Neutrino Flux Measurement Using Neutrino-Hydrogen Interactions in the DUNE Near Detectors

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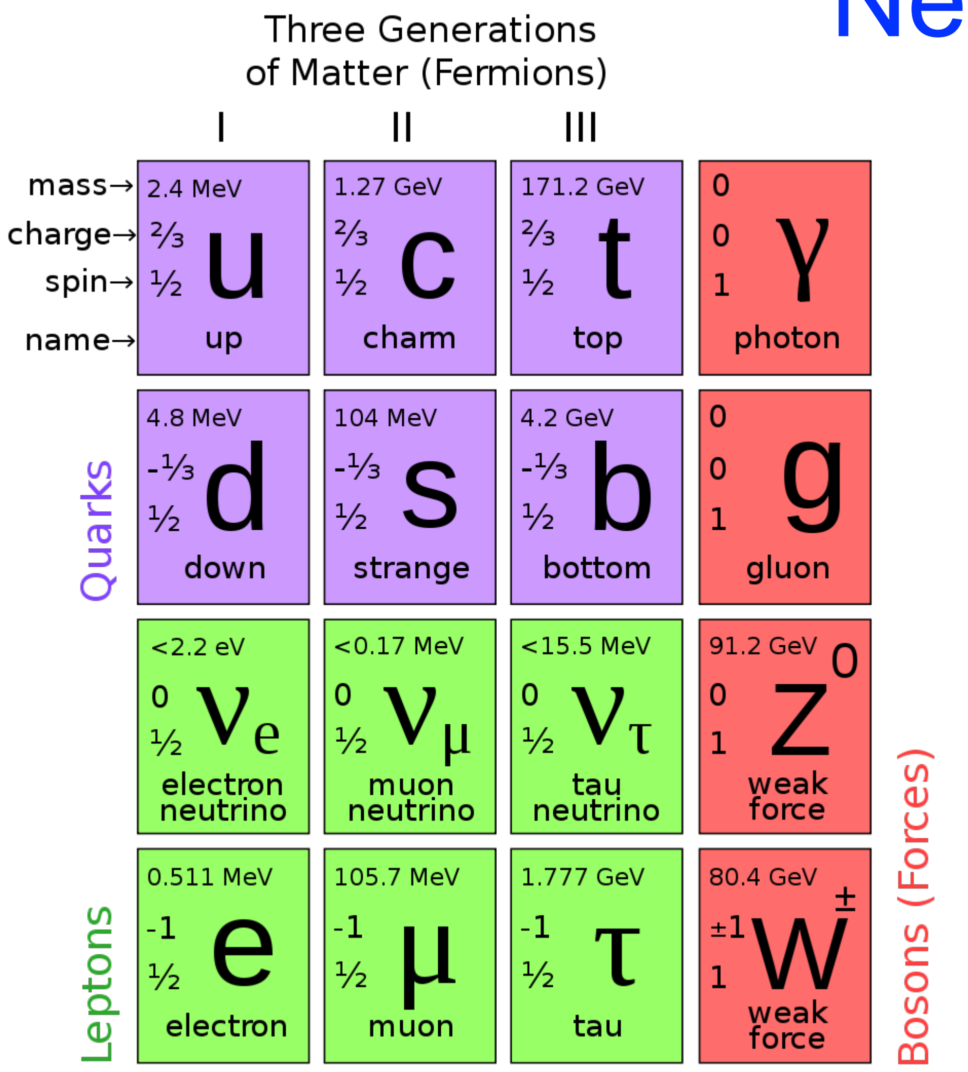
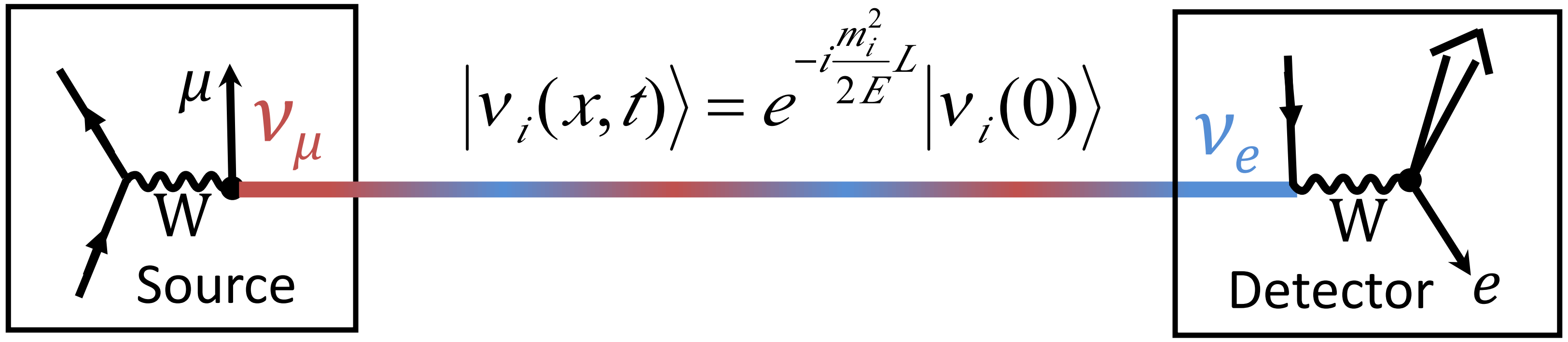
Seminar @BNL 07/11/2019

Neutrino Oscillation



- Neutrinos in standard model:
  - Massless, neutral leptons, week interactions only.
- Experiments has observed that neutrinos created in one flavor can be detected in another flavor at a distance.



$$|\nu_i(x,t)\rangle = e^{-i\frac{m_i^2}{2E}L}|\nu_i(0)\rangle$$

This means:

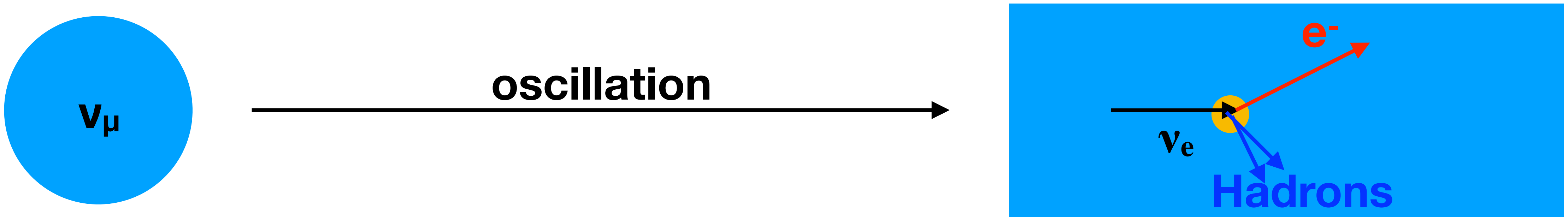
- Neutrinos have mass.
- Each flavor state is a superposition of different mass states.
- New physics beyond standard model!

Flavor **mass**

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

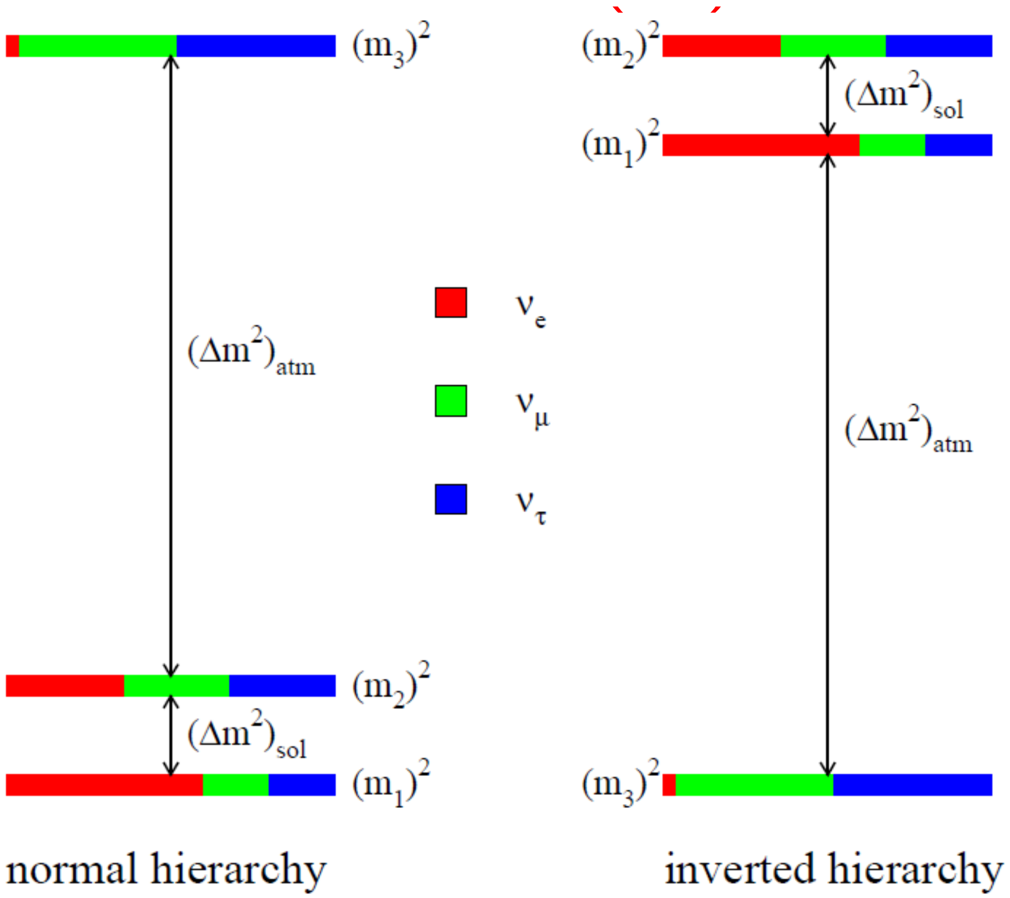
Neutrino Oscillation

Intensive Neutrino source **Massive Detector**



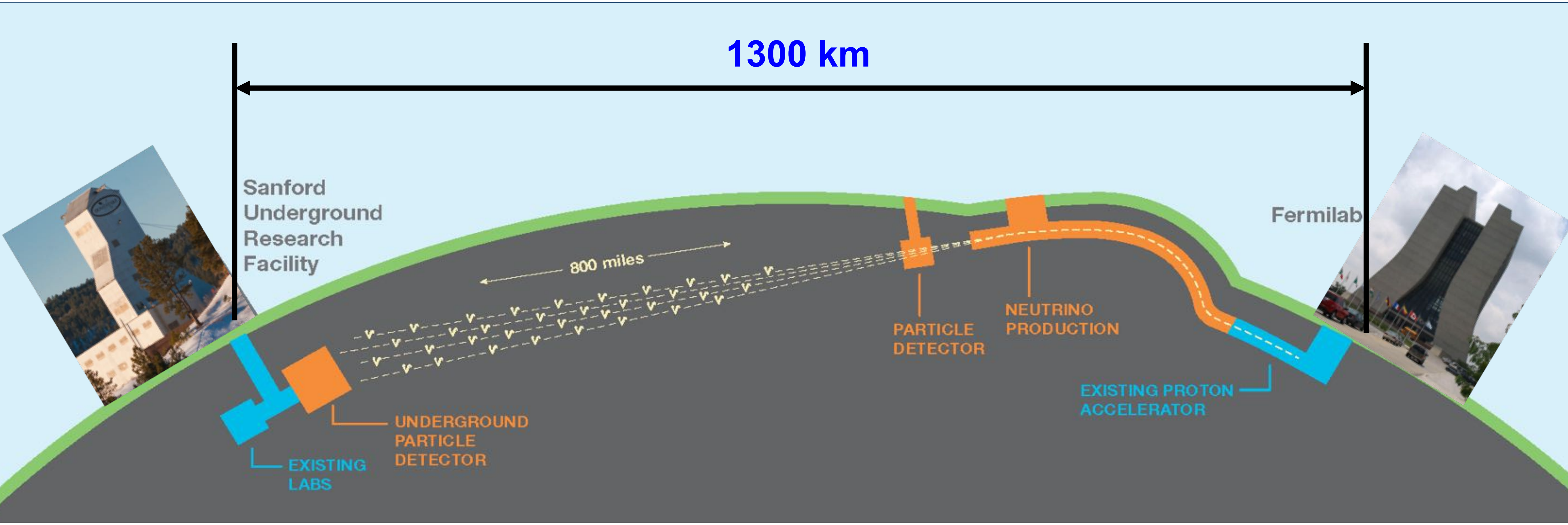
$$p(\nu_\mu \longrightarrow \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{13}L}{4E}$$

- Measurement of neutrinos oscillations could answer important questions like:
  - Mixing angles
  - Neutrino mass ordering
  - Leptonic CP-violation
- Still other questions: absolute mass scale, mass origin…



Introduction to DUNE

- **D**eep **U**nderground **N**eutrino **E**xperiment
- The next generation long-baseline neutrino oscillation experiment in the US



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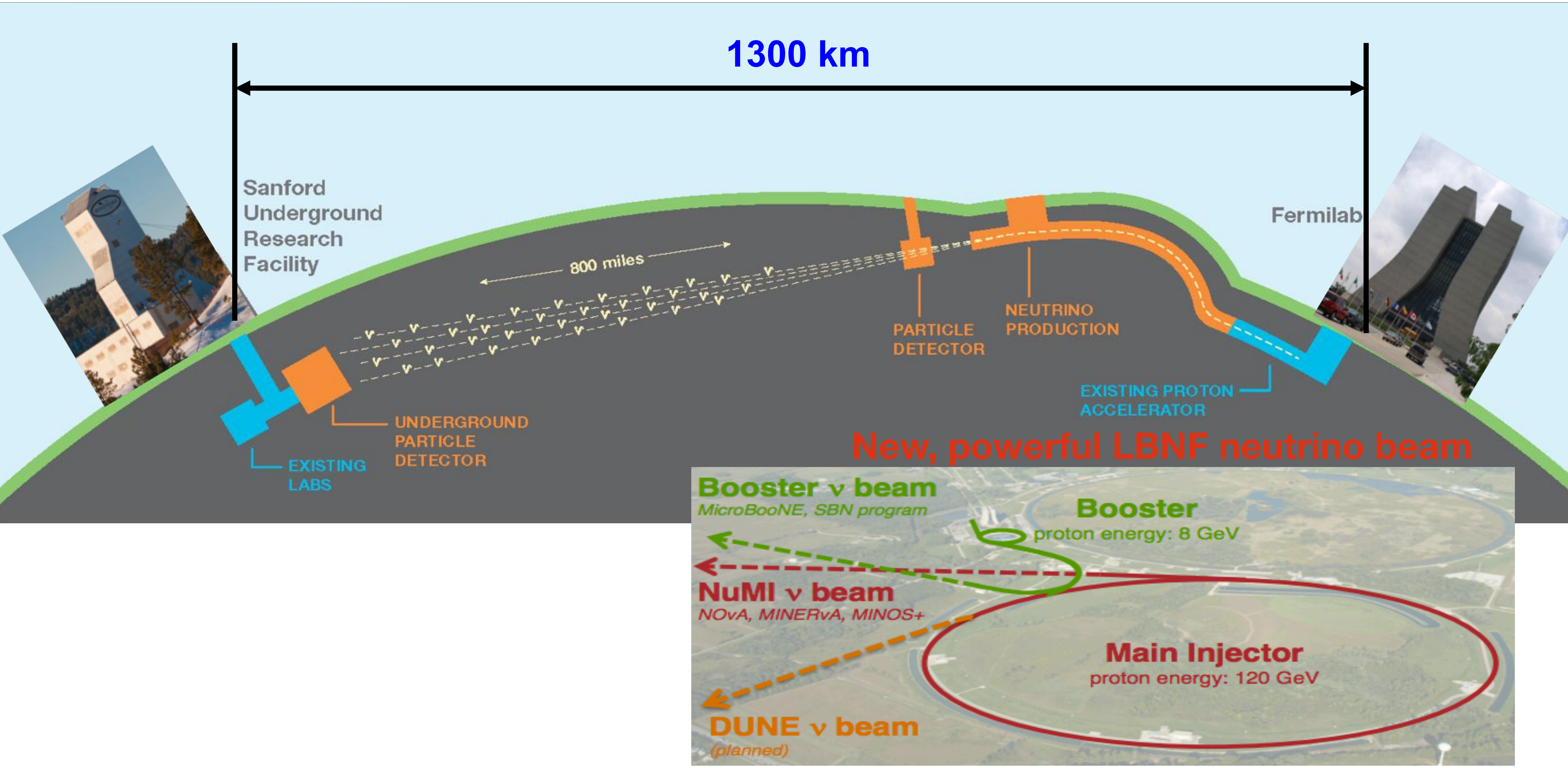

New, powerful LBNF neutrino beam

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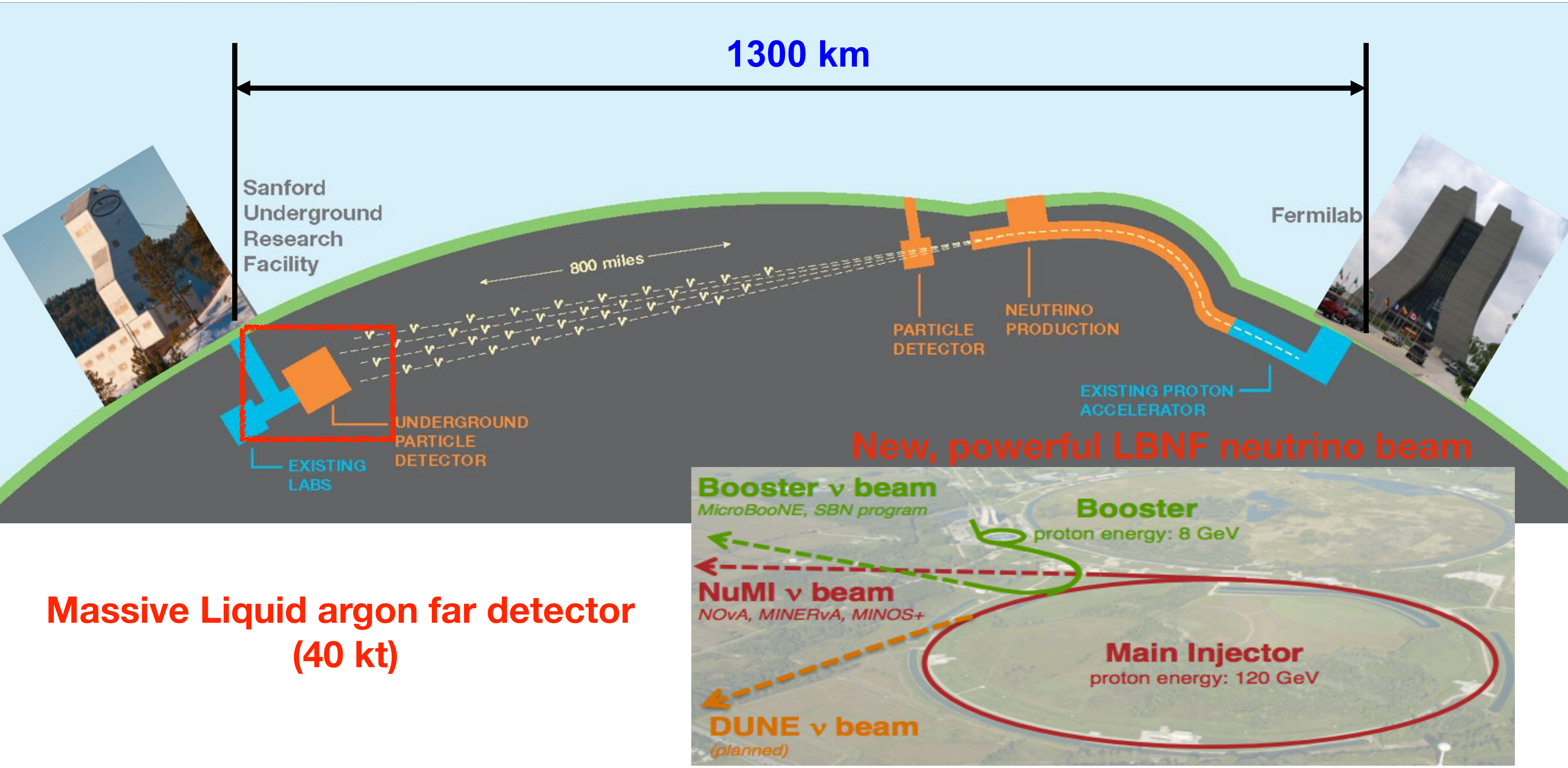

Massive Liquid argon far detector (40 kt)

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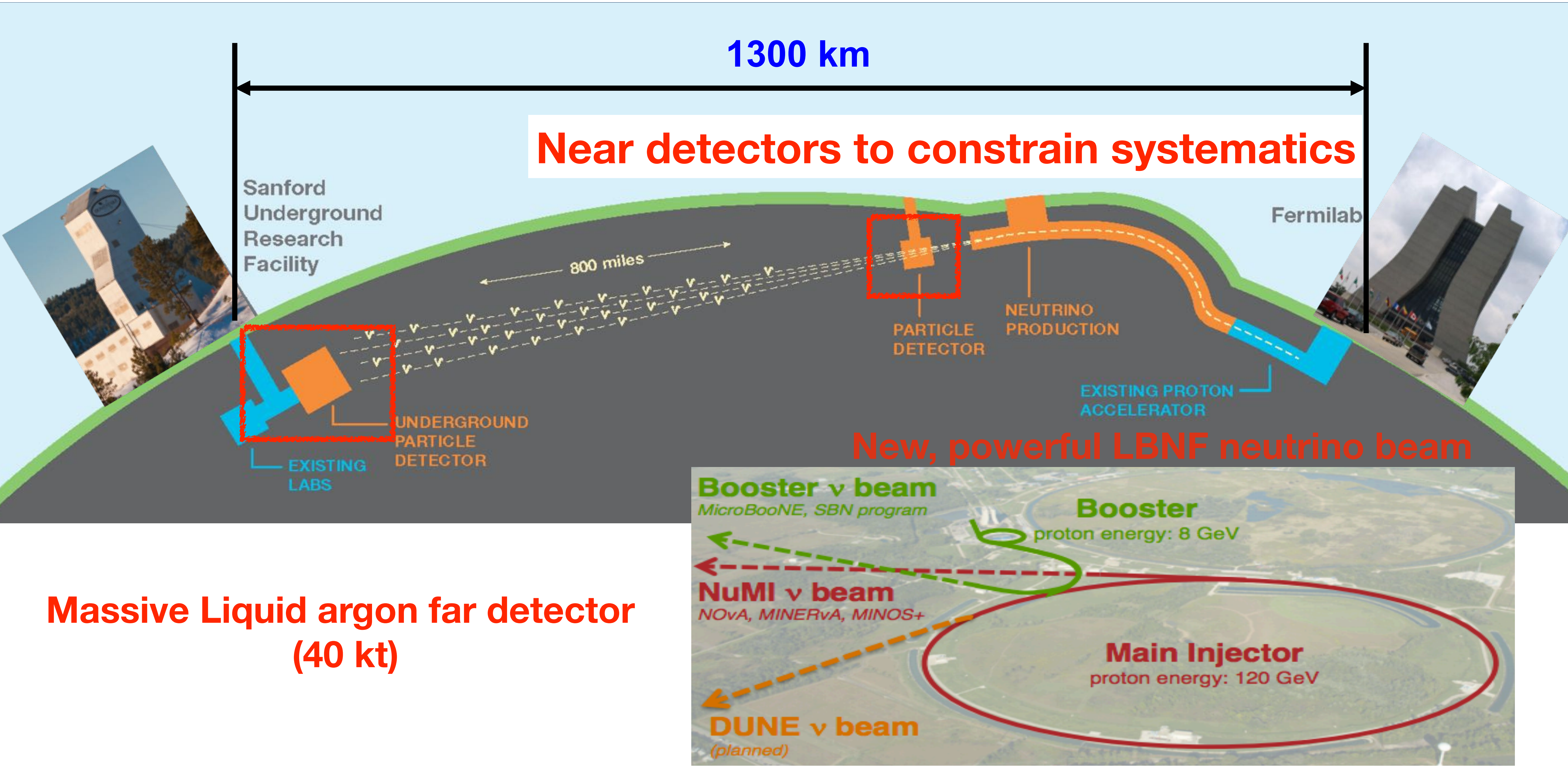

Near detectors to constrain systematics

New, powerful LBNF neutrino beam

Massive Liquid argon far detector (40 kt)

Why Do We Need Near Detectors?

FD:

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \Phi(E_\nu) \boxed{P_{osc}(E_\nu)} \sigma(E_\nu) R_{det}(E_\nu, E_{rec})$$

Number of events observed in the FD

Neutrino flux

Oscillation probability

Cross section

Detector response

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Number of events observed in the FD

Neutrino flux

Oscillation probability

Detector response

Cross section

Need to reconstruct Eν correctly!

ND:

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \Phi(E_\nu) \boxed{\xcancel{P_{osc}(E_\nu)}} \sigma(E_\nu) R_{det}(E_\nu, E_{rec})$$

Number of events observed in the ND

Not the same neutrino flux

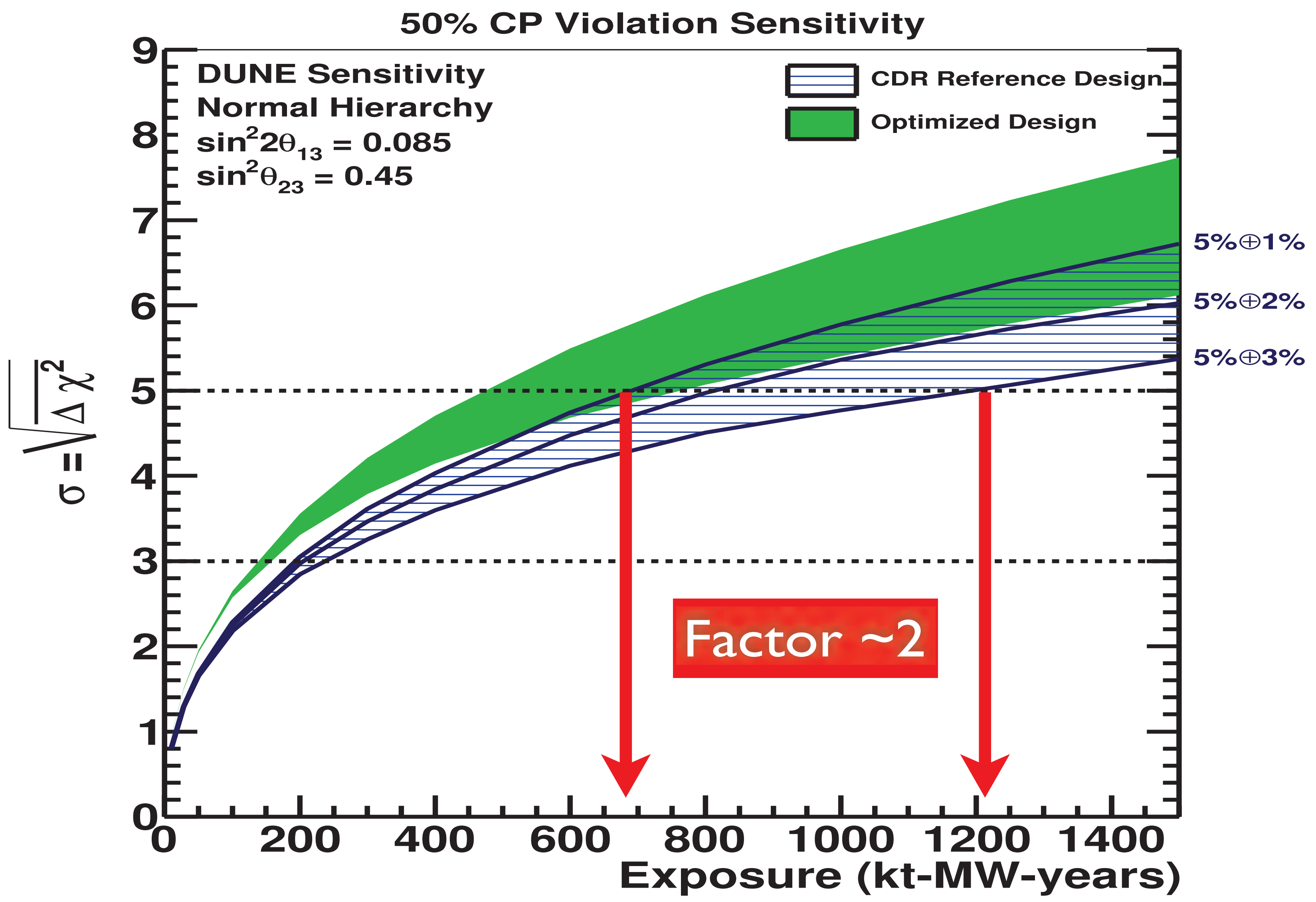
Oscillation probability (zero in the ND)

Not the same Detector response

Cross sections? Need Ar target

Need ways to disentangle those factors!

Uncertainties to Neutrino Oscillations



- **We need new detector technologies and new analysis approach to bring down the systematic uncertainties for DUNE.**

Flux Measurements

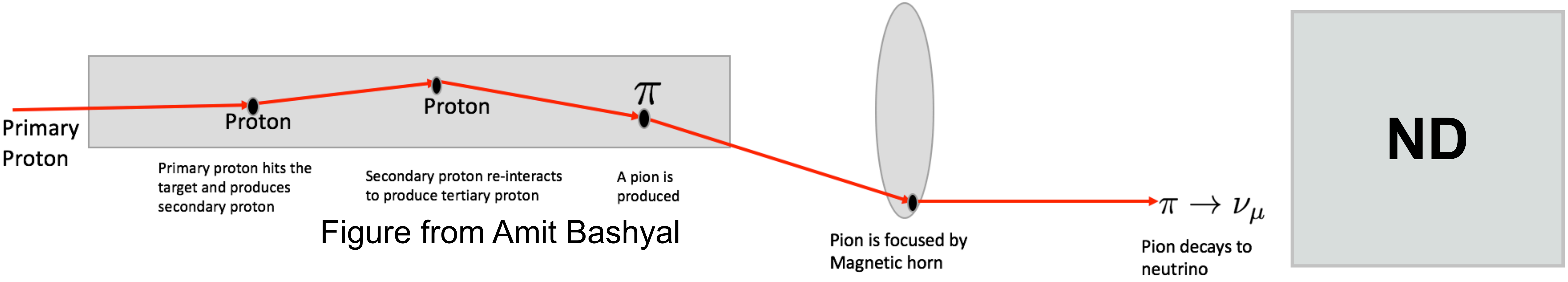


Figure from Amit Bashyal

Flux Measurements

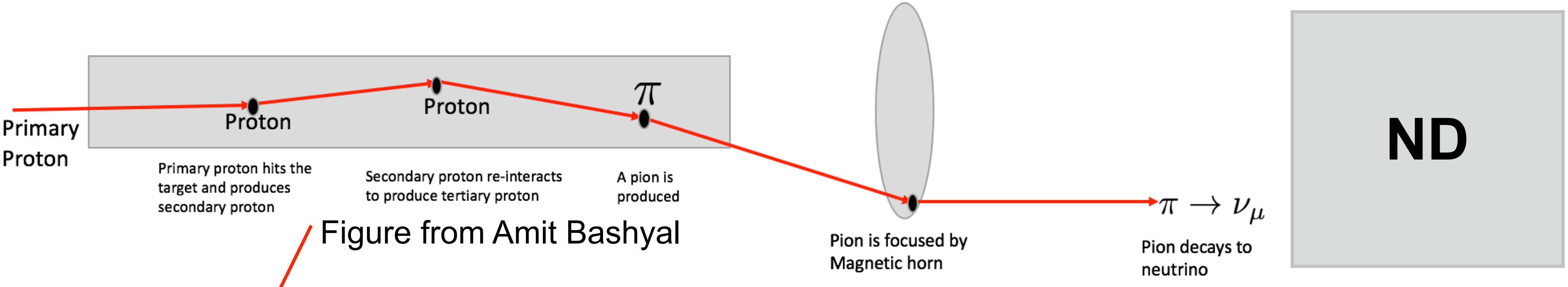
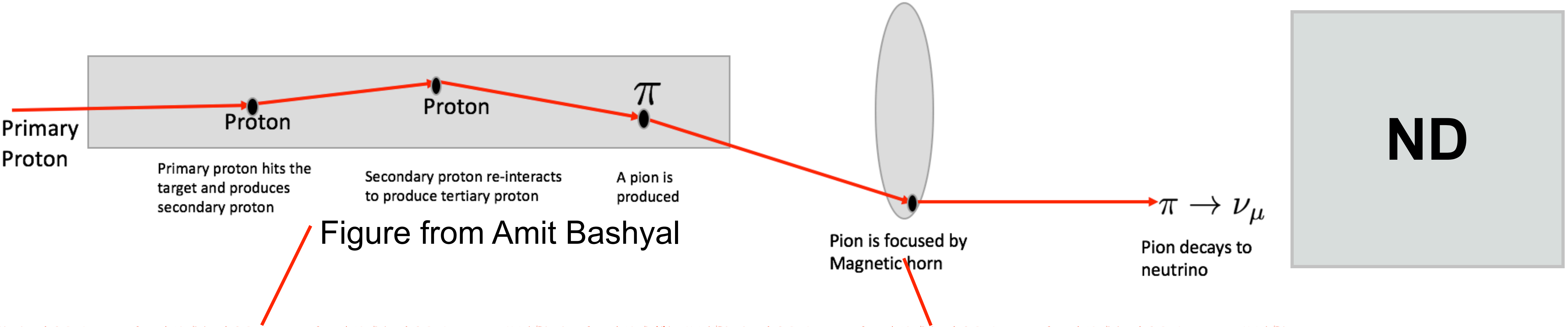


Figure from Amit Bashyal

Hadron production uncertainty (~8%)

Flux Measurements



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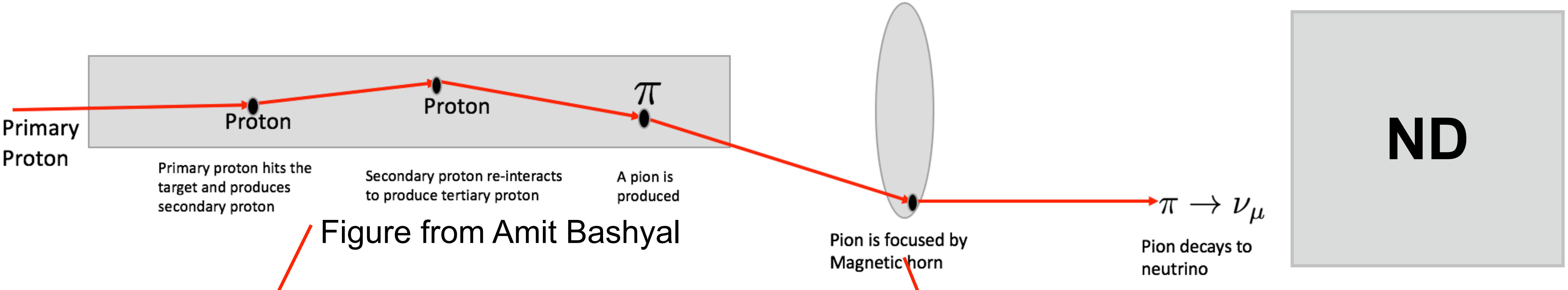
Hadron production uncertainty (~8%)

Beam focusing uncertainty (~4%)

