Neutrino Beamline and Flux Improvements

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on behalf of T2K Beam Group

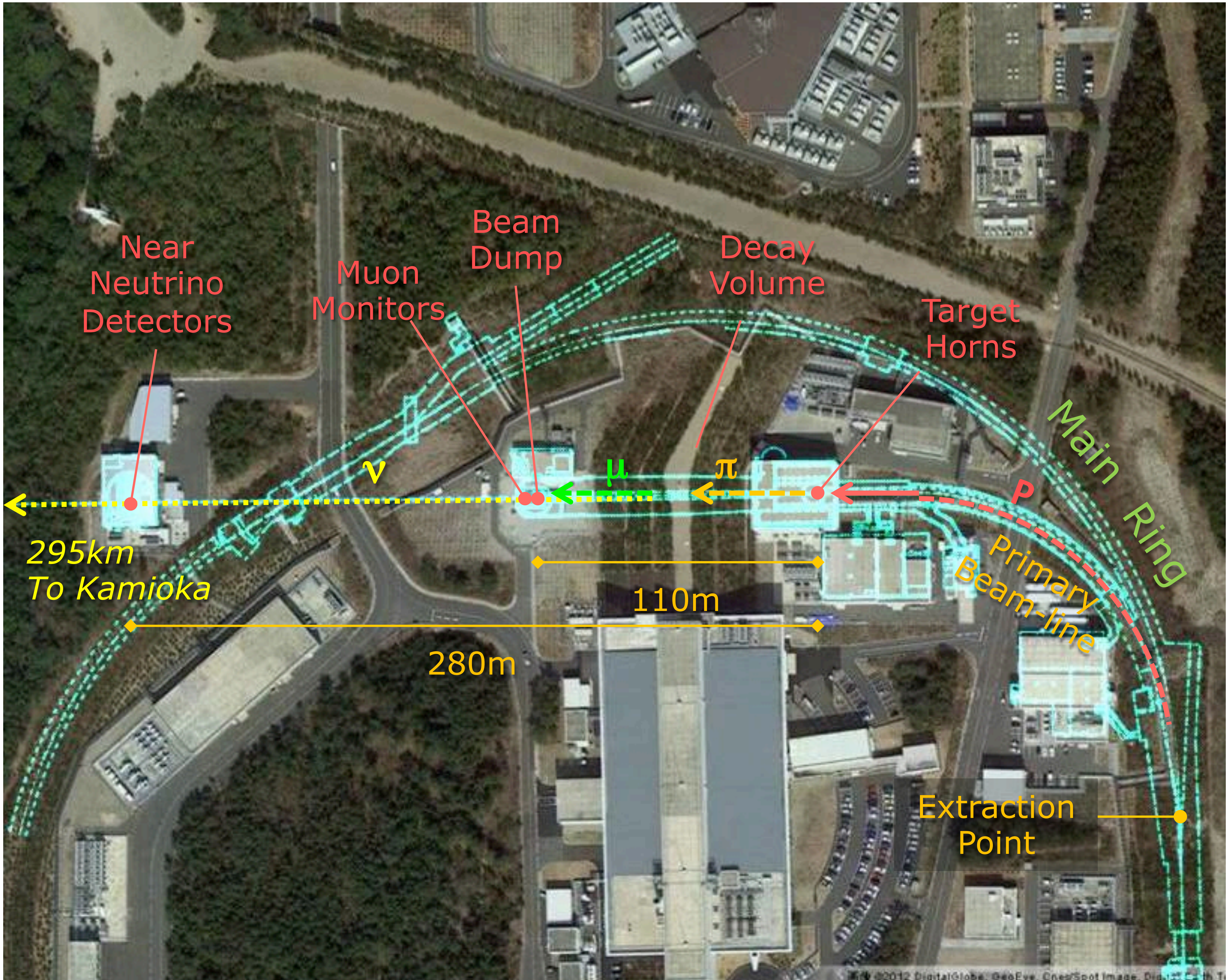
Contents

- **Overview**

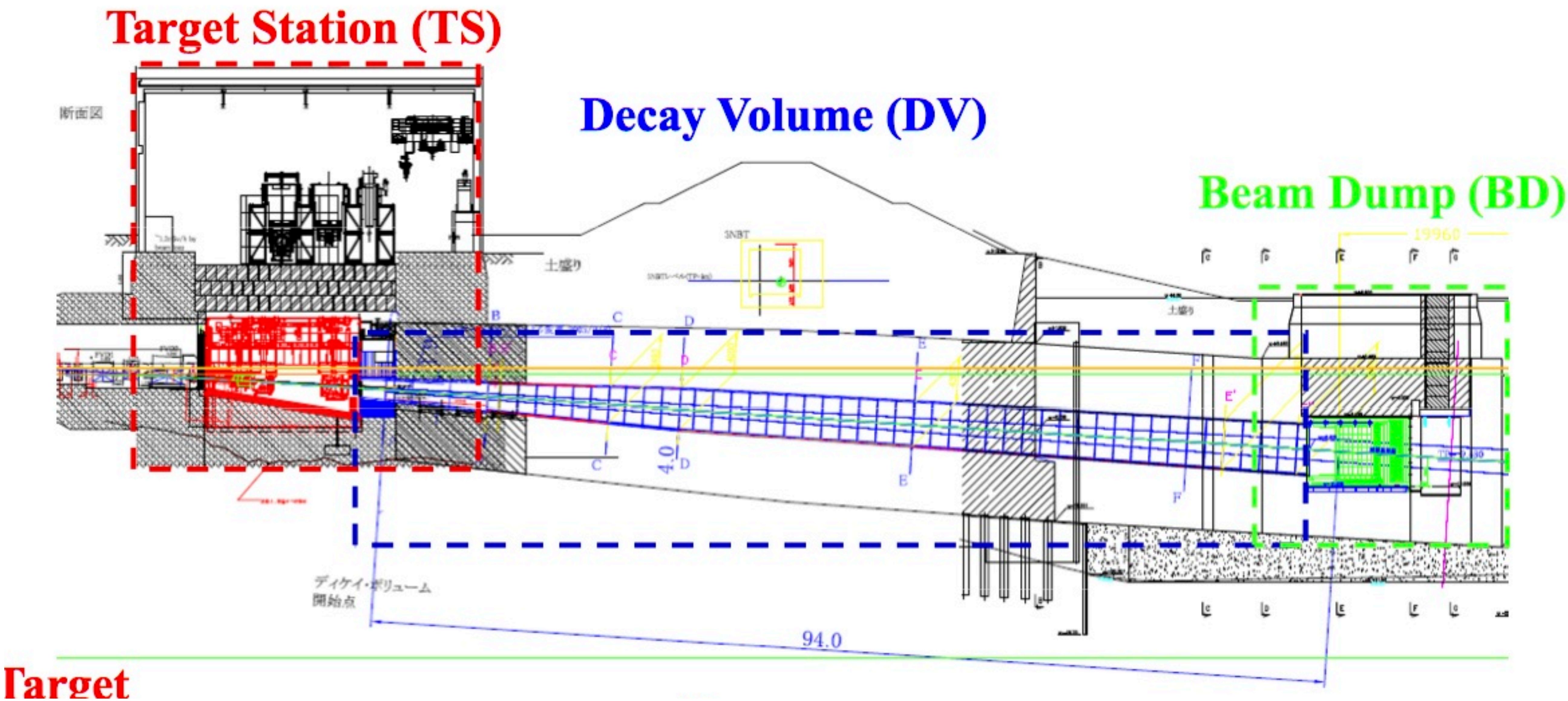
- **Hardware improvements**
  - Prospect for 1.3 MW beam power
  - Flux increase by neutrino beamline

- **Flux uncertainty improvements**
  - Reduction of systematic uncertainty

J-PARC Neutrino Beamline



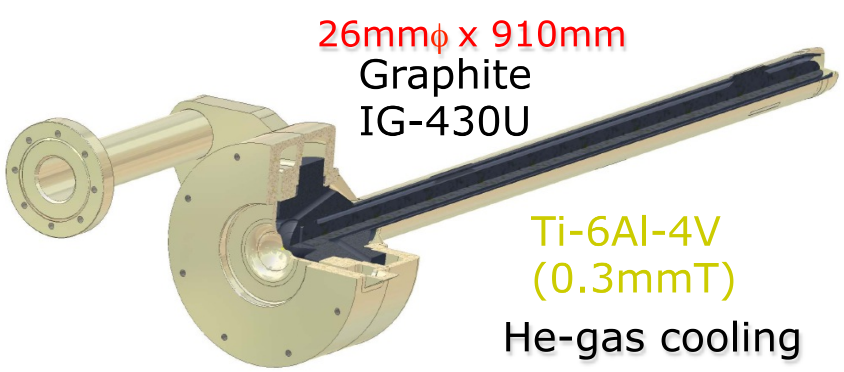
Secondary Beamline



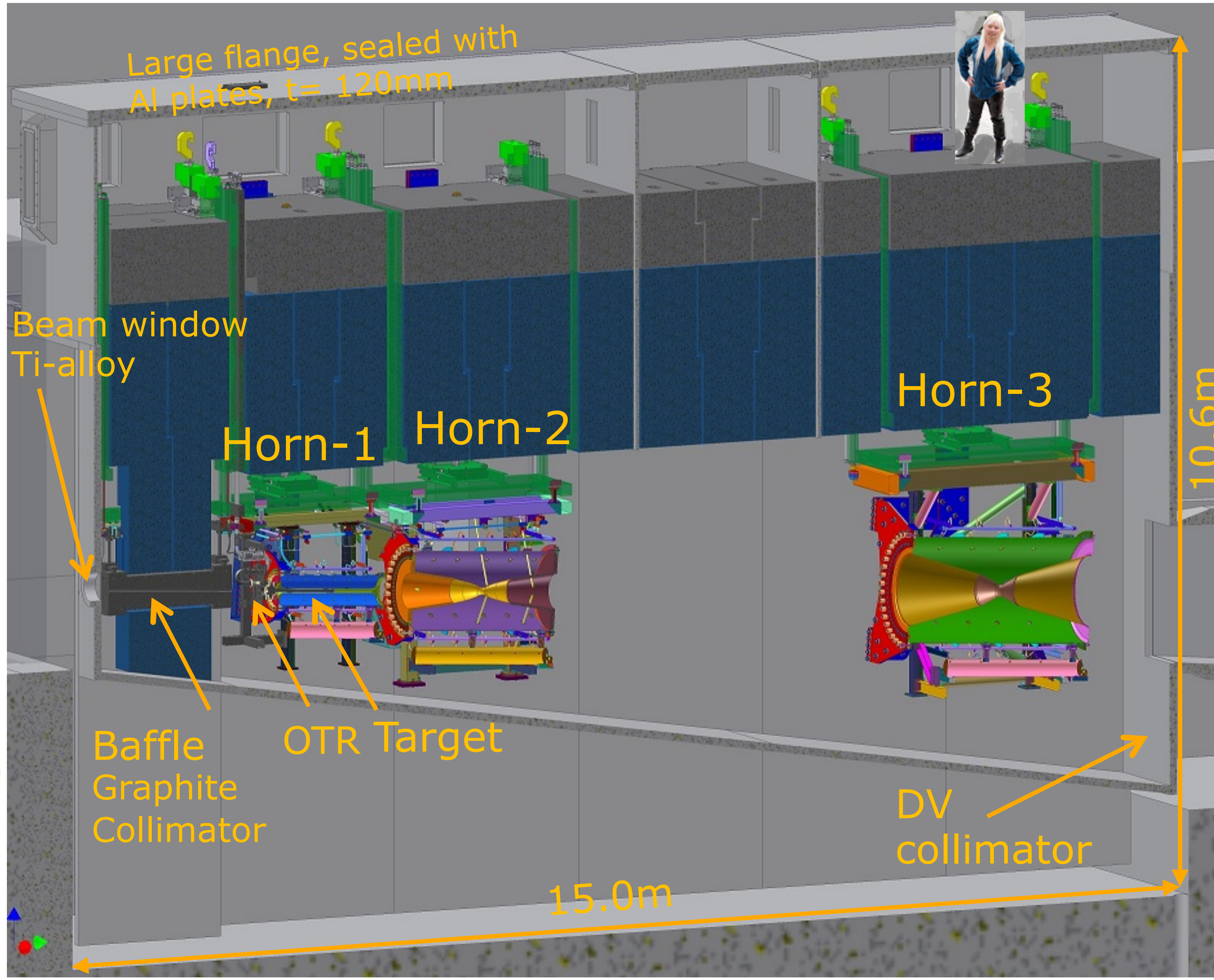
- Target Station (includes target and horns)
- Decay Volume
- Beam Dump

Target Station

Horn1



Target



All equipments inside Helium Vessel can be replaceable

How to Improve Statistics

- **Beam power improvement**
  - Straightforward way to increase statistics.

