Work of Aligarh group 2019

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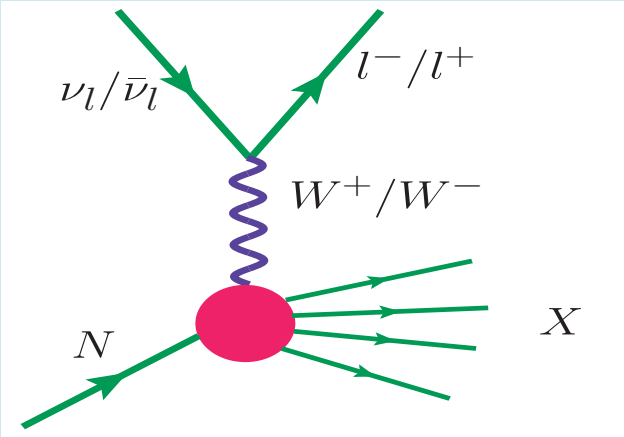
Charged current deep inelastic scattering process

$$\nu_l/\bar{\nu}_l(k) + N(p) \to l^-/l^+(k') + X(p')$$



$$\frac{d^2\sigma^N}{d\Omega' dE'} = \frac{G_F{}^2}{(2\pi)^2}\frac{|\mathbf{k}'|}{|\mathbf{k}|}\left(\frac{m_W^2}{q^2 - m_W^2}\right)^2 L^{\mu\nu} W^N_{\mu\nu}$$

Leptonic tensor

$$L^{\mu\nu} = k^\mu k'^\nu + k^\nu k'^\mu - k.k' g^{\mu\nu} \pm i\varepsilon^{\mu\nu\rho\sigma} k_\rho k'_\sigma$$

Hadronic tensor

$$\begin{aligned} \mathbf{W^N_{\mu\nu}} &= \left(\frac{\mathbf{q_\mu q_\nu}}{\mathbf{q^2}} - \mathbf{g_{\mu\nu}}\right)\mathbf{W_{1N}} + \frac{\mathbf{1}}{\mathbf{M_N^2}} \\ &\times \left(\mathbf{p_\mu} - \frac{\mathbf{p.q}}{\mathbf{q^2}}\mathbf{q_\mu}\right)\left(\mathbf{p_\nu} - \frac{\mathbf{p.q}}{\mathbf{q^2}}\mathbf{q_\nu}\right)\mathbf{W_{2N}} \\ &- \frac{\mathbf{i}}{\mathbf{2M_N^2}}\varepsilon_{\mu\nu\rho\sigma}\mathbf{p^\rho q^\sigma W_{3N}} \end{aligned}$$

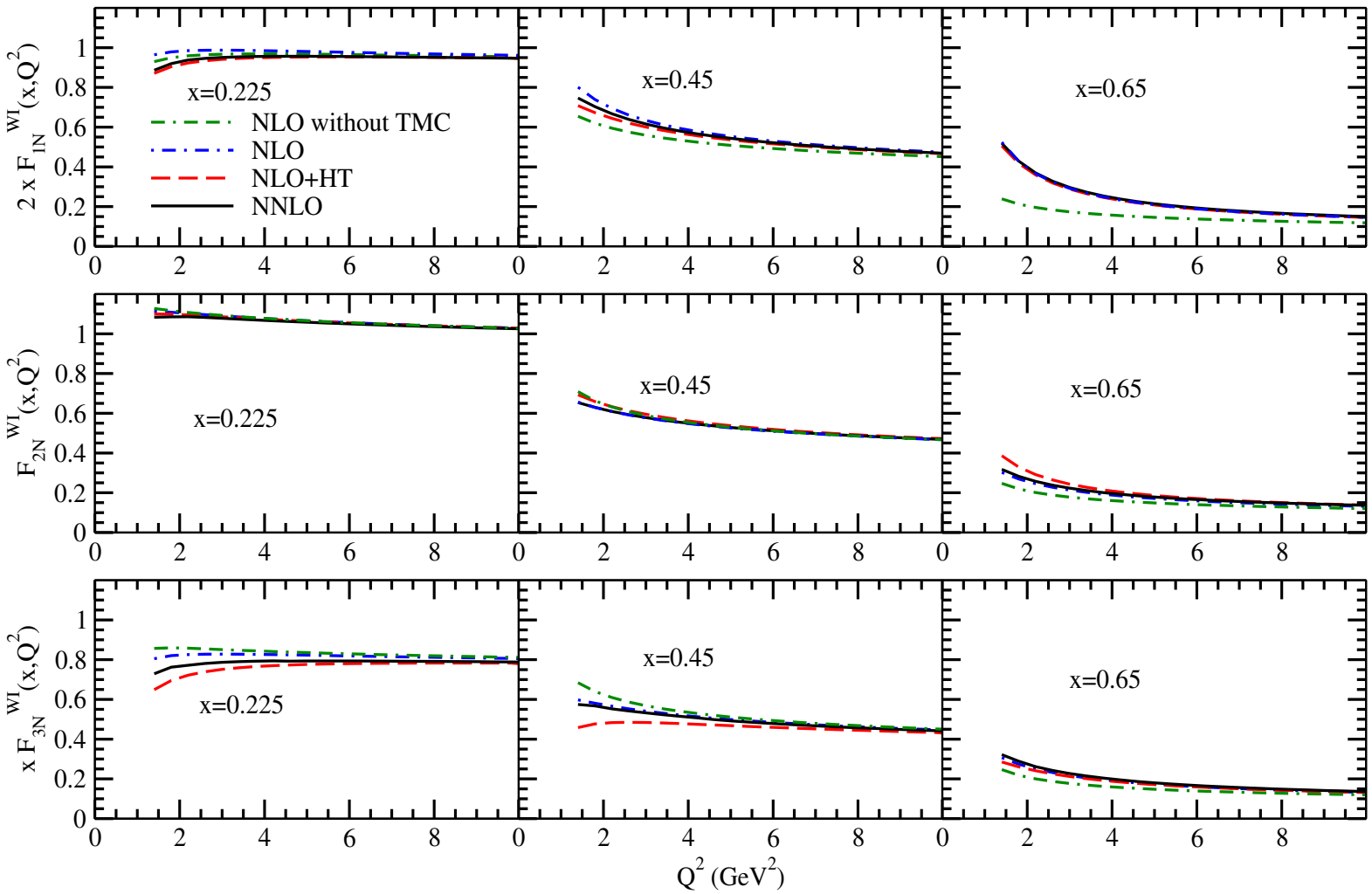
Dimensionless SF

$$\begin{aligned} \mathbf{M_N W_{1N}(\nu, Q^2)} &= \mathbf{F_{1N}(x, Q^2)}, \\ \mathbf{\nu W_{2N}(\nu, Q^2)} &= \mathbf{F_{2N}(x, Q^2)}, \\ \mathbf{\nu W_{3N}(\nu, Q^2)} &= \mathbf{F_{3N}(x, Q^2)}. \end{aligned}$$

