Comparison of Predictions of Neutrino MC Generators (Run in Electron-Mode) to a Global Extraction of the ^{12}C R_L and R_T Nuclear Electromagnetic Response Functions

1. Testing first principle nuclear theory predictions
2. Provide a platform for verification of electron and neutrino MC generators over the entire kinematic range of interest

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NuFact 2024: Sept 16 @ Argonne National Lab, IL

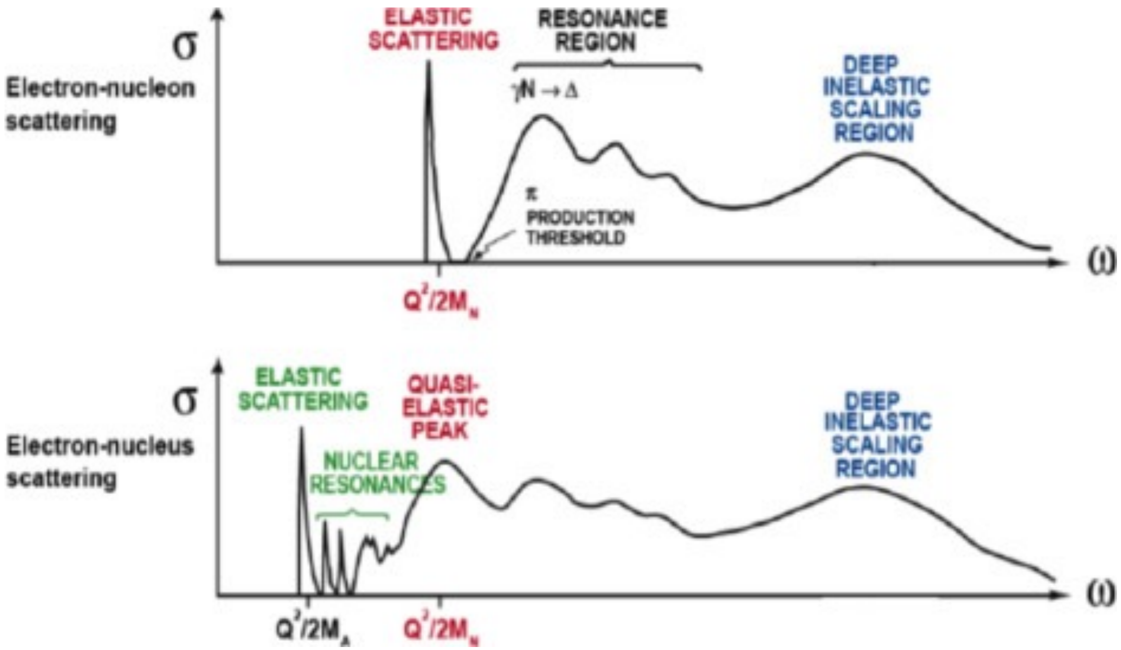
20 min talk + 4 min Q&A

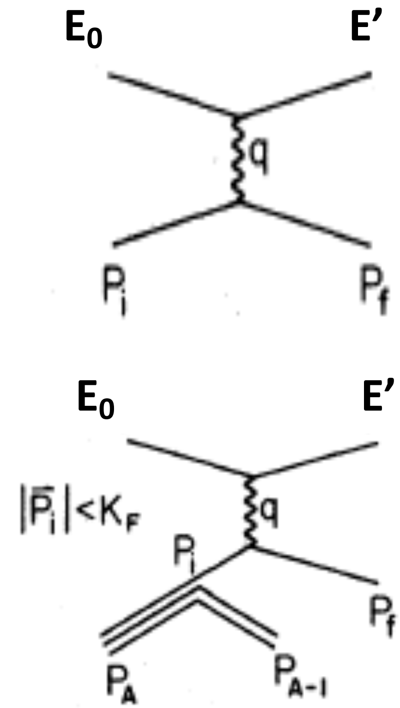
This work was supported in part by the US Department of Energy award DE-SC0008475.

Introduction

Electron scattering off nucleon and nucleus:

G.T. Garvey et al. / Physics Reports 580 (2015) 1-45





- Given the nuclear physics common to both electron and neutrino scattering from nuclei, we can study electron scattering to validate and tune MC generators for electron and neutrino interactions.

Introduction

Descriptions of electron scattering differential cross section used in the literature:

- In terms of longitudinal and transverse virtual photon cross sections:

$$\frac{d\sigma}{d\Omega dE'} = \Gamma[\sigma_T(W^2, Q^2) + \epsilon\sigma_L(W^2, Q^2)],$$

where Γ is the flux of virtual photons, ϵ is the virtual photon polarization;

- In terms of structure functions:

$$\frac{d\sigma}{d\Omega dE'} = \sigma_M \left[\mathcal{W}_2(W^2, Q^2) + 2\tan^2\left(\frac{\theta}{2}\right)\mathcal{W}_1(W^2, Q^2)\right],$$

where $\sigma_M = \frac{4\alpha^2 E'^2}{Q^4}\cos^2\left(\frac{\theta}{2}\right)$ is the Mott cross section; $\mathcal{W}_1, \mathcal{W}_2$ are related to the $\mathcal{F}_1, \mathcal{F}_2$ structure functions as $\mathcal{F}_1 = M\mathcal{W}_1, \mathcal{F}_2 = \nu\mathcal{W}_2$, M is nucleon mass.

- In terms of longitudinal and transverse electromagnetic response functions $R_L(Q^2, \nu), R_T(Q^2, \nu)$:

$$\frac{d\sigma}{d\nu d\Omega} = \sigma_M \left[\frac{Q^4}{\mathbf{q}^4} R_L(Q^2, \nu) + \left(\tan^2\left(\frac{\theta}{2}\right) + \frac{Q^2}{2\mathbf{q}^2}\right) R_T(Q^2, \nu)\right].$$

We use the R_L, R_T description.

Introduction

Descriptions of electron scattering differential cross section used in the literature:

- The three descriptions can translate to each other:

$$R_T = \frac{2\mathcal{F}_1}{M} = \frac{K}{2\pi^2\alpha}\sigma_T,$$

$$R_L = \frac{\mathbf{q}^2}{Q^2}\frac{\mathcal{F}_L}{2Mx} = \frac{\mathbf{q}^2}{Q^2}\frac{K}{2\pi^2\alpha}\sigma_L,$$

where $K = \frac{2M\nu - Q^2}{2M}, x = \frac{Q^2}{2M\nu}; \mathcal{F}_L = \mathcal{F}_2\left(1 + \frac{4M^2x^2}{Q^2}\right) - 2x\mathcal{F}_1$ is called longitudinal structure function.

- Important quantities:
  - energy transfer ν,
  - 4-momentum transfer Q,
  - 3-momentum transfer $\mathbf{q}$ where $\mathbf{q}^2 = Q^2 + \nu^2$,
  - nuclear target mass M_A where $M_A = 11.178 GeV$ for ^{12}C,
  - final state invariant mass W where $W^2 = M^2 + 2M\nu - Q^2$,
  - excitation energy $E_x = \nu - \frac{Q^2}{2M_A}$.

Experimental Method: Rosenbluth Separation

- "Rosenbluth quantity": [1]

$$\Sigma = \left(\frac{E_0}{E_0+V_{eff}}\right)^2 \frac{\mathbf{q}_{eff}^4}{4\alpha^2 {E'_{eff}}^2} \frac{1}{\cos^2\left(\frac{\theta}{2}\right)+2\left(\frac{\mathbf{q}_{eff}}{Q_{eff}}\right)^2 \sin^2\left(\frac{\theta}{2}\right)} \frac{d\sigma}{d\nu d\Omega}$$

$$= \epsilon R_L + \frac{1}{2}\left(\frac{\mathbf{q}}{Q}\right)^2 R_T$$

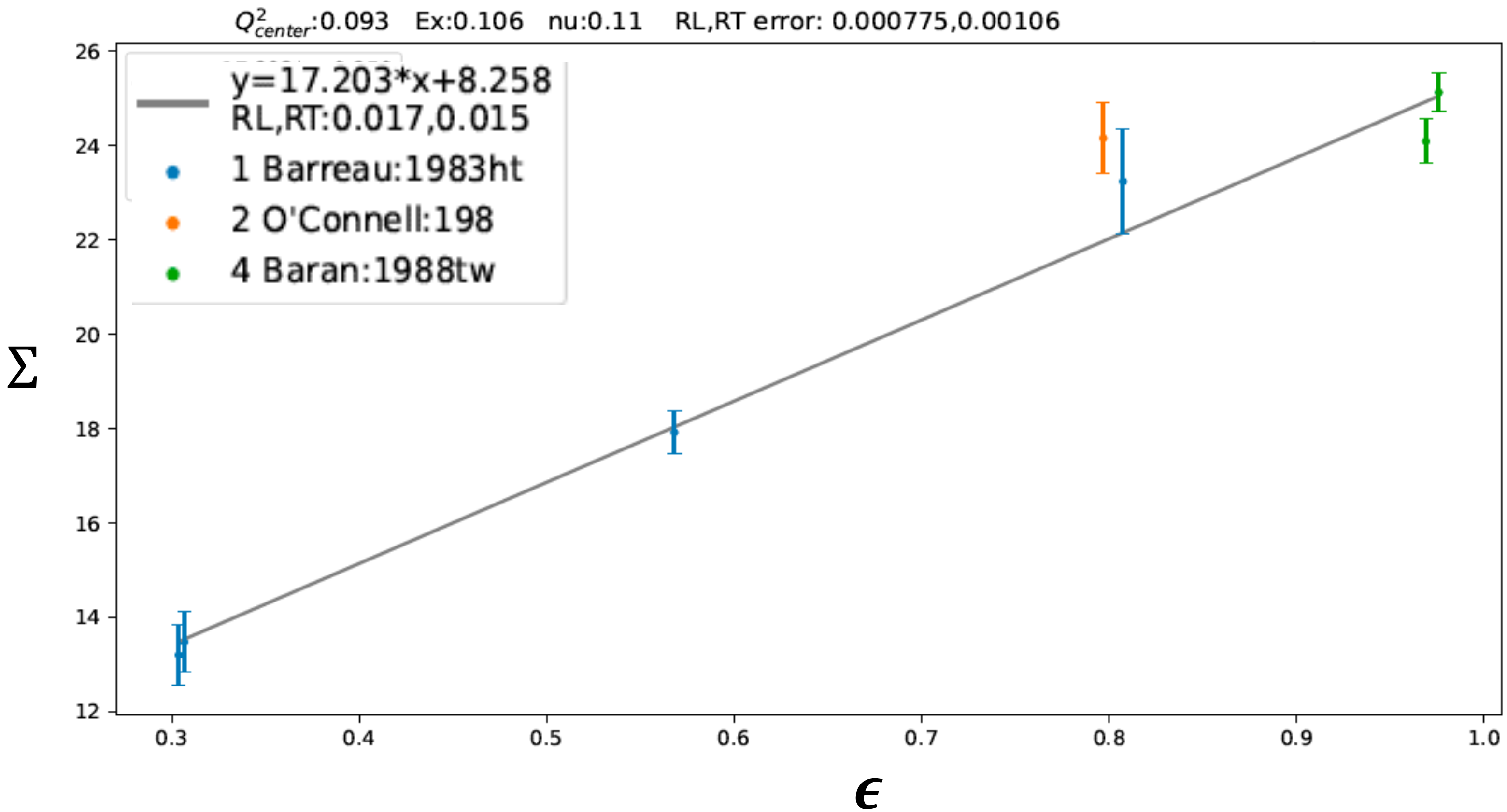
where $\epsilon = \left[1 + 2\left(1+\frac{\nu^2}{Q^2}\right)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}$ is the virtual photon polarization.

- Fit Σ against ϵ linearly in bins of $|\mathbf{q}|$ (or Q^2) and ν (or W^2, E_x), then we can extract $R_L = \text{slope}, R_T = 2\left(\frac{Q}{\mathbf{q}}\right)^2 \times \text{intercept}$.

[1] J. Jourdan, Phys. Lett. B 353, 189 (1995)

Experimental Method: Rosenbluth Separation

- An example:



Experimental Method: Christy-Bodek Universal Fit

- An update to Prof. Christy and Prof. Bodek's universal fit (A. Bodek, E. Christy. Phys. Rev. C 106, L061305 (2022)):
  - Now includes **a larger electron scattering dataset** on H, D, and nuclear targets.
- Fits for all kinematic regions:
  - Elastic scattering, nuclear excitations, Quasi-Elastic, resonance and pion production, deep inelastic.

Since the cross sections span a large range of energies and scattering angles, the fit can extract both the **longitudinal** $\boldsymbol{R_L}$ and **transverse** $\boldsymbol{R_T}$ contributions.

Experimental Method: Christy-Bodek Universal Fit

- Parameterizes both the **Transverse Enhancement / MEC** and the low $|\mathbf{q}|$ **Longitudinal Quenching** of QE cross section.