- **Flux improvement by neutrino beamline**
  - For a given POT, increasing number of produced neutrinos is another way to increase statistics.

10 Year Term Plan of Beam Power Improvement

- **Beam power improvement plan by 2026**
  - Proton intensity = **$3.2x10^{14}$ protons/pulse**.
  - Repetition cycle = **1.16 sec.** with new power supply.
- **Can we accommodate such beam power and operation condition?**

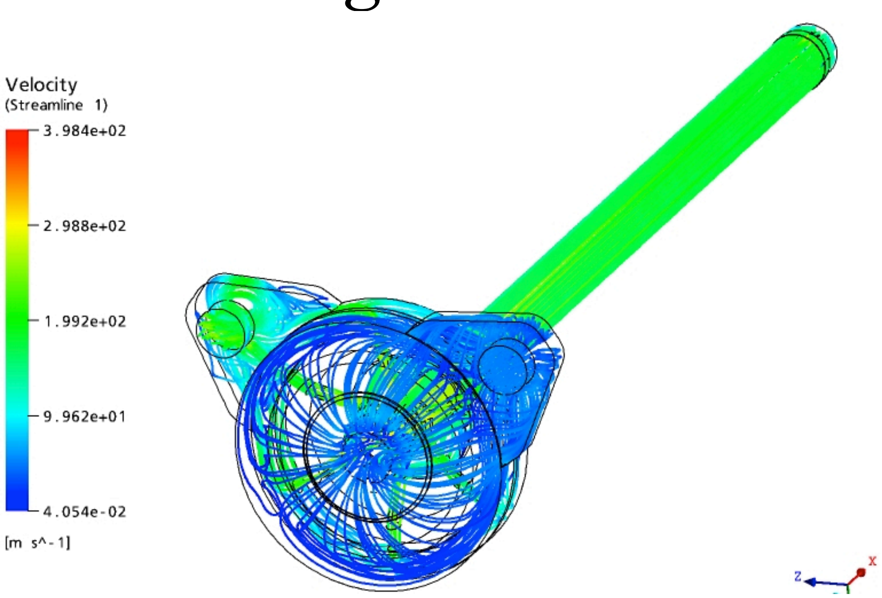
Beam Power	# of protons/pulse	Rep. rate
350 kW (current)	1.8x10	2.48 sec.
750 kW (revised)	2.0x10	1.30 sec.
750 kW (original)	3.3x10	2.10 sec.
1.3 MW (proposed)	3.2x10	1.16 sec.

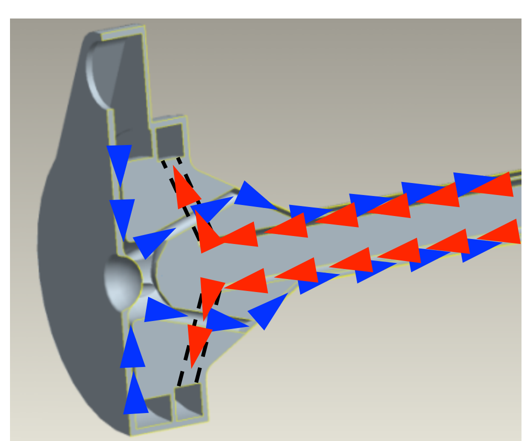
Current Acceptable Beam Power

Conponent	Limiting factor	Acceptable value
Target	Thermal shock	3.3x10
	Cooling capacity	0.75 MW
Horn	Conductor cooling	2 MW
	Stripline cooling	0.54 MW
	Hydrogen production	1 MW
	Operation	2.48 sec. & 250 kA
He Vessel	Thermal stress	4 MW
	Cooling capacity	0.75 MW
Decay Volume	Thermal stress	4 MW
	Cooling capacity	0.75 MW
Beam Dump	Thermal stress	3 MW
	Cooling capacity	0.75 MW
Radiation	Radioactive air disposal	1 MW
	Radioactive water	0.5 MW

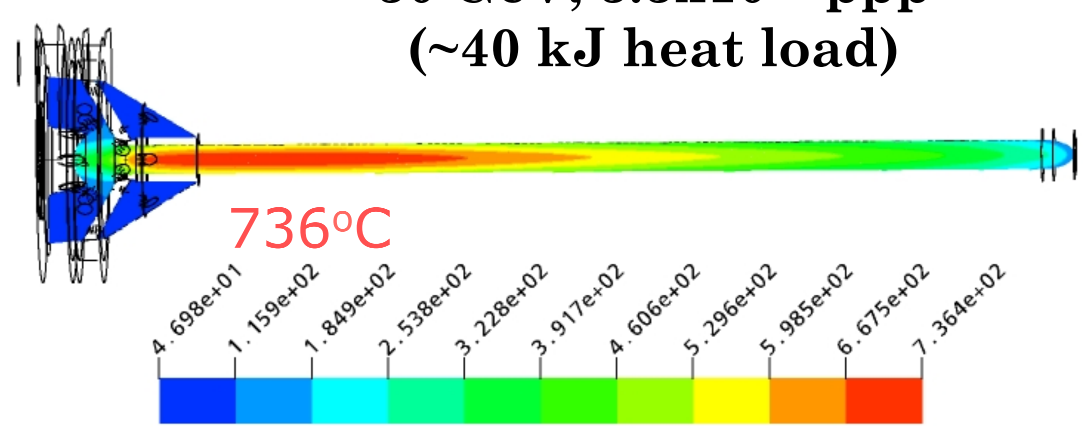
Target

- **Thermal shock**
  - Current design based on 3.3×10^{14} ppp
    - Thermal stress ~ 7 MPa ⟺ Tensile strength 37 MPa
    - Degradation of strength due to radiation damage is key issue
  - For > 3.3×10^{14} ppp, wider beam and larger target diameter is necessary to reduce thermal shock.
- **Helium cooling**
  - Cooling capacity: designed for 750 kW (+30% margin)
  - Higher helium flow rate needed for 1.3 MW
    - Need upgrade of cooling system for higher beam power.
    - Structure of Ti container may also be modified to accommodate higher He flow and higher pressure.





30 GeV, 3.3×10^{14} ppp
(~40 kJ heat load)



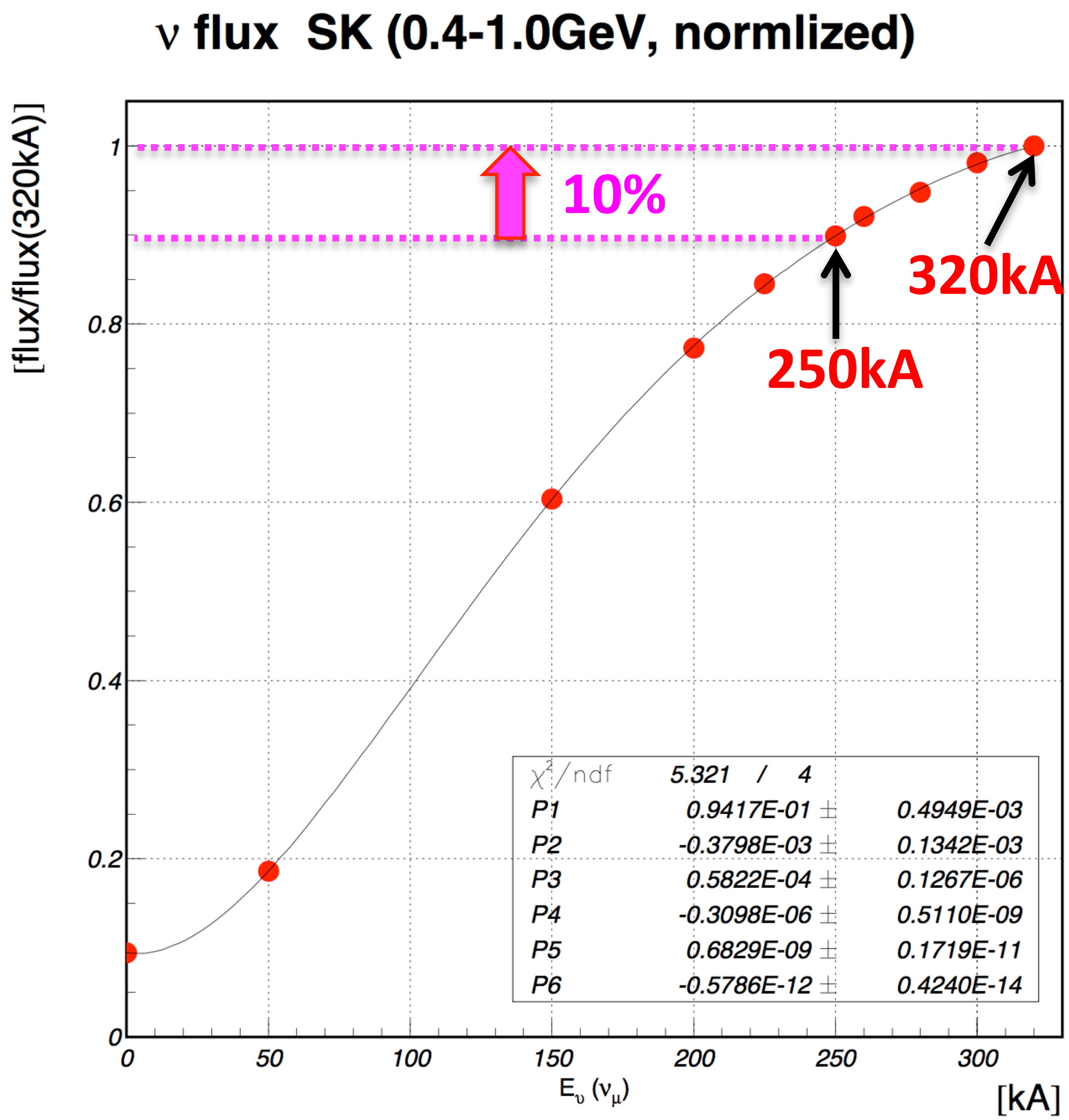
ΔT~200K ~7MPa (Tensile strength 37MPa)

Prospect for Hardware Upgrade

- **Cooling capacity**
  - Apparatuses themselves can withstand 1.3 MW beam.
  - Improvement of flow rate both for water and helium circulations is needed.
    - Replacement with larger pumps
    - Replacement with larger-size plumbing
    - ⟹ They will be feasible but need 1 year for modification.
- **Radiation**
  - Radioactive air
    - Reinforcement of air-tightness ⟹ 1.3 MW can be manageable.
  - Radioactive water disposal
    - Enlargement of dilution tank
      - Modification of existing tank ⟹ ~1.3MW
      - New facility building for water disposal ⟹ 2MW
        - 2 years for construction (no beam stop needed)

Flux Improvement by Neutrino Beamline

- **Magnetic horn current**
  - 250 kA ⟹ 320 kA (rated)
  - **10 % improvement of neutrino flux at far detector**