Flux Measurements



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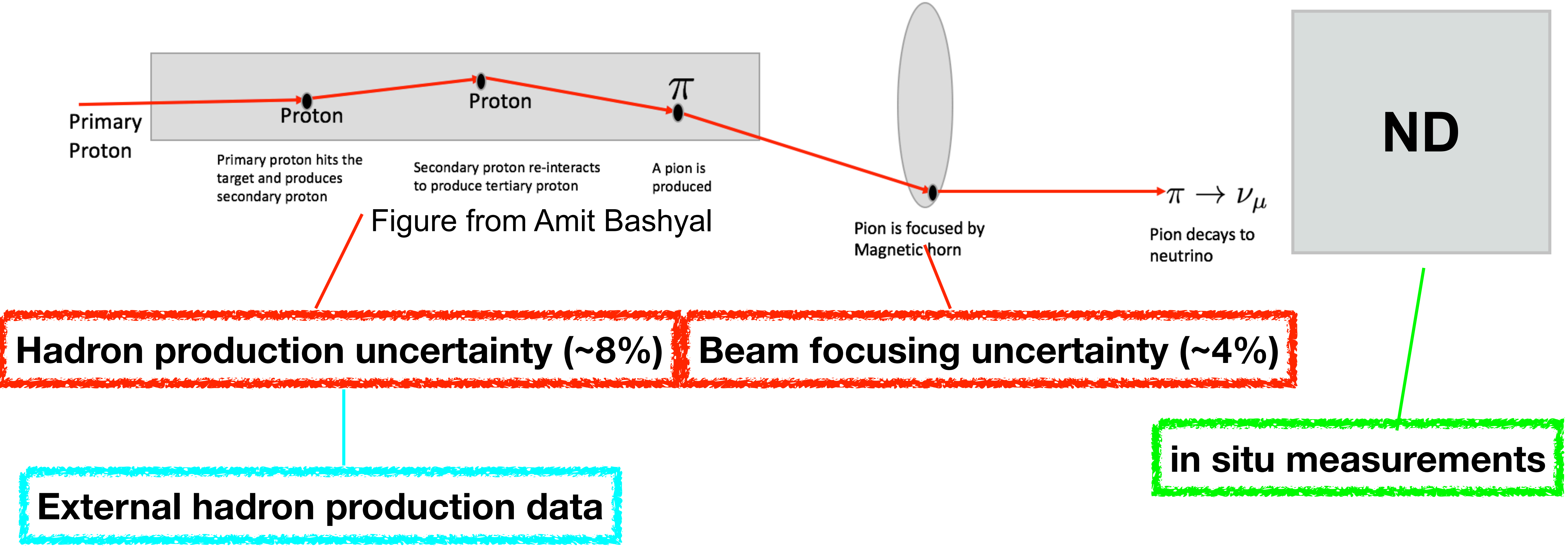
External hadron production data

Flux Measurements



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in situ measurements

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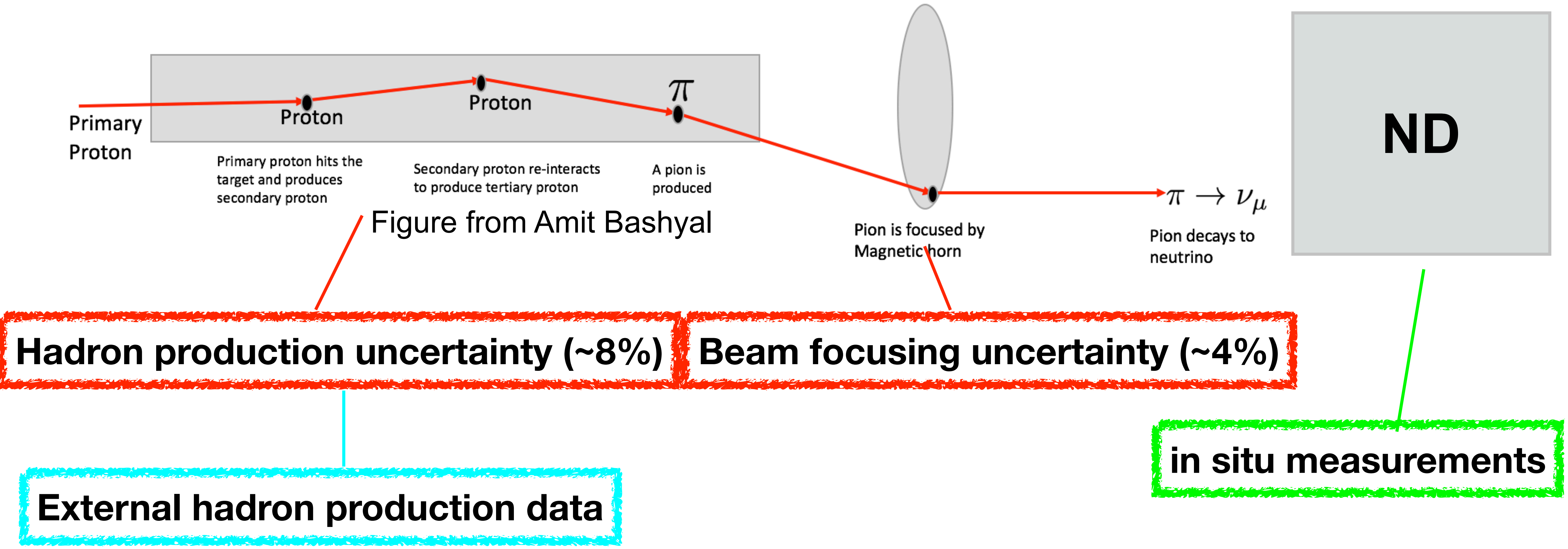

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in situ measurements

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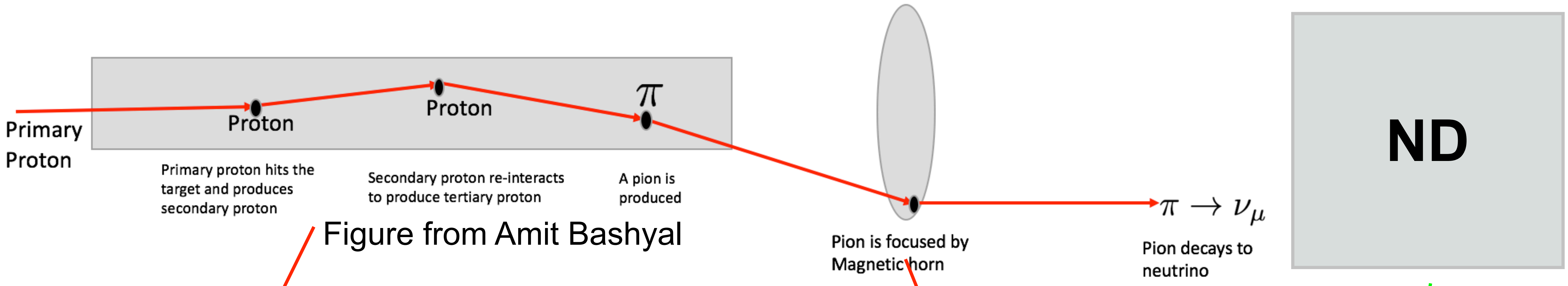
Flux Measurements



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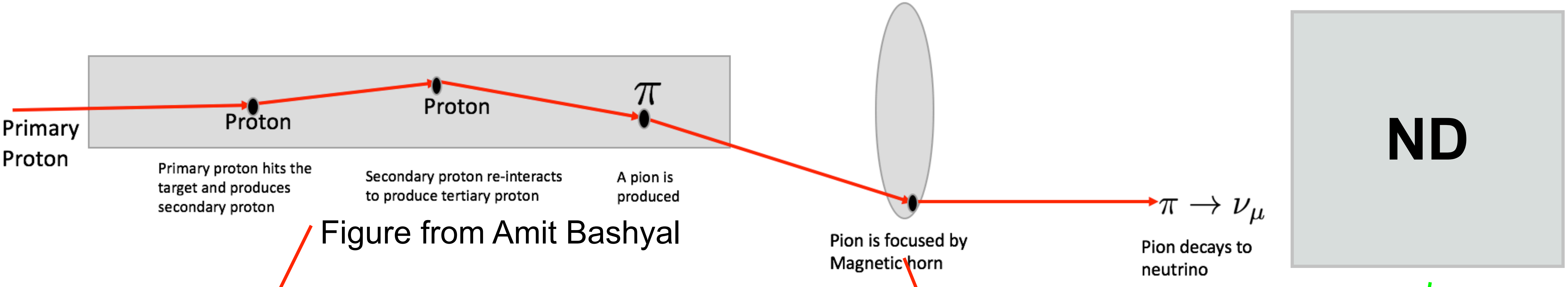
The observable

What to measure

Flux Measurements



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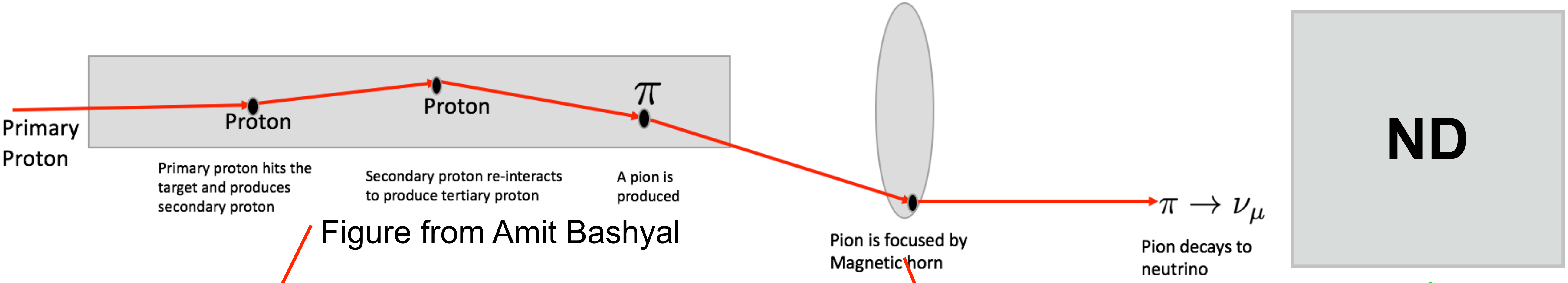
What to measure

Must has small uncertainty!

Flux Measurements



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The observable

What to measure

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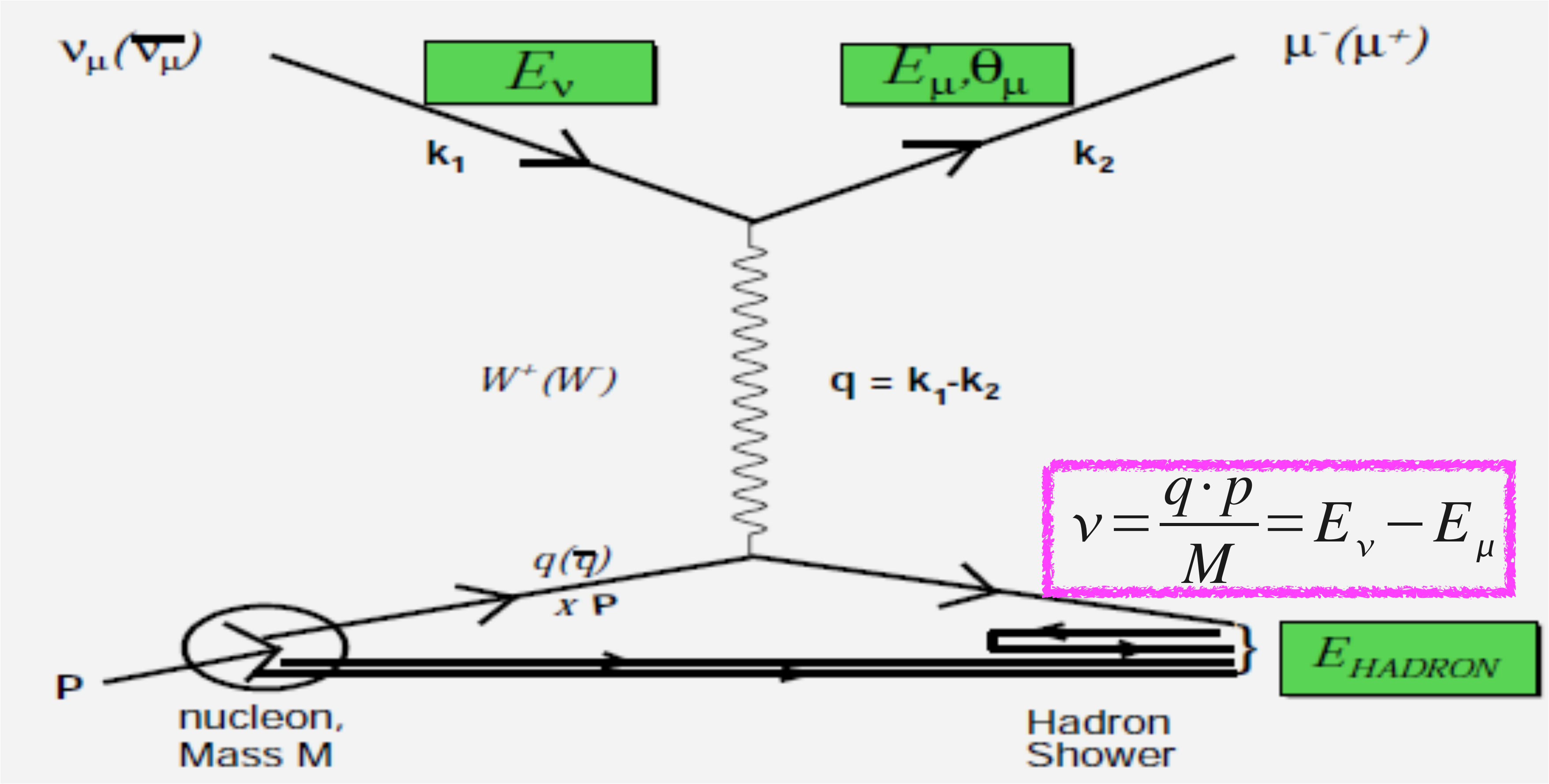
Neutrino-electron scattering

Low-ν method
(focus of this talk)

Low-ν Flux Measurement



- At very low $\nu = E_\nu - E_l$, the cross section is independent from E_ν:

$$\boxed{\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)} \qquad \nu/E \to 0.$$

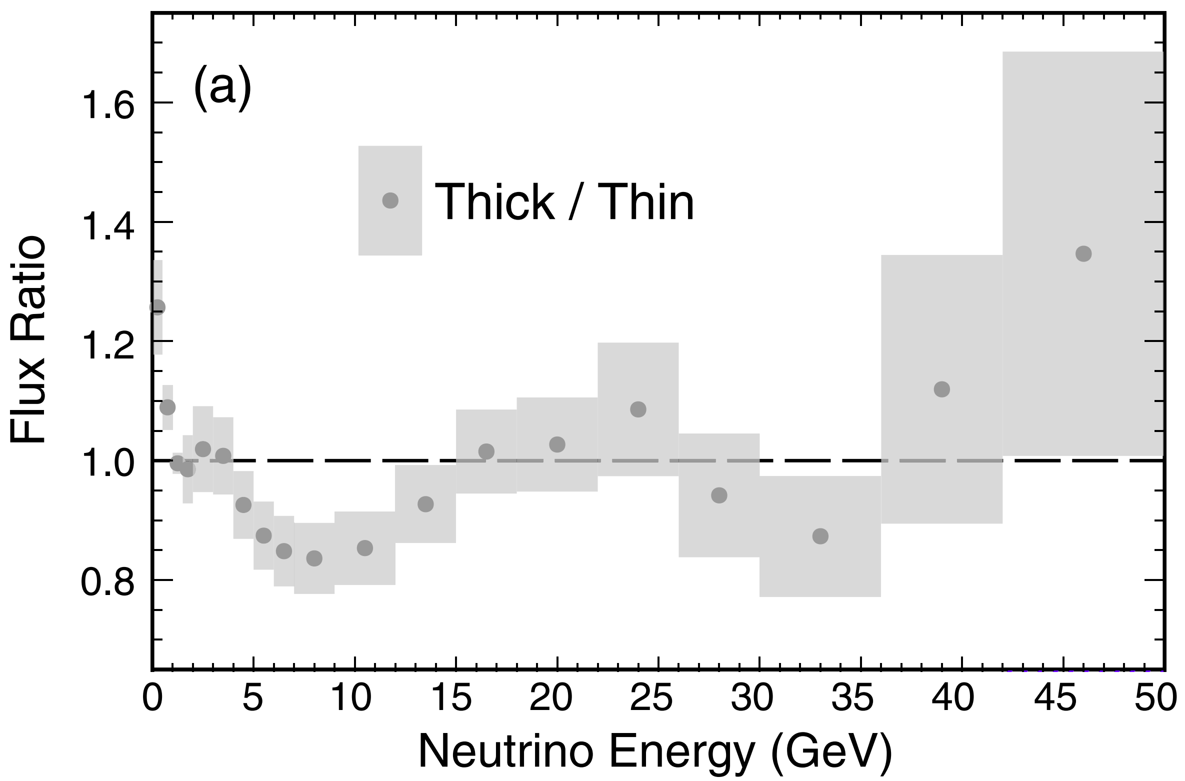
(A, B and C are parameters formed by nuclear structure functions and form factors.)

- The measurement of low-ν neutrino energy spectrum is approximately a measurement of flux shape.
- The effect of non-zero ν cut is accounted for by a correction by MC.

Previous Low-ν Measurements

- Low-ν has been used by past experiments including NOMAD, MINOS, MINERvA *etc*.
- MINERvA has an excellent example why we want *in situ* flux measurements.
  - External hadron production data (thin target or think target data from NA49 and MIPP) give inconsistent result.

PHYSICAL REVIEW D **94,** 092005 (2016)



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- MINERvA has an excellent example why we want *in situ* flux measurements.
  - External hadron production data (thin target or think target data from NA49 and MIPP) give inconsistent result.
  - Independent check by low-ν measurements confirms the thin target result.

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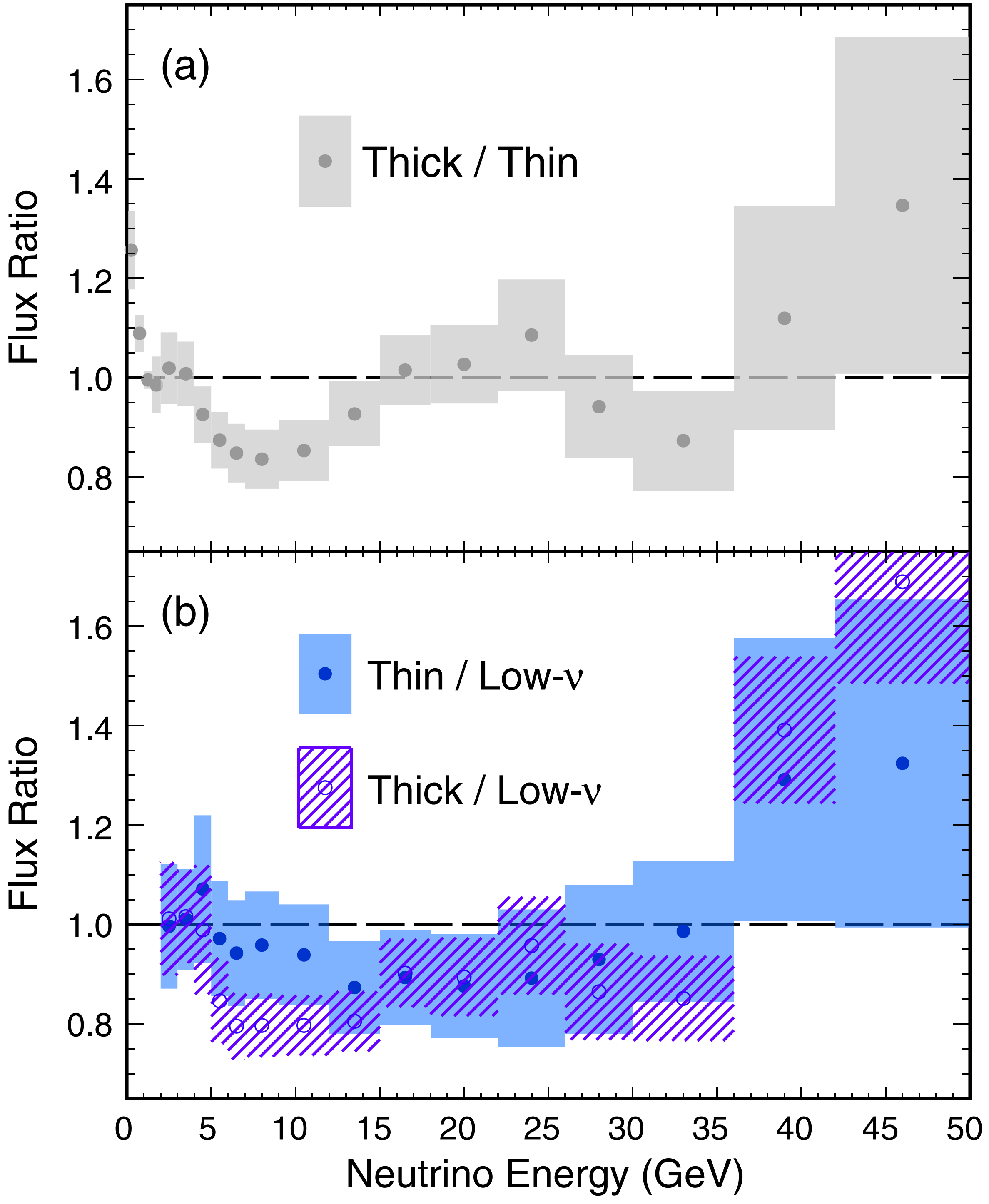
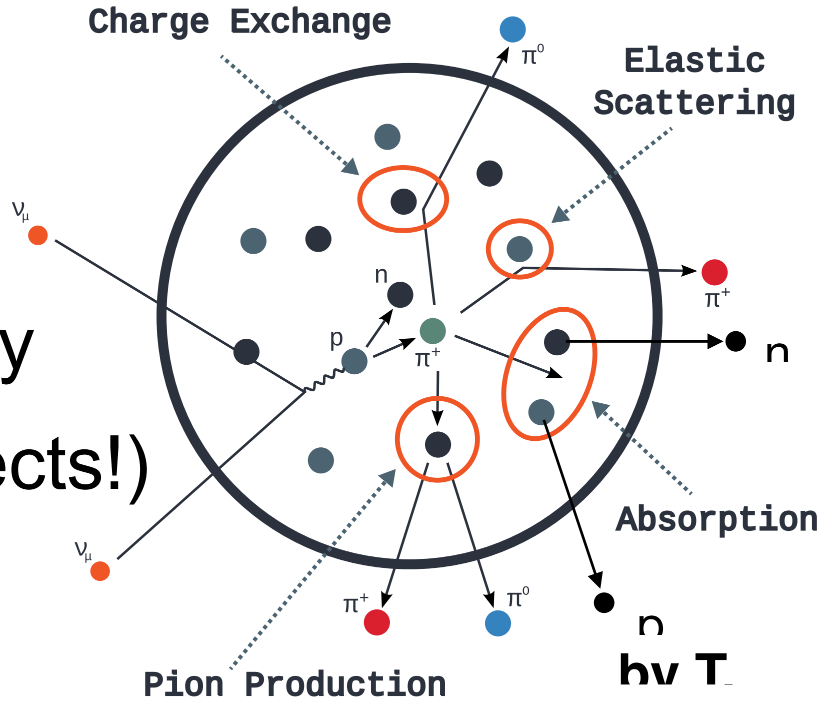


Uncertainties to the Low-ν Method

$$\boxed{\frac{d\sigma}{d\nu}=A\left(1+\frac{B}{A}\frac{\nu}{E}-\frac{C}{A}\frac{\nu^2}{2E^2}\right)}$$

- E_ν reconstruction: dominated by E_μ scale uncertainty
- E_{Had} (ν) uncertainty: is it really “low”-ν ? (nuclear effects!)
- MC shape correction: knowledge of the B/C terms



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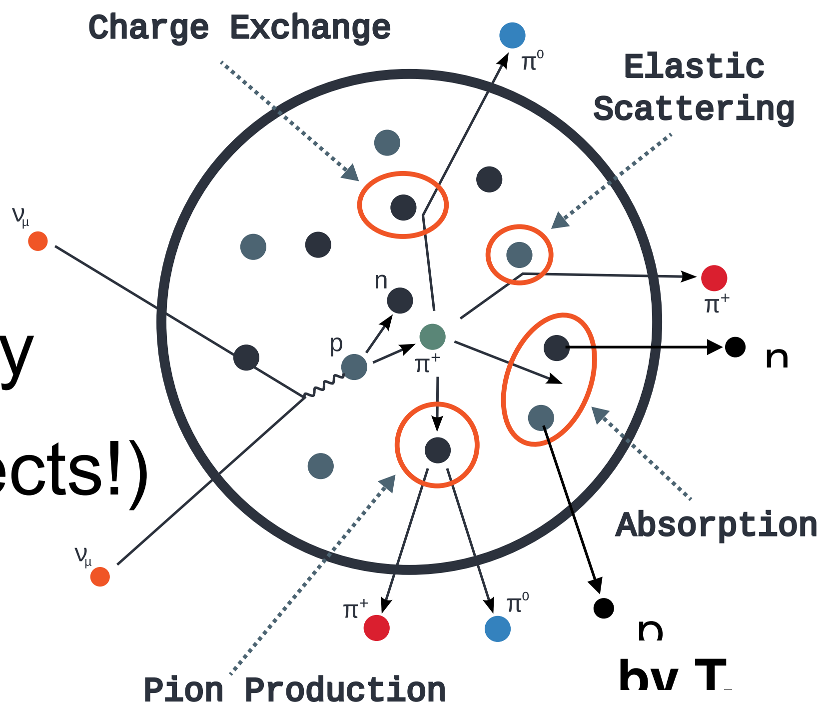

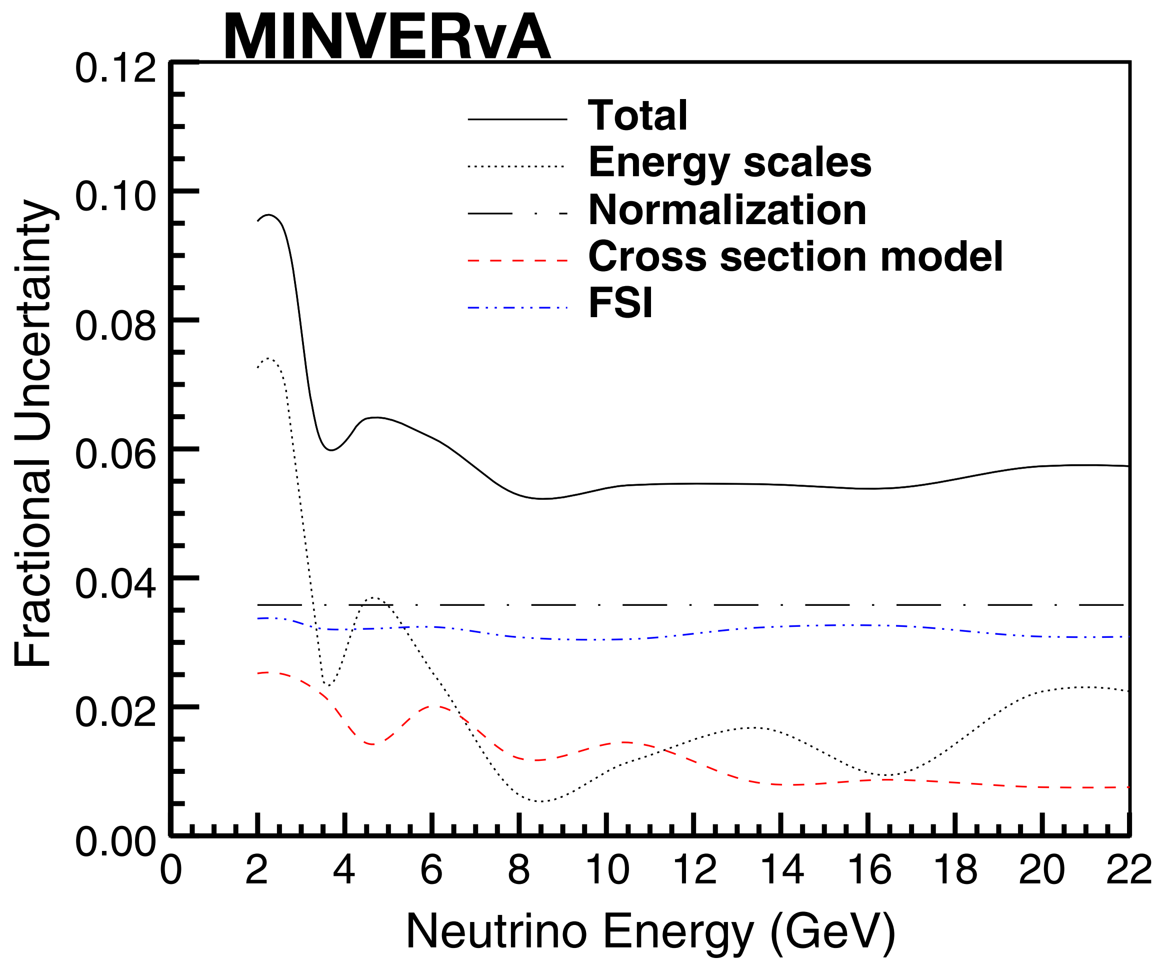

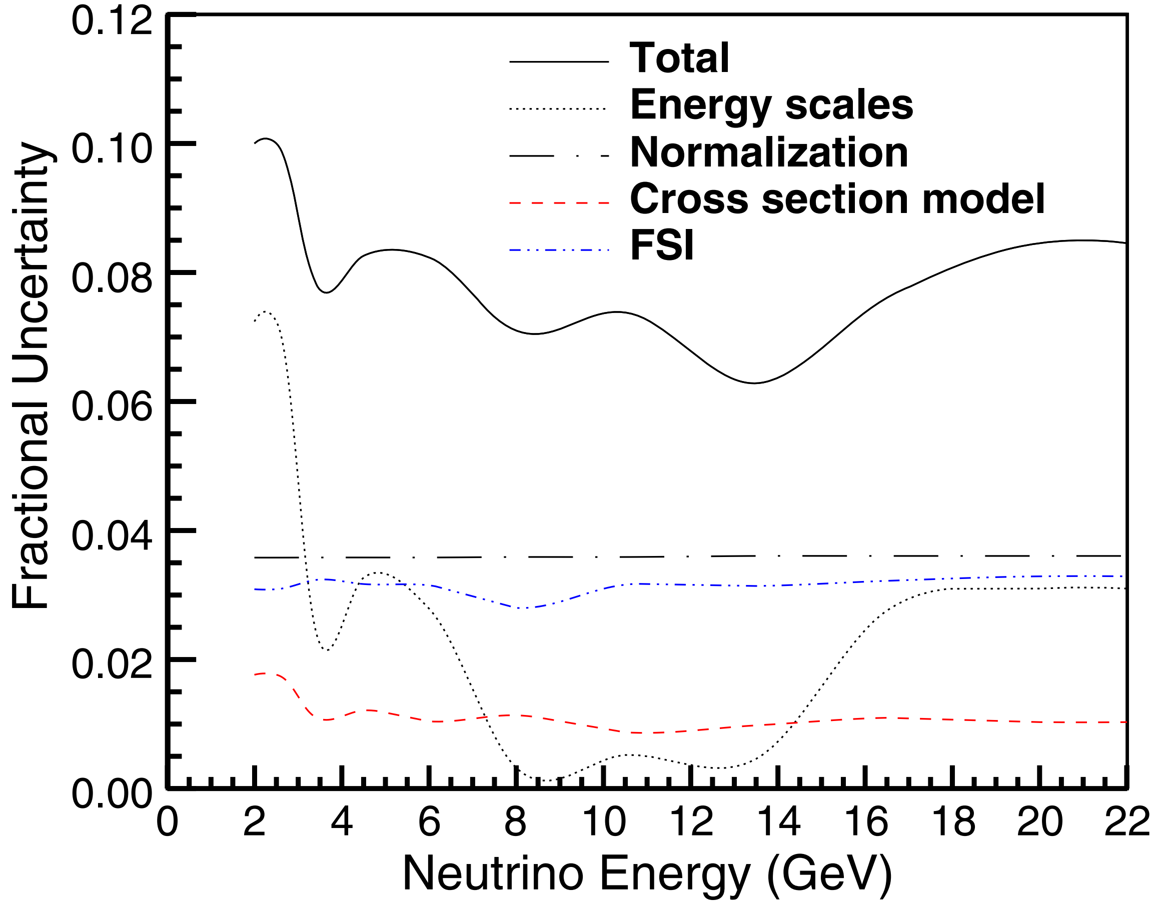

It is even more difficult to do it on Ar target

If We Have Hydrogen Target…

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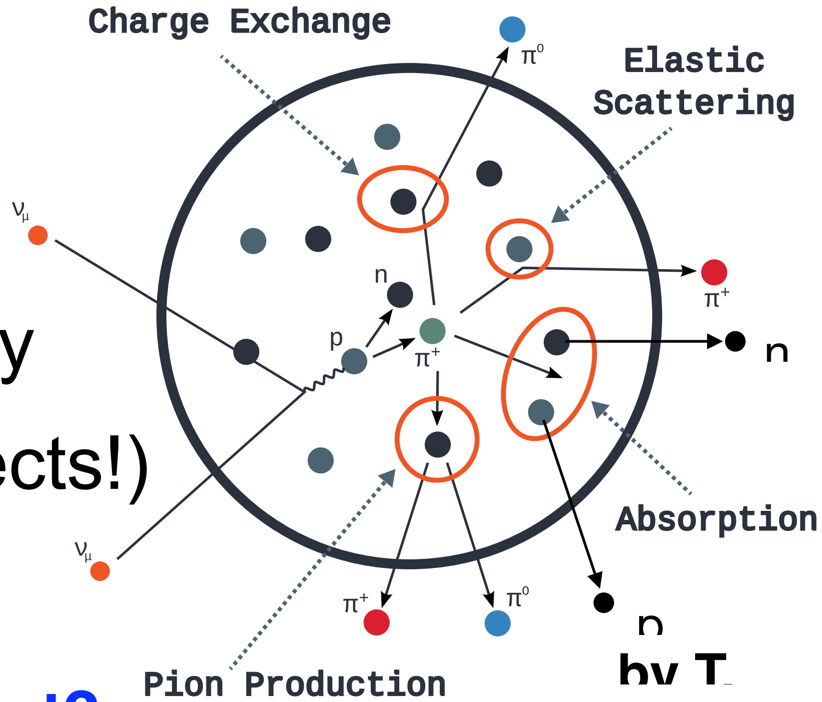

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What if we have hydrogen (free proton) target?

- No ambiguities in E_ν reconstruction.
- No ambiguities in ν due to final-state interactions.
- Much better known cross-section model.

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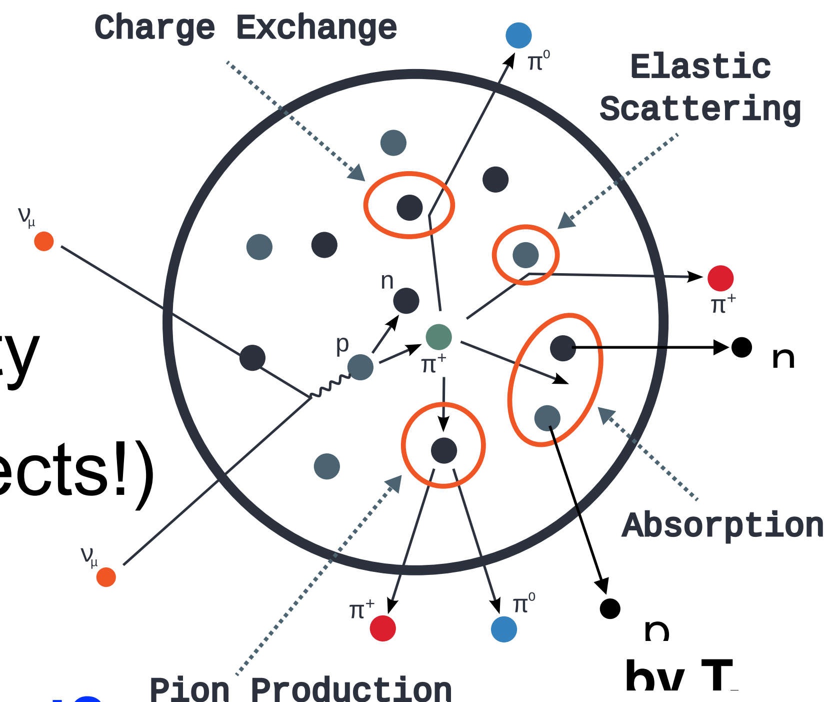

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Great! But how do we get hydrogen target?

