nuSTORM

Detailed Studies
of
Neutrino-Nucleus Scattering
with
νSTORM

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Introduction

- The effect ν interactions have on ν physics.
- The inherent difficulties of ν interaction measurements.
- The idea behind a νSTORM facility:
  - Beamline
  - Detector opportunities
- Status and prospects for νSTORM.

ν Oscillation Physics

- ν physics is very exciting right now:
  - 2012 saw first measurements of θ_{13}, the last unknown ν mixing angle (T2K, Daya Bay, RENO, Double Chooz).
  - Measurements of δ, the CP violating phase, are within reach (LBNE, LBNO, T2HK).
- This next phase will require a large increase in sensitivity...
  - Comparing ν_μ -> ν_e and $\bar{\nu}_\mu$ -> $\bar{\nu}_e$, or
  - Comparing 1st and 2nd oscillation maxima.

T2K Oscillation Result

- T2K observed ν_e app. in a ν_μ beam.
- Monte Carlo predicted ν beam, and interaction rates at near and far detectors.

	$\sin^2 2\theta_{13}=$	
Error source	0	0.1
Beam flux & ν int. (ND280 meas.)	8.5	5.0
ν int. (from other exp.)		
$x_{CCother}$	0.2	0.1
x_{SF}	3.3	5.7
p_F	0.3	0.0
x^{CCcoh}	0.2	0.2
x^{NCcoh}	2.0	0.6
$x^{NCother}$	2.6	0.8
x_{ν_e/ν_μ}	1.8	2.6
W_{eff}	1.9	0.8
$x_{\pi-less}$	0.5	3.2
$x_{1\pi E_\nu}$	2.4	2.0
Final state interactions	2.9	2.3
Far detector	6.8	3.0
Total	13.0	9.9

T2K Oscillation Result

- T2K observed ν_e app. in a ν_μ beam.
- Monte Carlo predicted ν beam, and interaction rates at near and far detectors.
- The dominant systematic errors come from ν int. uncertainties.
  - 7.8% (total 9.9%)

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arXiv:1304.0841

Current Status of ν Cross-Sections

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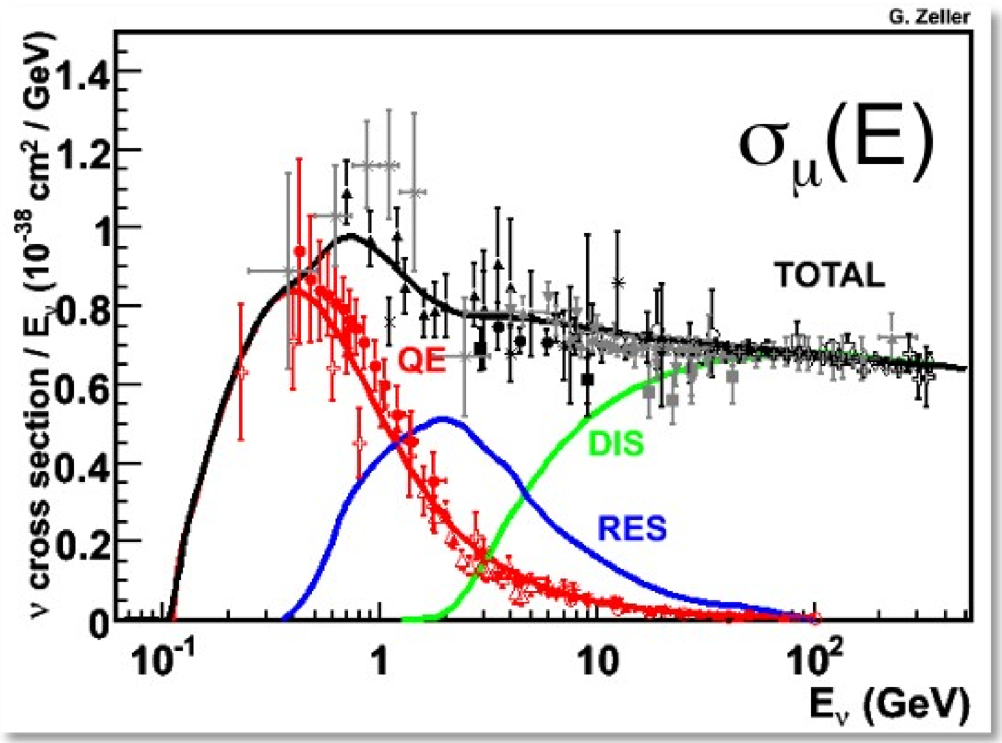
ν_μ Cross-section Summary



