MAID - new developments: going weak

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OUTLINE

Motivation: Neutrino Oscillation Experiments and more

MAID: unitary isobar model for e.m. pion production

New Developments

- Duality (Resonance-Regge)
- Electroweak MAID

Summary

Neutrino interactions with matter:
Play an important role in many physical processes

Astrophysics
- Dynamics of the core-collapse in supernovae
- r-process nucleosynthesis

Hadronic physics
- Nucleon and Nucleon-Resonance transition axial form factors
- Strangeness content of the nucleon spin

Nuclear physics
- Short- and long-range correlations, MEC, nuclear excitations
- Complement electron scattering studies

CKM unitarity — currently ~3σ deficit observed
- Nuclear matrix elements w. weak charged current
- relevant for nuclear β-decays accessible with neutrinos

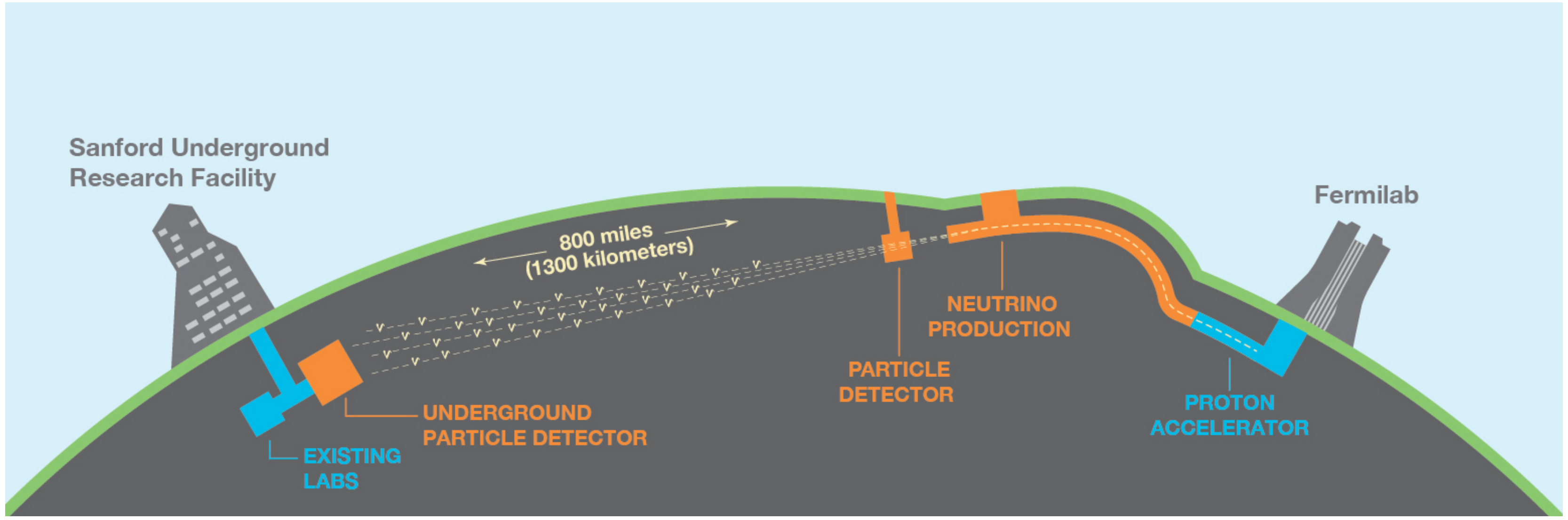
Motivation: Neutrino Experiments

Oscillation experiments (with accelerator ν in the few-GeV region):

T2K, NOvA, MicroBooNE, Hyper-K, DUNE

Future DUNE experiment

CERN-FNAL \$1.5B project



Goal: neutrino oscillation parameters — mass hierarchy; CP-violating phases

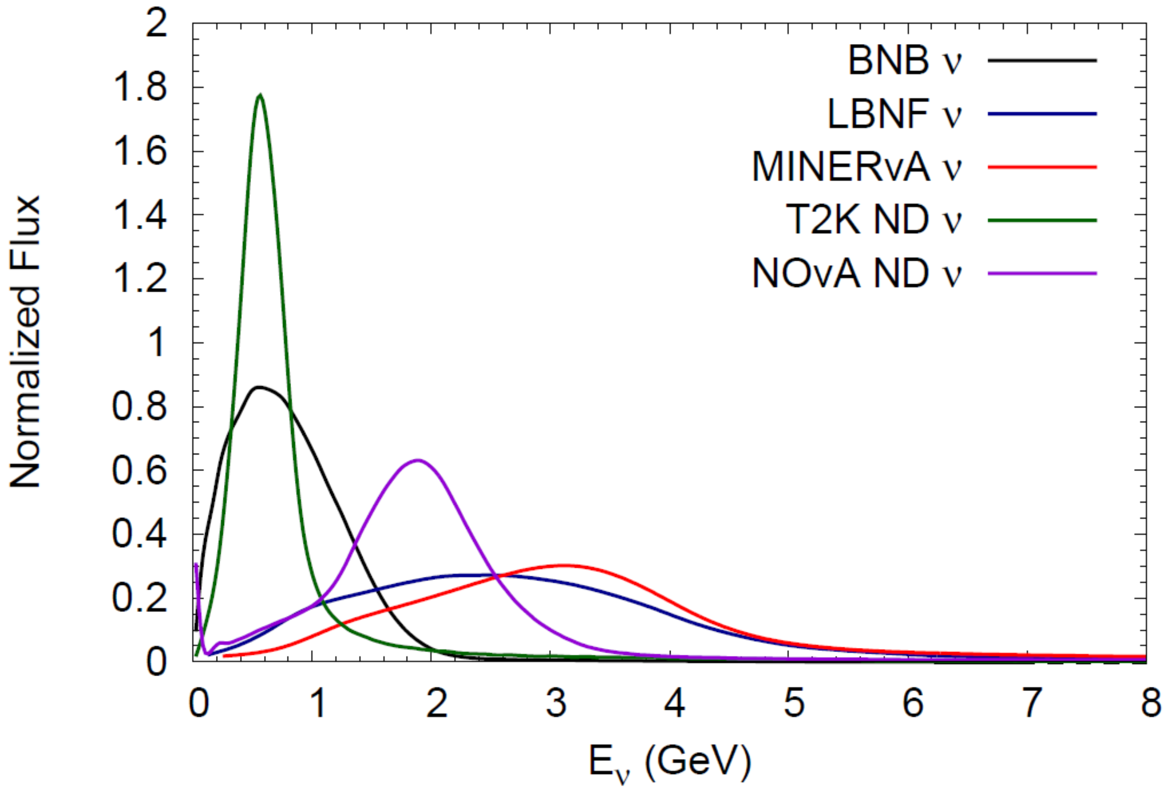
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4 E_\nu} \right)$$

Prerequisite: need to know the neutrino spectrum $N_\nu(E_\nu)$ for each specie

Motivation: Neutrino Experiments

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

Detect charge leptons originating from neutrinos hitting the far detector



Good understanding of neutrino interactions in the near detector for:

ν detection, flavor identification

E_ν reconstruction, ν flux calibration

determination of (irreducible) backgrounds

controlled precision at each step

Pion production: substantial part of inelastic events!

Motivation: Neutrino Experiments

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)

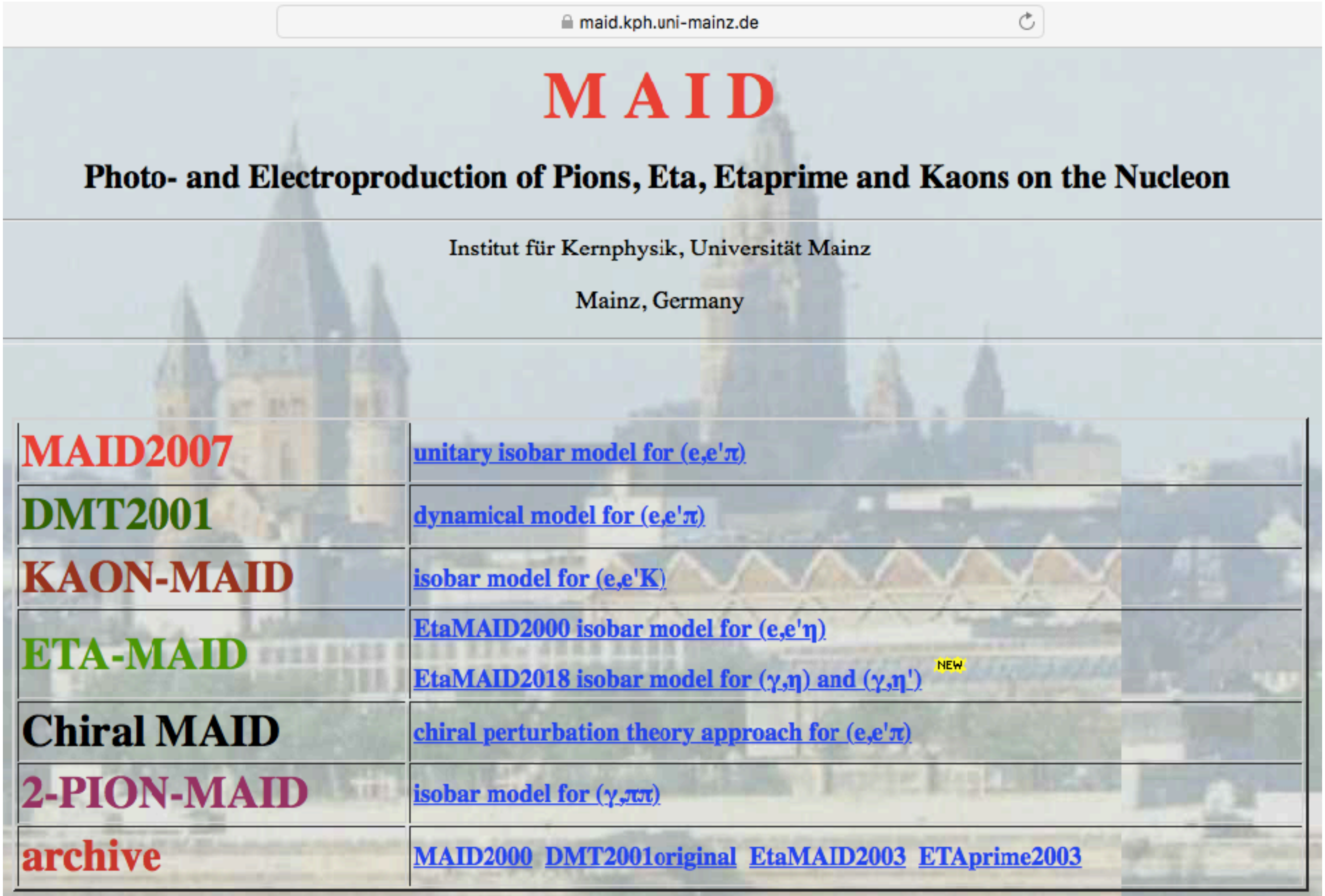
T2HK: < 50 MeV for neutrino spectrum 0.2 - 1.5 GeV

