T2K neutrino oscillation results

Ciro Riccio

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Università degli Studi di Napoli Federico II

INFN Napoli

Overview

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- Neutrino oscillations

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- T2K experimental setup

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- T2K latest results
- Conclusions

Neutrino oscillations

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

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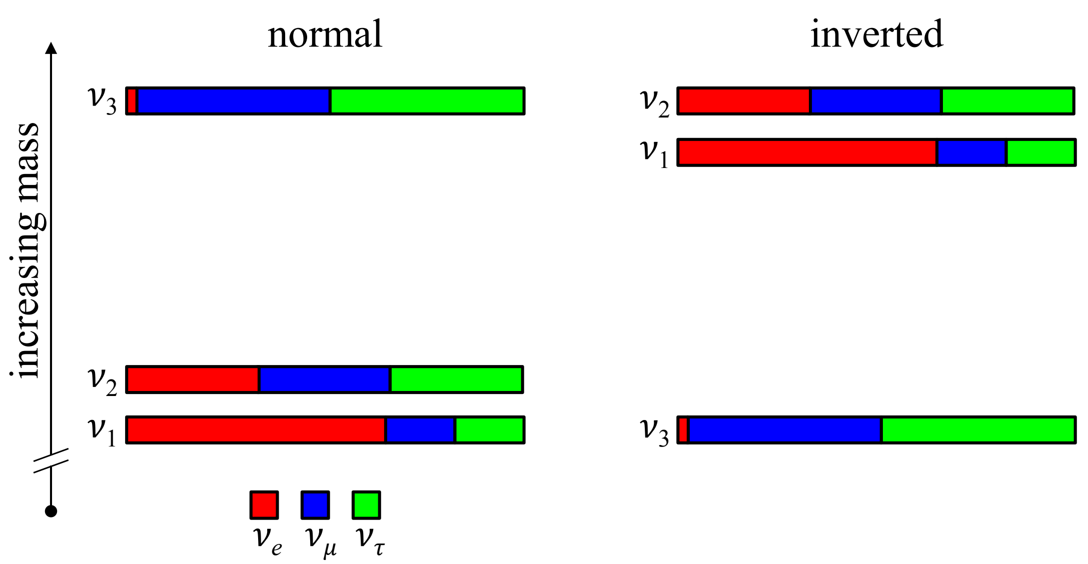
Open questions: δ_{CP}, θ_{23} octant and mass ordering



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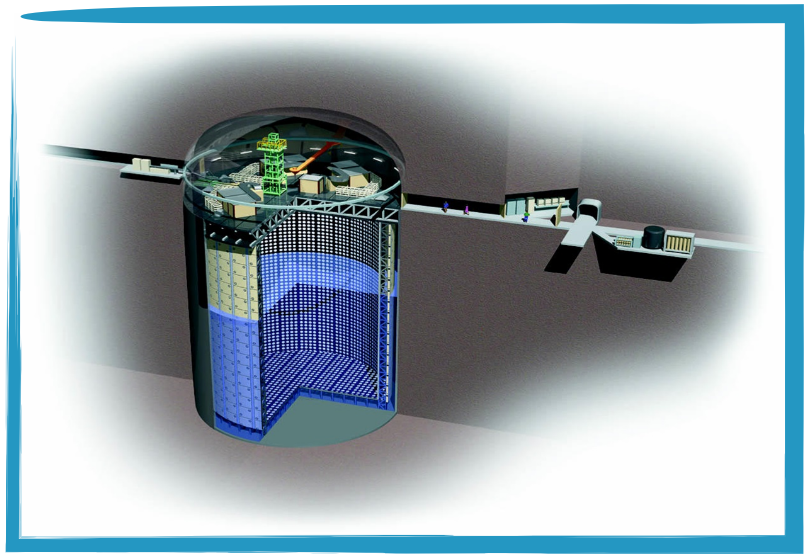
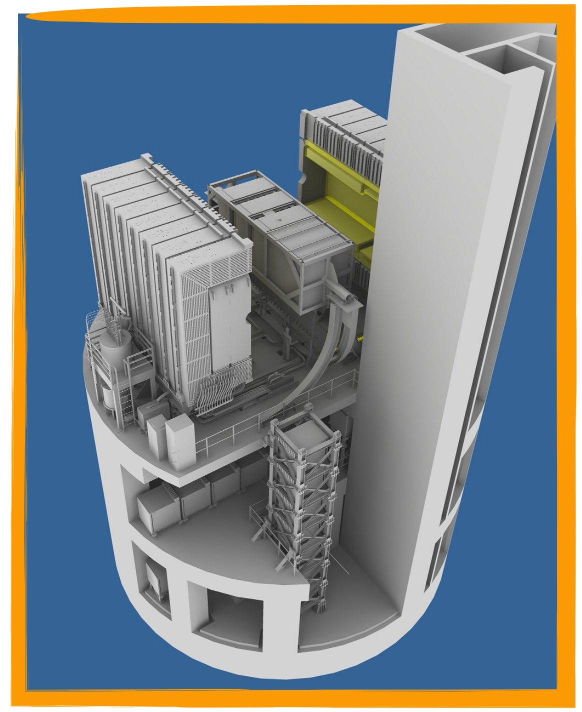
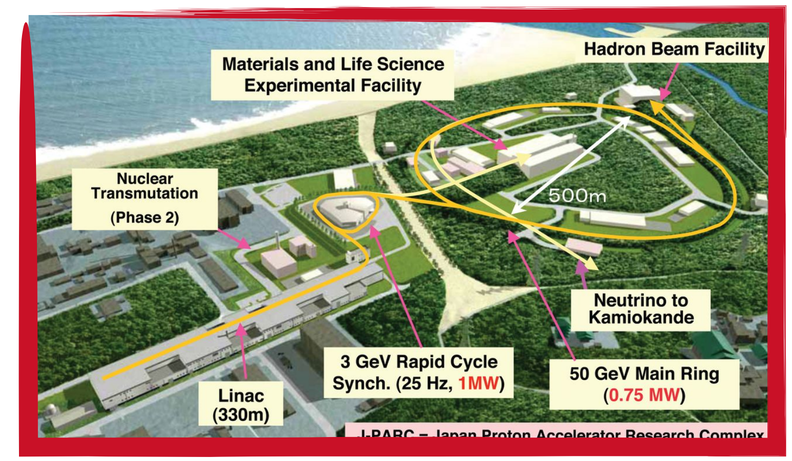
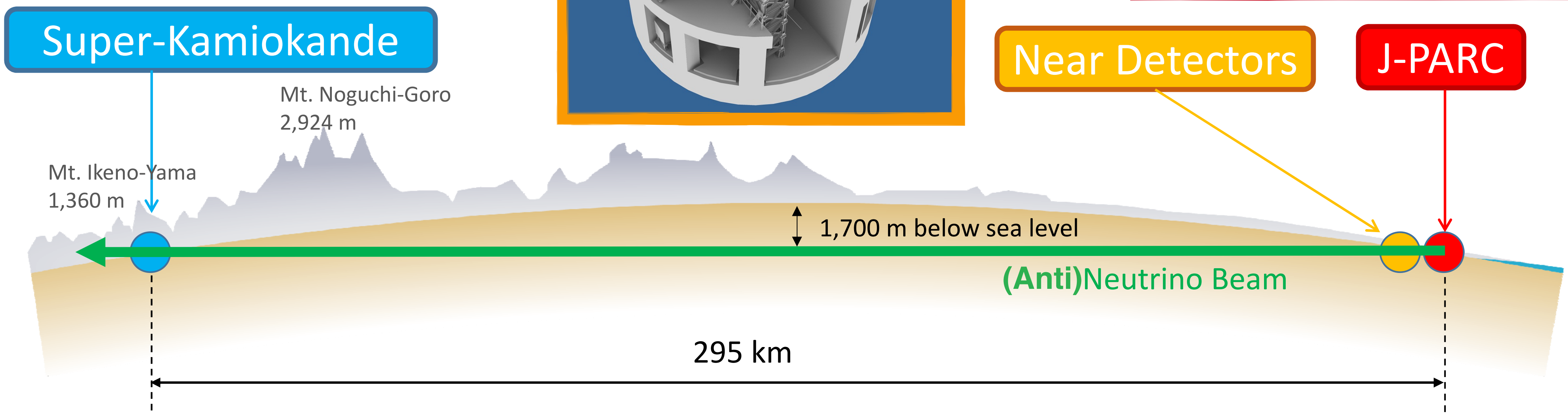
The T2K experiment









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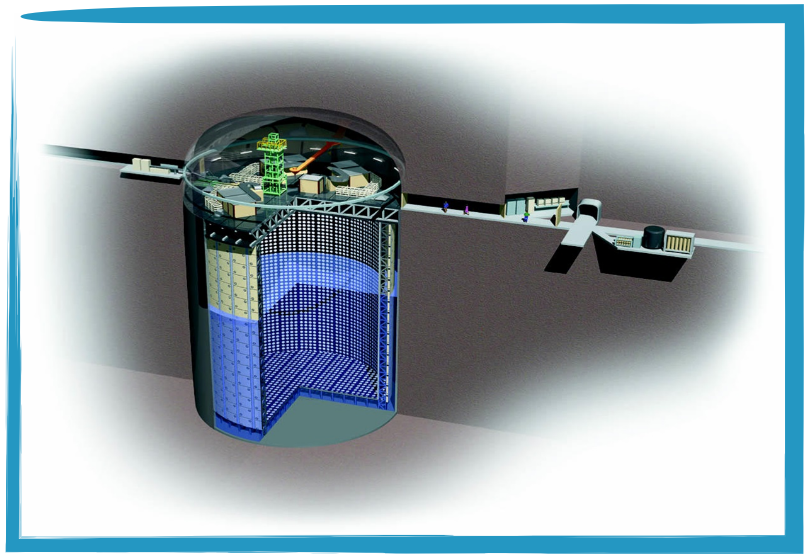
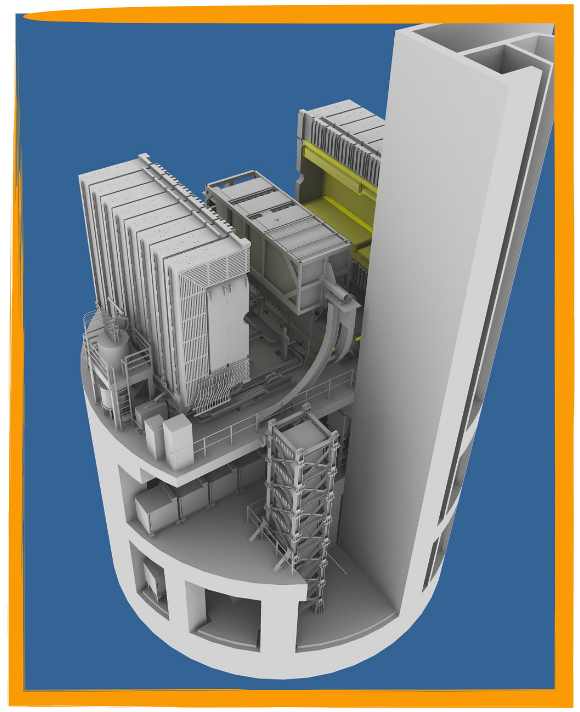
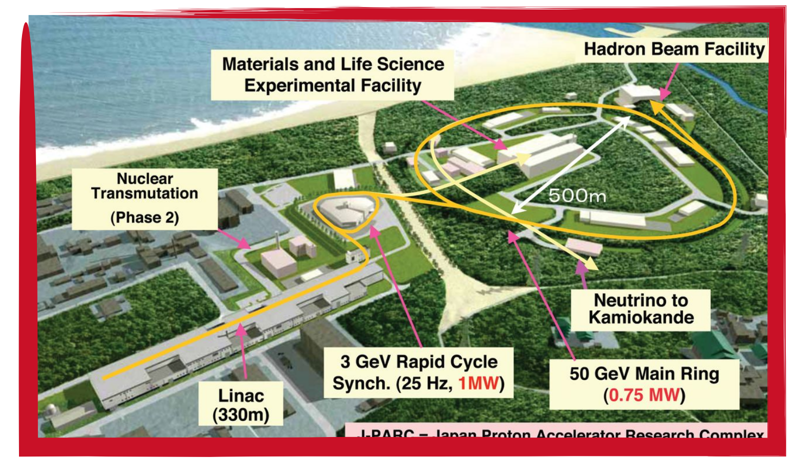


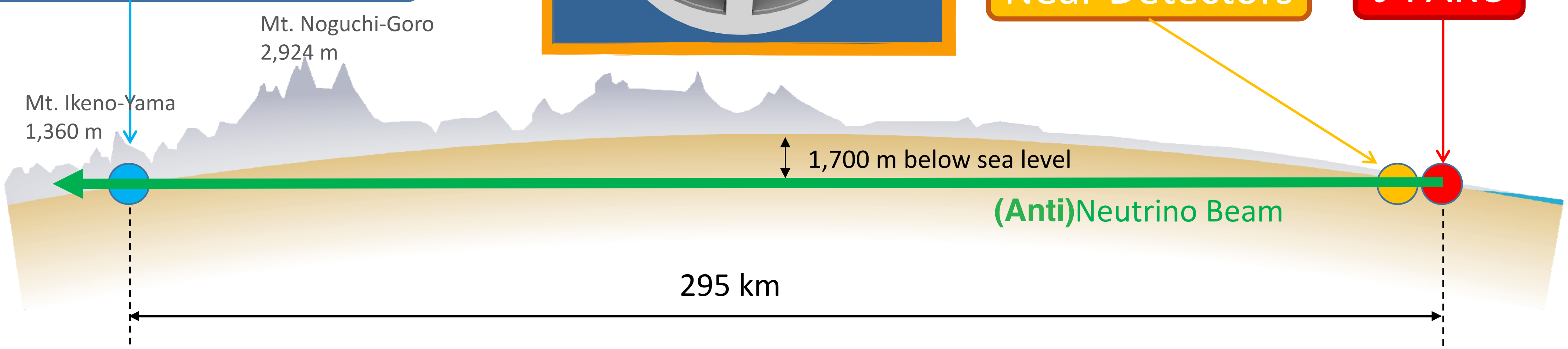
Super-Kamiokande





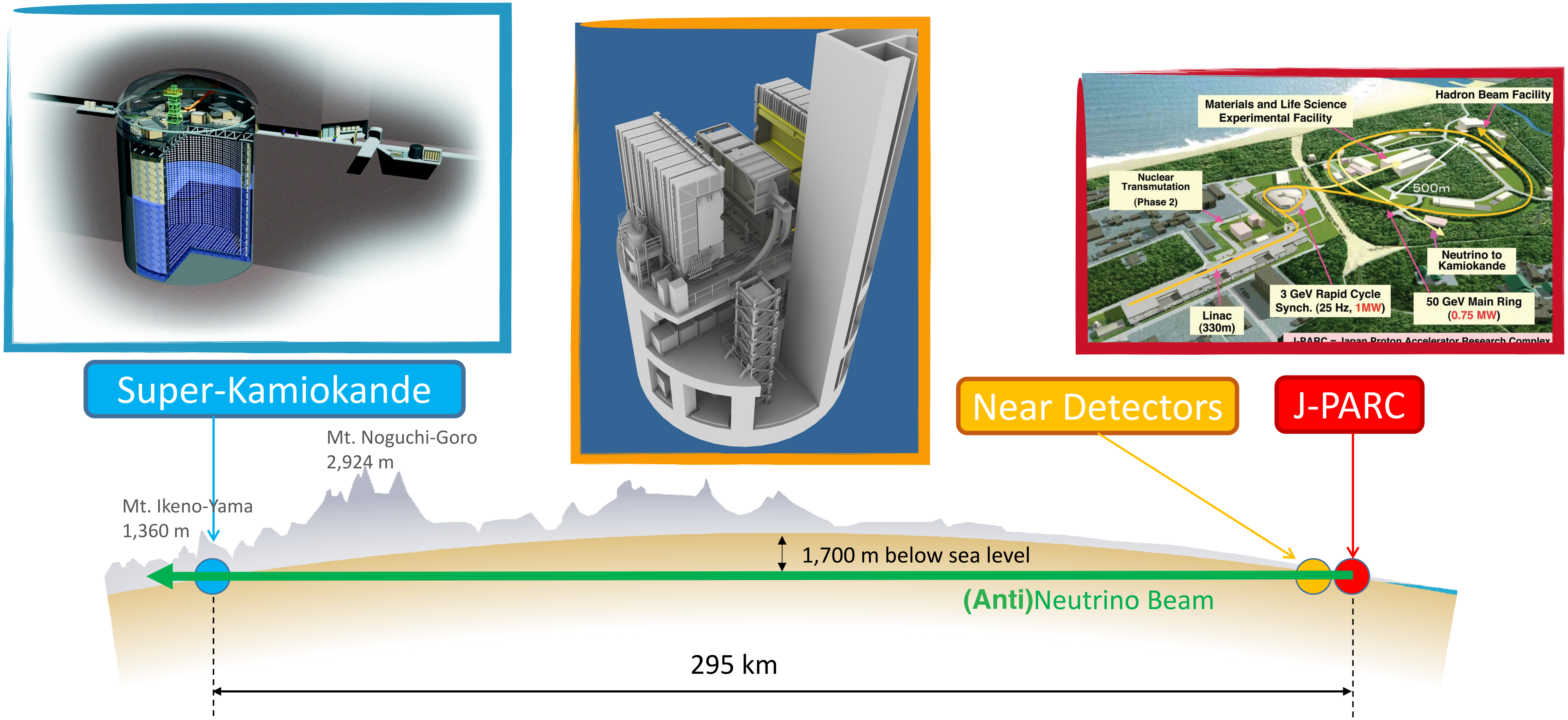
Near Detectors

J-PARC



Physics goals:

The T2K experiment



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- Precise measurement of θ_{23}, $|\Delta m_{32}^2|$

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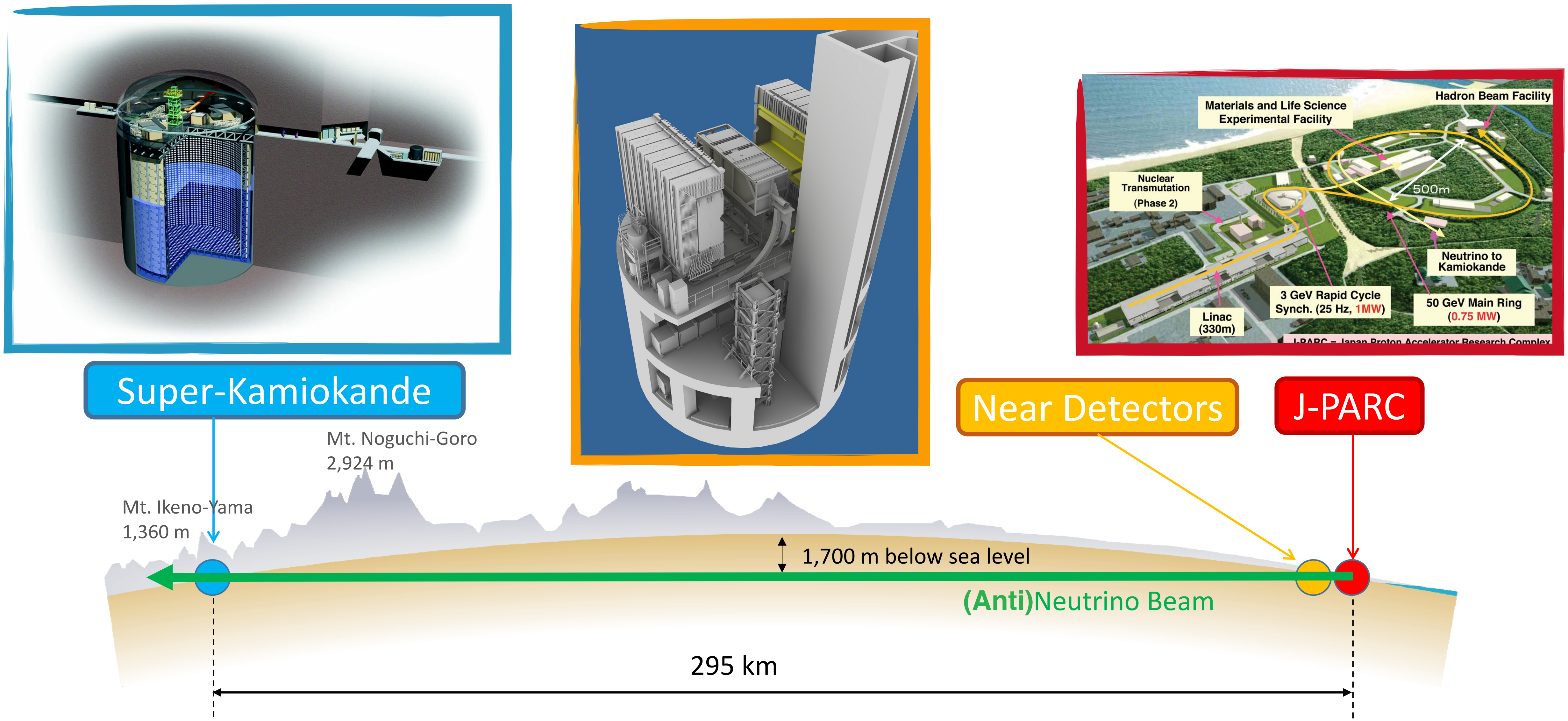

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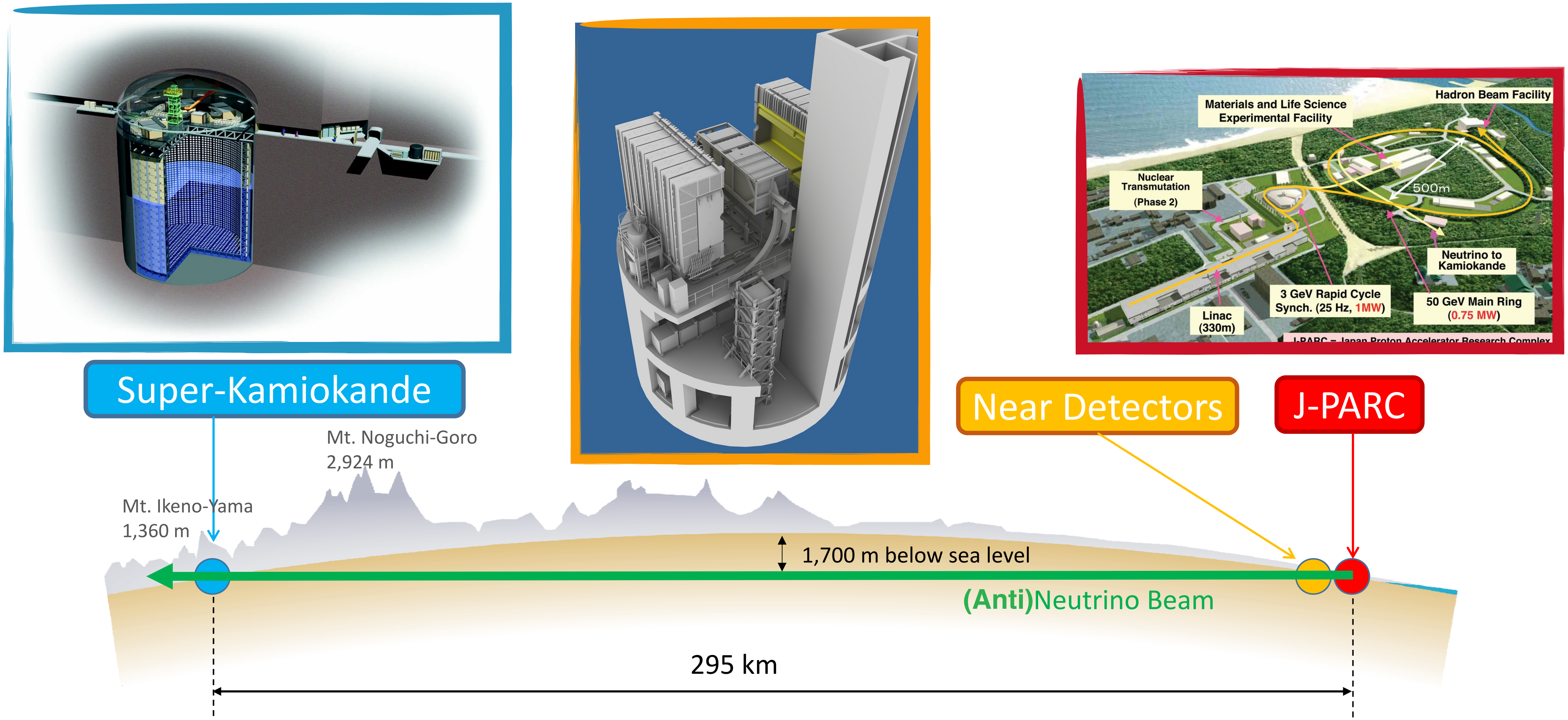

