Extraction of the ^{12}C Longitudinal (R_L) and (R_T) Nuclear Electromagnetic Response Functions from all Electron Scattering Measurements on Carbon

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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DPF-PHENO 2024: May 13-17 @ Pittsburgh, PA

12 min talk + 3 min Q&A

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Introduction

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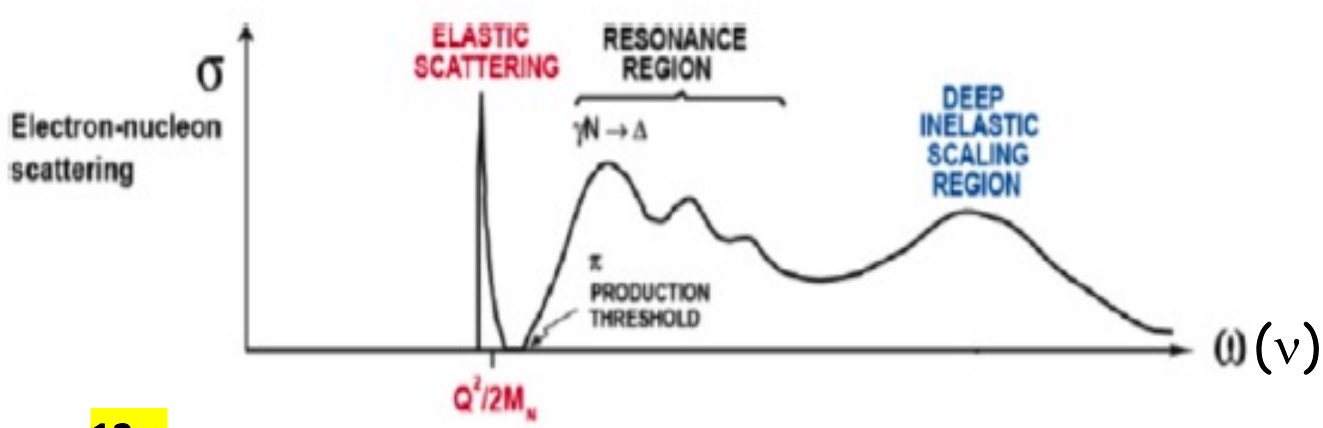
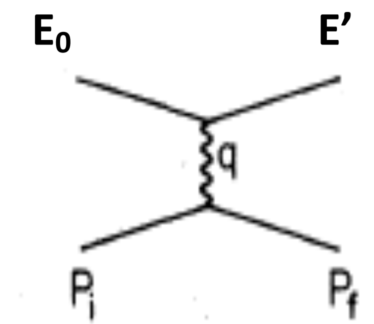
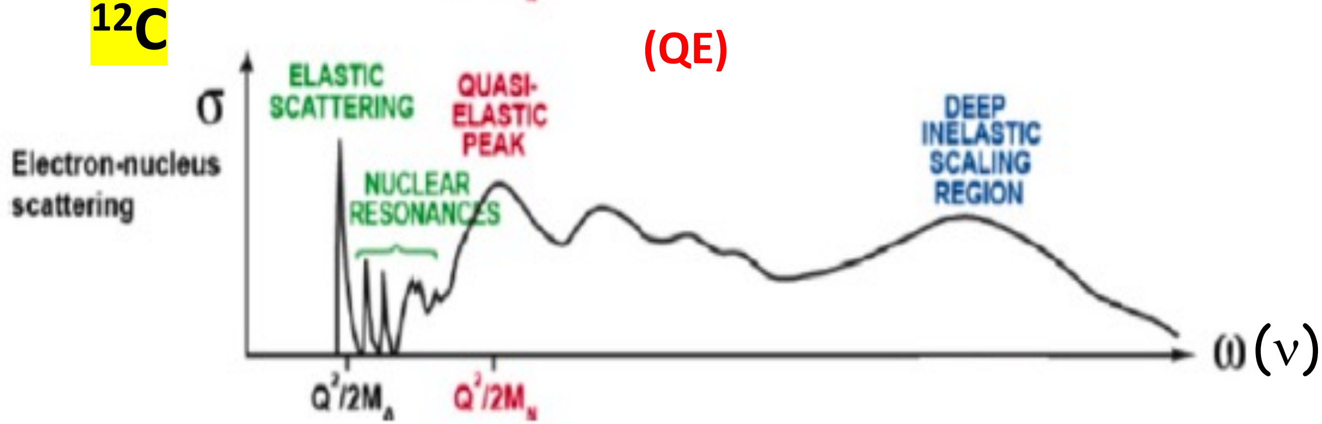
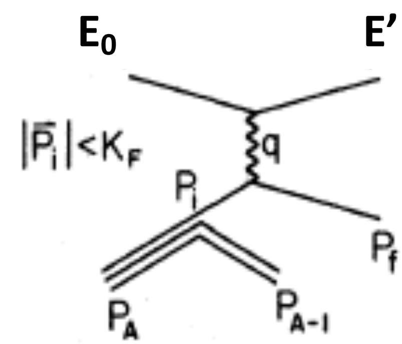
G.T. Garvey et al. / Physics Reports 580 (2015) 1–45





^{12}C





Nuclear corrections effect **quench the Longitudinal Response (R_L)** and **enhance the Transverse Response (R_T) in QE scattering**. There're 3 formalisms:

1. R_L and R_T 2. F_1 and F_L 3. σ_L and σ_T.

We use R_L and R_T.

Physical Quantities

Nuclear Physics:

This description is primarily used in the nuclear excitation and QE regions. The electron scattering differential cross section is written in terms of longitudinal $(\mathcal{R}_L(Q^2,\nu))$ and transverse $(\mathcal{R}_T(Q^2,\nu))$ nuclear response functions [24]

$$\frac{d\sigma}{d\nu d\Omega} = \sigma_M[A\mathcal{R}_L(Q^2,\nu) + B\mathcal{R}_T(Q^2,\nu)] \quad (20)$$

where σ_M is the Mott cross section, $A = (Q^2/\mathbf{q}^2)^2$ and $B = \tan^2(\theta/2) + Q^2/2\mathbf{q}^2$.

Particle Physics:

This description is primarily used in the inelastic continuum region. In the one-photon-exchange approximation, the spin-averaged cross section for inclusive electron-proton scattering can be expressed in terms of two structure functions as follows

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

$$\sigma_M = \frac{\alpha^2\cos^2(\theta/2)}{[2E_0 sin^2(\theta/2)]^2} = \frac{4\alpha^2 E'^2}{Q^4}\cos^2(\theta/2) \quad (10)$$

energy transfer = ν (or ω)

$$\nu = E_0 - E'.$$

Q^2 = 4-momentum transfer squared

$$Q^2 = (-q)^2 = 4E_0E'\sin^2\frac{\theta}{2},$$

W^2 =final state invariant mass squared

$$W^2 = M^2 + 2M\nu - Q^2$$

q = 3-momentum transfer

$$\mathbf{q}^2 = Q^2 + \nu^2$$

E_x = Excitation energy

$$E_x = \nu - \nu_{elastic}$$

$$x = Q^2/(2M\nu).$$

$$\mathcal{F}_1 = M\mathcal{W}_1 \text{ and } \mathcal{F}_2 = \nu\mathcal{W}_2.$$

$$\mathcal{F}_L(x,Q^2) = \mathcal{F}_2\left(1 + \frac{4M^2x^2}{Q^2}\right) - 2x\mathcal{F}_1,$$

$$\mathcal{R}_L(\mathbf{q},\nu) = \frac{\mathbf{q}^2}{Q^2}\frac{\mathcal{F}_L(\mathbf{q},\nu)}{2Mx}$$

$$\mathcal{R}_T(\mathbf{q},\nu) = \frac{2\mathcal{F}_1(\mathbf{q},\nu)}{M}$$

Project Overview

The RL RT extraction Project:

- **Extract RL and RT values on various nuclei using all available data**.
  Today: Carbon (16k electron scattering and photoproduction cross-section measurements.)

- **Cover all kinematic regions**: nuclear elastic, nuclear excitations, quasi-elastic (QE), resonance region and inelastic scattering.

- For Carbon, we use **Rosenbluth linear fit** to extract at 18 fixed Q^2 values: $0 < Q^2 < 3.45$ GeV^2,
  and at 18 fixed **q** values: $0.1 < |\mathbf{q}| < 2.78$ GeV,
  both as functions of ν.

- ν ranges from ν=0 GeV to the end of the resonance region (where W=2.0 GeV).

Project Overview

Goals:

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

Advantage: covers all kinematic regions, more comprehensive than comparison with a few cross-section measurements in limited kinematic regions.

Note: Where there is no data, we provide our universal fit.

Part 1: updated Christy-Bodek Universal Fit

- Includes **all the world's electron scattering data** on H, D and nuclear targets.

- Fits for all kinematic regions:
  - QE cross section (including Transverse Enhancement/MEC and longitudinal low **q** Quenching), Resonance and pion production, deep inelastic scattering, nuclear excitations, elastic scattering.

  Since the cross sections span a large range of energies and scattering angles, we can extract both the **longitudinal R_L** and **transverse R_T** contributions.

- Parameterizes both the **Enhancement of the Transverse QE** cross section and the **Quenching of the Longitudinal QE** cross section.
  - We also extract the most precise Coulomb Sum rule as a function of **q** and compare to theoretical calculations.