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

Build upon the detailed knowledge of e-m pion production w. MAID

Extend the energy range 2 GeV —> 6 GeV; include axial current

MAID: PWA Tool since 1998


maid.kph.uni-mainz.de

M A I D

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

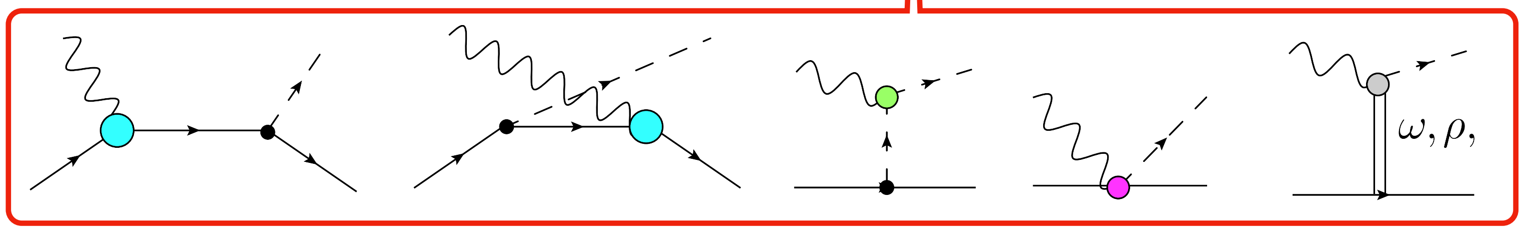
Institut für Kernphysik, Universität Mainz

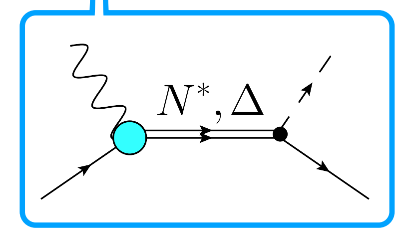
Mainz, Germany

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

MAID: pion photo- and electroproduction

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

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

Direct channel only (1 resonance - 1 partial wave)
Violates crossing but saves the HE behavior

Virtual photons —> phenomenological FF's

Brief history: 1998 MAID98 - (γ,π) and ($e,e'\pi$)

2007 MAID2007 - latest update on ($e,e'\pi$)

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

2001 DMT2001 - dynamical model for ($e,e'\pi$)

2001 EtaMAID2001 - isobar model for (γ,η) and ($e,e'\eta$)

2003 Reggeized EtaMAID

2007 2-PionMAID2007 - isobar model for ($\gamma,\pi\pi$)

2012 Chiral MAID2012 - ($e,e'\pi$) at threshold in rel. ChPT

2018 EtaMAID2018 - reggeized isobar model for ($\gamma,\eta(')$)

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

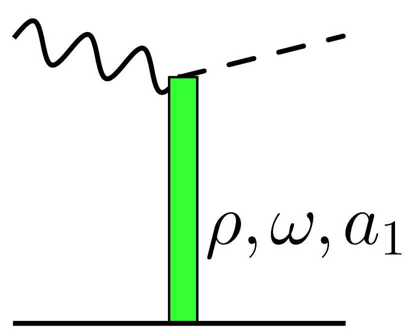
Towards MAID2022 and νMAID

Extending to high energy: Regge asymptotics

CQM and LQCD predict essentially infinite number of states

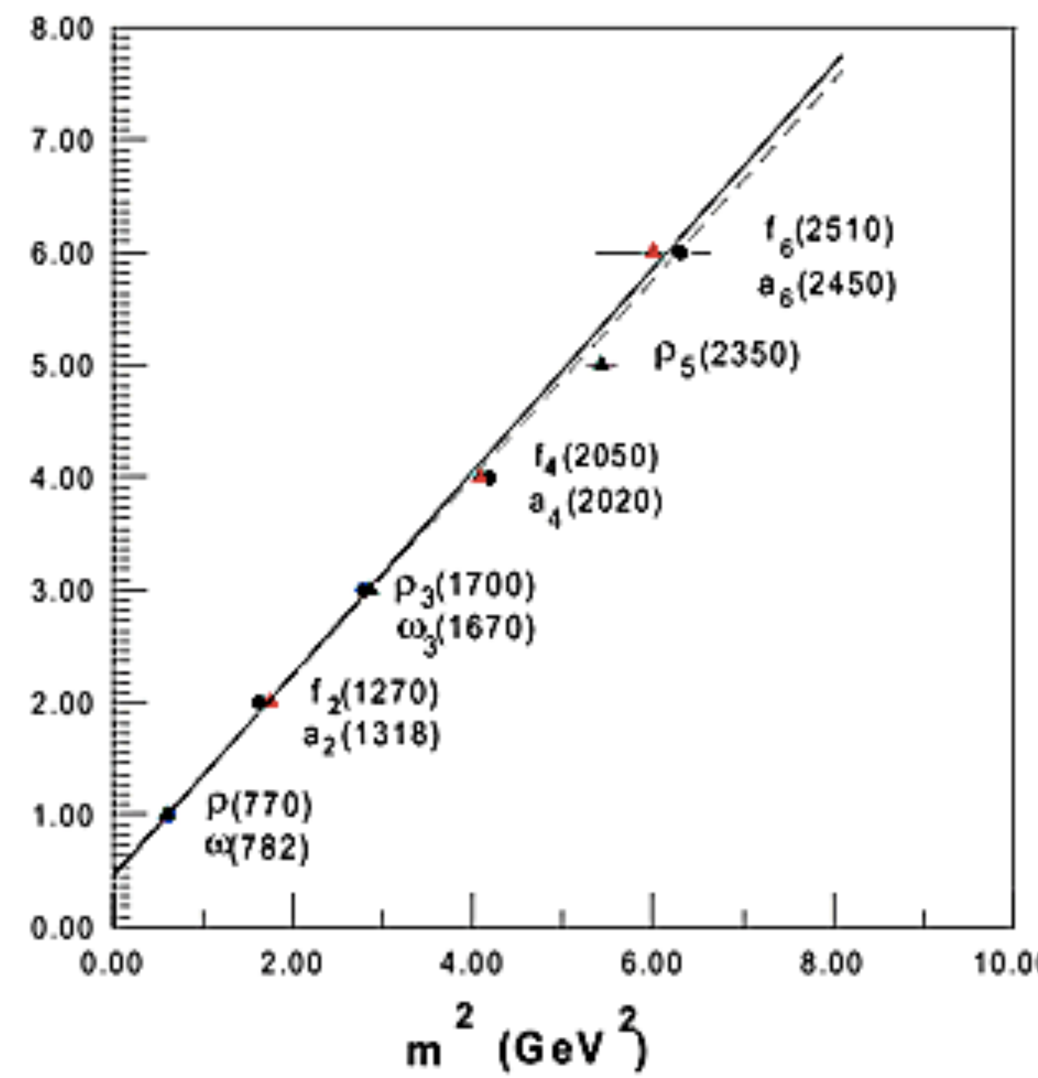
Empirical: above W=2.5 GeV s-channel resonances not prominent
High energies - t(u)-channel exchanges
- smooth W-dependence, strongly peaked at forward(backward) angles

VM exchanges: unphysical energy behavior



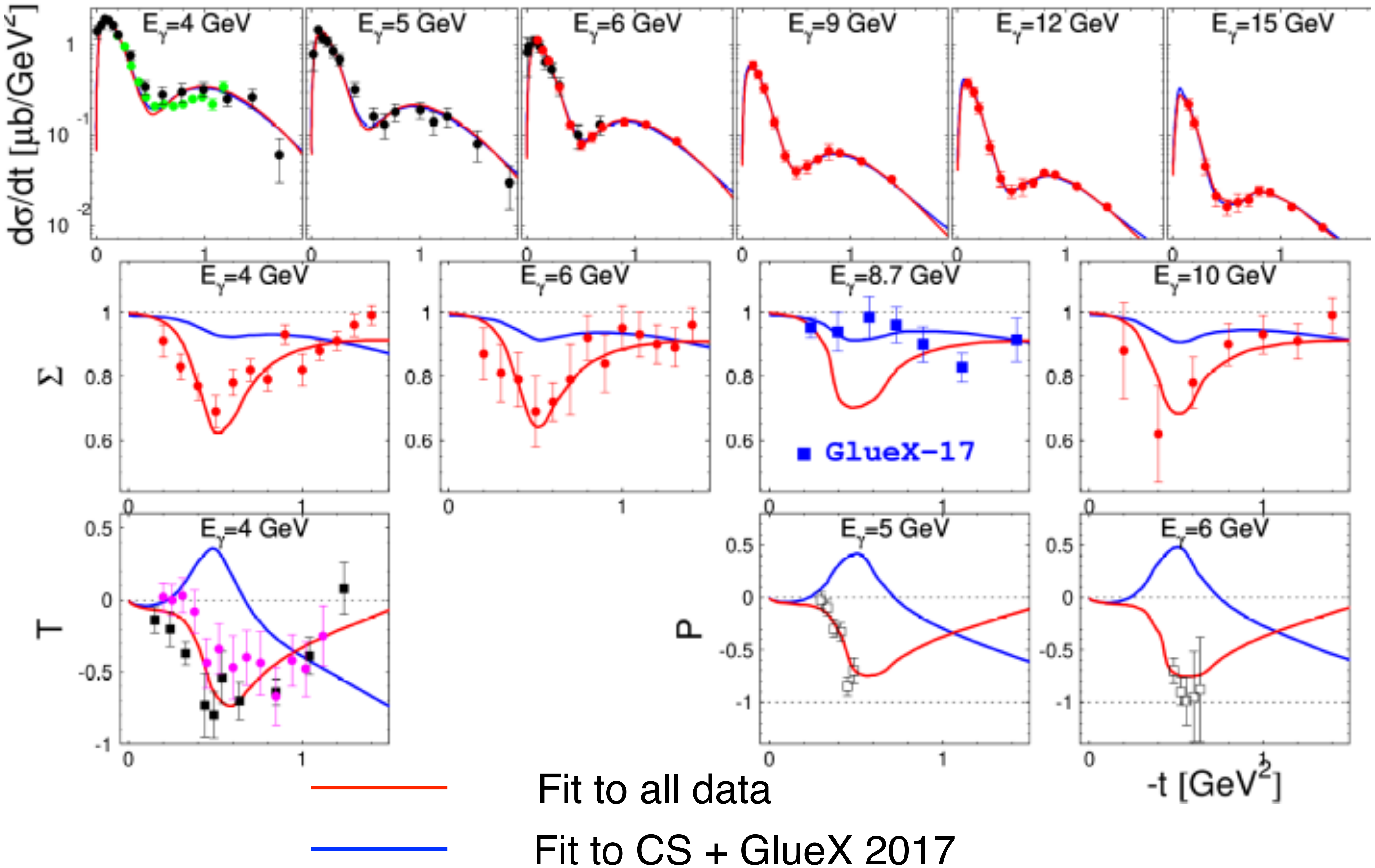
Regge - exchange a tower of states
Spectrum: $J = J_0 + \alpha' (M_J^2 - M_0^2)$
One coupling per trajectory