- The fit alone can be used to evaluate Monte Carlo predictions for electron-nucleus scattering.

- With Christy-Bodek universal fit and Rosenbluth separation, we carried out our $\boldsymbol{R_L}$ $\boldsymbol{R_T}$ **extraction project**.

R_L R_T Extraction Project

Goals:

- **To test first-principle nuclear theories;**
- **To validate and tune MC generators.**

Advantages:

- We extract R_L and R_T values on various nuclei **using all available data**
  - Prioritize nuclei of interests to neutrino experiments
  - Therefore, when we compare model predictions to measurements of R_L and R_T, we are effectively comparing to all electron scattering experiments at the same time.

- Large dataset, covering all kinematic regions (nuclear elastic, nuclear excitations, Quasi-Elastic, resonance, and inelastic scattering)
  - More comprehensive than comparison with a few cross-section measurements in limited kinematic regions.

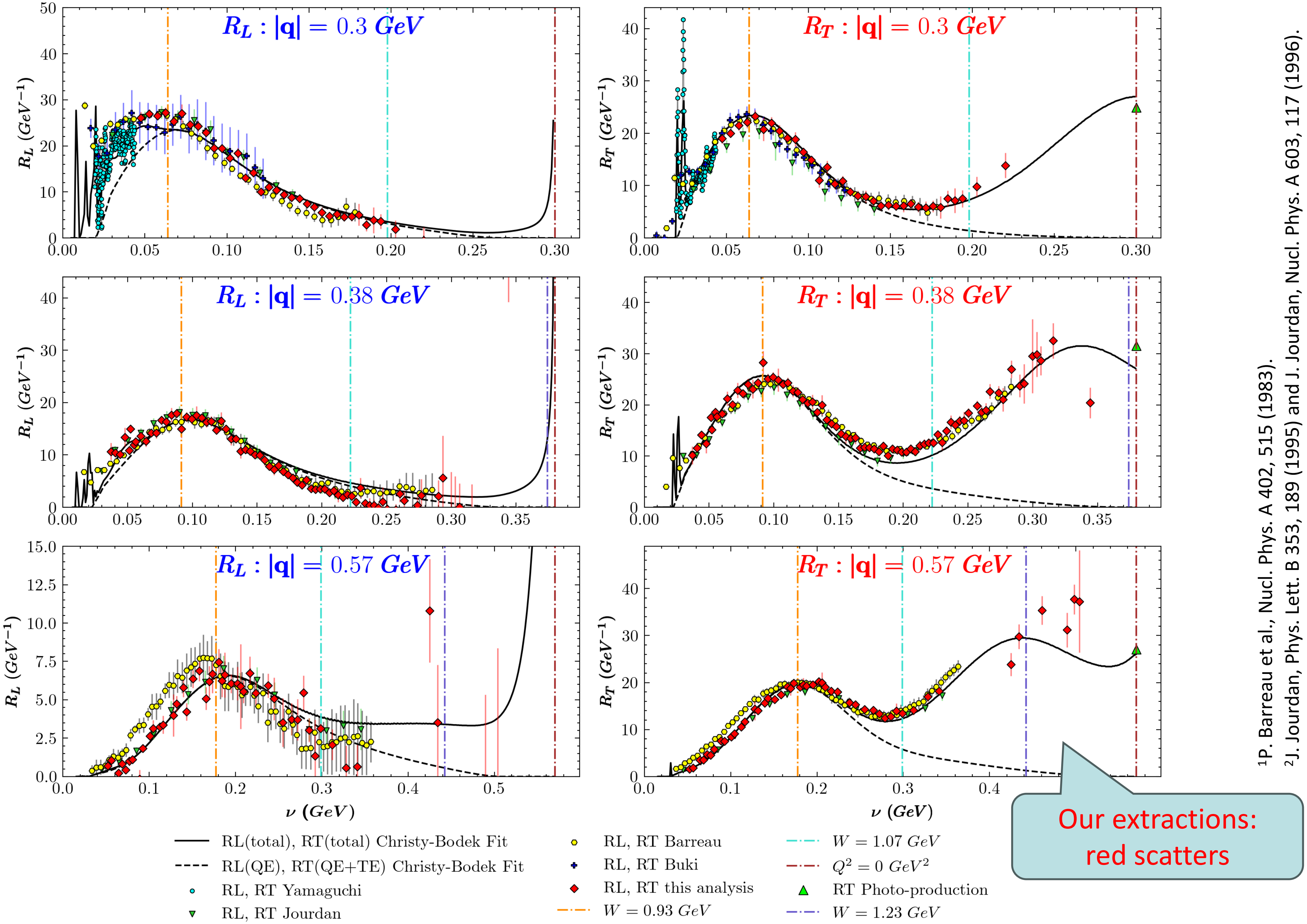
R_L R_T Extraction Project

- For Carbon, there are $\sim 10k$ electron scattering and photoproduction cross-section measurements;
  - We use **Rosenbluth Separation** to extract R_L, R_T at 18 fixed $|\mathbf{q}|$ values: $0.1 < |\mathbf{q}| < 2.78\ GeV$, and at 18 fixed Q^2 values: $0 < Q^2 < 3.45\ GeV^2$, both as functions of ν.
  - We apply **Coulomb** and **Bin-centering corrections** (need Christy-Bodek universal fit) to bin the data at effective $|\mathbf{q}|$ or Q^2.

- ν ranges from $\nu = 0\ GeV$ to the end of the resonance region where $W = 2.0\ GeV$.

- Calcium, Aluminum, … : analysis in progress.

Compare to Previous Extractions[1~4] at 3 Fixed in $|\mathbf{q}|$ Bins:



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R_L R_T Extraction: More Details

- Analysis in fixed $|\mathbf{q}|$ (or in fixed Q^2) bin:
  1. Bin all cross-section data in $|\mathbf{q}|$ (or Q^2);
  2. Apply **Coulomb corrections**; apply **bin-centering corrections**.

     For $\nu < 50 MeV$: bin-centered in E_x (excitation energy);

     For $\nu > 50 MeV$: bin-centered in W^2 (final state invariant mass squared);

     Later convert E_x and W^2 to ν.
  3. Bin again in ν.
  4. Finally, perform Rosenbluth fit to subdivisions of data to extract R_L and R_T.
- Note: Christy-Bodek fit is universal, while Rosenbluth fit uses only a small subset.

R_L R_T Extraction: More Details

- Coulomb correction[1]: account for ^{12}C effective potential,
  - There exists "focusing factor" $F_{foc}^2 = \left(\frac{E_0+V_{eff}}{E_0}\right)^2$ that modifies σ_M.
  - For ^{12}C, $V_{eff} = 3.1MeV$; $E_{0,eff} = E_0 + V_{eff}$, $E'_{eff} = E' + V_{eff}$.

- Bin-centering correction factor:
  - $C = \frac{\epsilon R_{L-center}^{fit} + \frac{1}{2}\left(\frac{\mathbf{q}_{center}}{Q_{center}}\right)^2 R_{T-center}^{fit}}{\epsilon R_{L-data}^{fit} + \frac{1}{2}\left(\frac{\mathbf{q}_{data}}{Q_{data}}\right)^2 R_{T-data}^{fit}} \rightarrow \Sigma_{bin-centered} = \mathrm{C} \times \Sigma$.

- Our fixed $|\mathbf{q}|$ bin-centers: 0.100, 0.148, 0.167, 0.205, 0.240, 0.300, 0.380, 0.475, 0.570, 0.649, 0.756, 0.991, 1.659, 1.921, 2.213, 2.500, 2.783, 3.500 GeV

- Our fixed Q^2 bin-centers: 0.00 (photo production), 0.010, 0.020, 0.026, 0.040, 0.056, 0.093, 0.120, 0.160, 0.265, 0.38, 0.50, 0.80, 1.25, 1.75, 2.25, 2.75, 3.25, 3.75 GeV^2

[1]P. Gueye et al., Phys. Rev. C **60**, 044308 (1999)

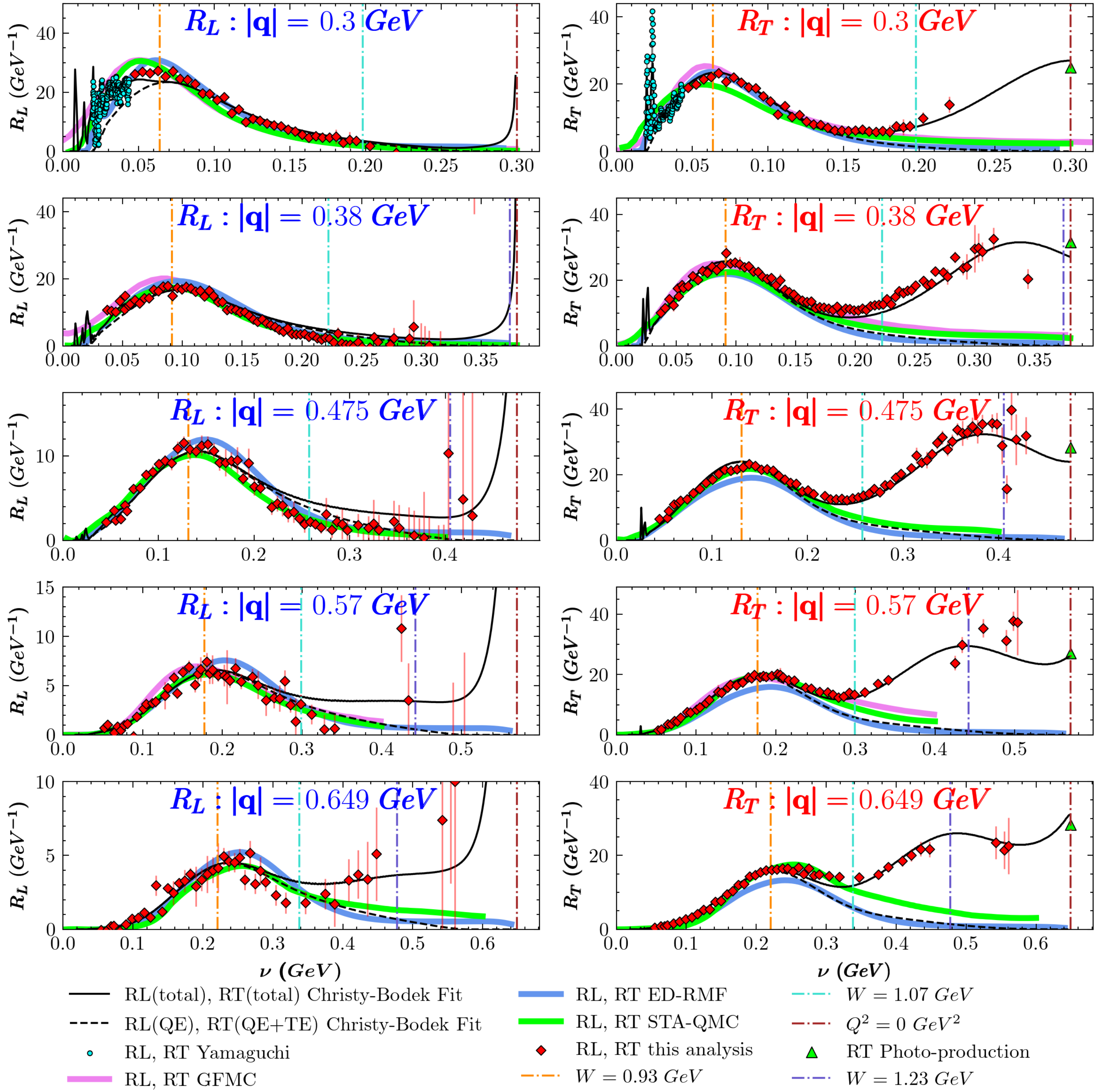
Theories and MC Generators comparison

- We compare our R_L, R_T fit and extracted values to:

  - 1st principle nuclear physics theories' predictions:
    - GFMC (Green's Function Monte Carlo)
    - ED-RMF (Energy Dependent Relativistic Mean Field)
    - STA-QMC (Short Time Approximation Quantum Monte Carlo)

  - MC generated predictions:
    - NuWro
    - ACHILLES
    - Correlated-Fermi-Gas
    - GENIE (manual extractions)

We gratefully thank the authors that provide us their predictions!
(See the list of reference)