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

Part 2: Individual R_L R_T extractions (Rosenbluth Linear Fits)

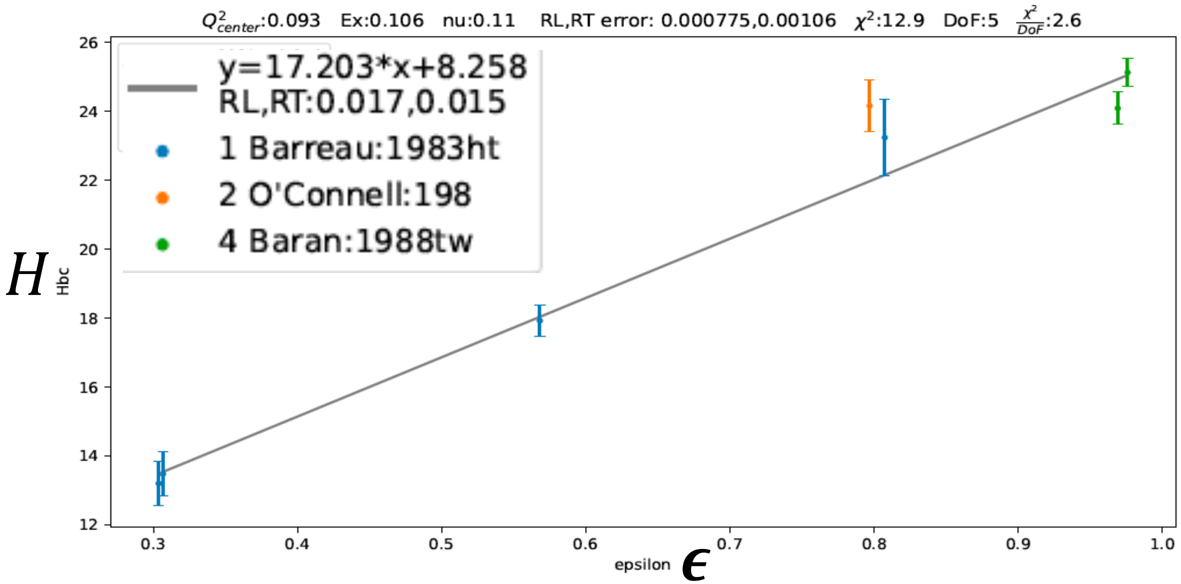
Rosenbluth linear fit with Coulomb corrections, bin-centering corrections to extract R_L, R_T :

Slope $\propto R_L$;

Intercept $\propto R_T$.

H: the "Rosenbluth quantity"

ϵ: virtual photon polarization



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

$$\epsilon = \left[1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}$$

Part 2: Individual R_L R_T extractions (Rosenbluth Linear Fits)

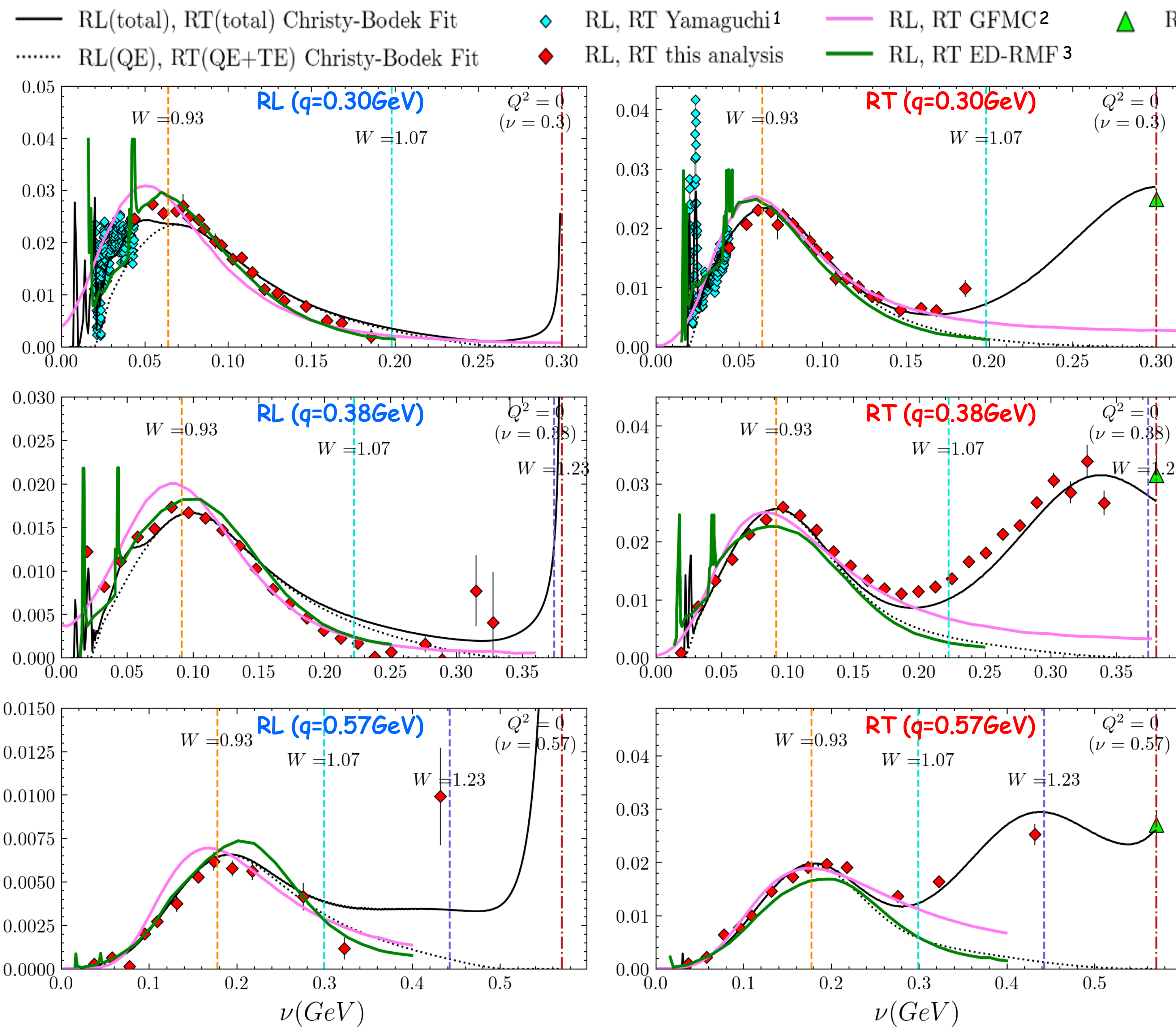
Analysis in fixed **q** (or in fixed Q^2) bin:

1. Bin all cross-section data in **q**;
2. Apply **Coulomb corrections**; apply **bin-centering corrections**.
   For $\nu < 50$MeV: bin-centered in Ex (excitation energy);
   For $\nu > 50$MeV: bin-centered in W^2 (final state invariant mass squared);
   Later convert Ex 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.

Our fixed **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 (photoproduction), 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

Note: Christy-Bodek fit is universal, while Rosenbluth fit uses only a small subset.

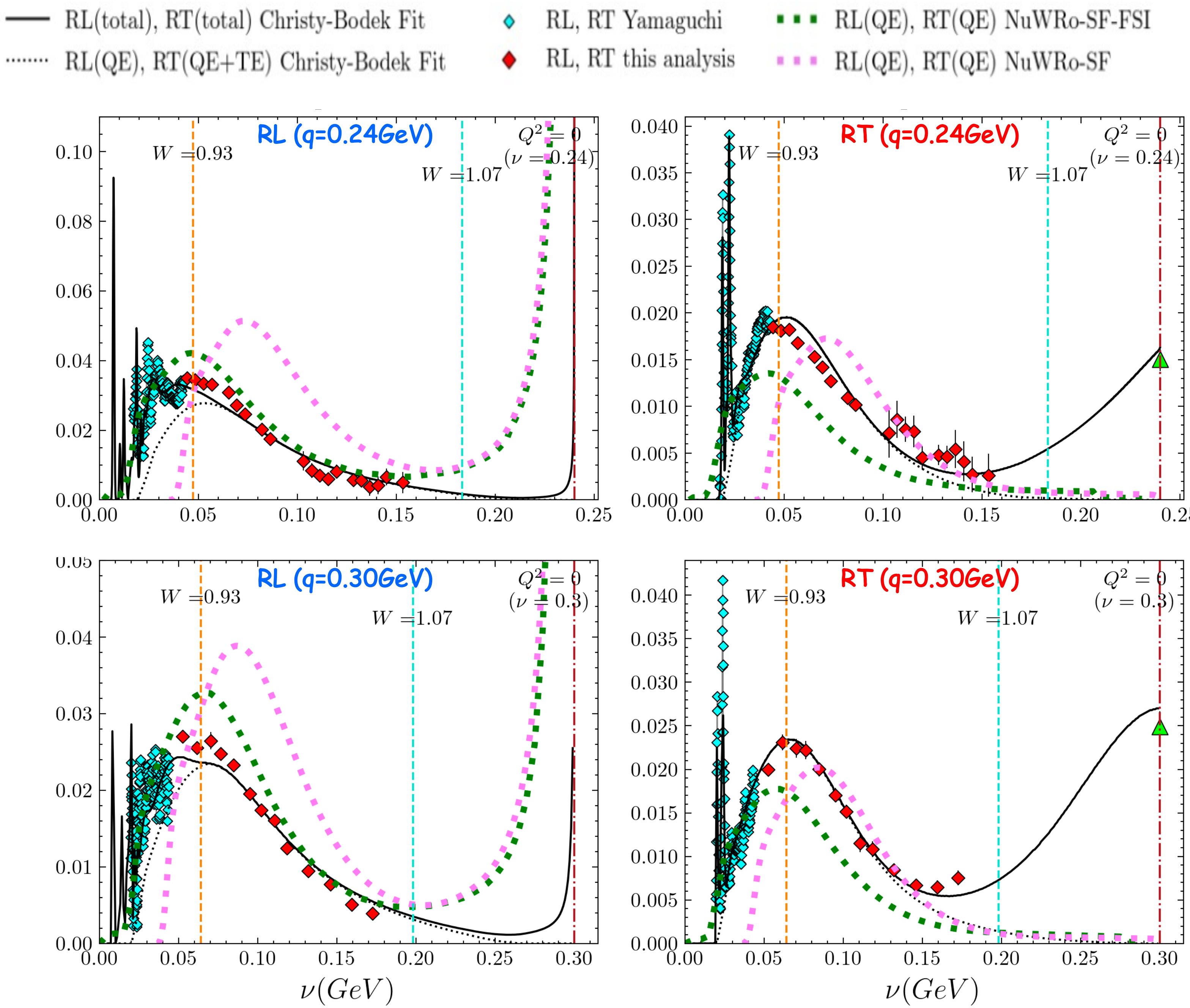


Comparison to Nuclear Theory (for QE 1p1h process only)