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- ν cross section measurements at the near detectors

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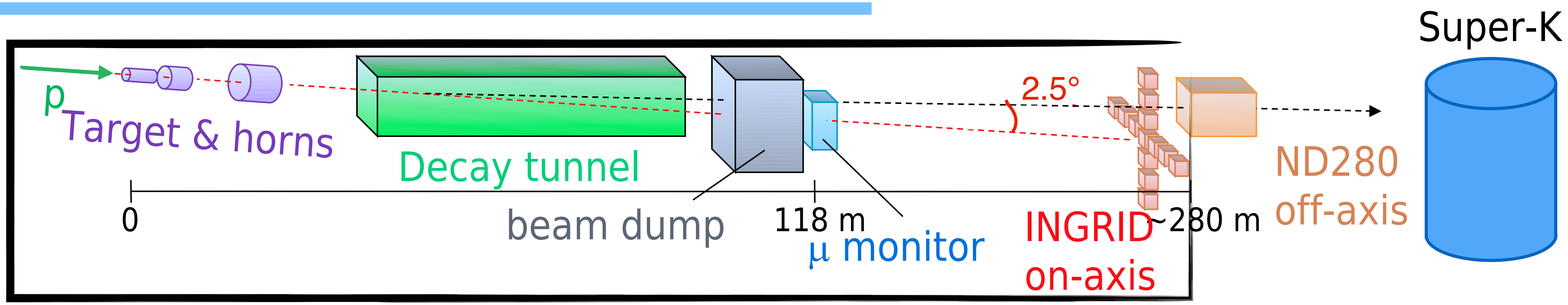
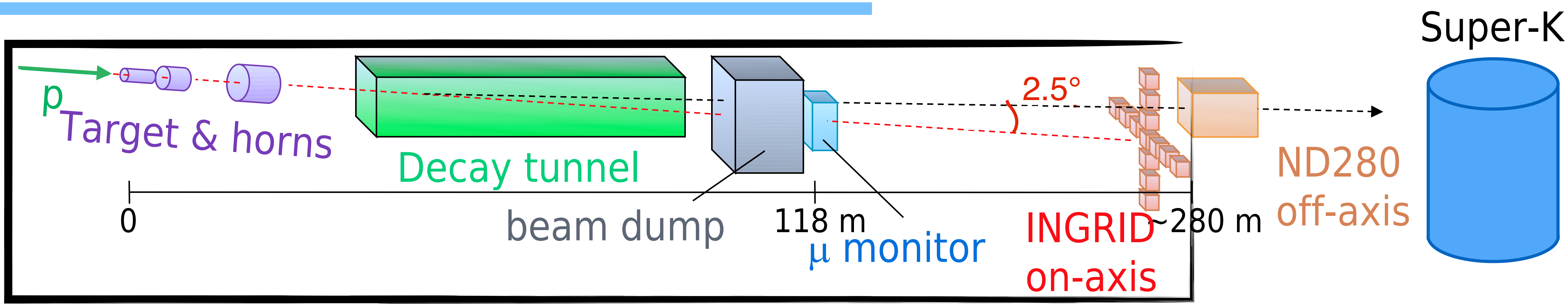
In the case of T2K δ_{CP} change the appearance probability by ±30% while the mass ordering has a ~10% effects

T2K Beam


p
Target & horns
Decay tunnel
beam dump
0
118 m
μ monitor
2.5°
INGRID
on-axis
~280 m
ND280
off-axis
Super-K

Beam



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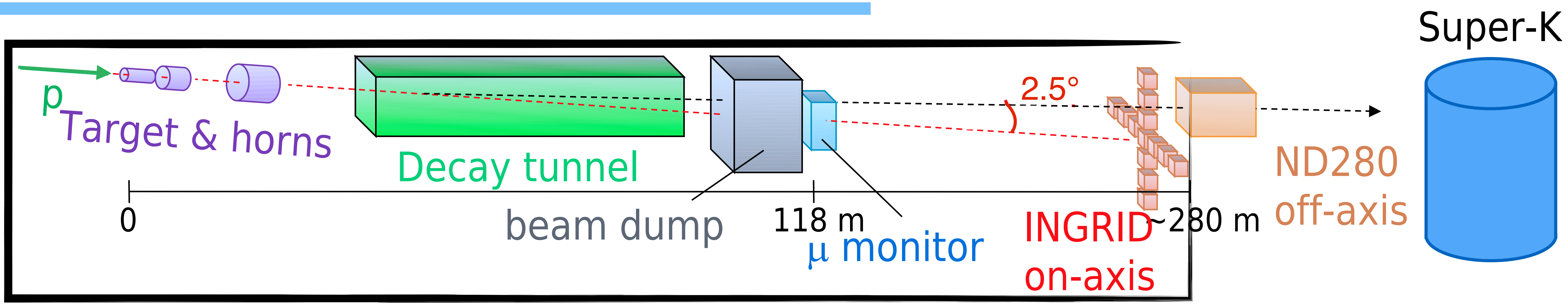

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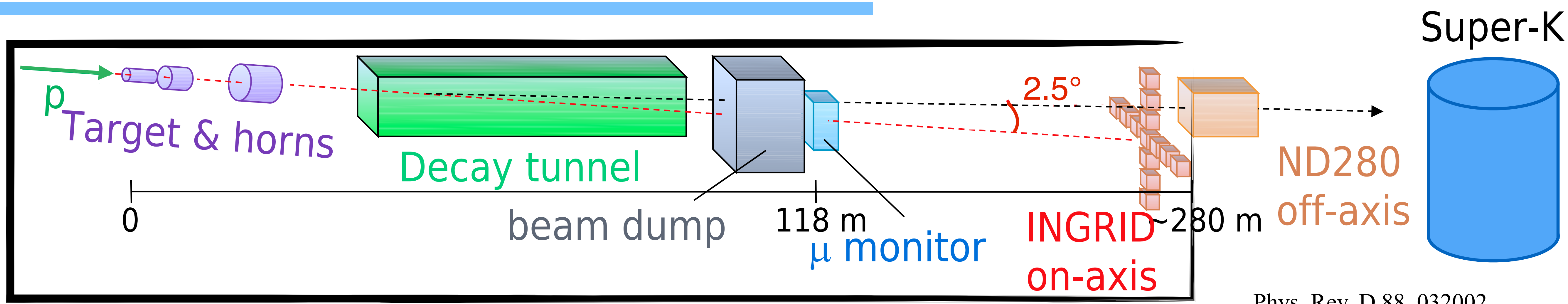

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Detectors 2.5° off the direction of the beam centered around 0.6 GeV. Off-axis method reduce high energy tail and maximize oscillation detection probabilities

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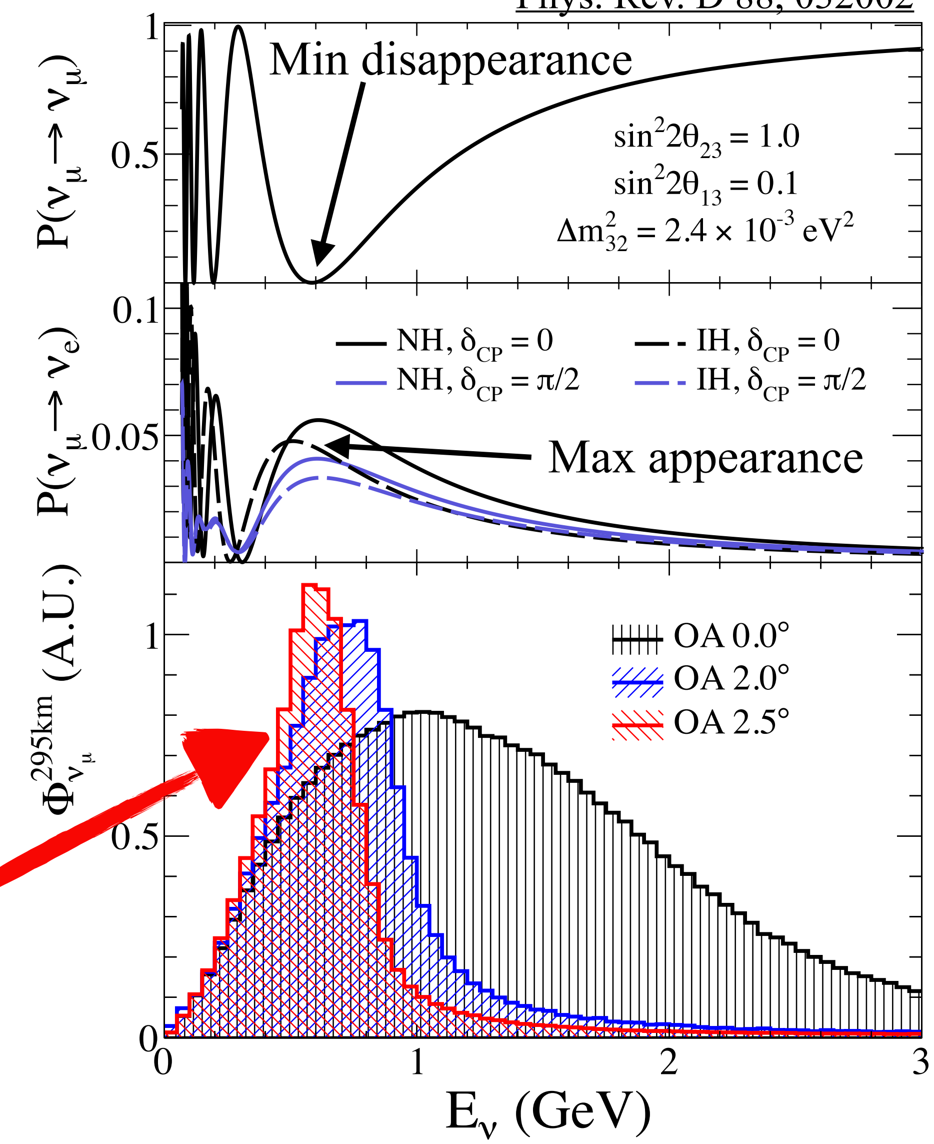
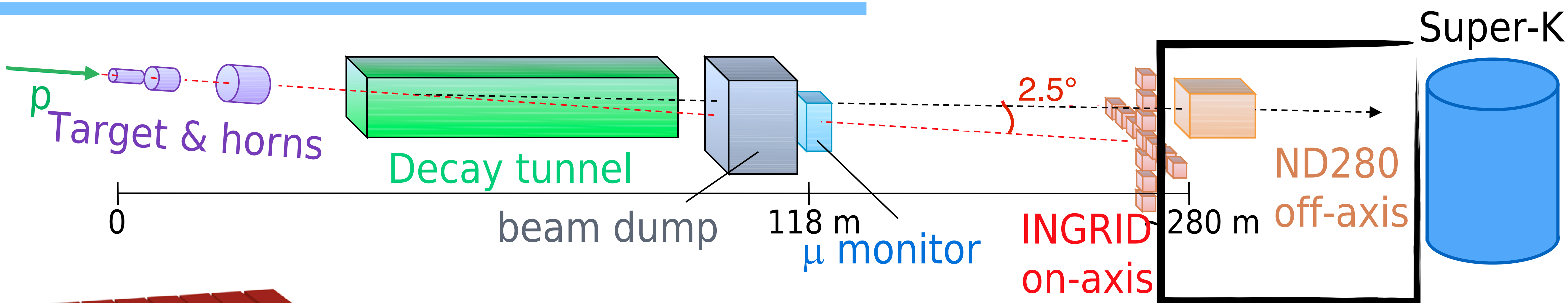
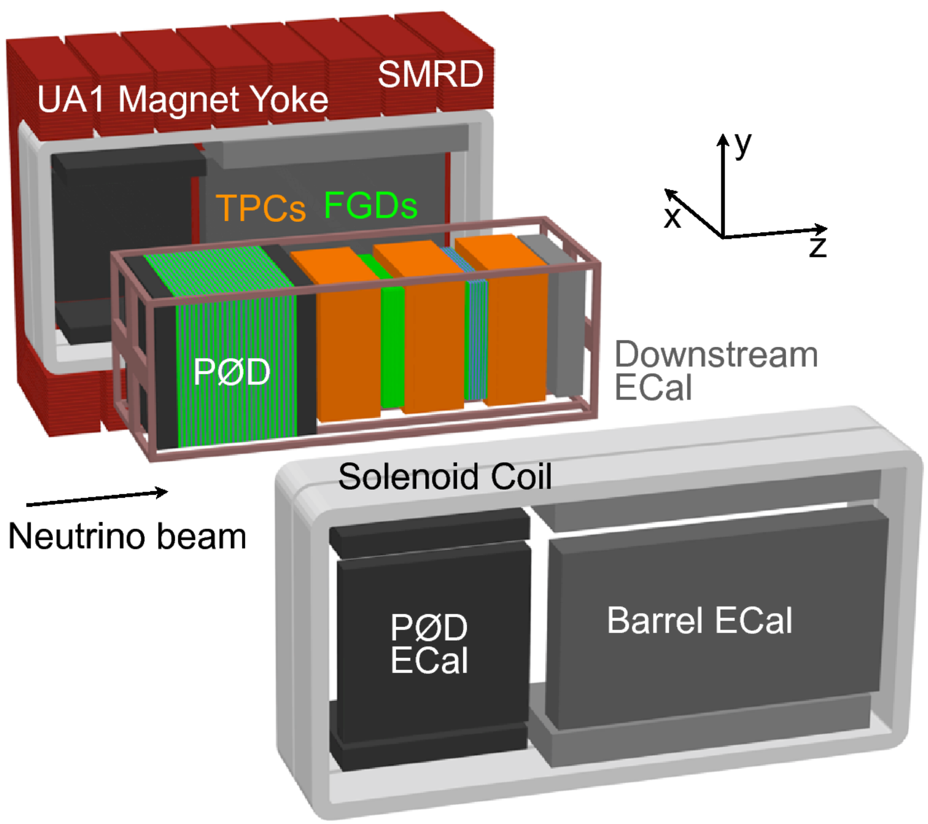


The off-axis near detector (ND280)





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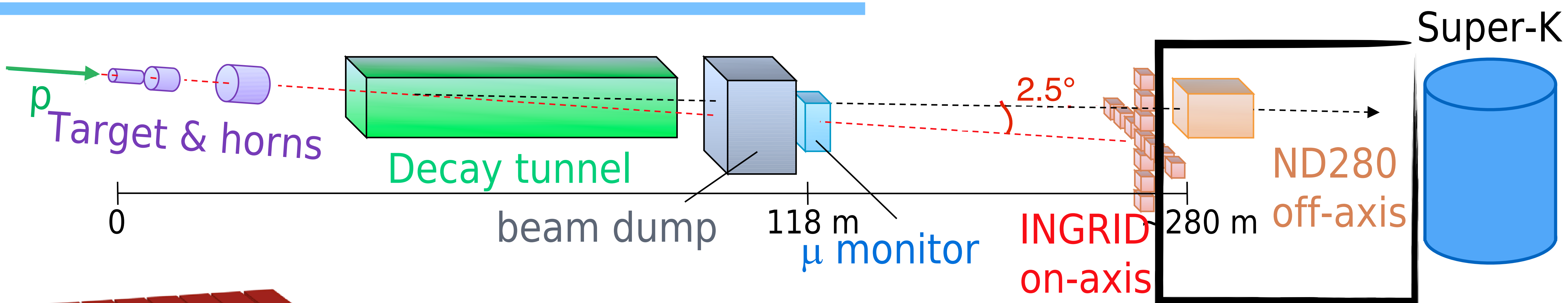

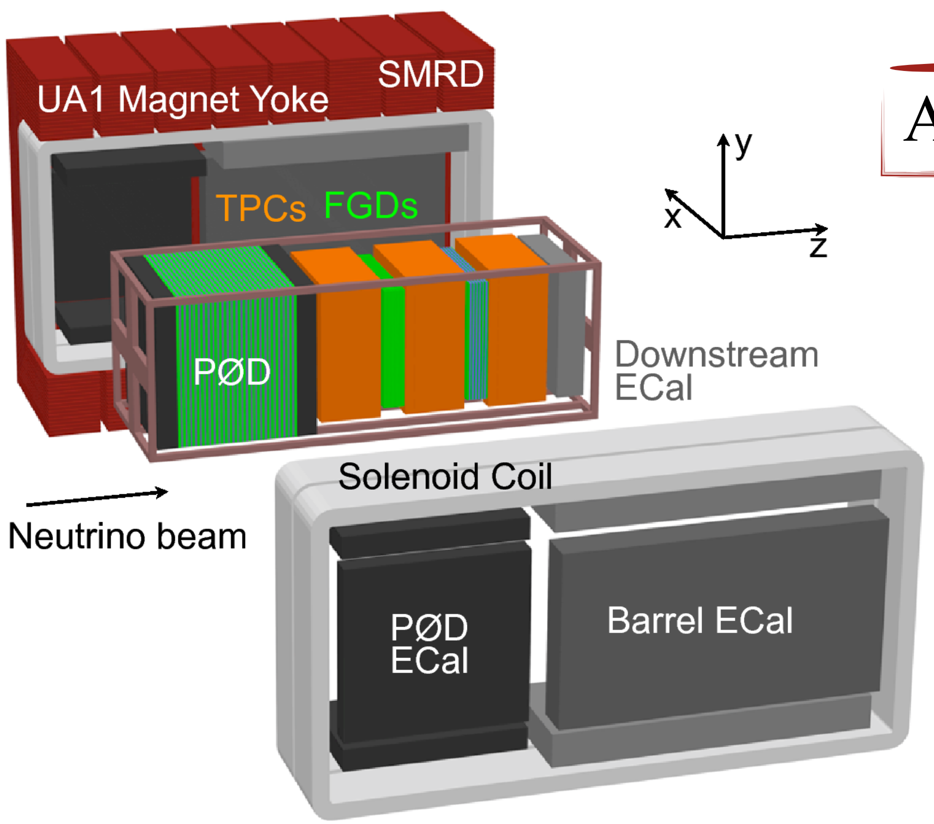

A large dipole magnet (UA1) produces 0.2 T.

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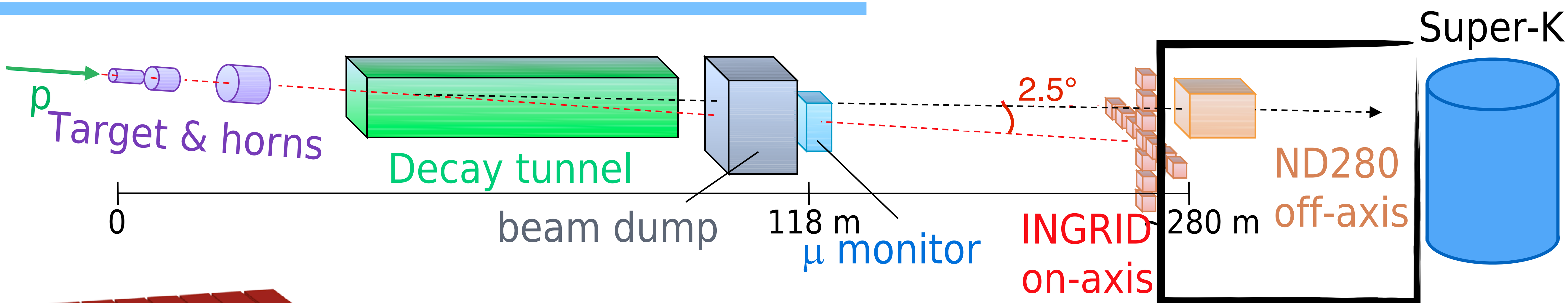

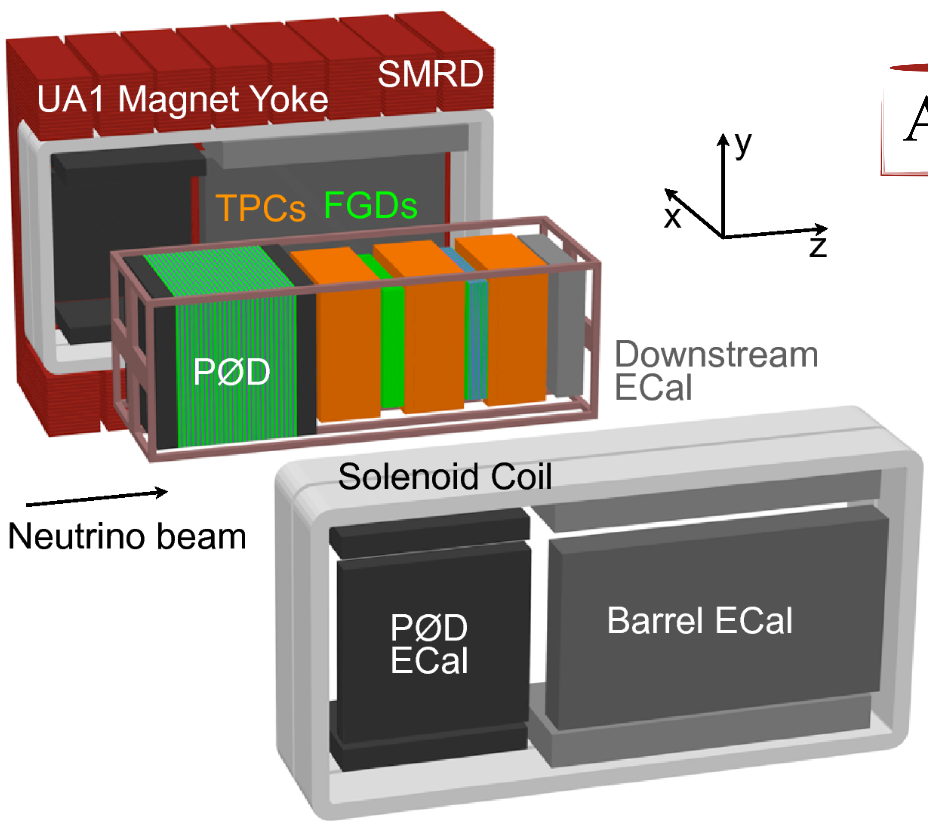

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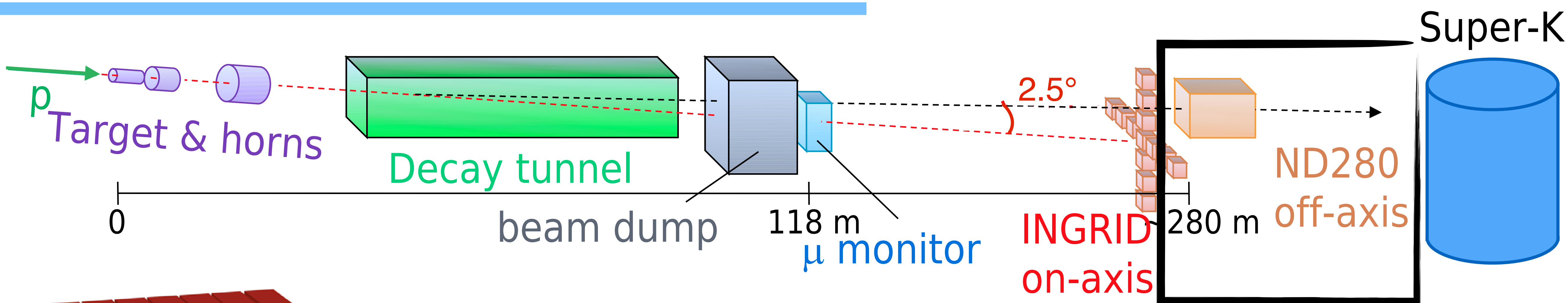