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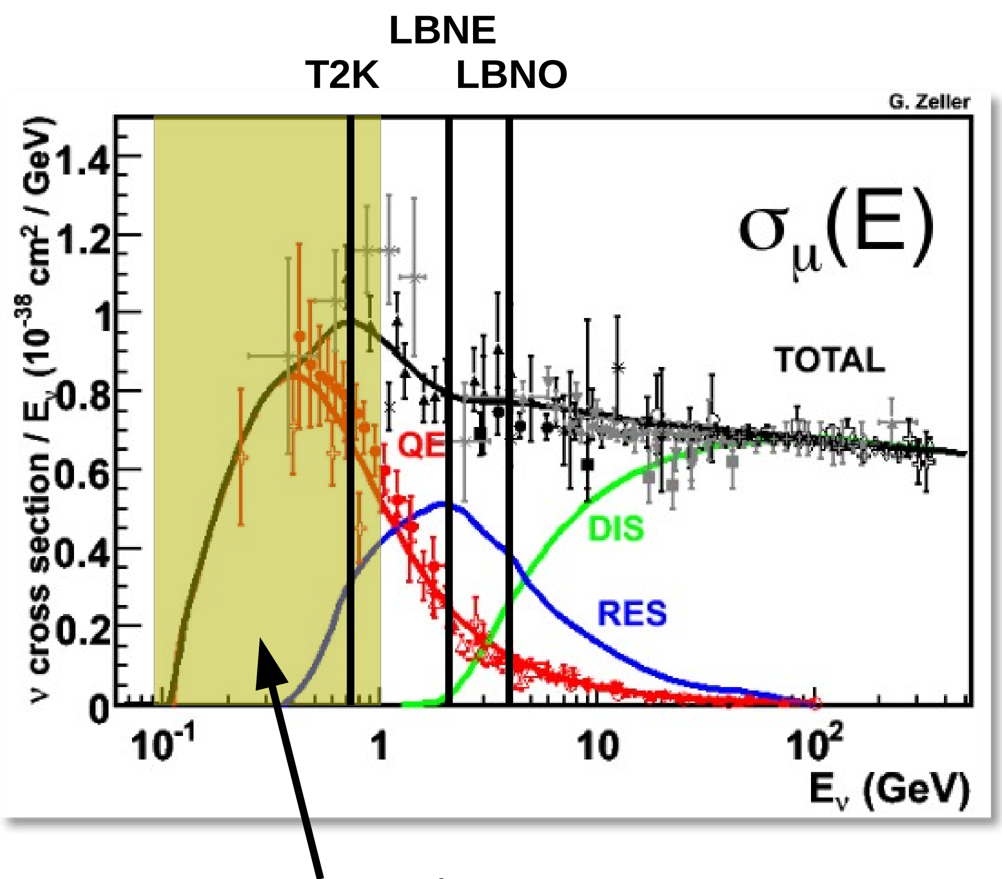
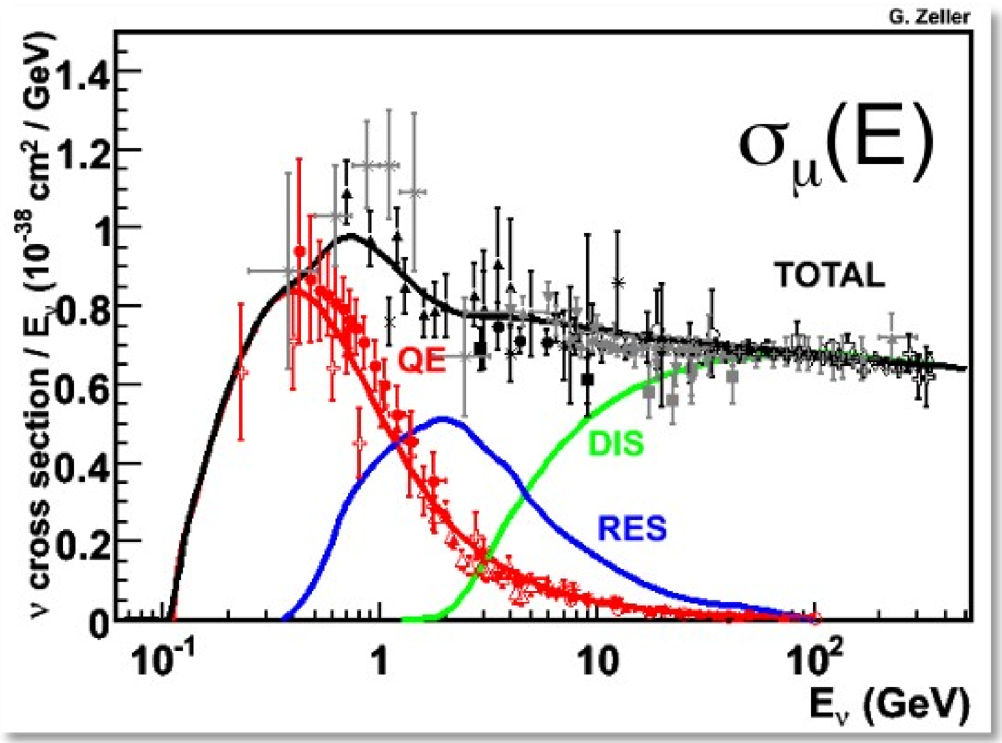
ν_μ Cross-section Summary



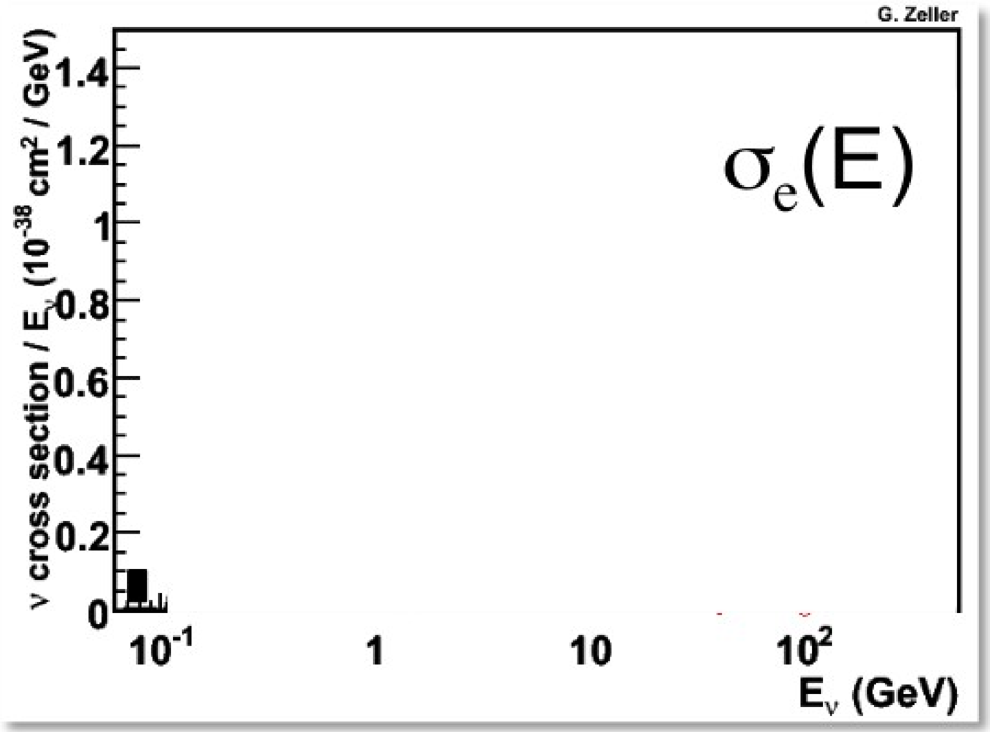
2nd oscillation maxima

Current Status of ν Cross-Sections

ν_μ Cross-section Summary



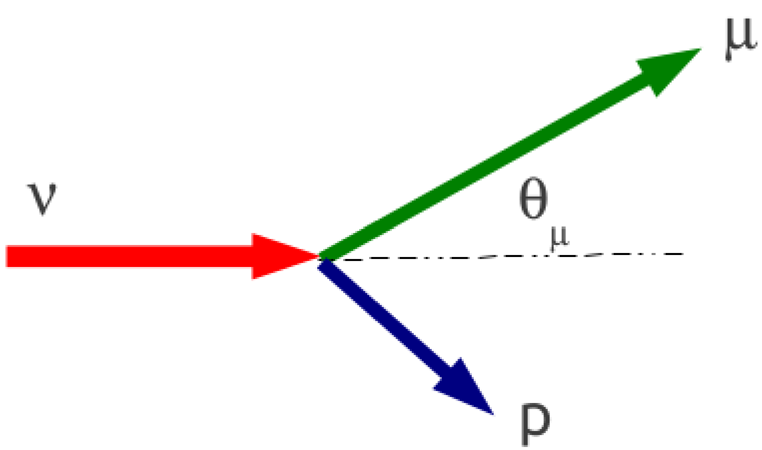
ν_e Cross-section Summary



All $\sigma_{\nu e}(E)$ are inferred from $\sigma_{\nu\mu}(E)$

QE: "Quasi-Elastic"
$\nu_\mu + n \rightarrow \mu^- + p$

- Very useful interaction:
  - Sometimes considered a "Standard Candle"
  - Used to normalise other processes
- Neutrino energy is reconstructable:



$$E_\nu^{rec} = \frac{m_N E_\mu - \frac{1}{2} m_\mu^2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

