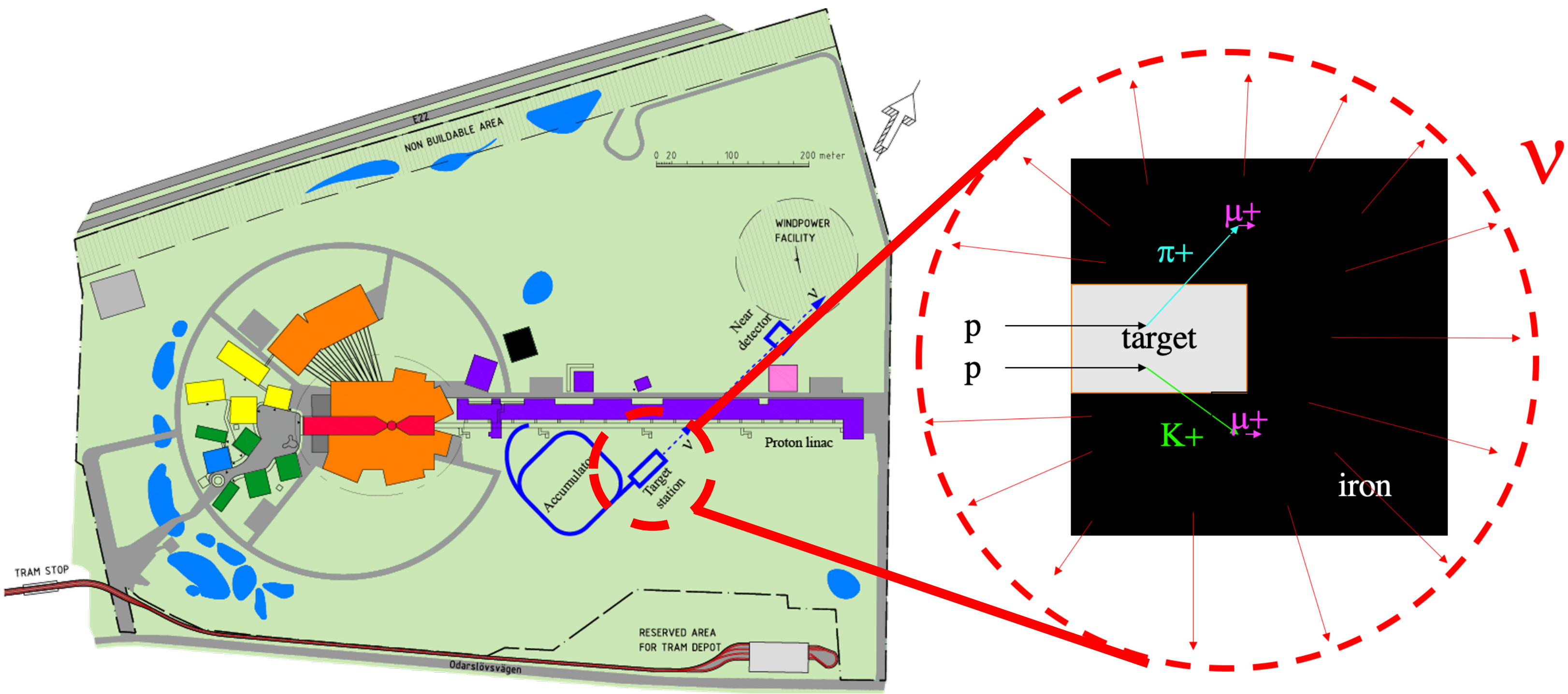
Neutrino "Decay-at-Rest" Experiments at ESS

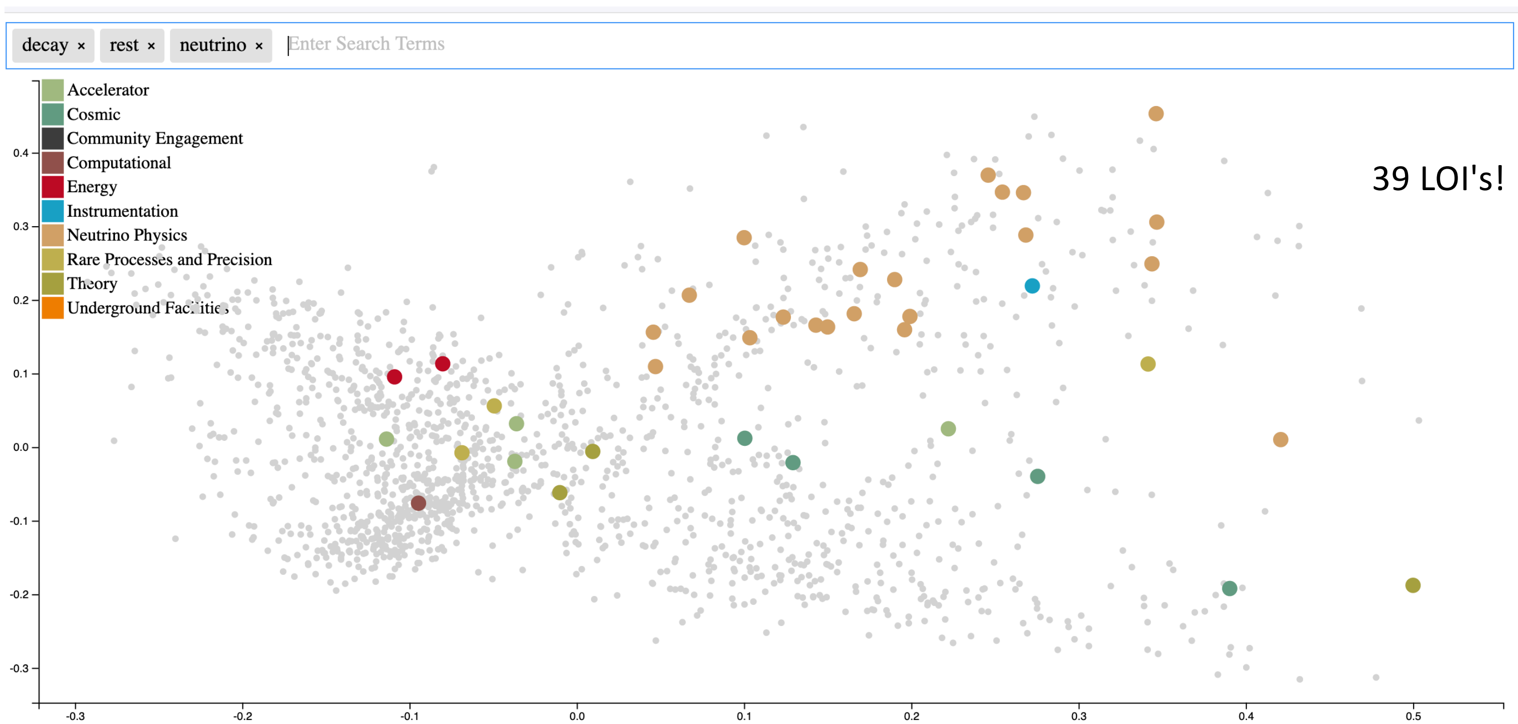
by Janet Conrad, MIT



ESSnuSB Workshop in UHH ,Oct 9, 2020

There is a lot of interest in use of neutrino fluxes from decay-at-rest!

Snowmass LOI's mentioning "neutrino"+"decay"+"rest":



https://gordonwatts.github.io/snowmass-loi-words/scatter/scatter.html

Why the interest?

Precision!
DAR flux energy distributions and flavor content are very well described.
There are 3 low-energy cross sections that are very well known!

Quick!
Most experiments being proposed are <$10M (US accounting)
Most experiments use "understood" technology
Many experiments use small detectors – even new state-of-art technology is affordable given size.

Not your same-old approach!
Opens new types of searches.

What do people who are engaged in these experiments wrestle with?

Isotropic beam

Any one experiment subtends a small solid angle

→ flux improves with energy, power and purpose-built target! ***(Go ESS!)***

Backgrounds in General

These are low energy experiments, so cosmic and neutron backgrounds are a big issue

→ improves with shorter pulses ***(Go ESS short pulse upgrade!)***

Neutrons Especially. Even with short pulses

Neutrons can mimic the neutral current interaction signals

→ improves with specialized, shielded target & detector design ***(Go ESS Neutrino Campus!)***

→ improves with higher energy decay-at-rest sources ***(Go KDAR@ESS!)***

Many labs do not see neutrino physics as part of their portfolio

There is resistance to fitting even small detectors onto site ***(Go ESS Open-Minded Management!)***

ESS is a very special site for DAR, in many ways!

Why DAR in the context of the larger ESSnu Program?

It is a path to first-physics fast:
This can be installed shortly after the accelerator upgrade is complete.

It builds a neutrino-user base at ESS before the large programs turn on
That will make construction and commissioning of the larger programs go faster.

A great place to train students:
A funnel for future collaborators into the longer-term ESS programs!

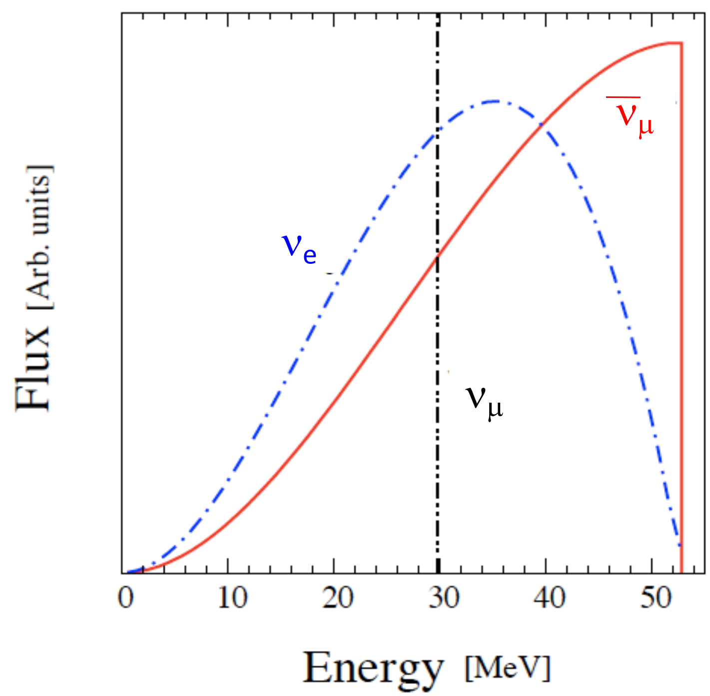
Additional studies, especially on new detectors, can be done inexpensively:
The new technologies may be very valuable to the longer-term program.

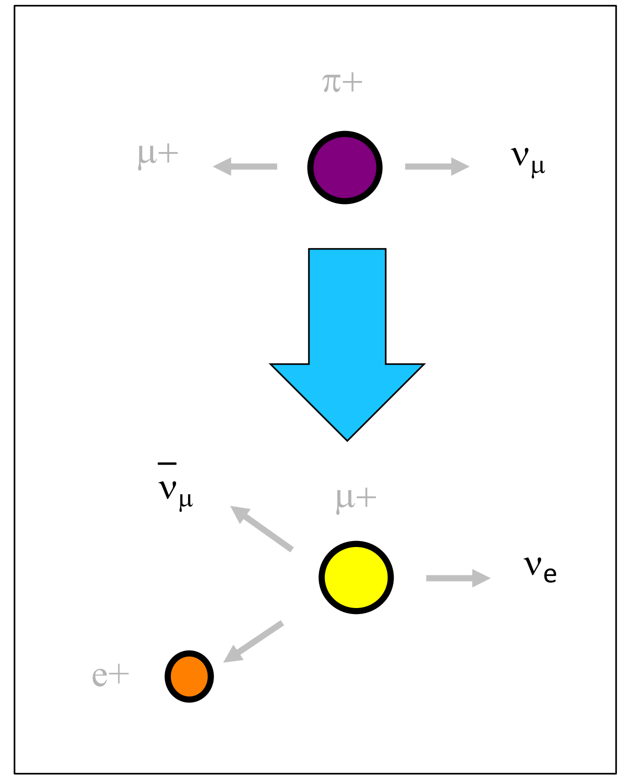
It is a path to understanding the beam and targeting issues for the larger experiments early:
A well-designed area for this program can allow targeting test stands.