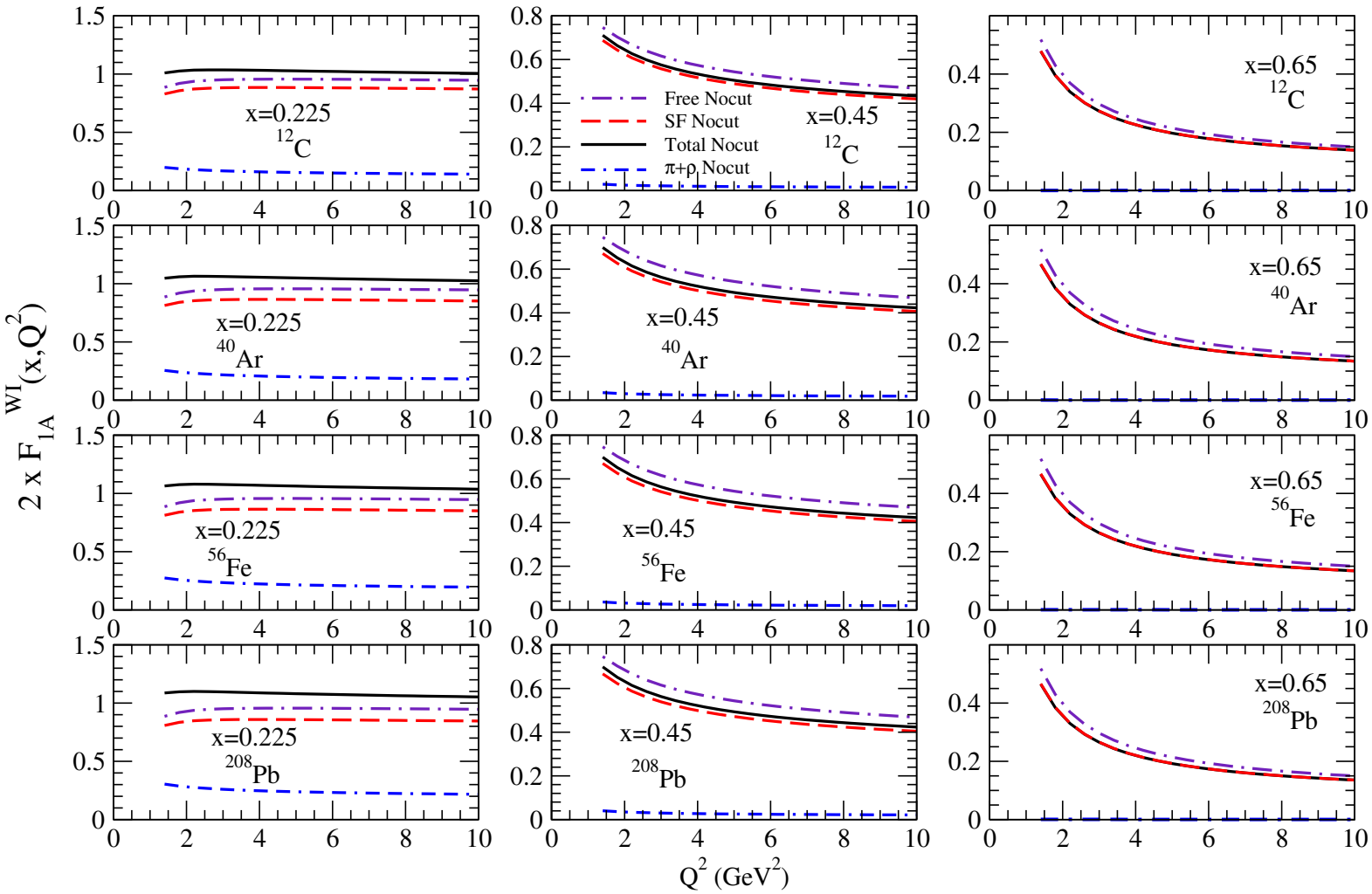
In terms of PDFs

$$\begin{aligned} \mathbf{F_2^{\nu p}} &= \mathbf{2x[d(x) + s(x) + \bar{u}(x) + \bar{c}(x)]}, \\ \mathbf{F_2^{\bar{\nu} p}} &= \mathbf{2x[u(x) + c(x) + \bar{d}(x) + \bar{s}(x)]}, \\ \mathbf{xF_3^{\nu p}} &= \mathbf{2x[d(x) + s(x) - \bar{u}(x) - \bar{c}(x)]}, \\ \mathbf{xF_3^{\bar{\nu} p}} &= \mathbf{2x[u(x) + c(x) - \bar{d}(x) - \bar{s}(x)]}. \end{aligned}$$

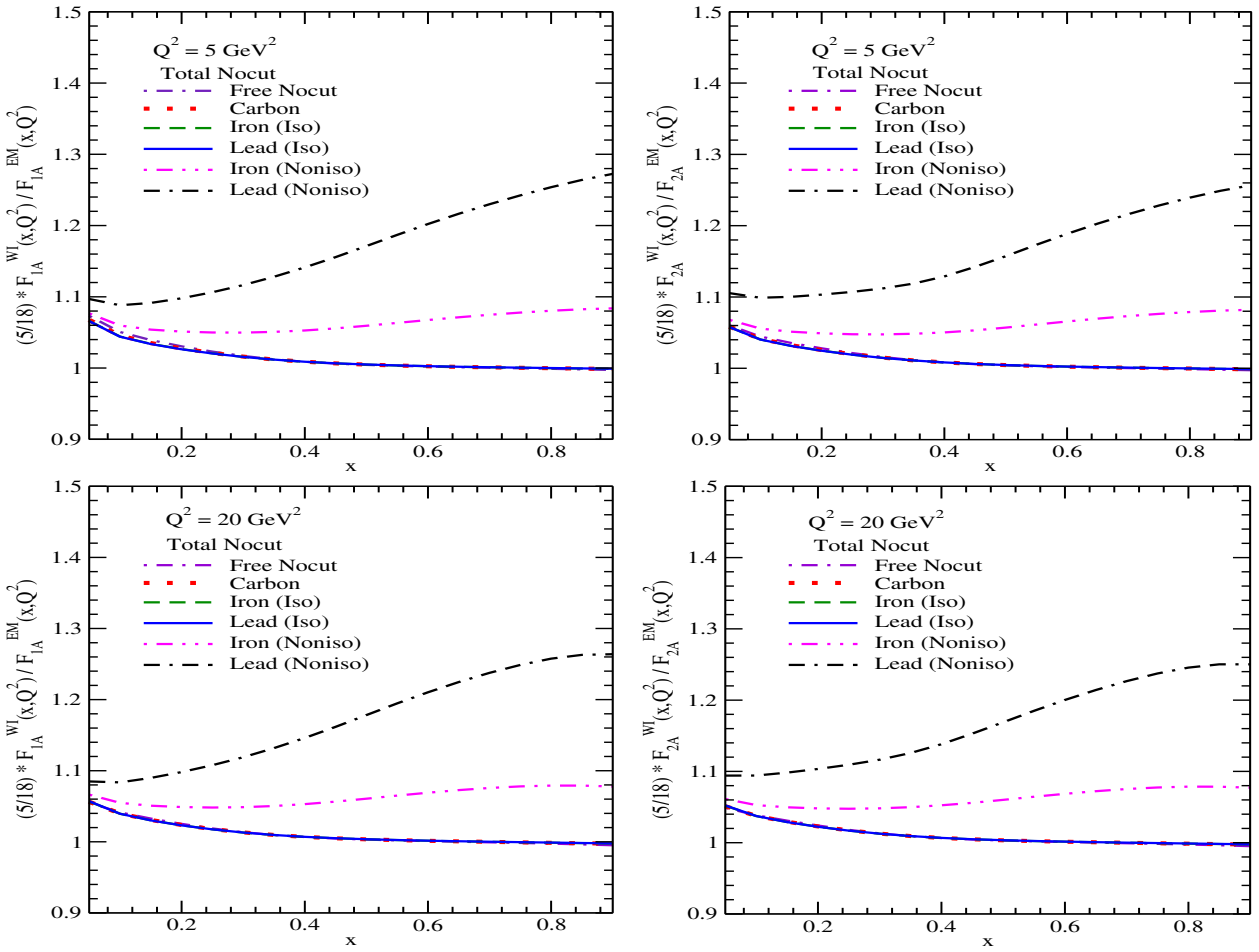
$F_{iN}^{WI}(x, Q^2)$ vs Q^2: *arXiv:1911.12573*



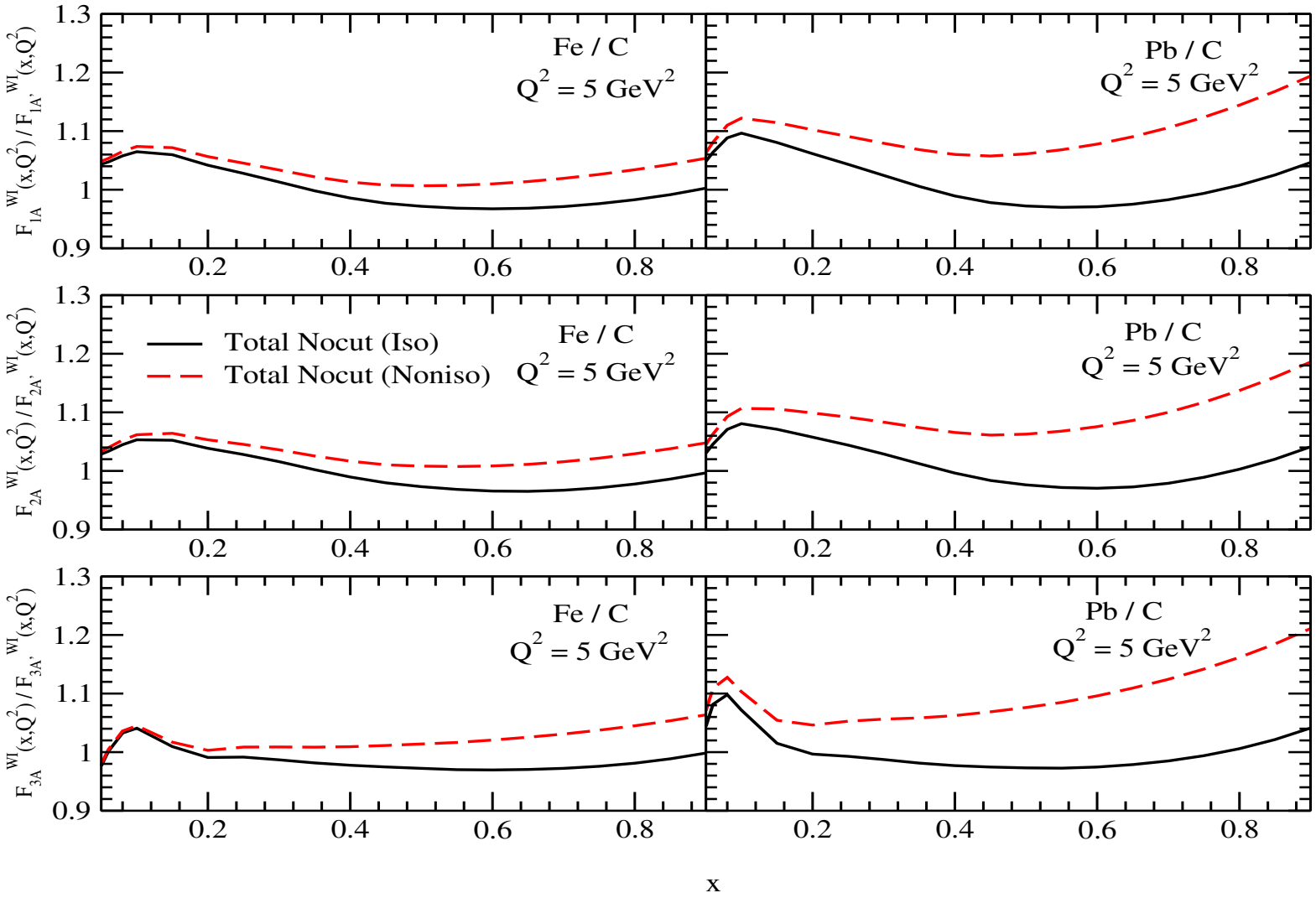
$2xF_{1A}^{WI}(x,Q^2)$ vs Q^2: *arXiv:1911.12573*