GFMC: Green's Function Monte-Carlo

ED-RMF: Energy Dependent Relativistic Mean Field

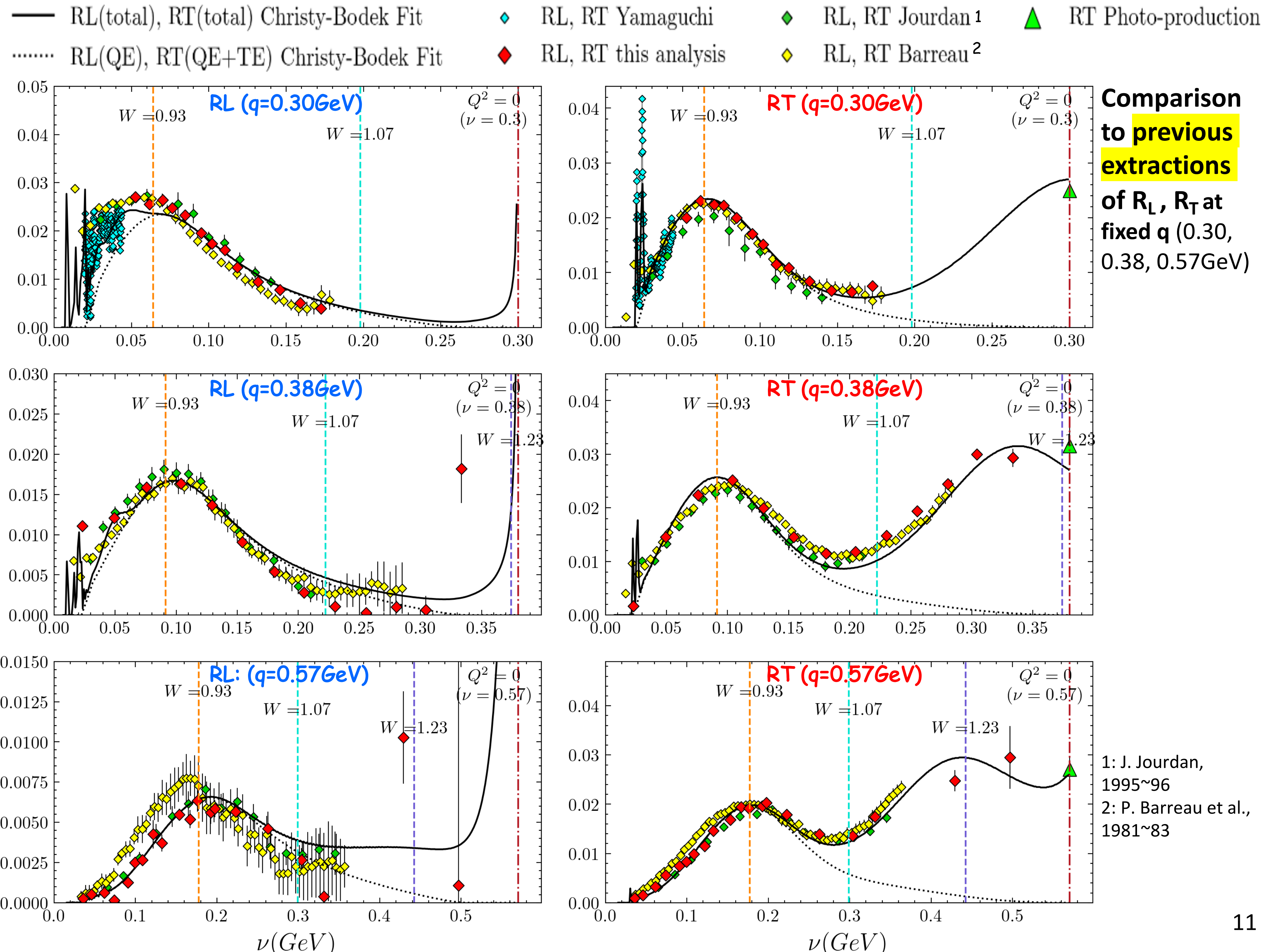
1: A. Yamaguchi et al, Phys. Rev. C 3, 1750 (1971).
2: A. Lovato et al, Phys. Rev. Lett. 117, 082501 (2016),
3: T. Franco-Munoz et al., (2022) arXiv:2203.09996



Comparison to NuWRo Neutrino MC generator for QE (in electron scattering mode)

SF:
Spectral function

FSI:
Final state interaction

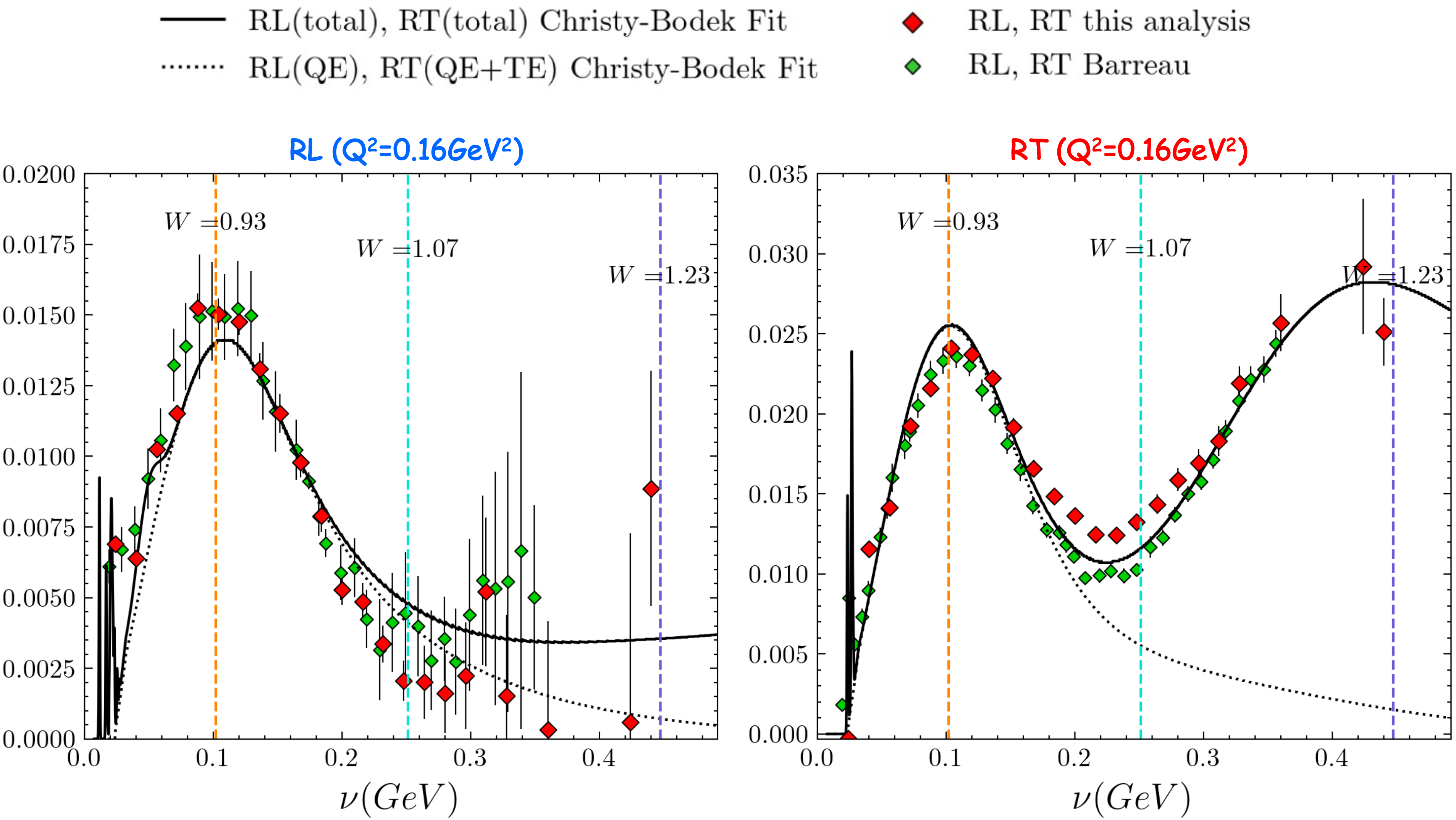


Comparison to previous extractions of R_L, R_T at fixed q (0.30, 0.38, 0.57GeV)

1: J. Jourdan, 1995~96

2: P. Barreau et al., 1981~83

Comparison to previous extractions of R_L R_T at fixed Q^2 (0.16 GeV^2)



Conclusion

- The 18 R_L and R_T extractions cover a large kinematic range. The values are in excellent agreement with the Christy-Bodek Universal fit to all cross-section values. The universal fit covers an even larger kinematic range.

- The R_L and R_T measurements as well as the universal fit provide a simple way to validate electron and neutrino MC generators over the entire kinematic range of interest.

- Good agreement in the QE region with nuclear theory for 3 values of q. Predictions for all other values of q not yet available.

In Supplemental Materials we will provide:

- Tables of the extracted R_L and R_T .
- Tables of the Christy-Bodek Universal fit values for R_L and R_T. The contributions of nuclear excitations, QE, transverse enhancement and inelastic scattering will be listed separately.
- Code for the Christy-Bodek Universal fit.

Thank you!

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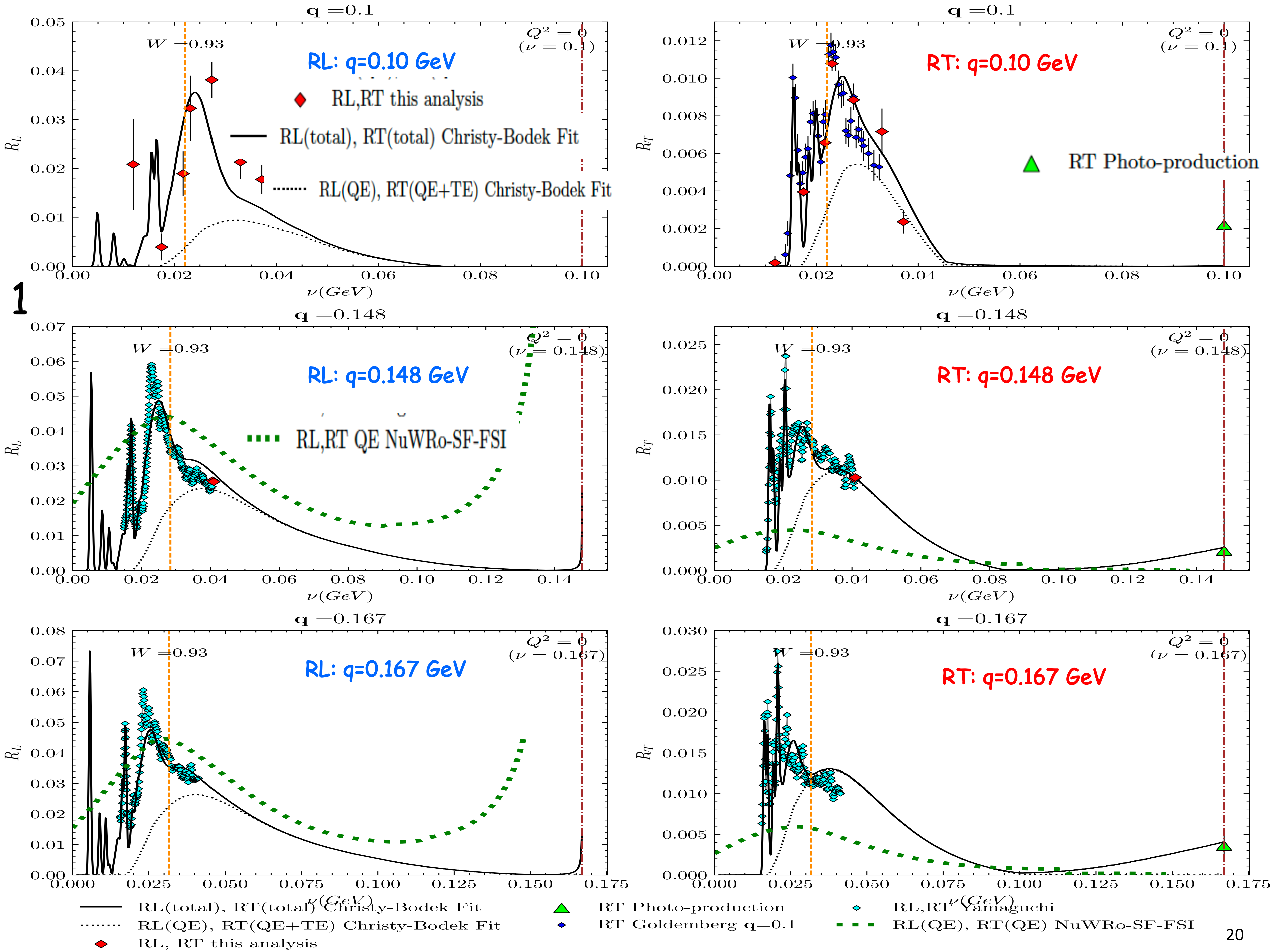
Backup slides

