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MK single pion production model

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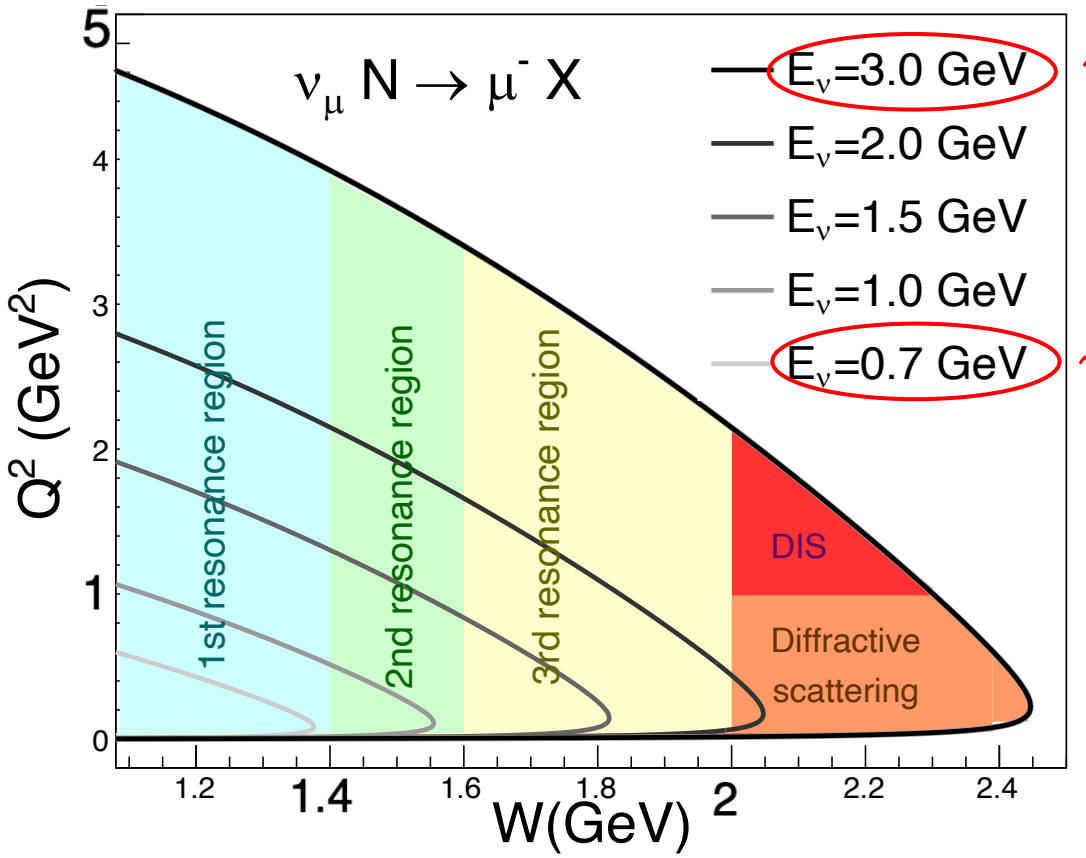
NuFACT

Seoul, Aug. 22, 2023

Meson production in ν-Nucleon interaction



~ MINERvA, DUNE

~ MiniBooNE

Shallow/Deep inelastic scattering (SIS/DIS) transition

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Meson production in ν-Nucleon interaction

