The Coh-γ channel: a NuSTEC project

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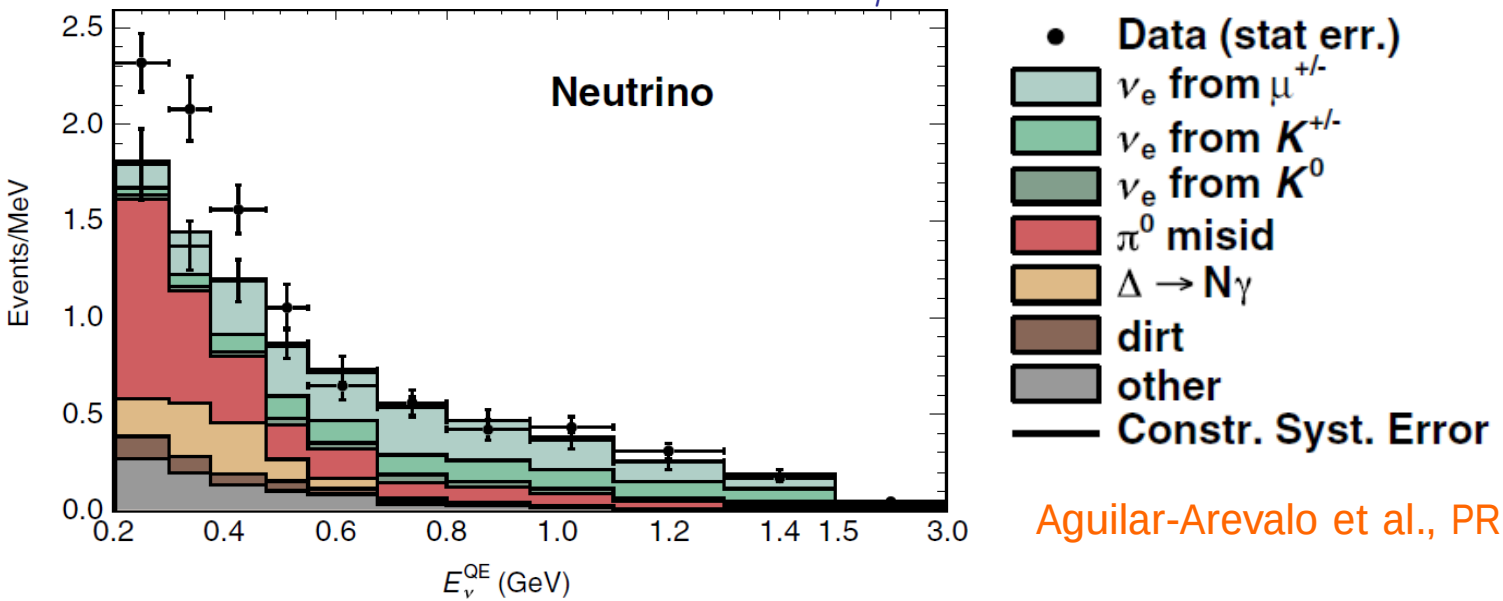
+
S. Dytman (GENIE), J. Morfin (MINERvA),
M. Roda (GENIE), K. Sutton (MicroBooNE),...

Introduction

- Single Photon emission in NC interactions:
  - Important background for $\nu_\mu \to \nu_e$ studies (θ_{13} , δ) if γ is misidentified as $e^\pm$ from CCQE $\nu_e\, n \to e^-\, p$ or $\bar{\nu}_e\, p \to e^+\, n$
- e-like events in the MiniBooNE $\nu_\mu \to \nu_e$ search:



Aguilar-Arevalo et al., PRL110 (2013) 161801

- Unexplained excess of events at 200 < E_ν^{QE} < 475 MeV
  - NC $\Delta \to N\,\gamma \leftarrow$ 2nd largest background after NC π^o production
- Ongoing MicroBooNE analysis: Public note 1041,

http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1041-PUB.pdf

Introduction

- Single Photon emission in NC interactions:
- on nucleons $\nu(\bar{\nu})\, N \rightarrow \nu(\bar{\nu})\, \gamma\, N$
- on nuclei $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, X \leftarrow$ incoherent

  $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, A \leftarrow$ coherent

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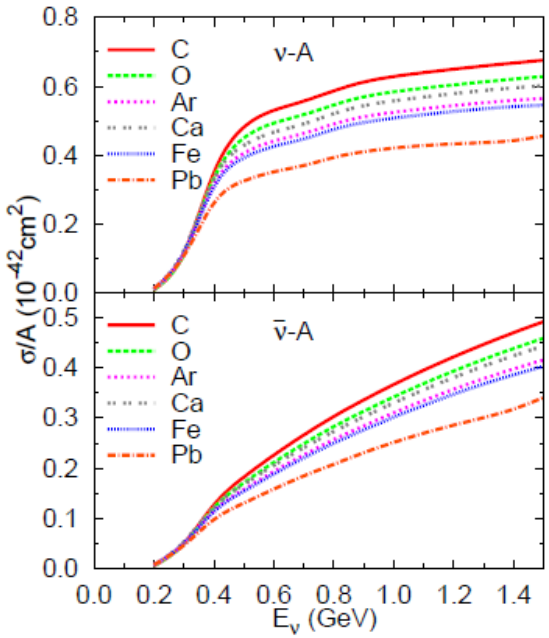
- $\boxed{\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, A}$ ← coherent
  - small cross section

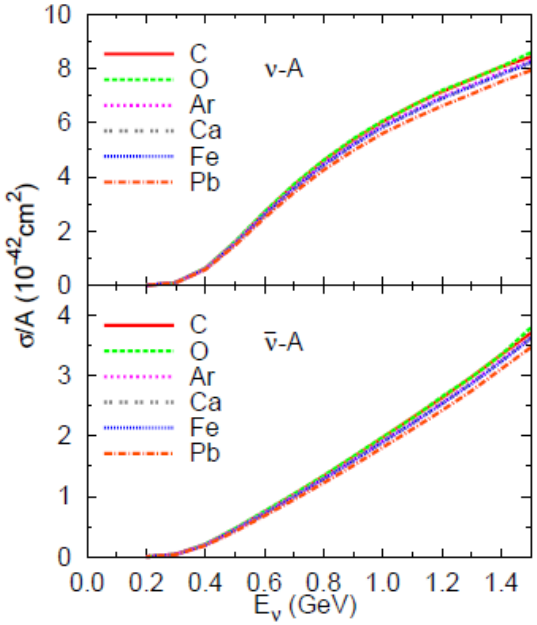
In GENIE:

$\Delta \rightarrow$ N γ decay

+ global Fermi gas

not available





E. Wang, LAR, J. Nieves, PRC 89 (2014) 015503

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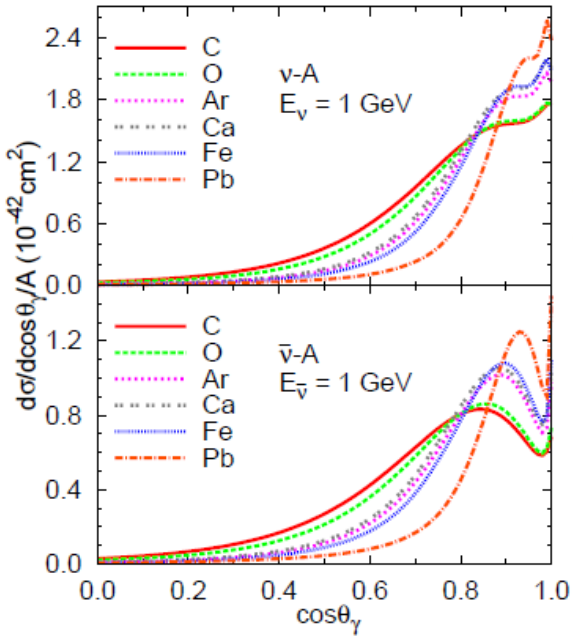

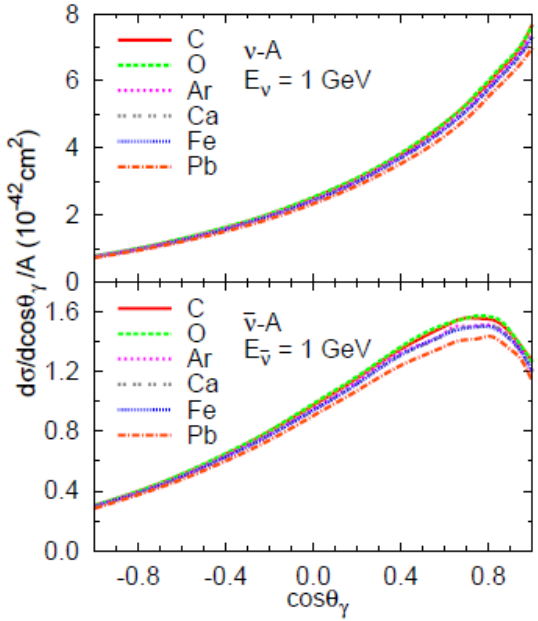

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  - $\boxed{\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, A}$ ← coherent
  - small cross section but forward peaked
  - possible background for ν-e measurements
  - possible background for BSM processes (with light mediators)
  - potential signal at MINERvA (for E_ν > 800 MeV)

In GENIE:

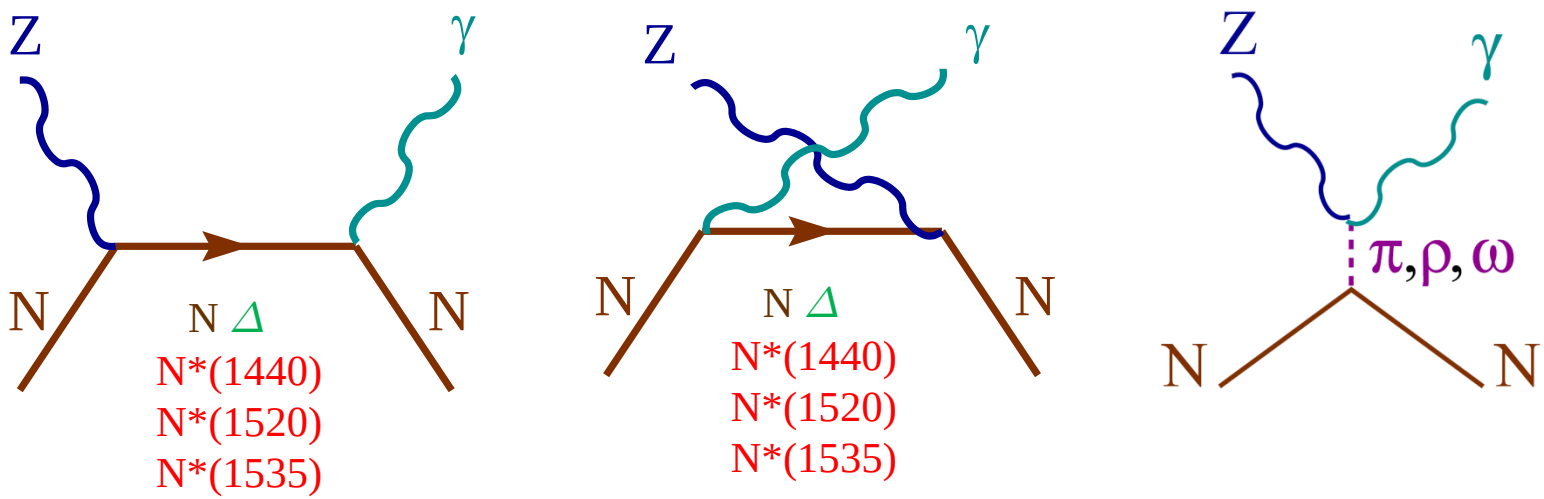
$\Delta \rightarrow$ N γ decay

+ global Fermi gas

not available

The model

- Feynman diagrams:

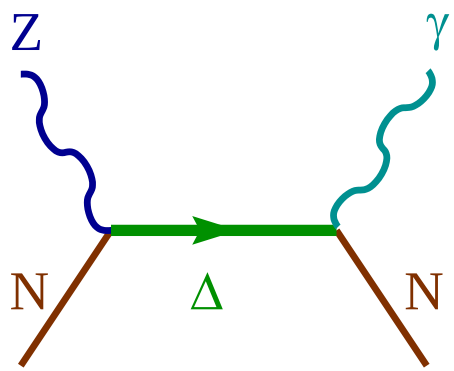


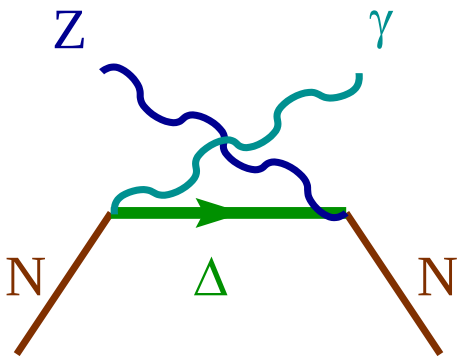
R. Hill, PRD 81 (2010)
Zhang & Serot, PRC 86 (2012)
Wang, LAR, Nieves, PRC 89 (2014)

The model

$$\mathcal{M}_r = \frac{G_F\, e}{\sqrt{2}}\, \epsilon_\mu^{*(r)}\, \bar{u}(p')\Gamma^{\mu\alpha} u(p) l_\alpha$$

- $\Delta(1232)$ pole terms:





$$\Gamma^{\mu\alpha} = \hat{J}^{\delta\mu}_{\rm EM}(p', q_\gamma) D^{\Delta}_{\delta\sigma}(p+q) J^{\sigma\alpha}_{\rm NC}(p,q) + \hat{J}^{\delta\alpha}_{\rm NC}(p', -q) D^{\Delta}_{\delta\sigma}(q_\gamma - p) J^{\sigma\mu}_{\rm EM}(p', -q_\gamma)$$

$$J^{\beta\mu}_{\rm NC}(p,q) = \left[\frac{\tilde{C}_3^V(q^2)}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{\tilde{C}_4^V(q^2)}{M^2}(g^{\beta\mu} q\cdot p_\Delta - q^\beta p_\Delta^\mu) + \frac{\tilde{C}_5^V(q^2)}{M^2}(g^{\beta\mu} q\cdot p - q^\beta p^\mu)\right]\gamma_5$$
$$+ \frac{\tilde{C}_3^A(q^2)}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{\tilde{C}_4^A(q^2)}{M^2}(g^{\beta\mu} q\cdot p_\Delta - q^\beta p_\Delta^\mu) + \tilde{C}_5^A(q^2) g^{\beta\mu}$$

$$J^{\beta\mu}_{\rm EM}(p,q_\gamma) = \left[\frac{C_3^{(p,n)}(0)}{M}(g^{\beta\mu}\not{q}_\gamma - q_\gamma^\beta\gamma^\mu) + \frac{C_4^{(p,n)}(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p_\Delta - q_\gamma^\beta p_\Delta^\mu) + \frac{C_5^{(p,n)}(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p - q_\gamma^\beta p^\mu)\right]\gamma_5$$

Coherent NCγ

- $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, A$

- Microscopic description:
  - Same NCγ mechanisms as in $\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N$ $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$
  - Nuclear corrections: $\Gamma_\Delta \to \tilde{\Gamma}_\Delta(\rho) - 2\,\mathrm{Im}\Sigma_\Delta(\rho)$
  - Coherent sum over all nucleons

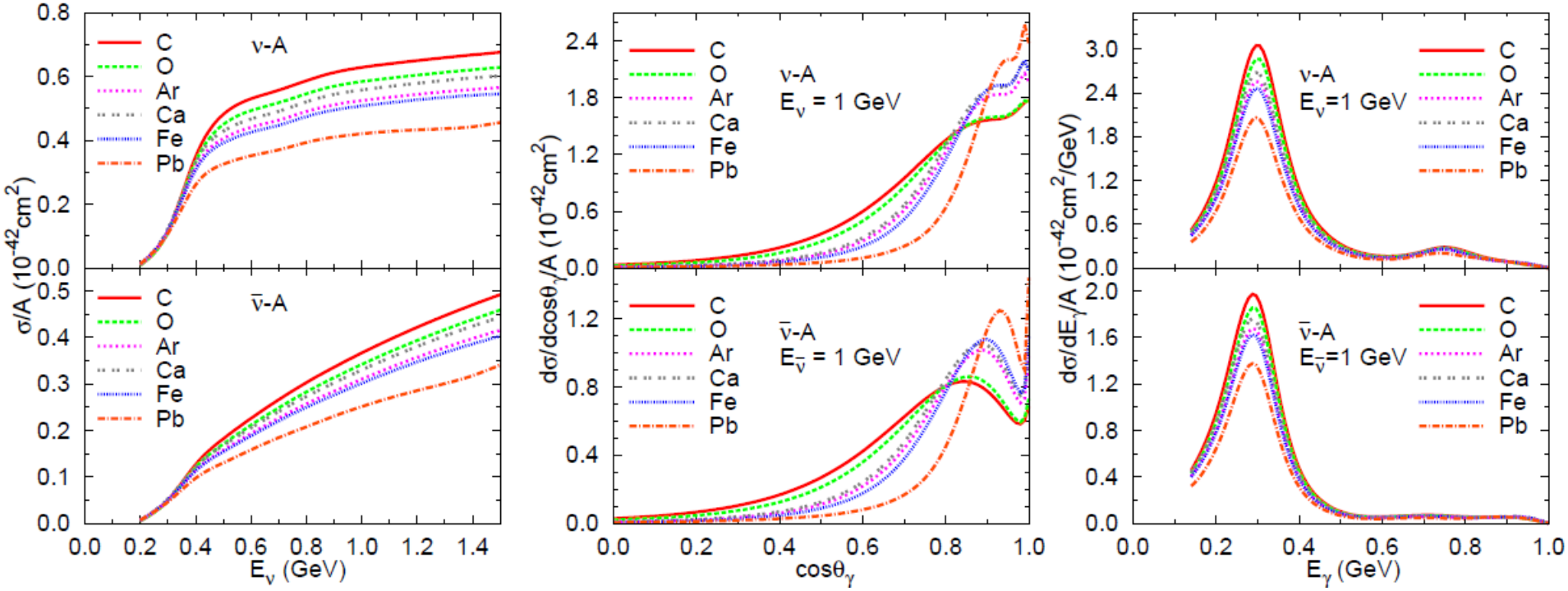
$$\mathcal{M}_r = \frac{G_F\, e}{\sqrt{2}}\, \epsilon_\mu^{*(r)}\, \bar{u}(p')\mathcal{A}^{\mu\alpha} u(p) l_\alpha$$

$$\mathcal{A}^{\mu\alpha} = \sum_{N=p,n} \int d\vec{r}\, e^{i(\vec{q}-\vec{q}_\gamma)\cdot\vec{r}} \rho_N(r) \hat{\Gamma}_N^{\mu\alpha}(\rho(r))$$

$$\hat{\Gamma}_r^{\mu\alpha} = \frac{1}{2} \sum_i \mathrm{Tr}\left[\bar{u}\, \Gamma_{i(r)}^\mu\, u\right]$$ ← sum over all mechanisms