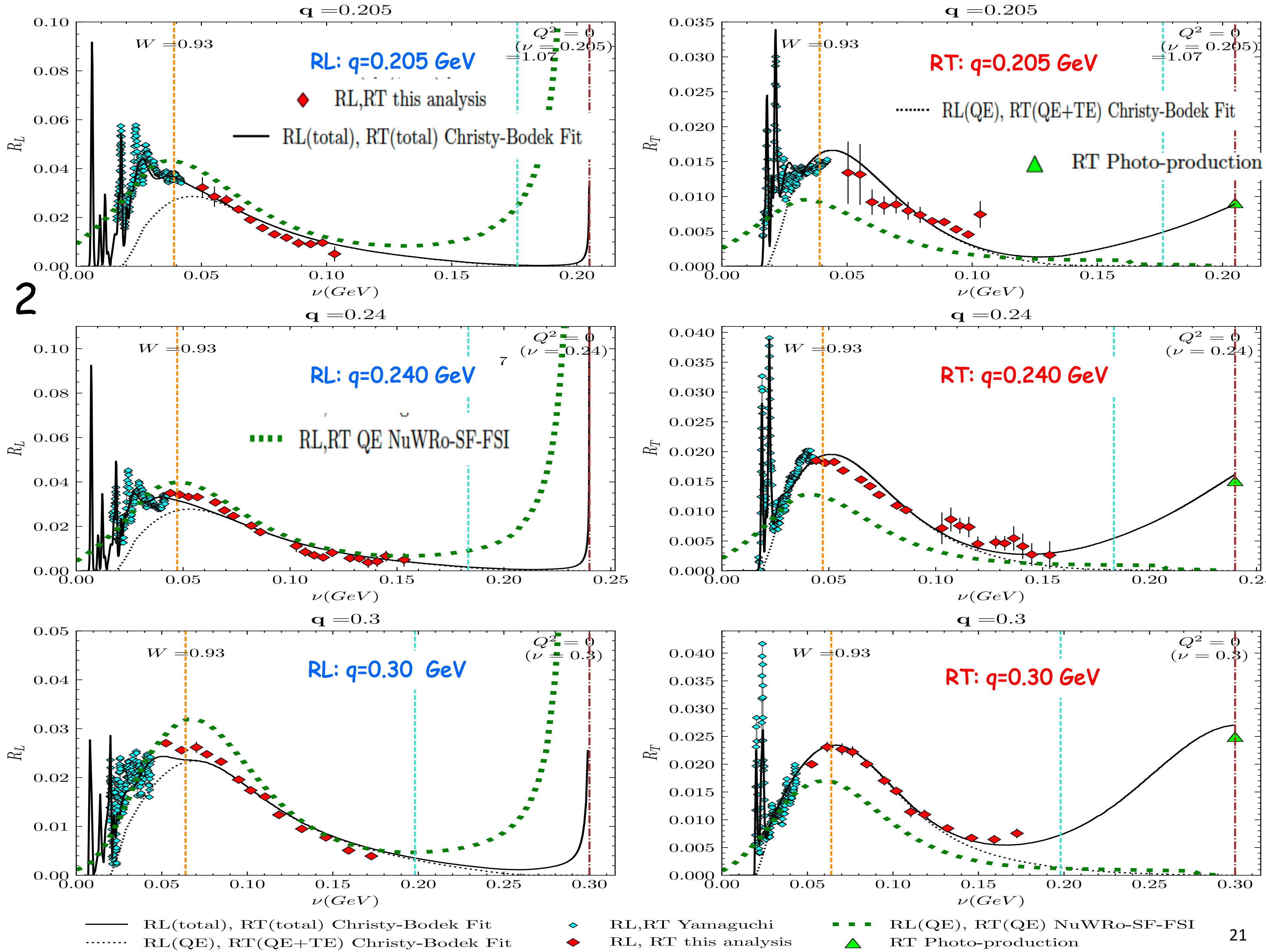
Data sets and normalizations:

	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)	-	-

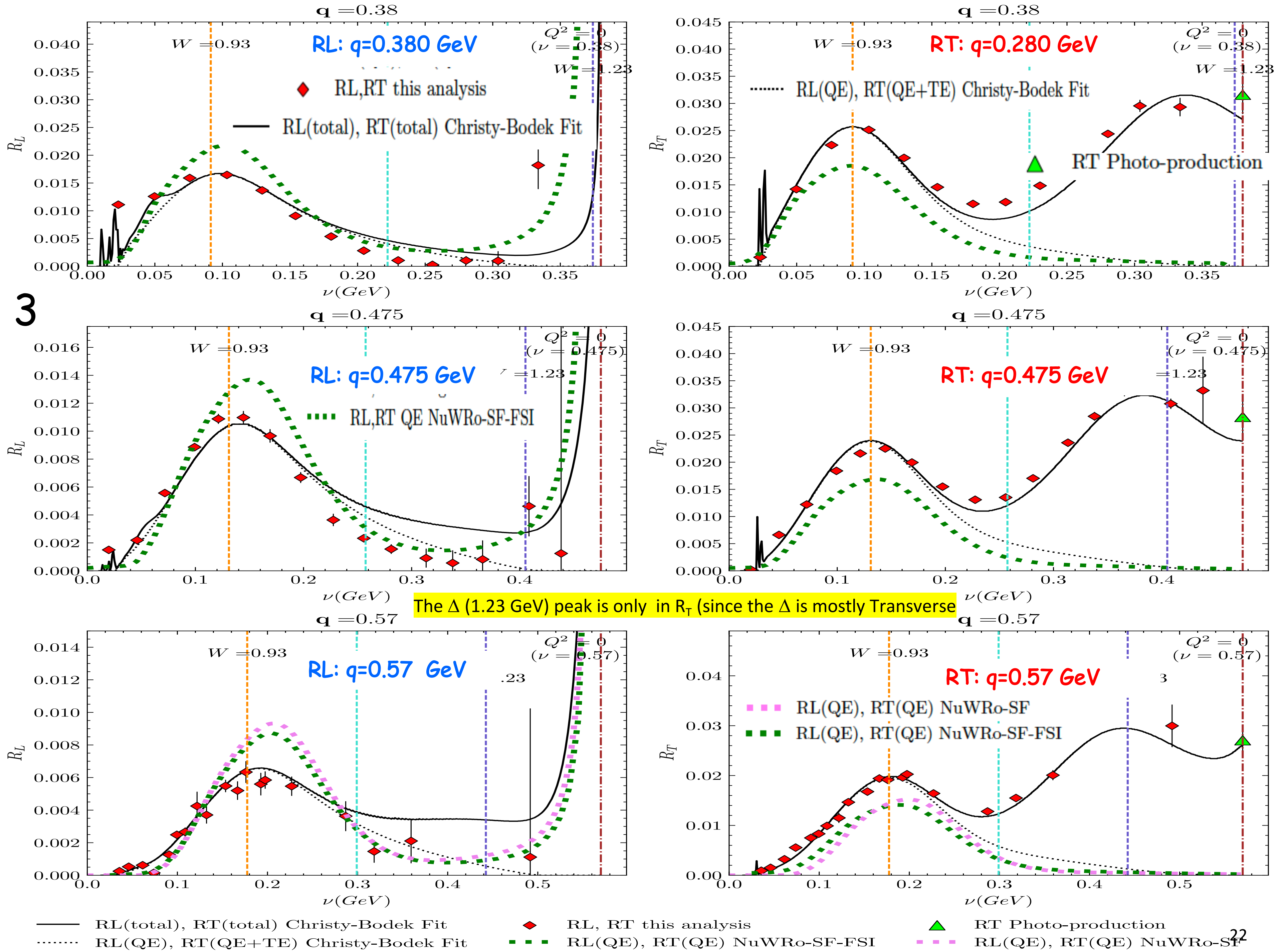
Comments

- The extracted RL and RT are in good agreement with the Christy-Bodek Universal Fit. The fit can be used for validation of MC generators over a more extended range of **q** and ν.
- The Christy-Bodek fit includes **Longitudinal Quenching** at low **q** and **Transverse Enhancement** at intermediate q. It also includes nuclear excitations
- The Δ (1.23 GeV) peak is only seen in R_T (since the Δ is mostly Transverse).
- For fixed **q** the maximum value of ν is **ν=q** (where R_T can also be extracted from photoproduction data).
- Validation of Neutrino Generator NuWRo in electron model: NuWRo only models QE with a spectral function, and adds Final State Interaction (FSI)
- NuWRo (spectral function) requires FSI for better agreement with the data.
- However, even with FSI for $q<0.3$ GeV NuWRo overestimates R_L **(requires Longitudinal Quenching)**
- NuWRo underestimates R_T (in neutrino mode it has Transverse Enhancement/MEC, but not in electron mode).
- Nuclear excitations are not included
- Comparisons with GENIE (in electron mode) will be available shortly.

