New MINERνA Results in the Hydrocarbon Target

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On Behalf of
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Neutrino flavors change

Neutrinos are produced in one of the three flavor eigenstates: e, μ, τ, but travels as a mixture of mass eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_{\mathbf{i}}\rangle$$

$$|\nu_j(t)\rangle = e^{-i(E_j t - \vec{p}\vec{x})}|\nu_j(0)\rangle$$

$$\approx e^{-i\left(\frac{m_j^2 L}{2E}\right)}|\nu_j(0)\rangle$$

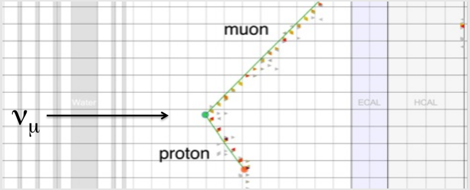
$$P_{\alpha\to\beta} = \langle\nu_\beta|\nu_\alpha\rangle$$

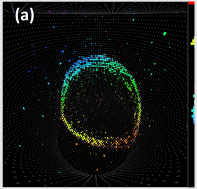
$$= \delta_{\alpha\beta} - 4\sum \mathcal{R}(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + \ldots$$

L: Distance
E: Energy

Neutrino energy reconstruction is challenging

- Neutrino energy needs to be reconstructed using observed reaction





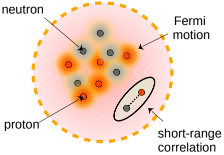
Reconstruction detail depends on:

- detector physics – incomplete knowledge but controllable.
- nuclear physics – incomplete knowledge, and nature.

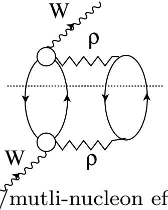
Nucleon and nuclear effects from charged current (CC) interactions

elastic inelastic

Quasi-elastic (QE): inseparable nucleon and nuclear effects.

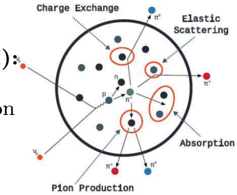


Initial States:
Fermi motion
short-range correlation
binding energy, etc.



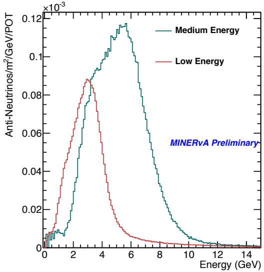
2p2h/mutli-nucleon effects

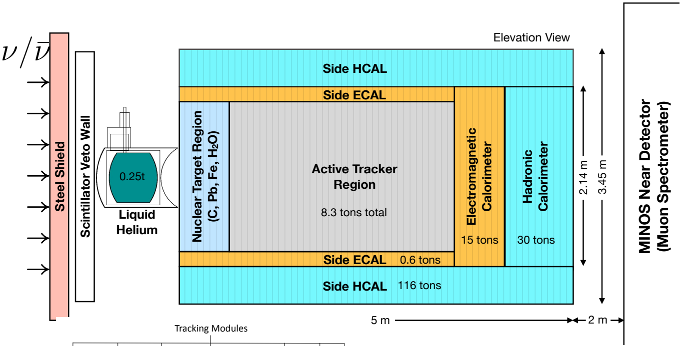
Final State Interactions (FSI):
elastic, inelastic, charge-exchange,pion production, pion absorption, etc.



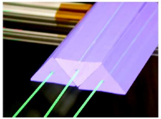
Quasi-elastic-like (QELike): only nucleons in the final states.

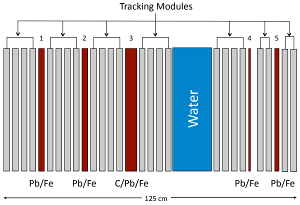
High resolution scintillator(CH) detector

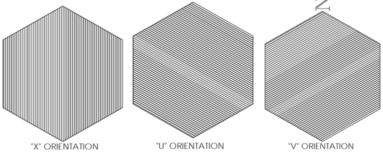




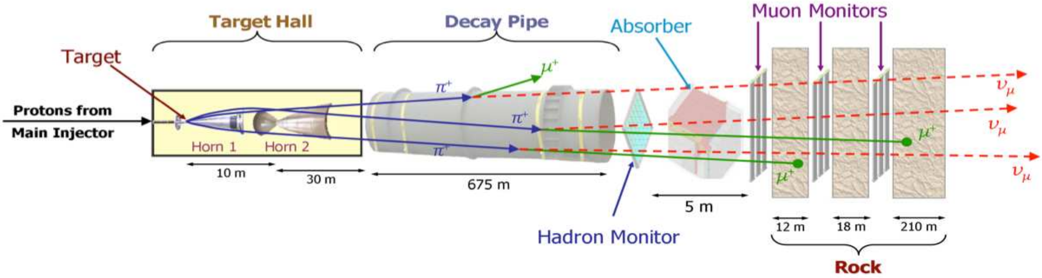
Nucl. Inst. and Meth. A743 (2014) 130.