Results

- $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, A$



E. Wang, LAR, J. Nieves, PRC 89 (2014) 015503

- Peak position:

$$E_\gamma \approx \frac{M_{\rm Res}^2 - m_N^2}{2m_N}$$

New developments

- LAR & E. Saúl Sala
- Part of the work performed during Eduardo's 6 week stay @ Fermilab
  - Financed by CSIC, MINERvA and Fermilab Theory Division

1. Original model optimized and simplified to make its implementation in GENIE feasible
2. Extension to higher E_γ (for MINERvA)
3. Implementation in GENIE

New developments

1. Original model optimized and simplified to make its implementation in GENIE feasible

$$\mathrm{Im}\Sigma_\Delta(\rho) \approx V_0 \frac{\rho(r)}{\rho(0)}$$ ← independent of kinematics

$$\tilde{\Gamma}_\Delta(\rho) - 2\,\mathrm{Im}\Sigma_\Delta(\rho) \approx \tilde{\Gamma}_\Delta(\rho_{\mathrm{ave}}) - 2\,\mathrm{Im}\Sigma_\Delta(\rho_{\mathrm{ave}}) \qquad \rho_{\mathrm{ave}} = \frac{A}{\frac{4}{3}\pi R^3}$$

$$\int d\vec{r}\, e^{i(\vec{q}-\vec{q}_\gamma)\cdot\vec{r}} \rho_N(r) \hat{\Gamma}_N^{\mu\alpha}(r) \approx \hat{\Gamma}_N^{\mu\alpha}(\rho_{\mathrm{ave}}) F_N(q^2)$$

- There are analytic expressions for the nuclear form factors $F_N(q^2)$
- Hadronic transiton currents were simplified by keeping the most important terms to calculate

$$\hat{\Gamma}_r^{\mu\alpha} = \frac{1}{2}\sum_i \mathrm{Tr}\left[\bar{u}\,\Gamma^\mu_{i(r)}\,u\right]$$

analytically (Mathematica): matrix multiplication + Tr -> (long) polynomials

New developments

2. Extension to higher E_γ (for MINERvA)

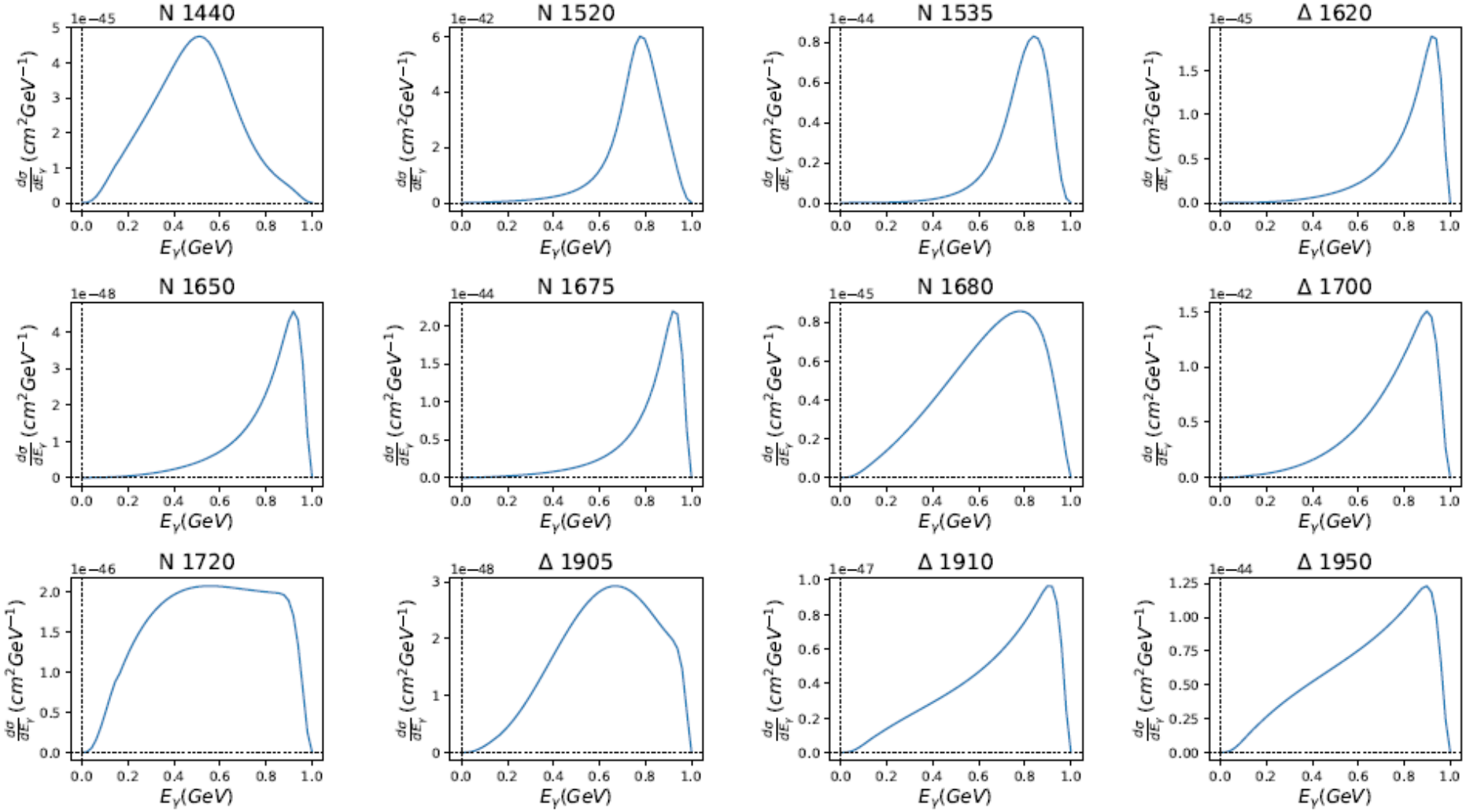
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\gamma$
$N(939)$	P_{11}			
$N(1440)$	P_{11}	****	****	***
$N(1520)$	D_{13}	****	****	****
$N(1535)$	S_{11}	****	****	***
$N(1650)$	S_{11}	****	****	***
$N(1675)$	D_{15}	****	****	****
$N(1680)$	F_{15}	****	****	****
$N(1700)$	D_{13}	***	***	**
$N(1710)$	P_{11}	***	***	***
$N(1720)$	P_{13}	****	****	**
$\Delta(1232)$	P_{33}	****	****	****
$\Delta(1600)$	P_{33}	***	***	**
$\Delta(1620)$	S_{31}	****	****	***
$\Delta(1700)$	D_{33}	****	****	***
$\Delta(1905)$	F_{35}	****	****	***
$\Delta(1910)$	P_{31}	****	****	*
$\Delta(1920)$	P_{33}	***	***	*
$\Delta(1930)$	D_{35}	***	***	**
$\Delta(1950)$	F_{37}	****	****	****

