Latest results from T2K

Ciro Riccio on behalf of the T2K collaboration

FPCapri2018, Anacapri

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Università degli Studi di Napoli Federico II

INFN Napoli

Overview

- Neutrino oscillations
- T2K experimental setup
- Oscillation analysis
- Cross section measurements
- Future prospects
- Conclusions

Neutrino oscillations

Neutrino mixing described by the PMNS matrix: 3 mixing angles and 1 complex CPV phase

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Open questions: δ_{CP}, θ_{23} octant and mass ordering

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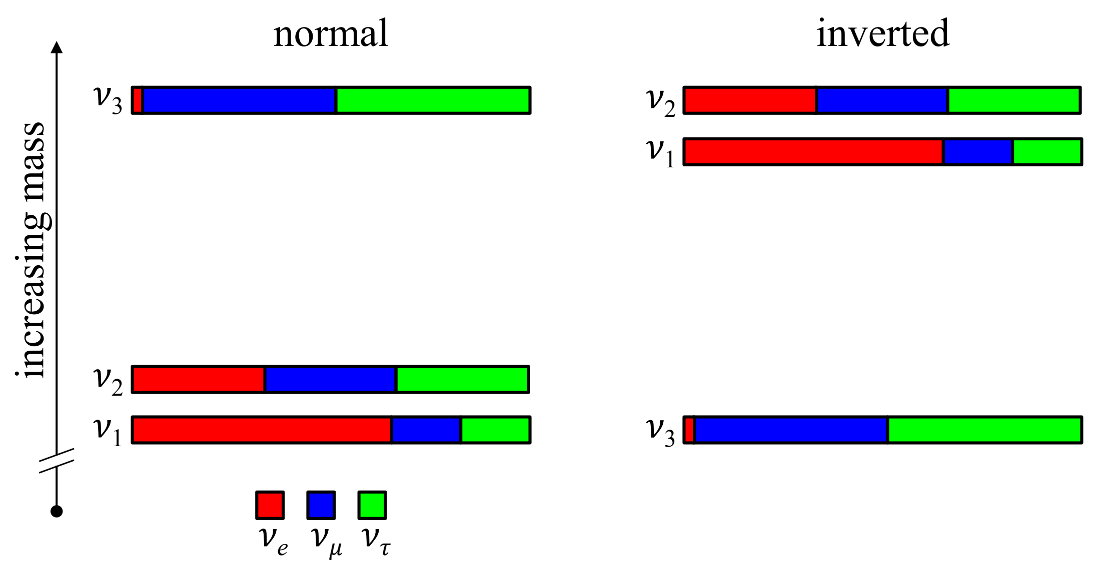
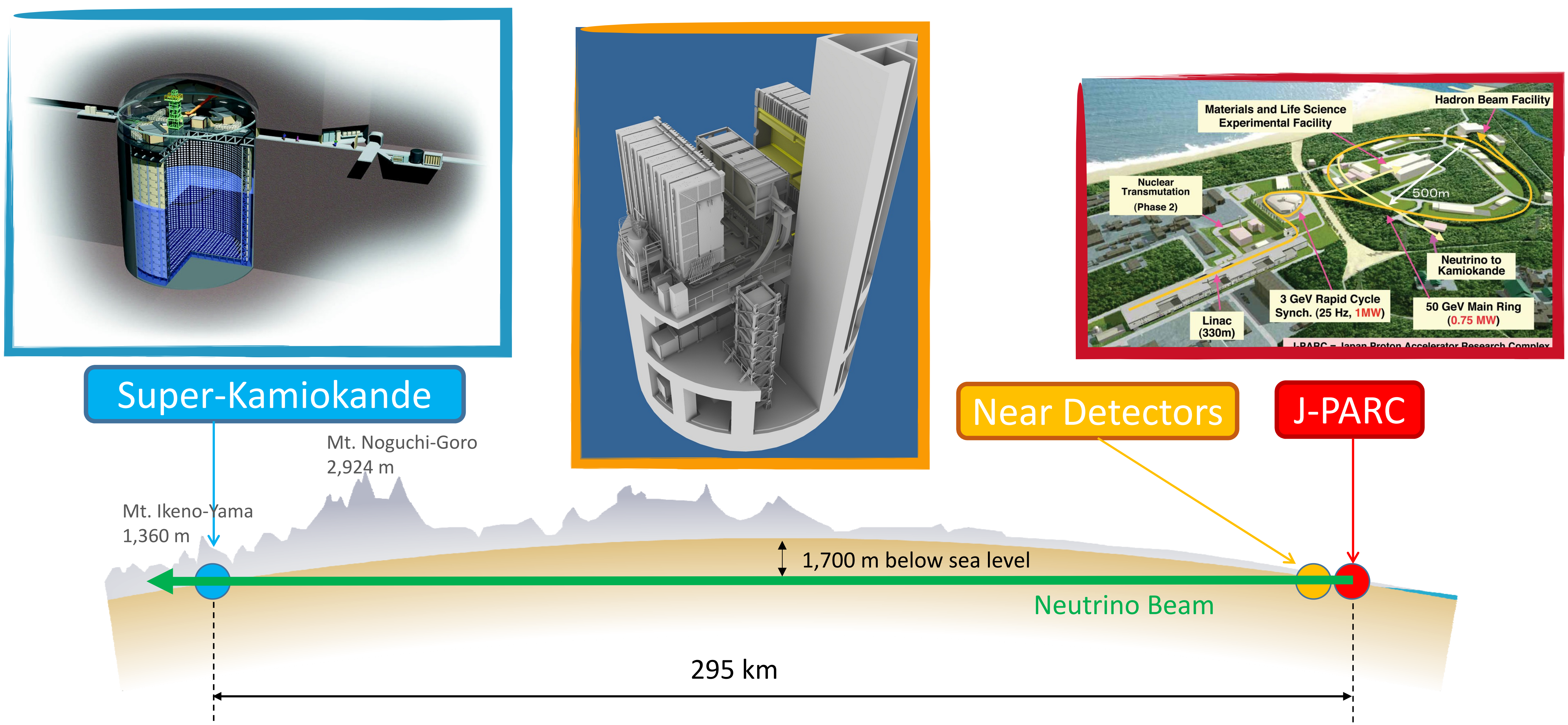


The T2K experiment



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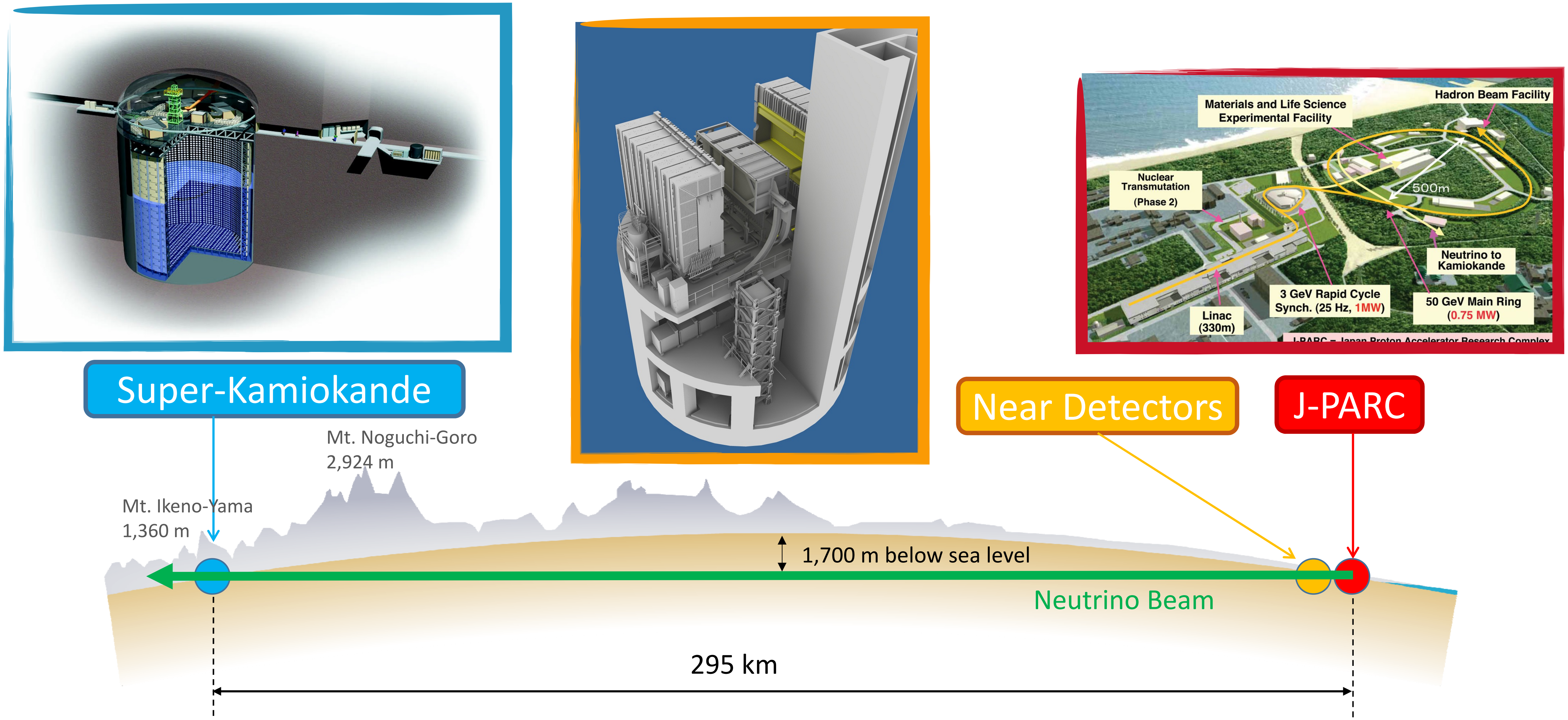

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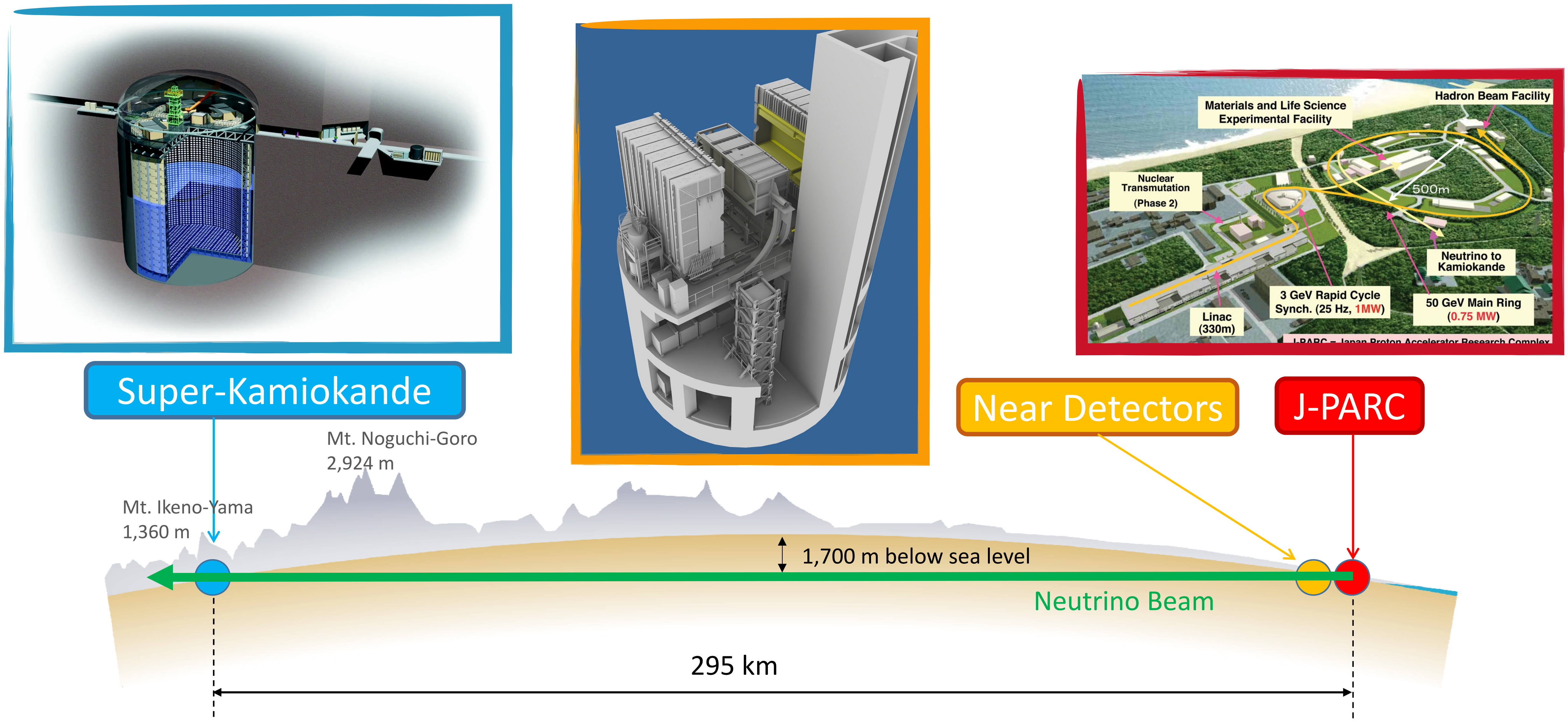
The T2K experiment



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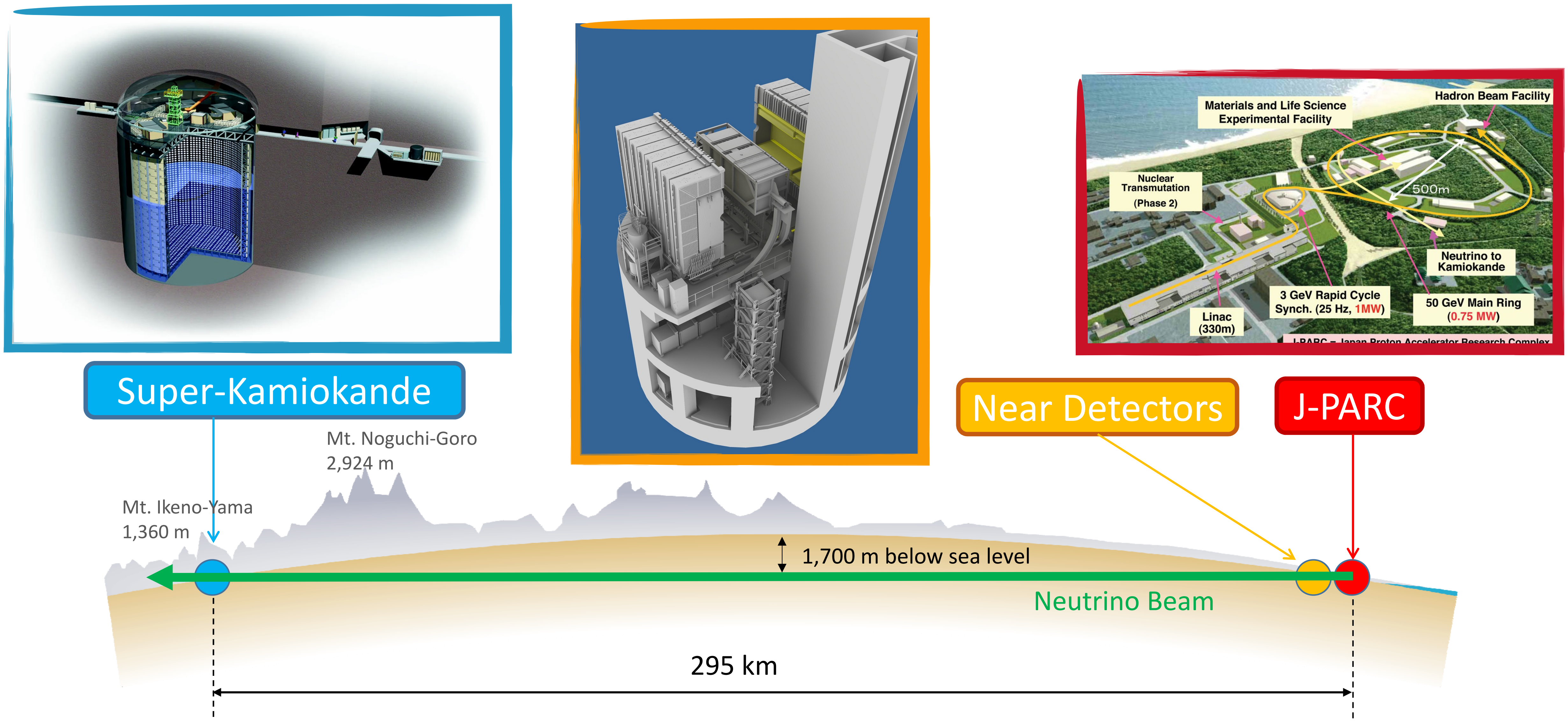

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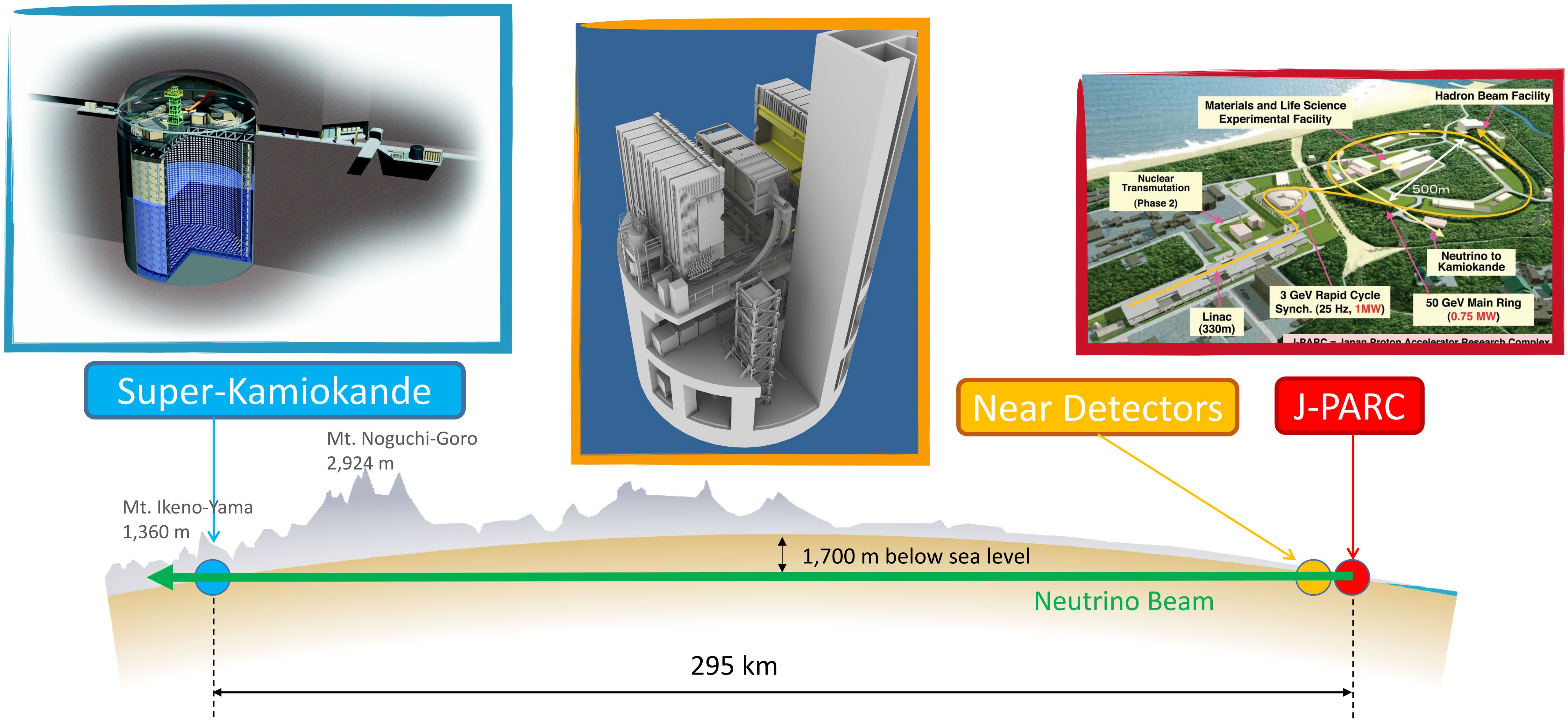

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- ν cross section measurements at the near detectors

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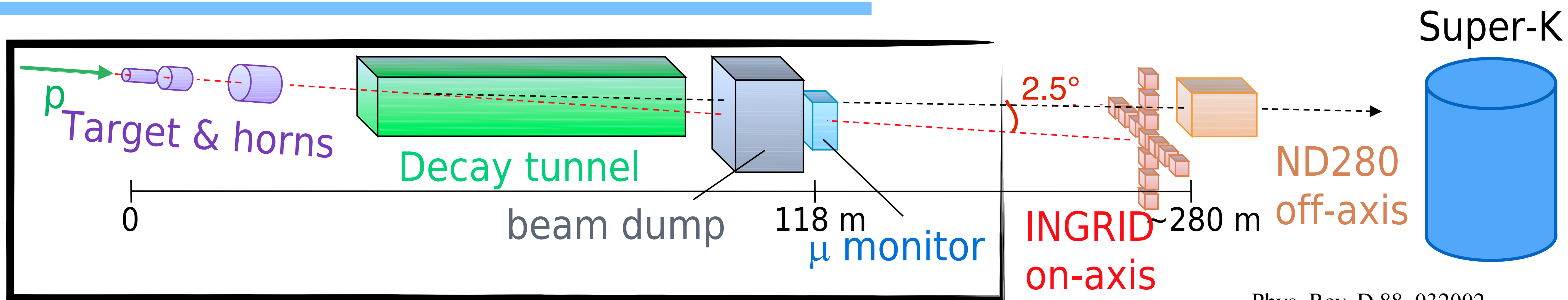
- (θ_{13}, δ_{CP}) depends on the $\nu_e/\overline{\nu}_e$ appearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) \overset{(-)}{+} O(\delta_{CP})$$

In the case of T2K δ_{CP} change the appearance probability by ±30% while the mass ordering has a ~10% effects

T2K Beam



Phys. Rev. D 88, 032002

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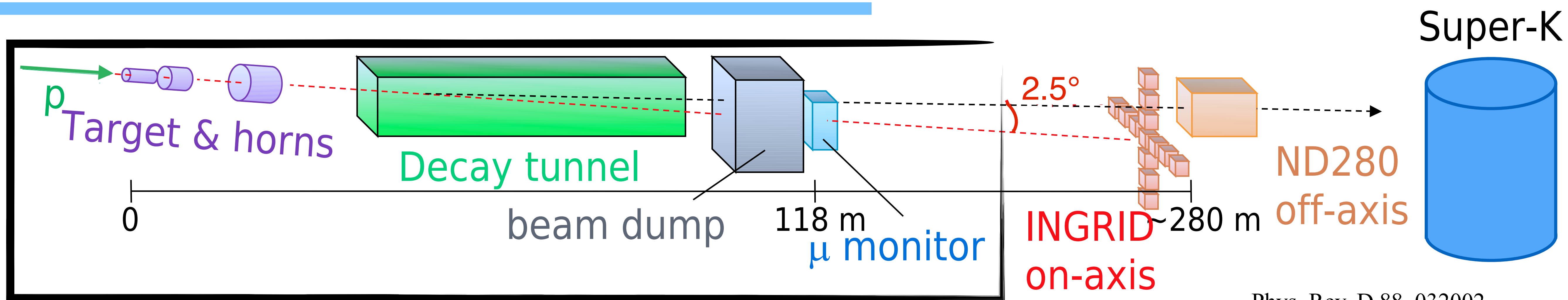

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30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target producing hadrons (mainly pions and kaons)

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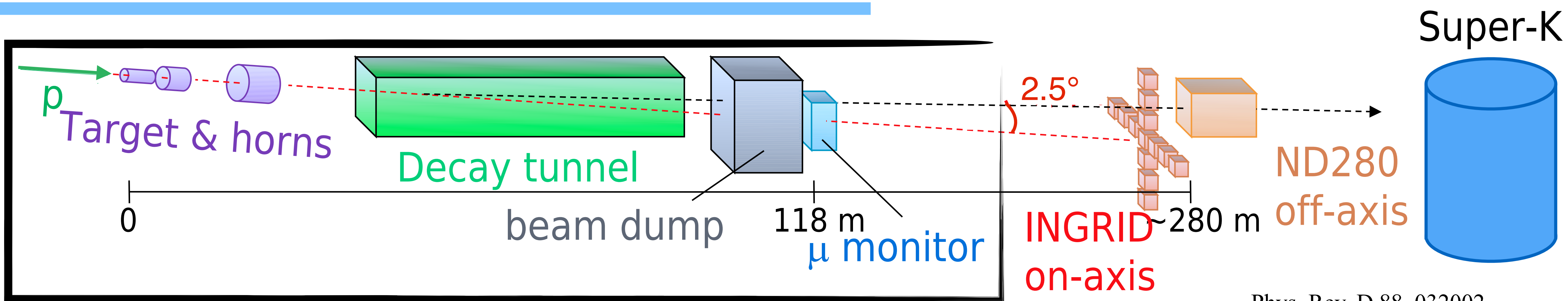

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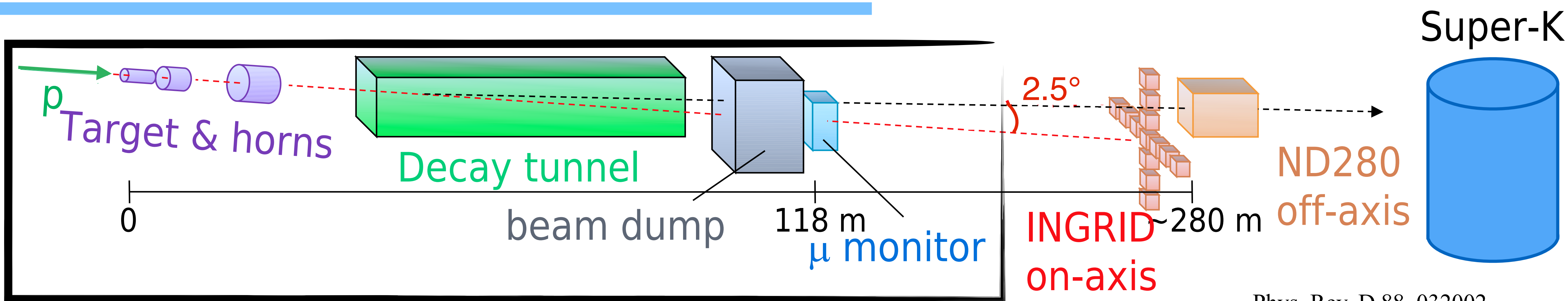

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Detectors 2.5° off the direction of the beam centered around 0.6 GeV. Off-axis method reduce high energy tail and maximize oscillation detection probabilities

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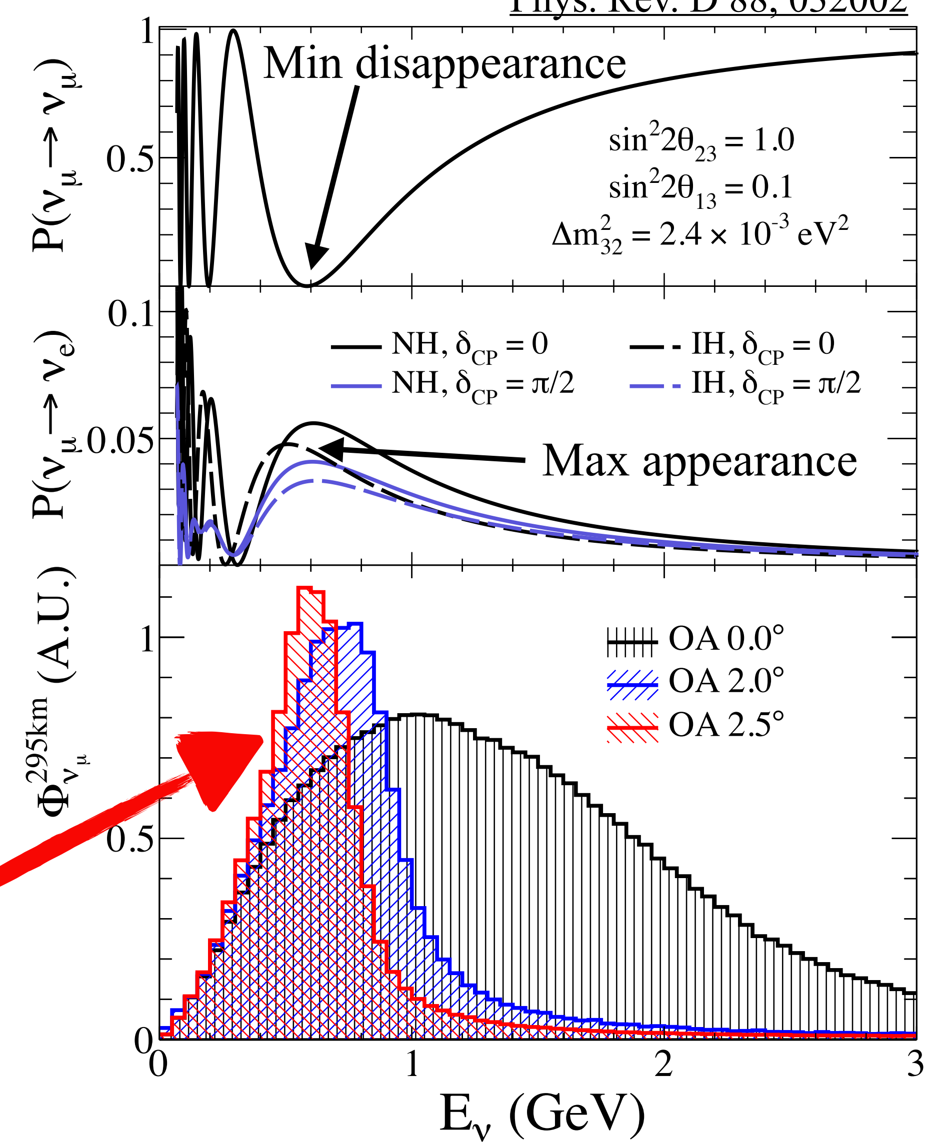
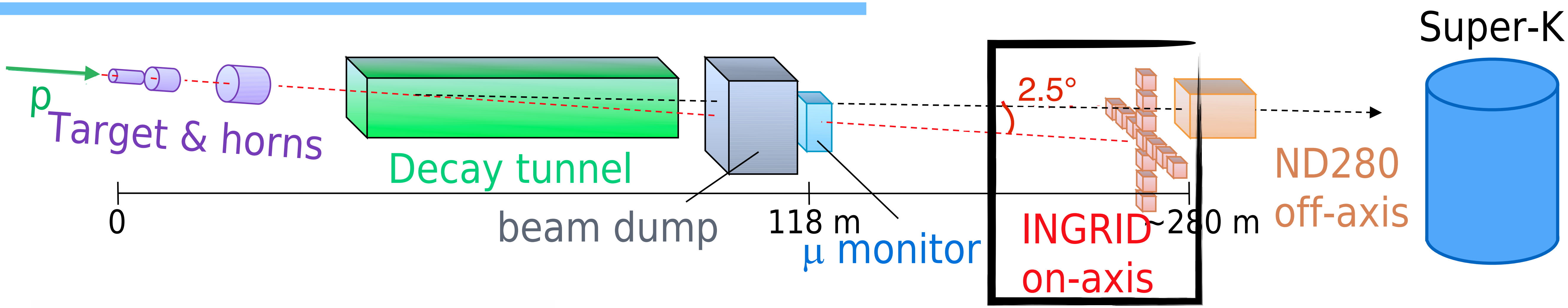
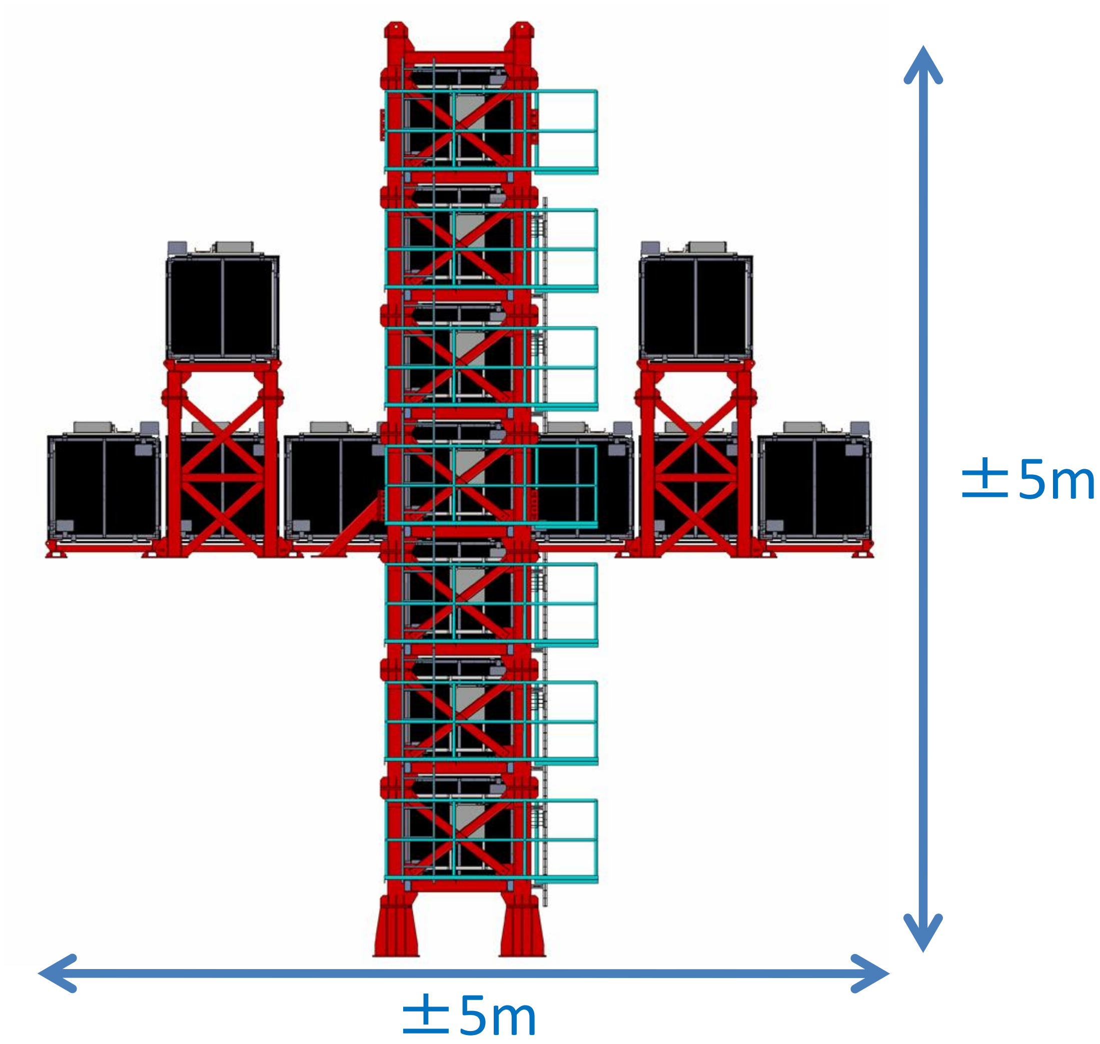


The on-axis near detector (INGRID)





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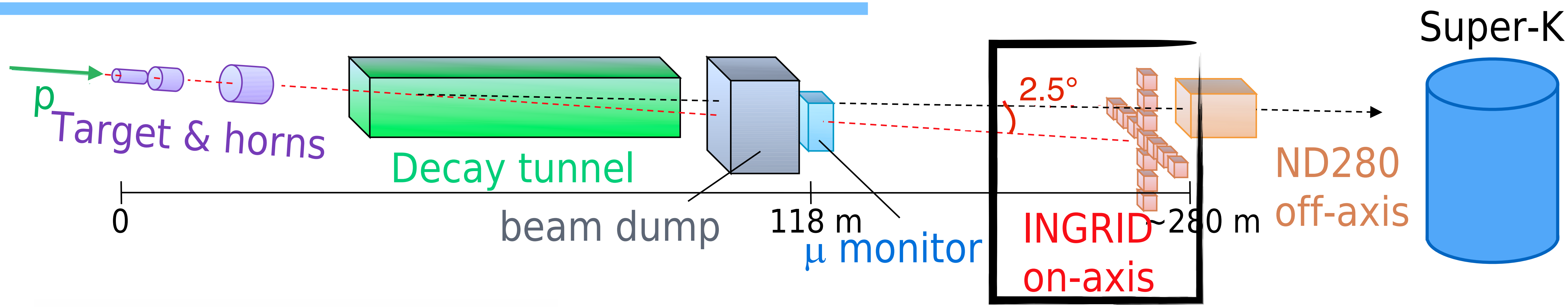

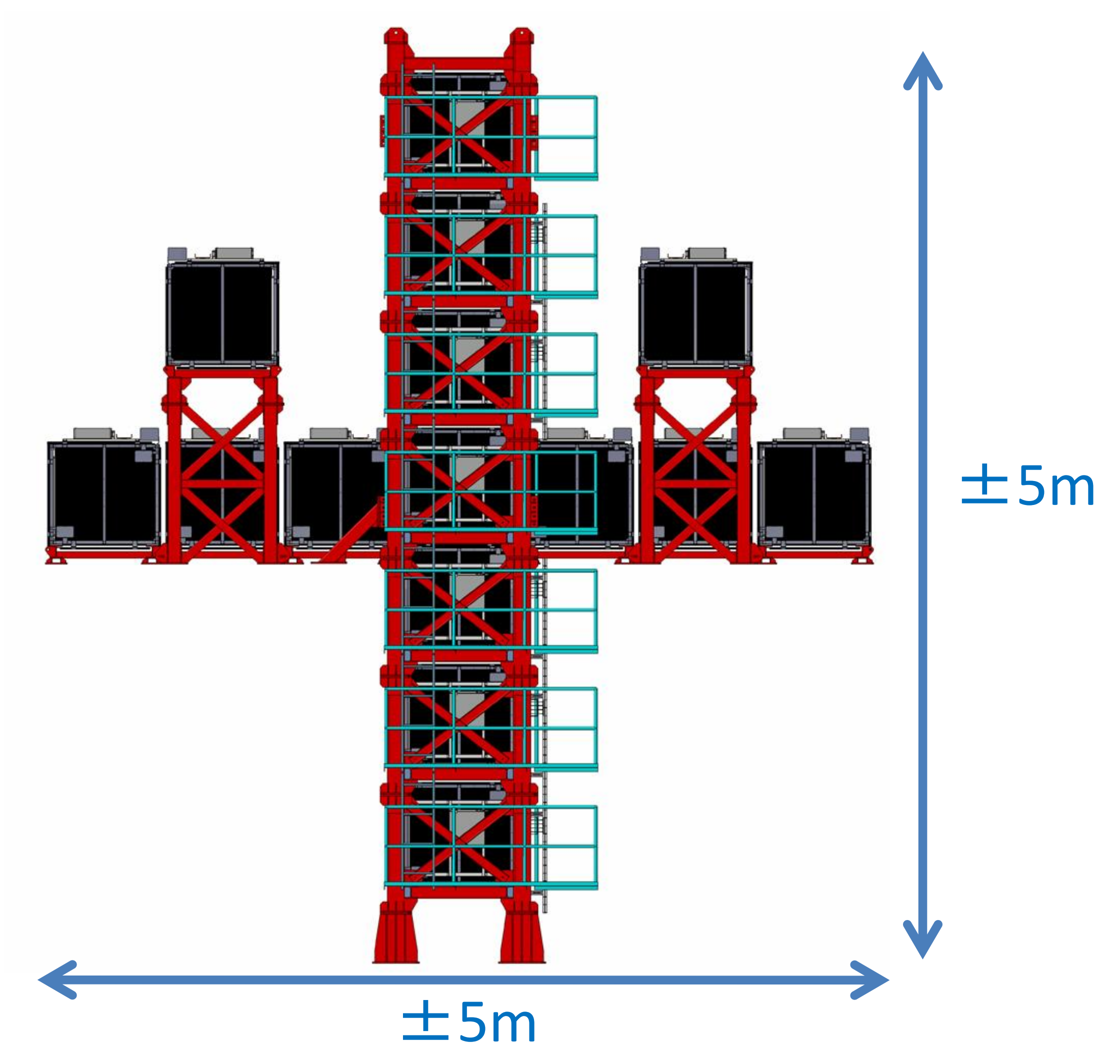

Monitor the beam stability and direction day-by-day looking at ν ($\overline{\nu}$) interactions

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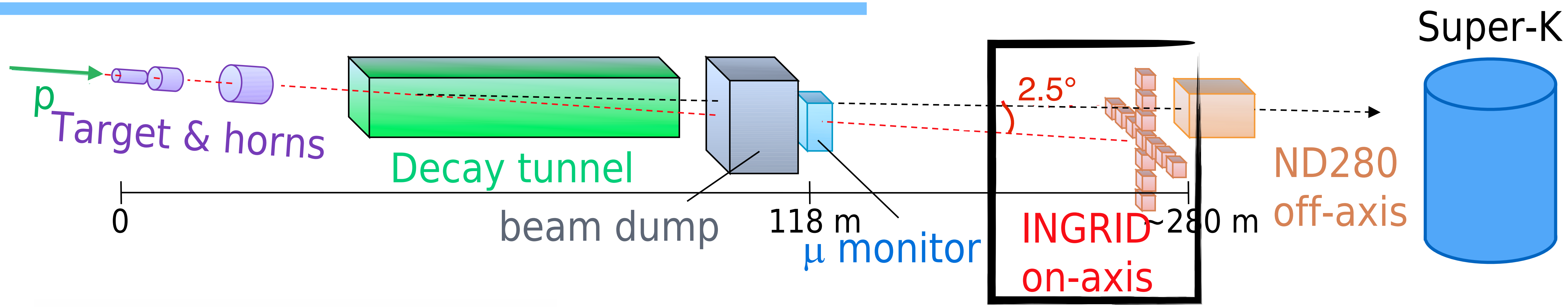