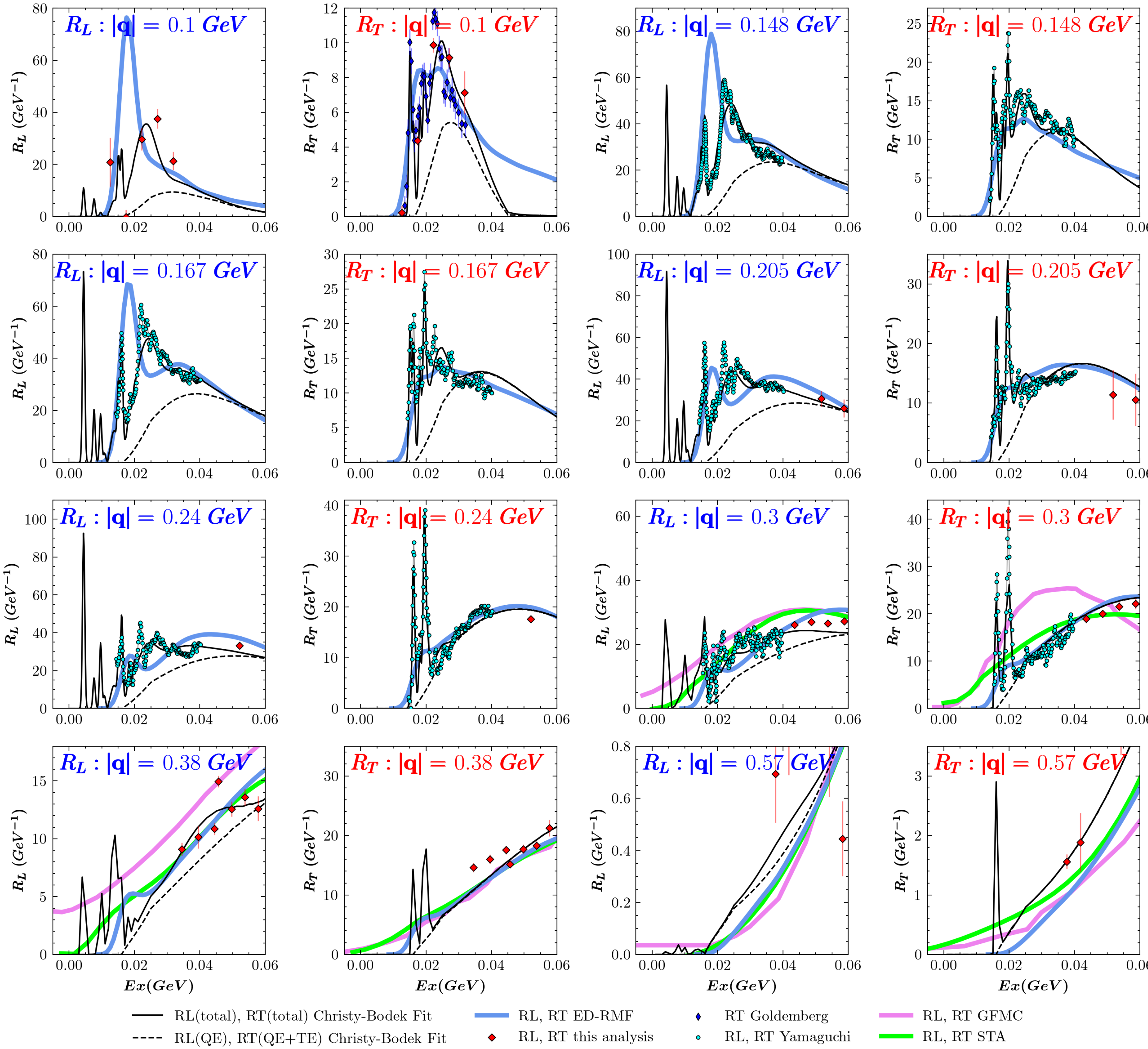
Theories Comparison in **q** Bins: ED-RMF, STA-QMC, GFMC

$|\mathbf{q}|$ values: 0.3, 0.38, 0.470, 0.570, 0.649 GeV

Note:

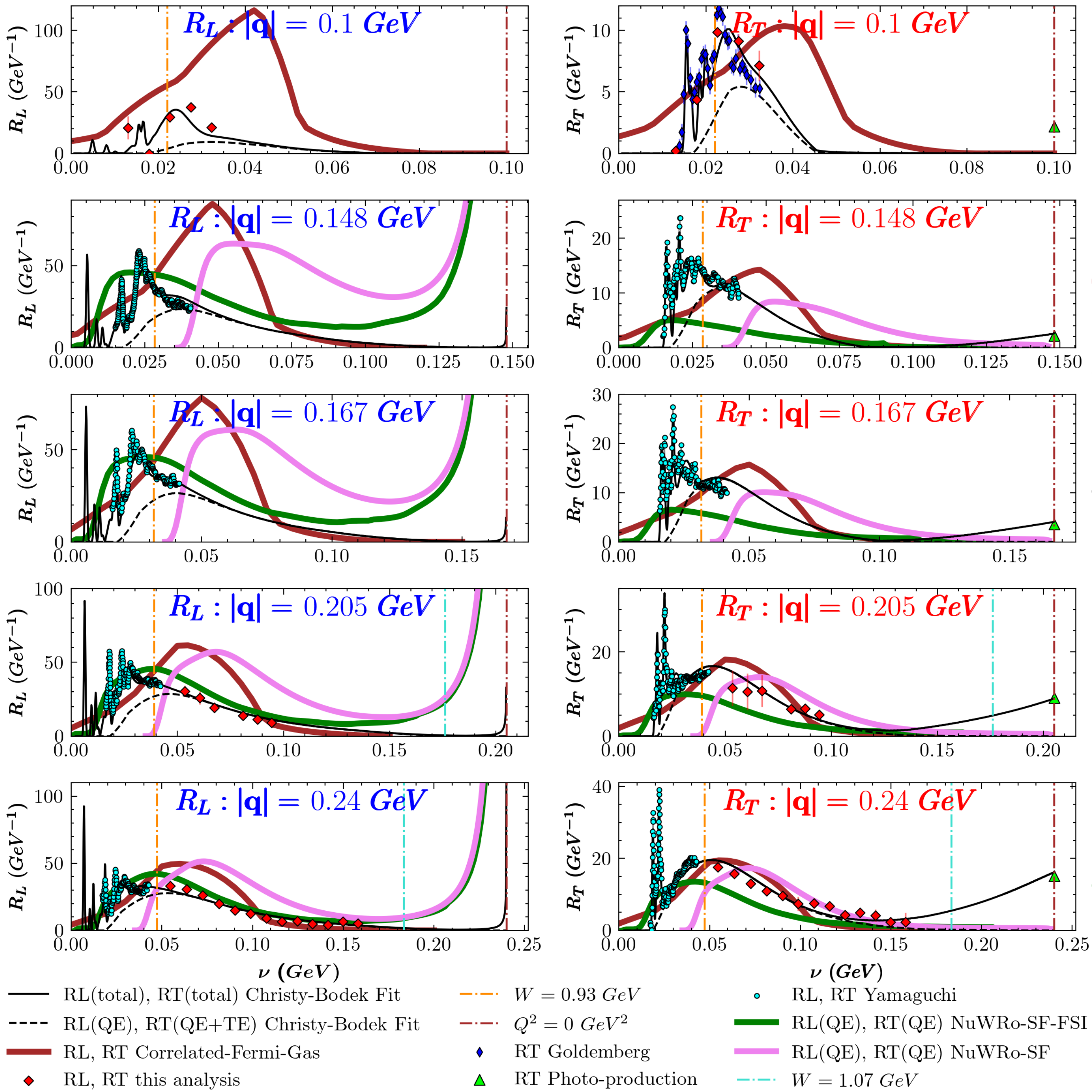
- All 3 predictions are for 1p1h single nucleon final states.
- All 3 predictions include contributions from 1-body and 2-body currents.
- GFMC is computationally expensive, only available for $0.3 \leq |\mathbf{q}| \leq 0.57$ GeV.
- STA-QMC is only valid for $0.3 \leq |\mathbf{q}| \leq 0.76$ GeV.

Theories Comparison in Excitation Region (|q| Bins)



Note:

- **ED-RMF**, available for all |**q**|, has good agreement with data in QE and Ex region (is now implemented in NEUT generator).

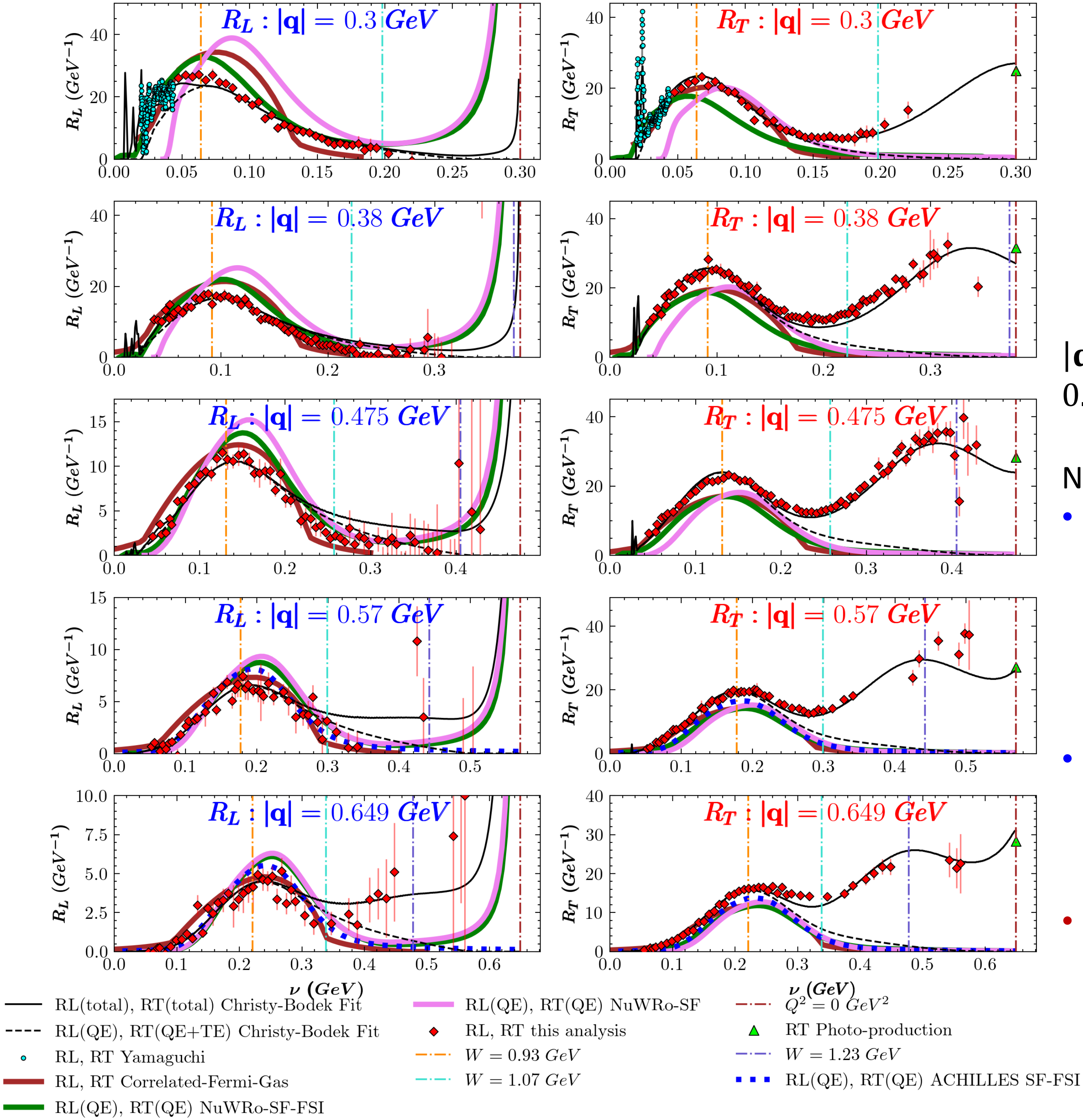


MC generators Comparison in **q** Bins: NuWro-SF, NuWro-SF-FSI, CFG, ACHILLES

|**q**| values: 0.1, 0.148, 0.167, 0.205, 0.240 GeV

Note:

- Here NuWro uses electron-mode that has QE-scattering only; not accounting for 2-body currents and the interference between 1-body and 2-body currents (which enhance R_T).
- NuWro-SF-FSI agrees with data better than NuWro-SF.