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



Regge fit to HE data

Kashevarov, Ostrich, Tiator 1706.07376, PRC 96



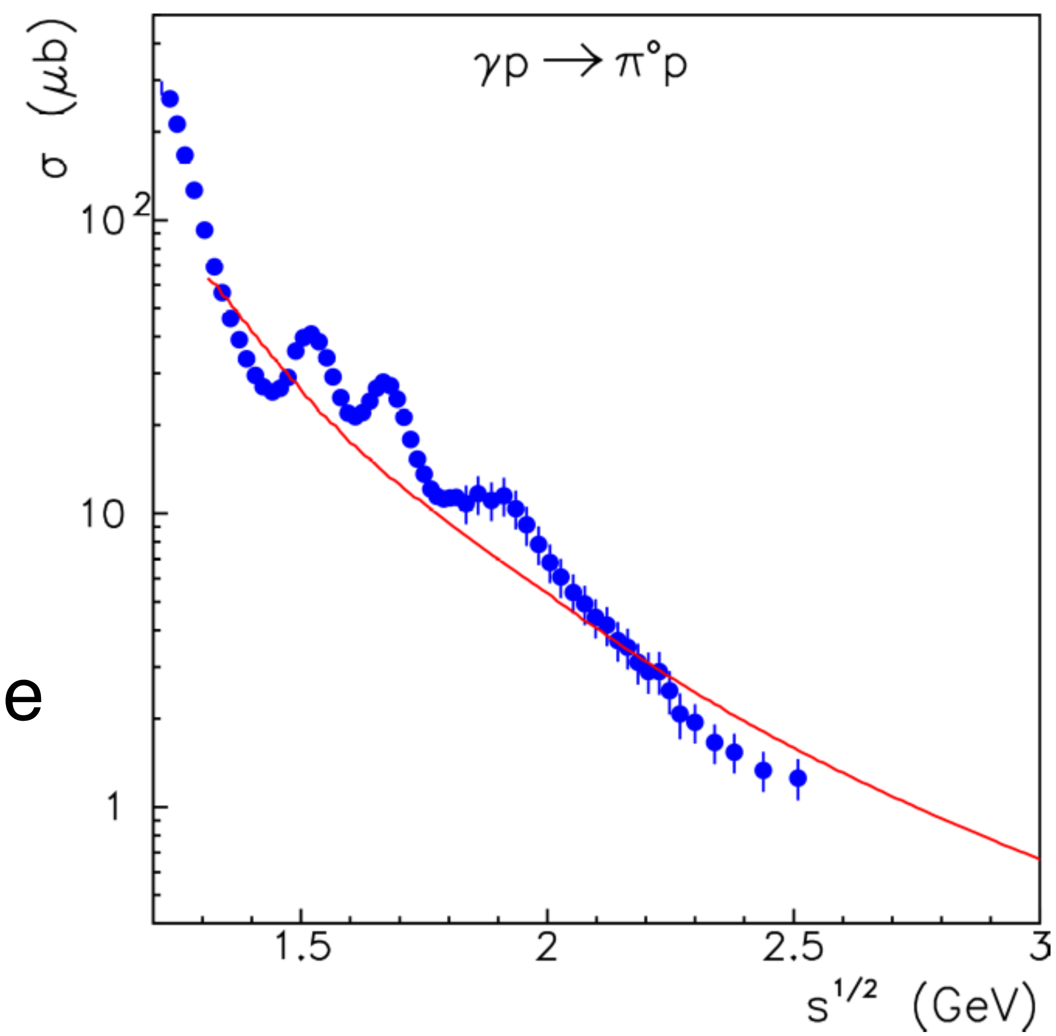
How is Regge related to baryon spectrum? — Duality

Regge + Resonances: Duality (Violation)

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

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

Infinite sum over t-channel residua = Regge



Duality in real world: integrated strength of s-channel resonances and Regge are the same

Including both s- and t-channel resonances —> double counting!

Regge + Resonances: Duality (Violation)

Exploit duality for extracting few low-lying resonances
Remove part of the strength of Regge in the resonance region

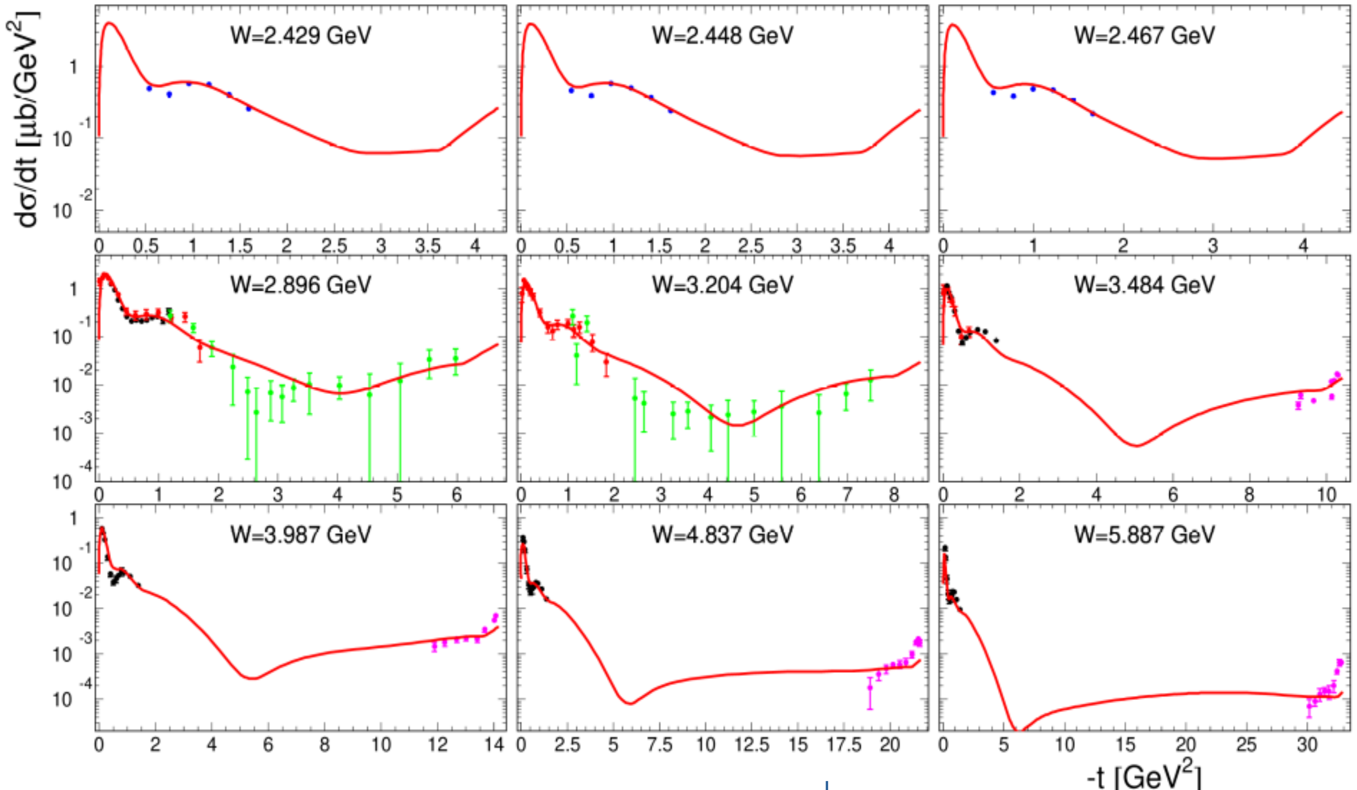
$$A(s,t,u) = \sum_{\mathrm{Res}_s=1}^{N} A^{\mathrm{Res}}(s,t,u) + \sum_{\mathrm{Res}_t}^{\infty} A^{t}(s,t,u) - \sum_{\mathrm{Res}_s=1}^{N} A^{\mathrm{Res}}(s,t,u)$$