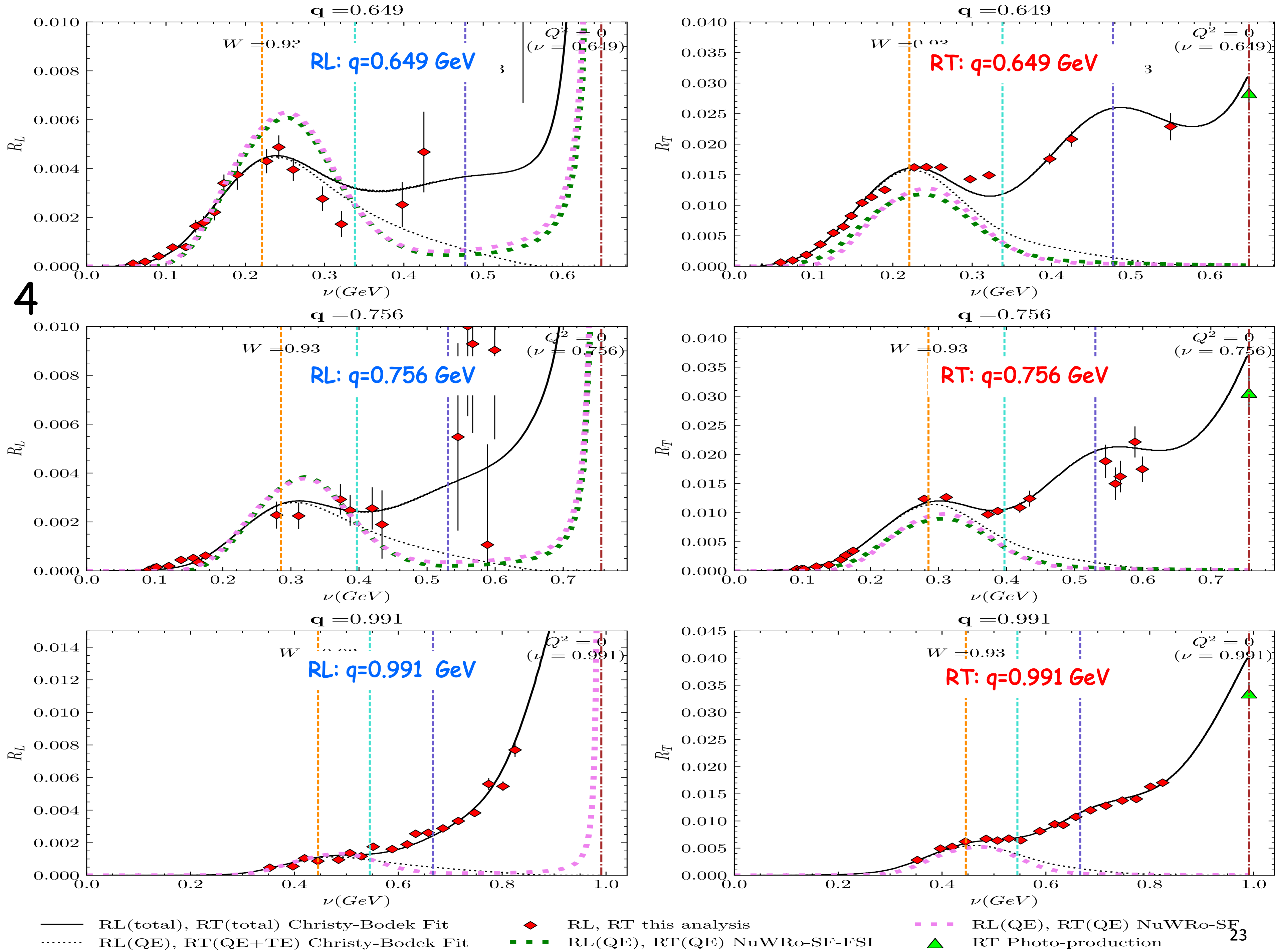

q =0.1
RL: q=0.10 GeV
RL,RT this analysis
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RT: q=0.10 GeV
RT Photo-production
q =0.148
RL: q=0.148 GeV
RL,RT QE NuWRo-SF-FSI
RT: q=0.148 GeV
q =0.167
RL: q=0.167 GeV
RT: q=0.167 GeV
W =0.93
$Q^2 = 0$
R_L
R_T
$\nu (GeV)$
1
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT this analysis
RT Photo-production
RT Goldemberg q=0.1
RL,RT Yamaguchi
RL(QE), RT(QE) NuWRo-SF-FSI

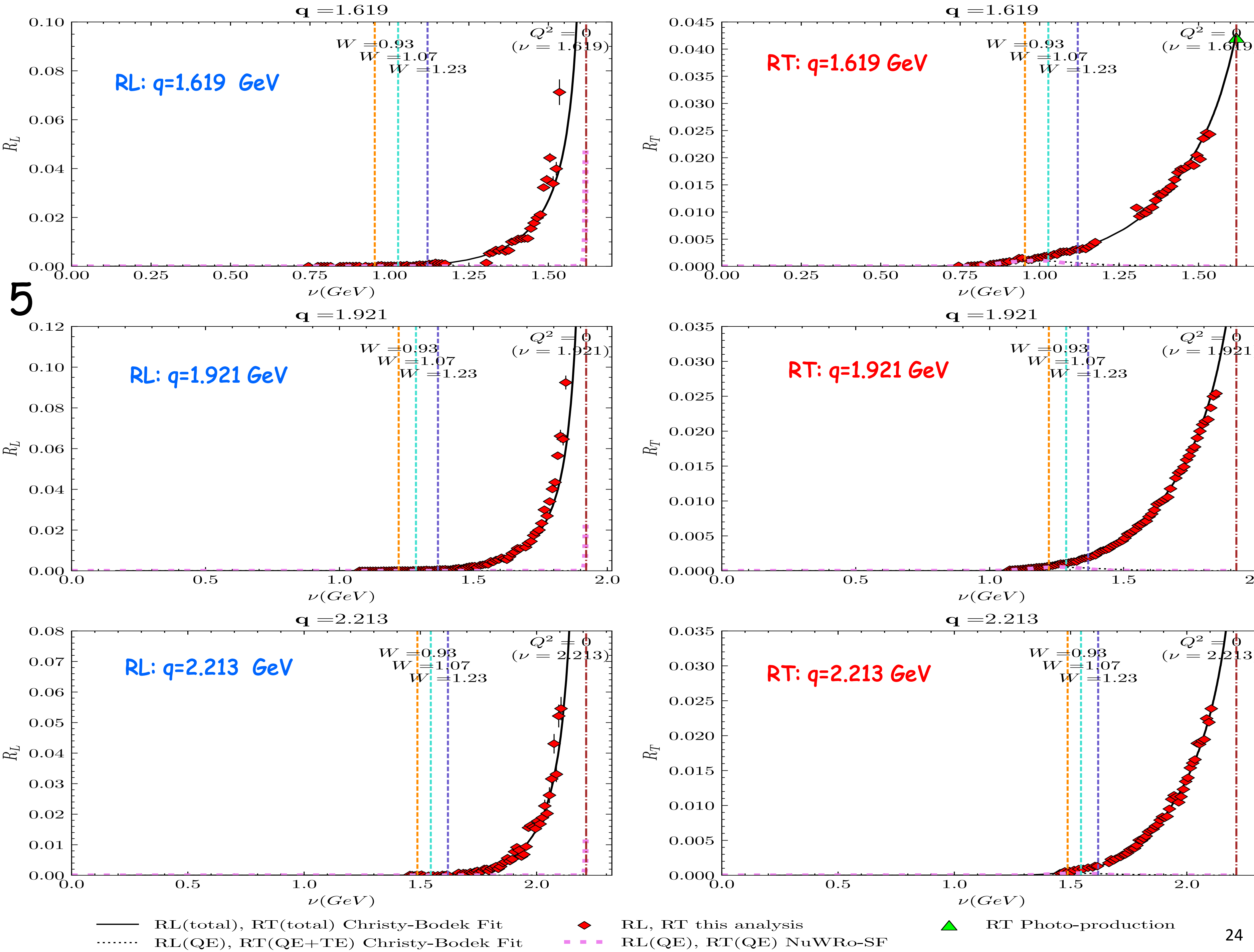


RL: q=0.205 GeV
RT: q=0.205 GeV
RL: q=0.240 GeV
RT: q=0.240 GeV
RL: q=0.30 GeV
RT: q=0.30 GeV
RL,RT this analysis
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RT Photo-production
RL,RT QE NuWRo-SF-FSI
2
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL,RT Yamaguchi
RL, RT this analysis
RL(QE), RT(QE) NuWRo-SF-FSI
RT Photo-production