- Build a hydrogen detector (fill GAr TPC with high-pressure hydrogen gas for example). Causes safety concerns. (A potential hydrogen bomb!)
- Use hydrocarbon and carbon-subtraction

Low-ν Method on Hydrogen

- Neutrino mode: $\nu_\mu p \rightarrow \mu^- p \pi^+$
- Anti-neutrino mode:
  - $\bar{\nu}_\mu p \rightarrow \mu^+ p \pi^-$
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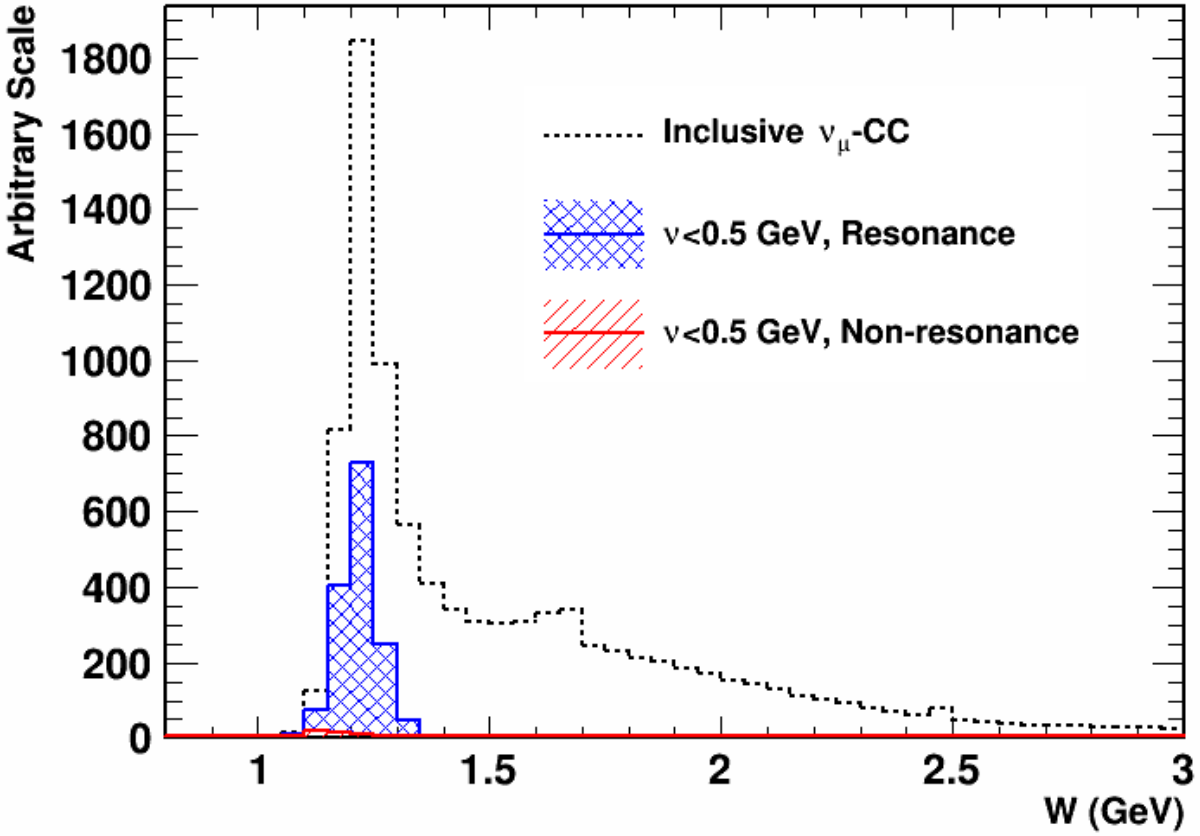

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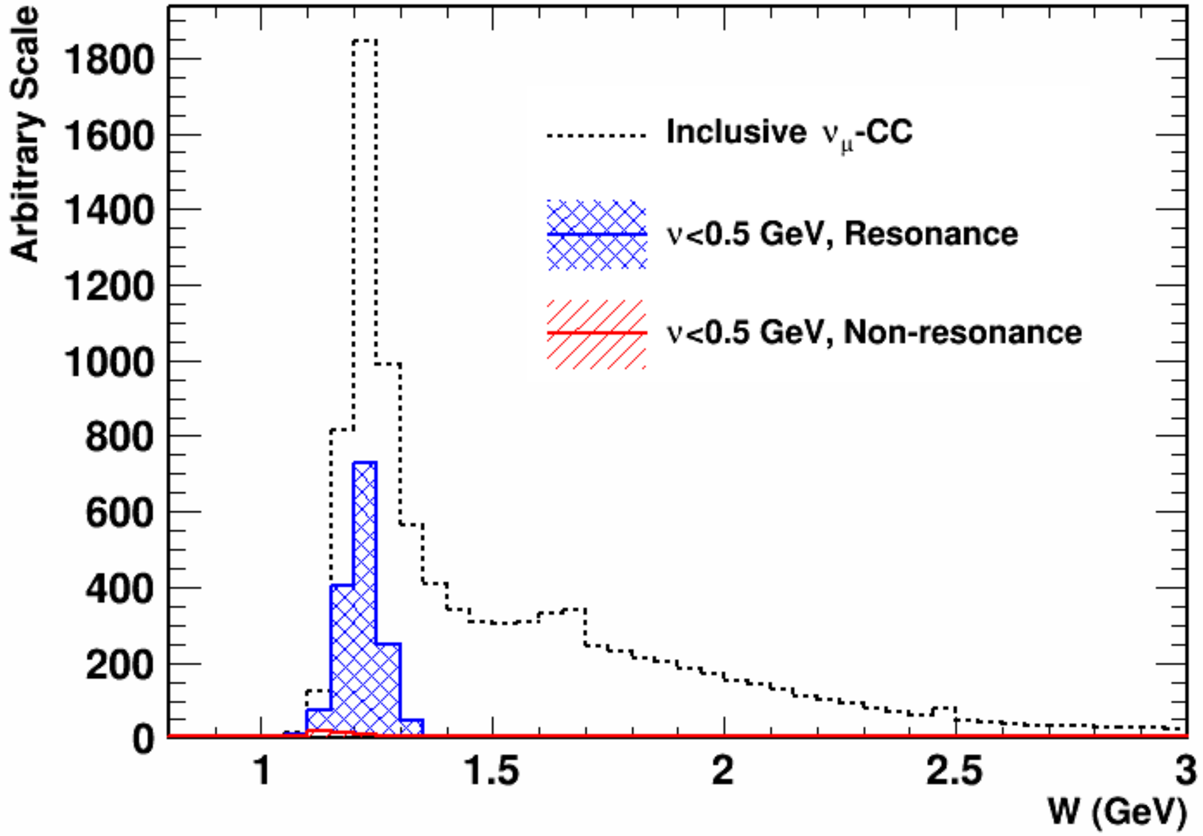

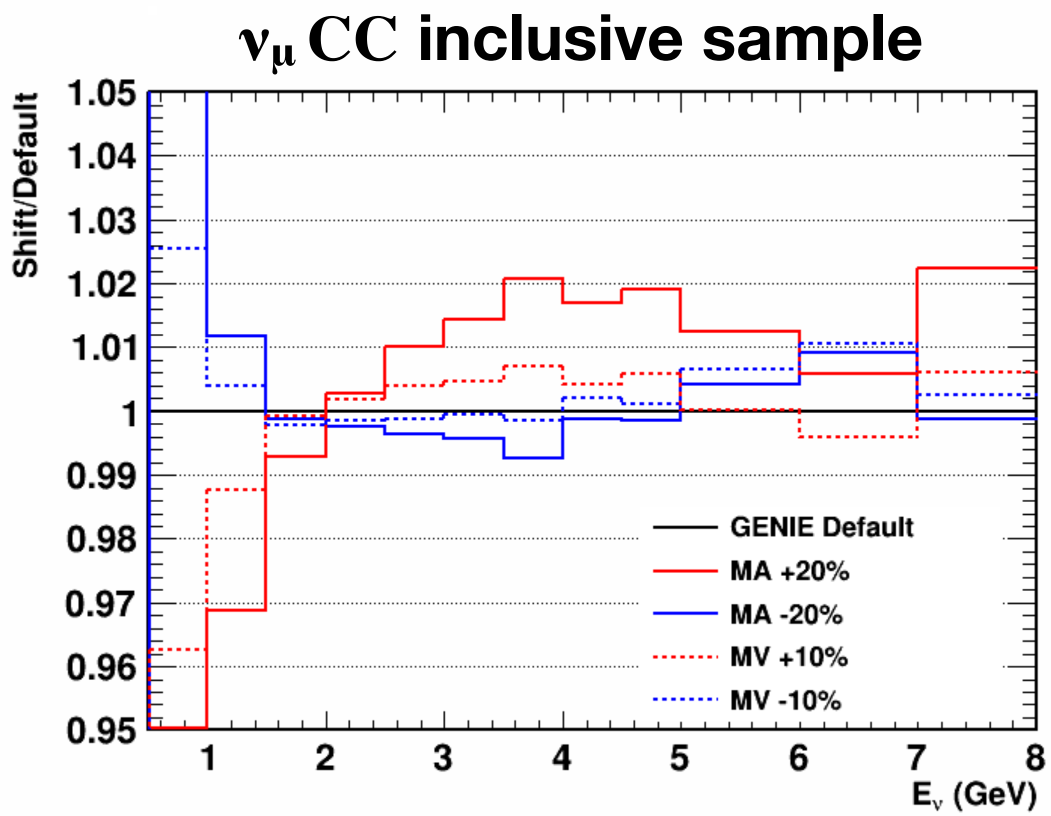

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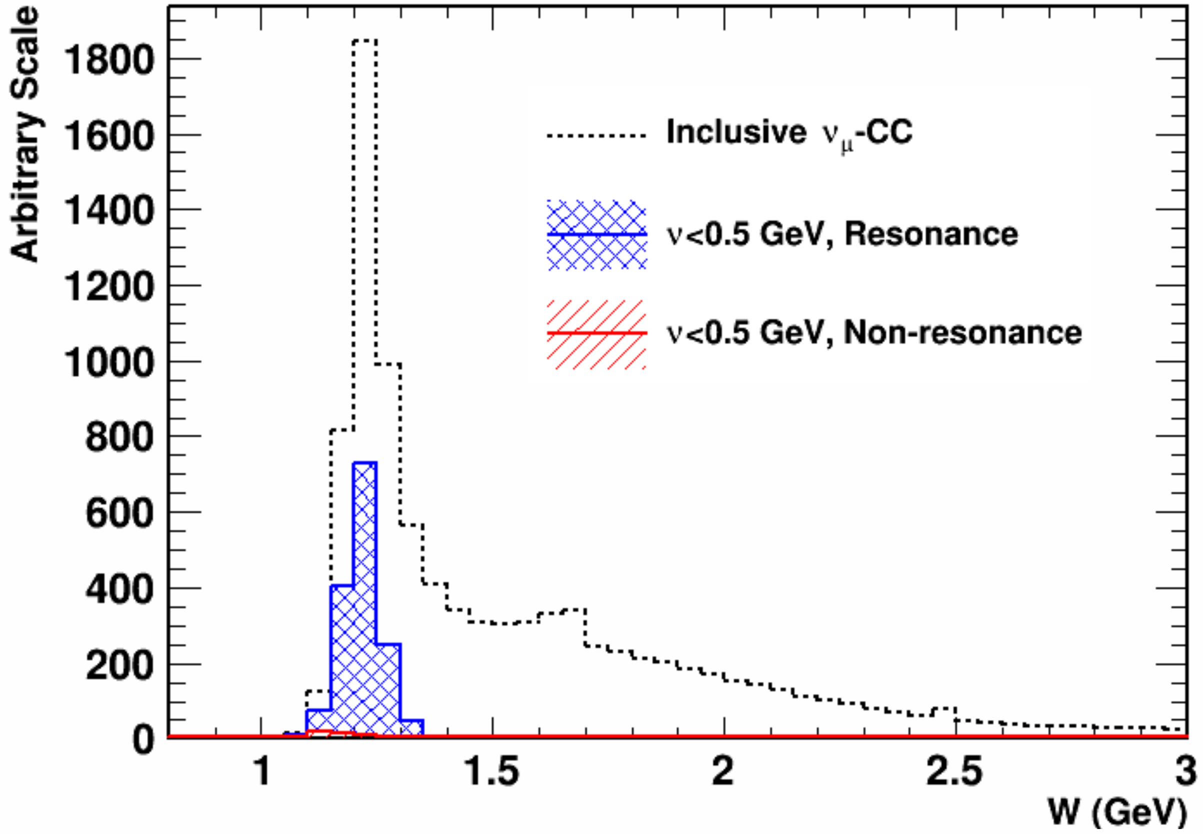
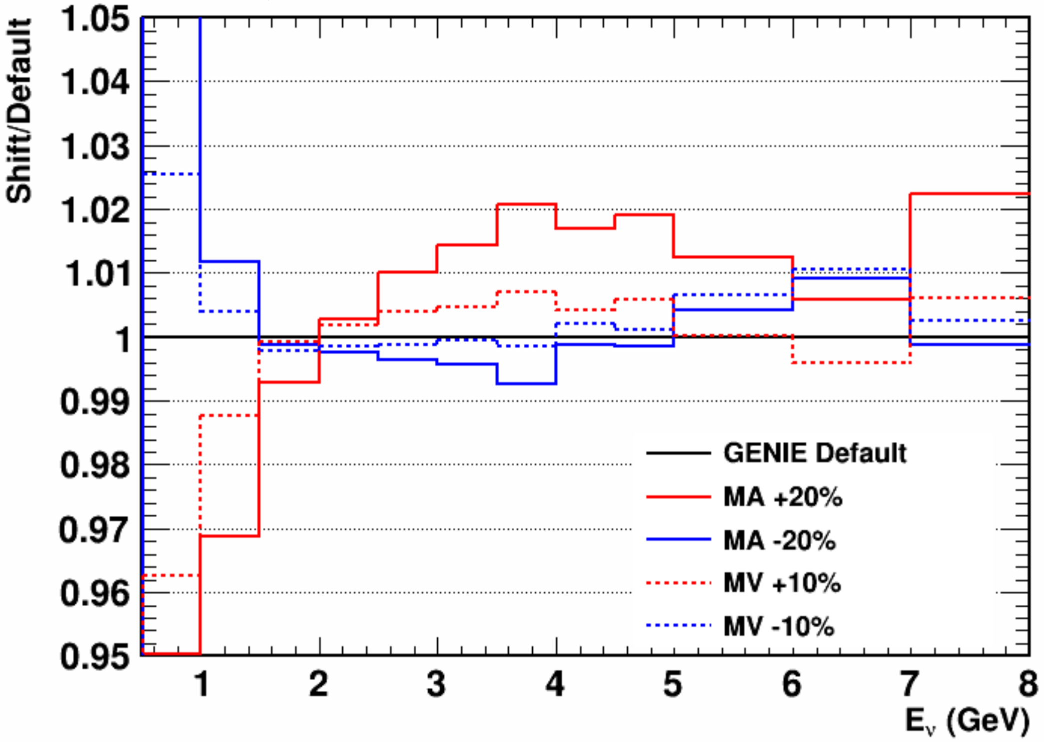
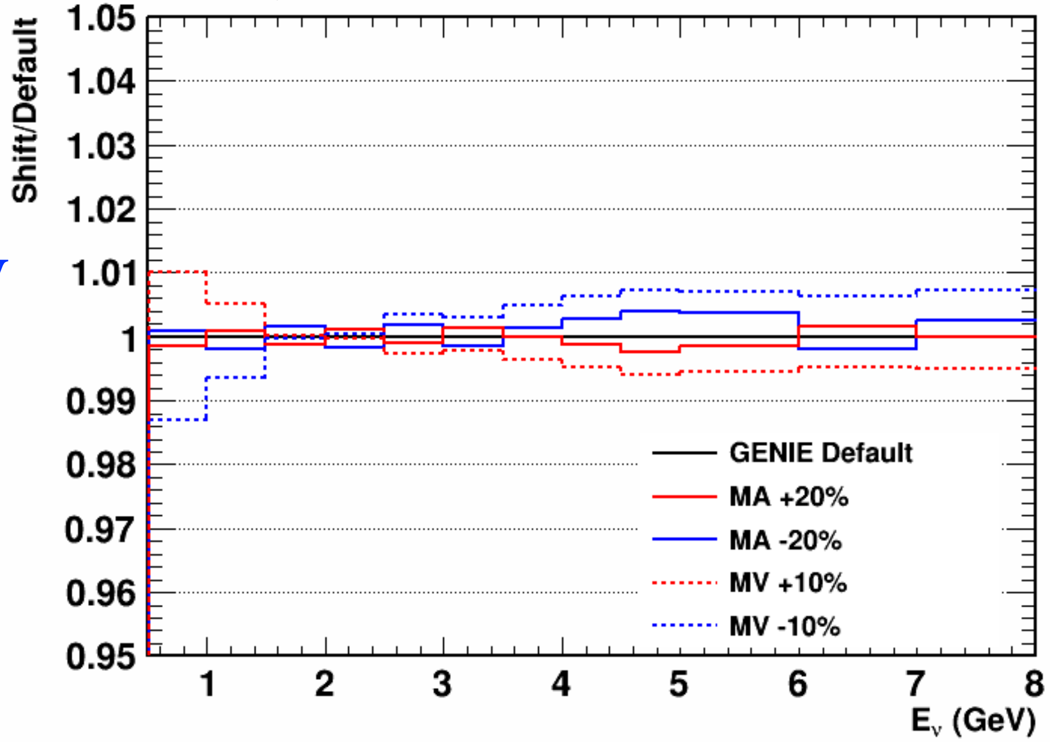


ν_μ CC inclusive sample



ν < 0.5 GeV

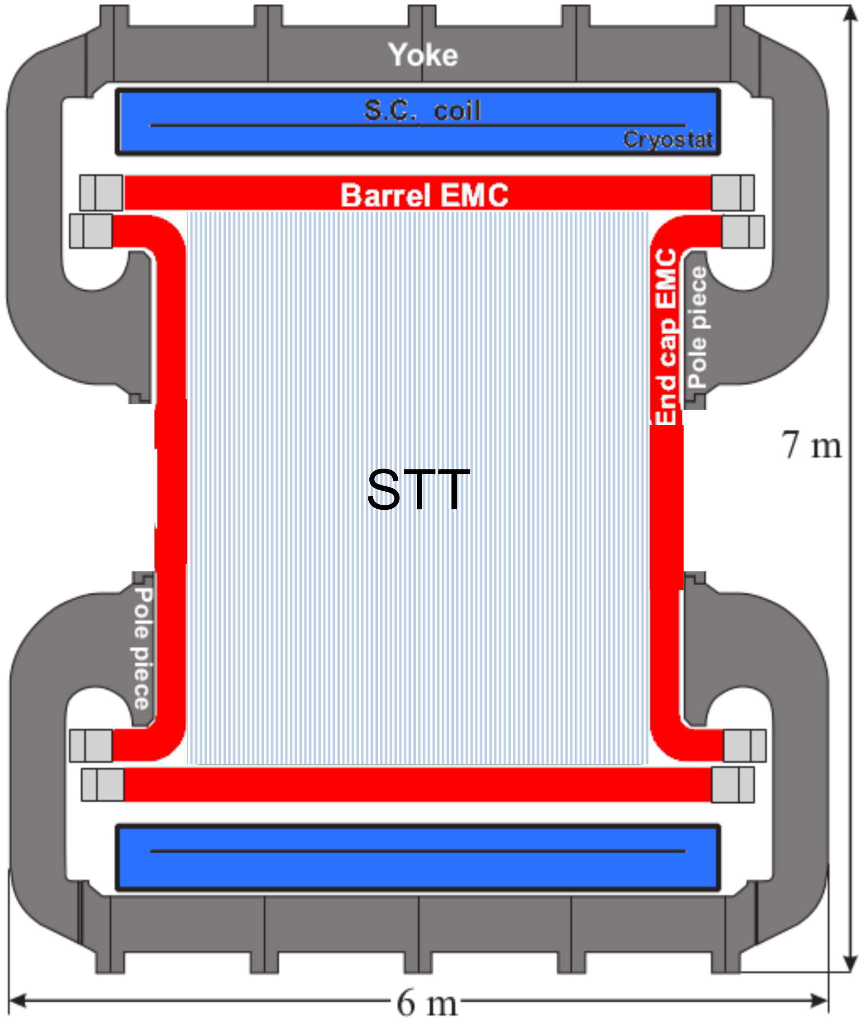
ν_μ CC low-ν sample

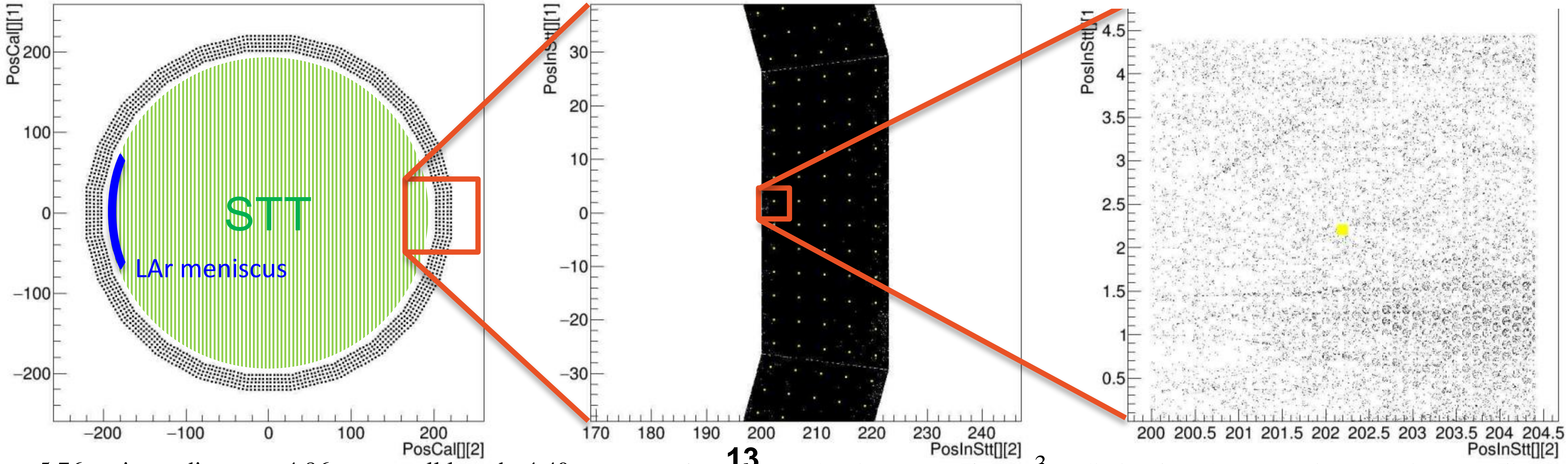


The low-ν cut significantly reduces the modeling uncertainties to <1%.

Introduction to KLOE-STT

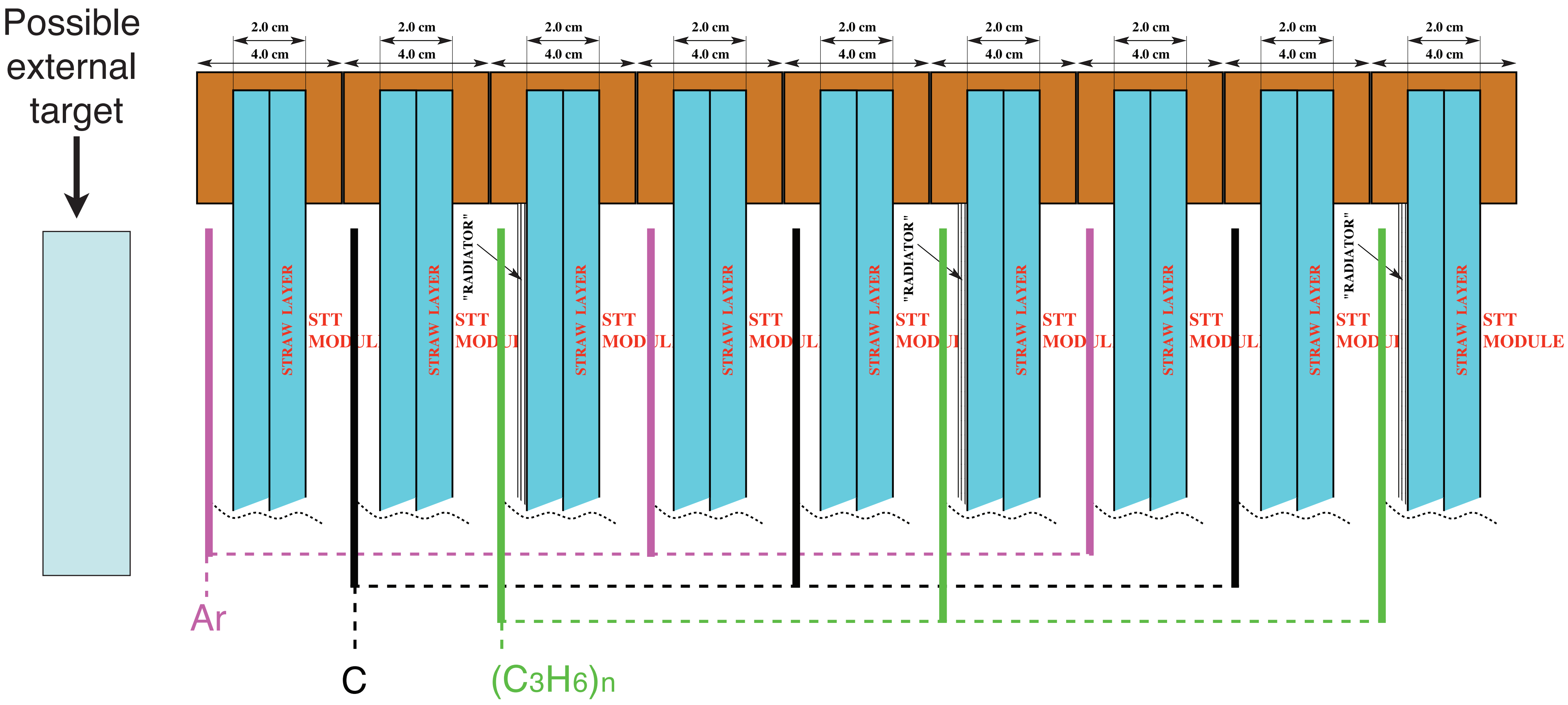
- Re-use of KLOE magnet (solenoid) and EM calorimeter (lead-scintillating fibers), which reduces the cost.
- Straw-Tube Tracker provide the tracking and target mass.
    - A compact version of DUNE CDR reference design
    - Low-density, high resolution.
    - Provide hydrogen!
- For more details see docdb #13262





outer diameter: 5.76 m, inner diameter: 4.86 m, overall length: 4.40 m   B = 0.6 T, average density ϱ ~ 0.16 g/cm^3, radiation length X0 ~ 3.5 m, tracking sampling 0.15 (0

Measurement of Neutrino-Hydrogen in STT



Possible external target

Ar

C

$(C_3H_6)_n$

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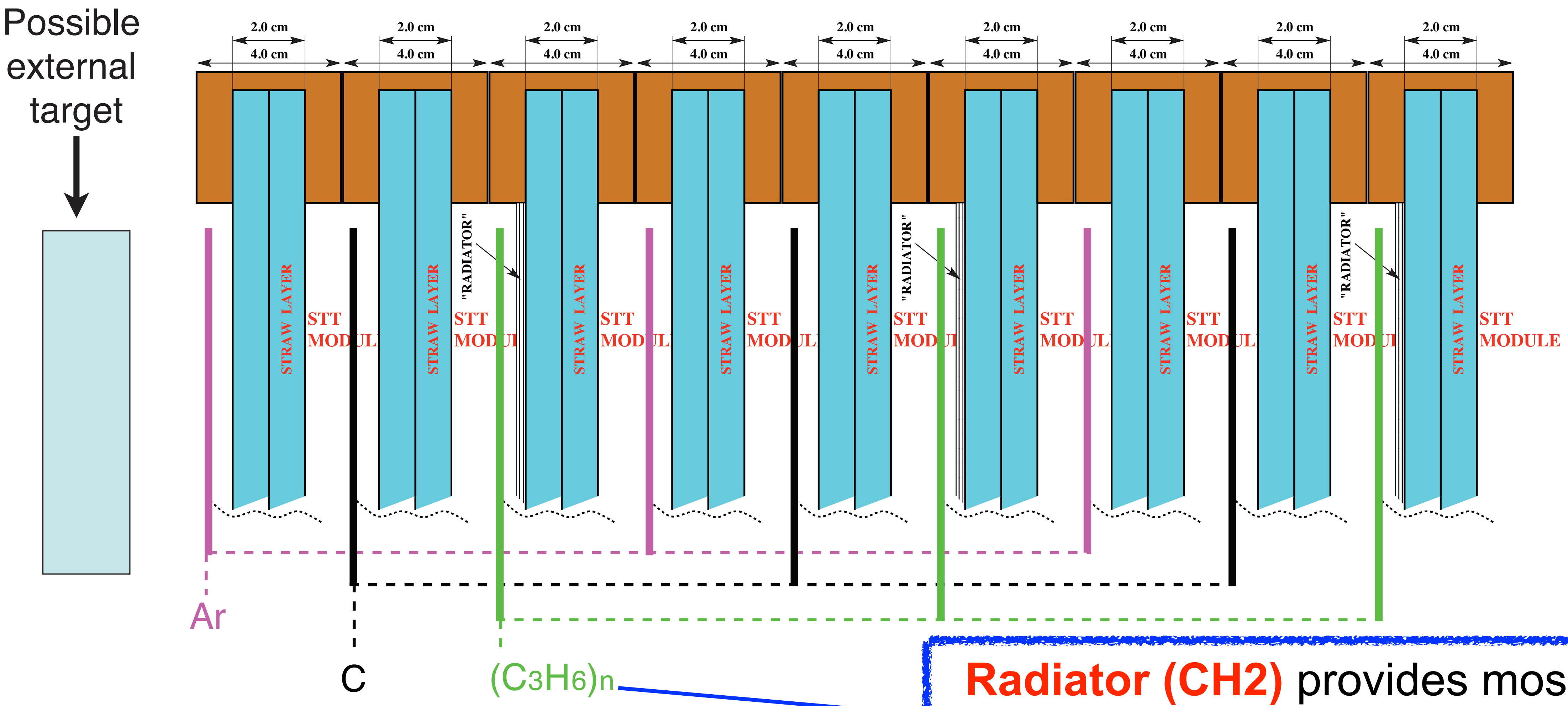
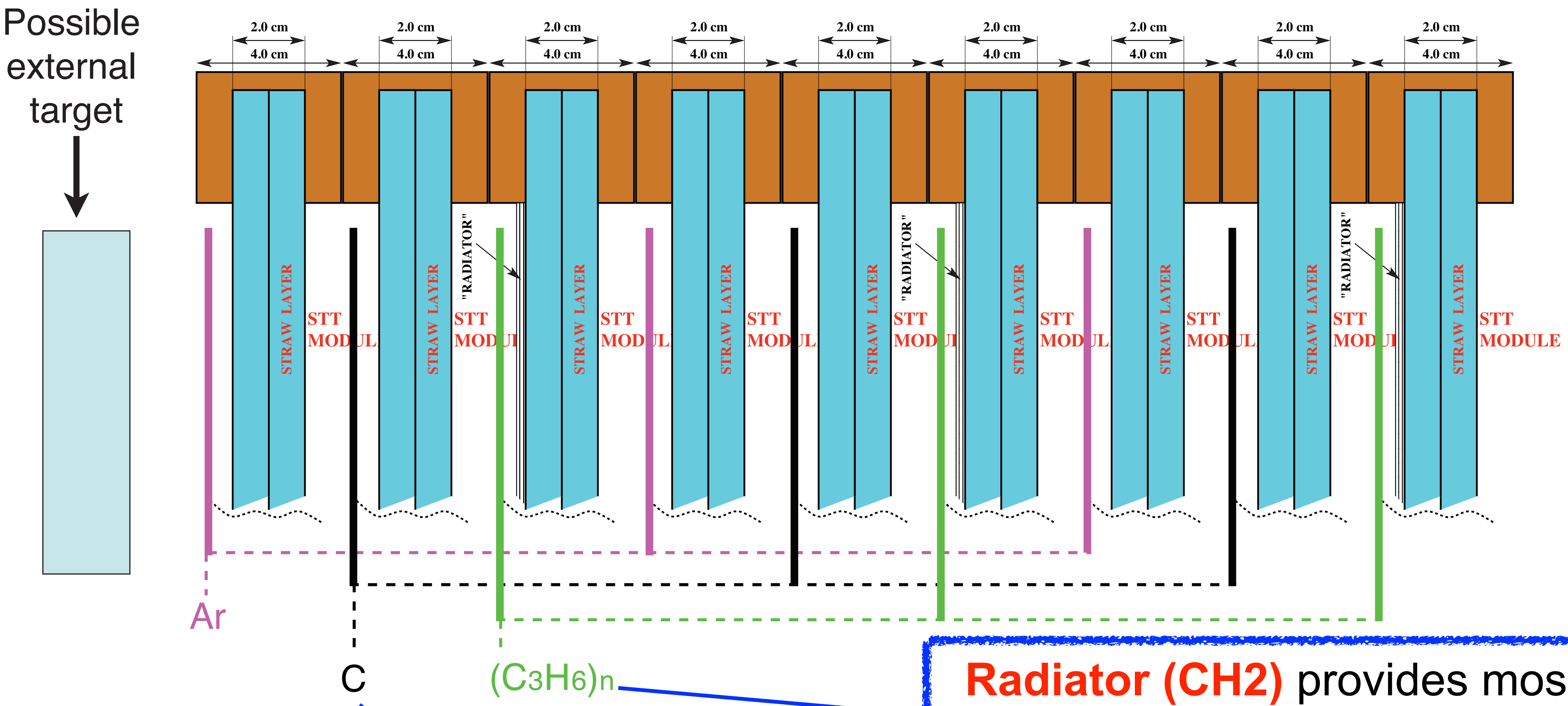


Radiator (CH2) provides most of the detector mass with abundant hydrogen

Measurement of Neutrino-Hydrogen in STT



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Dedicated **carbon (graphite) target** to measure carbon background

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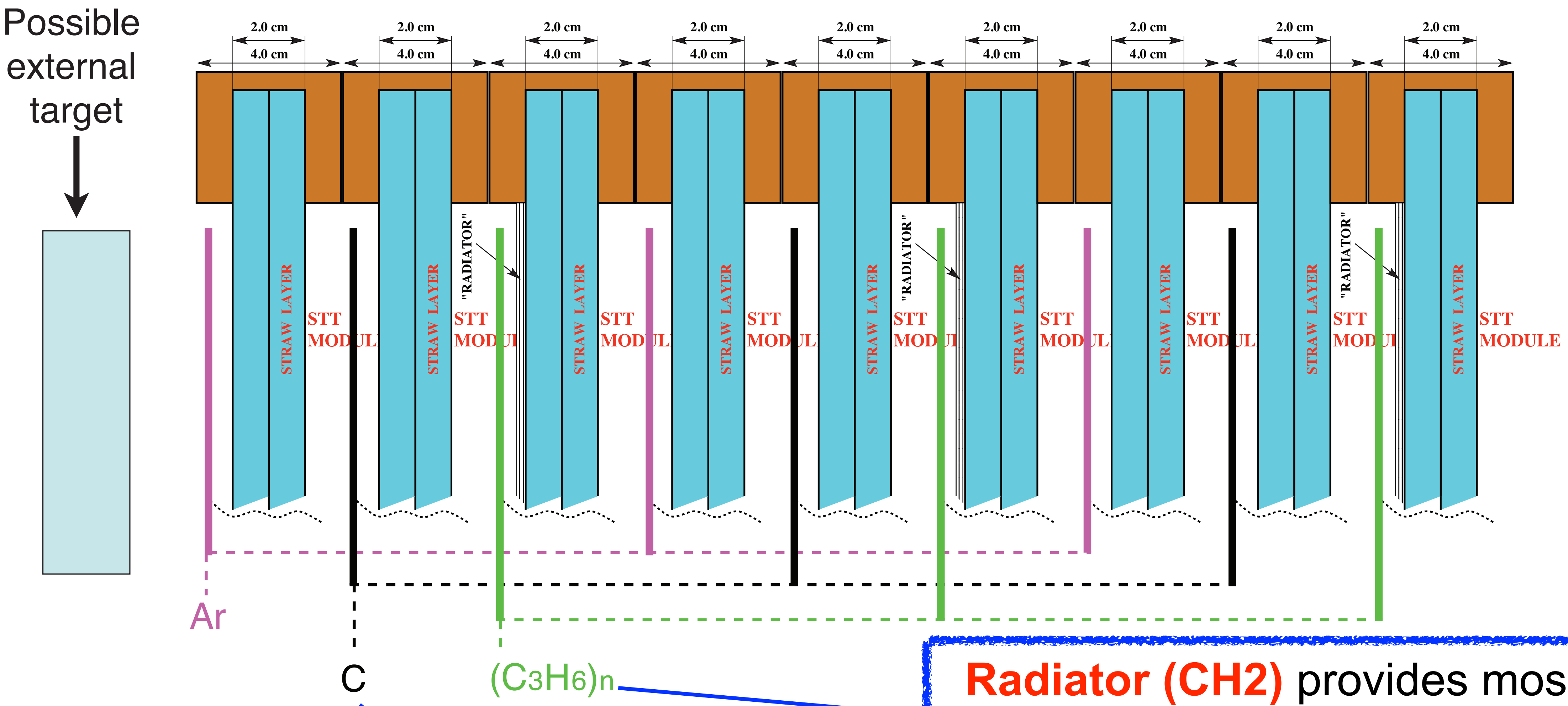