Tiator et al., Eur.Phys.J.ST 198 (2011)

New developments

2. Extension to higher E_γ (for MINERvA)

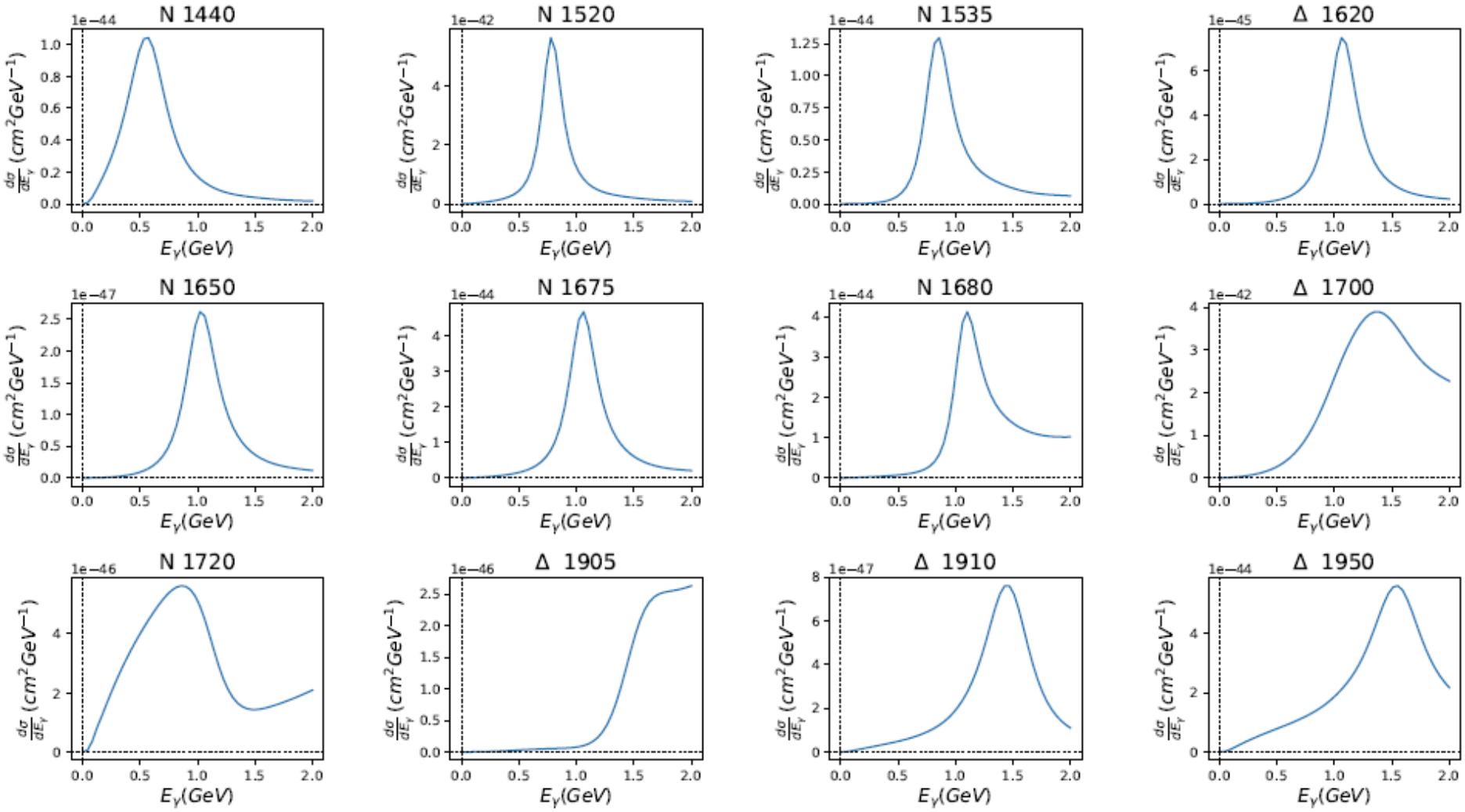
- Some preliminary results: $E_\nu = 1$ GeV on ^{12}C



