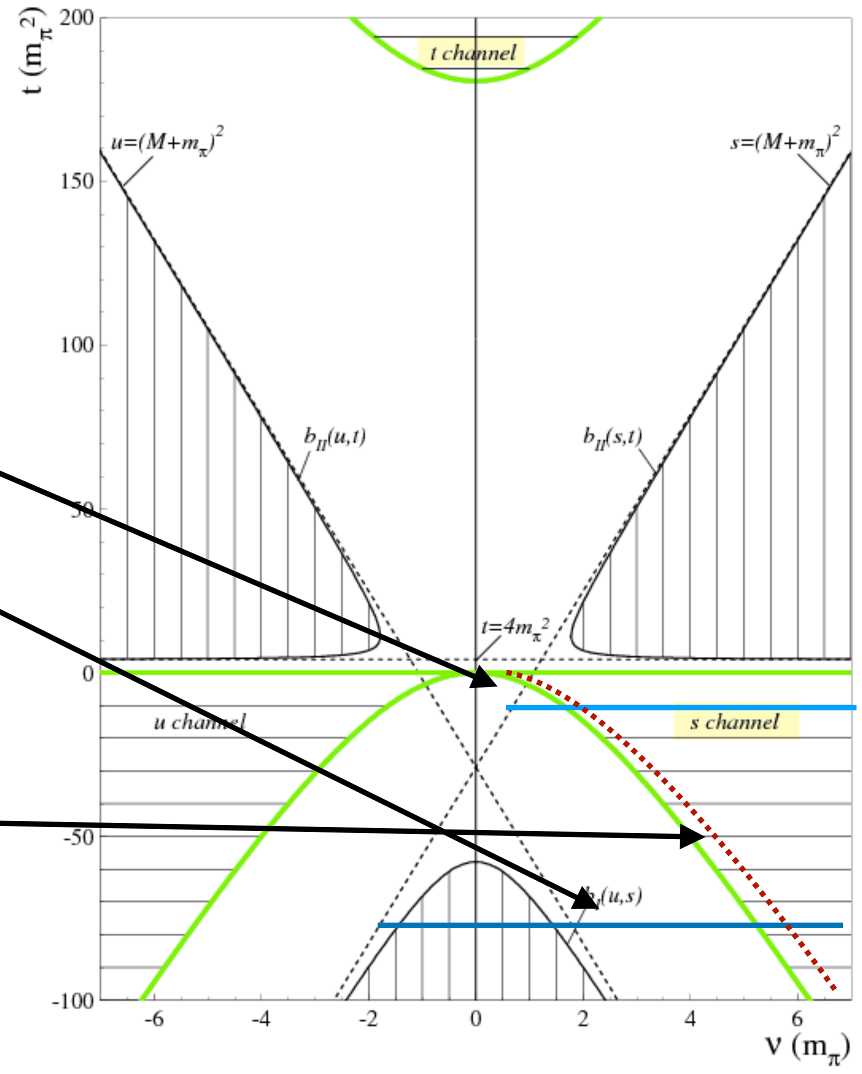
t-channel Regge exchanges: correct physics input at forward angles;
Saturated Regge removes artifacts from the backward angles;

To describe backward angles include baryon Regge exchanges - nontrivial
Formal problems - parity doubling (P^+ and P^- baryons trajectories degenerate?)

Fixed-t DR don’t work at large negative t

Small t: small contribution of unphysical region
Large t: unphysical region may dominate

Plausible idea: use fixed-t DR at small t;
Use fixed-angle DR at backward angles;
Reggeized u-channel exchanges needed
Match two approaches at intermediate angles