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Subtraction of **C** from **CH2** provides **hydrogen (free proton) target**

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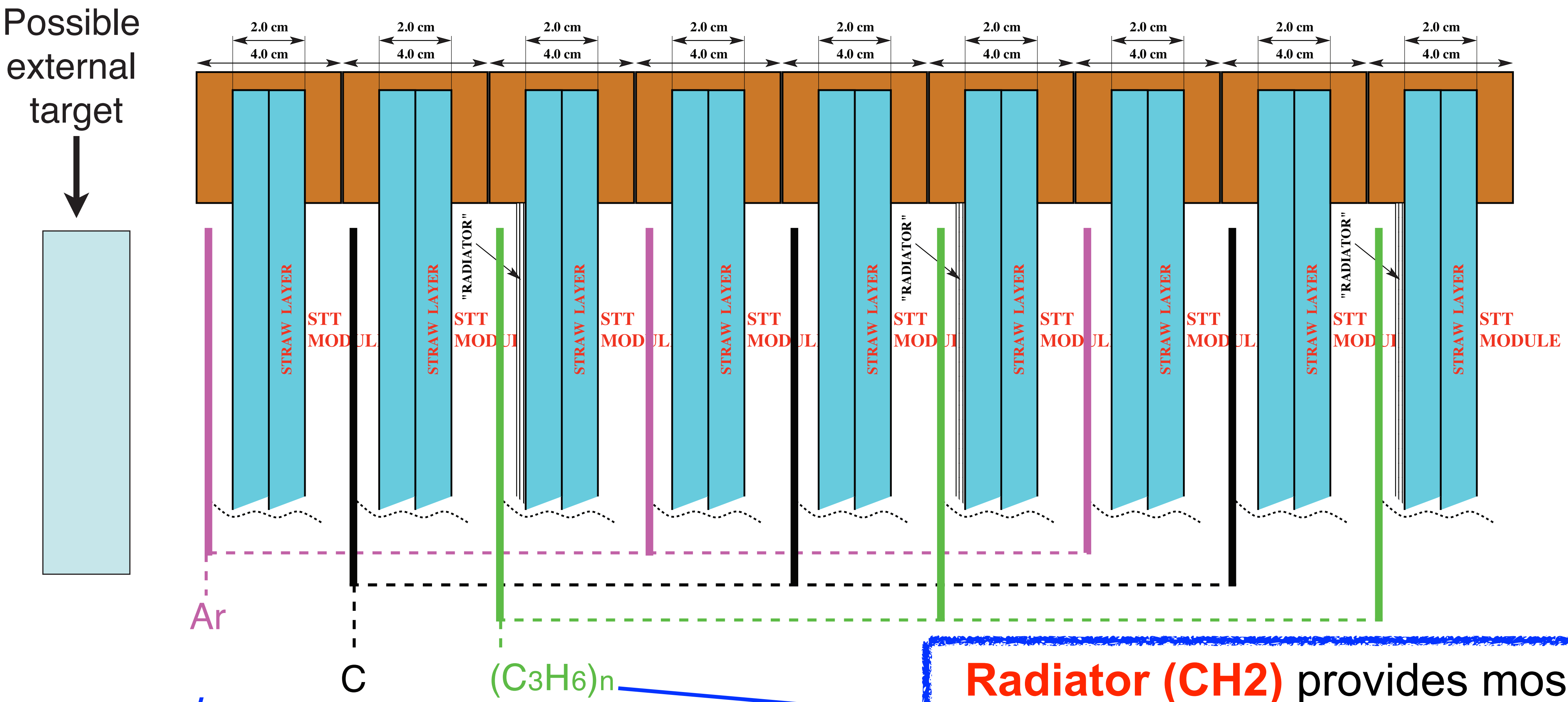

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Dedicated **carbon (graphite) target** to measure carbon background

Ar and other nuclear targets provide understanding of the **nuclear effects**

Subtraction of **C** from **CH2** provides **hydrogen (free proton) target**

Statistics

- Assuming 5-ton radiator (CH2) mass

	CP optimized beam		ν_τ optimized beam	
Process	FHC 1.2MW, 5y	RHC 1.2MW, 5y	FHC 2.4MW, 2y	RHC 2.4MW, 2y
ν_μ CC on CH_2	34,300,000	5,500,000	65,570,000	3,810,000
$\bar{\nu}_\mu$ CC on CH_2	1,680,000	13,100,000	1,152,000	24,000,000
ν_e CC on CH_2	508,000	242,000	665,000	181,000
$\bar{\nu}_e$ CC on CH_2	85,700	187,000	70,000	190,000
ν_μ CC on H	3,360,000	542,000	6,510,000	375,000
$\bar{\nu}_\mu$ CC on H	308,000	2,490,000	210,000	4,330,000
ν_e CC on H	49,700	23,900	65,800	17,800
$\bar{\nu}_e$ CC on H	15,400	34,400	12,600	33,900

Statistics

- Assuming 5-ton radiator (CH2) mass **0.7 ton of hydrogen mass**

	CP optimized beam		ν_τ optimized beam	
Process	FHC 1.2MW, 5y	RHC 1.2MW, 5y	FHC 2.4MW, 2y	RHC 2.4MW, 2y
ν_μ CC on CH_2	34,300,000	5,500,000	65,570,000	3,810,000
$\bar{\nu}_\mu$ CC on CH_2	1,680,000	13,100,000	1,152,000	24,000,000
ν_e CC on CH_2	508,000	242,000	665,000	181,000
$\bar{\nu}_e$ CC on CH_2	85,700	187,000	70,000	190,000
ν_μ CC on H	3,360,000	542,000	6,510,000	375,000
$\bar{\nu}_\mu$ CC on H	308,000	2,490,000	210,000	4,330,000
ν_e CC on H	49,700	23,900	65,800	17,800
$\bar{\nu}_e$ CC on H	15,400	34,400	12,600	33,900

Excellent hydrogen statistics

Statistics

- Assuming 5-ton radiator (CH2) mass **0.7 ton of hydrogen mass**

Process	CP optimized beam		ν_τ optimized beam	
	FHC 1.2MW, 5y	RHC 1.2MW, 5y	FHC 2.4MW, 3y	RHC 2.4MW, 3y
ν_μ CC on CH_2	34,300,000	5,500,000	65,570,000	3,810,000
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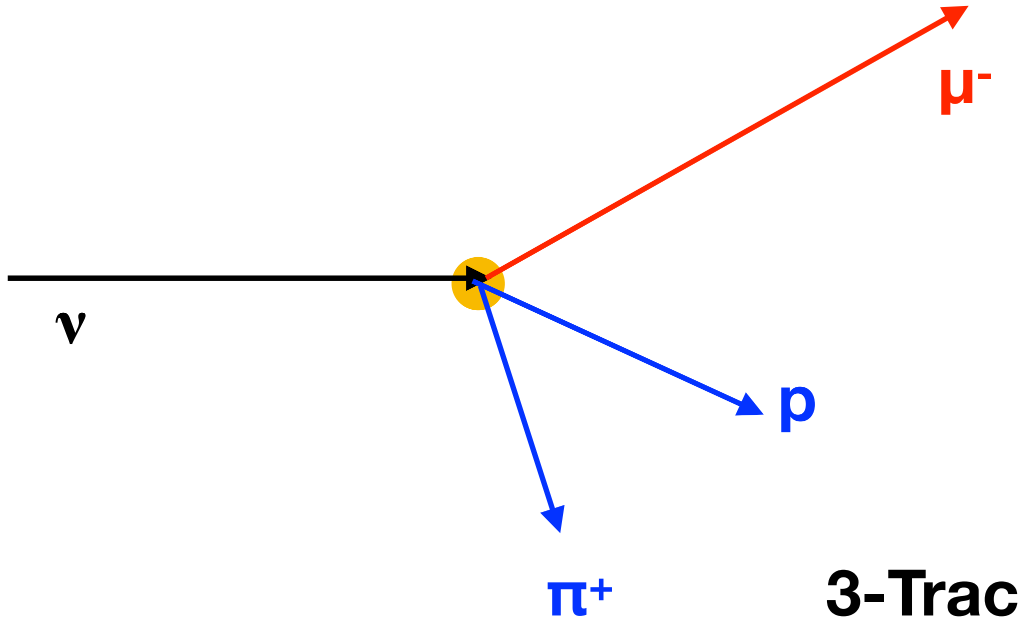
Large number of carbon background!

Excellent hydrogen statistics

- We don’t have to subtract carbon events from CH2 in full phase space.
- Kinematic cuts significantly reduces carbon background.

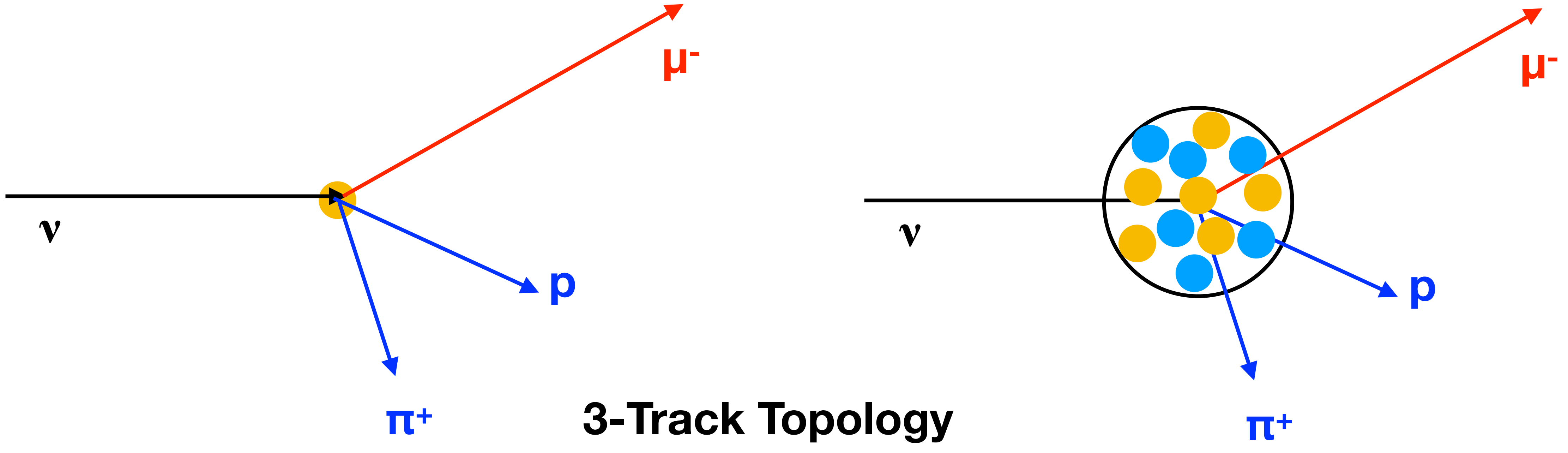
ν-H Event Selection



3-Track Topology

Free proton:
No fermi motion, no FSI…
easy final stat topology

ν-H Event Selection

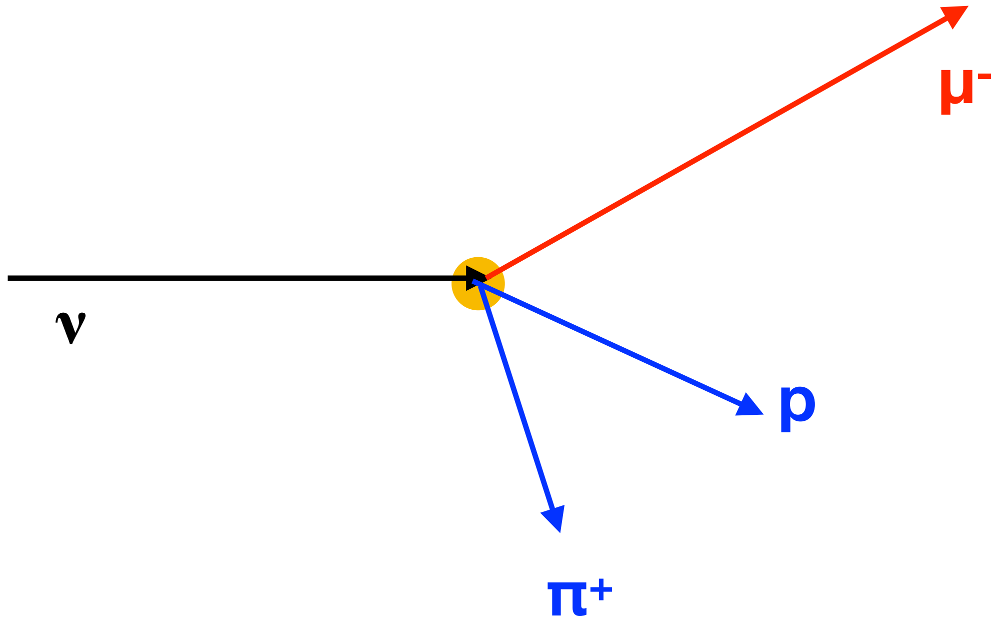


3-Track Topology

Free proton:
No fermi motion, no FSI…
easy final stat topology

Carbon nucleus:
Fermi motion, binding energy,
NN correlations, FSI…
low-energy proton, pion or neutrons
easily miss detection

ν-H Selection: Transverse Kinematics



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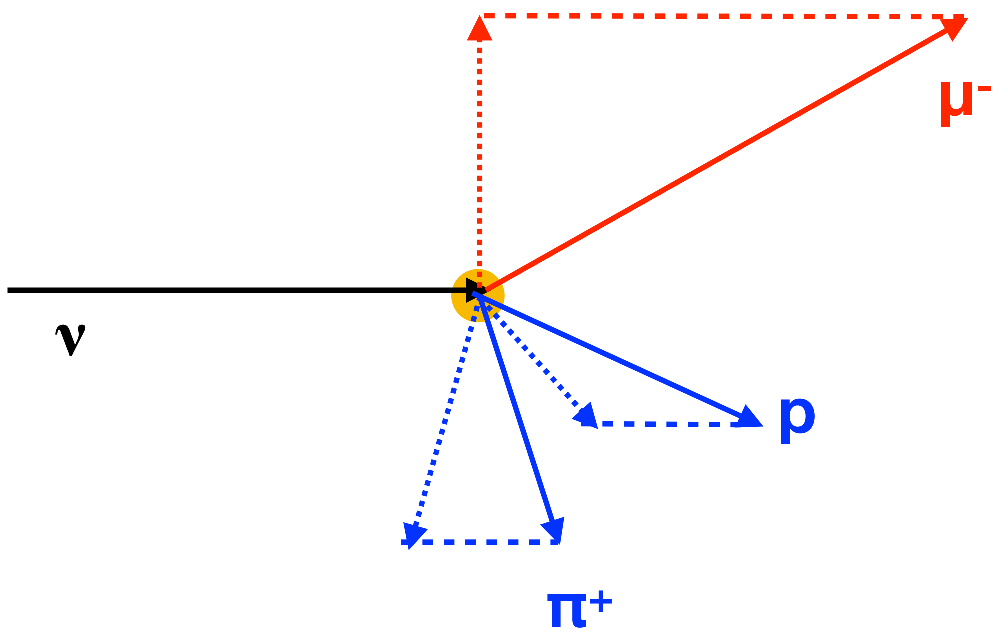
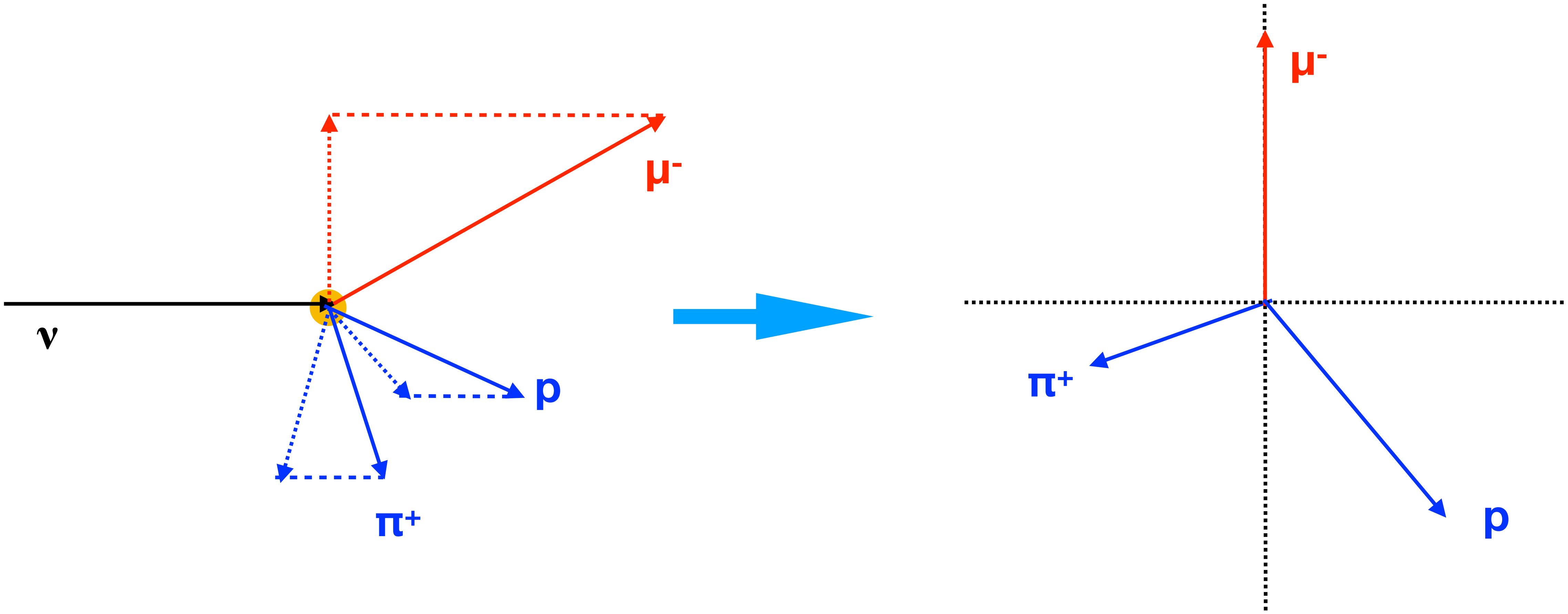


- **Hydrogen**: Momentums of final-state particles are balanced in the direction transverse to the beam direction without nuclear effects. The only smearing is detector effects.

ν-H Selection: Transverse Kinematics



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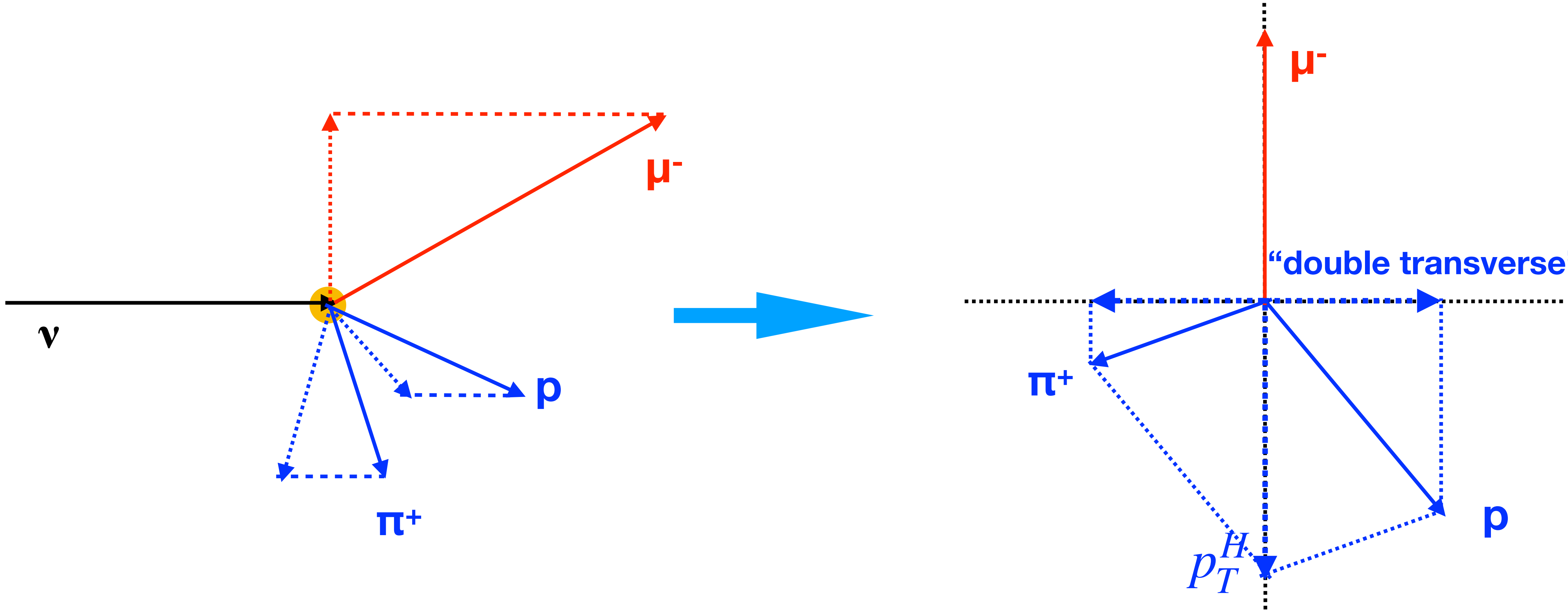

X. Lu et al.: Phys. Rev. D 92, no. 5, 051302 (2015)

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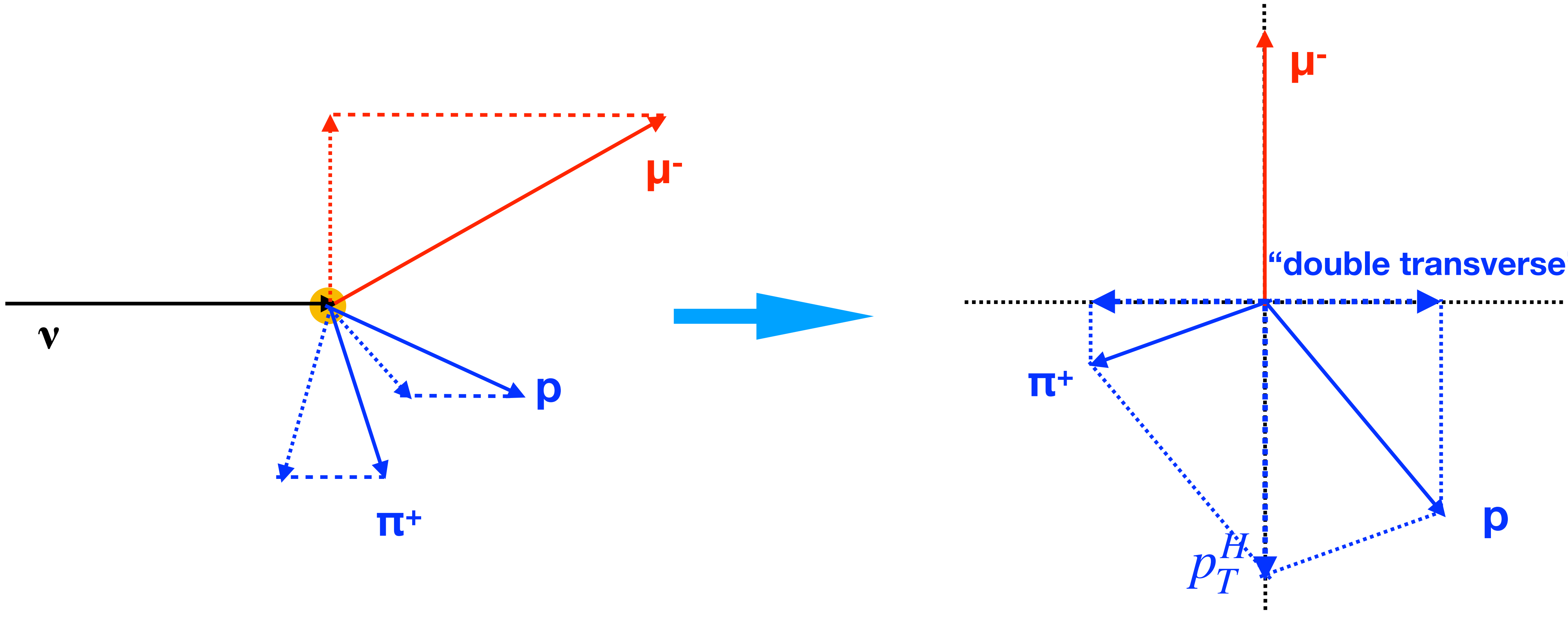
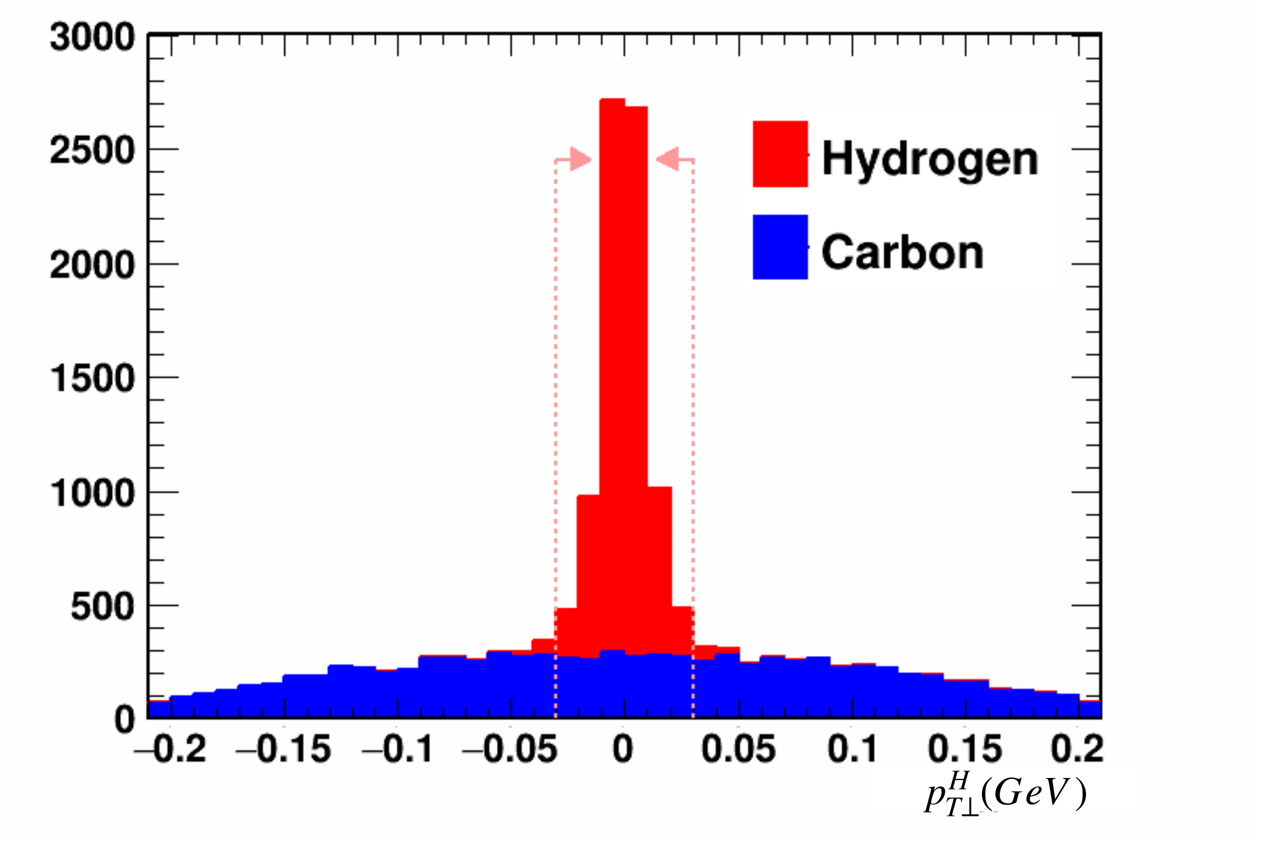
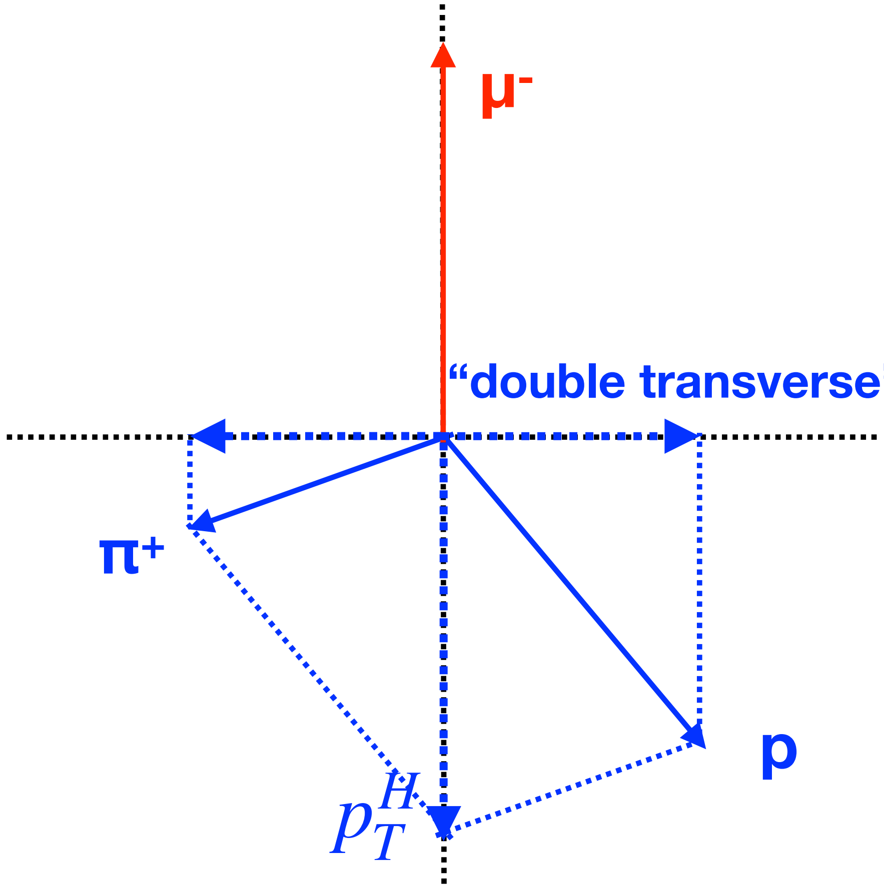


X. Lu et al.: Phys. Rev. D 92, no. 5, 051302 (2015)

- **Hydrogen**: Momentums of final-state particles are balanced in the direction transverse to the beam direction without nuclear effects. The only smearing is detector effects.
- **Carbon**: Nuclear effects causes imbalance on the transverse plane.
- Key detector features: low-threshold, high resolution measurement of all final-state particles as much as possible.

ν-H Selection: Resonance (3-Track Events)





X. Lu et al.: Phys. Rev. D 92, no. 5, 051302 (2015)

- Resonance pion production $\nu p \rightarrow \mu^- p \pi^+$
- Two simple transverse variables:
  - $p_{T\perp}^{H}$: momentum imbalance in the "double transverse" direction.