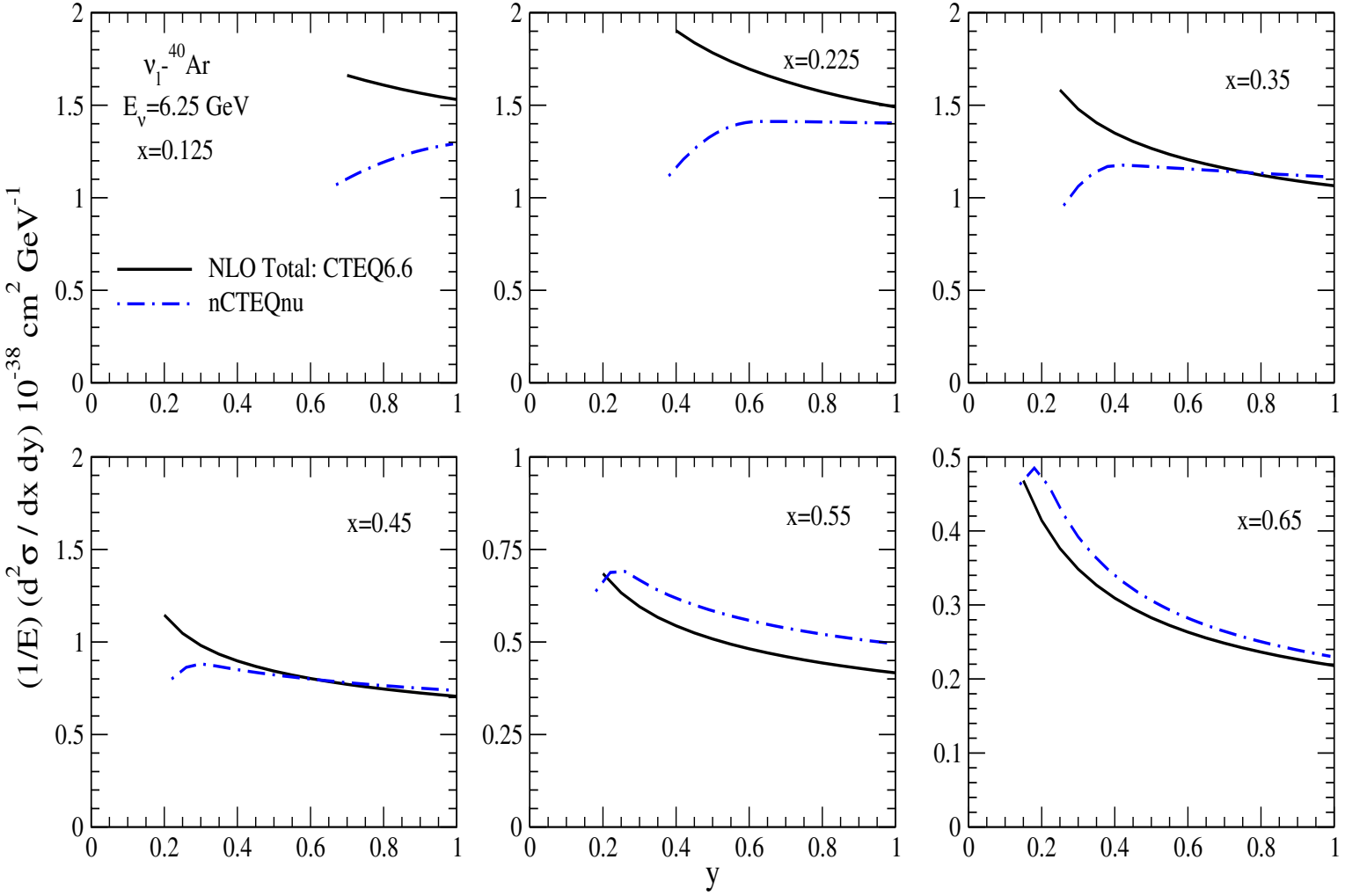
NME in Weak & Electromagnetic interactions: *JPG: Invited review*



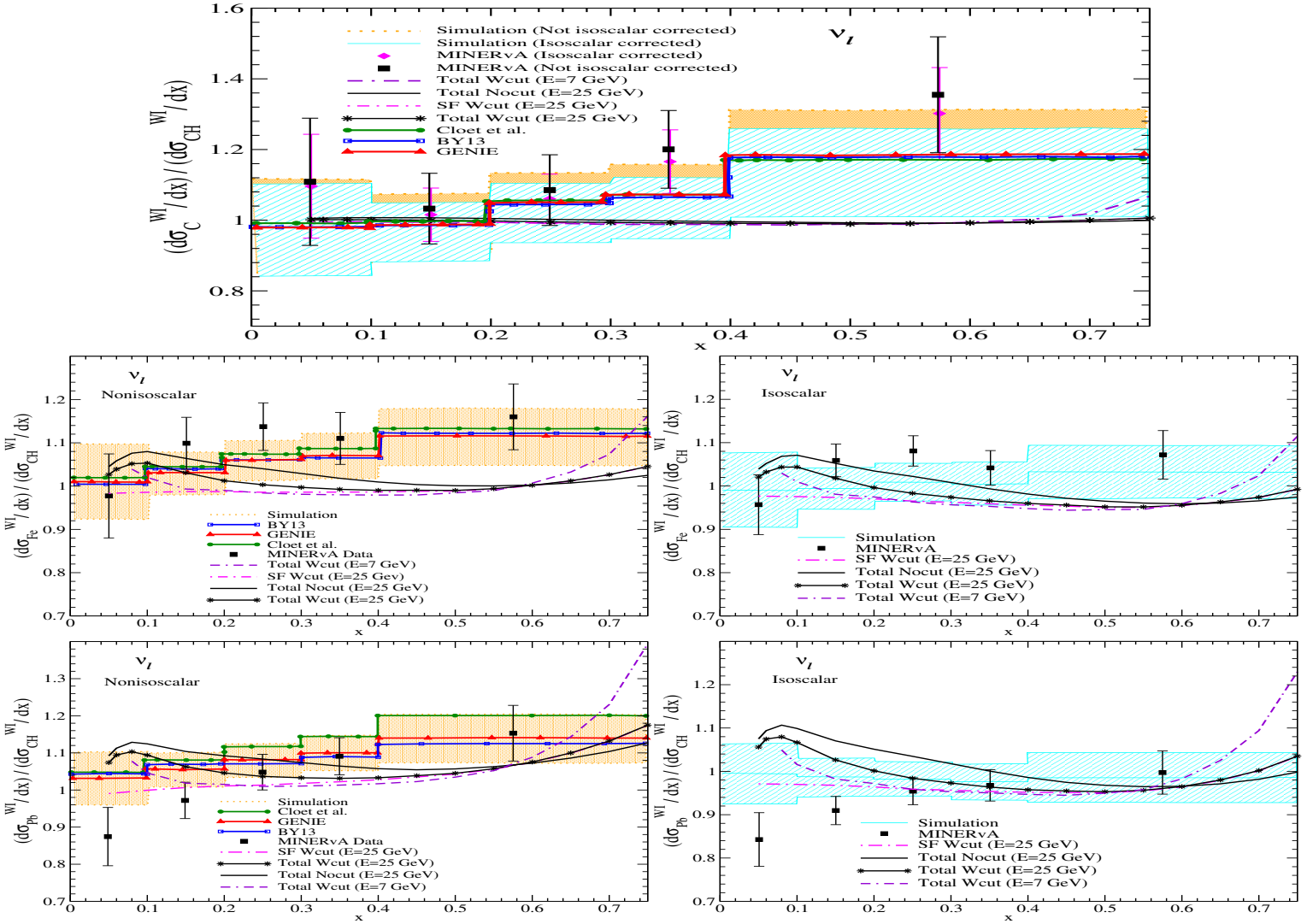
Isoscalar vs Nonisoscalar nuclei: *arXiv:1911.12573*



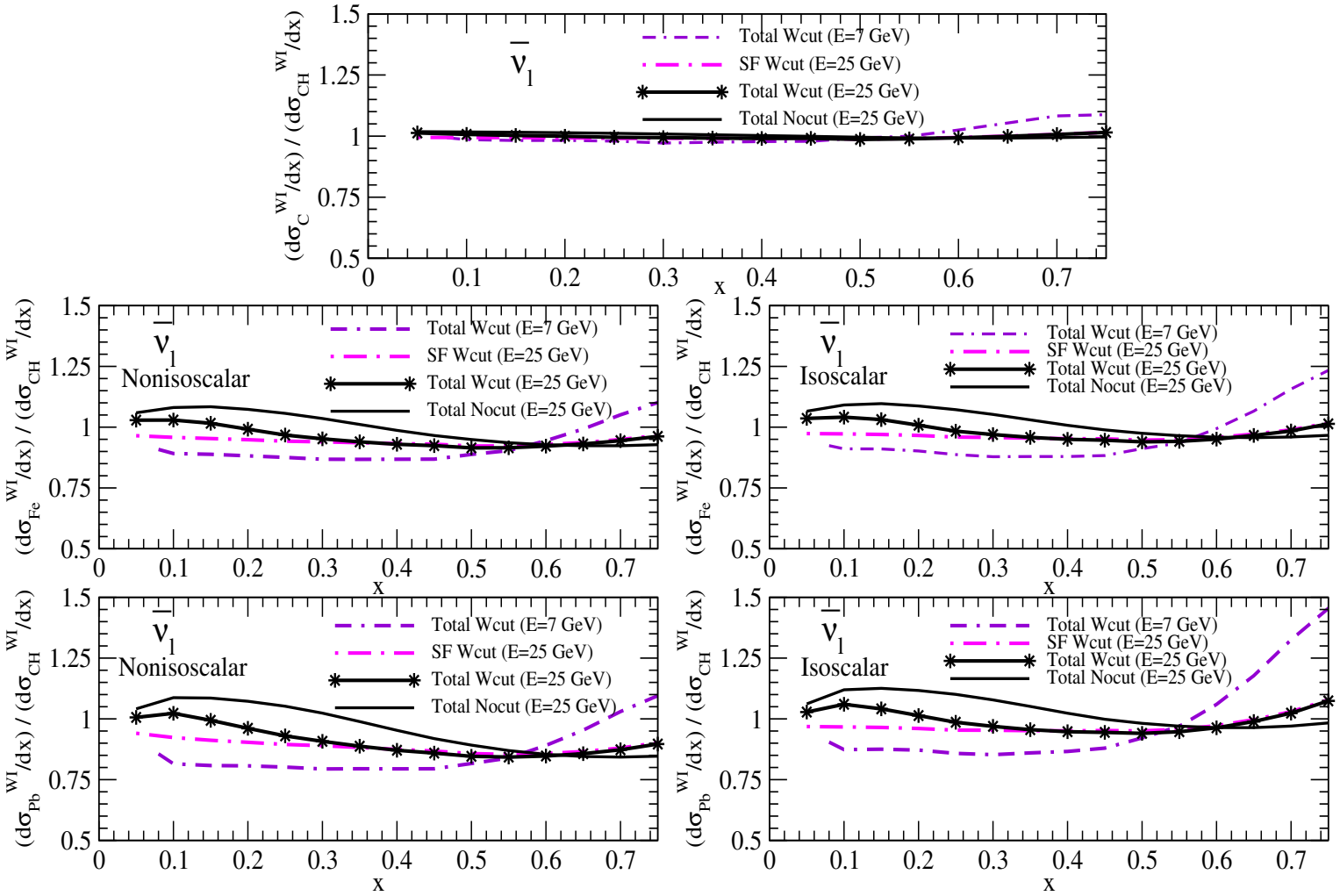
Theory vs Phenomenology: $\nu_l - {}^{40}Ar$: *JPG: Invited review*