QE: “Quasi-Elastic” $\nu_\mu + n \rightarrow \mu^- + p$

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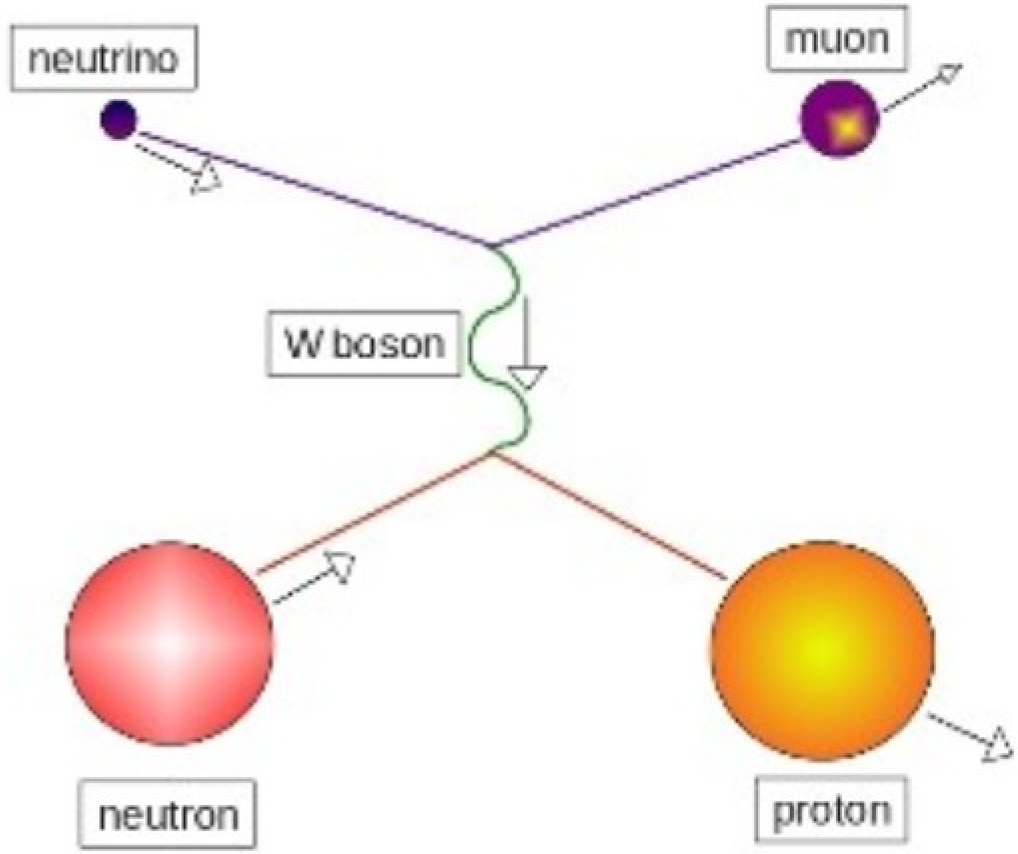
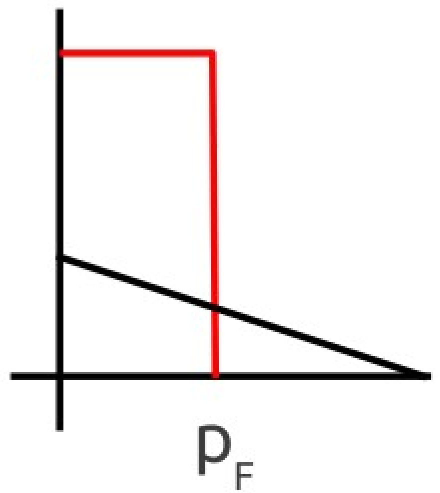


First I was told it was this...

QE: “Quasi-Elastic”
$\nu_\mu + n \rightarrow \mu^- + p$

Initial State:
Relativistic
Fermi Gas



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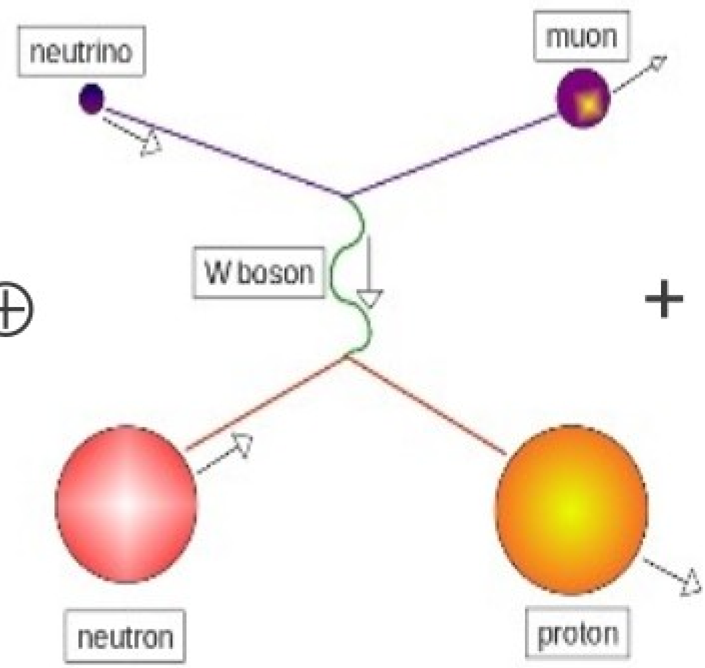

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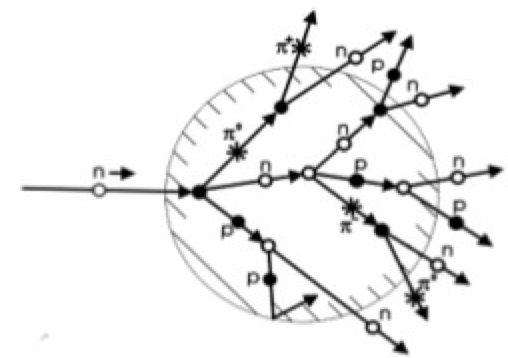
Final State:
Cascade Model



