Future Accelerator-based Neutrino Facilities and Synergies with Other Experimental Projects

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Outline

- General overview of the future neutrino experiments with accelerators
- Survey over high-power proton accelerators
- Synergy between neutrino and muon beams
- Synergy between neutrino and neutron facilities
- Synergy between neutrino experiments and large hadron colliders
- Summary

General overview of the future neutrino experiments with accelerators

Present and future neutrino experiments

- Neutrino oscillation experiments
  - Precise measurements of mixing angles
  - Mass hierarchy
  - CP violation phase
  - Unitary of PMNS matrix

Accelerator-based neutrinos

- Non-oscillation neutrino experiments
  - Sterile neutrino search
  - Cosmic/solar/atm neutrinos
  - Direct mass measurements
  - Non-standard interaction
  - …

- Present major accelerator-based neutrino experiments
  - T2K, NOvA
- Near-future accelerator-based neutrino experiments
  - LBNF/DUNE, T2HK
- Proposed accelerator-based neutrino experiments
  - nuSTORM, ESSnuSB, MOMENT, DAEdALUS, T2HKK

Survey over high-power proton accelerators

Present and future high-power proton accelerators

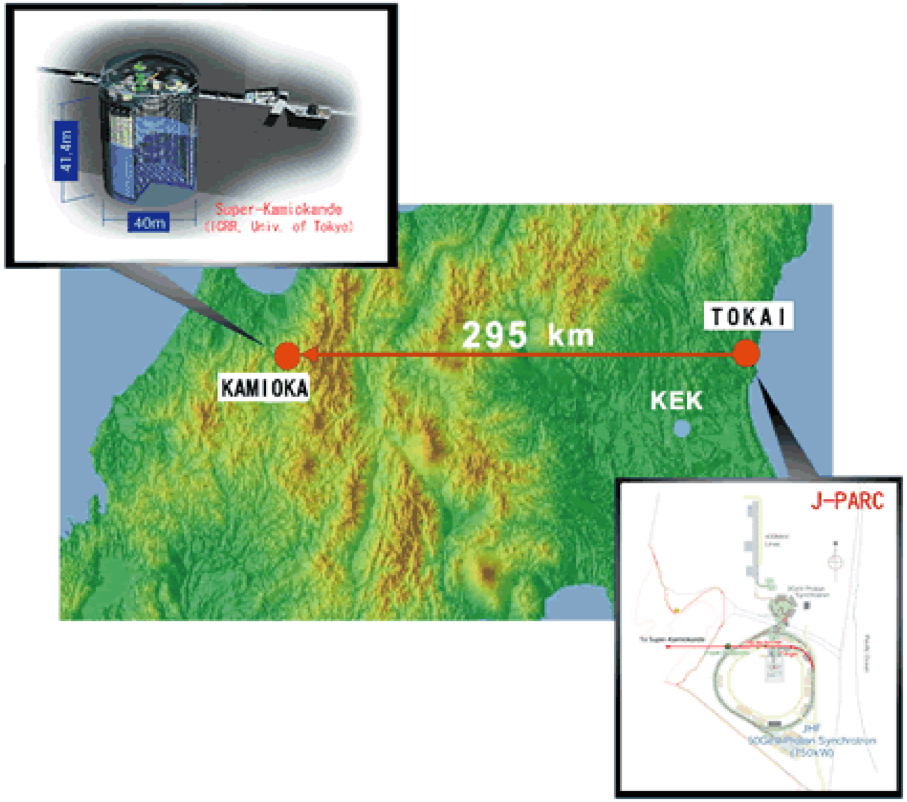
- High-power proton accelerators are scarce resources and very expensive to construct.
- Should benefit as more as possible research fields
- Hundred-kW beams mostly available now, energy range from 0.5 to 450 GeV
- MW beams:
  - two in 1-1.5 MW in operation (PSI, SNS)
  - one to reach the design goal 1-MW (J-PARC/RCS)
  - one 5 MW in construction (ESS)
  - one to start construction soon (CiADS, 2.5 MW)
  - two to upgrade: 2.4 MW (FNAL/PIP-II), 1.3 MW (J-PARC/MR)
- In April 2013, there was a Snowmass WG workshop on “High-intensity secondary beams driven by protons” held at BNL, a survey on HPPA was conducted. Below table is an update.

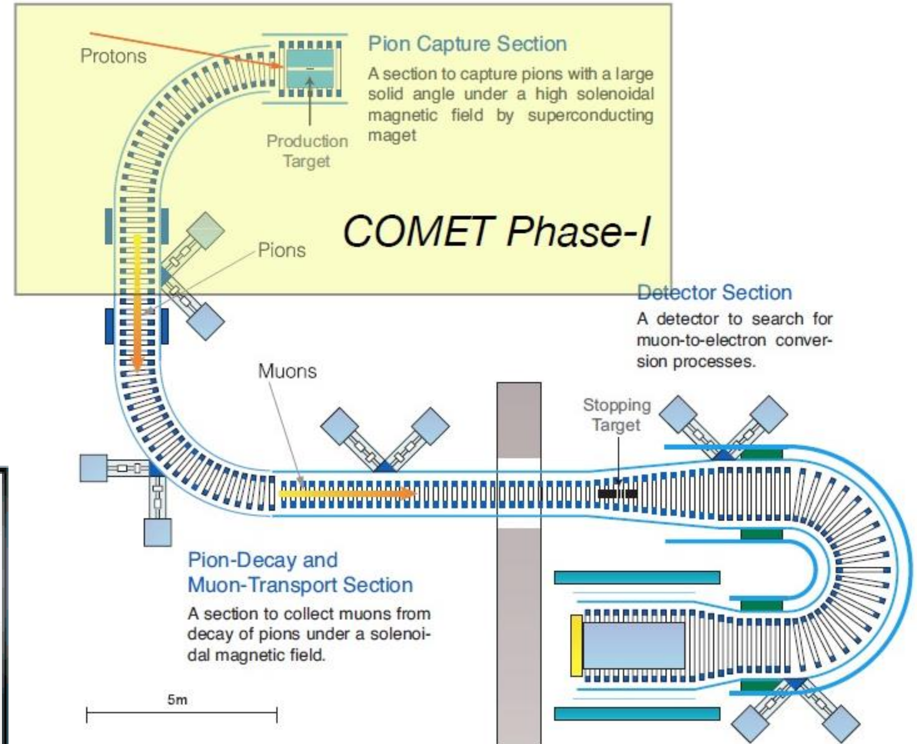
Lab	Proton beam (GeV/MW)	Main facility	Parastitic or possible extentions
LANL	0.8/0.08	Spallation neutron source, white neutron source	P: Isotope production
ISIS	0.8/0.2	Spallation neutron source, muon source	P: MICE experiment
FNAL	8/0.04; 120/0.75	Neutrino beams	P: Muon beams
BNL	2/0.03; 28/0.1	RHIC, hadron collider	P: Isotope production; Radiation damage;
			E: Neutrino beam
CERN	450/0.3	Hadron collider	P: SHiP: Heavy neutral leptons
			P: NA61: Hadron production
			E: SPL for neutrino beam, nuSTORM
PSI	0.59/1.3	Spallation neutron source, muon source	P: Radiation damage
SNS	1.0/1.4	Spallation neutron source	P: Decay-at-Rest (CEnS)
			E: muon source

