Based on: Phys. Rev. D **101**, 092003; Phys. Rev. D **110**, 032019; arXiv:1901.03750

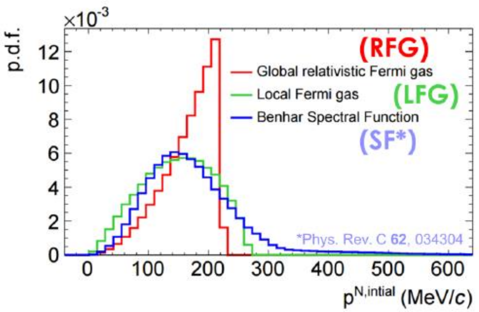
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

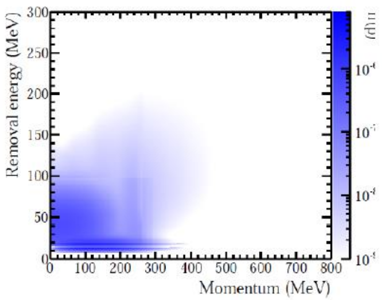
Isolating neutrino-hydrogen interactions using kinematic separation

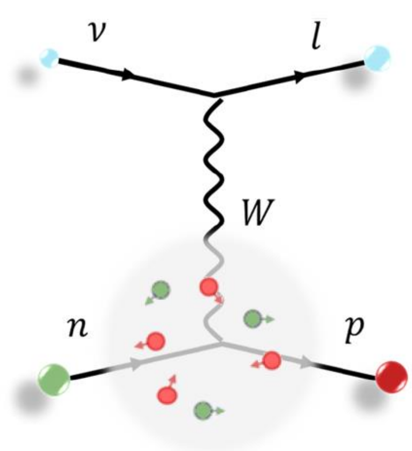
Stephen Dolan

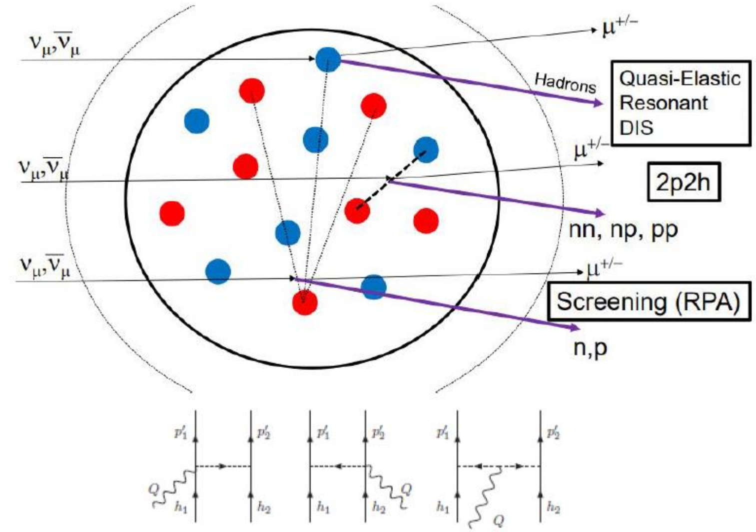
stephen.joseph.dolan@cern.ch

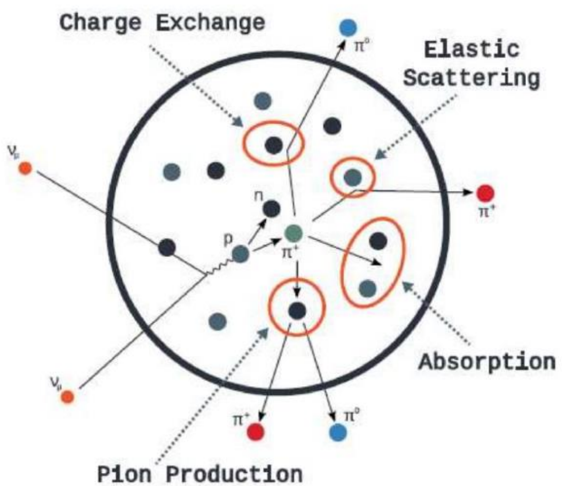
Nuclear targets are hard

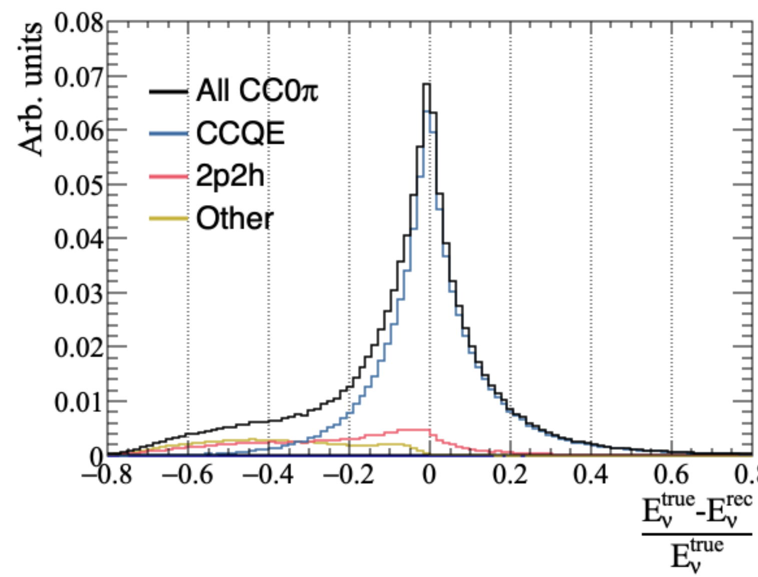












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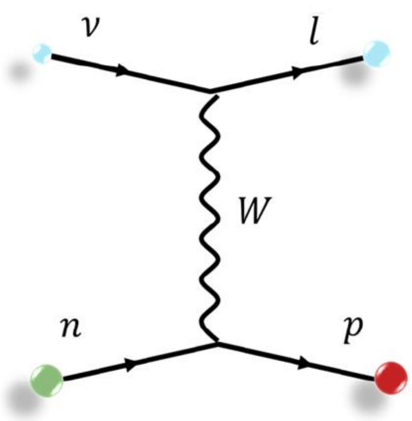

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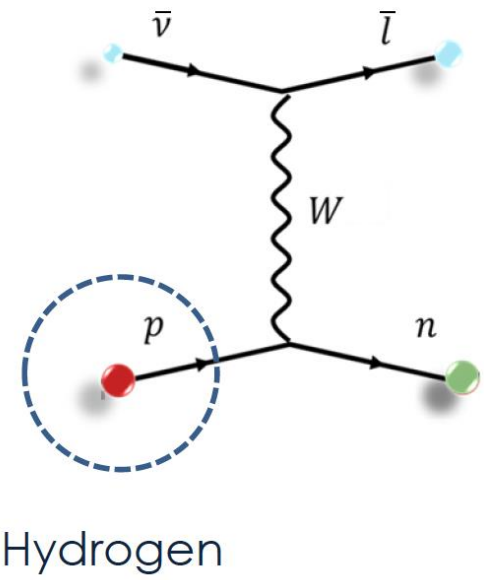

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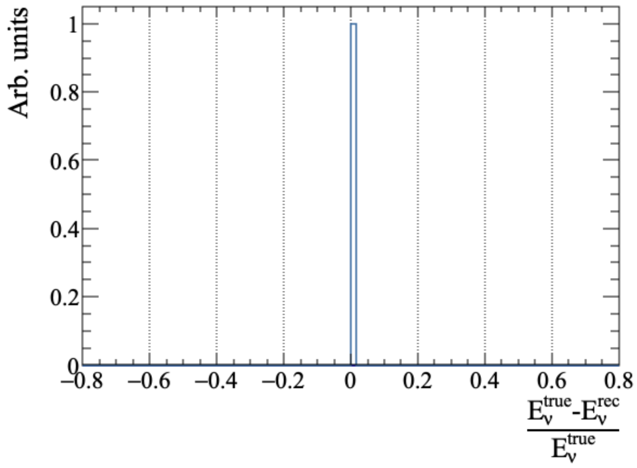
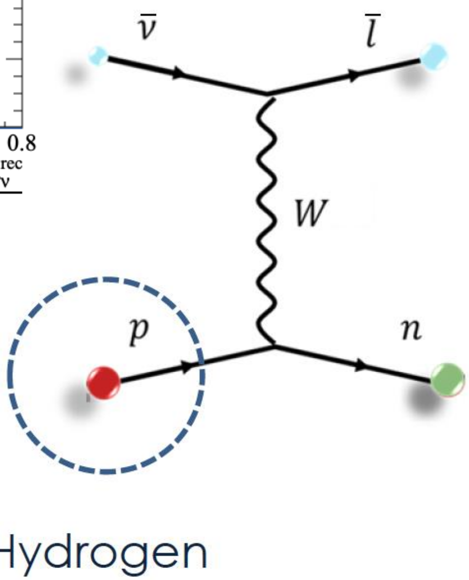


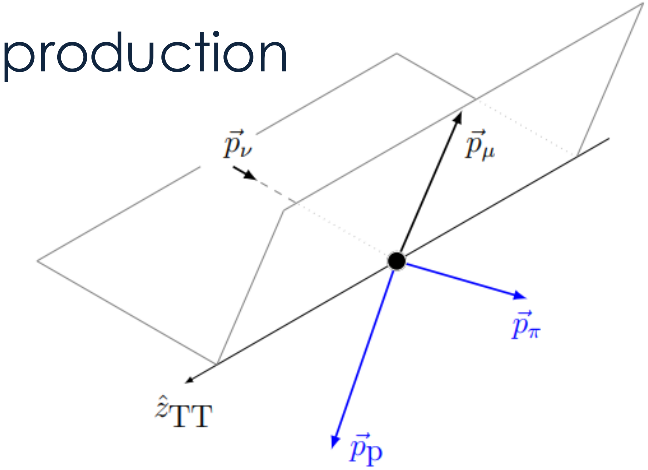


Where it started (2015)

- An extension of (S)TKI applied to single pion production defines double TKI

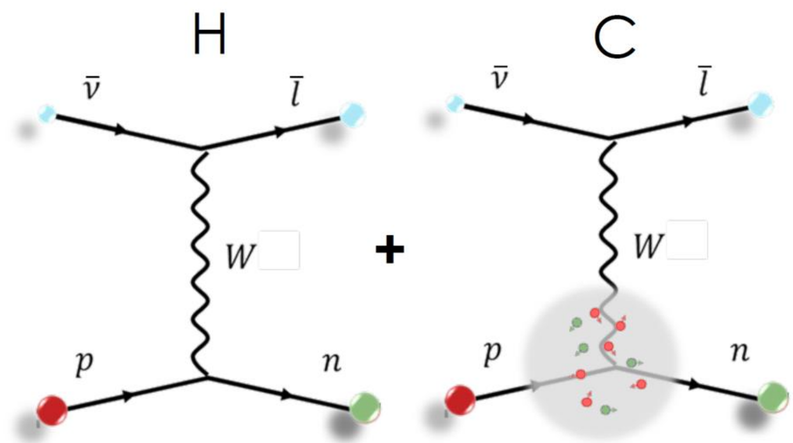
$$\delta p_{\mathrm{TT}} \equiv p_{\mathrm{TT}}^{\mathrm{p}} + p_{\mathrm{TT}}^{\pi}$$

X. Lu et. al.: Phys. Rev. D **92**, 051302(R)



- Single pion production happens on the H or CH in plastic scintillator

- δp_{TT} balances for H, but not for C:



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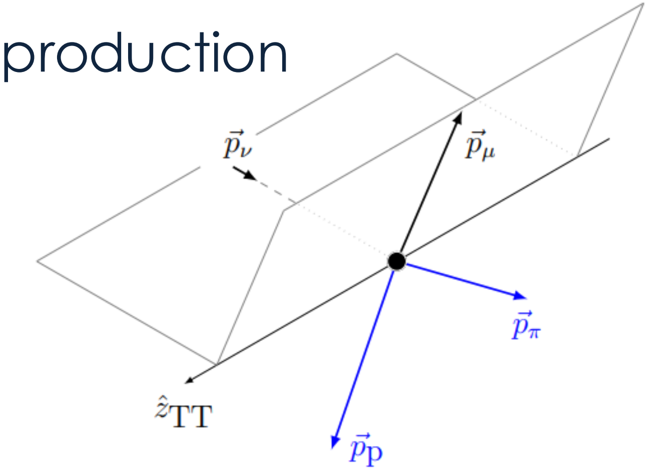