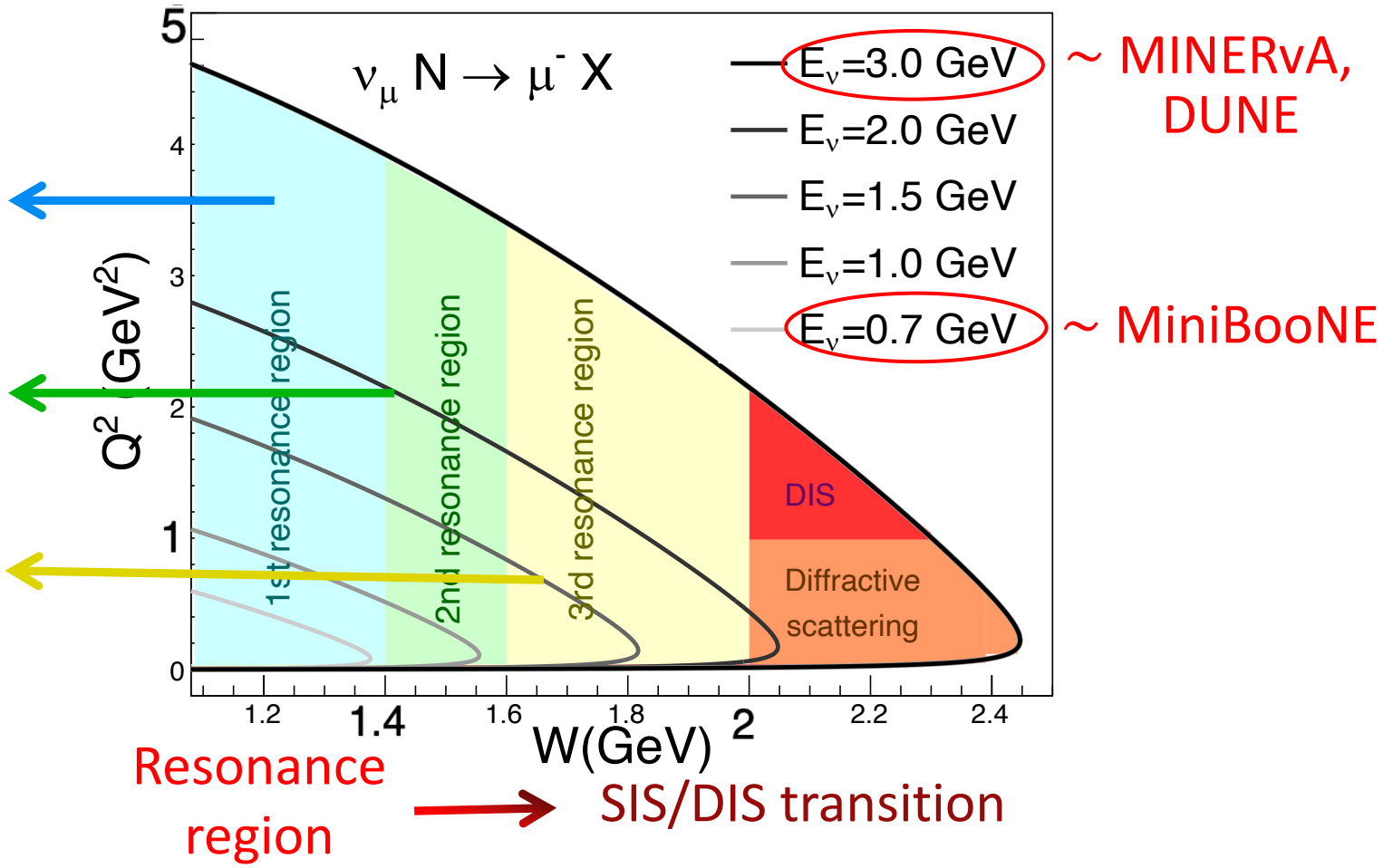
Resonant interaction

- $\Delta(1232)$ resonance
- 1-π production

- $P_{11}(1440), D_{13}(1520)$ and $S_{11}(1535)$

- 2-π, η, etc. production

- About 13 resonances overlap



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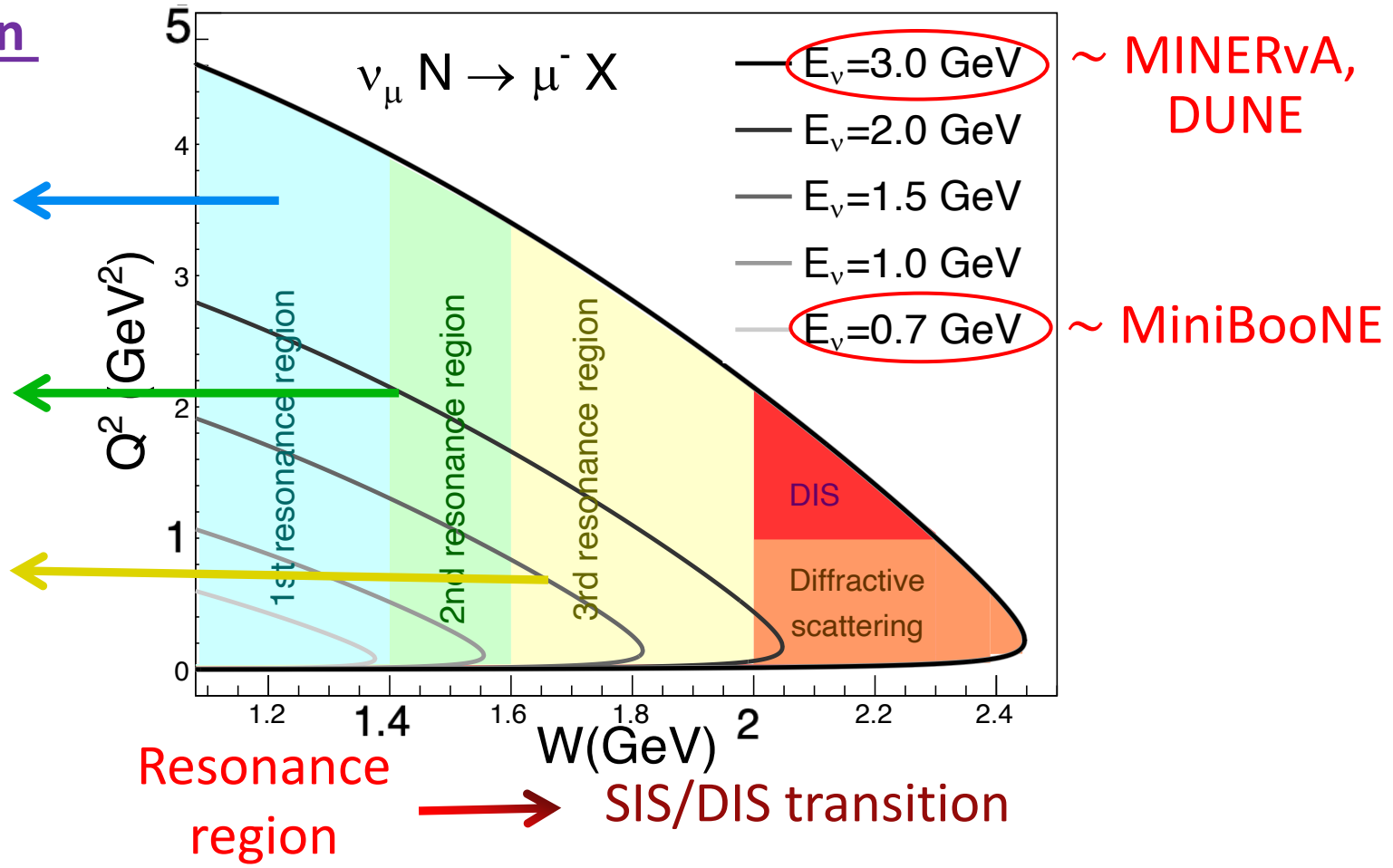
Meson production in ν-Nucleon interaction