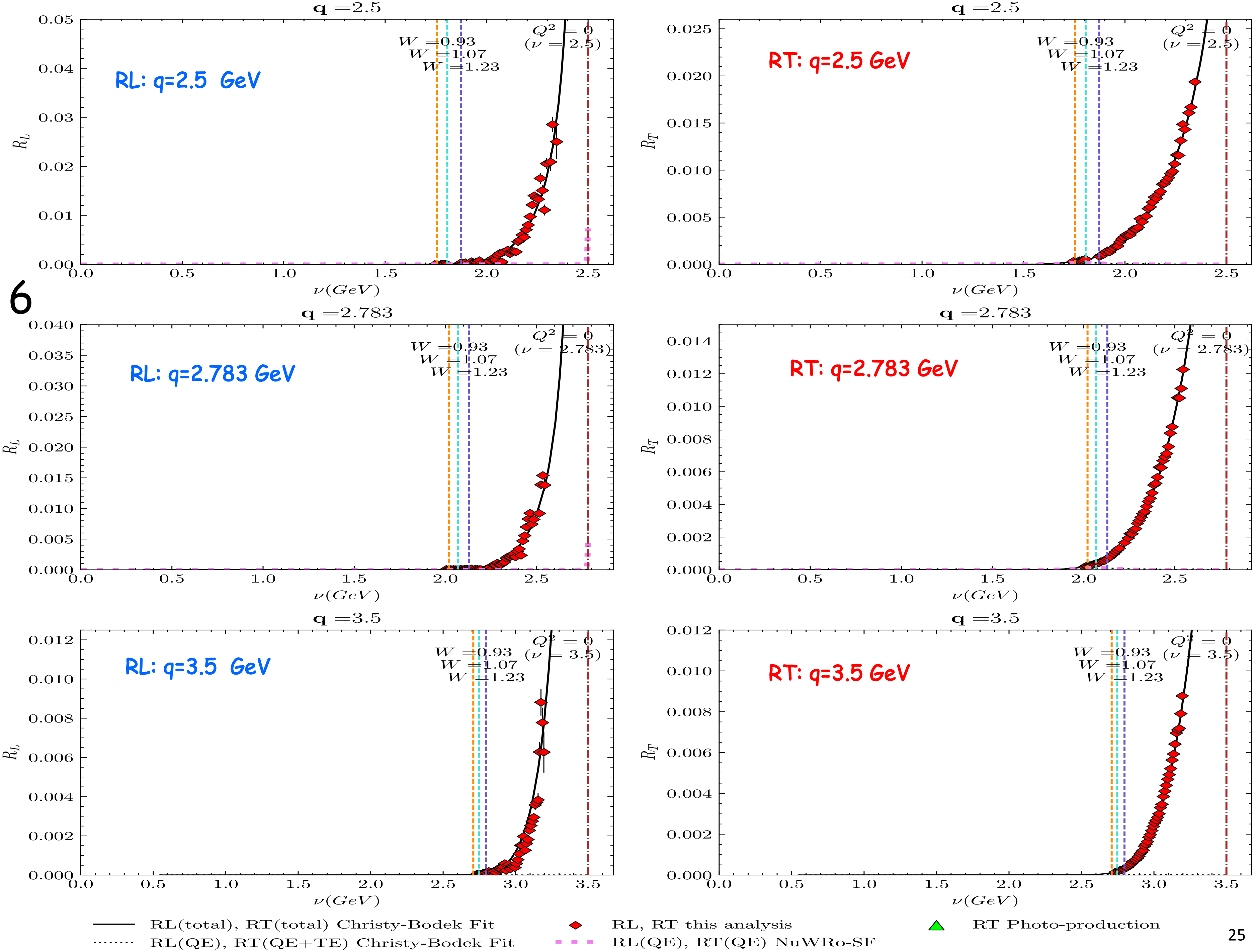


3
RL: q=0.380 GeV
RT: q=0.280 GeV
RL: q=0.475 GeV
RT: q=0.475 GeV
RL: q=0.57 GeV
RT: q=0.57 GeV
q =0.38
q =0.475
q =0.57
W =0.93
W =1.23
$Q^2 = 0$
$(\nu = 0.38)$
$(\nu = 0.475)$
$(\nu = 0.57)$
R_L
R_T
$\nu(GeV)$
RL,RT this analysis
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RT Photo-production
RL,RT QE NuWRo-SF-FSI
RL(QE), RT(QE) NuWRo-SF
RL(QE), RT(QE) NuWRo-SF-FSI
The Δ (1.23 GeV) peak is only in R_T (since the Δ is mostly Transverse
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT this analysis
RL(QE), RT(QE) NuWRo-SF-FSI
RT Photo-production
RL(QE), RT(QE) NuWRo-SF

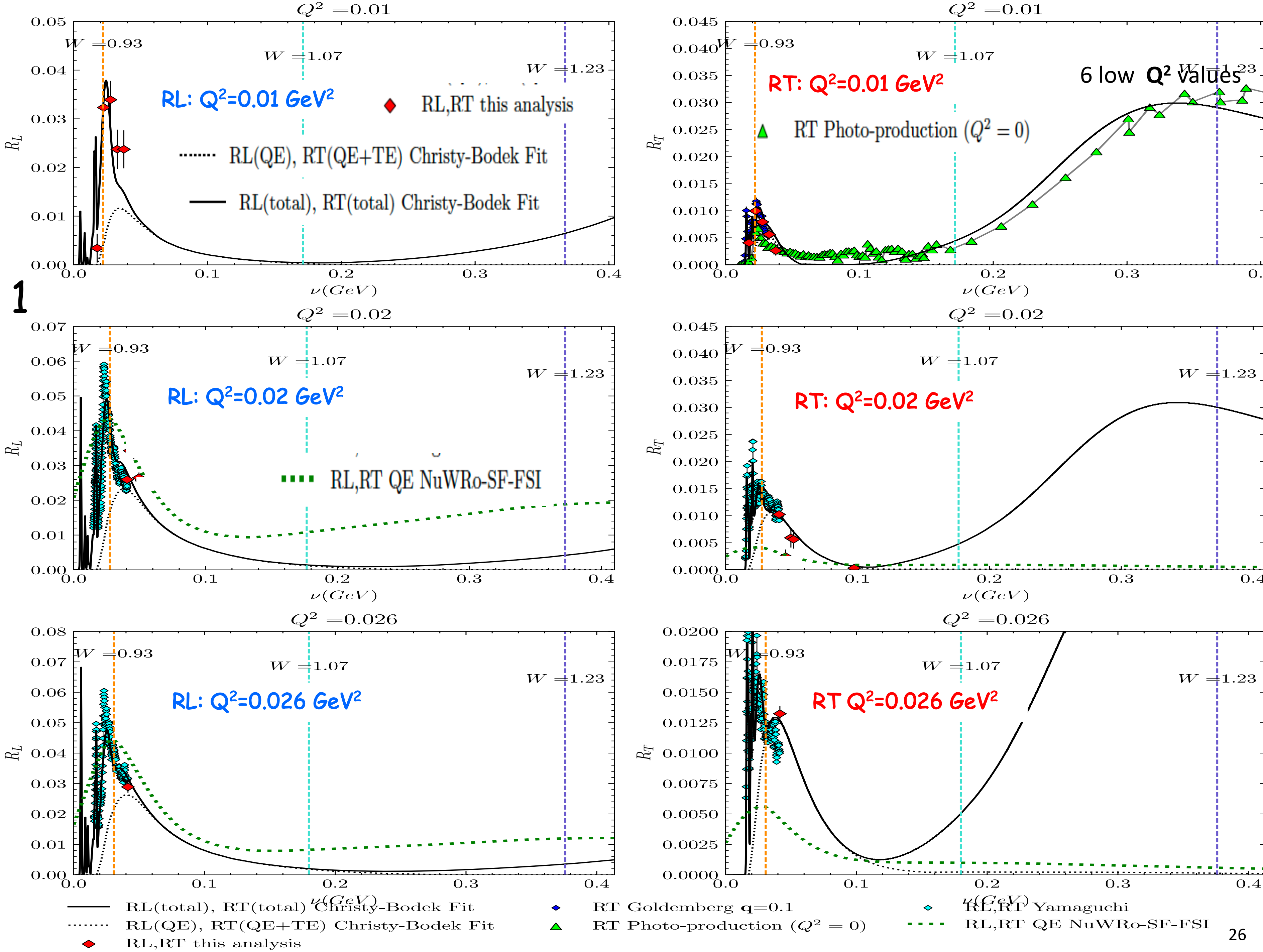

q =0.649
RL: q=0.649 GeV
W =0.93
$Q^2 = 0$
(ν = 0.649)
R_L
$\nu(GeV)$
q =0.649
RT: q=0.649 GeV
R_T
$\nu(GeV)$
4
q =0.756
RL: q=0.756 GeV
W =0.93
$Q^2 = 0$
(ν = 0.756)
R_L
$\nu(GeV)$
q =0.756
RT: q=0.756 GeV
W =0.93
$Q^2 = 0$
(ν = 0.756)
R_T
$\nu(GeV)$
q =0.991
RL: q=0.991 GeV
$Q^2 = 0$
(ν = 0.991)
R_L
$\nu(GeV)$
q =0.991
RT: q=0.991 GeV
W =0.93
$Q^2 = 0$
(ν = 0.991)
R_T
$\nu(GeV)$
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT this analysis
RL(QE), RT(QE) NuWRo-SF-FSI
RL(QE), RT(QE) NuWRo-SF
RT Photo-production