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

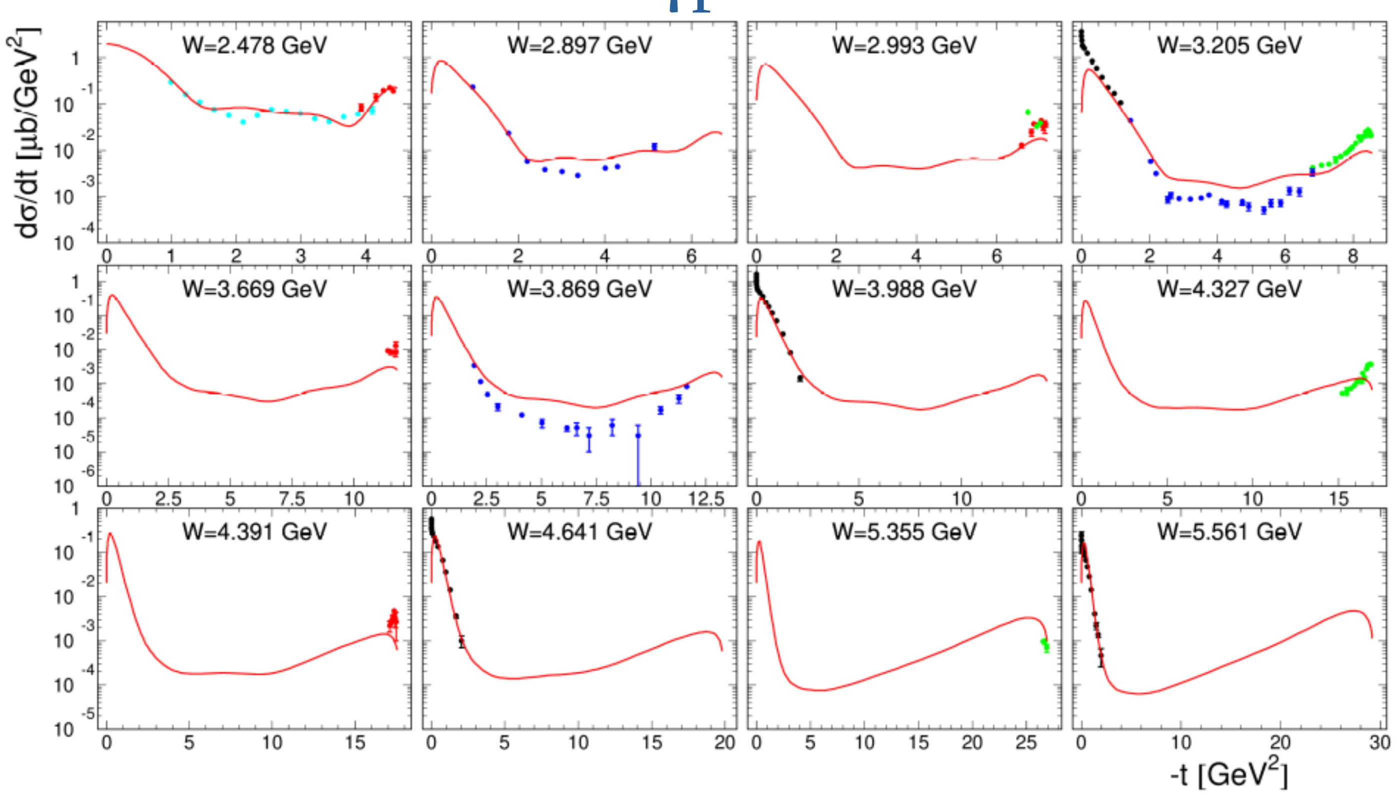
Damping factor removes double counting $DF \to 0$ at threshold, $DF \to 1$ at HE

HE fit: saturated Regge exchanges

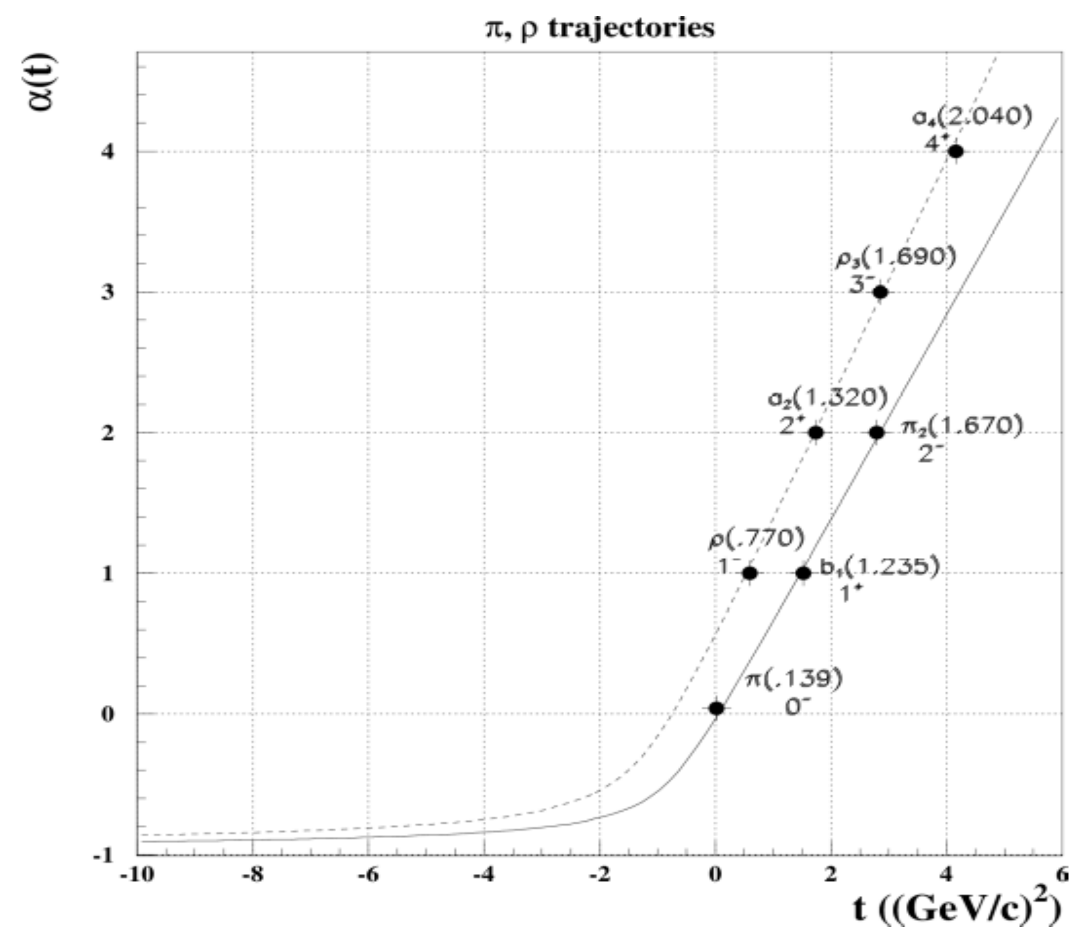
$\gamma p \rightarrow \pi^0 p$



$\gamma p \rightarrow \pi^+ n$



Saturation of Regge trajectories.
Example for ρ and π reggeons.



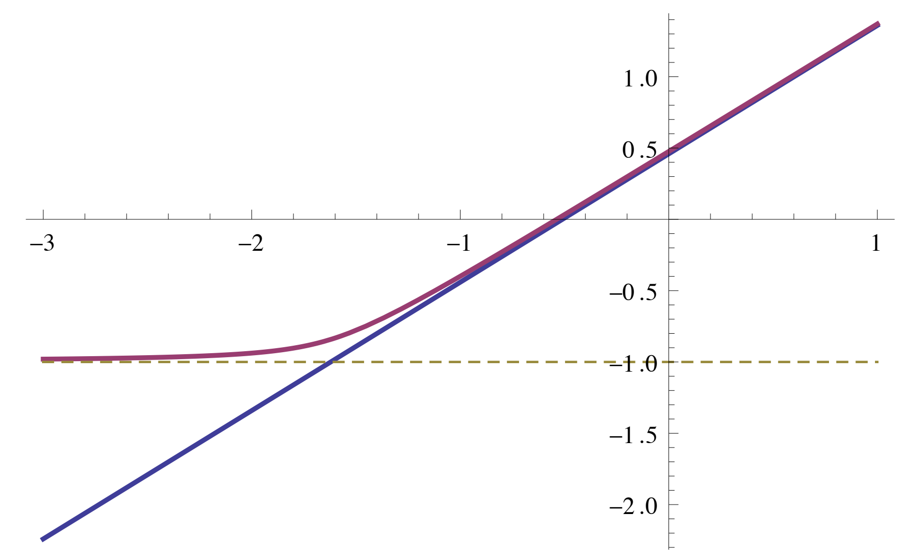
Plot: courtesy of V. Kashevarov

Joining Regge with low-energy description

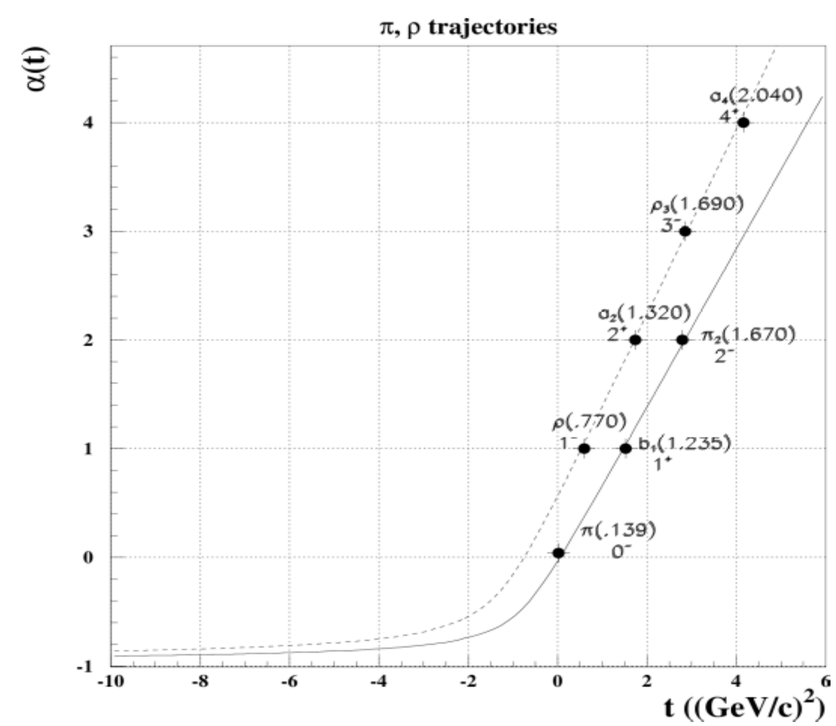
$$A(s)^{\text{Regge}} \sim (-\nu)^{\alpha(t)} \pm \nu^{\alpha(t)}$$

If α unbounded from below —> cross channel dominates over direct

Linear vs Saturated Regge trajectory



α(t) - linear at t>0 (Frautschi plot, meson poles)
-t~s >> : pQCD quark exchange - expect 1/t (1/s)



Turns out a crucial difference for PWA!