Non-resonant interaction

- Chiral-perturbation theory Lagrangian (ChPT)
- Hybrid model
- Reggeized Chiral-perturbation theory (ReChi)



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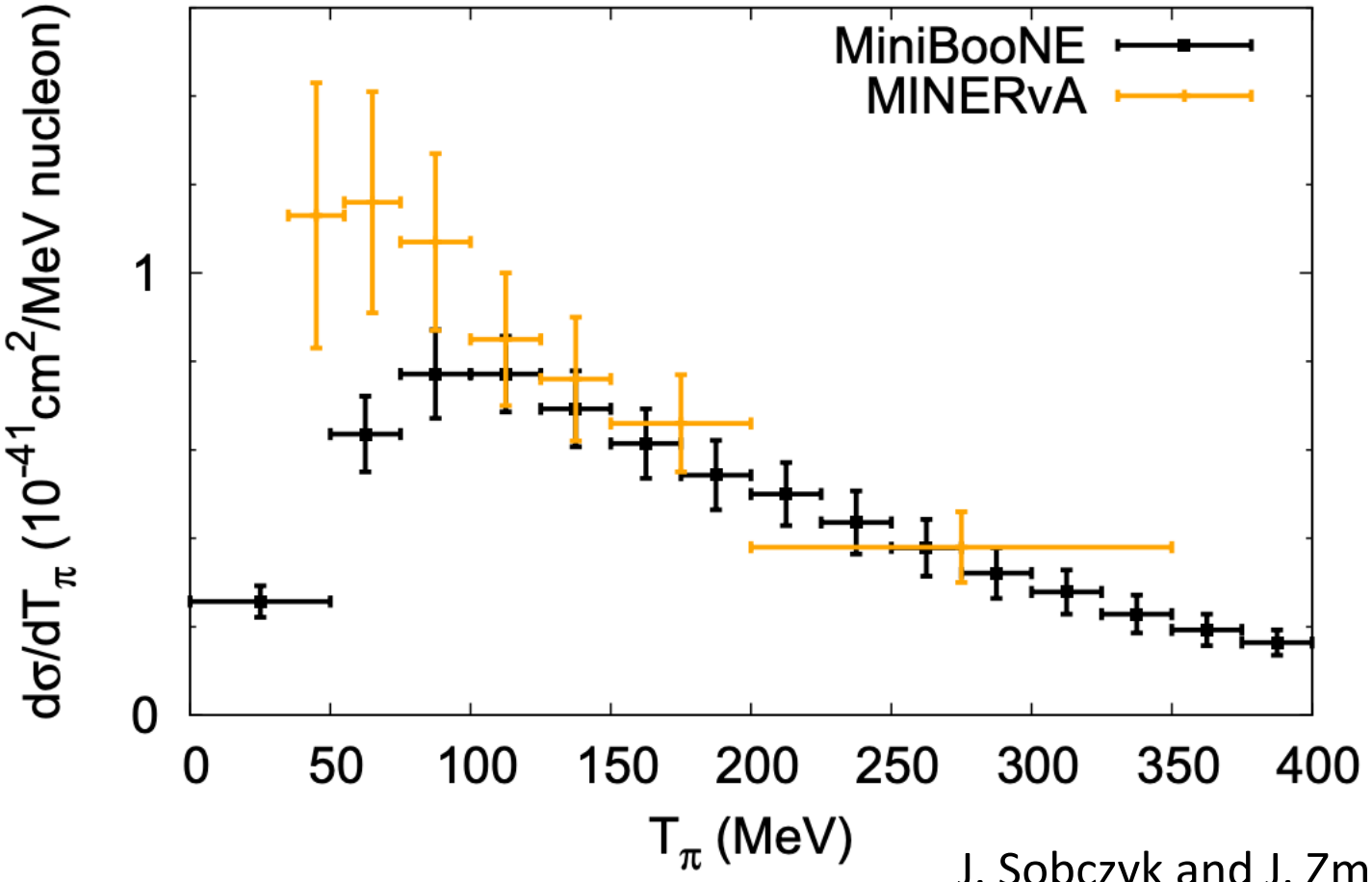
Tensions between **MiniBooNE** and **MINERvA**