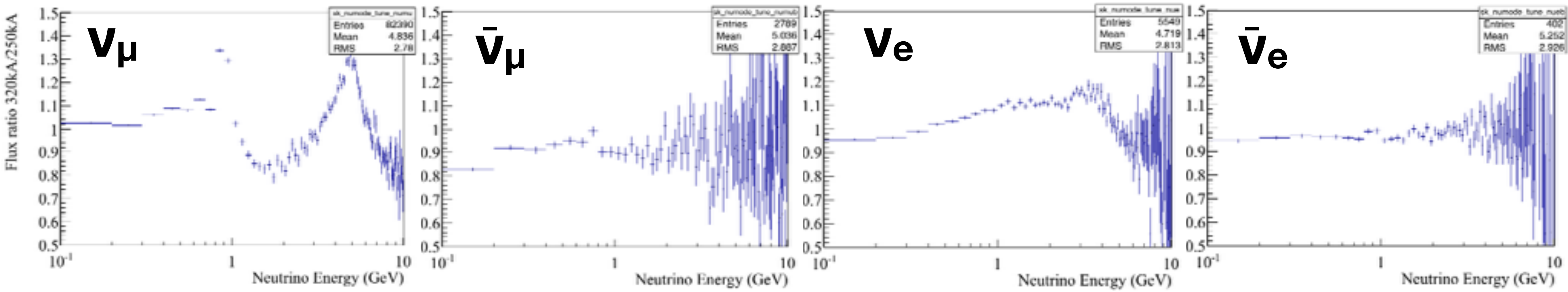


Courtesy of T.Nakadaira

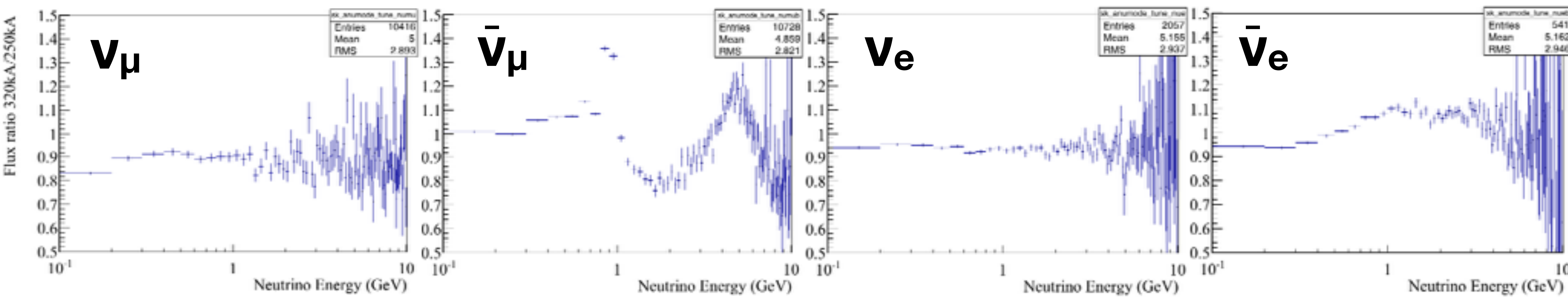
Flux Improvement by Neutrino Beamline

- **Another benefit of 320 kA operation**
  - **Low contamination of wrong-sign neutrino background**
    - 5~10% reduction at peak (E_ν~0.6 GeV)

Neutrino mode

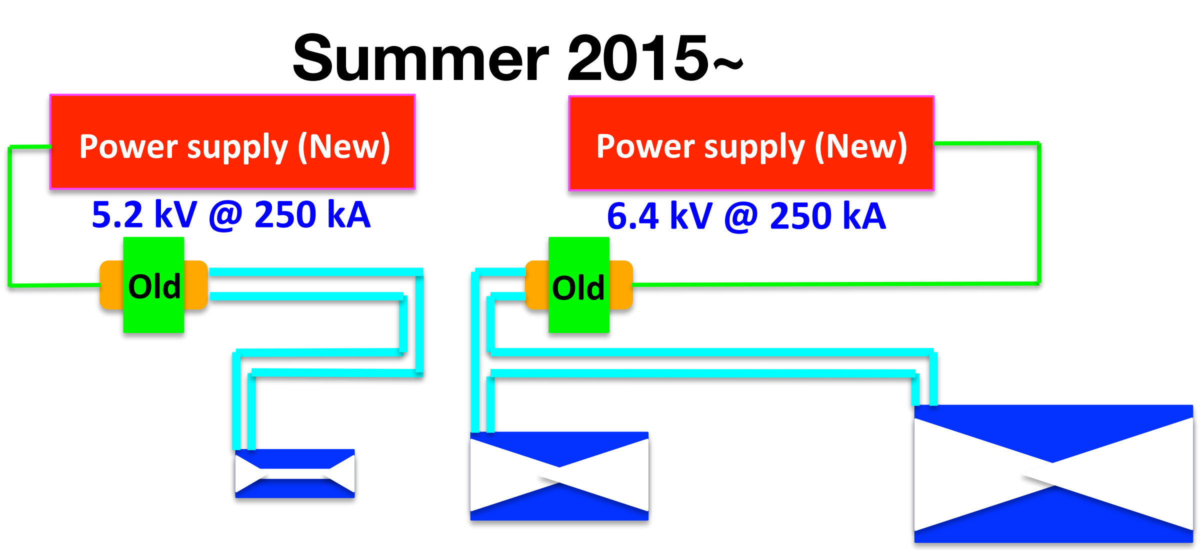


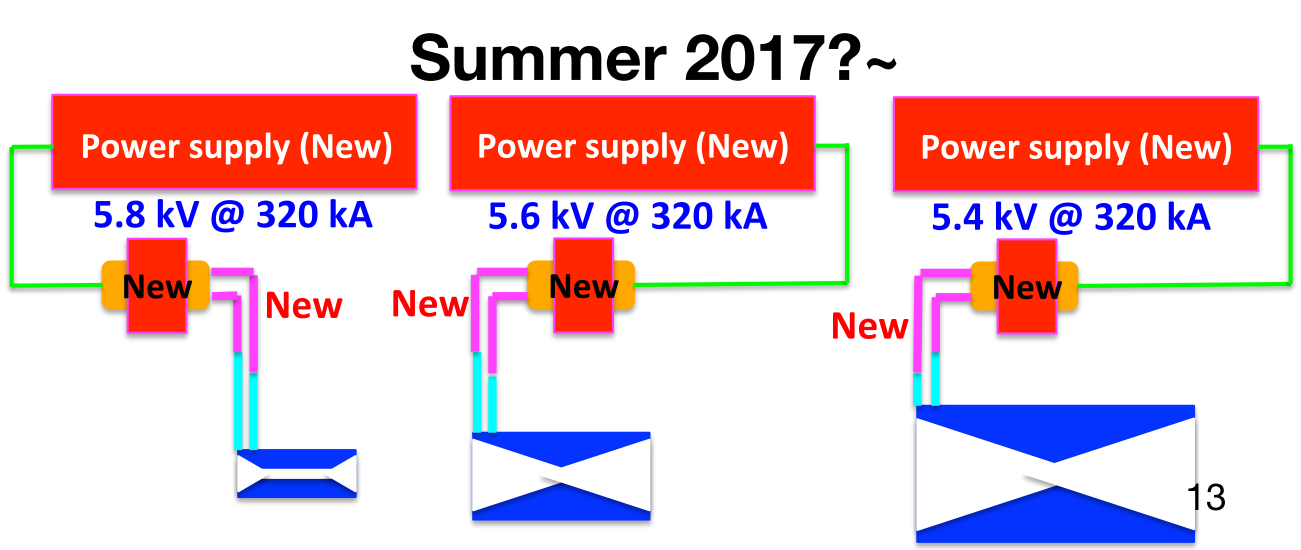
Anti-neutrino mode



320 kA and 1 Hz Operation

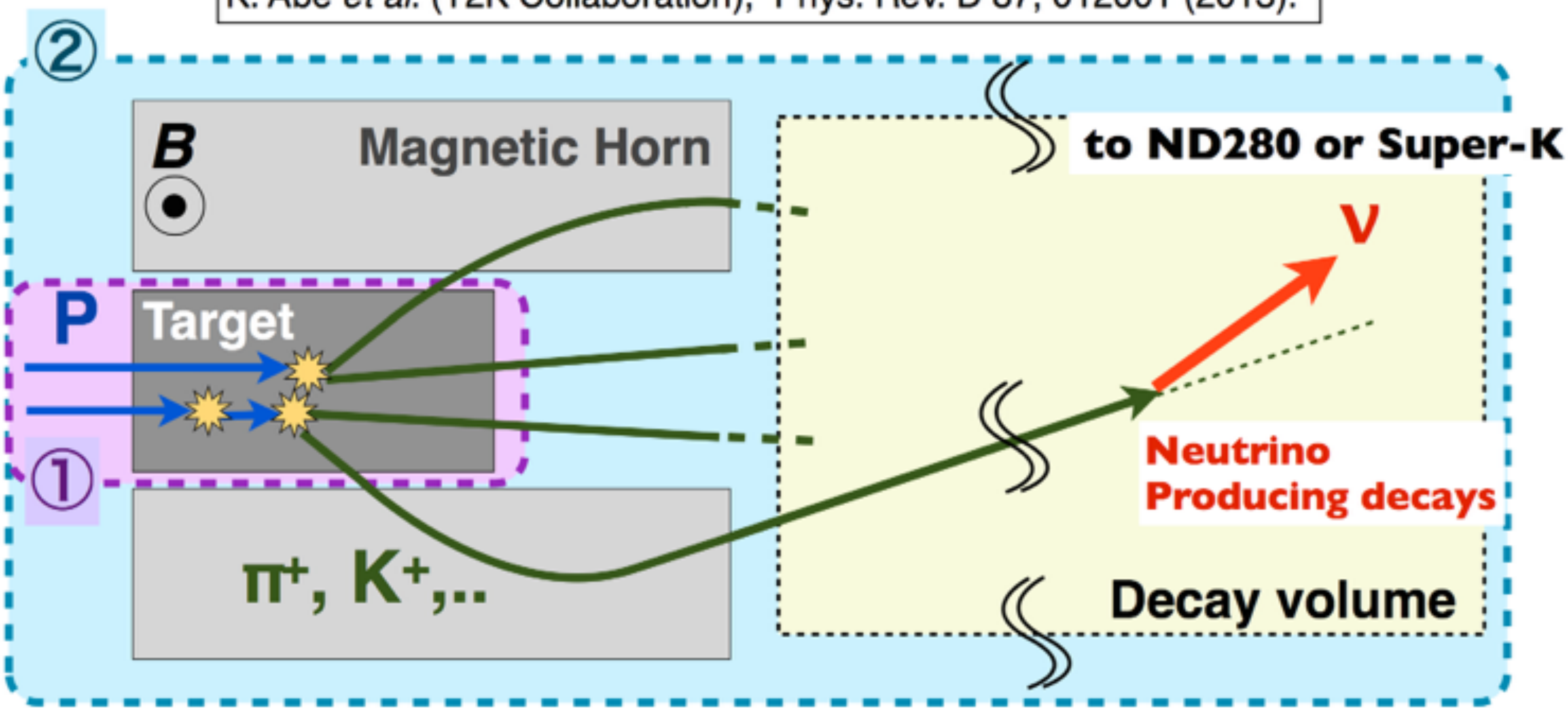
- **Requirement**
  - Low Joule heating ⟹ narrow pulse
  - Short charging time ⟹ energy recovery and low Joule loss
  - Low failure risk ⟹ low charging voltage
- **Configuration**
  - 1 horn operated by 1 PS ⟹ 3 PS in total
    - New power supply developed (2 PS's already produced).
    - Also, low impedance current transfer line newly developed.
- **Timeline**
  - Production of the last PS, transformers, part of transfer lines
  - Aim to start 320 kA operation from summer 2017.





Neutrino Flux Prediction

K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).