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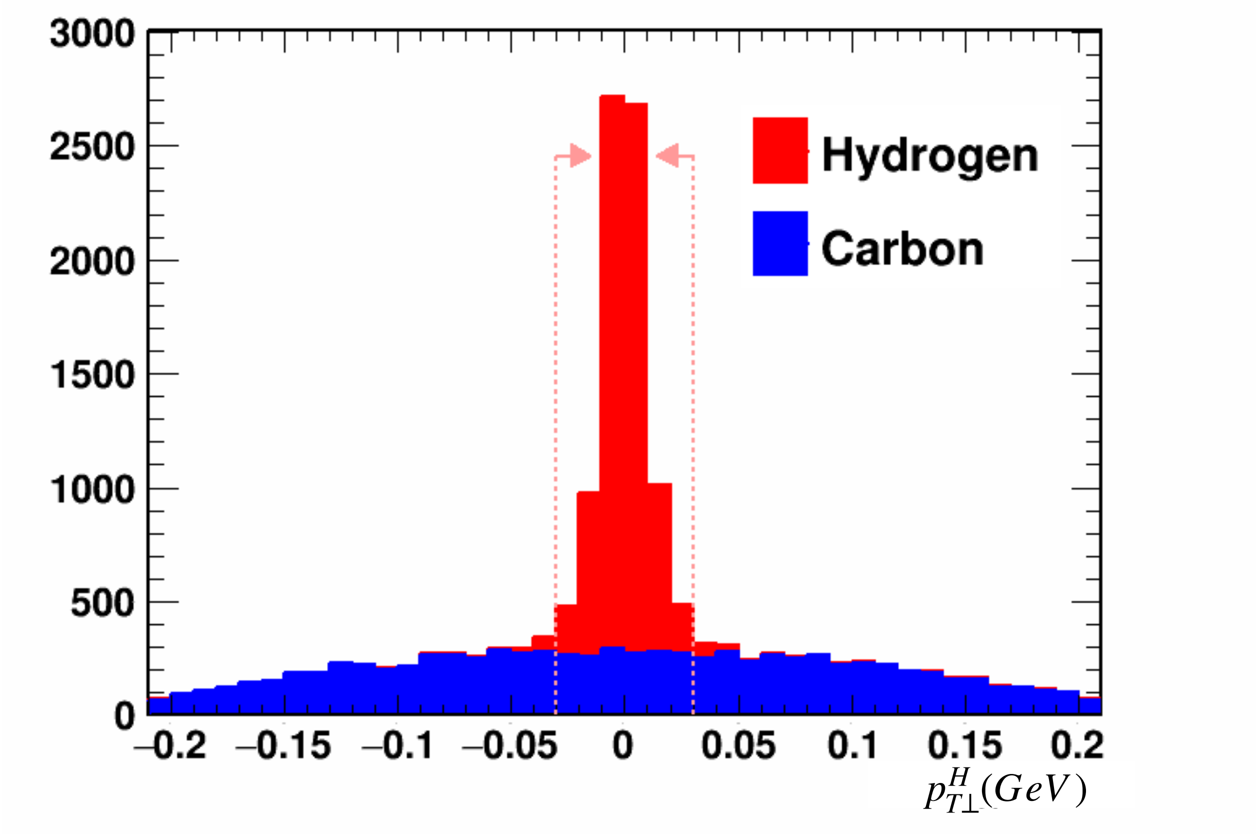
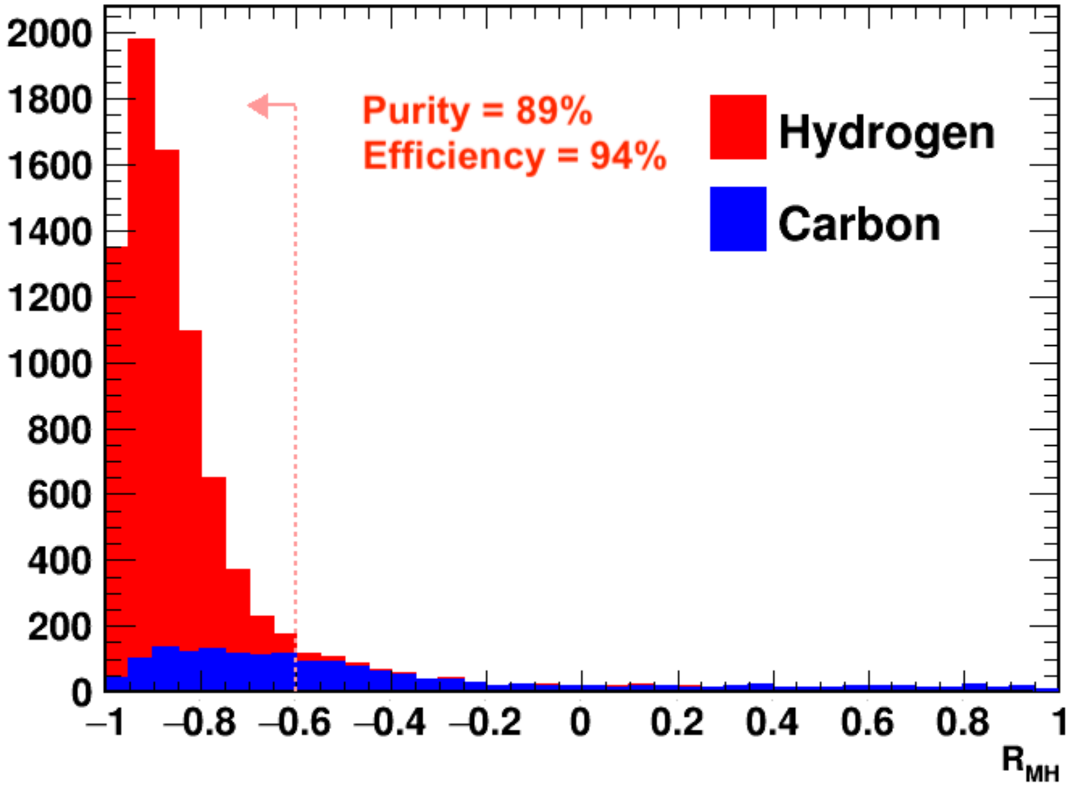
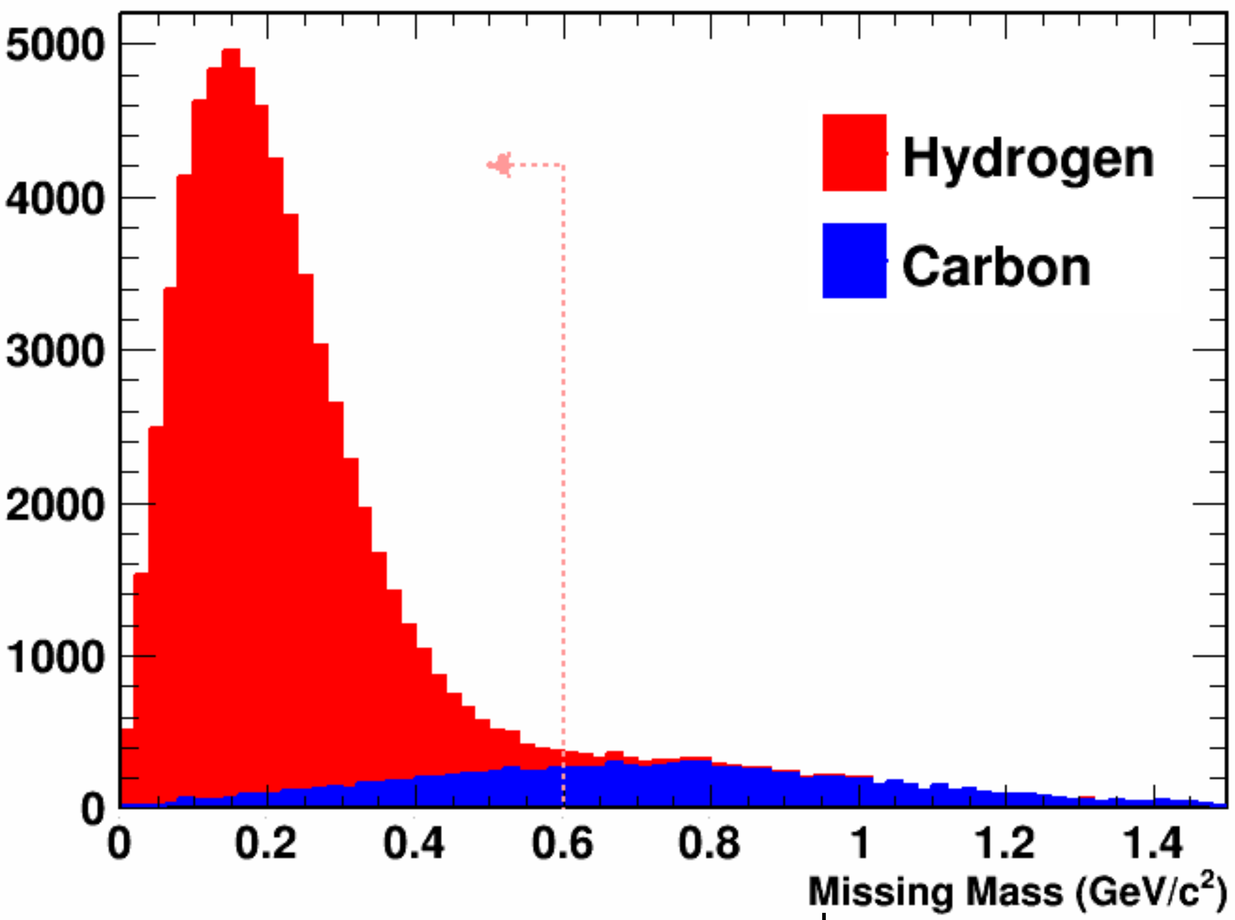




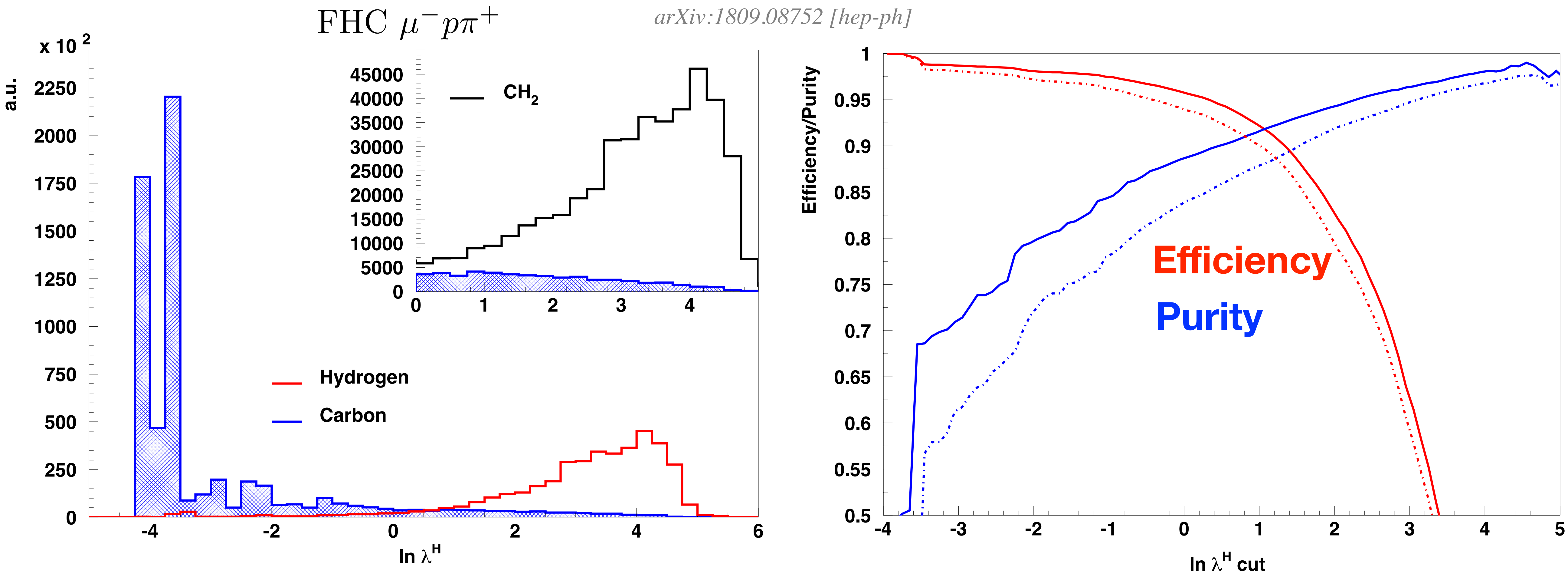
- Resonance pion production $\nu p \to \mu^- p \pi^+$
- Two simple transverse variables:
  - $p^H_{T\perp}$: momentum imbalance in the “double transverse” direction.
  - $R_{MH} = (P^M_T - P^H_T)/(P^M_T + P^H_T)$, where p^M_T and p^H_T are the missing p_T and total p_T of hadrons.
- **~90%** purity of hydrogen events (neutrino energy independent).

ν-H Selection: Resonance (More Variables)



- Resonance pion production $\nu p \rightarrow \mu^- p \pi^+$
- Two simple transverse variables:
  - $p_{T\perp}^H$: momentum imbalance in the "double transverse" direction.
  - $R_{MH} = (P_T^M - P_T^H)/(P_T^M + P_T^H)$, where p_T^M and p_T^H are the missing p_T and total p_T of hadrons.
  - **Missing mass: reconstructed invariant mass using all measured final state particles minus target proton at rest (Thanks to Xin!)**
- **~95%** purity of hydrogen events selection is achievable.

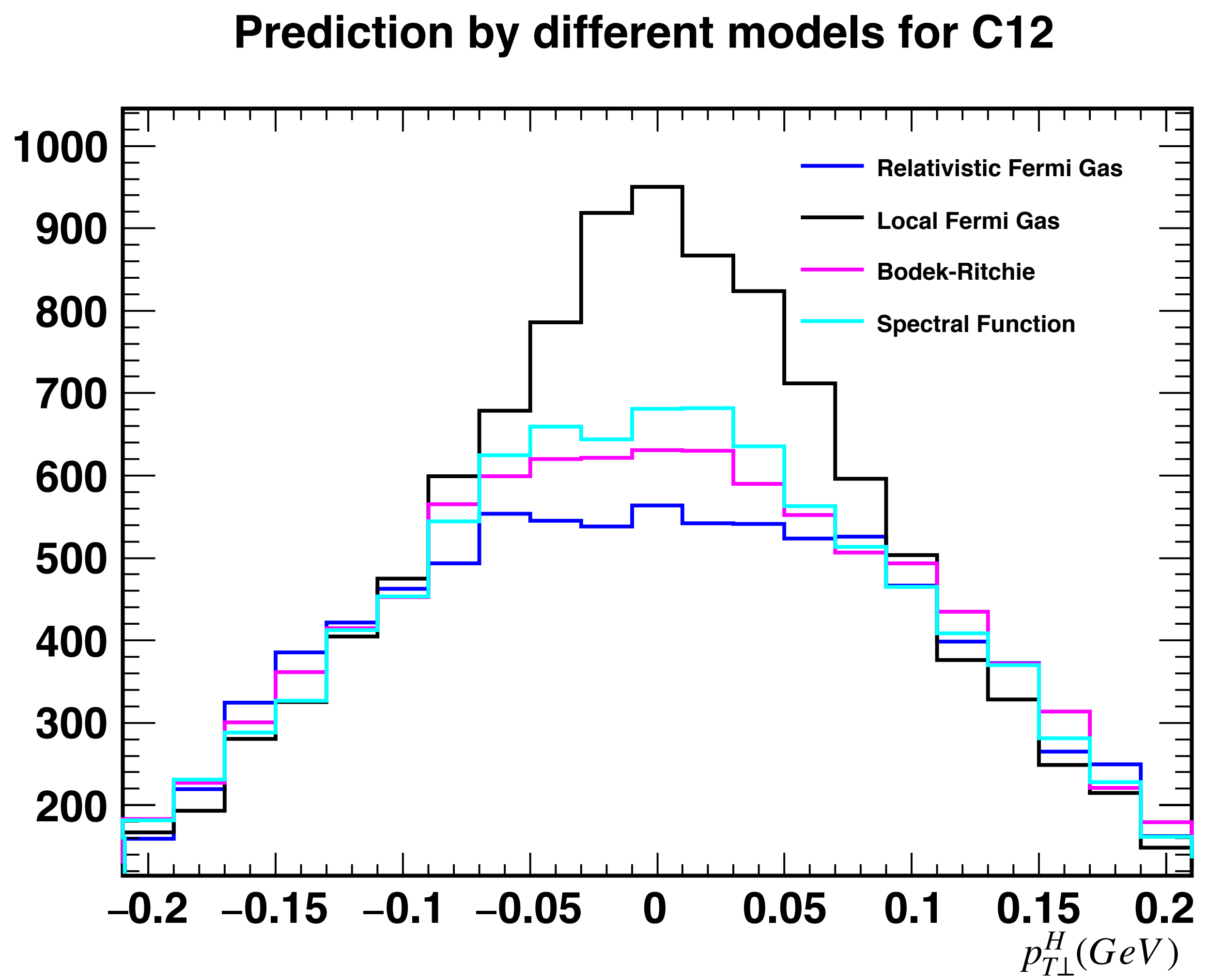
ν-H Selection: Likelihoods

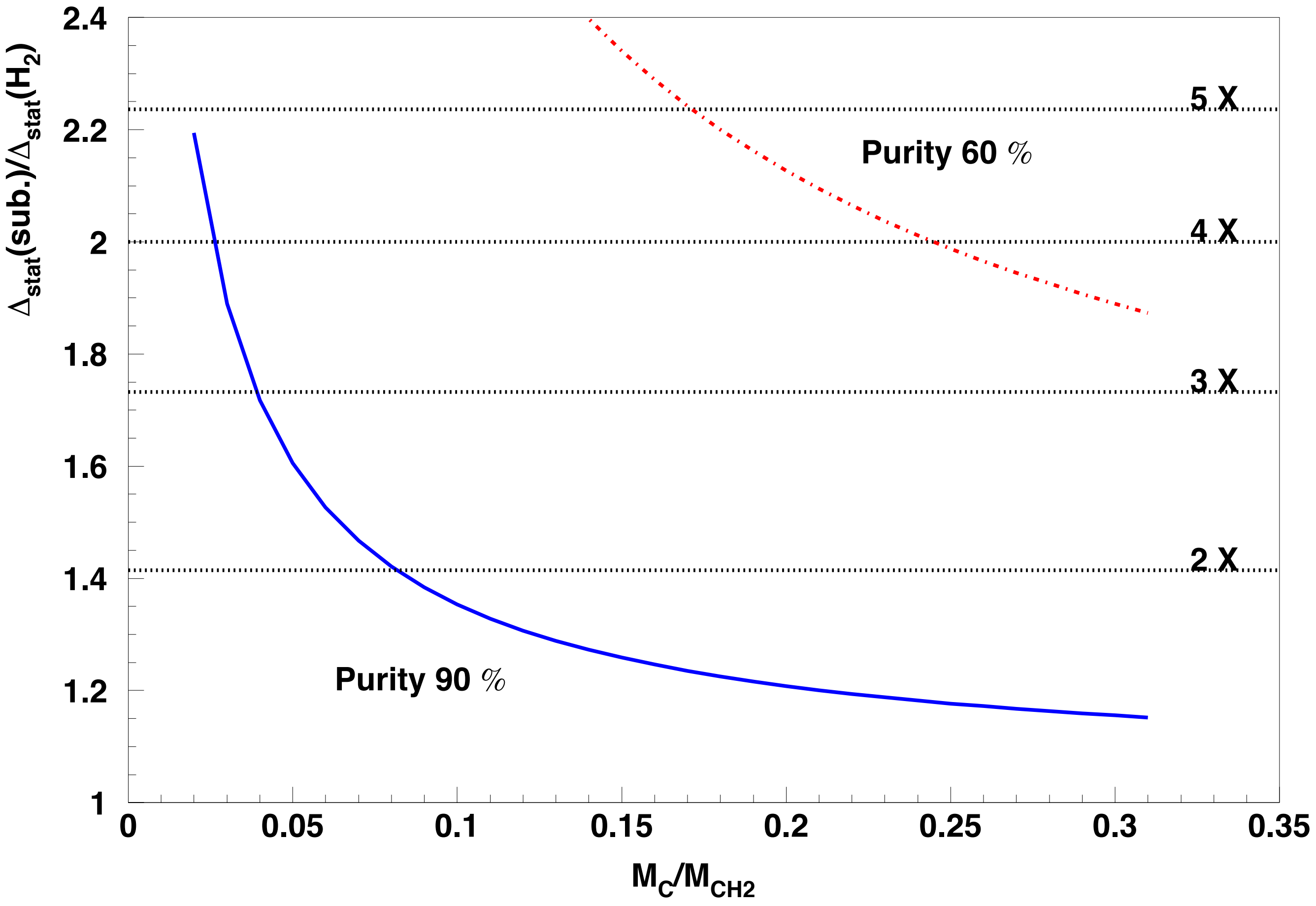

FHC $\mu^- p\pi^+$

arXiv:1809.08752 [hep-ph]

- Build log likelihood function using more variables ($R_{MH}, p_T^M, p_{TT}, \phi_{LH}, \theta_{\mu T}$) can achieve even better purity while maintains efficiency.

ν-H Selection: Background Subtraction



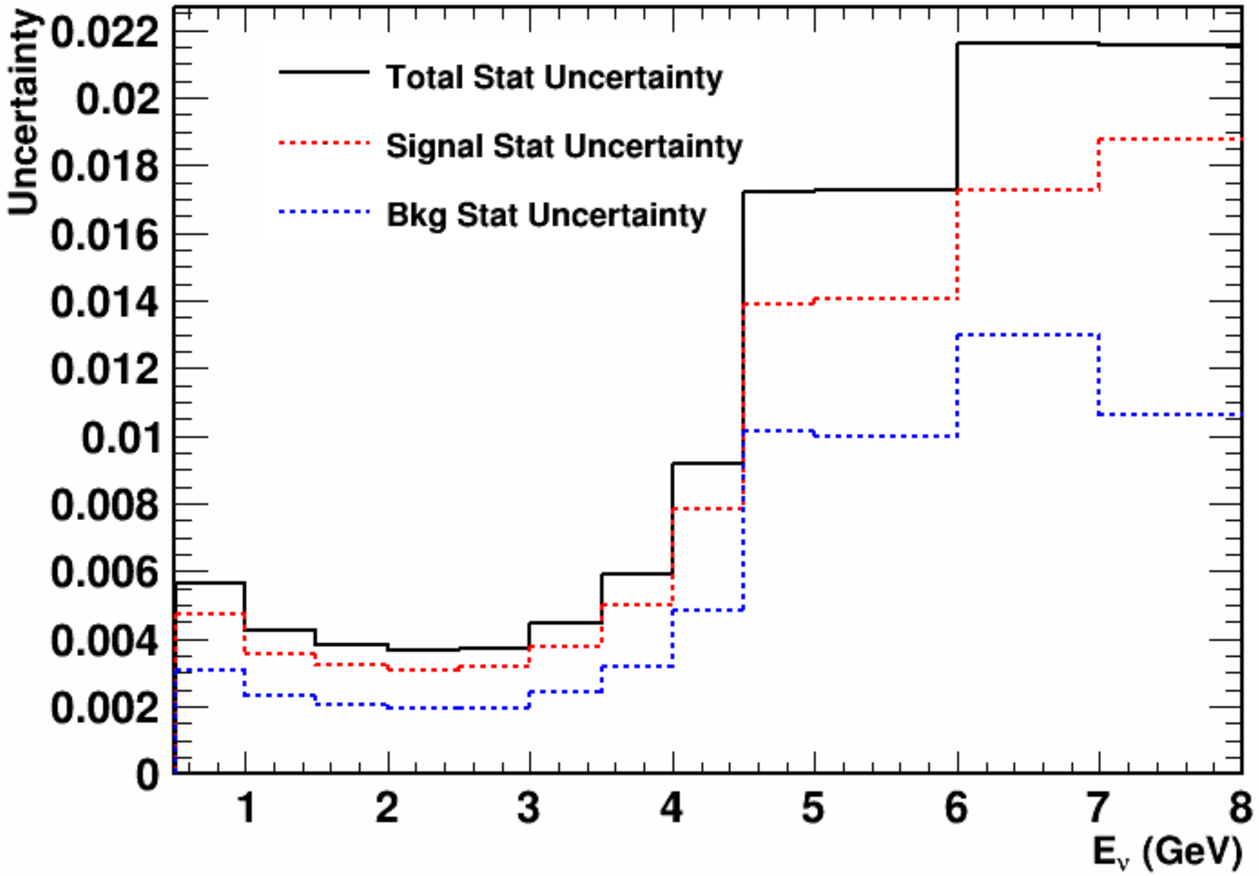


- We can not reply upon MC for the background subtraction.
- It has to be data-driven by the **graphite target** measurement.

$$N_H(\vec{x}) \equiv N_{CH_2}(\vec{x}) - N_C(\vec{x}) \times \frac{M_{C/CH_2}}{M_C}$$

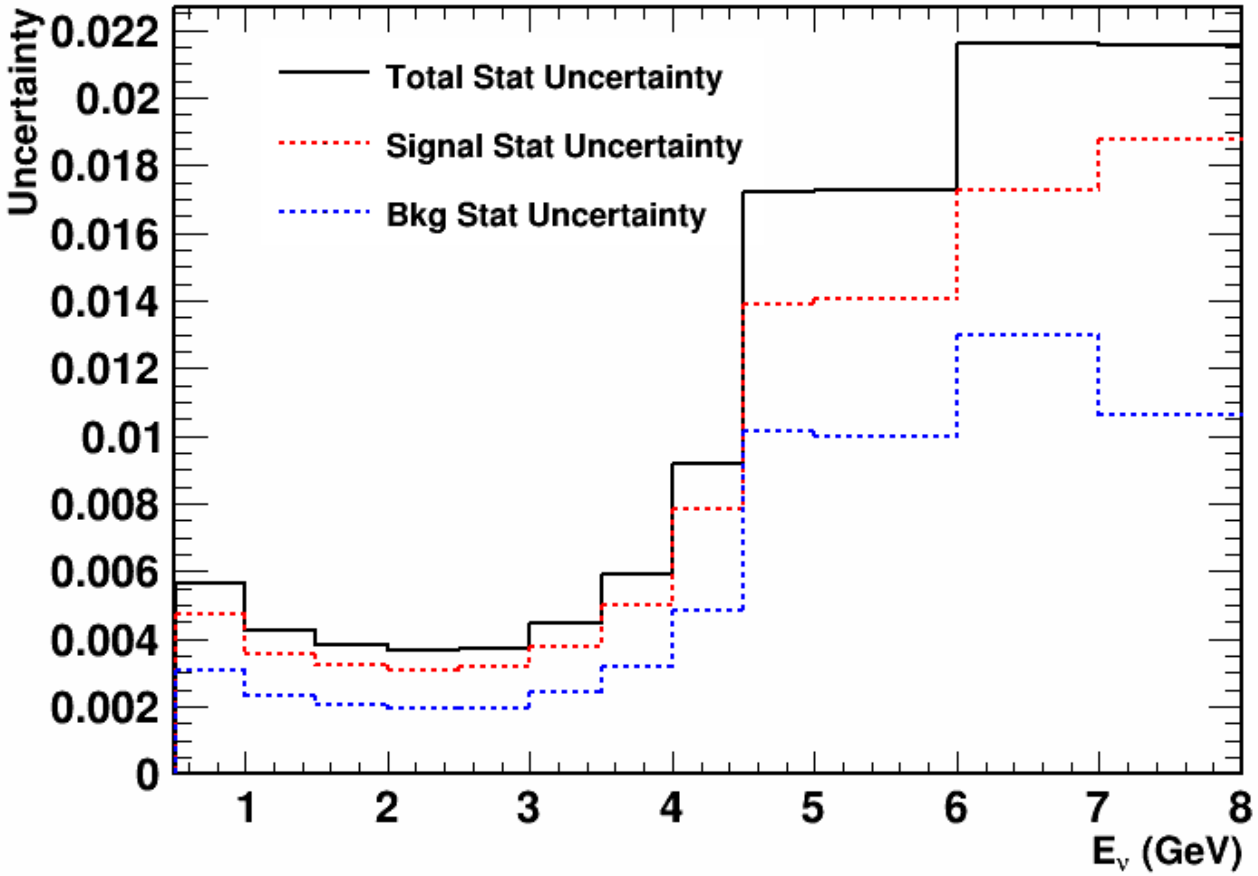
- Graphite mass can be optimized to minimize statistical uncertainty.

ν-H Selection: Background Subtraction



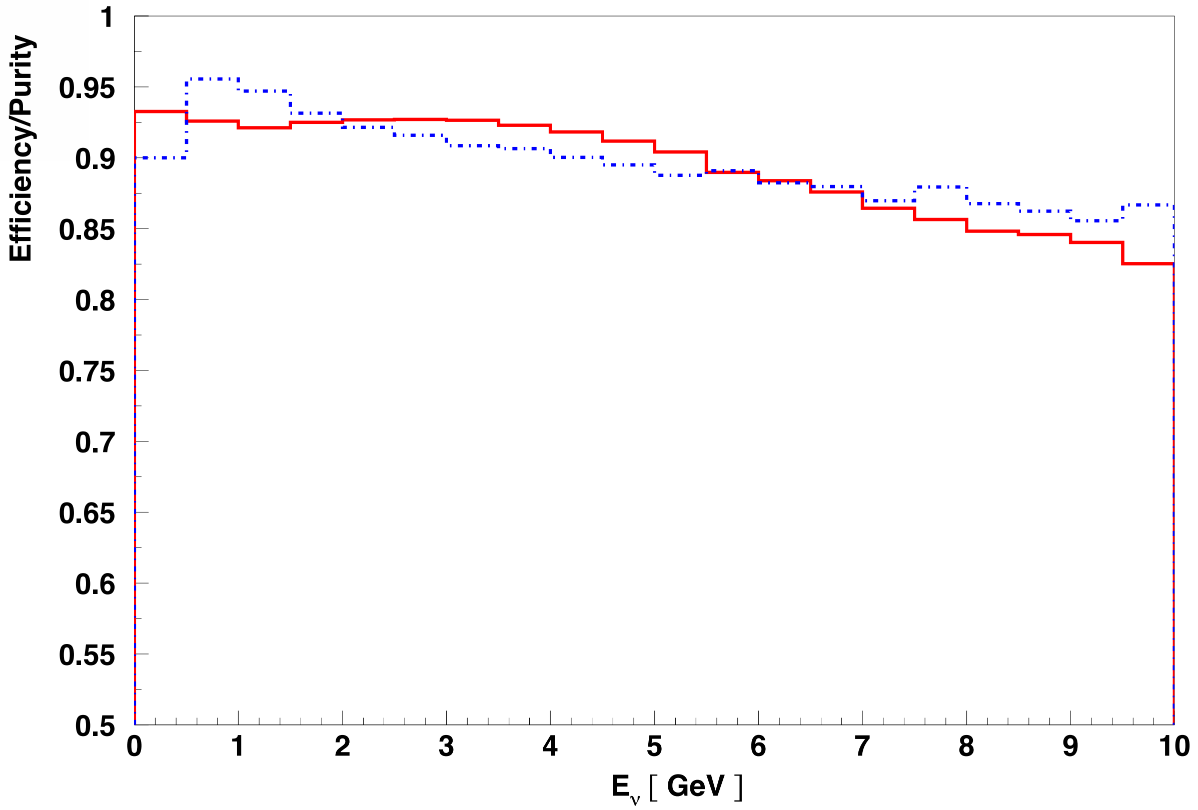
- Assuming 600 kg of graphite target, the subtraction only slightly increase the statistical uncertainty by ~20%.

ν-H Selection: Background Subtraction

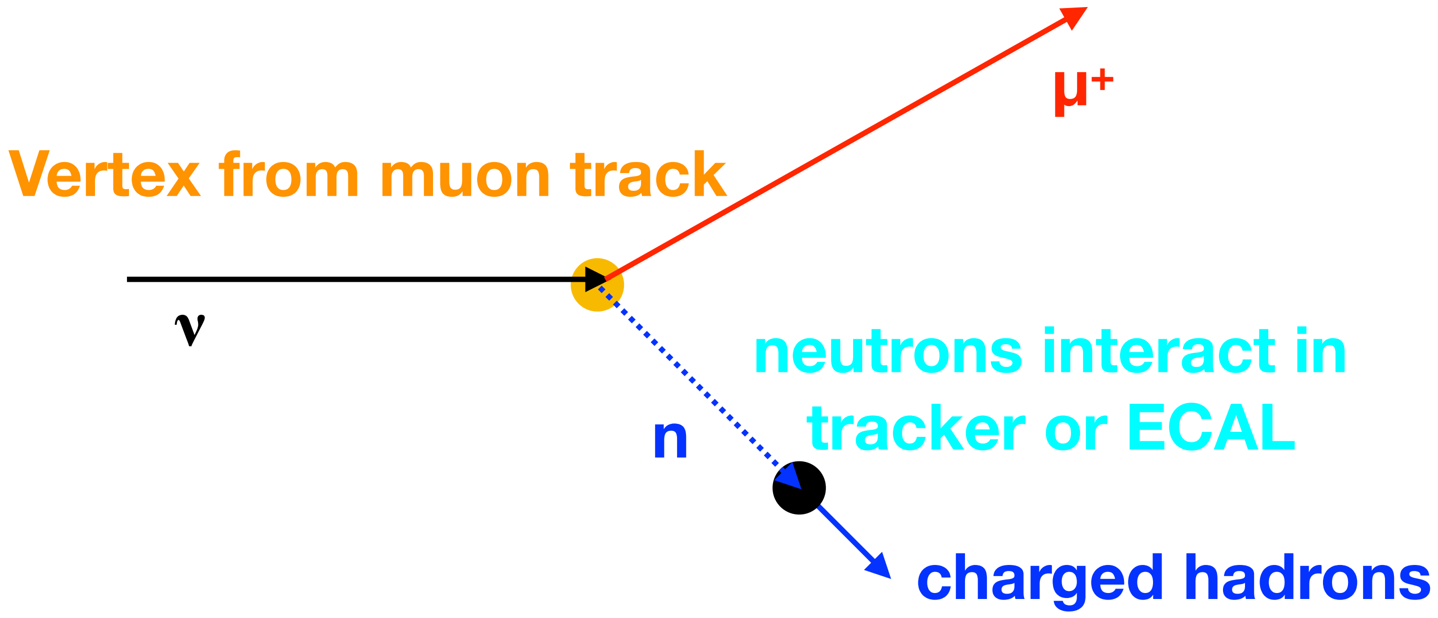


- Assuming 600 kg of graphite target, the subtraction only slightly increase the statistical uncertainty by ~20%.

- The selection efficiency is quite high and flat for neutrino energy < 5 GeV

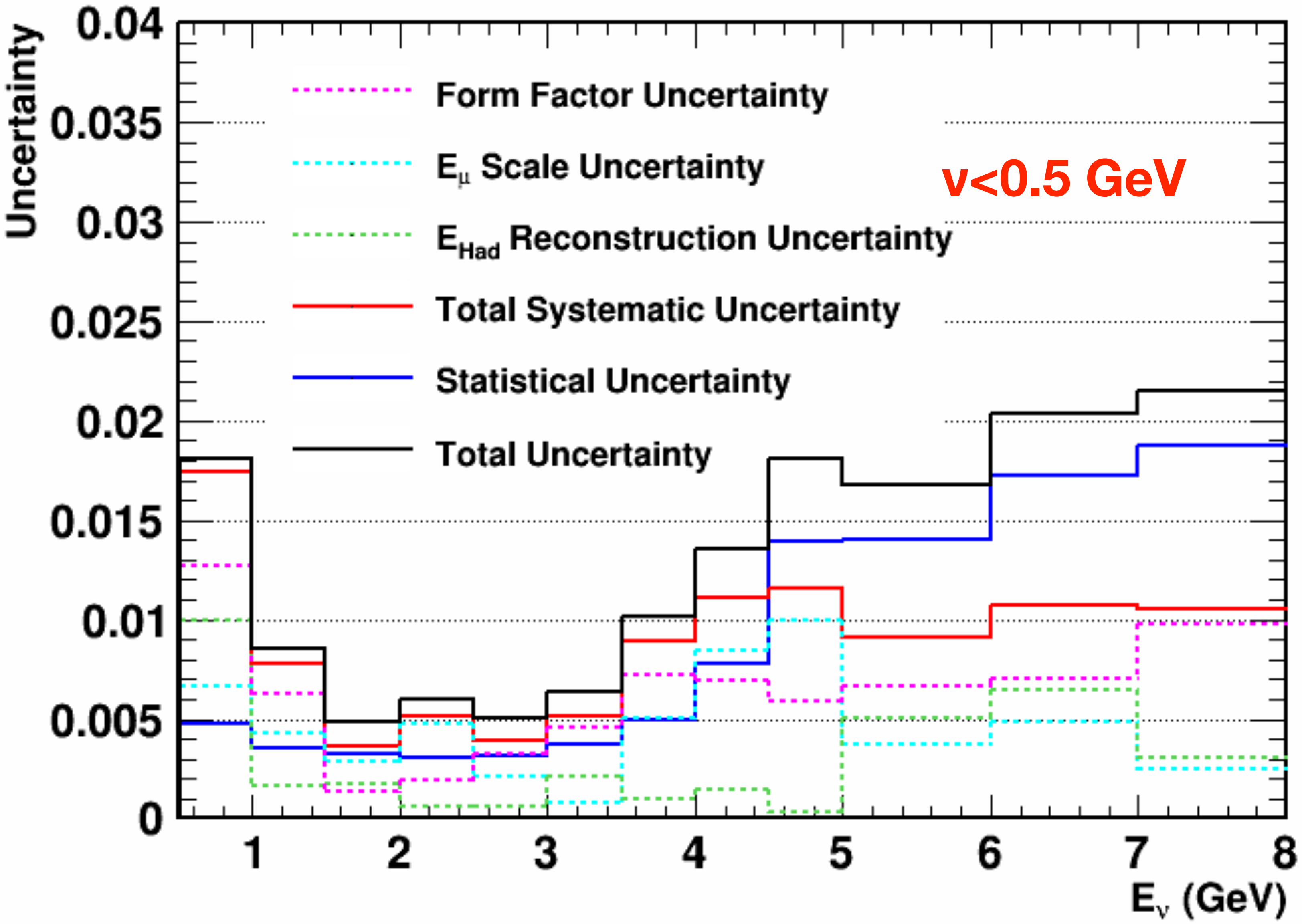


$\bar{\nu}_\mu$ CCQE



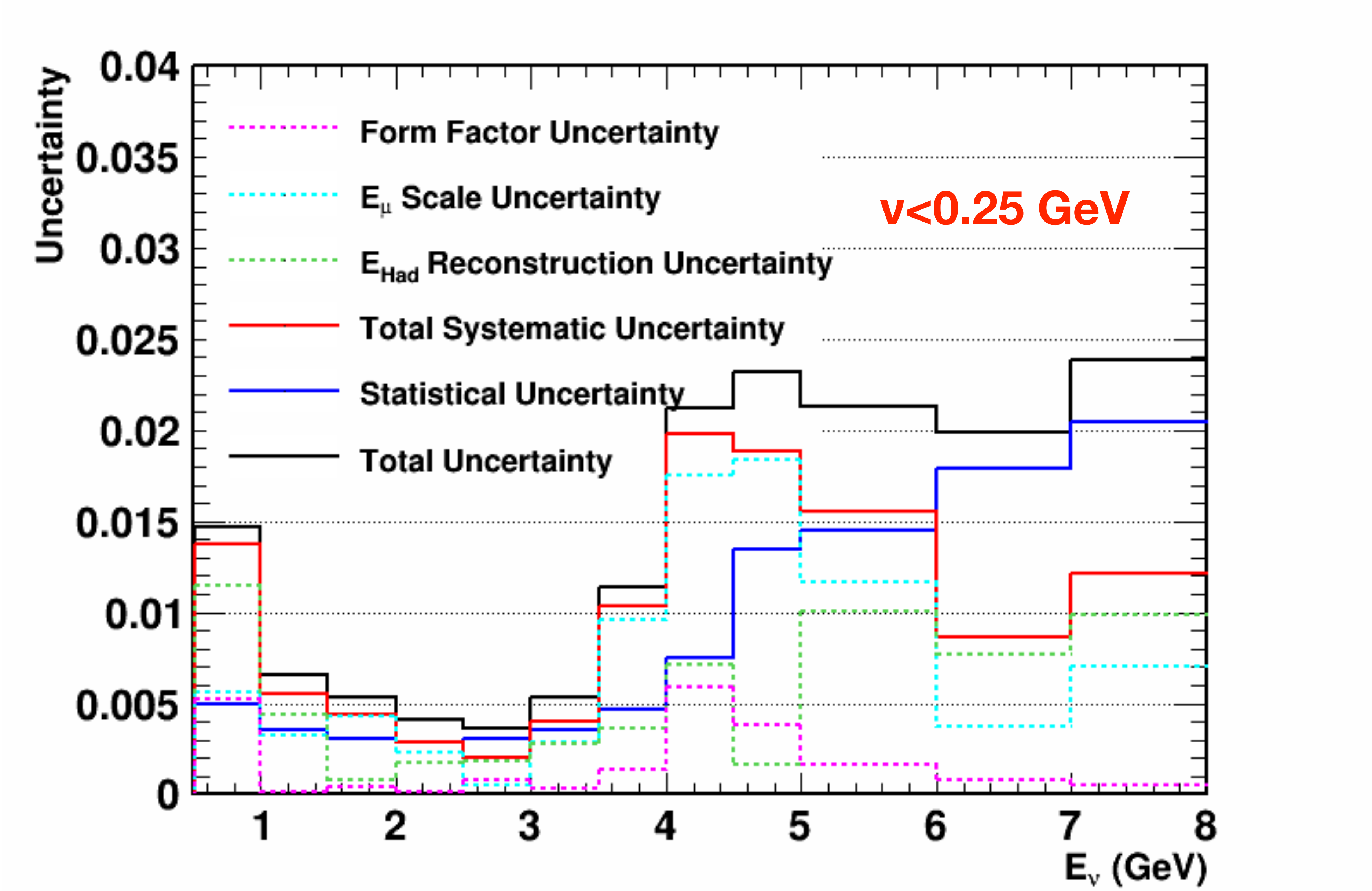
- Neutrons themselves are invisible.
- About 25-30% of the neutrons interact within STT 45-60% in ECAL producing charged secondary particles..
- Interaction vertex position is obtained from the muon.
- Get the neutron direction from the vertex to interaction point.
- Get the neutron energy from the muon kinematics with QE assumption.
- Similar hydrogen vs carbon selection with resonance events.