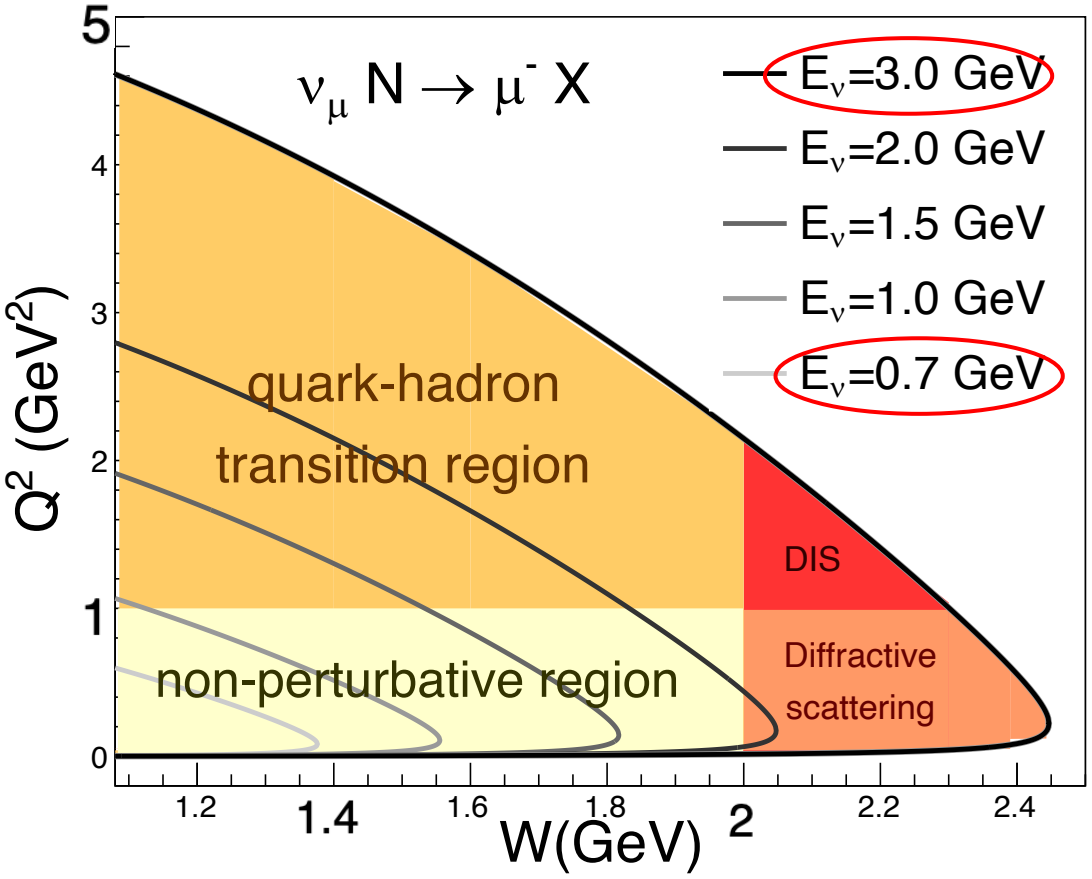
- Tensions between MiniBooNE and MINERvA for single pion production measurements on CH_2 and CH targets in the **first resonance region**.



J. Sobczyk and J. Zmuda
Phys. Rev. C **91** (2015)

Meson production in ν-Nucleon interaction

- Degree of freedom at E < 1 GeV (MiniBooNE) is **hadrons**
- Degree of freedom at E > 1 GeV (MINERvA) is a mixture of **hadrons** and **partons**



~ MINERvA, DUNE

~ MiniBooNE

perturbative region

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Goal: New approach for building models that have the **maximum impact** on our ability to extract and interpret interesting physics measurements.

1. Improving a model through detailed **theoretical calculations** (extension to a large enough Kinematic regions)
2. Transforming the model to something that could be easily and efficiently **incorporated into event generators**
3. Studying the **systematic uncertainties** of the theoretical model
4. Providing a few adjustable **physics-based parameters**, or ”knobs” which can be used in future measurements

MK model

M. Kabirnezhad
Phys. Rev. D **97** (2018)
Phys. Rev. D **102** (2020)
Phys.Rev.C **107** (2023)

- MK model describes single pion production in neutrino-nucleon interactions
- The calculation is based on **helicity amplitudes**
- **Vector Meson Dominance** (VMD) form factor model is used for both resonant and non-resonant interactions
- Q^2-evolution is made by using **QCD** calculations and **quark-hadron duality**.
- W-evolution is made by using Regge trajectory and Hybrid model

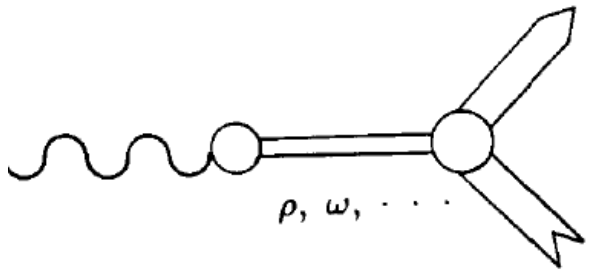
R. González-Jiménez, *et al*
Phys. Rev. D **95** (2017)

Vector Meson Dominance (VMD model)

Representation of electron scattering:

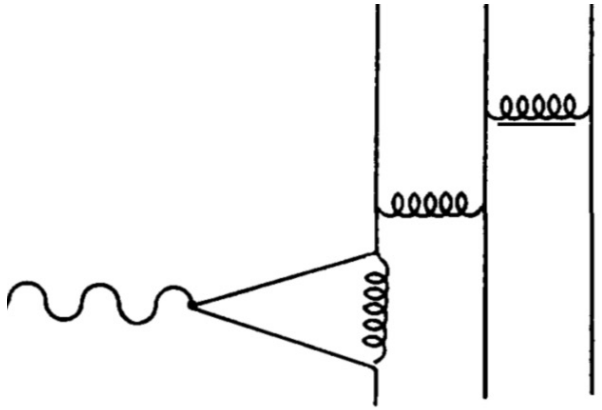
G. Vereshkov and N. Volchanskiy
PRD **76**, 073007 (2007)

Non-perturbative (low Q^2)