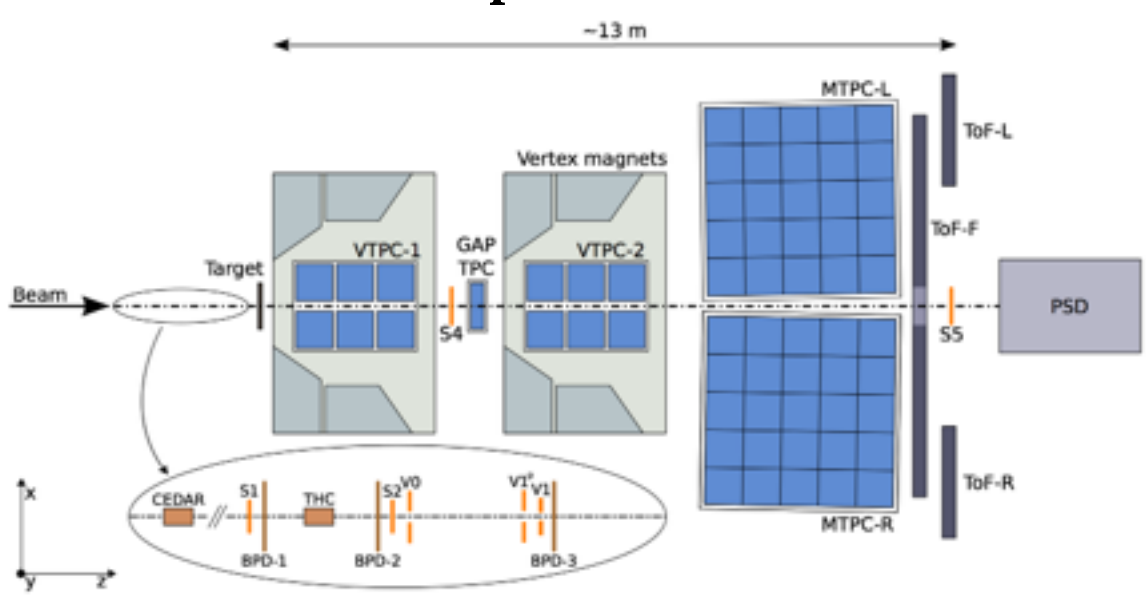


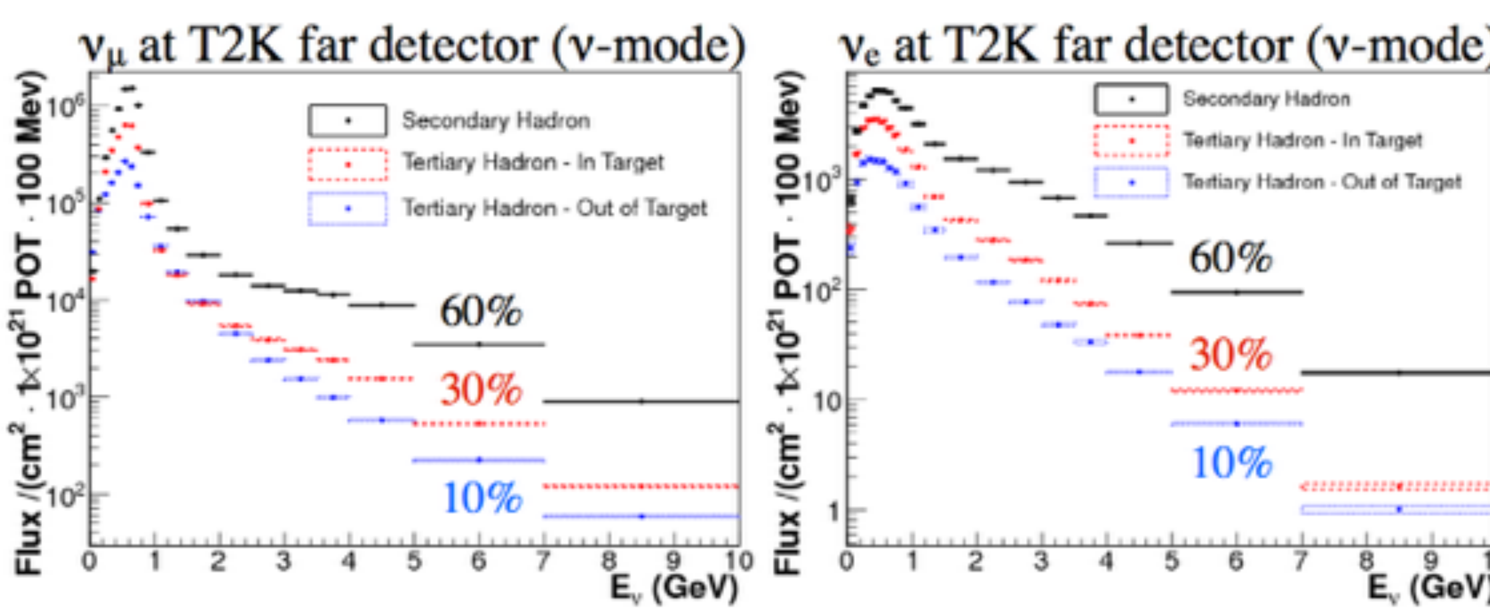
- **Neutrino flux at near/far detector simulated w/ MC**
  - Proton interaction inside target ⟹ FLUKA2011
    - propagation of secondary/tertiary particles inside target
  - Propagation/interaction/decay of particles outside target ⟹ GEANT3+GCALOR
- **Hadron production is tuned with NA61/SHINE data**

Hadron Production Measurement in NA61

- **NA61 measures 30 GeV p+C cross section for T2K**
  - NA61 spectrometer: TPCs + TOFs
  - Carbon target
    - Thin target(2cm) ⟹ primary p+C interactions (60%)
    - Replica target(90cm) ⟹ secondary interactions in target (30%)
  - Data for T2K
    - Data collected in 2007, 2009 and 2010
    - Results from 2009 thin target data recently released.

NA61 spectrometer

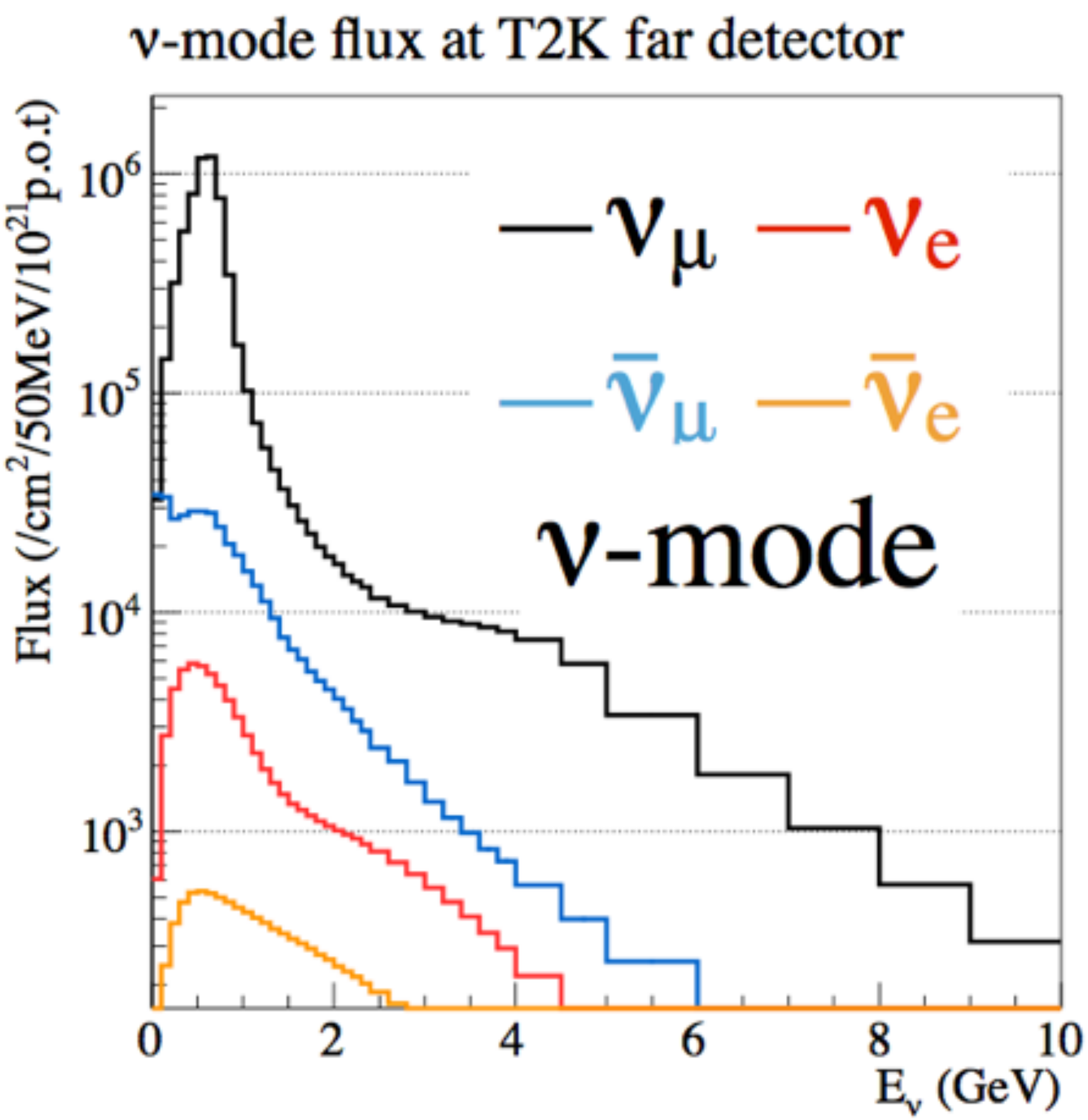


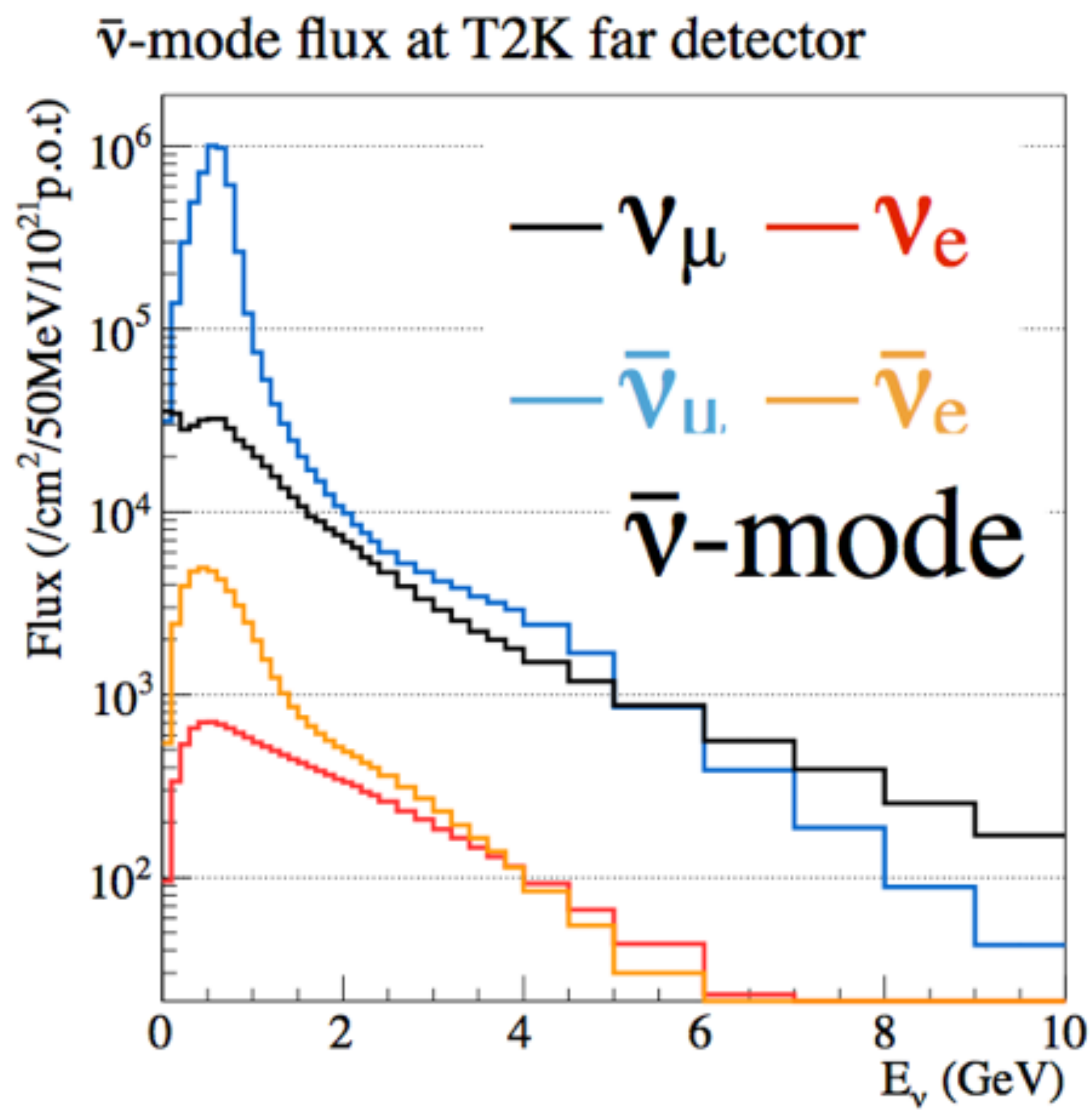


NIM A**701**, 99-114 (2013)