Differential cross section ratios: $\nu_l - A$: *arXiv:1911.12573*



Differential cross section ratios: $\bar{\nu}_l - A$: *arXiv:1911.12573*



Associated Particle Production

$$\gamma(q) + p(p) \longrightarrow K^{+}(p_k) + \Lambda(p')$$

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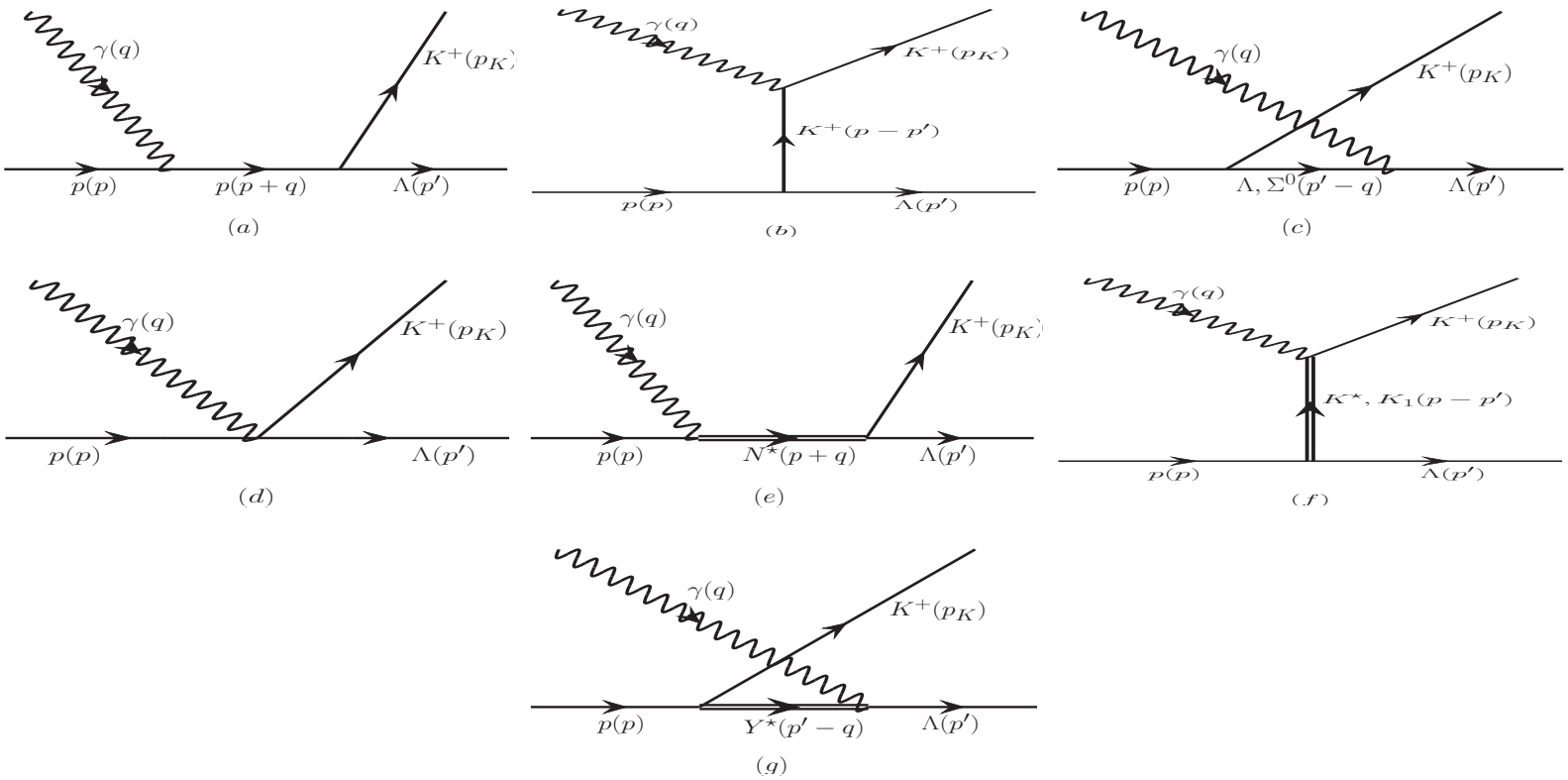

$$
\begin{aligned}
J^\mu|_s &= ieA_s\, F_s(s)\bar{u}(p')\, \not{p}_k\gamma_5\, \frac{\not{p}+\not{q}+M}{s-M^2}\left(\gamma^\mu F_1^p(0)+i\frac{F_2(0)}{2M}\sigma^{\mu\nu}q_\nu\right)u(p),\\
J^\mu|_t &= ieA_t\, F_t(t)\bar{u}(p')\left[(\not{p}-\not{p}')\cdot\gamma_5\right]u(p)\,\frac{(2p_k^\mu-q^\mu)}{t-M_k^2},\\
J^\mu|_{u\Lambda} &= ieA_u^\Lambda\, F_u^\Lambda(u)\bar{u}(p')\left(\gamma^\mu F_1^\Lambda(0)+i\frac{F_2^\Lambda(0)}{2M_\Lambda}\sigma^{\mu\nu}q_\nu\right)\frac{\not{p}'-\not{q}+M_\Lambda}{u-M_\Lambda^2}\;\not{p}_k\gamma_5 u(p),\\
J^\mu|_{u\Sigma^0} &= ieA_u^{\Sigma^0}\, F_u^{\Sigma^0}(u)\bar{u}(p')\left(\gamma^\mu F_1^{\Sigma^0}(0)+i\frac{F_2^{\Sigma^0}(0)}{2M_{\Sigma^0}}\sigma^{\mu\nu}q_\nu\right)\frac{\not{p}'-\not{q}+M_{\Sigma^0}}{u-M_{\Sigma^0}^2}\;\not{p}_k\gamma_5 u(p),\\
J^\mu|_{CT} &= -ieA_{CT}\, F_{CT}\bar{u}(p')\,\gamma^\mu\gamma_5\, u(p),
\end{aligned}
$$

$$
A_s = A_t = A_u^\Lambda = A_{CT} = -\left(\frac{D+3F}{2\sqrt{3}f_\pi}\right), \qquad A_u^{\Sigma^0} = \left(\frac{D-F}{2f_\pi}\right).
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J^\mu|_{u\Lambda} &= ieA_u^\Lambda\, F_u^\Lambda(u)\bar{u}(p')\left(\gamma^\mu F_1^\Lambda(0)+i\frac{F_2^\Lambda(0)}{2M_\Lambda}\sigma^{\mu\nu}q_\nu\right)\frac{\not{p}'-\not{q}+M_\Lambda}{u-M_\Lambda^2}\ \not{p}_k\gamma_5 u(p),\\
J^\mu|_{u\Sigma^0} &= ieA_u^{\Sigma^0}\, F_u^{\Sigma^0}(u)\bar{u}(p')\left(\gamma^\mu F_1^{\Sigma^0}(0)+i\frac{F_2^{\Sigma^0}(0)}{2M_{\Sigma^0}}\sigma^{\mu\nu}q_\nu\right)\frac{\not{p}'-\not{q}+M_{\Sigma^0}}{u-M_{\Sigma^0}^2}\ \not{p}_k\gamma_5 u(p),\\
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$$

A general dipole form for $F_x(x)$

$$
F_x(x) = \frac{\Lambda_i^4}{\Lambda_i^4+(x-M_x^2)^2}, \quad \Lambda_B = 0.52GeV \quad \Lambda_R = 1.1GeV
$$

Davidson-Workman[PRC 63, 025210 (2001)]

$$
F_{CT} = F_s(s)+F_t(t)-F_s(s)\times F_t(t).
$$

Resonances	M_R [GeV]	J	I	P	Γ (GeV)	$K\Lambda$ branching ratio (%)	$g_{K\Lambda R}$
$S_{11}(1650)$	1.655 ± 0.015	$1/2$	$1/2$	$-$	0.135 ± 0.035	10 ± 5	0.79
$P_{11}(1710)$	1.700 ± 0.020	$1/2$	$1/2$	$+$	0.120 ± 0.040	15 ± 10	1.32
$P_{13}(1720)$	1.675 ± 0.015	$3/2$	$1/2$	$+$	$0.250 \pm^{0.150}_{0.100}$	4.5 ± 0.5	2.92
$P_{11}(1880)$	1.860 ± 0.040	$1/2$	$1/2$	$+$	0.230 ± 0.050	20 ± 8	0.91
$S_{11}(1895)$	1.910 ± 0.020	$1/2$	$1/2$	$-$	0.110 ± 0.030	18 ± 5	0.41
$P_{13}(1900)$	1.920 ± 0.020	$3/2$	$1/2$	$+$	0.150 ± 0.050	11 ± 9	1.028

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- The helicity amplitudes for the resonances $S_{11}(1650)$, $P_{13}(1720)$ and $P_{13}(1920)$ are taken from MAID 2011 while for the resonances $P_{11}(1710)$, $P_{11}(1880)$ and $S_{11}(1895)$, the helicity amplitudes are taken from PDG.