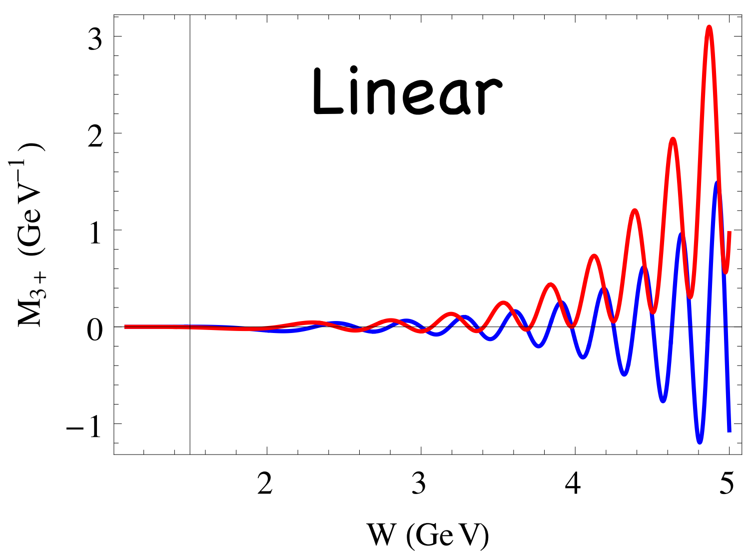
Joining Regge with low-energy description

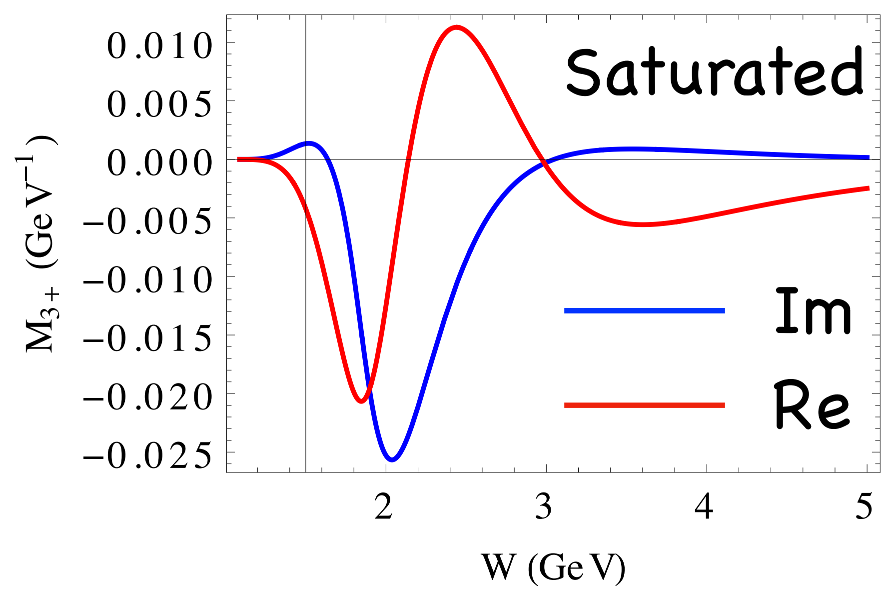
Proper unitarization in each partial wave below 1.5 GeV:
phase of γ*N —> π N = phase of πN-amplitude

Regge amplitude predicts the phase

Smooth transition between two regimes on the level of partial waves?

Decomposing a Regge exchange into multipoles:

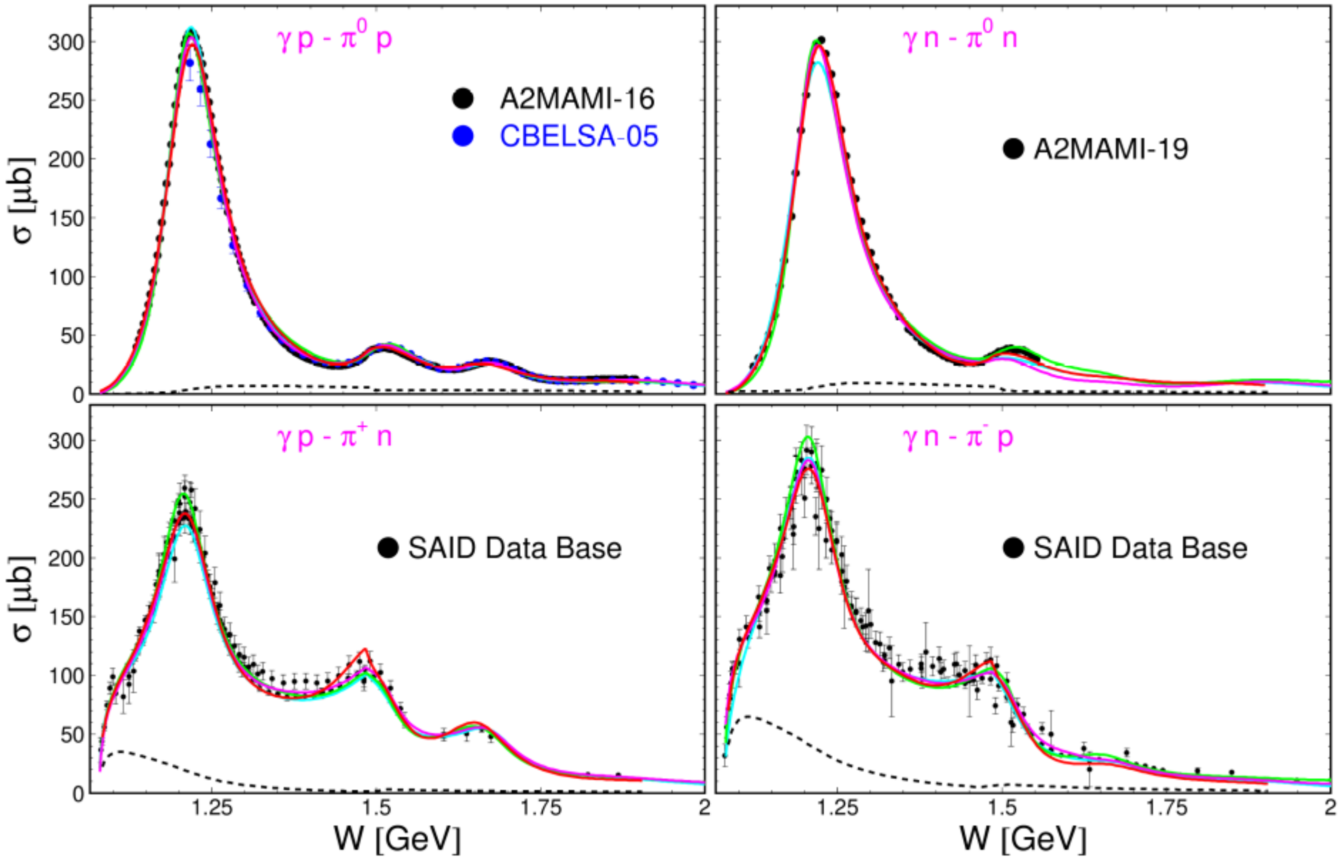




Linear trajectory — no reasonable matching to LE model

Resonance-like structures not associated with poles of S-matrix (“Schmid loops”)
Shows why Resonances + Regge is not a great model