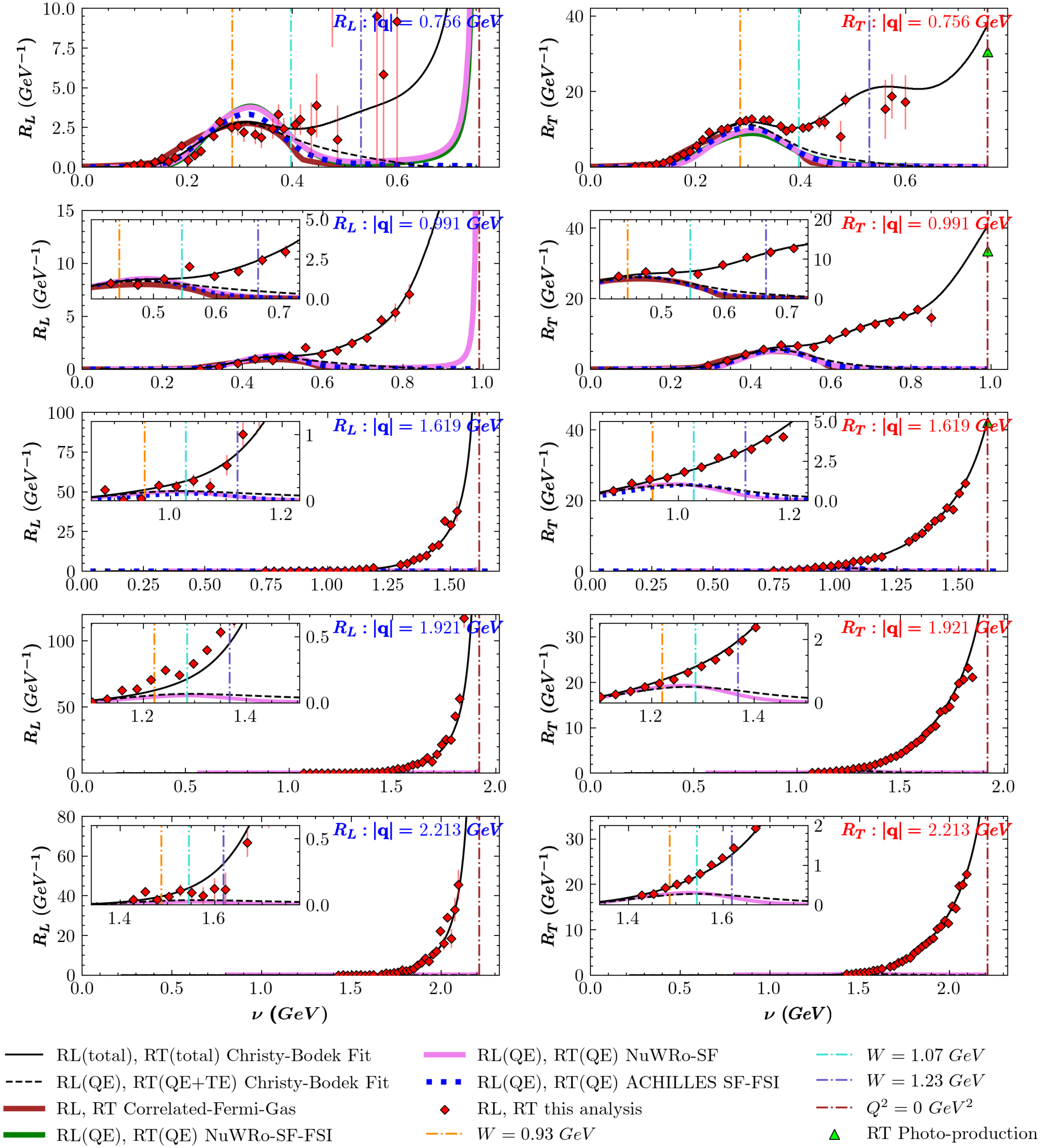


MC generators Comparison in $\mathbf{q}$ Bins: NuWro-SF, NuWro-SF-FSI, CFG, ACHILLES

$|\mathbf{q}|$ values: 0.300, 0.380, 0.470, 0.570, 0.649 GeV

Note:

- **ACHILLES** models the contribution of 2-body currents, so it's in better agreement than **NuWro-SF-FSI**.
- **ACHILLES** predictions are only available for $|\mathbf{q}| > 0.5$ GeV.
- **CFG** (Correlated-Fermi-Gas) is a simpler model, works better at higher $|\mathbf{q}|$.



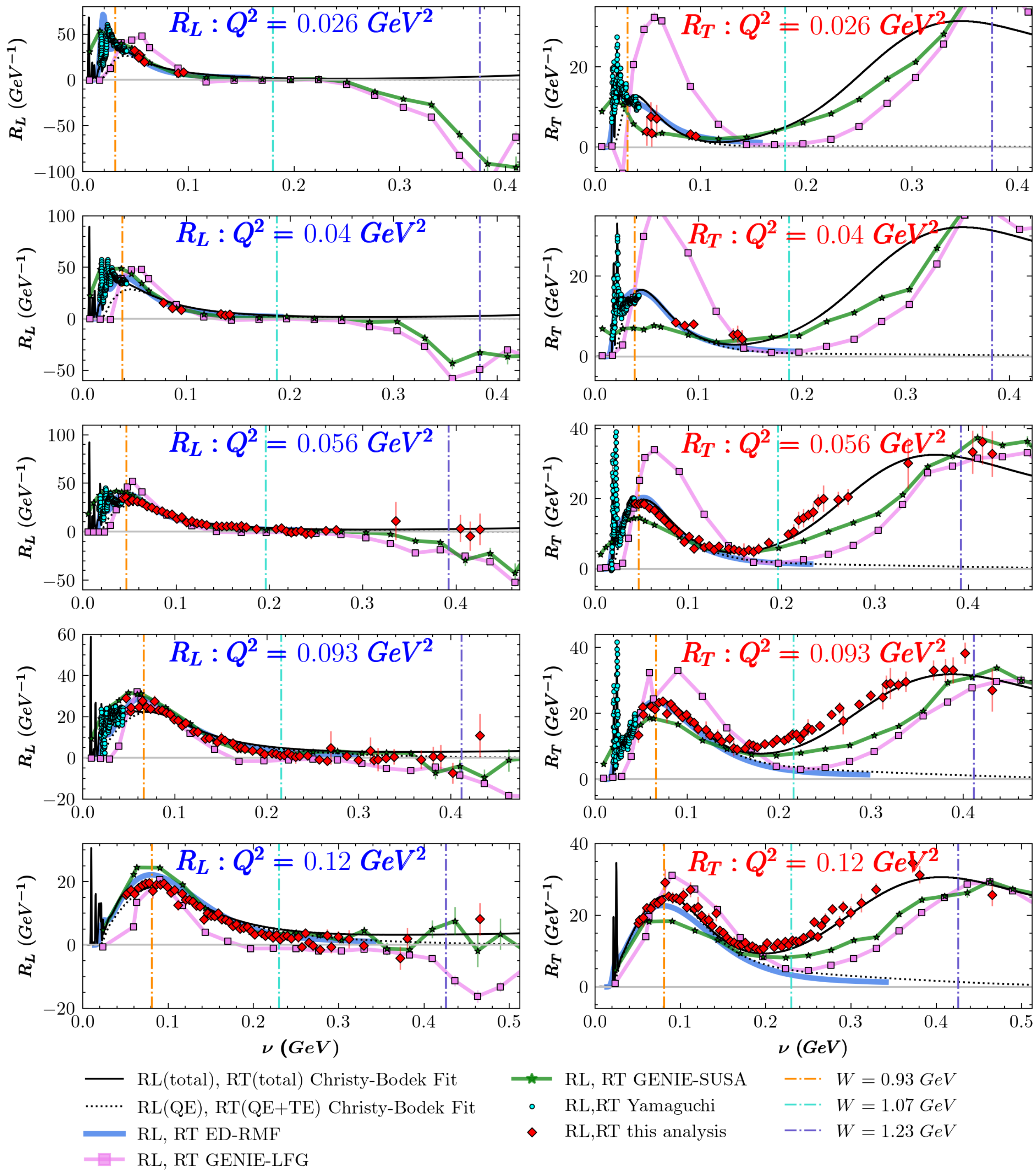
MC generators Comparison in $\mathbf{q}$ Bins: NuWro-SF, NuWro-SF-FSI, CFG, ACHILLES

$|\mathbf{q}|$ values: 0.756, 0.991, 1.619, 1.921, 2.213 GeV

Note:

- FSI effects above $|\mathbf{q}| = 0.65$ GeV is small, so **NuWro-SF-FSI** is the same as **NuWro-SF** at higher $|\mathbf{q}|$.

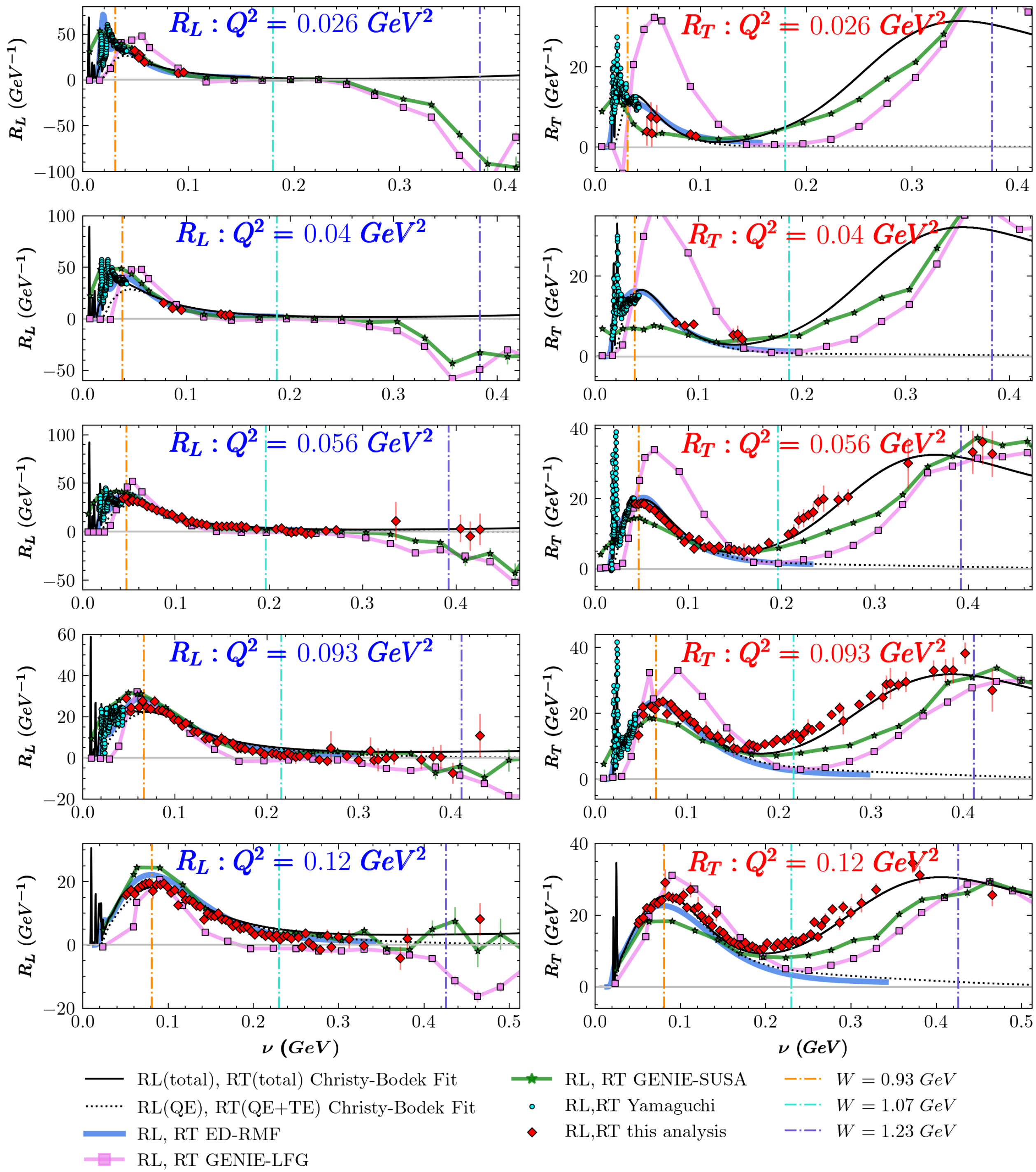
Comparison with GENIE-LFG, GENIE-SUSA, and ED-RMF in Q^2 Bins



Q^2 values: 0.026, 0.040, 0.056, 0.093, 0.12 GeV^2

Note:

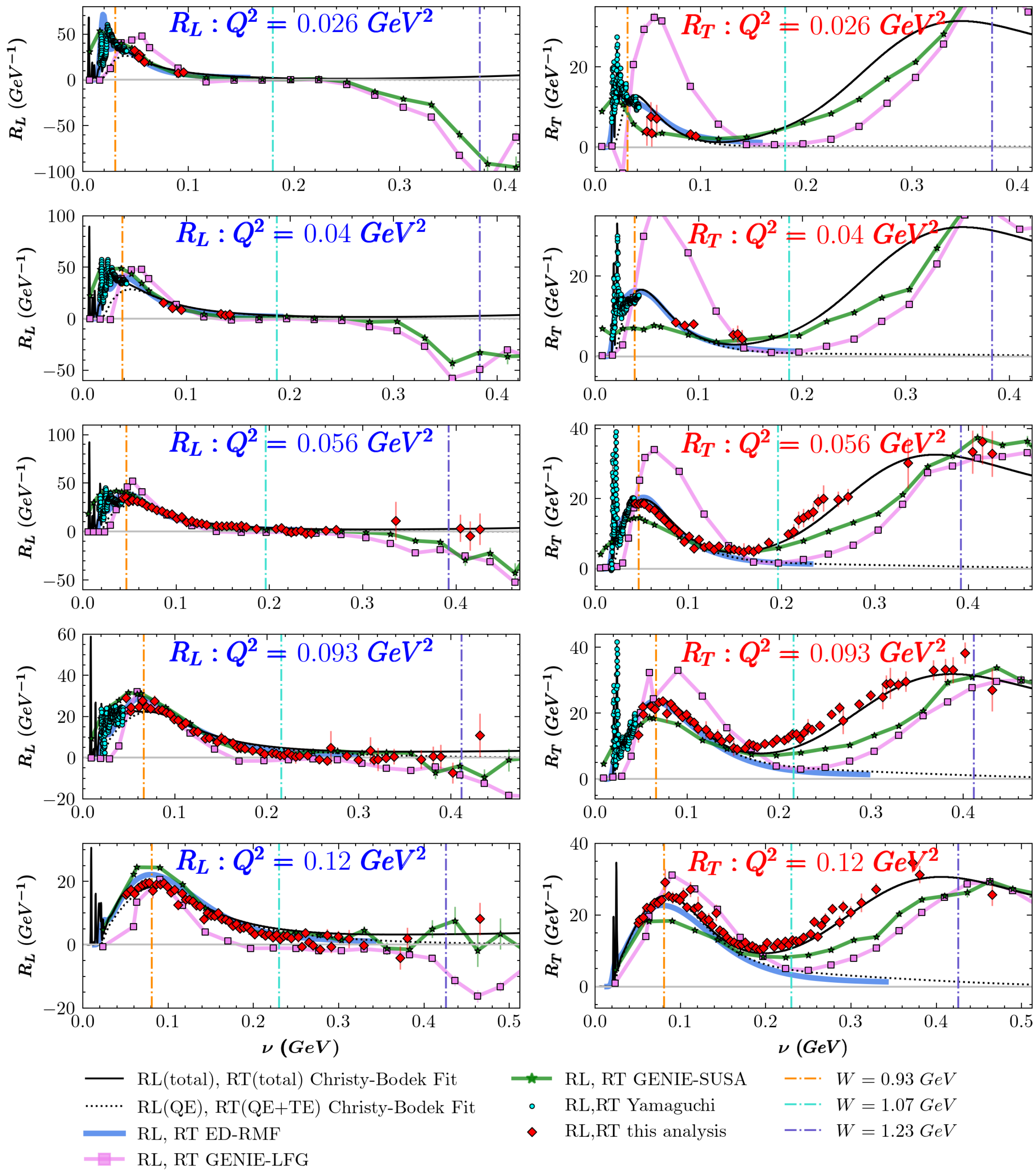
- **GENIE-LFG** (Local Fermi Gas) is GENIE v3 with tune G18-10a-00-000. It uses LFG for the nucleon momentum distribution for QE scattering and an empirical Meson Exchange Currents (MEC) model (preliminary).
- **GENIE-SUSA** (Super Scaling Approach) is GENIE v3 with tune GEM21-11a-00-000. It also uses LFG but with a modified SUSA to model QE and MEC (preliminary).



Comparison with GENIE-LFG, GENIE-SUSA, and ED-RMF in Q^2 Bins

Note:

- For now, we are comparing with GENIE at $Q^2 > 0.026\ GeV^2$; we are investigating lower Q^2.
- Unlike other MC predictions, GENIE's R_L R_T values shown are extracted with Rosenbluth separation using GENIE generated events/cross-sections.
- At present, GENIE is the only generator that includes the resonance and inelastic continuum in its predictions.

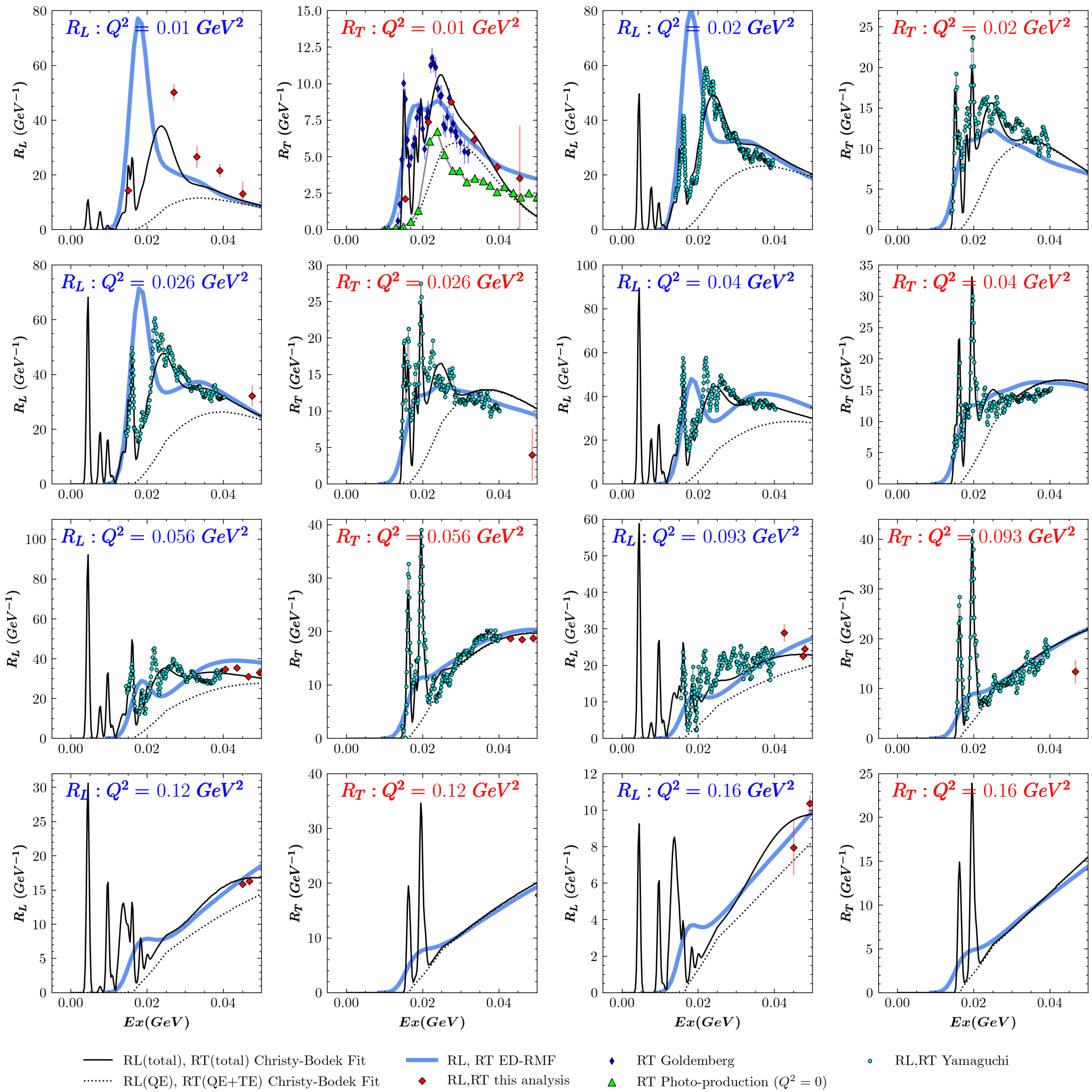


Comparison with GENIE-LFG, GENIE-SUSA, and ED-RMF in Q^2 Bins

Note:

- GENIE-SUSA is closer to data than GENIE-LFG in QE region. However, neither are as good as ED-RMF's prediction.
- At higher ν, GENIE has unphysical negative R_L values.
- As seen in R_T plots, GENIE's $\Delta(1232)$ peak is shifted to higher ν than data.
  - This can be remedied by using an "effective optical potential."

ED-RMF in Excitation Region in Q^2 Bins



Note:

- Among all QE theoretical predictions, ED-RMF is the only one that includes nuclear excitation contributions.
- ED-RMF includes the enhancement of R_T from the interference of 1b and 2b currents (leading to 1p1h final state).
- However, ED-RMF doesn't include enhancement of R_T from 2p2h final states (originating from 2b currents). Therefore, a model for the contribution of 2p2h final states to R_T is needed.

Conclusions

- We compare to GFMC, STA-QMC, ED-RMF's theoretical predictions of R_L and R_T in QE region. ED-RMF has the best description of data overall and is available for all values of $|\mathbf{q}|$ (or Q^2) and ν.

- We compare to GENIE (extracted from MC generated cross-sections), NuWro, ACHILLES, and CFG's MC predictions of R_L and R_T. Thoughts on MC tuning:
  - One can implement effective optical potentials specific to QE and Delta processes;
  - Can implement a longitudinal quenching, transverse enhancement factors that account for 1b 2b currents interference;
  - Can add a model in Excitation region for nuclear excitation.
  - Alternatively, use ED-RMF as implemented in NEUT.
  - Note: nuclear excitations for Ex < 20MeV are not modeled by ED-RMF, because these excitations only decay to α particles and γ's.

- The R_L and R_T extractions cover a large kinematic range. The values are in good agreement with the Christy-Bodek Universal fit to all cross-section values. The universal fit covers an even larger kinematic range.
  - In addition to individual R_L, R_T extractions, the fit also provide a simple way to validate electron and neutrino MC generators over a larger kinematic range.

References and Acknowledgements

We thank Noah A. Steinberg for providing the predictions from the ACHILLES MC generator. We thank Lorenzo Andreoli for providing the predictions from STA-QMC. We thank Sam Carey for providing the predictions from CFG. We thank Tania Franco Muñoz for providing the predictions from ED-RMF, and José Manuel Udías Moinelo and Raúl González Jiménez for clarification of the predictions of ED-RMF.

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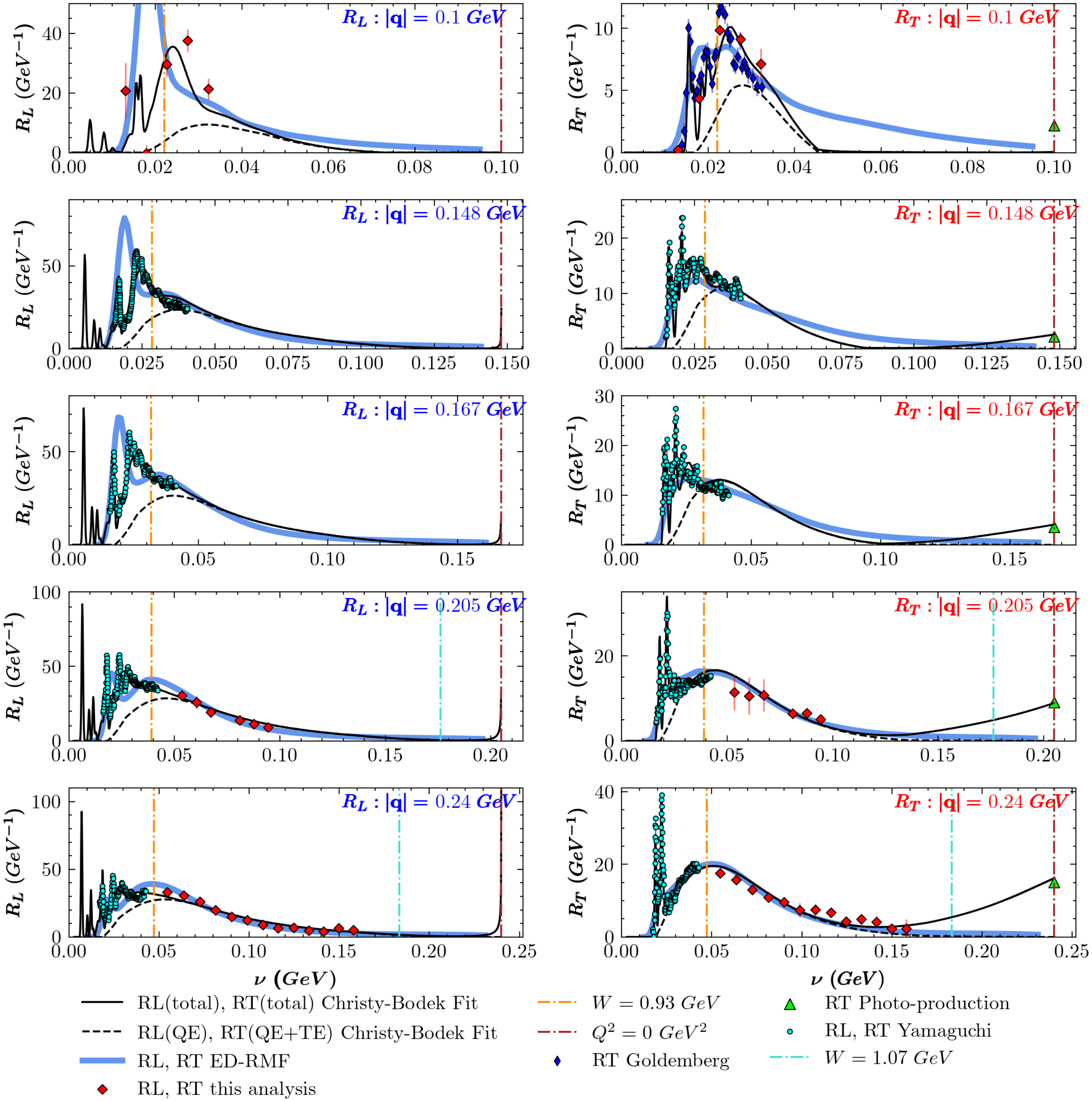
Thank you!