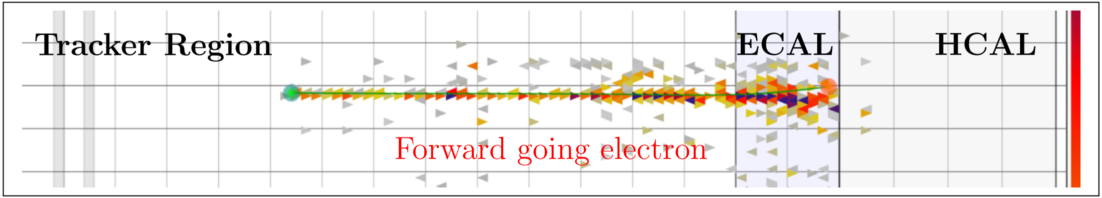
Improving flux constraints



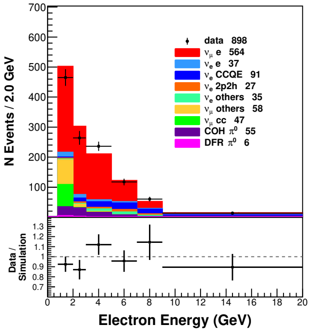
Flux normalization: $\nu - e$ scattering

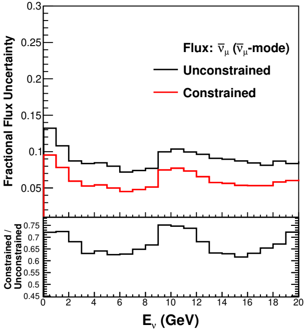
- ☹ Flux is not known precisely
- ☹ Needs in-situ constraints
- ☺ $\nu(\bar{\nu})e \to \nu(\bar{\nu})e$ is a standard electroweak process with precisely predicted cross section

- At $m_e \ll E_\nu$, electrons are very forward going
  - cannot calculate neutrino energy
- The total number of $\nu - e$ events provides strong constraint on the flux normalization



New result: improved constraint on NuMI flux





Joint constraint of $\nu(\bar{\nu})$ flux using

- νe scattering (Valencia et al., 2019[2])
- inverse muon decay (Ruterbories et al., 2021[3])
- $\bar{\nu}e$ scattering (Zazuesta eta al., 2022[1])

Type	uncertainty improvement
ν_μ flux	7.6% → 3.3%
$\bar{\nu}_\mu$ flux	7.8% → 4.7%

Results in CH:

ν triple differential QELike cross section

Ruterbories et al.,2022[4]

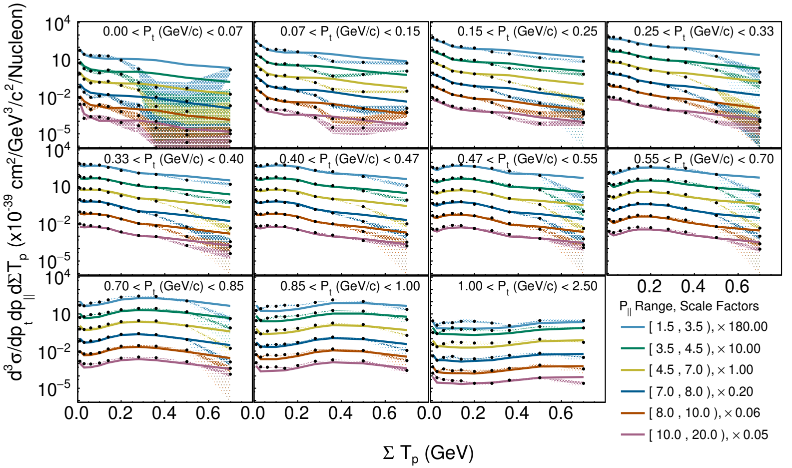
Muon $p_\parallel$ vs muon p_T vs total proton KE ($\sum T_p$)

QELike: 1 muon and no mesons in the final states

First high statistics triple differential measurement.