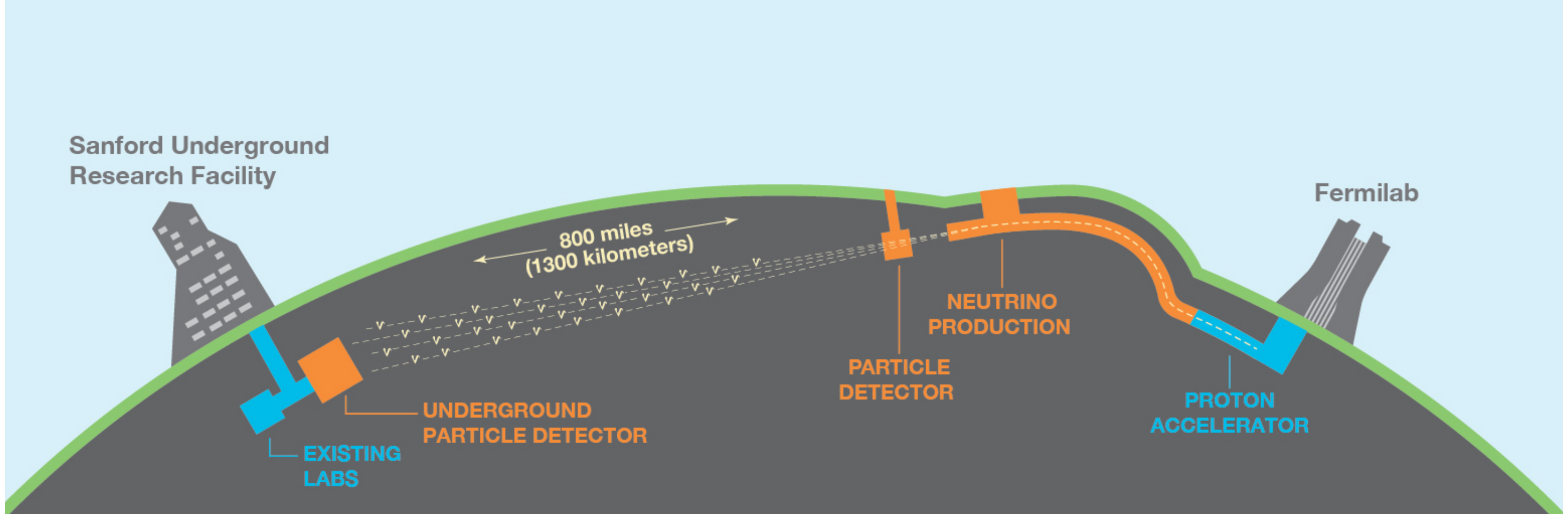
Electroweak MAID

Input to neutrino event generators

Discussed matching resonance region description onto Regge in some detail

Pion production in neutrino scattering - will be important!

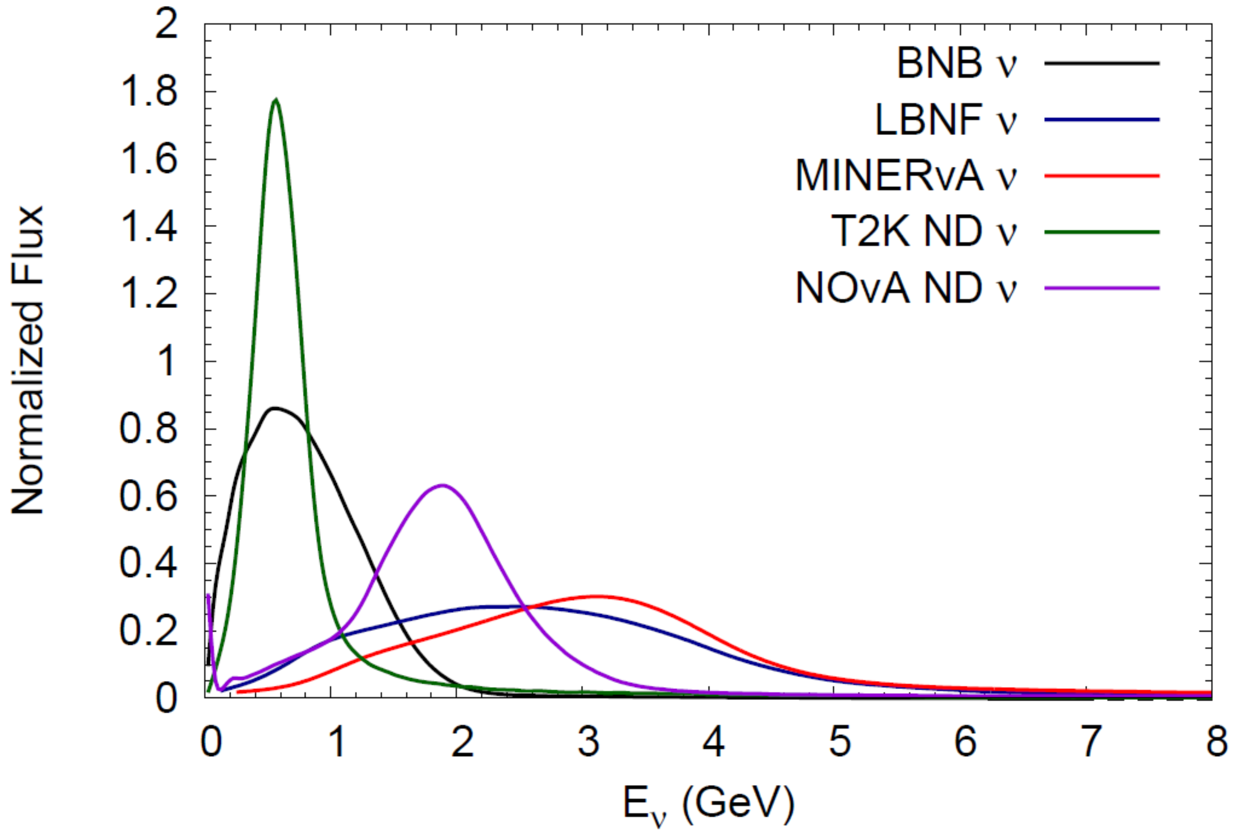
Future DUNE experiment
2027 on
CERN-FNAL $1.5B project