J-PARC	3.0/1.0, 30/0.75	JSNS: spallation neutron source, T2K: neutrino beam, MUSE: muon beams	P: COMET, muon physics
CSNS	1.6/0.1 (0.5)	Spallation neutron source	E: EMuS muon source, neutrino cross-section; E: Decay-at-Rest; E: neutrino superbeam
ESS	2.0/5.0	Spallation neutron souce	E: Neutrino beam
CIADS	0.5/2.5 (1.0/15)	Accelerator-drivern system	E: Decay-at-Rest, MOMENT, muon source
SPPC	10/3.6, 180/3.8	Hadron collider	P: Injectors: neutrino beams
DAEdALUS	0.8/2.4	Neutrinos (Decay-at-Rest)	P: Isotope production
MOMENT	1.5/15	Neutrino beams, DAR neutrino, muon source	P: Isotope production

Synergy between neutrino and muon beams

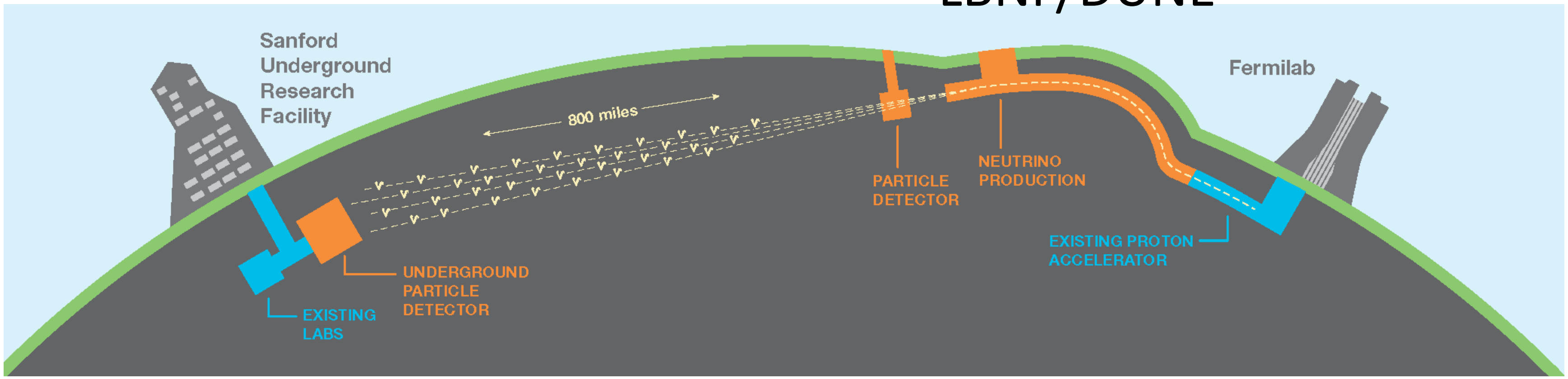
- Muon physics is a very active research direction, including particle physics and nuclear physics.
  - Muon rare decays, muon g-2, muonic atoms, Muonium, muon capture
- Muon beams are also widely used for interdisciplinary research based muSR and other muon beam techniques.
- Many issues in common between neutrino beams and muon beams:
  - proton source, target, muon capture and transport
  - neutrinos from muon decays: Neutrino factory, nuSTORM, MOMENT

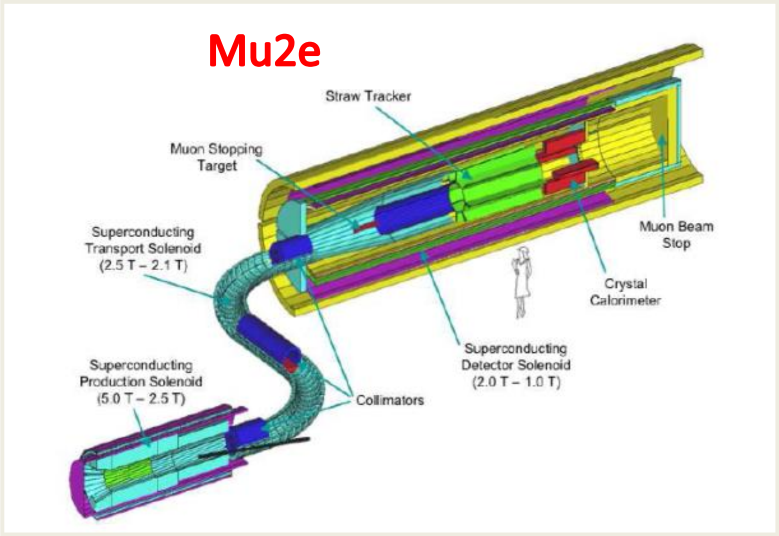




J-PARC hosts one major neutrino experiment (T2K, future T2HK) and a few muon experiments (COMET; DeeMe, g-2/EDM)