The remainder of this talk:

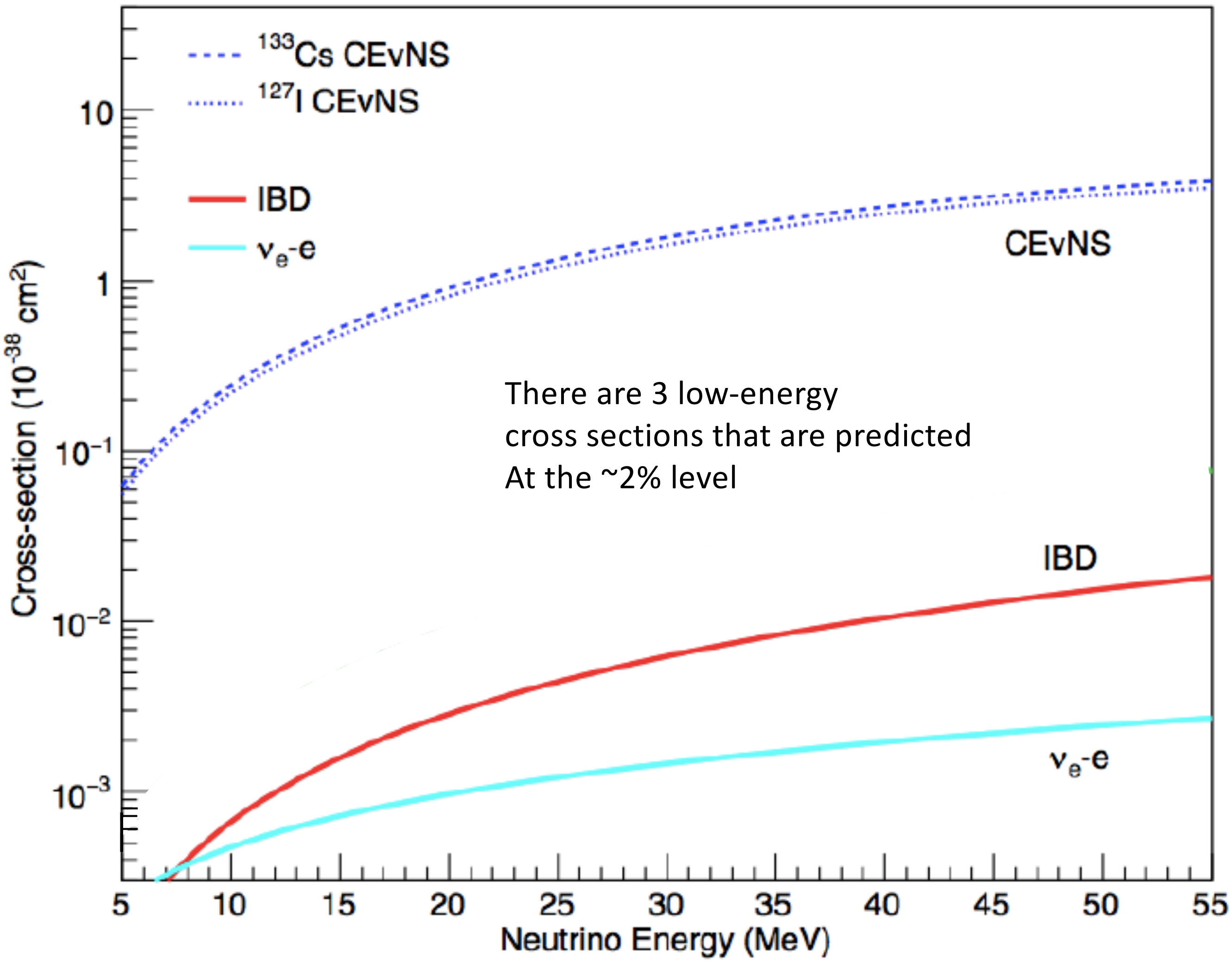
- Intro to DAR Flux and Physics
- World-wide Opportunities, including Power vs. Backgrounds
- My own interest: A KDAR-based ν_μ Disappearance Experiment

Most of the running
and proposed experiments use
Pion/muon decay-at-rest fluxes

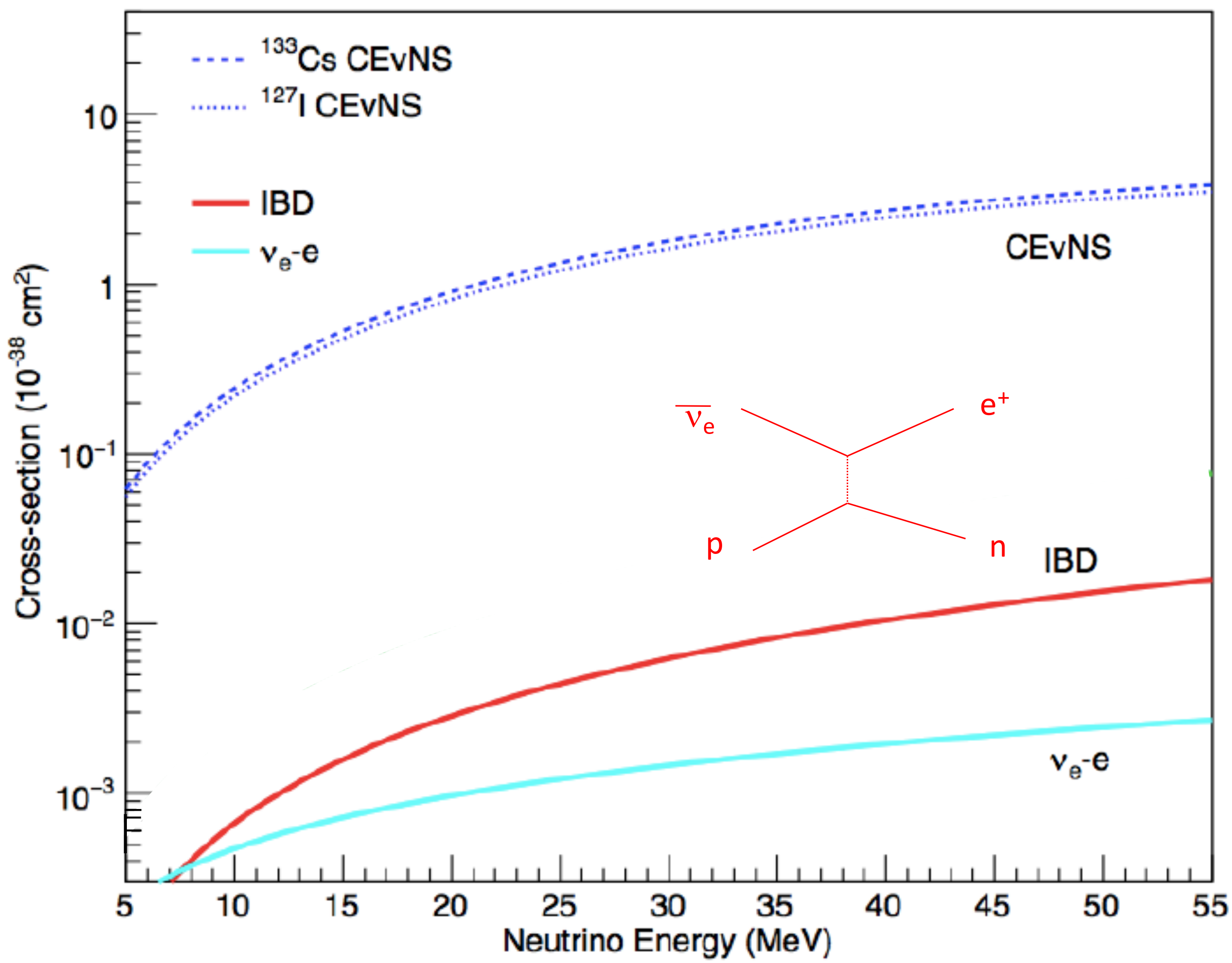




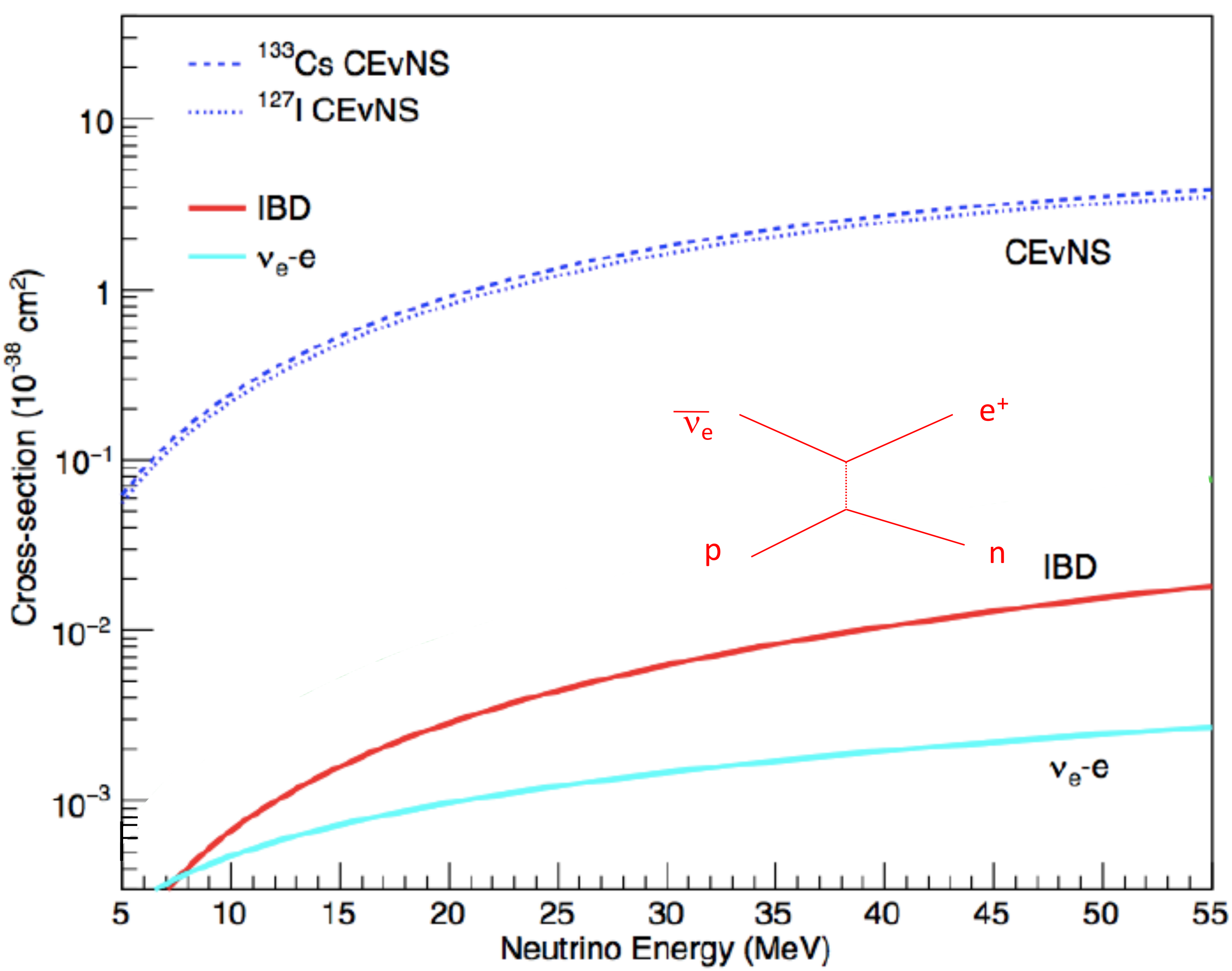
A great place to search for
$\bar{\nu}_\mu \to \bar{\nu}_e$



Already
discussed,
Subject
of many
of the
Snowmass LOIs!



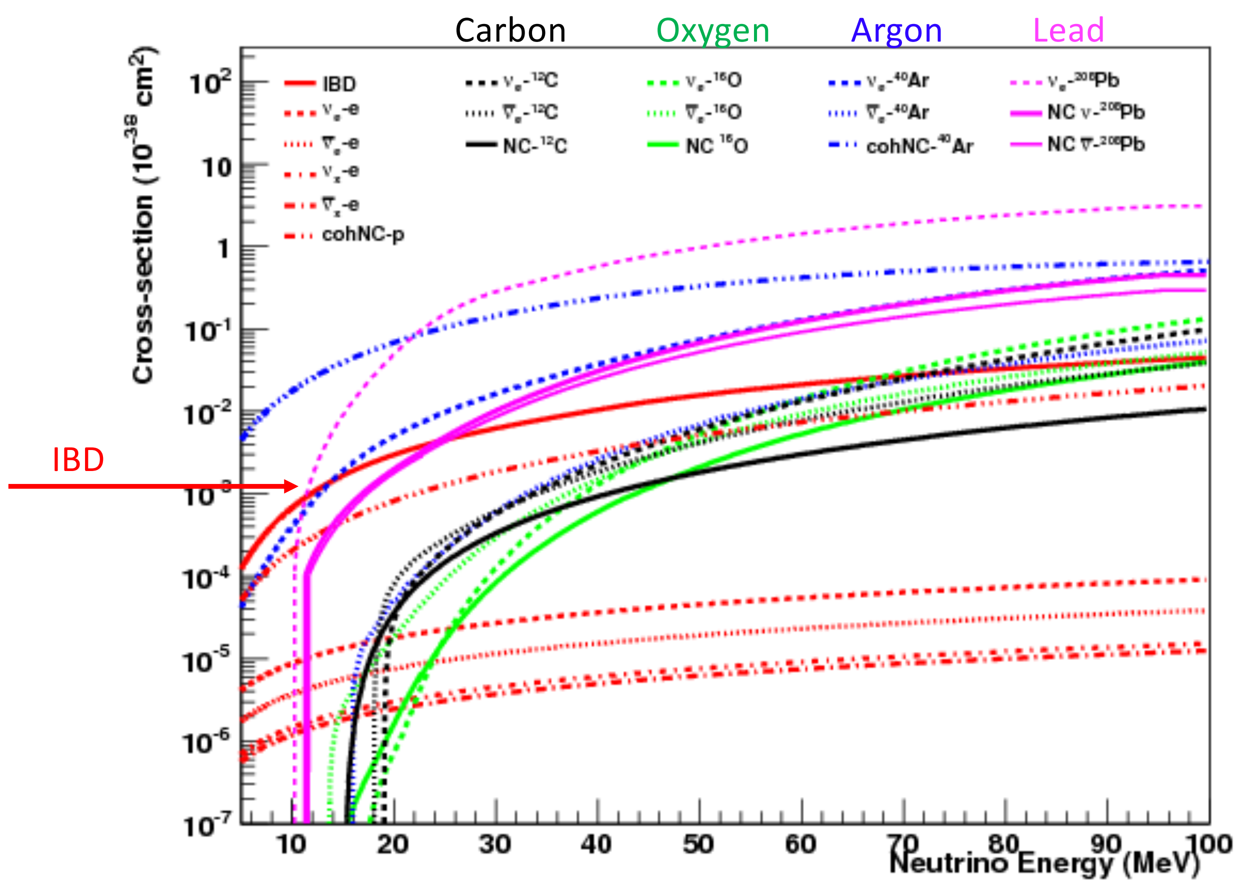
Neutrino energy is fully reconstructed!