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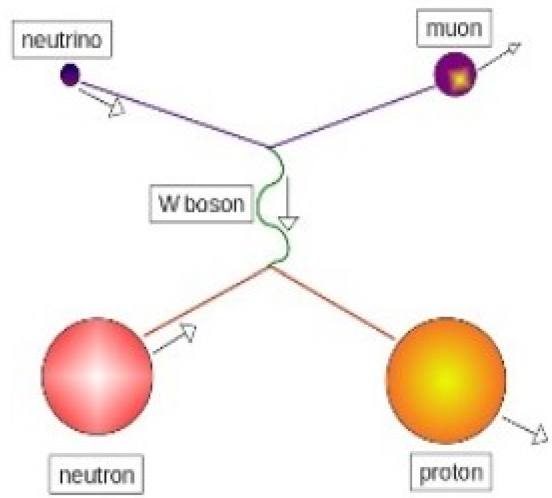
QE: “Quasi-Elastic”

$\nu_\mu + n \rightarrow \mu^- + p$



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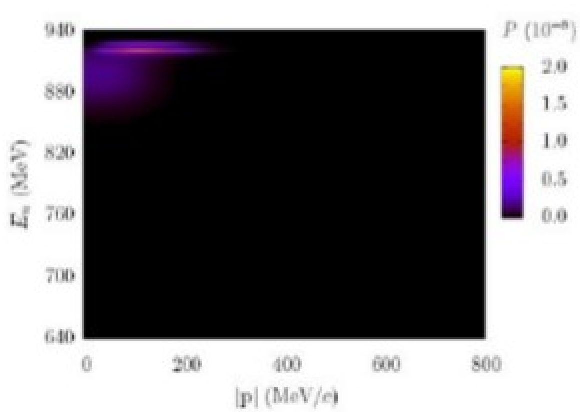

Spectral Functions

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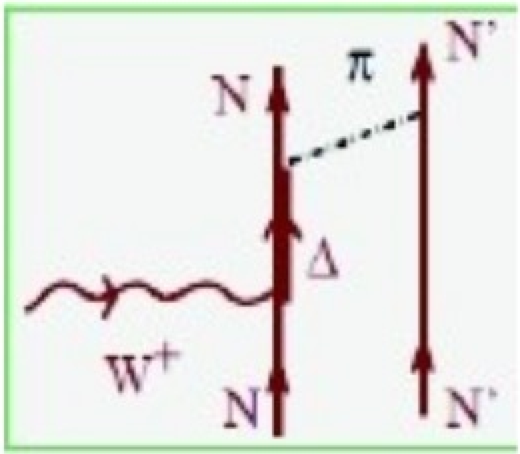
2p-2h effects



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Cascade Models
In-medium effects

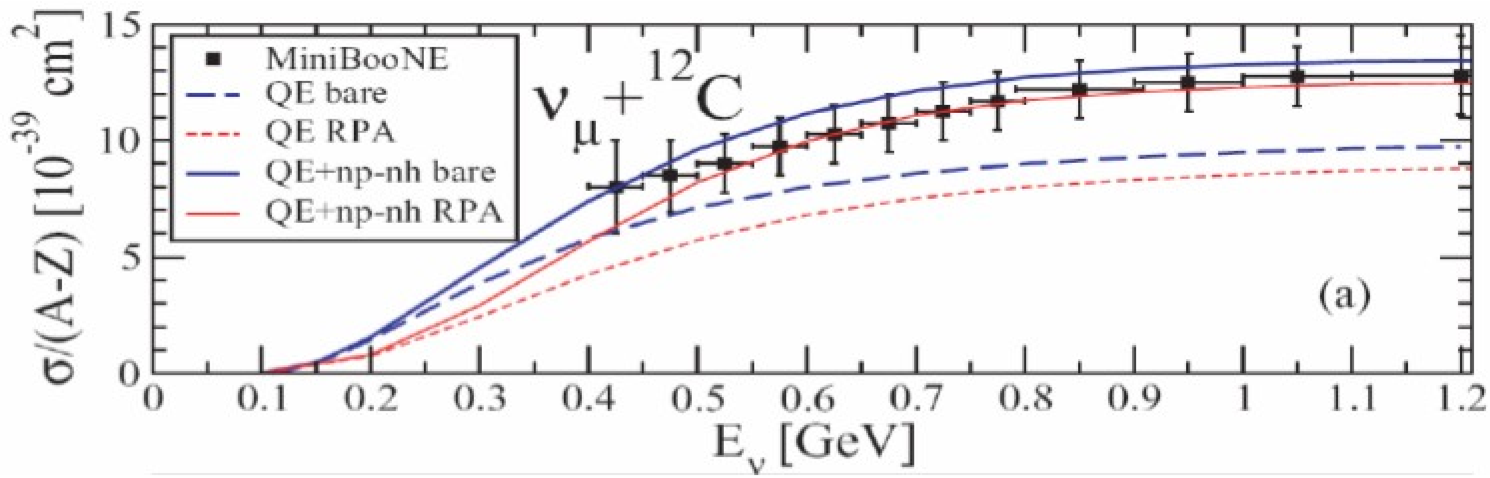
... but it is probably this (I hope).

Nuclear Effects

- The events we observe in detectors are:

$$Y_{\text{c-like}}(E) \propto \Phi(E' \geq E) \otimes \sigma_{\text{c,d,e..}}(E' \geq E) \otimes \text{Nuc}_{\text{c,d,e..}\to\text{c}}(E' \geq E)$$

- The last two terms are the effective cross-section, convolving:
  - the initial ν+nucleon interaction, and
  - the nuclear effects (getting particles out of a nucleus!)

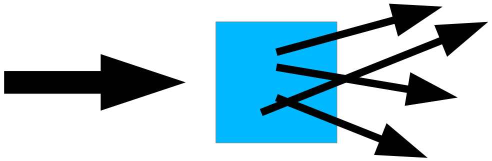


Martini et al, PRC 81, 045502 (2010)

Recent Cross-Section Measurements

- MiniBooNE and T2K have recently produced some very nice cross-section measurements:
  - Double differential wrt momentum and angle of produced particle.
  - Precise on particles measured
- Limited by Statistics and Beam Uncertainties.