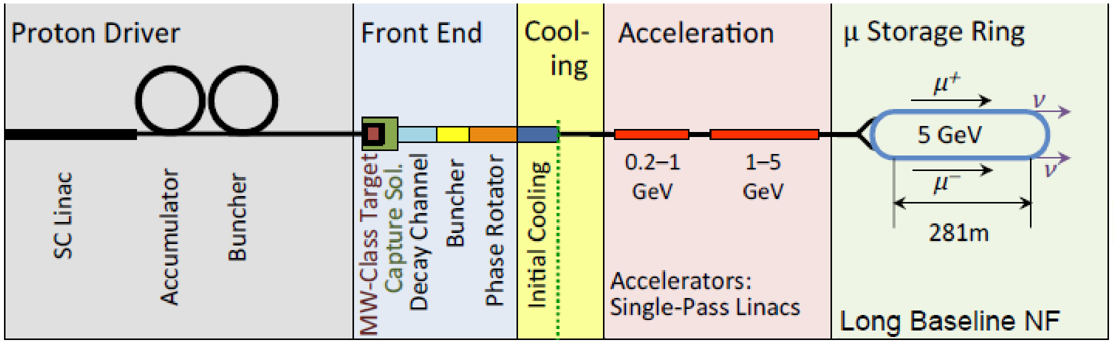
LBNF/DUNE

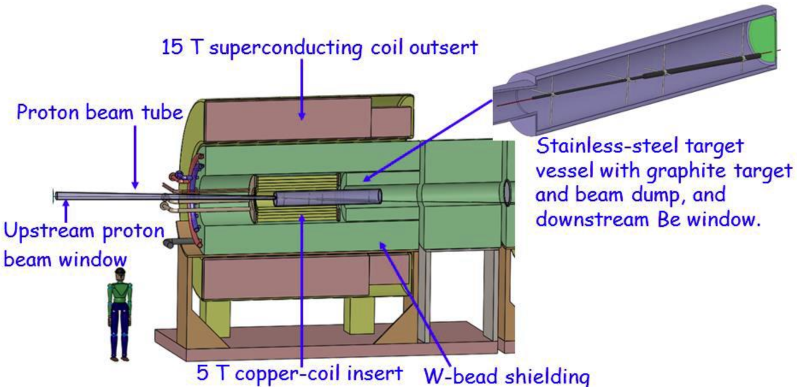




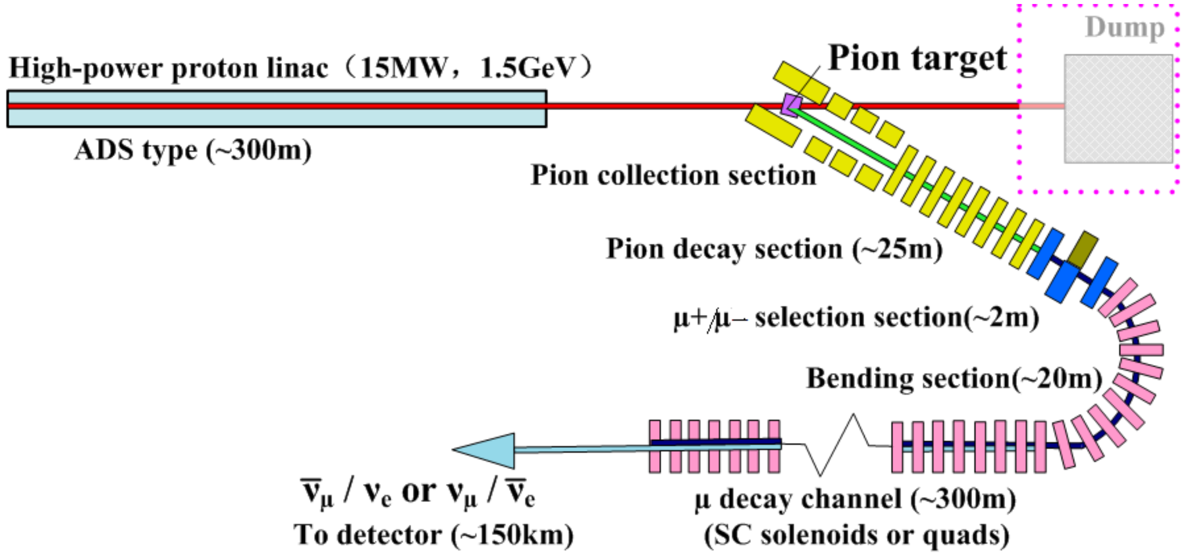
Fermilab supports different neutrino experiments and muon experiments with its proton accelerator complex: NOvA, MicroBOONE, LBNF; Mu2e, muon g-2

For those neutrino beams based on muon-decays





NF accelerator scheme, target station: proton driver, muon production and transport (front-end), muon cooling

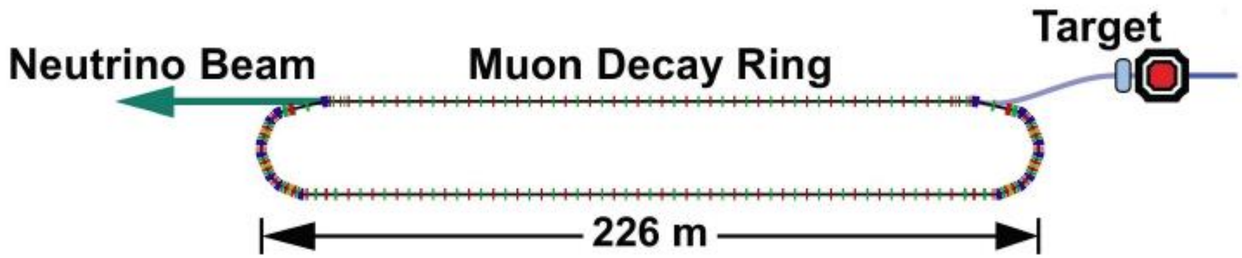


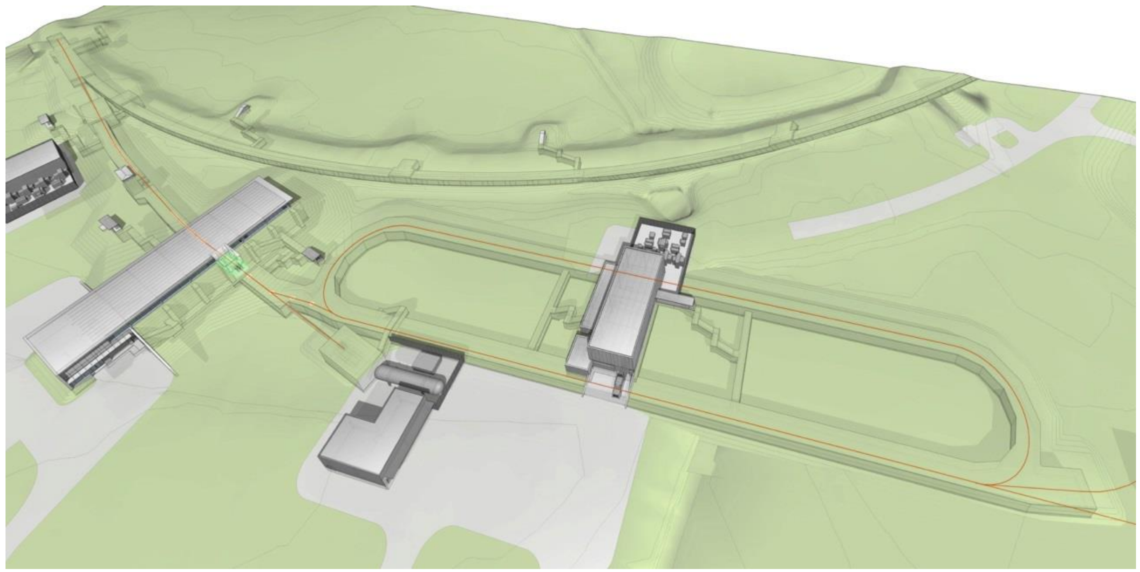
MOMENT:

Proton linac

Target station

Muon channel

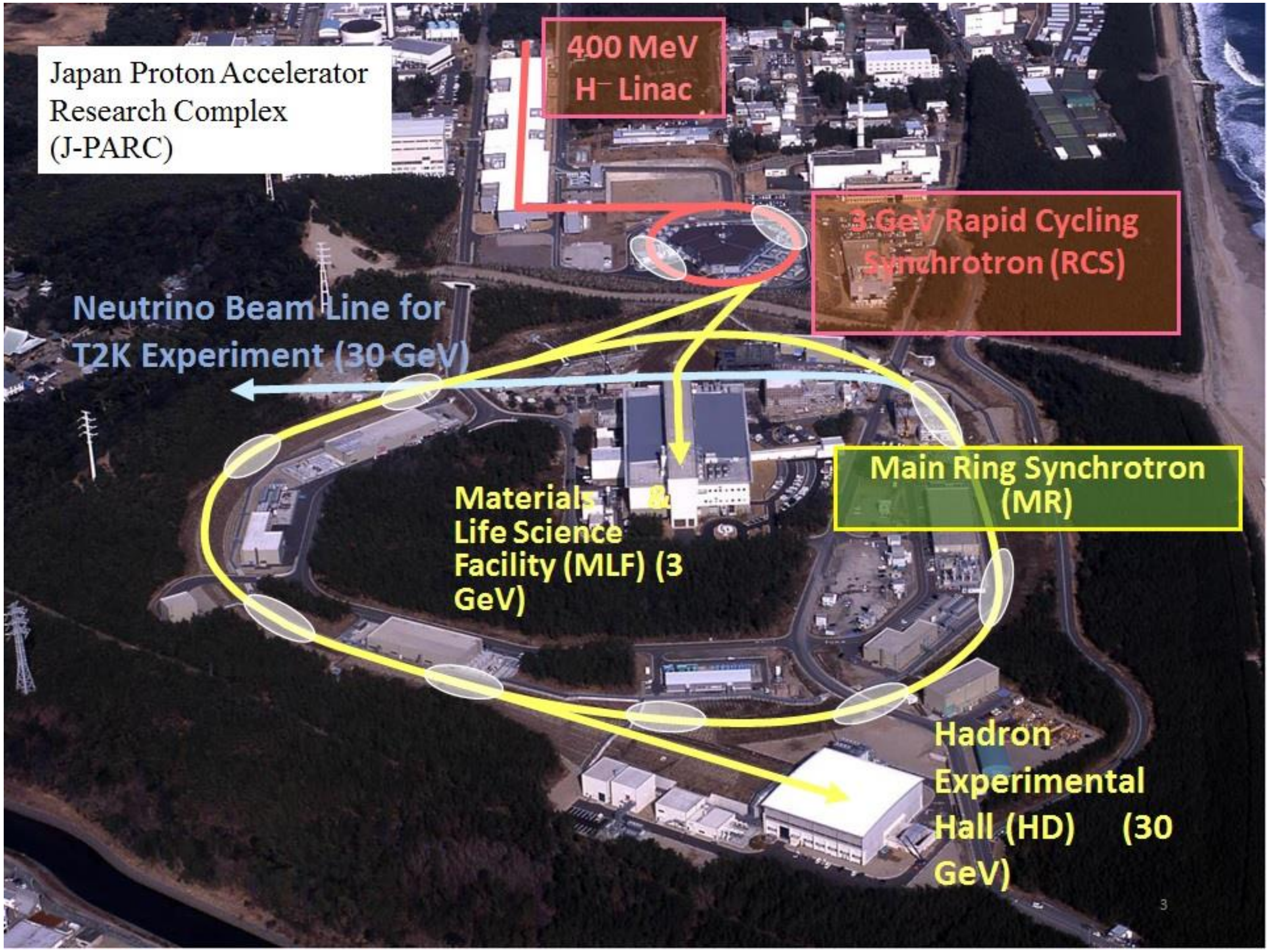




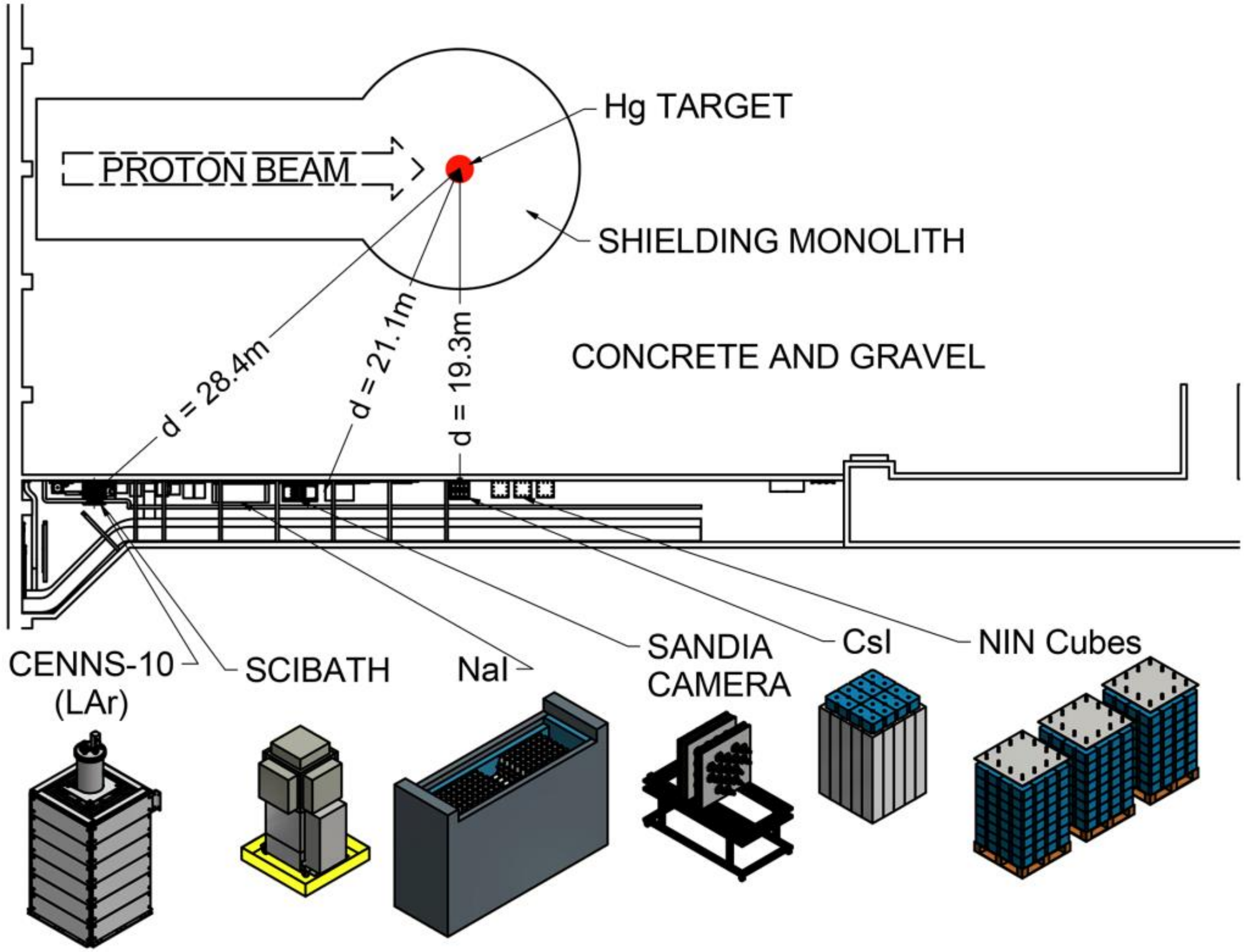
nuSTORM at FNAL: cross-section measurements, sterile neutrinos, R&D for neutrino factory and muon collider
Synergy: proton driver, muon production and storage, muon decay

Synergy between neutrino and neutron facilities

- Nowadays most high-power proton accelerators serve for spallation neutron sources which play as extremely important multidisciplinary platforms
- Some points and synergies:
  - Proton energy is relatively lower for producing neutron beams (0.8-3 GeV)
  - Proton accelerators as intermediate stage for higher energy accelerator for neutrino beam production (energy booster, T2K) or short-bunch compressing (accumulator ring, ESSnuSB)
  - High-power spallation targets are good as DAR neutrino sources (SNS, ESS)
  - Proton beams for cross-section measurements