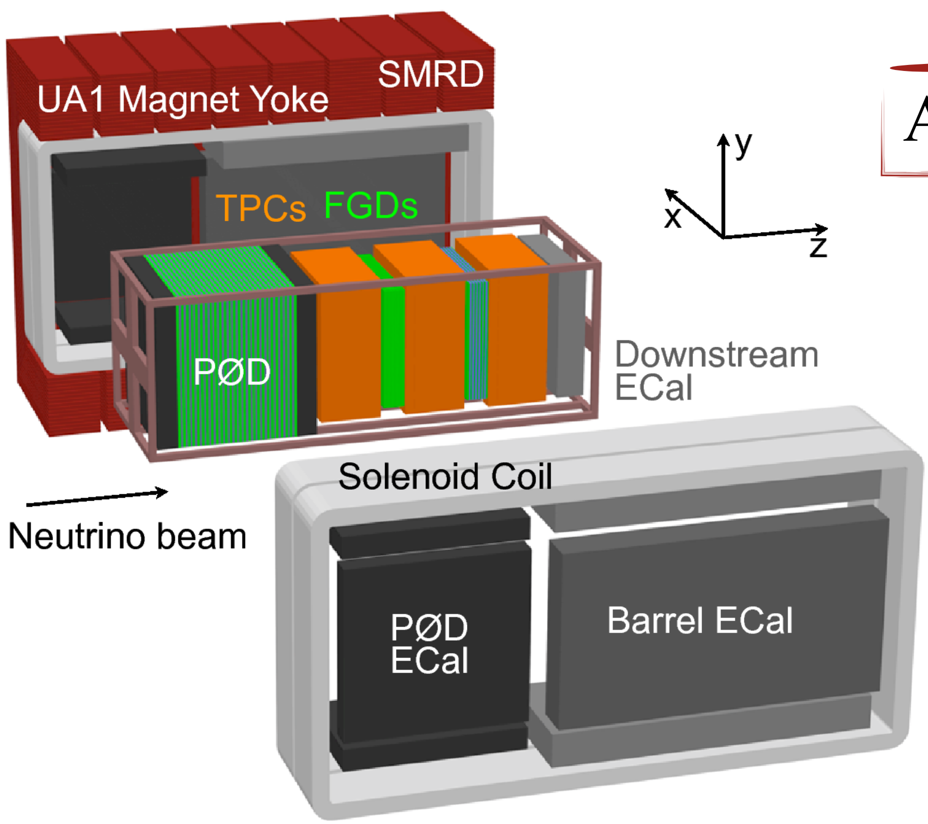

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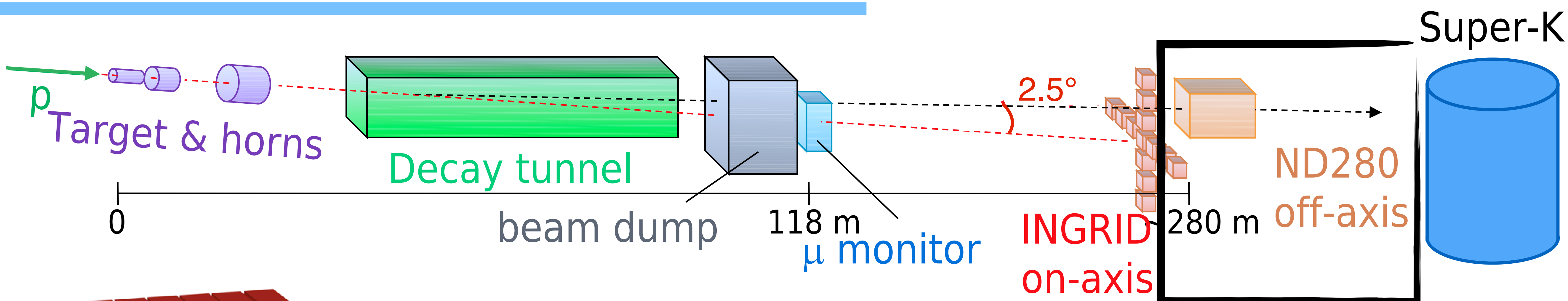

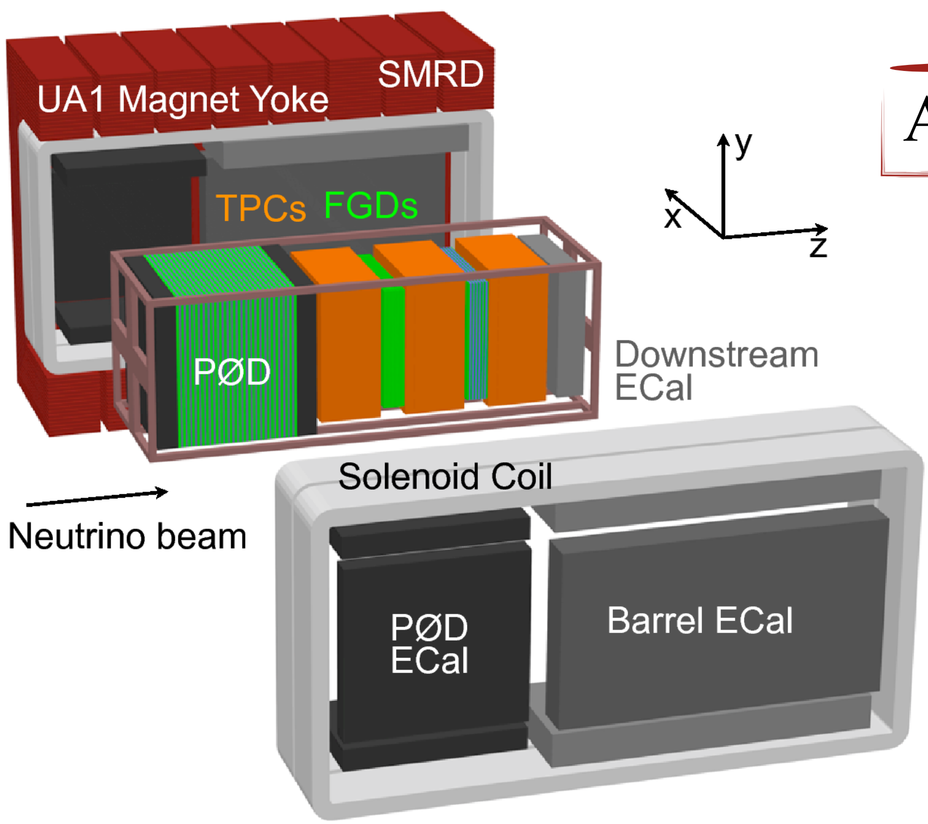

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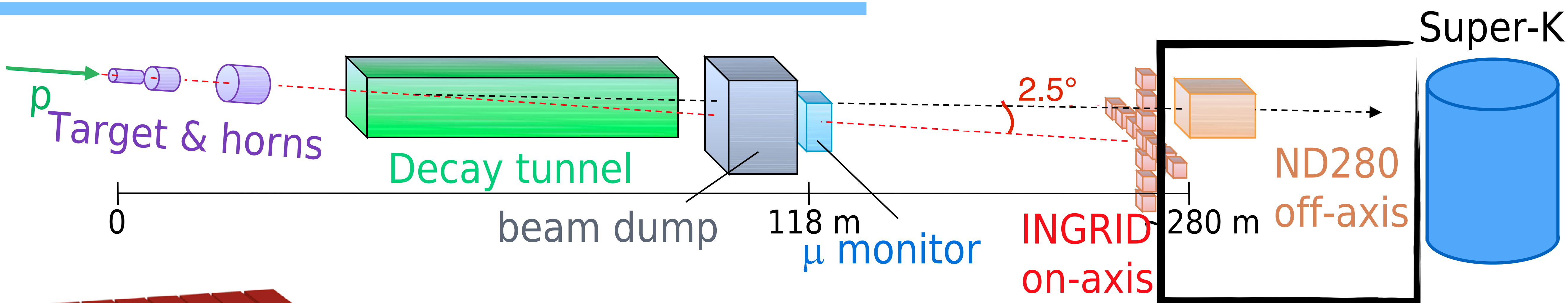

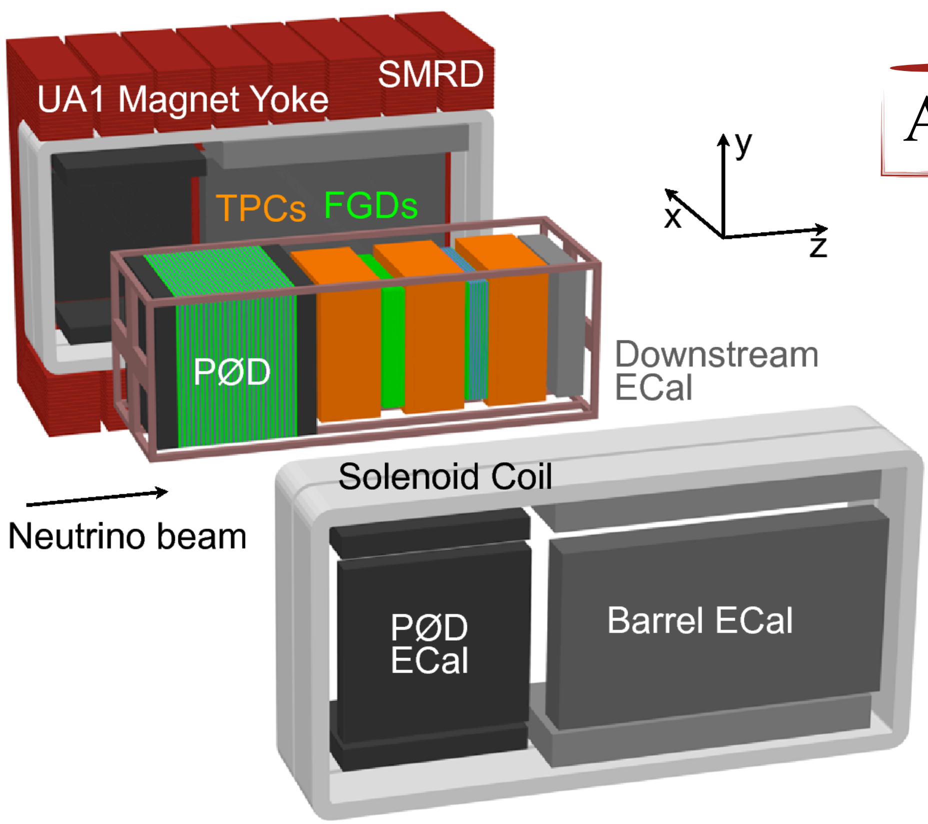

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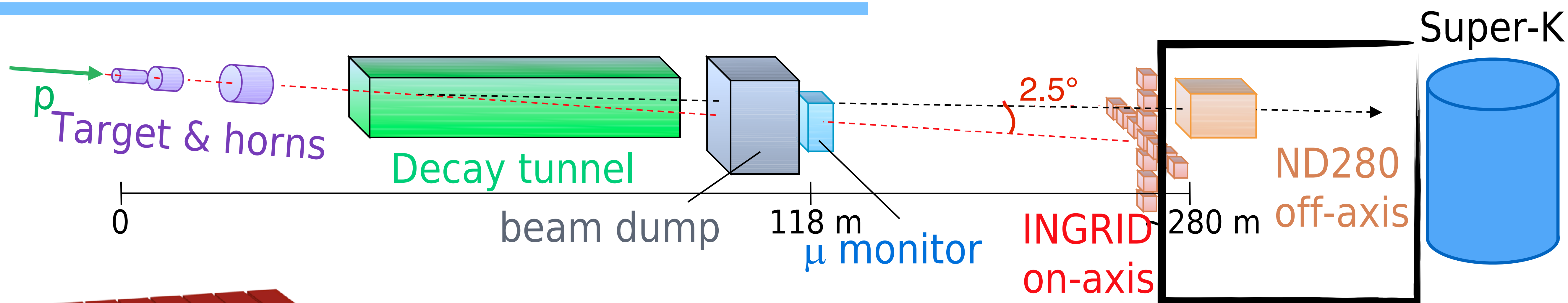

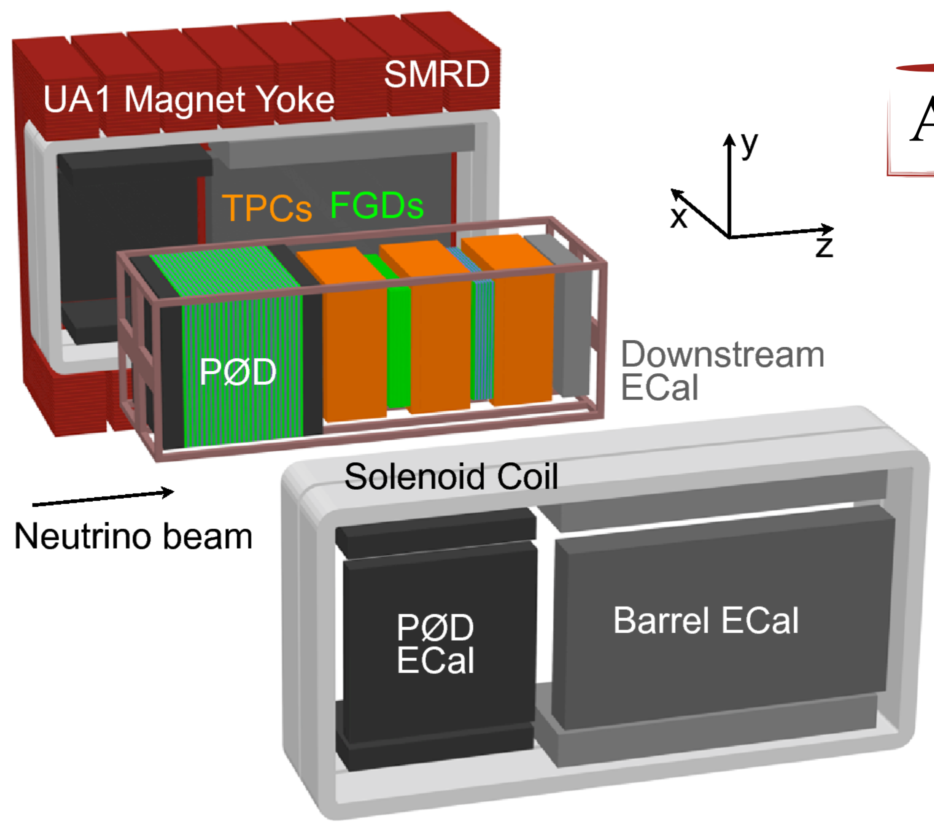

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An electromagnetic calorimeter (ECal) is used to distinguish tracks from showers

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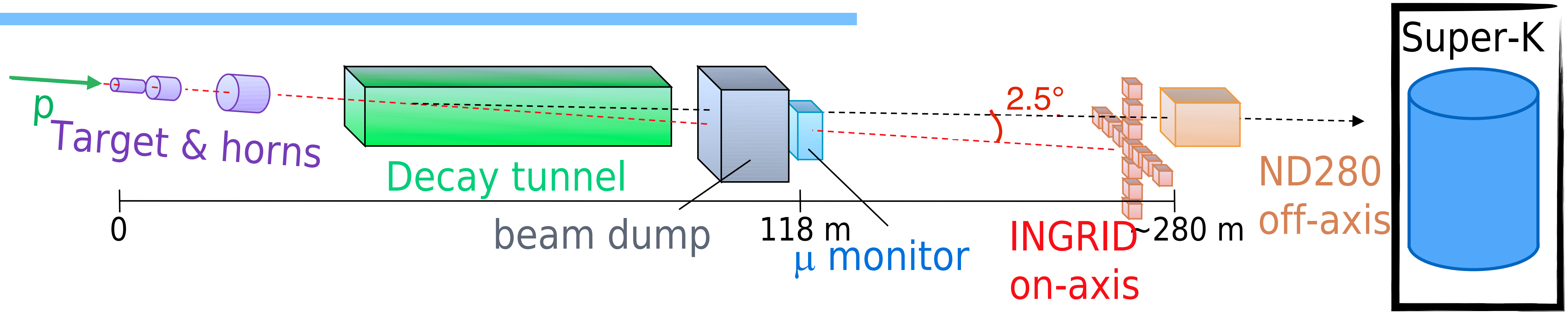

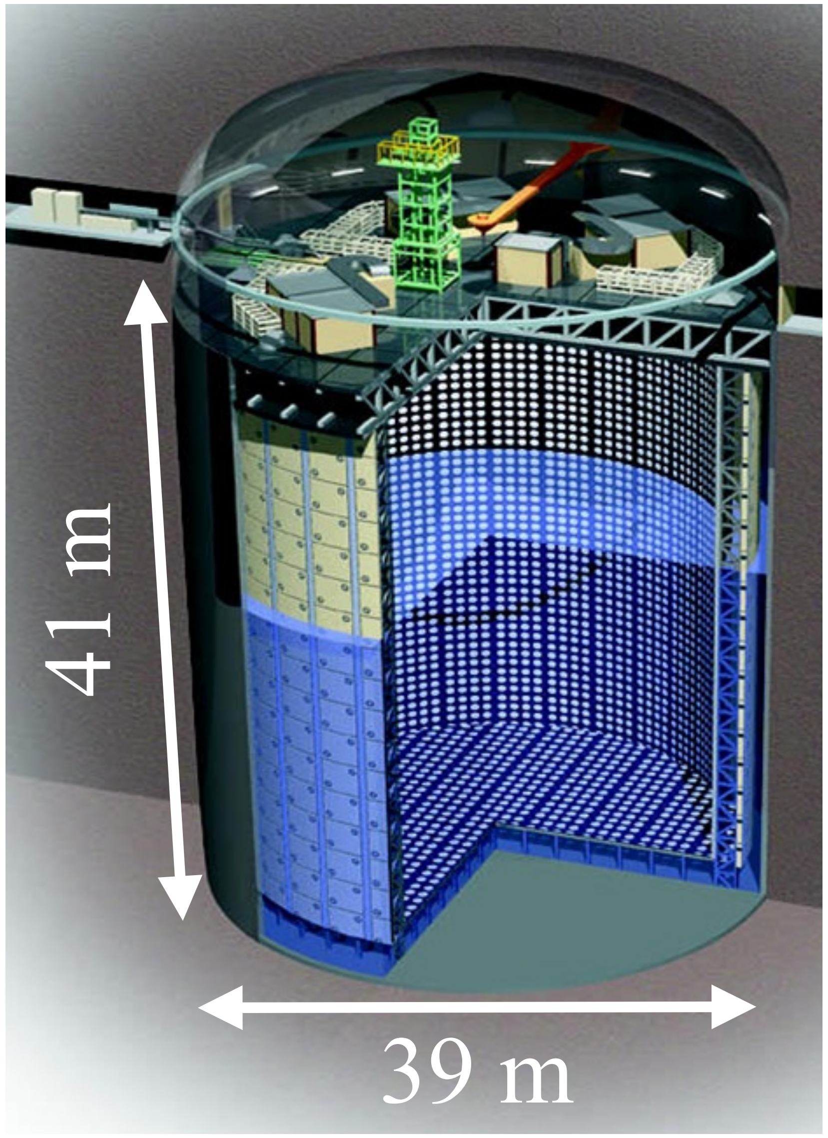

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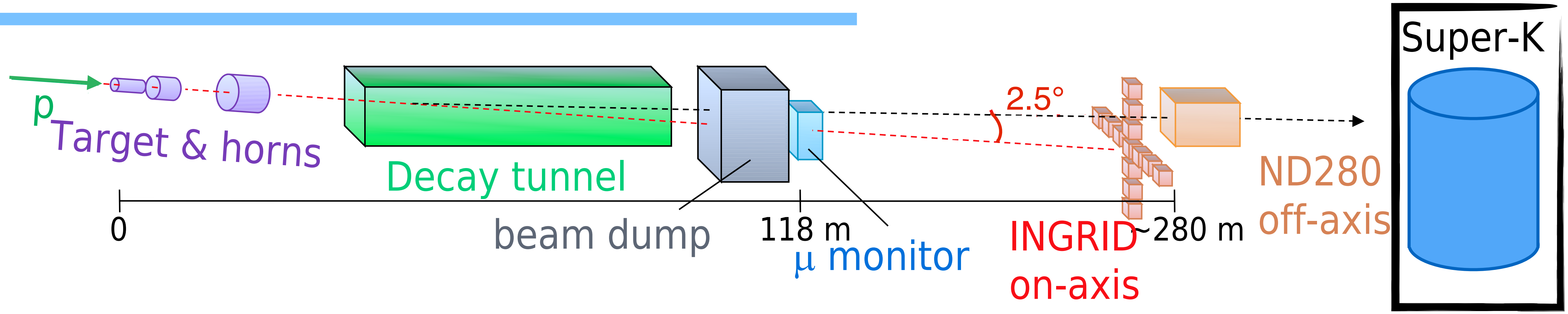

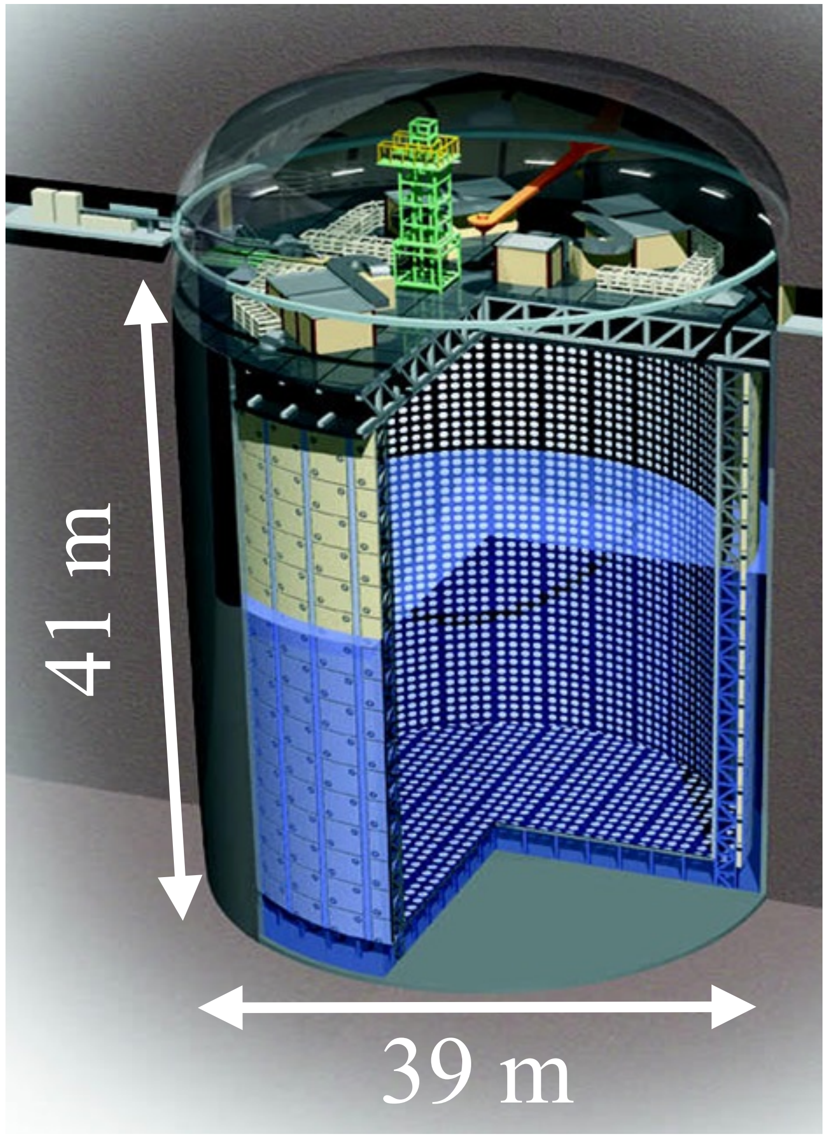

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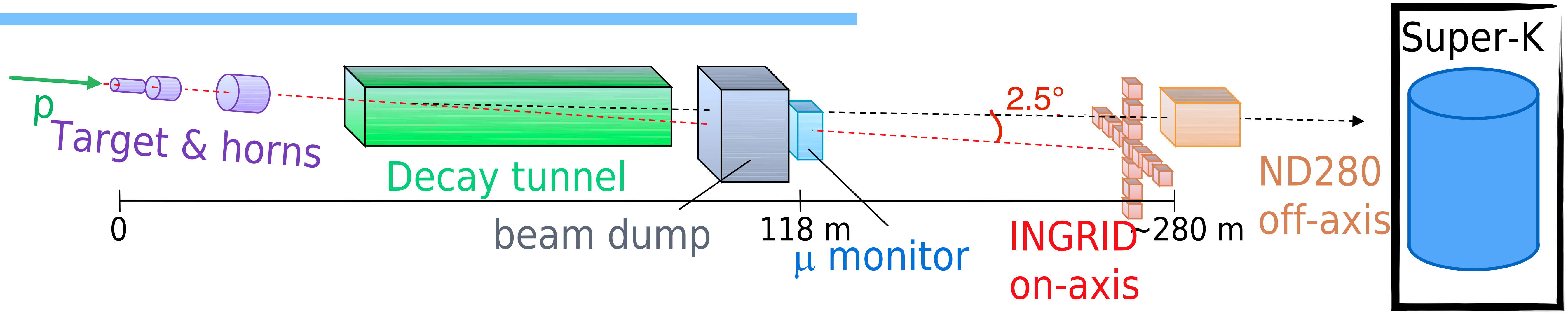

