MOMENT as multiple neutrino sources

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- Motivation and opportunity
- MOMENT: muon decay source
- MOMENT plus: pion decay source and decay at rest
- Summary

Measurement of CP

ν_μ-ν_e oscillations in a 3 ν scheme

$$p(\nu_\mu - \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] \quad \theta_{13}\ \text{driven}$$

$$+\ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{CPeven}$$

$$\mp\ 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{CPodd}$$

$$+\ 4s_{12}^2 c_{13}^2 \{ c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta \} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven}$$

$$\mp\ 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1 - 2s_{13}^2) \quad \text{matter effect (CP odd)}$$

Method

- Compare $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (CP violation)
- Measure $\nu_\mu \rightarrow \nu_e$ (absolute measurement)
- Compare $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ (T violation)

International effort on CP measurement

Long baseline accelerator experiments

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

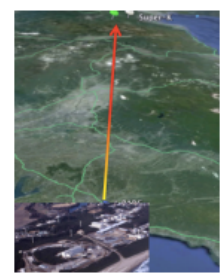
MINOS (+)
FNAL to Soudan
734 km, 400 kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 700 kW

T2K
J-PARC to Kamioka
295 km, 380-750 kW

LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2.3 MW)



Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔..)

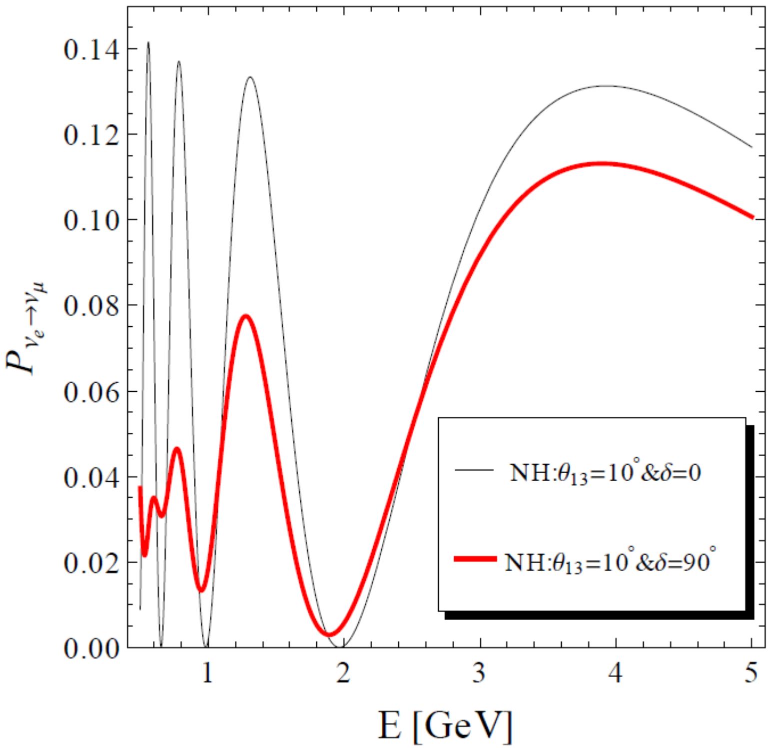
And beyond...
ESSnuB,
neutrino factories
DAEδALUS

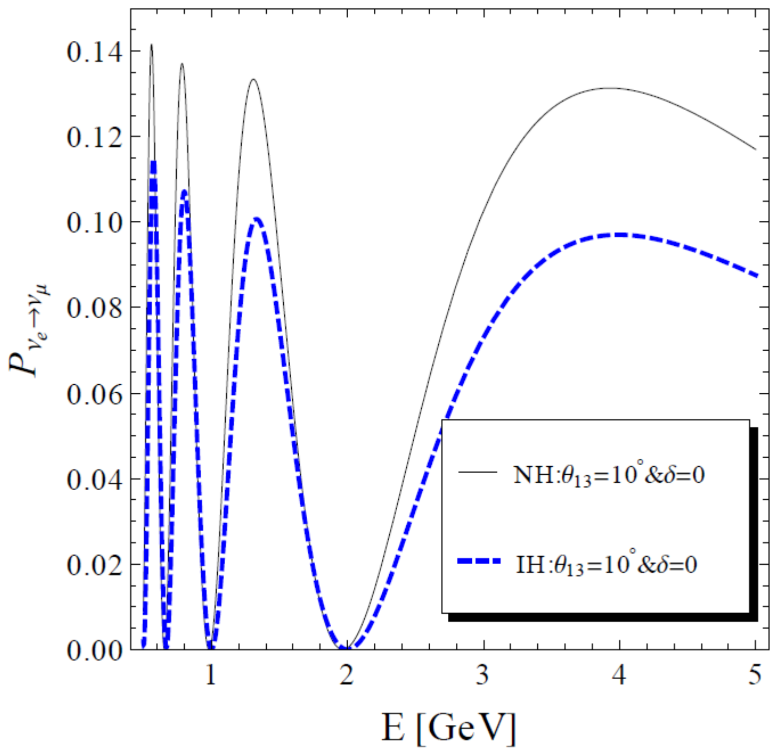
Aim for CP (and other osc. pars)