New developments

2. Extension to higher E_γ (for MINERvA)

- Some preliminary results: $E_\nu = 10$ GeV on ^{12}C



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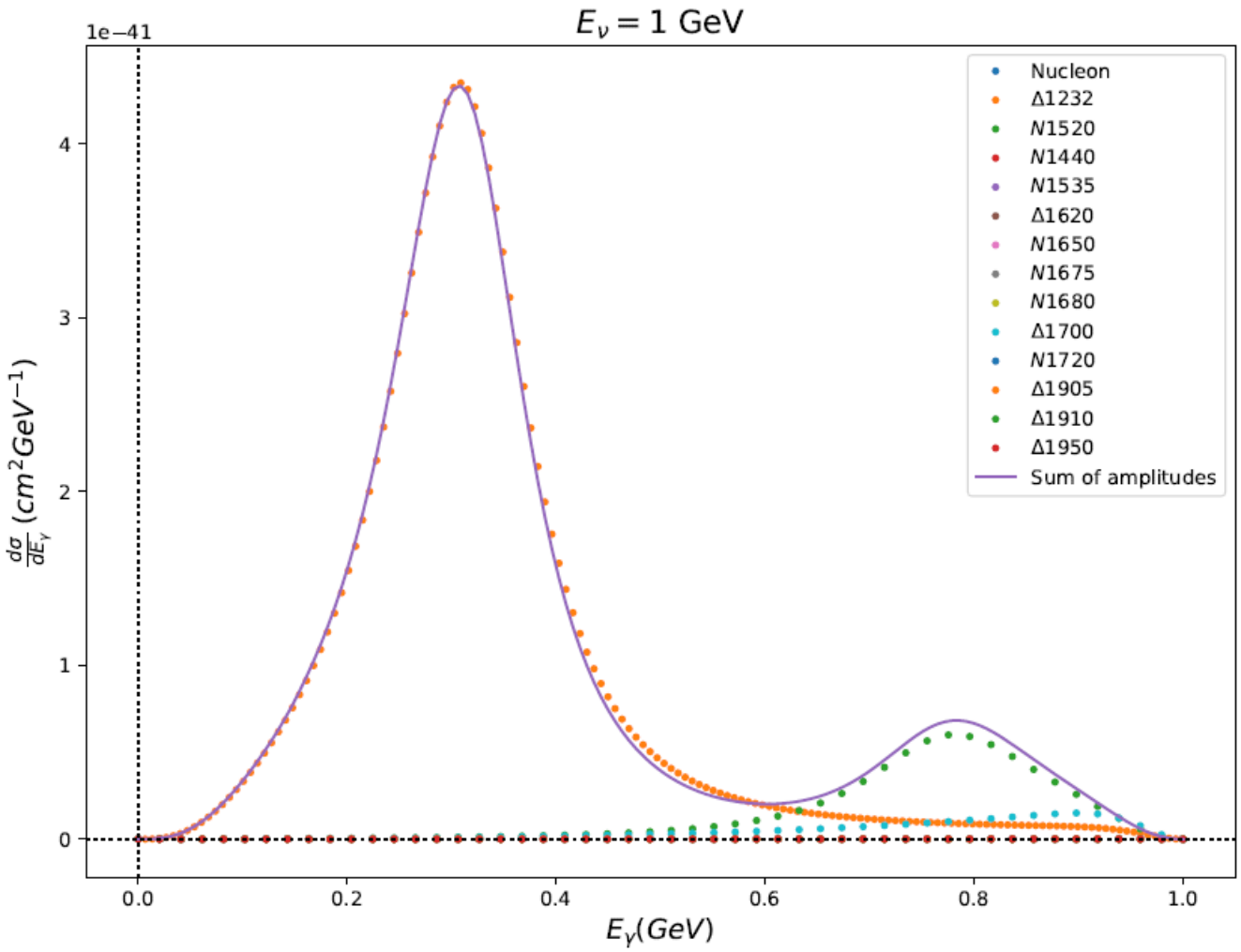

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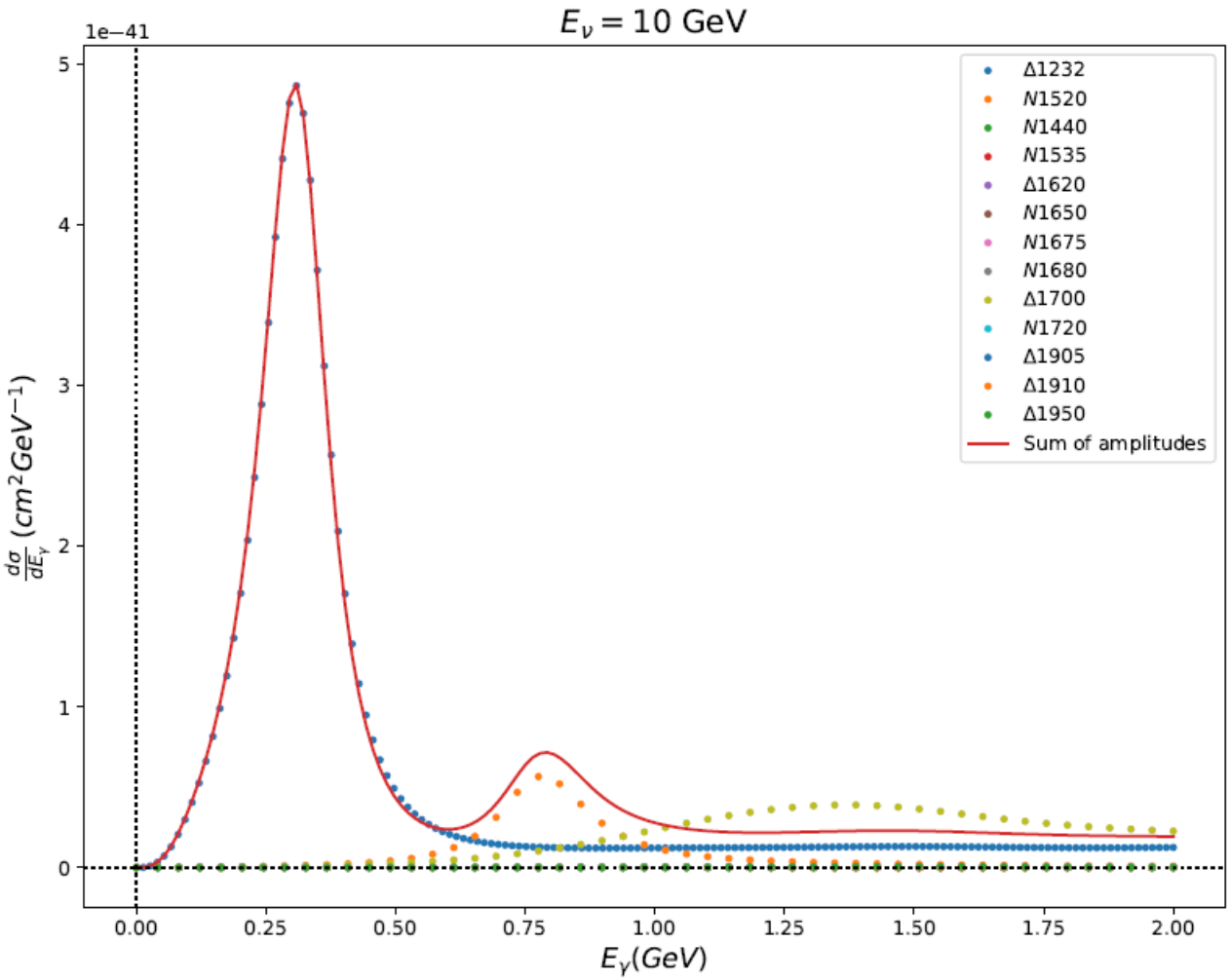