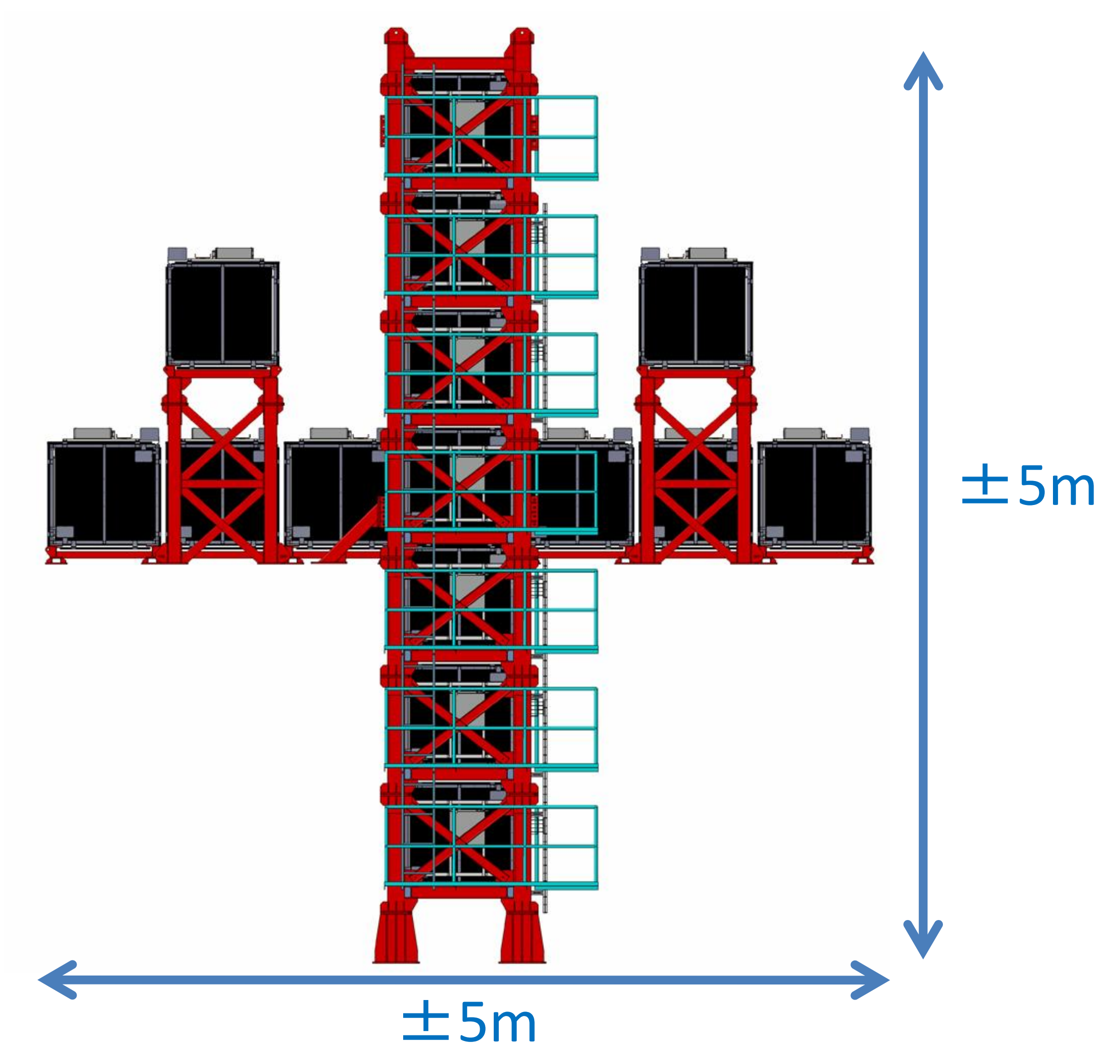

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14 modules arranged in a cross; two others placed at off-diagonal positions

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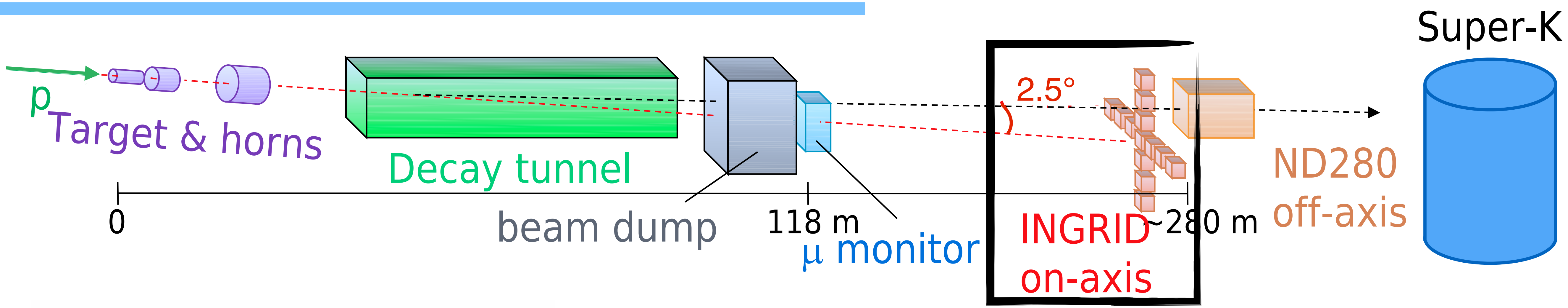

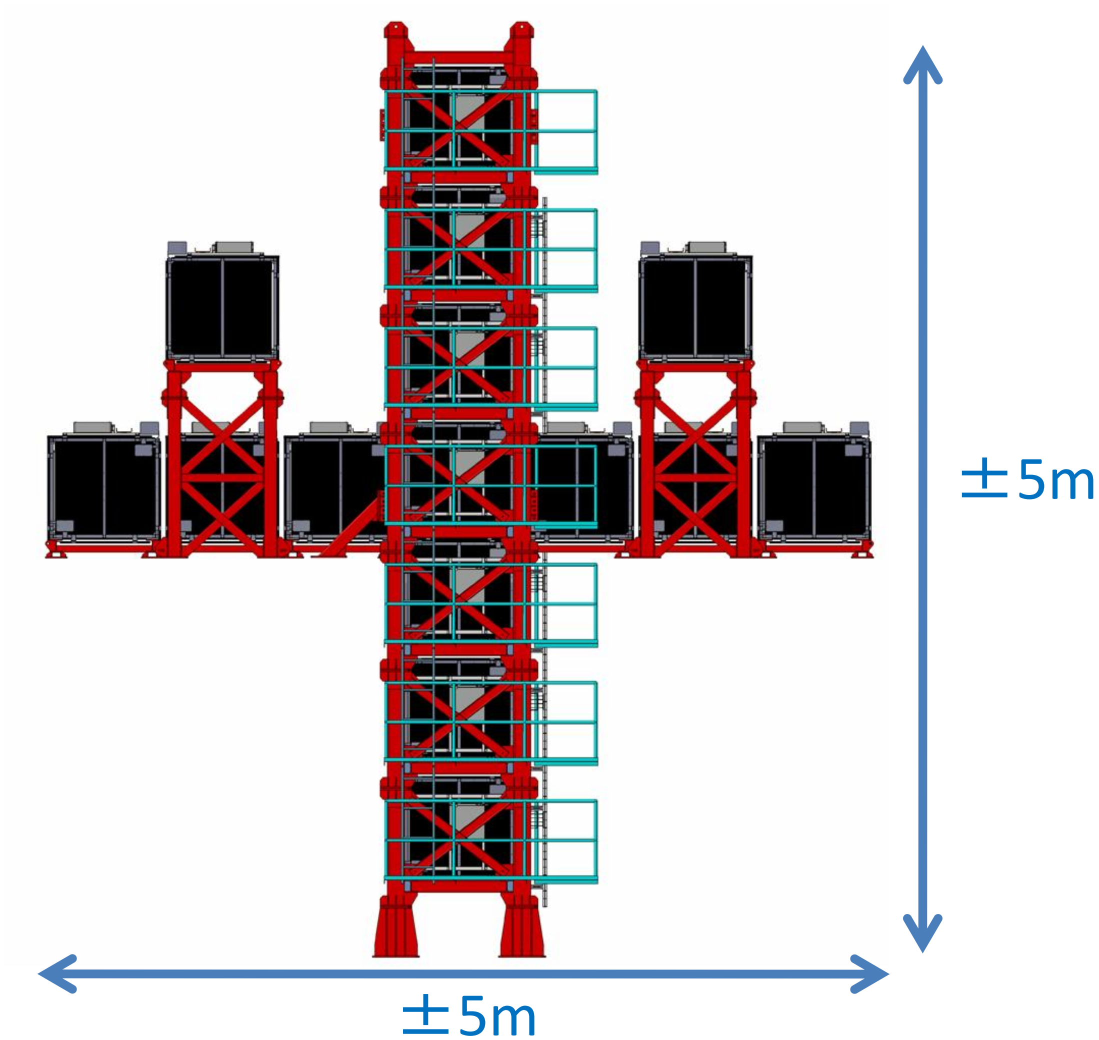

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1 extra module made of scintillators and water at the center of the cross

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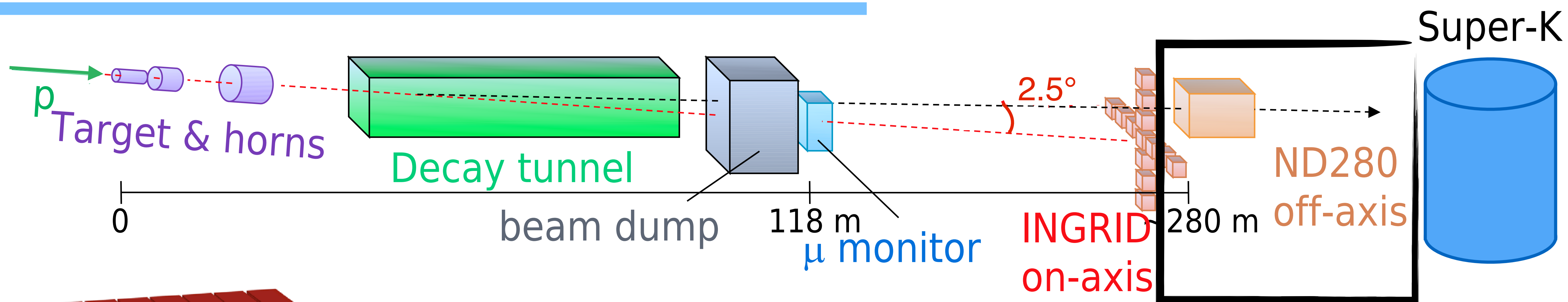

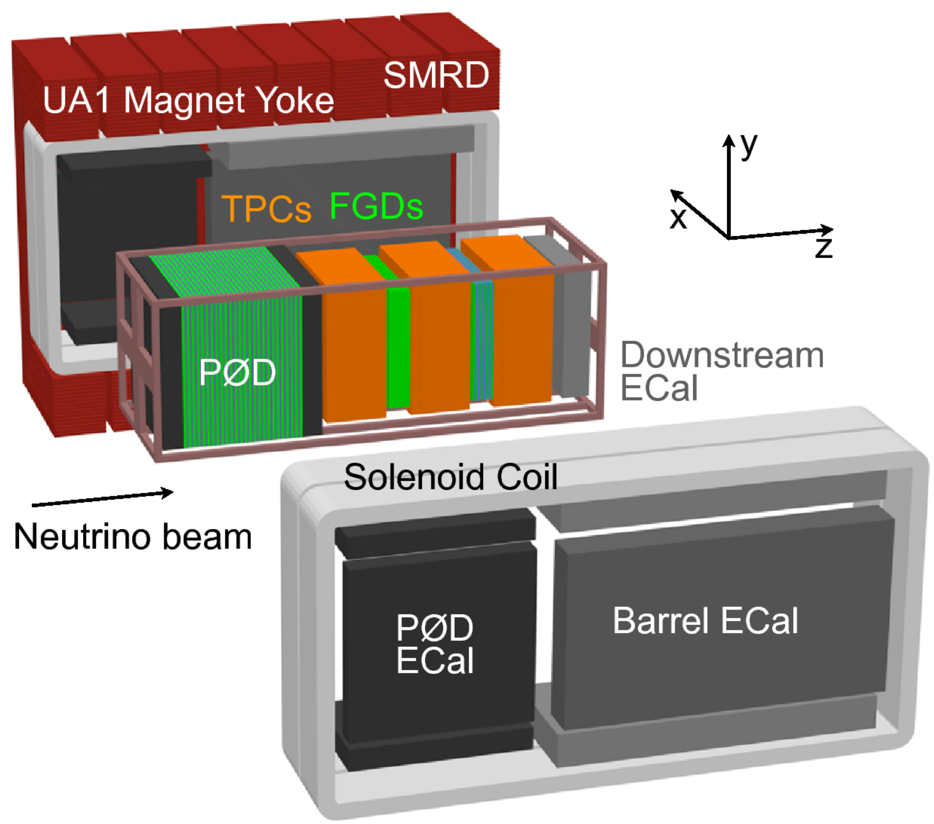

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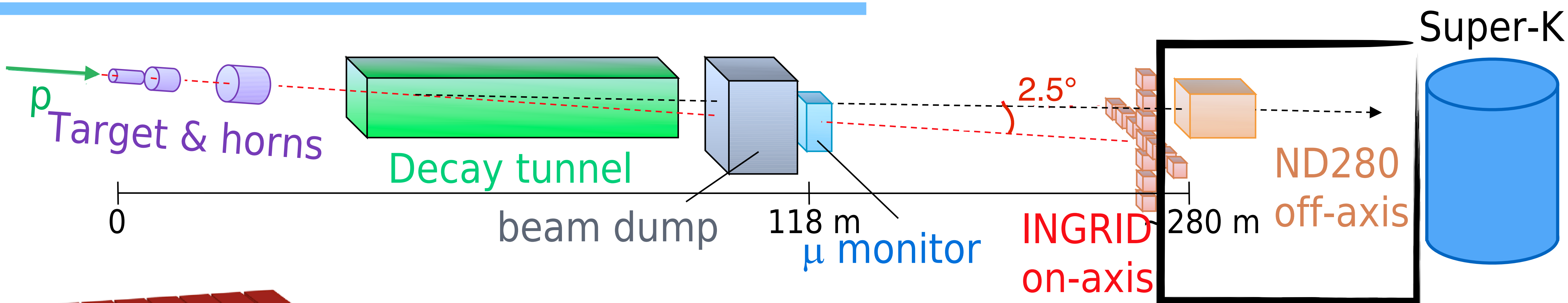

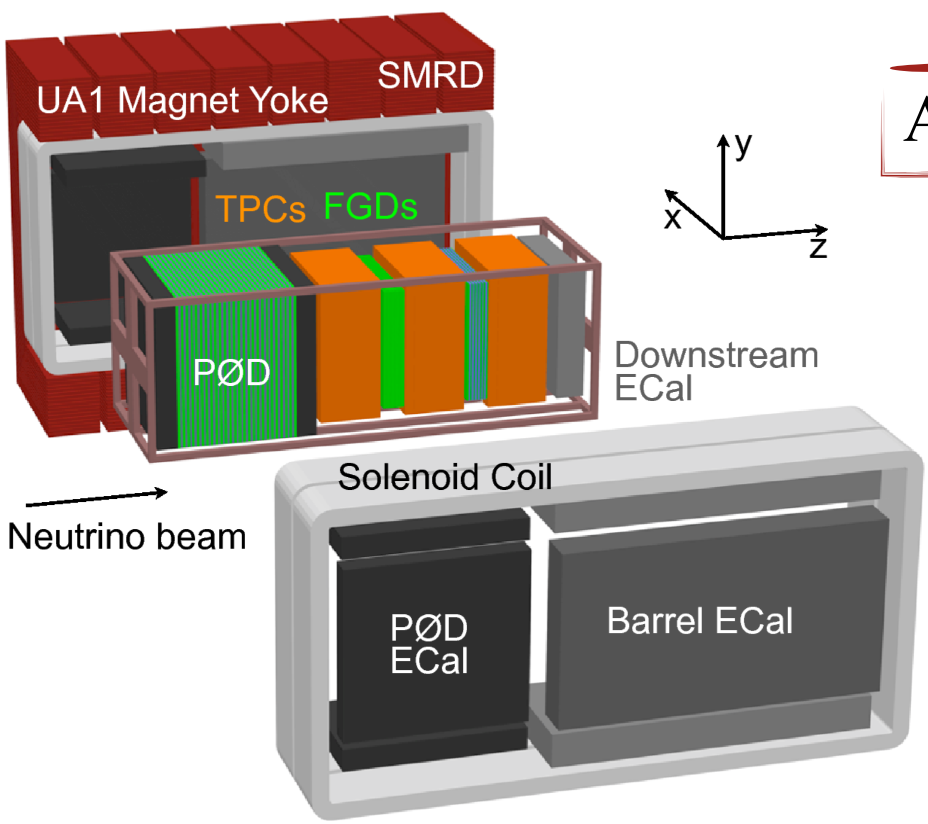

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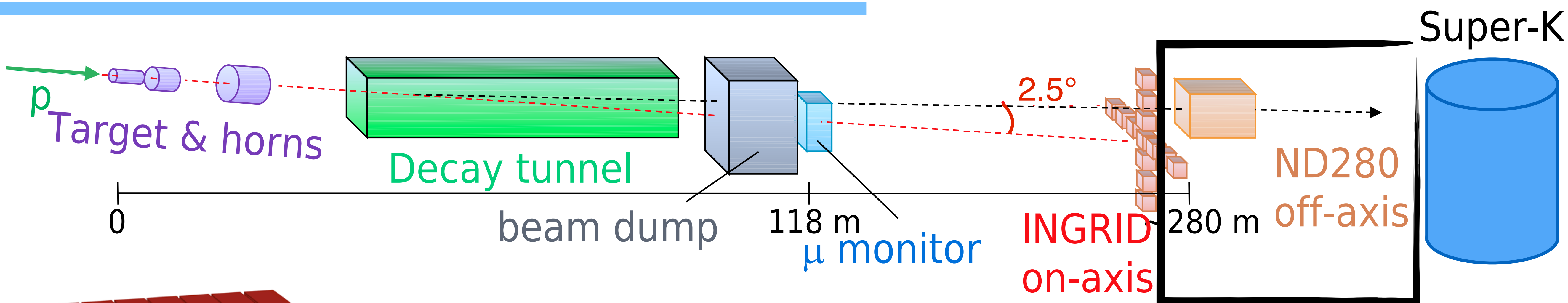

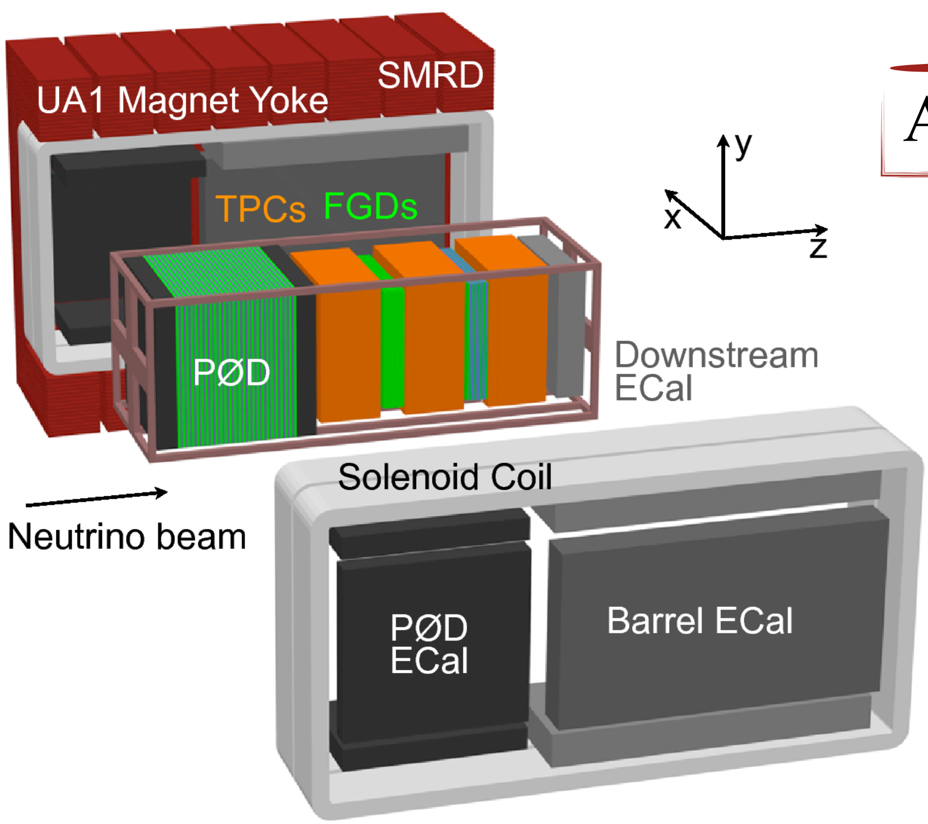

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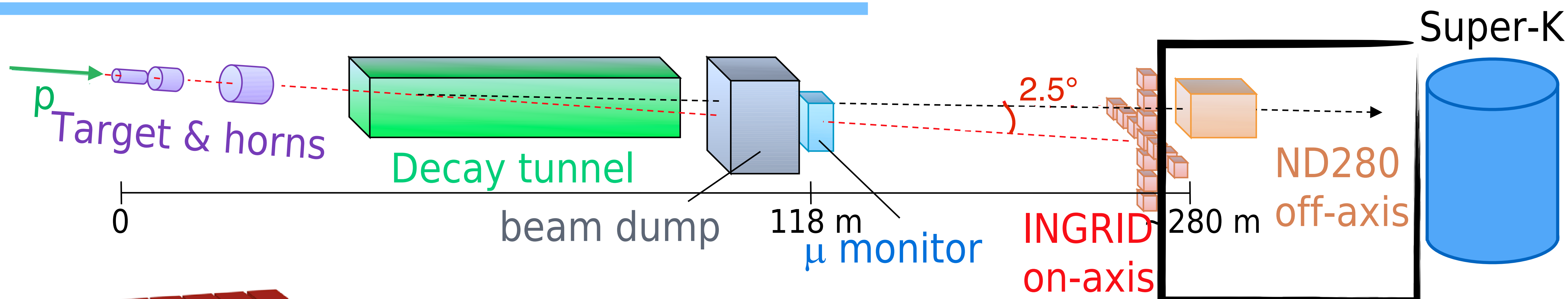

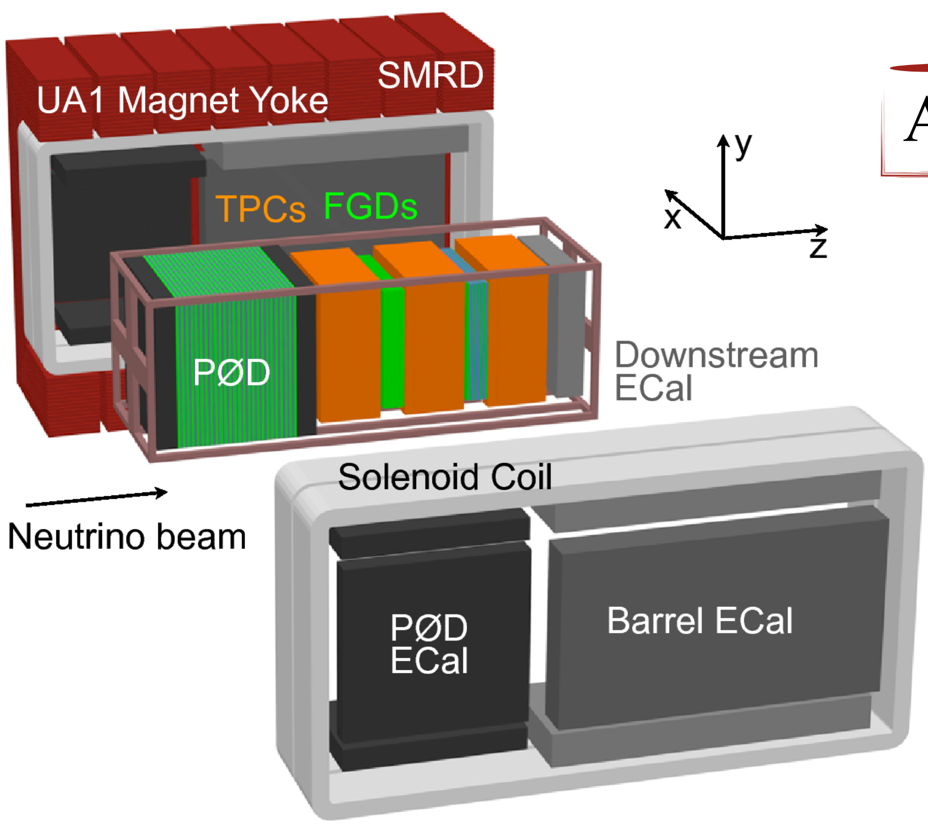

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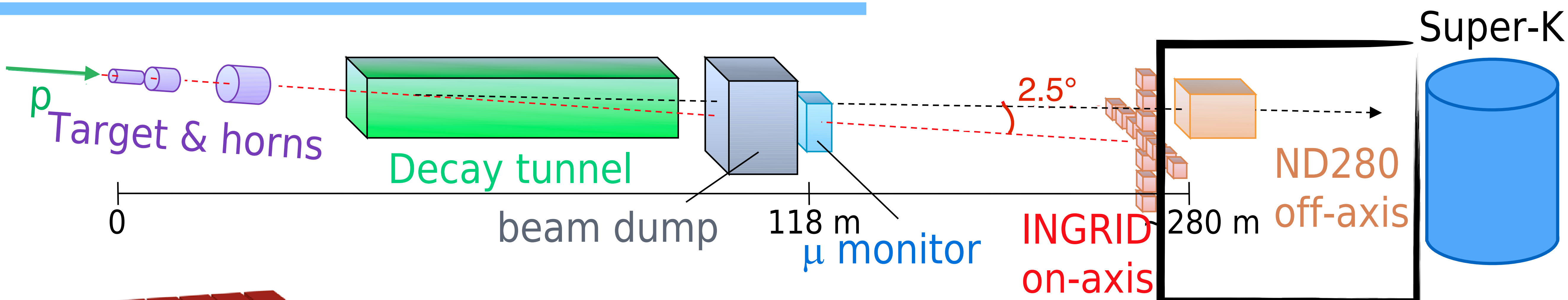

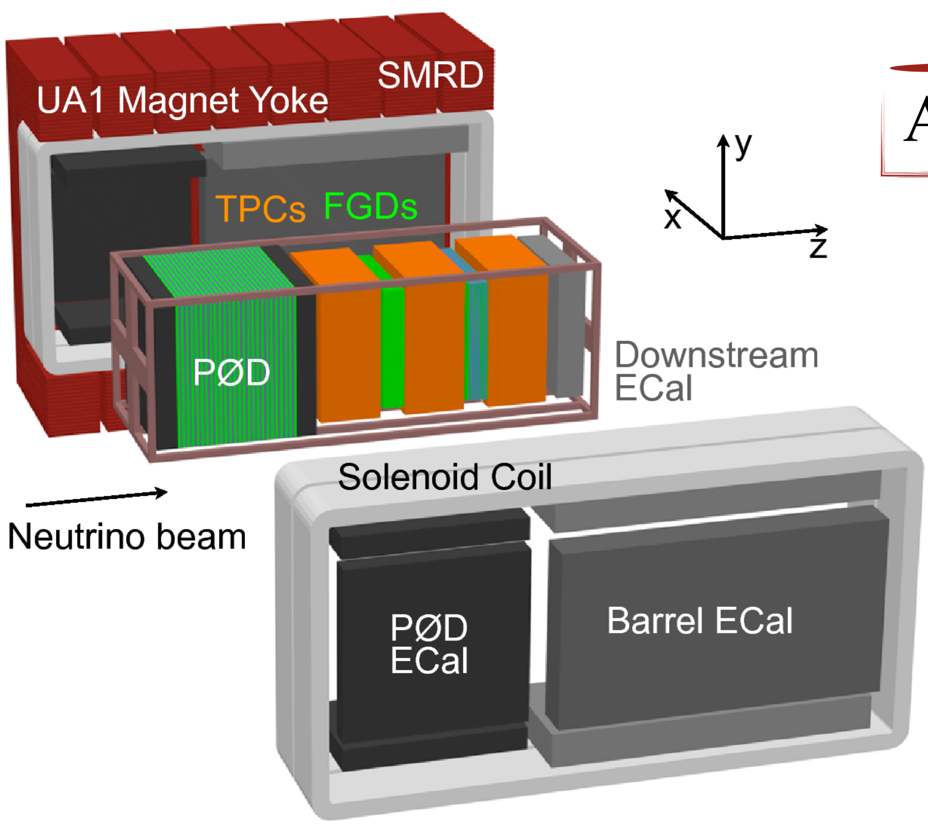

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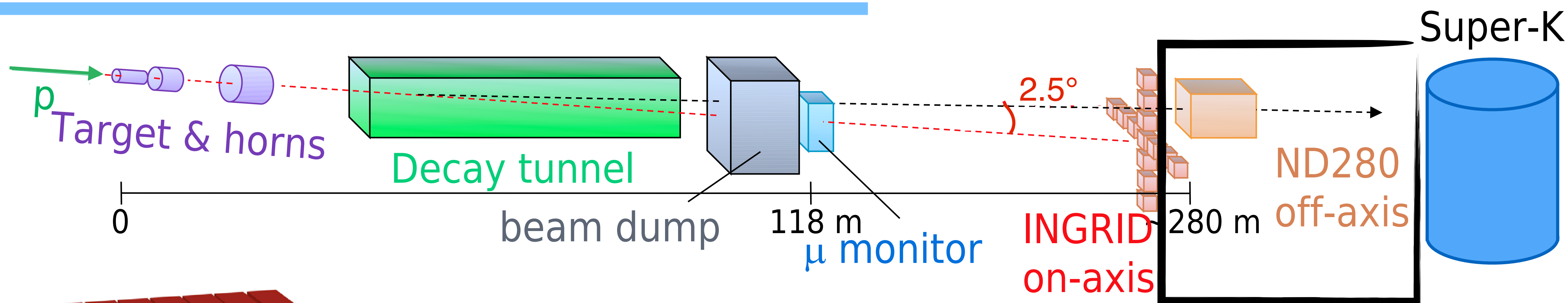

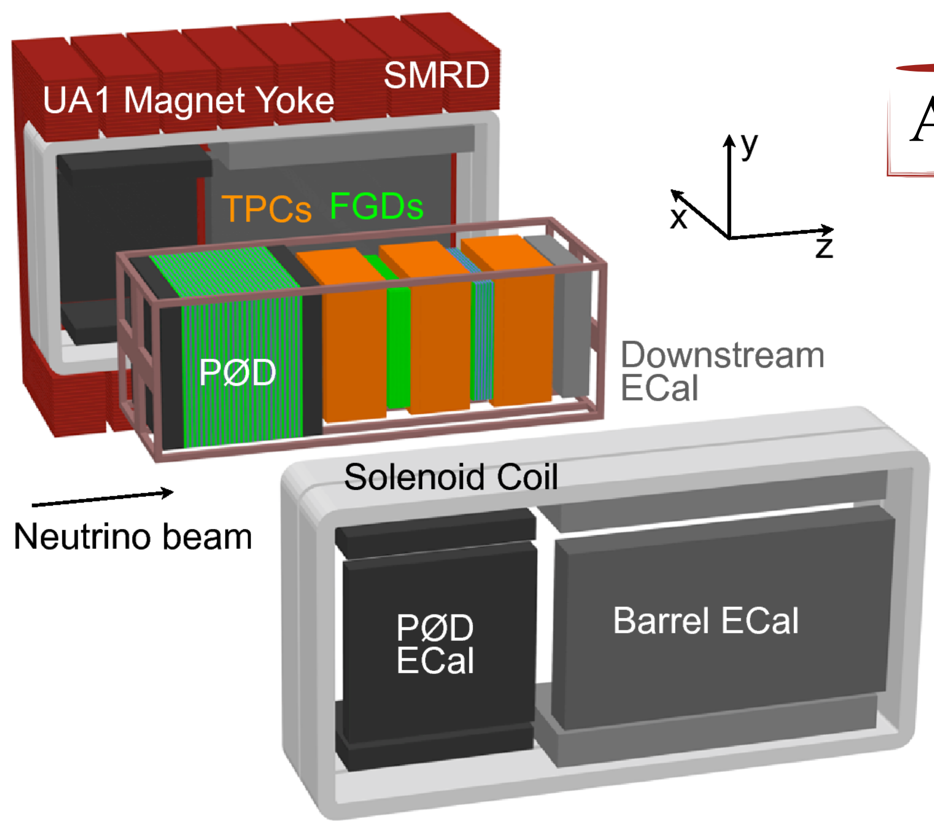

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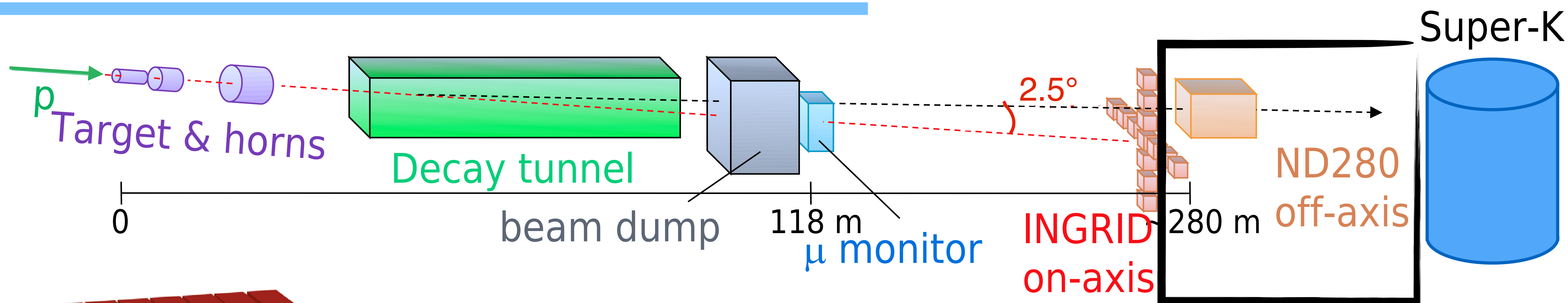

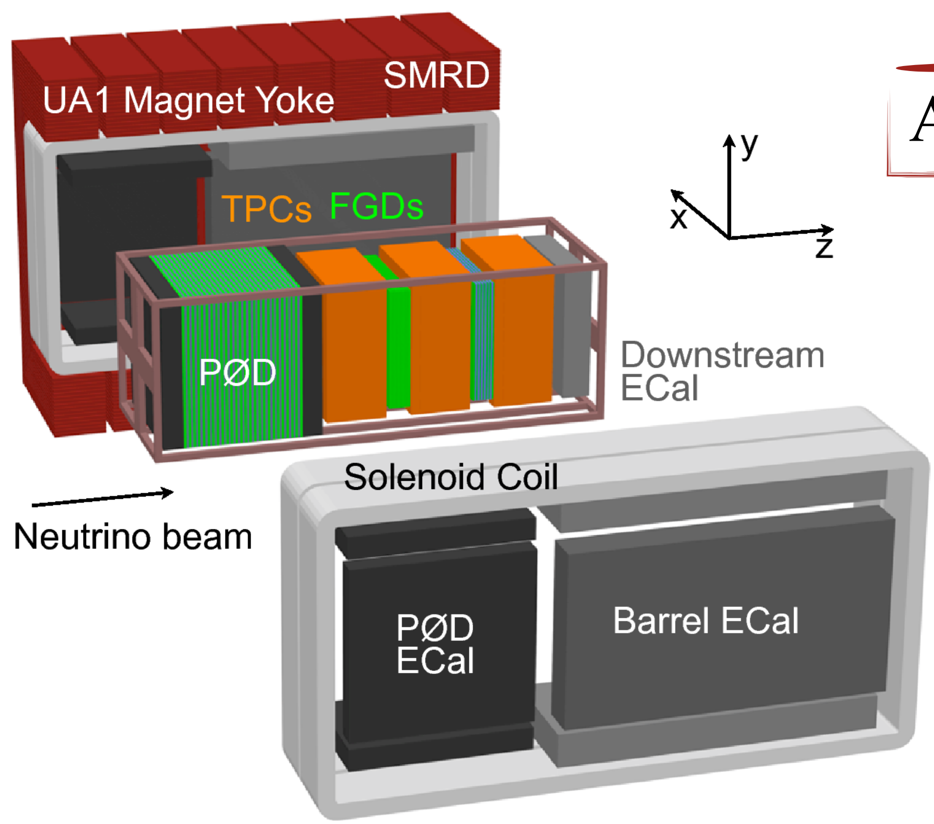

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An electromagnetic calorimeter (ECal) is used to distinguish tracks from showers

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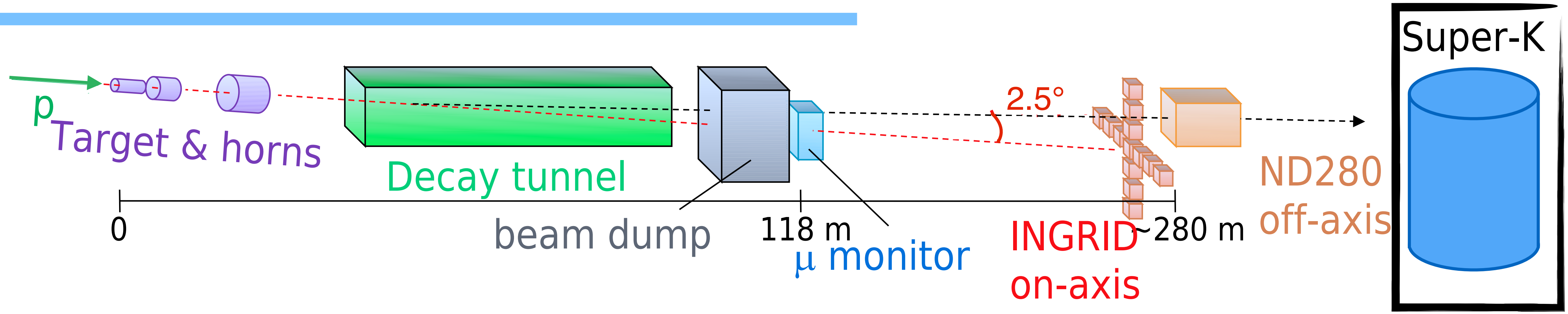

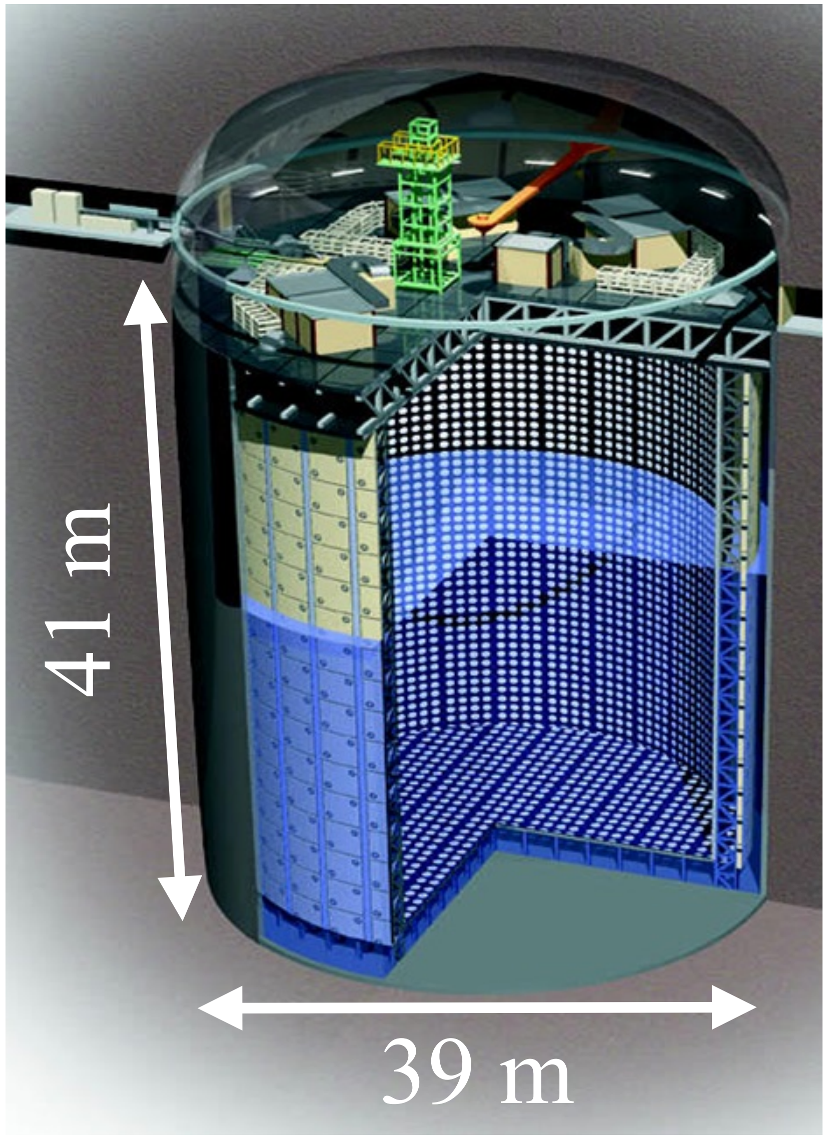

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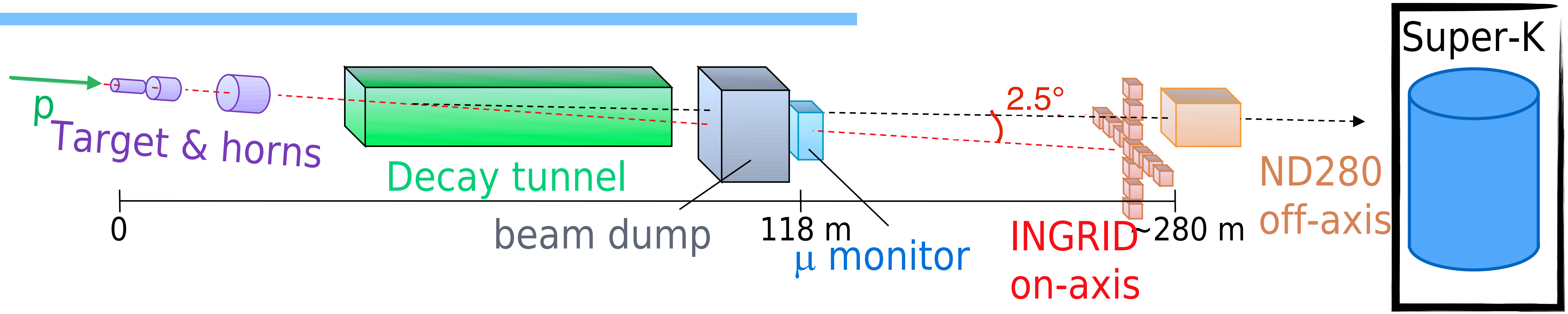