Kate Scholberg @ WIN2015

Oscillation probability

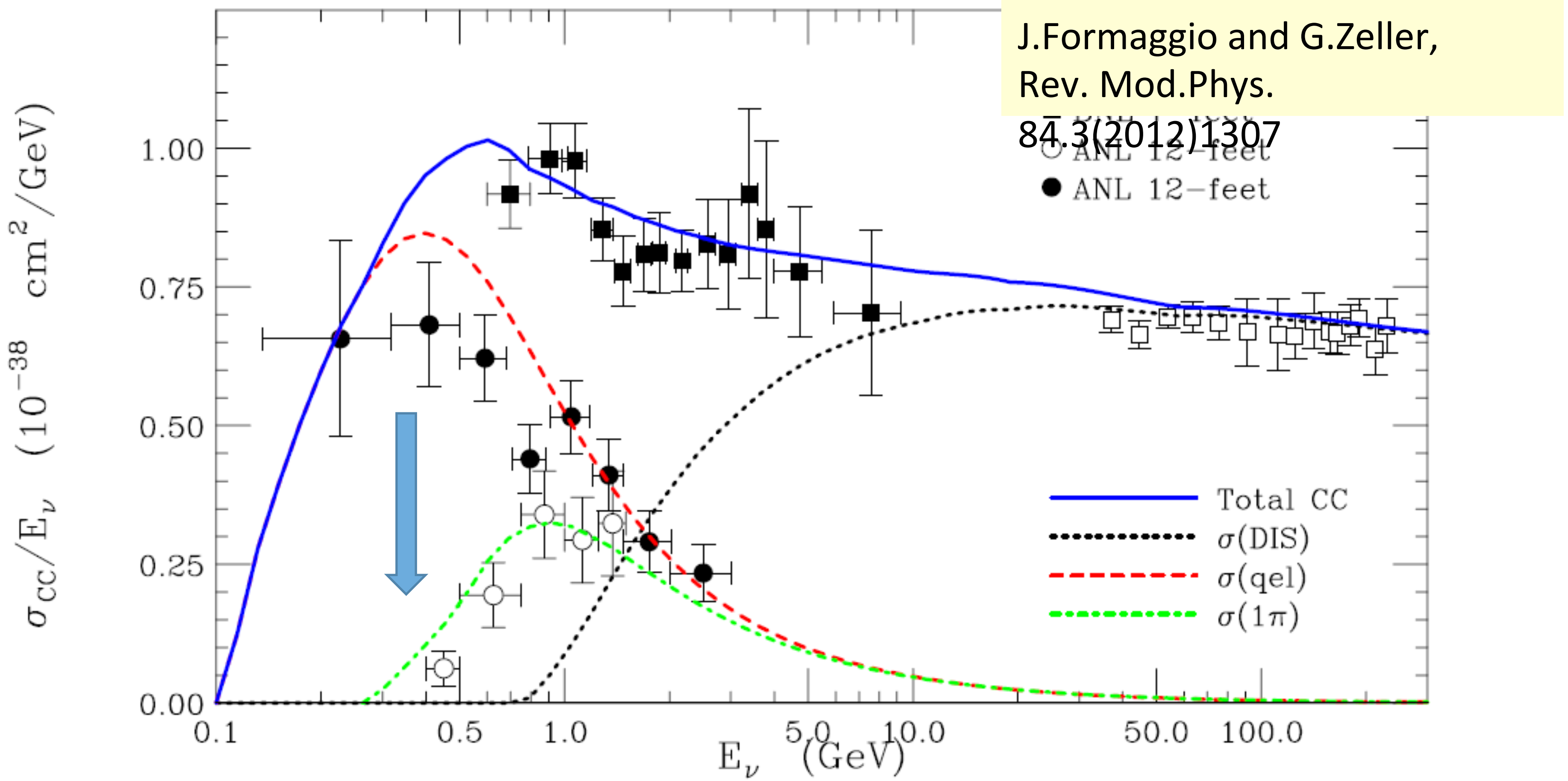
- **θ_{13}** controls the amplitude.
- **CP** is a low energy effect.
- **MH** is determined in the high energy part.





How low is the best for CP ?

- **Below in-elastic threshold: ~ 300 MeV ➔ baseline = 150 km**
- **Such a threshold is similar for CC/NC & ν/νbar**
- **Although we loose statistics due to the lower cross section, but we have less systematics by being π^0 free**