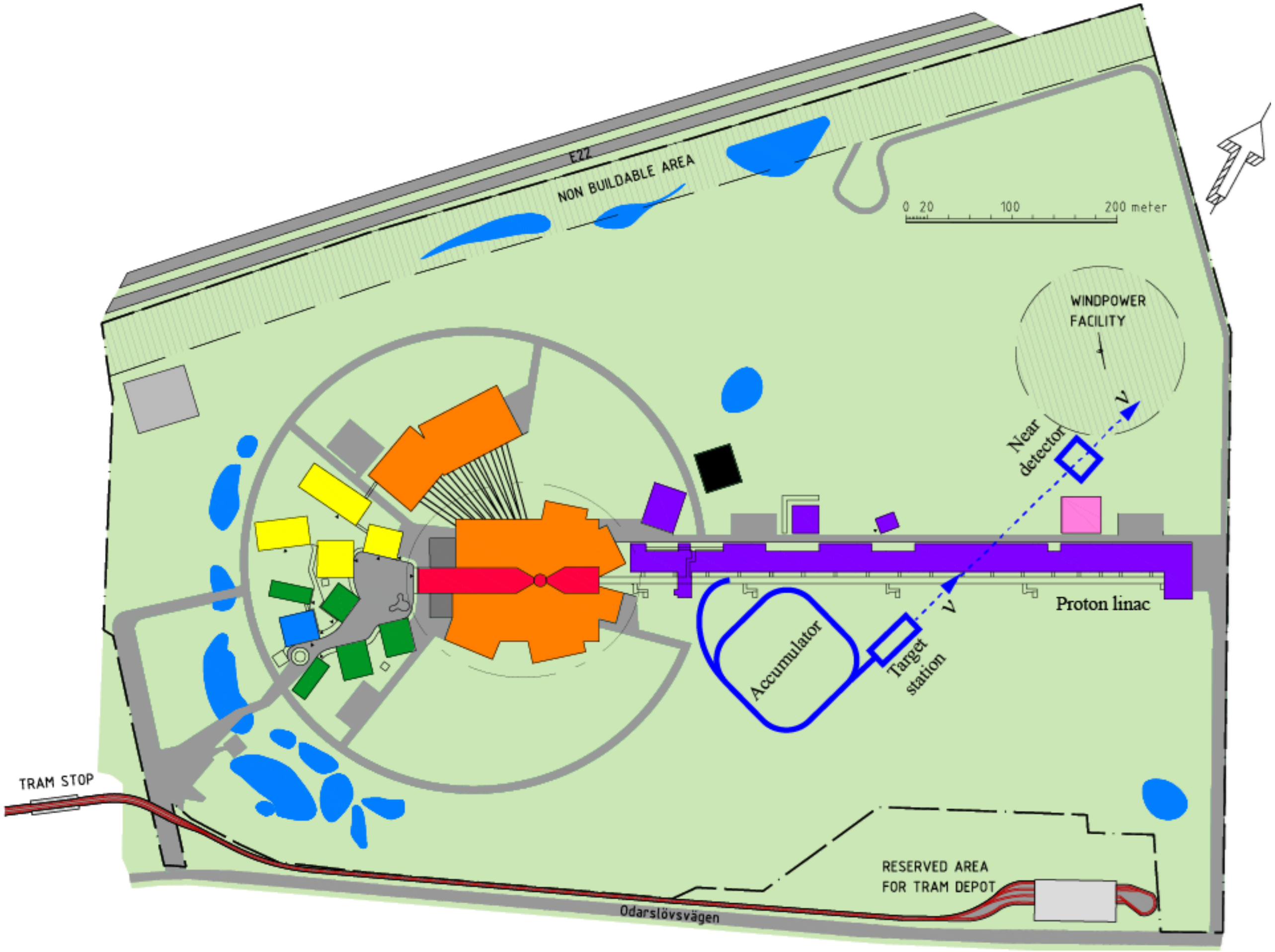


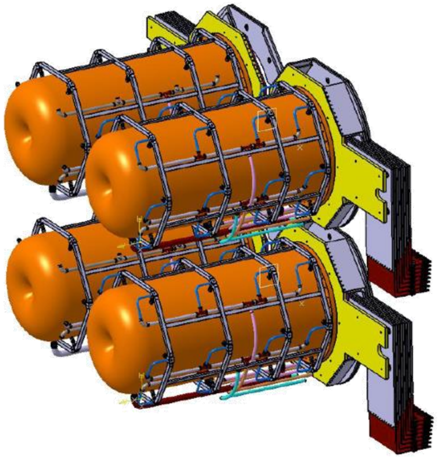
J-PARC: 3-GeV RCS as the driver for spallation neutron source and muon facility (MLF), and also injector to the main ring (MR) for neutrino beam (T2K)



SNS: 1.0GeV-1.4MW, Hg target, Decay-at-rest neutrinos, first successful experiment showing coherent neutrino-nucleus scattering (CEνNS)

[D. Akimov *et al*., *Science* 10.1126/science.aao0990 (2017)]

