Glashow Resonometer

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Glashow resonance

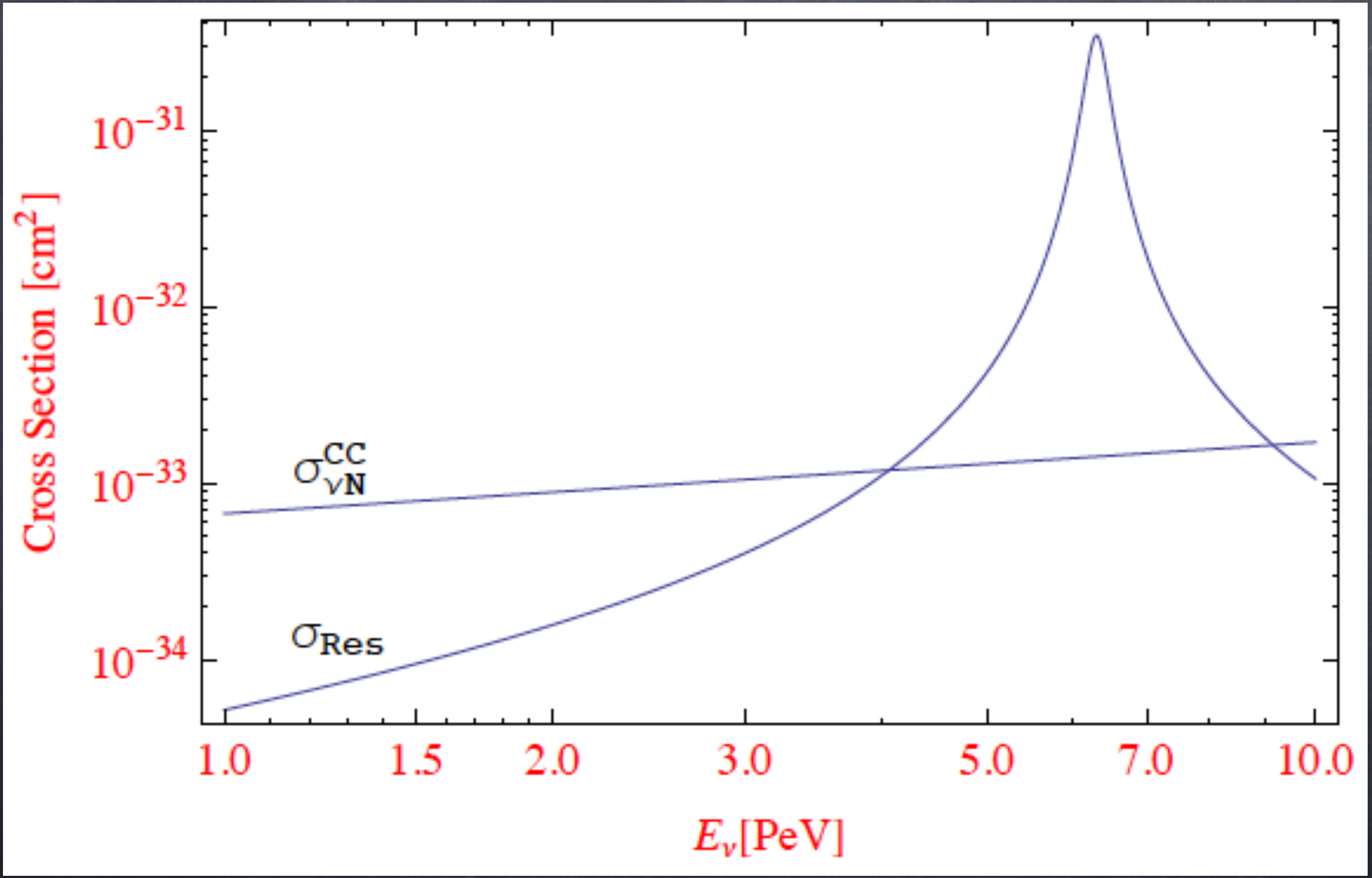
$\bar{\nu}_e$ is unique because of resonant scattering at

$$E_\nu = \frac{M_W^2}{2m_e} = 6.3\ \mathrm{PeV}$$

$$\bar{\nu}_e e^- \rightarrow W^- \rightarrow \mathrm{anything}$$

Differentiate between primary sources by comparing Glashow resonance signal to the continuum event rate