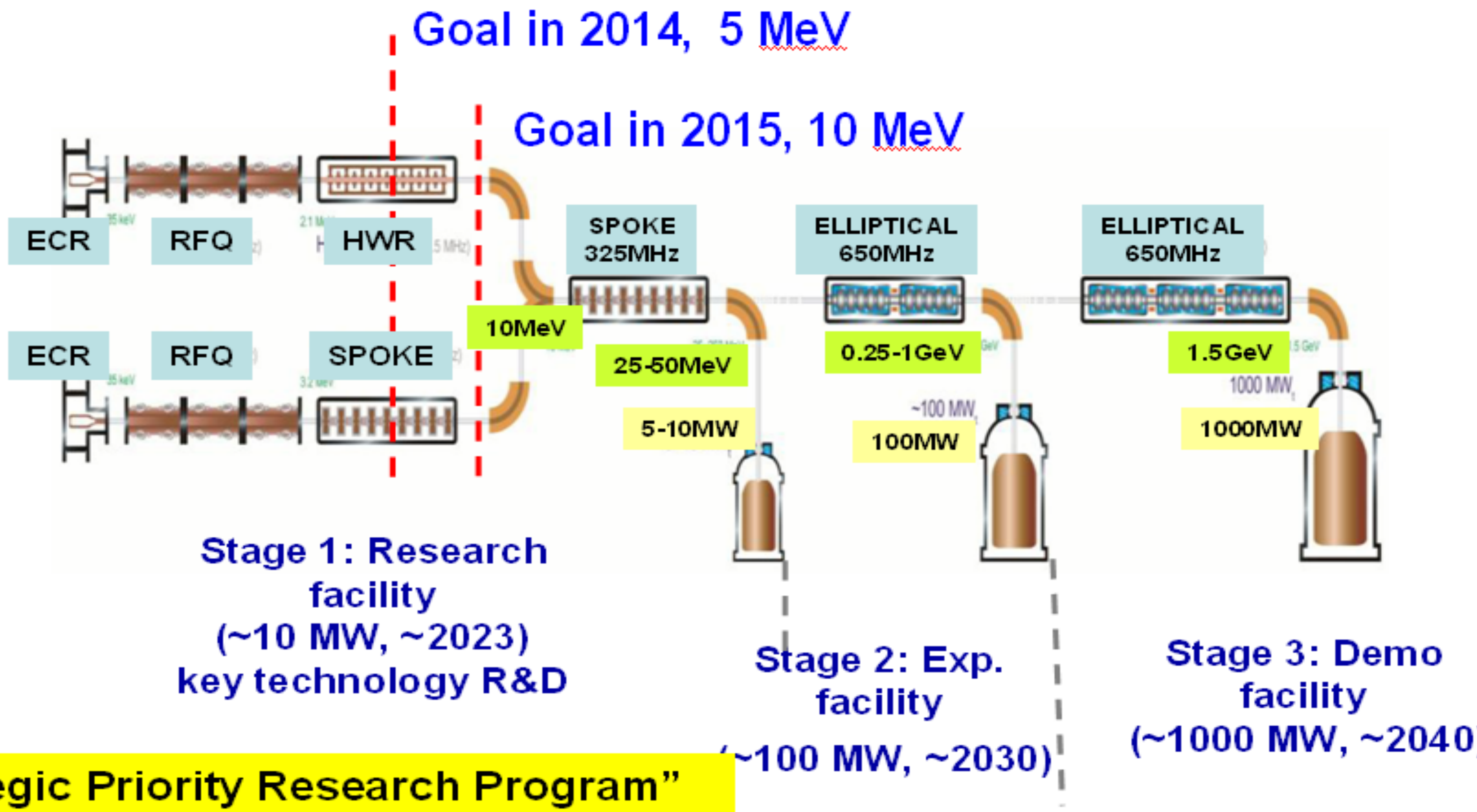


J.Formaggio and G.Zeller, Rev. Mod.Phys. 84.3(2012)1307

Very high intensity proton beam is needed！

China-ADS Roadmap

- A proton LINAC for ADS is now under development in China
- If R&D is successful, a CW Linac based ~15 MW proton driver can be used for neutrino beams