Predicted Neutrino Flux at Far Detector

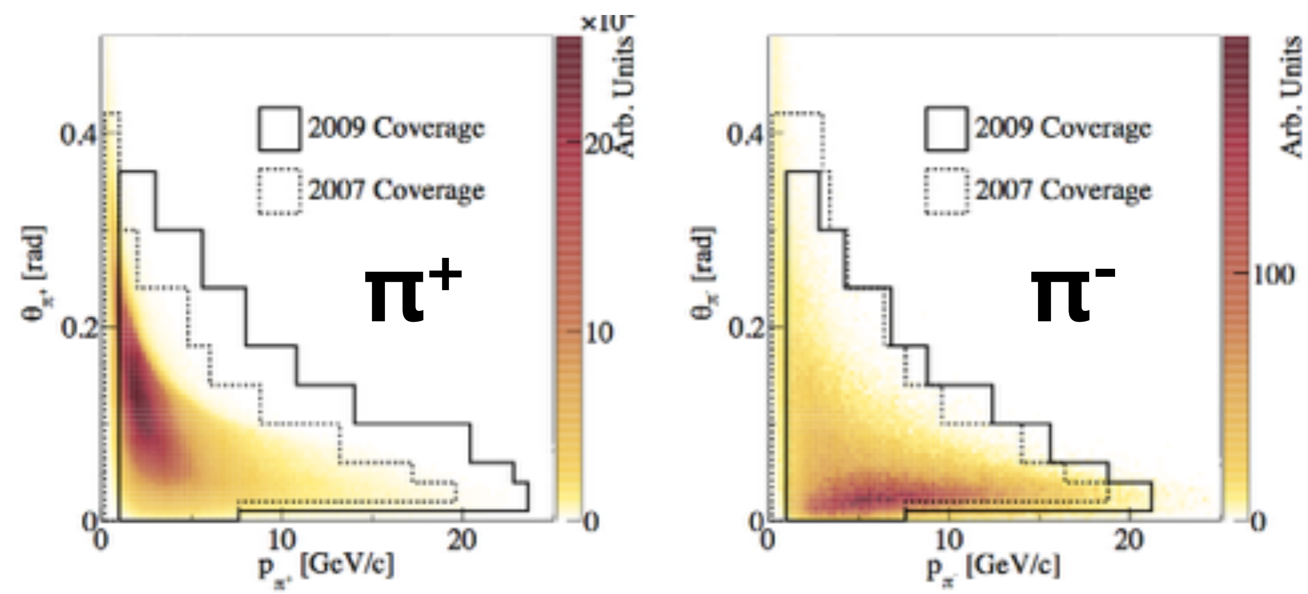
- Neutrino flux tuned with NA61 data



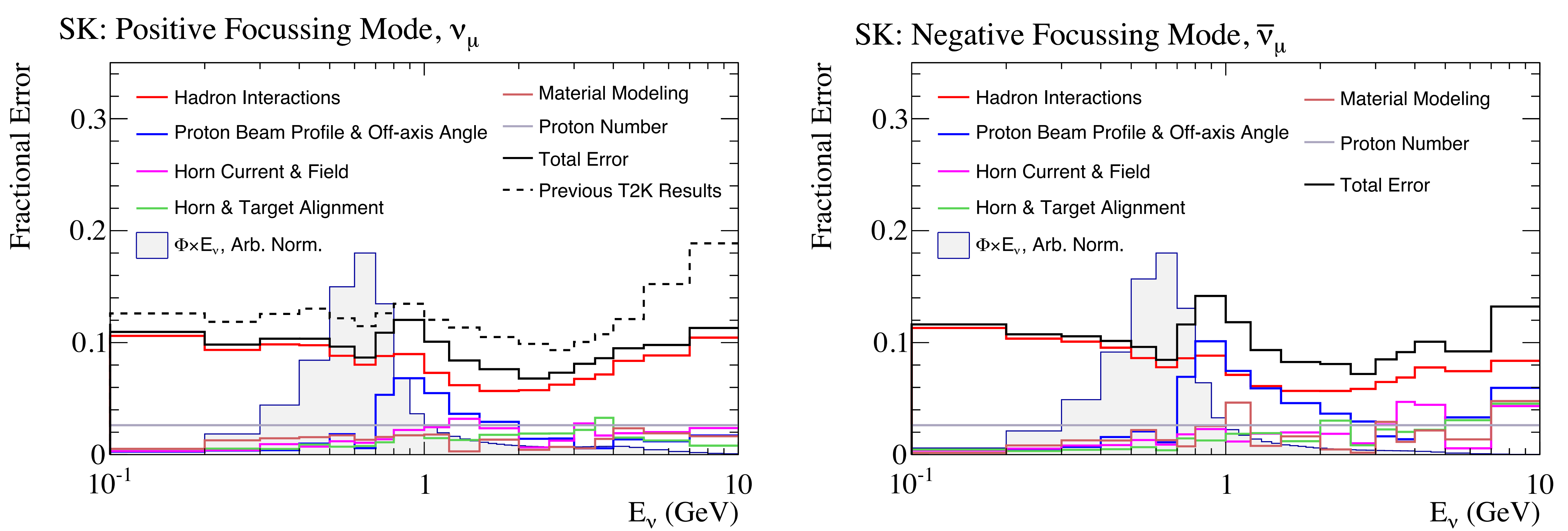


Recent Update on Flux Prediction

- **Update on flux prediction with NA61 2009 data**
  - Thin target data
  - Larger statistics
  - Wider coverage of phase space
  - $\pi^{\pm}$, $K^{\pm}$, $K^0{}_s$, Λ production data



- **Uncertainties at flux peak reduced from 12% to 9%**
  - Dominant uncertainty is still from Hadron production modeling.