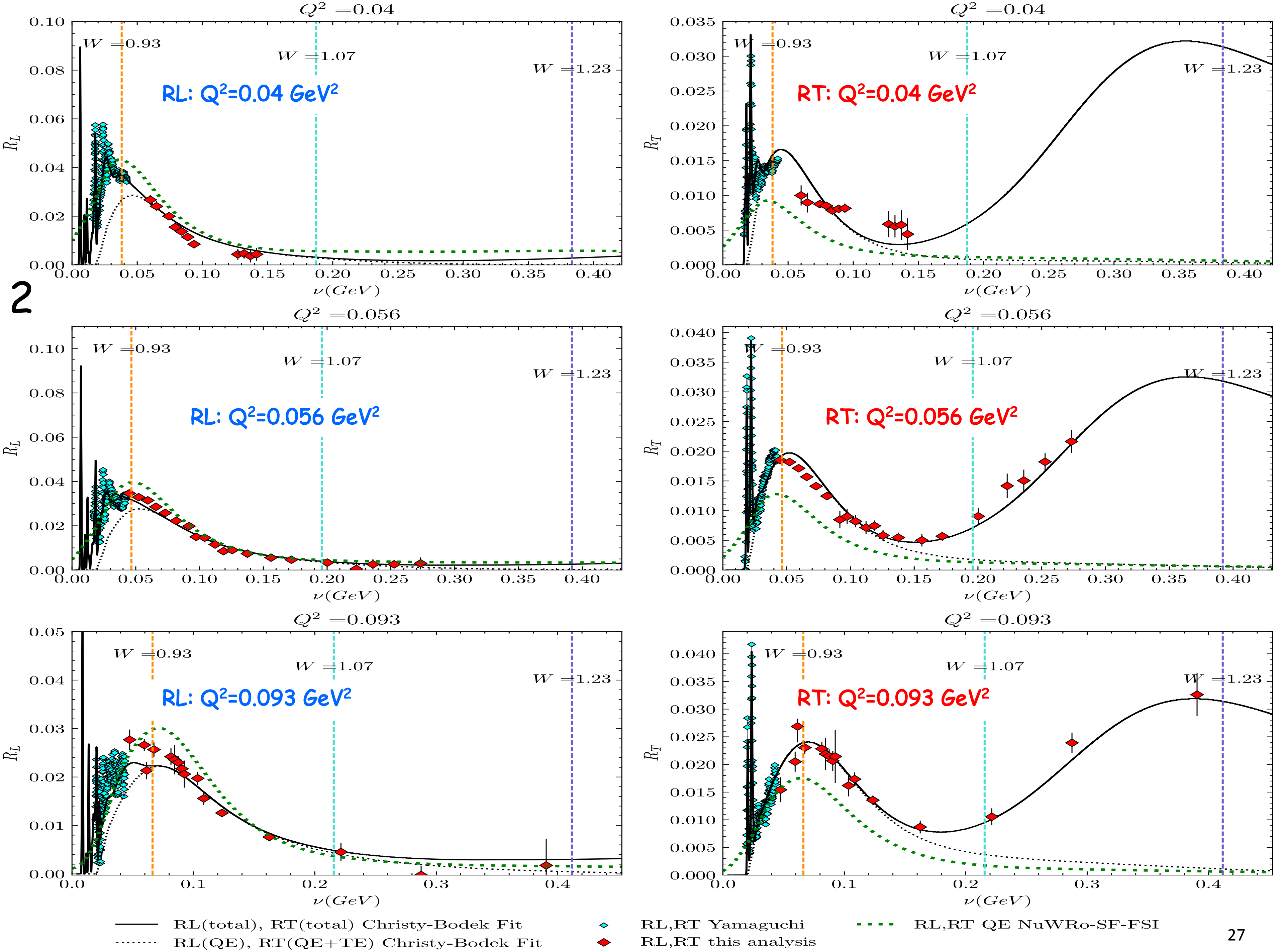


5
q =1.619
RL: q=1.619 GeV
RT: q=1.619 GeV
q =1.921
RL: q=1.921 GeV
RT: q=1.921 GeV
q =2.213
RL: q=2.213 GeV
RT: q=2.213 GeV
W =0.93
W =1.07
W =1.23
$Q^2 = 0$
$(\nu = 1.619)$
$(\nu = 1.921)$
$(\nu = 2.213)$
R_L
R_T
$\nu(GeV)$
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT this analysis
RL(QE), RT(QE) NuWRo-SF
RT Photo-production

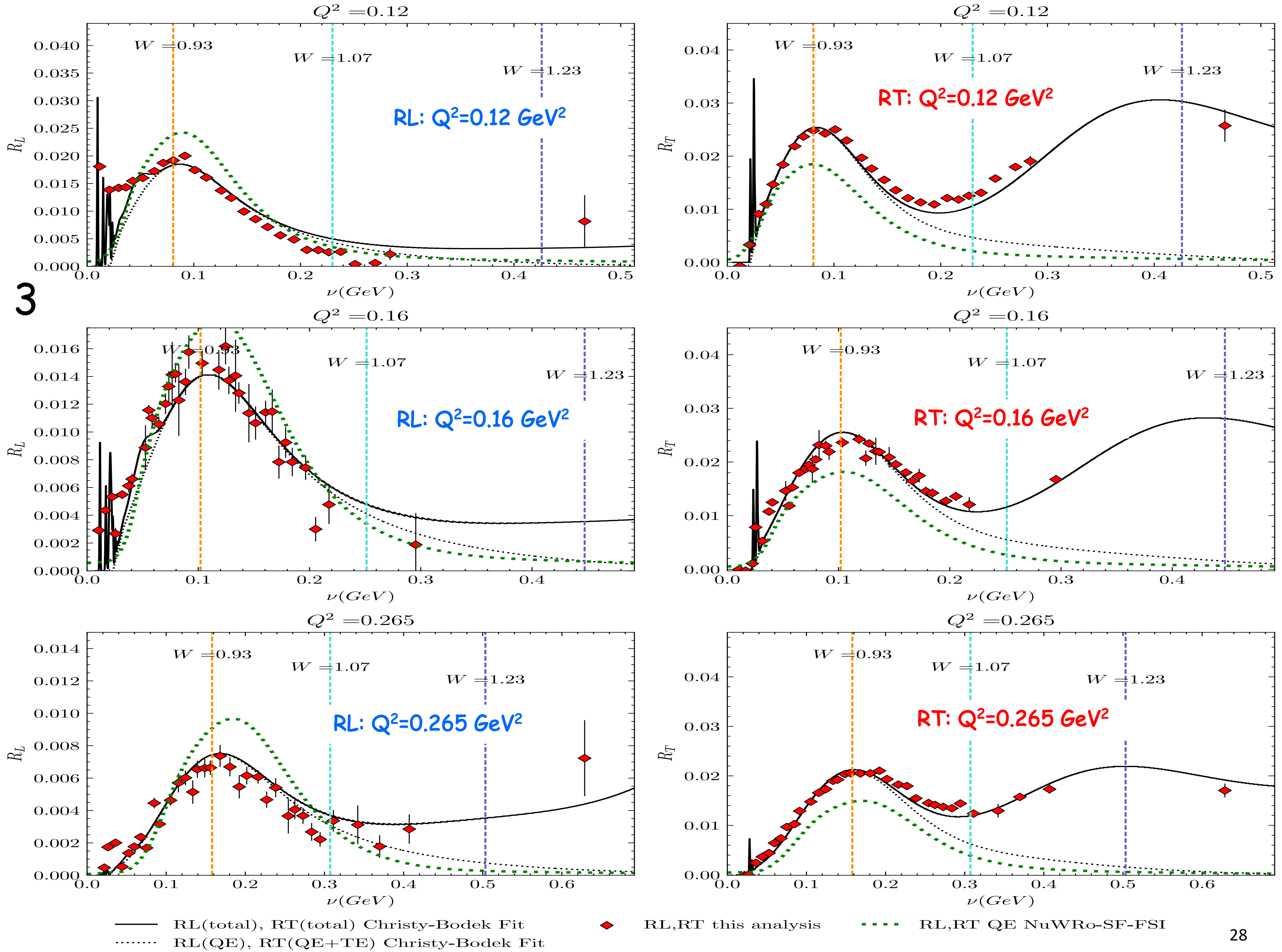


6
q =2.5
RL: q=2.5 GeV
RT: q=2.5 GeV
q =2.783
RL: q=2.783 GeV
RT: q=2.783 GeV
q =3.5
RL: q=3.5 GeV
RT: q=3.5 GeV
W =0.93
W =1.07
W =1.23
$Q^2 = 0$
R_L
R_T
$\nu(GeV)$
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL, RT this analysis
RL(QE), RT(QE) NuWRo-SF
RT Photo-production


6 low Q² values
RL: Q²=0.01 GeV²
RT: Q²=0.01 GeV²
RL: Q²=0.02 GeV²
RT: Q²=0.02 GeV²
RL: Q²=0.026 GeV²
RT Q²=0.026 GeV²
Q² =0.01
Q² =0.02
Q² =0.026
W =0.93
W =1.07
W =1.23
ν(GeV)
R_L
R_T
RL,RT this analysis
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL(total), RT(total) Christy-Bodek Fit
RT Photo-production (Q² = 0)
RL,RT QE NuWRo-SF-FSI
RT Goldemberg q=0.1
RL,RT Yamaguchi
1

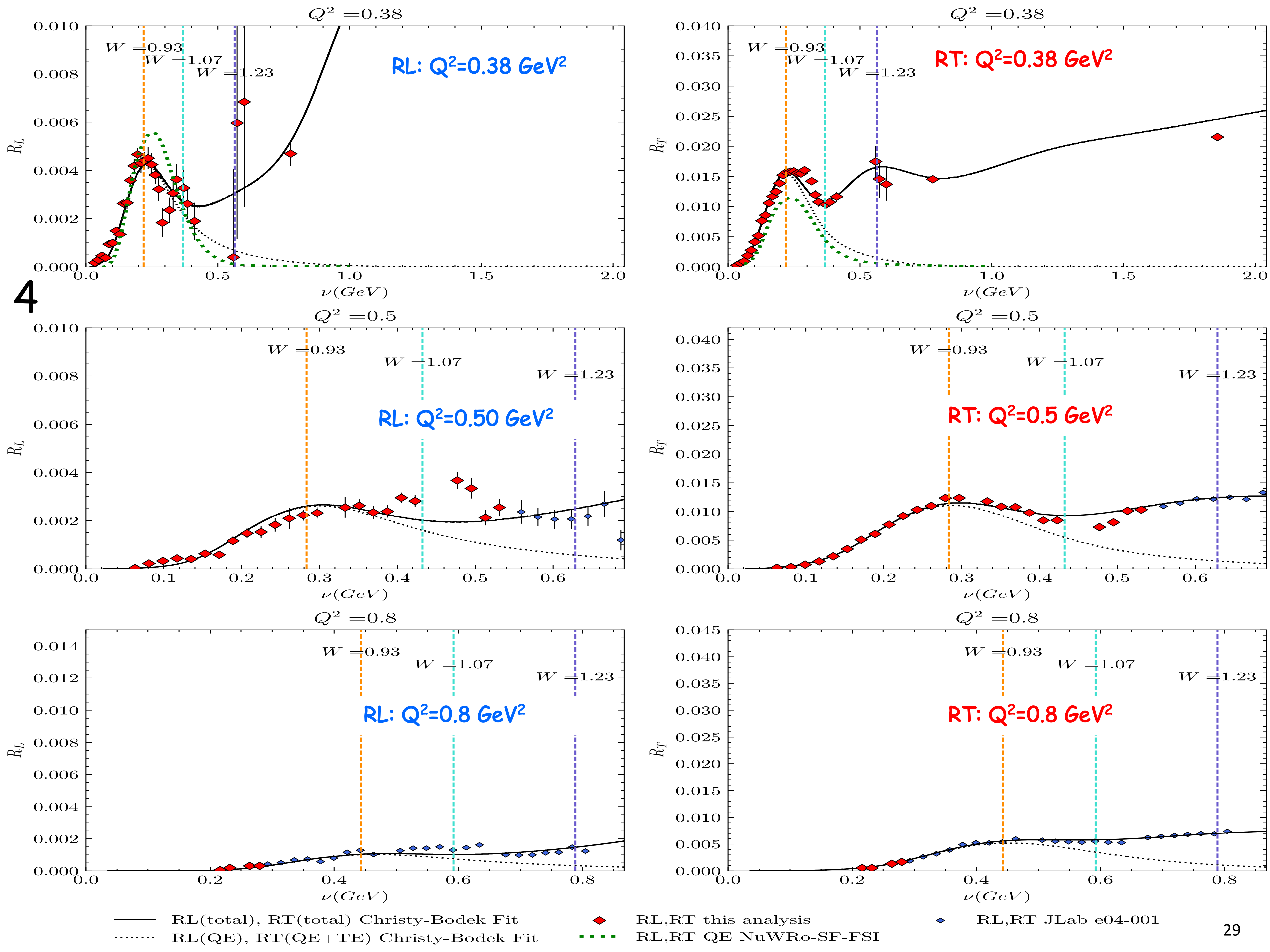


Q^2 =0.04
RL: Q²=0.04 GeV²
RT: Q²=0.04 GeV²
Q^2 =0.056
RL: Q²=0.056 GeV²
RT: Q²=0.056 GeV²
Q^2 =0.093
RL: Q²=0.093 GeV²
RT: Q²=0.093 GeV²
W =0.93
W =1.07
W =1.23
R_L
R_T
$\nu(GeV)$
2
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL,RT Yamaguchi
RL,RT this analysis
RL,RT QE NuWRo-SF-FSI