Backup Slides

Data sets and normalizations:

	Data Set	Normalization	Error
1	Barreau83 [11–13]	0.9919	0.0024
2	O'Connell87 [26]	0.9787	0.0086
3	Sealock89 [27]	1.0315	0.0048
4	Baran88 [28]	0.9924	0.0046
5	Bagdasaryan88 [29]	0.9878	0.0083
6	Dai19 [30]	1.0108	0.0053
7	Arrington96[31]	0.9743	0.0133
8	Day93 [32]	1.0071	0.0033
9	Arrington99 [33]	0.9888	0.0034
10	Gaskell21 [34, 35]	0.9934	0.0051
11	Whitney74 [36, 37]	1.0149	0.0153
12	E04-001-2005 [14–16]	0.9981	0.0067
13	E04-001-2007 [14–16]	1.0029	0.0070
14	Gomez74 [38, 39]	1.0125	0.0149
15	Fomin10 [40, 41]	1.0046	0.0031
16	Yamaguchi71 [7]	1.0019	0.0029
17	Ryan84 [8] (180^0)	1.0517	0.0130
18	Czyk63 [42]	1.0	0.1
19	Bounin63 [43, 44]	1.15	0.23
21	Spamer70 [7, 45]	1.2	0.1
22	Goldemberg64 [24](180^0)	1.1	0.1
23	Deforest65 [25](180^0)	0.85	0.1
	Donnelly68 [46, 47] (not used) Zeller73 [48] (not used)	(Inconsistent with other datasets)	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R_T (GeV^{-1})
ν (GeV)
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RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT ED-RMF
RL, RT this analysis
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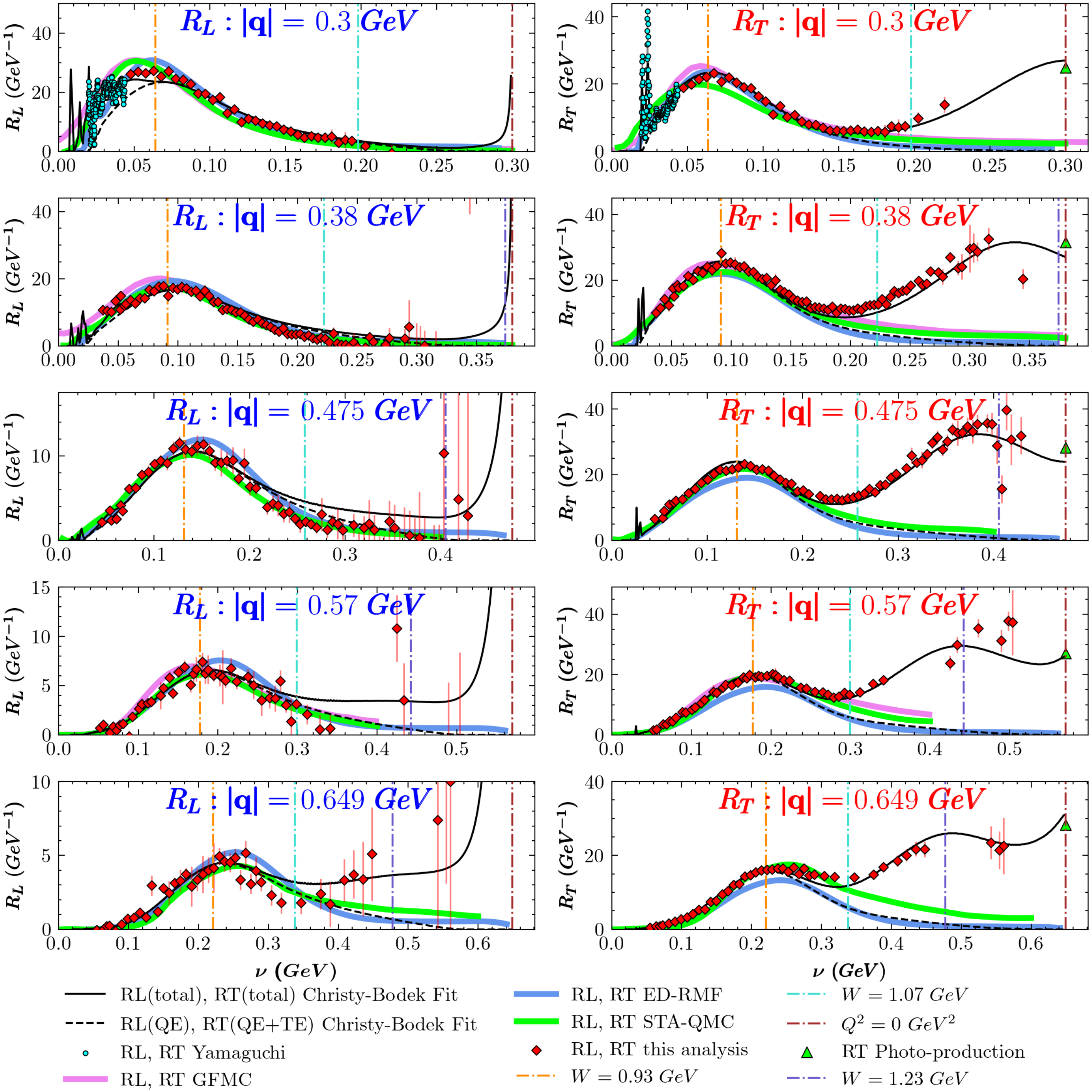
$Q^2 = 0$ GeV^2
RT Goldemberg
RT Photo-production
RL, RT Yamaguchi
$W = 1.07$ GeV



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R_L (GeV^{-1})
R_T (GeV^{-1})
ν (GeV)
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RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT Yamaguchi
RL, RT GFMC
RL, RT ED-RMF
RL, RT STA-QMC
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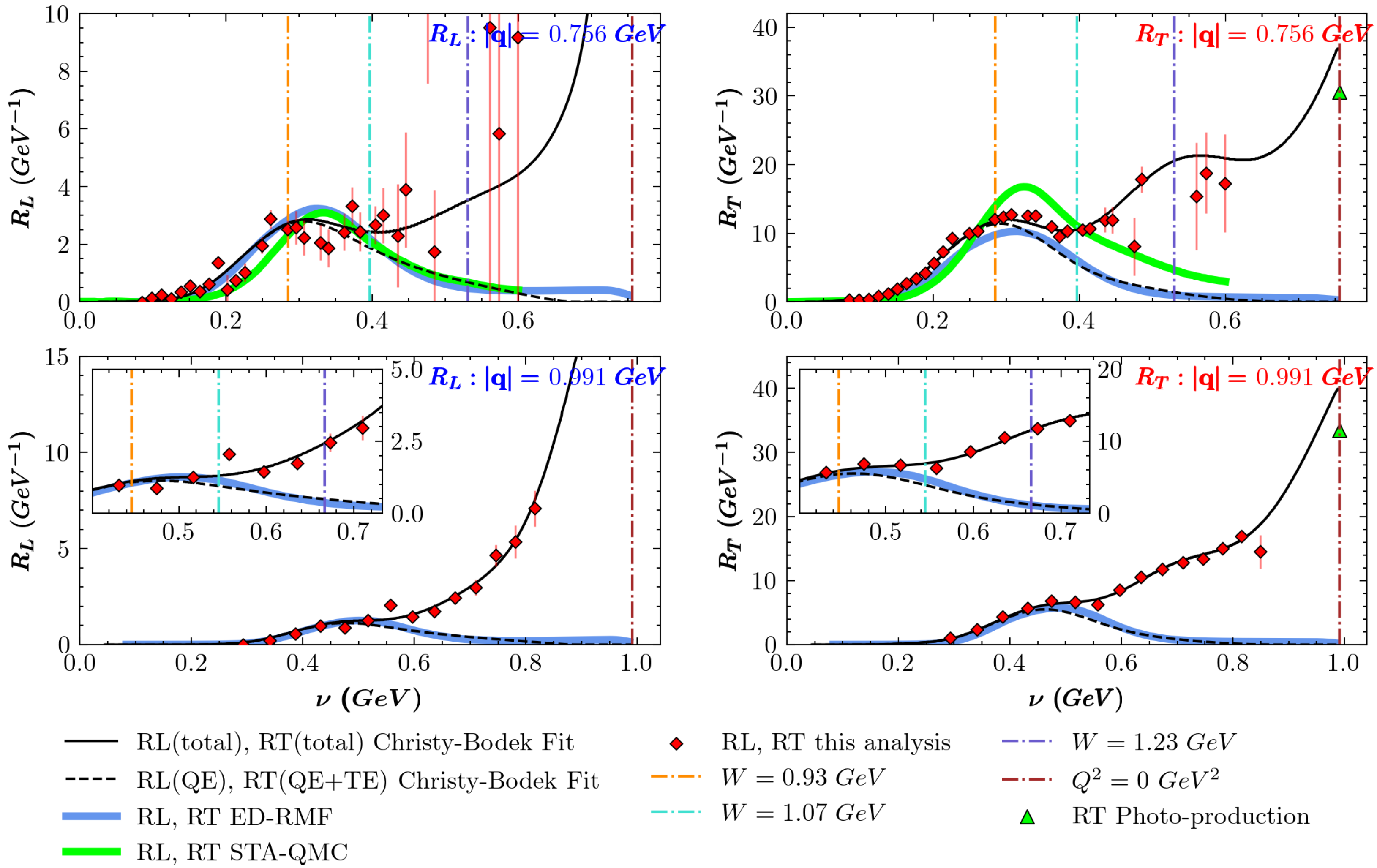
$W = 0.93$ GeV
$W = 1.07$ GeV
$Q^2 = 0$ GeV^2
RT Photo-production
$W = 1.23$ GeV



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R_L (GeV^{-1})
R_T (GeV^{-1})
ν (GeV)
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT ED-RMF
RL, RT STA-QMC
RL, RT this analysis
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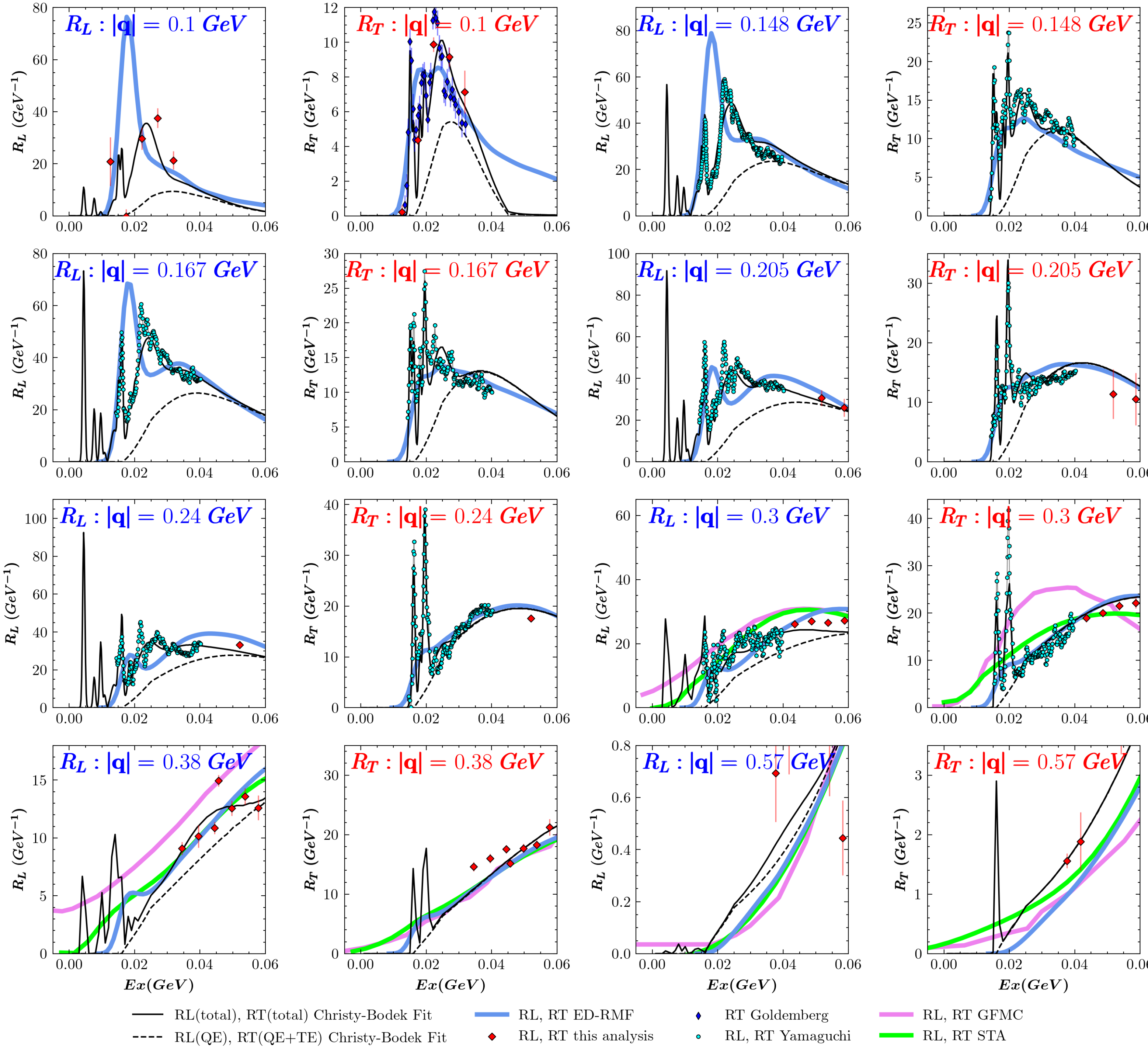
$W = 1.23$ GeV
$Q^2 = 0$ GeV^2
RT Photo-production