Hadronic current for the s-channel processes where a resonant state $R^{\frac{1}{2}}$ is produced

$$j^{\mu}\Big|_{R}^{\frac{1}{2}\pm} = ie\,\bar{u}(\vec{p}\,')\frac{g_{K\Lambda R\frac{1}{2}}}{M_K}\not{p}_K\Gamma_s\frac{\not{p}+\not{q}+M_R}{s-M_R^2+iM_R\Gamma_R}\Gamma^{\mu}_{\frac{1}{2}\pm}u(\vec{p}\,),$$

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The most general expression of the hadronic current for the s-channel where a resonant state $R^{\frac{3}{2}}$ (with positive or negative parity) is produced and decays to a kaon and a lambda in the final state

$$j^{\mu}\Big|_{R}^{\frac{3}{2}\pm} = ie\,\frac{g_{K\Lambda R}}{M_K}\frac{p_K^{\alpha}\Gamma_s}{s-M_R^2+iM_R\Gamma_R}\bar{u}(\vec{p}\,')P^{3/2}_{\alpha\beta}(p_R)\Gamma^{\beta\mu}_{\frac{3}{2}\pm}(p,q)u(\vec{p}\,), p_R = p+q,$$

where $\Gamma_s = 1(\gamma_5)$ for positive (negative) parity resonances, $g_{K\Lambda R}$ is the coupling strength for $R \to K\Lambda$, where R, determined from partial decay widths. M_R is the mass of the resonance and Γ_R is its decay width.

Resonances	M_R [GeV]	J	I	P	Γ (GeV)	G	G_K^v	G_K^t
Λ^* (1405)	$1.405\pm^{0.0013}_{0.001}$	$1/2$	0	$-$	0.0505 ± 0.002	-10.18	-	-
Λ^* (1800)	$1.800\pm^{0.080}_{0.050}$	$1/2$	0	$-$	0.300 ± 0.100	-4.0	-	-
$K^*(892)$	0.89166 ± 0.00026	1	$1/2$	$-$	0.0508 ± 0.0009	-	-0.18	0.02
$K_1(1270)$	1.272 ± 0.007	1	$1/2$	$+$	0.090 ± 0.020	-	0.28	-0.28

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The values of G, G_K^V and G_K^t are fitted to the experimental data and contains both the electromagnetic and strong coupling strengths.

The hadronic current for the Λ^* resonance exchange may be written as

$$J_\mu\big|_{\Lambda^{*\pm}} = ie\bar{u}(p')\frac{G}{M_\Lambda + M_{\Lambda^*}}\sigma_{\mu\nu}q^\nu\Gamma_5\left(\frac{\not{p}' - \not{q} + M_{\Lambda^*}}{u - M_{\Lambda^*}^2 + iM_{\Lambda^*}\Gamma_{\Lambda^*}}\right)\not{p}_k\gamma_5\Gamma u(p)$$

with $G = \kappa_{\Lambda\Lambda^*}g_{pK\Lambda^*}/f_\pi$, M_{Λ^*} and Γ_{Λ^*} being the mass and the decay width of Λ^*.

The hadronic current for the K^* exchange is obtained as

$$J_\mu\big|_{K^*} = ie\bar{u}(p')\varepsilon_{\mu\nu\rho\sigma}q^\rho(p'-p)^\sigma\left(\frac{-g^{\nu\alpha} + (p-p')^\nu(p-p')^\alpha/M_{K^*}^2}{t - M_{K^*}^2 + iM_{K^*}\Gamma_{K^*}}\right)\left[G_{K^*}^v\gamma_\alpha + \frac{G_{K^*}^t}{M + M_\Lambda}(\not{p}' - \not{p})\gamma_\alpha\right]u(p),$$

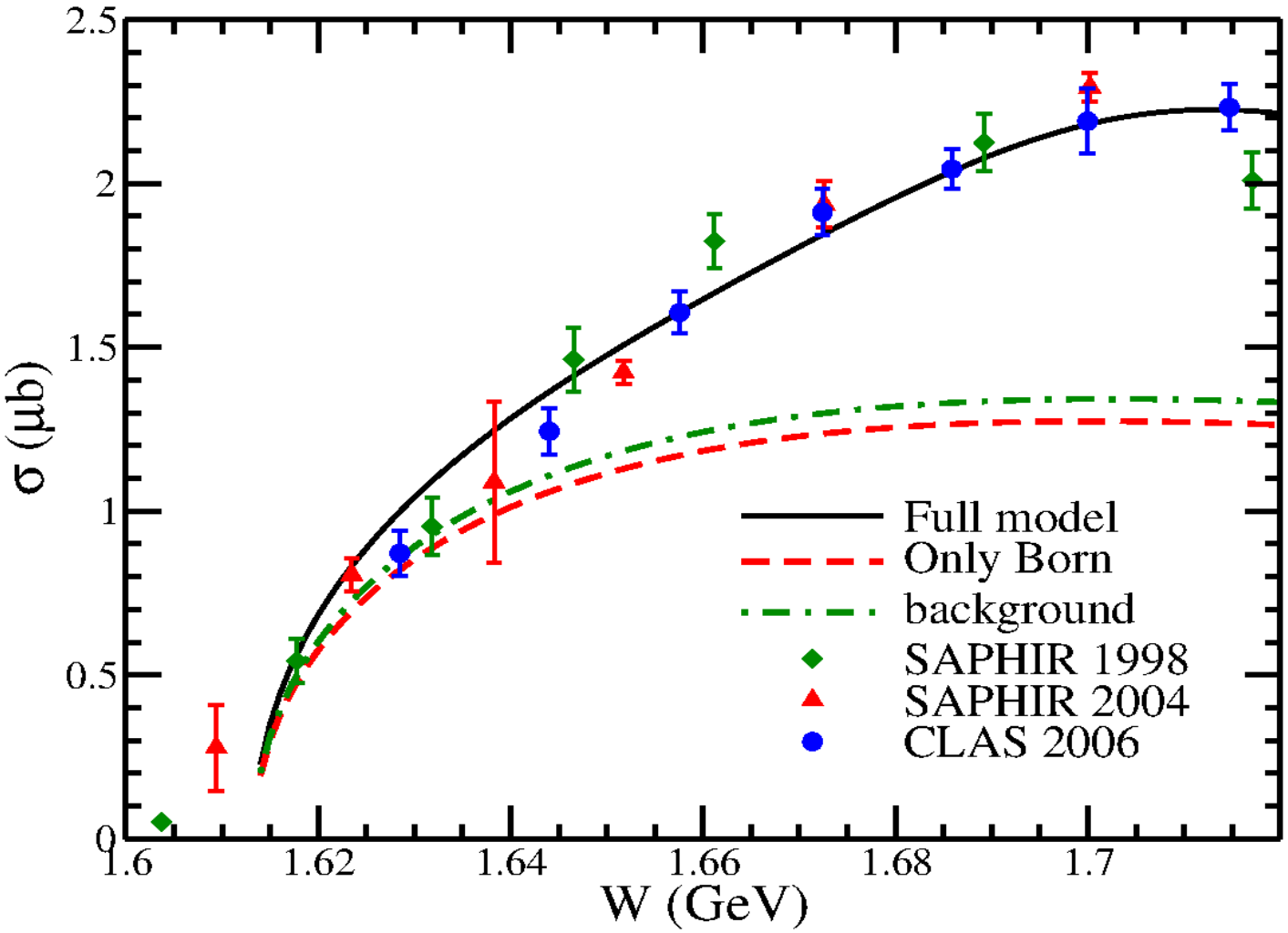
with $G_{K^*}^v = \kappa_{KK^*}g_{K^*\Lambda p}^v/\mu$ and $G_{K^*}^t = \kappa_{KK^*}g_{K^*\Lambda p}^t/\mu$. M_{K^*} and Γ_{K^*} are the mass and width of the K^* resonance,