A purely lepton-lepton interaction

There are many other materials used for detectors!
But many cross sections are poorly known.

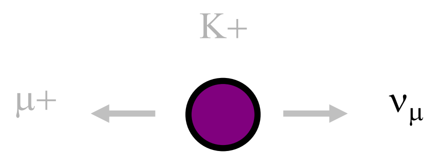
Materials commonly used in Supernova detection:

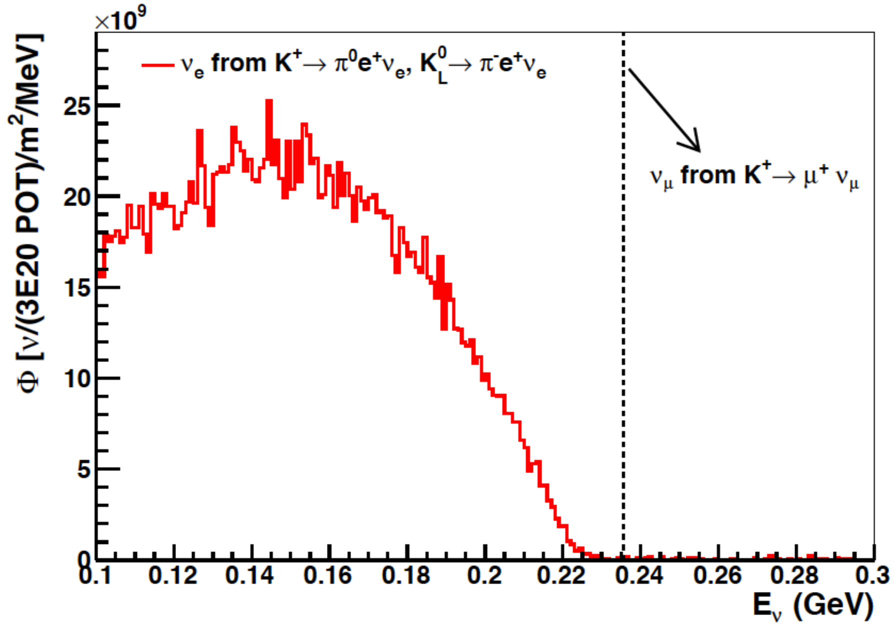


NC (solid) and CC ν_e (dashed) scattering from nuclei

Scattering from electrons

Kaon decay-at-rest ("KDAR")



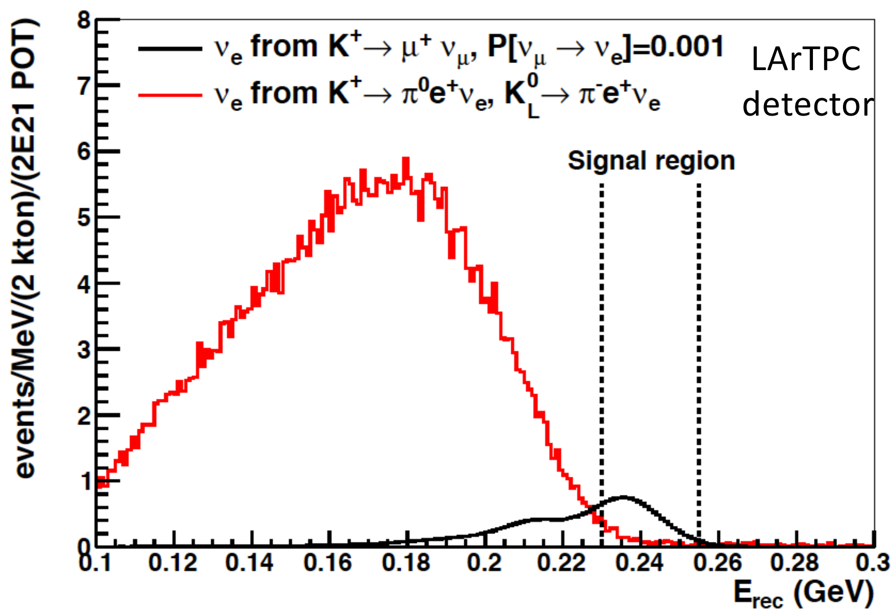


A high energy
monoenergetic
muon neutrino!

Electron neutrino content,
that extends above 100 MeV
and lies below the
monoenergetic line

Spitz, arXiv:1203.6050

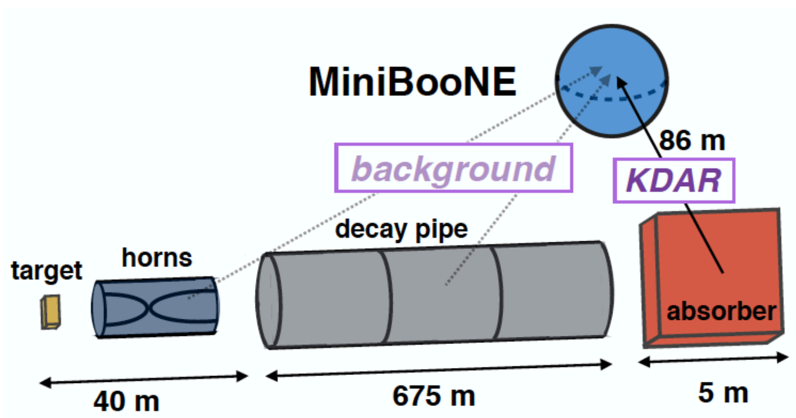
If you are interested in short baseline $\nu_\mu \rightarrow \nu_e$,
Or NSI's with instantaneous flavor conversion, this is really nice!



Spitz, arXiv:1203.6050

https://journals.aps.org/prl/abstract
/10.1103/PhysRevLett.120.141802

KDAR 236 MeV ν_μ interactions have been seen at MiniBooNE!



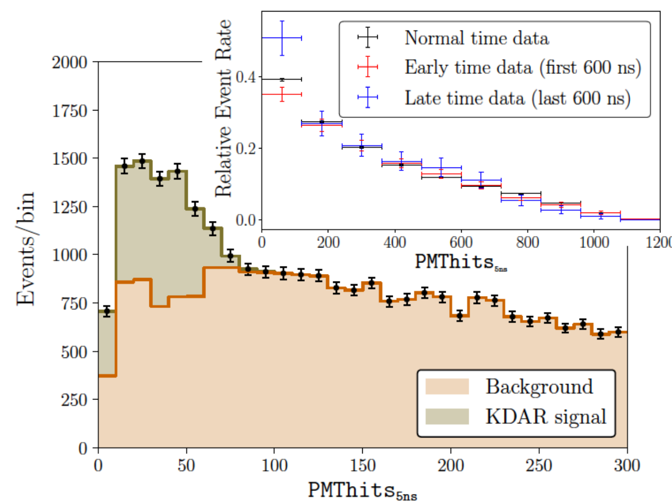

Physics ABOUT BROWSE PRESS COLLECTIONS

FOCUS

Neutrinos with a Single Energy

April 6, 2018 • *Physics* 11, 35

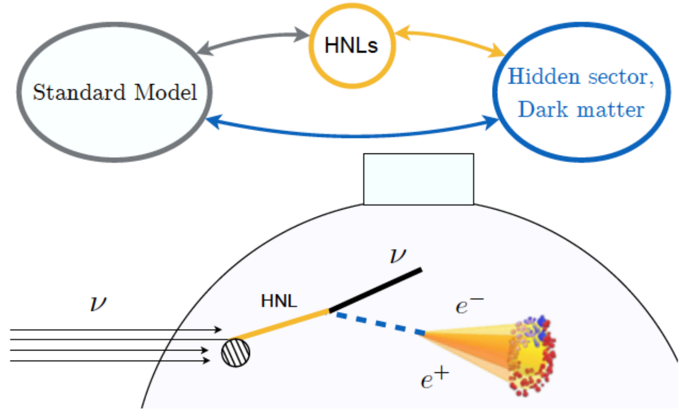
Neutrinos in a beam have a wide range of energies, but a new trick allowed researchers to isolate fixed-energy neutrinos, which can improve the precision in future experiments.



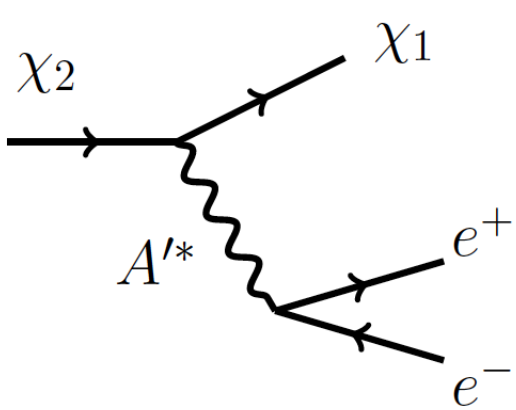
An example of why running
With DIF as well as DAR is painful

C. Arguelles, M. Hostert, Y. Tsai, PhysRevLett. 123, 261801 (2019)

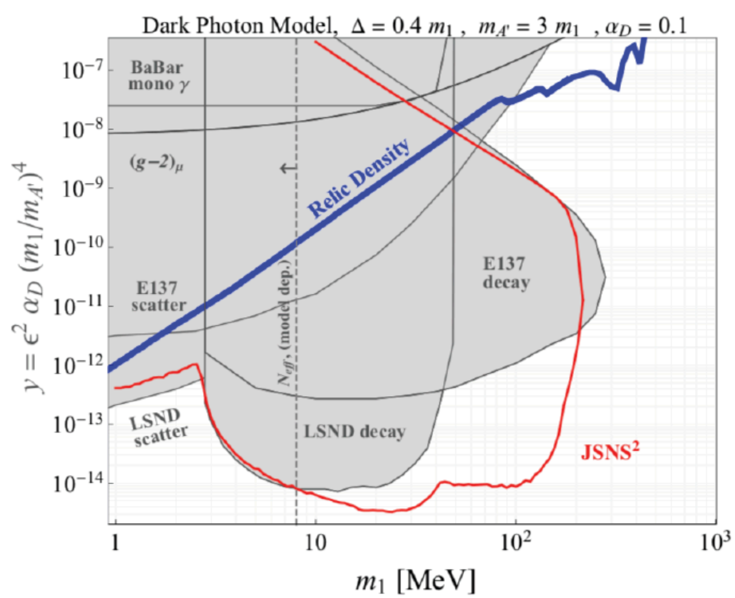
Testing
Many new models for
Heavy Neutral Leptons/
Dark photons