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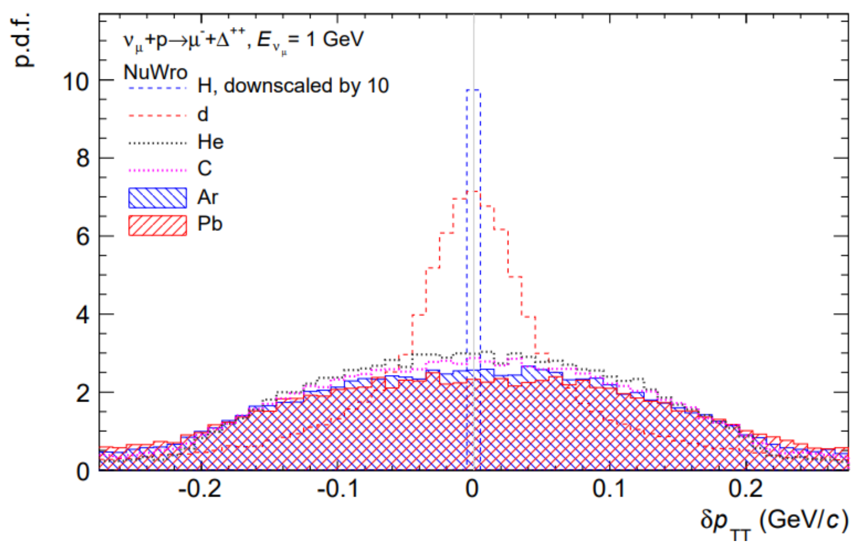


- Unfortunately, this was a tricky topology to measure at the time
  - Limited statistics (~350 evts for T2K)
  - Low purity (~50%)

Meanwhile, at Fermilab (~2018)

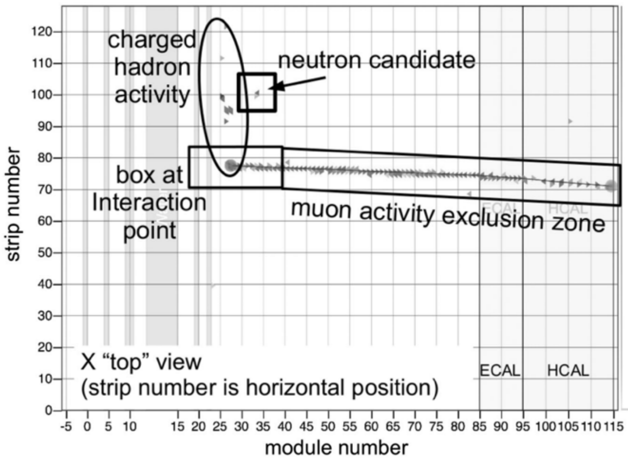
Neutron measurements from antineutrino hydrocarbon reactions

M. Elkins,[1,*] T. Cai,[2] J. Chaves,[3] J. Kleykamp,[2] F. Akbar,[4] L. Albin,[1] L. Aliaga,[5,6] D. A. Andrade,[7] M. V. Ascencio,[6] A. Bashyal,[8] L. Bellantoni,[9] A. Bercellie,[2] M. Betancourt,[9] A. Bodek,[2] A. Bravar,[10] H. Budd,[2] G. Caceres,[11] M. F. Carneiro,[8] D. Coplowe,[12] H. da Motta,[11] S. A. Dytman,[13] G. A. Díaz,[2,6] J. Felix,[7] L. Fields,[9,14] A. Filkins,[5] R. Fine,[2] N. Fiza,[15] A. M. Gago,[6] R. Galindo,[16] A. Ghosh,[16,11] R. Gran,[1] J. Y. Han,[13] A. Habig,[1] D. A. Harris,[9] S. Henry,[2] S. Jena,[15] D. Jena,[9] M. Kordosky,[5] D. Last,[3] T. Le,[17,18] J. R. Leistico,[1] A. G. Lopez,[1] A. Lovlein,[1] X.-G. Lu,[12] E. Maher,[19] S. Manly,[2] W. A. Mann,[17] C. M. Marshall,[2,†] C. Mauger,[3] A. M. McGowan,[2] K. S. McFarland,[2,9] B. Messerly,[13] J. Miller,[16] J. G. Morfín,[9] J. Mousseau,[20,‡] D. Naples,[13] J. K. Nelson,[5] C. Nguyen,[20] A. Norrick,[9,5] Nuruzzaman,[18,16] A. Olivier,[2] V. Paolone,[13] G. N. Perdue,[9,2] M. A. Ramírez,[7] R. D. Ransome,[18] H. Ray,[20] D. Rimal,[20] P. A. Rodrigues,[12,21,2] D. Ruterbories,[2] H. Schellman,[8,14] C. J. Solano Salinas,[22] H. Su,[13] V. S. Syrotenko,[17] S. Sánchez Falero,[6] E. Valencia,[5,7] J. Wolcott,[2,§] and B. Yaeggy[16]

(MINERvA Collaboration)

Phys. Rev. D **100**, 052002

- MINERvA demonstrates neutron-tagging!



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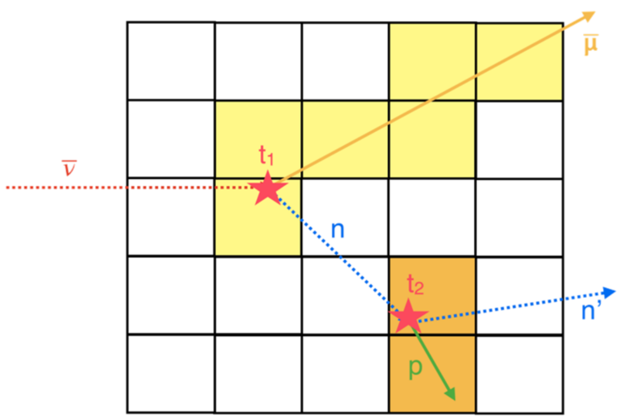
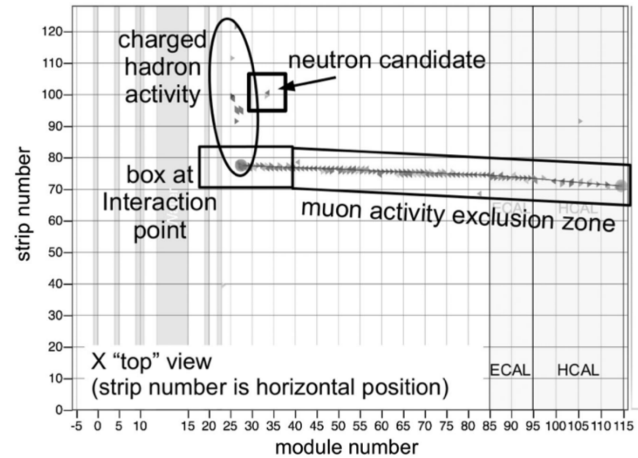
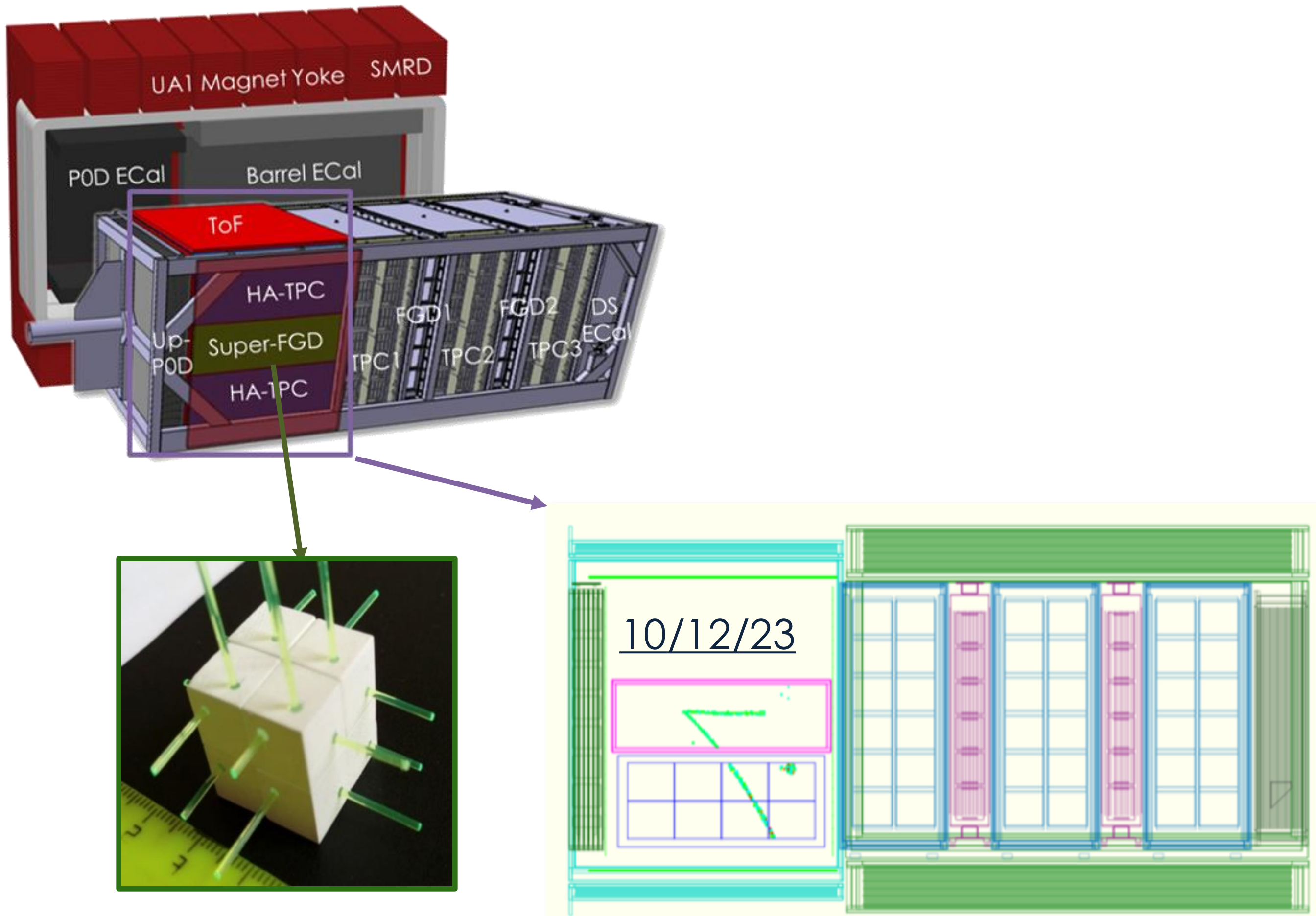




- With a 3D position and sufficient timing resolution, the neutron energy could be reconstructed. But this isn't doable at MINERvA (Kevin's fault).

Meanwhile, within T2K (~2018)

- T2K is busy building an upgrade to its near detector (arXiv:1901.03750)



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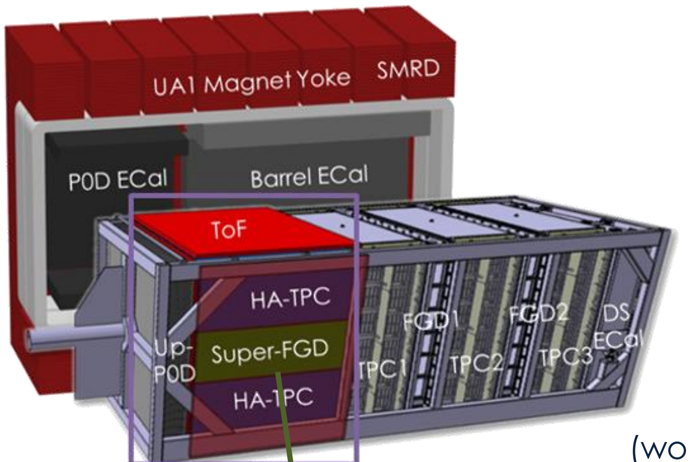
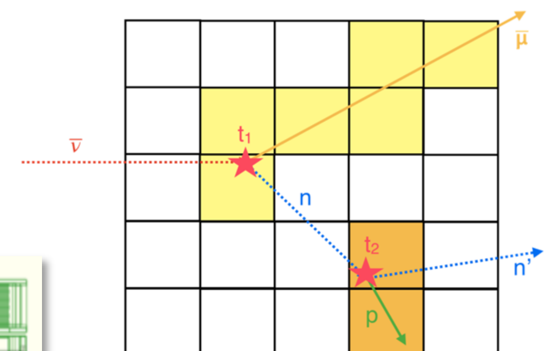
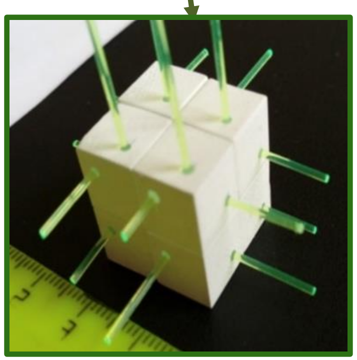
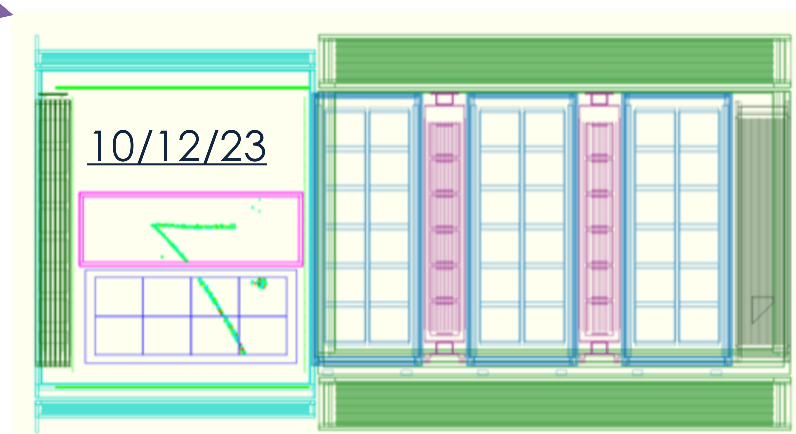


Couldn't the Super-FGD be perfect for seeing neutrons?