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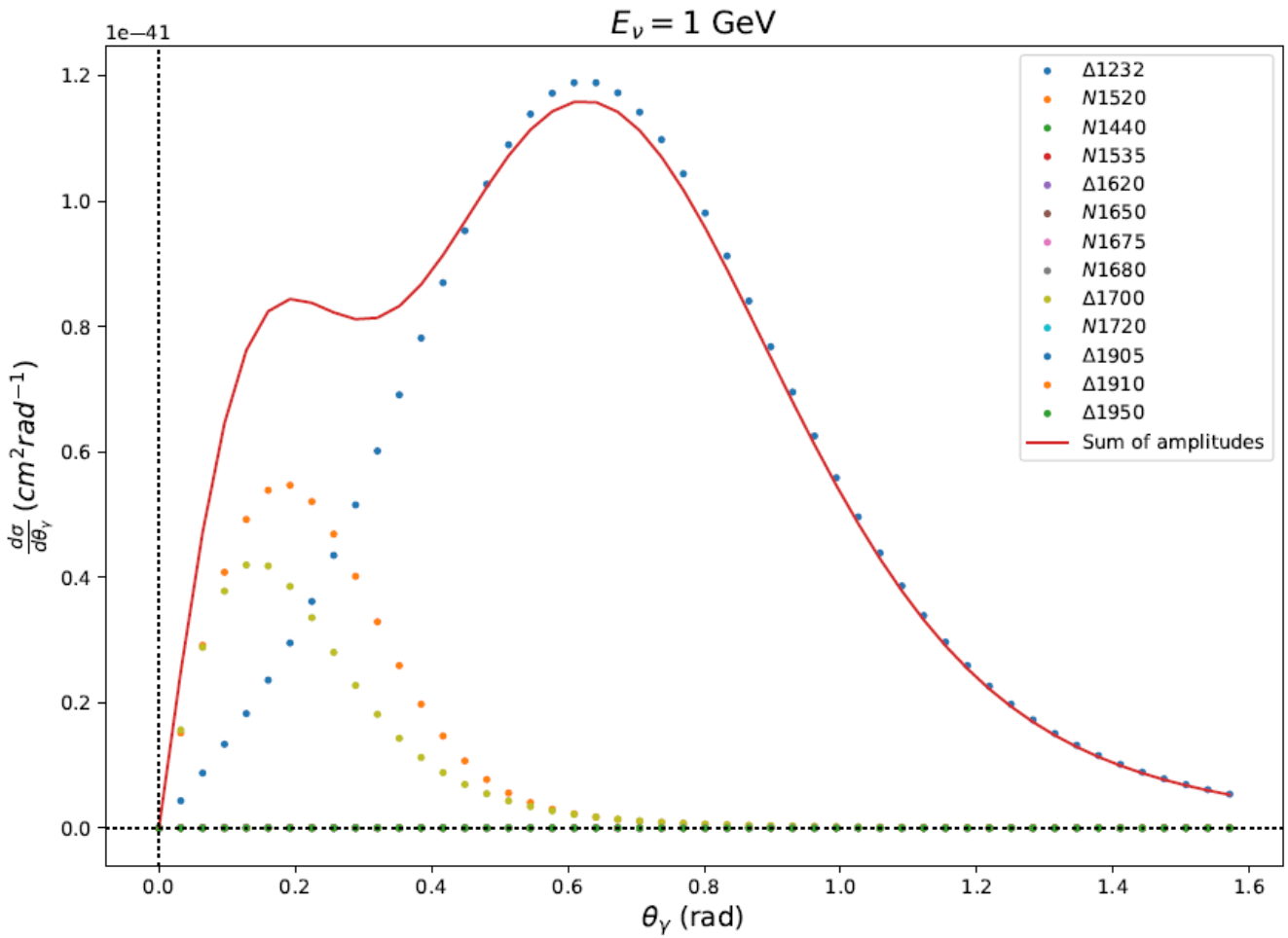