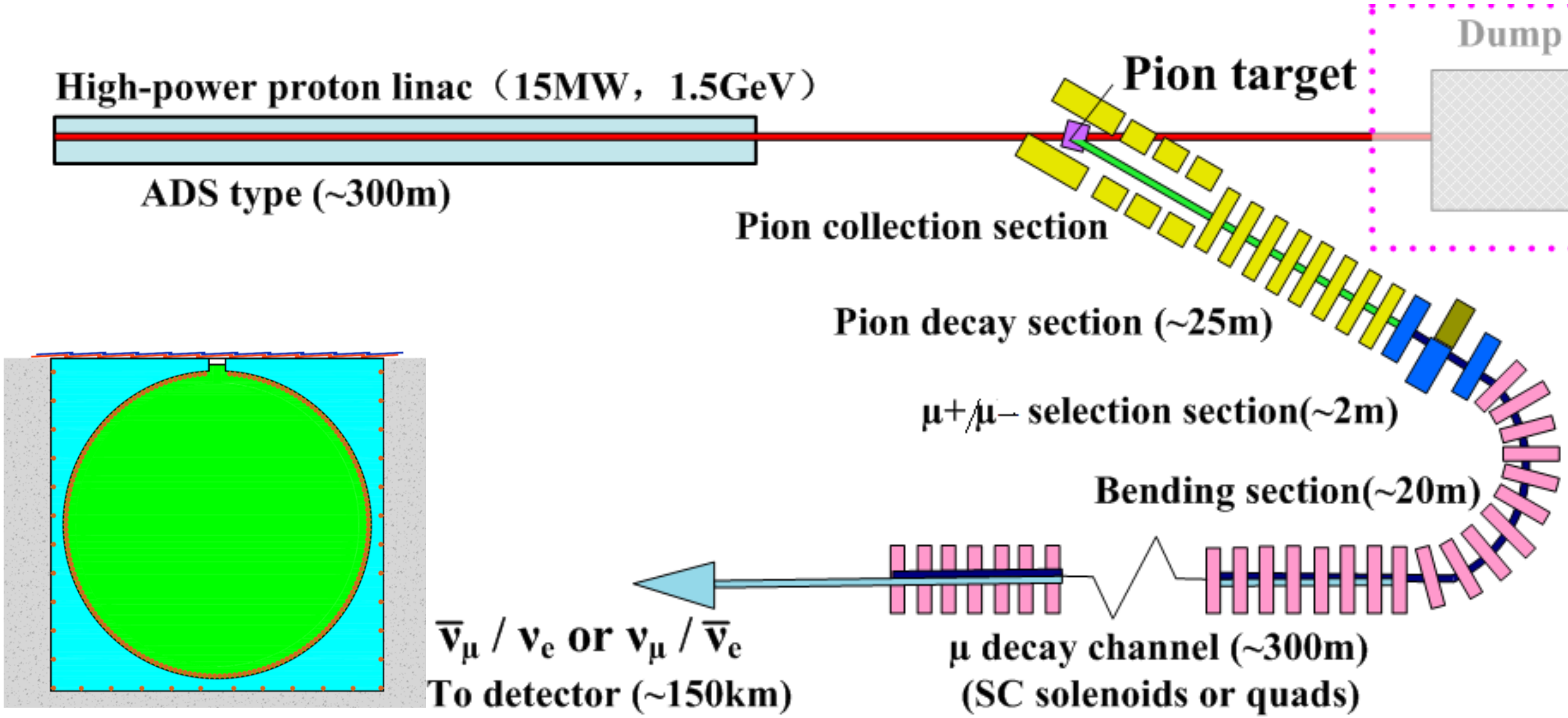


"Strategic Priority Research Program" of the Chinese Academy of Sciences

Baseline design: muon decay neutrino source

MOMENT: Muon-decay medium-baseline neutrino beam facility

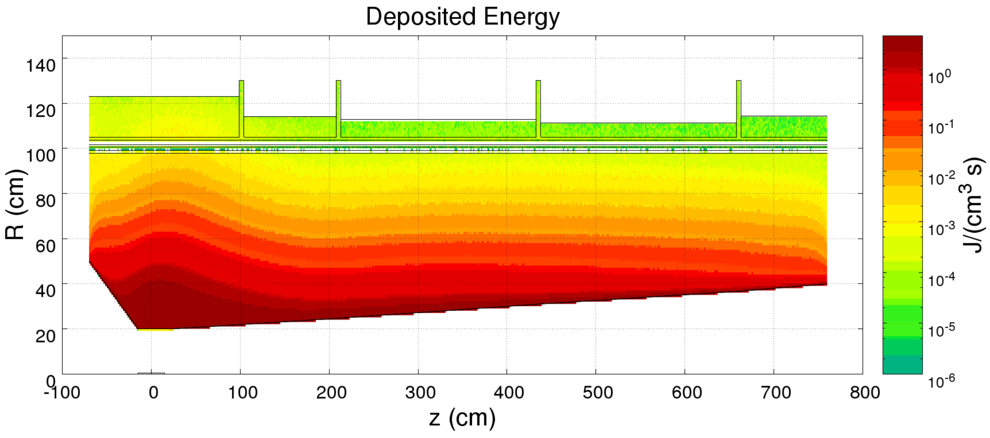
PhysRevSTAB.17.090101

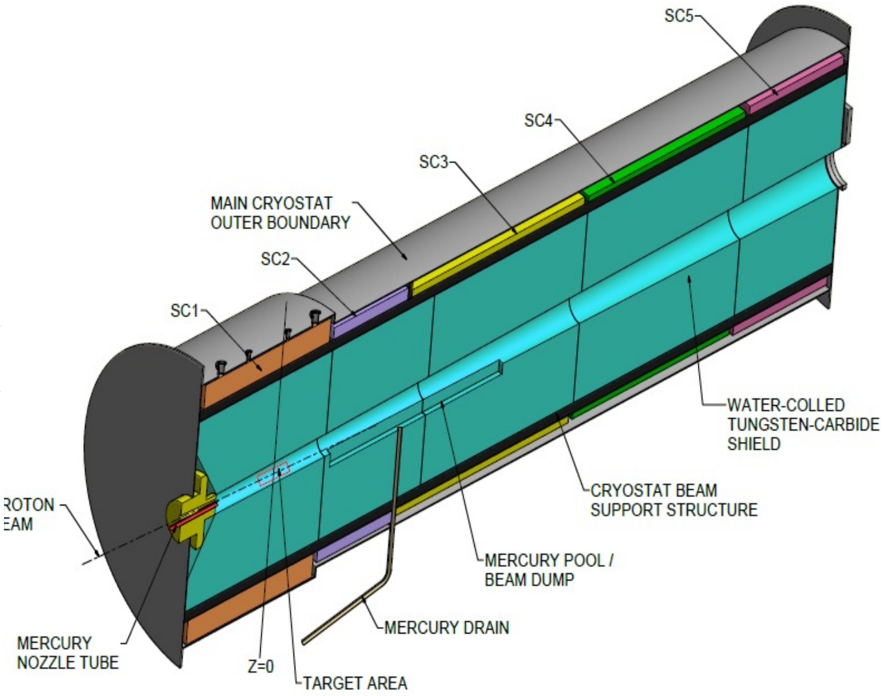


Detector

Target and pion/muon capture

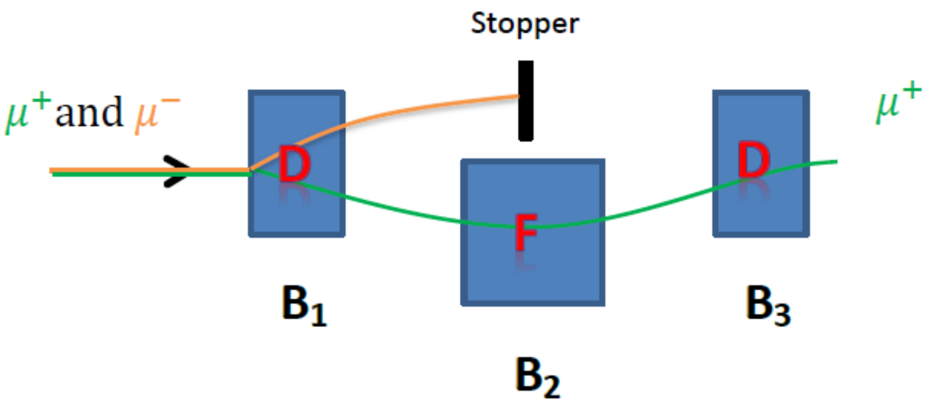
- Mercury jet target (similar to NF design, MERIT experiment)
  - Easier to some extent due to CW proton beam (no shock-wave problem)
  - fluidized tungsten-powder target or granular tungsten-ball target can also been considered
- High field(14T) SC capture solenoid
  - High beam power: heat load, radioactivity, challenge to shielding, cooling, deal with spent protons

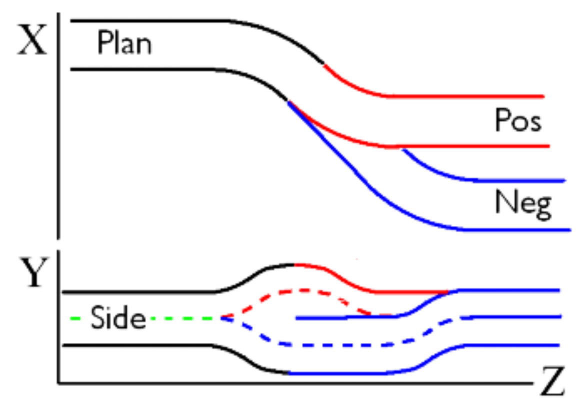




Secondary beamline

- Transporting both pions and muons
  - A straight section in SC solenoids for the pions to decay into muons
- A selection section to select $\pi+/\mu+$ from $\pi-/\mu-$