S. Manly
(working on T2K and MINERvA)

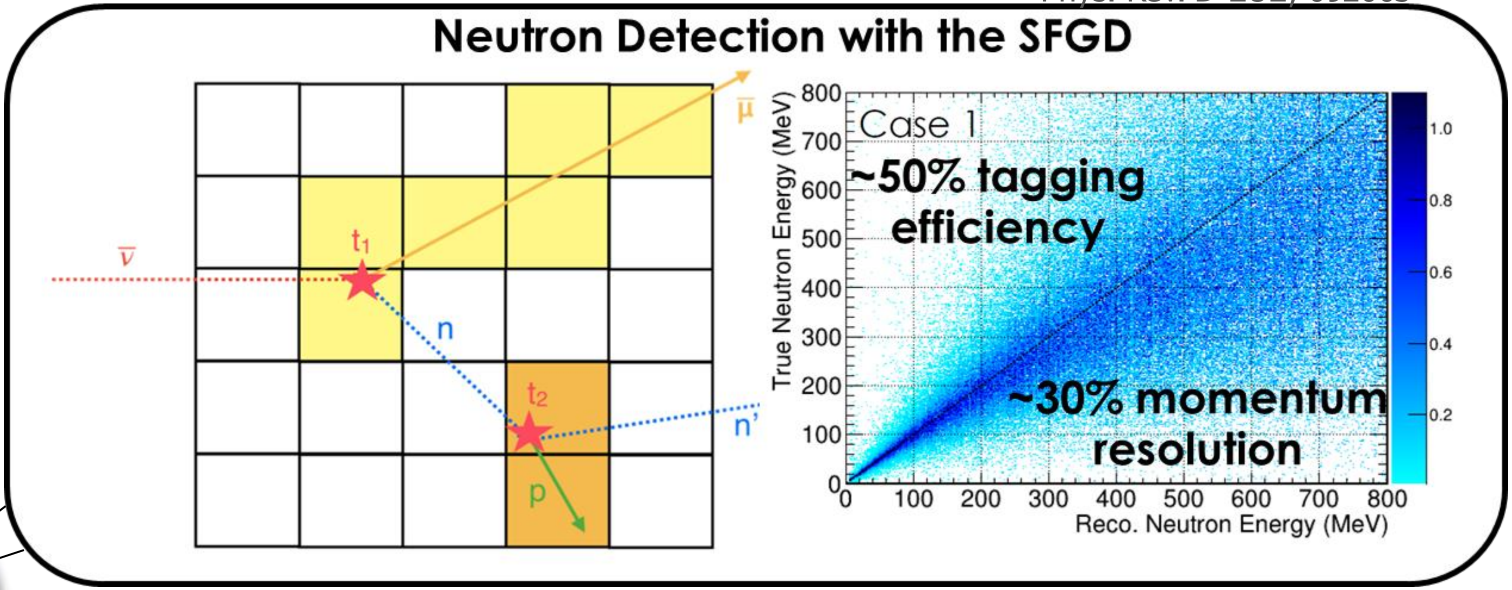






Super-FGD: a neutron detector (2018)

Phys. Rev. D **101**, 092003

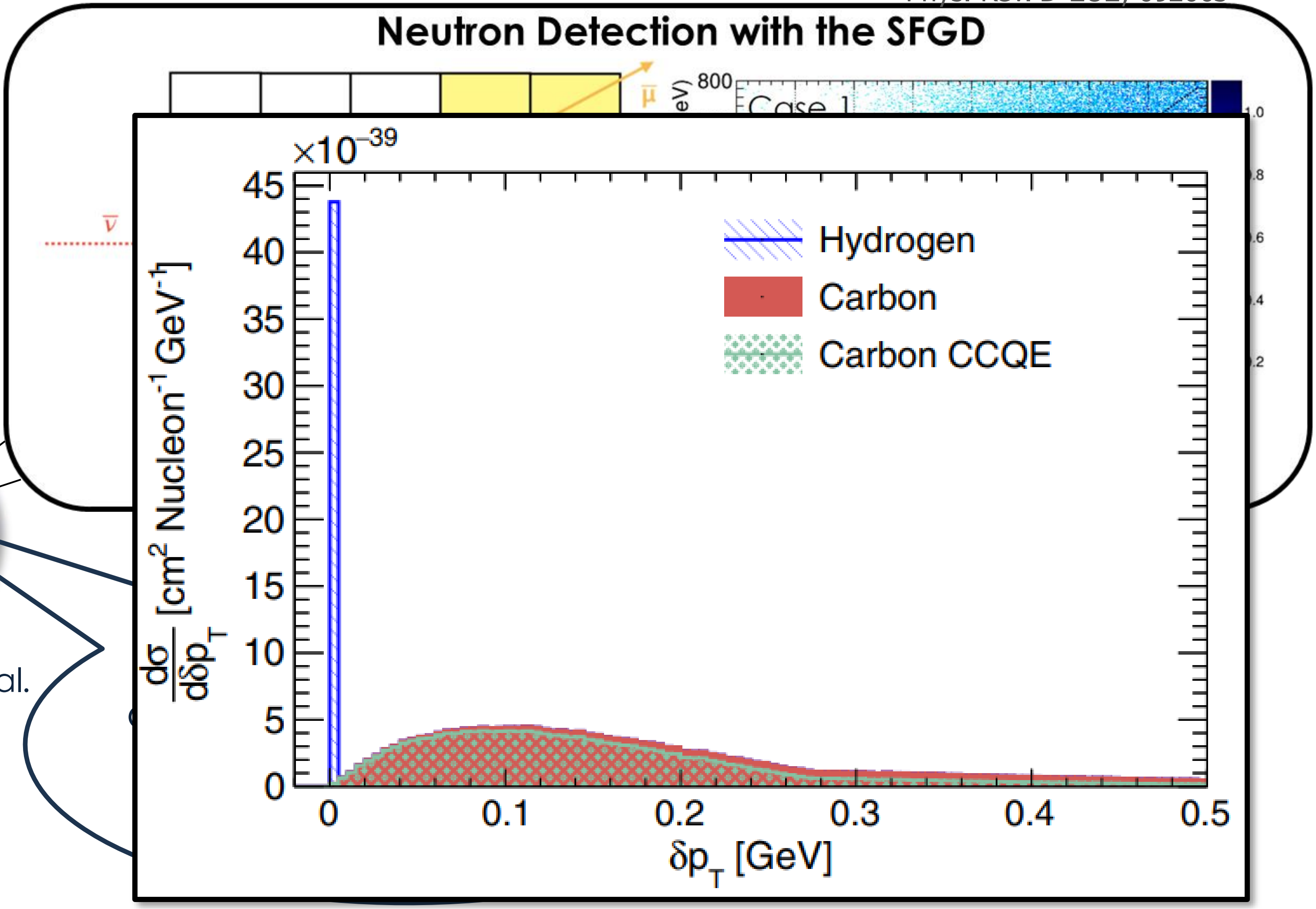


L. Munteanu et. al.

It's a great neutron detector! Wouldn't TKI with $\bar{\nu}$CC0π be great?

Super-FGD: a neutron detector (2018)

Phys. Rev. D **101**, 092003



L. Munteanu et. al.

Super-FGD: a neutron detector (2018)

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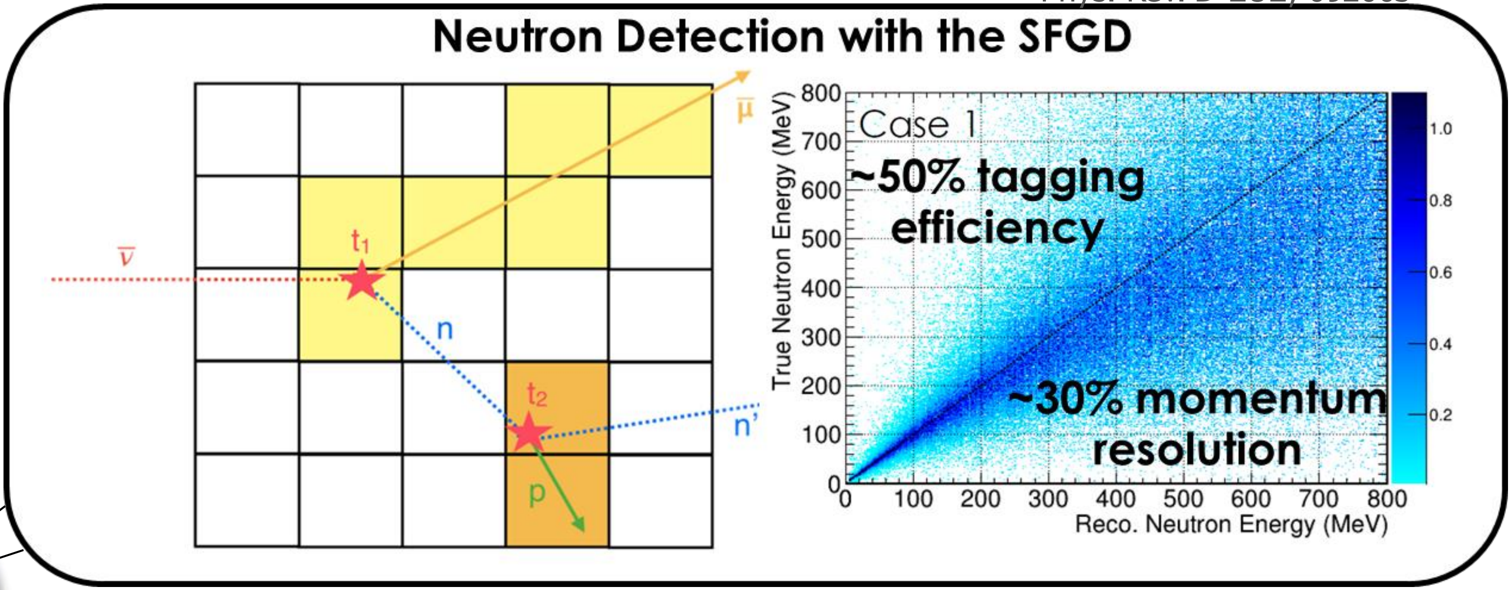
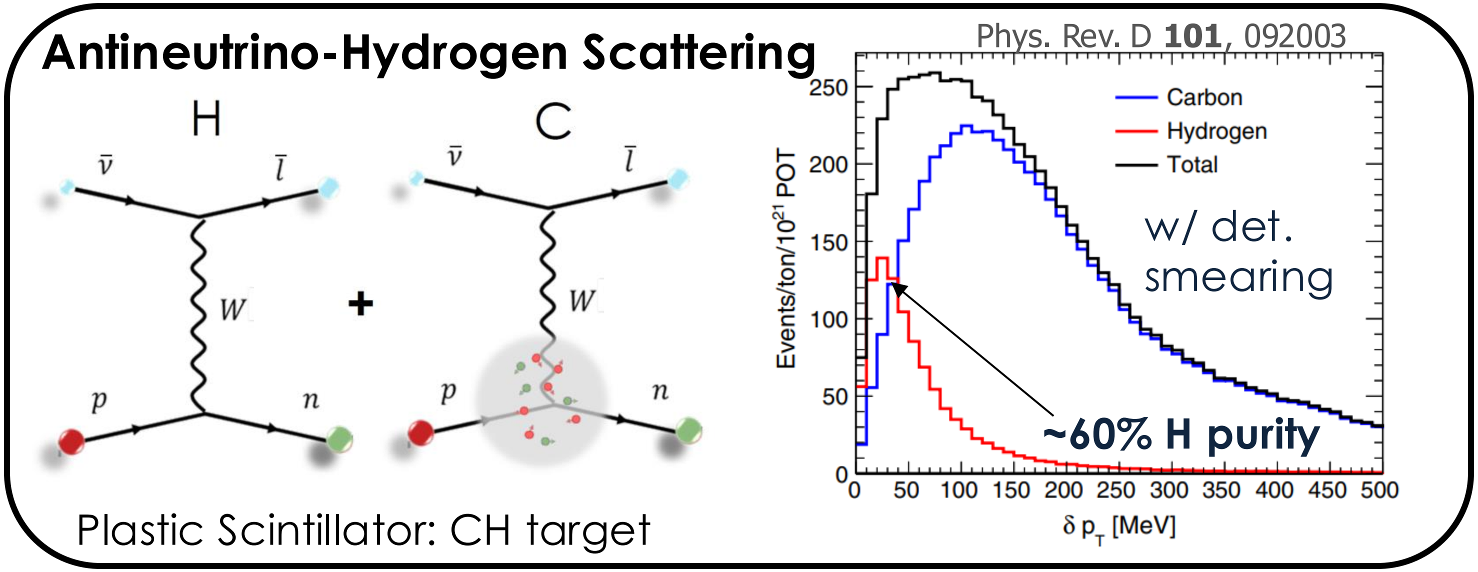


L. Munteanu et. al.

Proposal of kinematic separation using TKI reconstructed from neutrons!