How to Make a ν Beam: T2K Example



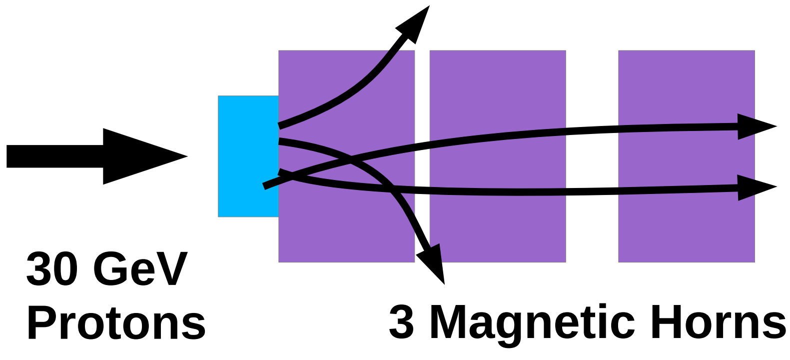
30 GeV Protons

Graphite Target

- 30 GeV Protons hit a graphite target.

$$p + p \rightarrow \pi^{\pm} + K^{\pm}$$

How to Make a ν Beam: T2K Example

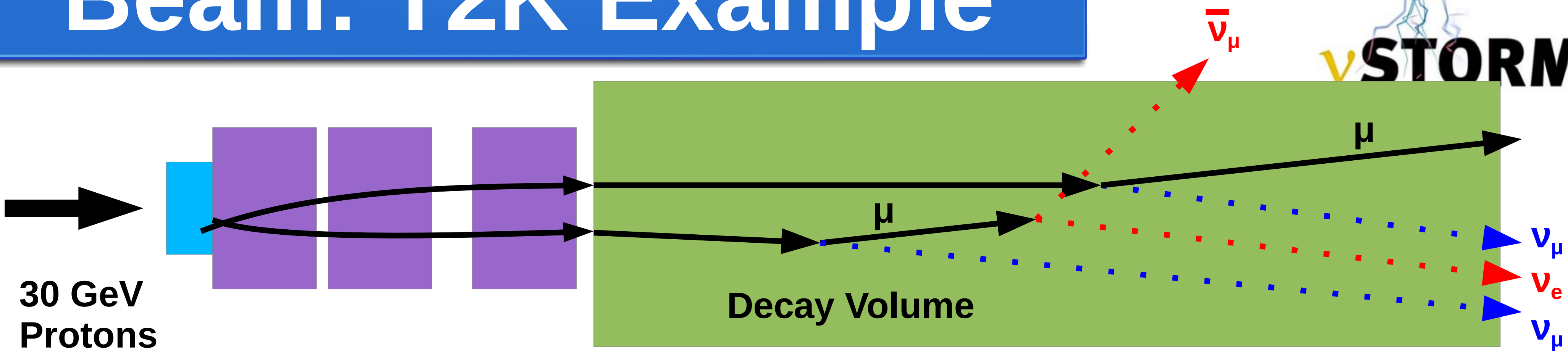


- Focus +ve particles, defocus -ve.

$$\pi^+$$

$$K^+$$

How to Make a ν Beam: T2K Example



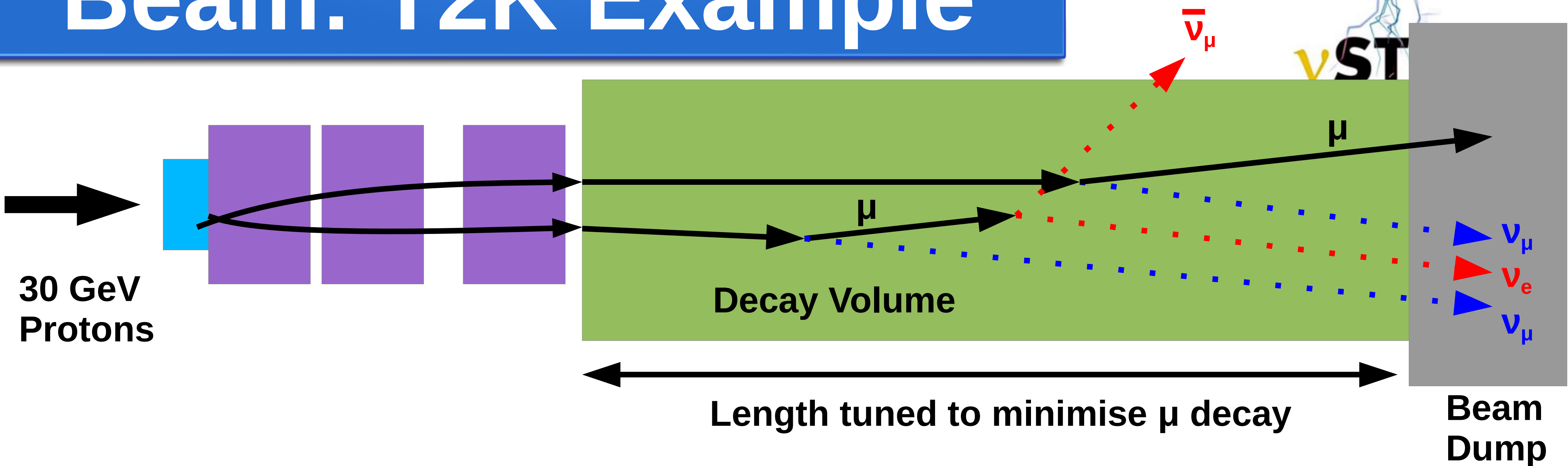
- Particles decay in flight, producing ν

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$K^+ \rightarrow \mu^+ + \nu_\mu \; , \; \pi^+ + \pi^0$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

How to Make a ν Beam: T2K Example



- Beam dump limits decays of high E μ

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$K^+ \to \mu^+ + \nu_\mu, \;\; \pi^+ + \pi^0$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Beam Uncertainties

- Characterising beams relies on complicated MC and indirect measurements (e.g. μ from π decay)
- Therefore, large systematic uncertainties in:
  - the absolute number of neutrinos, and
  - the energy distribution of the neutrinos.
- These are an irreducible limit on cross-section measurements.
  - MiniBooNE anti-ν flux: 9.6%
  - T2K ν flux: 10.9%

Beam Uncertainties

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- Characterising beams relies on complicated MC and indirect measurements (e.g. μ from π decay)