Expose nuclear effects with lepton-hadron correlation

Culprits of discrepancies can be traced.

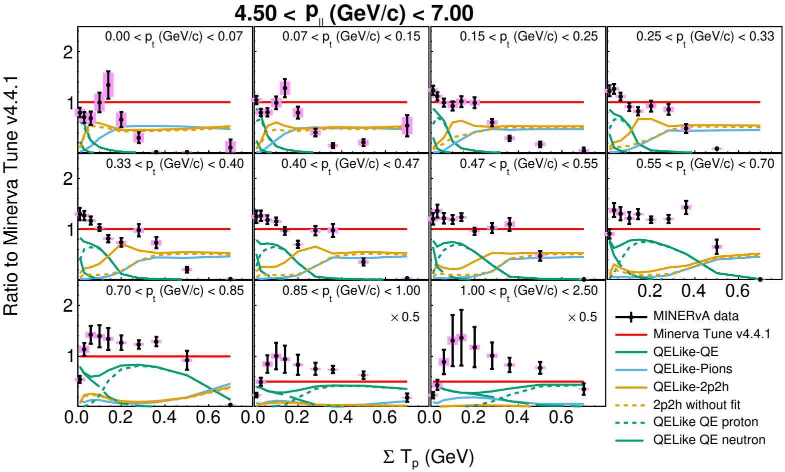


Ruterbories et al.,2022[4]

Muon $p_{\parallel}$ vs muon p_T vs total proton KE ($\sum T_p$)

QELike: 1 muon and no mesons in the final states

MC excess can be traced to different model contributions.



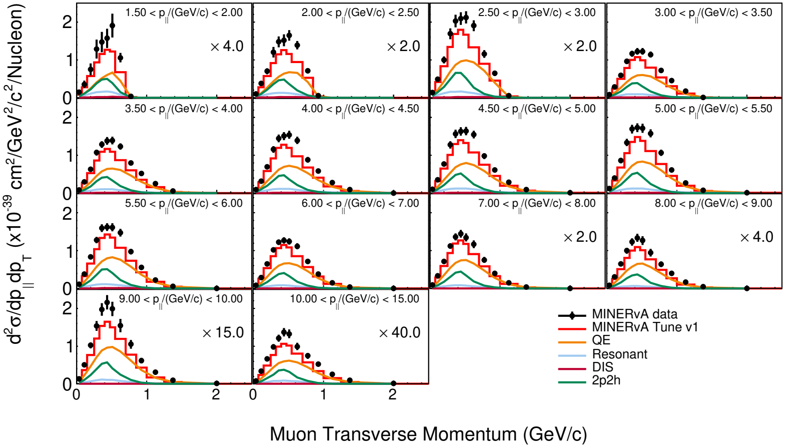
Results in CH:

$\bar{\nu}$ high statistics QELike cross section

Bashyal et al.,2022[5]

Muon $p_{\parallel}$ vs muon p_T

QELike: 1 μ^+, no mesons, no protons with $T_p > 120$ MeV



General disagreement between data and MC, especially at high muon p_T.
$p_T \sim$ momentum transfer, linked to Q^2.
Dominated by QE.

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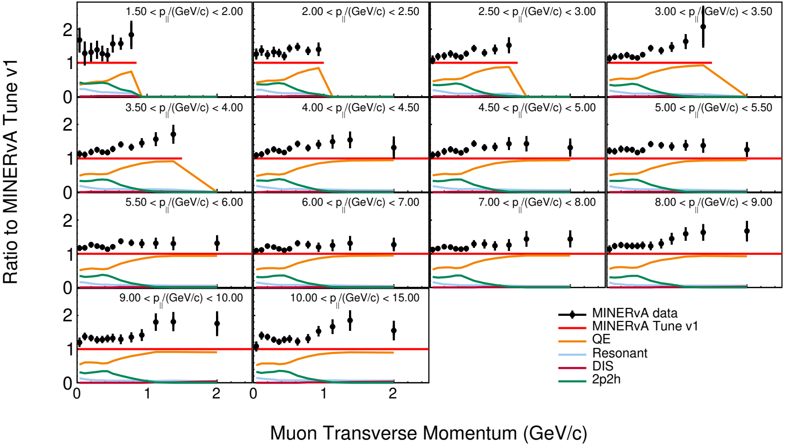

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p_T ~ momentum transfer, linked to Q^2.