- Vector mesons propagate between the virtual photon and the nucleon

Perturbative (high Q^2)



- schematic quark model of VMD model

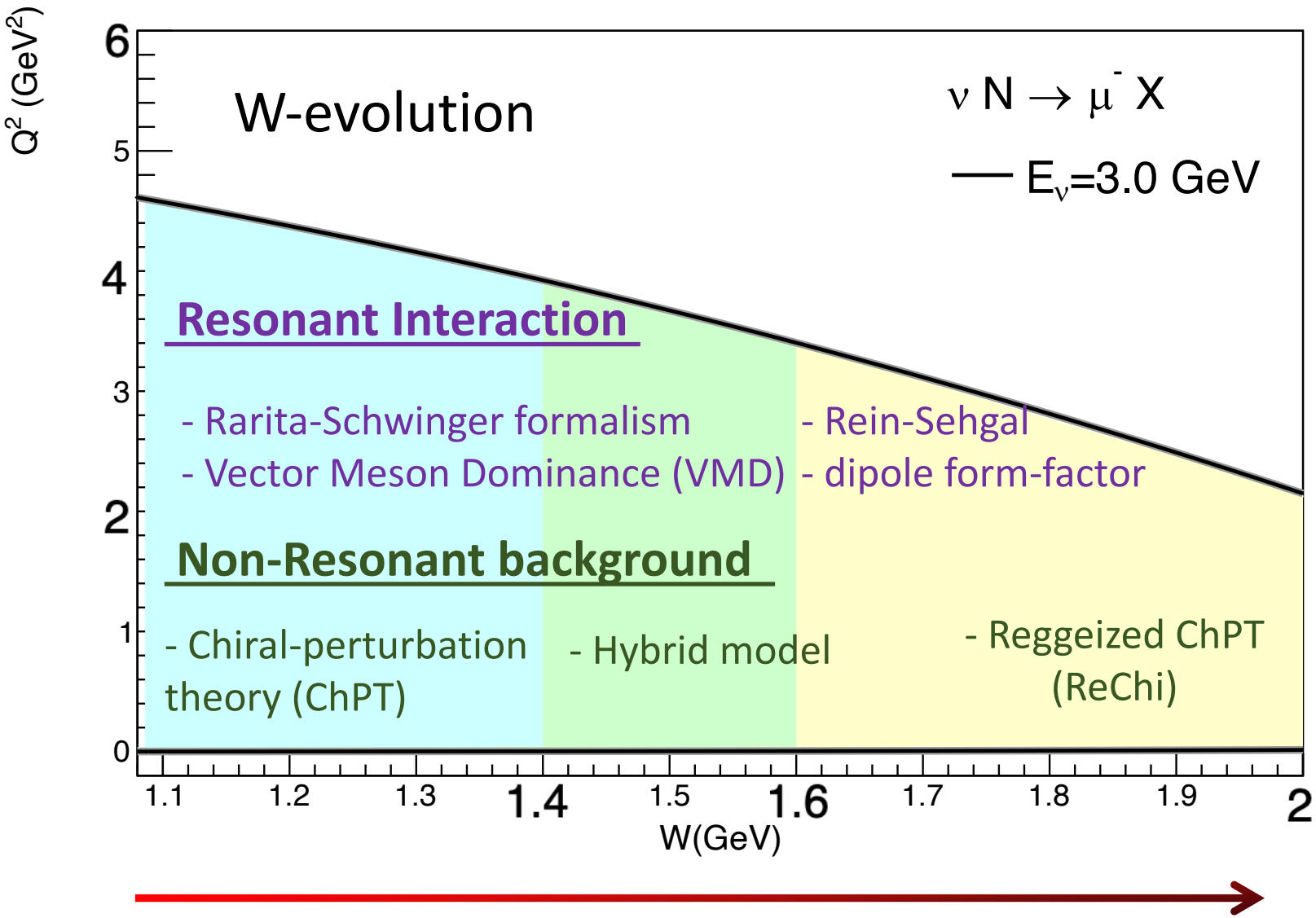
MK model

Resonant interaction

- Several resonances contribute at different invariant mass (W)

Non-resonant bkg

- Chiral perturbation at low W < 1.4 GeV
- Regge trajectory at high W
- Hybrid model