ESS will have sensitivity to models that can explain the MiniBooNE Excess



Jordan,Kahn,Krnjaic,Moschella,Spitz, https://arxiv.org/abs/ 1806.05185



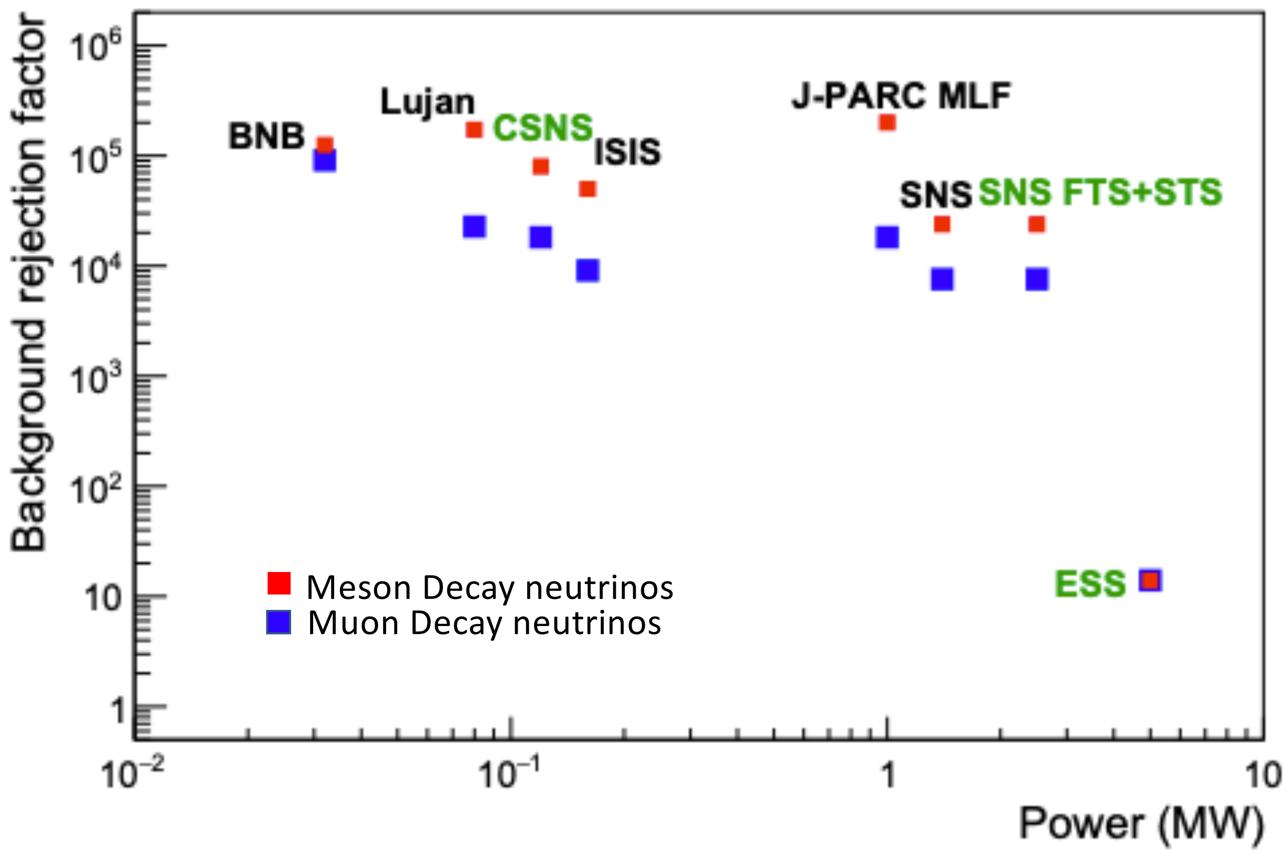
ESS has greater reach due to More than twice the power and more space for an optimized detector!

Power, Energy and Backgrounds: The Landscape of Sites

All existing and planned π/μ DAR sources are on-surface or very shallow
→ Cosmic ray rates with similar topologies occur at very high rate

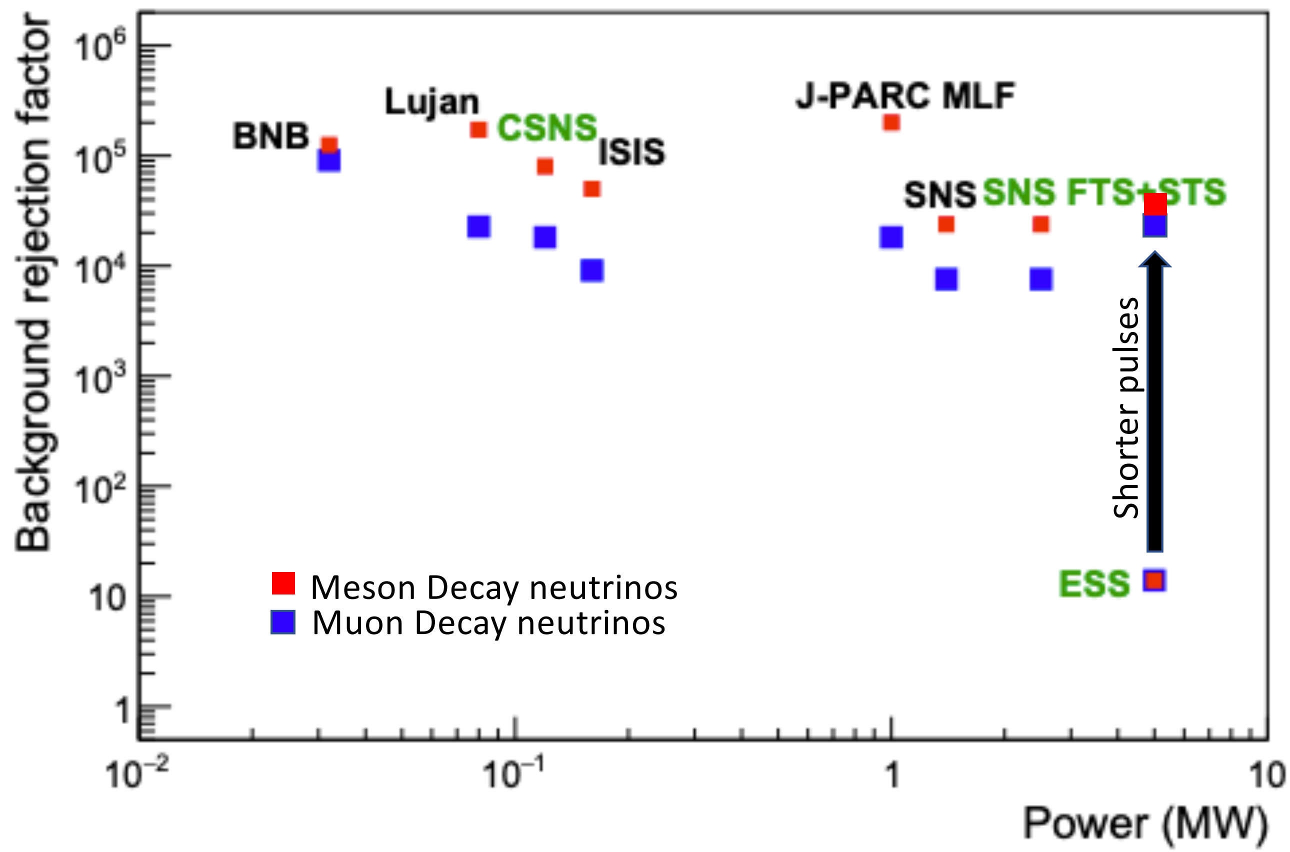
It is hard to win against these backgrounds through power alone.
That is why ESS needs the short-pulse structure too.

The π/μ DAR landscape

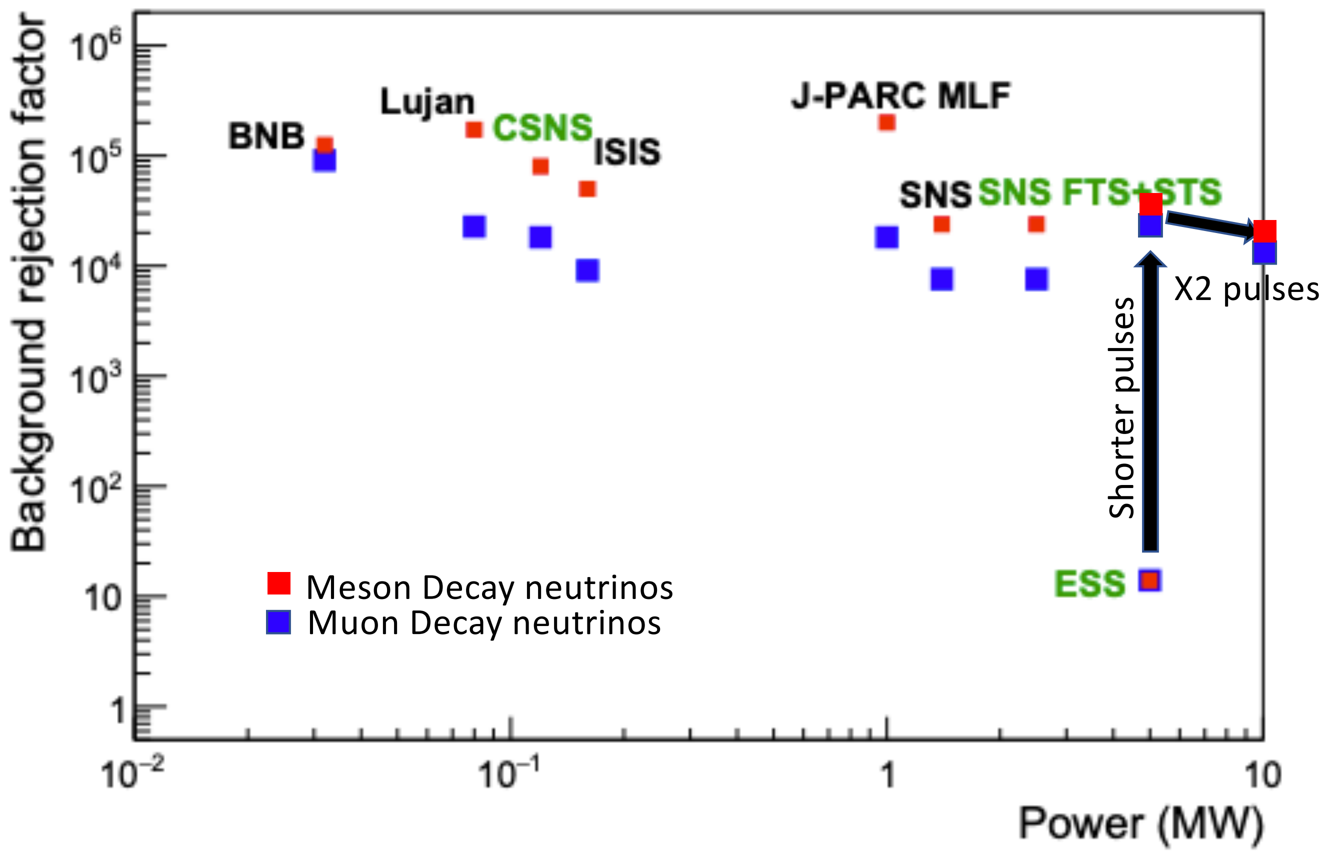


To be in the game, ESS must have the short-pulse upgrade!

The π/μ DAR landscape



The π/μ DAR landscape

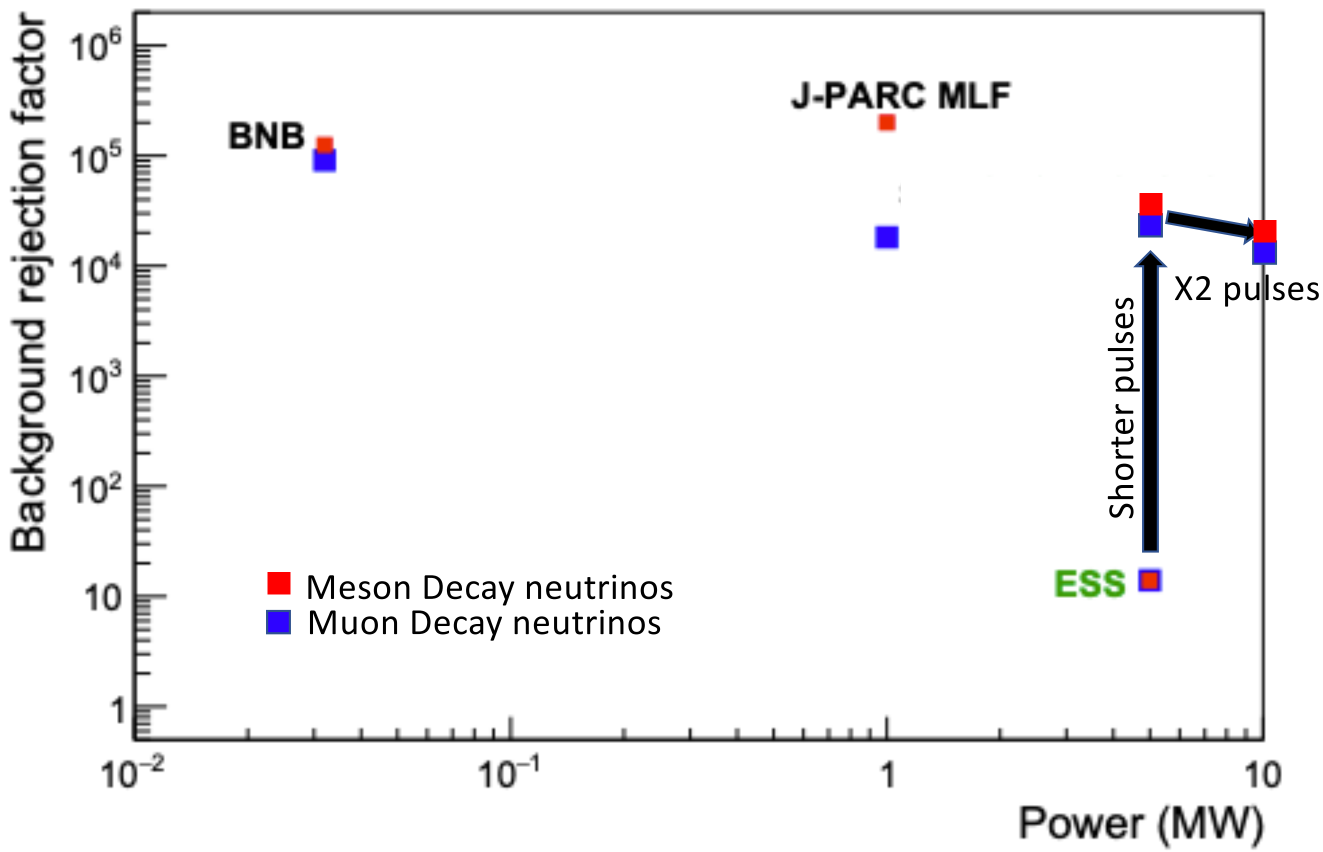


Next: Beam Energy!