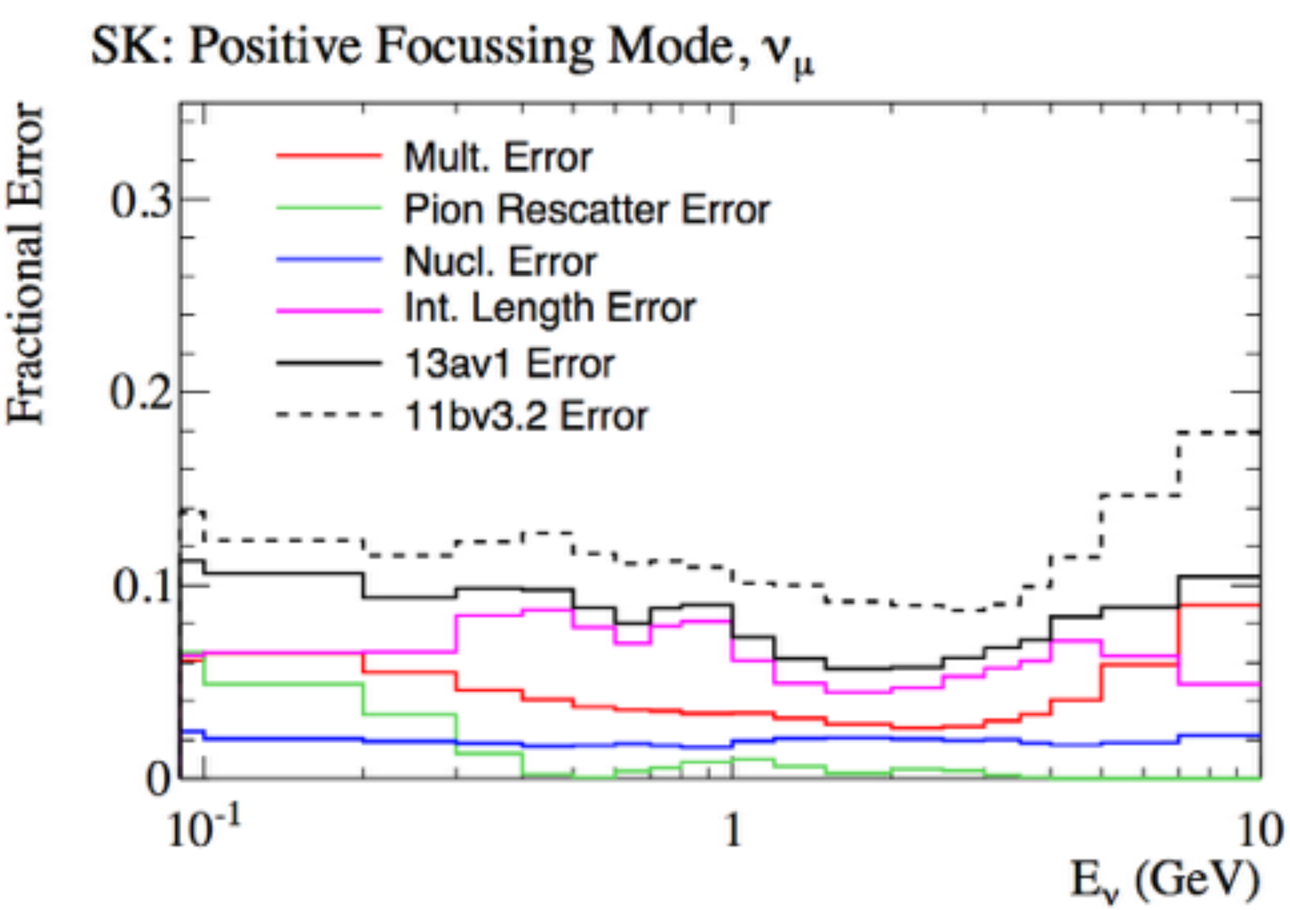


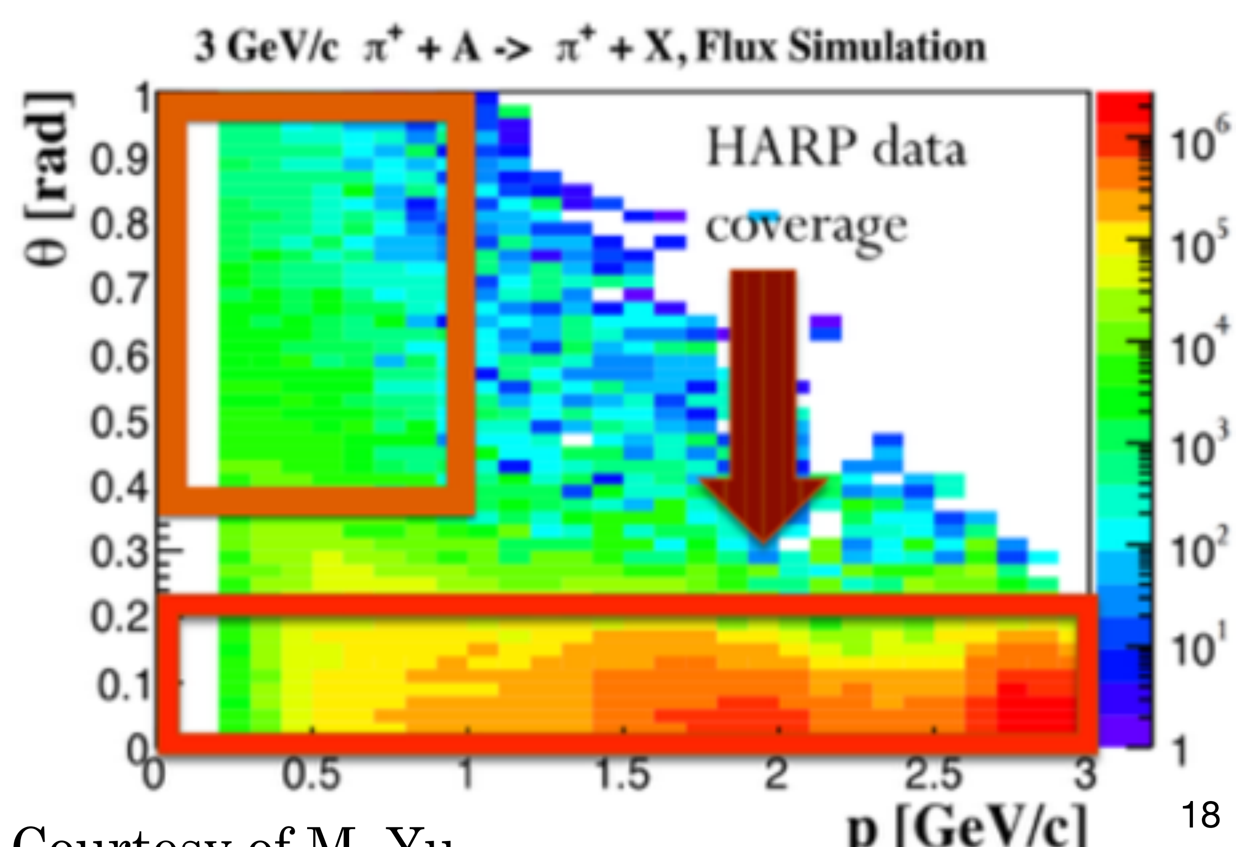
Possible improvement of Flux Prediction

- **Reduction of Hadron production uncertainties**
  - **Hadronic interaction length**
  - **Pion multiplicity**

  } Replica target data

  - Pion re-scattering $\pi^{\pm}+A\rightarrow\pi^{\pm}+X$
    - Low angle HARP data is used
      - important for low energy wrong sign muon neutrino flux
    - Inclusion of large angle HARP data.

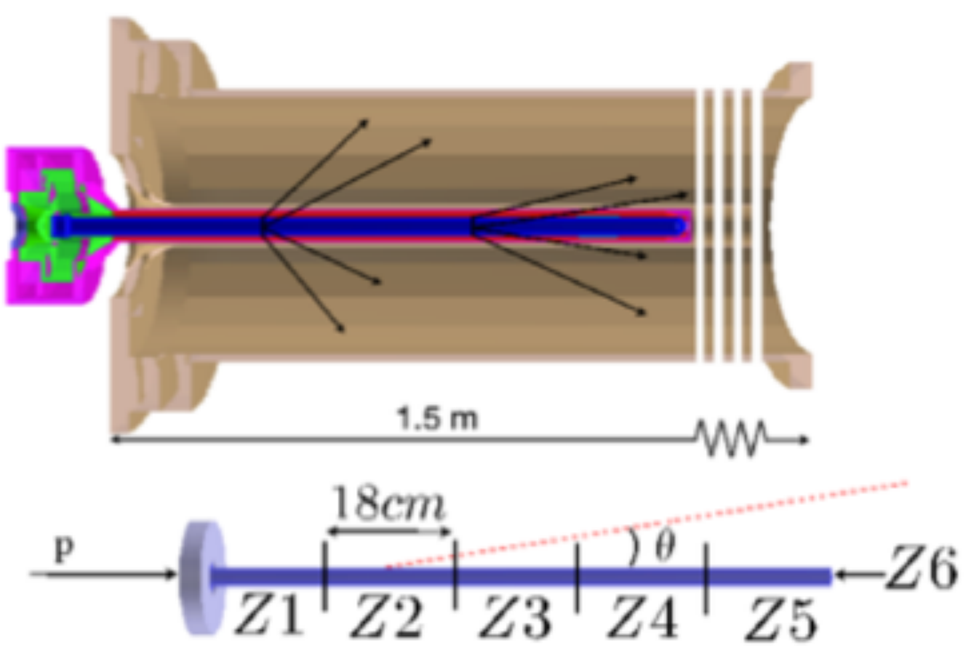


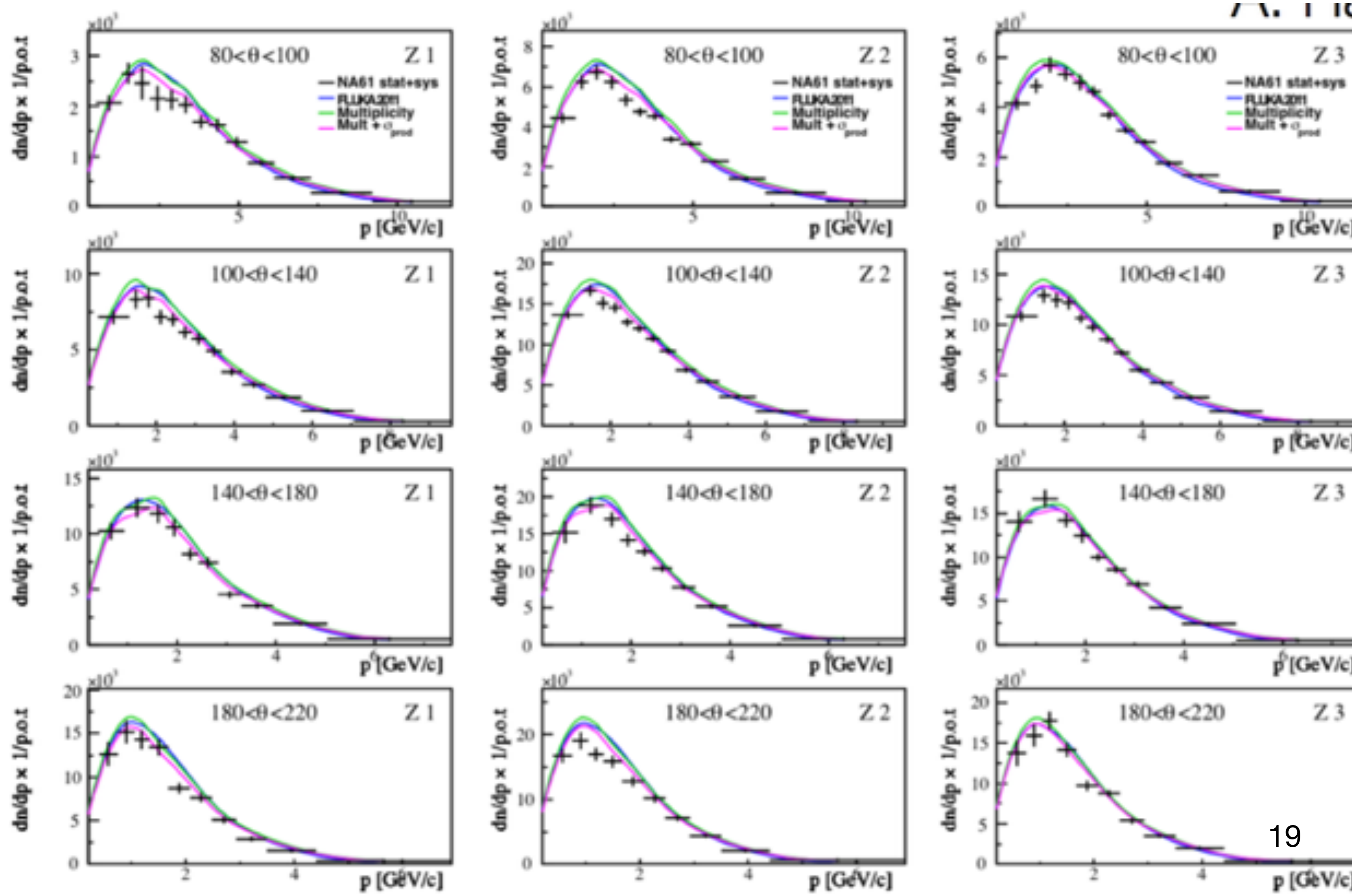


Courtesy of M. Yu

Replica Target Measurement

- Replica target data can constrain up to 90% of the flux.
- Data set: 0.6×10^{6}(2007), 4×10^{6}(2009), 10×10^{6}(2010) POT.
  - 2009 data were already released as ph.D thesis of A. Heasler. CERN-THESIS-2015-103
- Multiplicities of particles exiting the target in bins of Z, p, θ are measured.
  - These uncertainties are replaced by systematic uncertainties from the replica target measurement
- Comparison to thin target data partly agrees well, but not perfect.



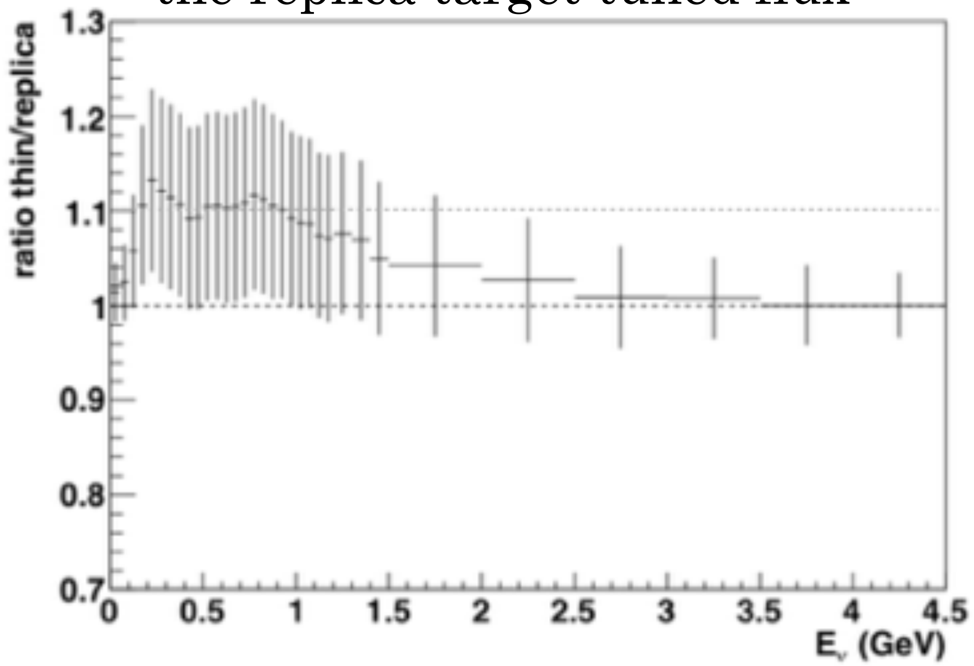


Flux Tuning with Replica Target Data

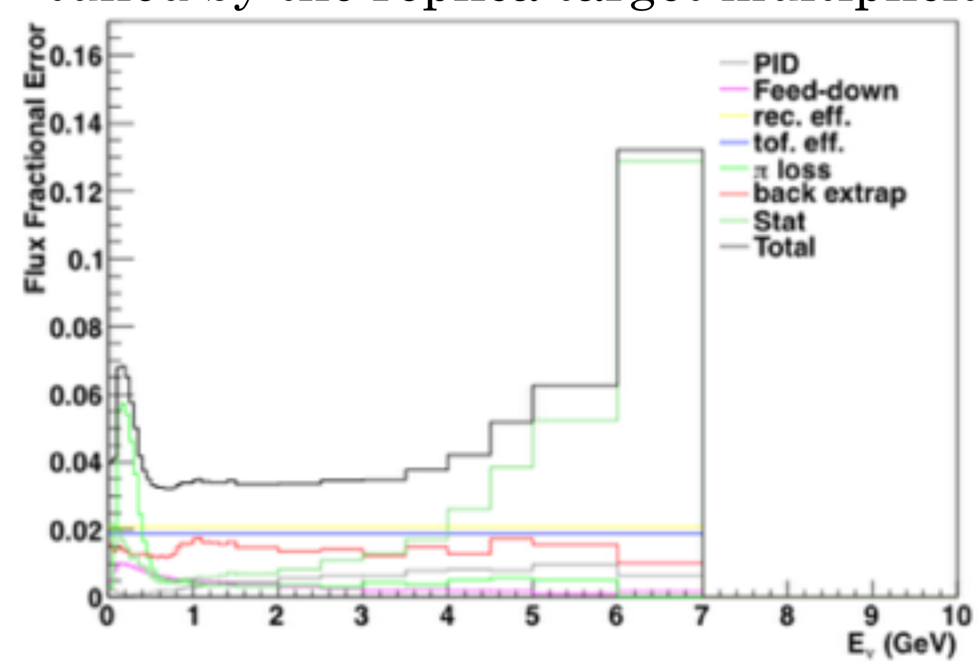
- **Tuning of flux using the 2009 replica target data (A. Heasler)**
  - Flux weighted by ratio of the measured over the simulated particle production from the replica target

$$w(p,\theta,z) = N^{corr}_{NA61}(p,\theta,z)/N^{sim}_{T2K}(p,\theta,z)$$

Ratio of the thin target tuned flux over the replica target tuned flux



Systematic uncertainty on the fraction of the flux tuned by the replica target multiplicities