Selected results: total cross sections

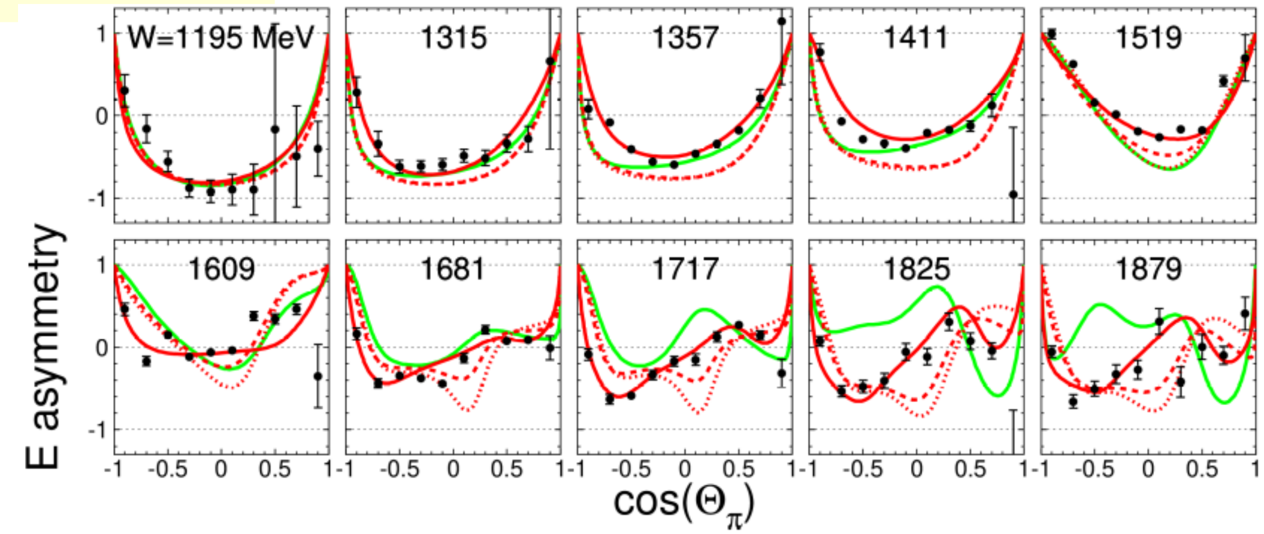


Red line: PionMAID2021, green: MAID2007, magenta: SAID SM12, cyan: BnGa-2019

Black dashed: PionMAID2021 background

Selected results: helicity asymmetry E

$\gamma\ n \rightarrow \pi^0\ n$



Red lines: PionMAID2021

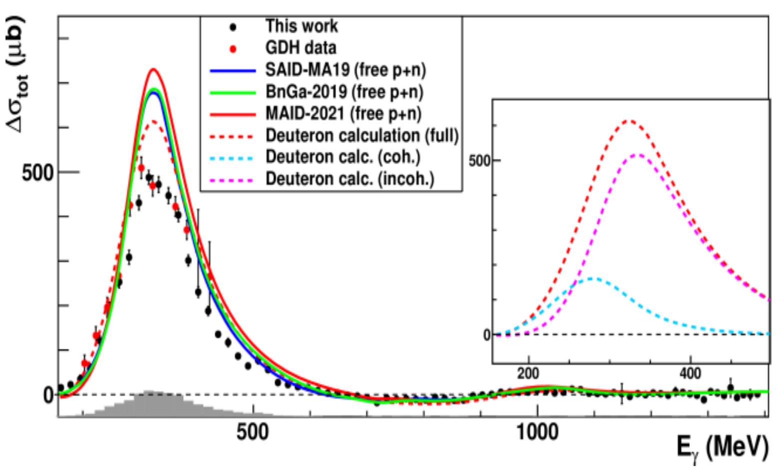
dotted – all pi0 data not fitted

dashed – new A2MAMI not fitted

solid – full solution

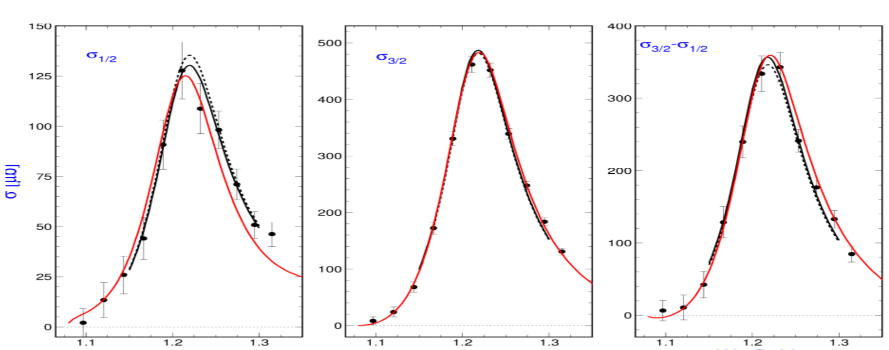
green: MAID2007

Selected results: polarized total cross sections



F. Cividini et al., Eur. Phys.J. A (2022) 58:113

$\gamma\ n \rightarrow \pi^0\ n$

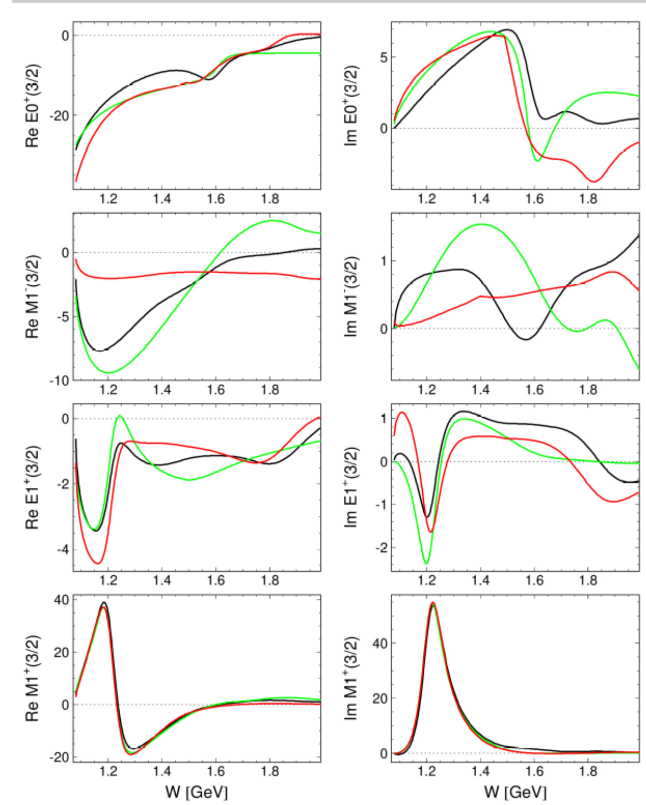


Red: PionMAID2021,

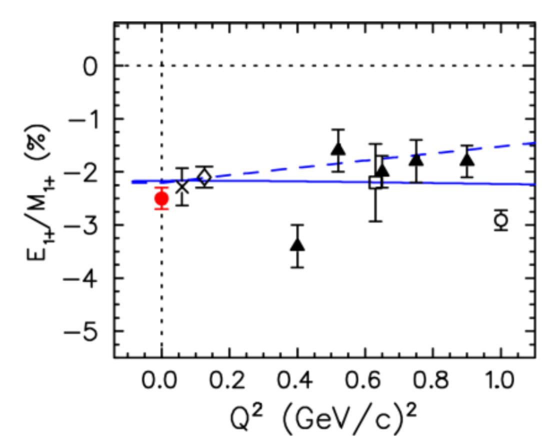
black: BnGa-2019 (solid),
BnGa-2014-02(dashed).

Data: A2MAMI-04

Selected results: multipoles



Red line: PionMAID2021,
green: MAID2007,
black:BnGa-2019



solid line: MAID2007
dashed line: MAID2003

Red point: $(-2.5 \pm 0.2 \pm 0.2)$%
R. Beck et al., PRL 78 (1997) 606

PDG2020 estimate: (-2.5 ± 0.5) %
(min: -1.6%, max: 3.9%)

Our result:
$E_{1+}/M_{1+} = -2.66$ %

Models on weak pion production on the nucleon

S. Adler, Ann. Phys. 50, 189 (1968) — Born, PCAC, P33 + dispersion relations

Rein, Sehgal Ann. Phys 1981 — PCAC only (πN constraint)

Alvarez-Ruso, Singh, Vicente Vacas nucl-th/9712058, nucl-th/9804007 — P33

Lalakulich, Paschas nucl-th/0501109, hep-ph/0602210 — Resonances

Leitner, Alvarez Ruso, Mosel nucl-th/0601103 — Born + Resonances

Hernandez, Nieves, Valverde hep-ph/0701149 — Born + P33 (later with P33 unitarization)

Serot, Zhang 1206.3812 — ChEFT w pions, Resonances and VM

Sato, Lee Nakamura, Kamano, Sato 1506.03403— dynamical coupled-channel model

Gonzalez-Jimenez et al 1612.05511 — Born + Resonances + Regge

Yao, Alvarez Ruso, Hiller Blin, Vicente Vacas 1806.09364 — Covariant ChPT with dynamical P33
…

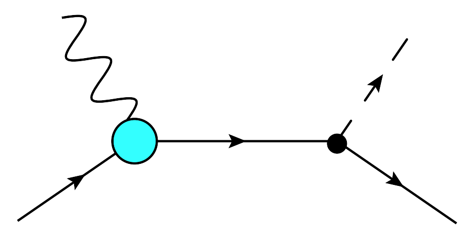
No model with unitarity in all PW with $\ell \leq 3$;
Many models “validated” or “calibrated” vs em pion production
they do not build upon know-how of isobar models (crucial Res - Backgr interference)
When Regge background — duality violation

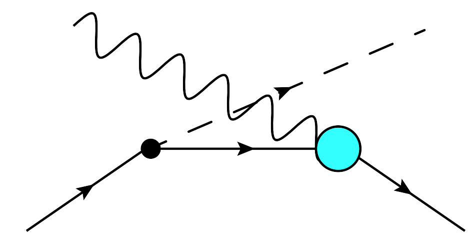
νMAID: generalize to charged weak current

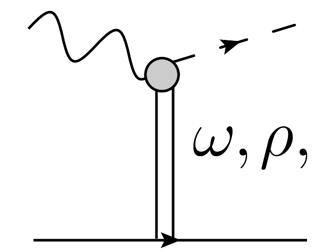
$$M_{CC} = \frac{G_F}{\sqrt{2}} \bar{\nu}\gamma_\mu(1-\gamma_5)\ell \, \langle N'\pi | V^\mu - A^\mu | N \rangle$$

Vector weak CC: isovector e.m. — known from MAID (isospin symmetry)

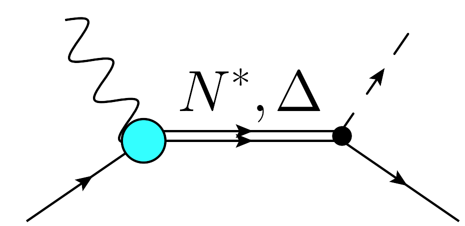
Axial weak CC — new







Ingredients:
some old (Born, Resonances, Regge, unitarization)

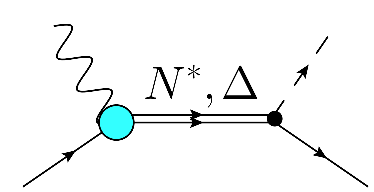


some new (axial form factors, pion pole, PCAC)

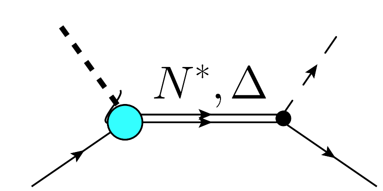
PCAC $\quad i\partial_\mu \langle N'\pi | V^\mu - A^\mu | N \rangle = -\, i\partial_\mu \langle N'\pi | A^\mu | N \rangle \to \begin{cases} 0, & m_\pi = 0 \\ -f_\pi T_{\pi N}, & Q^2 = 0 \end{cases}$