Only consider W decays to hadrons



6 sources:

- $pp \to \pi^{\pm}$ pairs $\to \nu_e + \bar{\nu}_e + 2\nu_\mu + 2\bar{\nu}_\mu$

- Since muon lifetime is 85 times longer than pion lifetime, pion decay could occur with the subsequent muon decay inhibited by energy losses (mixing)

  $pp \to \pi^{\pm}$ pairs $\to \nu_\mu + \bar{\nu}_\mu$ only

- Alternative to pp collisions is $p\gamma \to \pi^+ \to \nu_e + \nu_\mu + \bar{\nu}_\mu$ via the Δ^+ resonance (mixing)

- If muons damped $p\gamma \to \pi^+ \to \nu_\mu$ only (hopeless)

- pp collisions produce charmed mesons that decay semileptonically (before losing energy) to $\nu_e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$

- If heavy nuclei are emitted and photo-disintegrated, and the protons deflected by a magnetic field, then decays of the nearly pure neutron beam produce $\bar{\nu}_e$

Caveats and notes:

- Consider each source in isolation
- Neglect multipion contributions
- Assume muon damping is complete, when it exists
- Effect of kaon decays on source neutrino flavor ratio is small in the energy range of interest

Treat our results as suggestive with more careful analysis required if resonance events are observed

Propagation

Only interested in down-going events since up-going events are significantly attenuated

Tribimaximal mixing good approximation given current data

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sum_j |U_{\alpha j}|^2 \, |U_{\beta j}|^2 = \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$

	Source flavor ratio		Earthly flavor ratio		$\bar{\nu}_e$ fraction in flux ($\mathcal{R}$)
$pp \to \pi^{\pm}$ pairs	(1:2:0)		(1:1:1)		$18/108 = 0.17$
w/ damped $\mu^{\pm}$	(0:1:0)		(4:7:7)		$12/108 = 0.11$
$p\gamma \to \pi^{+}$ only	(1:1:0)	(0:1:0)	(14:11:11)	(4:7:7)	$8/108 = 0.074$
w/ damped μ^{+}	(0:1:0)	(0:0:0)	(4:7:7)	(0:0:0)	0
charm decay	(1:1:0)		(14:11:11)		$21/108 = 0.19$
neutron decay	(0:0:0)	(1:0:0)	(0:0:0)	(5:2:2)	$60/108 = 0.56$

Glashow events:

$$\left(\frac{N}{T\Omega}\right)_{\rm Res} = \frac{N_p}{2m_e}\,(\pi M_W \Gamma_W)\,\sigma_{\rm Res}^{\rm peak}\,\frac{dF_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}}\bigg|_{E_{\bar{\nu}_e}=6.3{\rm PeV}}$$

$$\sigma_{\rm Res}^{\rm peak} = \frac{24\pi\,{\rm B}(W^- \to \bar{\nu}_e e^-)\,{\rm B}(W^- \to {\rm had})}{M_W^2} = 3.4\times 10^{-31}{\rm cm}^2$$

Nonresonant events:

- Assume $E^{0.4}$ dependence for CC cross section
- Neglect the < 5% NC contribution per flavor
- Neglect 8% contribution from $\nu O \to \ell W O$ arising from $\nu \to \ell W$ conversion in the Coulomb field of the oxygen nucleus
- Spectral index of flux is -α

$$\left(\frac{N}{T\Omega}\right)_{\rm non-Res} = \frac{N_{n+p}}{(\alpha - 1.40)} \left[\left(\frac{6.3\,{\rm PeV}}{E_\nu^{\rm min}}\right)^{(\alpha-1.40)} - \left(\frac{6.3\,{\rm PeV}}{E_\nu^{\rm max}}\right)^{(\alpha-1.40)} \right]$$

$$\times \left(\sigma_{\nu N}^{\rm CC}(E_\nu) \frac{E_\nu\, dF_\nu}{dE_\nu} \right)_{E_\nu = 6.3\,{\rm PeV}}$$