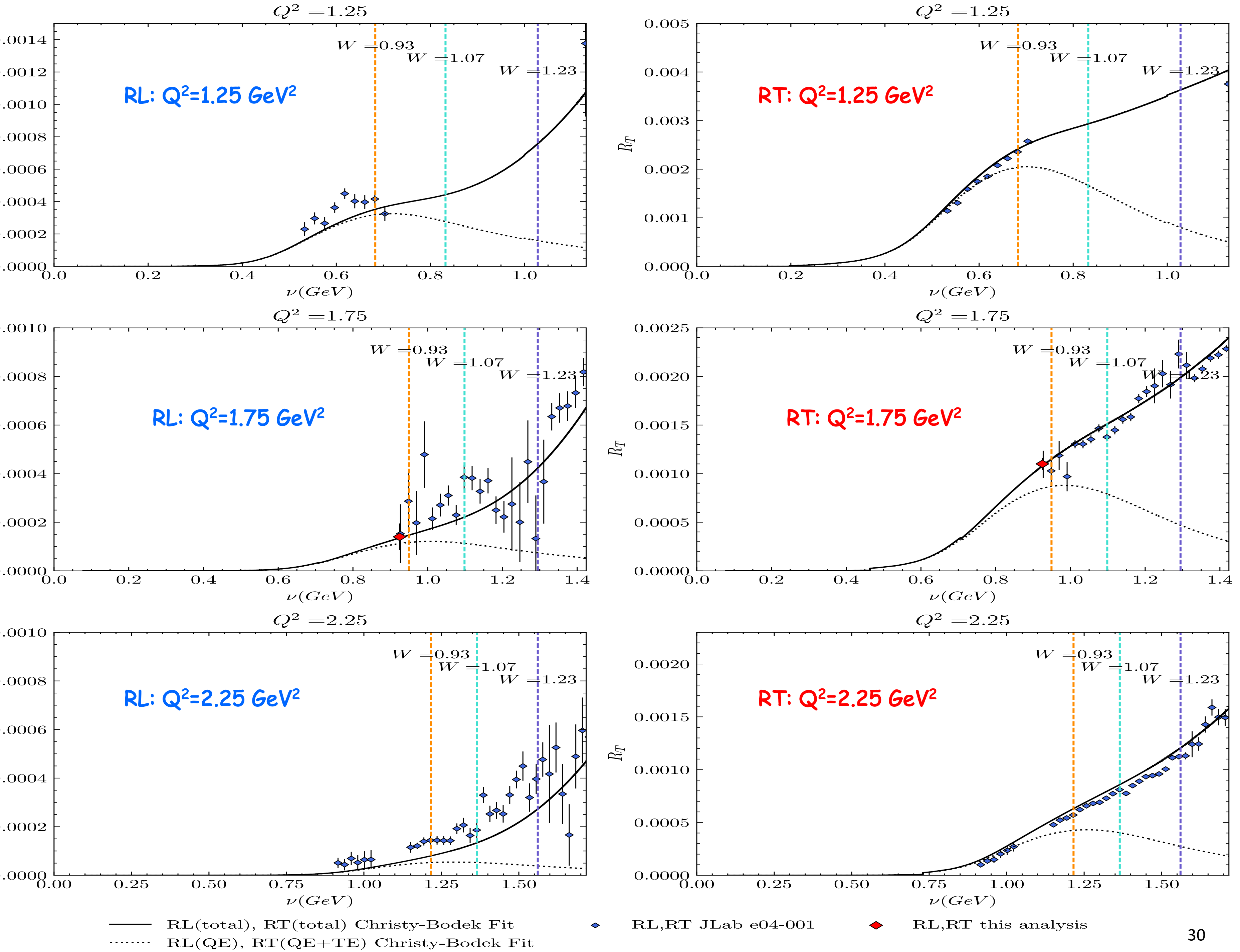
3
$Q^2 = 0.12$
RL: Q²=0.12 GeV²
RT: Q²=0.12 GeV²
$Q^2 = 0.16$
RL: Q²=0.16 GeV²
RT: Q²=0.16 GeV²
$Q^2 = 0.265$
RL: Q²=0.265 GeV²
RT: Q²=0.265 GeV²
W =0.93
W =1.07
W =1.23
R_L
R_T
$\nu (GeV)$
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL,RT this analysis
RL,RT QE NuWRo-SF-FSI

4

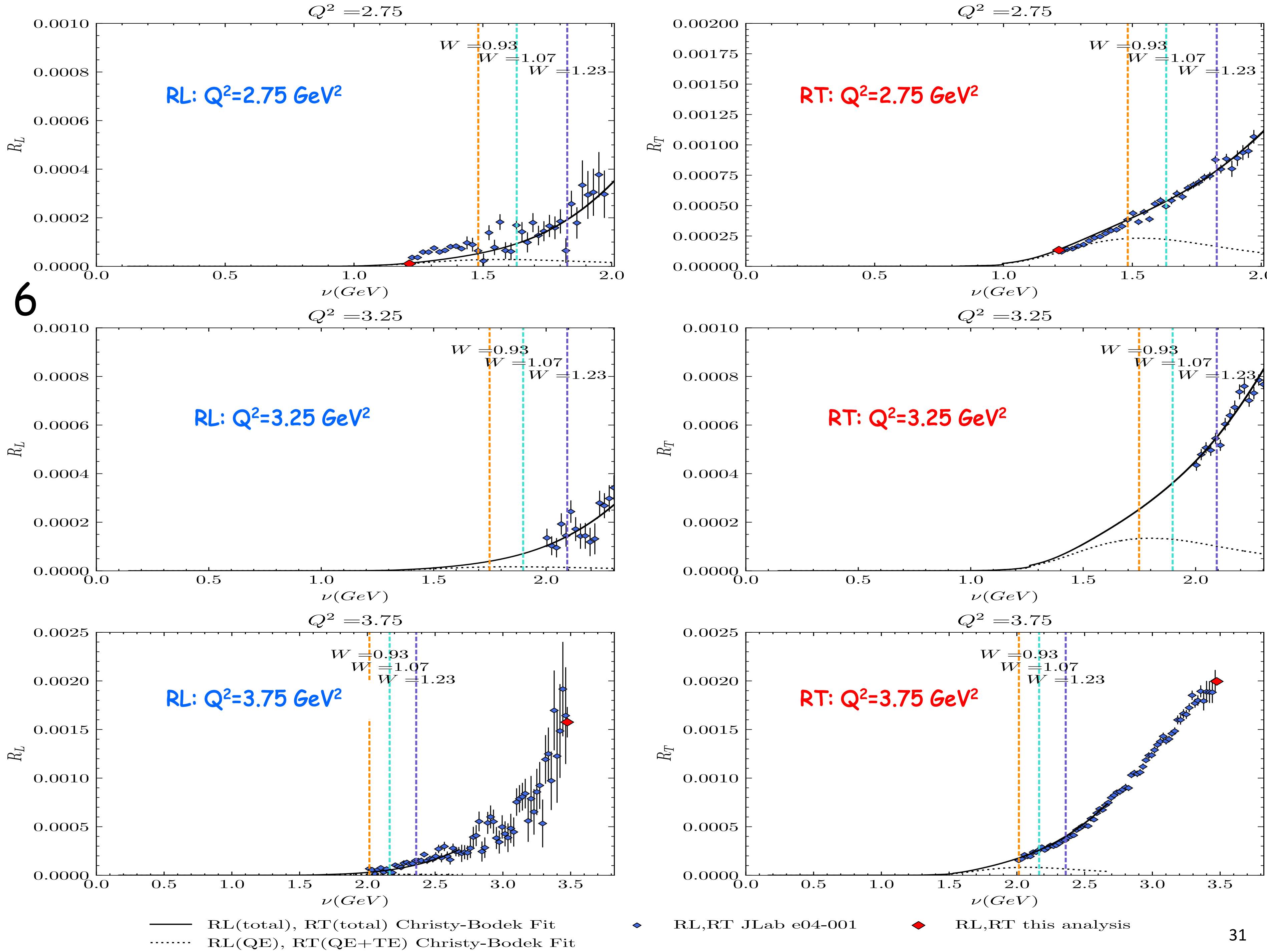


$Q^2 = 0.38$
RL: Q^2=0.38 GeV^2
RT: Q^2=0.38 GeV^2
$Q^2 = 0.5$
RL: Q^2=0.50 GeV^2
RT: Q^2=0.5 GeV^2
$Q^2 = 0.8$
RL: Q^2=0.8 GeV^2
RT: Q^2=0.8 GeV^2
$W = 0.93$
$W = 1.07$
$W = 1.23$
R_L
R_T
$\nu(GeV)$
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL,RT this analysis
RL,RT QE NuWRo-SF-FSI
RL,RT JLab e04-001

5



$Q^2 = 1.25$
RL: Q²=1.25 GeV²
RT: Q²=1.25 GeV²
$Q^2 = 1.75$
RL: Q²=1.75 GeV²
RT: Q²=1.75 GeV²
$Q^2 = 2.25$
RL: Q²=2.25 GeV²
RT: Q²=2.25 GeV²
$W = 0.93$
$W = 1.07$
$W = 1.23$
R_L
R_T
$\nu (GeV)$
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL,RT JLab e04-001
RL,RT this analysis



Q^2 =2.75
RL: Q^2=2.75 GeV^2
RT: Q^2=2.75 GeV^2
6
Q^2 =3.25
RL: Q^2=3.25 GeV^2
RT: Q^2=3.25 GeV^2
Q^2 =3.75
RL: Q^2=3.75 GeV^2
RT: Q^2=3.75 GeV^2
W =0.93
W =1.07
W =1.23
R_L
R_T
$\nu (GeV)$
RL(total), RT(total) Christy-Bodek Fit
RL(QE), RT(QE+TE) Christy-Bodek Fit
RL,RT JLab e04-001
RL,RT this analysis