- A long decay channel of muon designed for production of neutrinos

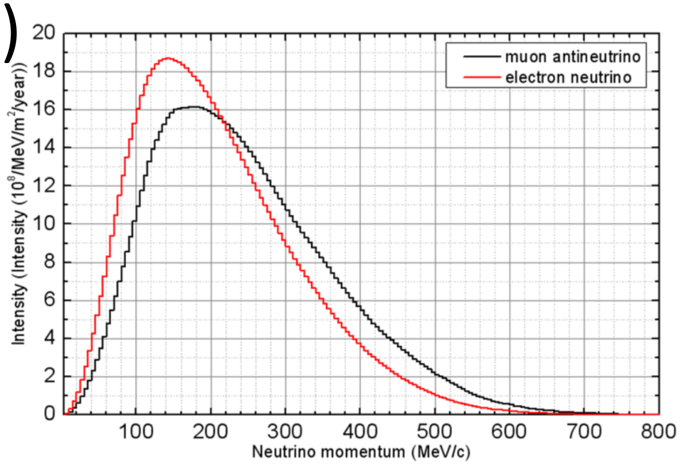
Neutrino flux

- POT (5000 h): 1.125×10^{24} proton/year
- Muon yield: 1.62×10^{-2} μ /proton
- Total neutrino yield: 4.8×10^{-3} ν/proton (in pair)

  5.4×10^{21} ν/year (in pair)

  (NF: 1.1×10^{21} ν/year)
- Neutrino flux at detector: dependent on the distance

  4.7×10^{11} ν/m^2/year (@150 km)



✧Many challenges have been mentioned in Jingyu Tang's report this morning

✧Plenty works needed to be done and are under studying, some of them about target station and beamline will be showed in this session:

- Studies on pion/muon capture at MOMENT
- Cooling structure at the MOMENT target
- Protons after bombarding the target at MOMENT
- Studies on charge selection at MOMENT

Detector

- μ decay
  - μ^+ :
    $$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
    $$\nu_e \leftrightarrow \nu_\mu \qquad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$$
  - μ^- :
    $$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
    $$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu \qquad \nu_\mu \leftrightarrow \nu_e$$

- Requirement to the detector
  - **Flavor sensitive**
    - e/μ identification: water Cherenkov detector; liquid Argon; liquid scintillator (challenge)
  - **Charge sensitive**
    - Neutrino/antineutrion identification: magnetized detector, liquid scintillator or Gd-doped water for IBD
  - **NC/CC sensitive**
    - NC background rejection: negligible at low energies

Detector performance

<table>
<tr><th></th><th>LS</th><th>Water</th><th>Gd water</th></tr>
<tr><td>e/μ id</td><td>• μ id： micheal electron，eff~70%， e mis-id: 4×10^{-4}
• Tracking threshold, e：250MeV， μ： 100-200MeV
(LENA)</td><td colspan="2">• electron efficiency： 62%
• μ mis-id： 0.1%
(T2K)</td></tr>
<tr><td rowspan="2">Antineutrino tagging (IBD)</td><td>IBD for electron-antineutrino, H capture(2.2MeV)
eff>63%</td><td>nH(2.2MeV)
eff~20%， B/S~2%
(SuperK)</td><td>nGd(8MeV)
eff~67%
accidental~2×10^{-4}
(SuperK)</td></tr>
<tr><td colspan="3">Positronium</td></tr>
<tr><td>NC/CC</td><td>N/A</td><td colspan="2">NC mis-id： 1%</td></tr>
</table>

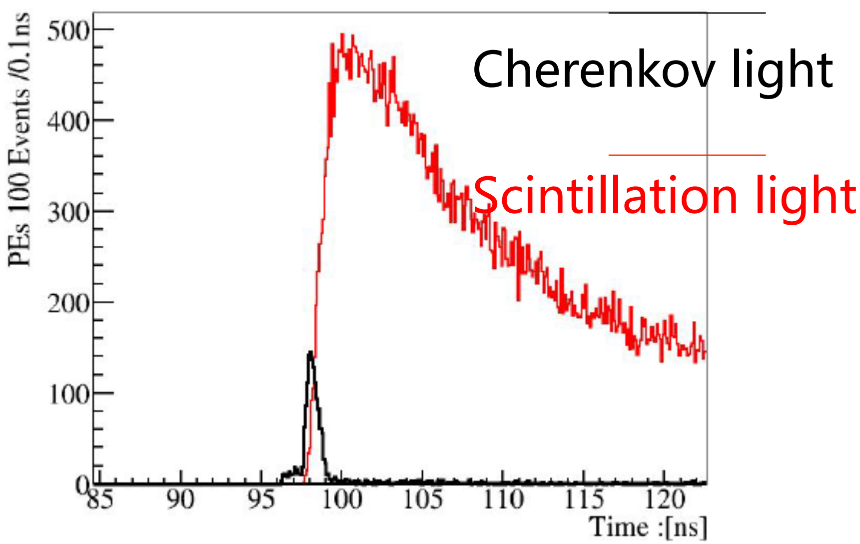
IBD eff in Gd water： 62%×67%≈40%

Issues in MOMENT

- Intrinsic background of IBD
  - Spallation neutron from CC with $^{12}C/^{16}O$: cross section has large uncertainty
- Atmospheric neutrino background
  - Major background for continuous-wave (CW) beam
- e/μ identification
  - Not fully explored in liquid scintillator detector

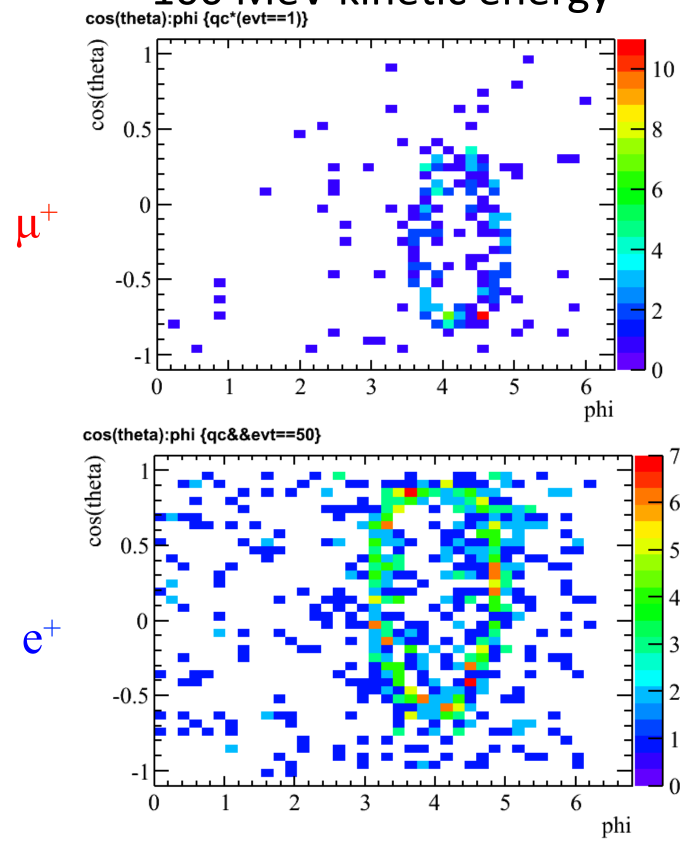
e/μ identification in liquid scintillator