“Transition Goldberger-Treiman relations” fix WN —> R strength at $Q^2 = 0$

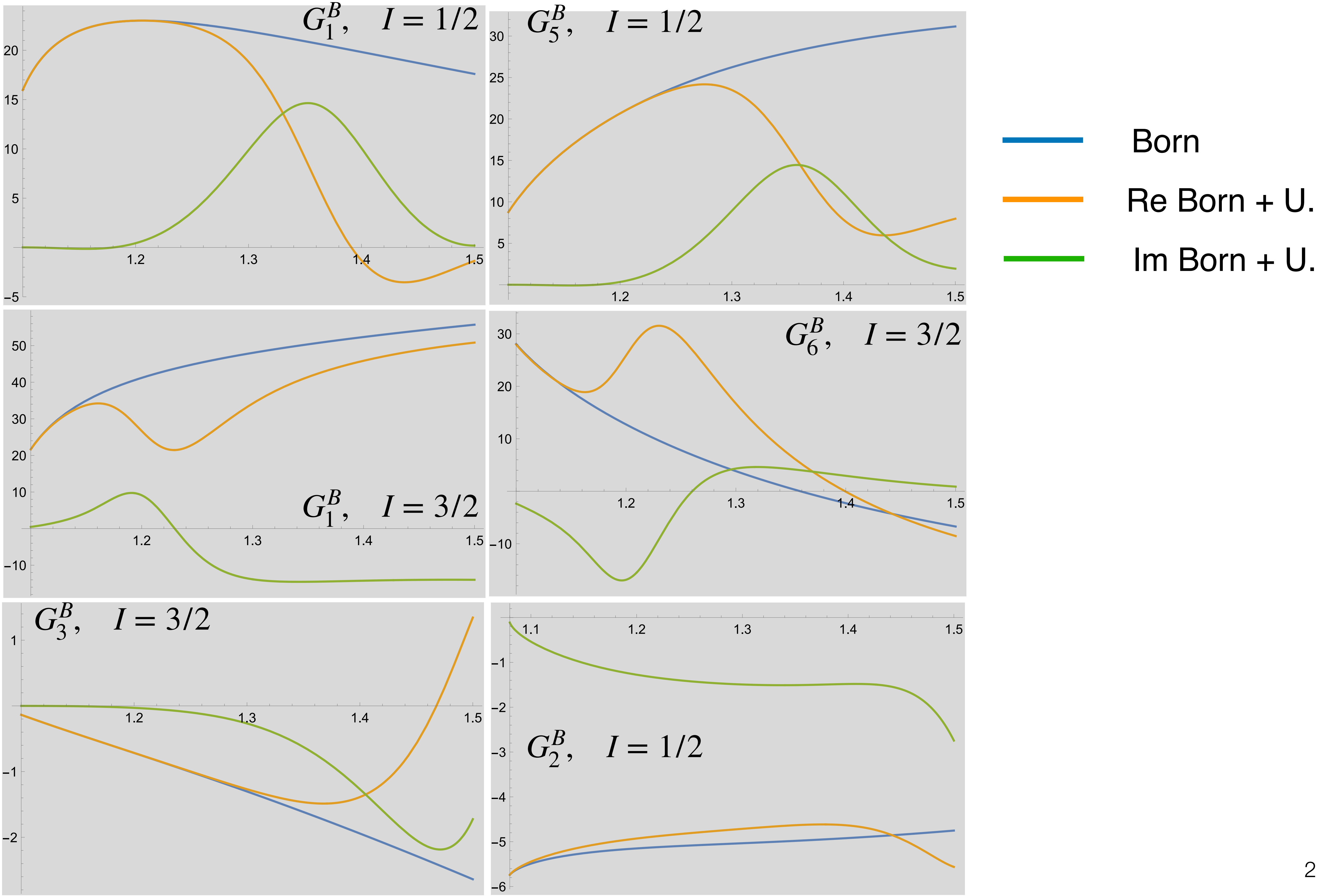
$$G_{WNR} \propto G_{\pi NR}$$



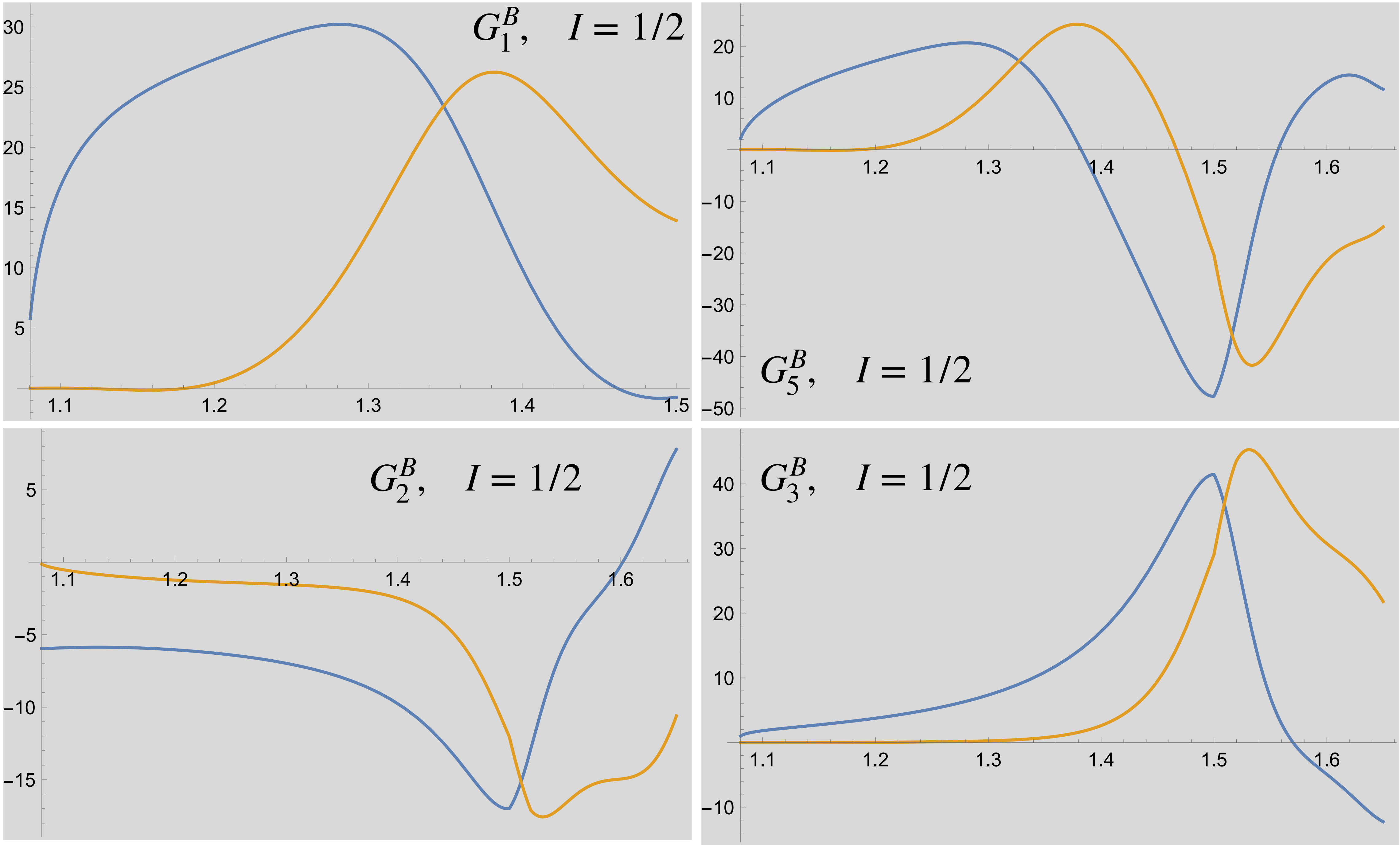
$\propto$



Unitarized Born contribution (CGLN basis)



Including resonances with unitary phase



Re Born + Res.

Im Born + Res.

Showing few selected amplitudes

Work in progress

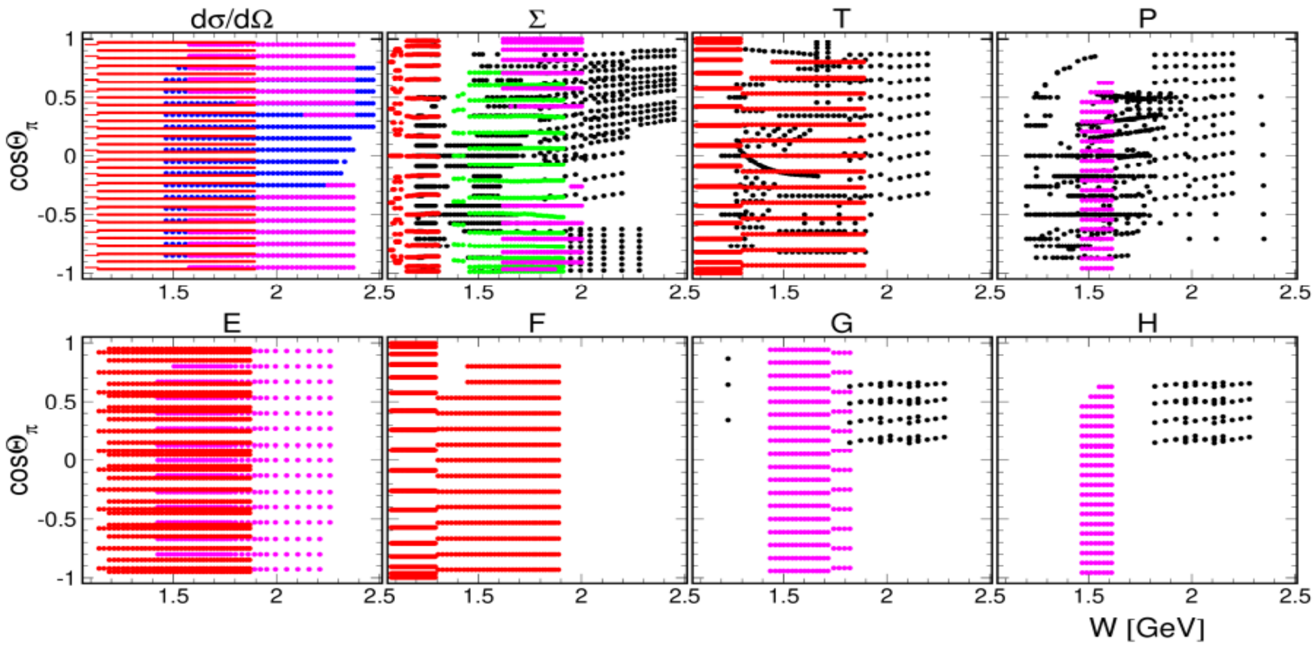
Summary

- Neutrino oscillation experiment needs: understand inelastic CC cross sections on few % level
- MAID: valuable PWA tool for e-m meson production since 1998
- Unitary isobar model - simple and efficient, good tool for extracting properties of baryons
- Recent improvements: incorporate Regge asymptotics and duality
- Extension to neutrino-induced reactions: work in progress
- Outlook: embed in neutrino event MC simulators

Backup

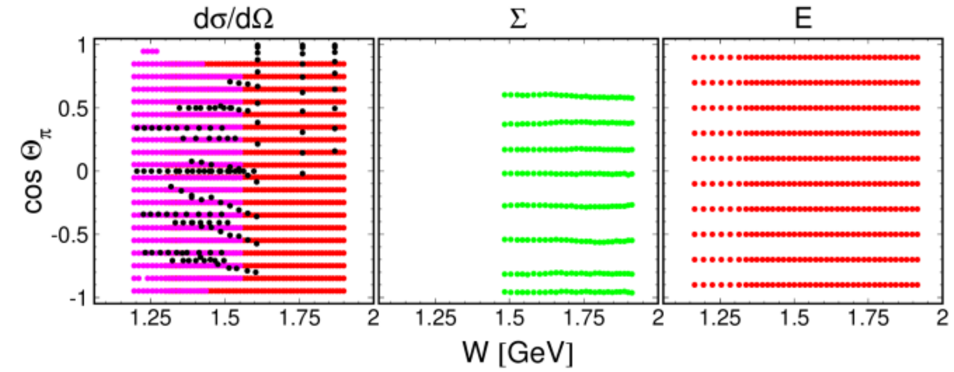
Data base for $\gamma p \to \pi^0 p$

The biggest data set exist for this reaction:
200 publications with experimental results for 10 observables.
For dσ/dΩ in resonance region used only latest data from A2MAMI and CLAS Collaborations



A2MAMI (red), CB/ELSA (magenta), CLAS (blue), GRAAL (green).
Black points correspond to the old data.