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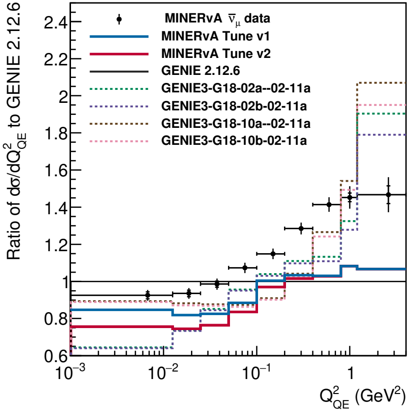
Cross section ratio in terms of Q^2

μ^+, no mesons, no protons with $T_p > 120$ MeV



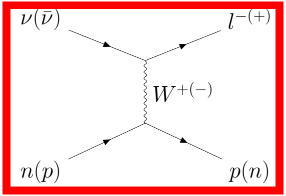
Q^2: inverse of 4-momentum transfer squared.

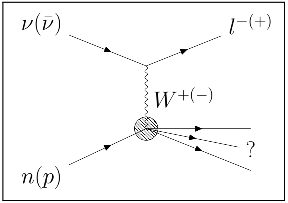
- Ratio of data and models to some reference model.
- Some models agree better than others.
- We could gain more information with lepton-hadron correlations.

Results in CH:

with neutron correlation: charged current elastic $\bar{\nu}$-proton cross section

Nucleon and nuclear effects from charged current (CC) interactions



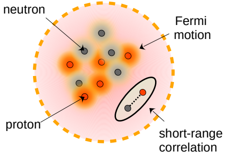


ω

elastic

inelastic

Quasi-elastic (QE): inseparable nucleon and nuclear effects.



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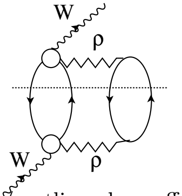

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Final State Interactions (FSI):
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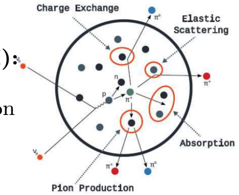


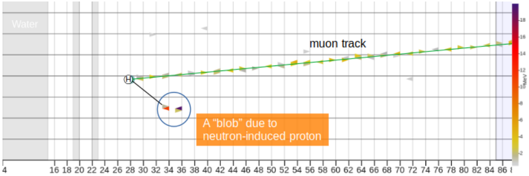
Quasi-elastic-like (QELike): only nucleons in the final states.

Cai et al.,2023[6]

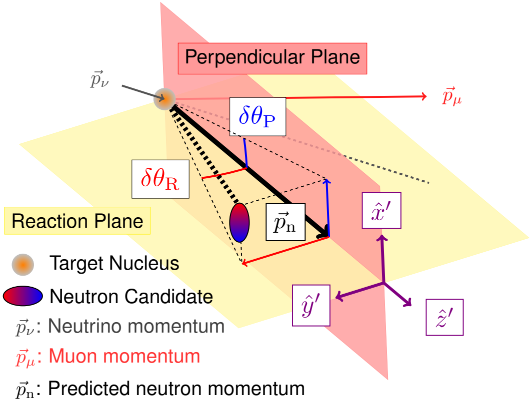
QELike: $\bar{\nu}$ scattering on free proton

Neutron reconstruction:

- measures neutron point of interaction,
- derive neutron direction,
- potentially separate H and C from hydrocarbon



$\bar{\nu}$ QELike with neutrons



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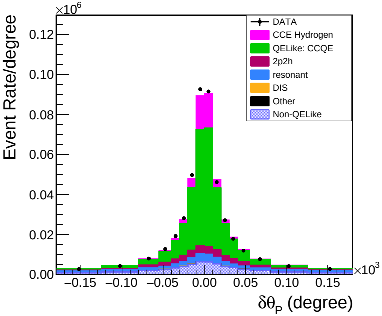
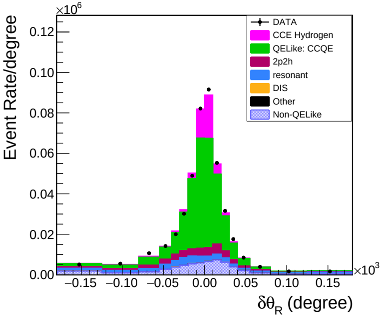