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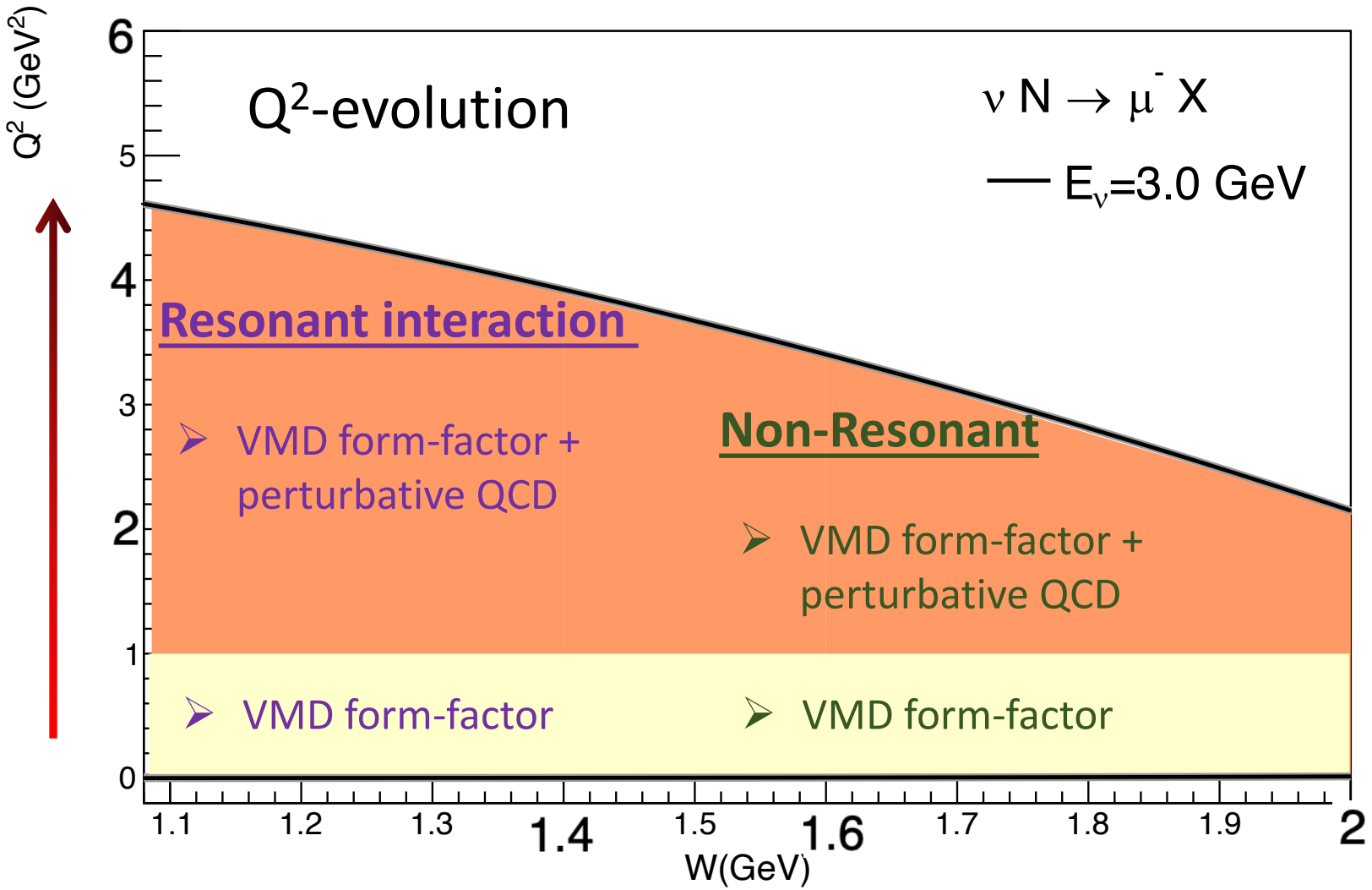
MK model

- Vector Meson Dominance (VMD) model describes form-factors in non-perturbative domain
- It can reproduce Q^2-evolution of form-factors to asymptotically join QCD expectations



Valid kinematic region region for MK model

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Electron scattering data

- A variety of measurements of single pion electroproduction on protons and "neutrons" have been performed at CLAS in a wide range of Q^2 $(0.16 - 6.00)$ GeV^2 and W$(1.1 - 2.01)$ GeV

CLAS database

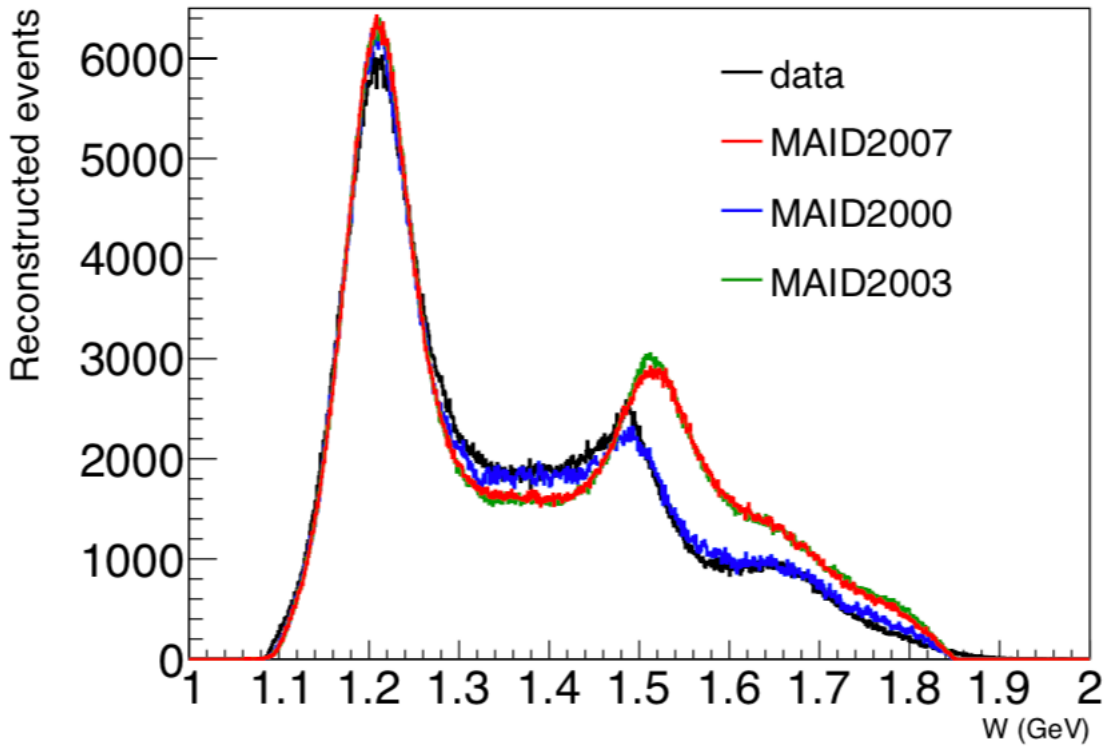
Channels	Beam Energy (GeV)	Q^2 Range $(GeV/C)^2$	W Range (GeV)	# data points	# experiments
$ep \rightarrow en + \pi^+$	1.05 – 5.75	0.16 – 4.16	1.10 – **2.01**	≈ 15000	5 data sets
$ep \rightarrow ep + \pi^0$	1.05 – 5.75	0.16 – **6.00**	1.10 – 1.68	≈ 16000	6 data sets
NEW $en \rightarrow ep + \pi^-$	2.030	0.40 – 1.00	1.10 – 1.83	≈ 7000	1 data set