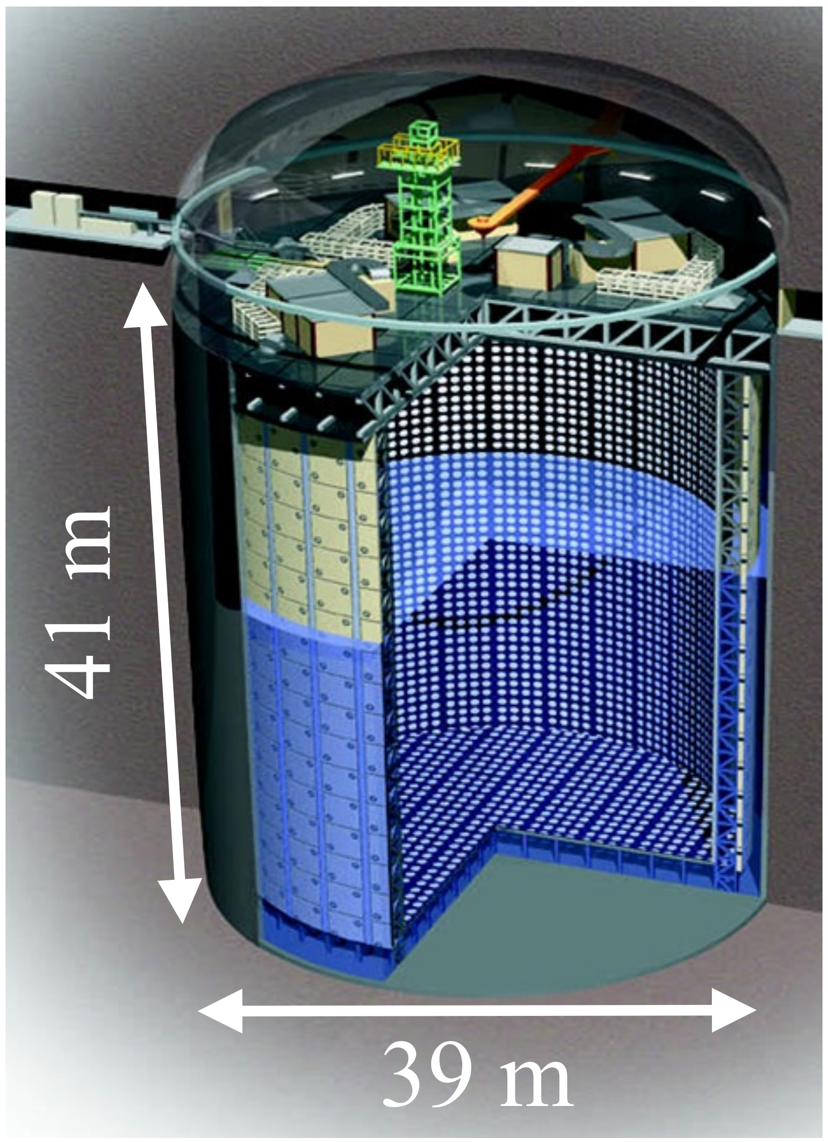

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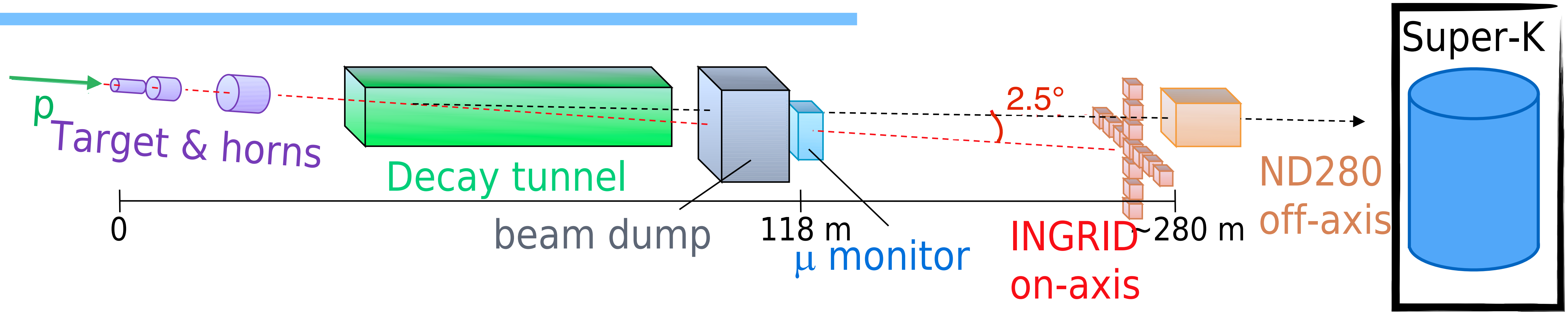

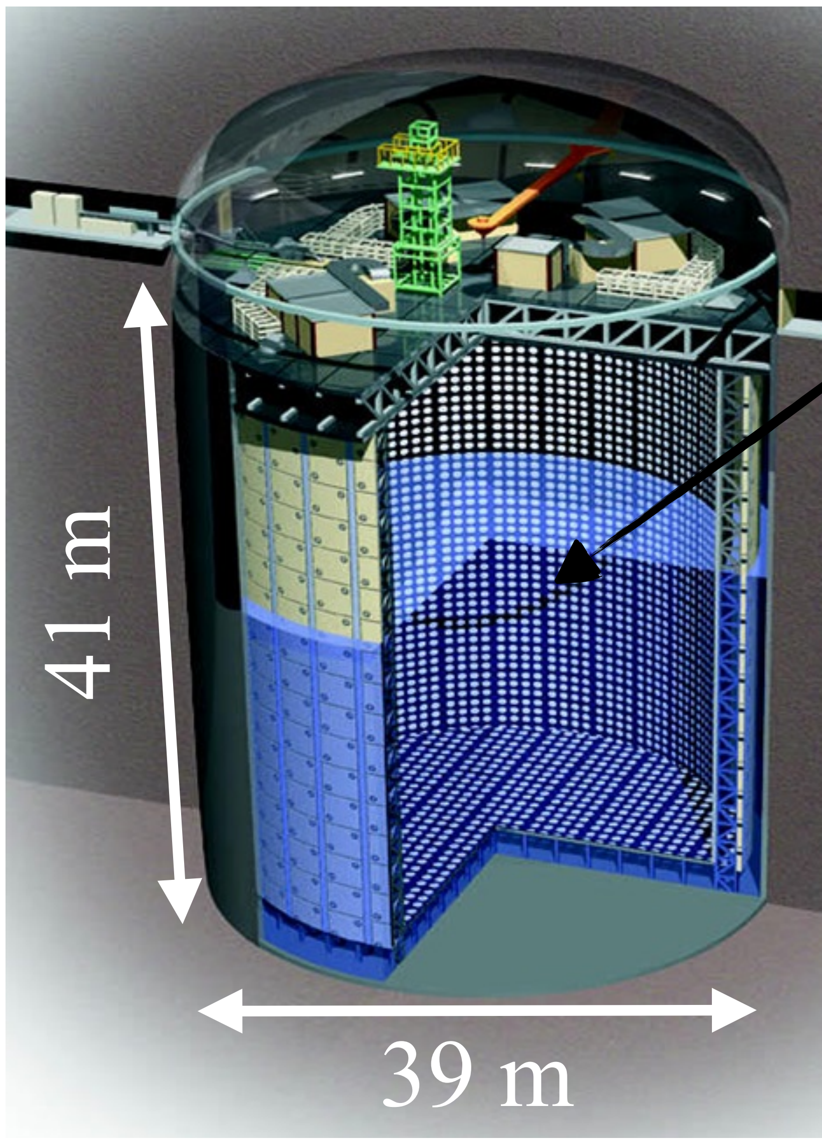

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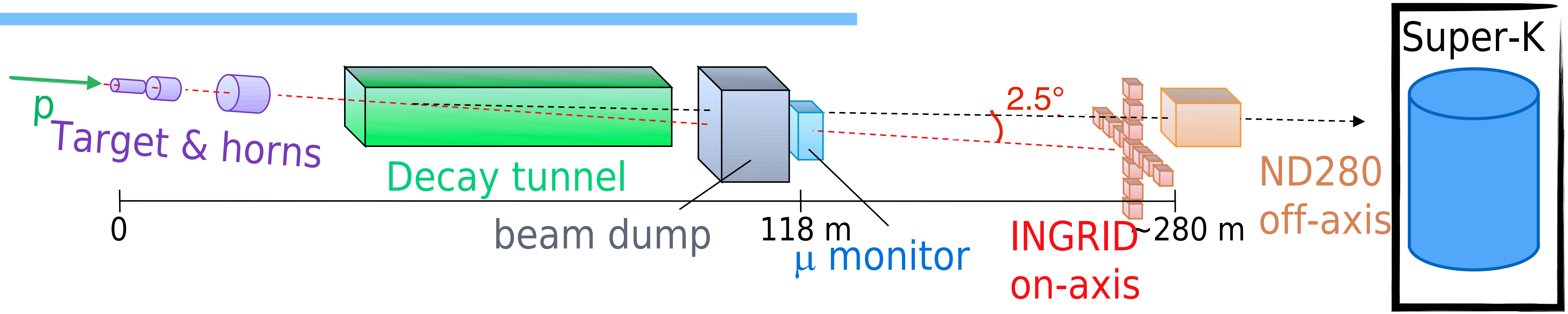

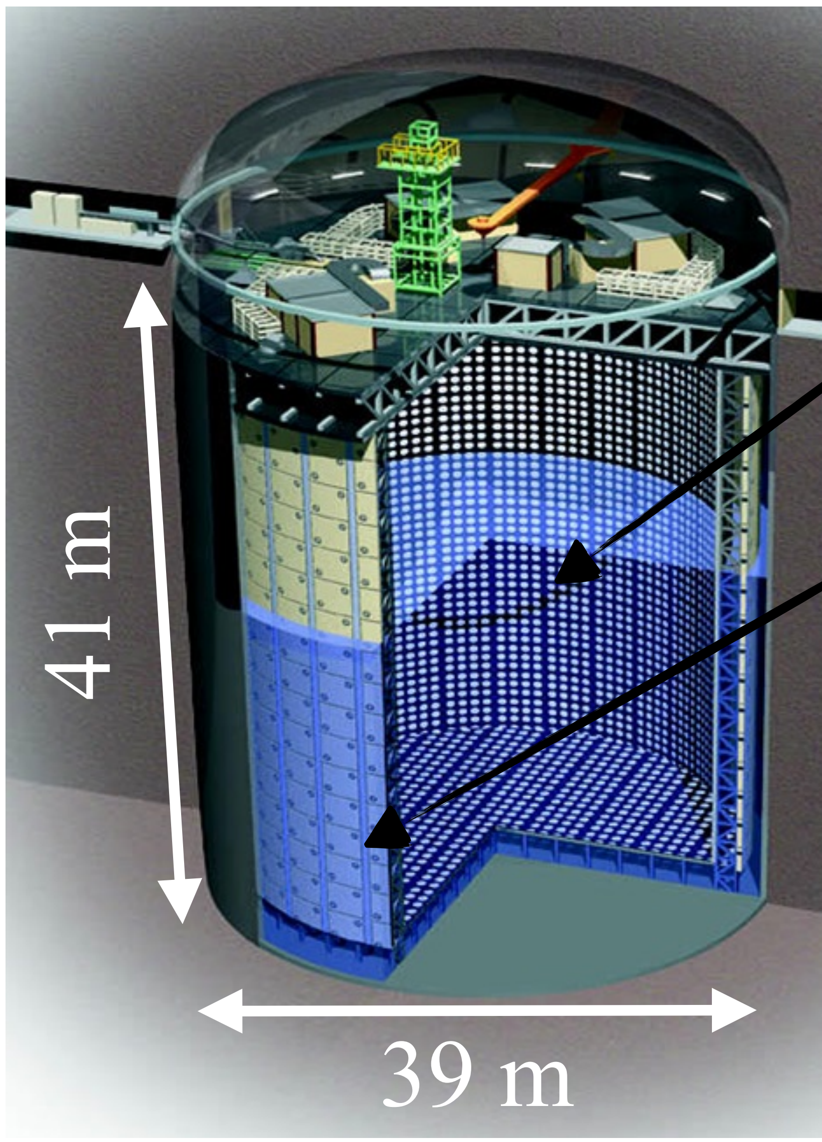

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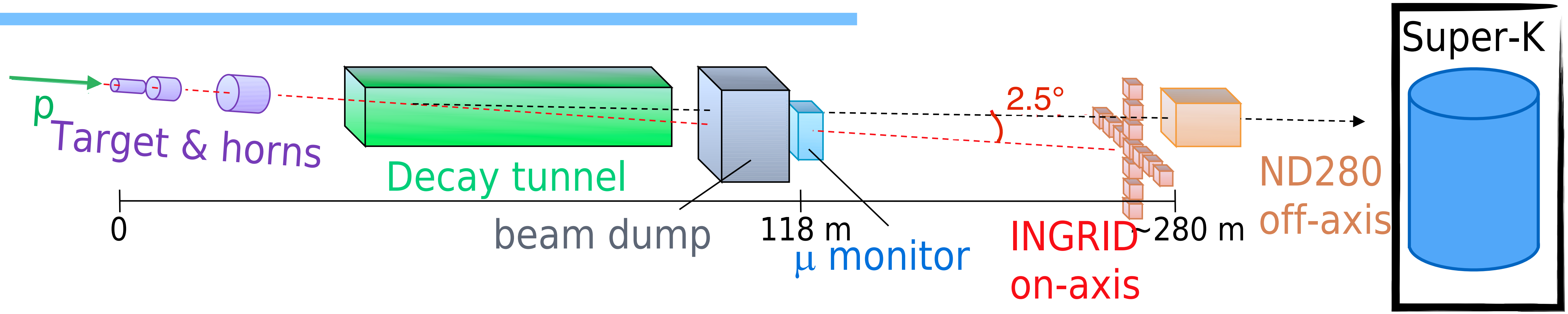
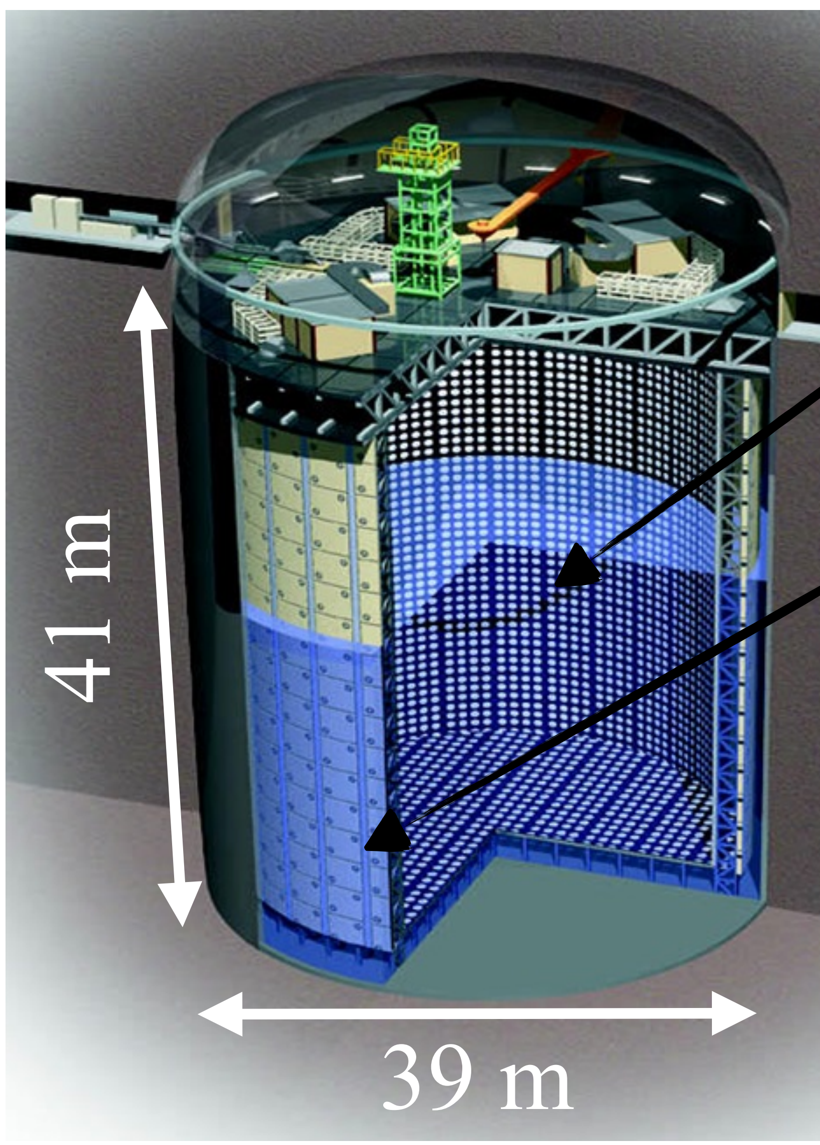
20 inch PMTs

Outer detector ~2000
8 inch PMTs

Super-Kamiokande (SK)





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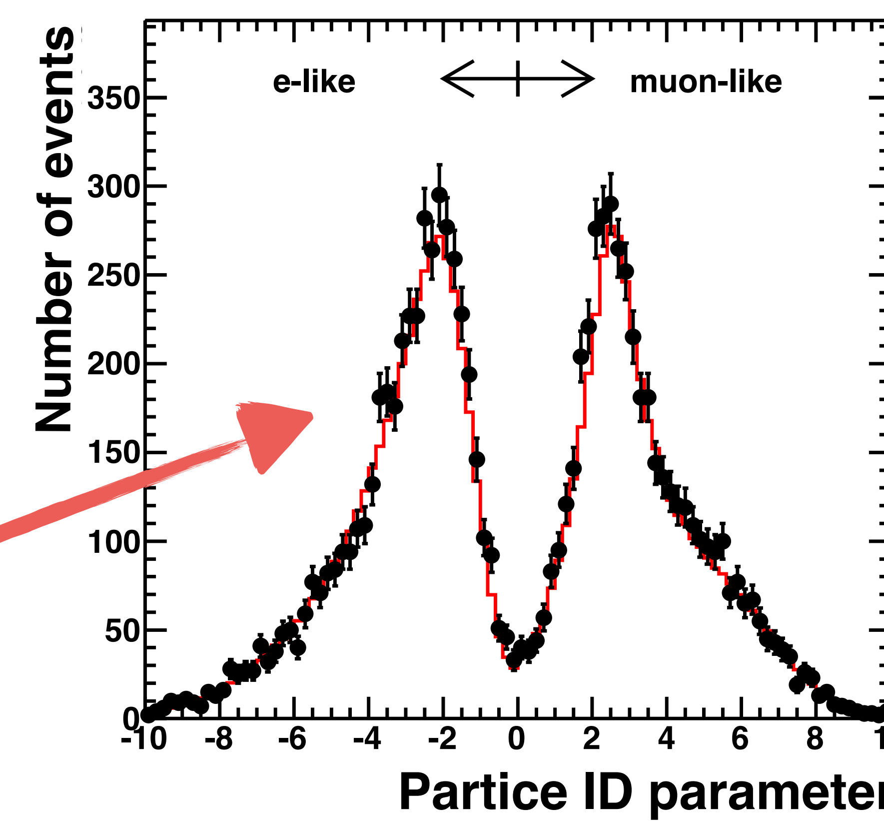
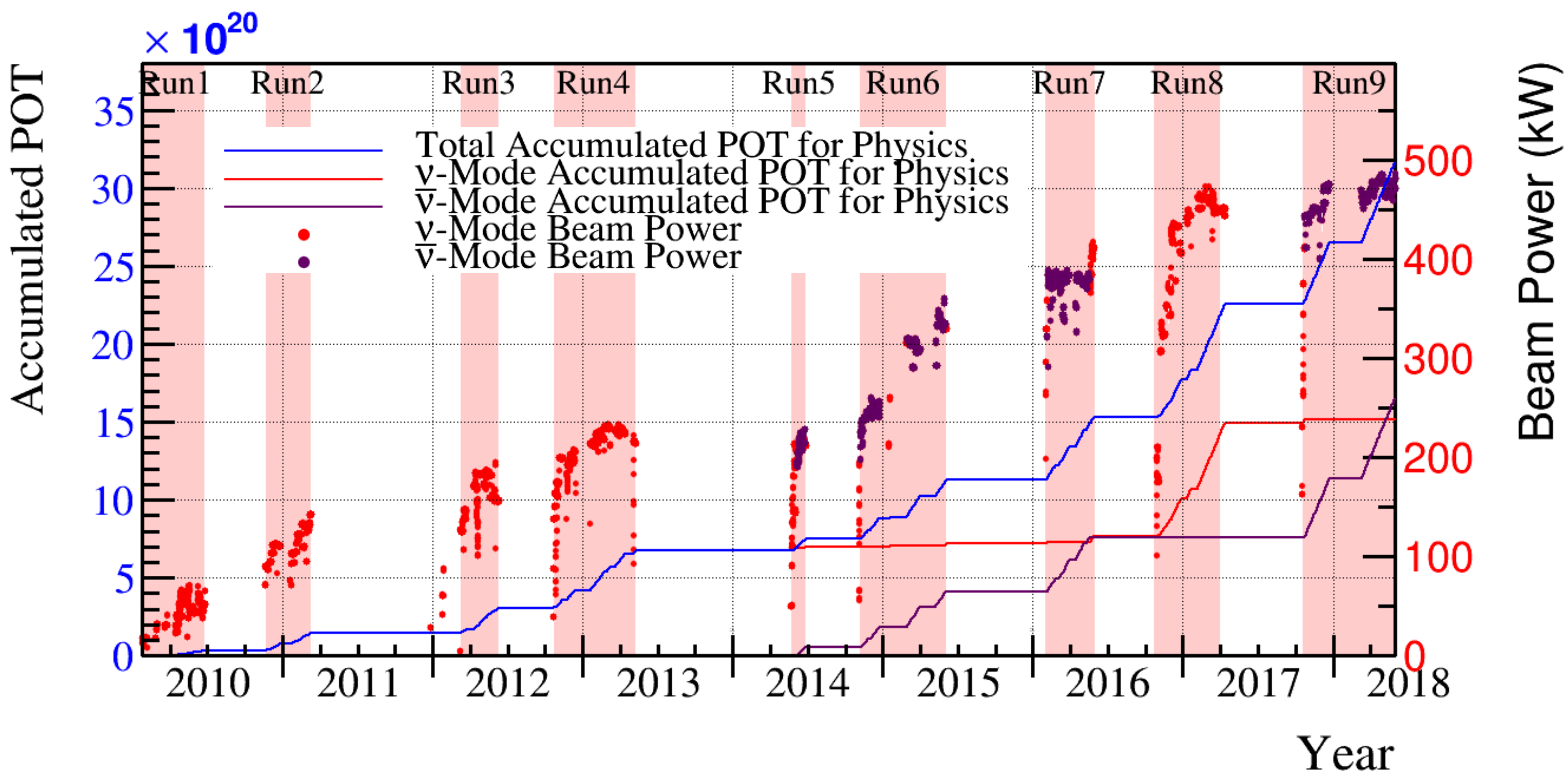
Very good μ/e separation



Collected data

- Total proton on target (POT) collected: 3.1×10^{21} (48% in ν mode and 52% in $\bar{\nu}$ mode)
- Analysis results presented today: 1.5×10^{21} POT (53%) in ν mode and 1.3×10^{21} POT(46%) in $\bar{\nu}$ mode
- Achieved a beam power of ~500 kW!



T2K oscillation analysis strategy

T2K oscillation analysis strategy

Flux prediction:
proton beam measurements and external hadron production measurements

Neutrino interactions model:
tuned using external data

T2K oscillation analysis strategy

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ND280 measurements:
select CC ν_μ and $\overline{\nu}_\mu$ interactions
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ND280 measurements predict the expected events at SK

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Select CC $\nu_\mu/\overline{\nu}_\mu$ and $\nu_e/\overline{\nu}_e$ candidates
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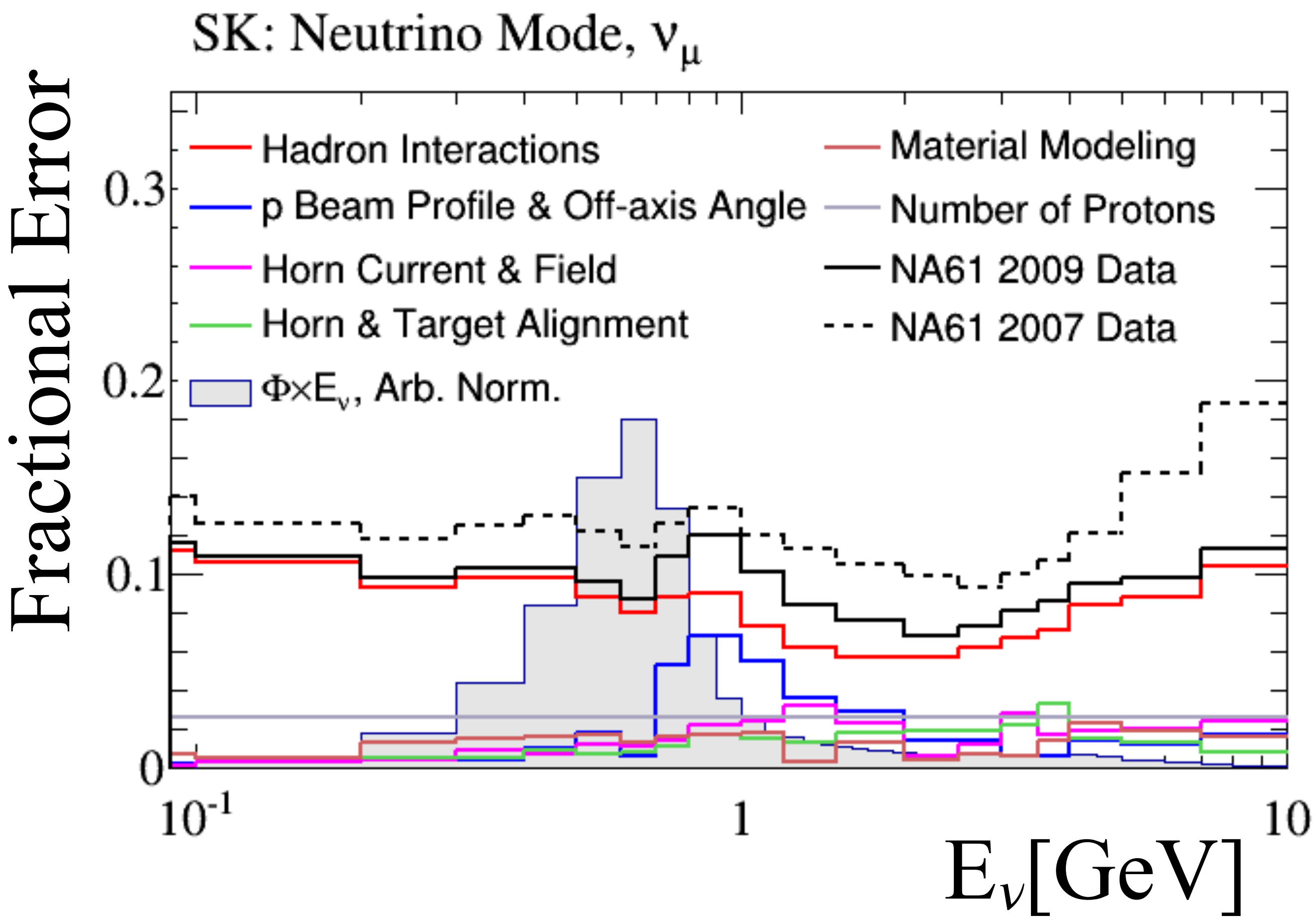
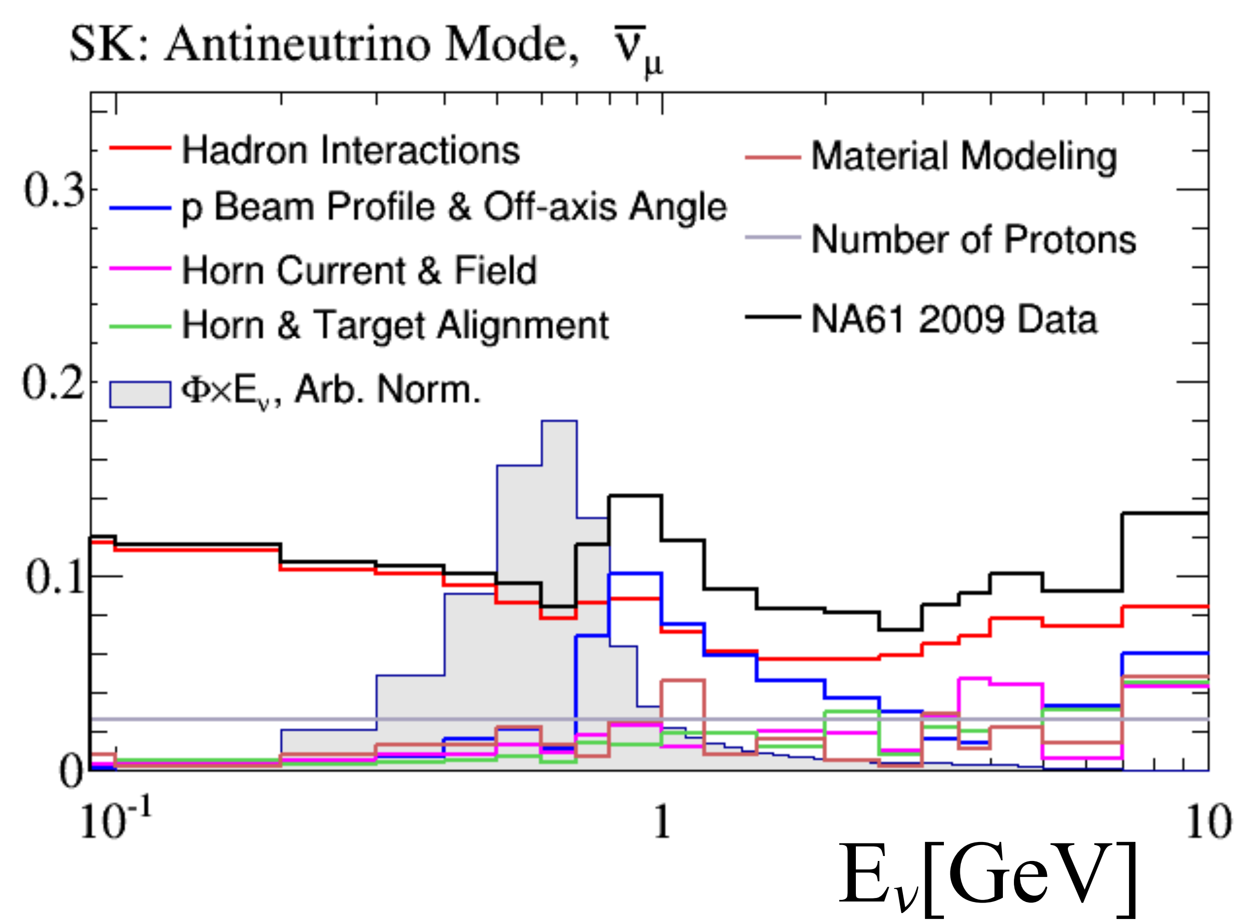
after the oscillations

Neutrino interactions model:
tuned using external data

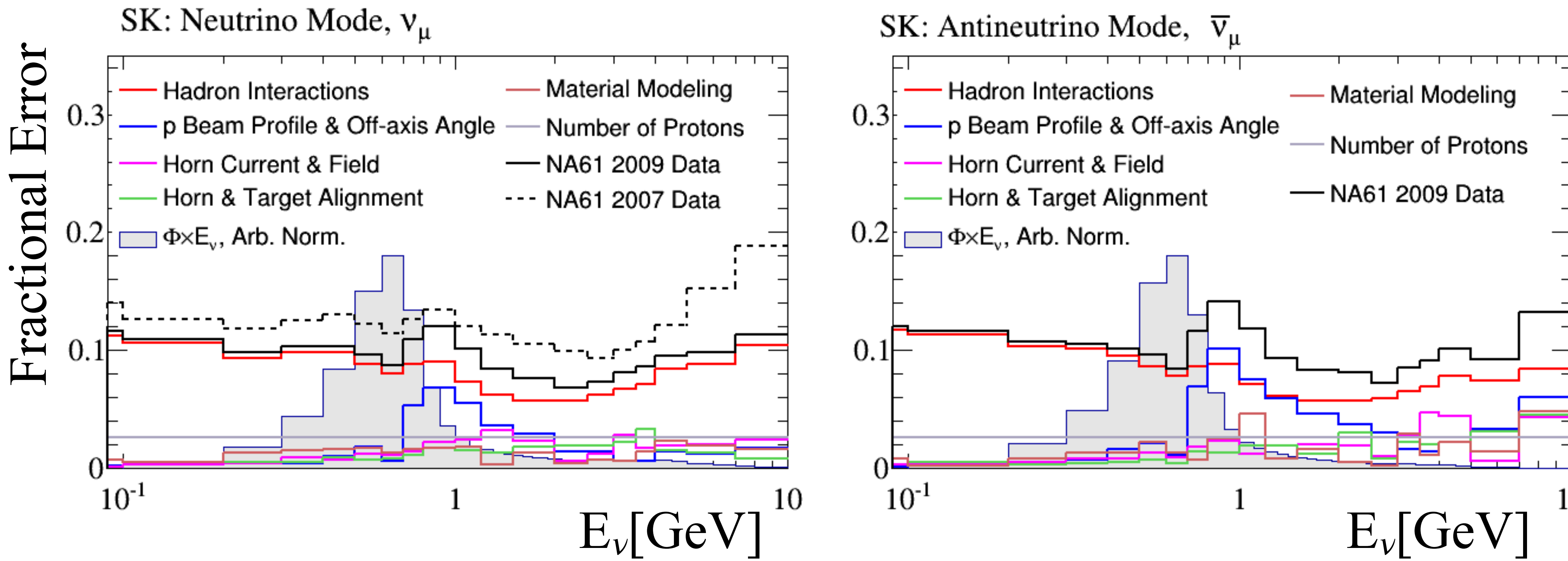
Extract oscillation parameters

Neutrino fluxes



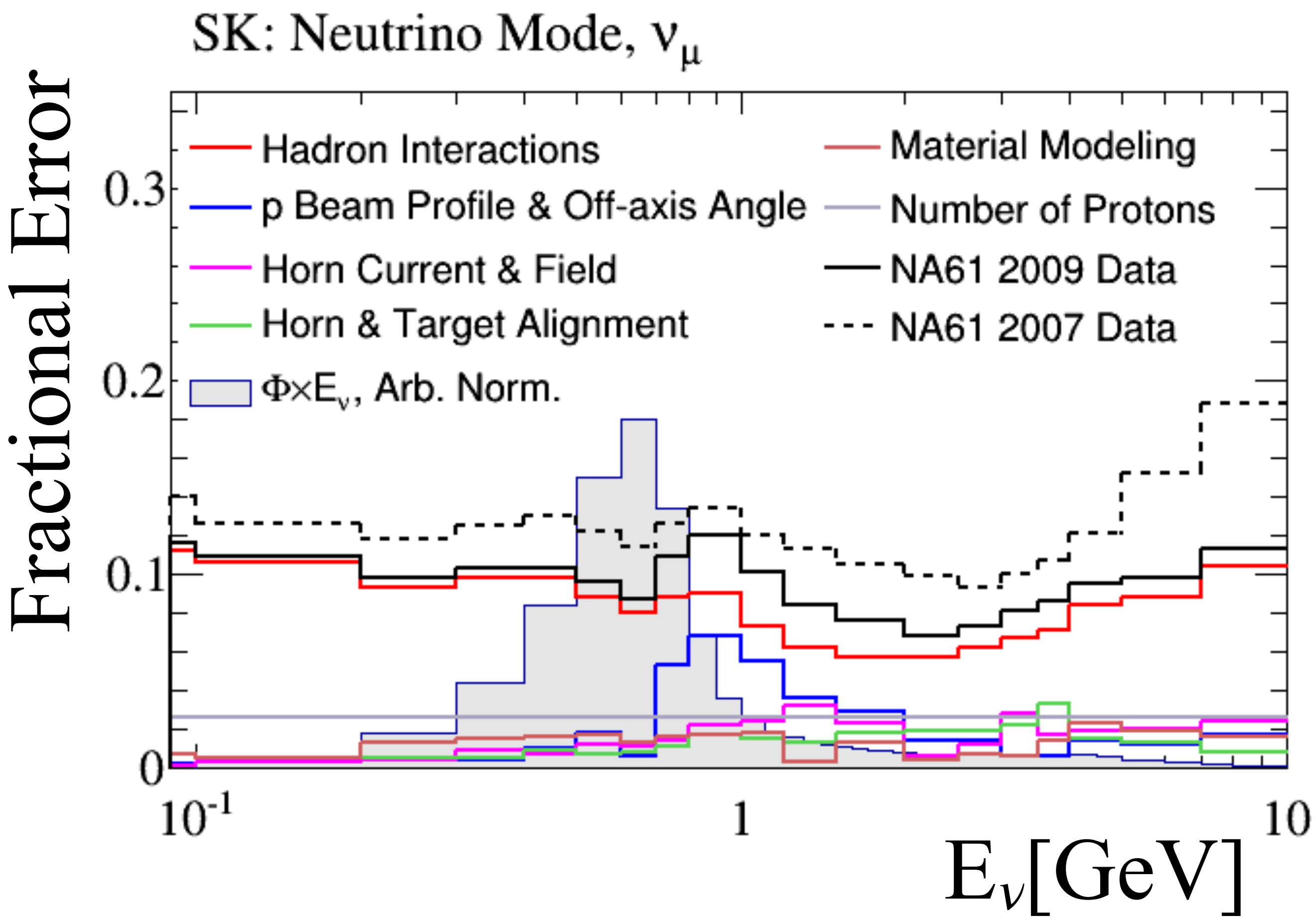


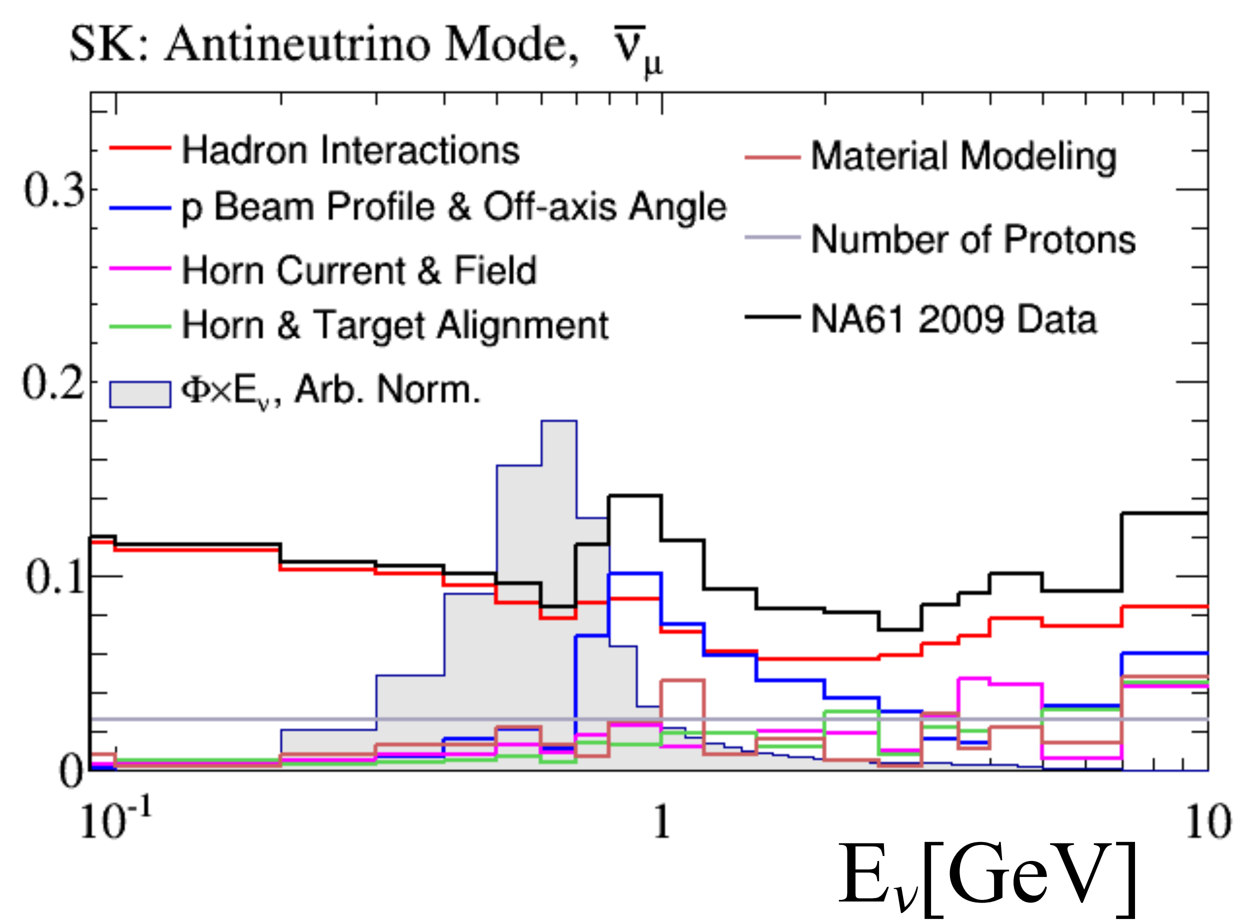
Neutrino fluxes



Fluxes known with uncertainties smaller than 10% based on NA61/SHINE thin-target measurements