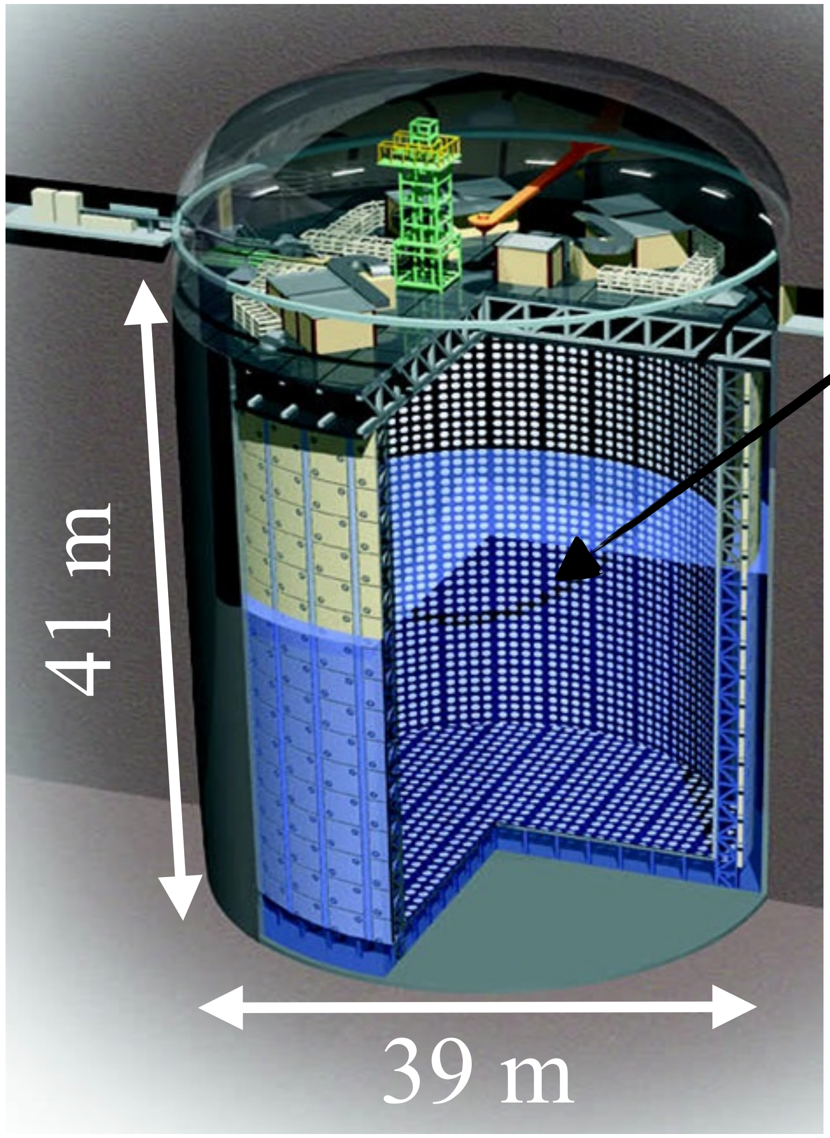

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Inner detector ~11000
20 inch PMTs

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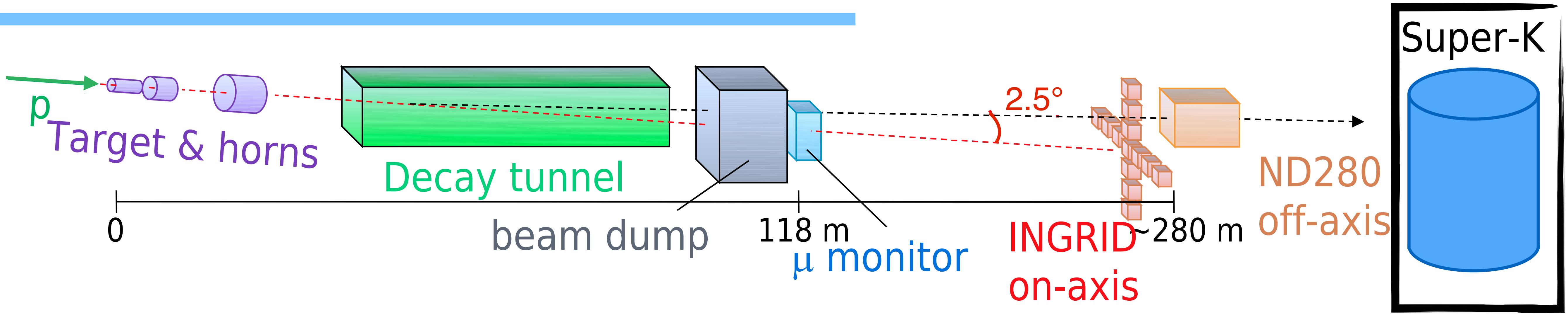

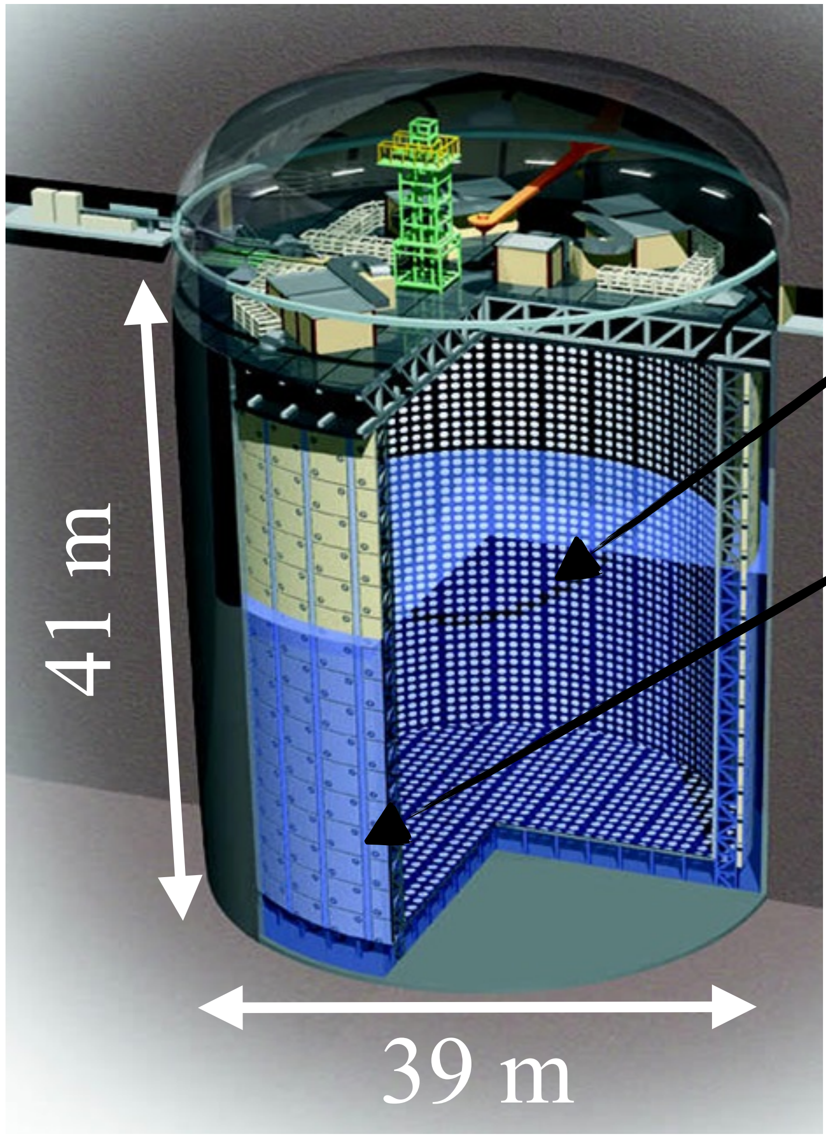

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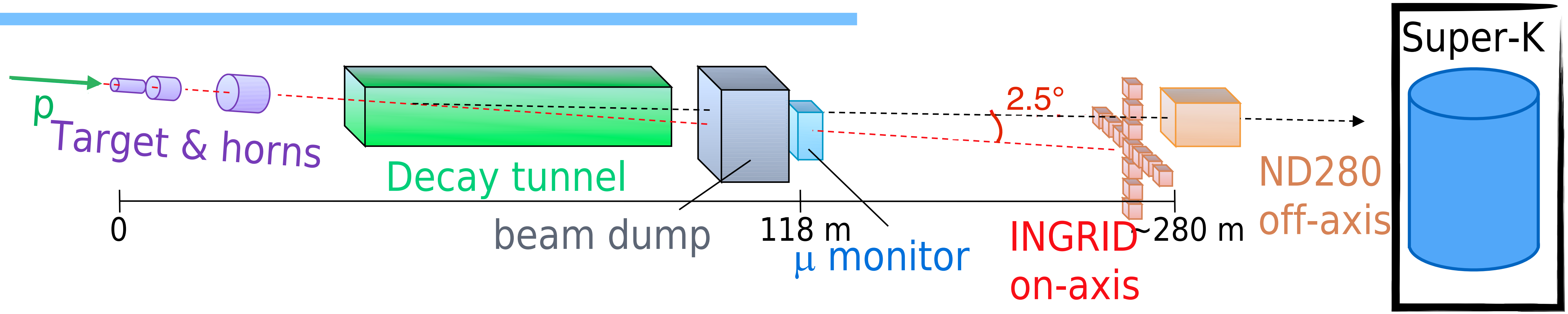
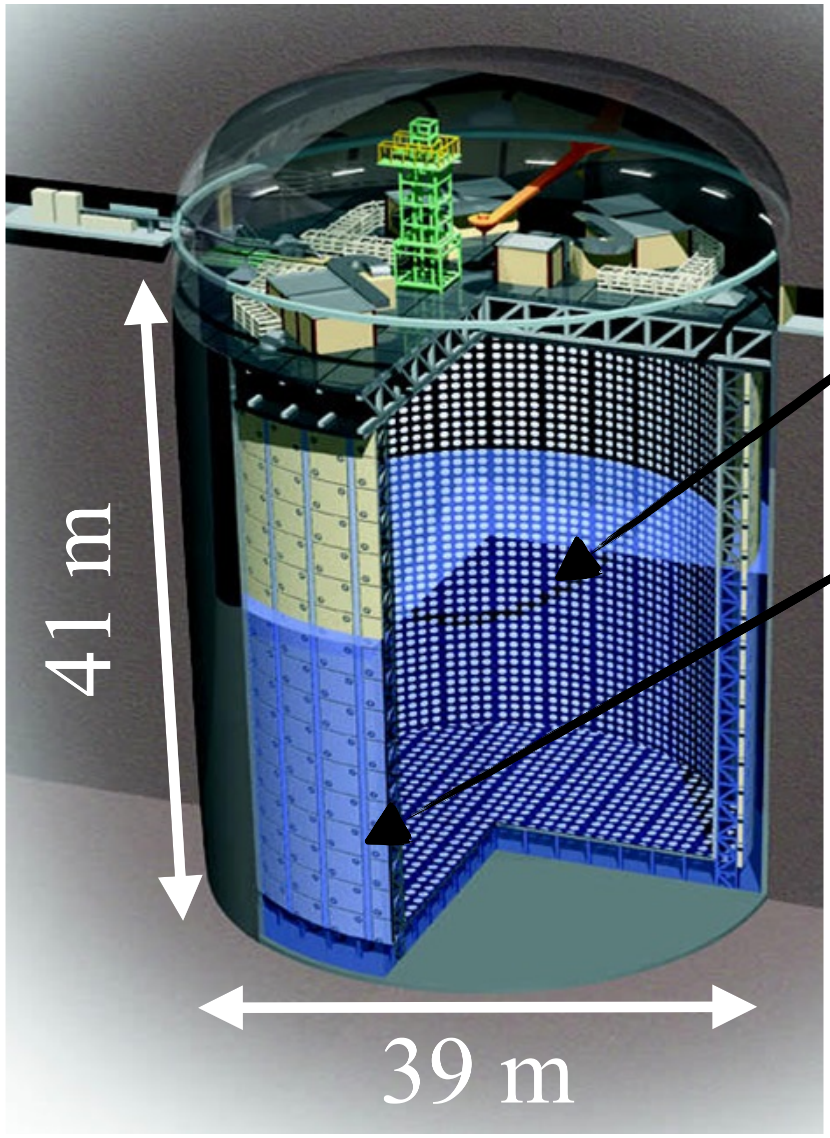
Outer detector ~2000 8 inch PMTs

Super-Kamiokande (SK)



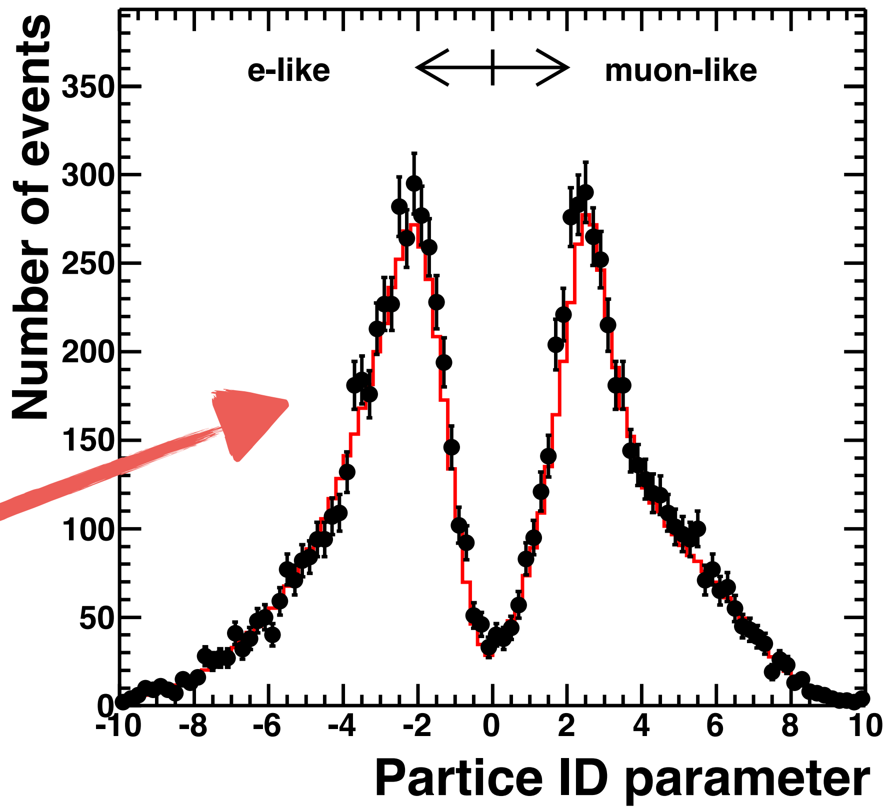


SK is a 50 kton water Cherenkov detector

Inner detector ~11000 20 inch PMTs

Outer detector ~2000 8 inch PMTs

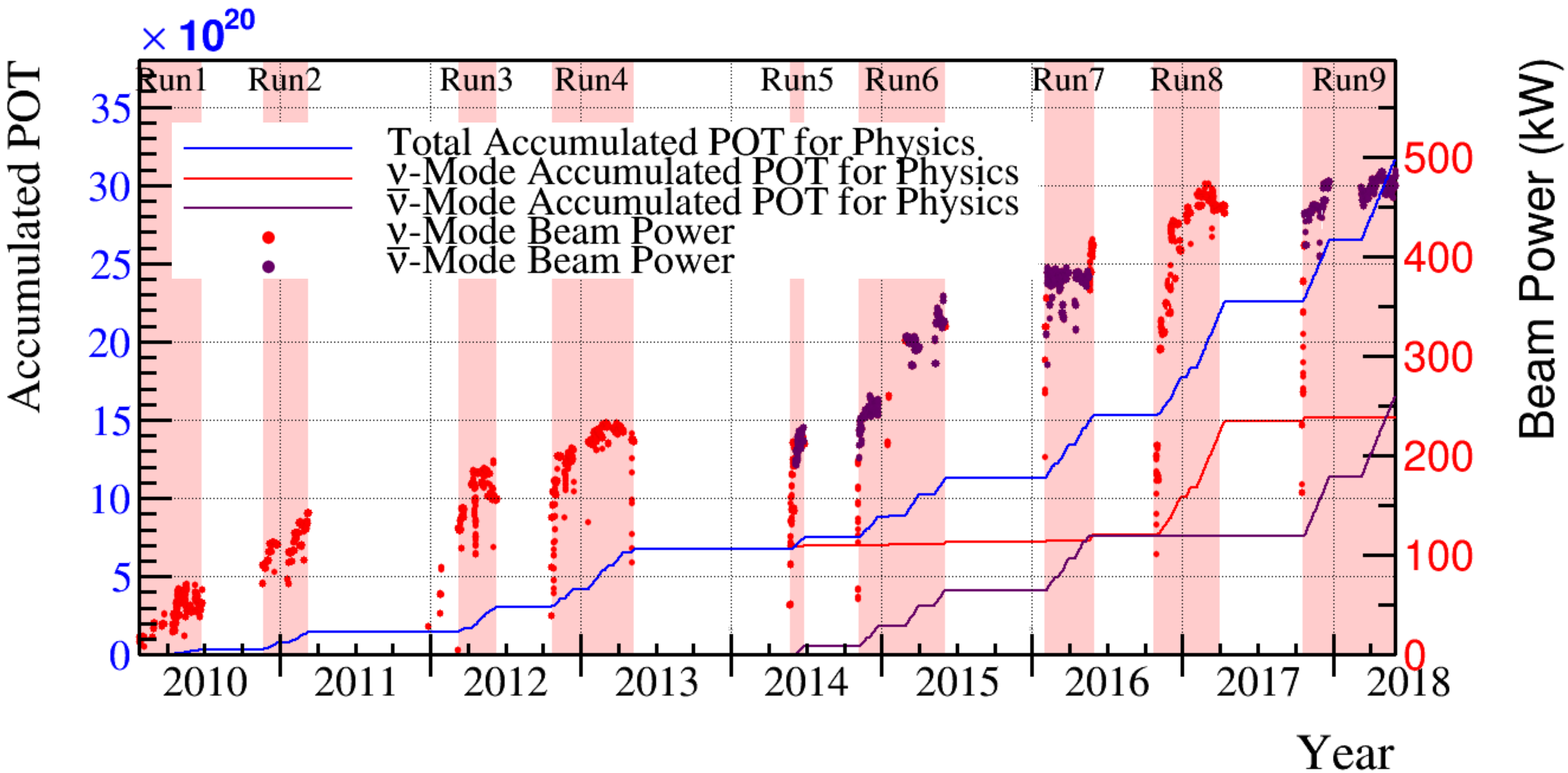
Very good μ/e separation



Collected data

- Total proton on target (POT) collected: 3.1×10^{21} POT: 1.5×10^{21} POT in ν mode and 1.6×10^{21} POT in $\bar{\nu}$ mode

- Beam power 500 kW!



T2K oscillation analysis strategy

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Flux prediction:
proton beam measurements and external hadron production measurements

Neutrino interactions model:
tuned using external data

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select CC ν_μ and $\overline{\nu}_\mu$ interactions
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Extract oscillation parameters

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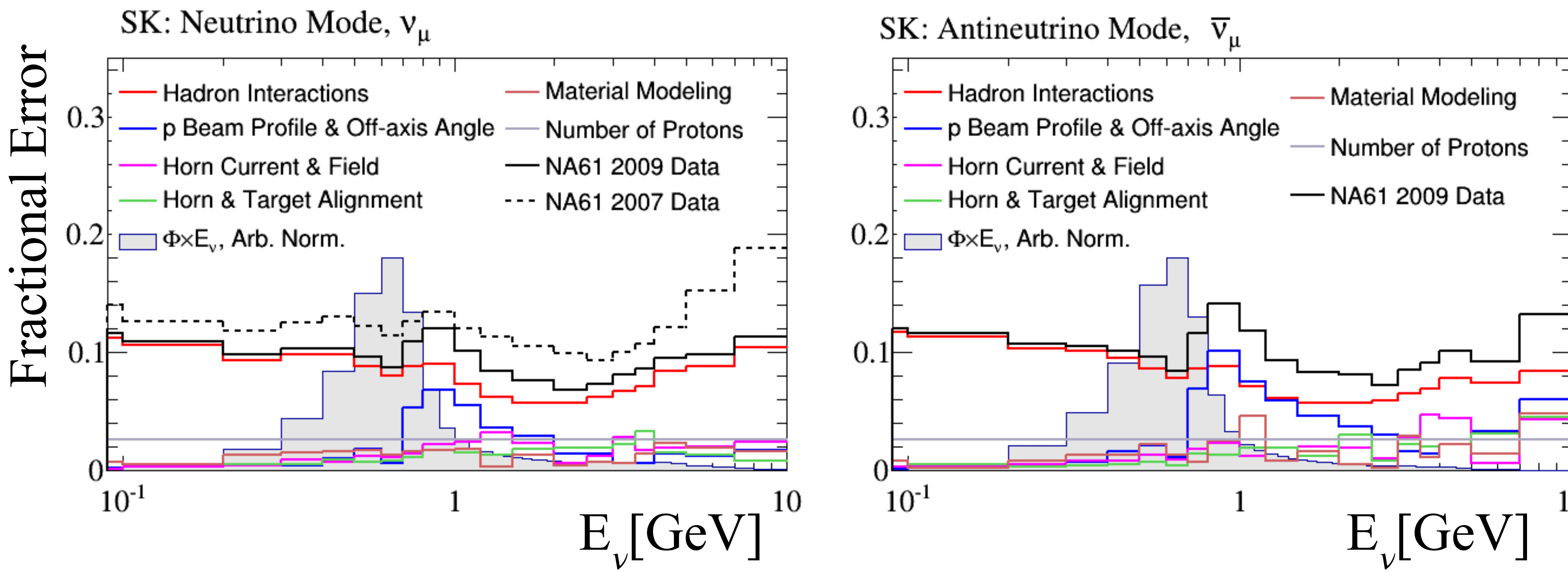
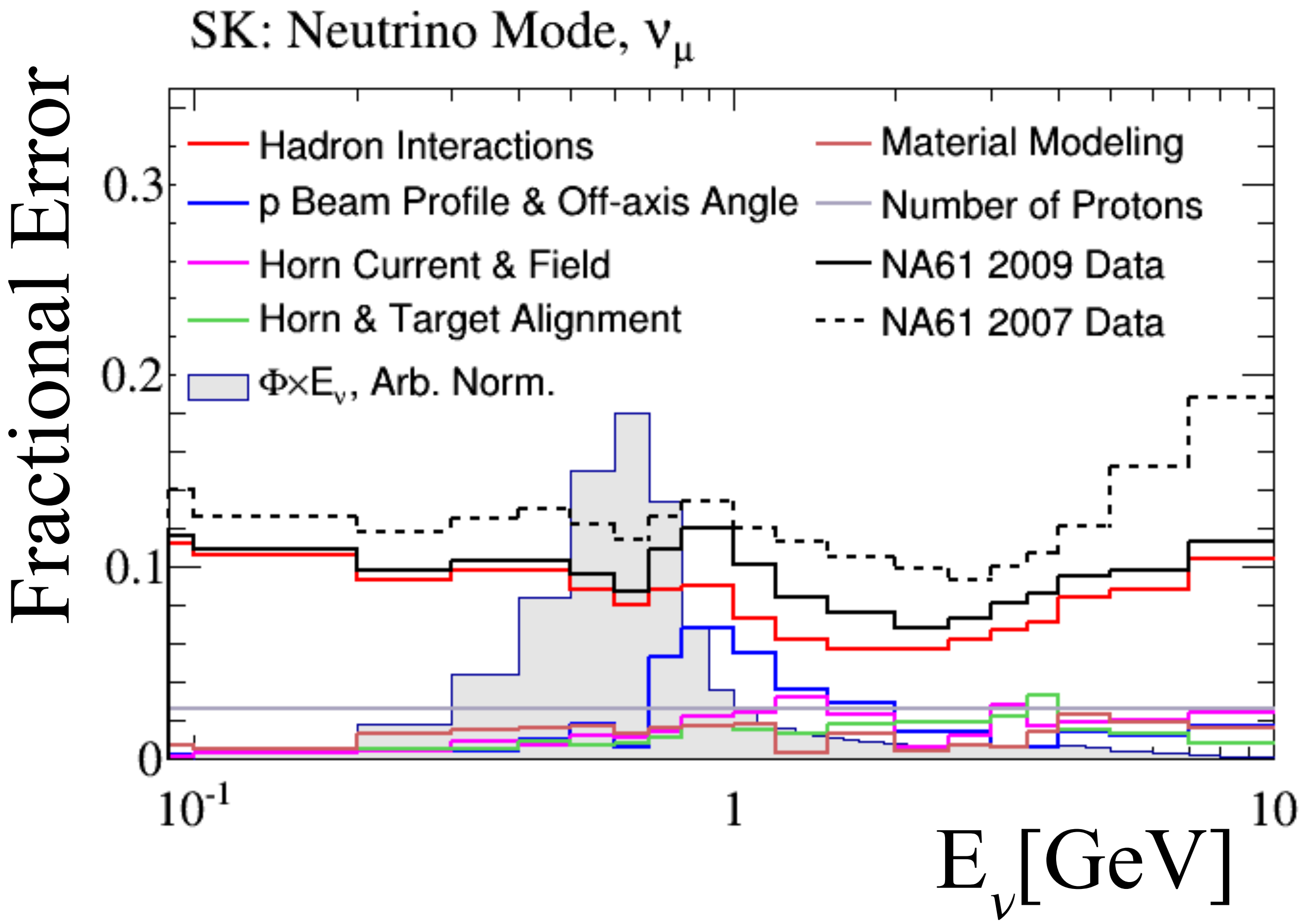
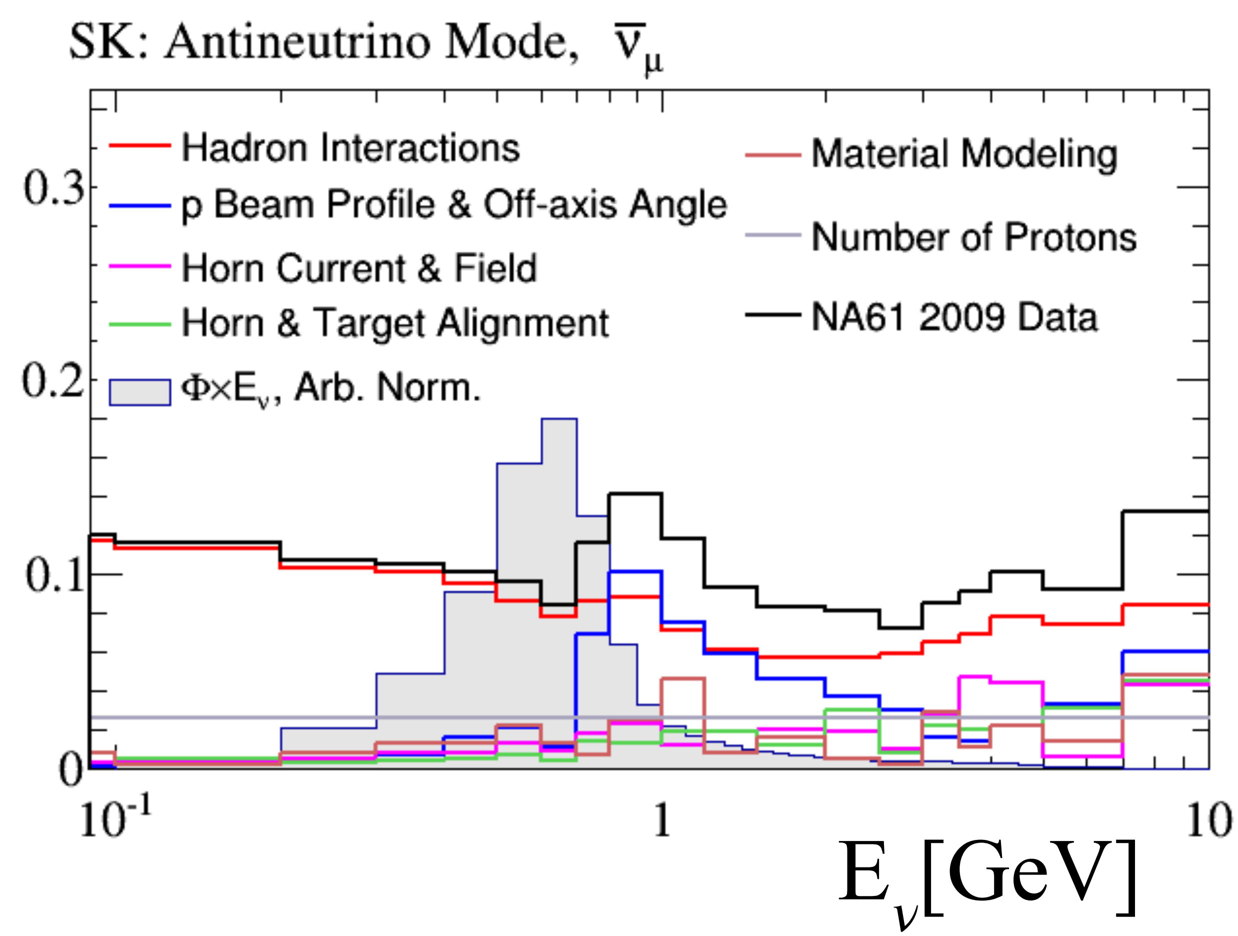
Extract oscillation parameters