- Michel electron from muon decay
- Separation of Cherenkov light and scintillation light
  - Detected Cherenkov light < 1%
  - Cherenkov light is faster
  - Need very good time resolution



Detected hit time

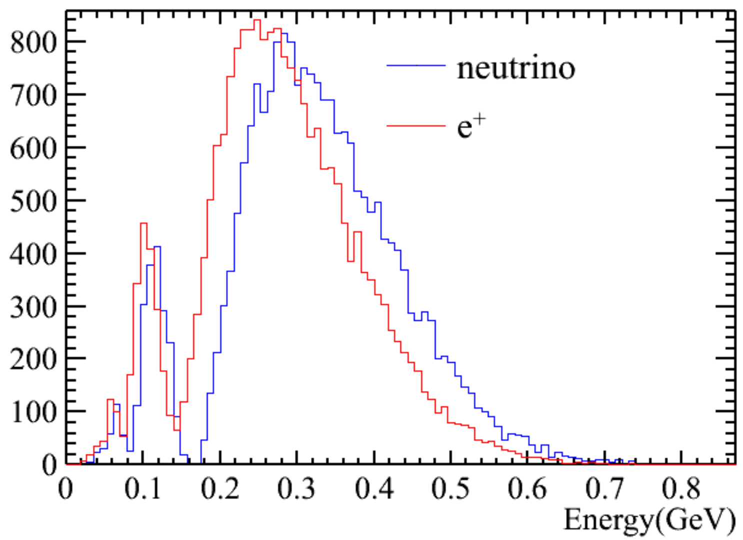
100 MeV kinetic energy



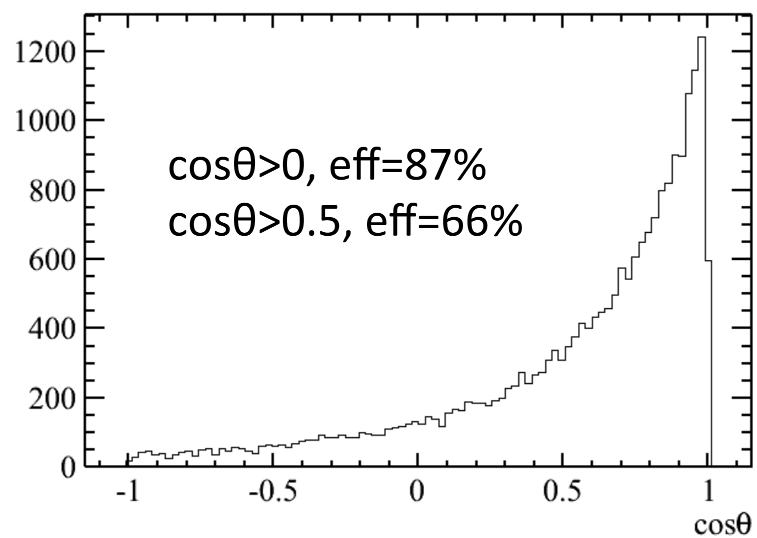
Cherenkov ring from MC truth

Neutrino direction

- Forward scattering of positron
- Strong suppression of atmospheric neutrino background with a good tracking