Then,

$$\frac{N_{\rm Res}}{N_{\rm non-Res}(E_\nu > E_\nu^{\rm min})} = 11\, \mathcal{R}\, (\alpha - 1.40) \left(\frac{E_\nu^{\rm min}}{6.3\,{\rm PeV}} \right)^{\alpha - 1.40}$$

$$\mathcal{R} \equiv \left[\left(\frac{dF_{\bar\nu_e}}{dE_{\bar\nu_e}} \right) \Big/ \left(\frac{dF_\nu}{dE_\nu} \right) \right]_{E = 6.3\,{\rm PeV}}$$

Ratio of Glashow event rate to nonresonant event rate

$E_\nu^{\min}$ (PeV)	1 $\alpha = 2\ (2.3)$	2	3	4	5
$pp \to \pi^\pm$ pairs	0.37 (0.32)	0.56 (0.59)	0.71 (0.85)	0.84 (1.1)	0.96 (1.3)
w/ damped $\mu^\pm$	0.24 (0.20)	0.37 (0.38)	0.47 (0.56)	0.54 (0.71)	0.62 (0.88)
$p\gamma \to \pi^+$ only	0.16 (0.13)	0.24 (0.26)	0.31 (0.37)	0.37 (0.48)	0.42 (0.59)
w/ damped μ^+	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
charm decay	0.41 (0.36)	0.62 (0.67)	0.80 (0.95)	0.94 (1.2)	1.1 (1.6)
neutron decay	1.2 (1.0)	1.9 (2.0)	2.3 (2.8)	2.8 (3.6)	3.2 (4.4)

Glashow events at IceCube

- 3 events observed between 1-2 PeV
- No events above 2 PeV
- Can we predict the expected number of Glashow events from these 3 observed events?
- Need the expected number of nonresonant events above $E_\nu^{\rm min}$
- Normalize to expected number between 1-2 PeV:

$$N^{\text{expected}}_{\geq E_\nu^{\text{min}}} = \frac{(E_\nu^{\text{min}})^{-(\alpha-1.40)}}{1-2^{-(\alpha-1.40)}} N^{\text{expected}}_{1-2\ \text{PeV}}$$

For 3 observed events, the Feldman-Cousins expectation at 95% C.L. is 0.82 - 8.25 events in the 1-2 PeV bin!

α	$N^{\text{expected}}_{\geq 2\ \text{PeV}}$	N_{Res}
2.0	$1.94 N^{\text{expected}}_{1-2\ \text{PeV}}$	$6.4\mathcal{R}\, N^{\text{expected}}_{1-2\ \text{PeV}}$
2.3	$1.15 N^{\text{expected}}_{1-2\ \text{PeV}}$	$4\mathcal{R}\, N^{\text{expected}}_{1-2\ \text{PeV}}$
2.5	$0.87 N^{\text{expected}}_{1-2\ \text{PeV}}$	$3\mathcal{R}\, N^{\text{expected}}_{1-2\ \text{PeV}}$

- To reduce tension with unpopulated bins at higher energy suppose $N^{\rm expected}_{\rm 1-2\ PeV} = 1, 2, 3$

- The Poisson probabilities to observe 3 events when expecting 1, 2, 3 events are 6%, 18%, 22%

- All 3 possibilities are viable

Suppose $\alpha = 2.3, \; \mathcal{R} = 0.17$

$N_{1-2 \text{ PeV}}^{\text{expected}}$	$N_{\geq 2 \text{ PeV}}^{\text{expected}}$	N_{Res}
1	1.15	0.68
2	2.3	1.36
3	3.45	2.04

The Poisson probabilities for not observing any Glashow events are 50%, 26% and 13%

The Poisson probabilities for not observing any events above 2 PeV are 16%, 2.6% and 0.4%

Summary

- Fraction of Glashow events are a discriminator of astrophysical source models
- Need to observe more PeV events to make robust estimates of Glashow event numbers
- As more data become available our resonometer will need to be refined
- Absence of Glashow events suggests that the neutron decay source is mildly disfavored
- Should this absence of events continue, the $p\gamma$ damped muon source will become favored