Neutrino fluxes



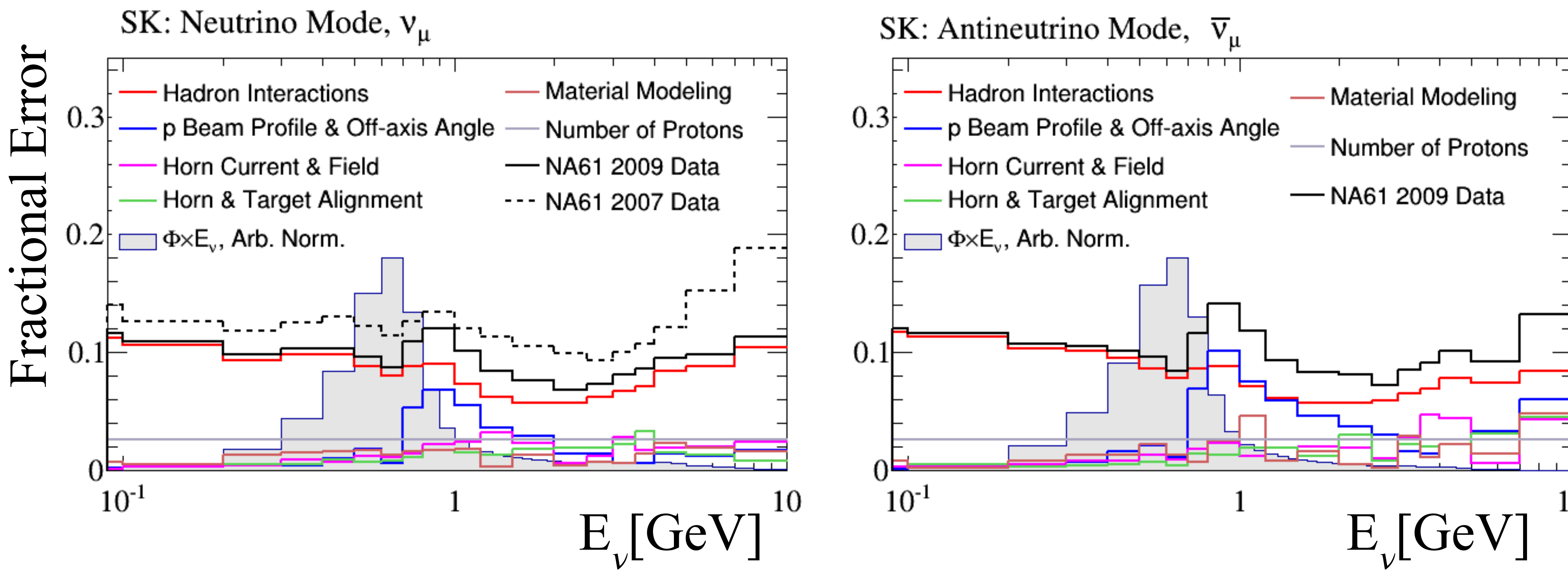
Neutrino fluxes





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

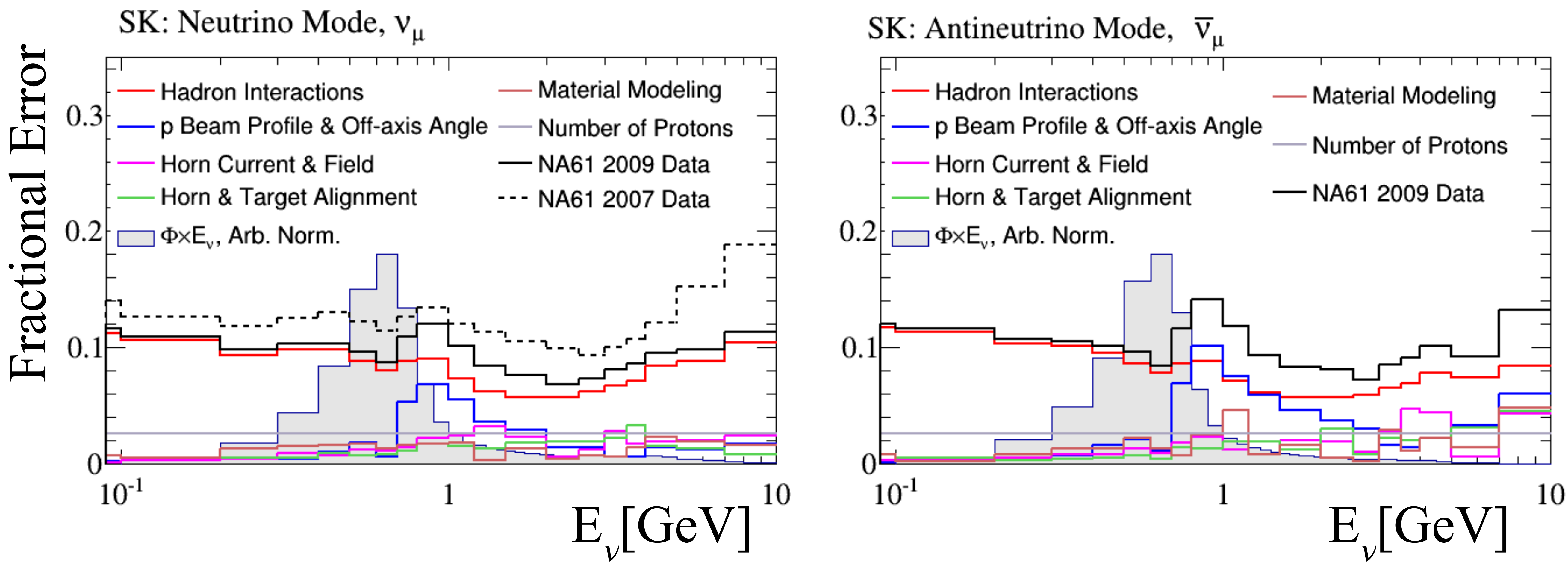
Neutrino fluxes



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

Dominant systematics due to the hadron interactions modeling

Neutrino fluxes

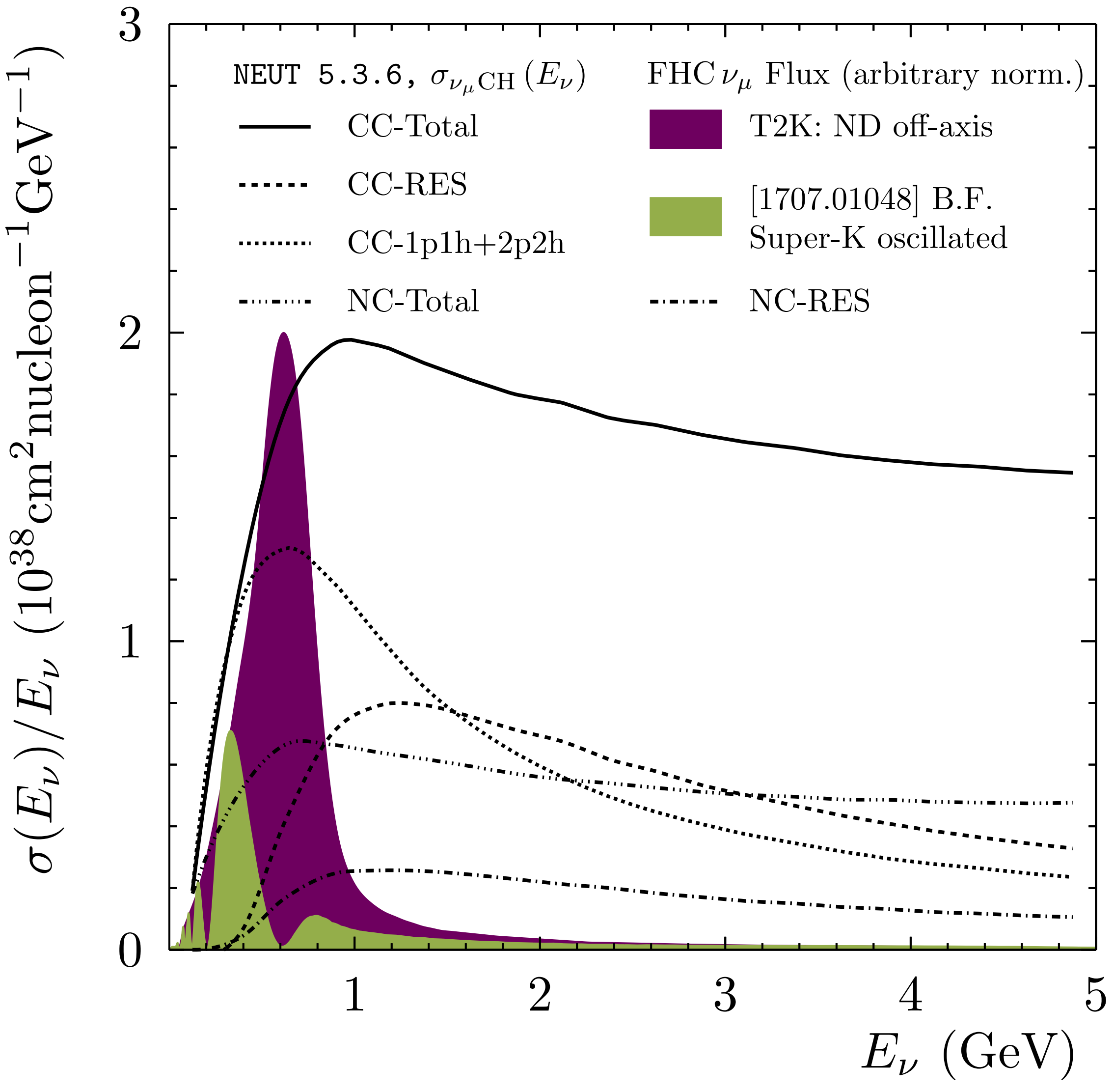


Fluxes known with uncertainties smaller than 10% based on NA61/SHINE thin-target measurements

Dominant systematics due to the hadron interactions modeling

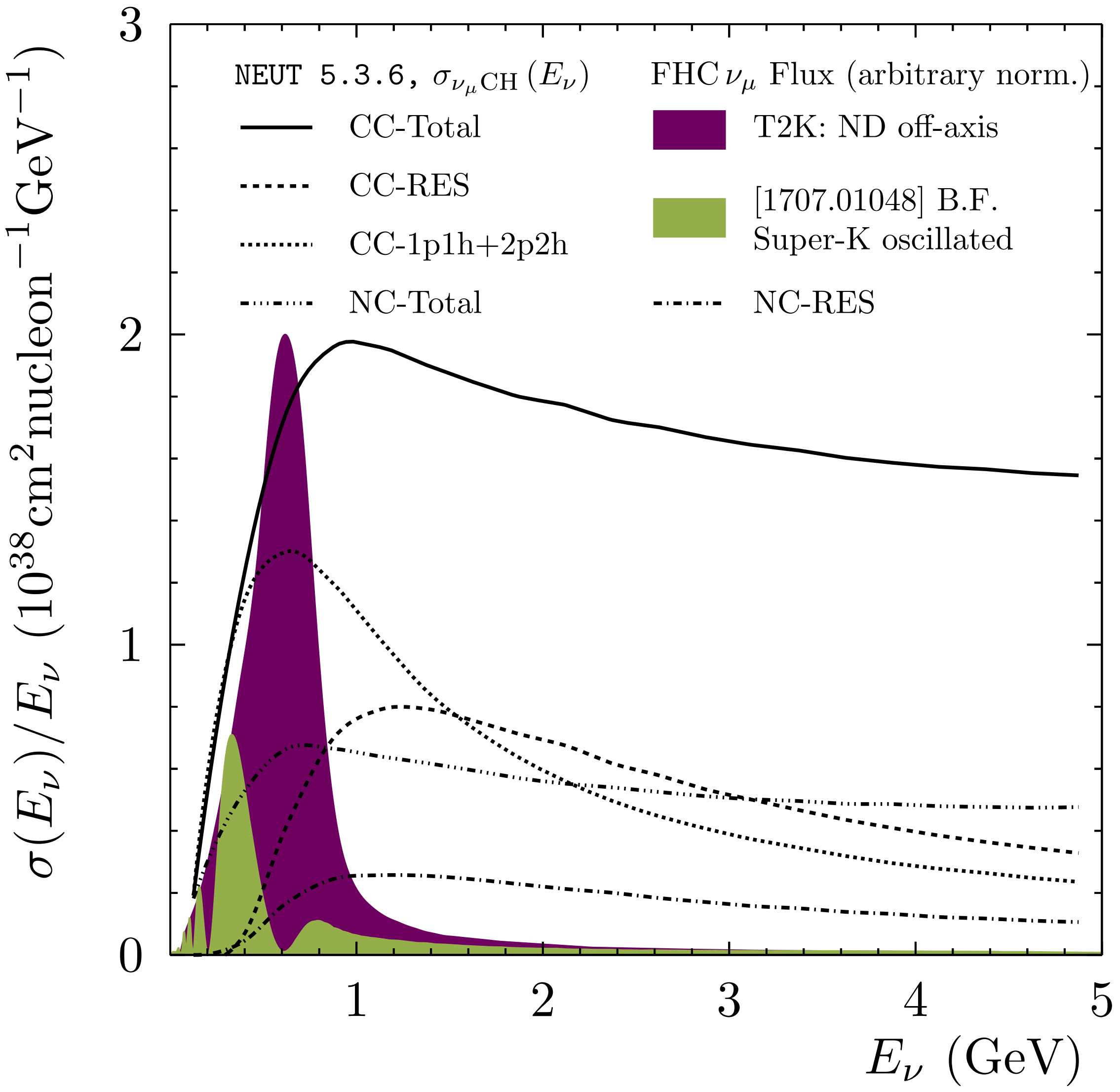
It will be reduced to ~5% by using NA61/SHINE measurements of T2K replica target

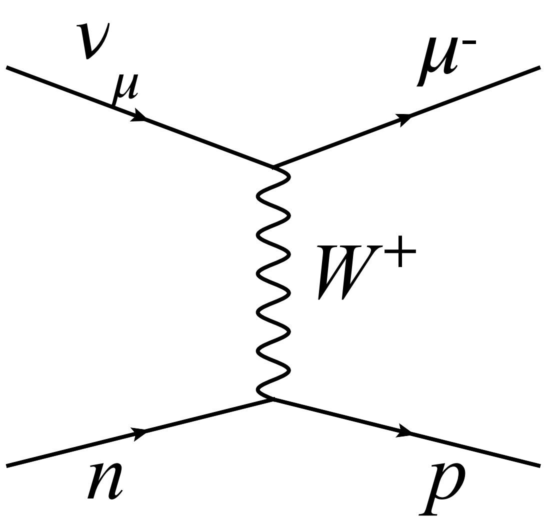
Relevant ν interactions at T2K



Relevant ν interactions at T2K

CCQE
(Charged-Current Quasi-Elastic)





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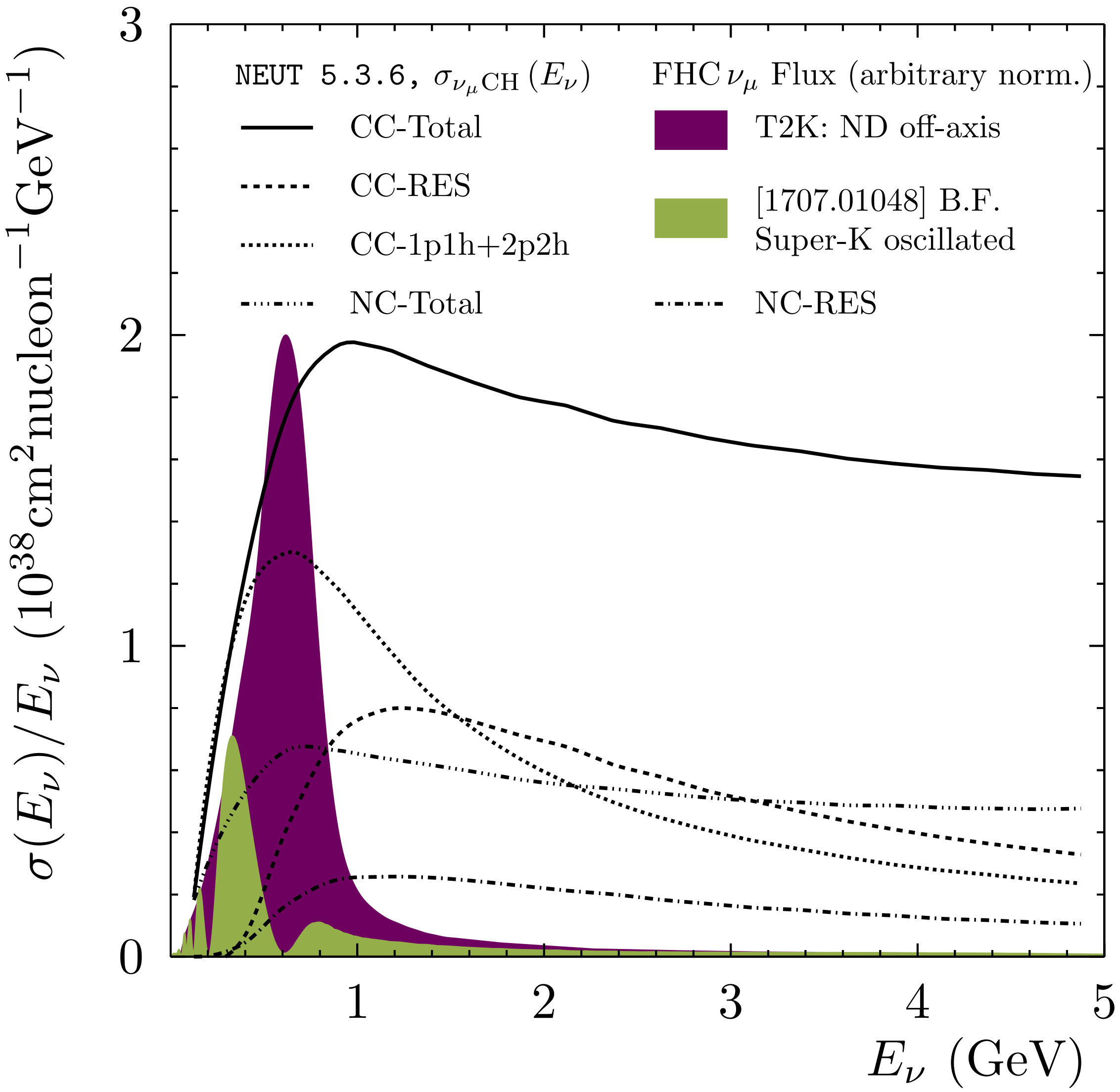