The hadronic current for the pseudovector kaon K_1 exchange in the t-channel as

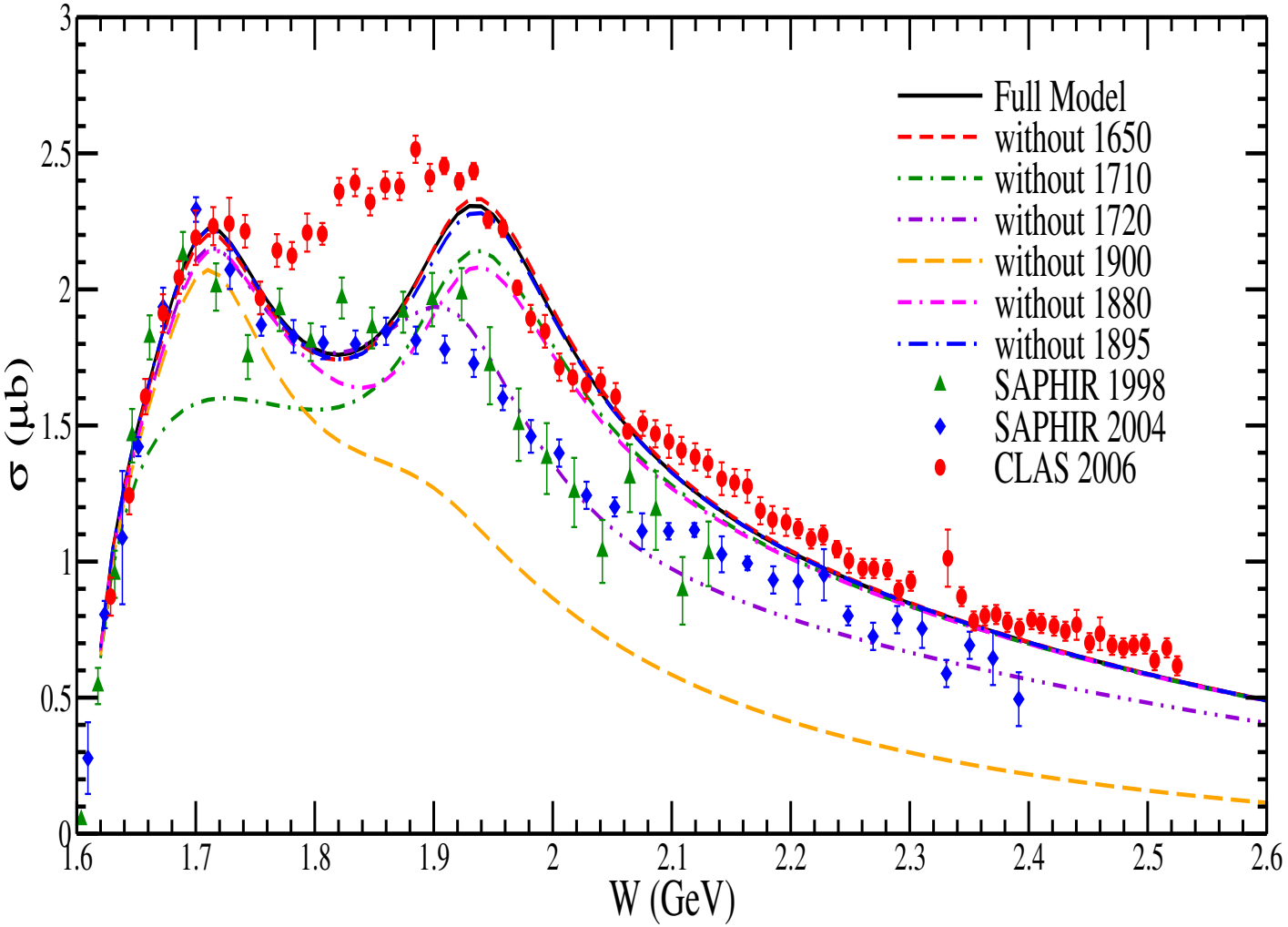
$$
\begin{aligned}
J_\mu\big|_{K_1} &= ie\bar{u}(p')[g_{\alpha\mu}q\cdot(p-p')-q_\alpha(p-p')_\mu] \\
&\times \left(\frac{-g^{\alpha\rho}+(p-p')^\alpha(p-p')^\rho/M_{K_1}^2}{t-M_{K_1}^2+iM_{K_1}\Gamma_{K_1}}\right) \\
&\times \left[G_{K_1}^v\gamma_\rho\gamma_5+\frac{G_{K_1}^t}{M+M_\Lambda}(\not{p}'-\not{p})\gamma_\rho\gamma_5\right]u(p),
\end{aligned}
$$

with $G_{K_1}^v=\kappa_{KK^*}g_{K_1\Lambda p}^v/\mu$ and $G_{K_1}^t=\kappa_{KK^*}g_{K_1\Lambda p}^t/\mu$. M_{K_1} and Γ_{K_1} are the mass and width of the K_1 resonance, respectively.

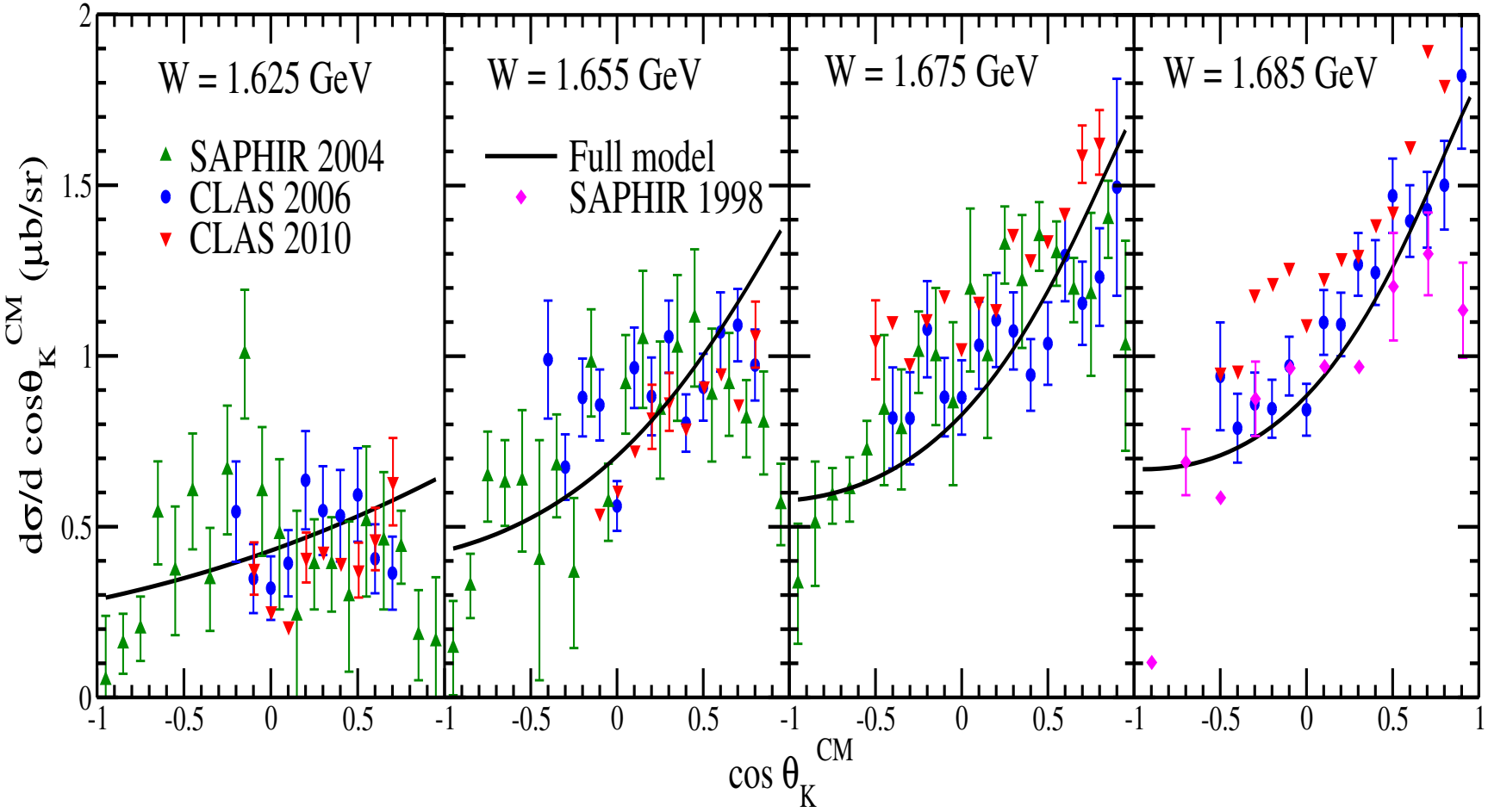
σ vs. W for the process $\gamma + p \longrightarrow K^+ + \Lambda$



σ vs. W for the process $\gamma + p \longrightarrow K^+ + \Lambda$: *PRD in submission*



$\frac{d\sigma}{d\cos\theta_K^{CM}}$ *vs.* $\cos\theta_K^{CM}$ *for the process* $\gamma + p \longrightarrow K^+ + \Lambda$ *PRD in submission*



Hyperon production

$$\bar{\nu}_l(k) + N(p) \longrightarrow l^+(k') + Y(p')$$

$$V^{\mu}_{B'B}(p',p) = f_1^{B'B}(Q^2)\gamma_\mu + \frac{i\sigma^{\mu\nu}q_\nu}{M_B+M'_B} f_2^{B'B}(Q^2) + \frac{2q_\mu}{M_B+M'_B} f_3^{B'B}(Q^2)$$

$$A^{\mu}_{B'B}(p',p) = g_1^{B'B}(Q^2)\gamma_\mu\gamma_5 + i\sigma_{\mu\nu}\gamma_5 \frac{q^\nu}{M_B+M'_B} g_2^{B'B}(Q^2) + \frac{2q^\mu}{M_B+M'_B}\gamma_5 g_3^{B'B}(Q^2)$$