Phys. Rev. D **101**, 092003



Super-FGD: a neutron detector (2018)

Phys. Rev. D **101**, 092003

ECT* 2018

L. Munteanu et. al.

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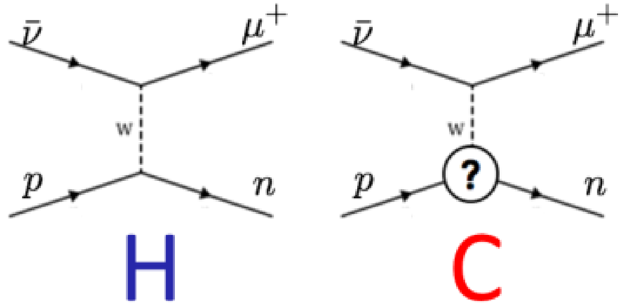
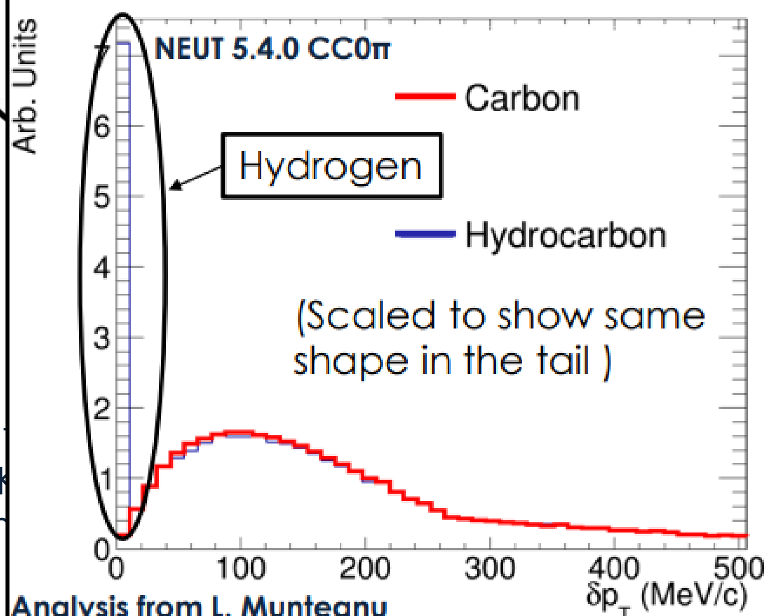
Identification of H interactions

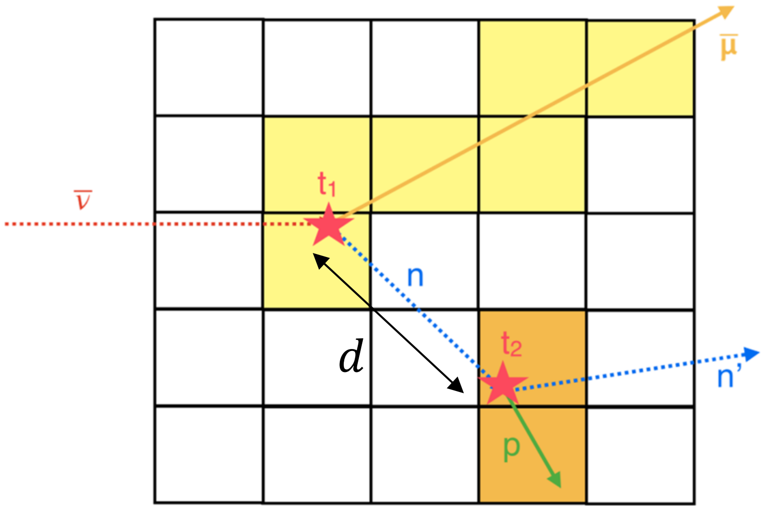




- $\bar{\nu}_\mu CC0\pi$ allows a H contribution
- H has no nuclear effects, so no transverse imbalance
- Could use STV to extract H and make a ~ nuclear-effect free cross-section!
- Factorise nuclear from nucleon physics
- Can also have near perfect kinematic neutrino energy reconstruction

Key concept: lever arm cuts

Phys. Rev. D **101**, 092003



The idea:

- Absolute time resolution is fixed
- Time resolution relative to neutron travel time is better when d is large
- Cut: $d > L$, the "lever arm" required

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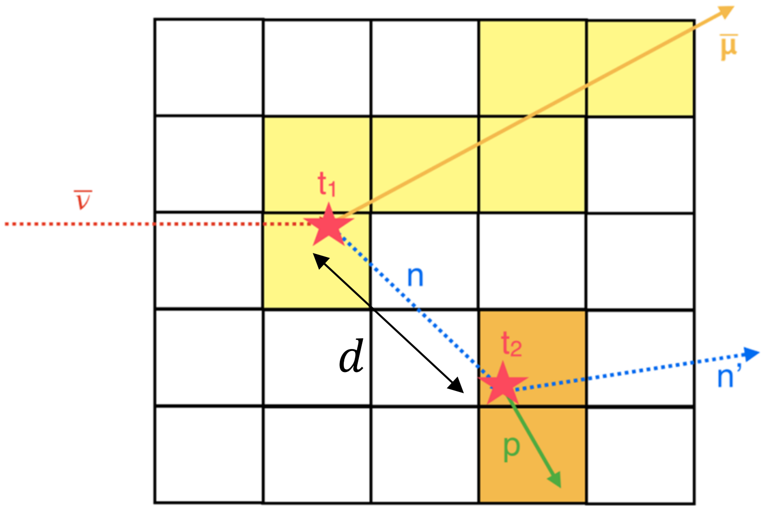

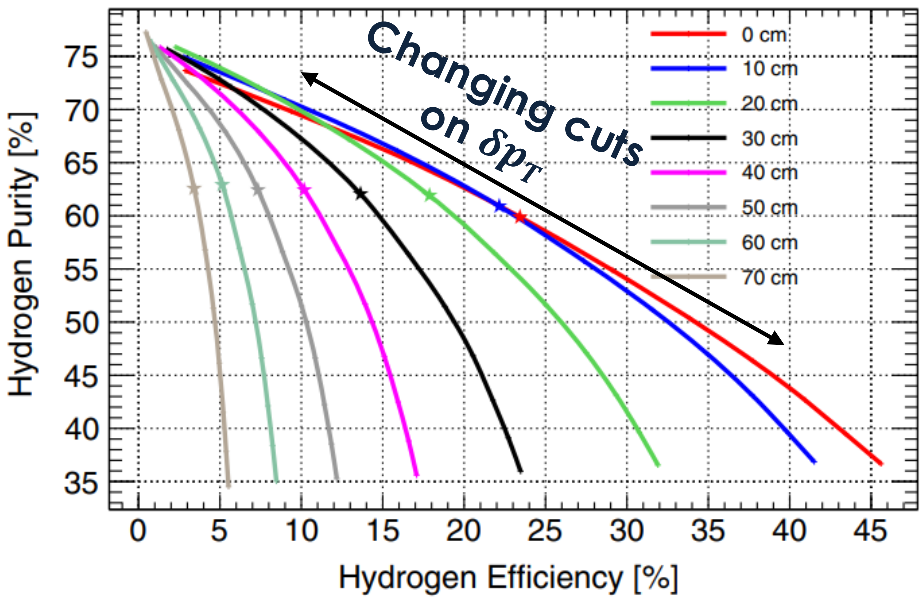

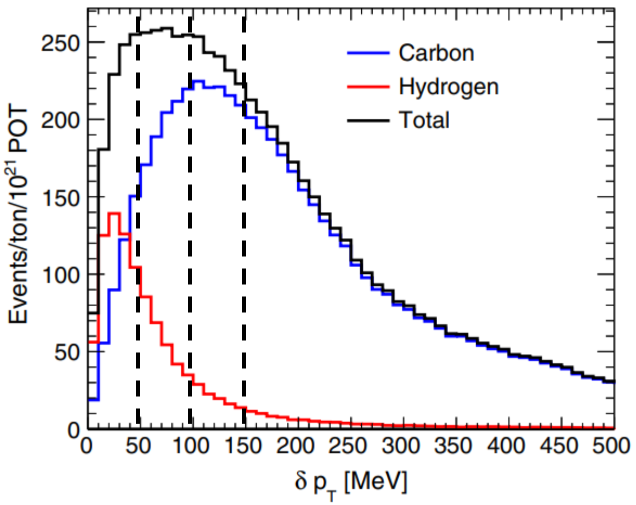

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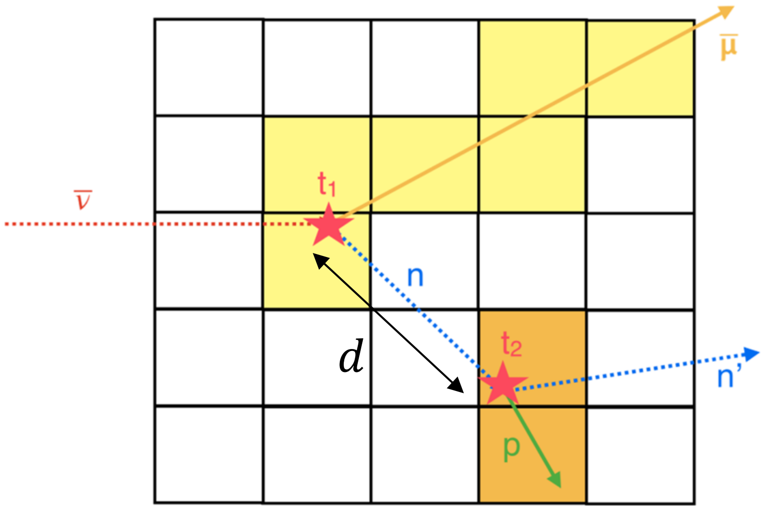