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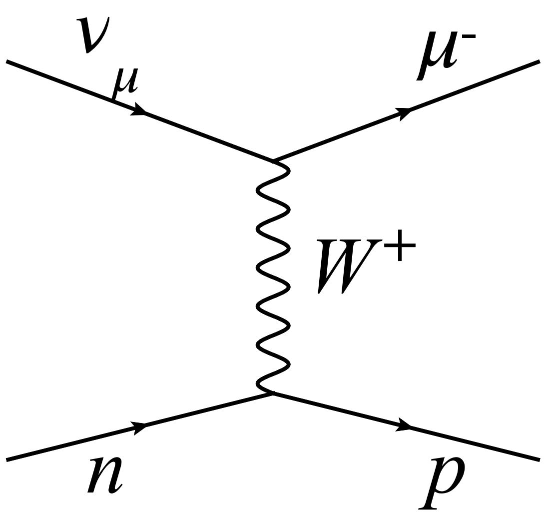
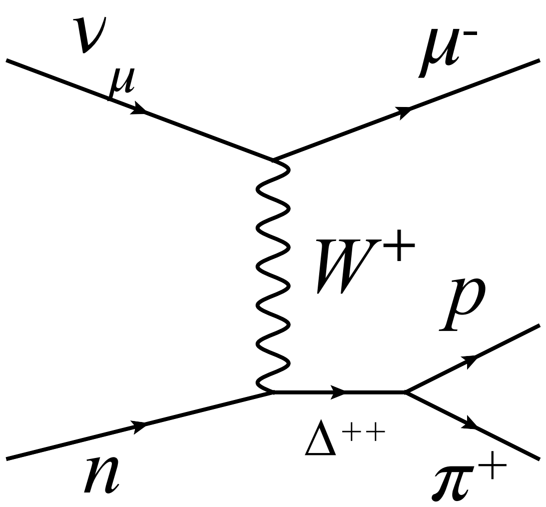
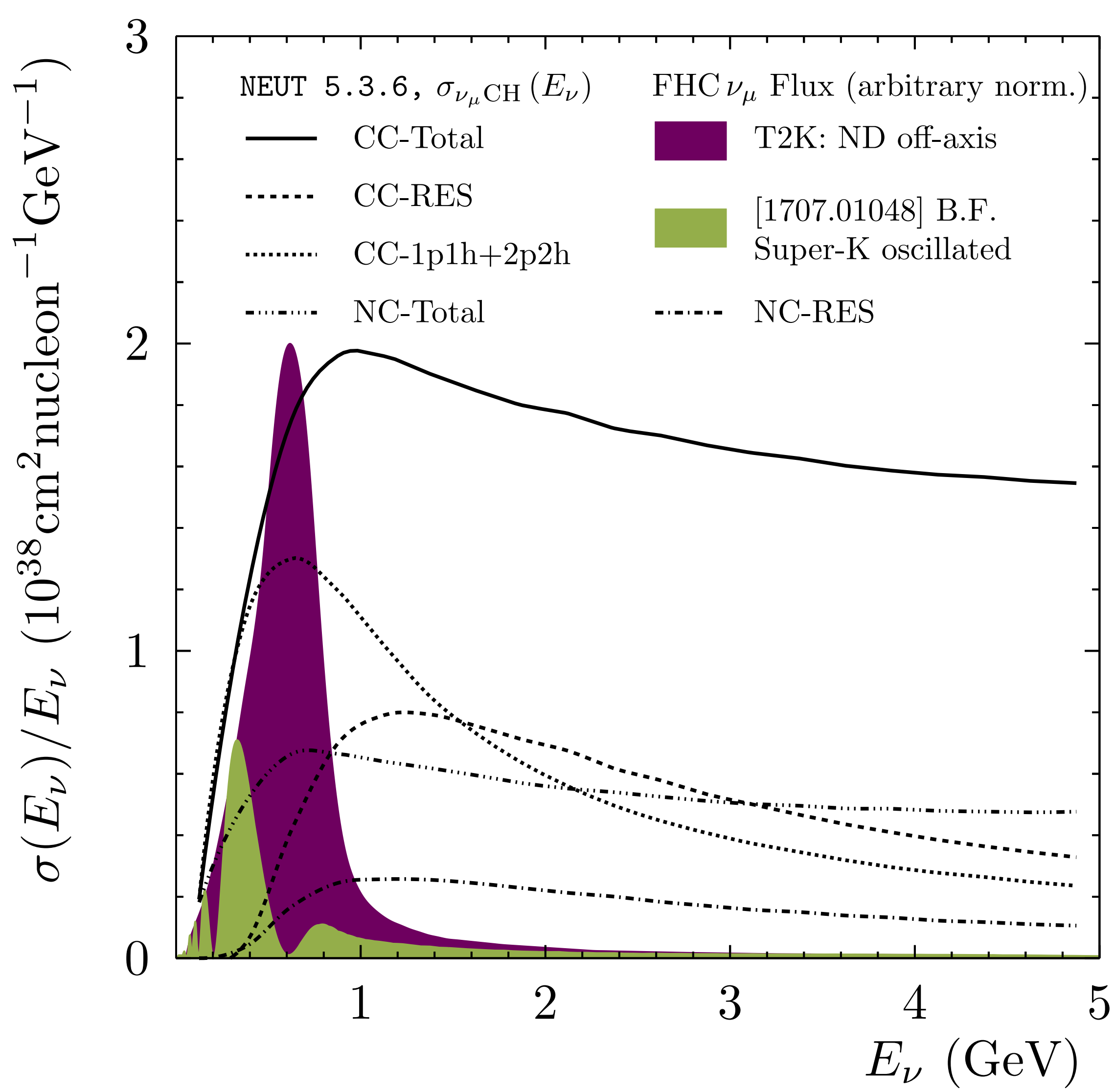


CCRES
(Charged-Current
Resonant pion production)



Relevant ν interactions at T2K



CCQE
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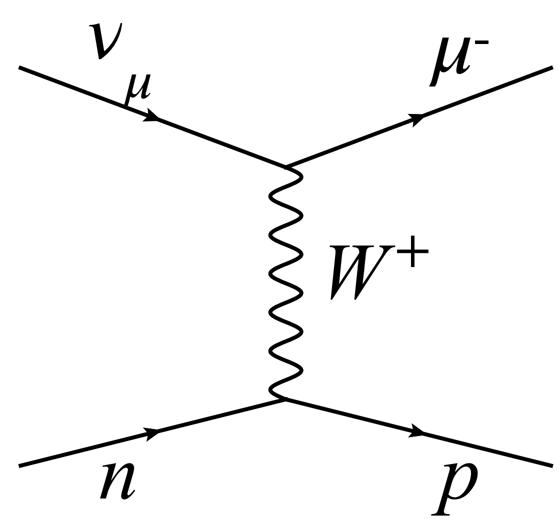

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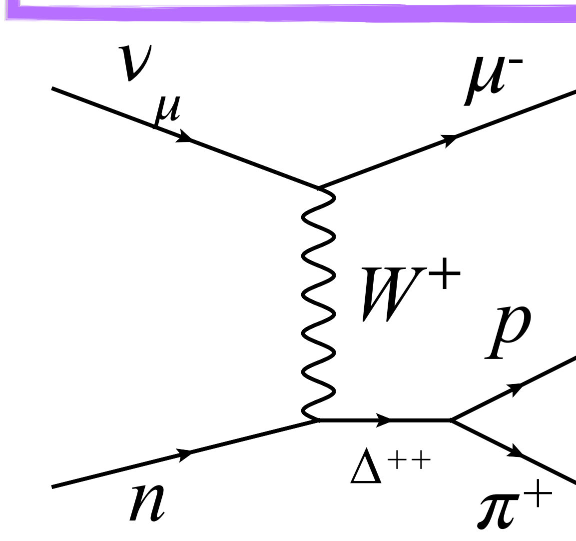
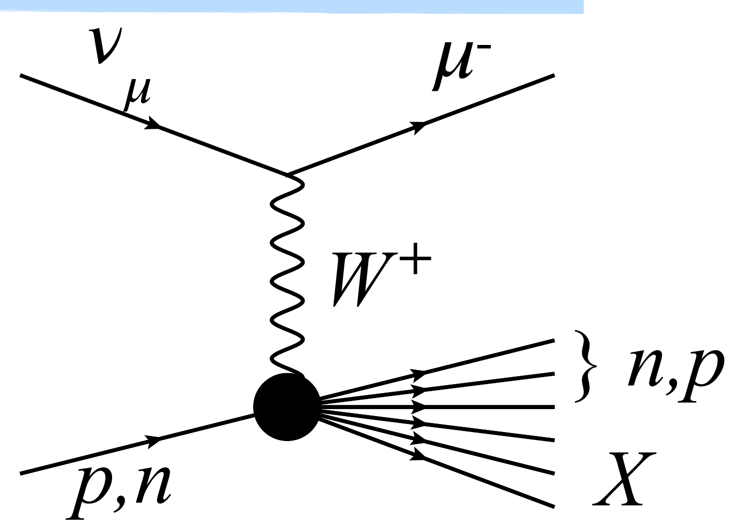


CCDIS
(Charged-Current Deep Inelastic Scattering)



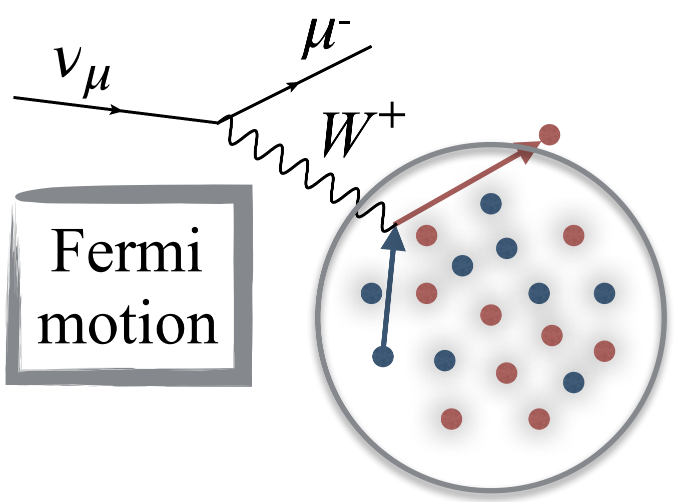
Nuclear effects

Nuclear effects

Nucleons bound in the nucleus $\Rightarrow$ Nuclear effect!

Nuclear effects

Nucleons bound in the nucleus ⇒ Nuclear effect!



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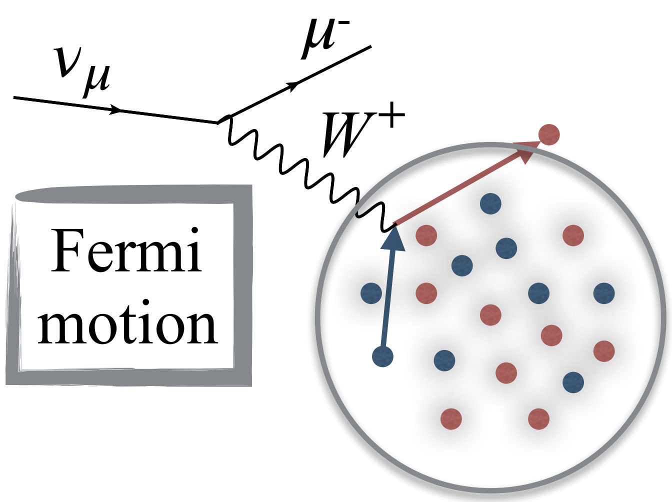

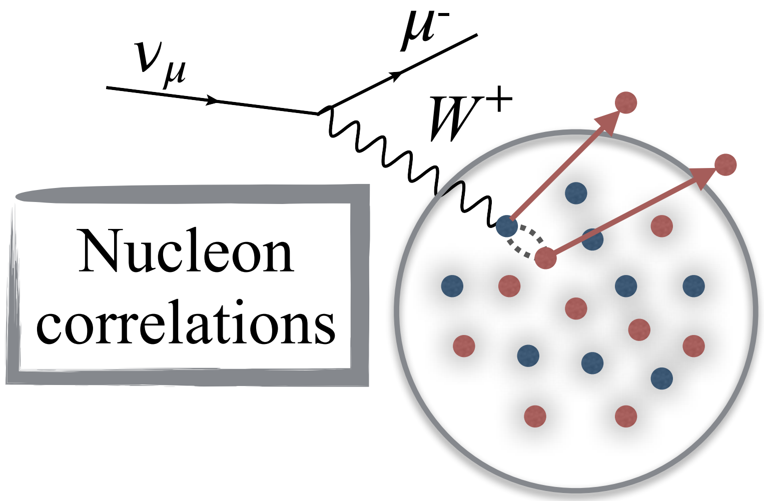

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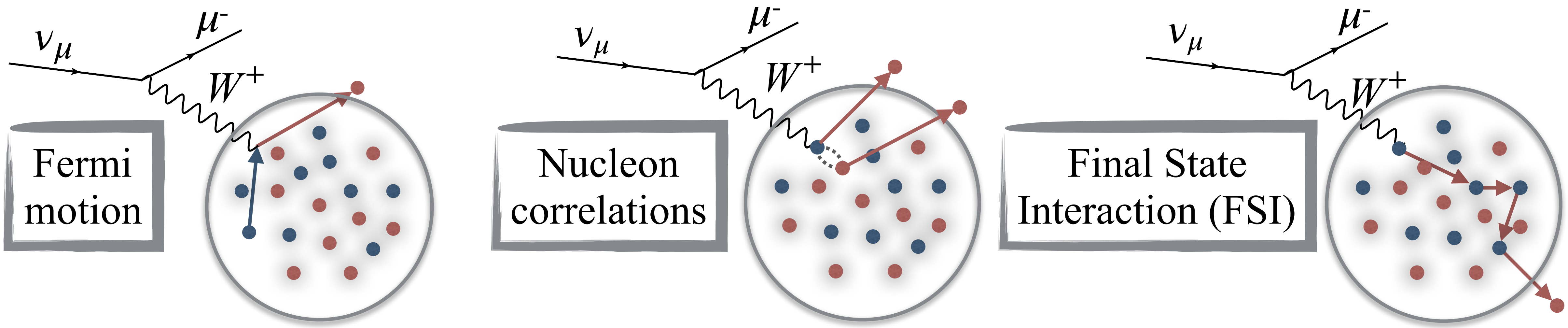

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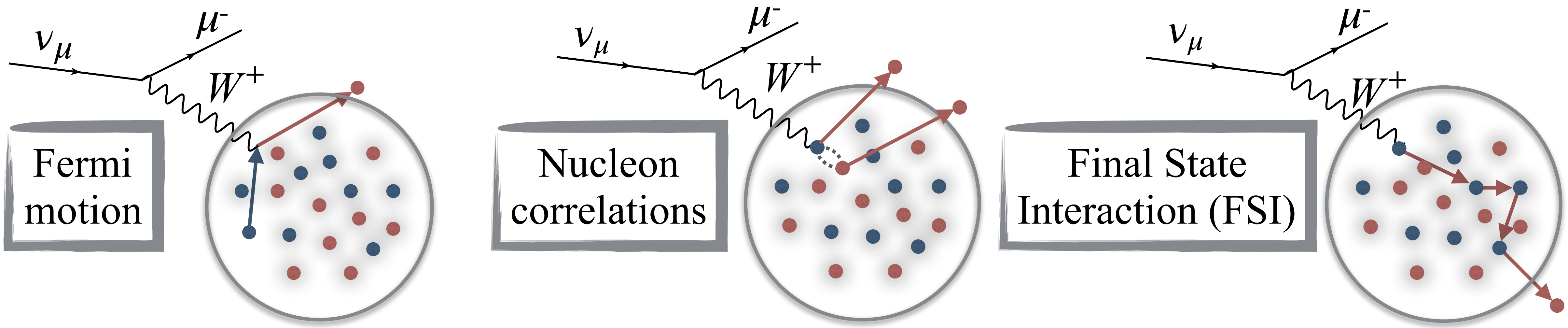

Neutrino Energy reconstructed using CCQE hypothesis

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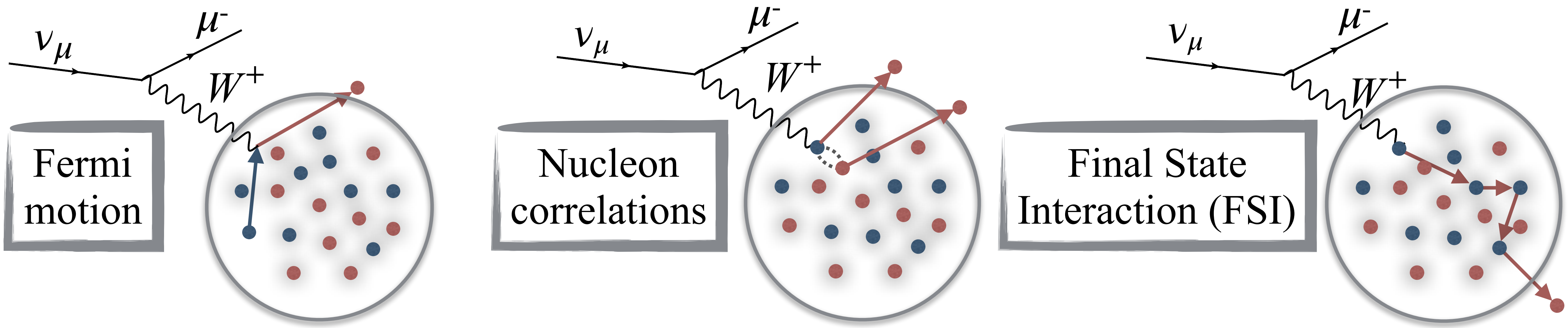
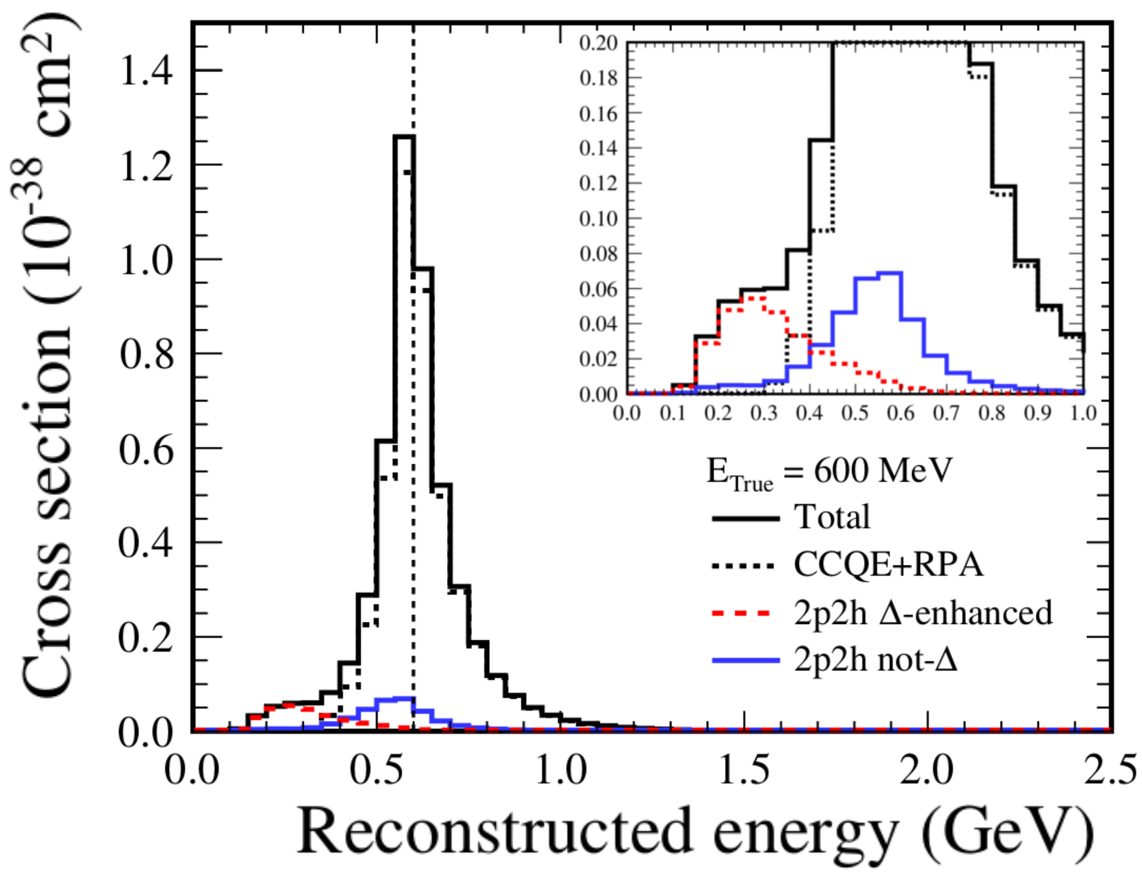


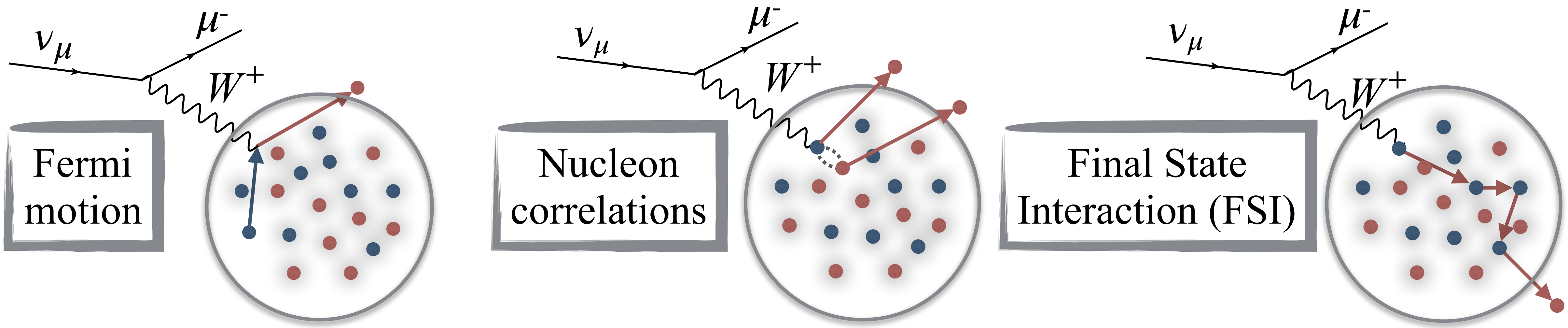
Neutrino Energy reconstructed using CCQE hypothesis

Nuclear effects introduce a bias in neutrino energy reconstruction



Detector acceptance

Nucleons bound in the nucleus ⇒ Nuclear effect!



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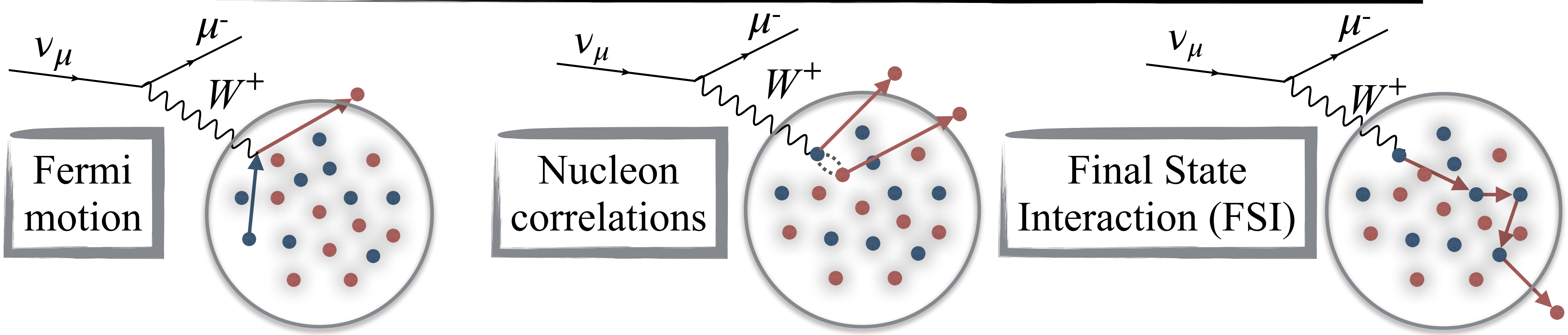

Limited detector acceptance

Detector acceptance

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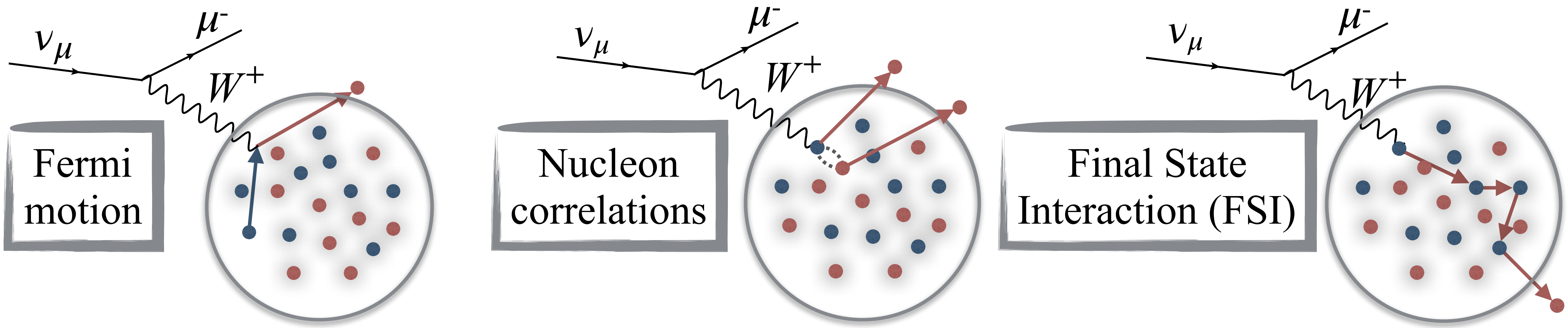