Joint fit

Total ≈ **38000** data points

First measurements on “neutron” target

- In the first resonance peak the neutron and proton form-factors are the same for the Δ resonance
- Even though MAID2007 is the latest version, the second resonance peak from this version is shifted relative to the experimental neutron data



Experimental W distribution event in comparison to various MAID models

Y. Tian *et al.* [CLAS]
Phys. Rev. C **107** (2023)

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Vector current

- Performed a Joint fit to determine the **proton** and "**neutron**" form-factor (for nucleon & 17 resonances in nonresonant interactions) in order to determine the vector form-factor in the neutrino pion production model
- Covariance matrix is obtained and systematic uncertainties are studied. Reduced $\chi 2 \approx 2.2$

- The vector form-factors are obtained from proton and neutron form-factors

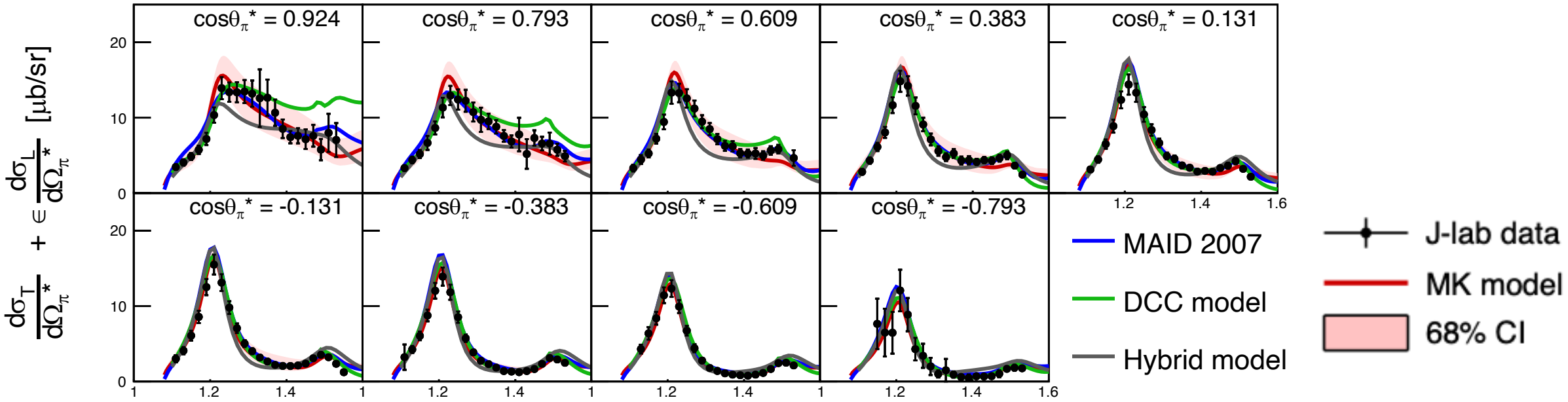
$$F_i^V = F_i^n - F_i^p \left(I = \frac{1}{2}\right)$$

$$F_i^V = F_i^{p(n)} \left(I = \frac{3}{2}\right)$$

Data/models comparison at low Q^2

M. Kabirnezhad
Phys.Rev.C 107 (2023)

$$ep \rightarrow en + \pi^+$$



E= 1.515 GeV

Q^2=0.4 GeV^2

1.1<W<1.41 GeV

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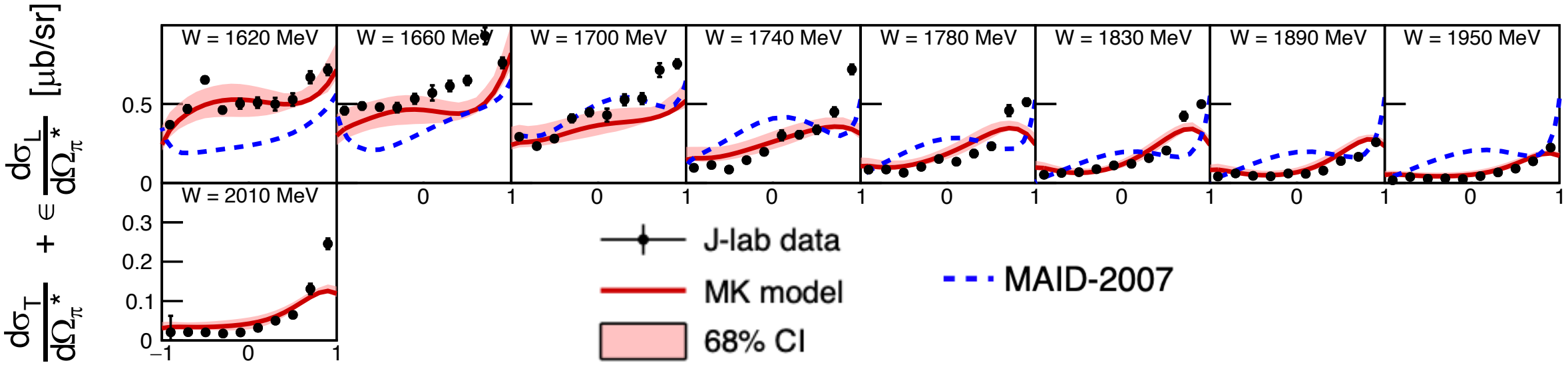
Data/models comparison at high Q^2