Neutrino fluxes

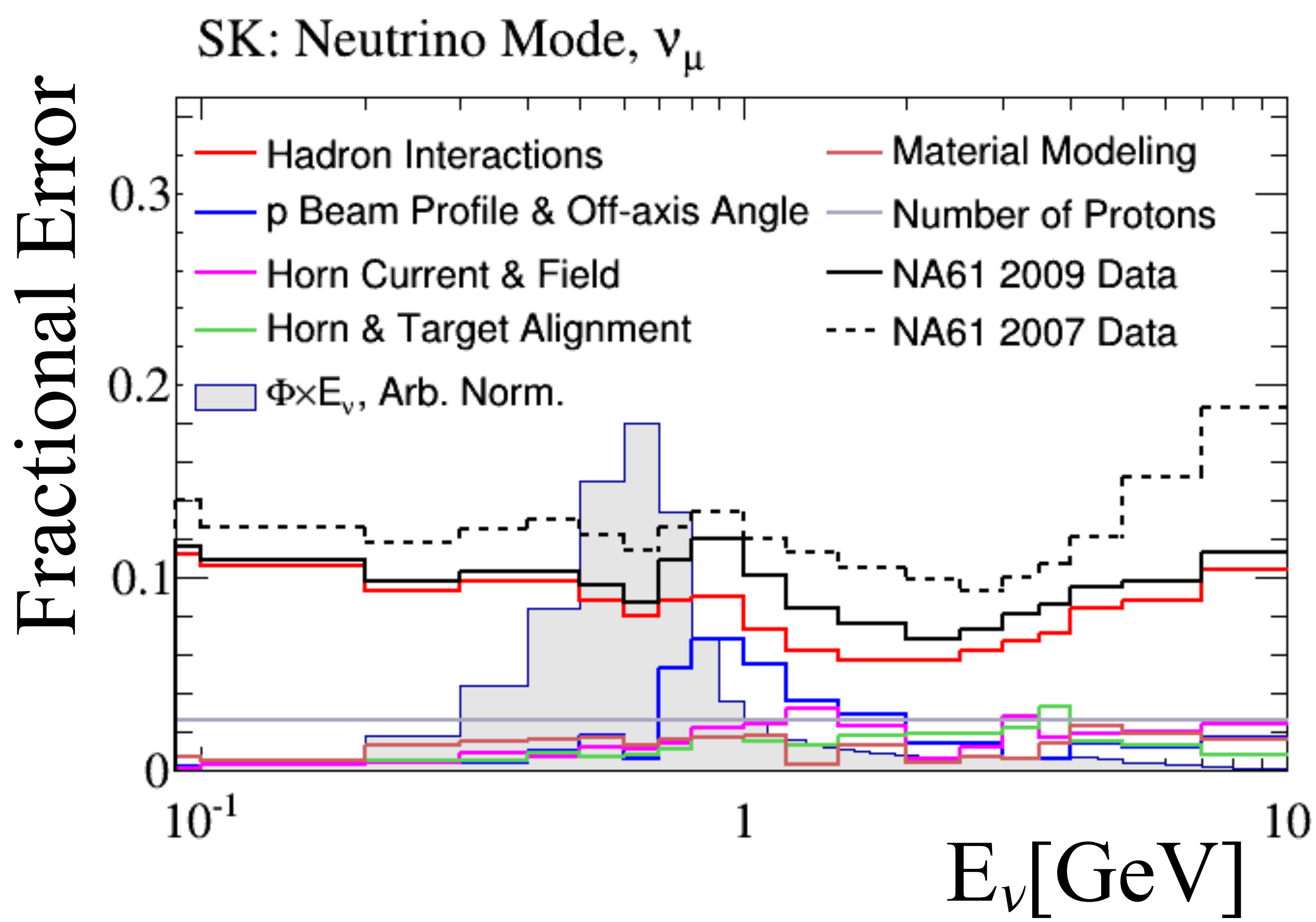


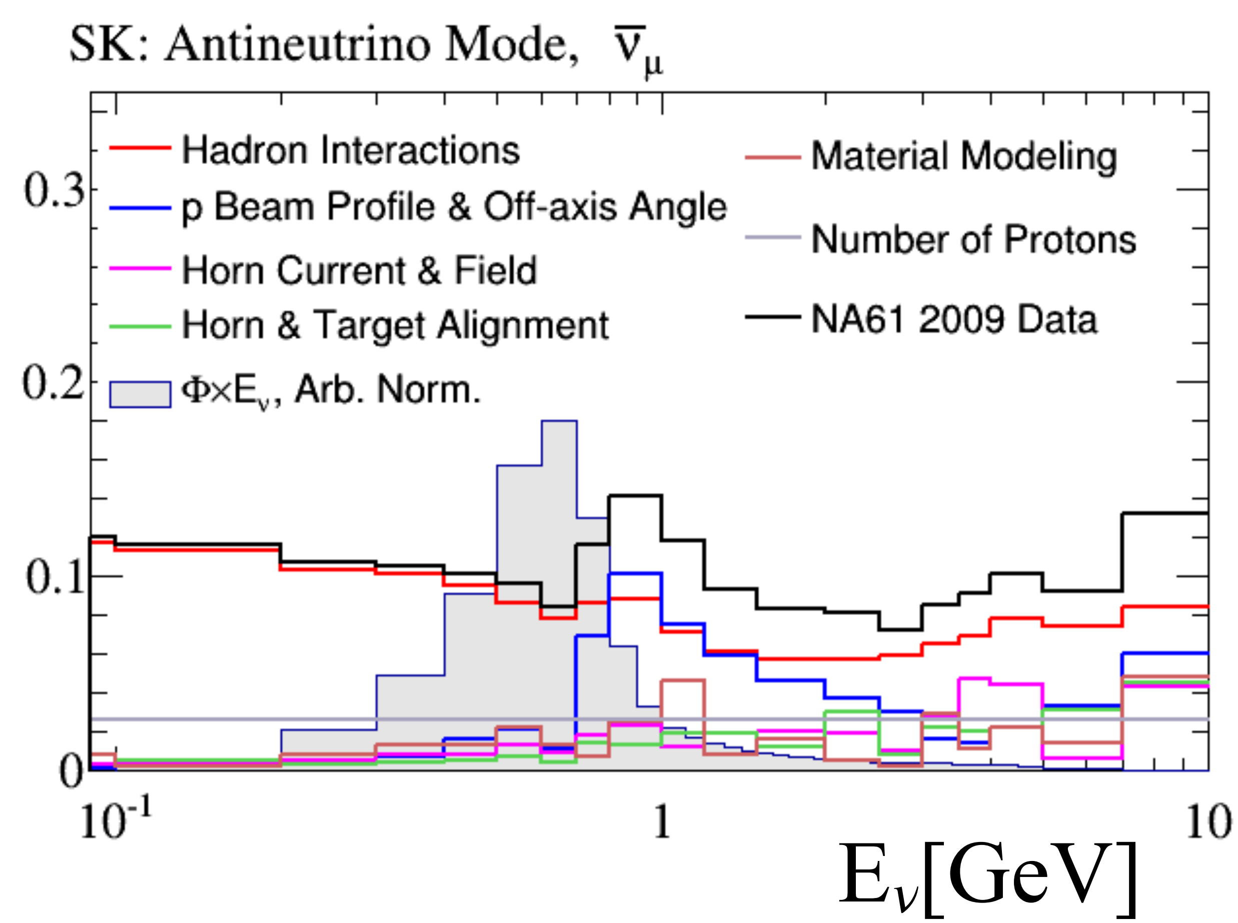


Fluxes known with uncertainties smaller than 10% based on NA61/SHINE thin-target measurements

Dominant systematics due to the hadron interactions modeling

Neutrino fluxes



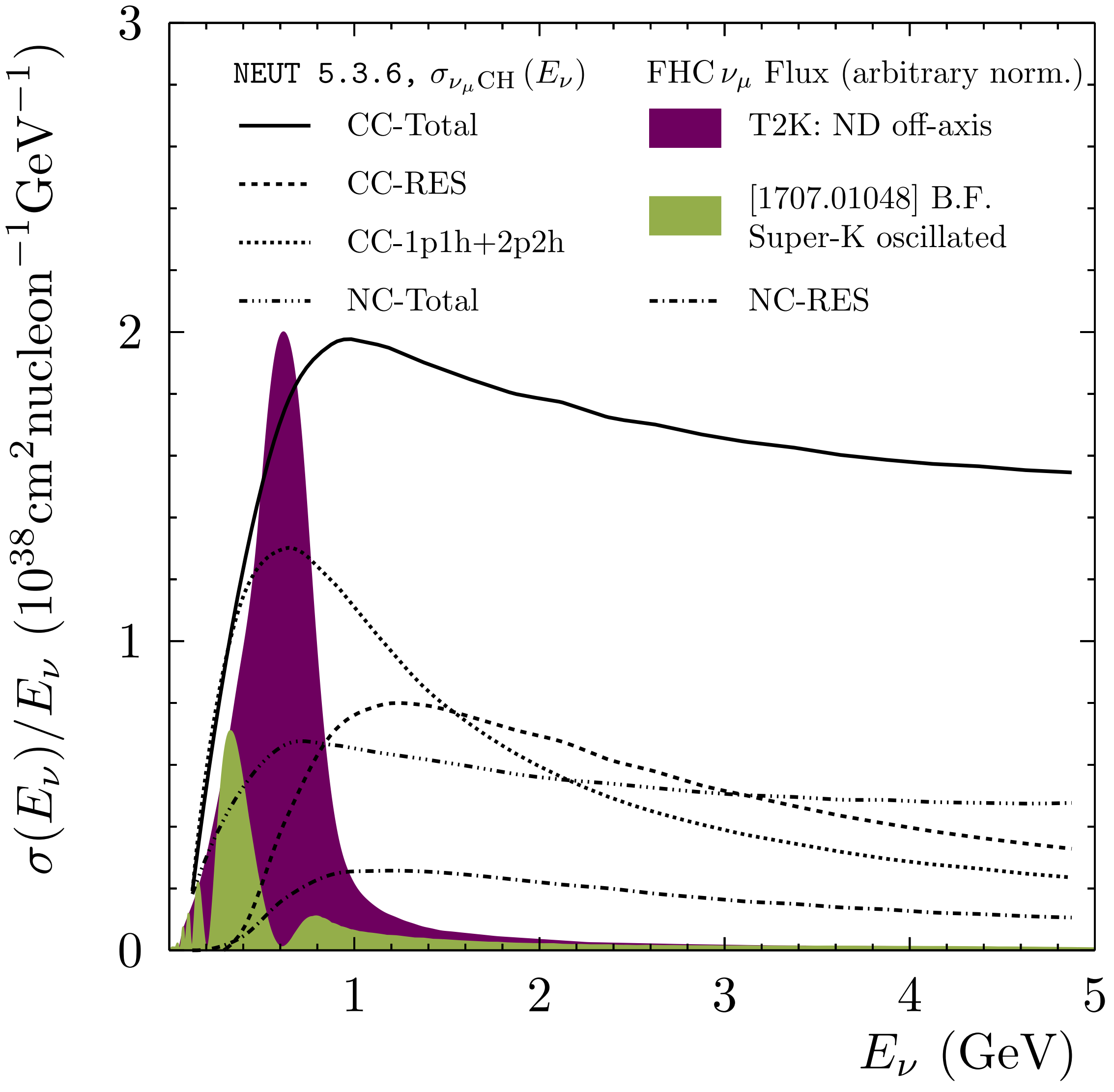


Fluxes known with uncertainties smaller than 10% based on NA61/SHINE thin-target measurements

Dominant systematics due to the hadron interactions modeling

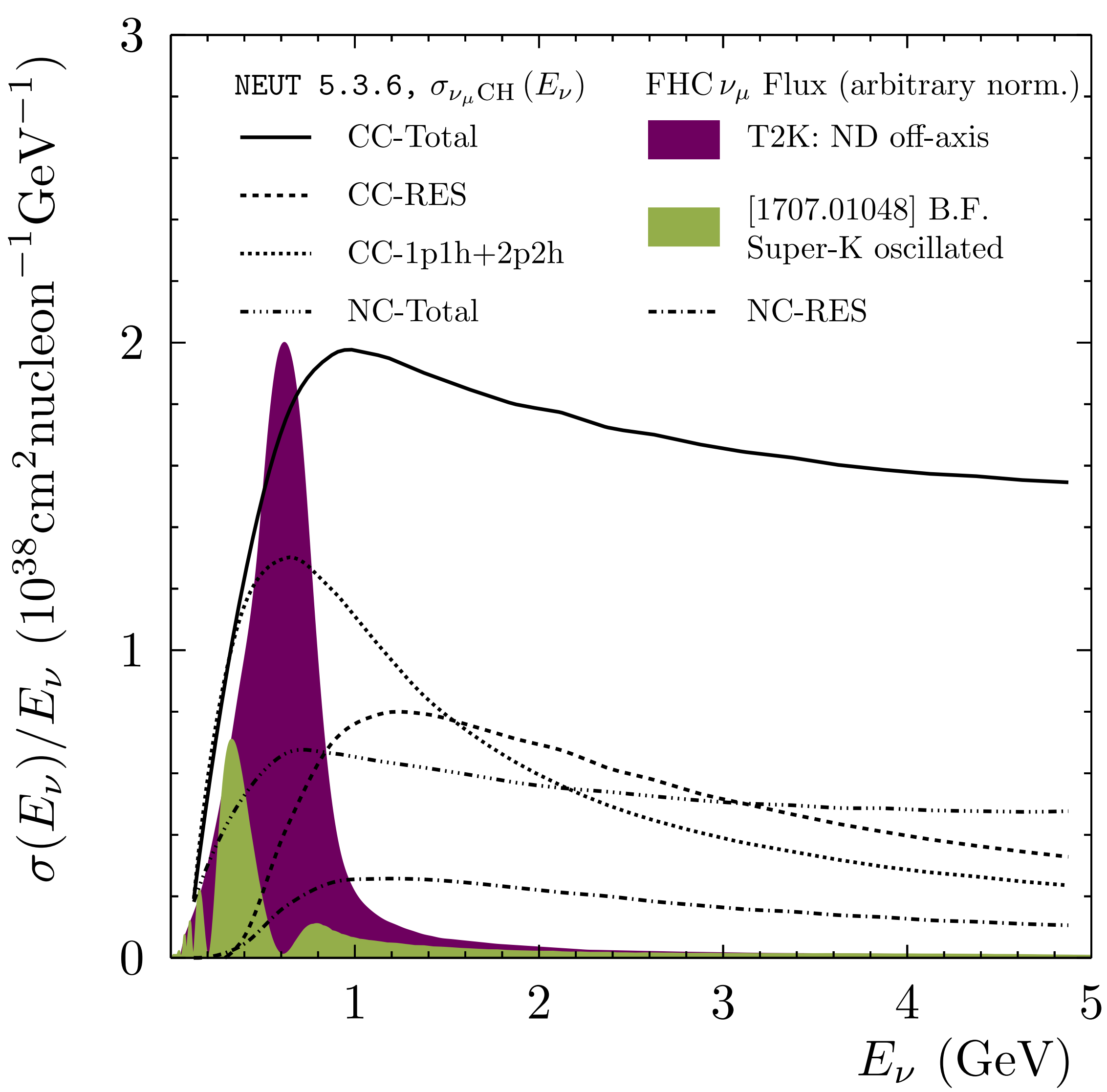
It will be reduced to ~5% by using NA61/SHINE measurements of T2K replica target

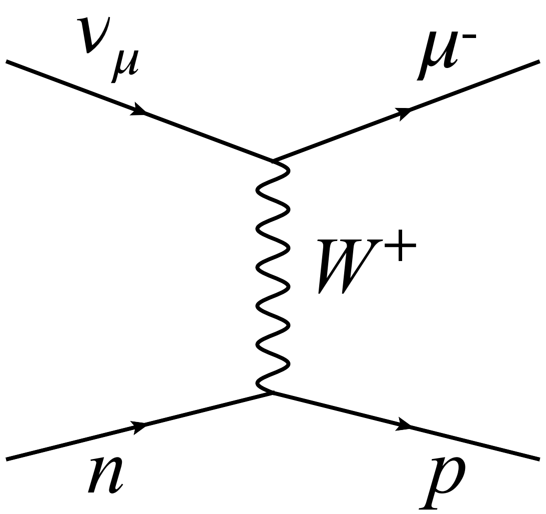
Relevant ν interactions at T2K



Relevant ν interactions at T2K

CCQE
(Charged-Current Quasi-Elastic)





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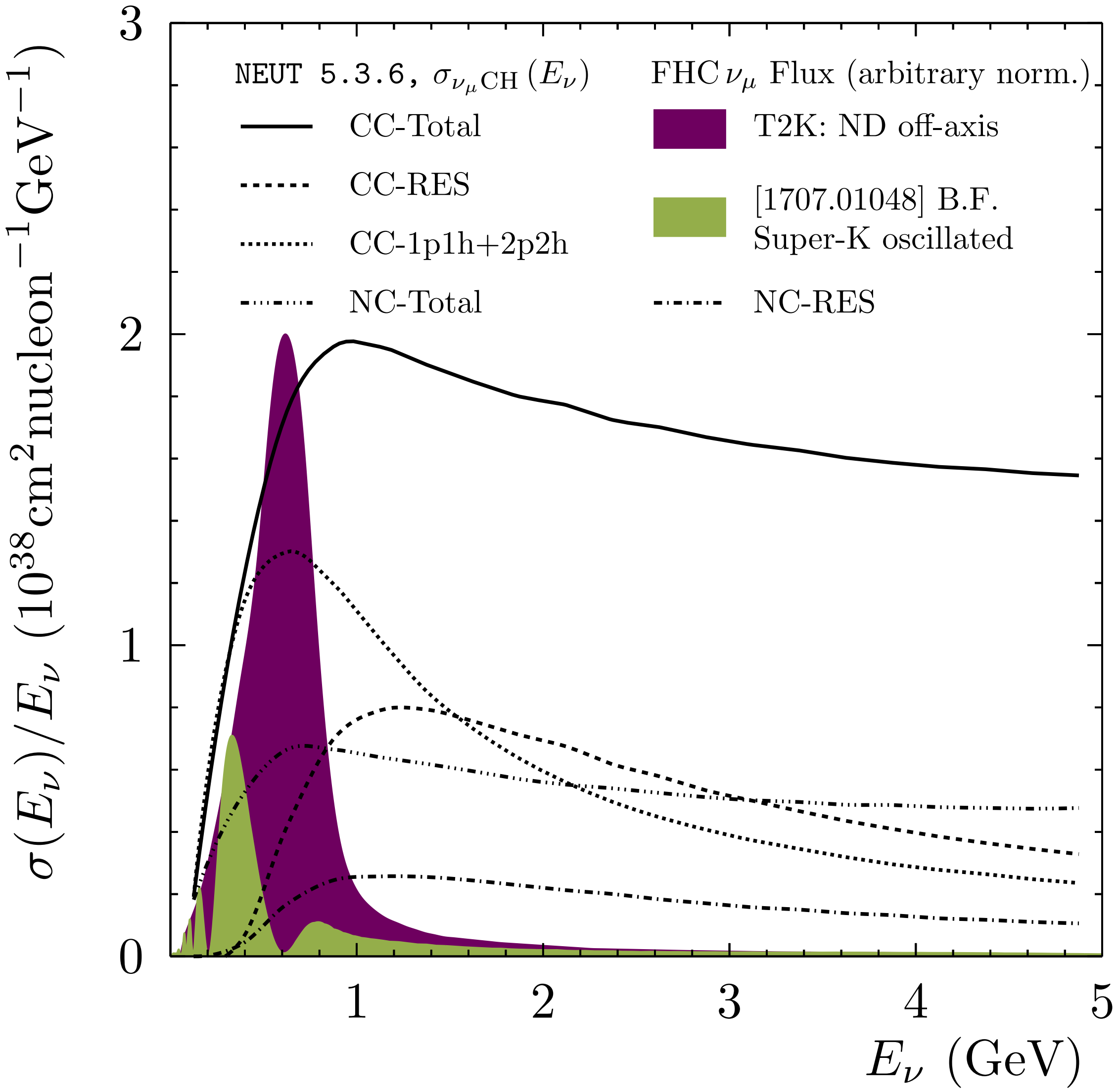

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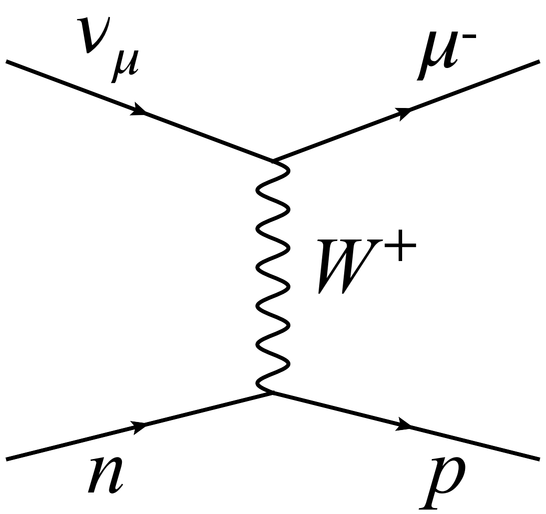
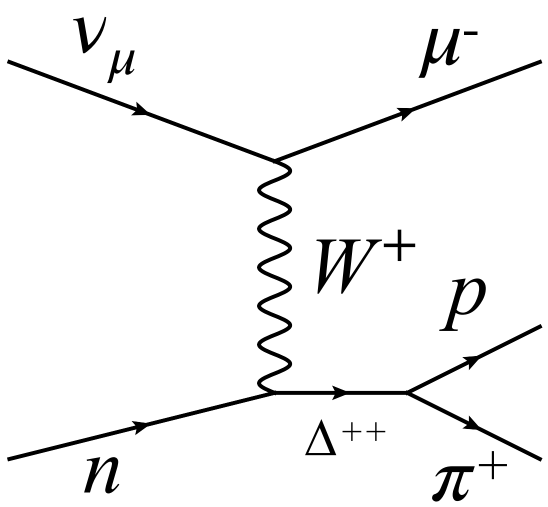
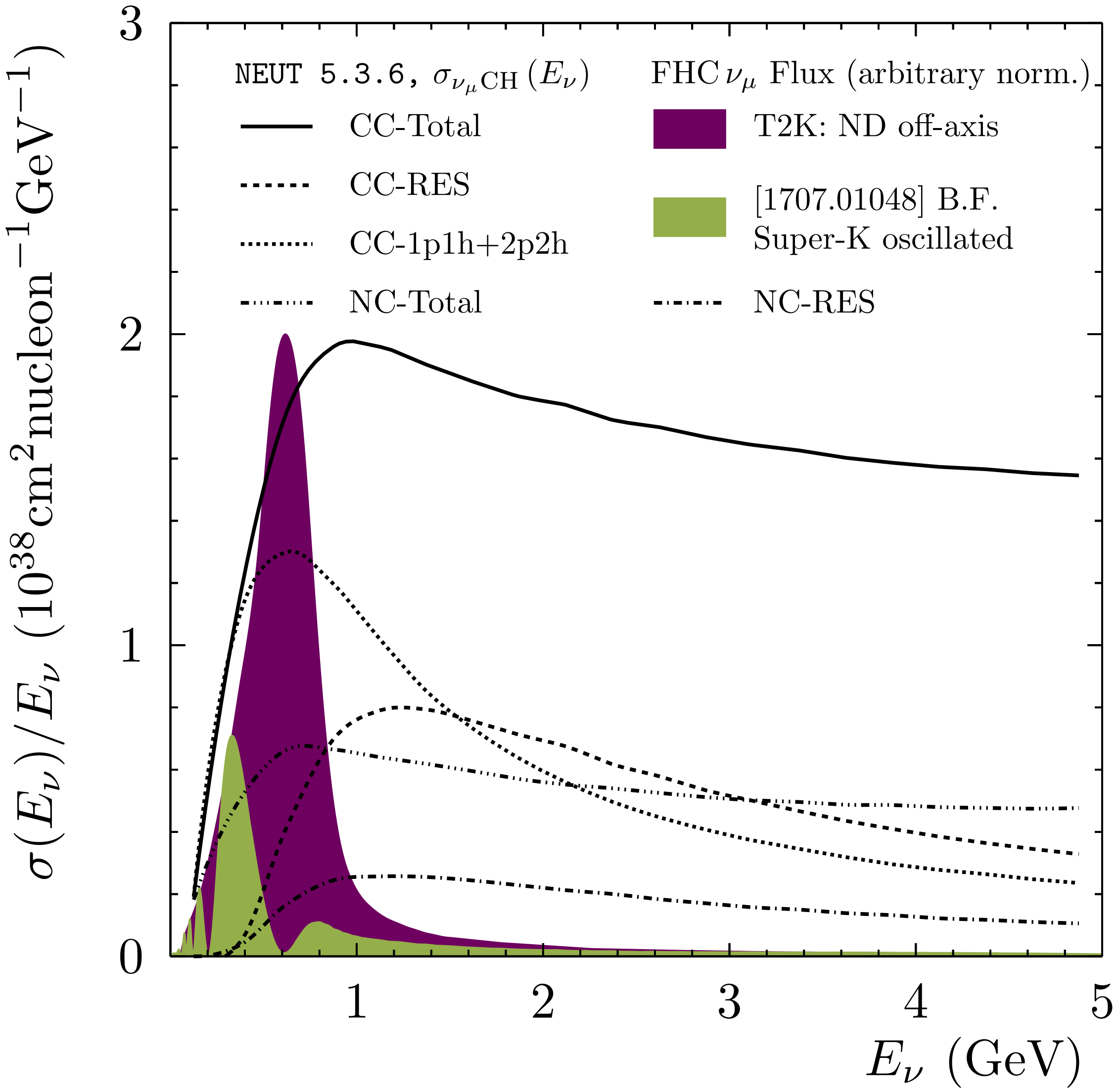


CCRES
(Charged-Current Resonant pion production)



Relevant ν interactions at T2K



CCQE
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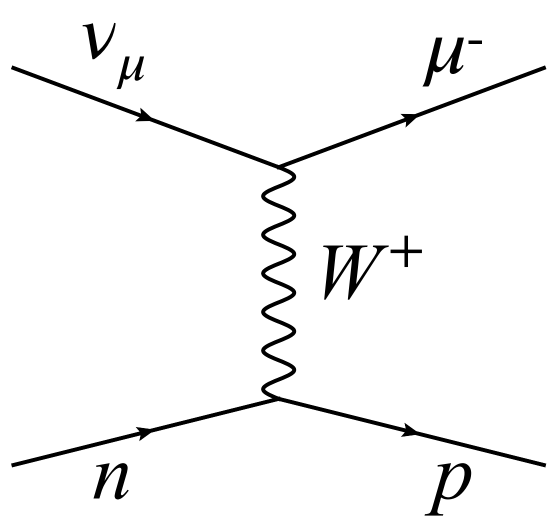
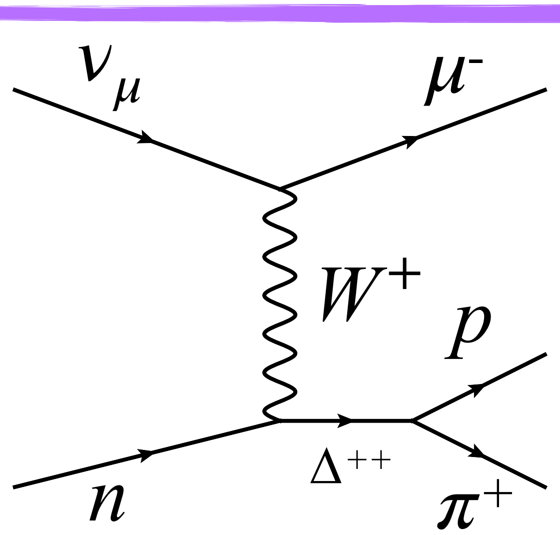
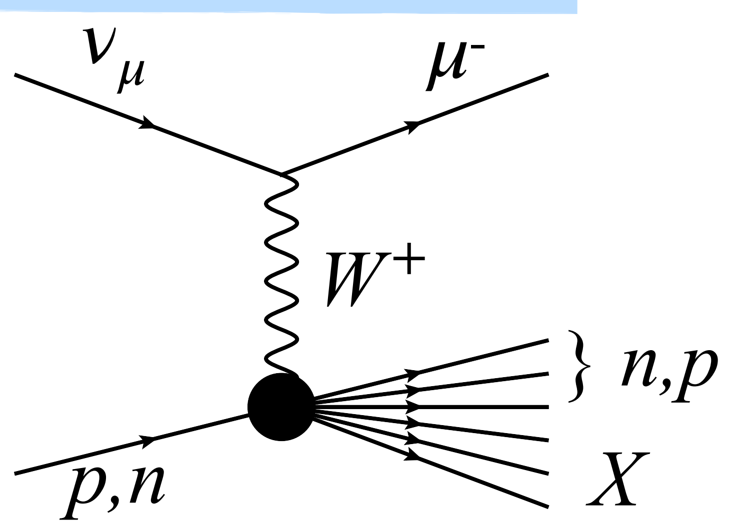


CCRES
(Charged-Current
Resonant pion production)



CCDIS
(Charged-Current Deep
Inelastic Scattering)



Nuclear effects

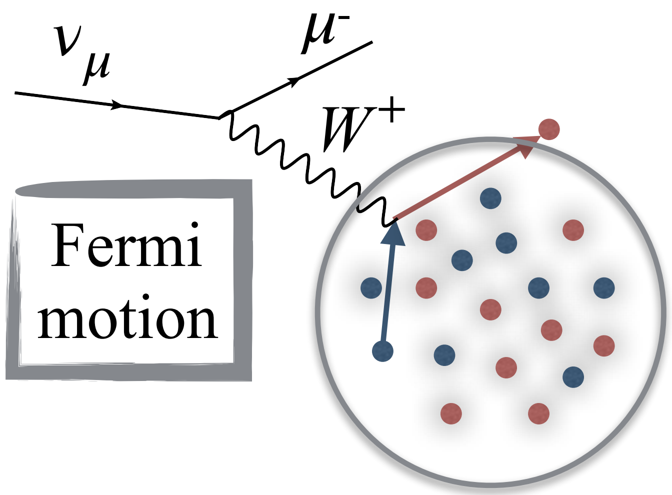
Nuclear effects

$\boxed{\text{Nucleons bound in the nucleus} \Rightarrow \text{Nuclear effect!}}$

Nuclear effects

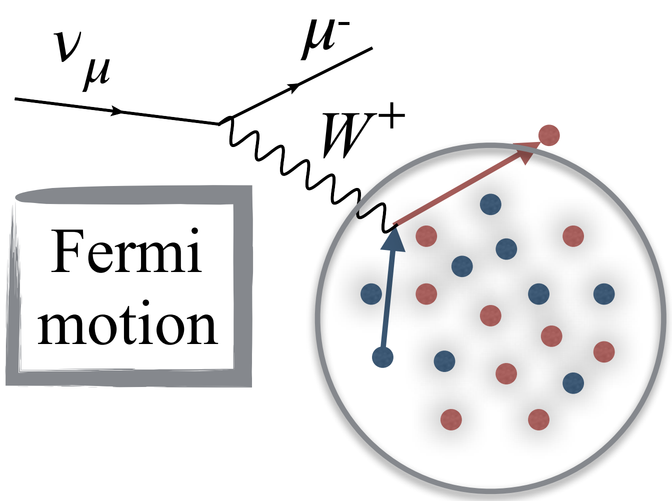
Nucleons bound in the nucleus ⇒ Nuclear effect!

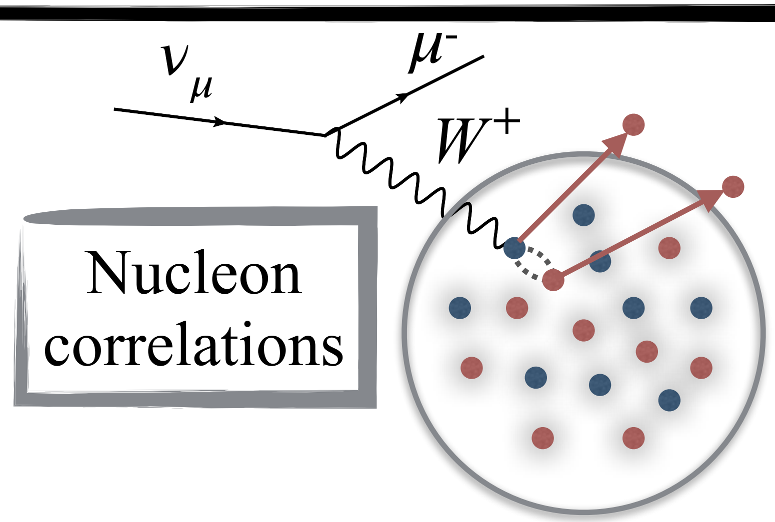
Fermi motion



Nuclear effects

Nucleons bound in the nucleus ⇒ Nuclear effect!





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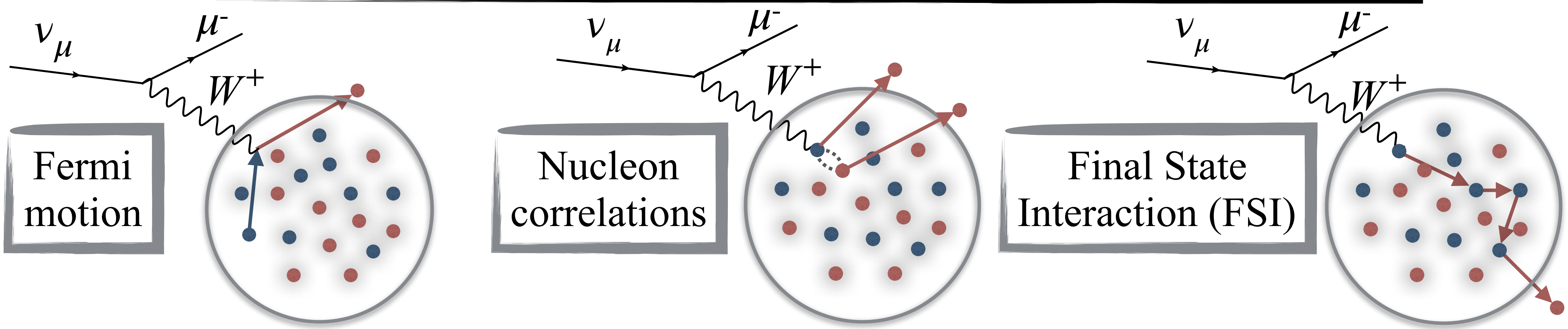

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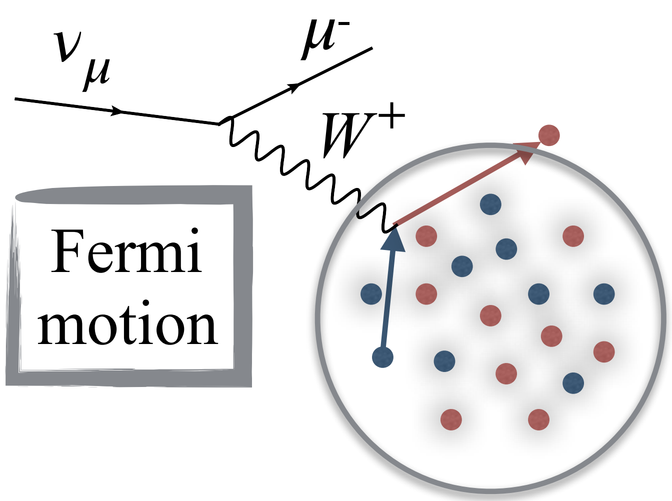
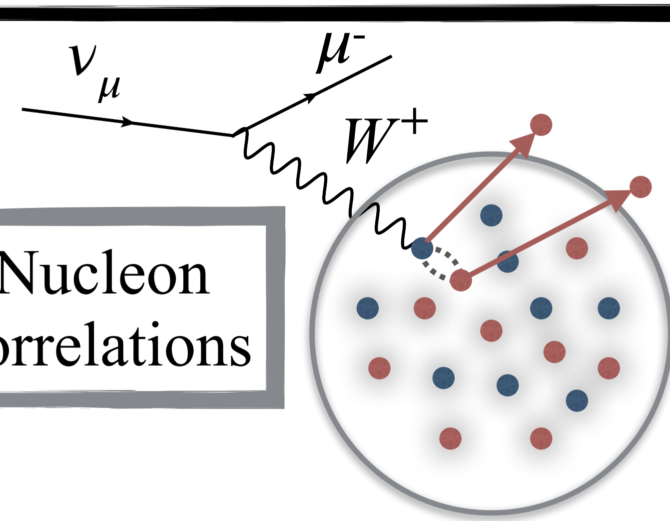
Nucleons bound in the nucleus ⇒ Nuclear effect!

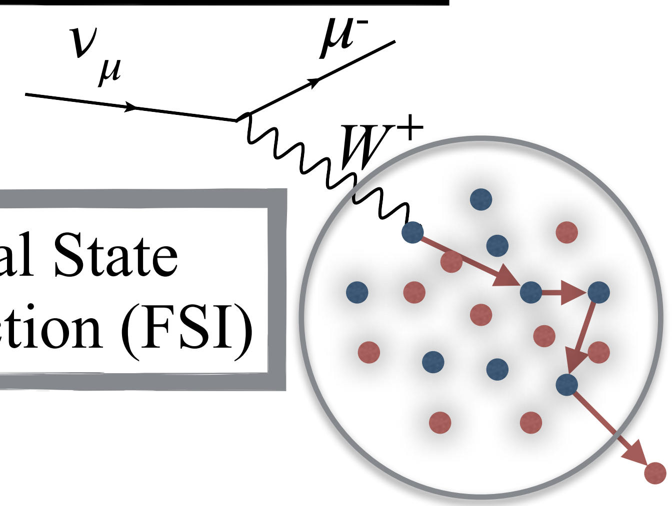
Fermi motion



Nucleon correlations



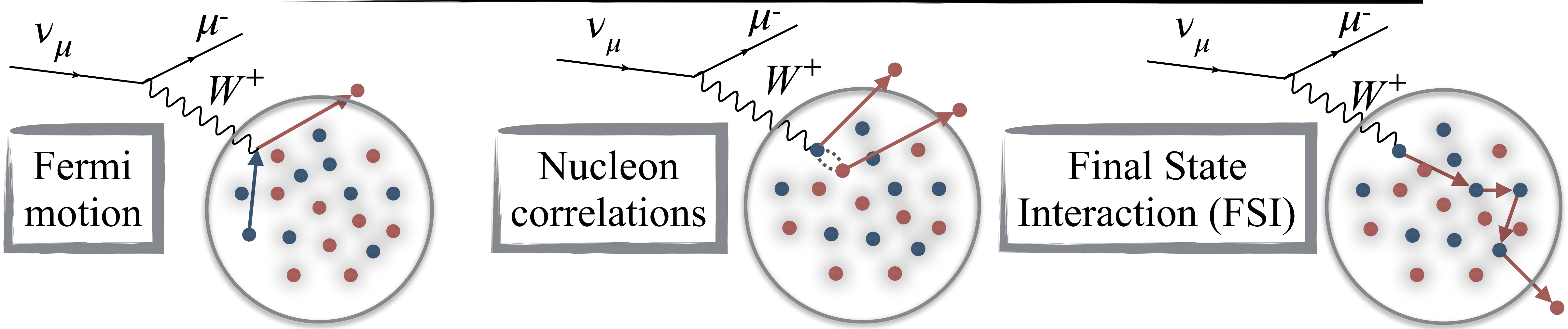
Final State Interaction (FSI)



Neutrino Energy reconstructed using CCQE hypothesis

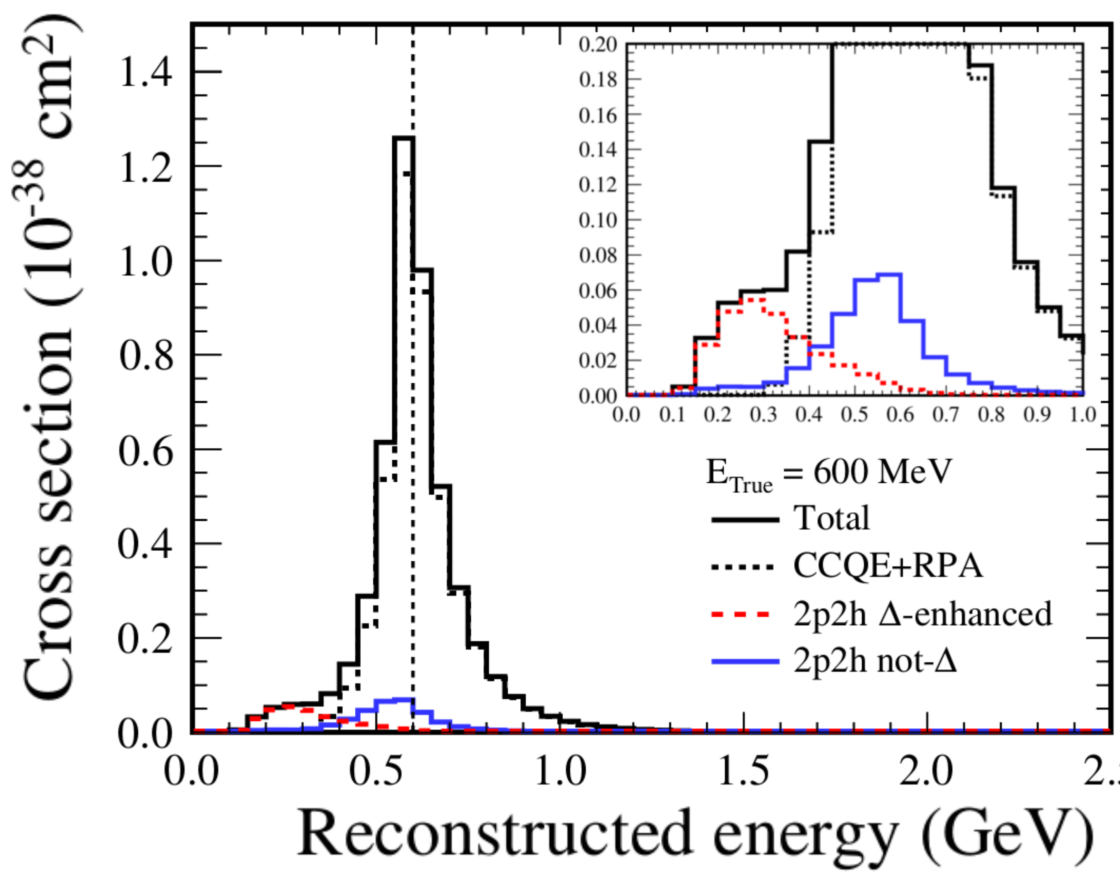
Nuclear effects

Nucleons bound in the nucleus ⇒ Nuclear effect!