Low-ν Method on Hydrogen (Resonance 3-Track)



- Systematic uncertainty sources:
  - Muon energy scale: 0.2%
  - Hadronic reconstruction.
  - Cross-section modeling: 20% M_A, 10% M_V.

Low-ν Method on Hydrogen: $\bar{\nu}_{\mu}$- CCQE



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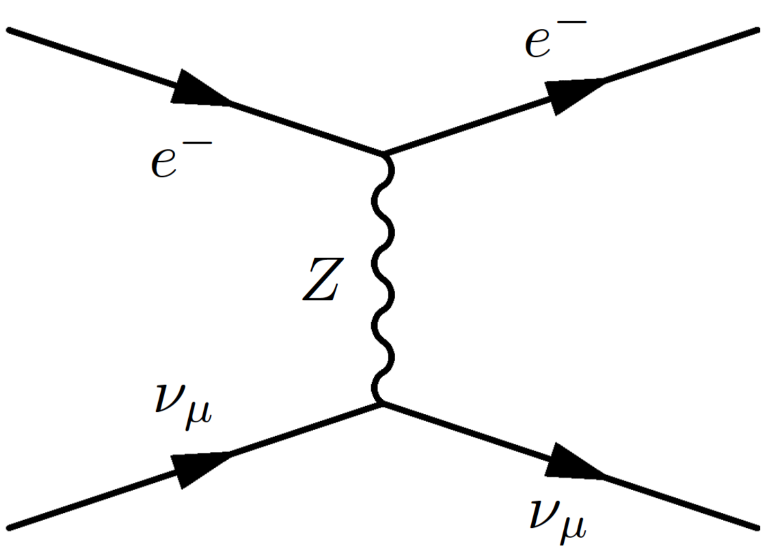
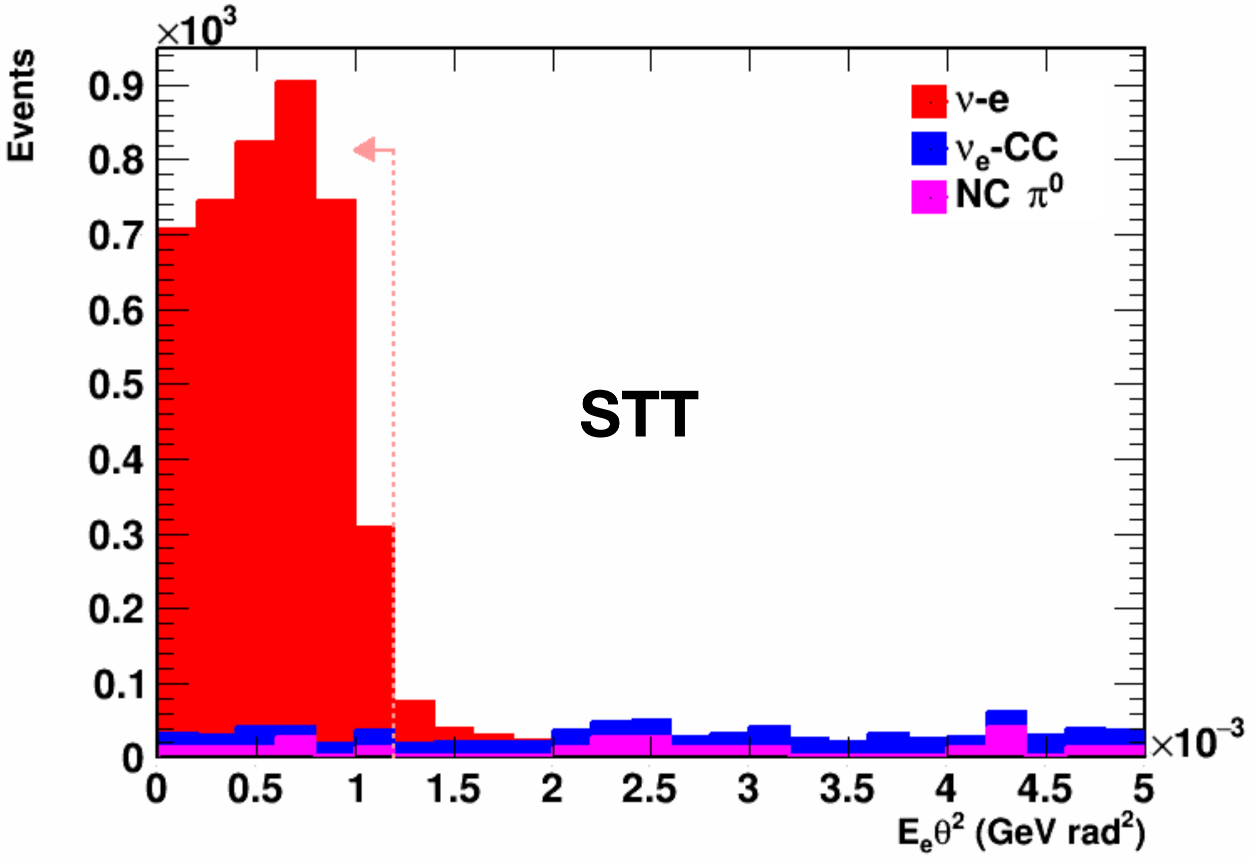
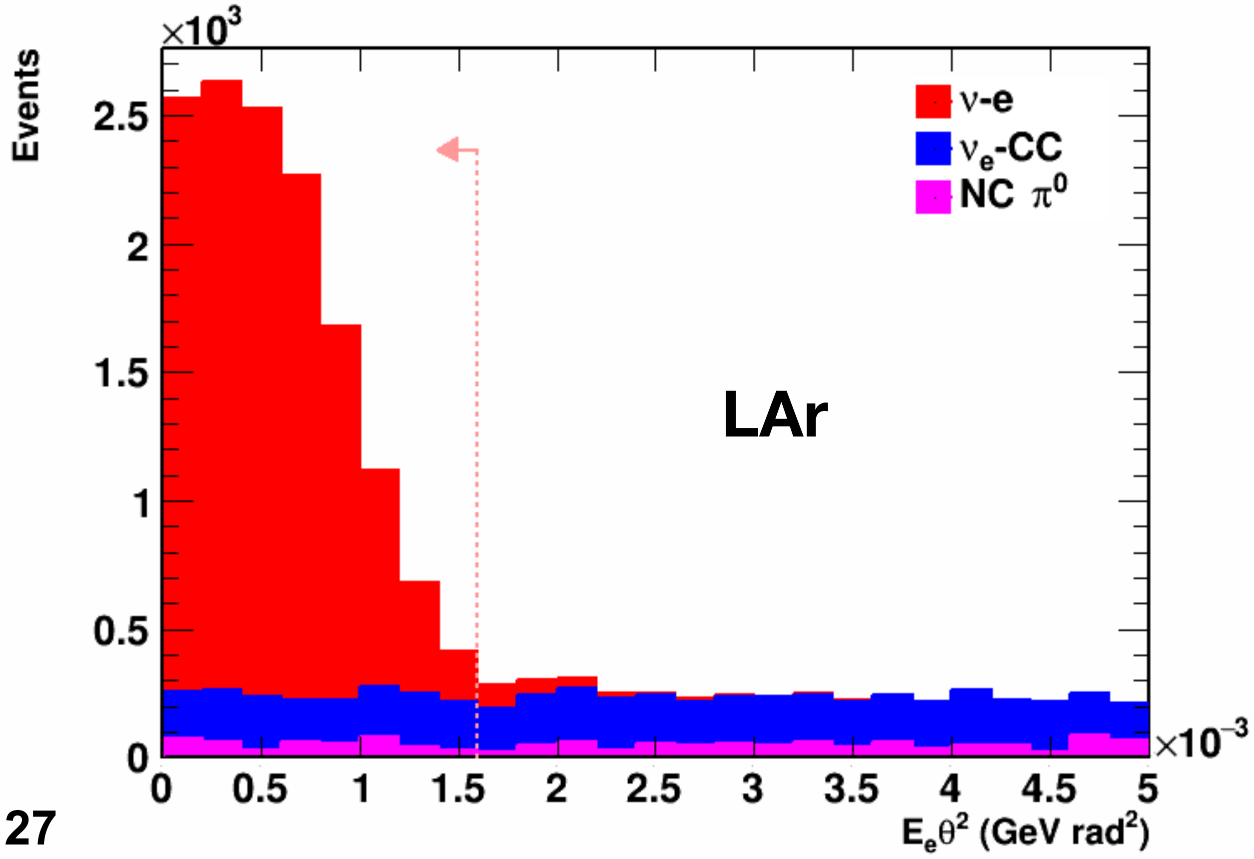
Flux Normalization Measurement by ν-e Scattering



- Pure electroweak process with small, but very well known cross section:
- Better statistics in LAr, but significantly larger background from ν_e-QE where proton absorbed/ below threshold due to nuclear effects.
- STT gives low-systematic measurement complementary to LAr.
- ~2% uncertainty on flux normalization.





Summary

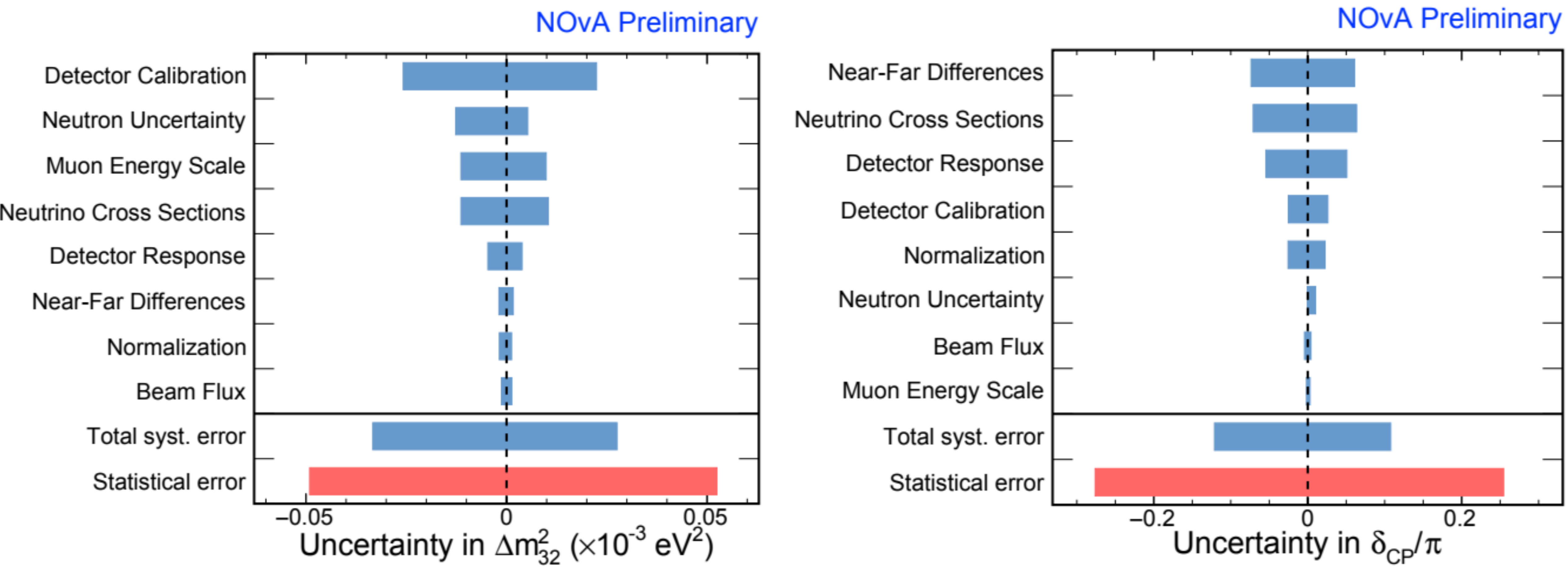
- Flux uncertainty is an important uncertainty source to DUNE.
- KLOE-STT provides possibility to measure neutrino-hydrogen interactions, combined with low-ν technique it provides precise flux measurements.
- Key detector features for the hydrogen measurements:
  - Abundant hydrogen in CH2
  - High-resolution, low-threshold measurements of final state particles for signal vs background separation
  - Dedicated carbon target with same detector response as CH2 for background subtraction.
- KLOE-STT's constraint on the beam modeling is complementary to other ND detectors and the DUNE-prism concept.
- For more details: **Phys.Lett. B795 (2019) 424-431**

Back up slides

Outline

- Introduction to nu-oscillation and DUNE
- why do we need a near detector (or near detectors)
- Why do we need to know the neutrino flux
- low-nu in general
- low-nu on hydrogen
- Introduction to KLOE-STT
- low-nu on hydrocarbon with bkg subtraction: CH2
- what if we have CH?

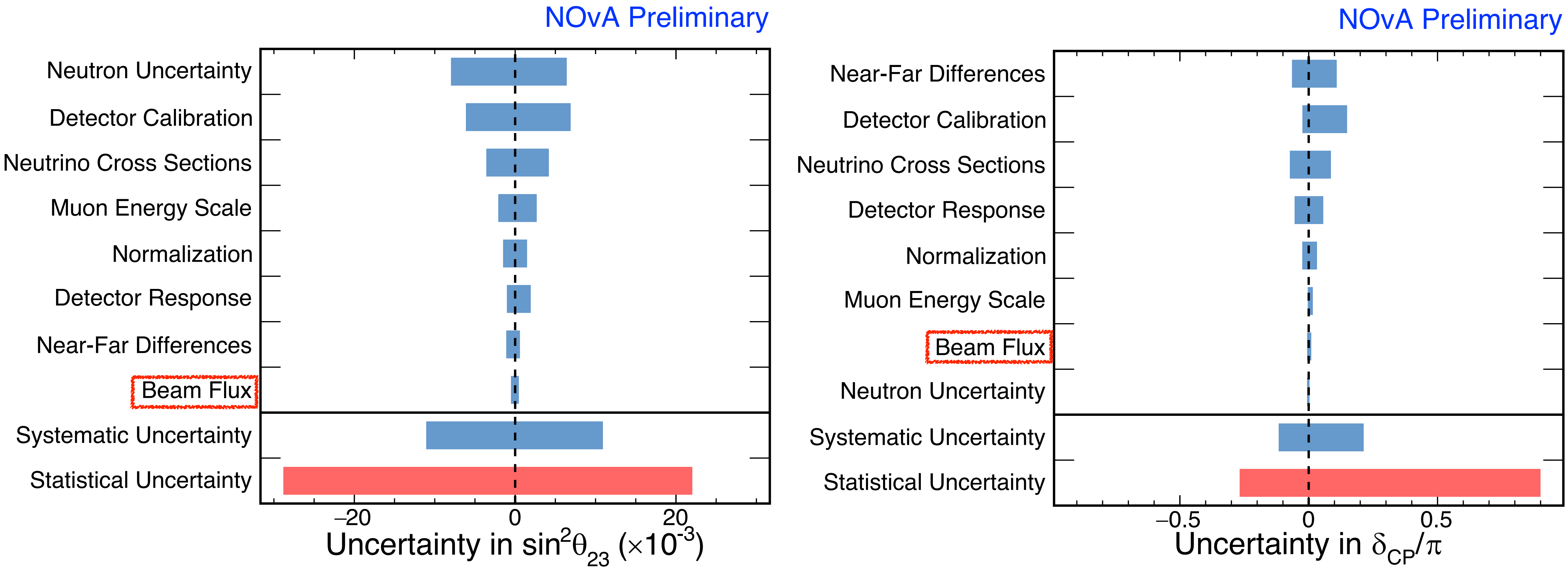
Uncertainties to Neutrino Oscillations



NOvA's new 2019 neutrino/antineutrino oscillation measurement

- Until now statistical uncertainty is still the dominant uncertainty source to oscillation measurements.
- This is no longer true in the DUEN era.

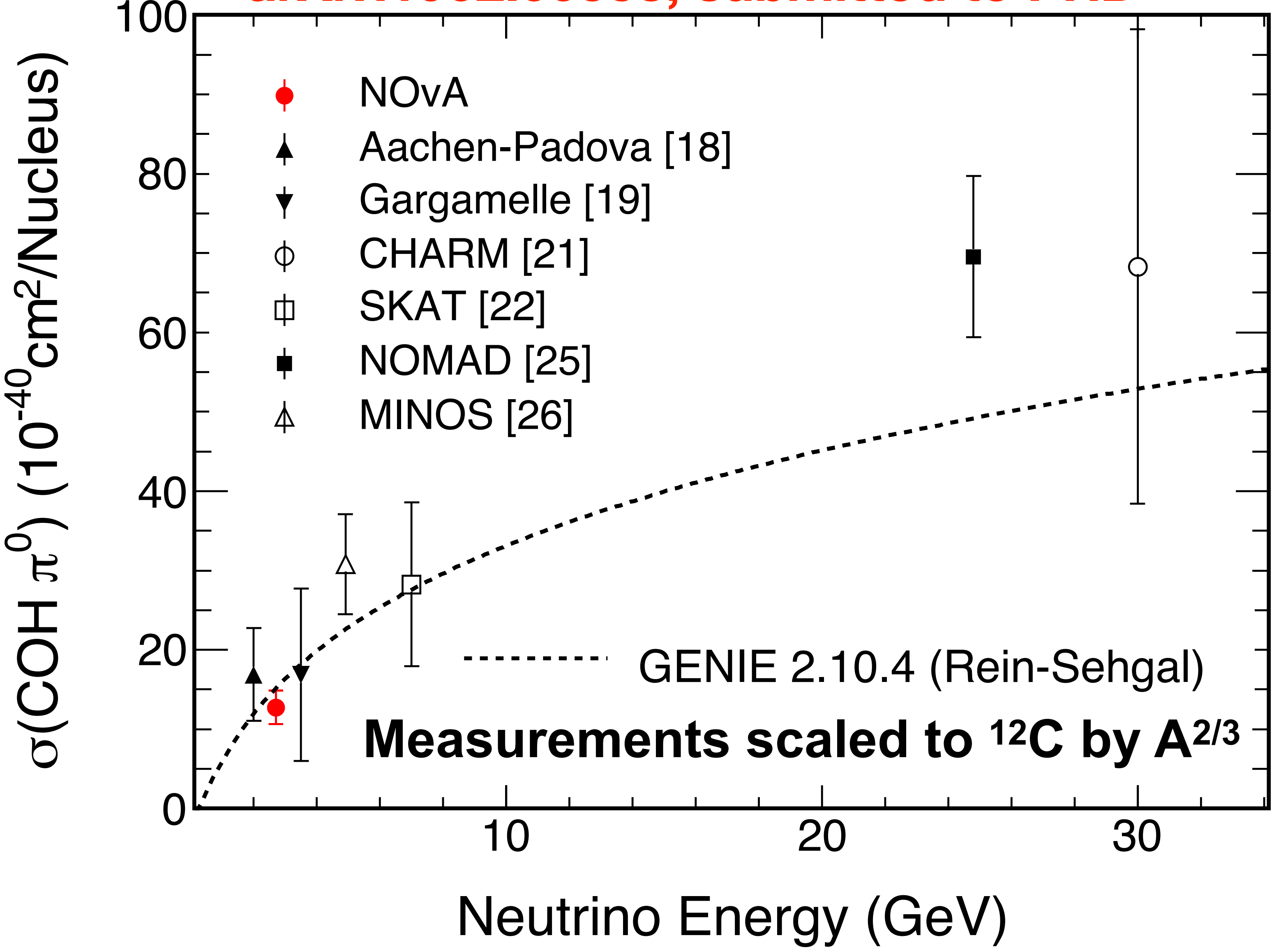
Uncertainties to Neutrino Oscillations



NOvA's 2018 neutrino/antineutrino oscillation measurement

Cross Section Uncertainties

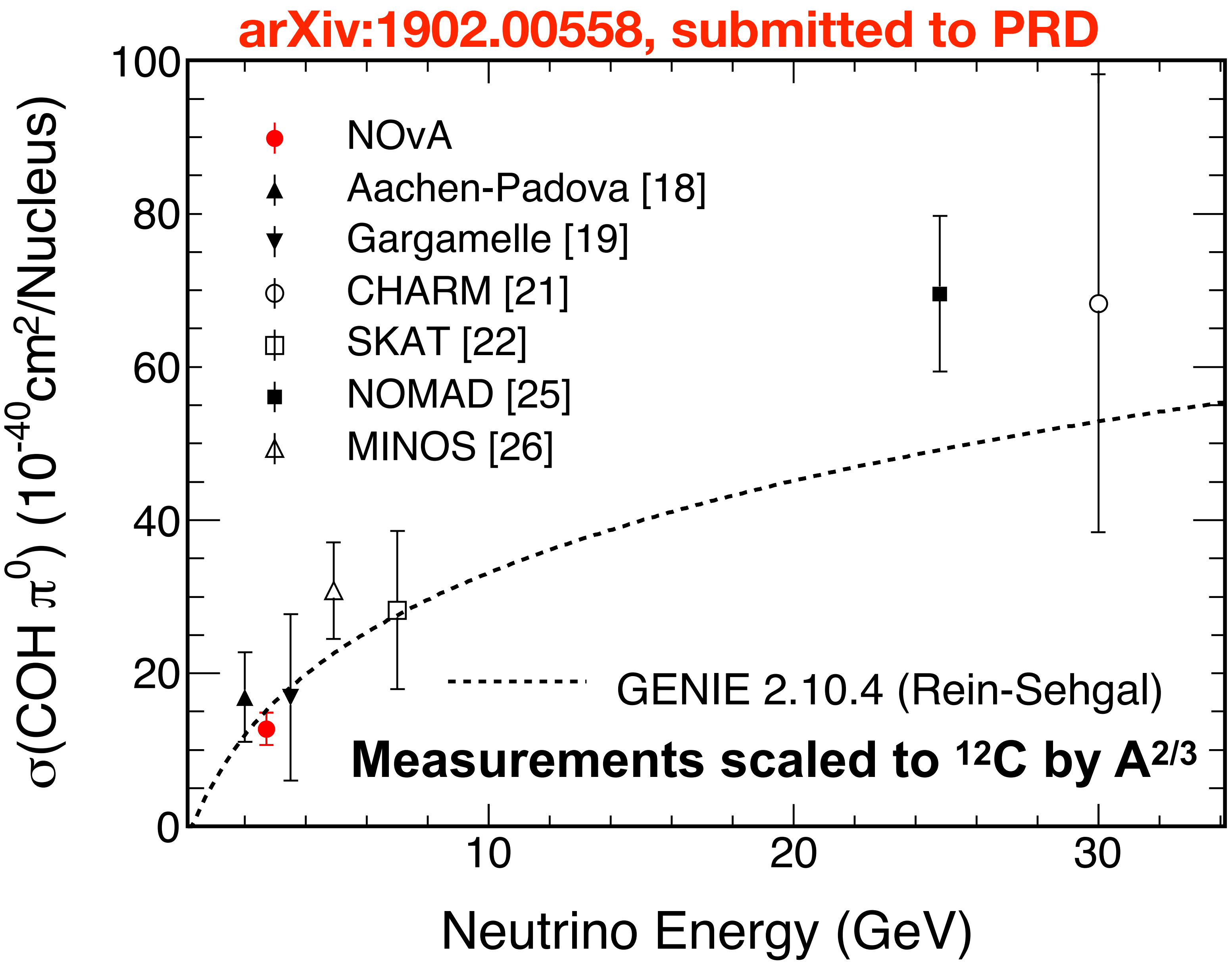
arXiv:1902.00558, submitted to PRD



Source	$\delta(\%)$
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Event	2.4
Alignment	2.0
Flux	9.4
Total Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7

- Example of NOvA's NC Coherent π^0 measurement, one of the background channel to ν_e appearance oscillation measurement.
- Flux is one of the dominant systematic uncertainty sources.
  - The "background modeling uncertainty" also limited by flux.

Cross Section Uncertainties



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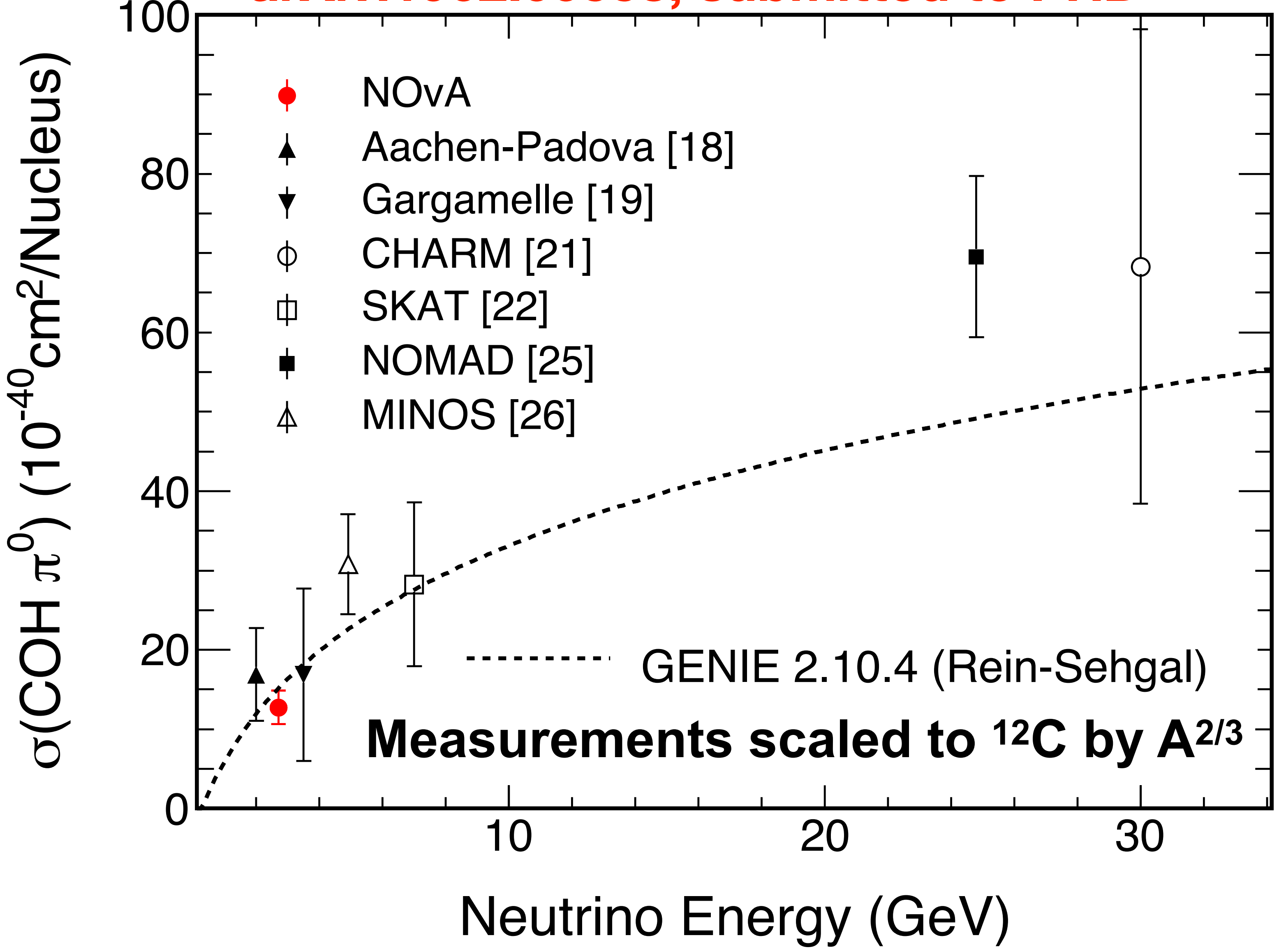

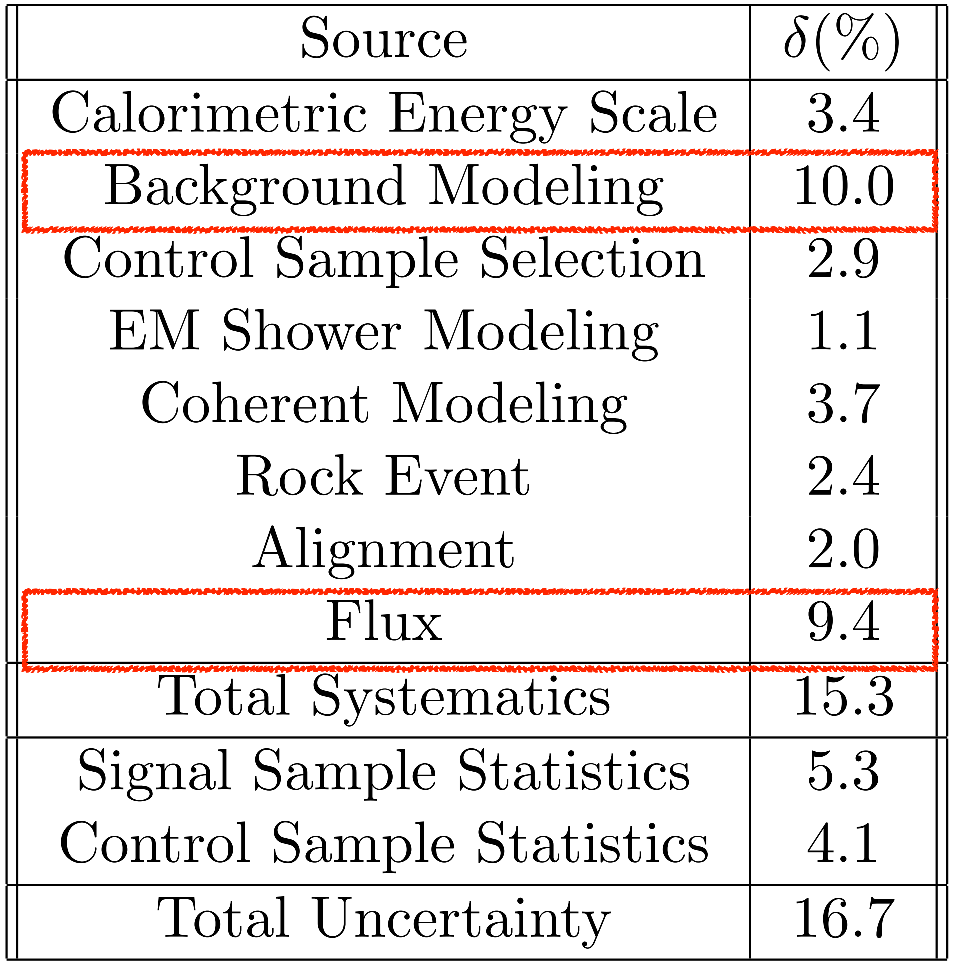

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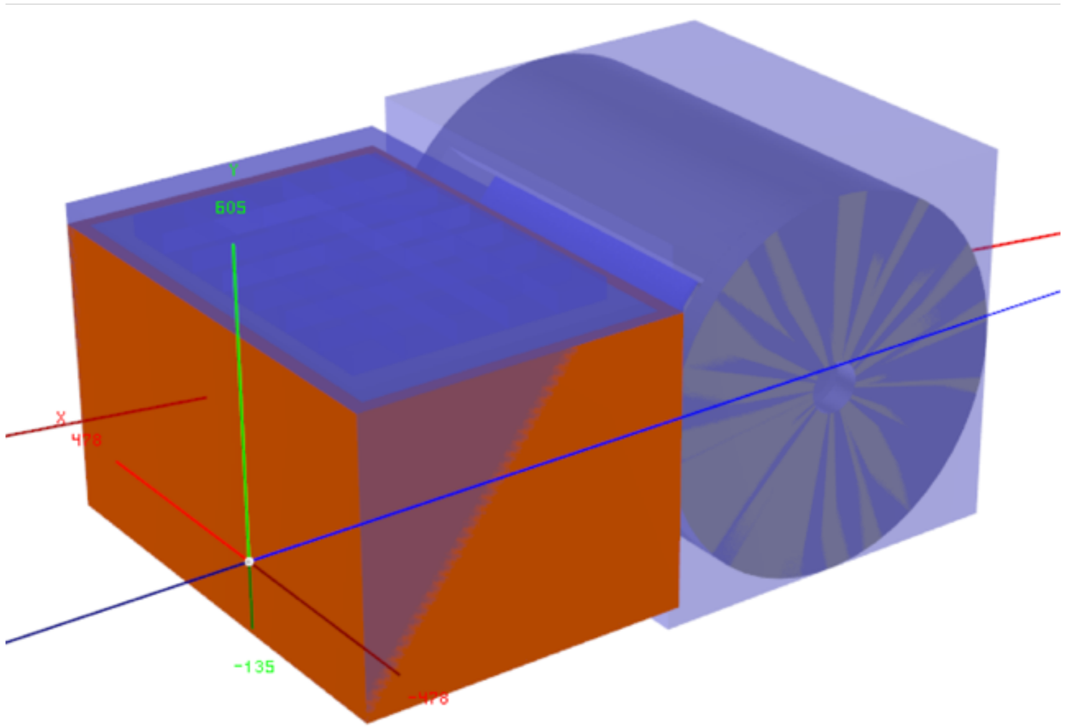
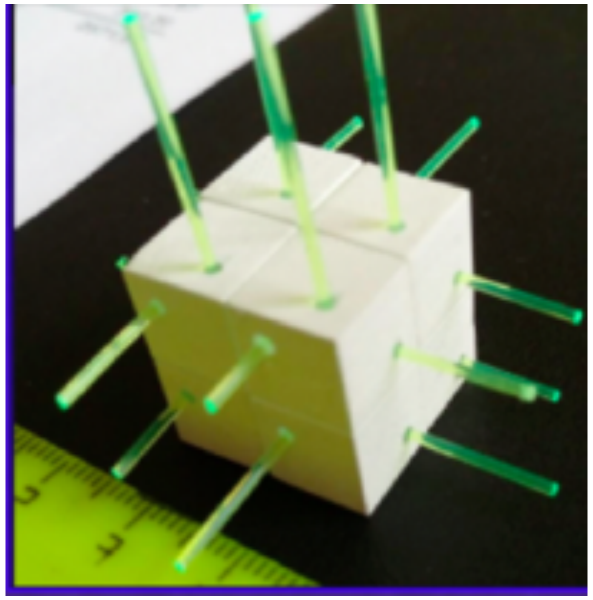
DUNE Near Detectors





- LAr + HP ArG TPC + 3DST
- DUNE prism

Can We Cancel All Systematics by ND?

$$\underbrace{N(E_{rec})}_{\text{Number of events observed in the detector}} = \int_{E_\nu} dE_\nu \underbrace{\Phi(E_\nu)}_{\text{Neutrino flux}} \underbrace{\boxed{\xcancel{P_{osc}(E_\nu)}}}_{\text{Oscillation probability (zero in the ND)}} \underbrace{\sigma(E_\nu)}_{\text{Cross section (E-38 cm}^{2}\text{)}} \underbrace{R_{det}(E_\nu, E_{rec})}_{\text{Detector response}}$$

- Ideally, the ND would have zero oscillation probability, and all the other factors the same as FD, which allows cancellation of systematics.
- However in practice…
  - **Flux** is never the same between ND and FD.
  - **Detector response** is never the same between ND and FD.
  - Some ND even uses different **nuclear targets** from FD.
  - And we still need to know **Eν**!

Statistical vs Systematic Uncertainties

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \Phi(E_\nu) P_{osc}(E_\nu) \sigma(E_\nu) R_{det}(E_\nu, E_{rec})$$

Number of events observed in the detector

Neutrino flux

Oscillation probability

Cross section (E-38 cm^2)

Detector response

Very small cross section => Limited number of events observed in the detector

⬇

Statistical uncertainty has been the dominant uncertainty source in most of the neutrino experiments so far

- Solutions:
  - Massive detectors.
  - **Heavy nuclear targets (Ar).**
  - Powerful neutrino beams.