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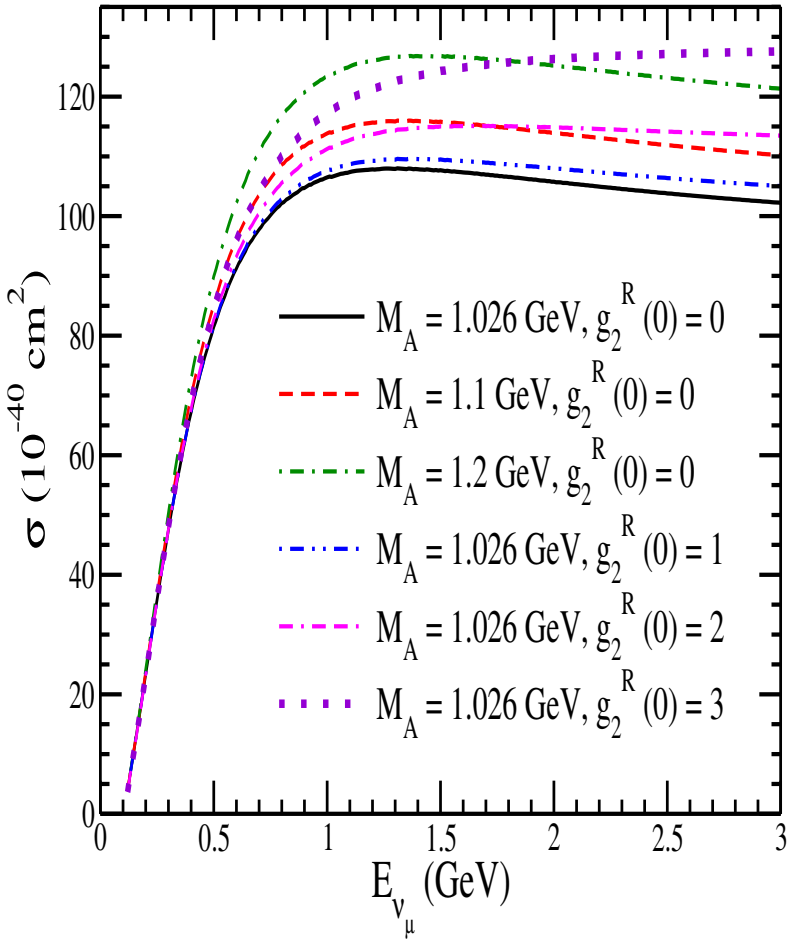
Vector FF **Magnetic FF** **Scalar FF**

$$A^{\mu}_{B'B}(p',p) = g_1^{B'B}(Q^2)\gamma_\mu\gamma_5 + i\sigma_{\mu\nu}\gamma_5 \frac{q^\nu}{M_B+M'_B} g_2^{B'B}(Q^2) + \frac{2q^\mu}{M_B+M'_B}\gamma_5 g_3^{B'B}(Q^2)$$

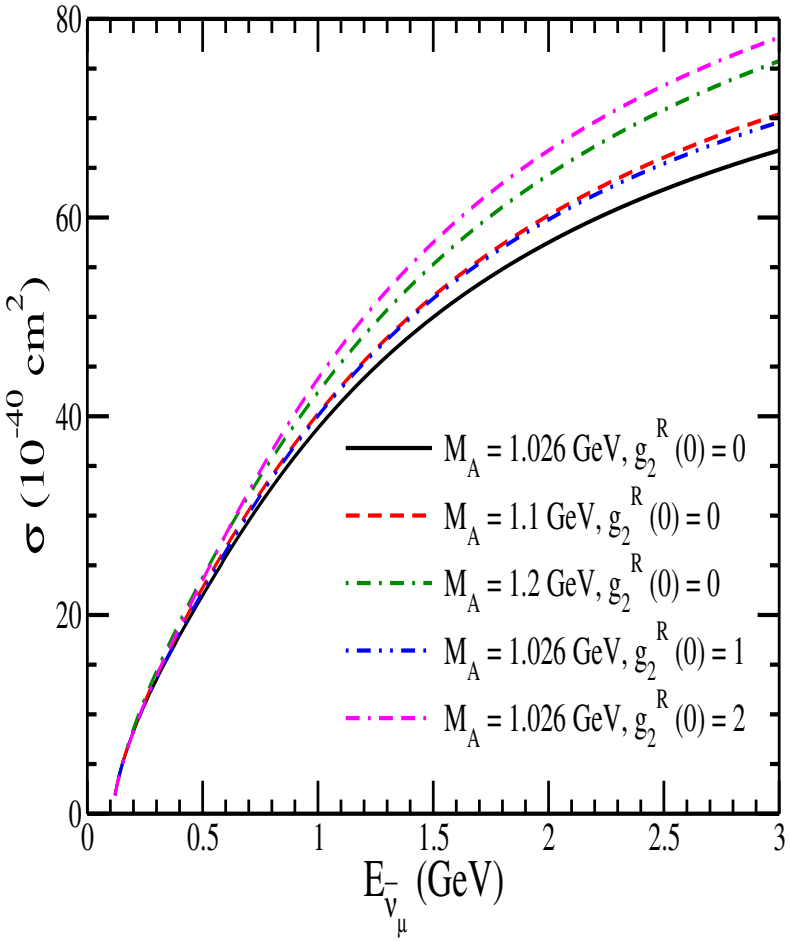
Axial vector FF **Electric FF** **Pseudoscalar FF**

σ vs $E_{\bar{\nu}_\mu}$: *Phys. Rev. D. 98, 033005 (2018)*

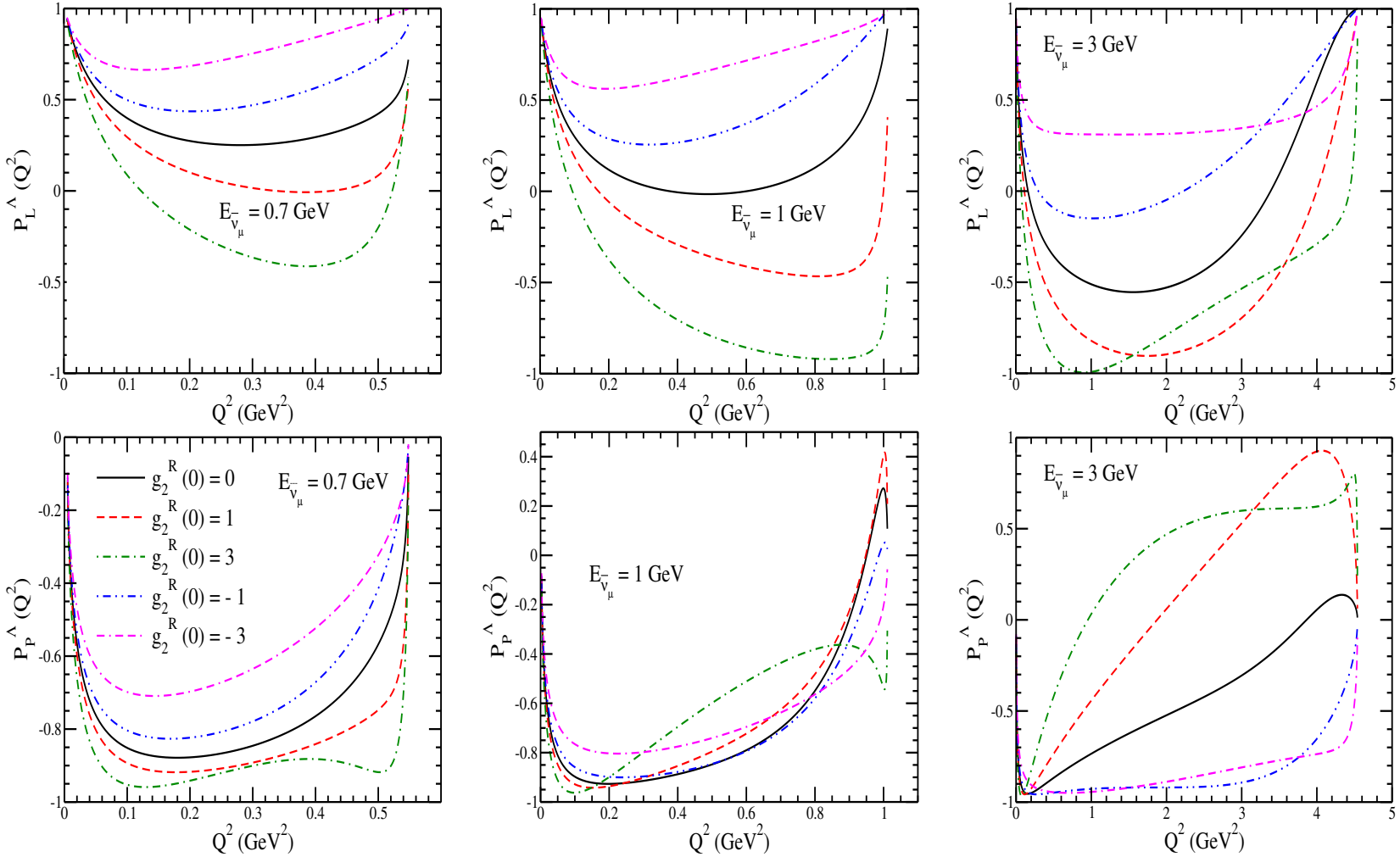
$\nu_\mu + n \longrightarrow \mu^- + p$



$\bar{\nu}_\mu + p \longrightarrow \mu^+ + n$



Polarization components vs Q^2 for the process $\bar{\nu}_\mu + p \longrightarrow \mu^+ + \Lambda$: *Front. in Phys. 7, 13 (2019)*