$$\bar{\nu}_e + p \rightarrow e^+ + n$$



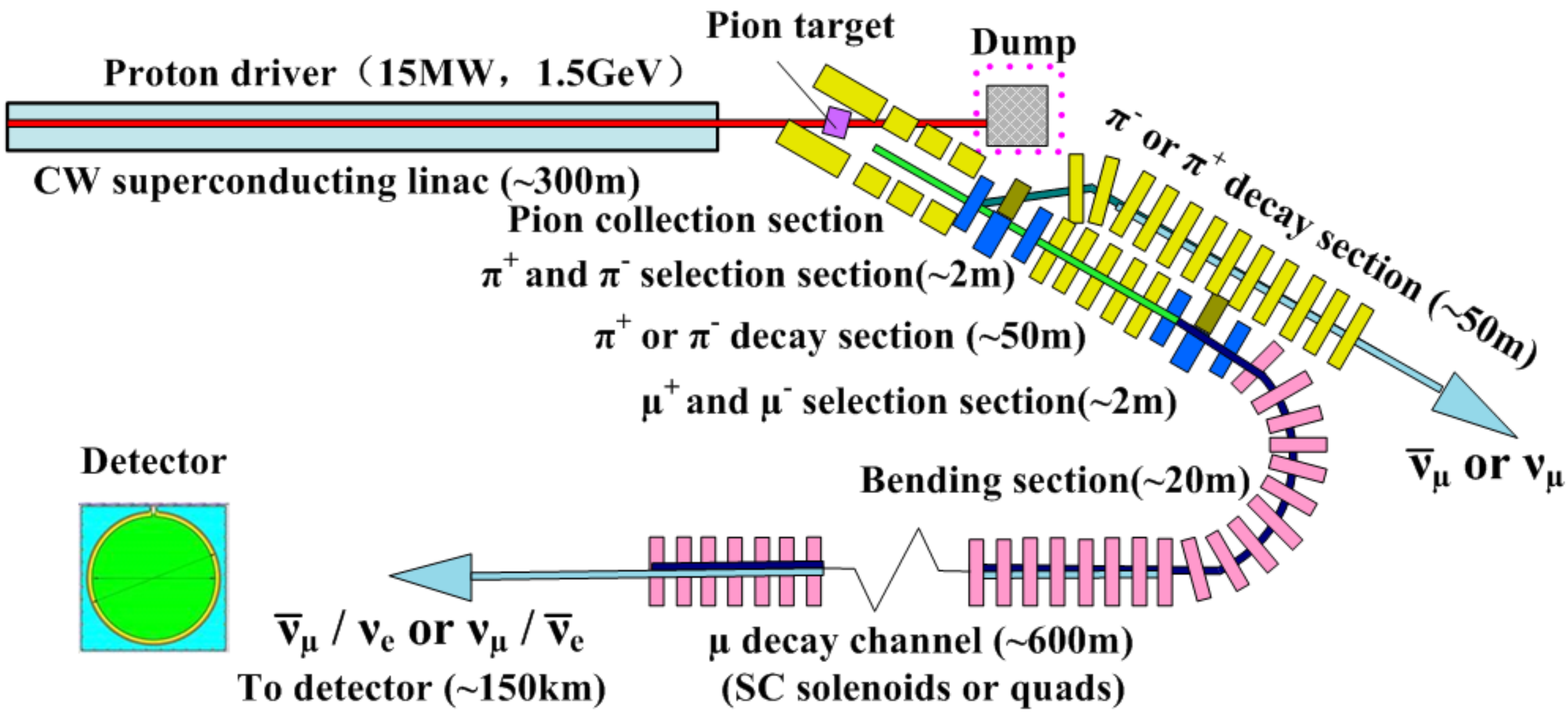
- Magnetized detector for muon decay beam?

…

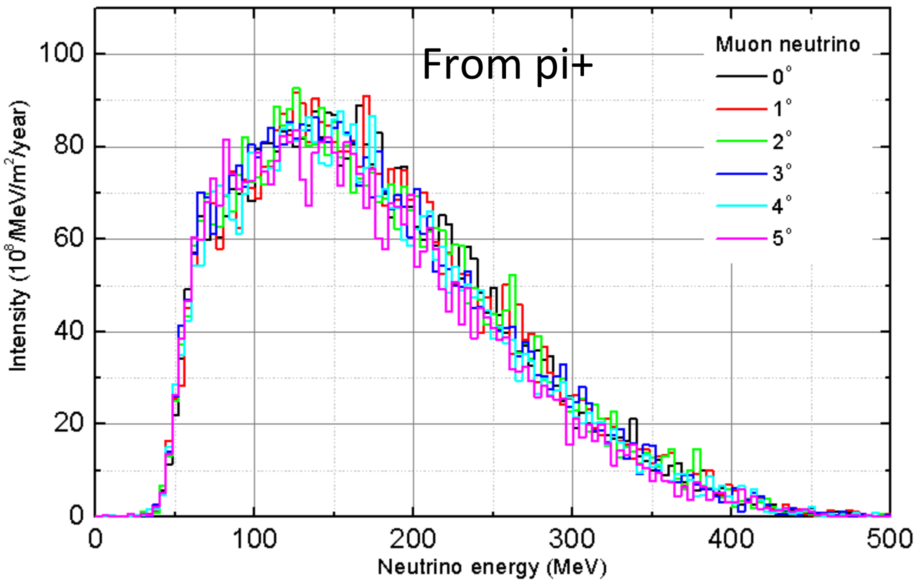
Your ideas are welcome!