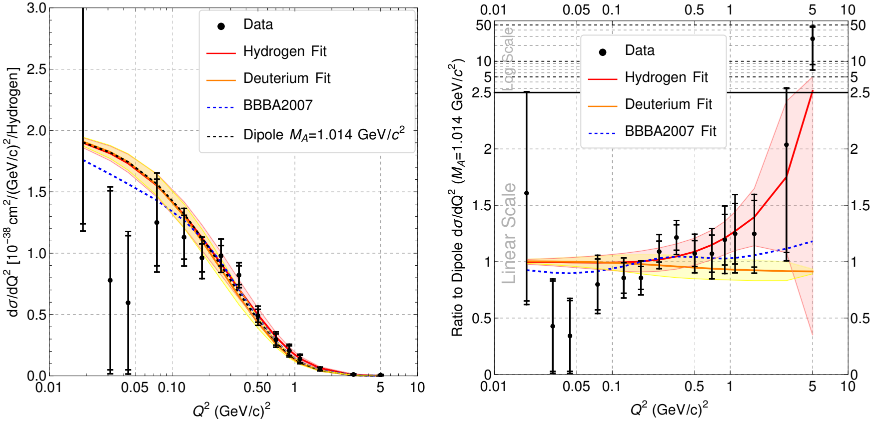


Elastic on hydrogen concentrated in central $\delta\theta_{\mathrm{P}} - \delta\theta_{\mathrm{R}}$ plane, with dominant CCQE background.

Outlying regions are used to constrain backgrounds.

Cai et al.,2023[6]

QELike: $\bar{\nu}$ scattering on free proton



First statistically significant measurement of elastic $\bar{\nu}-p$ scatter cross section.
~ 5000 proton elastic scatters. Result recently appeared in *Nature*.

MINERνA's hydrocarbon target has yielded many important measurements over the last year.

- Pushing the boundary of precision neutrino measurements in
  - understanding of flux
  - diagnosis of nuclear models
  - measuring free proton cross section on CH for the first time
- There are more lepton-hadron correlation measurements in the pipeline. Please stay tuned!

Backup

Sensitivities to Many Final States

- MINERνA's plastic scintillators are sensitive to small energy deposits
- Hadronic recoils are measured from calorimetry
- Tracking threshold (KE) for proton is ~ 100MeV
- Neutrons can deposit visible energies (albeit small) after recoil inside scintillator

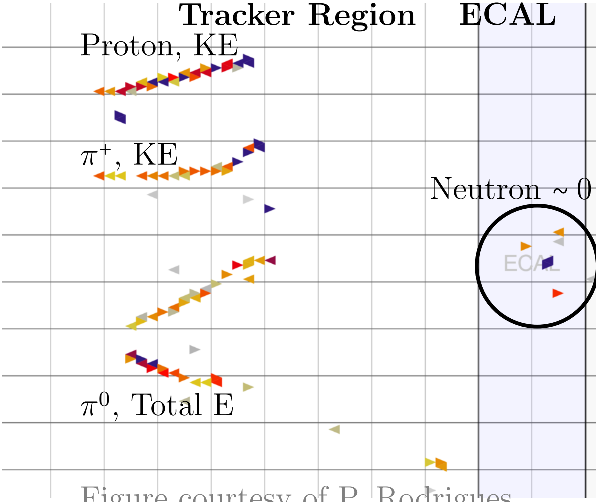
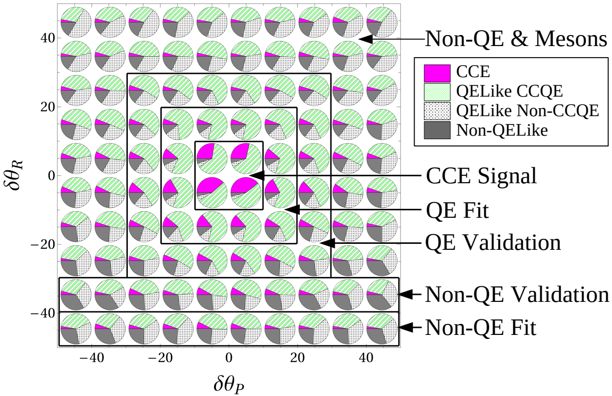
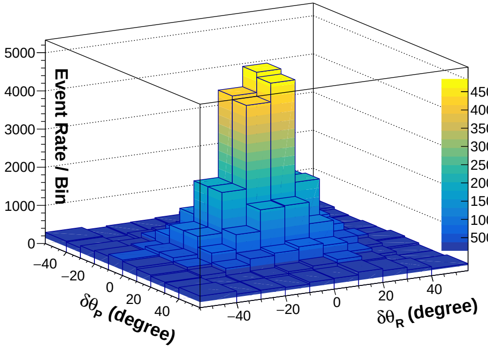