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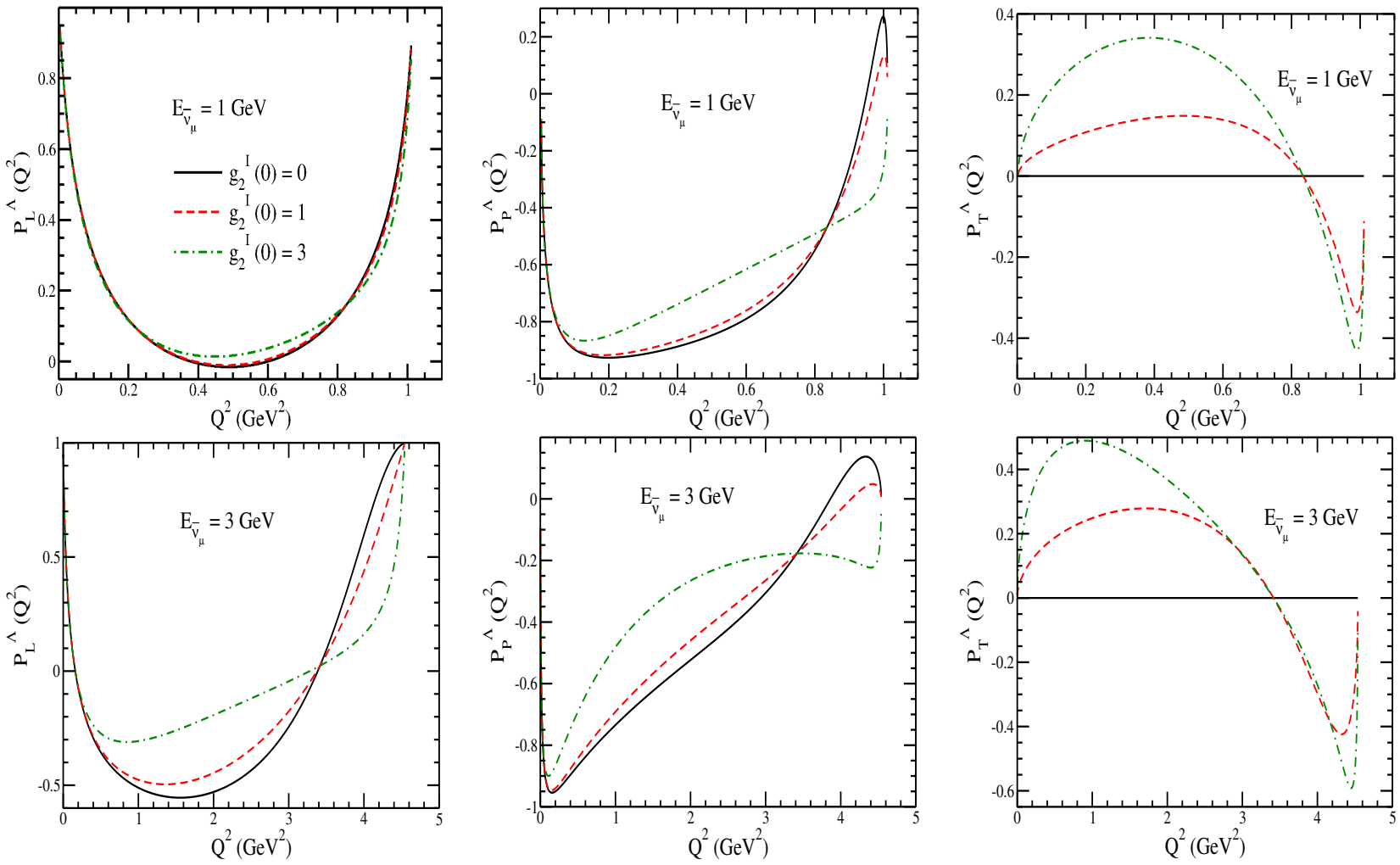
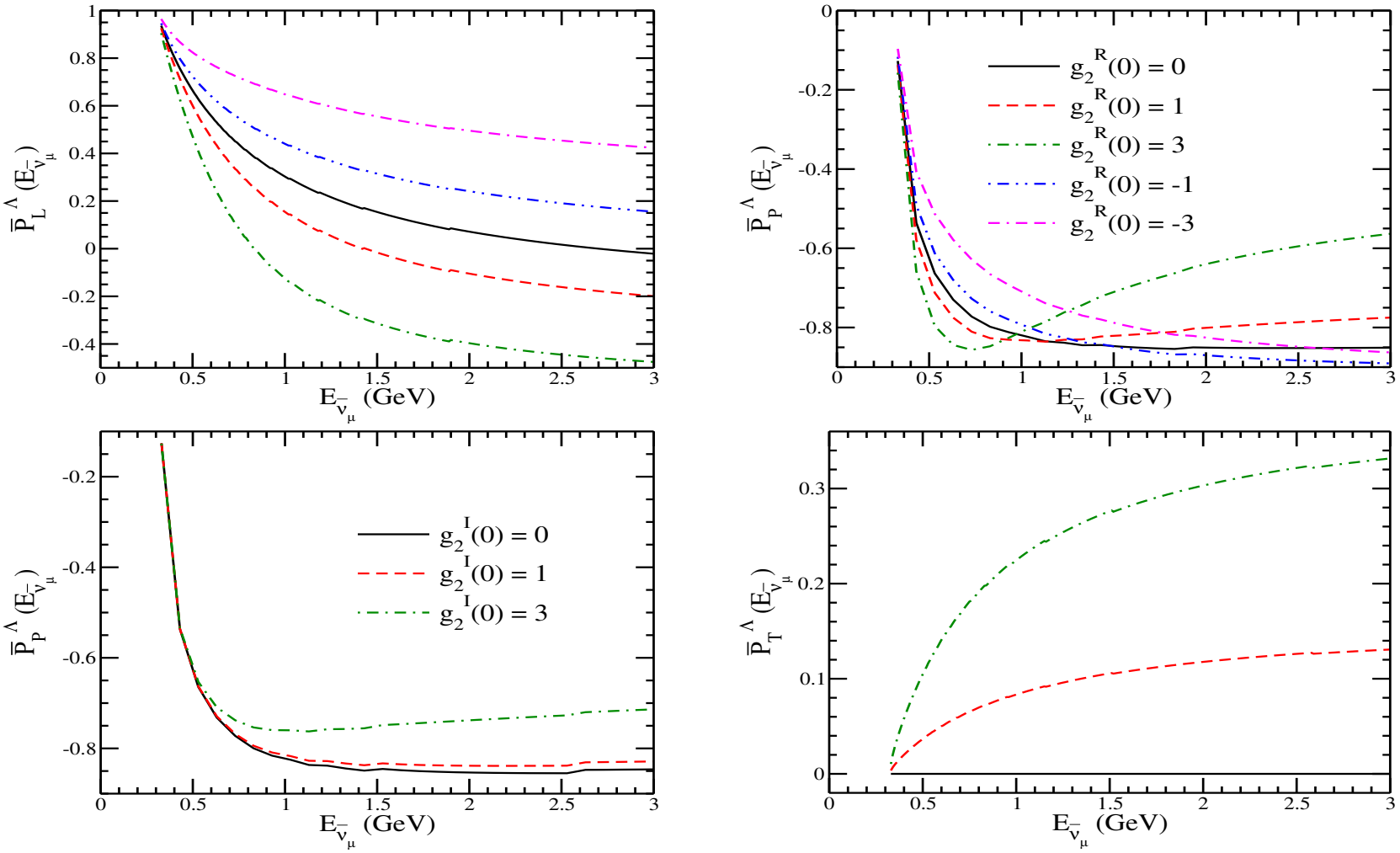


Polarization components vs $E_{\bar{\nu}_\mu}$ for the process $\bar{\nu}_\mu + p \longrightarrow \mu^+ + \Lambda$: *Phys. Rev. D. 98, 033005 (2018)*



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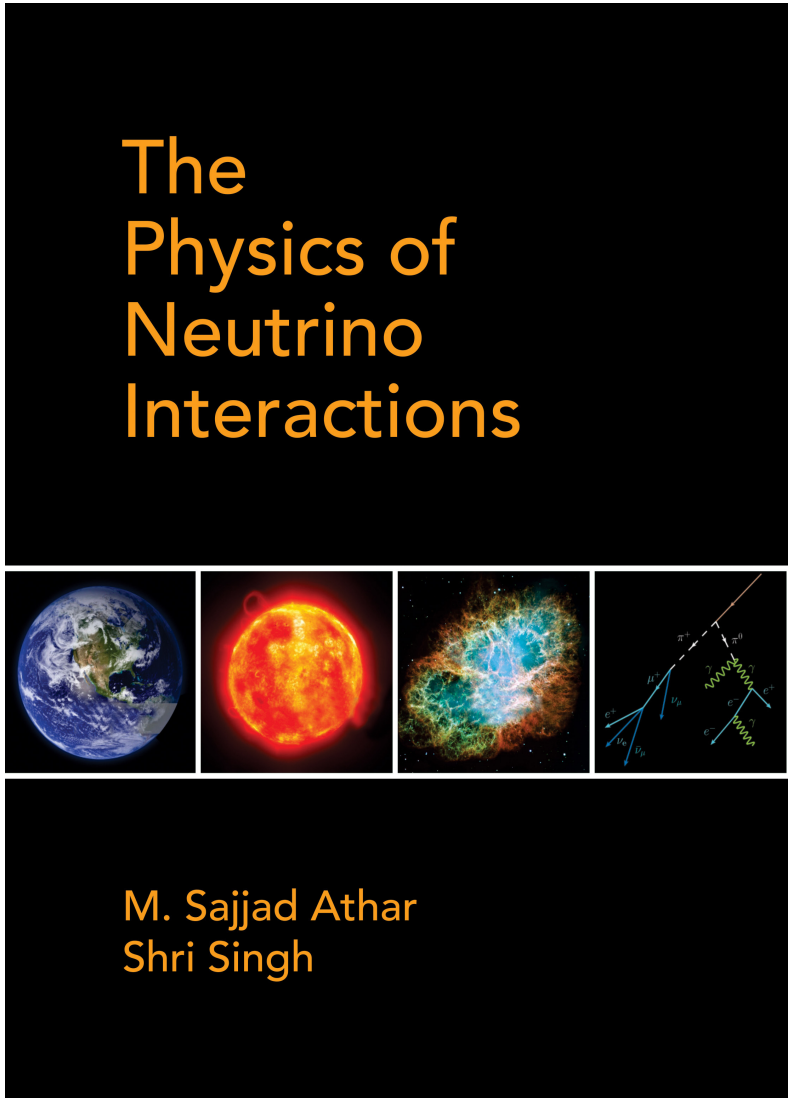

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