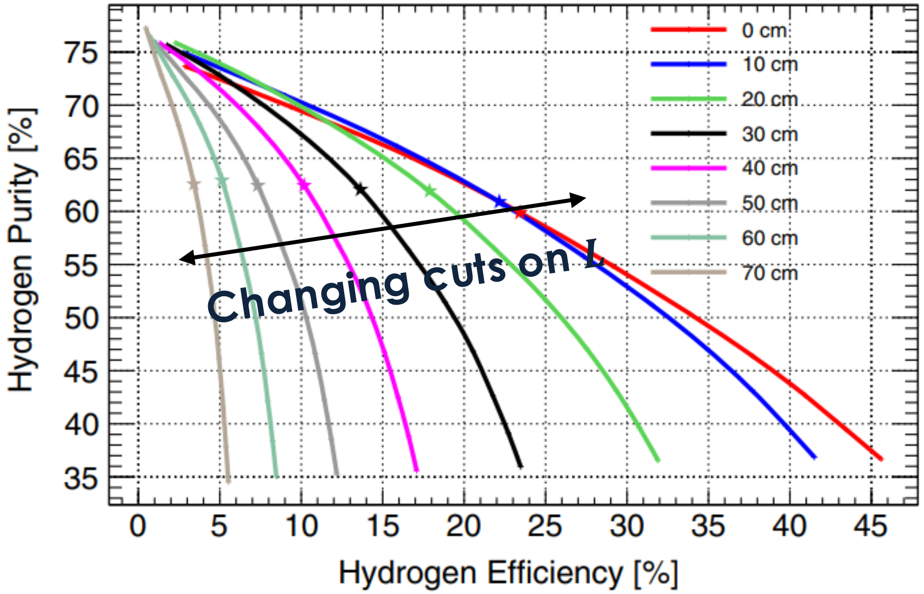

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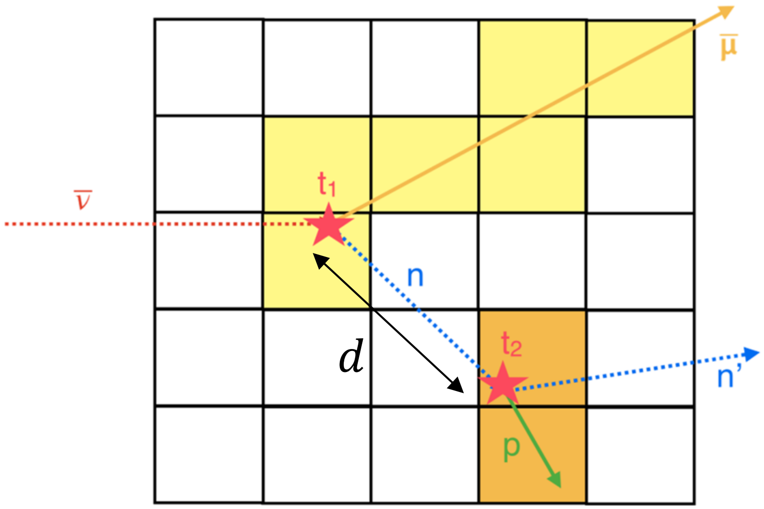
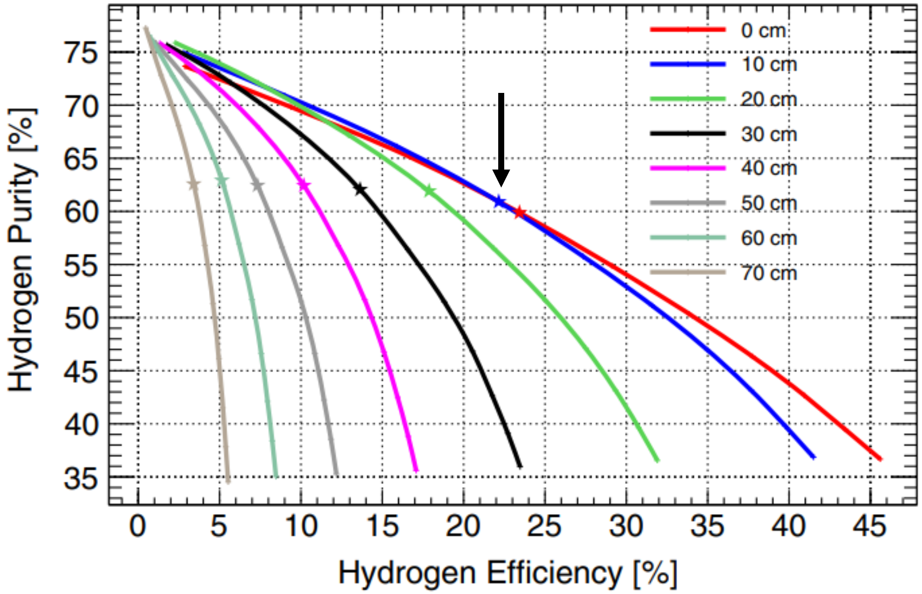
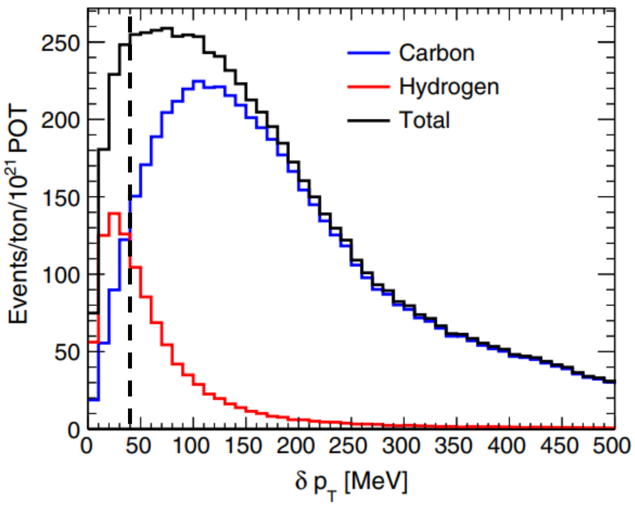
Best combination: $L = 10\ cm,\ \delta p_T < 40$ MeV







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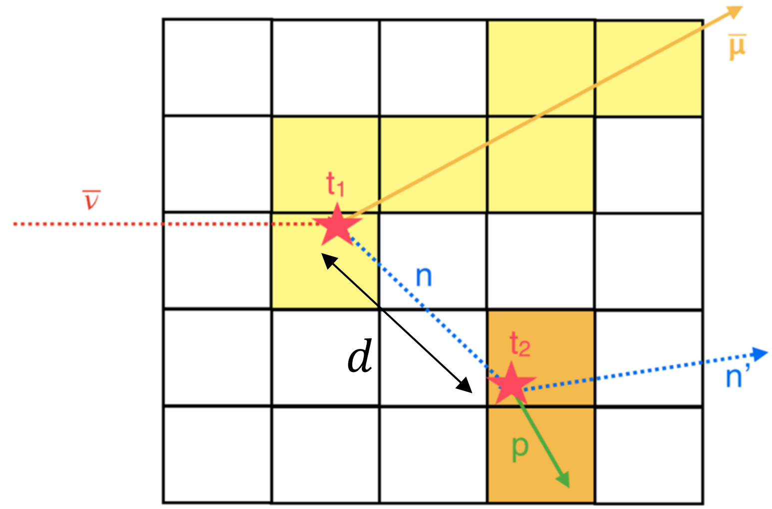

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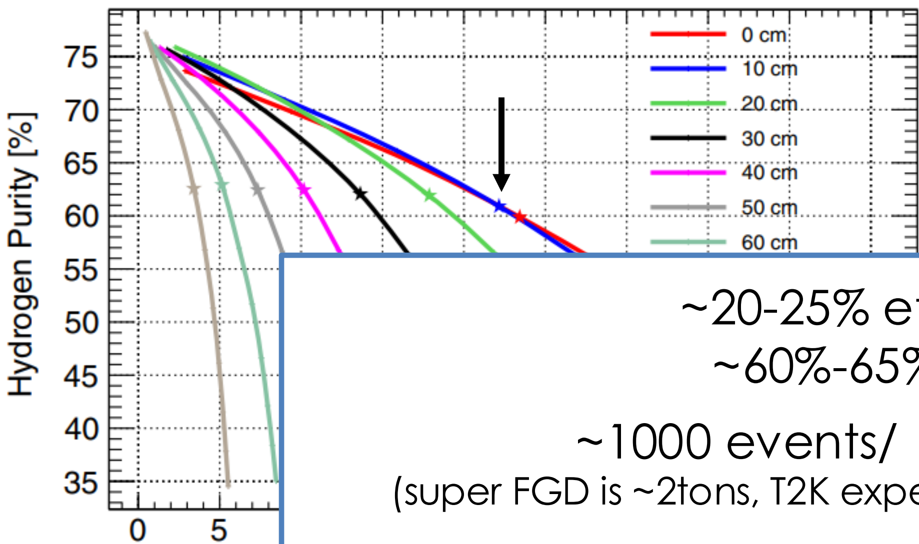
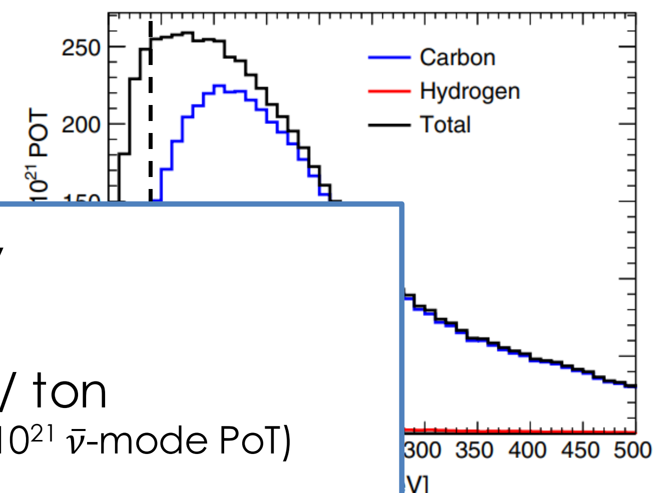




~20-25% efficiency
~60%-65% purity

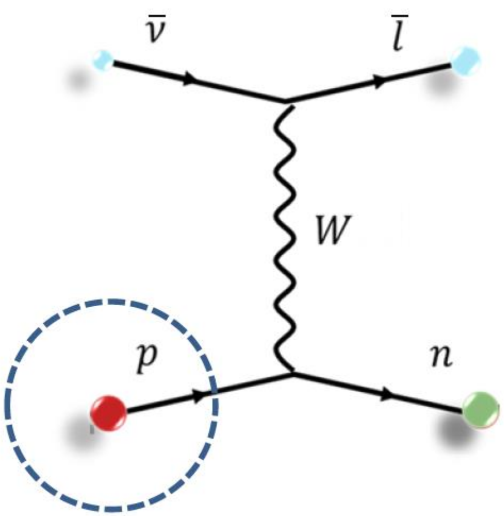
~1000 events/ 10^{21} POT/ ton
(super FGD is ~2tons, T2K expects ~4-5×10^{21} $\bar{\nu}$-mode PoT)

Note: 1st T2K CCinc double-differential analysis had 4485 events

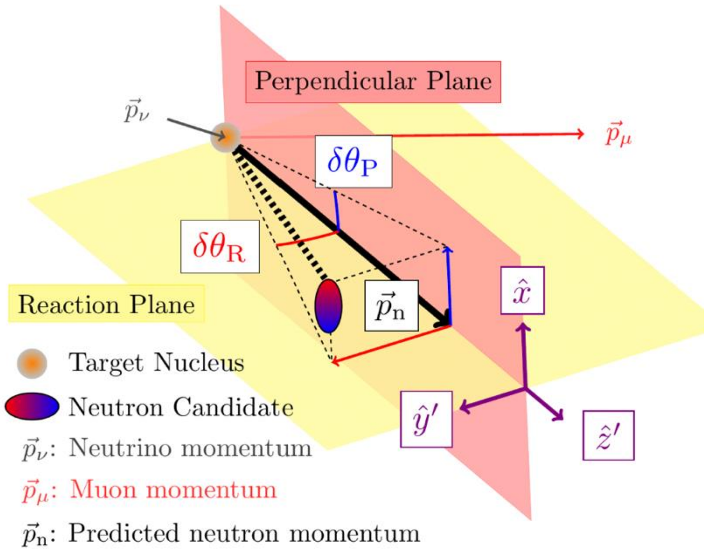
Back to MINERvA (~2023)

Kinematic imbalance for using neutrons to get at H? Sounds like a good idea!

Nature, 614, 48-53 – see next talk!