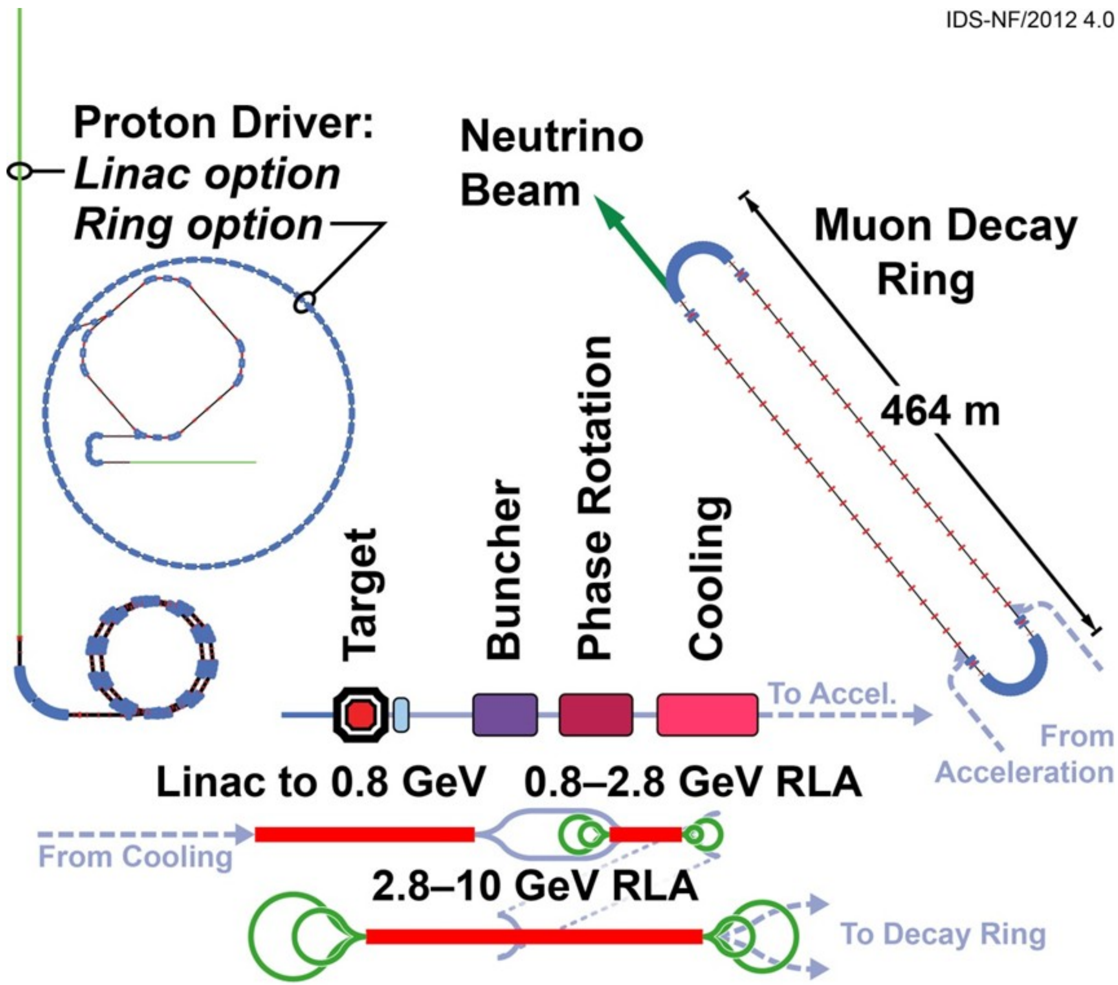
10% Errors on Flux

Only produces ν_μ / $\bar{\nu}_\mu$

ν_e / $\bar{\nu}_e$ are still out of reach

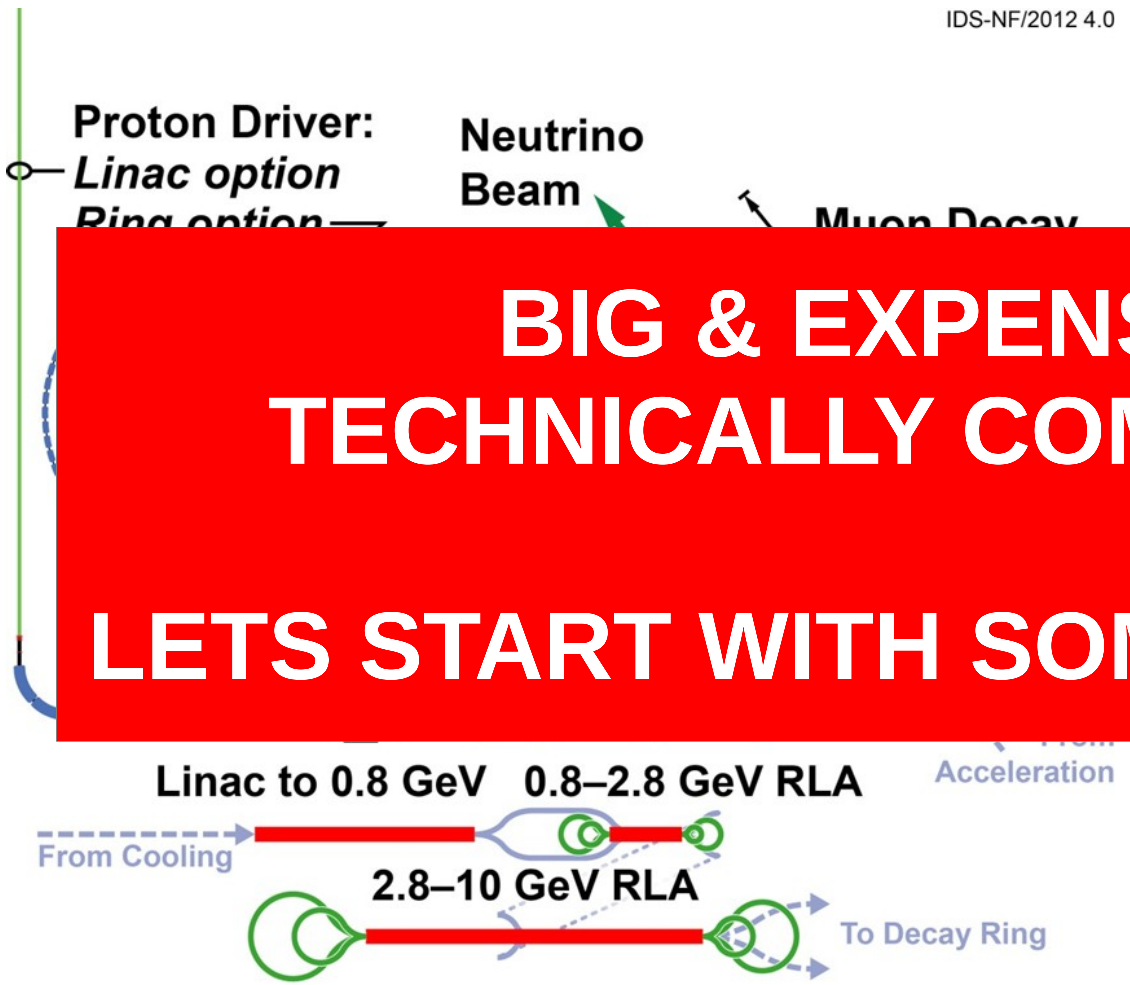
  - MiniBooNE anti-ν flux: 9.6%
  - T2K ν flux: 10.9%

A Better ν Beam: Neutrino Factory



- Accelerate Protons
- Protons + Target make pions
- Pions decay to Muons
- Muons are cooled + bunched, then accelerated
- Muons enter a decay ring with straight sides.
- Muons decay in flight to produce muon neutrinos and electron anti-neutrinos.