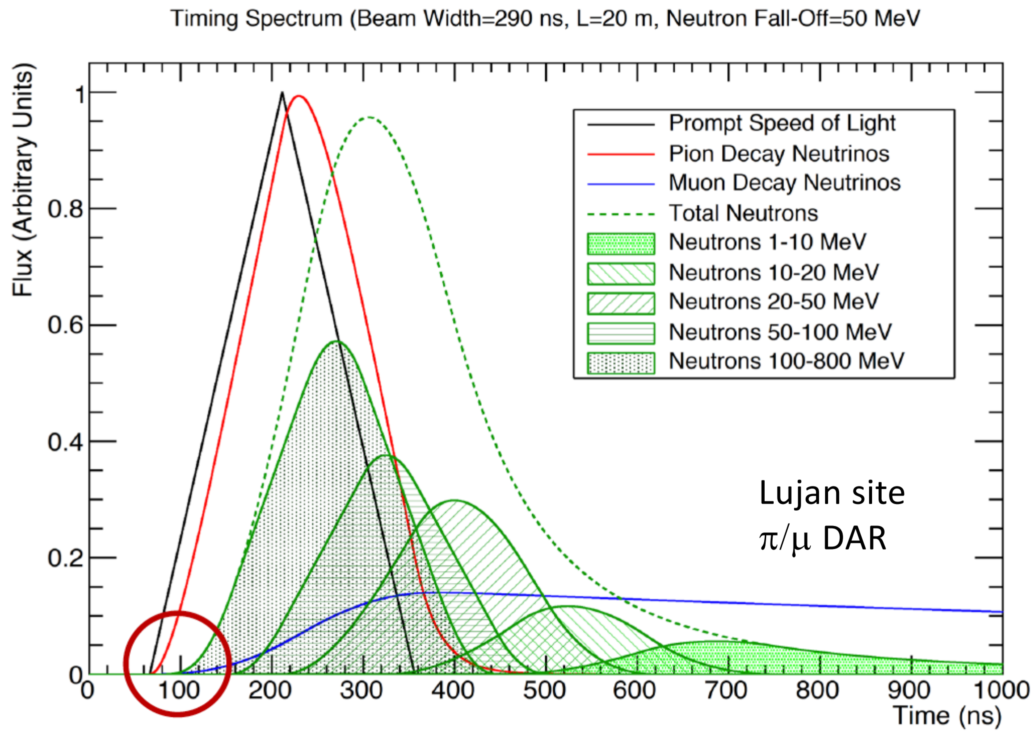
Production data on p+Be target…

Produced Hadron	Exclusive Reaction	M_X (GeV/c^2)	$\sqrt{s_{thresh}}$ (GeV)	E^{beam}_{thresh} GeV	KE of beam (MeV)	
π^+	$pn\pi^+$	1.878	2.018	1.233	295	
π^-	$pp\pi^+\pi^-$	2.016	2.156	1.54	602	
π^0	$pp\pi^0$	1.876	2.011	1.218	280	
K^+	$\Lambda^0 pK^+$	2.053	2.547	2.52	1582	*Very few locations!*
K^-	ppK^+K^-	2.37	2.864	3.434	2496	
K^0	$p\Sigma^+K^0$	2.13	2.628	2.743	1805	

The KDAR landscape



Short pulses also help with neutron backgrounds...



The shorter the pulse the better! -- ESS will have a relatively long "short pulse"

But the neutron background can be mitigated with a for-DAR target hall design.
Yes, you will add a lot of neutron shielding but also...

Minimize neutron production

- Don't waste beam energy!
- Do decrease $\pi-$ background (if p knocks out n, n can produce $\Delta^0 \to \pi- \, p$)
- Do make shielding for neutron backgrounds easier.

Solutions: Use a light target (C, H_2O)
Use a lot of surrounding shielding to absorb n's

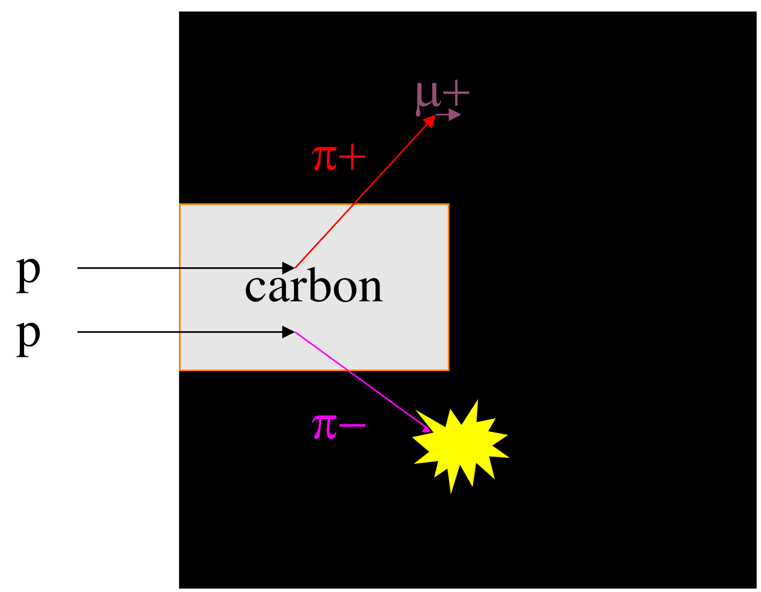
Note that spallation sources produce neutrons on purpose, so they are not very efficient neutrino sources!

→ Optimizing against neutrons at a dedicated target site will give ESS additional flux compared to competitors

Also: Remove the π– that are produced -- Minimize DIF

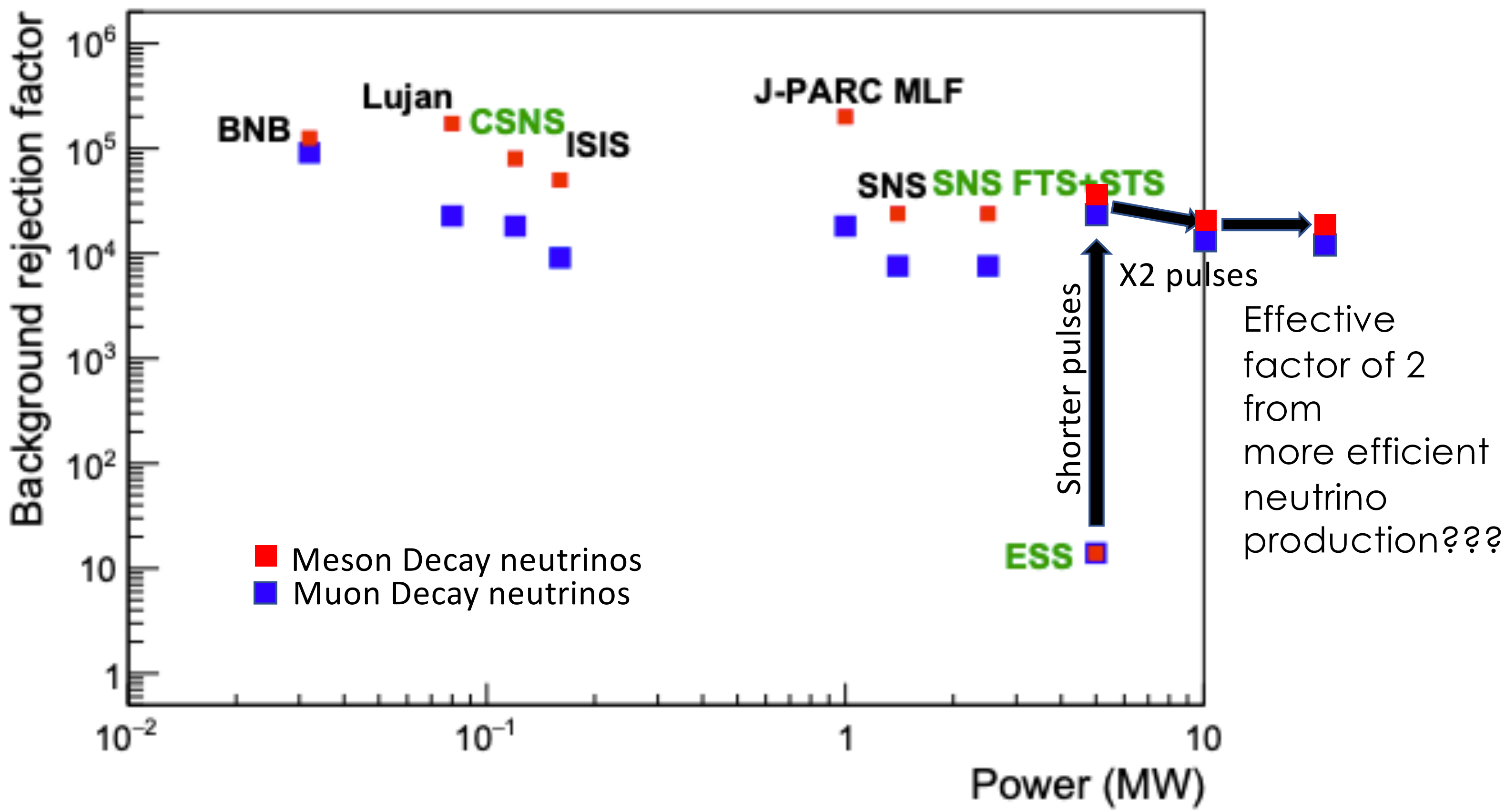
- π– capture when they stop
- all flavors of DIF neutrinos are a problem because they do not have a well-defined spectrum

Solution: Light target embedded in a heavy target/shield



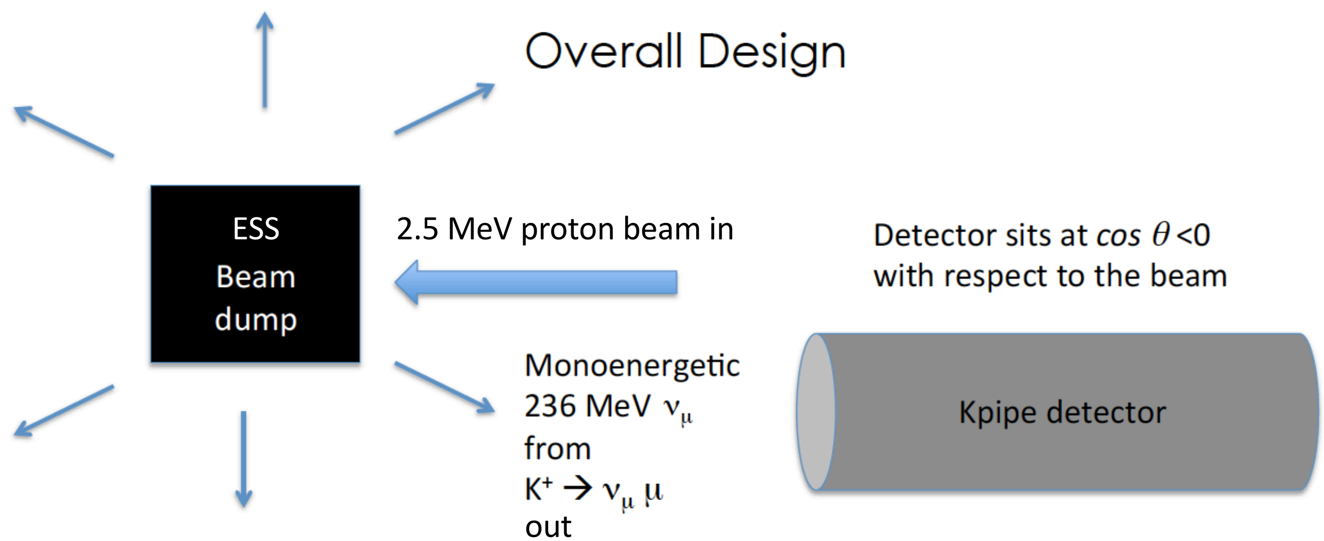
Also,
no upstream
targets please!