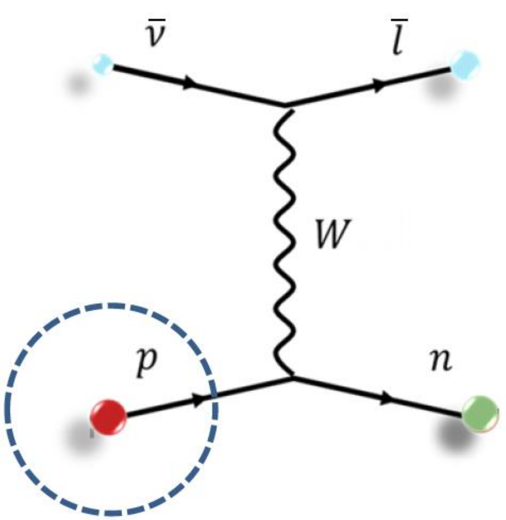


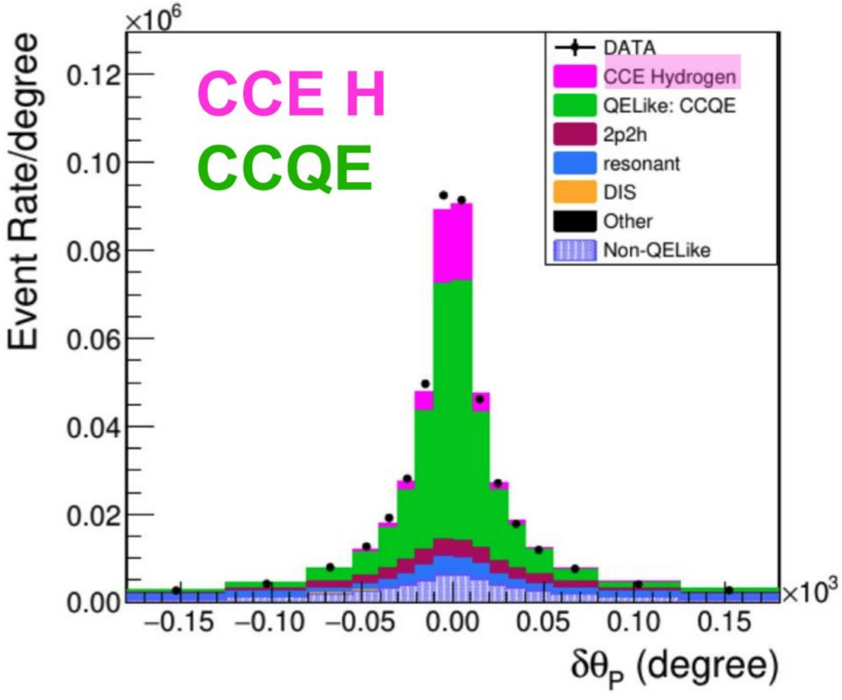
Back to MINERvA (~2023)



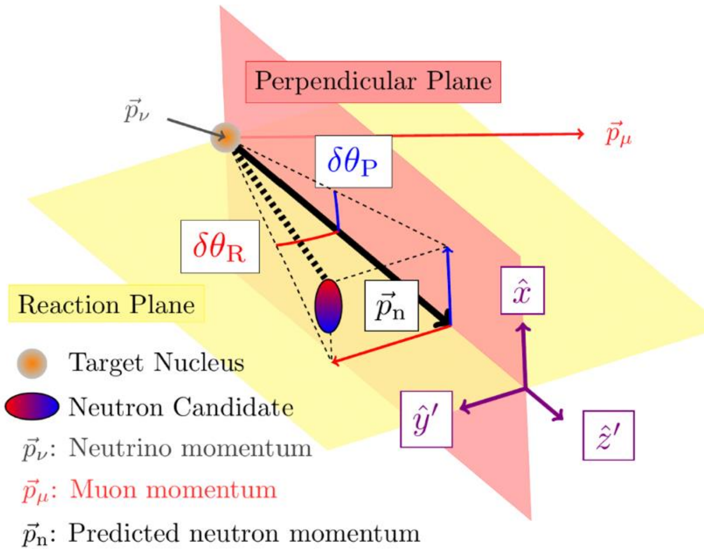
Even without neutron momenta, we can use angular imbalance

Nature, 614, 48-53 – see next talk!



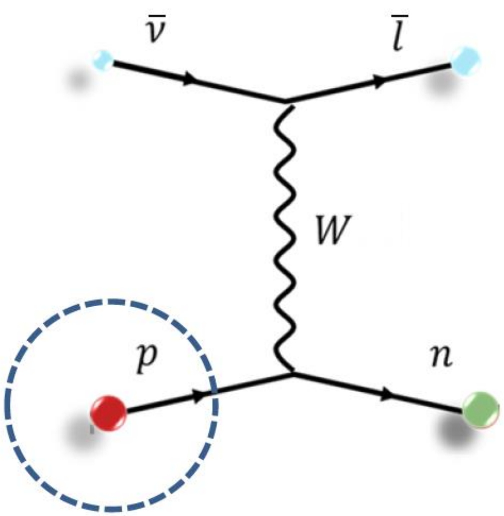


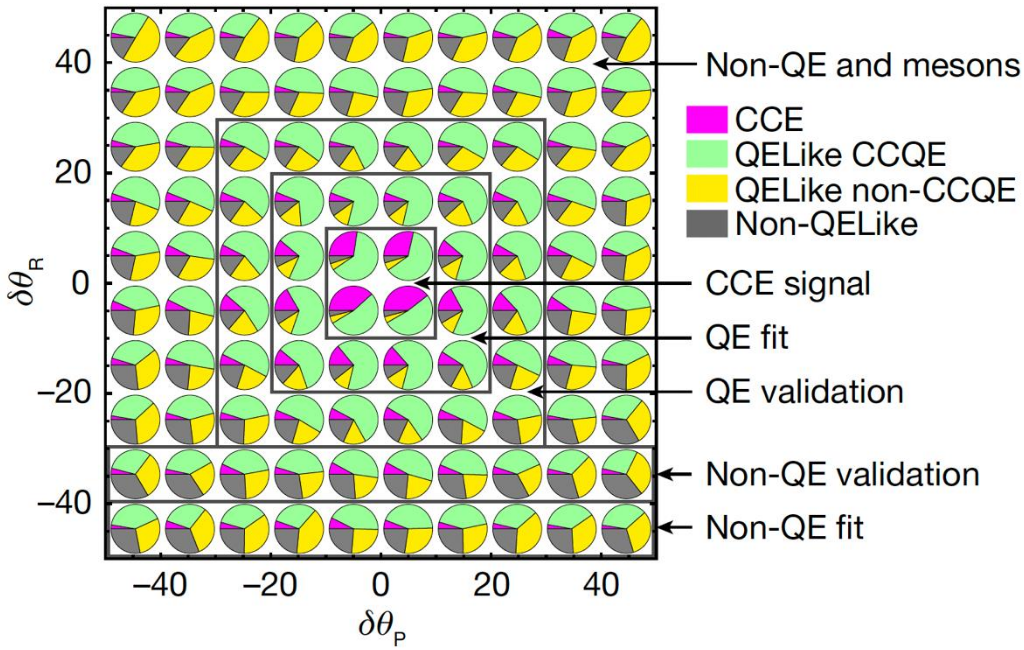
Back to MINERvA (~2023)



And why stop with the transverse plane?

Nature, 614, 48-53 – see next talk!





Back to MINERvA (~2023)

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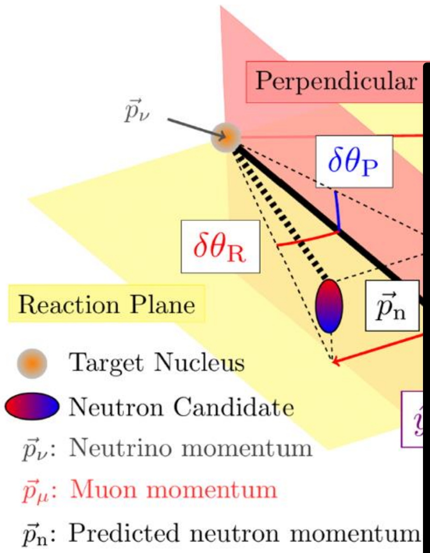
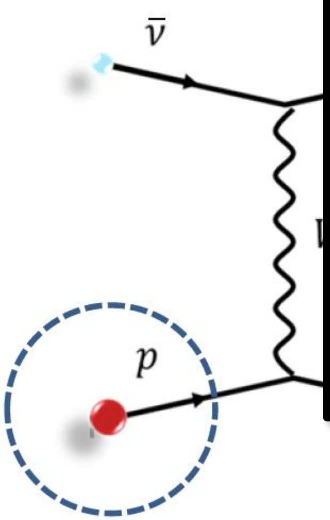
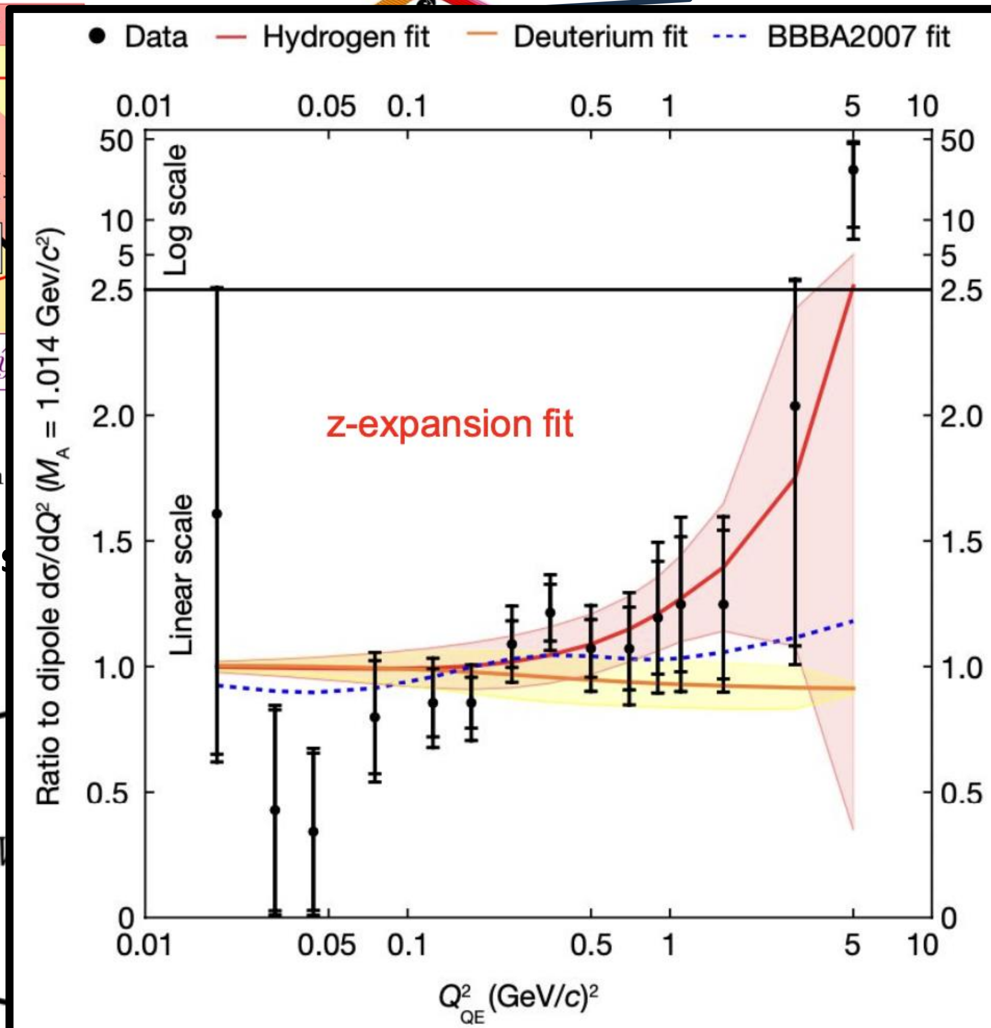
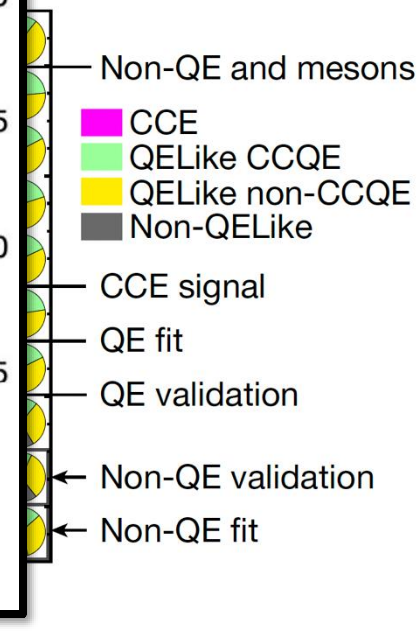


Nature, 614, 48-53 – s

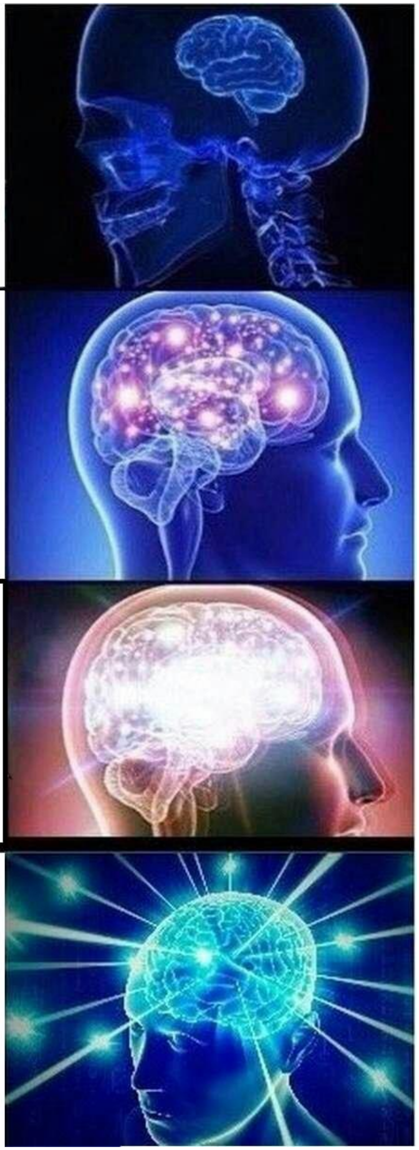


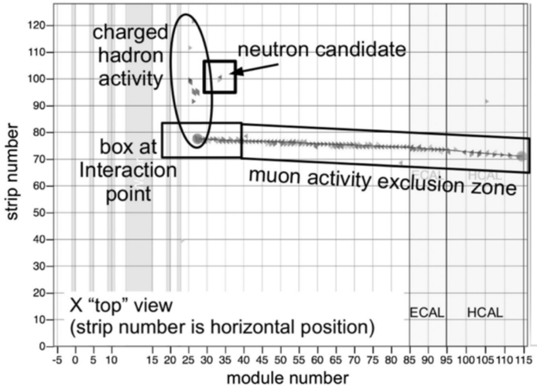




Where are we so far?