Figure courtesy of P. Rodrigues

Angular regions and MC fraction

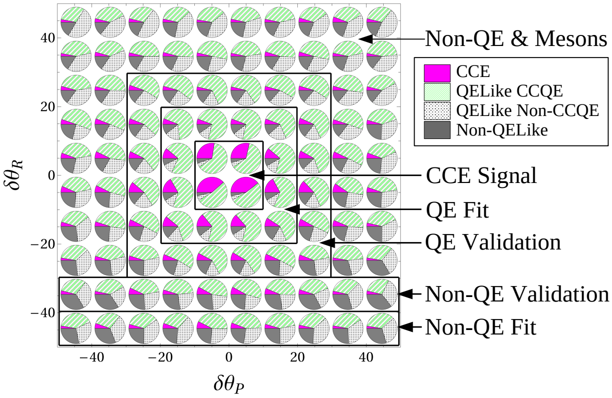


Total data event rate

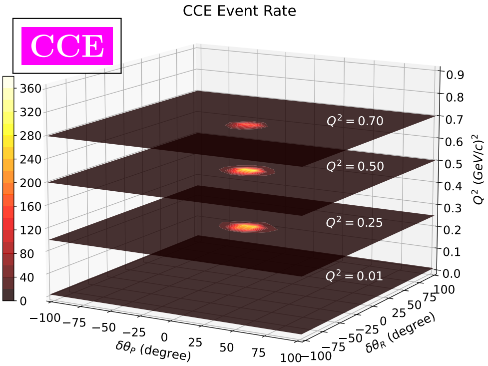


Created different angular regions – Hydrogen signal in the center. Outer regions are used for fit and validation – expand each region in Q^2

Angular regions and MC fraction

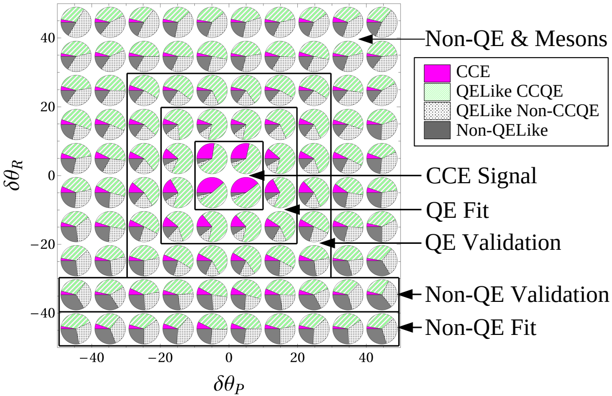


MC events in slices of Q^2



Predicted hydrogen angles – concentrated in the center.

Angular regions and MC fraction



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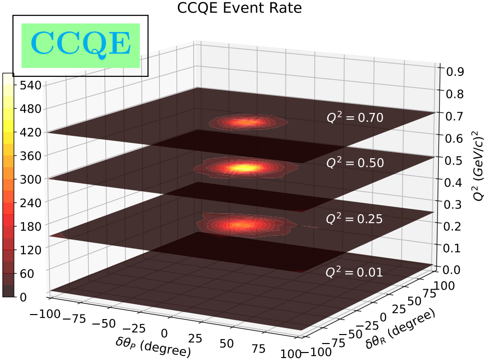
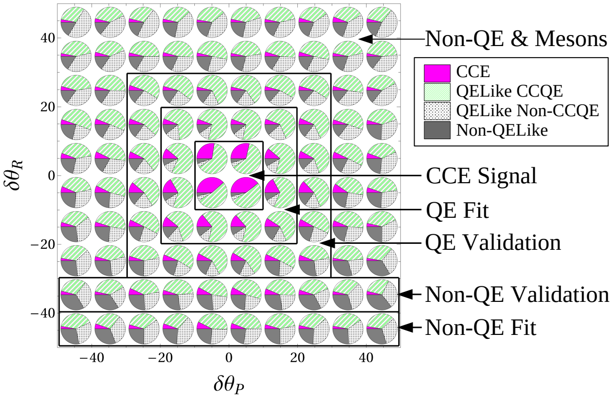


Carbon QELike (CCQE) – more spread out due to Fermi motion and final state interactions.