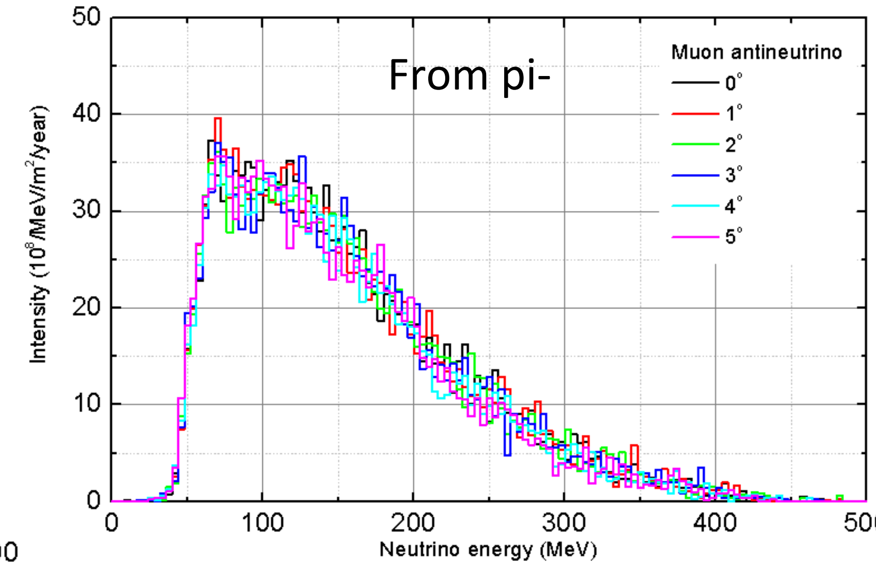
Multiple sources with MOMENT

- Pion decay neutrino beam based on MOMENT



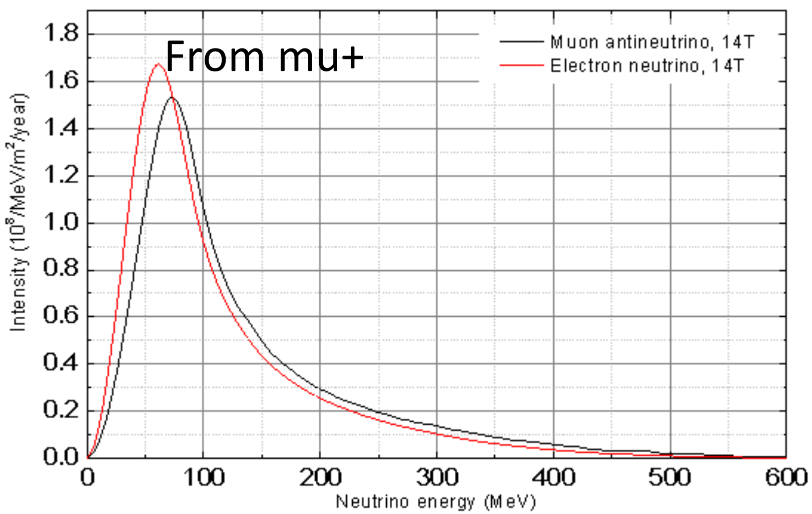
Neutrino spectrum

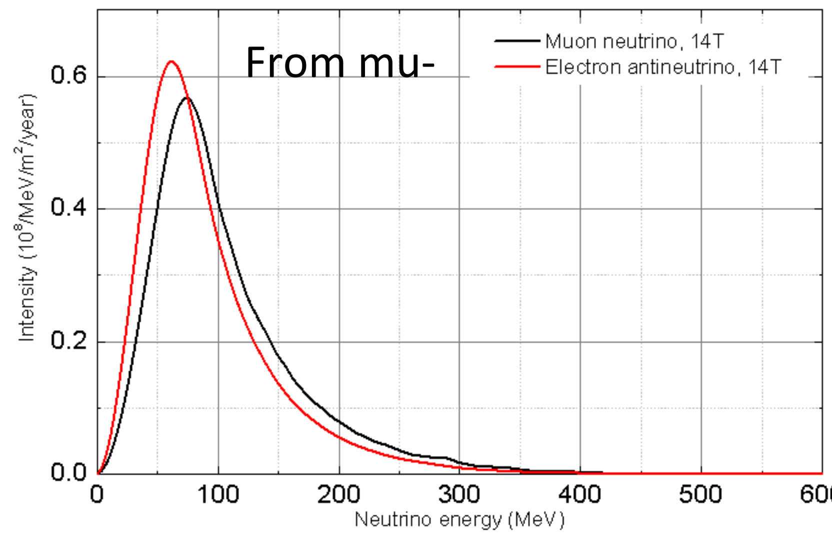




Type	Mag. field, off-axis angle	Mean Value (MeV)	Yield (0km) (/year)	Yield (150km) (/ m^2/year)
ν_μ (pion+)	14 T, 0°	175MeV	2.80E+22	1.71E12
Anti ν_μ (pion-)	14 T, 0°	152MeV	1.24E+22	5.75E11

Background





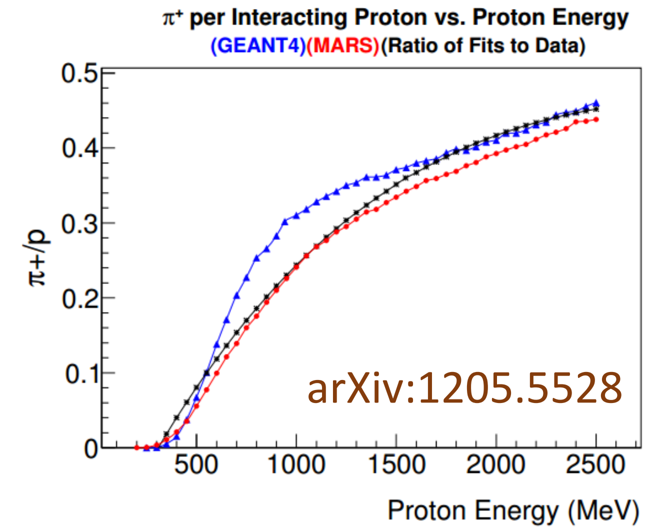
Type	Mag. field，Off-axis ang.	Mean Value (MeV)	Yield (0km) (/year)	Yield (150km) (/ m^2/year)
Anti ν_{μ} (mu+)	14 T, 0^{o}	134MeV	1.29E+21	1.78E10
ν_{μ} (mu-)	14 T, 0^{o}	107MeV	5.26E+20	5.82E9

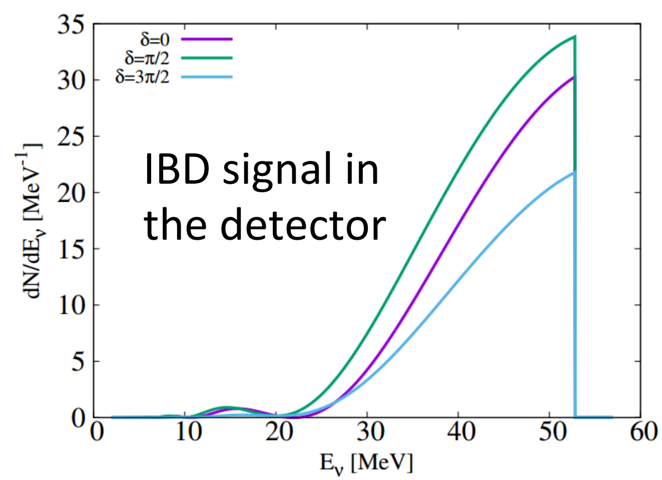
Decay-at-rest neutrino sources

- An absolute measurement of CP phase in the antineutrino mode
- Advantages
  - High efficiency of neutrino production: no focusing, decay pipe, charge separation …
  - No ν_μ CC contamination
  - Lower energy, shorter baseline -> lower matter effect
  - Known spectrum
- A concept by DAEδALUS: PRL 104, 141802 (2010)
- Neutrino flux at MOMENT-DAR
  - POT: 1.1×10^{24}/year
  - Flux at 20km: $7.6\times10^{9}/cm^{2}$/year

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

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





Summary

- MOMENT offers a good opportunity to CP measurement from low energy side
- Studies on target station, beam line and detector are making progress
- Potential for multiple neutrino sources has been considered

Thanks!