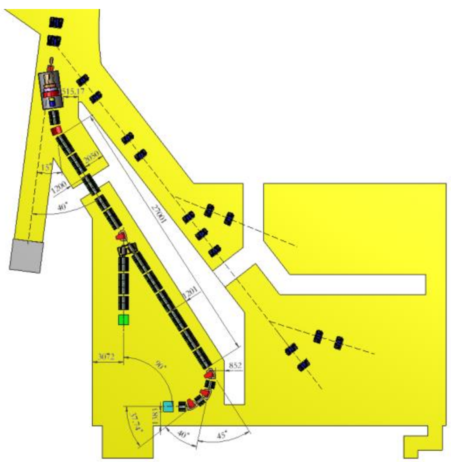




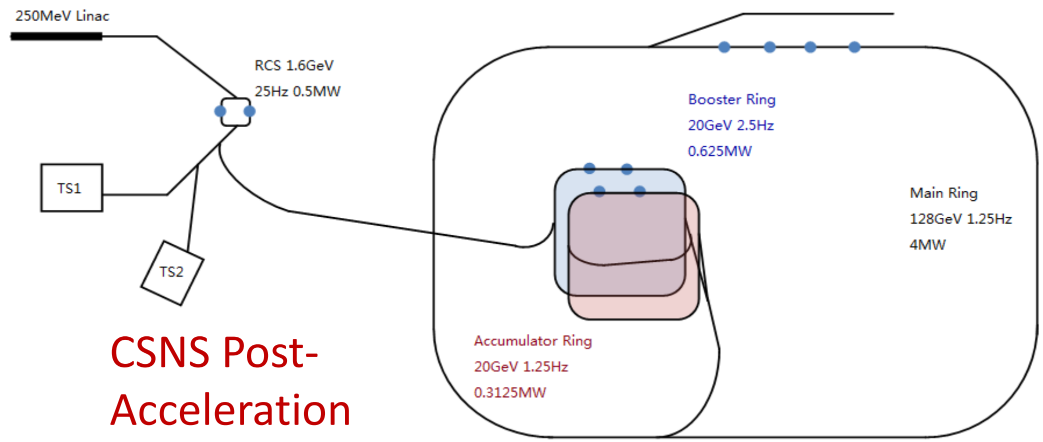
ESS: spallation neutron source

Synergy: dual-beam acceleration: 2GeV-5MW proton beam for neutrons, additional 5-MW H- beam for neutrino beam production

EMuS



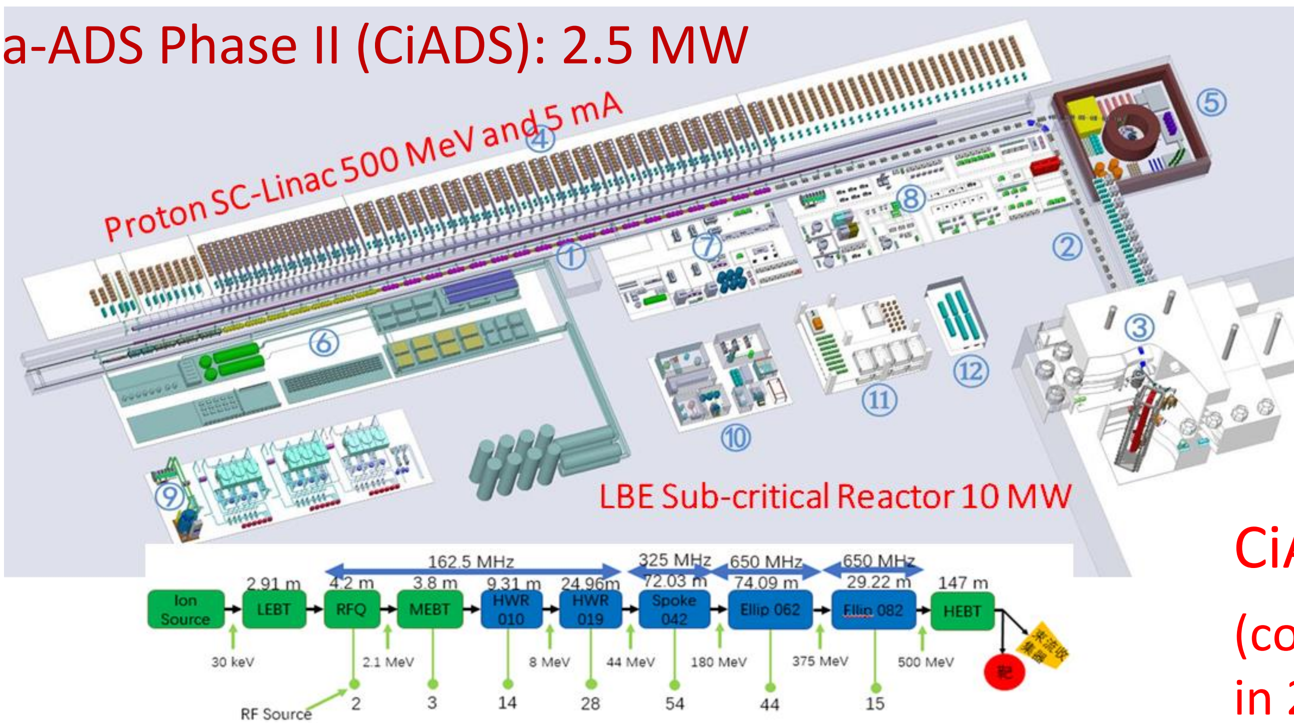
CSNS Post-Acceleration



CSNS: neutron source and muon source, multidisciplinary research
Synergy: proton driver, muon production and transport, cross-section measurement, neutrino superbeam