A Better ν Beam: Neutrino Factory



BIG & EXPENSIVE & TECHNICALLY COMPLICATED

LETS START WITH SOMETHING EASY

- Accelerate Protons

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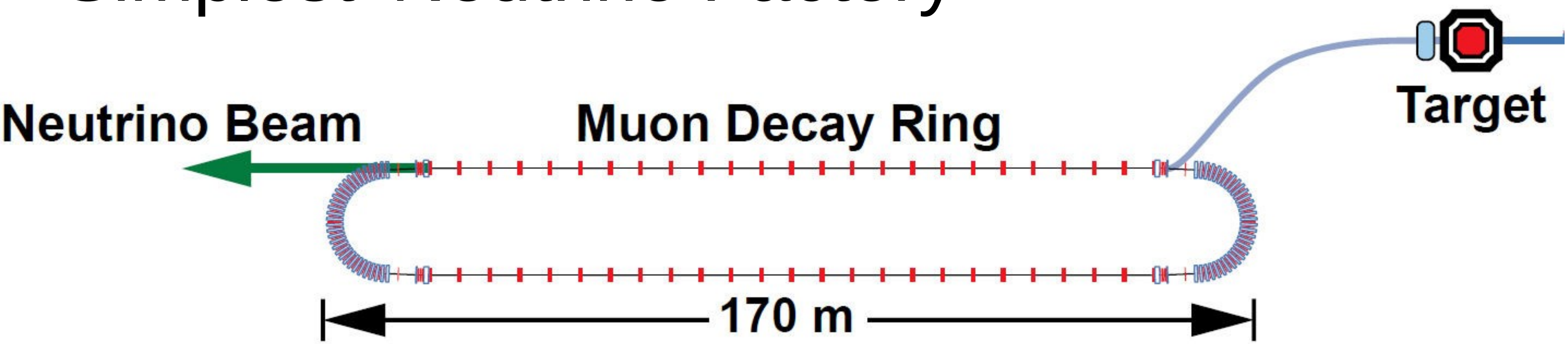
duce muon neutrinos and electron anti-neutrinos.

νSTORM
ν from STORed Muons

- Simplest 'Neutrino Factory'

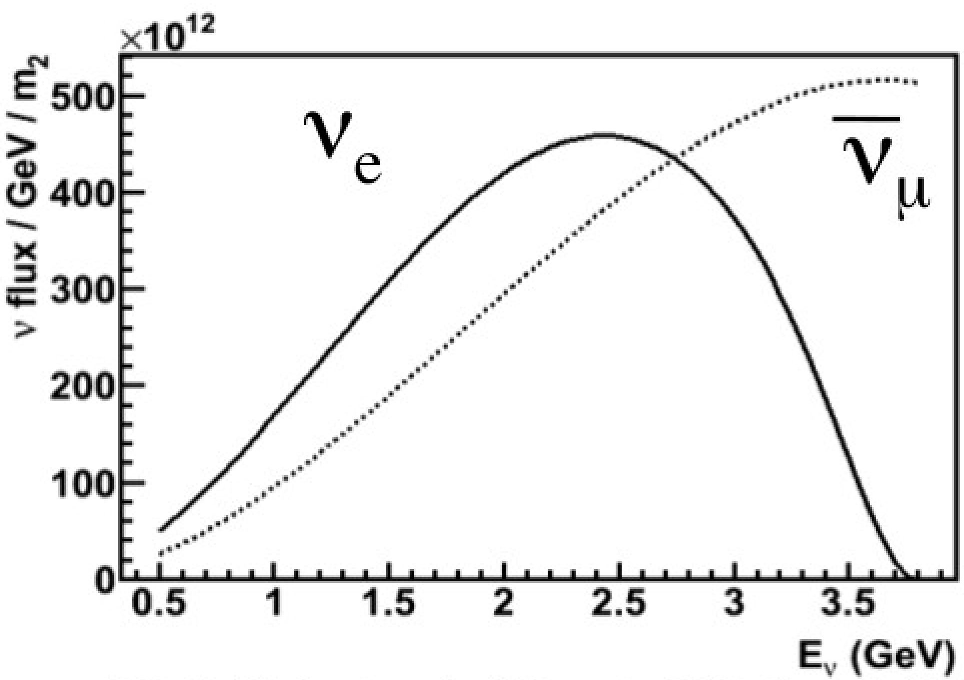


- π^+ enter ring, decay to μ^+
- Only μ^+ make it around the ring.
  - Second 'lap' is pure muons, which decay.

Very Precise Beam

- The νSTORM beam will provide a very well-known (δ Φ(E) ≤ 1%) beam of ν and $\bar{\nu}$.

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \textbf{ or } \mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$$



3.8 GeV μ^+ stored, 150m straight, flux at 100m

μ^+

Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

μ^-

Channel	N_{evts}
$\bar{\nu}_e$ NC	709,576
ν_μ NC	1,584,003
$\bar{\nu}_e$ CC	1,784,099
ν_μ CC	4,626,480

event rates per 1E21 POT - 100 tons at 50m

Equivalent to 4-5 yr

νSTORM @ FNAL

A CERN based proposal is also being prepared, either site is feasible.

FNAL LOI: arXiv:1206.0294 **CERN EOI: SPSC-EOI-009**

νSTORM: 3 Goals

- An accelerator and detector technology test bed:
  - Toward Neutrino Factory & Muon Collider
- A final answer to the sterile ν anomaly of LSND & MiniBooNE.
- ν cross-section measurements:
  - Improvements for all neutrino types.
  - Especially true for ν_e.
  - A ν "Light Source".