Neutrinos produced from
charged pion decay in HE pA collisions;
Broad energy spectrum;

Goal: neutrino oscillation parameters

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

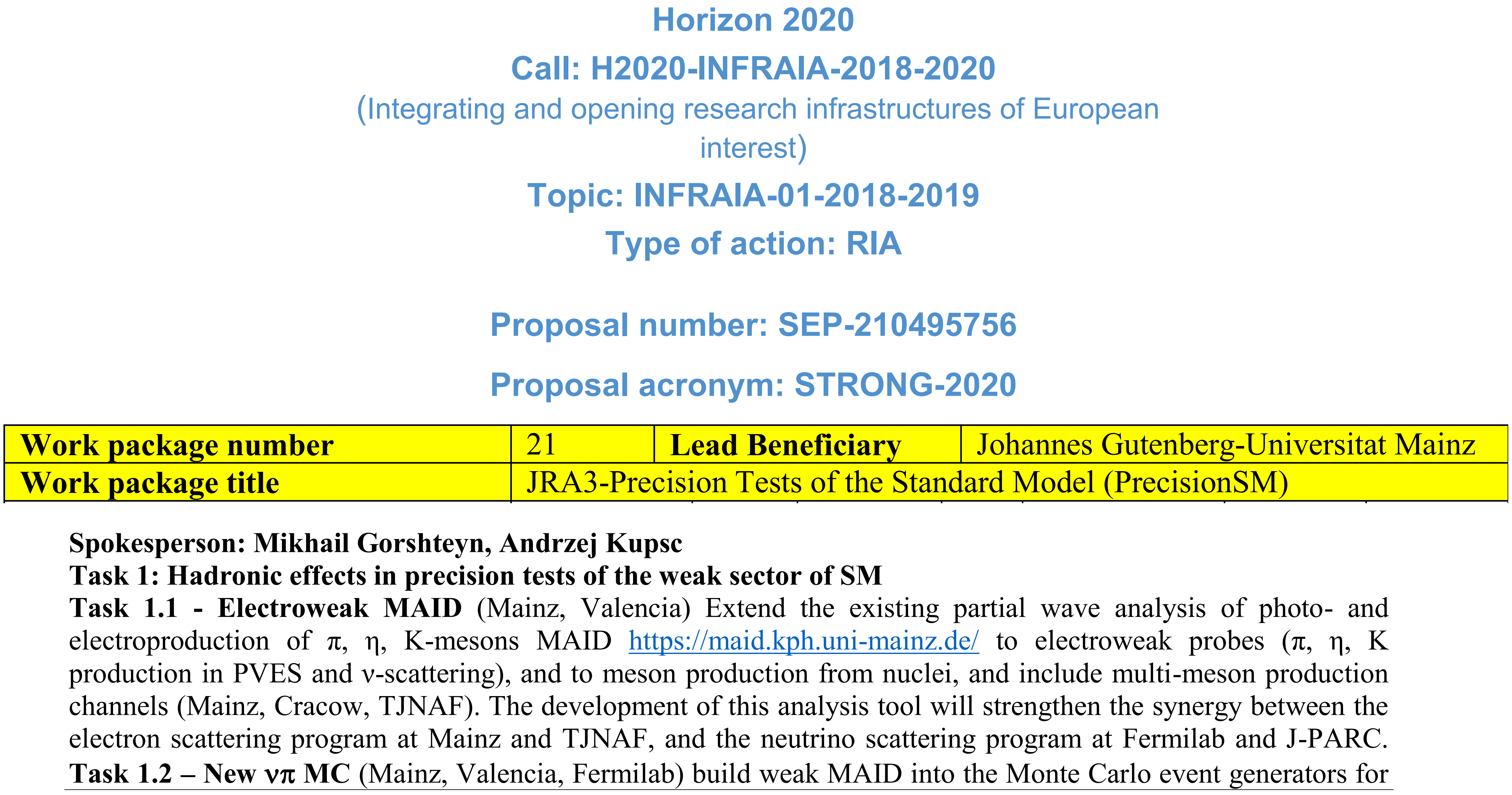


Inelastic processes - crucial background
for energy reconstruction from observed final state

Electroweak MAID: funded subproject within
STRONG 2020: Integrating initiative in hadronic physics

Makes part of PRECISION Joint Research Activity
(Theory for muon anomaly, neutrino scattering and electroweak rad. corr.)

Runtime: 2019-2023 (started now)



Horizon 2020

Call: H2020-INFRAIA-2018-2020

(Integrating and opening research infrastructures of European interest)

Topic: INFRAIA-01-2018-2019

Type of action: RIA

Proposal number: SEP-210495756

Proposal acronym: STRONG-2020

Work package number	21	**Lead Beneficiary**	Johannes Gutenberg-Universitat Mainz
Work package title	JRA3-Precision Tests of the Standard Model (PrecisionSM)		

Spokesperson: Mikhail Gorshteyn, Andrzej Kupsc
Task 1: Hadronic effects in precision tests of the weak sector of SM
Task 1.1 - Electroweak MAID (Mainz, Valencia) Extend the existing partial wave analysis of photo- and electroproduction of π, η, K-mesons MAID https://maid.kph.uni-mainz.de/ to electroweak probes (π, η, K production in PVES and ν-scattering), and to meson production from nuclei, and include multi-meson production channels (Mainz, Cracow, TJNAF). The development of this analysis tool will strengthen the synergy between the electron scattering program at Mainz and TJNAF, and the neutrino scattering program at Fermilab and J-PARC.