- Price:
  - Resolution/calibration?
  - **Nuclear effects?**
  - Flux uncertainties?

Why Do We Need Near Detectors?

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \Phi(E_\nu) \boxed{P_{osc}(E_\nu)} \sigma(E_\nu) R_{det}(E_\nu, E_{rec})$$

Number of events observed in the detector

Neutrino flux

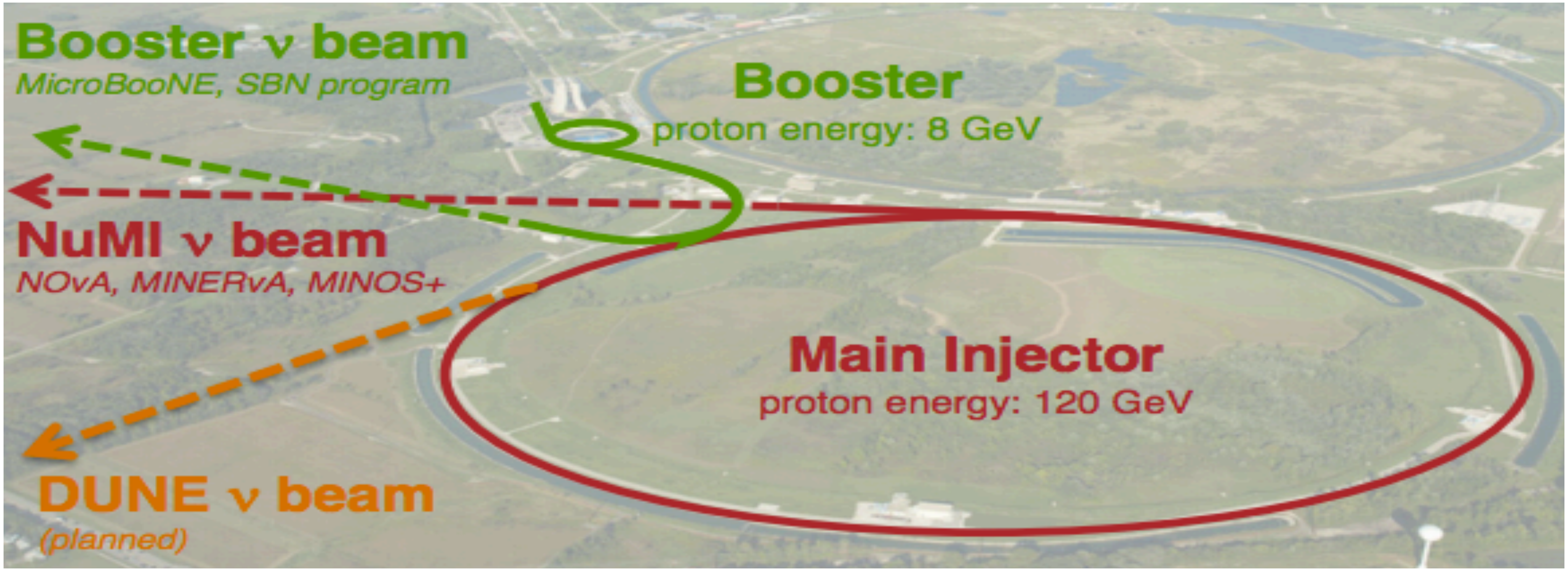
Oscillation probability

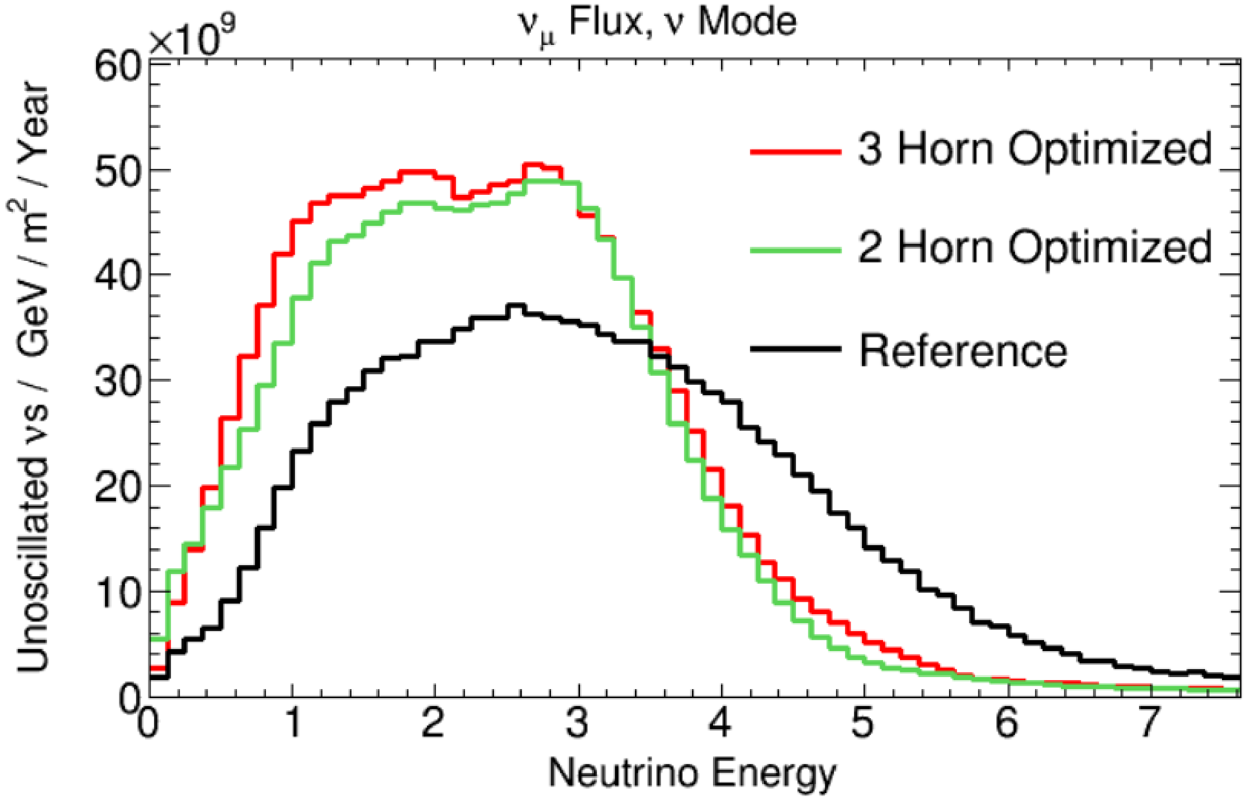
Cross section (E-38 cm^2)

Detector response

- Ideally, we could measure oscillation by measuring number of interactions (as function of neutrino energy), if all the other factors are known.
- However in practice…
  - Flux has >10% uncertainty.
  - Cross-sections are not well-known.
  - Detector simulation and calibration can also be difficult.
  - Therefore we need ND.

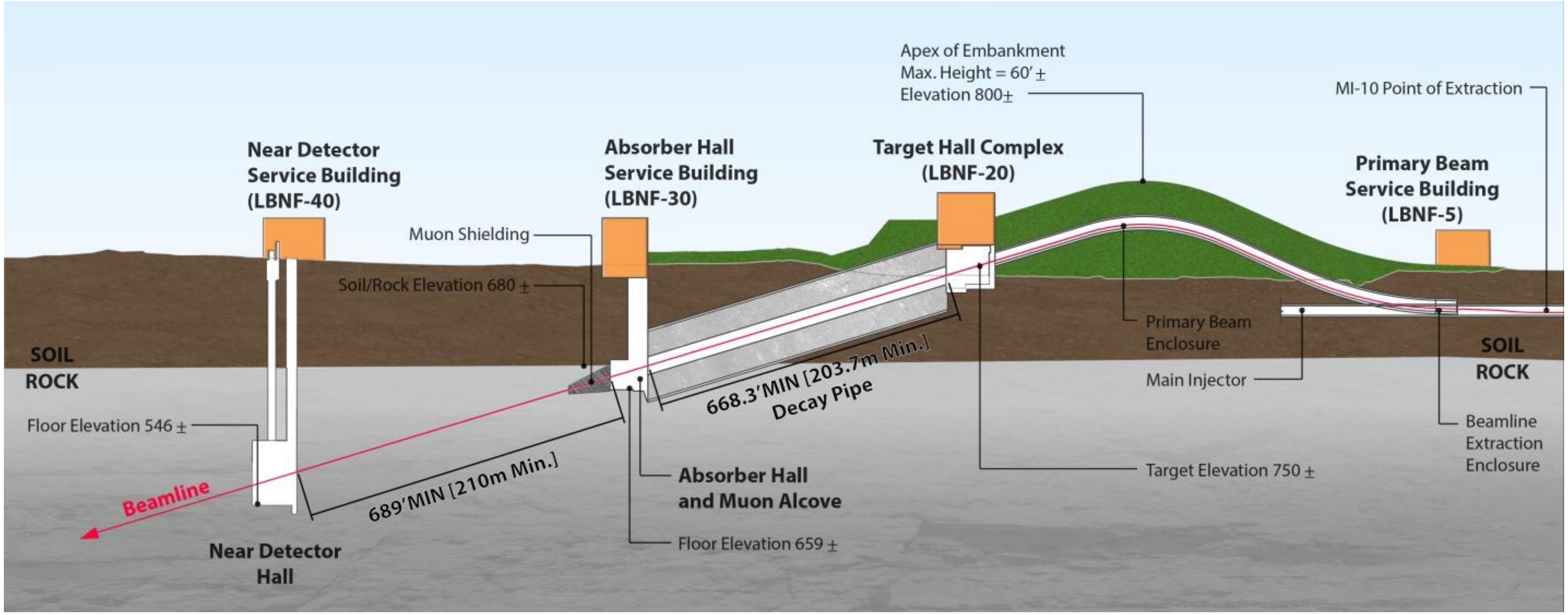
Neutrino Flux at DUNE

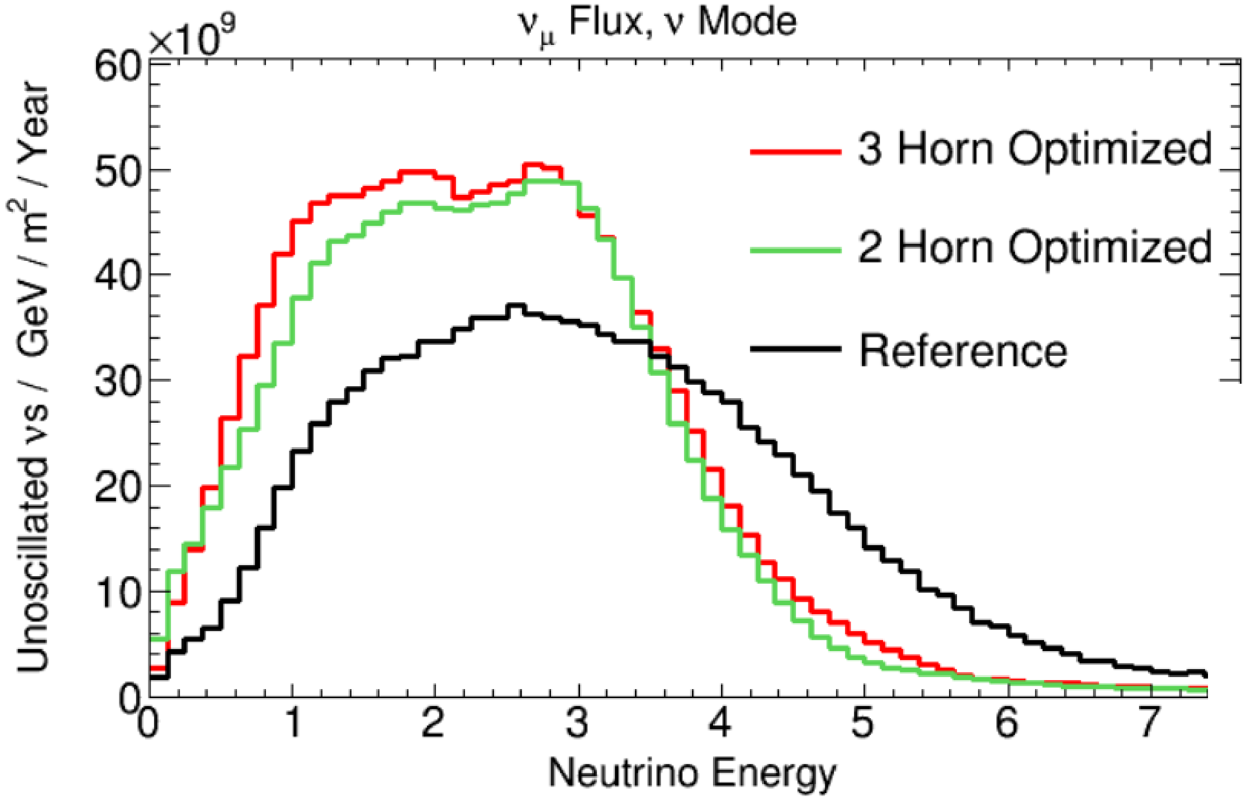




- DUNE will use the new LBNF neutrino beam.
- Flux uncertainty comes from hadron production and beam focusing.

Neutrino Flux at DUNE





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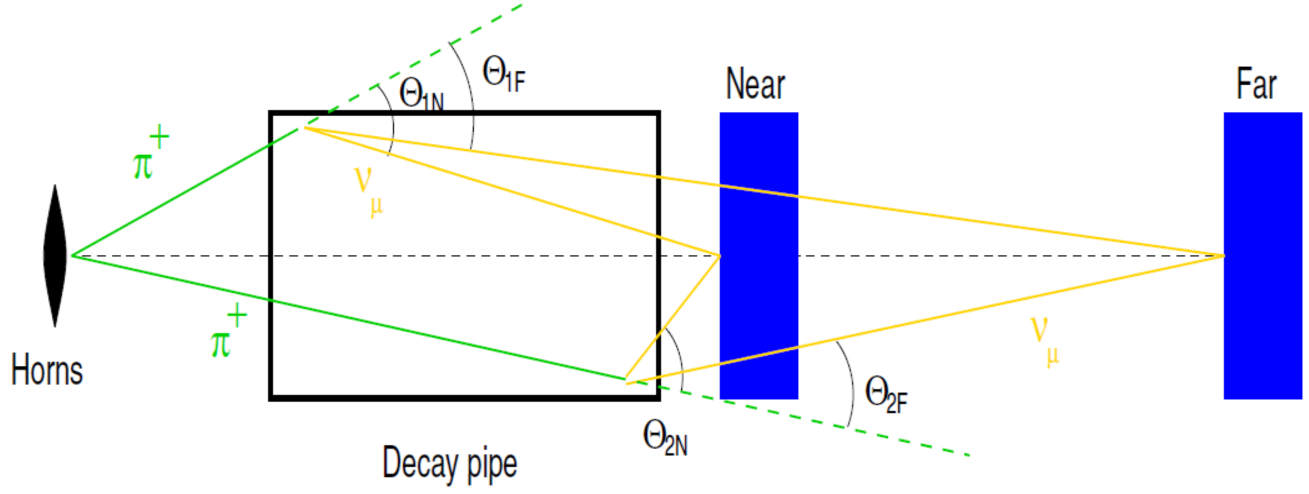
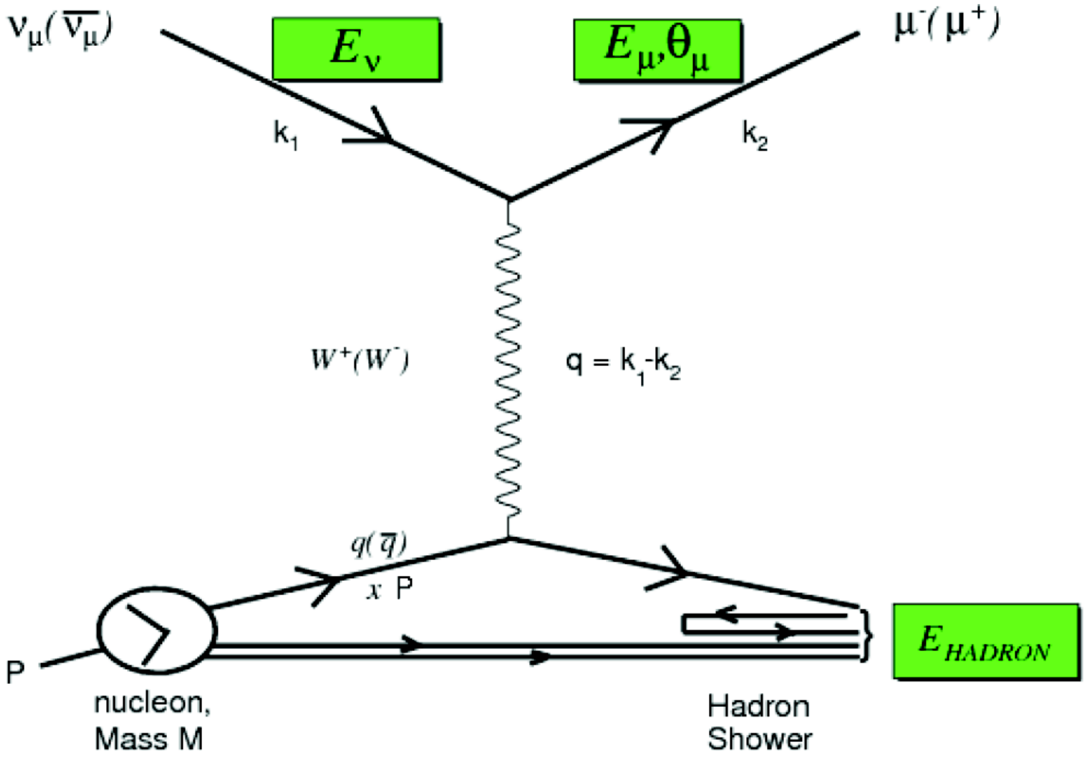


Low-ν Method

$$\frac{d\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi} \times \left[\left(1 - y - \frac{Mxy}{2E}\right) F_2^{\nu(\bar{\nu})} + \frac{y^2}{2} 2xF_1^{\nu(\bar{\nu})} \pm y\left(1 - \frac{y}{2}\right) xF_3^{\nu(\bar{\nu})}\right]$$



- Bjorken scaling variable:

$$x = \frac{Q^2}{2P \cdot q}, \qquad y = \frac{P \cdot q}{P \cdot k_1}$$

- energy transfer to the hadronic system:

$$\nu = \frac{P \cdot q}{M} = E \cdot y$$

- Structure function: F_1, F_2, F_3

Low-ν Method

$$\frac{d\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi} \times \left[\left(1 - y - \frac{Mxy}{2E}\right) F_2^{\nu(\bar{\nu})} + \frac{y^2}{2} 2xF_1^{\nu(\bar{\nu})} \pm y \left(1 - \frac{y}{2}\right) xF_3^{\nu(\bar{\nu})}\right]$$

Integrating the differential Xsec given above over x (from 0 to 1)

$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

$$\begin{aligned} A &= \frac{G_F^2 M}{\pi} \int F_2(x) dx \\ B &= -\frac{G_F^2 M}{\pi} \int (F_2(x) \mp xF_3(x)) \\ C &= B - \frac{G_F^2 M}{\pi} \int F_2(x) R_{TERM} dx \end{aligned}$$

$$N(E)_{(\nu \leq 1)} = \Phi(E) \cdot A \int_0^1 \left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right) d\nu$$

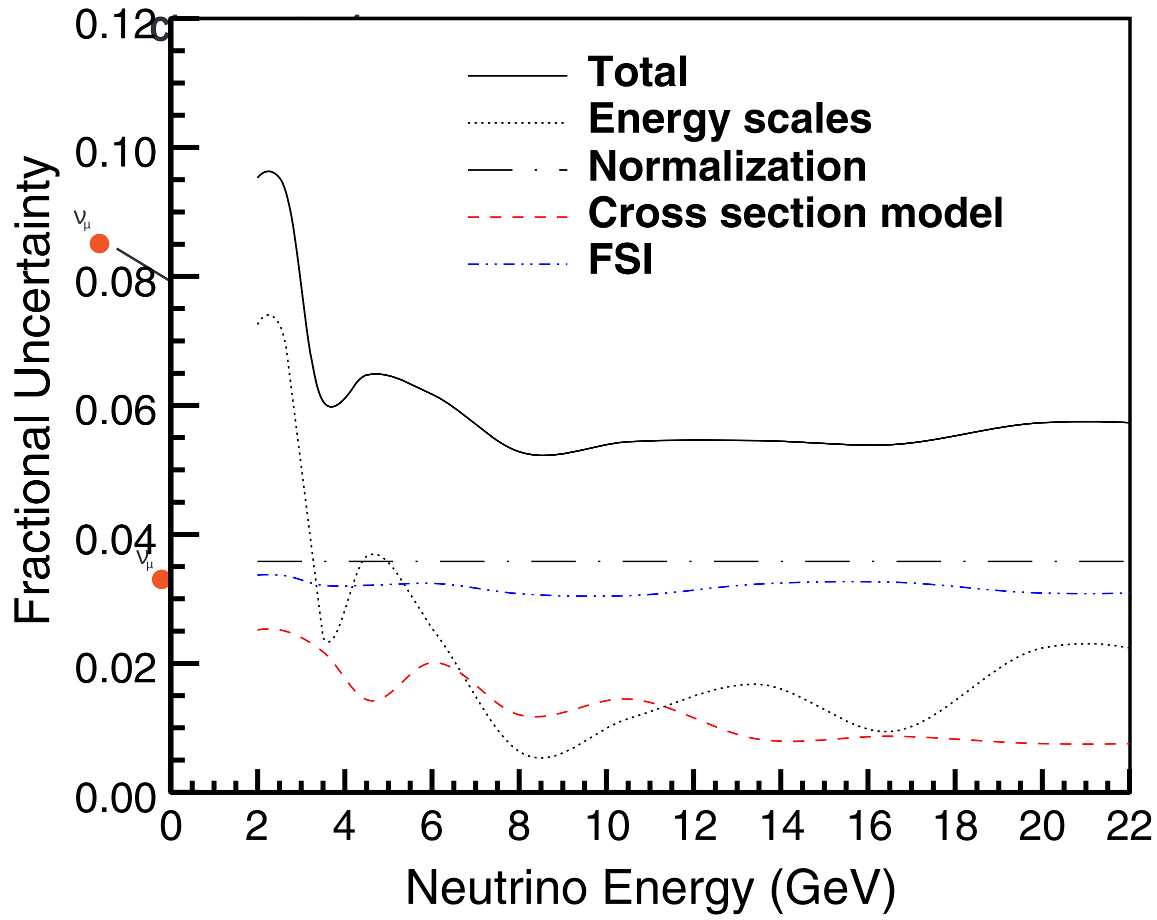
Uncertainties to the Low-ν Method

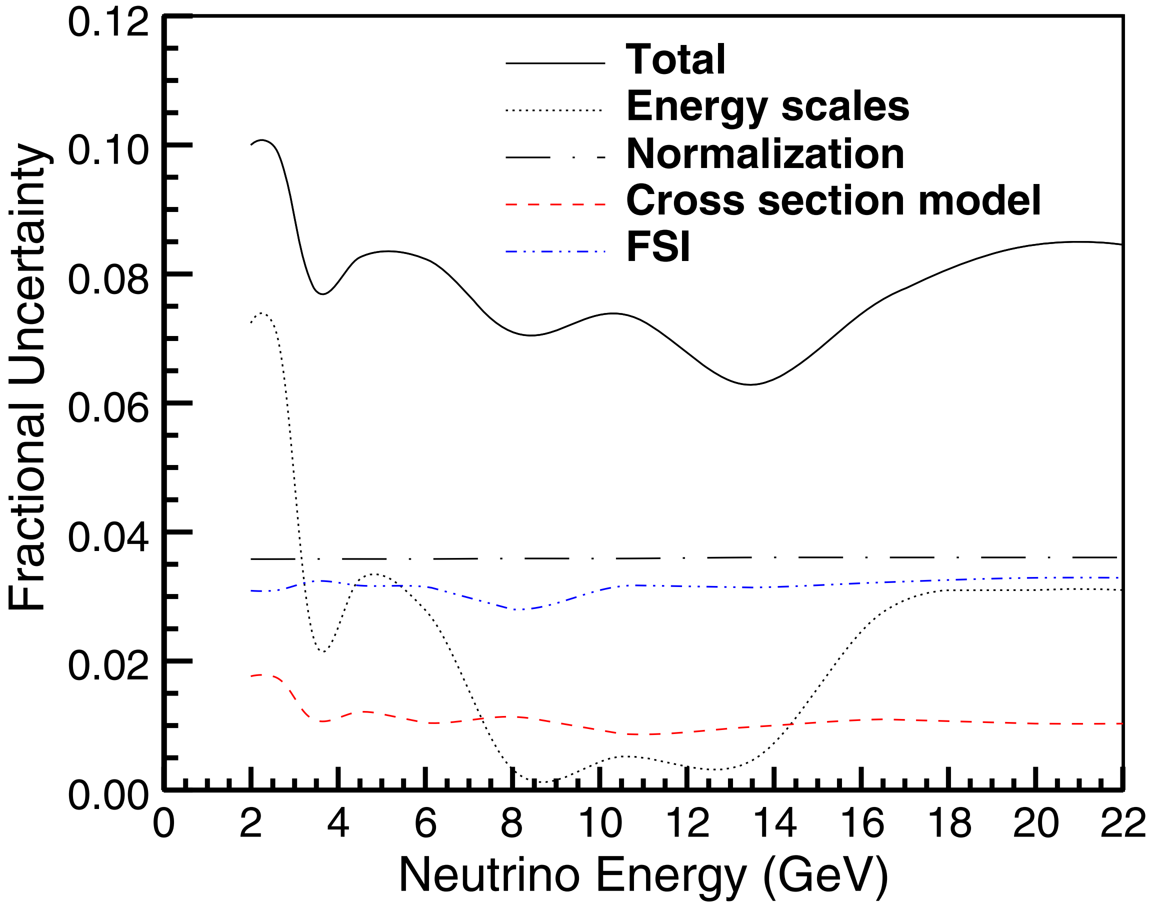
$$\boxed{\frac{d\sigma}{d\nu}=A\left(1+\frac{B}{A}\frac{\nu}{E}-\frac{C}{A}\frac{\nu^2}{2E^2}\right)}$$

E_{Had} (ν) uncertainty:
it need to be correct to
ensure the sample is "low-nu"

Eν reconstruction:
dominated by
Eμ uncertainty

MC shape correction:
knowledge of the B/C terms





It is even more difficult to do it on Ar target!

What if we have hydrogen (free proton) target?

$$\frac{d\sigma}{d\nu}=A\left(1+\frac{B}{A}\frac{\nu}{E}-\frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

E_{Had} (ν) uncertainty:
it need to be correct to
ensure the sample is “low-nu”

Much easier modeling

Eν reconstruction:
dominated by
Eμ uncertainty

MC shape correction:
knowledge of the B/C terms

Much easier modeling

It is even more difficult to do it on Ar target!

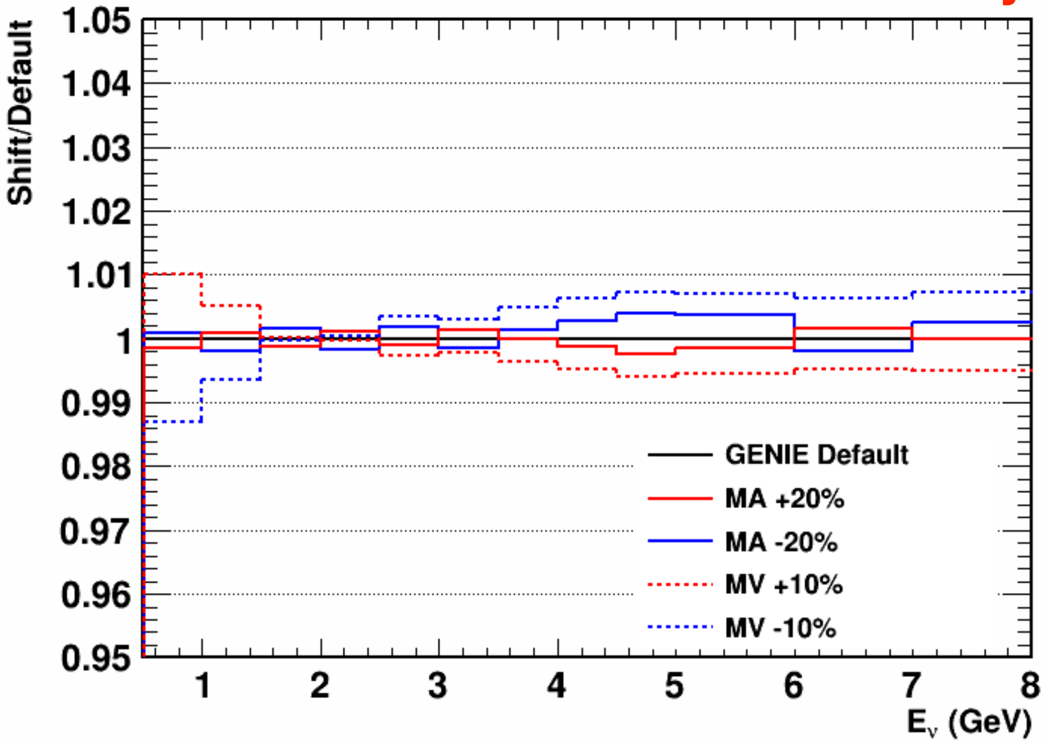
Flux Measurements: Low-ν Method

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \boxed{\Phi(E_\nu)} \cancel{P_{osc}(E_\nu)} \boxed{\sigma(E_\nu)} R_{det}(E_{rec}, E_\nu)$$

Need a process with small cross-section uncertainty

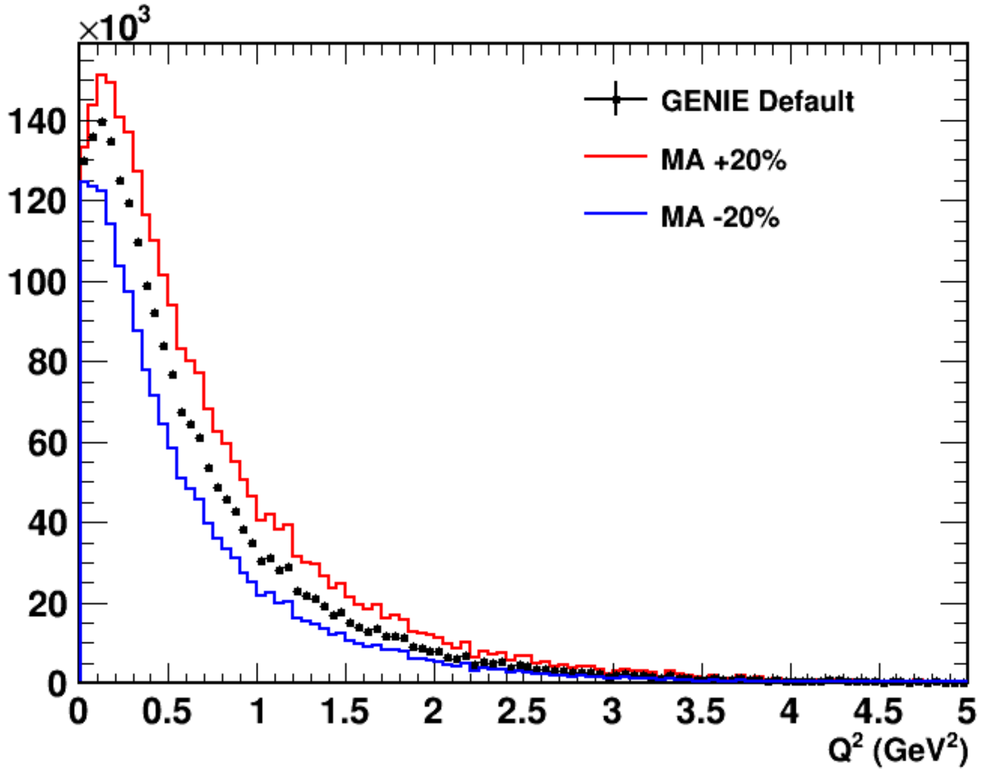
Nuclear effects!

- Cross section is flat at low $\boxed{\nu = E_\nu - E_\mu}$ with smaller uncertainty: flux shape measurement (used by NOMAD, MINOS, MINERvA).
- The cross-sections of ν-H are better understood than heavy nucleus and free from uncertainties from nuclear effects.



ν<0.5 GeV: ~25% efficiency

Cross-section uncertainty < 1%



Uncertainties further constrained by differential measurements in inclusive sample.

Low-ν method

- At very low $\nu = E_\nu - E_l$, the cross section is independent from E_ν:

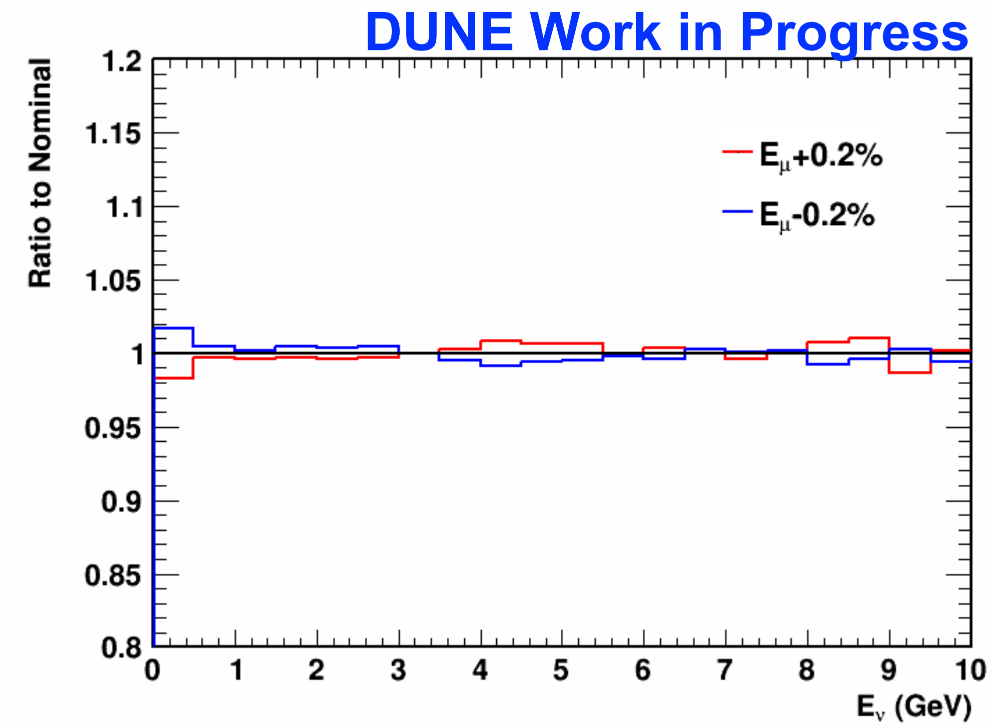
$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

(A, B and C are parameters formed by nuclear structure functions.)