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R_T (GeV^{-1})
$Ex(GeV)$
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RL(QE), RT(QE+TE) Christy-Bodek Fit
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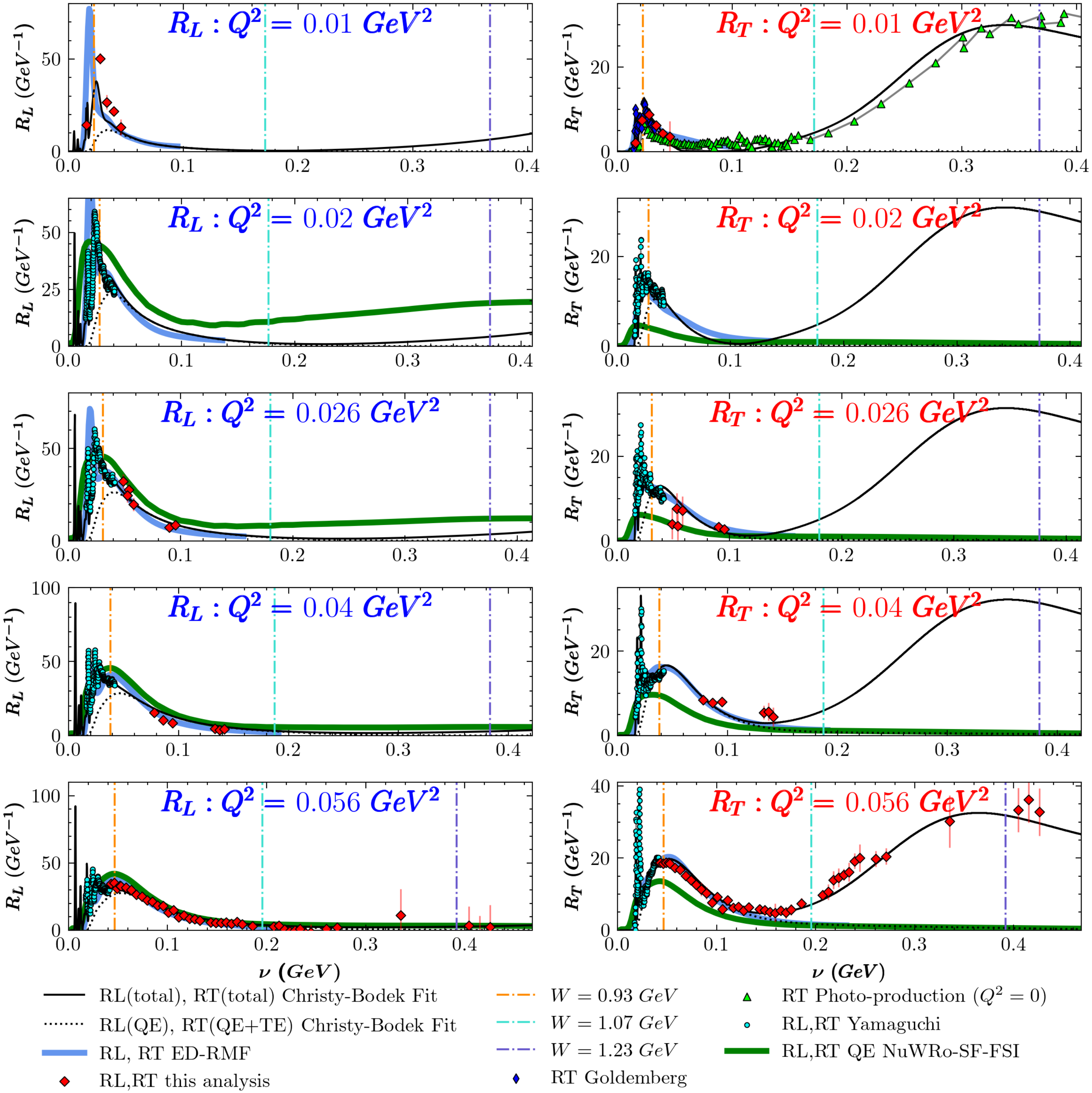
RT Goldemberg
RL, RT Yamaguchi
RL, RT GFMC
RL, RT STA



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$R_L\ (GeV^{-1})$
$R_T\ (GeV^{-1})$
$\nu\ (GeV)$
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT ED-RMF
RL,RT this analysis
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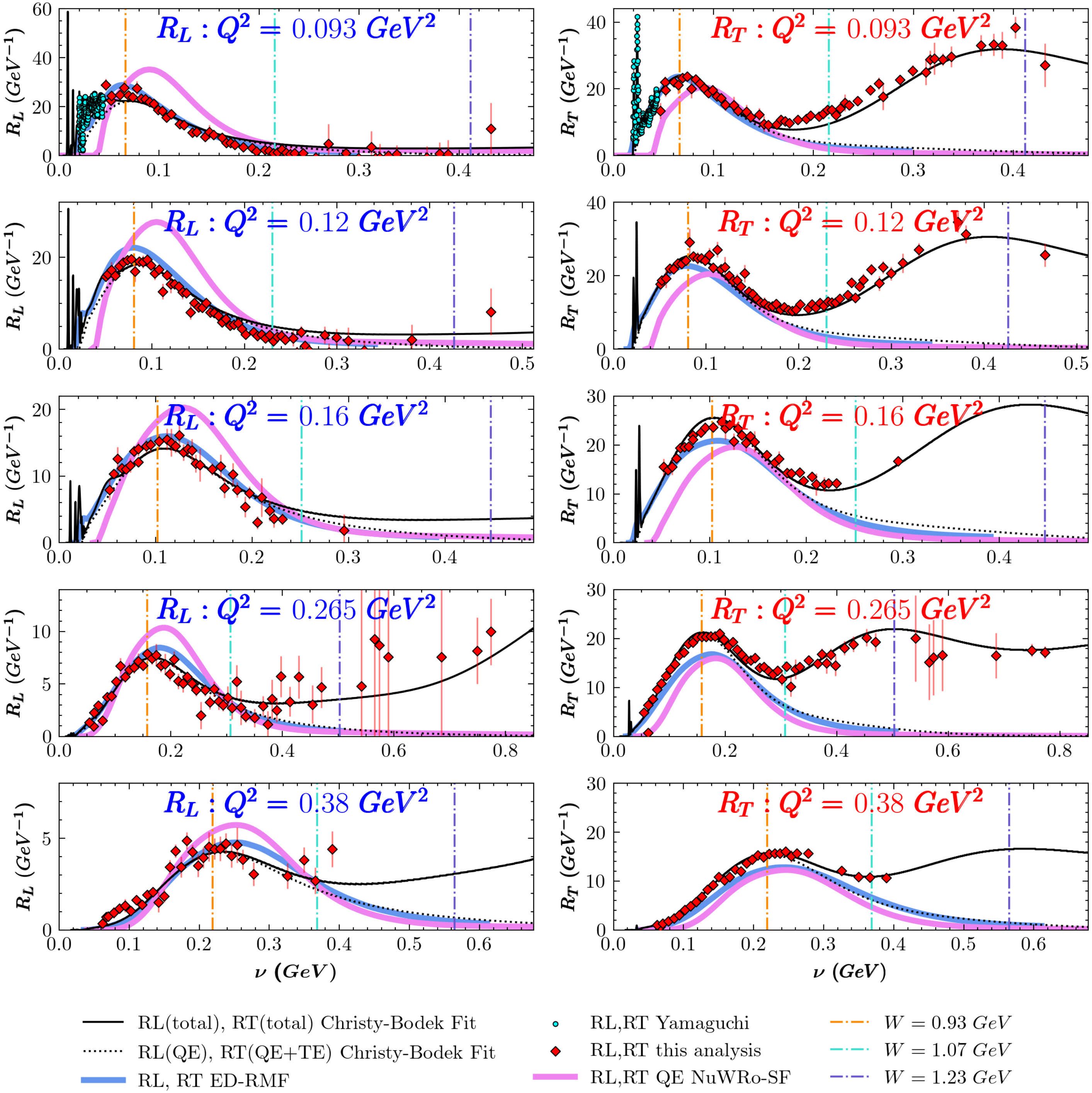
$W = 1.07\ GeV$
$W = 1.23\ GeV$
RT Goldemberg
RT Photo-production ($Q^2 = 0$)
RL,RT Yamaguchi
RL,RT QE NuWRo-SF-FSI



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RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT ED-RMF
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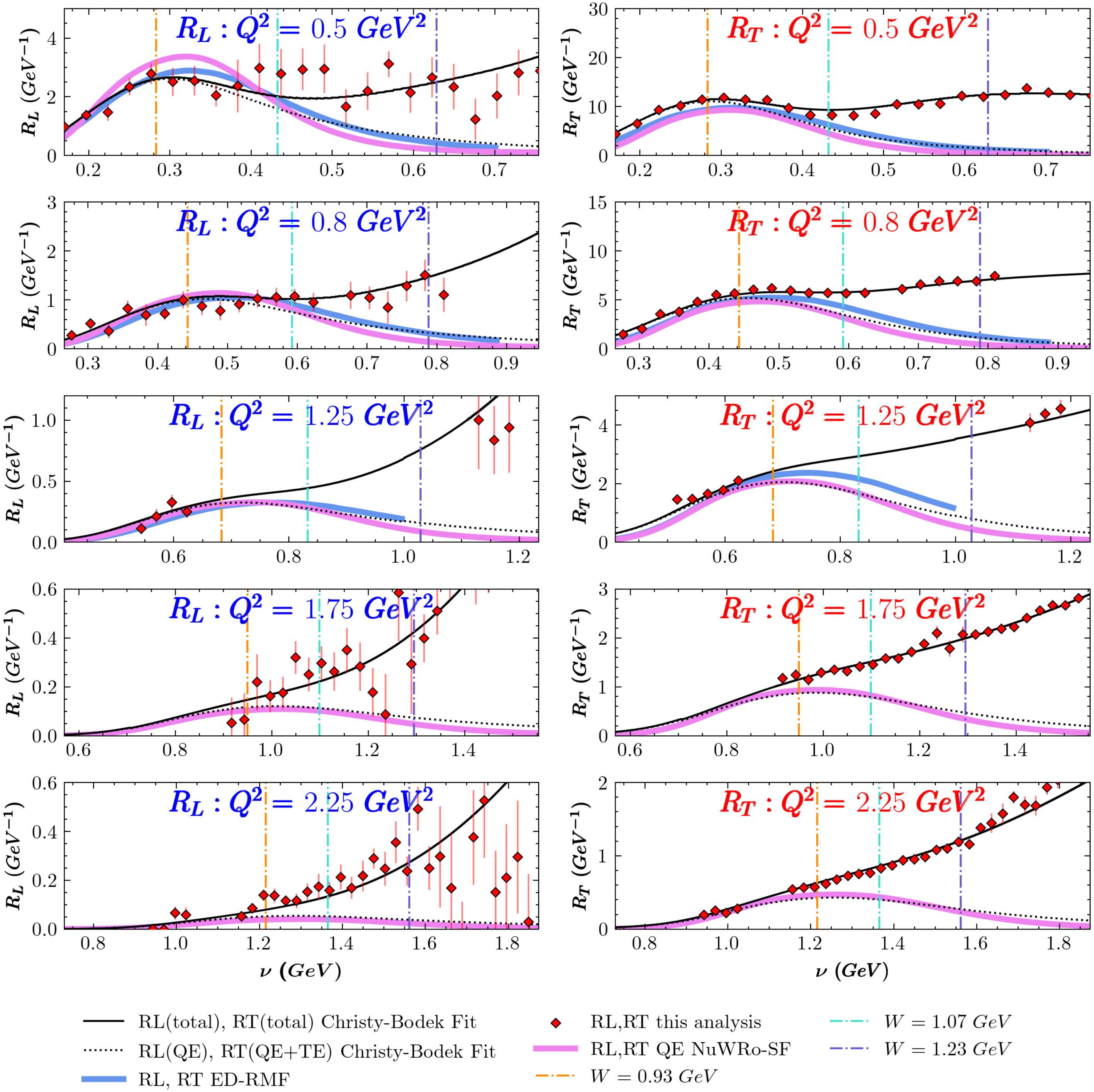