Task 1.2 – New νπ MC (Mainz, Valencia, Fermilab) build weak MAID into the Monte Carlo event generators for

Currently: neutrino event generators use simplified reaction mechanisms
for pion production

Until now the exp. uncertainties have been very forgiving;

DUNE: need to achieve 100 MeV resolution in reconstructed energy
(neutrino spectrum spans 0.5 - 5 GeV)

T2HK: 50 MeV for neutrino spectrum 0.2 - 1.5 GeV

Should be based on analyzing inelastic events in the near detector;
Pion production is among most prominent channels

Include and extend the detailed knowledge of e-m pion production w. MAID
Convolute with nuclear effects
Feed into MC event generators

Summary

EtaMAID: a new hybrid Ansatz incorporating isobar and Regge models
Provides very good fit of all data in 4 channels (ηp, ηn, η’p, η’n)

Analyticity, unitarity and crossing can be restored applying fixed-t DR:
Effect on the description of observables is surprisingly small (wrt isobar model)

Matching low-energy (multipole expansion-based) models to Regge is tricky!
If decomposed into multipoles, Regge oscillates - how reliable is matching?
Possible solution - saturated Regge trajectory
Double counting should be studied for higher resonances

Reliable matching across resonances and Regge regimes highly important for
Neutrino pionproduction in DUNE@Fermilab: neutrino energies 500 MeV - 5 GeV
Electroweak MAID will be developed for that purpose