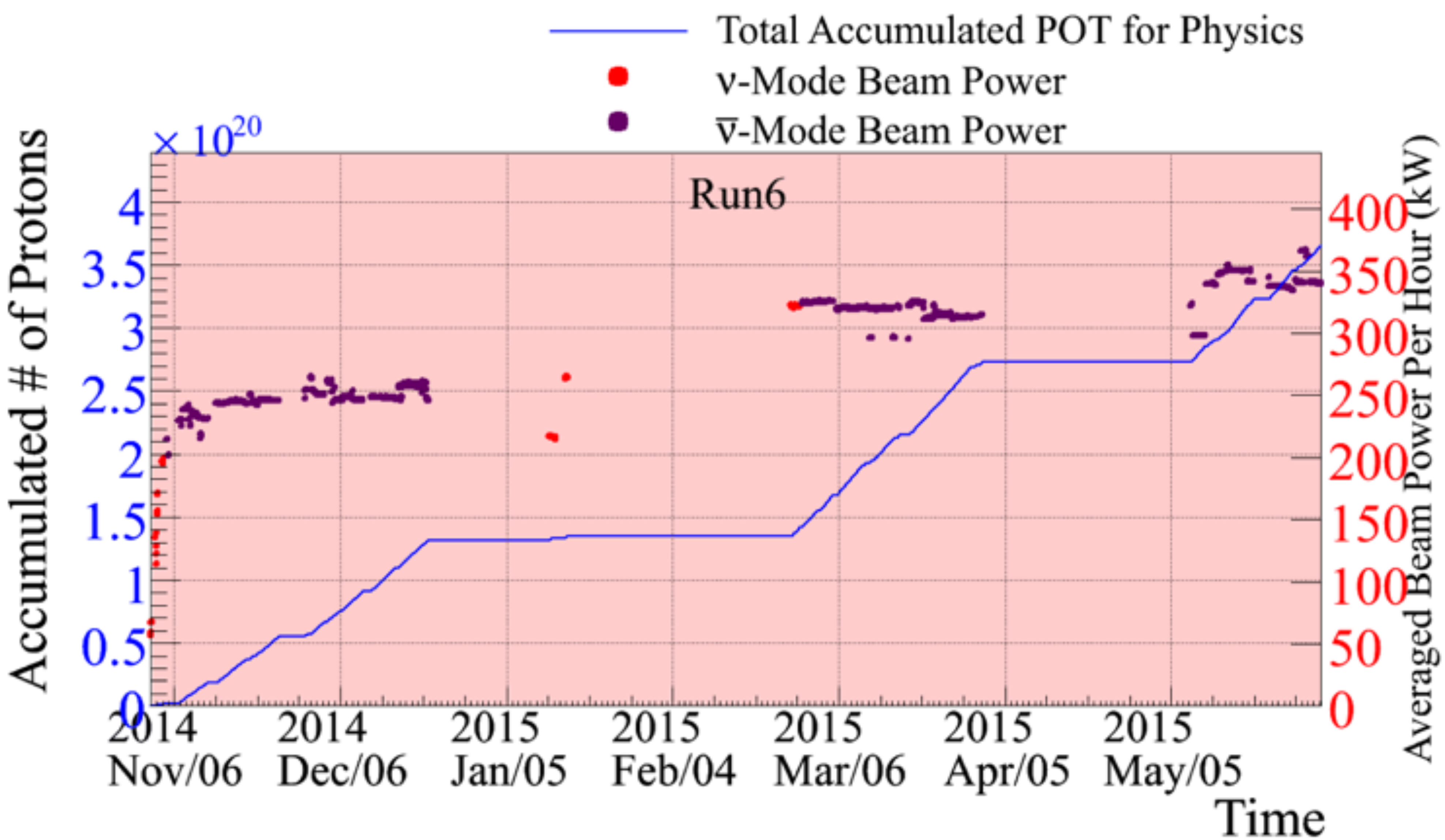
- **Further improvements on the replica target measurement**
  - Better precision w/ more statistics of 2010 data.
  - Further reduction by improving backward extrapolation of tracks to the target by bringing it closer to the spectrometer.

Summary

- **Beam power upgrade**
  - 1.3 MW beam until 2026.
  - Neutrino beamline will be upgraded for 1.3 MW beam.
- **Neutrino flux improvement by 320kA operation**
  - 10% flux gain
  - Hardware upgrade done by summer 2017 if budget is timely approved.
- **Improvement on the flux uncertainties**
  - Flux update with NA61 2009 data: 12% $\Longrightarrow$ 9%
  - 2009 replica target data was released.
  - Further reduction of flux uncertainties can be achieved.

Supplemental Slides

Where We Are Now



- Achieved beam power so far
  - 371 kW at maximum.
  - **335~350 kW continuous operation**

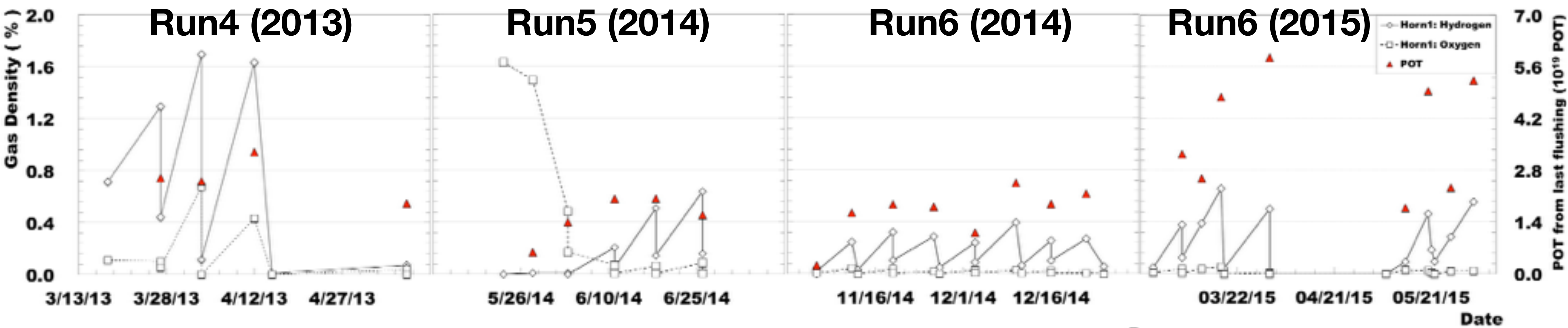
Stripline Cooling

- **Forced helium flow for stripline cooling.**
  - Large heat deposit at Horn2 (due to defocused pions)
  - Insufficient helium flow rate for Horn2. → 0.54 MW
  - **Double flow rate for Horn2** → **1.25 MW**
- **Water-cooled striplines**
  - Necessary when beam power goes beyond 1 MW.
  - Under conceptual design.

	Horn1	Horn2	Horn3
Heat flux per stripline plate (J/m			
Total (Beam + Joule)	214	1066	141
Acceptable Beam Power			
w/ current flow rate	2.10	0.54	3.46
w/ double flow rate	-	1.25	-

Hydrogen Production Problem

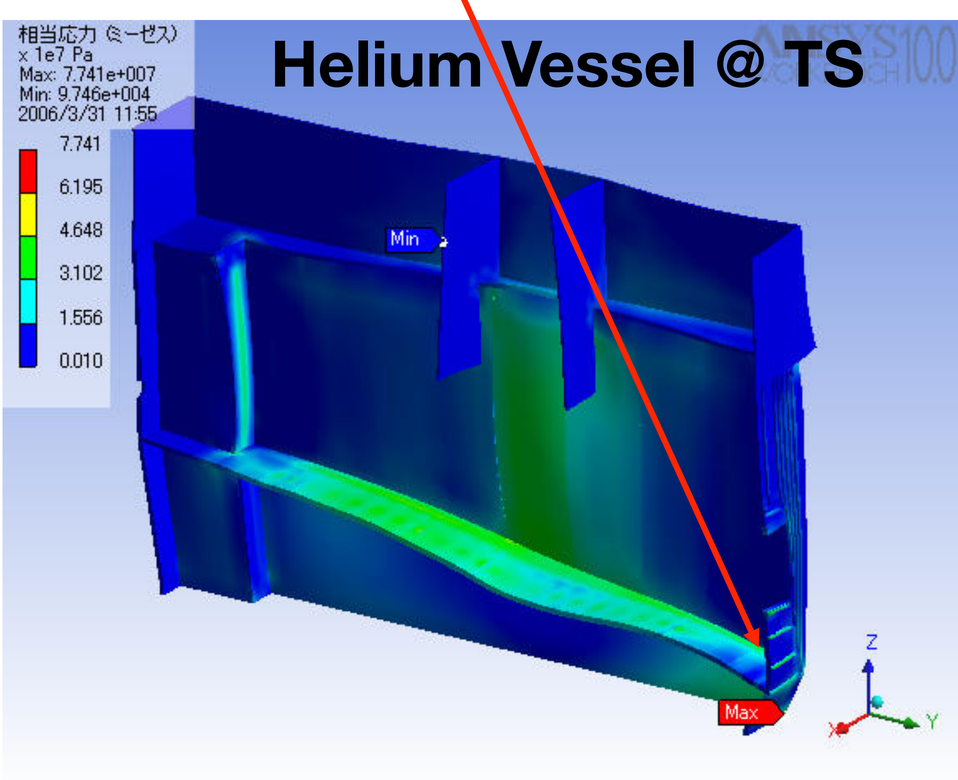
- H_2 production by water radiolysis.
- **Hydrogen recombination system**
  - Forced helium circulation **inside** Horns drastically improved H_2 removal.
  - 2-week continuous operation w/ 335 kW → $H_2 < 0.7\%$.
  - Current limit : Low O_2 density due to resolution in water.
    - 1 MW beam is acceptable (w/ keeping H_2 density < 2%)
  - Degasifier system will be introduced for higher recombination efficiency.