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$R_T\ (GeV^{-1})$
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RL(QE), RT(QE+TE) Christy-Bodek Fit
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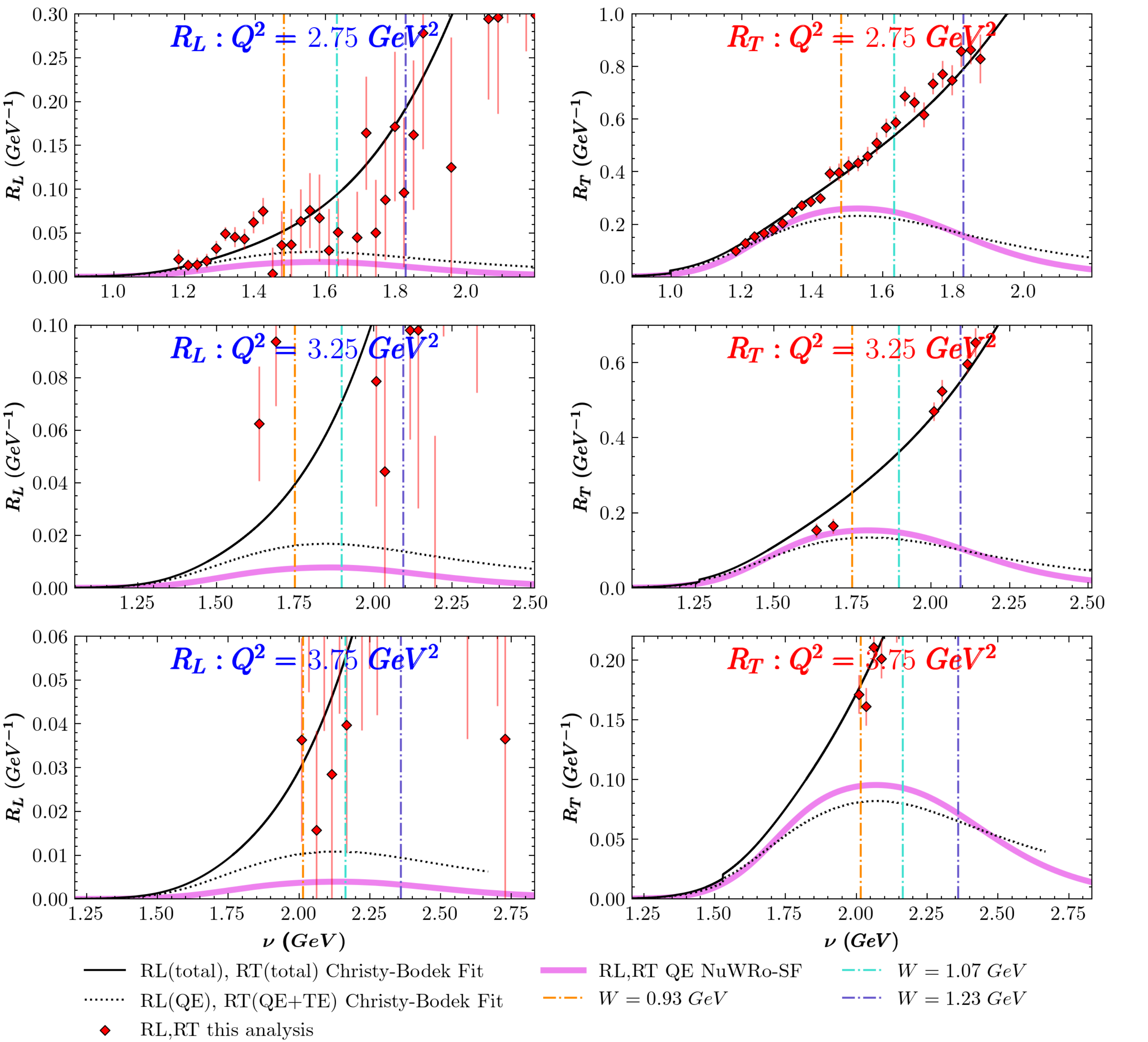

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$R_T\ (GeV^{-1})$
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RL(QE), RT(QE+TE) Christy-Bodek Fit
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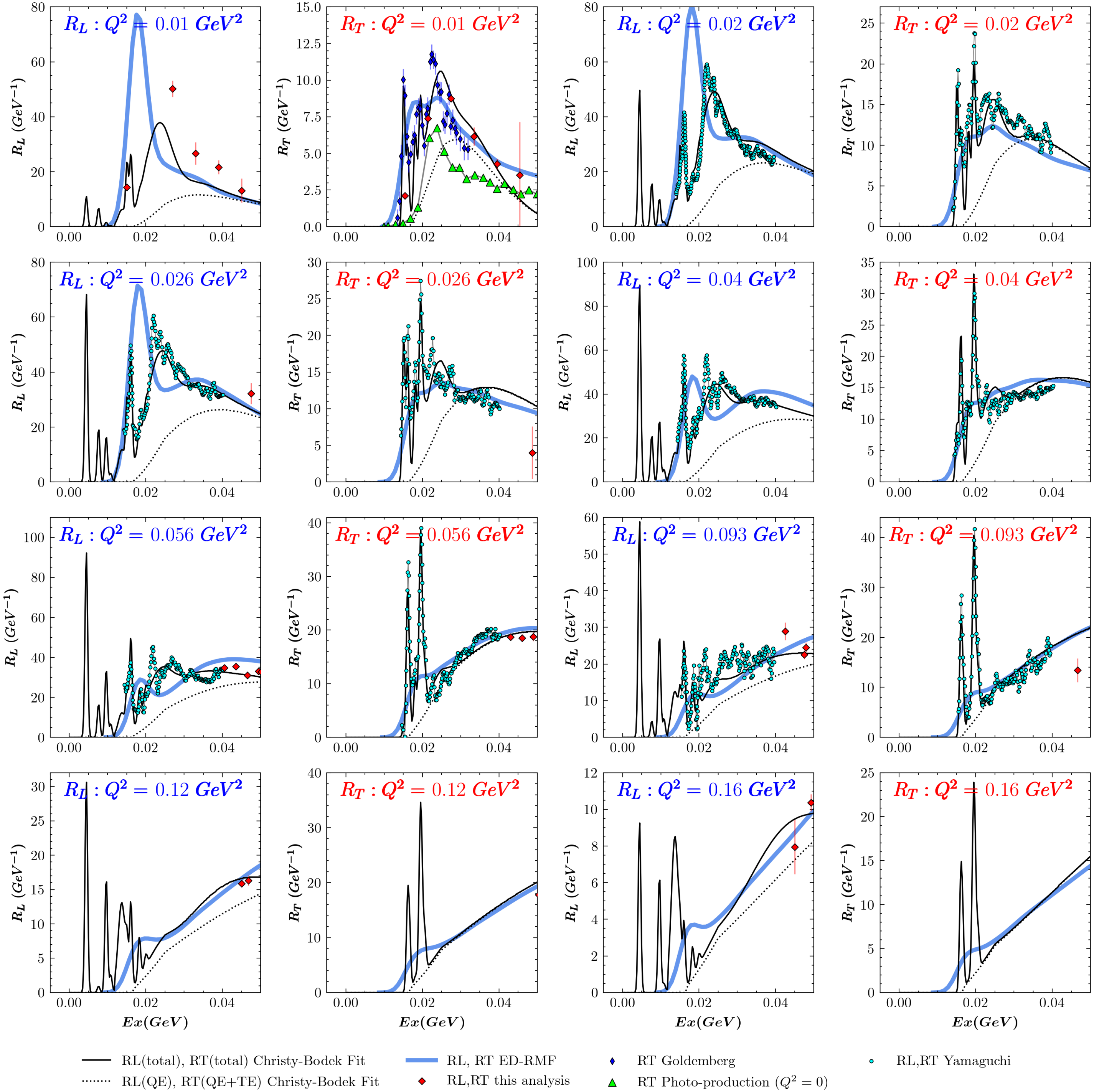

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$R_T\ (GeV^{-1})$
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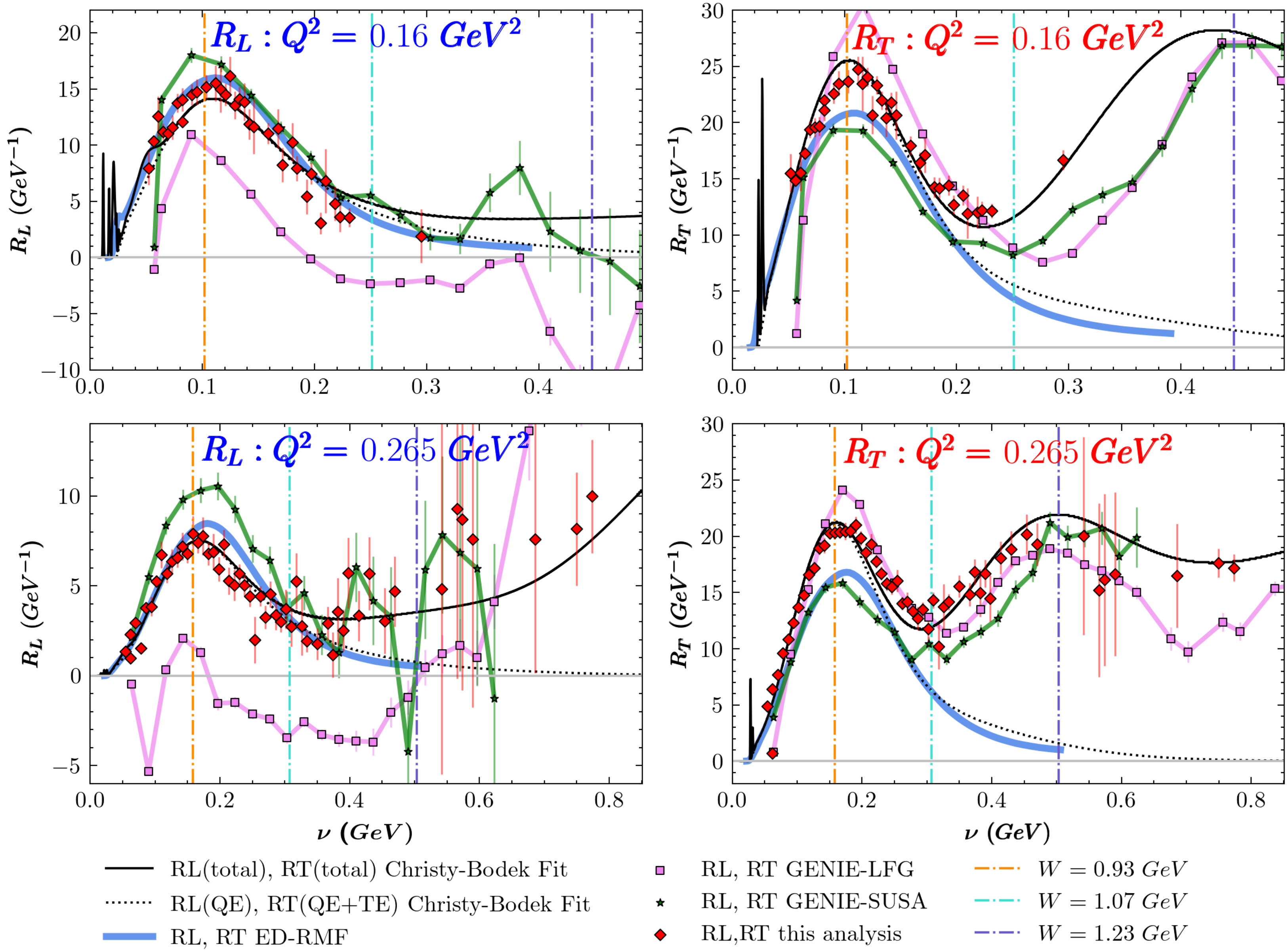
RL,RT Yamaguchi



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