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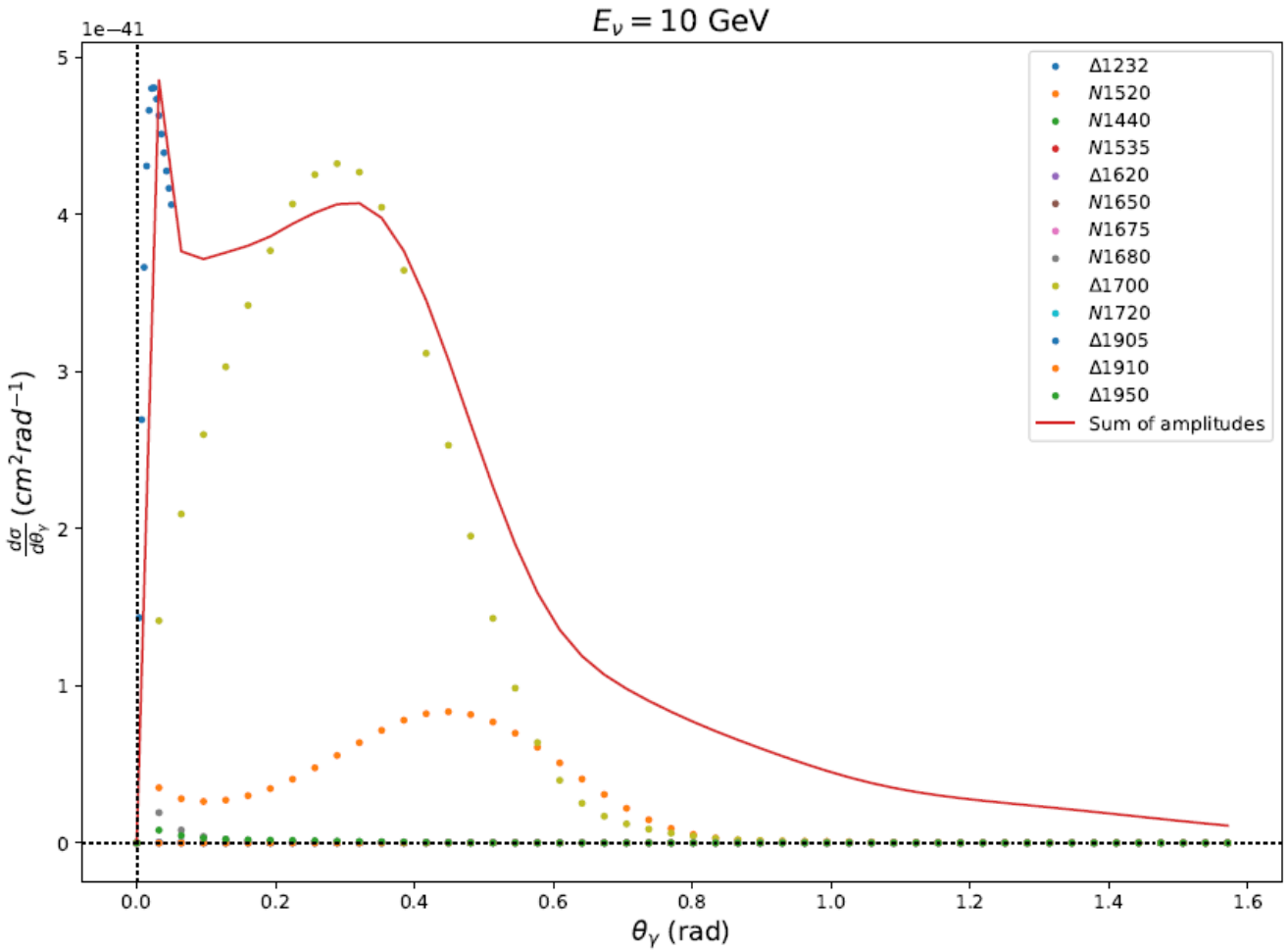
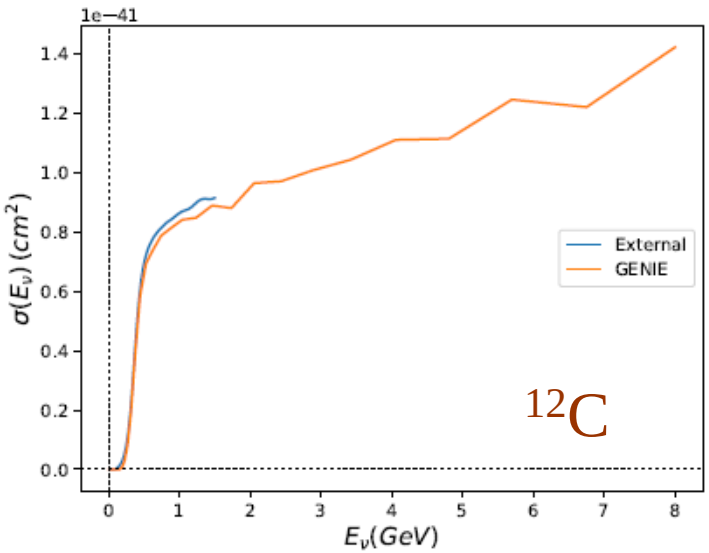
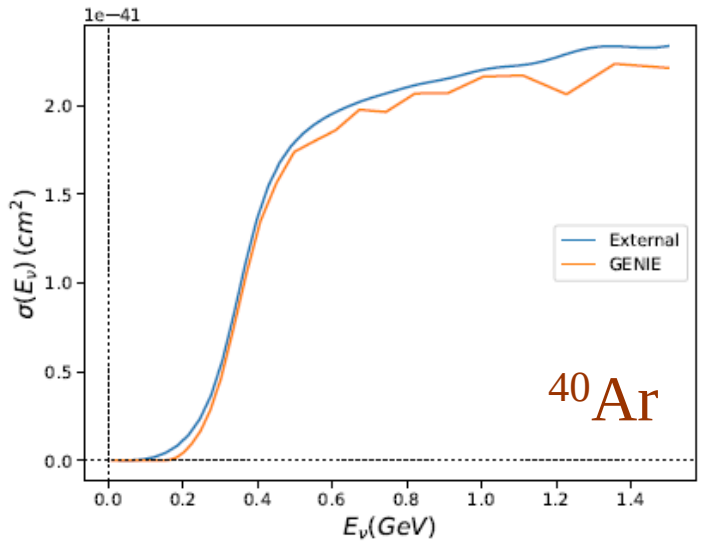


New developments

3. Implementation in GENIE
   - Incubator project
   - Cross section code written by Eduardo and implemented with Steve D.'s help
   - Cross section validation with external code:





   - Code being re-written by Marco Roda for proper integration in GENIE
   - Kathryn Sutton (MicroBooNE): event generation. Can be challenging

Summary

Coherent NCγ

1. Original model optimized and simplified to make its implementation in GENIE feasible
2. Extension to higher E_γ (for MINERvA)
3. Implementation in GENIE

- Reaction dominated by $\Delta(1232)$ excitation but other resonances
- Theoretical error dominated by Res properties
- Interesting and/or potentially relevant for T2K, MicroBooNE, MINERvA

Nuclear effects

- $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, X$
- In-medium modification of the $\Delta(1232)$ resonance
  - In $\dfrac{1}{p^2 - m_\Delta^2 + i m_\Delta \Gamma_\Delta(p^2)}$

replace

$$M_\Delta \rightarrow M_\Delta + \mathrm{Re}\Sigma_\Delta(\rho)$$

$$\frac{\Gamma_\Delta}{2} \rightarrow \frac{\tilde{\Gamma}_\Delta(\rho)}{2} - \mathrm{Im}\Sigma_\Delta(\rho)$$

$\tilde{\Gamma}_\Delta \leftarrow$ Free width $\Delta \rightarrow$ N π modified by Pauli blocking

$$\mathrm{Re}\Sigma_\Delta(\rho) \approx 0$$

$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$ many-body processes:

- Δ N $\rightarrow$ N N
- Δ N $\rightarrow$ N N π
- Δ N N $\rightarrow$ N N N