M. Kabirnezhad
Phys.Rev.C 107 (2023)

$$ep \rightarrow en + \pi^+$$



E= 5.449 GeV
Q^2=2.6 GeV^2
1.62 <W< 2.01 GeV
Third resonance region

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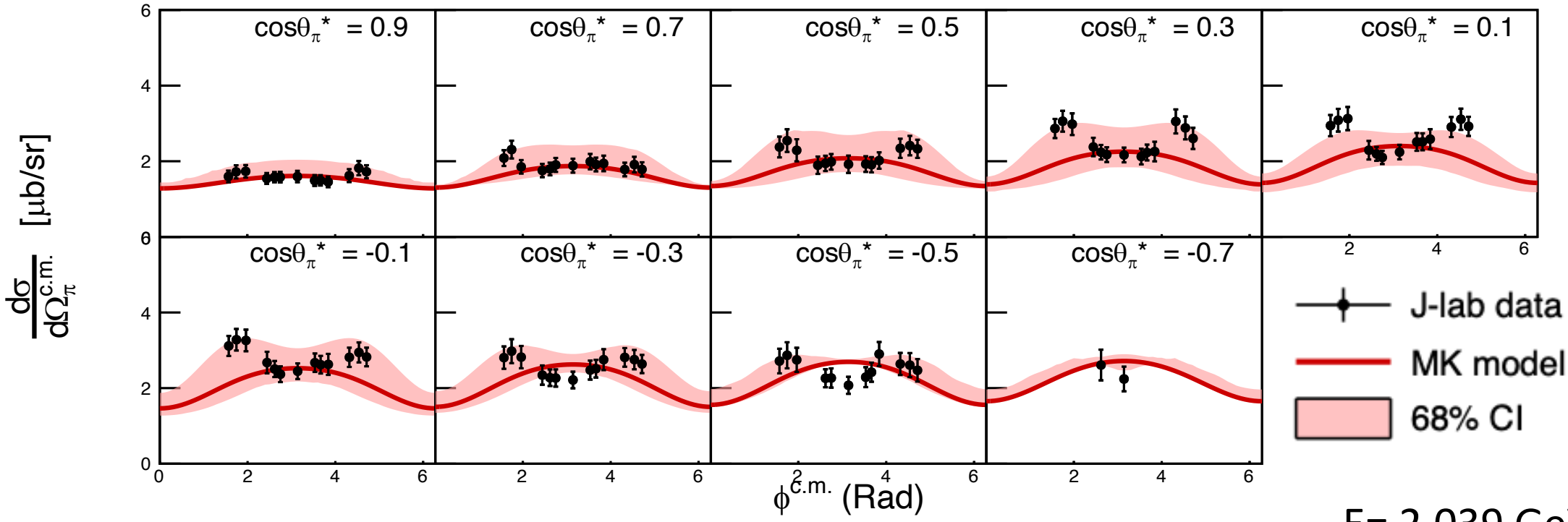
PRELIMINARY

MK model prediction after a joint-fit

$$e\,n \rightarrow e\,p + \pi^-$$



E= 2.039 GeV

Q^2=0.7 GeV^2

W=1.13 GeV

Neutrino interactions

- Using **vector** and **axial-vector** meson dominance form-factor model
- I assume that the gauge bosons hadronized to a set of vector and axial mesons, so interaction between neutrino and nucleon occurs via meson exchange
- Chiral symmetry of strong interactions requires coupling constants of left and right fields to be equal. Therefore the asymptotic behaviour of vector and axial form-factors are the same
- Chiral symmetry reduces number of parameters in the axial form-factors!

Axial current (form-factor)

- Used **Axial-vector Meson Dominance** model for the axial form factor
- Used a joint fit to determine the axial current using:

  1. ANL & BNL measurements ($E_\nu \approx 1\ GeV$)
  2. BEBC measurements ($E_\nu \approx 20\ GeV$)
  3. Pion scattering data to satisfy Partially Conserved Axial Current at $\mathrm{Q}^2 = 0\ \mathrm{GeV}^2$

- The Axial current is not finalised yet. The result is satisfactory for the first resonance region so far

Conclusion

- The MK model is extended to high Q^2 (up to 6 GeV^2) and W (up to 2 GeV)
- Neutron and proton form-factors (full vector form-factors) are determined in a joint fit using all single pion production data on proton and neutron (about 38000 data points)
- Systematic uncertainty of the model is evaluated . The free parameters (knobs) can be used in neutrino measurements
- The data-model agreements is due to model improvements, the use of significant amount of experimental data and developments in the methodology of analysis and evaluation