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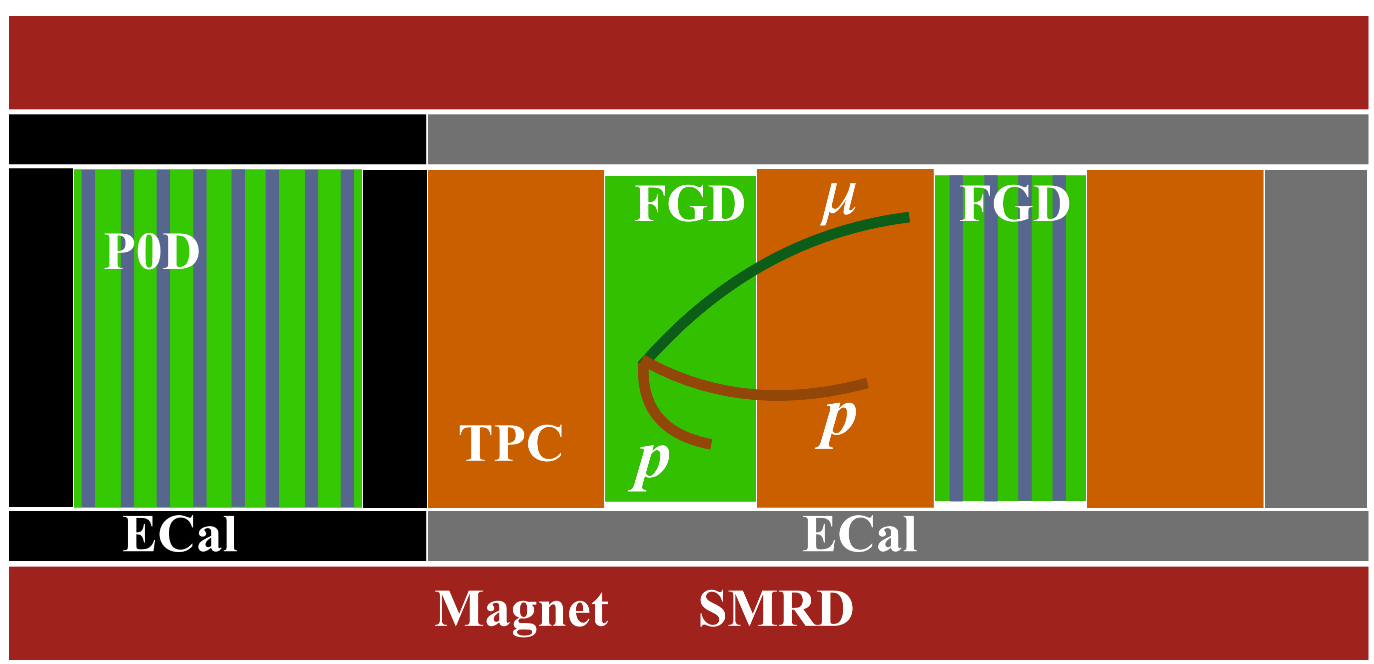

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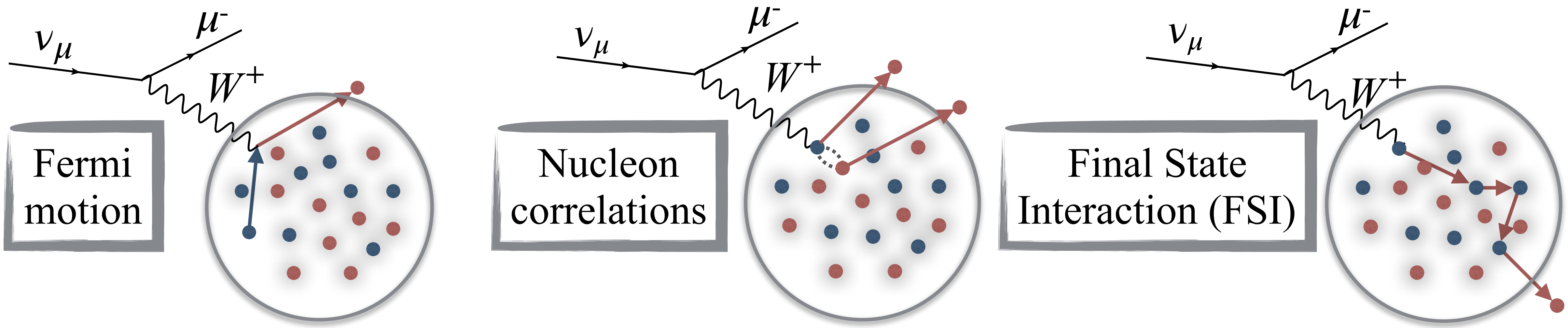

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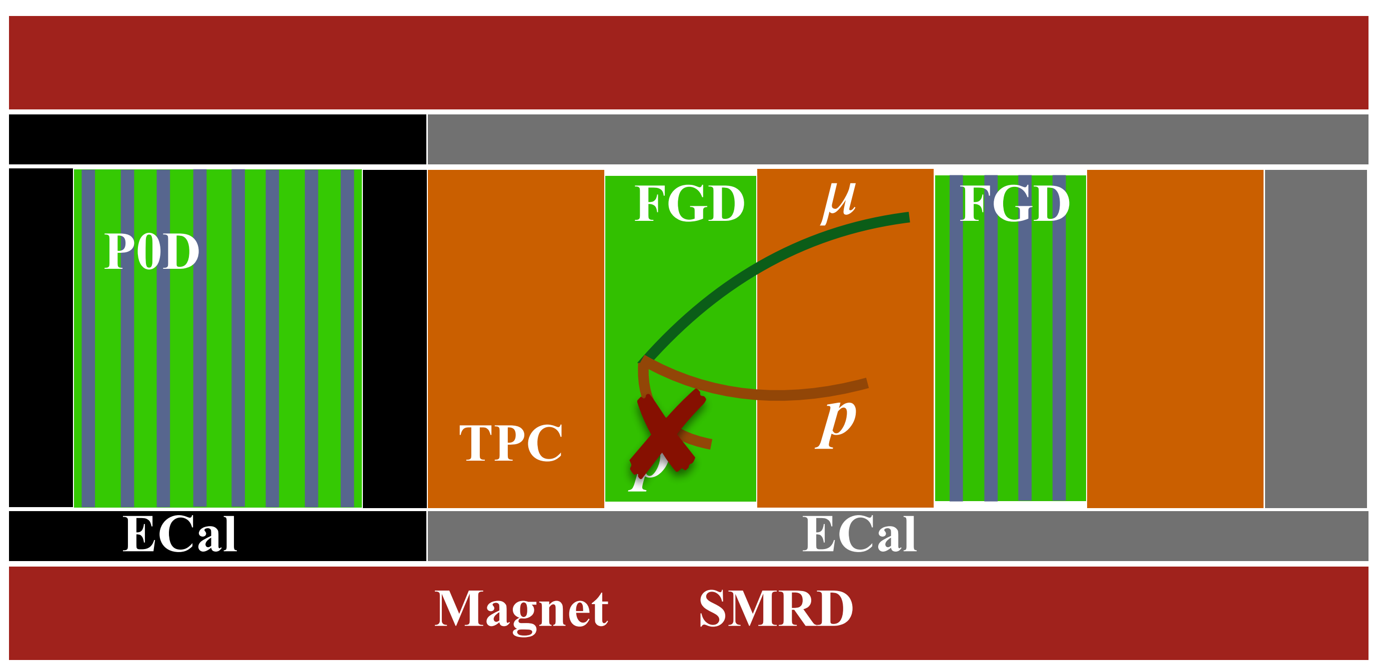

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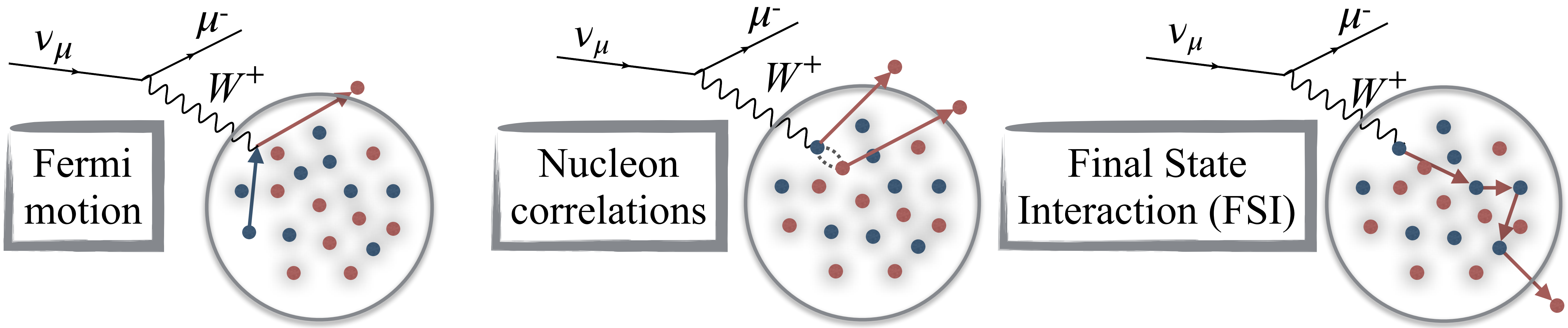

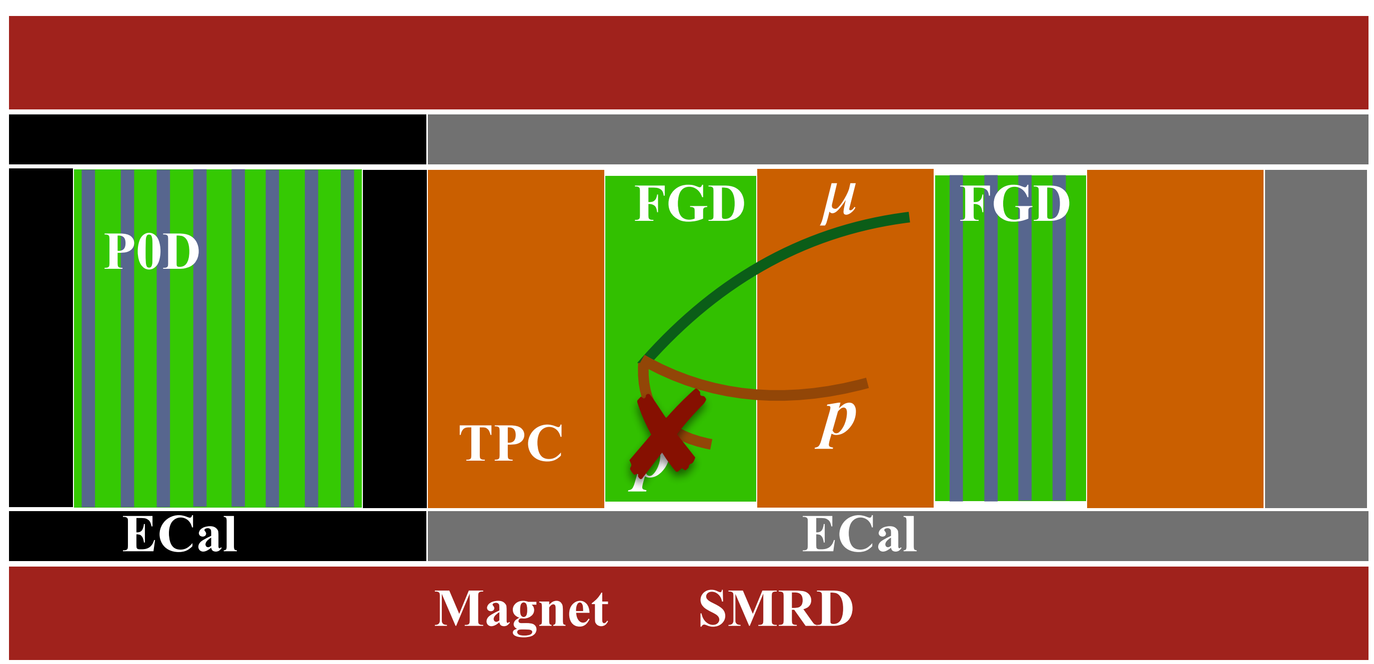

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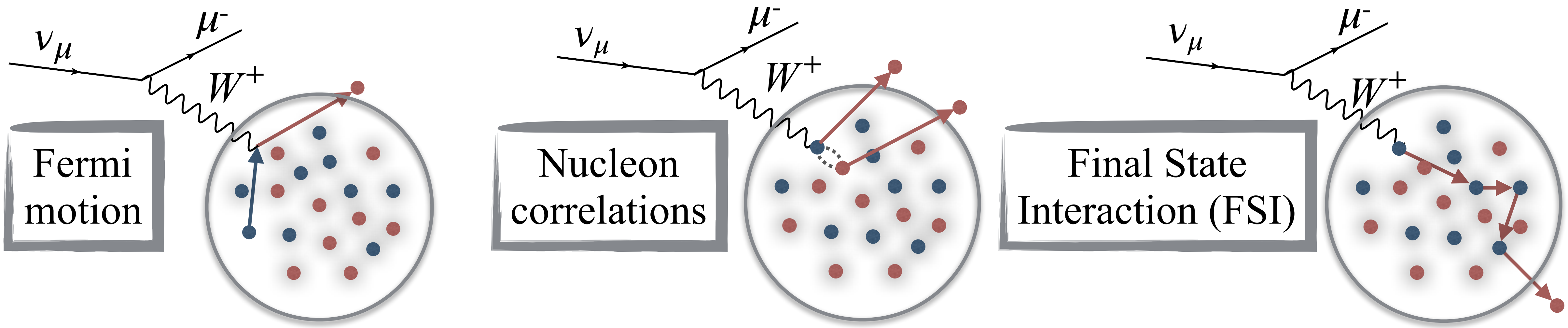
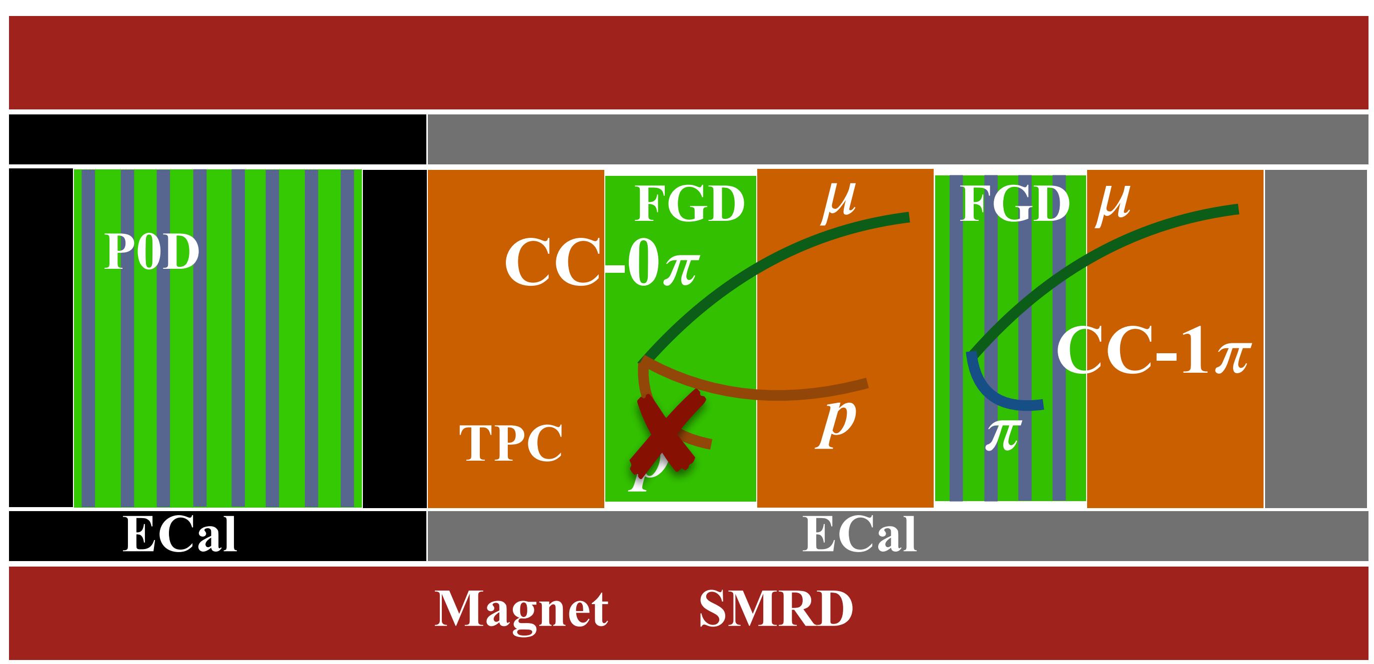


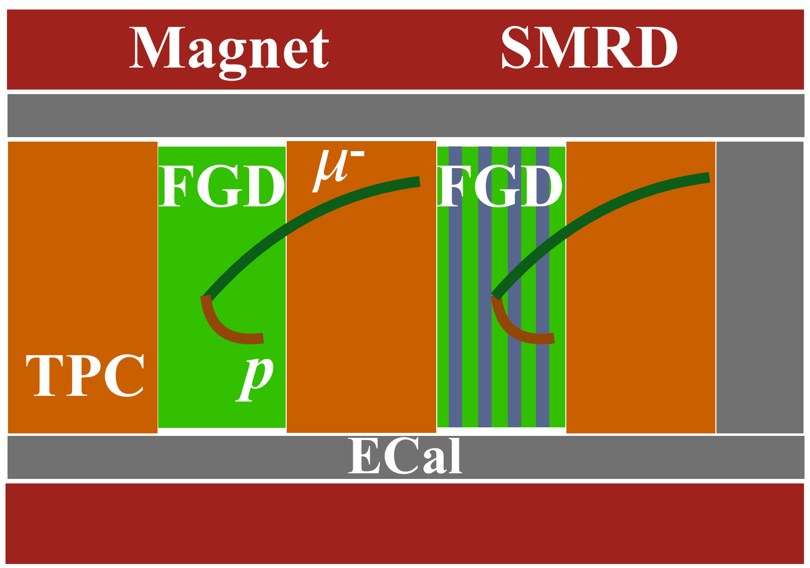
Increase acceptance and reduce the dependence from the cross-section modeling measuring interaction topologies

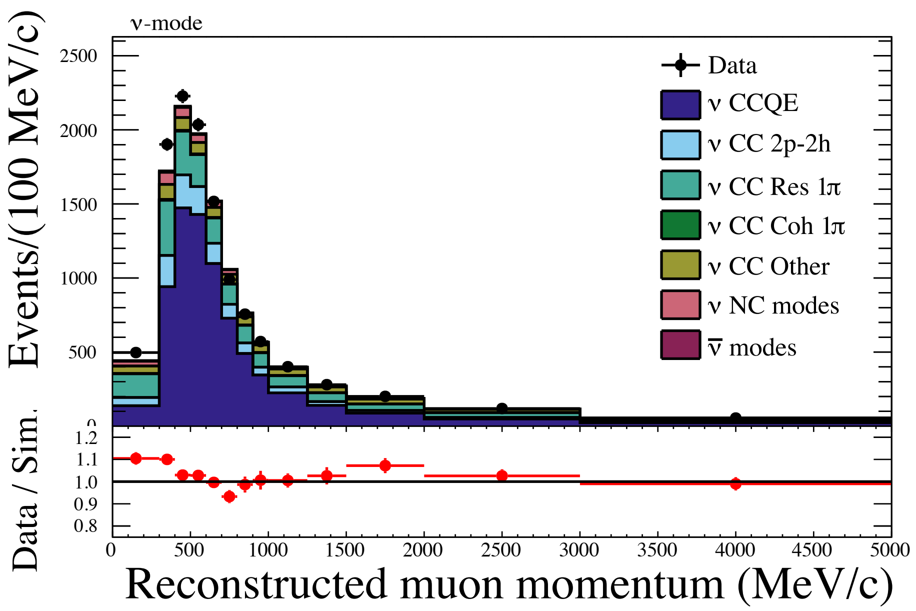


ND280 measurements: ν beam

ND280 measurements: ν beam

CC-0π





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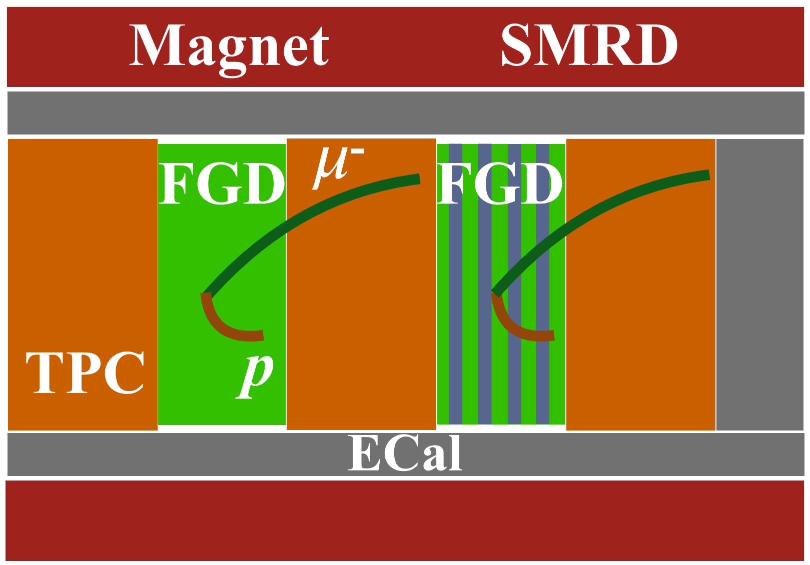
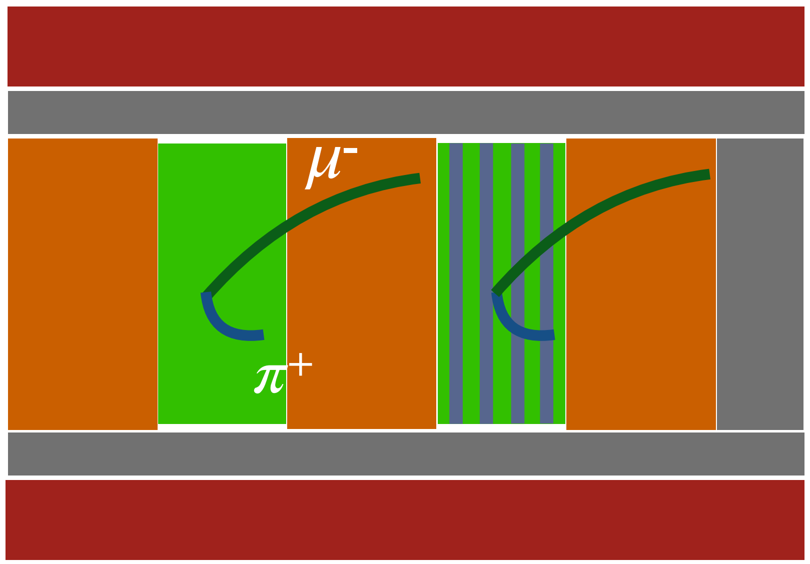
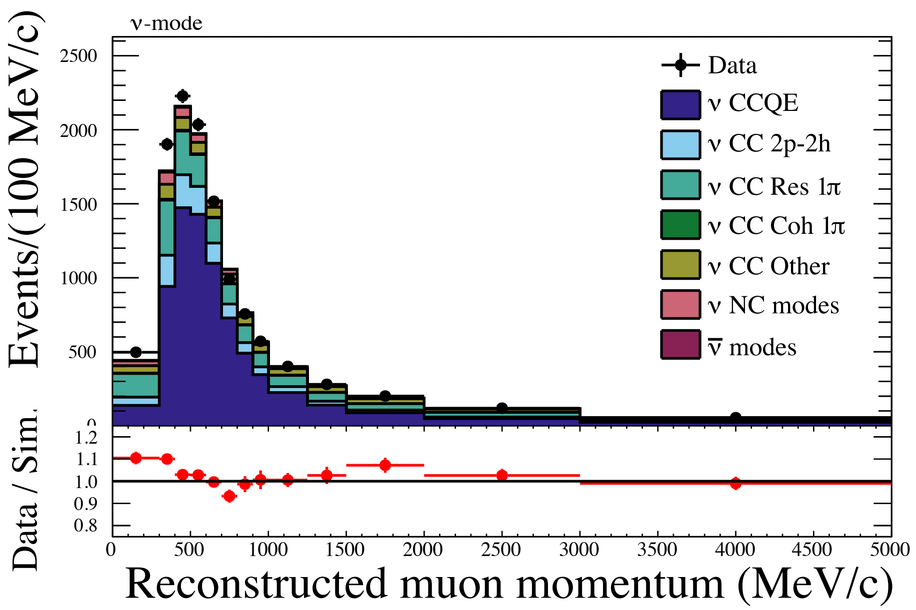
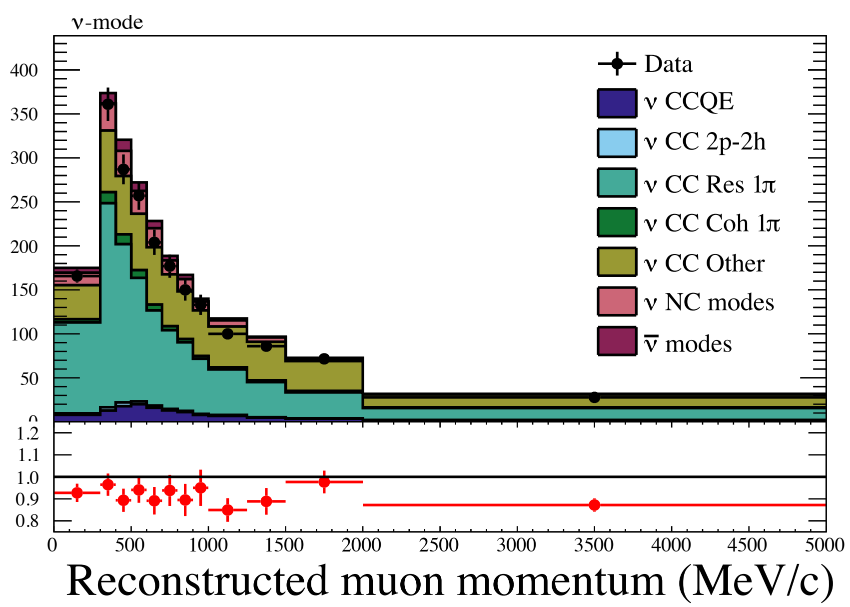