Angular regions and MC fraction



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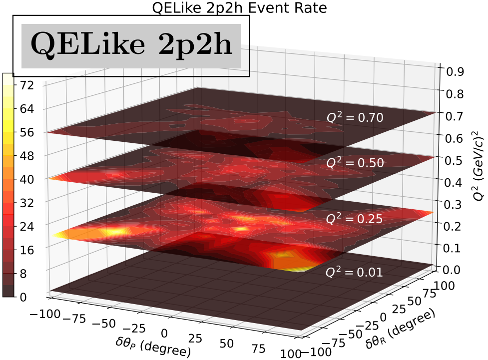
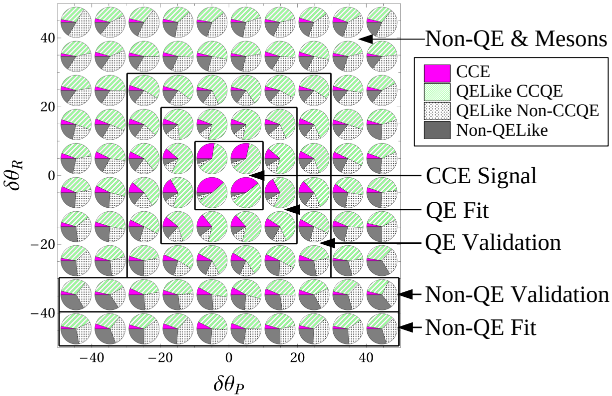


2p2h and resonant – all over the place but different.

Angular regions and MC fraction



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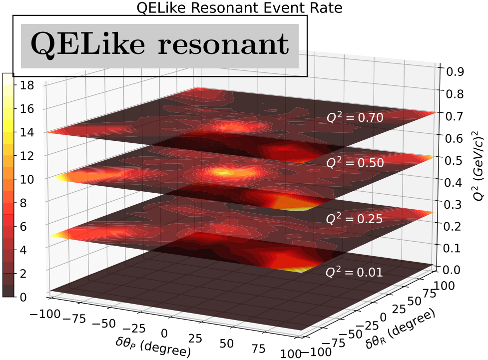

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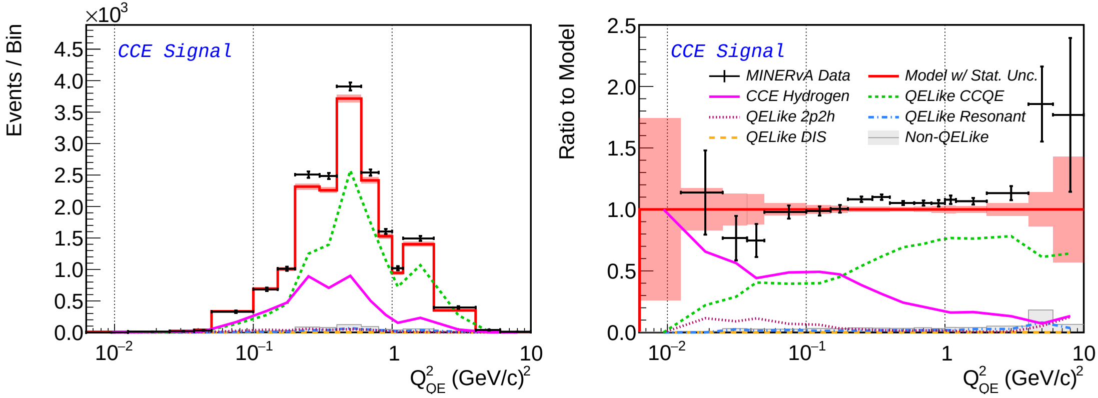
$\bar{\nu}p$ measurement: signal region event rate



Projecting the fit into the signal region. Difference between data and background is the physics. More than 5000 hydrogen events!