- ADS uses white neutrons (also by spallation) to drive a subcritical reactor (transmutation/clean energy). China is hosting a long-term ADS program which develops 10-15 MW CW proton beam.
  - ADS linac (1.5 GeV/15 MW) as the MOMENT driver
  - ADS accelerator technology to be used by a dedicated MOMENT driver
  - DAR neutrino experiments

China-ADS Phase II (CiADS): 2.5 MW



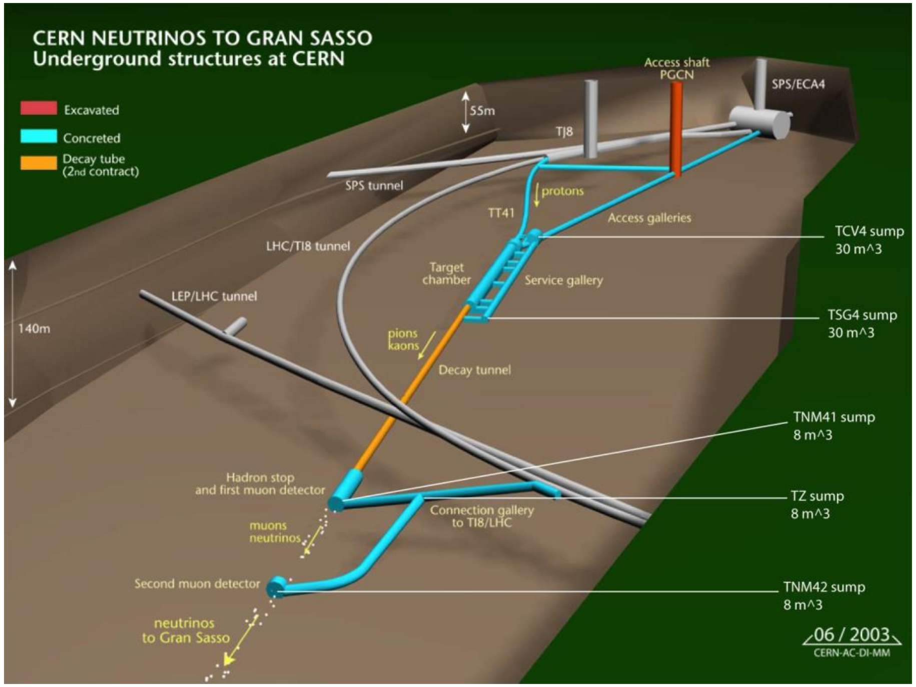
CiADS schematic

(construction to start in 2018-19)

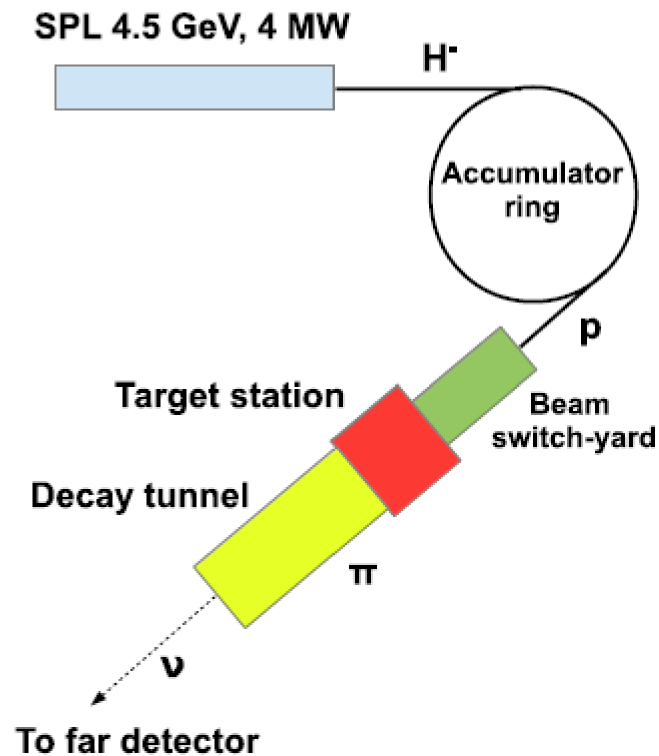
Synergy between neutrino experiments and large hadron colliders

- Large hadron colliders need powerful injectors to feed the colliding beams
  - High bunch current is required for high colliding luminosity; high-repetition rate of injection can reduce the turnaround time → High beam power for the proton injector, suitable for production of neutrino beam
  - From Tevatron (Main Injector and lower-energy accelerator stages) to LHC (SPS and lower-energy accelerator stages); both MI and SPS is or was used as proton driver for neutrino beams
  - However, RHIC/AGS failed to be exploited as a part of neutrino experiment
  - Future hadron colliders FCC-hh (or HE-LHC) and SPPC also consider very powerful injector chains, which beams can be used as proton drivers for neutrino beams

At CERN



CNGS: 2006-2012, 400 GeV- 500 kW



There were/is also other studies at CERN:

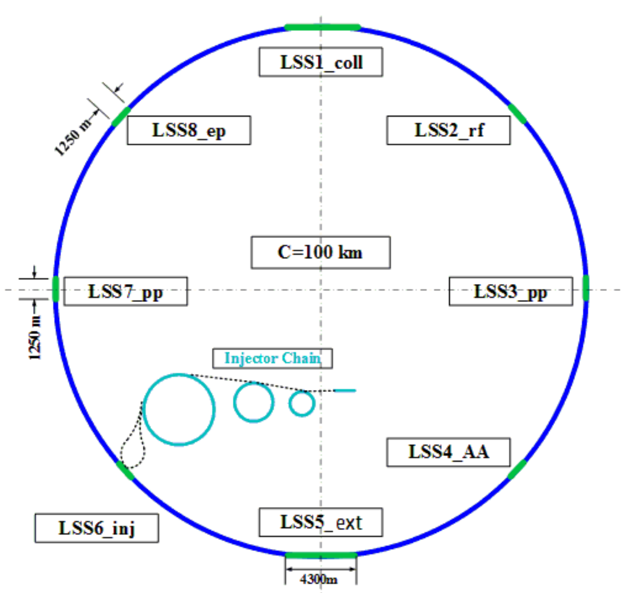
- Beta-Beam based on heavy-ion acceleration;
- LAGUNA-LBNO based on SPS beam to Finland
- nuSTORM (still undergoing) → PBC study

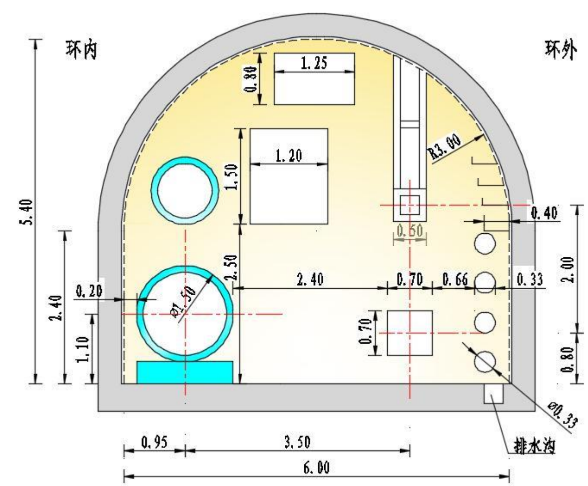
- SPL linac was proposed to replace the old Linac2+ Booster, in order to meet the high luminosity requirement by HiLumi-LHC.
- The RT part of 160 MeV (Linac4) is under construction.
- SPL was considered as the proton driver for a neutrino beam (Frejus Super Beam)

SPPC as the 2nd Phase of the CEPC-SPPC project

- CEPC-SPPC is a two-stage project, with CEPC of 240-GeV e+e- collider for high-precision Higgs studies, and SPPC of >70 TeV p-p collider for studying new physics beyond the Standard Model and also Higgs physics.
- Dream timeline: CEPC: 2022-2030/+10 runs; SPPC: 2033-2043

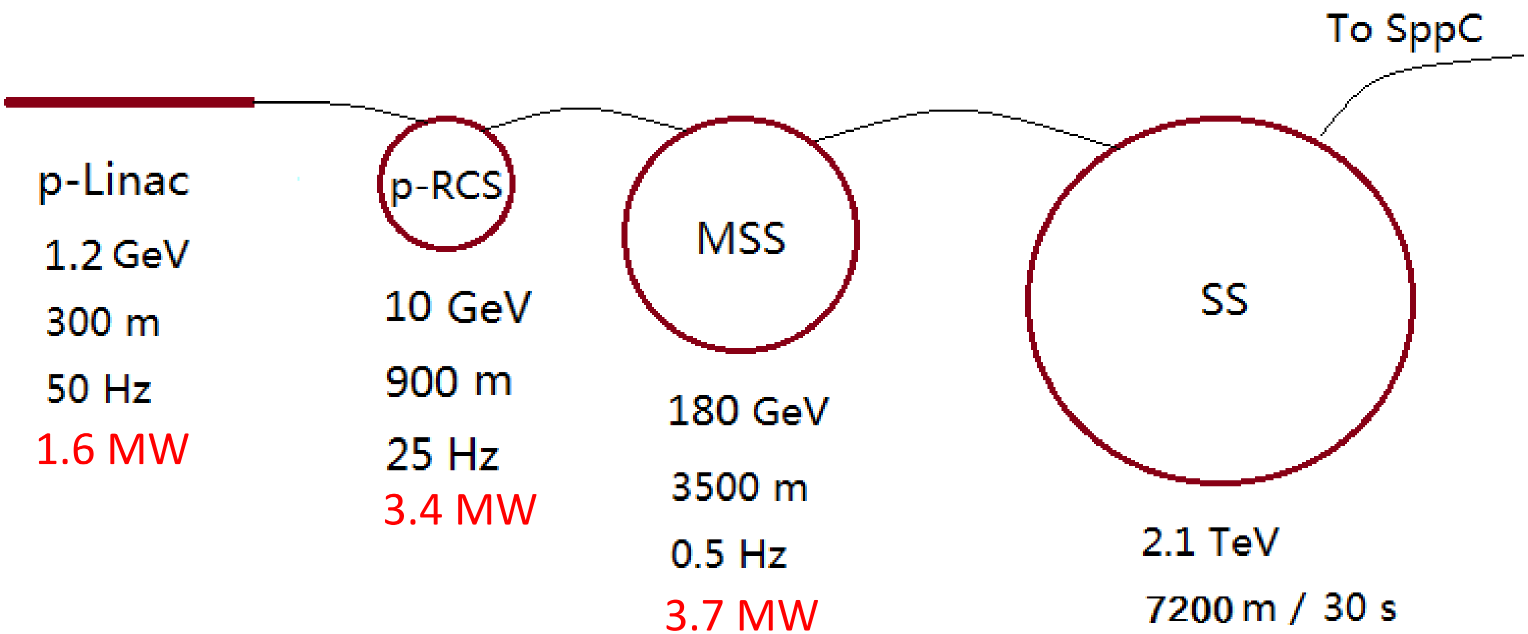
SPPC Layout





CEPC and SPPC share the same tunnel

Powerful injector beams for neutrino physics



Very powerful injector beams to support rich physics programs including neutrino physics

- Three proton beams in MW level: 1.2 GeV, 10 GeV, 180 GeV

Summary

- Accelerator-based neutrino experiments have played, are playing and will play key roles in neutrino physics
- High-power proton accelerators are very precious resources, sharing between neutrino experiments and other applications is very important
  - Hundred-kW beams mostly available, multi-MW beams are coming
- Synergies between neutrino experiments and other experiments
  - Muon sources: proton driver, target, muon capture/transport
  - Neutron sources: proton accelerator, DAR, proton beam for cross-section measurements
  - Hardon colliders: sharing injector beams as proton drivers and for cross-section measurements

Thank you for attention!