The π/μ DAR landscape

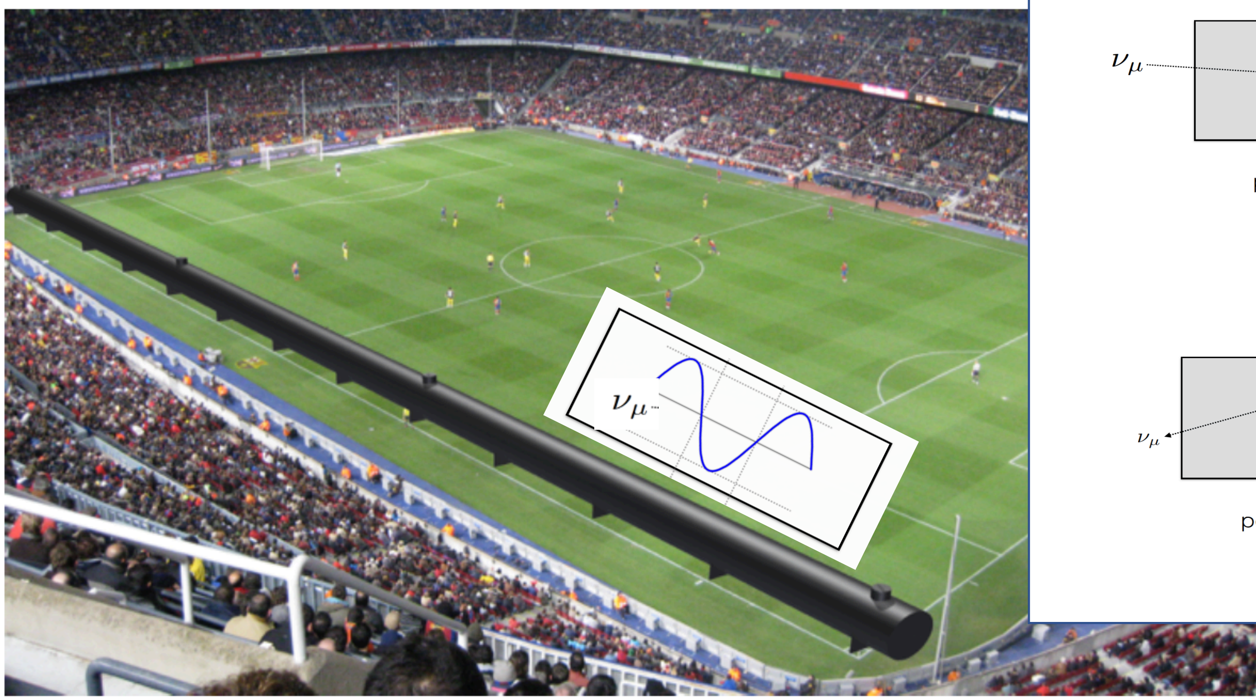


My personal interest: KPIPE --

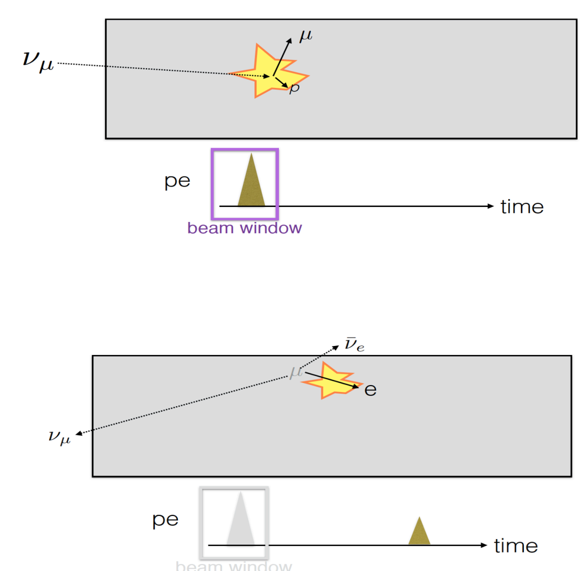
a search for ν_μ disappearance at short baseline

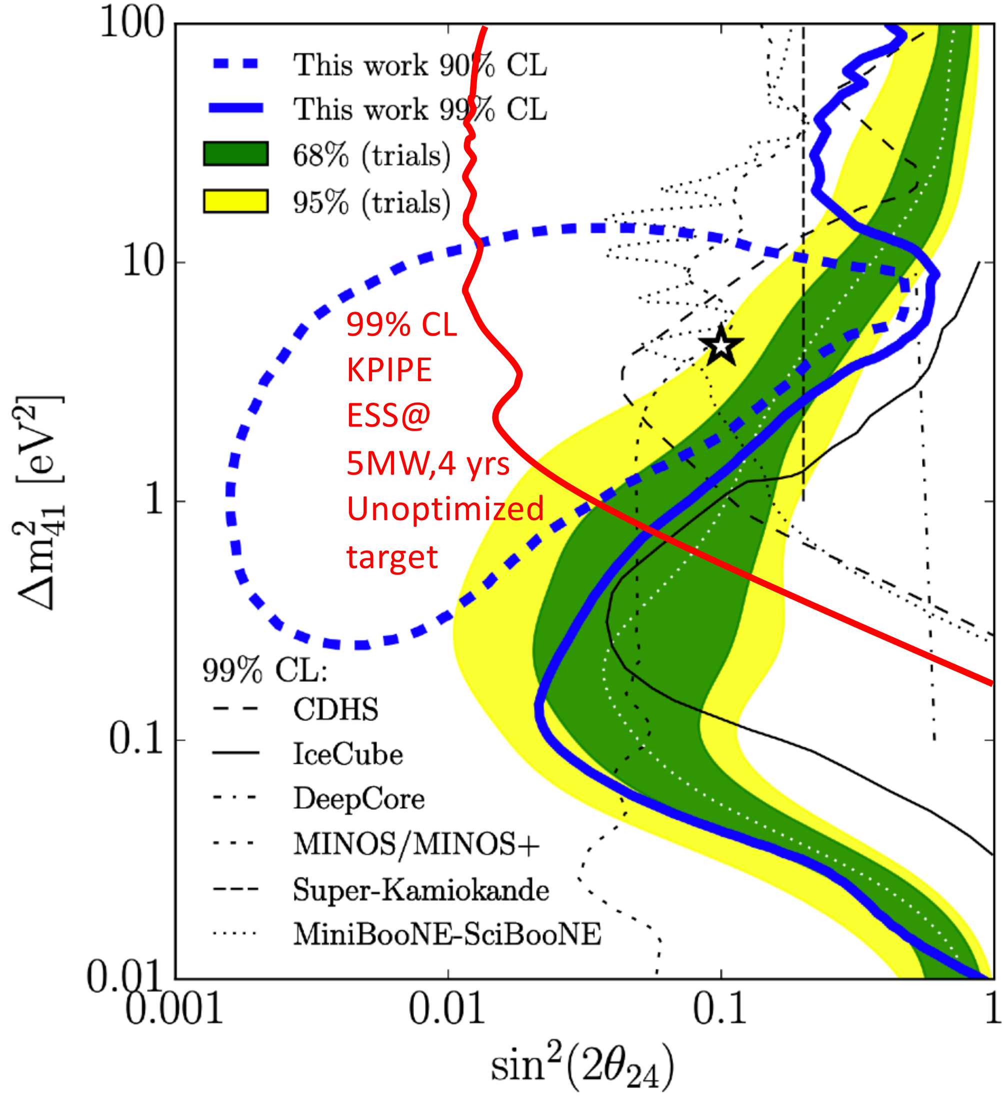


A (BIG) pipe, 3 m diameter and 120 m long, filled with liquid scintillator



A coincident signal





s://arxiv.org/abs/2005.12942

Take aways:

Interesting and timely physics: SBL oscillations, cross sections, dark photons,
BSM tests through CEvENS and neutrino-electron scattering... More!

ESS is a unique opportunity for those interested in decay-at-rest sources.
It wins on power, energy, ability to optimize the neutrino production
With the short-pulse upgrade, it ties other sites on cosmic background.

The DAR program is also a unique opportunity for ESS
to start-up the neutrino program quickly.

It is a real opportunity, all around.

Thank you!

Back ups

What are the axes on that plot of LOIs?

Short answer: LOI's are clustered, approximately, by their content. Axes just spread out the results.

Medium answer: Each document is reduced to a vector of 4000 potential words. Principle Component Analysis is used to reduce that 4000D space into 2D space. PCA tries to find the axes that maximizes the spread.

The really long version of the answer... Look here: snowmass-loi-words/04-ScatterPlot Visualization Data.ipynb at master · gordonwatts/snowmass-loi-words (github.com)

(Many thanks to Gordon Watts for producing this code!)

Many thanks to Kate Scholberg for producing the plot below.

Kudos for showing the muon decay capability (blue) separately from the meson decay (red)!

Reference for Rejection Factor vs Power Plot:

SNOWMASS21-NF6_NF9-CF1_CF0-TF11_TF0-IF2_IF8_Kate_Scholberg-161.pdf

Which is for SNS...

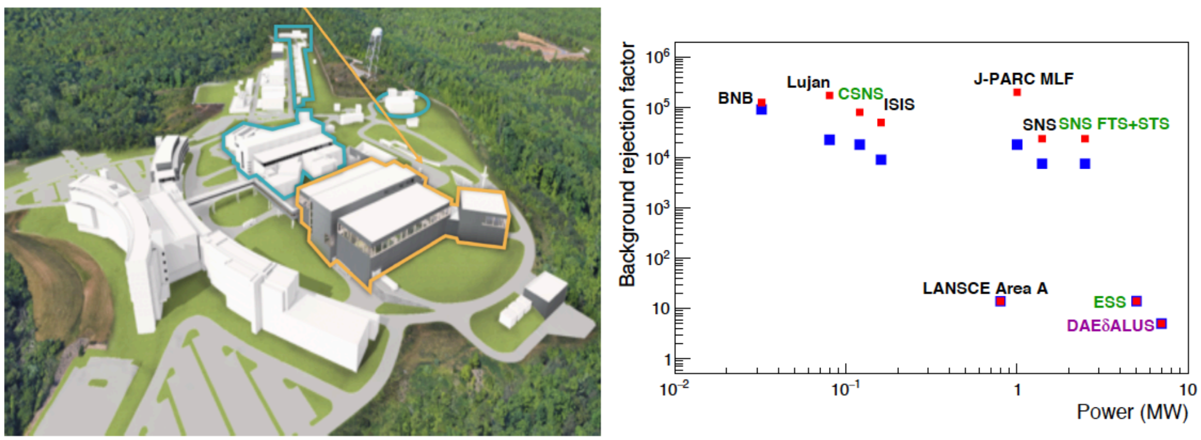
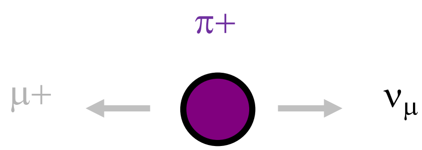
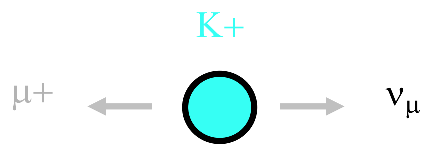


Fig. 1: Left: Spallation Neutron Source [21]. STS buildings are outlined in orange. Right: Approximate figures of merit for different stopped-π sources for neutrino physics. The upper right corner is the most desirable region. Proton power is approximately proportional to neutrino flux. Red squares represent prompt ν_μ flux; blue squares represent $\bar{\nu}_\mu$ and ν_e. The y-axis shows the reciprocal of the maximum of the beam pulse length and the parent particle decay timescale, times pulse frequency, which quantifies steady-state background rejection. Well-separated blue and red squares indicate that flavor separation is possible. Past facilities are indicated in black; future ones are in green; concepts are in purple.