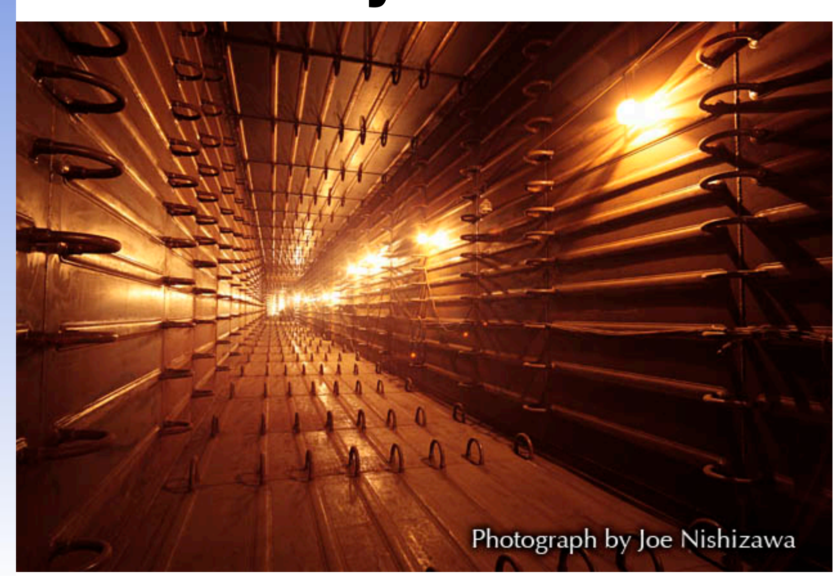
Target Station / Decay Volume / Beam Dump

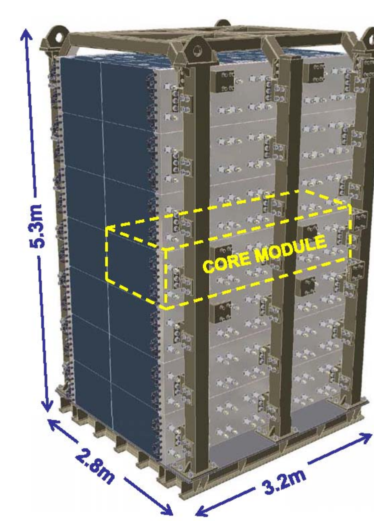
- **Tolerance for thermal stress**
  - Designed for 4 MW (TS, DV) and 3 MW (BD) beam
    - No access is allowed after beam exposure.
- **Cooling**
  - Cooling capacity designed for 750 kW.
  - Need upgrade of cooling system for higher beam power.

Maximum 77 MPa

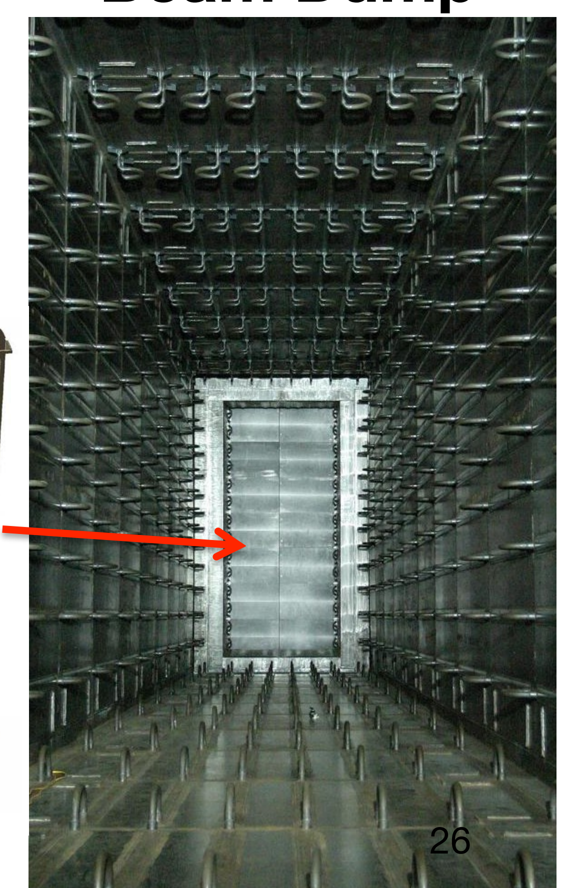


Decay Volume





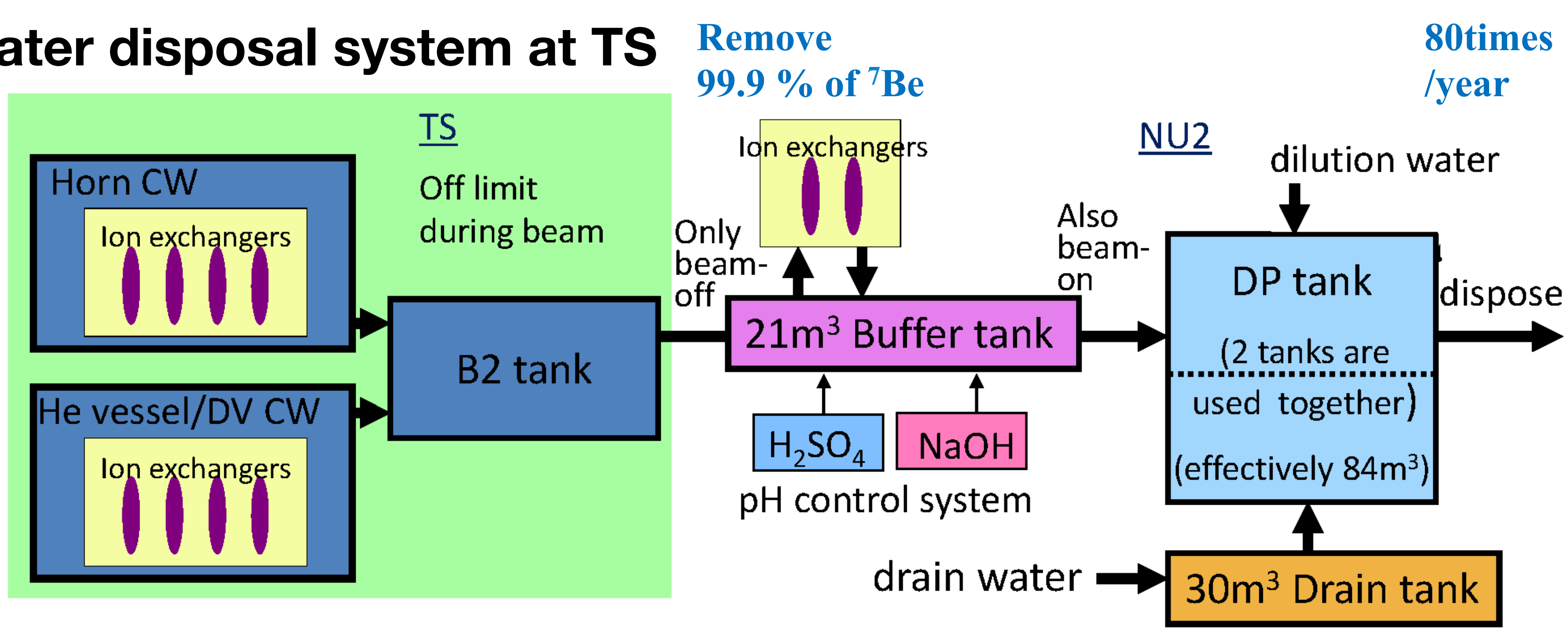
Beam Dump



Radio-active Water Disposal

- **Radio-active water**
  - **^{7}Be**: 99.9% removed by Ion Exchangers.
  - **^{3}T**: Diluted many times (80 times/year)
- **Limited dilution tank size → 0.5 MW**
  - Highly-activated water can be taken by tanker truck.
    - 750 kW will be accepted.
    - For BD/DV downstream cooling water, connection equipment for tanker truck was prepared and tested.

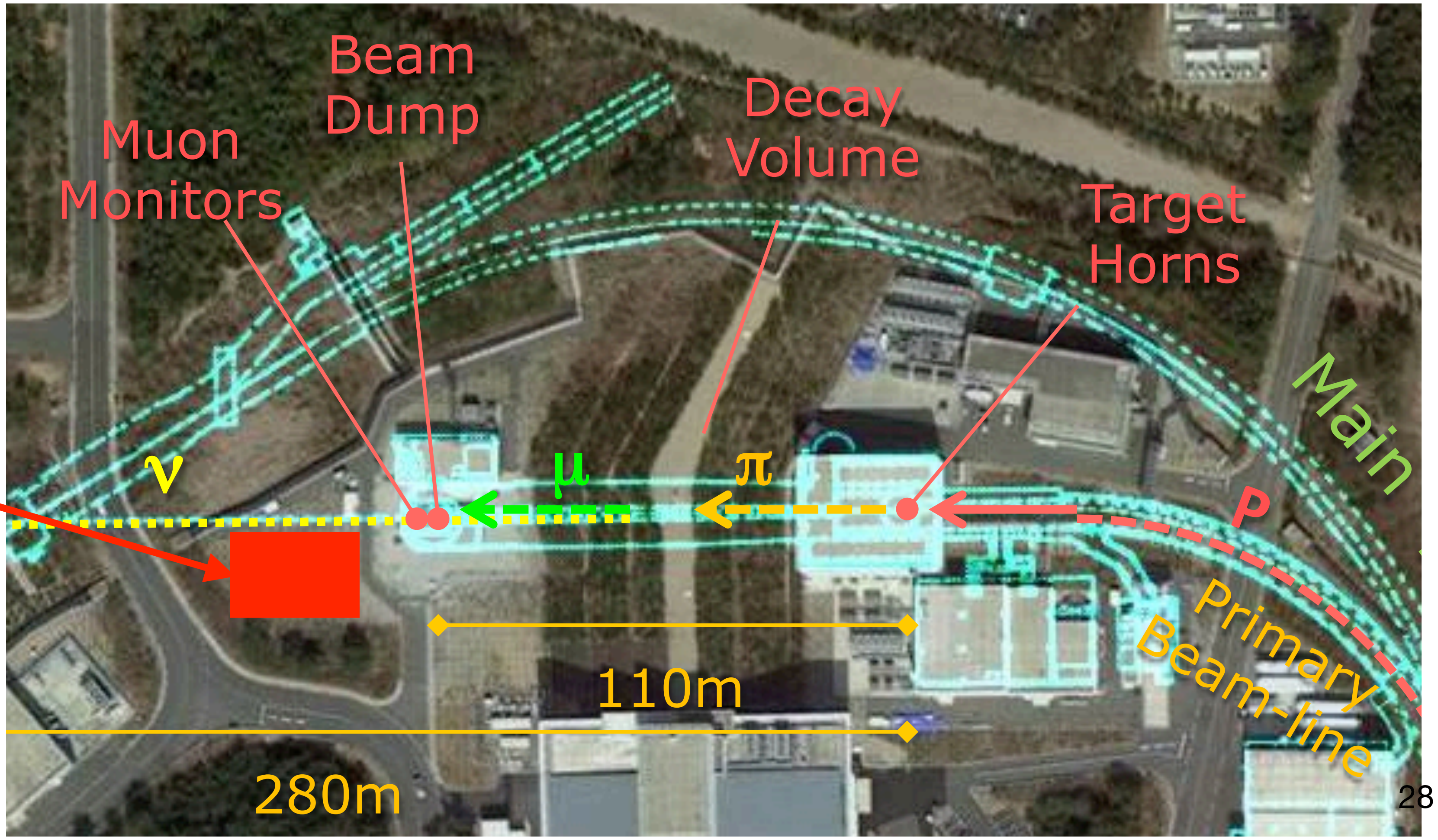
Water disposal system at TS



Radio-active Water Disposal

- For beam power > 750 kW, construction of larger dilution tanks is necessary.
- **New facility building for radio-active water disposal**
  - New dilution tanks is designed for **2 MW**.
  - We are applying budget for this facility.

New facility building



Acceptable Beam Power

- **Target and Beam Window**
  - Thermal shock : 3.3×10^{14} ppp
  - Helium cooling : 750 kW
- **Horn**
  - Horn conductor cooling : 2 MW
  - Stripline cooling : 540 kW → 1.25 MW
  - Hydrogen production : 1 MW
  - Operation : 0.4 Hz & 250 kA → 1 Hz & 320 kA
- **He Vessel / Decay Volume / Beam Dump**
  - Thermal stress : 4 MW (HV, DV), 3 MW (BD)
  - Cooling capacity: 750 kW
- **Radio-active air** : 1 MW
- **Radio-active water disposal**: 0.5 MW → 0.75 MW → 2 MW