Deuterium Fit[7], BBBA2007[8], LQCD[9]

F_A fit and axial radius of the nucleon

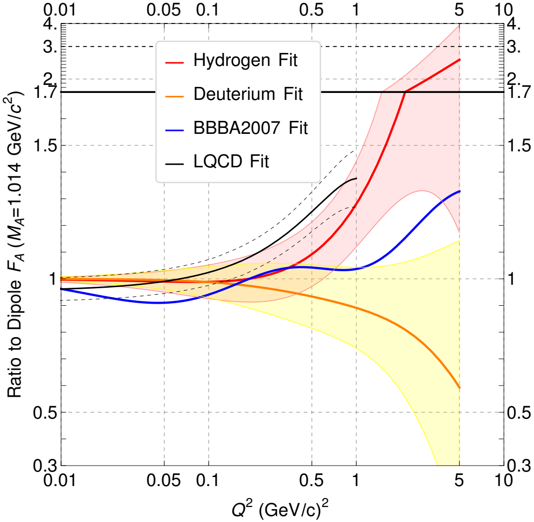
Favors larger F_A at higher Q^2.

Calculate proton radius from F_A for $Q^2 \to 0$.

$$F_A(Q^2) = F_A(0)\left(1 - \frac{\langle r_A^2\rangle}{3!}Q^2 + \frac{\langle r_A^4\rangle}{5!}Q^4 + \dots\right),$$

$$\frac{1}{F_A(0)}\frac{dF_A}{dQ^2}\bigg|_{Q^2=0} = -\frac{1}{6}\langle {r_A}^2\rangle$$

- $\langle r_A^2\rangle = 0.53(25)\mathrm{fm}^2$
- $\sqrt{\langle r_A^2\rangle} = 0.73(17)\mathrm{fm}$



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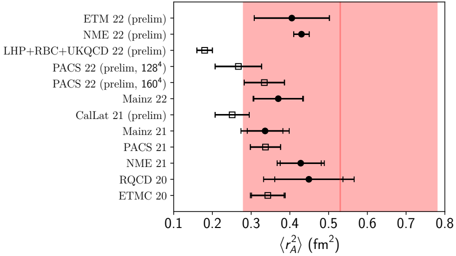

Filled circle: full error budget.
Open square: incomplete.
Red band: this result.
Courtesy of Aaron Meyer.

Reference

Reference I

[1] L. Zazueta et al. "Improved constraint on the MINERvA medium energy neutrino flux using $\bar{\nu}e^- \to \bar{\nu}e^-$ data". In: (Sept. 2022). arXiv: 2209.05540 [hep-ex].

[2] E. Valencia et al. "Constraint of the MINERνA medium energy neutrino flux using neutrino-electron elastic scattering". In: *Phys. Rev. D* 100.9 (2019), p. 092001. DOI: 10.1103/PhysRevD.100.092001. arXiv: 1906.00111 [hep-ex].

[3] D. Ruterbories et al. "Constraining the NuMI neutrino flux using inverse muon decay reactions in MINERvA". In: *Phys. Rev. D* 104.9 (2021), p. 092010. DOI: 10.1103/PhysRevD.104.092010. arXiv: 2107.01059 [hep-ex].

Reference II

[4] D. Ruterbories et al. “Simultaneous Measurement of Proton and Lepton Kinematics in Quasielasticlike $\nu\mu$-Hydrocarbon Interactions from 2 to 20 GeV”. In: *Phys. Rev. Lett.* 129.2 (2022), p. 021803. DOI: 10.1103/PhysRevLett.129.021803. arXiv: 2203.08022 [hep-ex].

[5] A. Bashyal et al. “High-Statistics Measurement of Antineutrino Quasielastic-li scattering at $E_\nu \sim 6$˜GeV on a Hydrocarbon Target”. In: (Nov. 2022). arXiv: 2211.10402 [hep-ex].

[6] T. Cai et al. “Measurement of the axial vector form factor from antineutrino–p scattering”. In: *Nature* 614.7946 (2023), pp. 48–53. DOI: 10.1038/s41586-022-05478-3.

Reference III

[7] Aaron S. Meyer et al. "Deuterium target data for precision neutrino-nucleus cross sections". In: *Phys. Rev. D* 93.11 (2016), p. 113015. DOI: 10.1103/PhysRevD.93.113015. arXiv: 1603.03048 [hep-ph].

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