Neutrino Energy reconstructed using CCQE hypothesis

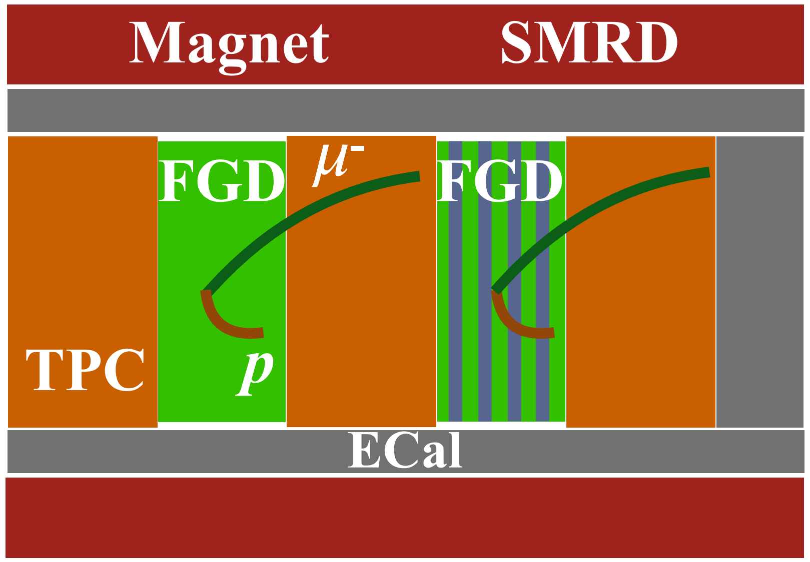
Nuclear effects introduce a bias in neutrino energy reconstruction

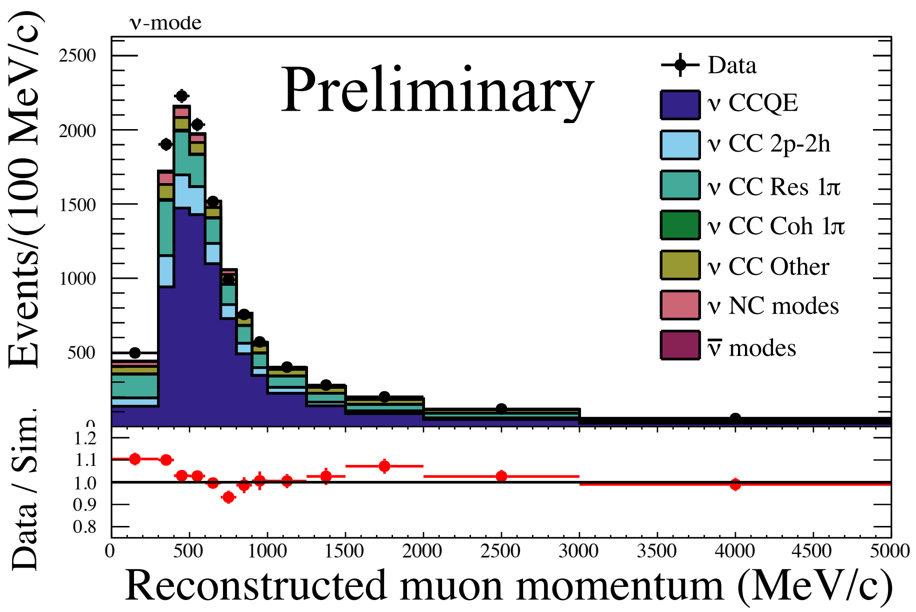


ND280 measurements: ν beam

ND280 measurements: ν beam

CC-0π





ND280 measurements: ν beam

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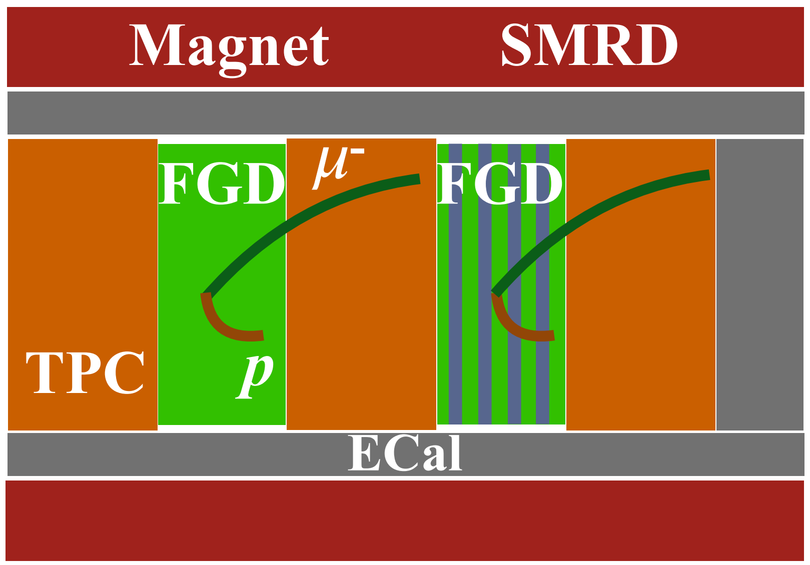
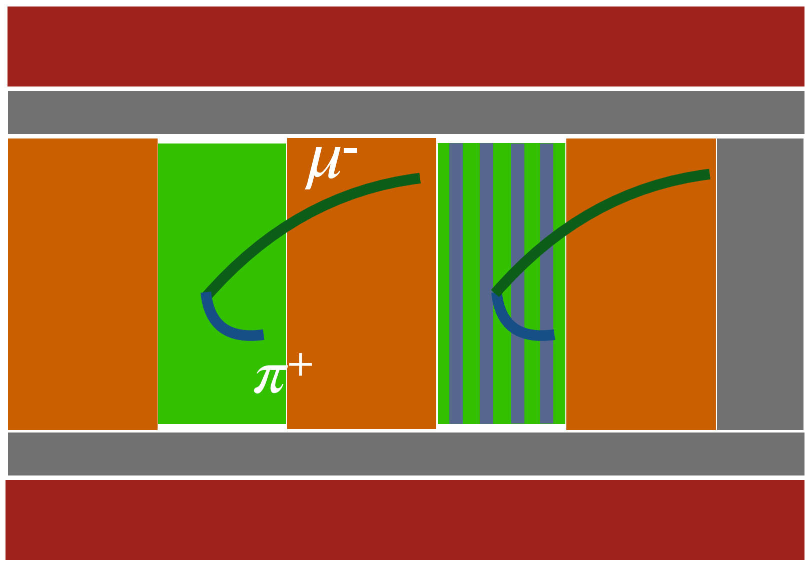
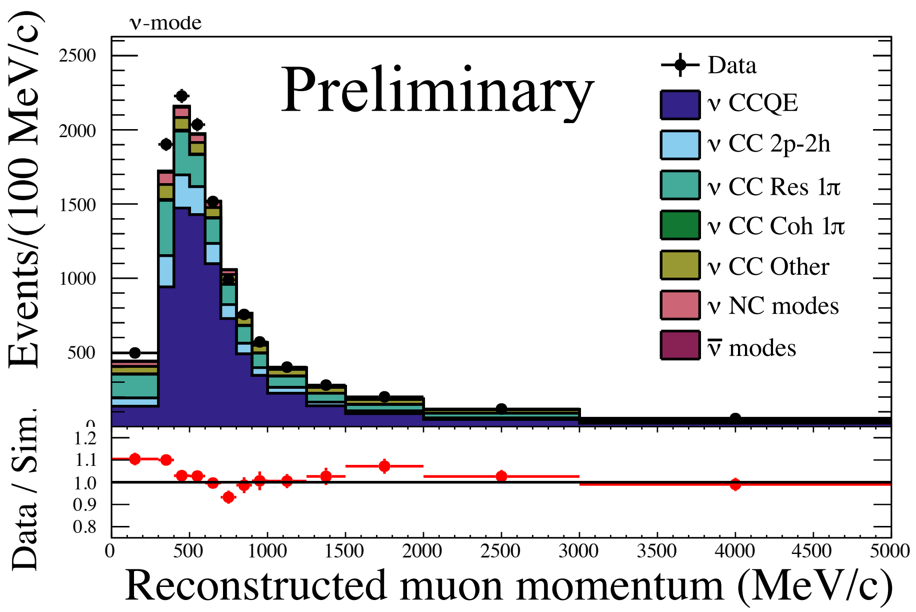
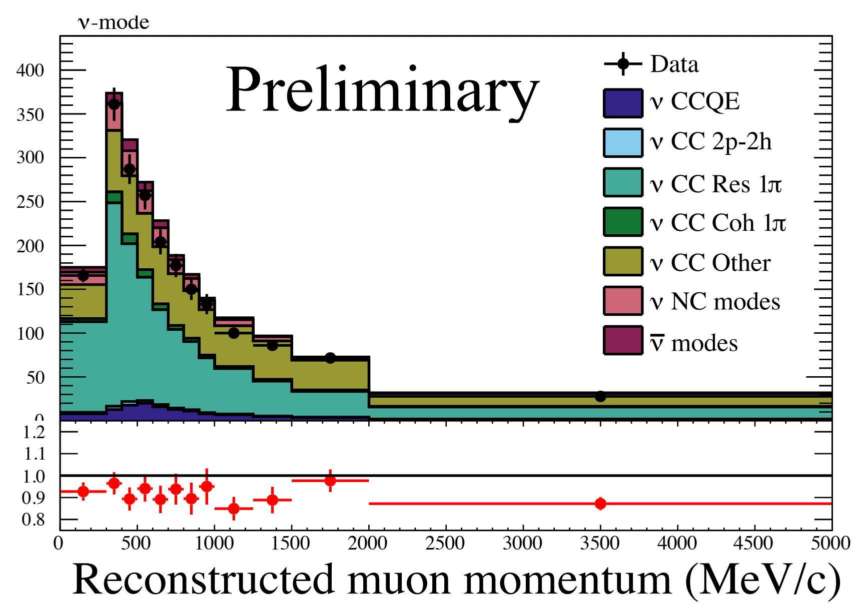


CC-1π+

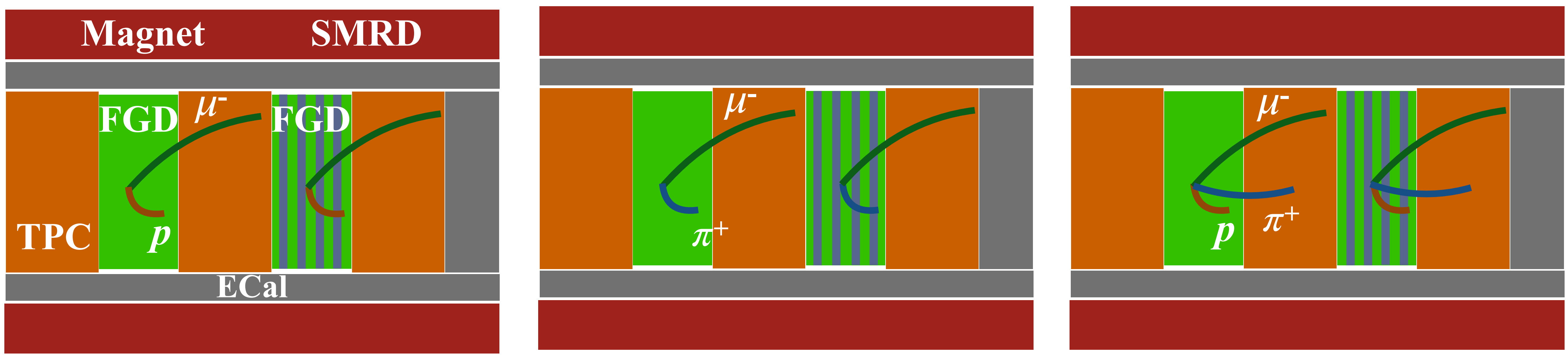


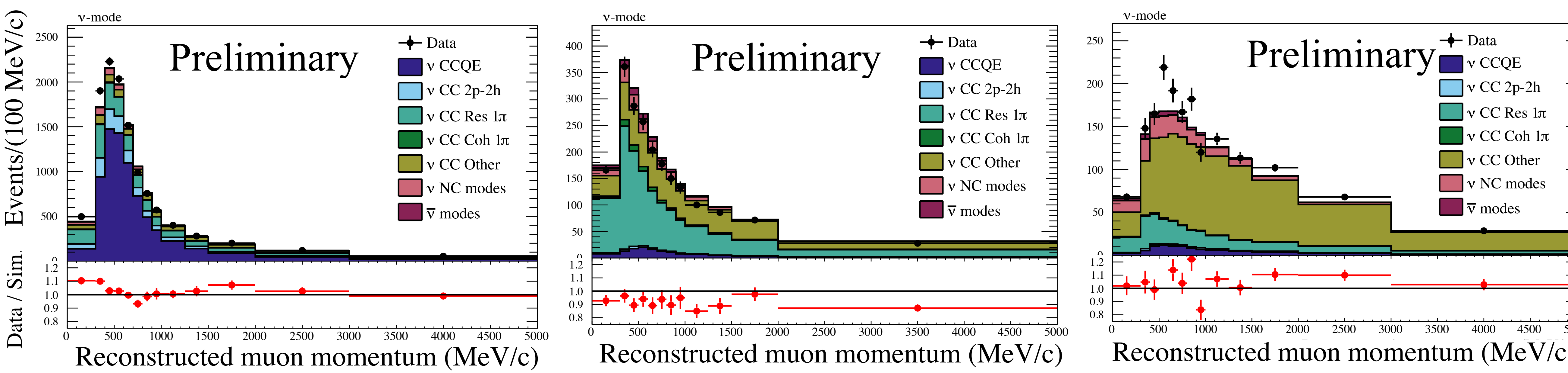




ND280 measurements: ν beam

CC-0π | CC-1π^+ | CC-Other

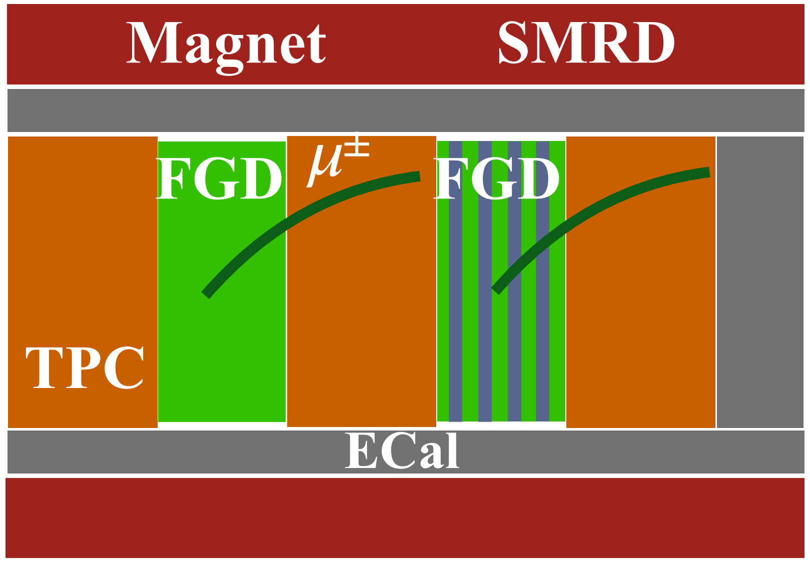




ND280 measurements: $\overline{\nu}$ beam

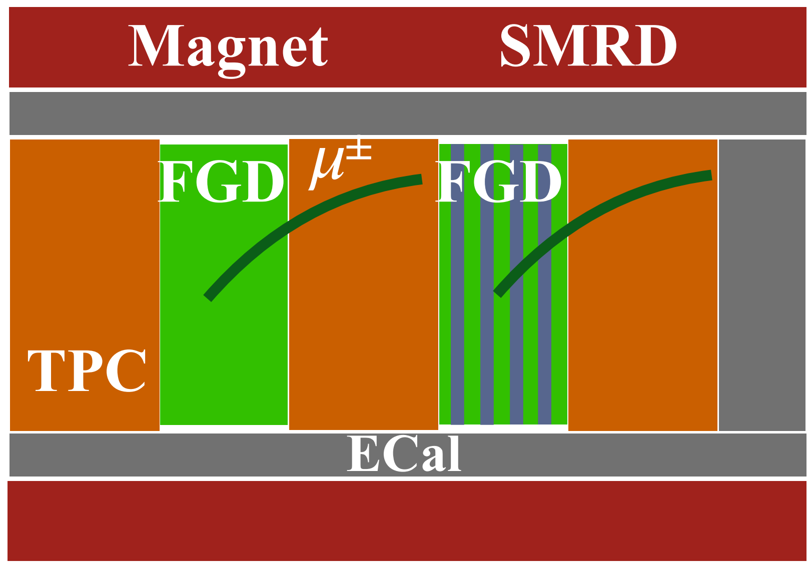
ND280 measurements: $\overline{\nu}$ beam

CC-1Track

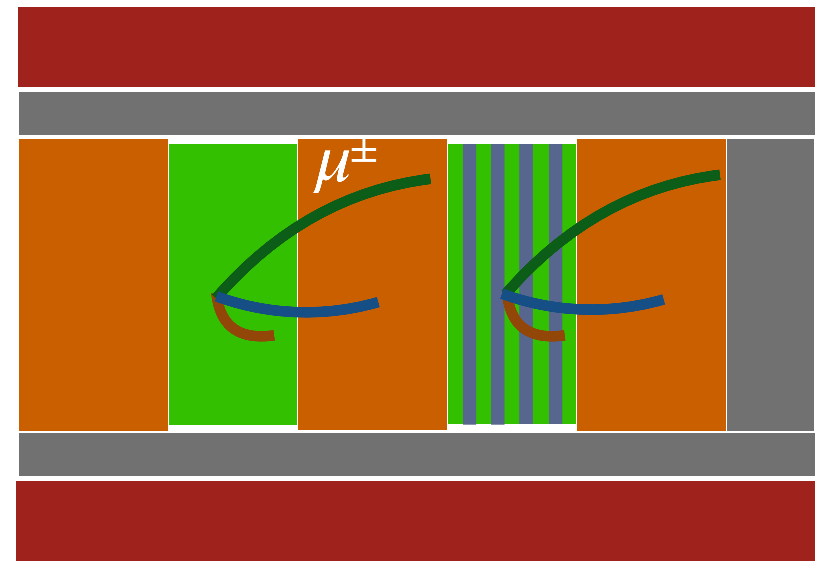


ND280 measurements: $\overline{\nu}$ beam

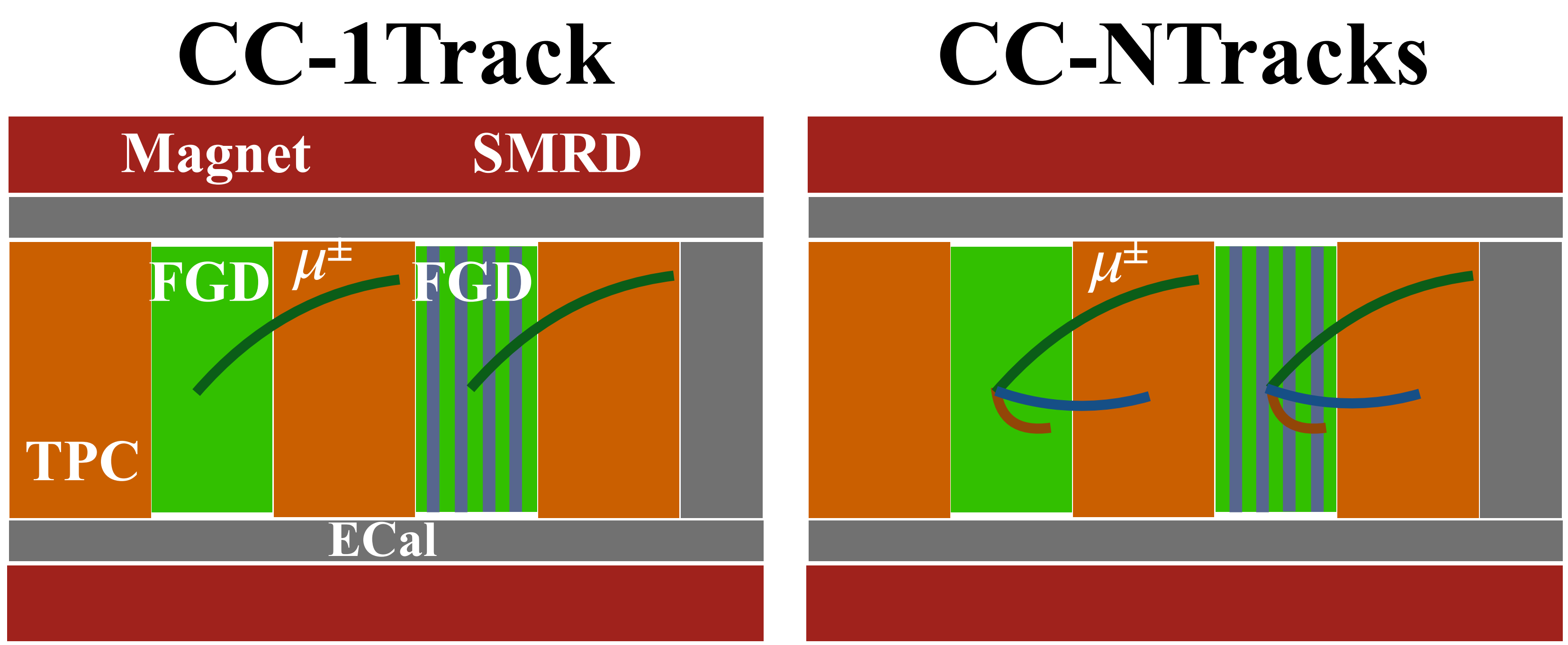
CC-1Track

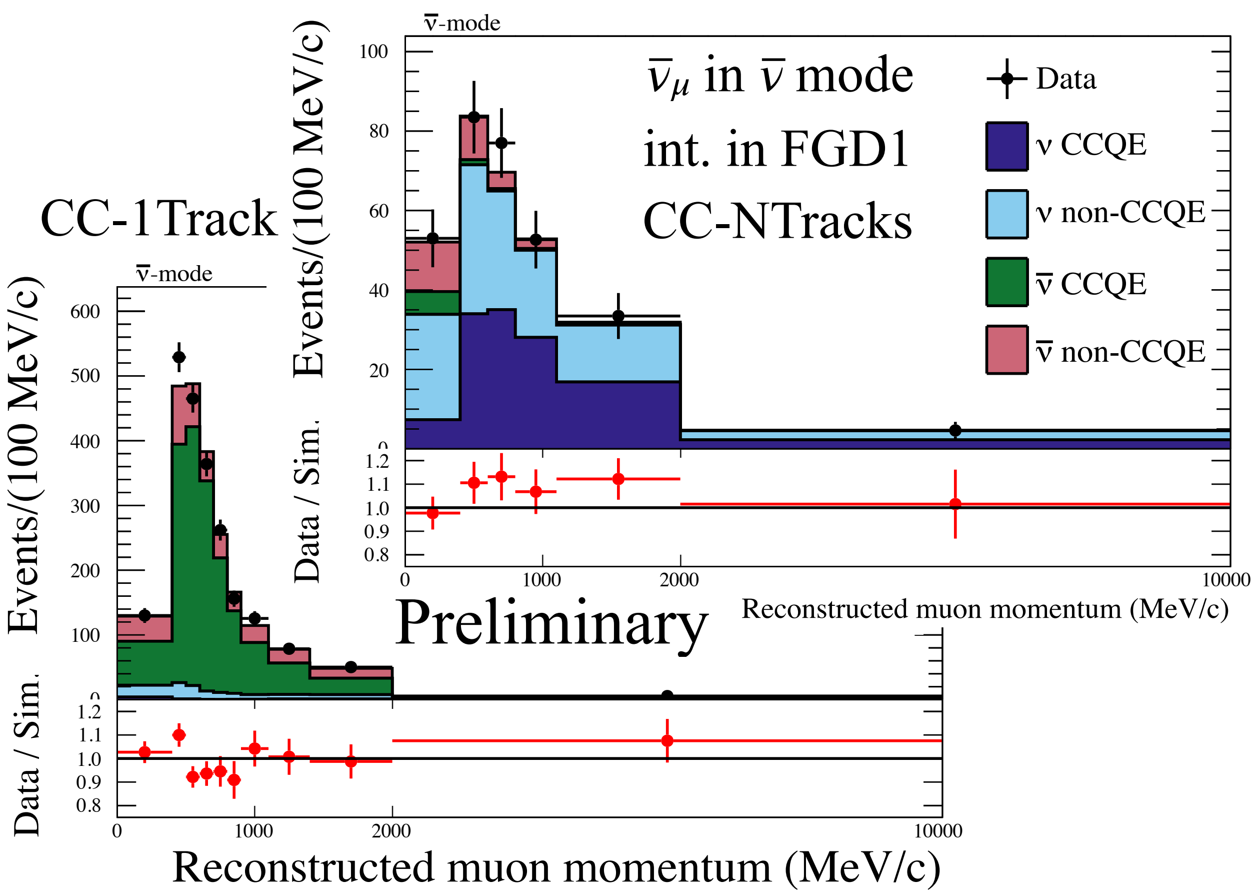


CC-NTracks



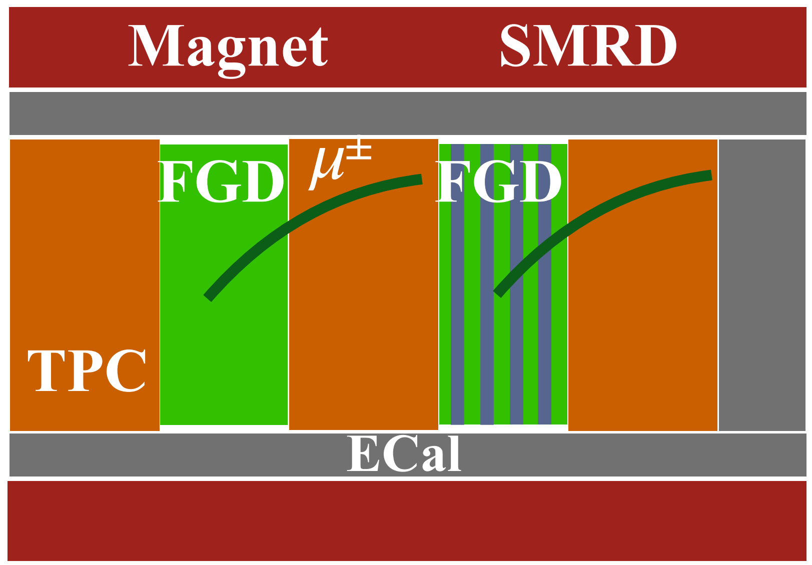
ND280 measurements: $\bar{\nu}$ beam



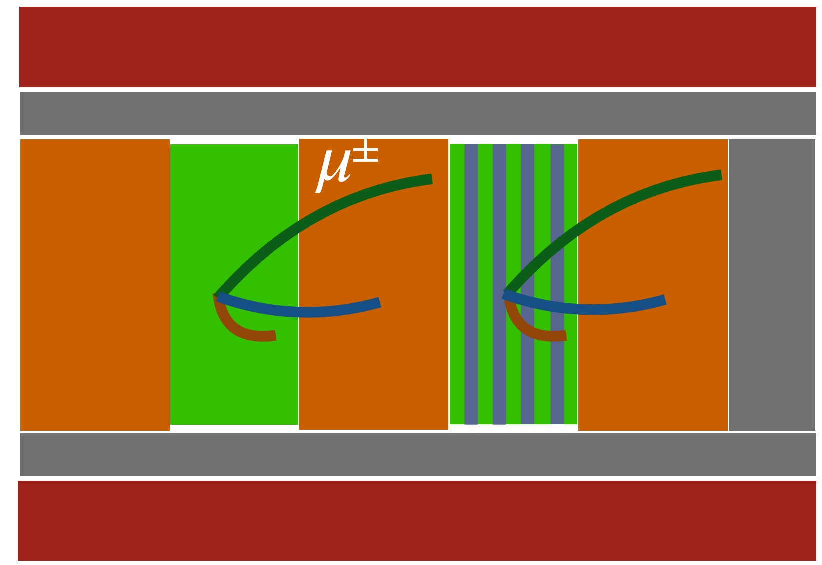


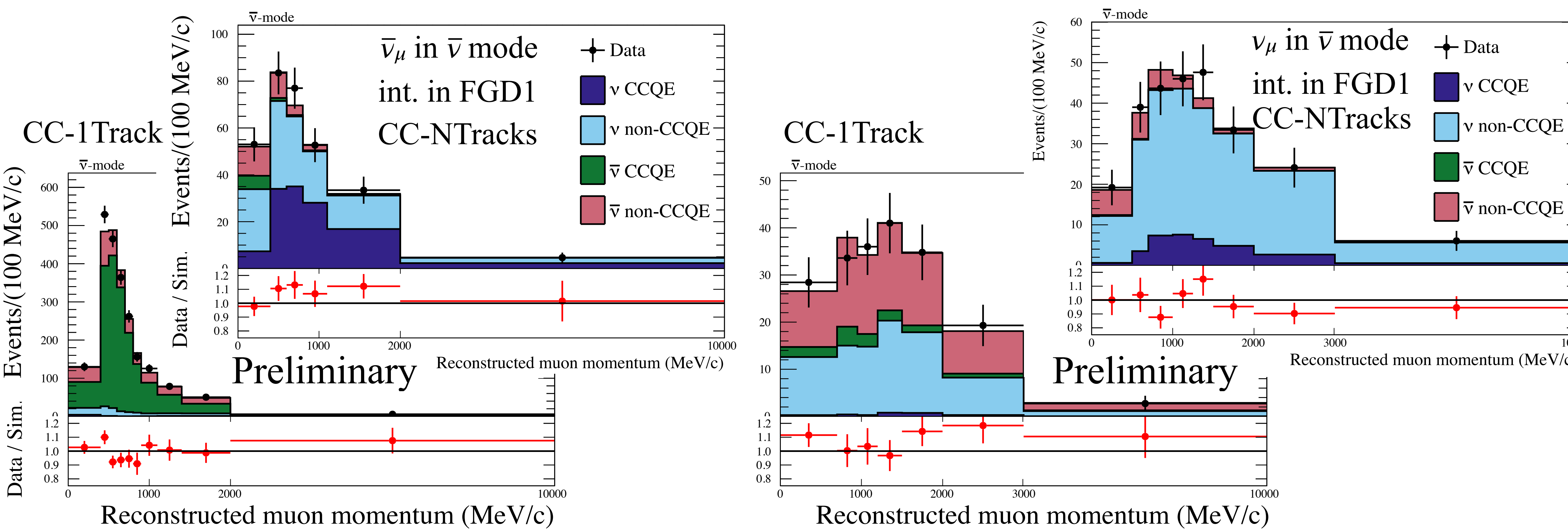
ND280 measurements: $\bar{\nu}$ beam

CC-1Track

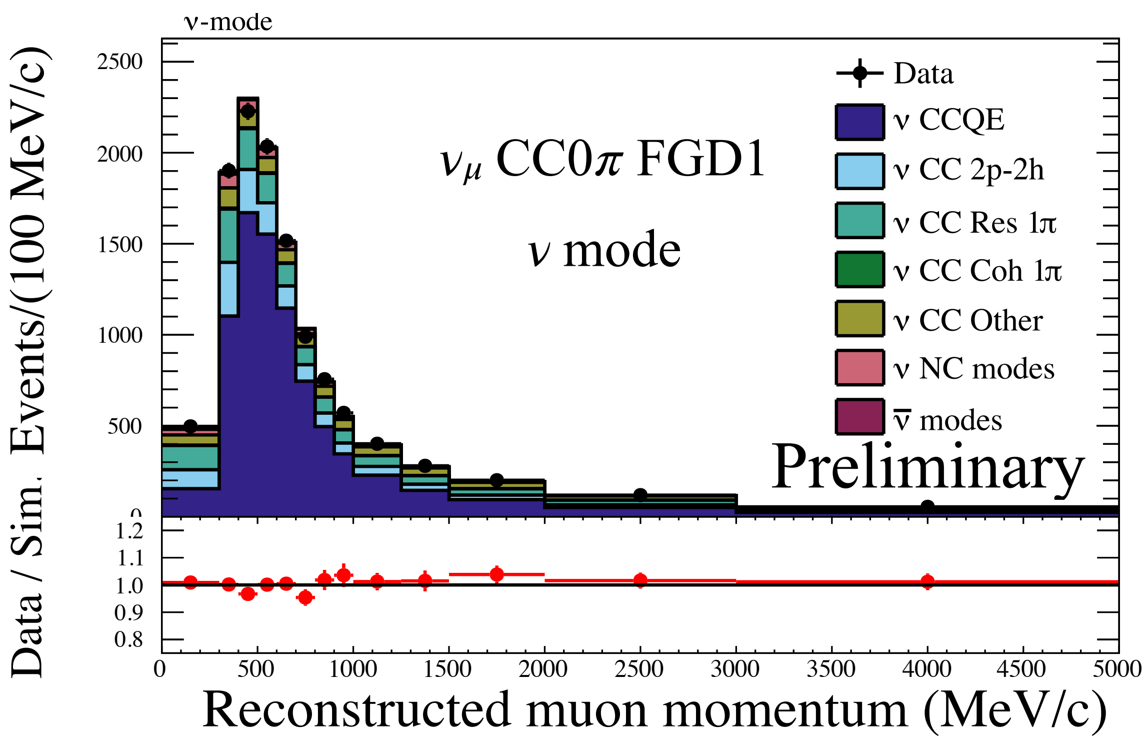


CC-NTracks

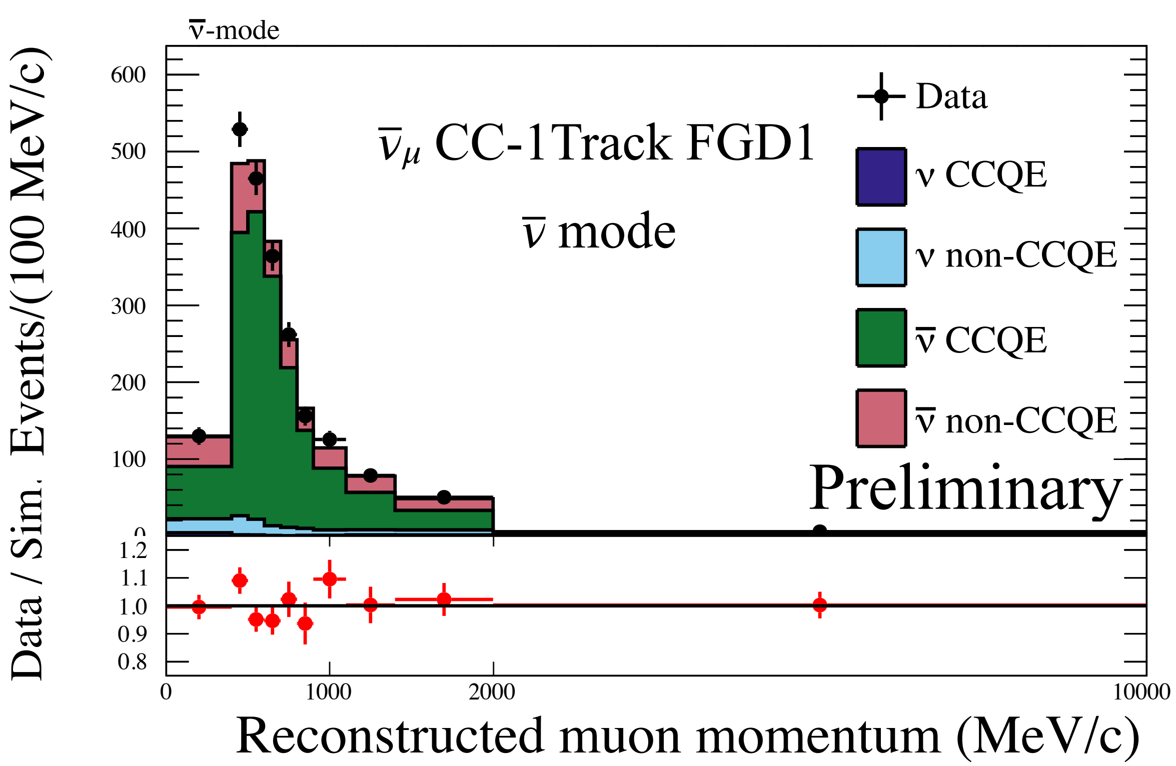




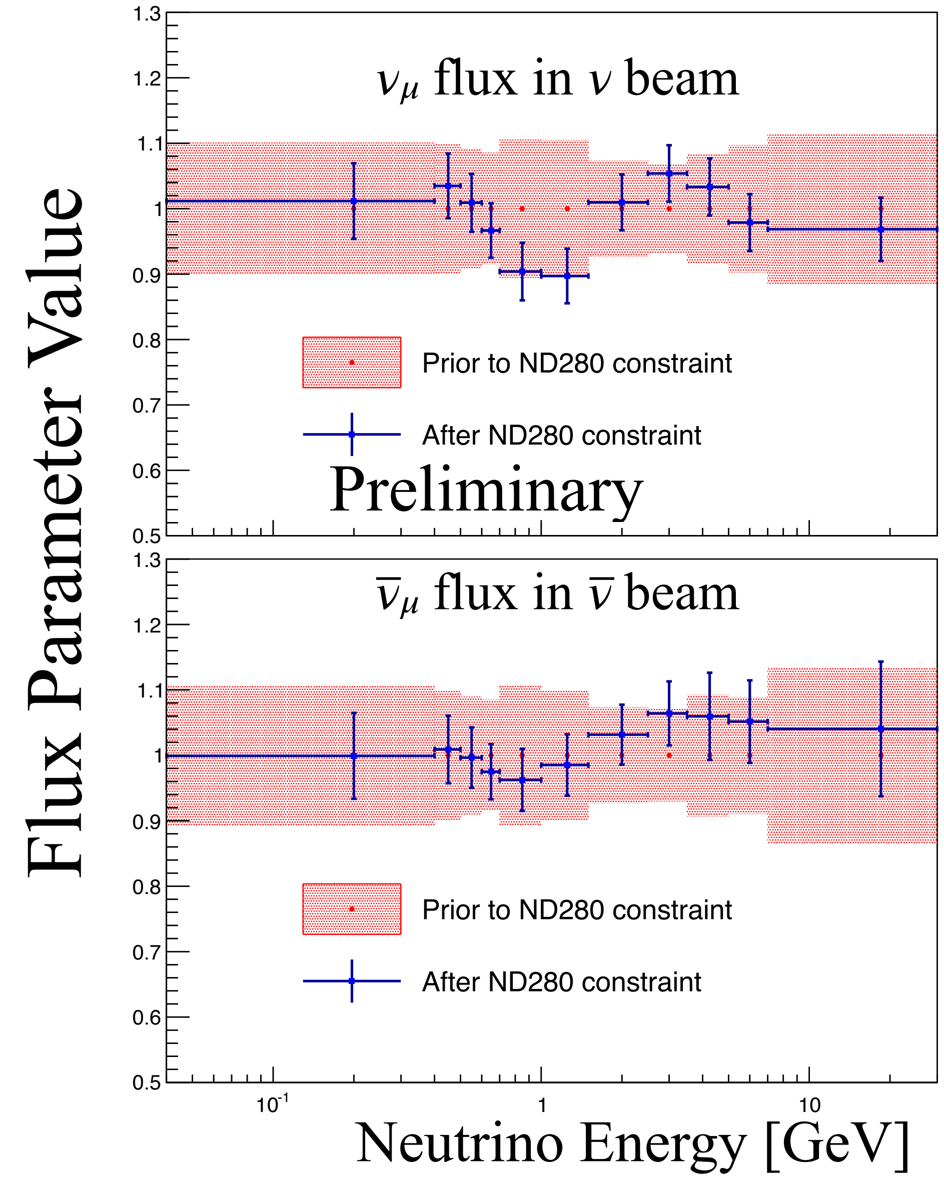
ND280 fit



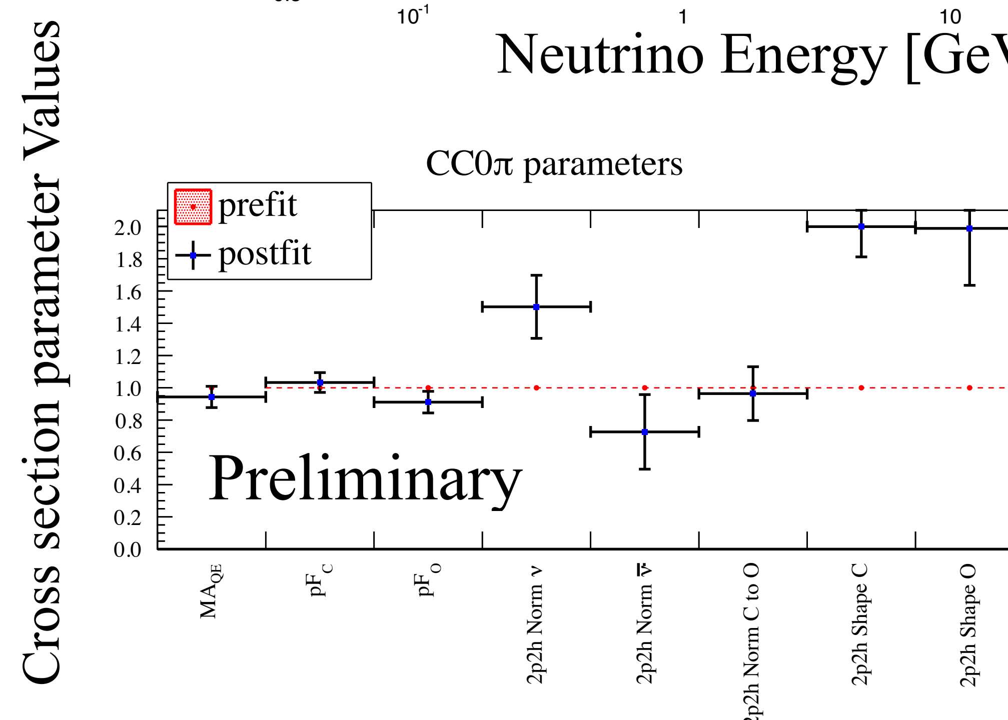
ν-mode
ν_μ CC0π FGD1
ν mode
Data
ν CCQE
ν CC 2p-2h
ν CC Res 1π
ν CC Coh 1π
ν CC Other
ν NC modes
$\bar{\nu}$ modes
Preliminary
Events/(100 MeV/c)
Data / Sim.
Reconstructed muon momentum (MeV/c)