Tag some neutrons

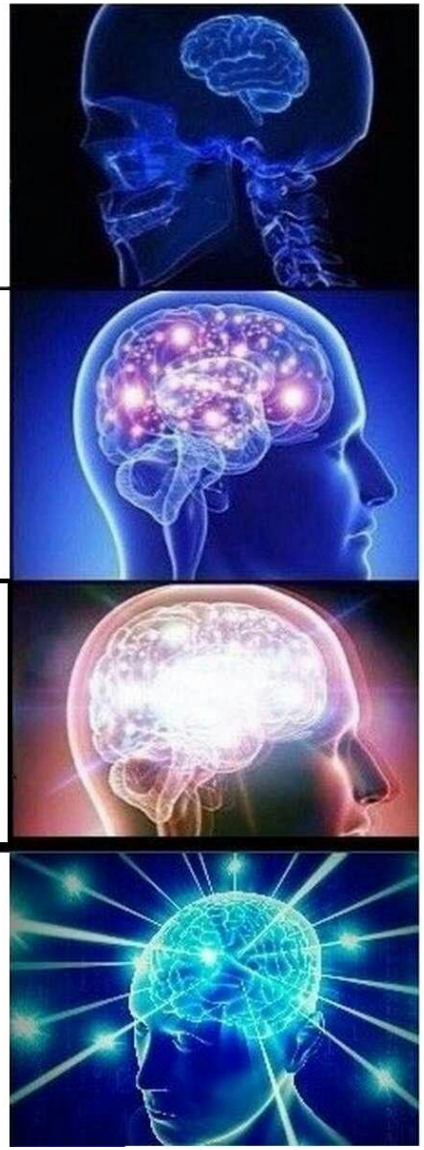


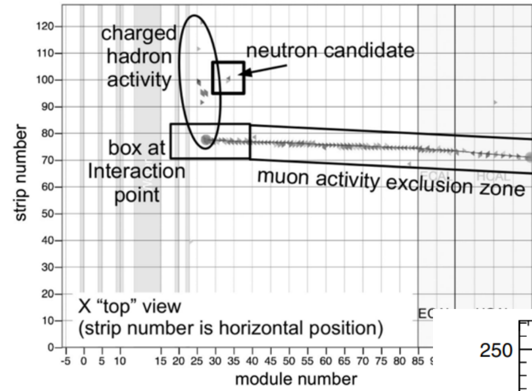


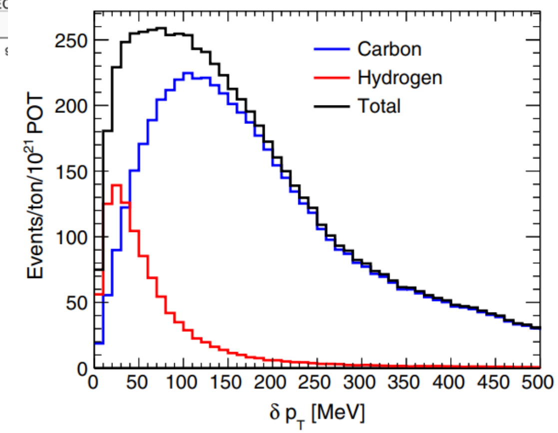
Where are we so far?

Tag some neutrons

Get at H via transverse imbalance





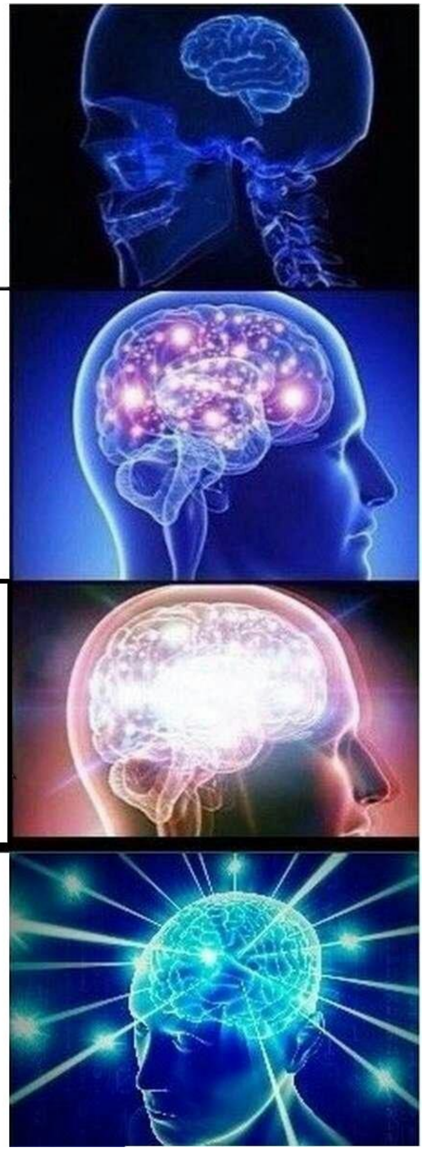


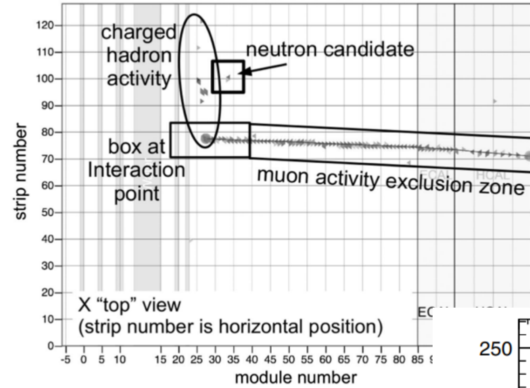
Where are we so far?

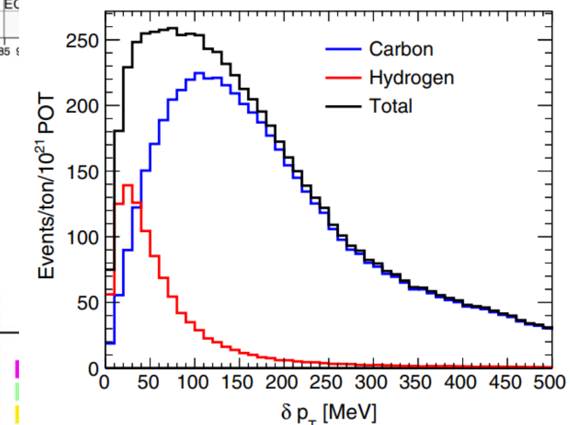
Tag some neutrons

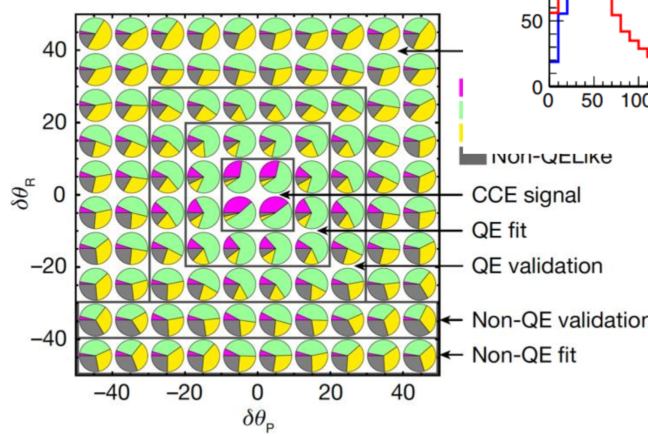
Get at H via transverse imbalance

Get at H via transverse & longitudinal angular imbalance









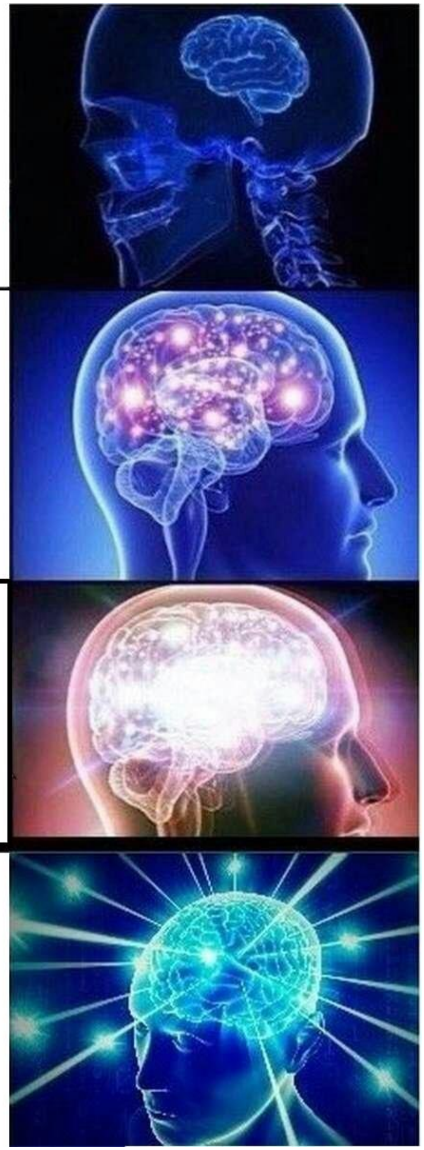
Where are we so far?

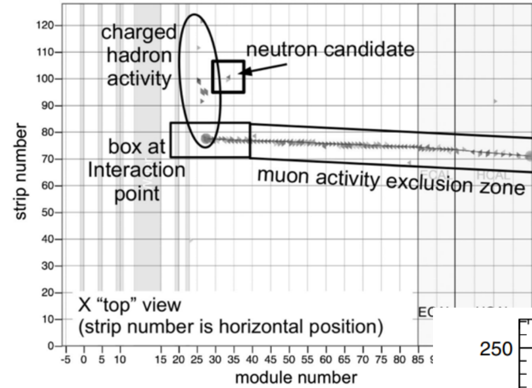
Tag some neutrons

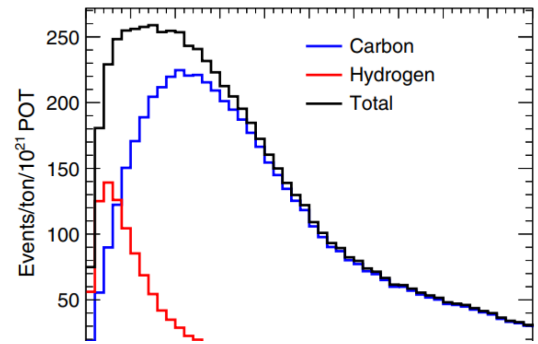
Get at H via transverse imbalance

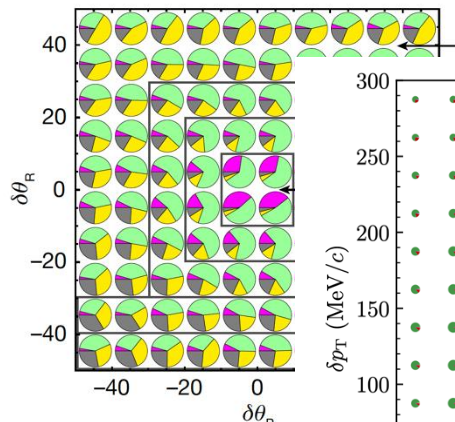
Get at H via transverse & longitudinal angular imbalance