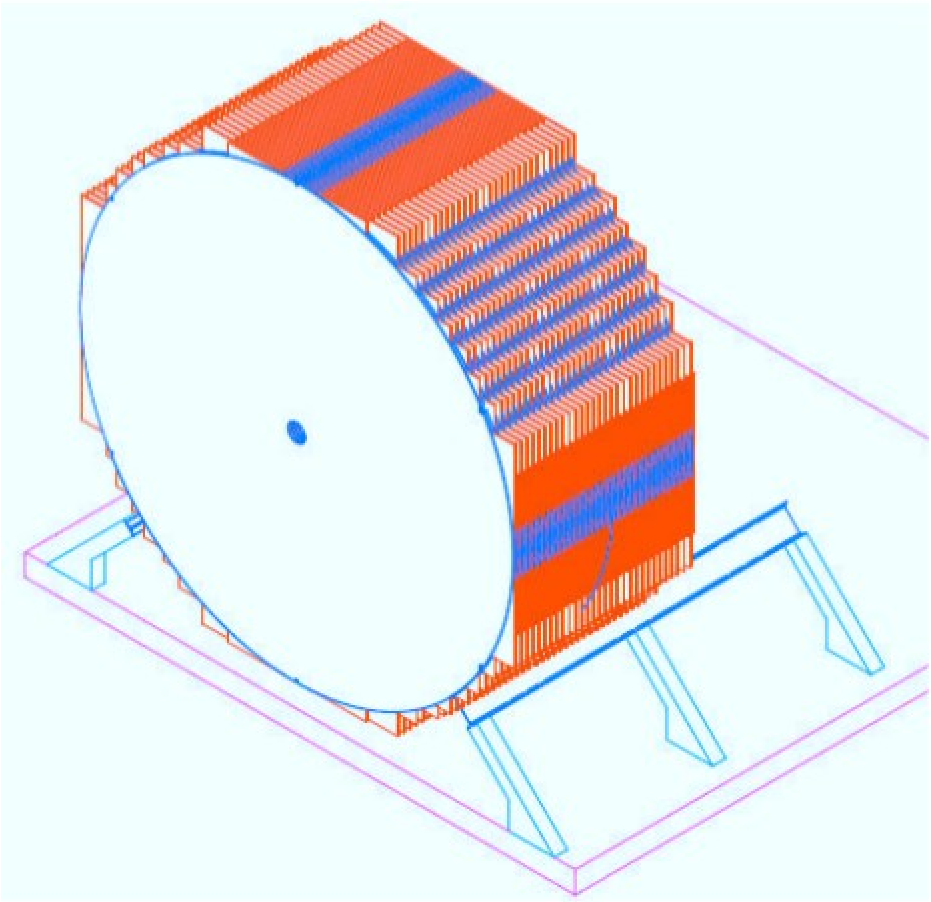
Cross-Section Measurement Facility

- The νSTORM Facility would have three near detector slots
  - @ 20m FNAL, @300m CERN.
- Experimental collaborations would construct and install detectors.

Detector Slots

- Sterile ν search near detector.
- Test of ND for future long baseline experiment.
- Dedicated to ν cross-section detectors, each potentially only running for shorter periods of time (~2 years).

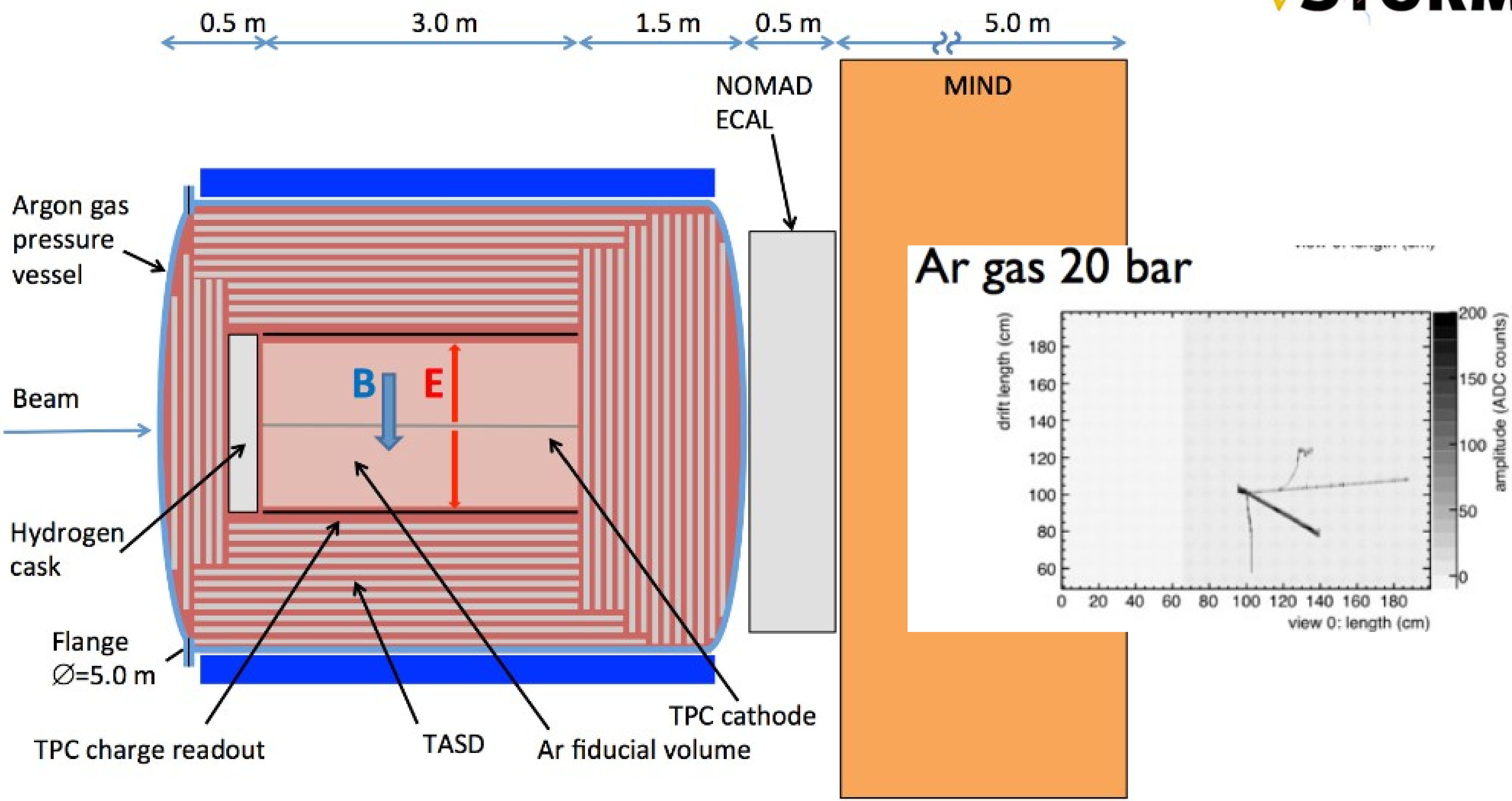
Sterile ν detector: SuperBIND



SuperBIND Detector

- Steel-scintillator calorimeter
- 6 m diameter; 16 m length
- 1.5 cm steel plates.
- Sci planes provide space points
  - 2 layer of 1×1 cm^2 bars.
- Double ended readout with SiPM.

Long Baseline ND: e.g. LBNO ND



Cross-Section Detectors

- Multiple detectors over the life of the facility
  - Different detector technologies
  - Targeted designs for specific cross-sections
    - 200 MeV π^0 ID very different from 2 GeV μ
- Multiple targets
  - Nuclear effects depend on nucleus, so match targets of other ν experiments (C, H_2O, Ar).

One Crazy Suggestion

- Rapid Cycling H_2 Bubble Chamber
  - A hydrogen target removes all nuclear effects, directly accesses initial ν+p interaction.
  - Fast CMOS detectors makes this possible, given the cycling rate of a νSTORM beam.
  - Fully instrumented detector, great for vertex activity and particle identification.
- Obvious safety issues of working with H_2, under investigation.

Summary

- A νSTORM facility would allow for world leading ν interaction measurements.
  - μ decay beam gives precise flux, $\delta\,\Phi(E) \leq 1\%$
- Proposals are being prepared for facilities at either FermiLab or CERN.
- Opportunities to fully understand nuclear effects in ν physics, by comparing results from different targets.
- Interested parties: please get in touch...
  - Bross@FNAL.GOV, Elena.Wildner@CERN.CH