Data base for $\gamma n \to \pi^0 n$



Black: old data [1], Red: A2MAMI [2, 5], Magenta: A2MAMI [3], Green: GRAAL [4]

References

1. Clinesmith, PhD theris, CIT (1967);
   C. Bacciet et al., Phys. Lett. C 39, 559 (1972);
   Y. Hemmiet et al., Nucl. Phys. B 55, 333 (1973);
   A. Ando et al., Physik Daten, Fachinformationszentrum, Karlsruhe (1977).
2. M. Dieterle et al. (A2 Collaboration at MAMI), Phys. Rev. C 97, 065205 (2018).
3. W. J. Briscoe et al. (A2 Collaboration at MAMI), Phys. Rev. C 100, 065205 (2019).
4. R. Di Salvo et al. (GRAAL Collaboration), Eur. Phys. J. A 42, 151 (2009).

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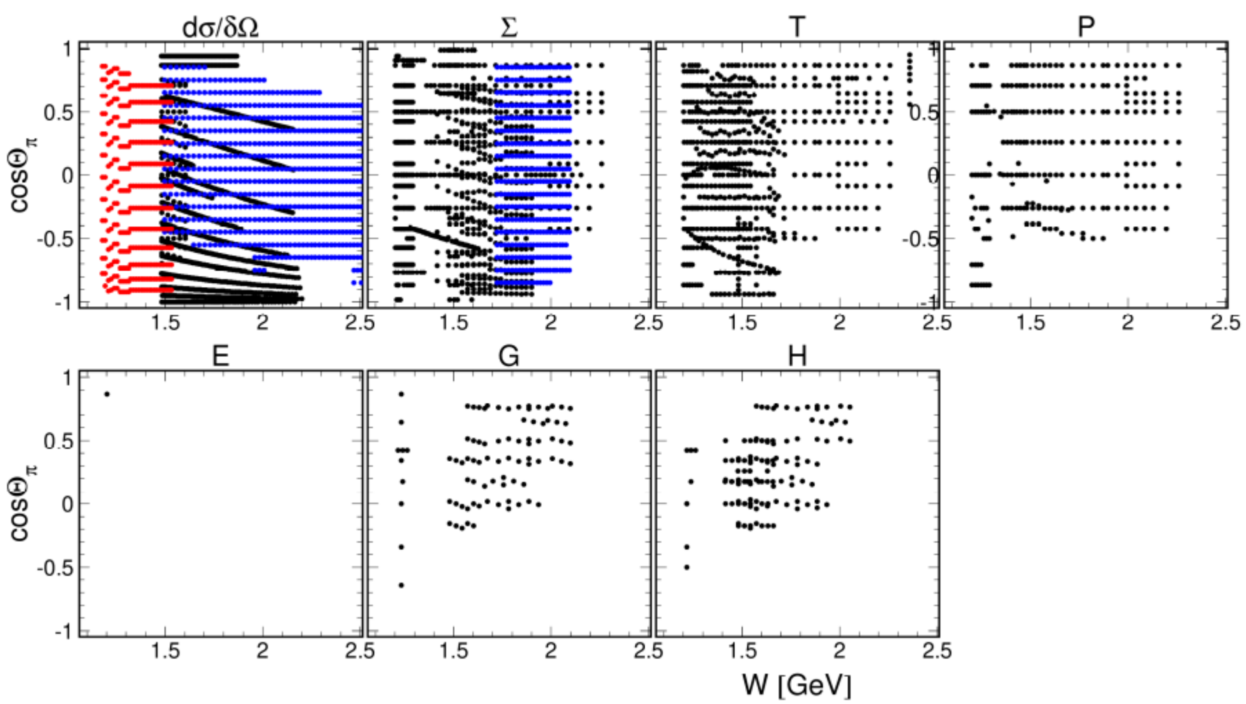
5. F. Cividini et al., (A2 Collaboration at MAMI), Eur. Phys. J. A 58:113 (2022).

New publication (data are not presented in the plot) :

6. C. Mullen et al. (A2 Collaboration at MAMI), Eur. Phys. J. A 57, 205 (2021).
   (Σ asymmetry, W = 1271 – 1424 MeV, cosΘ = from -0.85 to 0.66, 189 experimental points.)

Data base for $\gamma p \to \pi^+ n$



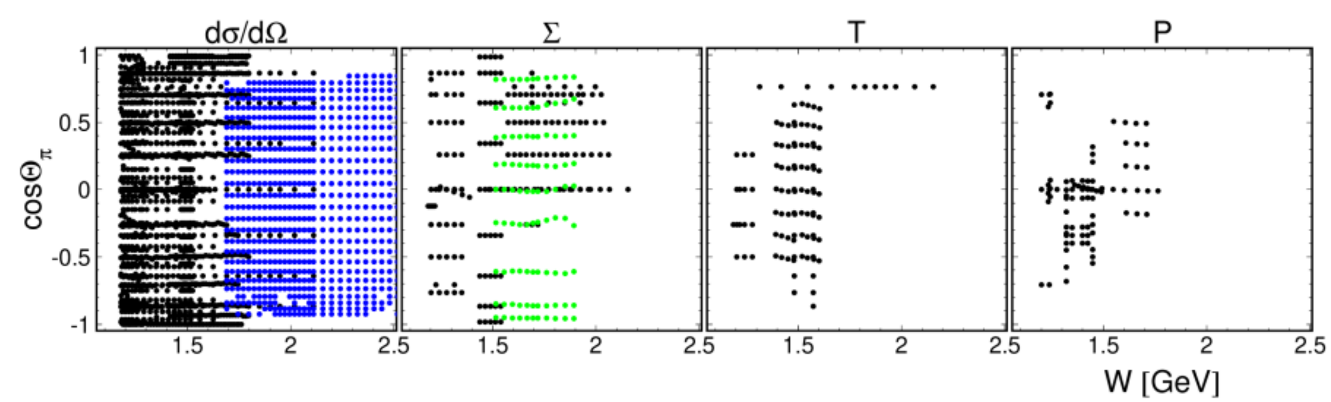
A2MAMI (red), CLAS (blue)
Black points correspond to the old data.

Data base for $\gamma n \to \pi^- p$

For this reaction beside results on quasi-free neutron target exist data from reaction:

$$\pi^- p \to \gamma n$$

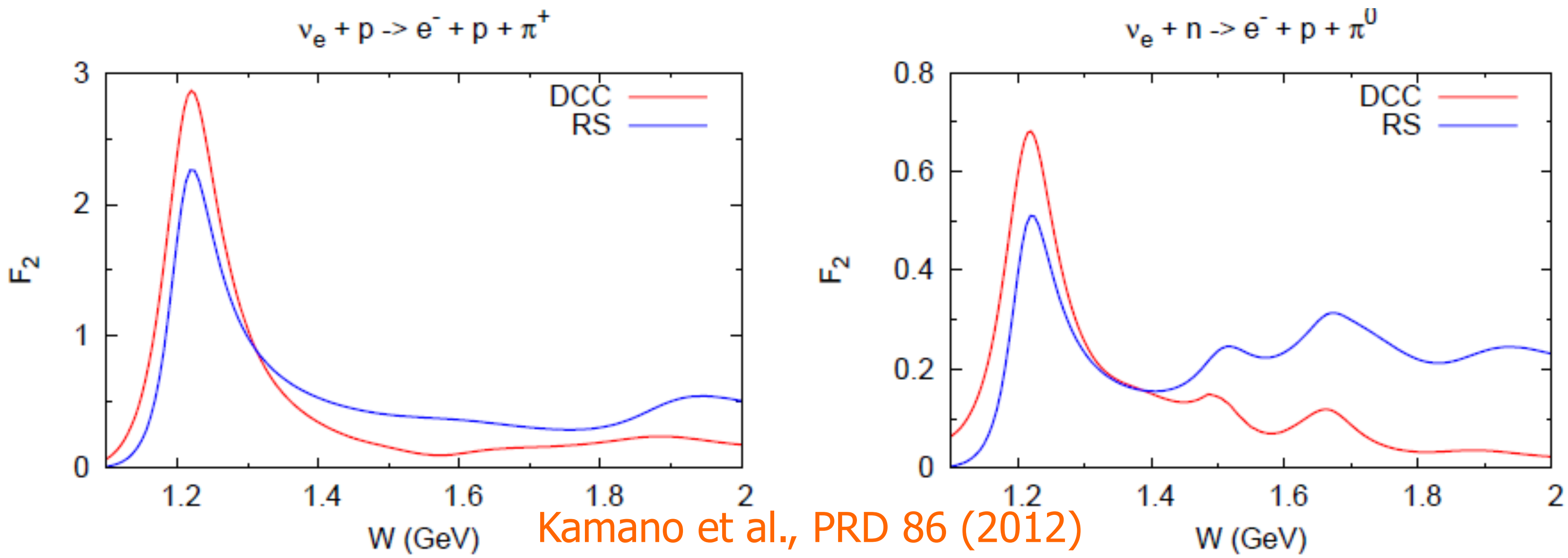
that are in good agreement with neutron data.
So, we use both of them.



A2MAMI (red), CLAS (blue), GRAAL (green).
Black points correspond to the old data.

PCAC: constraint from πN scattering

$$\left.\frac{d\sigma_{\mathrm{CC}\pi}}{dE_l d\Omega_l}\right|_{q^2=0} = \frac{G_F^2 V_{ud}^2}{2\pi^2}\frac{2f_\pi^2}{\pi}\frac{E_l^2}{E_\nu - E_l}\sigma_{\pi N}$$



Kamano et al., PRD 86 (2012)

$$F_2(W, q^2 = 0) \propto \sigma_{\pi N \to X}(\sqrt{s} = W)$$

- DCC = Dynamical coupled channel model; RS=Rein-Sehgal model

Plot: courtesy of L. Alvarez Ruso

Vector current does not contribute for $q^2 = 0$;
Hence no V $\times$ A interference (ν and $\bar{\nu}$ cross sections exactly the same)