$\bar{\nu}$-mode
$\bar{\nu}_\mu$ CC-1Track FGD1
$\bar{\nu}$ mode
Data
ν CCQE
ν non-CCQE
$\bar{\nu}$ CCQE
$\bar{\nu}$ non-CCQE
Preliminary
Events/(100 MeV/c)
Data / Sim.
Reconstructed muon momentum (MeV/c)

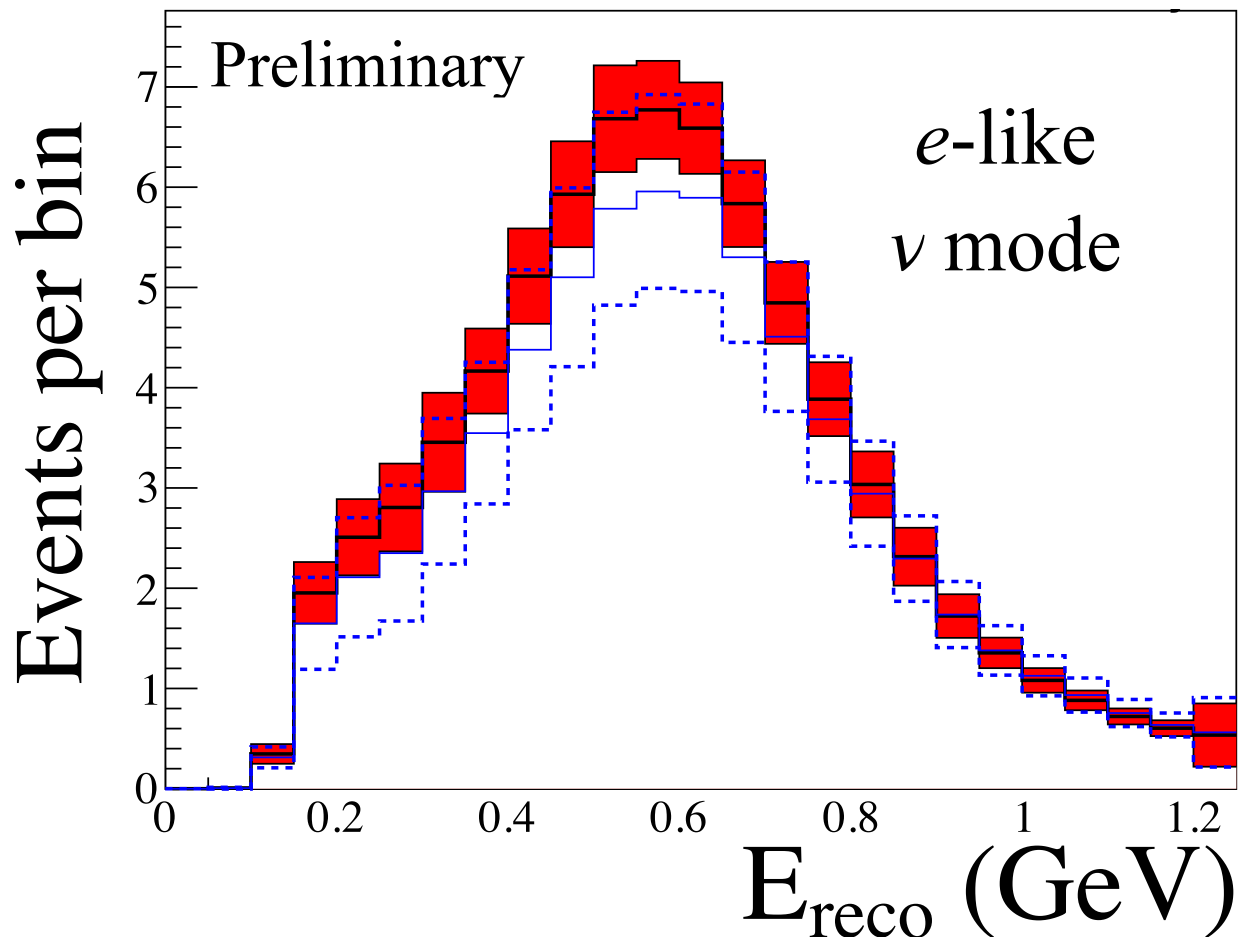


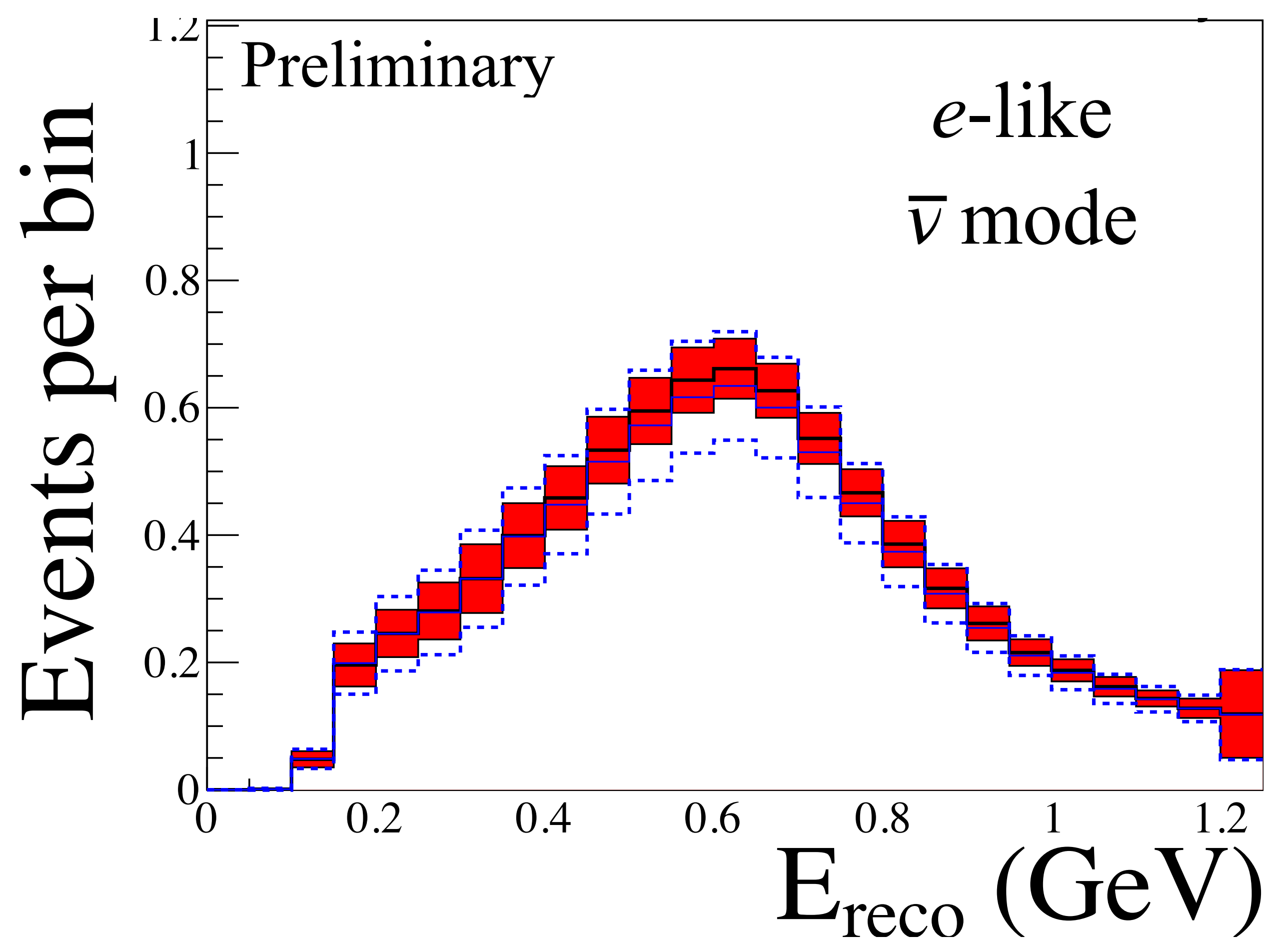
Flux Parameter Value
ν_μ flux in ν beam
Prior to ND280 constraint
After ND280 constraint
Preliminary
$\bar{\nu}_\mu$ flux in $\bar{\nu}$ beam
Prior to ND280 constraint
After ND280 constraint
Neutrino Energy [GeV]



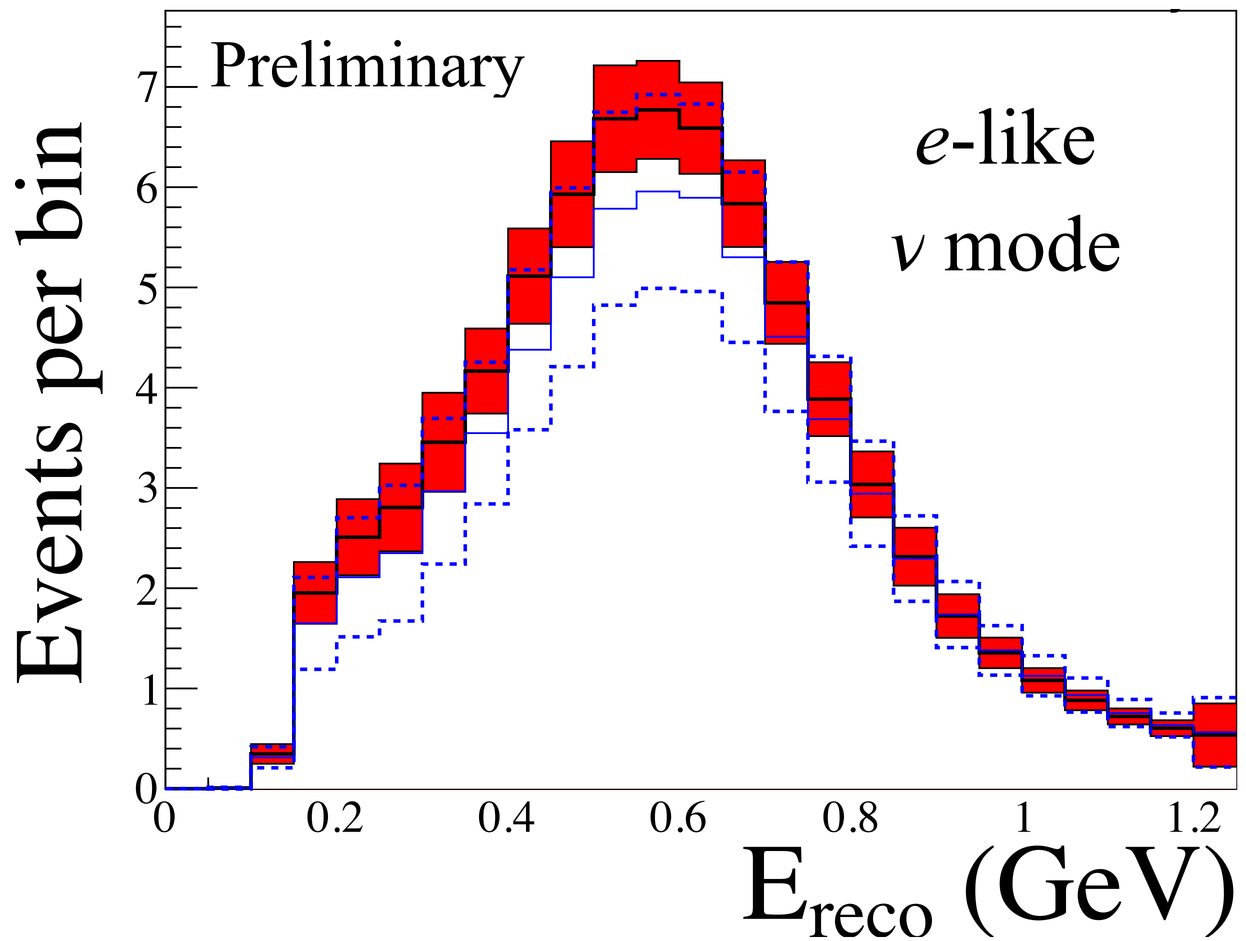
CC0π parameters
prefit
postfit
Preliminary
Cross section parameter Values
MA_QE
pF_C
pF_O
2p2h Norm ν
2p2h Norm $\bar{\nu}$
2p2h Norm C to O
2p2h Shape C
2p2h Shape O

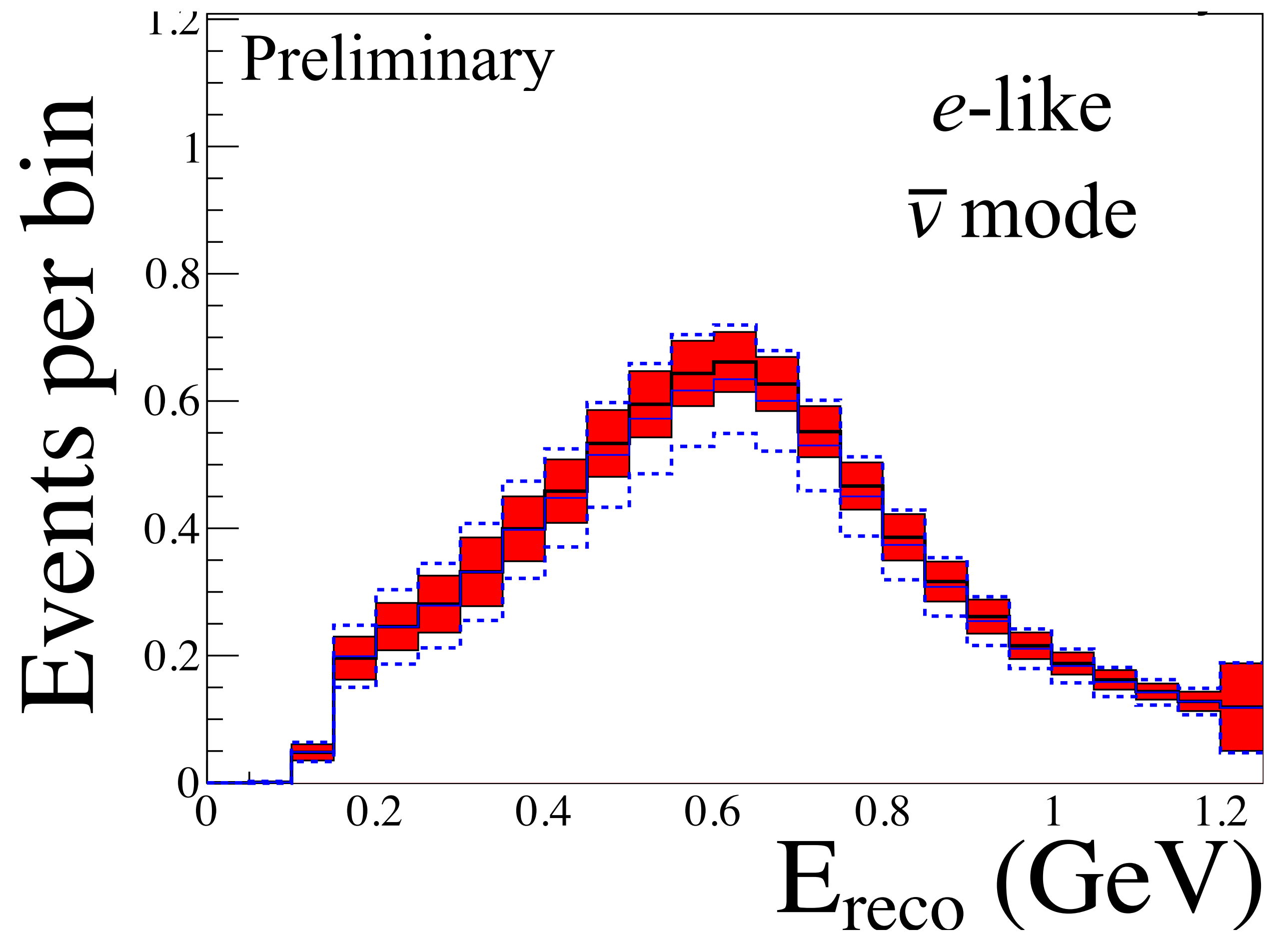
Expectation at SK





Expectation at SK



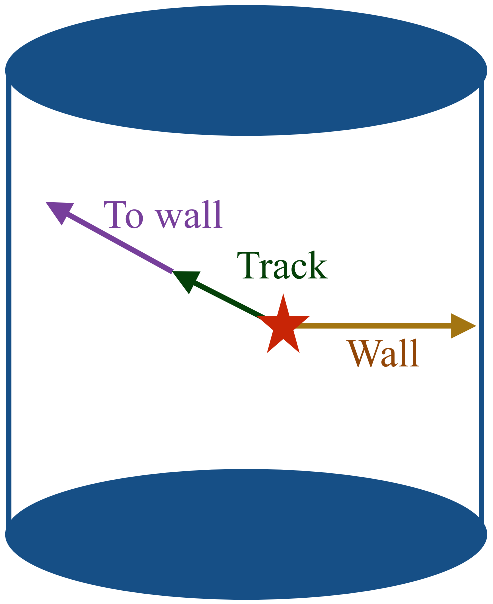


ND280 constraints are crucial for oscillation analysis precision

	ν mode			$\bar{\nu}$ mode	
	μ-like	e-like	e-like+$1\pi^+$	μ-like	e-like
Total w/o ND280	14.5%	17.1%	22.0%	12.2%	14.6%
Total w/ ND280	4.9%	9.6%	18.7%	4.3%	7.9%

SK reconstruction

- New reconstruction algorithm is used for SK
- It combines time and charge likelihood for a given ring hypothesis
- New definition of fiducial volume combining distance of the vertex from the wall and direction to the wall (previously only distance from the wall was used)
    - ~30% more statistics for ν-mode *e*-like samples
    - ~20% more statistic for $\bar{\nu}$-mode *e*-like
    - Better purity for μ-like samples by reducing NC background



Samples	New SK selection	Old SK selection
	Purity	**Purity**
μ-like ν mode	80%	68%
***e*-like ν mode**	81%	81%
***e*-like+1π^+ ν mode**	79%	72%
μ-like $\bar{\nu}$ mode	80%	71%
***e*-like $\bar{\nu}$ mode**	62%	64%

Observed events at SK

	Observed	$\delta = -\pi/2$	$\delta = 0$	$\delta = +\pi/2$	$\delta = \pi$
***e*-like ν mode**	75	73.8	61.6	50.1	62.2
***e*-like+1π^+ ν mode**	15	6.9	6	4.9	5.8
***e*-like $\overline{\nu}$ mode**	9	11.8	13.4	14.9	13.2
μ-like ν mode	243	268.5	268.2	268.4	268.8
μ-like $\overline{\nu}$ mode	102	95.5	95.3	95.5	95.7

Observed events at SK

	Observed	$\delta = -\pi/2$	$\delta = 0$	$\delta = +\pi/2$	$\delta = \pi$
e-like ν mode	75	73.8	61.6	50.1	62.2
e-like+1π^+ ν mode	15	6.9	6	4.9	5.8
e-like $\bar{\nu}$ mode	9	11.8	13.4	14.9	13.2
μ-like ν mode	243	268.5	268.2	268.4	268.8
μ-like $\bar{\nu}$ mode	102	95.5	95.3	95.5	95.7

T2K data prefer $\delta = -\pi/2$: maximize ν_e appearance and minimize $\bar{\nu}_e$ appearance

Observed events at SK

	Observed	$\delta = -\pi/2$	$\delta = 0$	$\delta = +\pi/2$	$\delta = \pi$
***e*-like ν mode**	75	73.8	61.6	50.1	62.2
***e*-like+1π^+ ν mode**	15	6.9	6	4.9	5.8
***e*-like $\overline{\nu}$ mode**	9	11.8	13.4	14.9	13.2
μ-like ν mode	243	268.5	268.2	268.4	268.8
μ-like $\overline{\nu}$ mode	102	95.5	95.3	95.5	95.7

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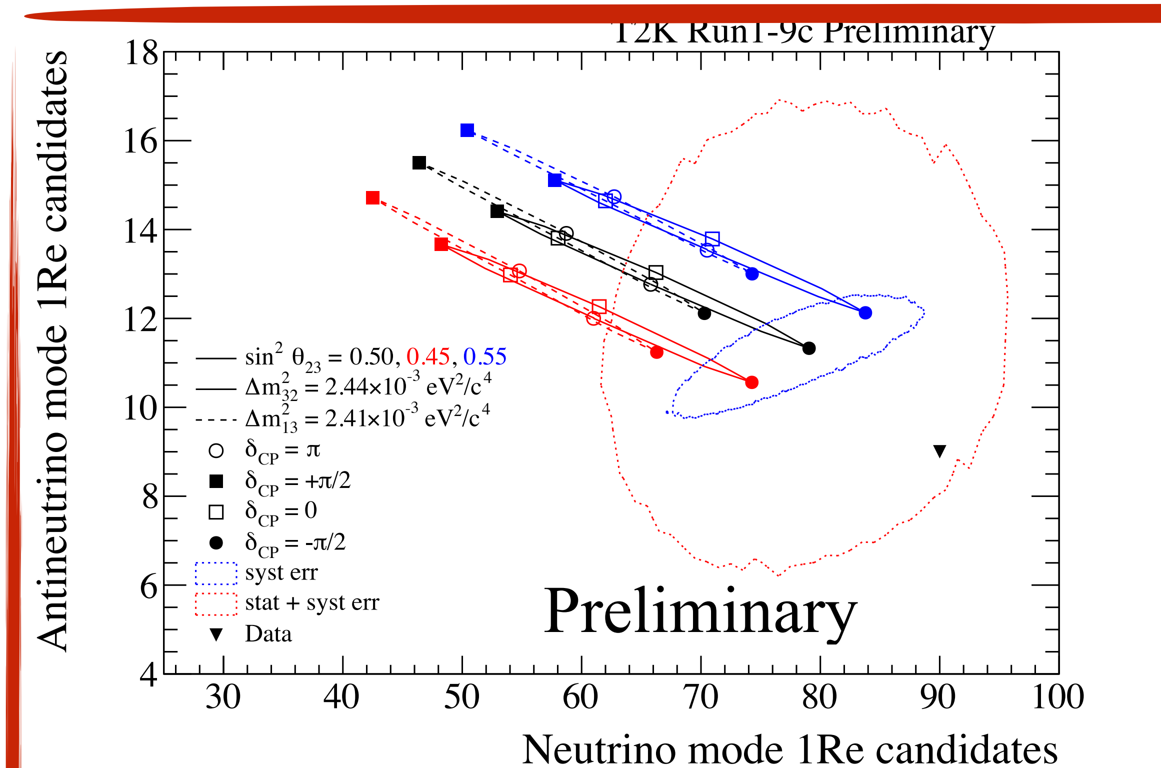

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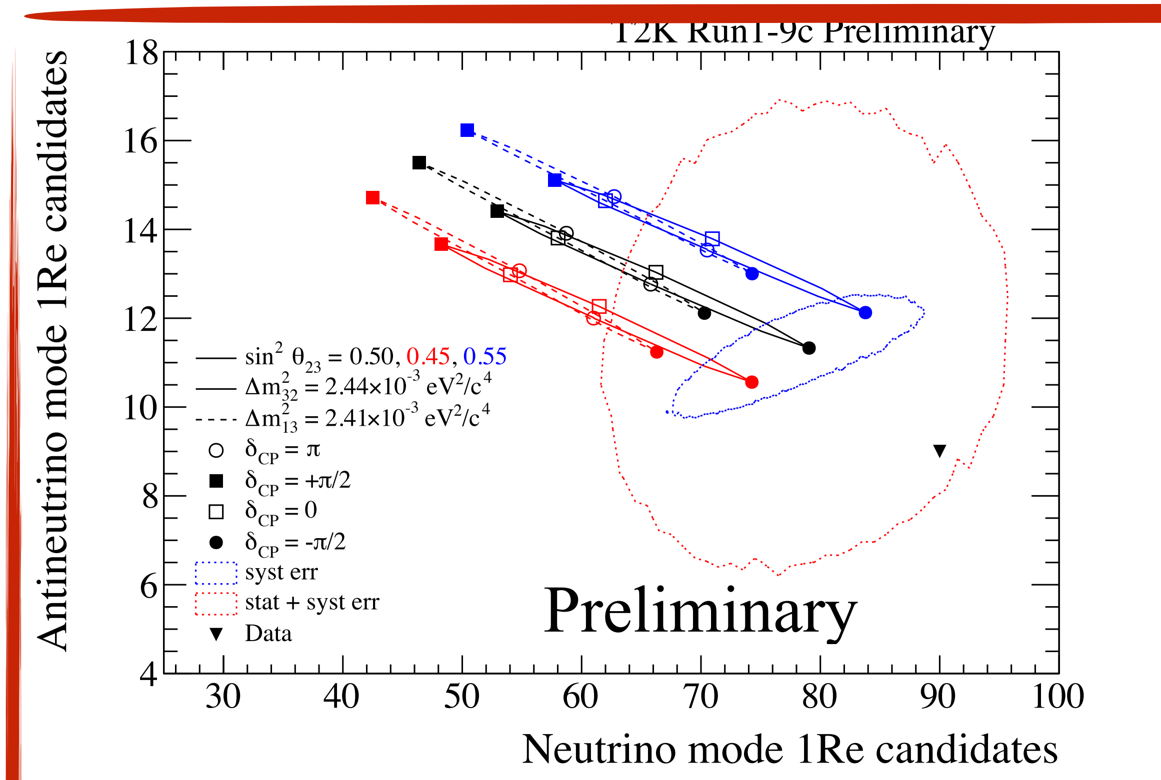
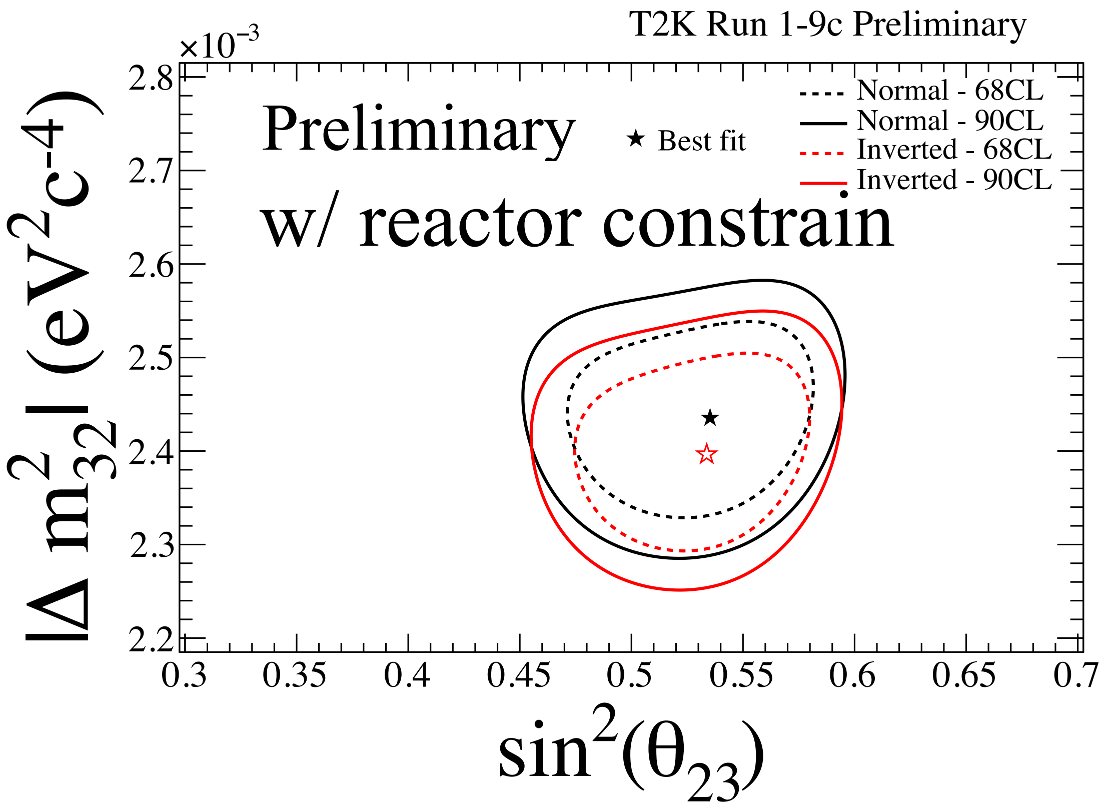
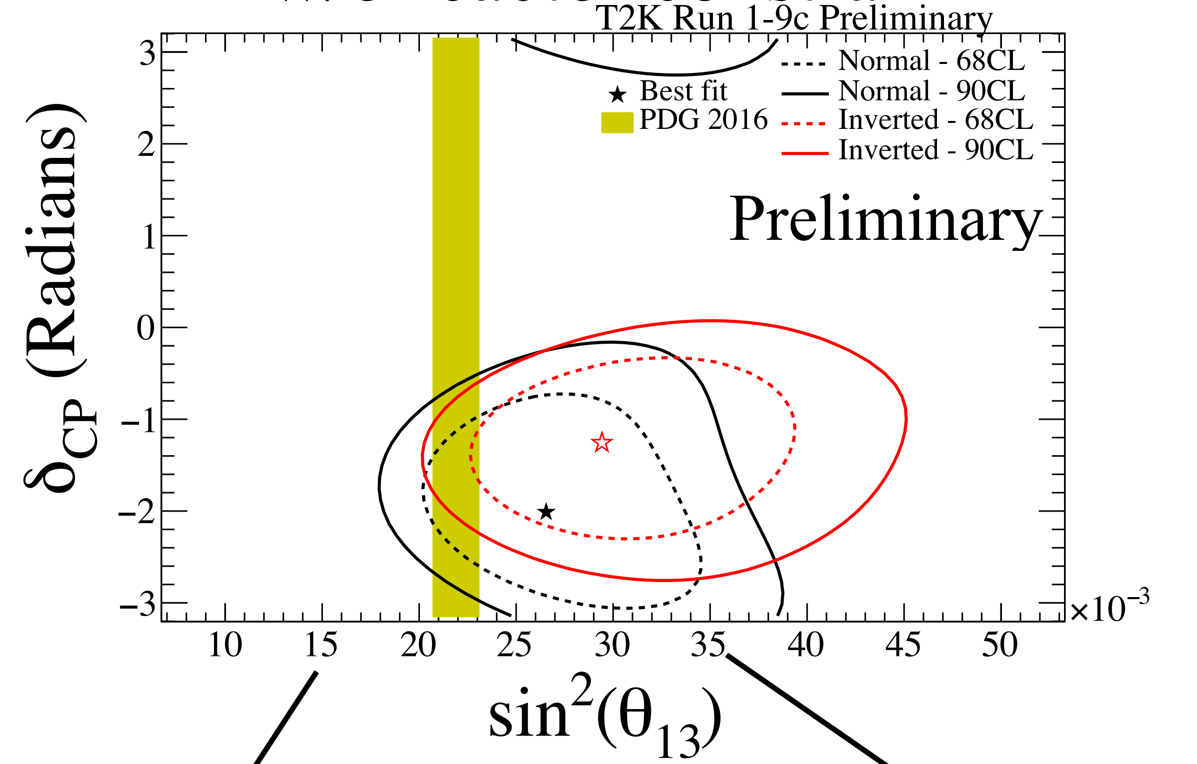
In ν-mode the deficit of μ-like events is compatible with statistical and systematic uncertainties



Oscillation results (θ_{23}, $|\Delta m^2_{32}|$, θ_{13}, δ_{CP})

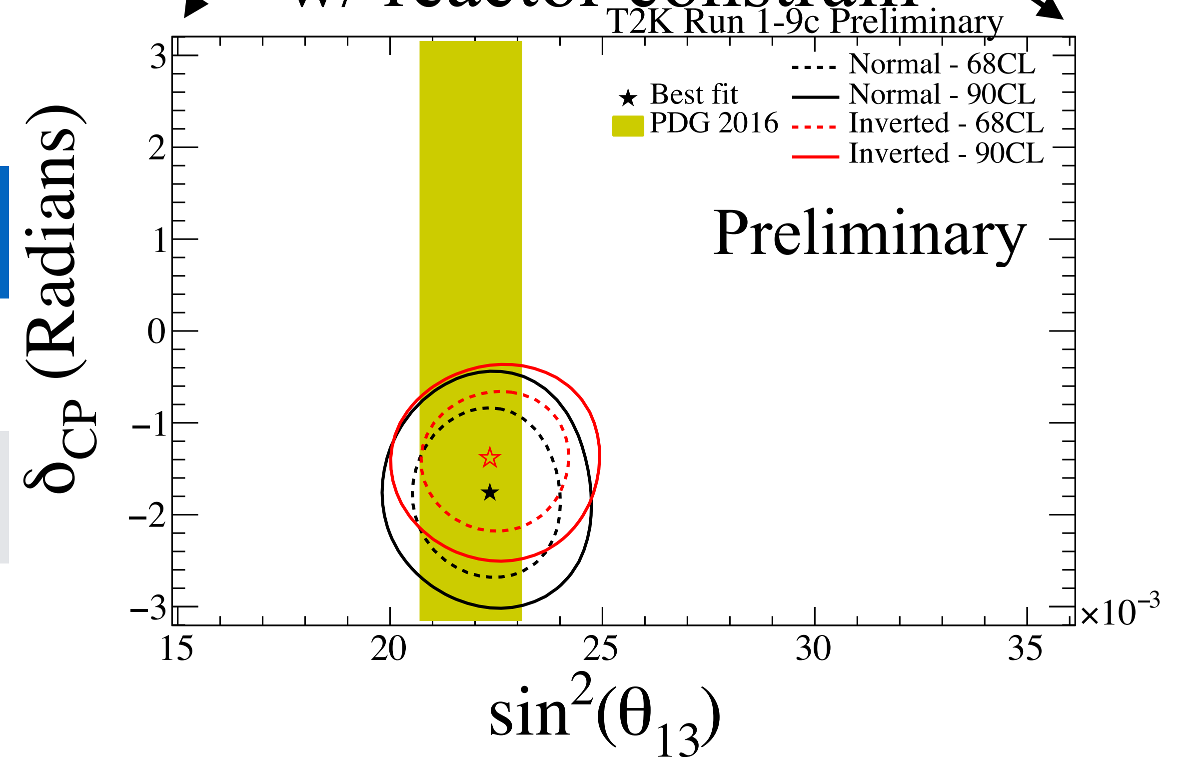


w/o reactor constrain



T2K data compatible with maximal mixing

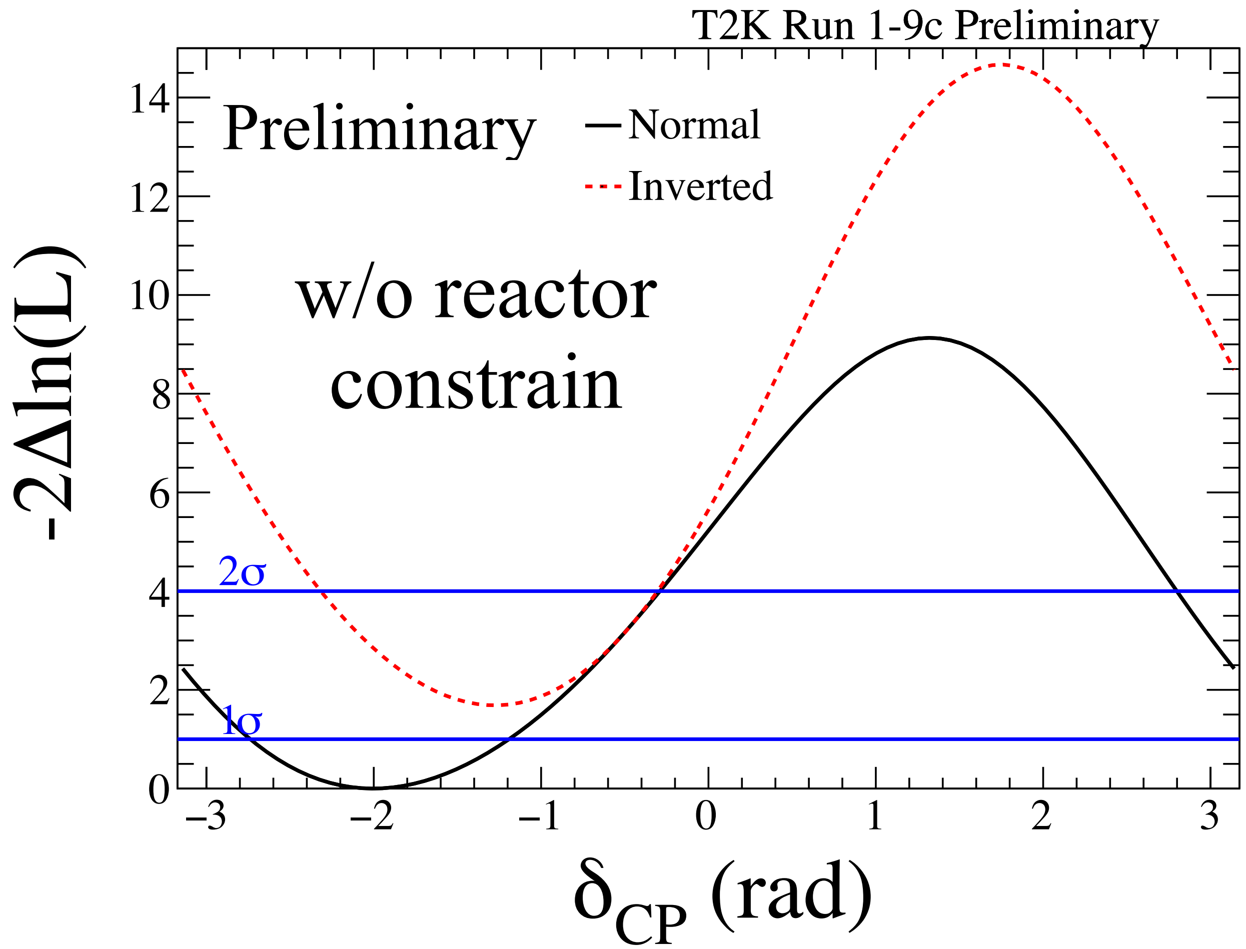
w/ reactor constrain

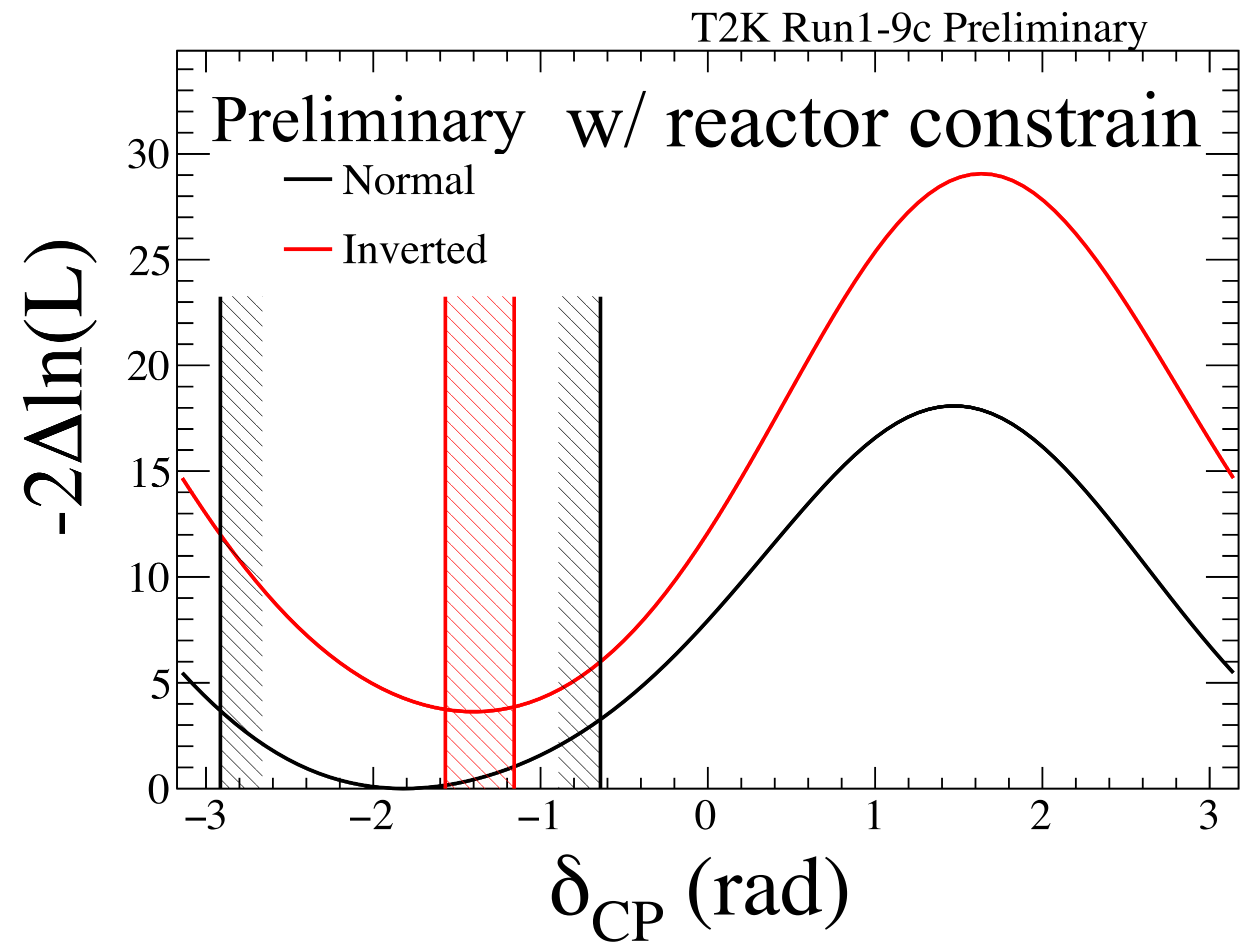


Parameter	Best Fit NH (HI)	$\pm1\sigma$ NH (IH)
$\sin^2\theta_{32}$	0.54 (0.54)	[0.490,0.567] ([0.495,0.567])
$|\Delta m^2_{32}|$ ($10^{-3}eV^2/c^4$)	2.43 (2.41)	[2.370,2.498] ([2.347,2.472])
$\sin^2\theta_{13}$	0.0268 (0.0305)	[0.0222,0.0319]([0.0253,0.0369])