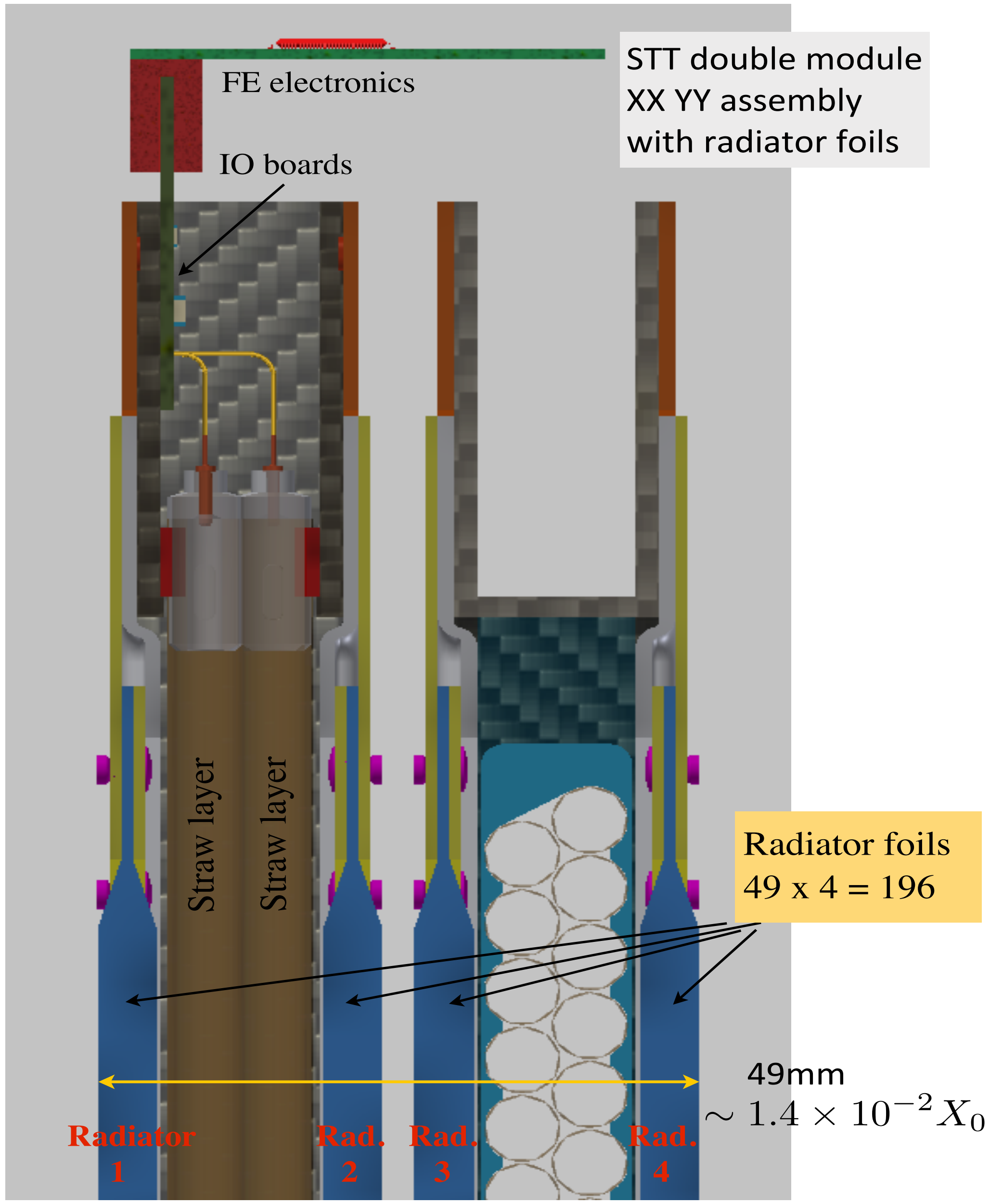
- the measurement of low ν spectrum is approximately a measurement of flux shape.
- The effect of non-zero ν cut is account for by a theoretical correction:

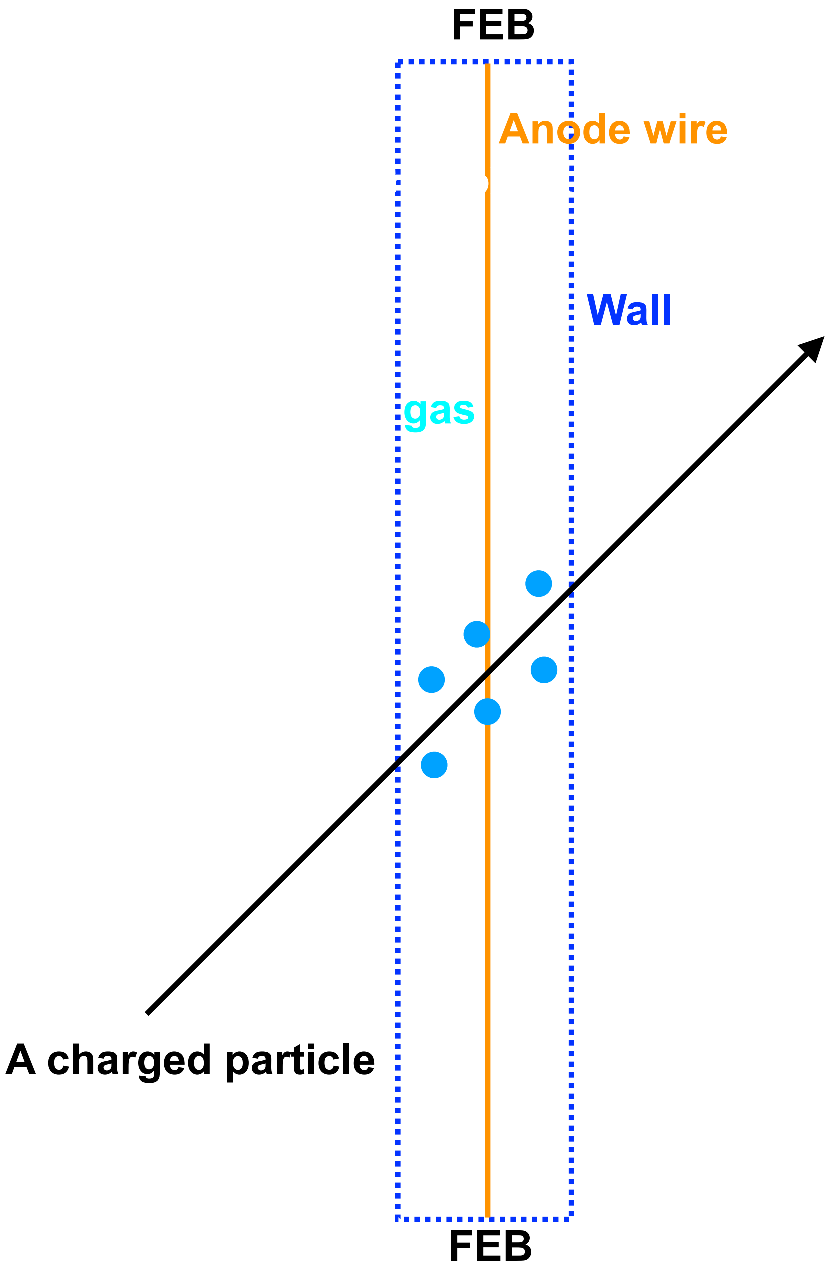
$$S(E) = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E)^{\nu\to 0}} = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E\to\infty)^{\nu<\nu_0}}$$

- Systematic uncertainty dominant:
  - Muon energy
  - Hadronic energy (ν)
  - Theoretical correction
- See Lu Ren's talk on Tuesday for MINERvA's Low-ν flux measurement



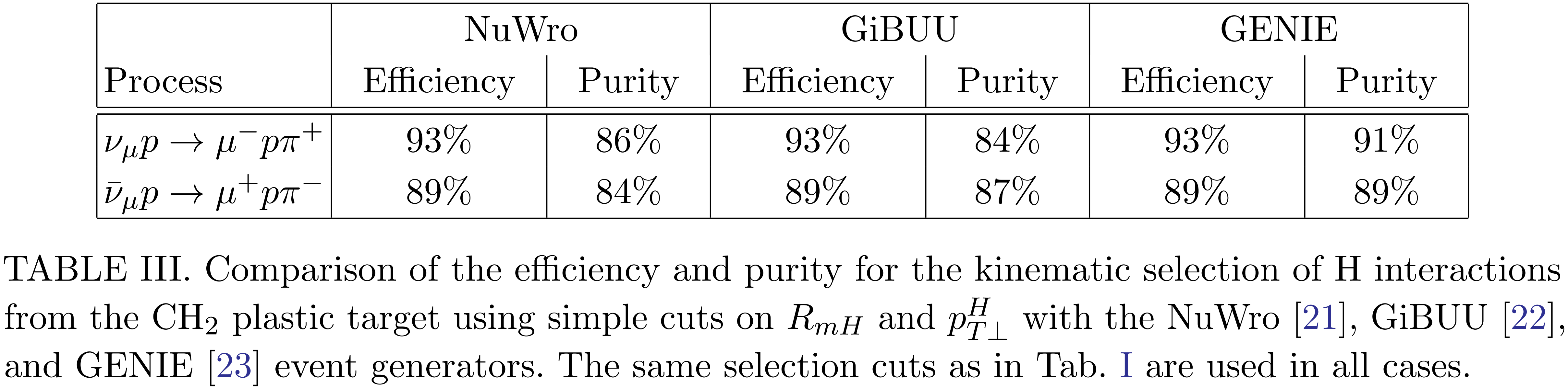
Introduction to the Straw Tube Tracker (STT)





- We are proposing a new detector for the DUNE near detector complex to help break the degeneracy.

Generator Comparisons

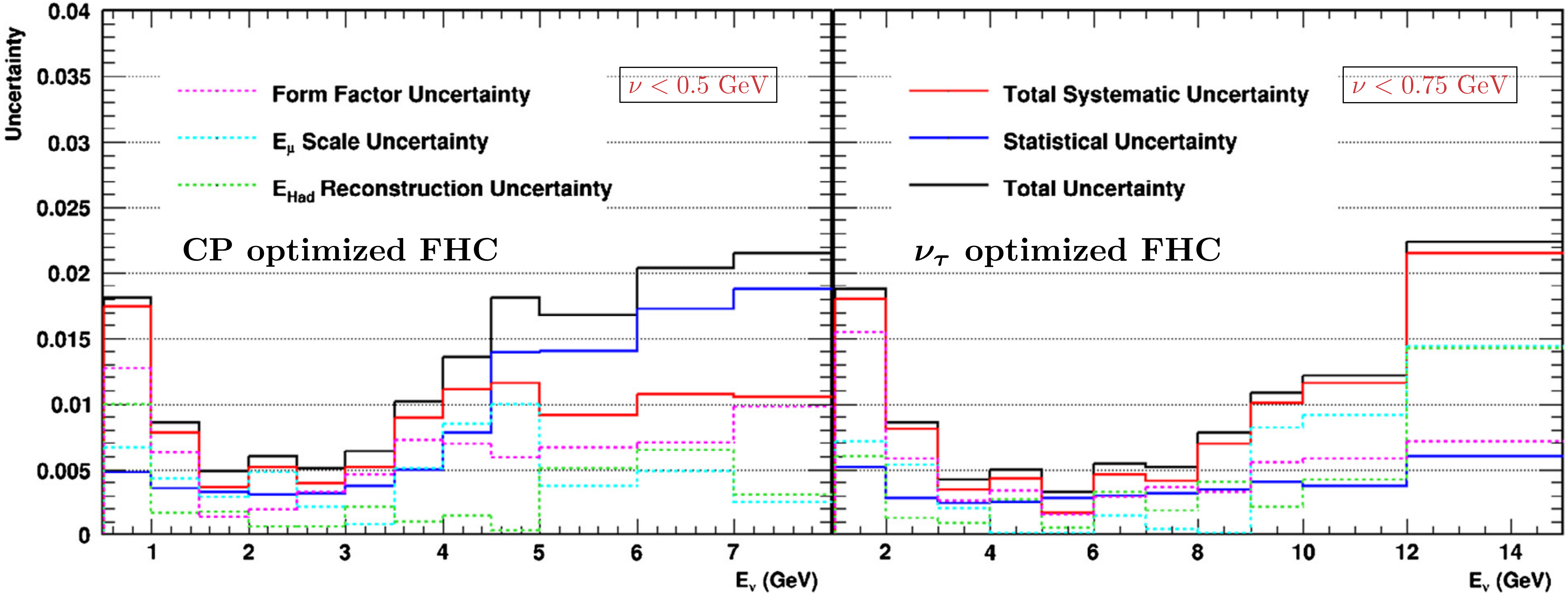


	NuWro		GiBUU		GENIE	
Process	Efficiency	Purity	Efficiency	Purity	Efficiency	Purity
$\nu_\mu p \rightarrow \mu^- p \pi^+$	93%	86%	93%	84%	93%	91%
$\bar{\nu}_\mu p \rightarrow \mu^+ p \pi^-$	89%	84%	89%	87%	89%	89%

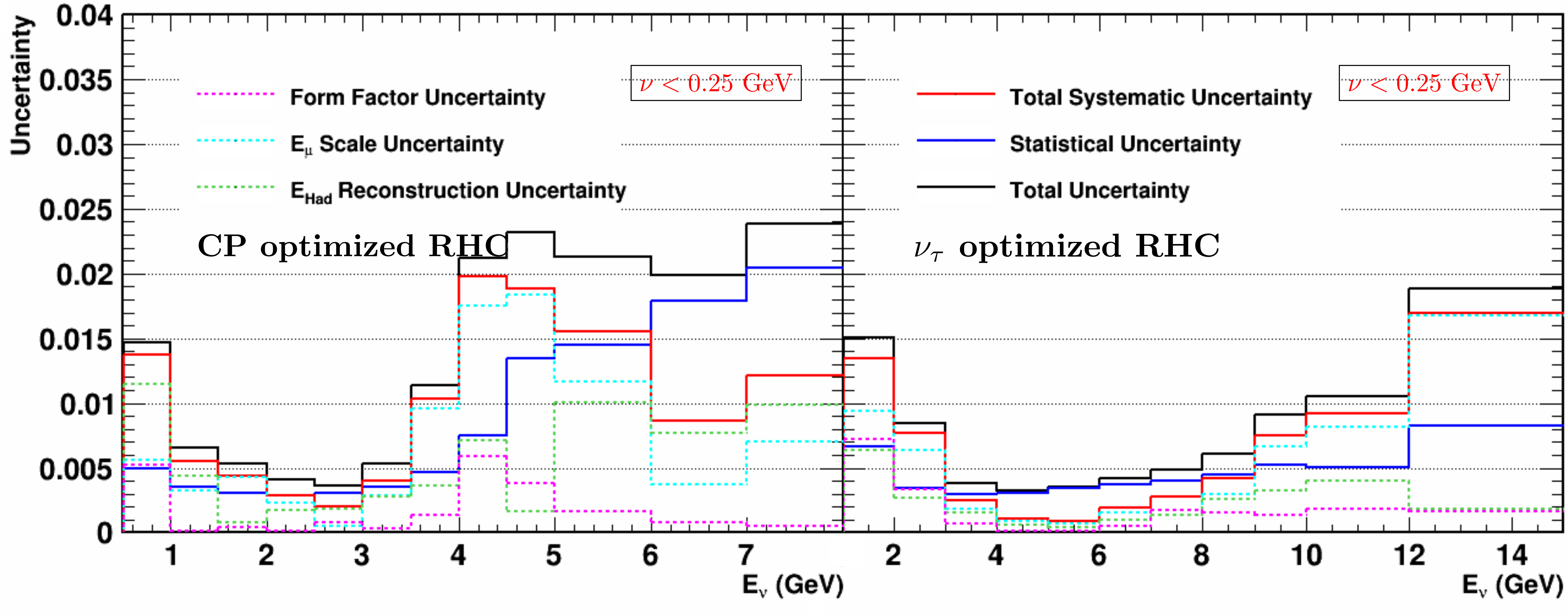
TABLE III. Comparison of the efficiency and purity for the kinematic selection of H interactions from the CH_2 plastic target using simple cuts on R_{mH} and $p^H_{T\perp}$ with the NuWro [21], GiBUU [22], and GENIE [23] event generators. The same selection cuts as in Tab. I are used in all cases.

This is to show that the number of efficiencies and purities we estimate is realistic. the difference between generators here will not be systematics because we will have carbon data to measure them

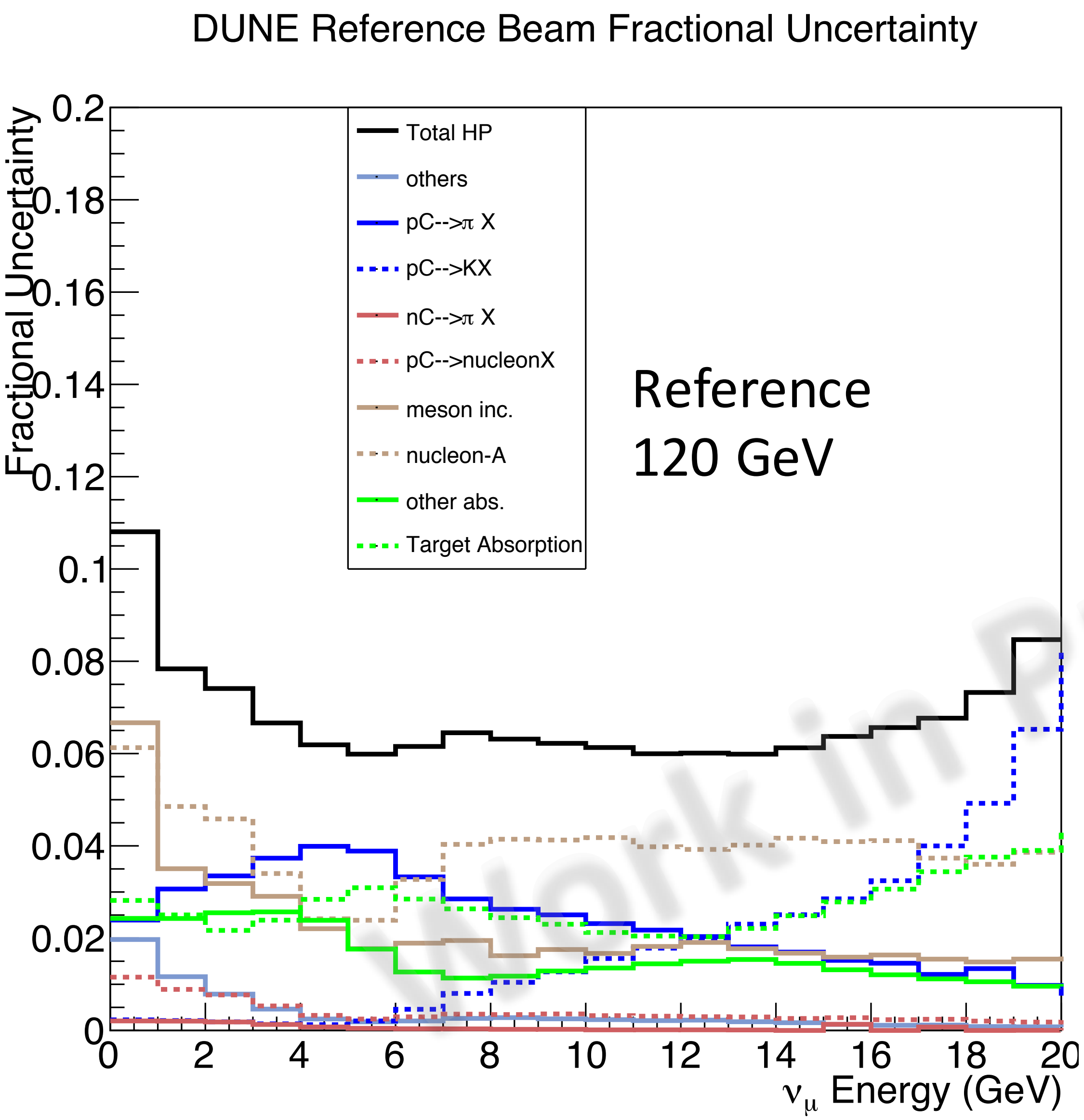
Low-ν Method on Hydrogen (3-Track)



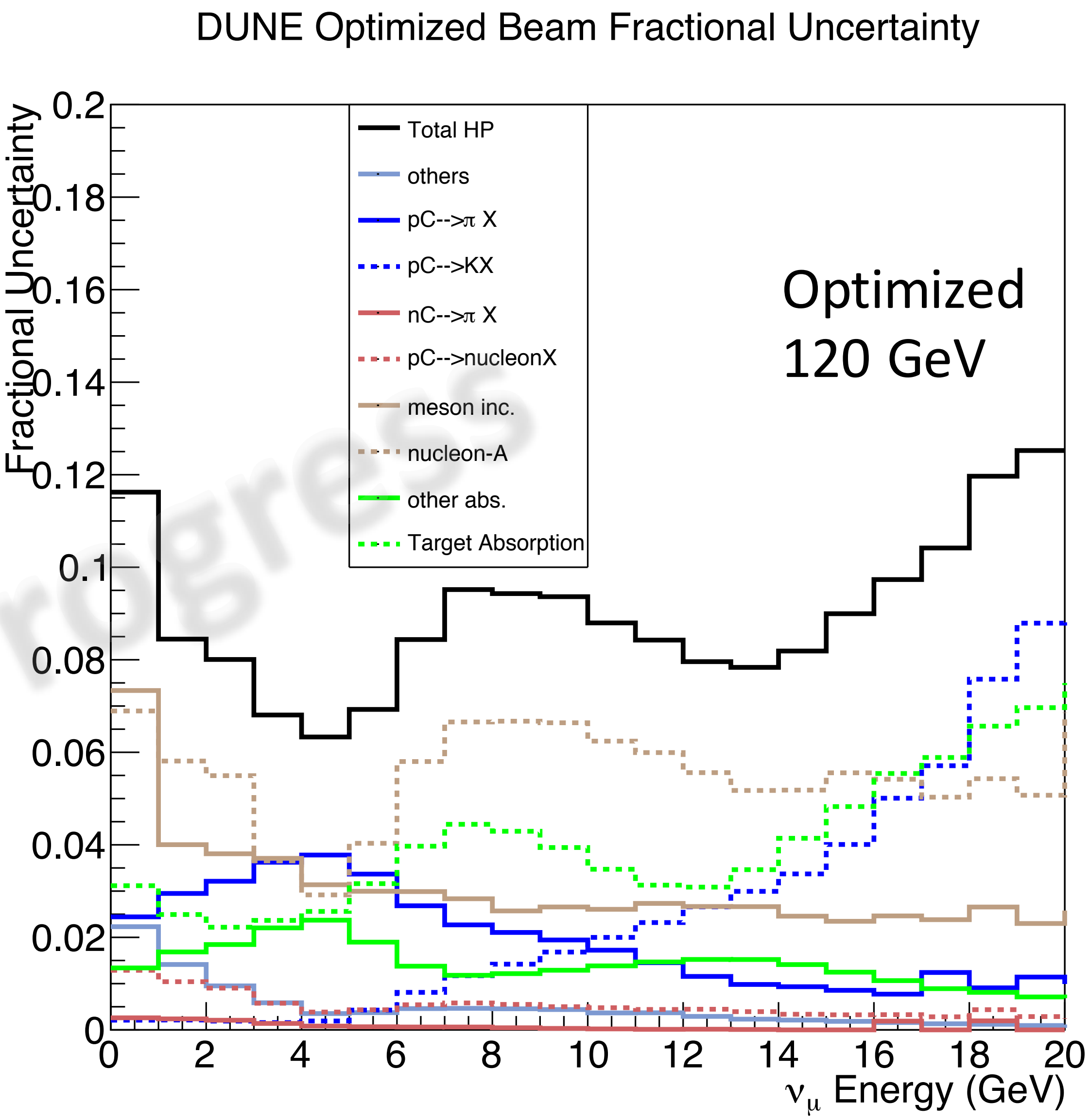
Low-ν Method on Hydrogen (RHC QE)



Hadron Production Uncertianties

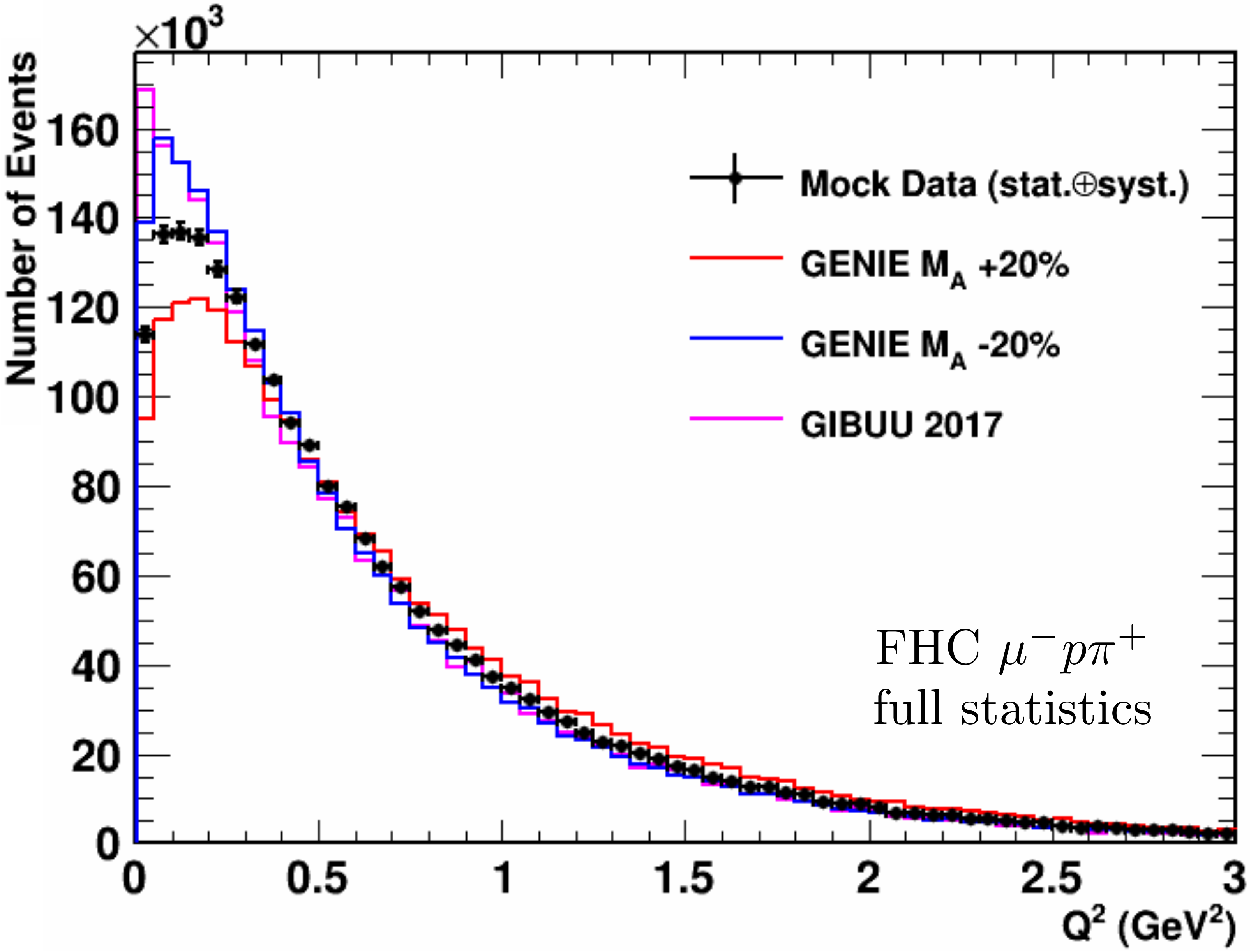


DUNE Reference Beam Fractional Uncertainty



DUNE Optimized Beam Fractional Uncertainty

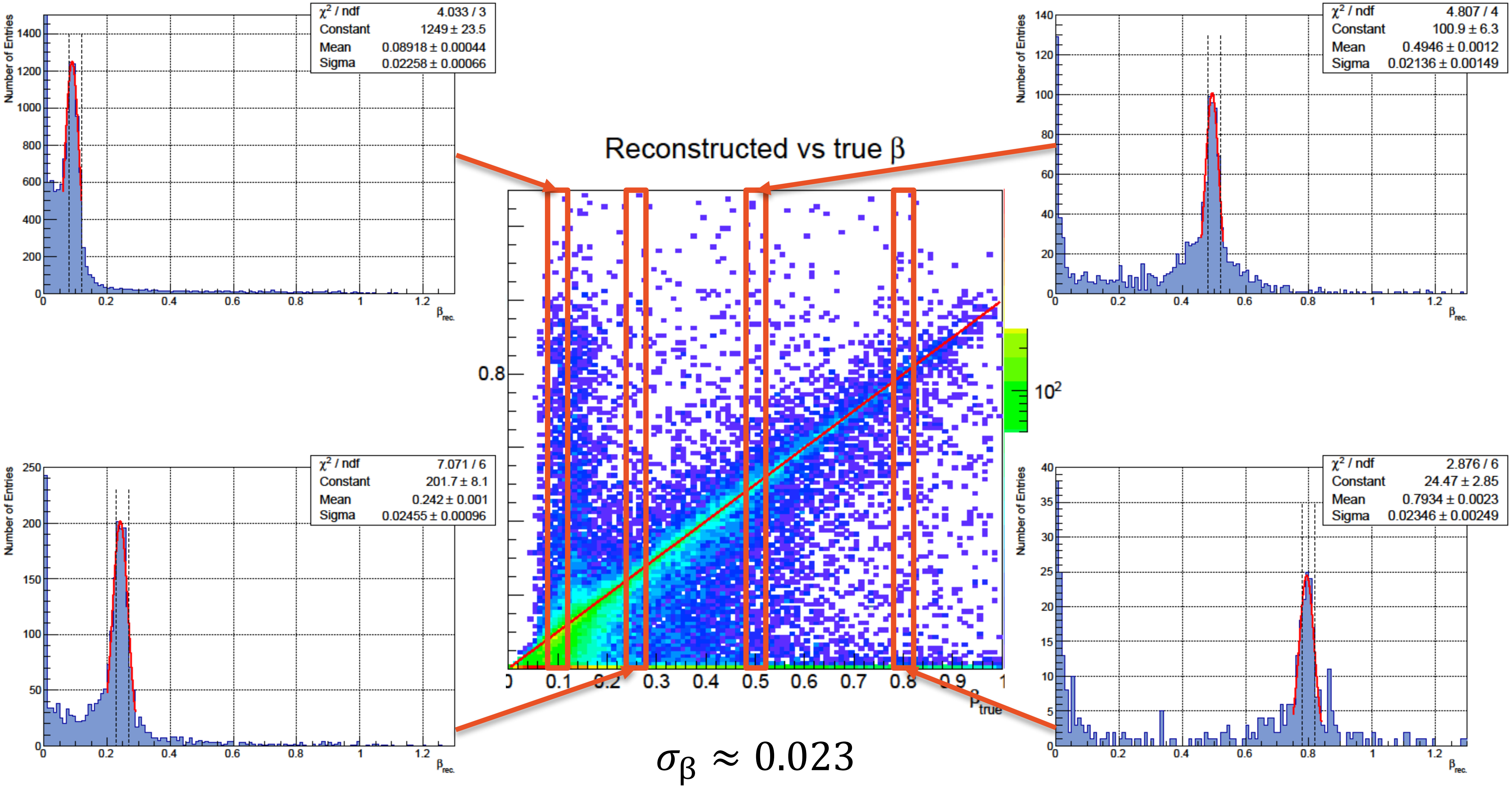
Data-Driven Form Factors



Low-ν Method on CH2 (Alternatives)

- CH2 minus carbon is definitely the best choice
  - high H statistics => low stat uncertainty
  - Low background => low background uncertainty
- Alternatives:
  - CH minus carbon
  - CH2 minus CH
- Challenges:
- Need good resolution and low threshold for H vs C separation as much as possible.
- need as similar as possible detector response for CH and carbon, or CH2 and CH.

Neutron Detections



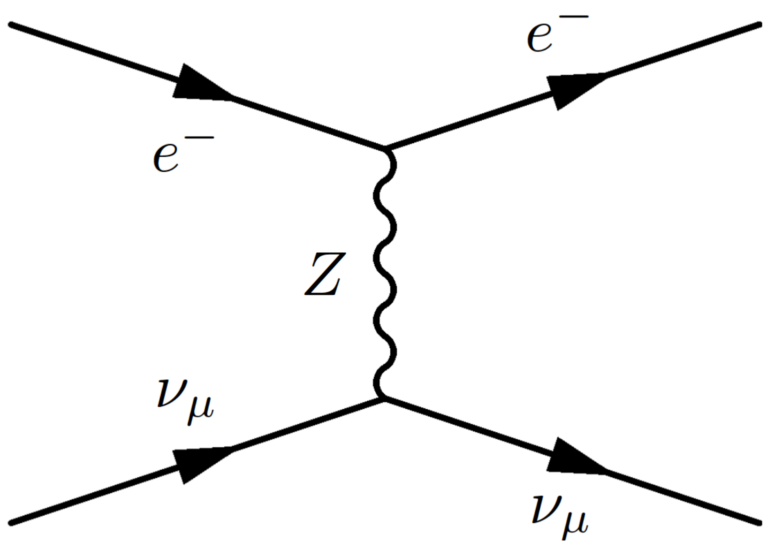
Reconstructed vs true β

$\sigma_\beta \approx 0.023$

$\frac{\beta_{reco}-\beta_{true}}{\beta_{true}} < 0.30$ for 27% of the neutrons generated in ν interactions in LAr

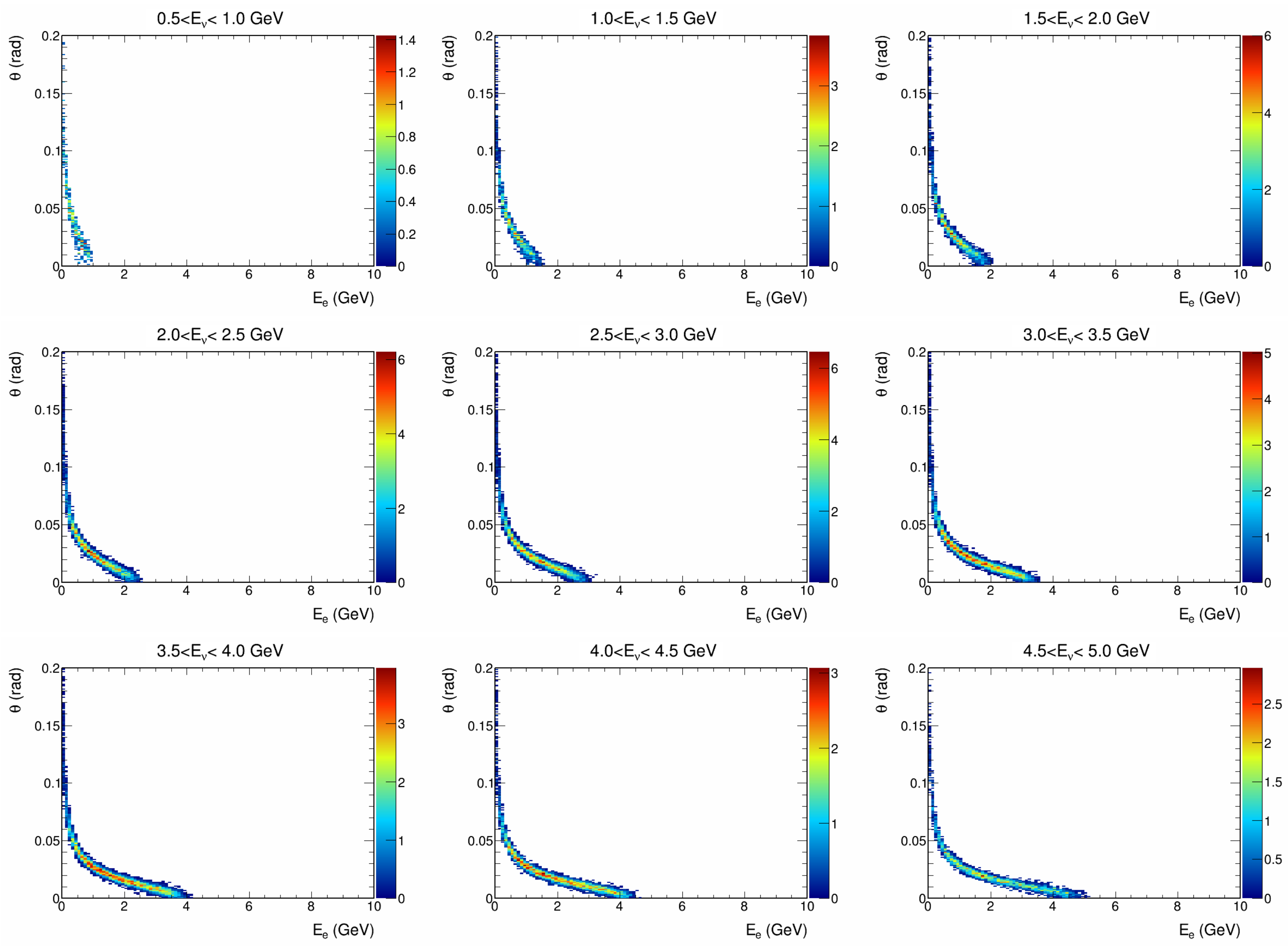
(or for 60% of the neutrons with β_{reco}>0.01)

Flux Shape Information by ν-e Scattering



- It is also possible to measure flux shape by ν-e scattering.
- Each neutrino energy bin corresponding to a unique distribution of electron energy and angle.

- A template fit in electron energy vs angle space.
- The precision not quite comparable to Low-ν on H.



Complementary of KLOE-STT to DUNE-Prism

Other opportunities from Nu-H Measurement