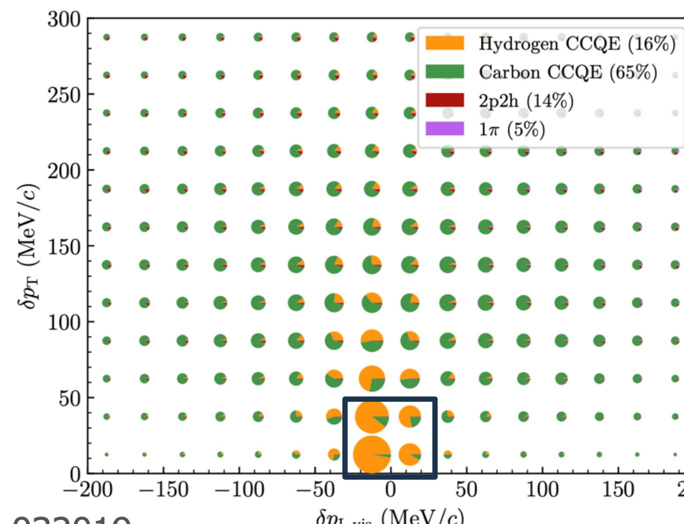
Get at H via transverse & longitudinal angular & momentum imbalance











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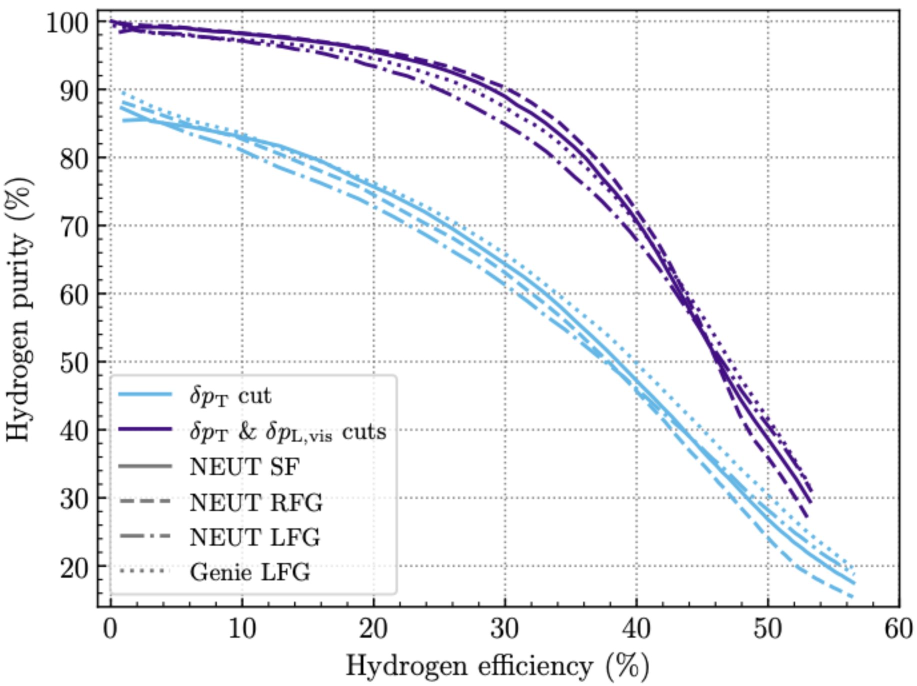
Adding a new variable for the Super-FGD

Considering longitudinal and transverse imbalance in both momenta and angle may allow Hydrogen purities of over 90%



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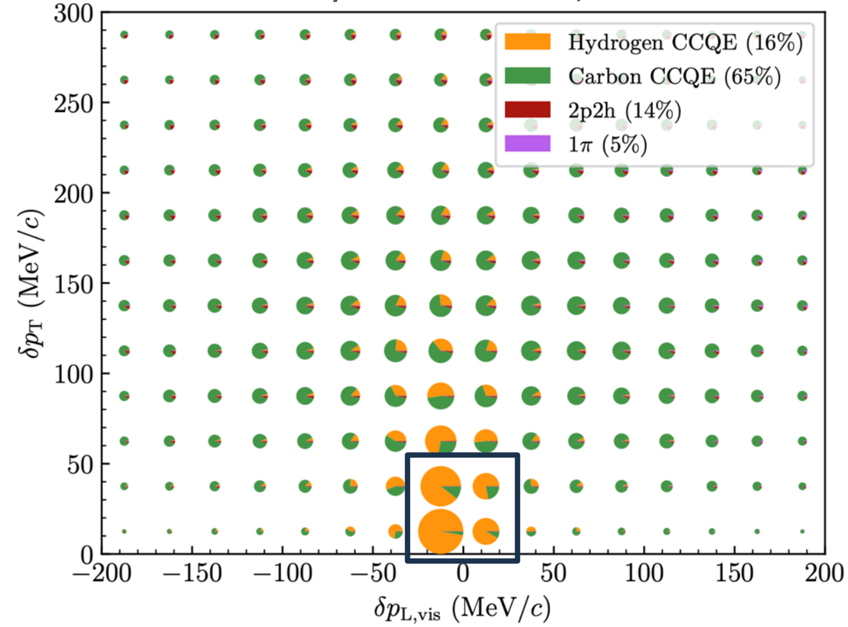

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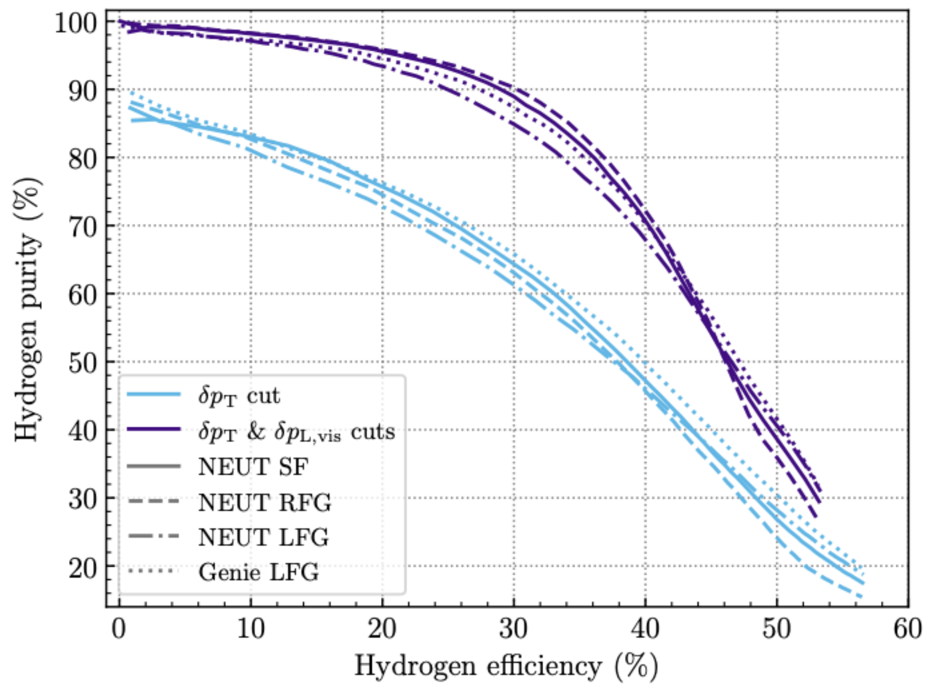

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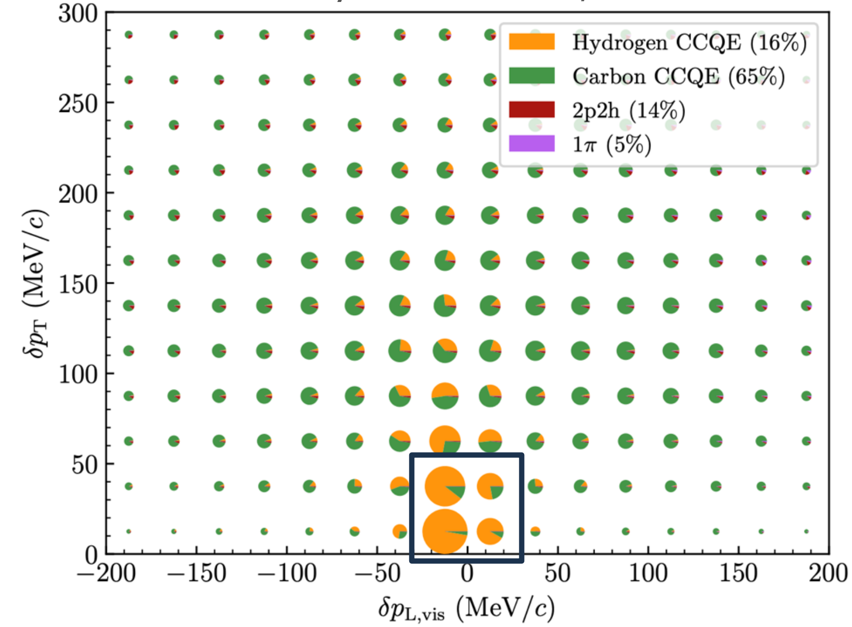

Good news for precision form-factor tests (and potential in-situ flux constraints)

Also important: STT in DUNE (~2018)

- Proponents of using an STT CH_2 detector for DUNE's SAND ND complete a more general analysis: arXiv:1809.08752

Idea:

- Cut generally in a multi-dimensional space covering TKI and simple particle kinematics to maximise H purity for fixed efficiency
- Consider multiple interaction topologies

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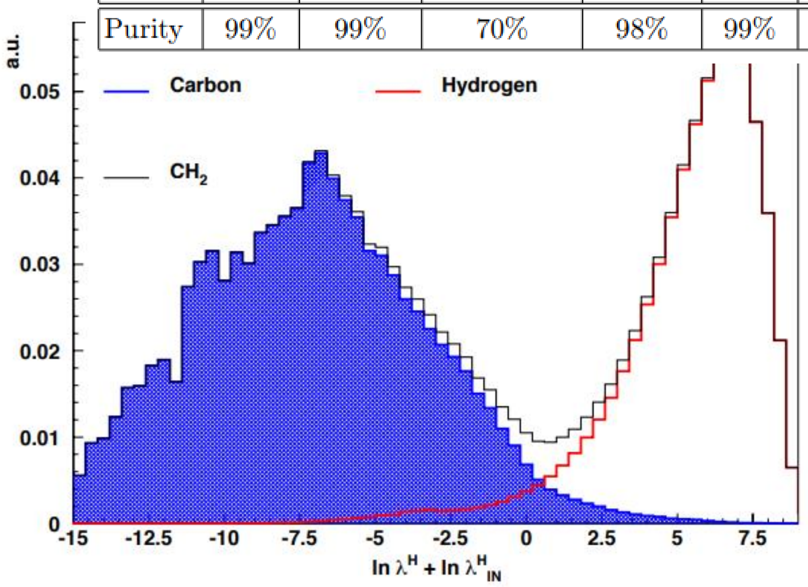
	ν_μ-H CC, $\varepsilon \equiv 75\%$				$\bar{\nu}_\mu$-H CC, $\varepsilon \equiv 75\%$					
Process	$\mu^- p \pi^+$	$\mu^- p \pi^+ X$	$\mu^- n \pi^+ \pi^+ X$	Inclusive	$\mu^+ p \pi^-$	$\mu^+ n \pi^0$	$\mu^+ n$	$\mu^+ p \pi^- X$	$\mu^+ n \pi \pi X$	Inclusive
Purity	99%	99%	70%	98%	99%	90%	80%	98%	90%	86%



Very high efficiency + purity, but note:

- Assumes a simple detector smearing
- Controlling model dependence in such complicated multi-dimensional cuts may be challenging

Summary and next steps

- Measuring neutrino interactions on hydrogen is useful:
  - In-situ flux shape constraints (perfect energy reconstruction)
  - Untangle nucleon and nuclear interaction physics
- Deviations from kinematic imbalance allows separation of interactions on H from a CH target (scintillator)
- Reconstruction of neutrons provides a measure of kinematic imbalance for $\bar{\nu}$CCQE interactions
- First measurement from MINERvA: constraints on F_A!
  - No information on neutron momentum (insufficient ToF resolution) leads to a relatively low purity ~30%
- T2K's new SuperFGD offers potential for measurements
  - Use of TKI: ~60% purity, use of T+GKI: ~90% purity
  - Expect first measurements in the next ~2 years
- Further improvements possible with DUNE's ND