δ_{CP} measurement

T2K data prefer values of $\delta_{CP} \sim -\pi/2$ mostly driven by the large number of events observed in the *e*-like sample in neutrino mode





C.L.	Normal hierarchy	Inverted hierarchy
68%	[-2.44, -1.23]	-
90%	[-2.74, -0.85]	-
2σ	[-2.91, -0.64]	[-1.57, -1.16]

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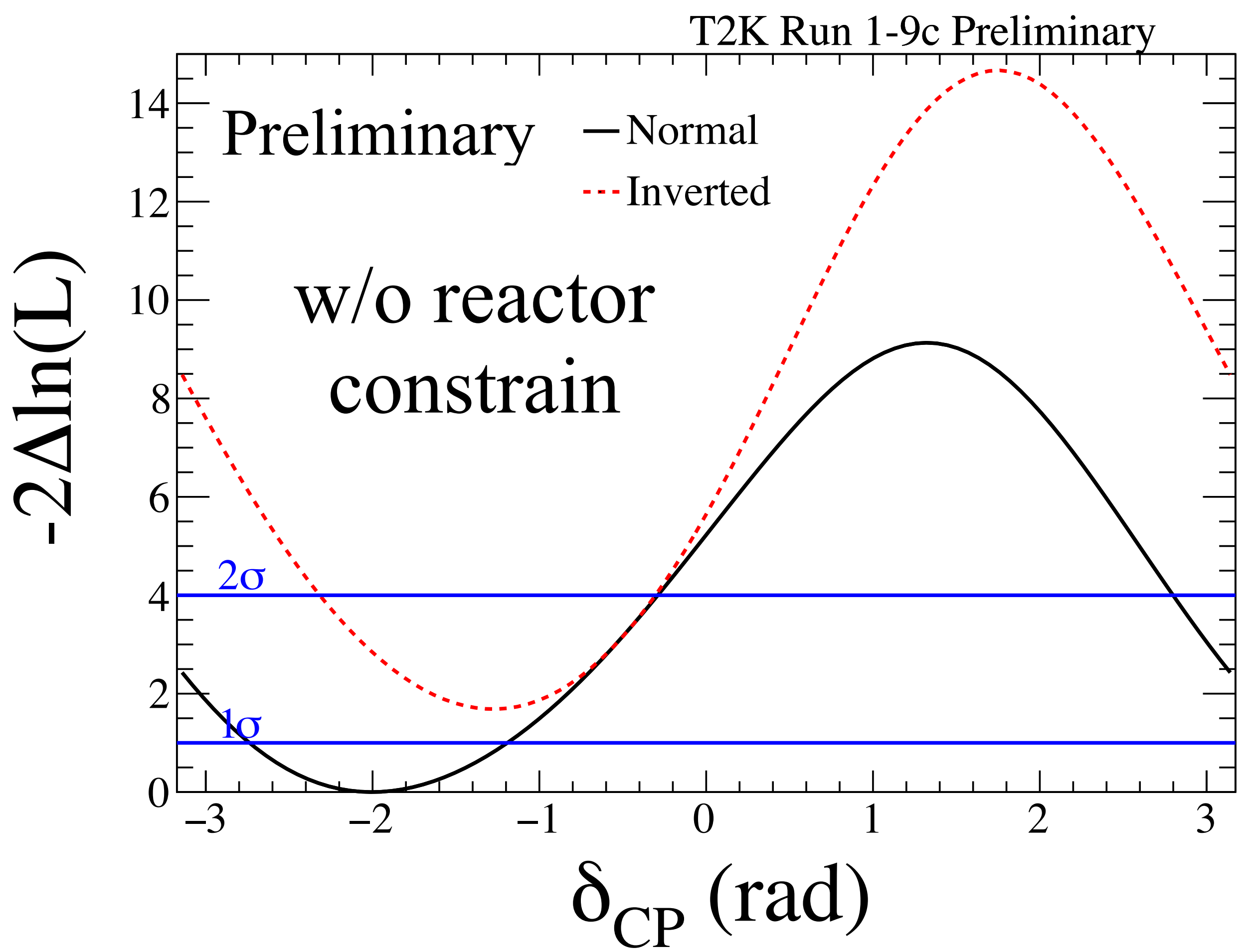

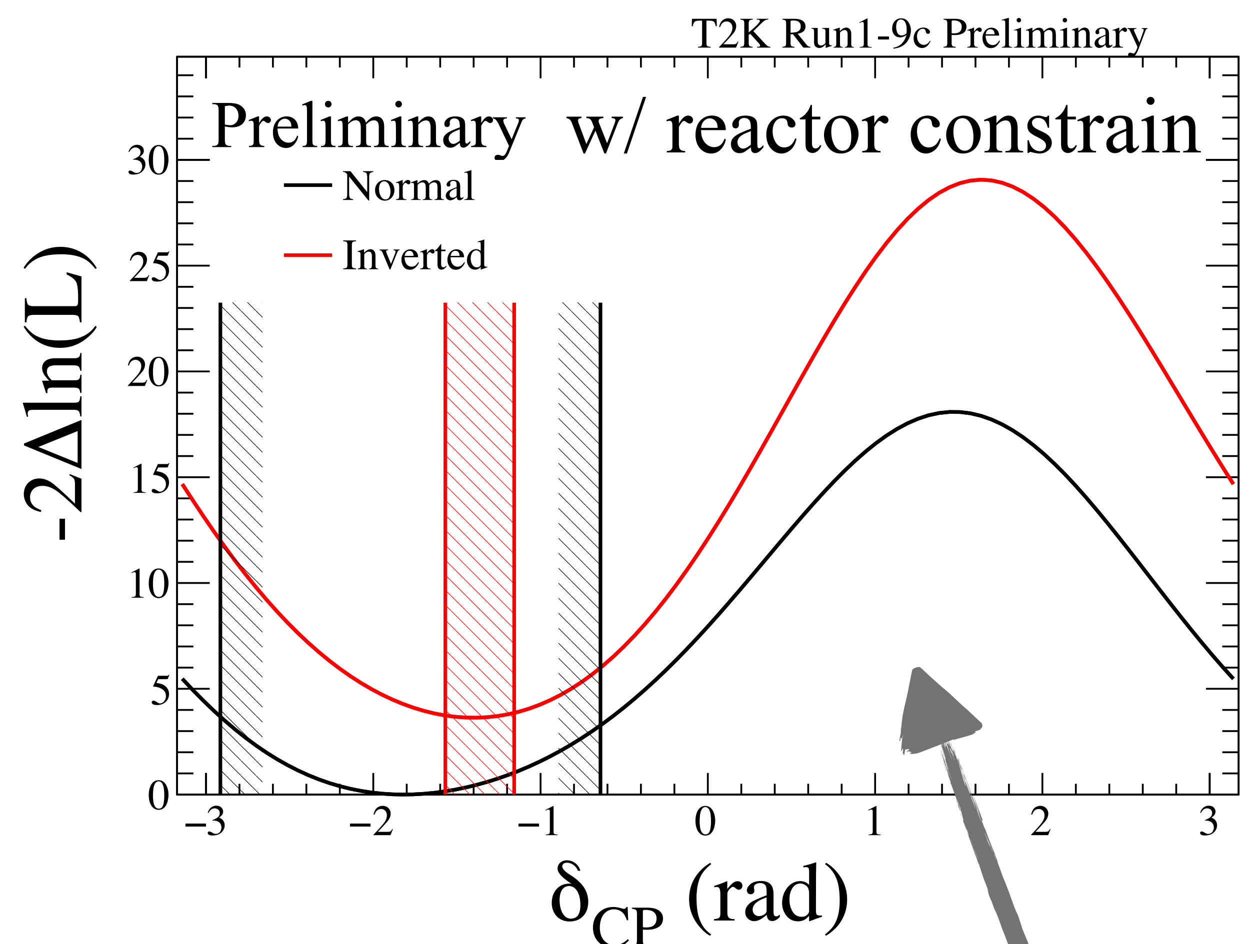

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$\delta_{CP} = 0, \pi$ fall outside 2σ interval

Cross section measurements

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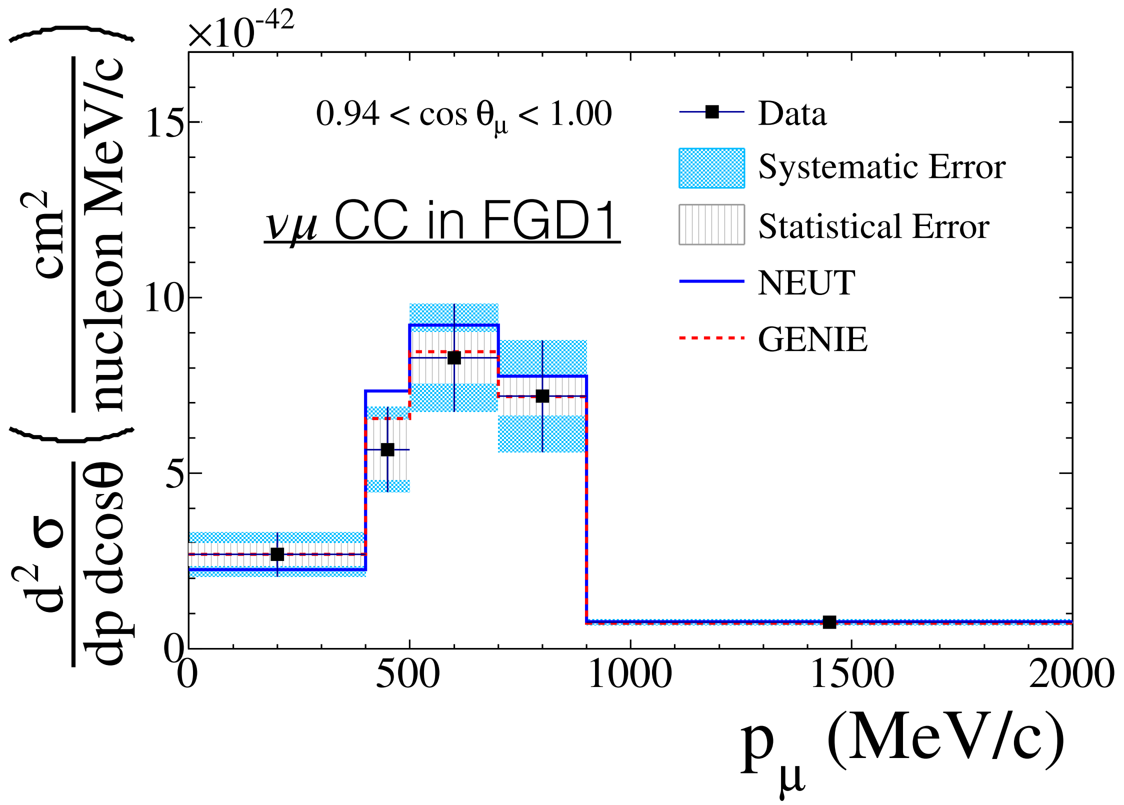
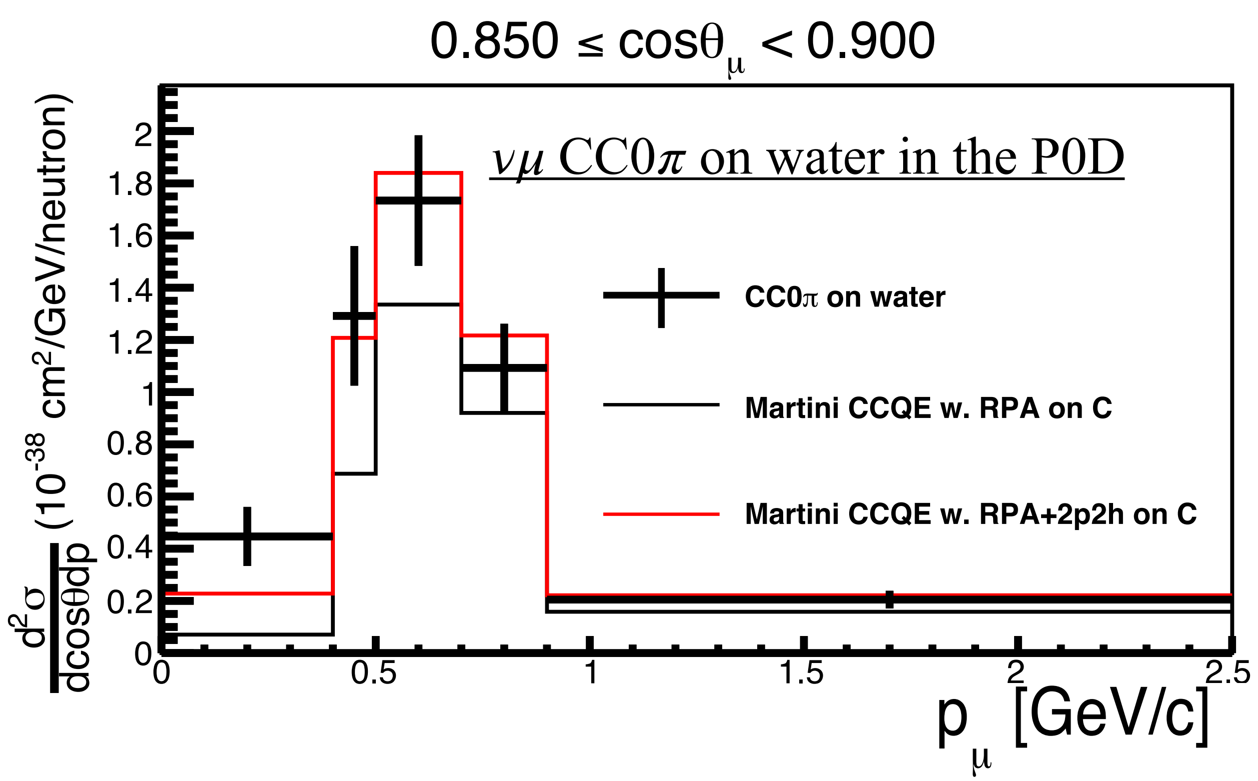
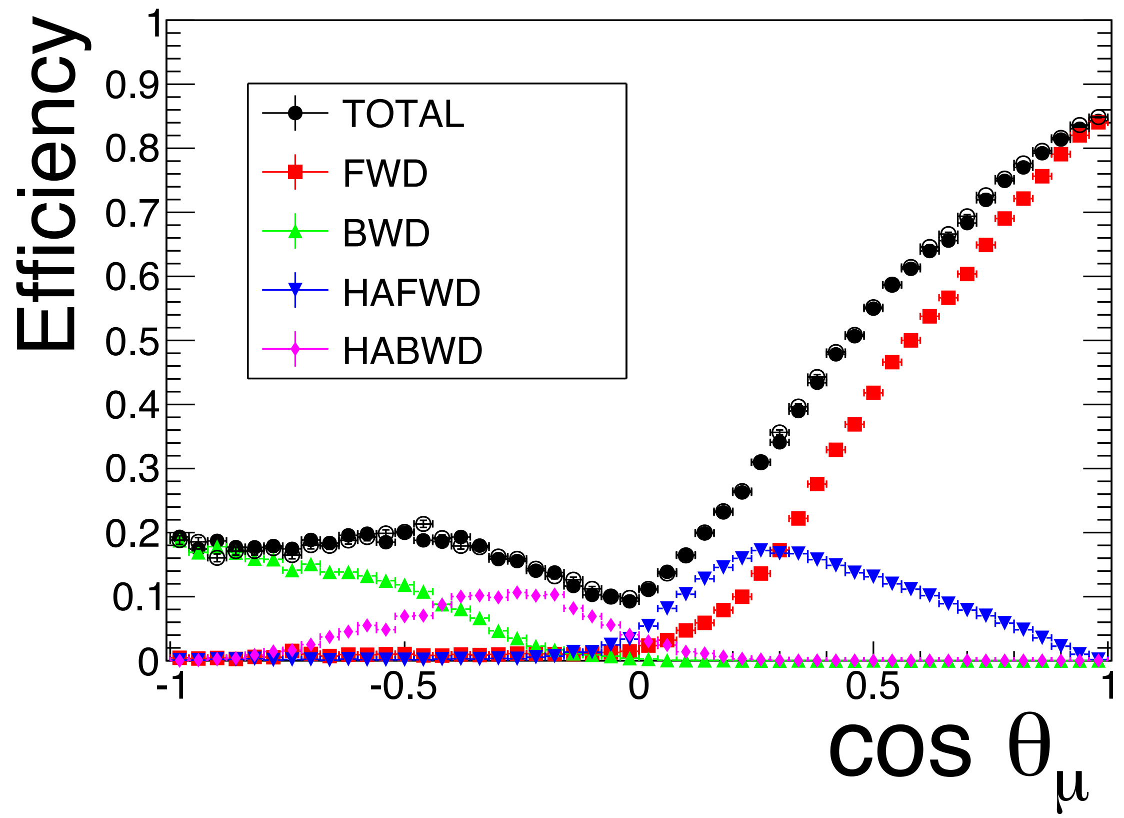




ν_μ CC Inclusive on CH at ND280

arXiv:1801.05148

- Next generation measurement
- Increased angular acceptance for high-angle and backward-going muons using the timing information between the sub-detectors
- Increased purities and efficiency



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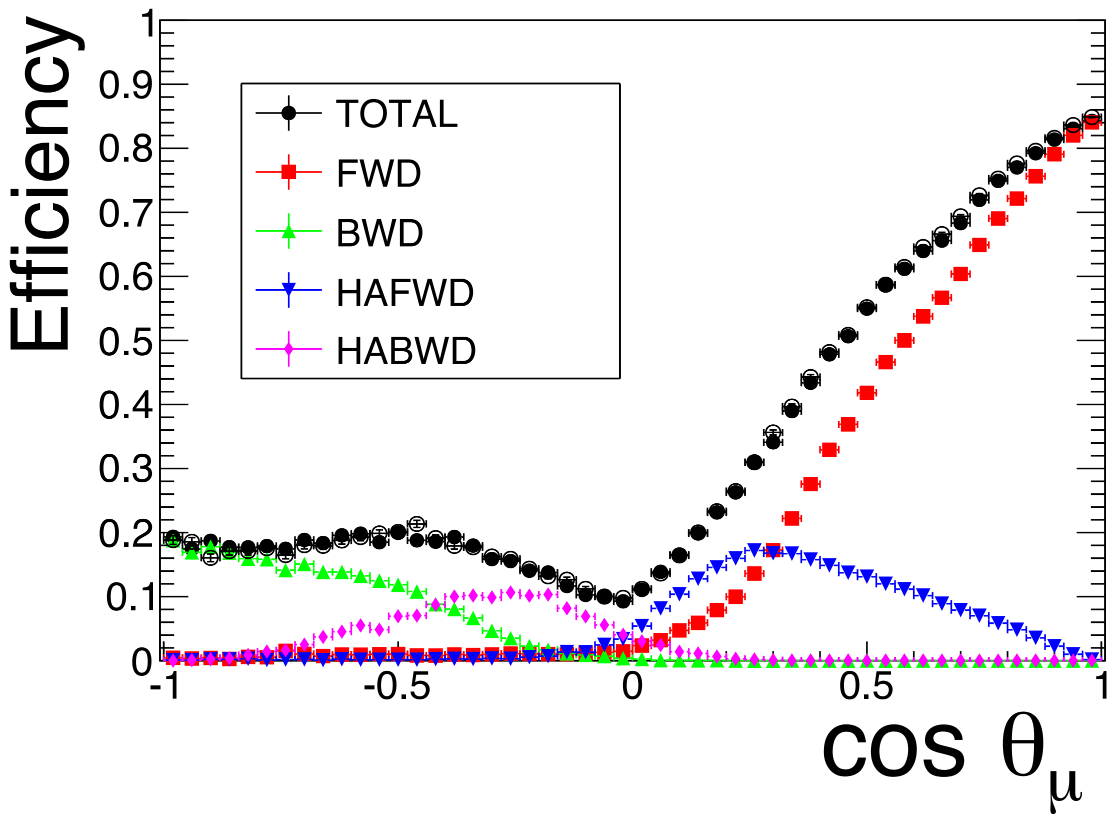

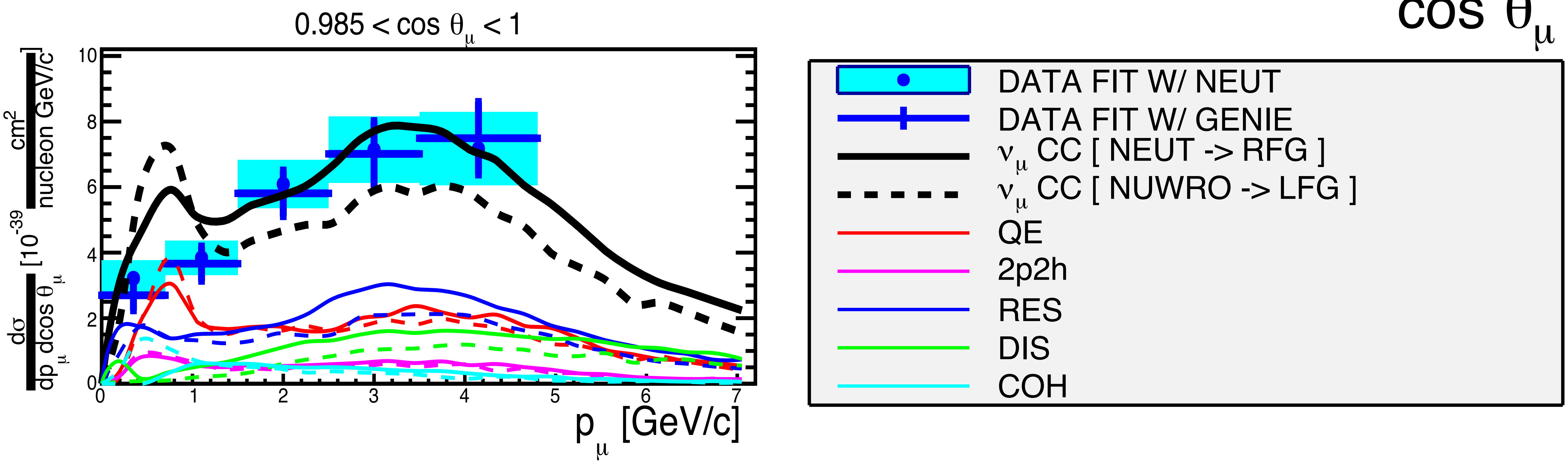

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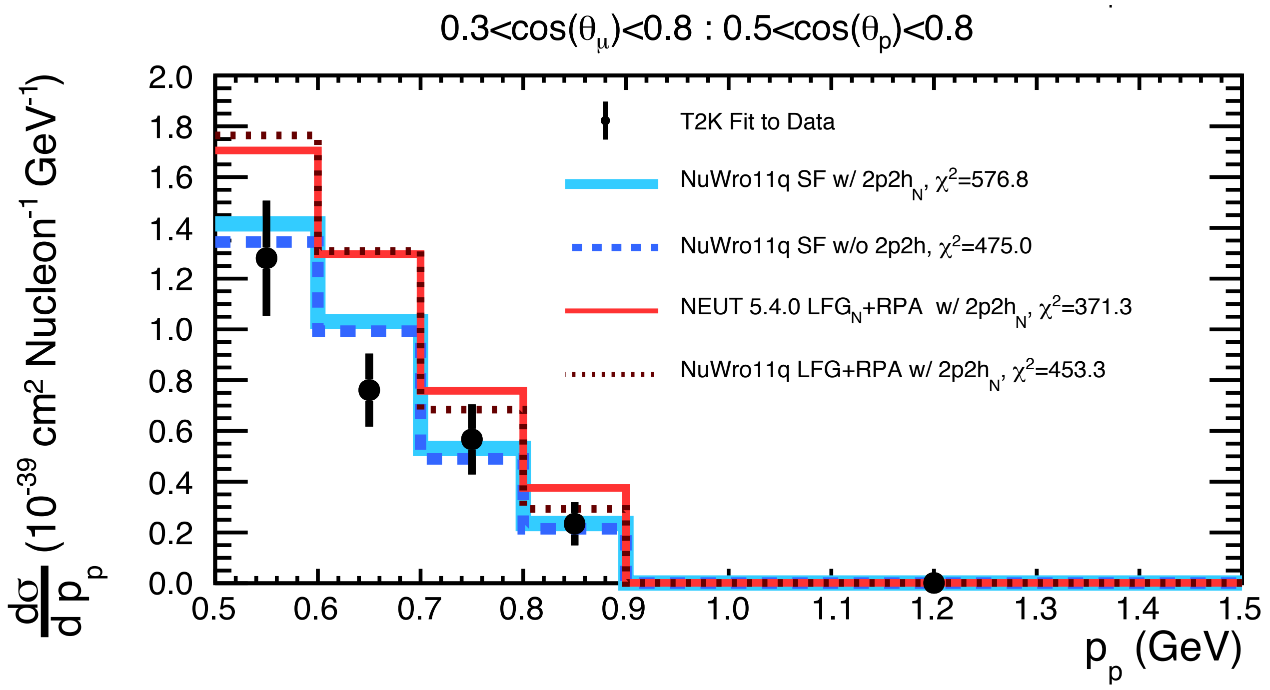

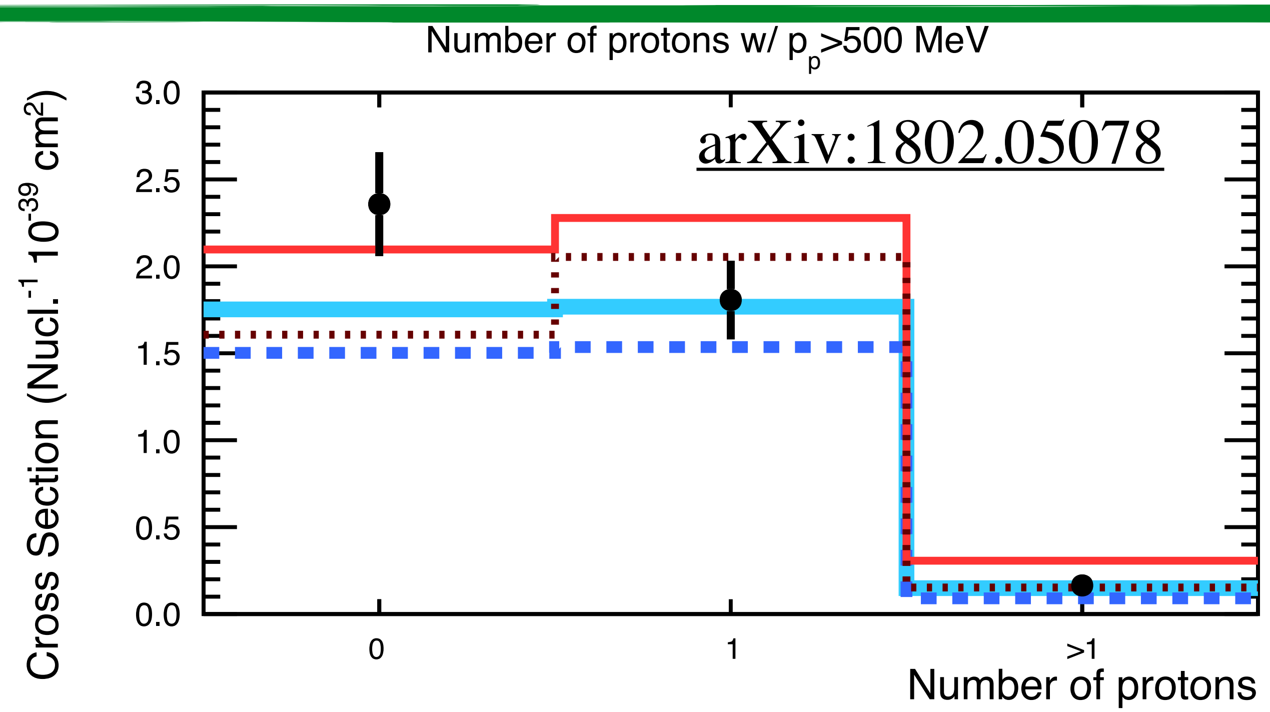

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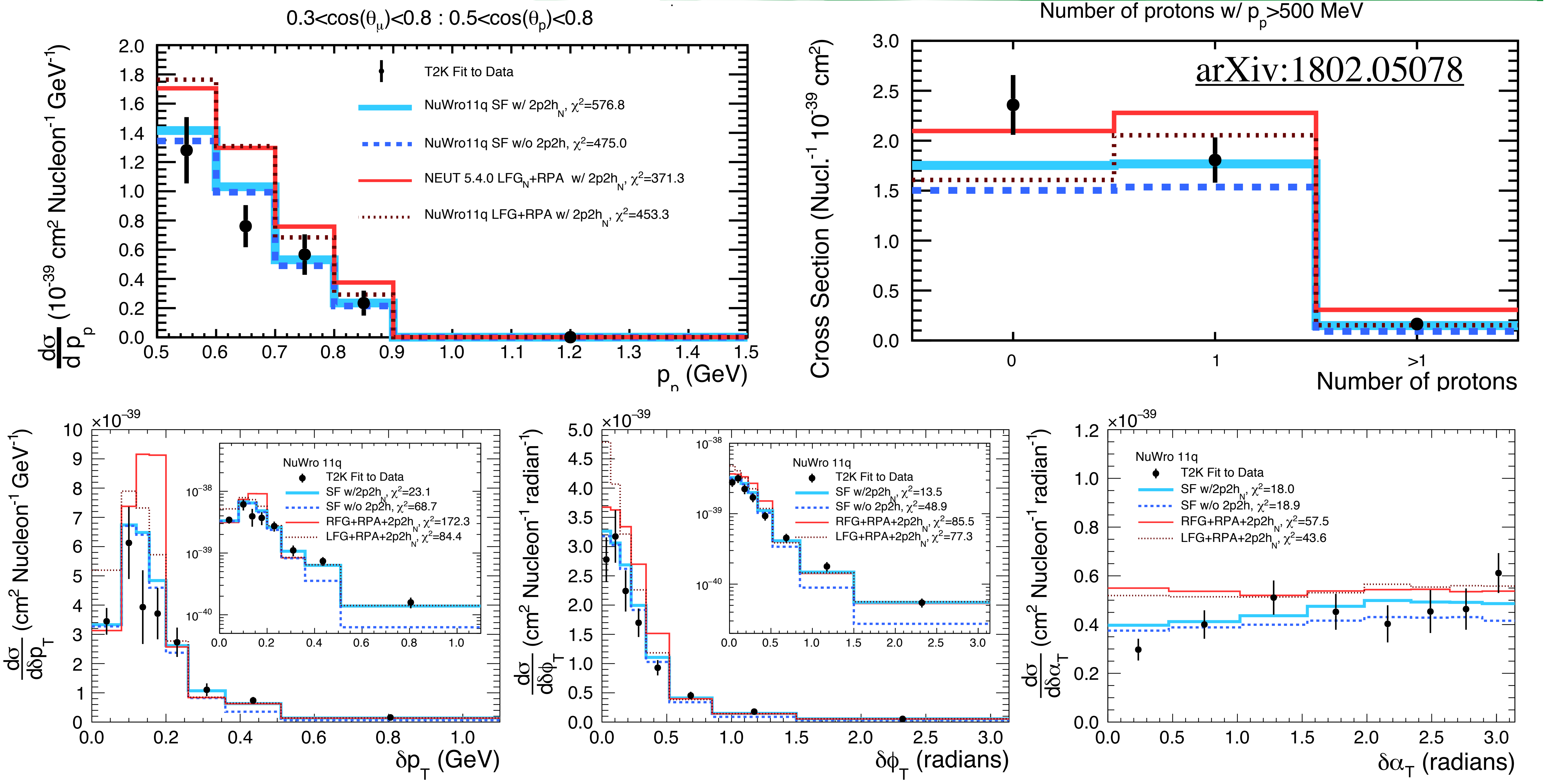

Some ongoing measurements

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M. Martini et al., Phys. Rev. C81 (2010)

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  - Joint fit of ν_μ - $\bar{\nu}_\mu$ CC0π cross section
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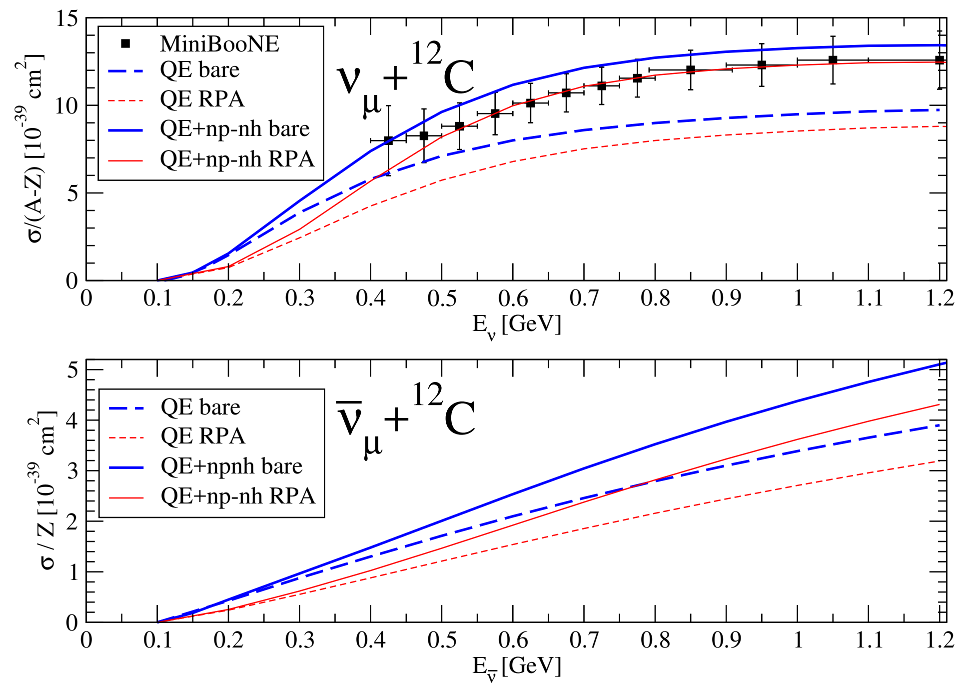

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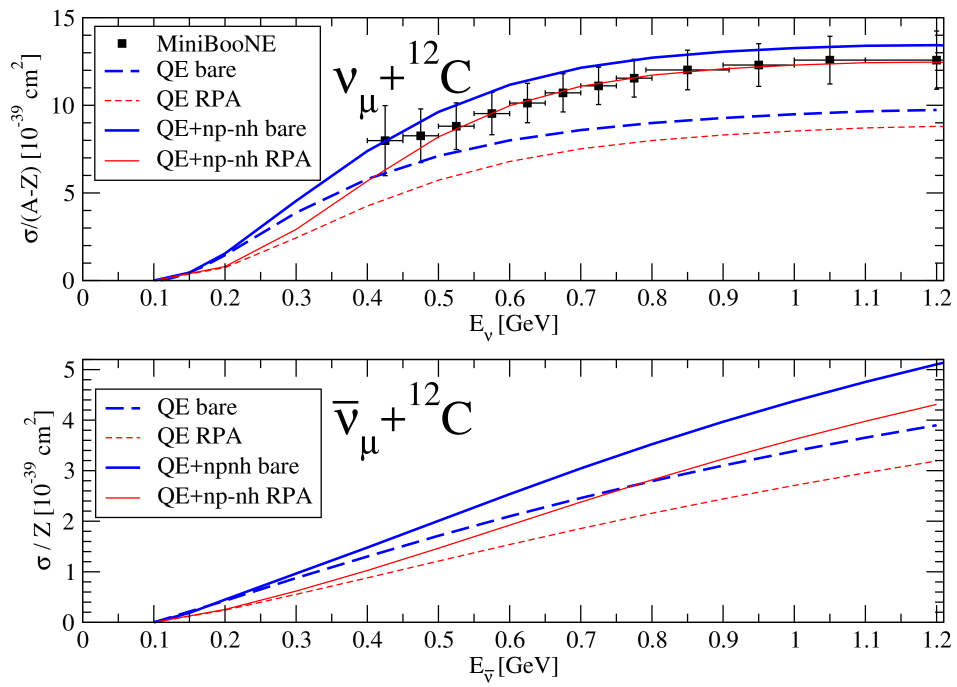

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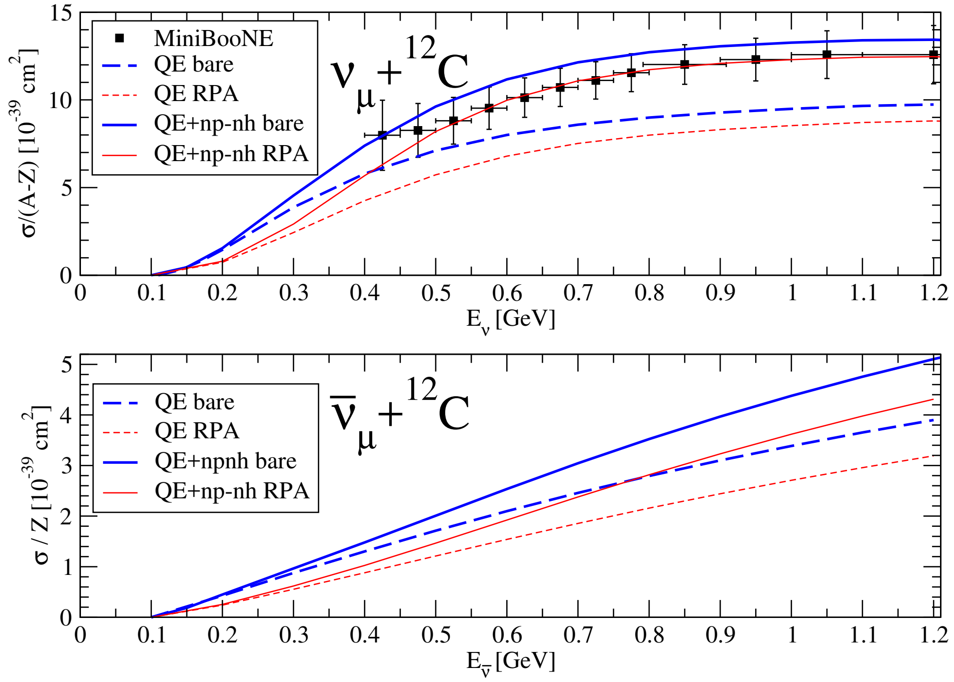

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- **$\bar{\nu}_\mu$ CC0π on water:**
  - Use P0D water layers
  - Cross section extracted in μ-kinematics

Future prospect: T2K-II

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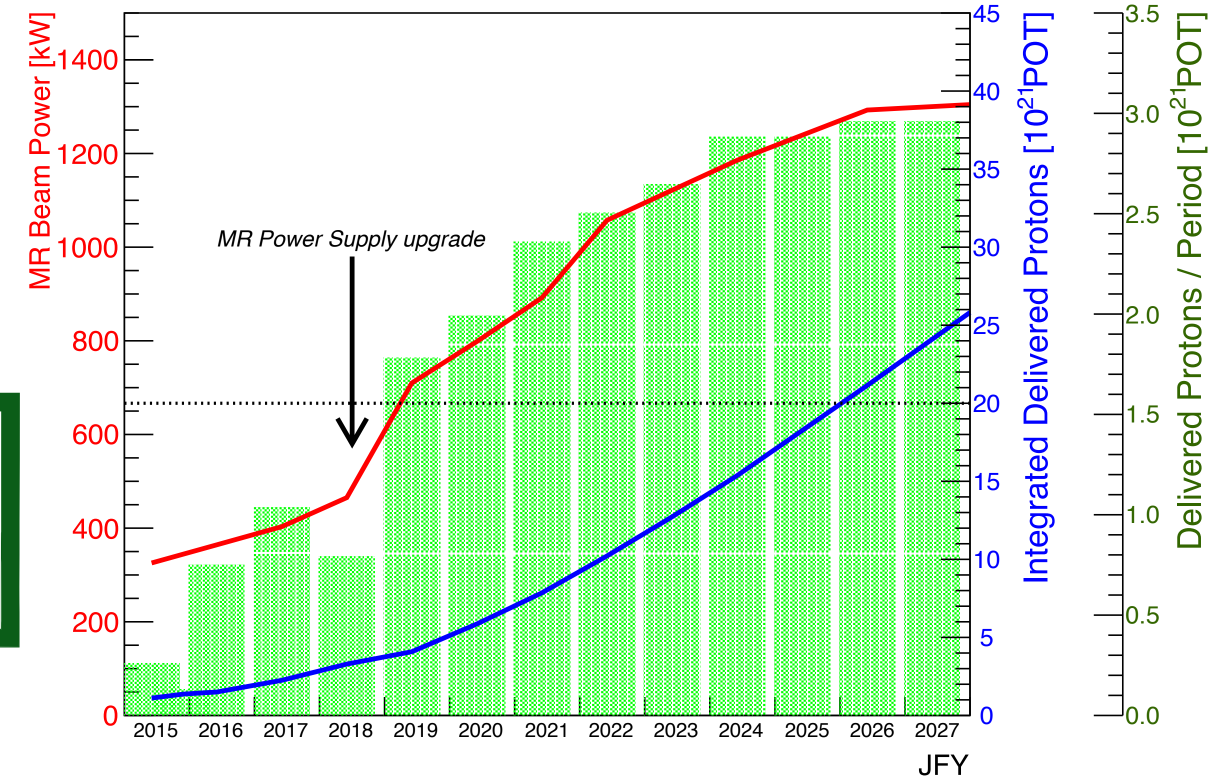