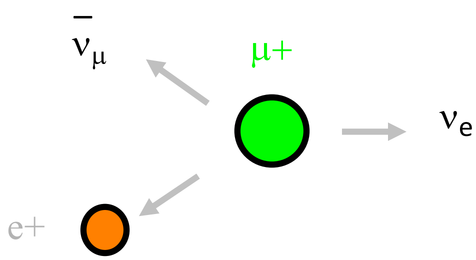
Reminder of lifetimes compared to the ESS planned pulse length of 1.3 μs,
& consideration of timing cuts for neutrino-cleanness



26 ns → initial ν flux will precede neutron flux,
early timing cuts reduce useable flux but flux is neutron-clean



12 ns → initial ν flux will precede neutron flux
early timing cuts reduce useable flux but flux is neutron-clean
(less of an issue given the high 236 MeV energy)

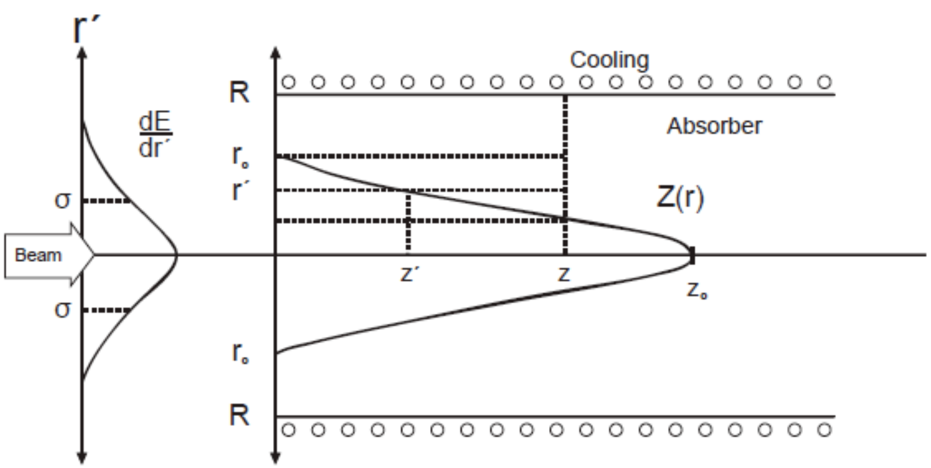


2.2 μs → ν flux will overlap and extend later than neutron flux,
late timing cuts reduce useable flux, but flux is less contaminated

Wanted: A source size which is small vs osc. wavelength

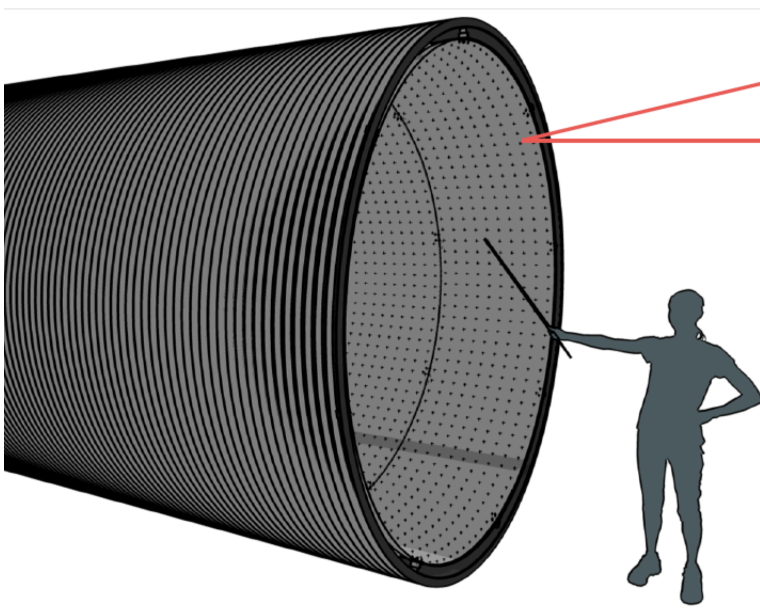
The size of the neutrino production region depends on…

1) Number of times an incoming proton will interact to produce a $\pi+$ (length ~25 cm)
2) stopping length of the $\pi+$ (length ~10 cm)
3) tapering introduced to spread the beam across the target

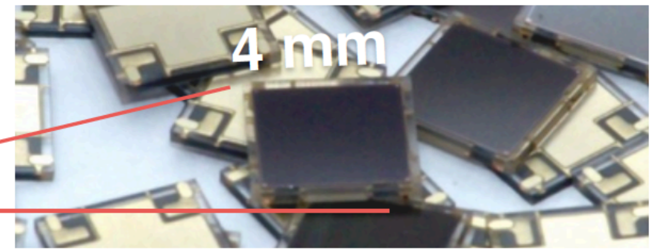


total smearing will be <50 cm for DAR

Many thanks to KPIPE collaborator Taritree Wongjirad
for KPIPE images appearing in main talk and
these next 3 back-up slides



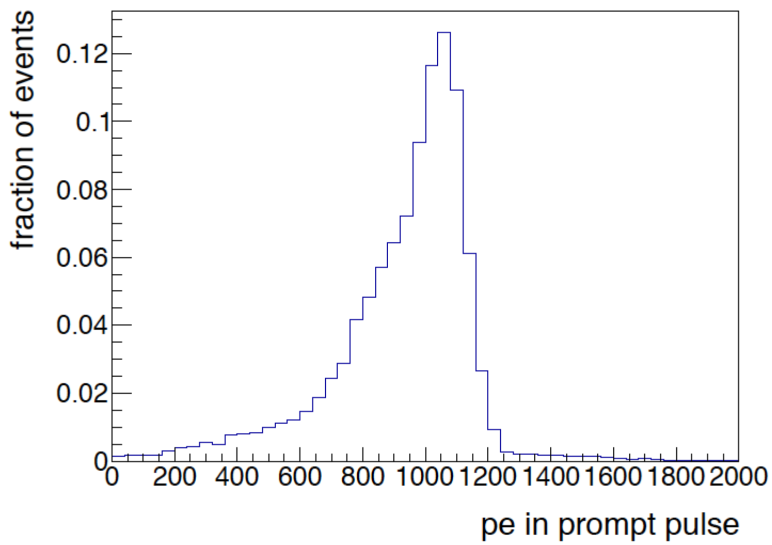
- Use SiPMs to detect light

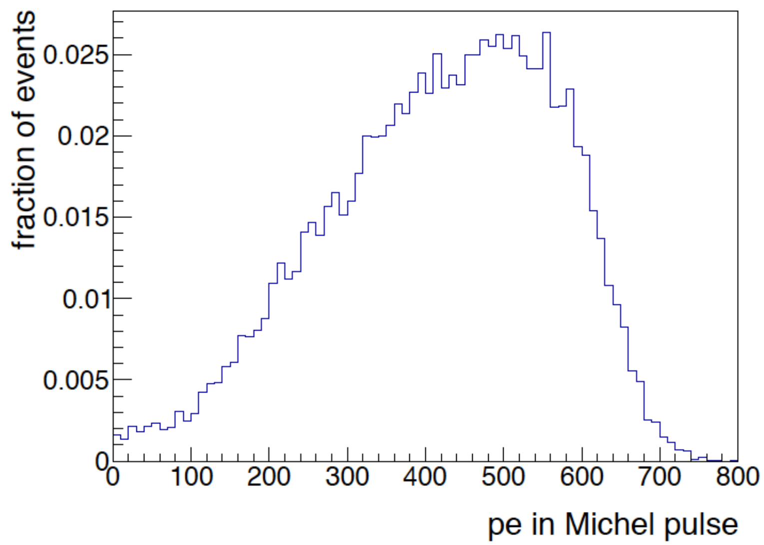


  - compact
  - low voltage ~ 27 V bias needed
  - inexpensive when ordered in bulk: ~$20/SiPM

KPIPE

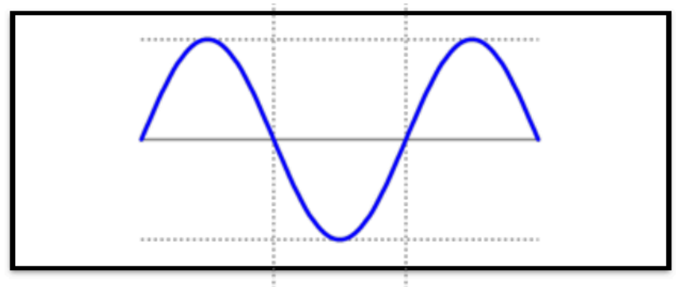
- Estimated photons collected
- MC scintillator produces ~4500 photons/MeV
- With current coverage, seems to be enough light
- Estimate about 80 cm position resolution





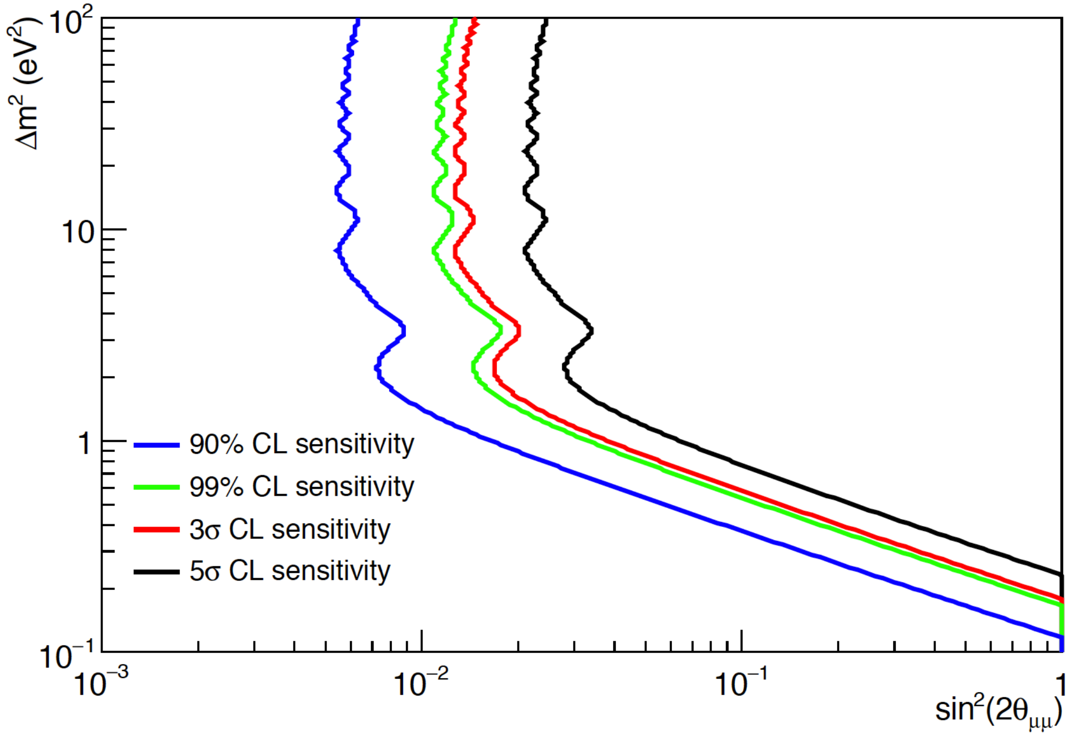
KPIPE

- We use a shape only analysis

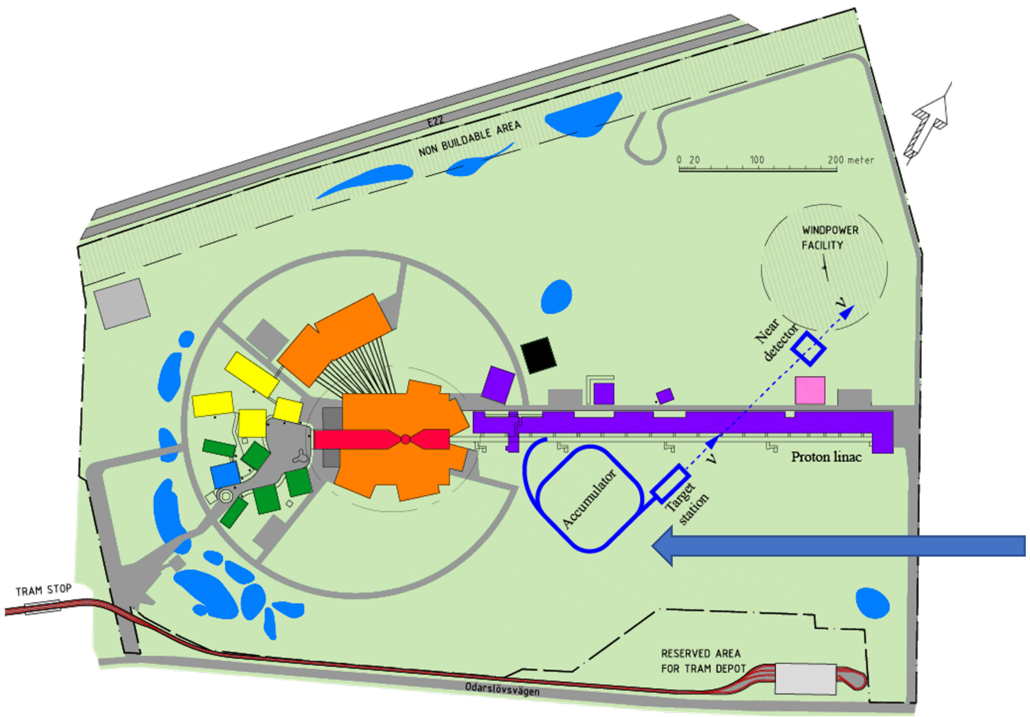


- Note: uncertainty primarily from statistics of signal and cosmic ray events
  - Uncertainty from flux and cross section only affect normalization which is not used in the analysis
  - Uncertainty from neutrino energy mis-reconstruction minimized due to relatively pure (98%) flux of KDAR neutrinos
  - Decoupling from these systematics is one of the attractive features of this setup

KPIPE estimated sensitivity at many confidence levels...



Will KPIPE Fit at ESS? (It doesn't fit at MLF!)



We think there is space here!
(we want to be oriented behind the target, so this direction is perfect!)