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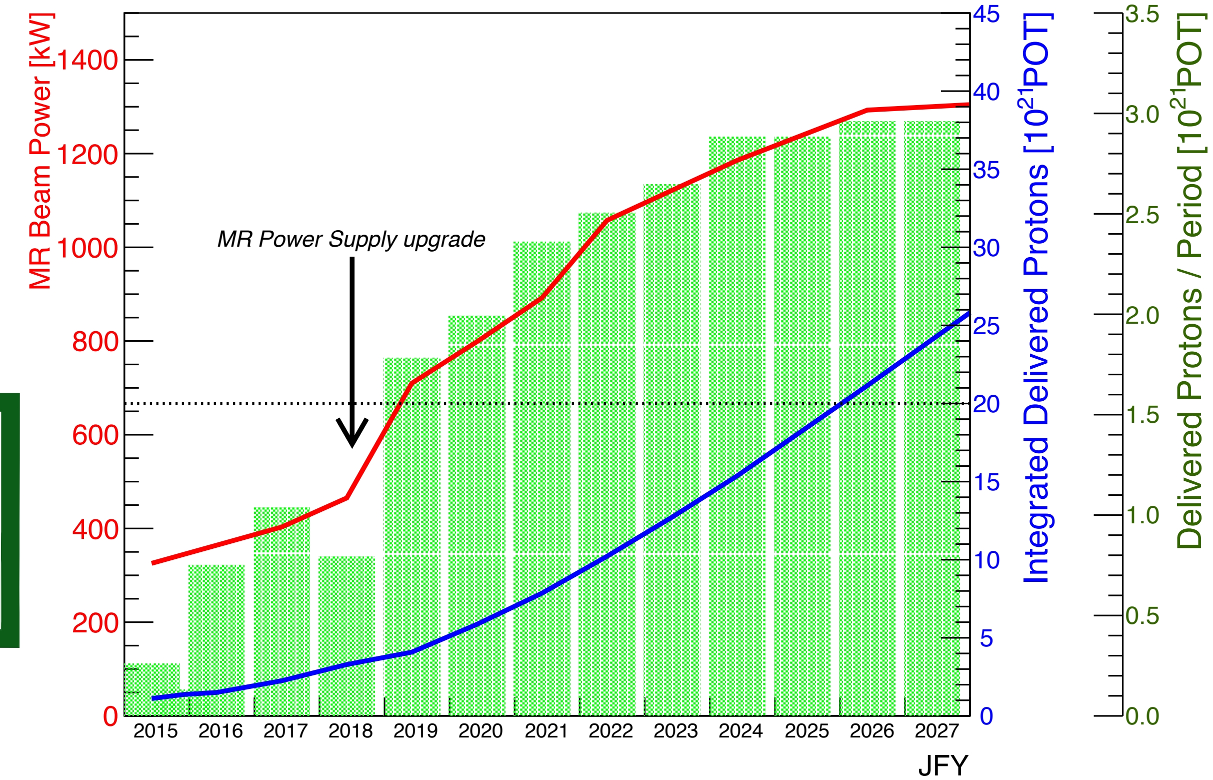

SK plan to start to dope water with Gadolinium from next year:

- Enhance neutron detection capability
- Improves low energy antineutrino detection
- Provides wrong sign bkg constraint in T2K antineutrino data

T2K-II: ND280 upgrade

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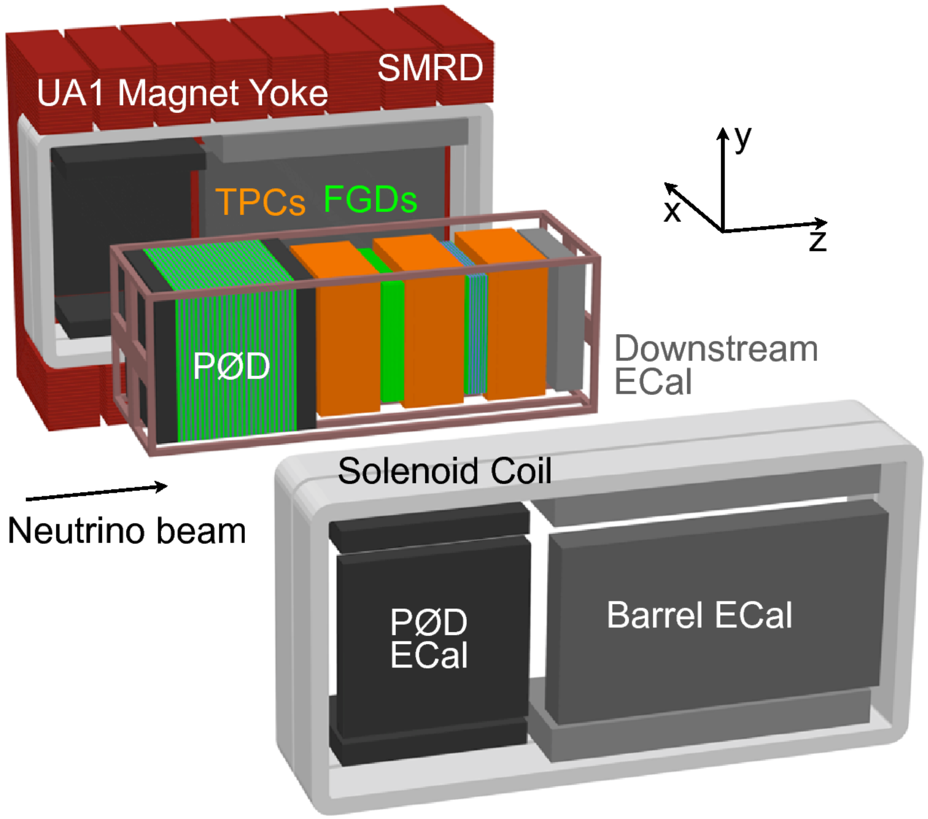

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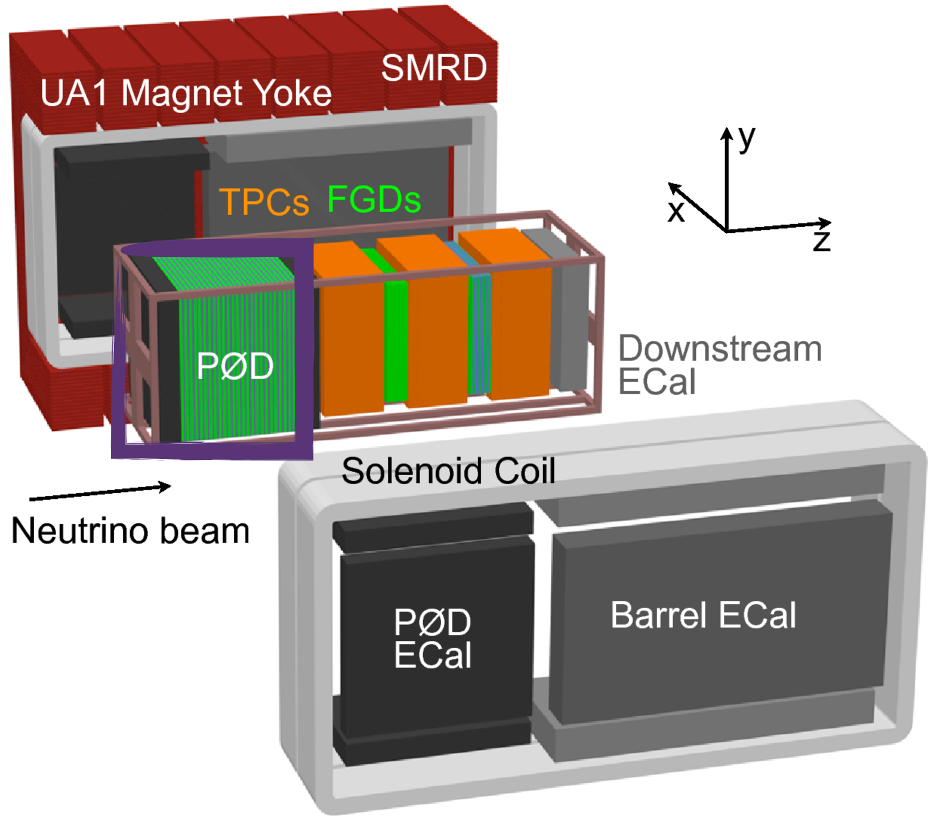

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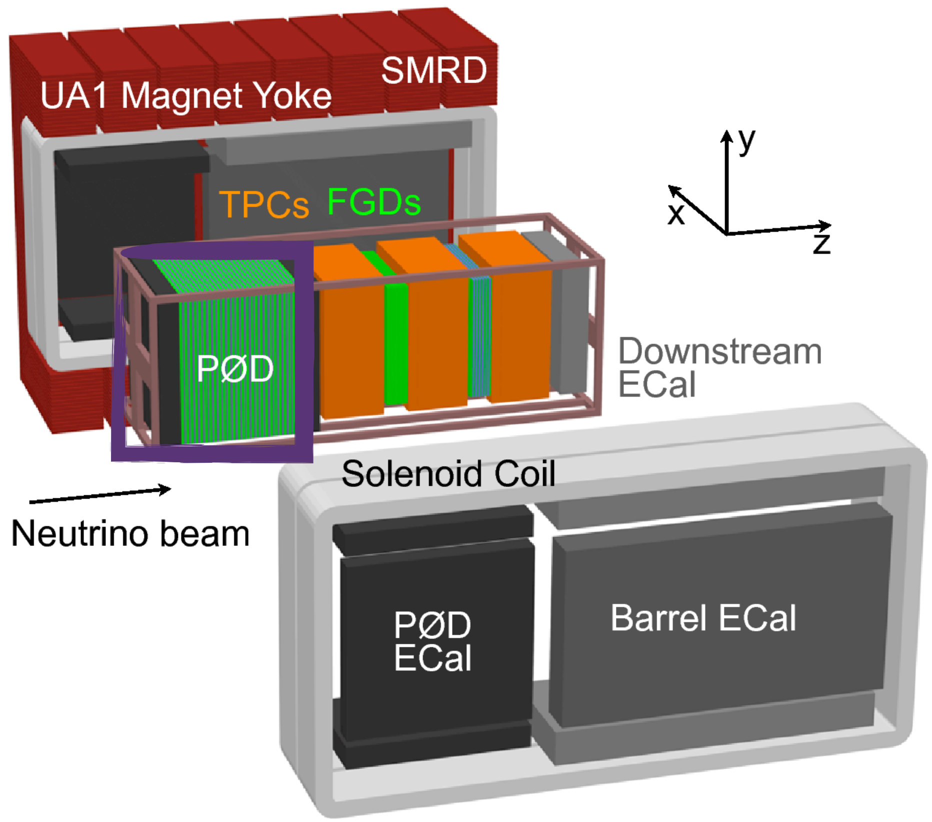

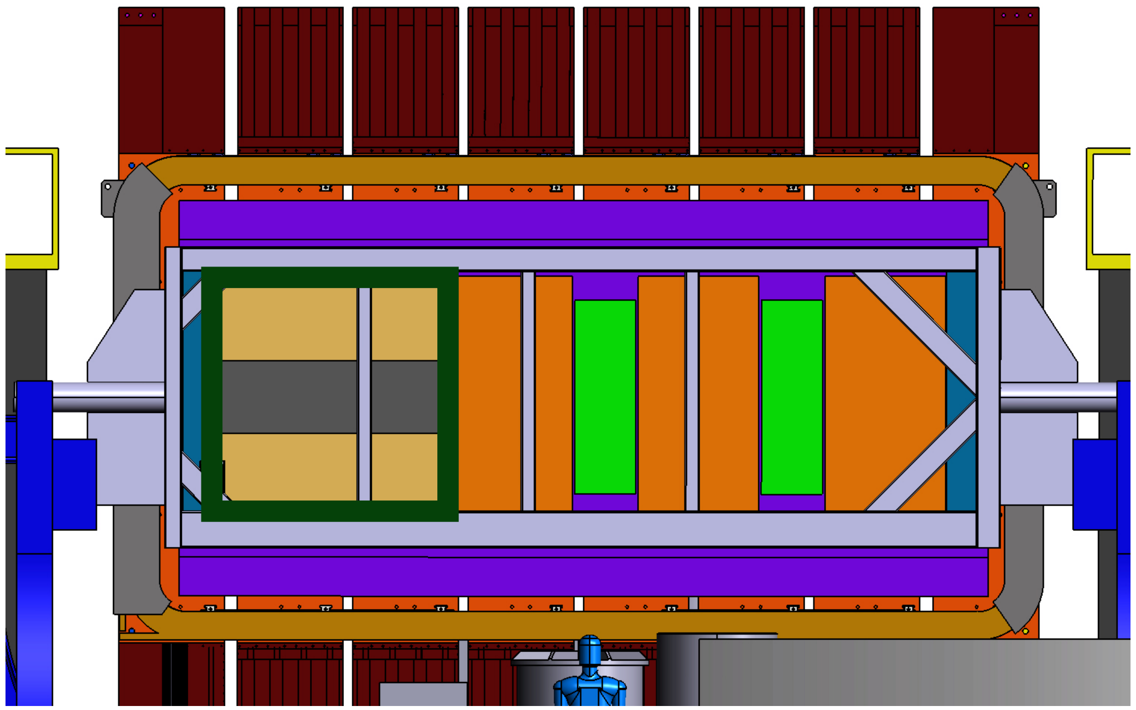

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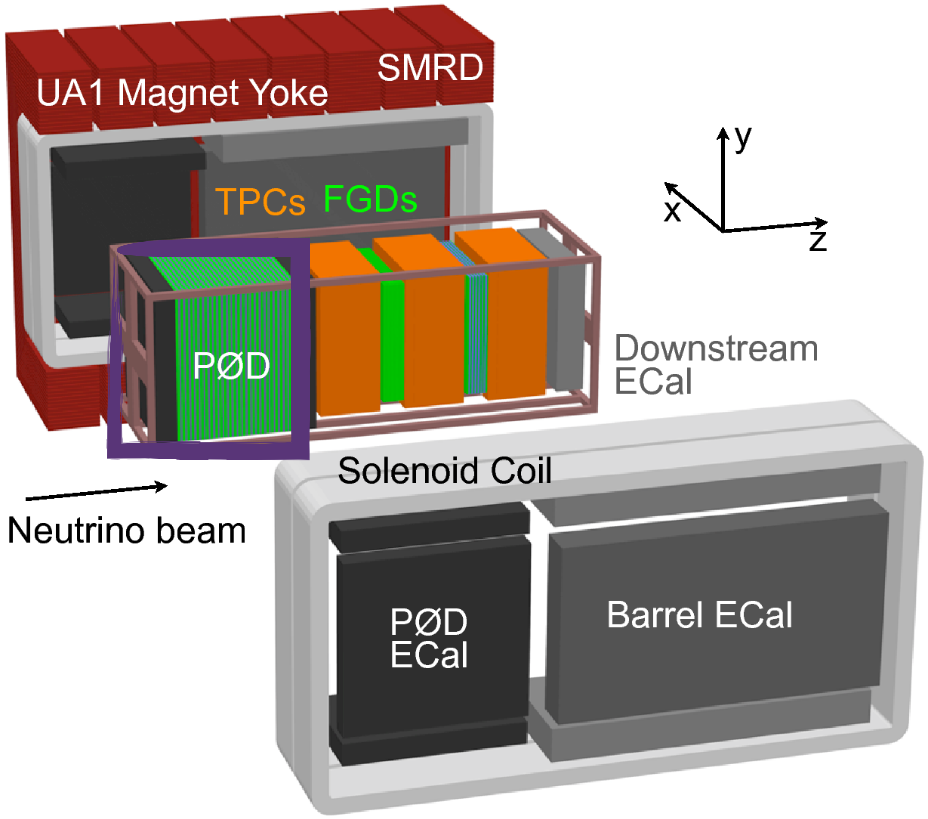

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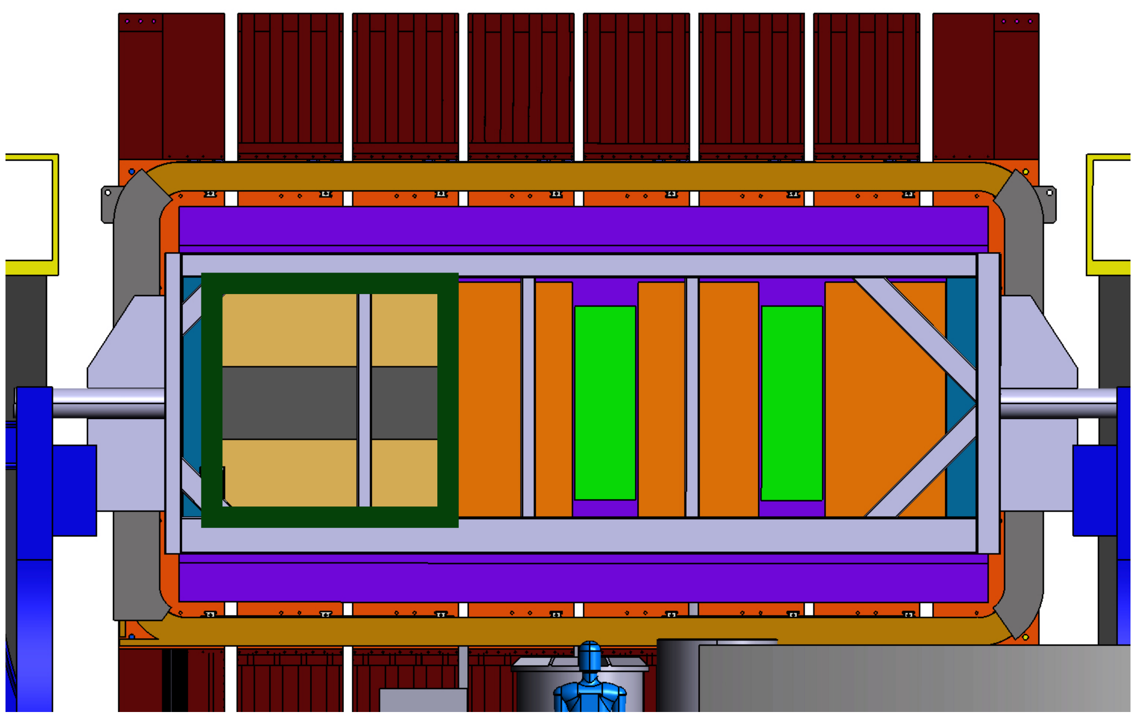
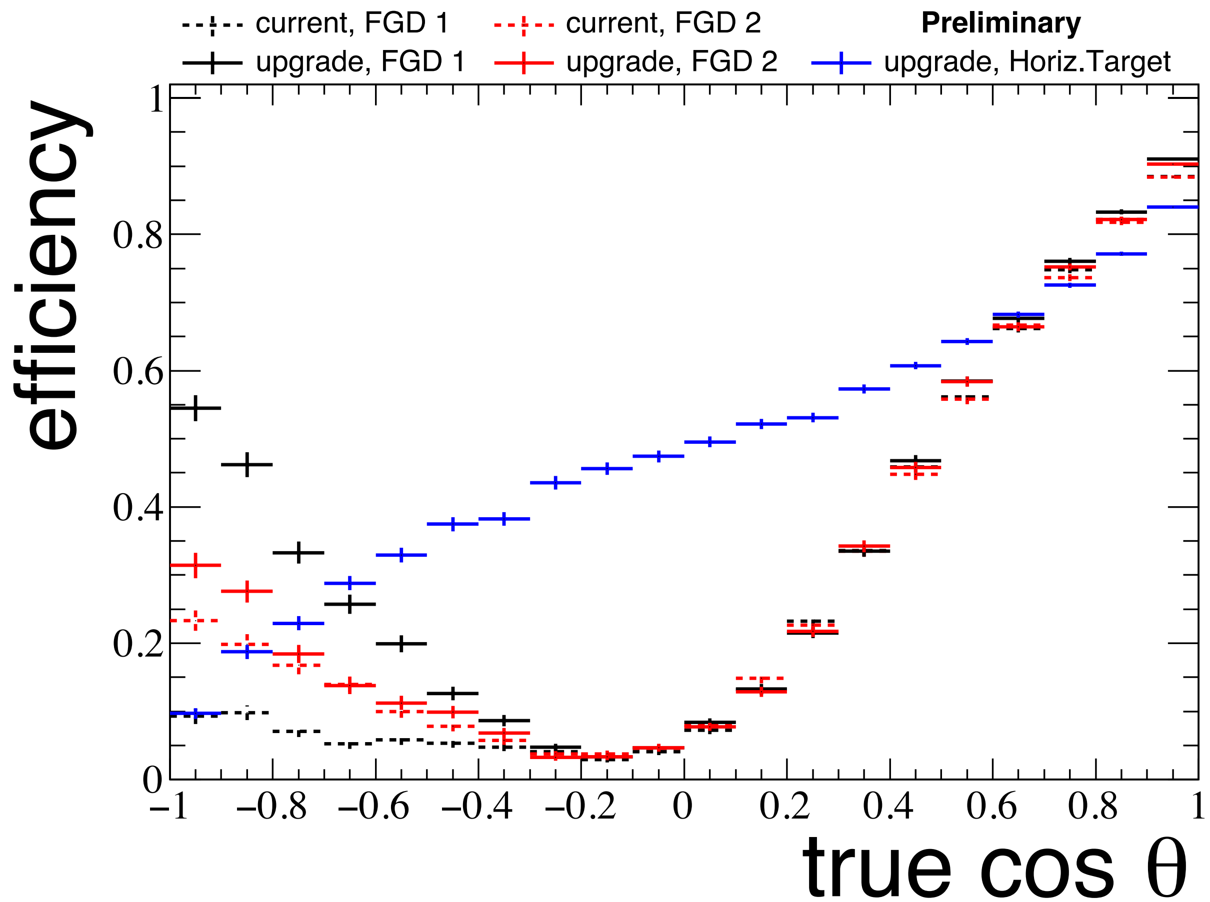
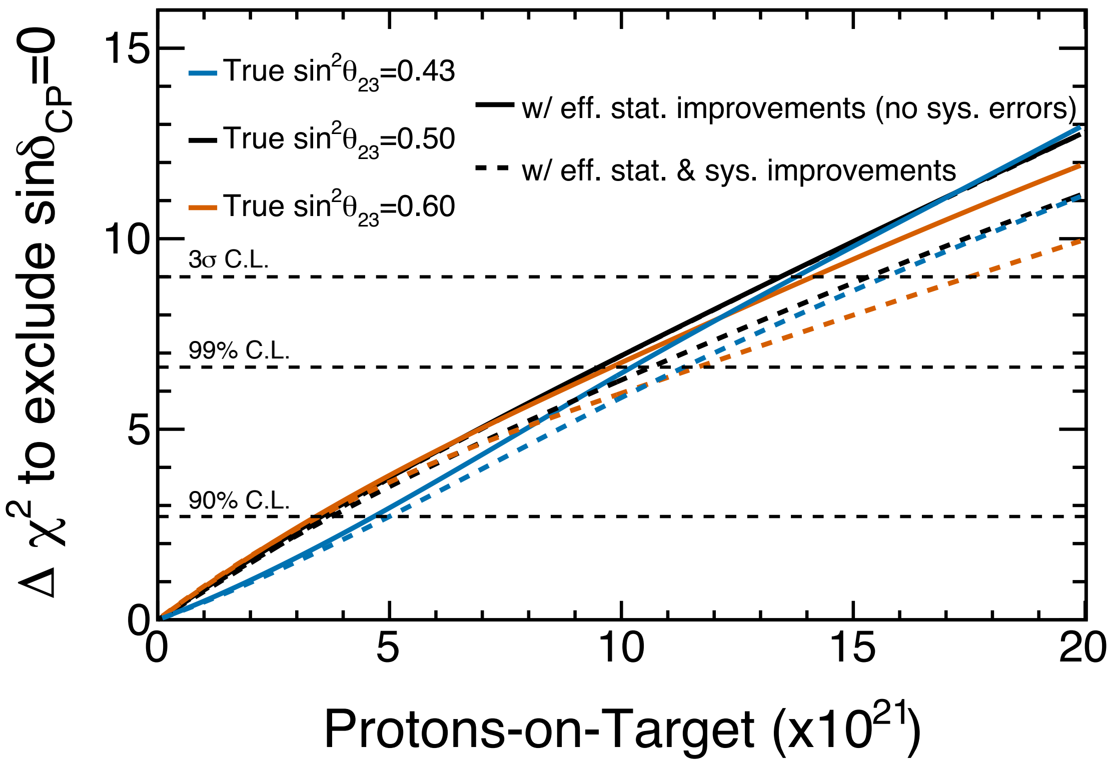
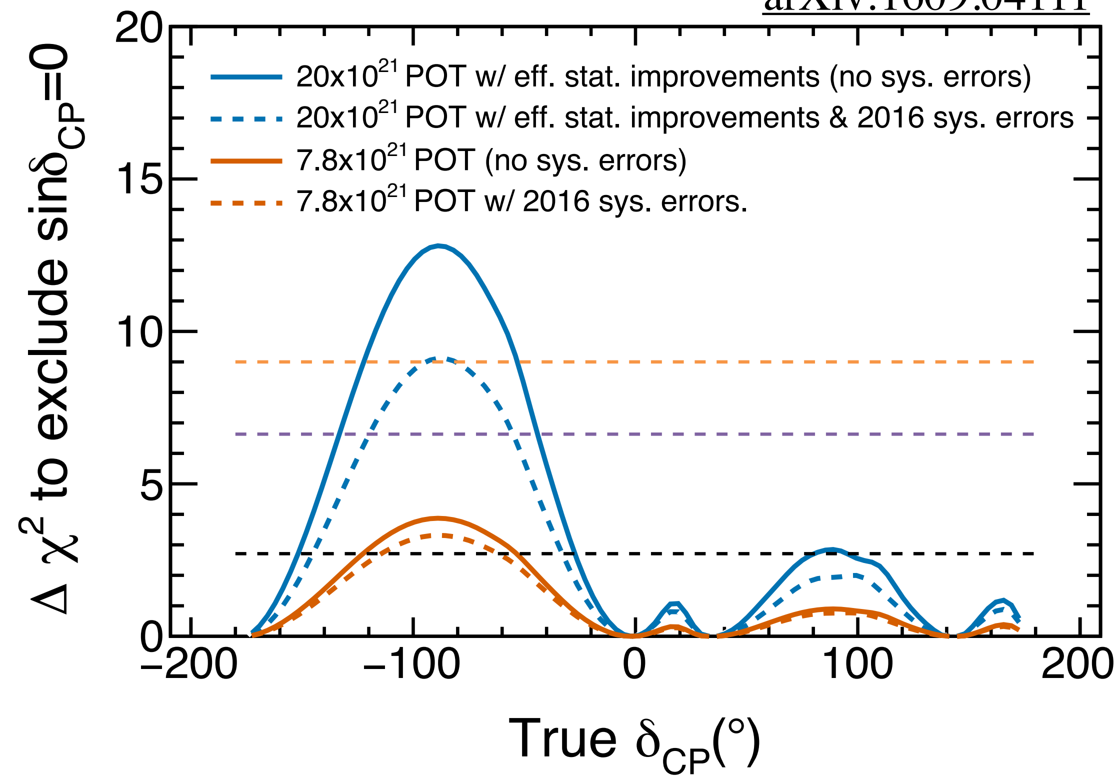




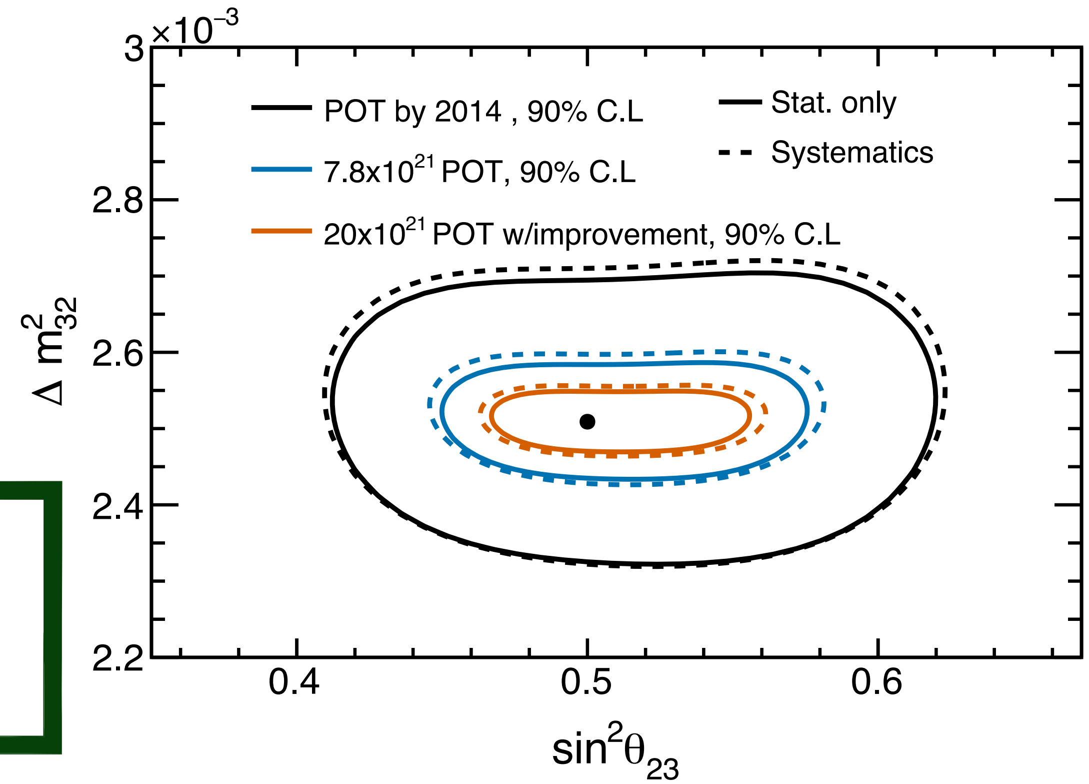
T2K-II physics case



arXiv:1609.04111



~3σ sensitivity to CP-violation for favorable (and currently favored) parameters



Important to reduce systematics with respect to what we have today

Conclusions

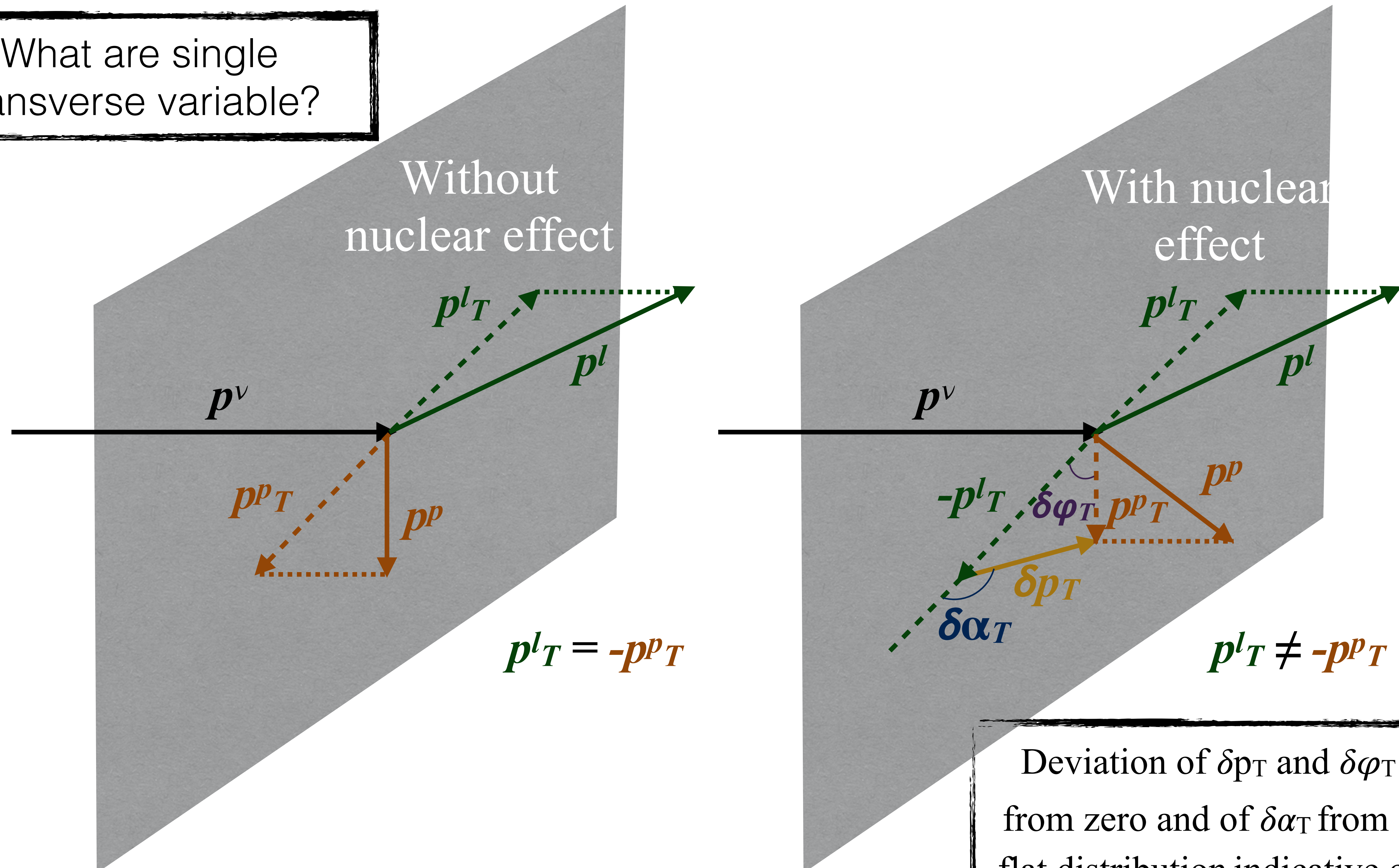
- T2K released results with 2.8×10^{21} POT (2/3 ν-mode, 1/3 ν-mode)
- New SK reconstruction increased by ~30% the expected number of e-like events
- With these data CP conserving values are excluded at more than 2σ
- T2K near detectors provide a perfect opportunity to make precise cross-section measurements
- Collect 7.8×10^{21} POT by 2020 and then start T2K-phase II 20×10^{21} POT
- ND280 upgrade project launched in order to fully profit of the additional statistics need to reduce systematics

Thank you for your attention

Backup

ν_μ CC0π using single transverse variables

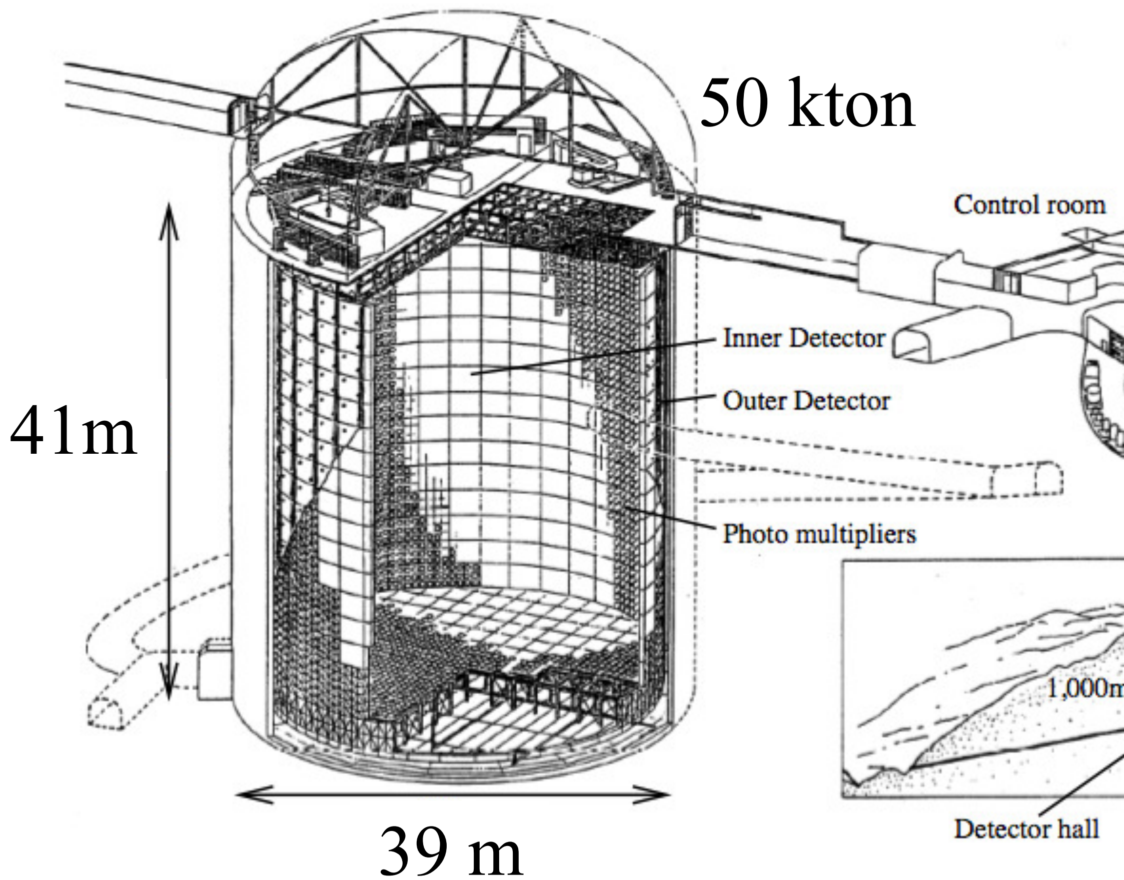
What are single transverse variable?

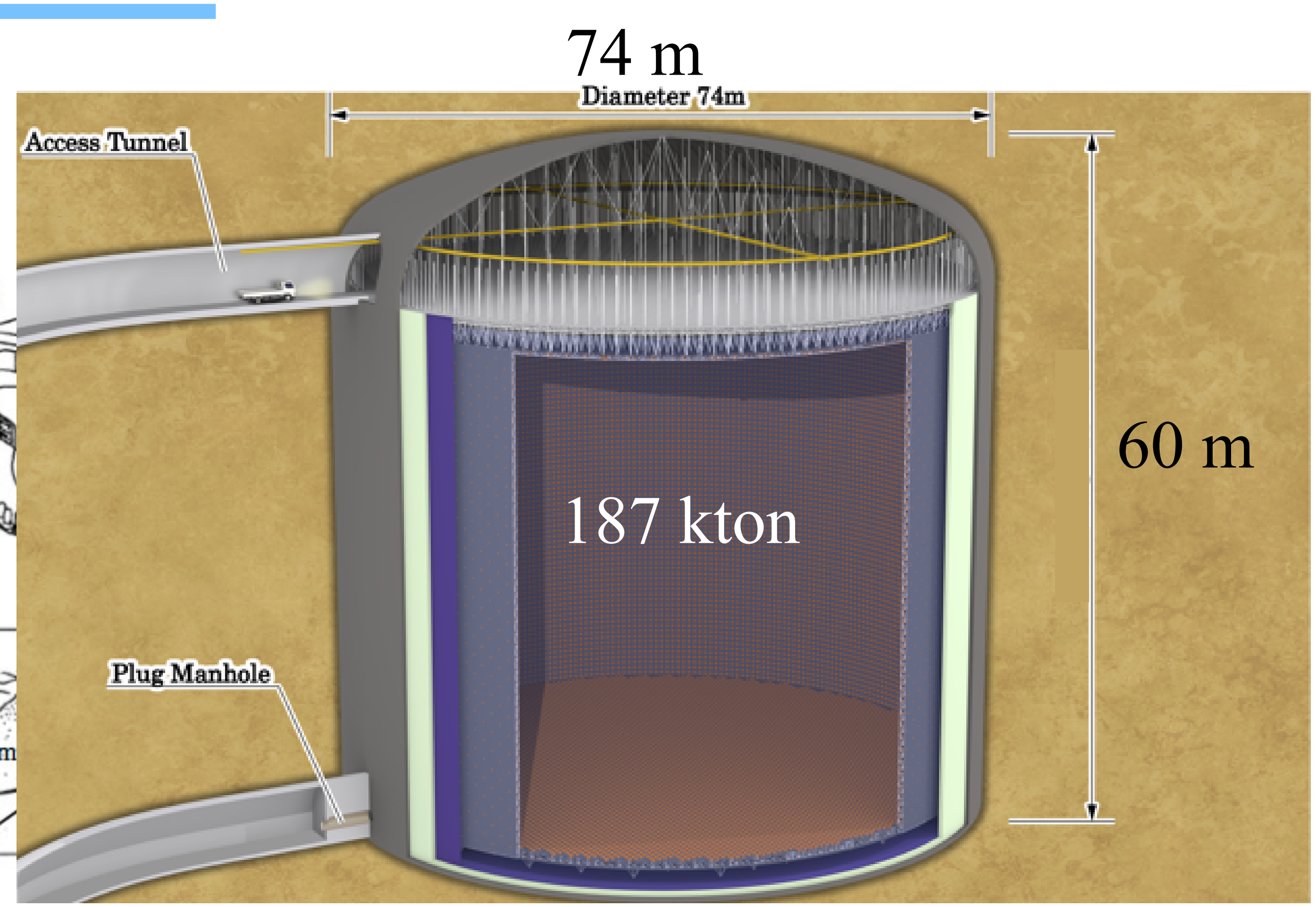


Deviation of δp_T and $\delta\varphi_T$ from zero and of $\delta\alpha_T$ from a flat distribution indicative of nuclear effects

X.-G. Lu et al., Phys. Rev. C 94, 015503 (2016)

Future prospect: Hyper-Kamiokande





Start operation 2026

Wide range of phenomena investigated:

- Far detector for the LBL program: T2HK
- Atmospheric, solar and supernova neutrinos
- Nucleon decay search

Event generators: details

	NEUT 5.3.2	GENIE 2.8.0
CCQE	SF (Benhar et al., 2000) BBA05 (Bradford et al., 2005) M_A^{QE} = 1.21 GeV/c^2 p_F [^{12}C] = 217 MeV/c E_B [^{12}C] = 25 MeV	RFG (Bodek et al., 1981) BBA05 (Bradford et al., 2005) M_A^{QE} = 0.99 GeV/c^2 p_F [^{12}C] = 221 MeV/c E_B [^{12}C] = 25 MeV
2p2h	Nieves et al., 2011	-
CCRES	W<2 GeV Rein-Sehgal, 1981 FF (Graczyk et al., 2008)	W<1.7 GeV Rein-Sehgal, 1981 FF (Kuzmin et al., 2016)
CCDIS	W>1.3 GeV (w/o single π) GRV98 PDF (Glück et al. 1998) BY corr. at low Q2 (Bodek et al. 2003)	W>1.7 GeV (for W<1.7 GeV is tuned) GRV98 PDF (Glück et al. 1998) BY corr. at low Q2 (Bodek et al. 2005)
Hadronization	W < 2 GeV KNO scaling (Koba et al. 1972) W > 2 GeV PYTHIA/JETSET	W < 2.3 GeV AGKY (Koba et al. 1972) 2.3 GeV < W < 3 GeV AGKY (Koba et al. 1972) + PYTHIA/JETSET W > 3 GeV PYTHIA/JETSET
FSI	Intra-nuclear cascade	Intra-nuclear cascade (INTRANUKE hA)