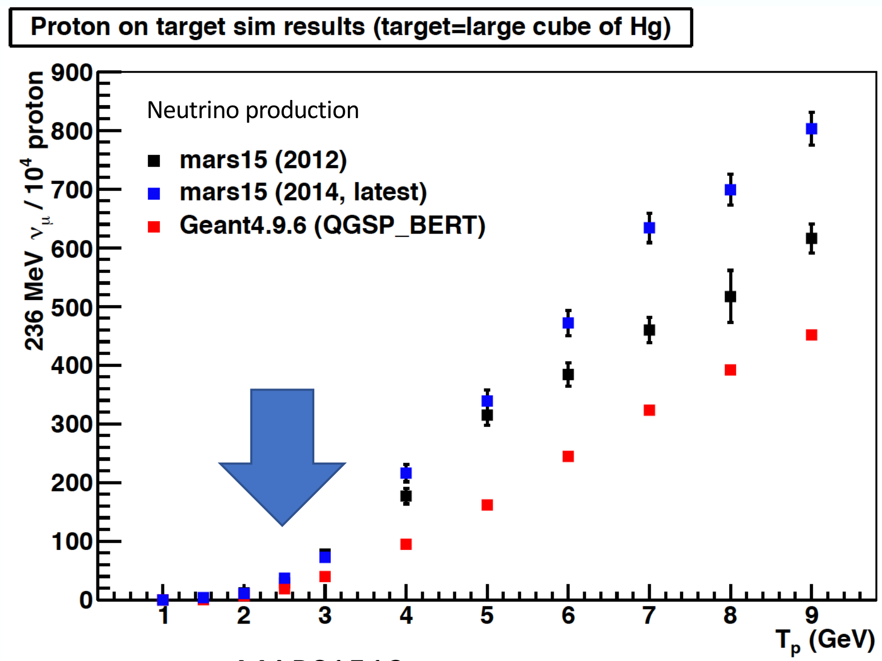
Another summary of the "Landscape"

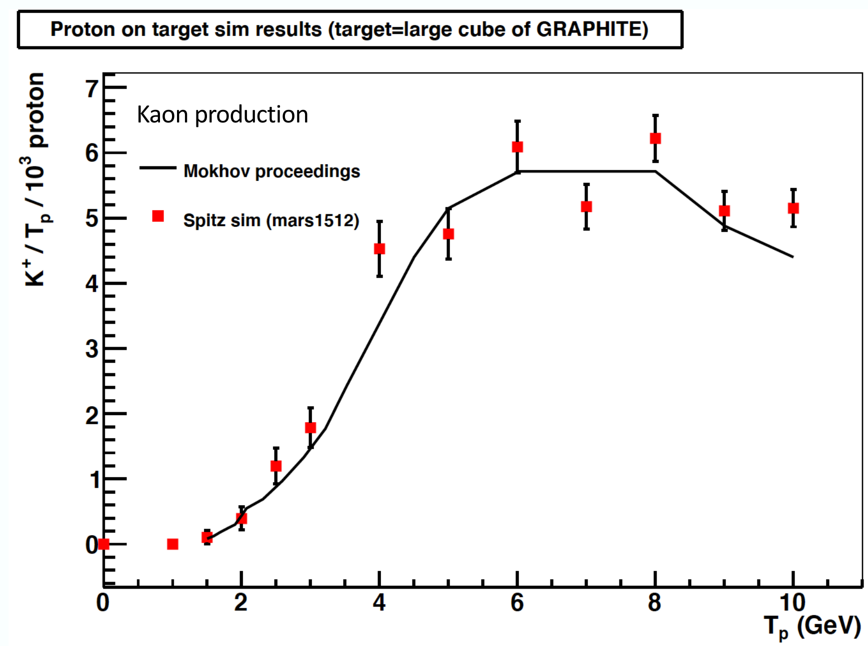
	Facility	Proton Energy (GeV)	Power (MW)	Bunch Structure	Rate
No longer running	LAMPF	0.8	0.8	600 µs	120 Hz
	Lujan	0.8	0.08	290 ns (triangular pulse)	20 Hz
	ISIS	0.8	0.16	2 x 100 ns	50 Hz
	SNS	1.0	1.4 (2.4 w/ STS)	600 ns	60 Hz
	MLF	3	1	2 x 100 ns (540 ns apart)	25 Hz
	CSNS	1.6	0.1	<500 ns	25 Hz
	ESS	2.5	5	2.86 ms (~1.3µs with PSR)	14 Hz
	PSI	0.6	1.4	CW	CW
	BNB	8	0.032	1.6 µs	5 Hz
Future Idea	PIP-II LINAC	0.8	1.6	CW	CW

Table by M. Toups

MLF vs ESS and thoughts on KDAR rates

MLF is running at 3 GeV protons on target. The ESS plan is for 2.5 GeV protons.
The reduced energy causes ~x2 reduction of the KDAR rate:





MARS1512:
34 KDAR numu per 10000 POT.

Geant4.9.6 (QGSP_BERT):
20 KDAR numu per 10000 POT

} Large differences in absolute
Predicted rate!
Needs further study is absolute rate must be known well.
(this should be able to be greatly improved!)

MLF neutrino flux -- Note the Decay-in-Flight (DIF) content due to unoptimized target

pi/mu DAR (<53 MeV) and KDAR (<236 MeV):

Solutions:
Optimize the target
Place detectors in backward direction

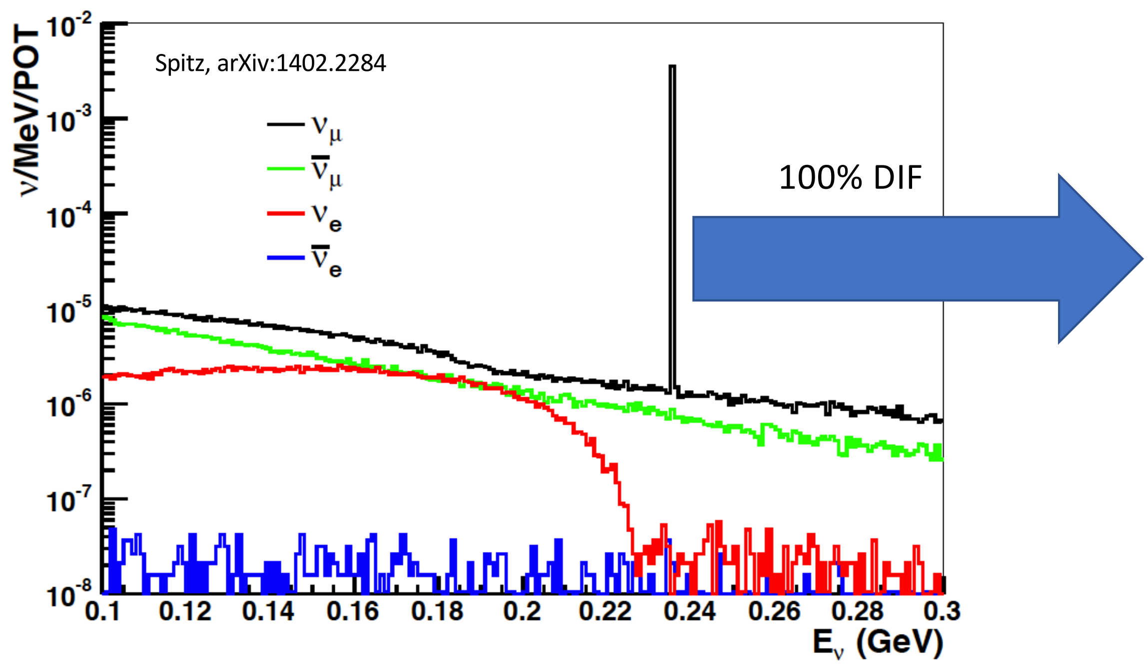
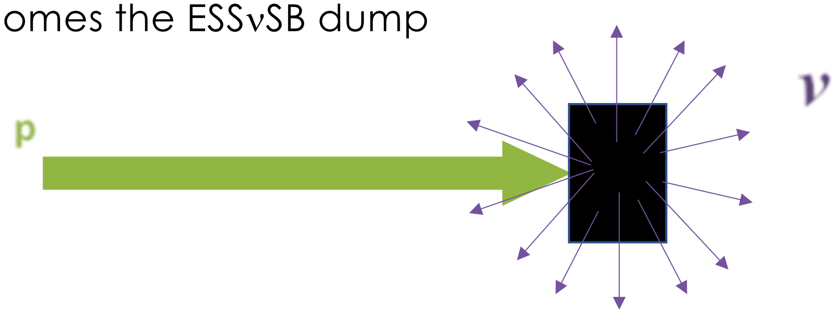


FIG. 1. The neutrino flux from 100-300 MeV provided by the 3 GeV proton-on-mercury JPARC-MLF source. The 236 MeV charged kaon decay-at-rest daughter ν_μ is easily seen.

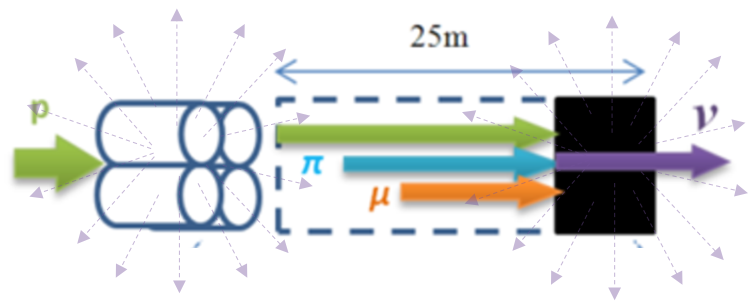
How might this be coordinated with the larger program? Some ideas for discussion...

Option 1: DAR target becomes the ESSνSB dump

Before and during ESSνSB Construction:



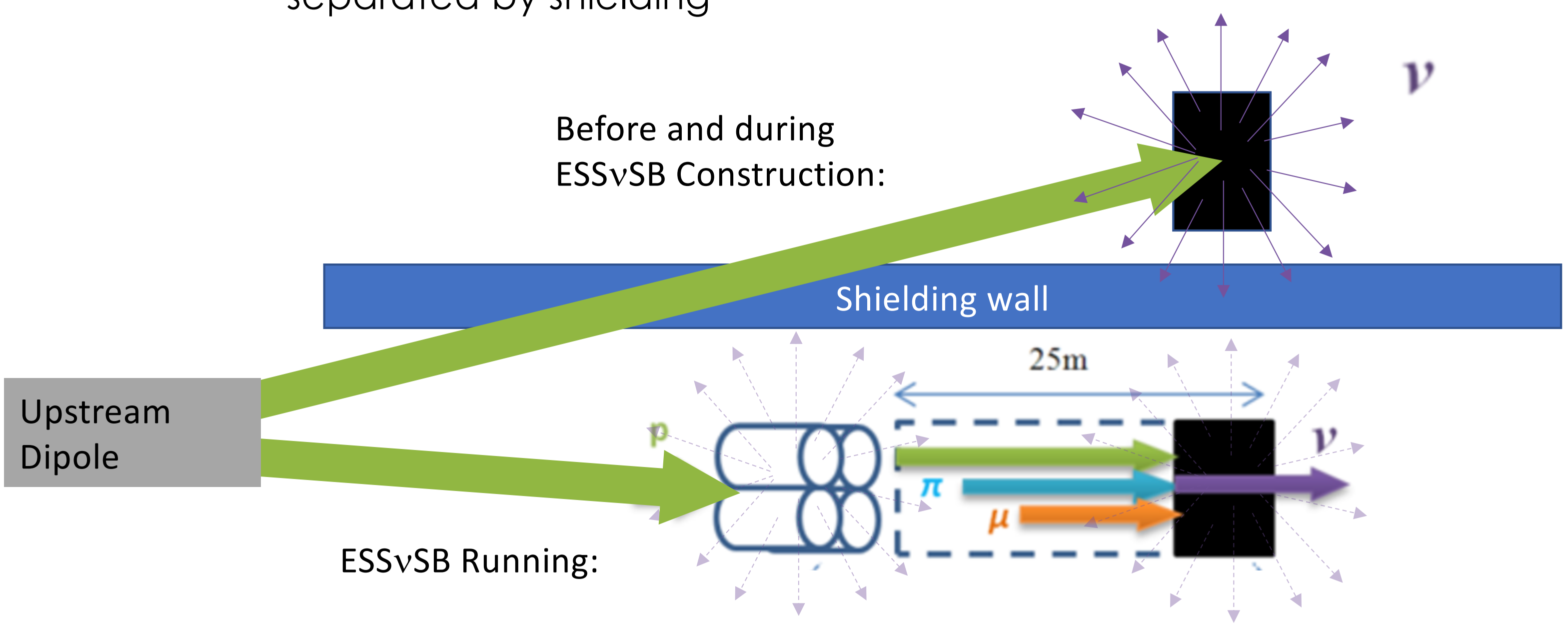
ESSνSB Running:



Needs careful beamline installation planning. Benefit vs Cost?

How might this be coordinated with the larger program? Some ideas for discussion...

Option 2: Separate DAR target, same space,
separated by shielding



More cost, but easier installation,
Old DAR target can act as an emergency beam dump.