CC-1π+

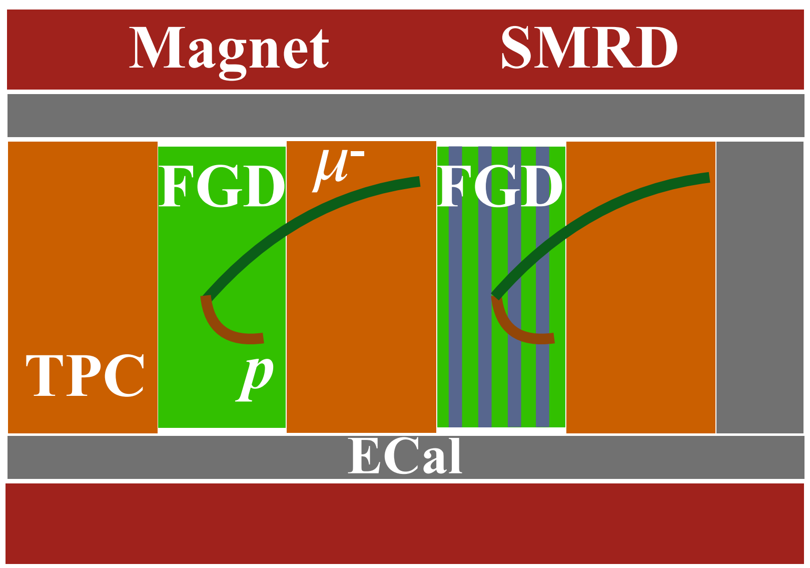


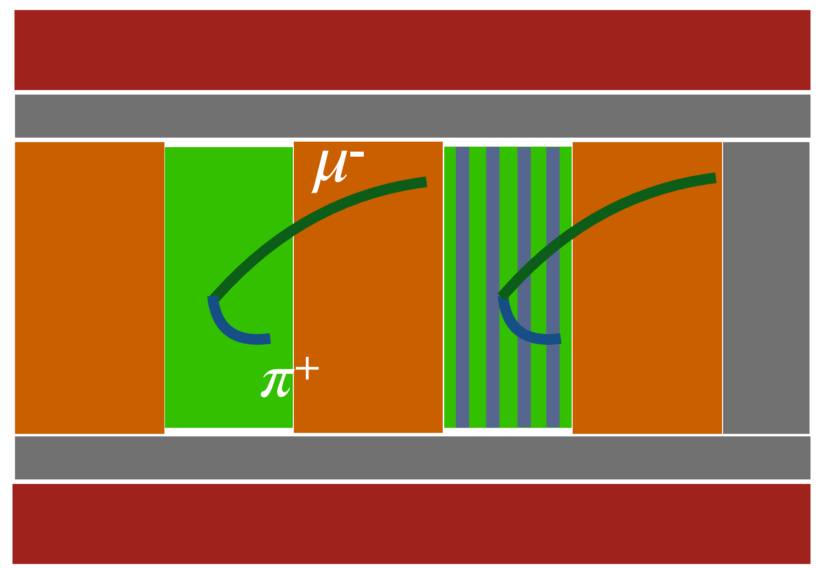


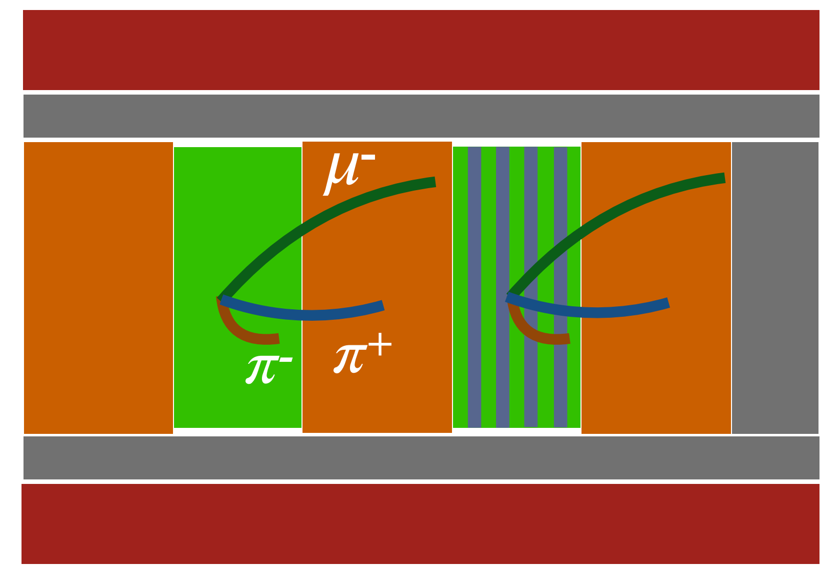


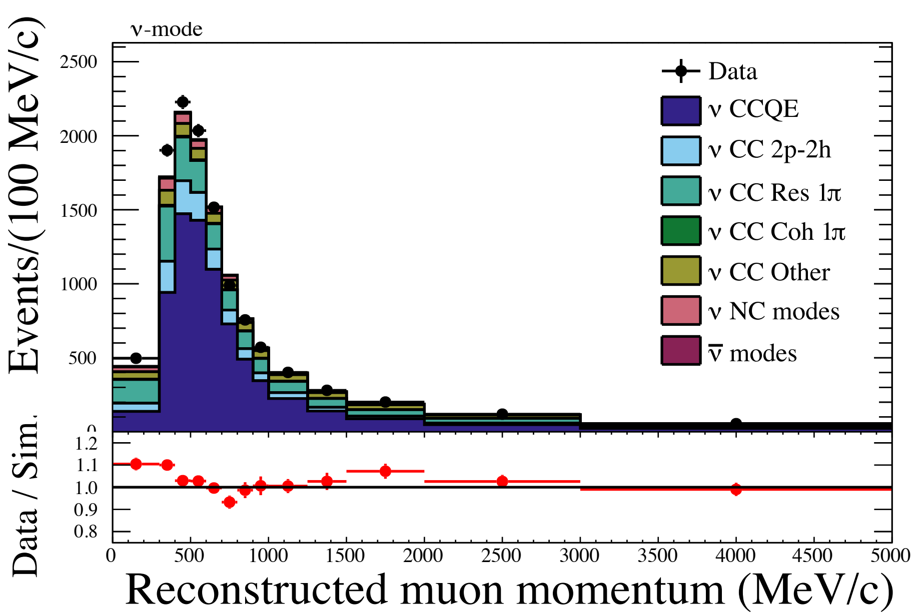
ND280 measurements: ν beam

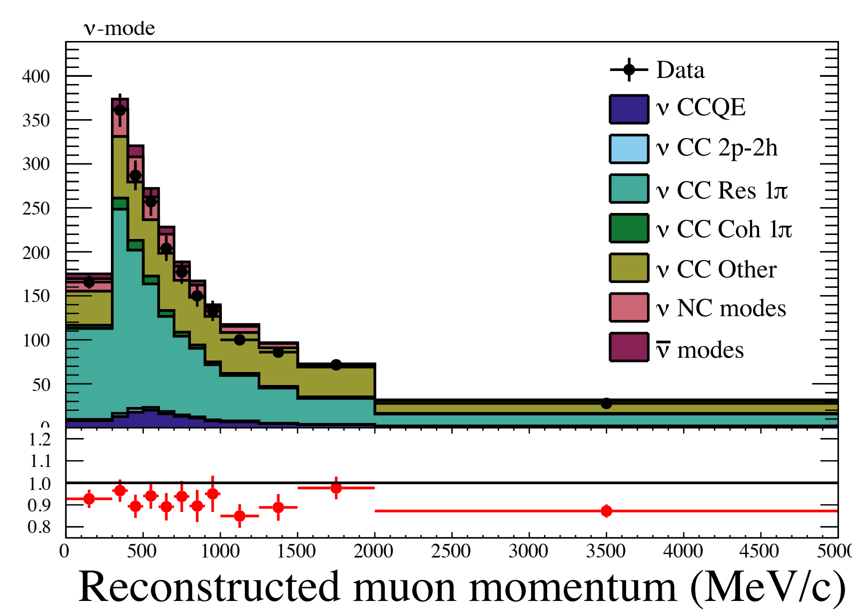
CC-0π | CC-1π^+ | CC-Other

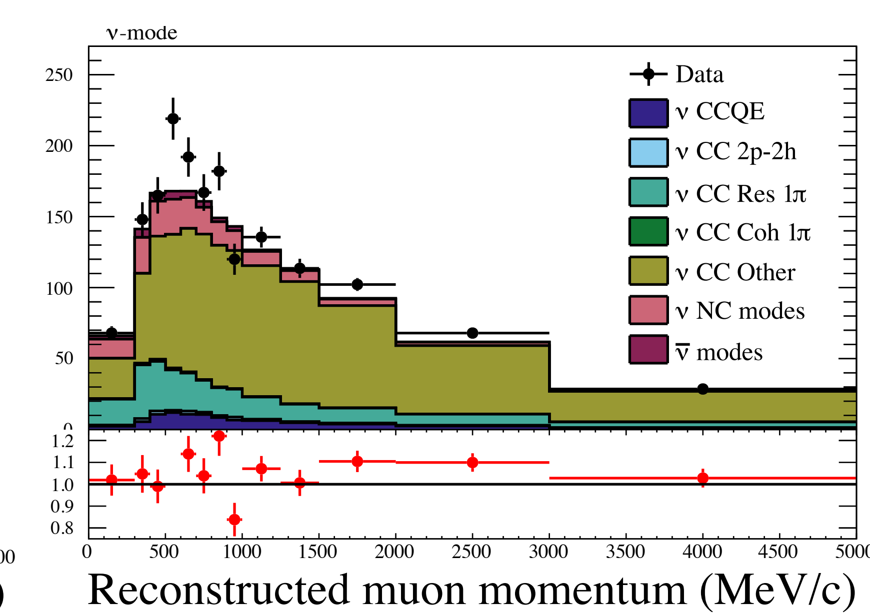












ND280 measurements: $\overline{\nu}$ beam

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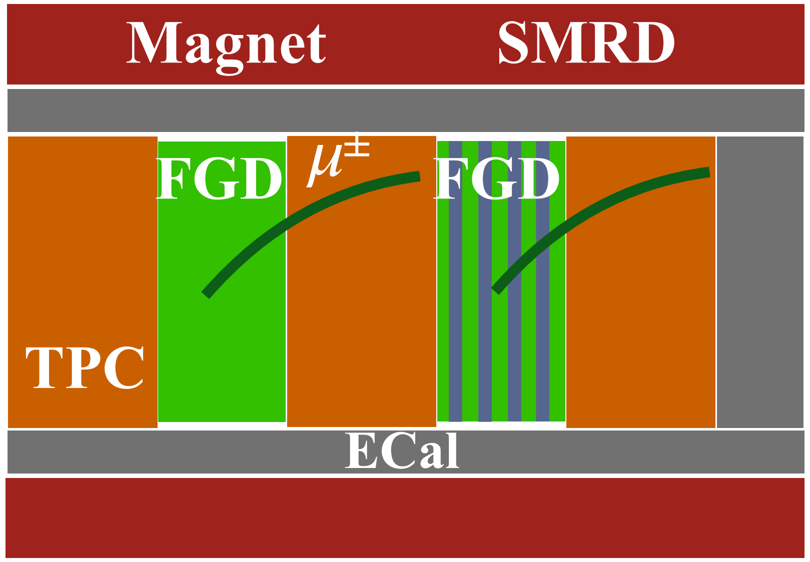
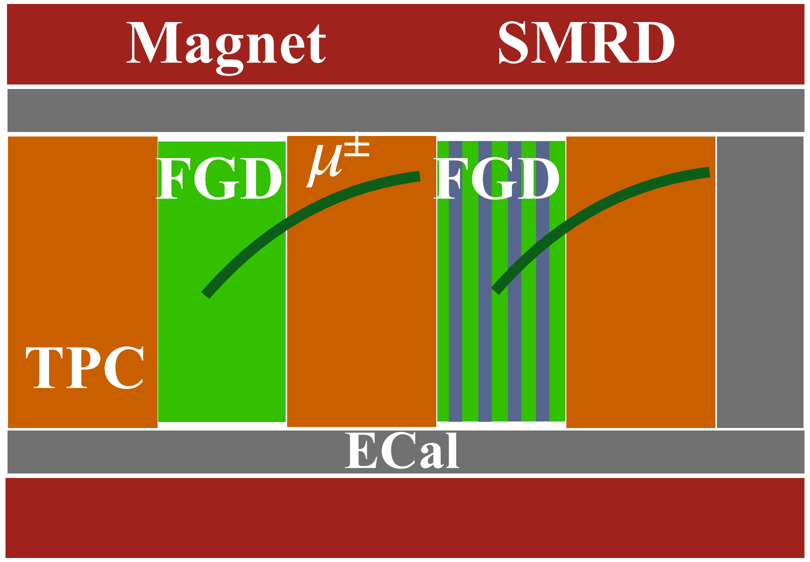
CC-1Track

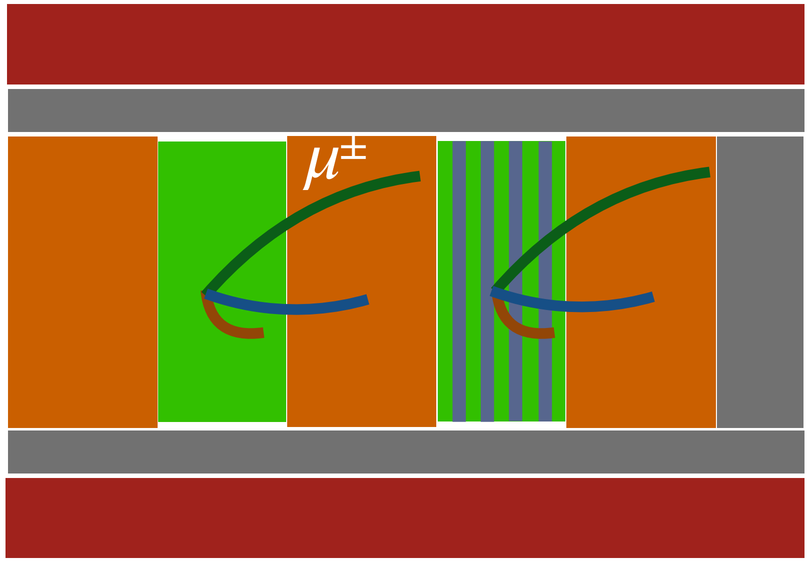


ND280 measurements: $\bar{\nu}$ beam

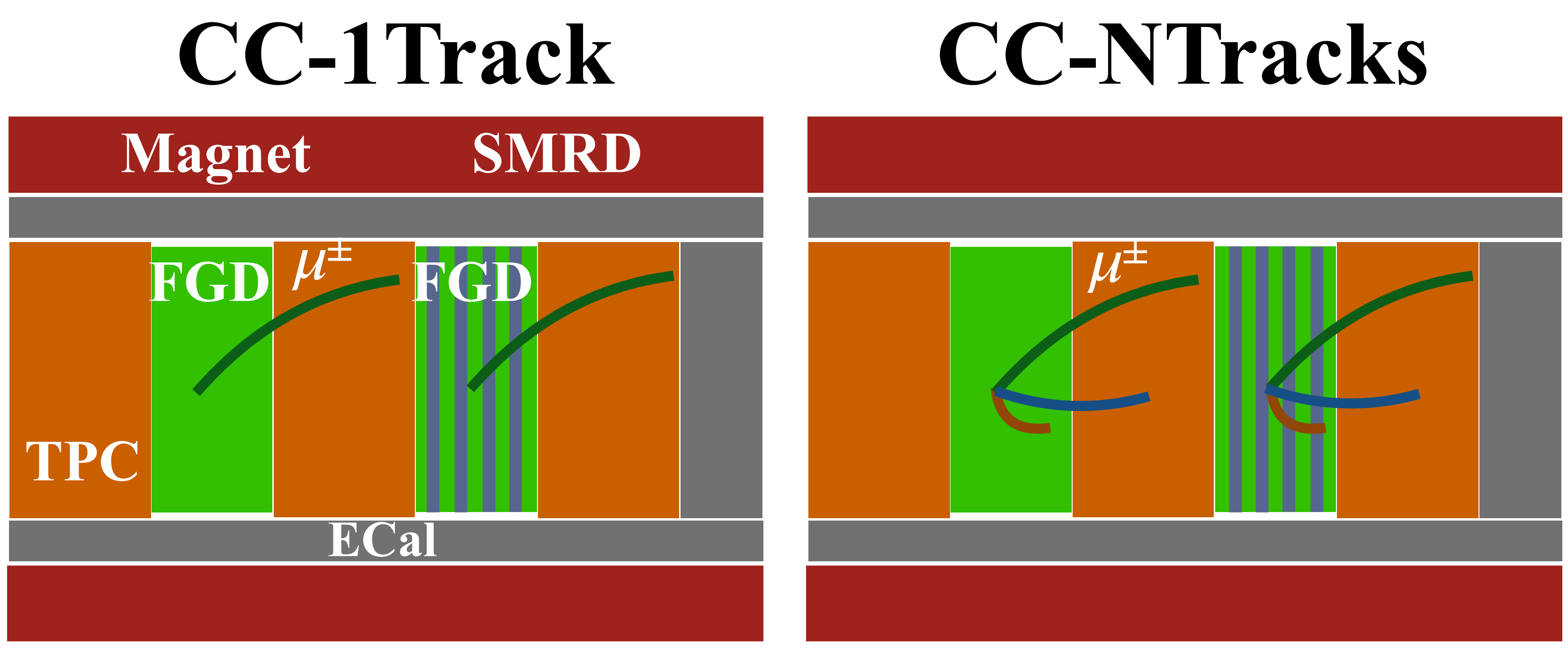
CC-1Track

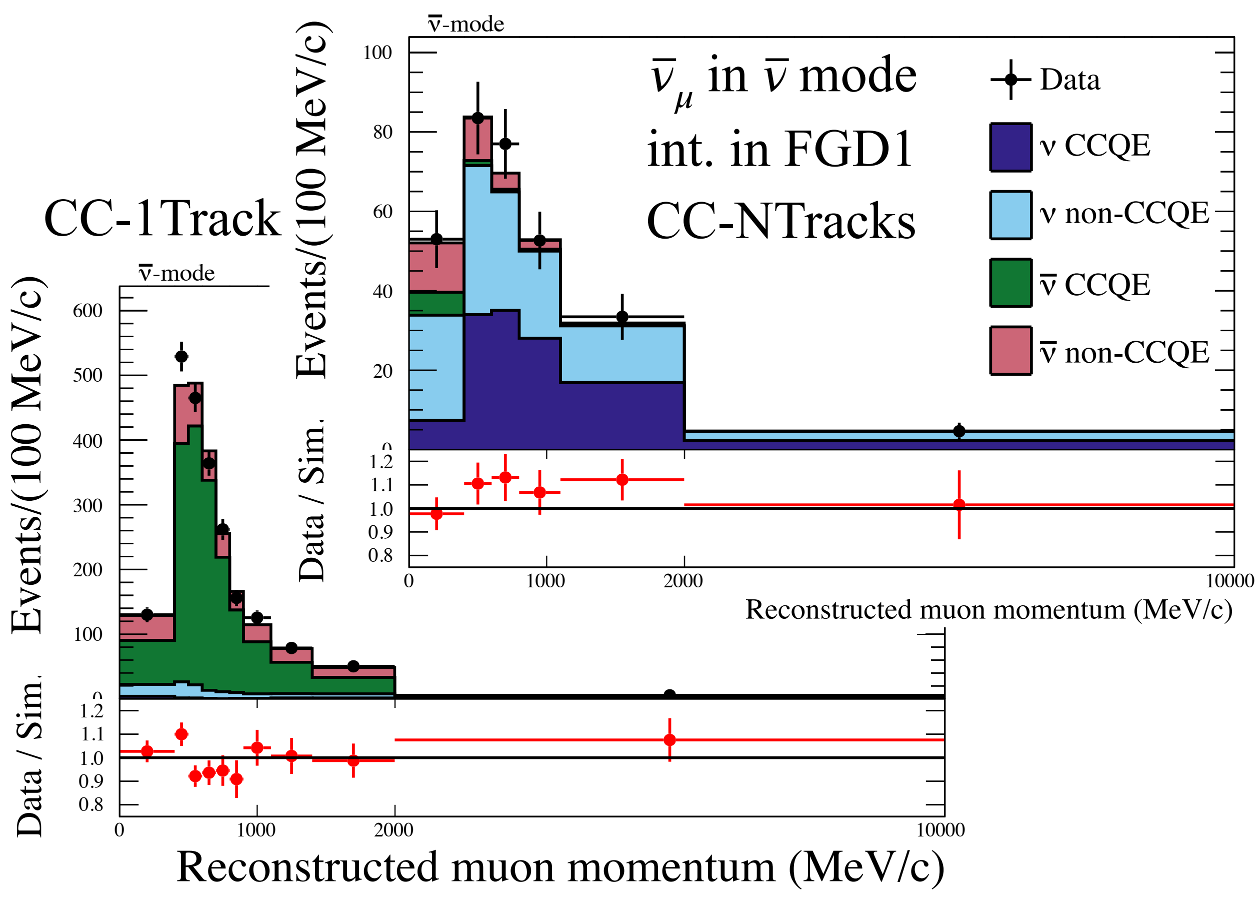


CC-NTracks



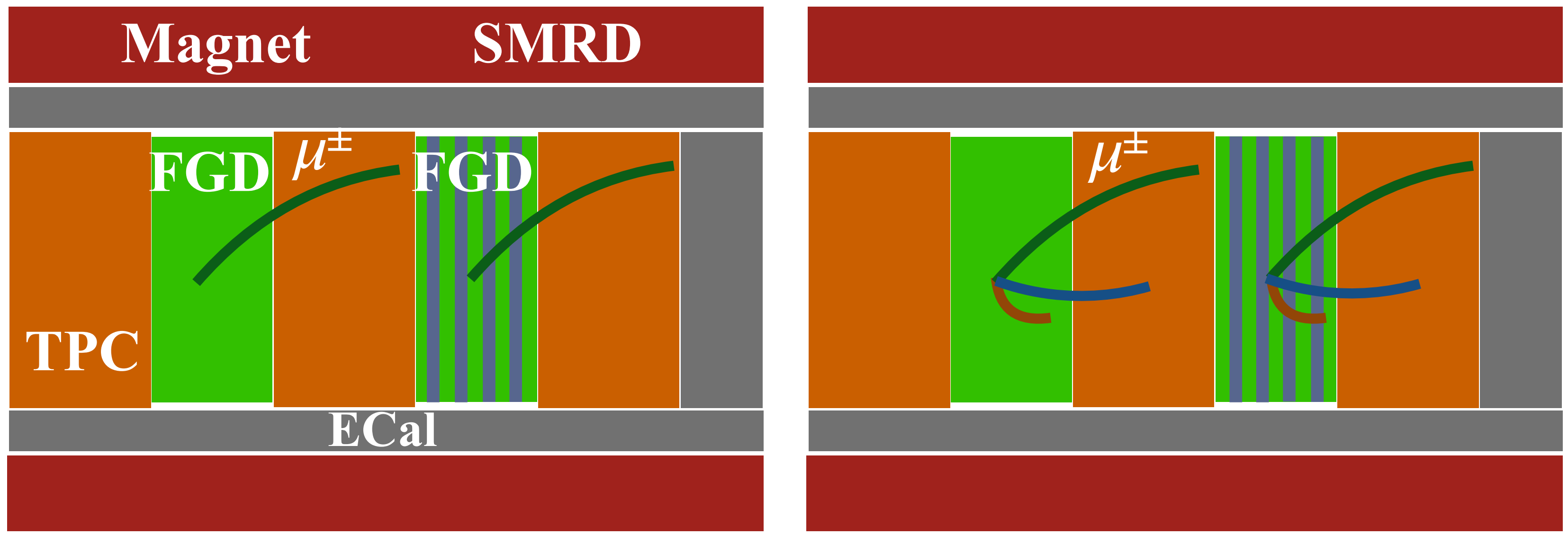
ND280 measurements: $\bar{\nu}$ beam

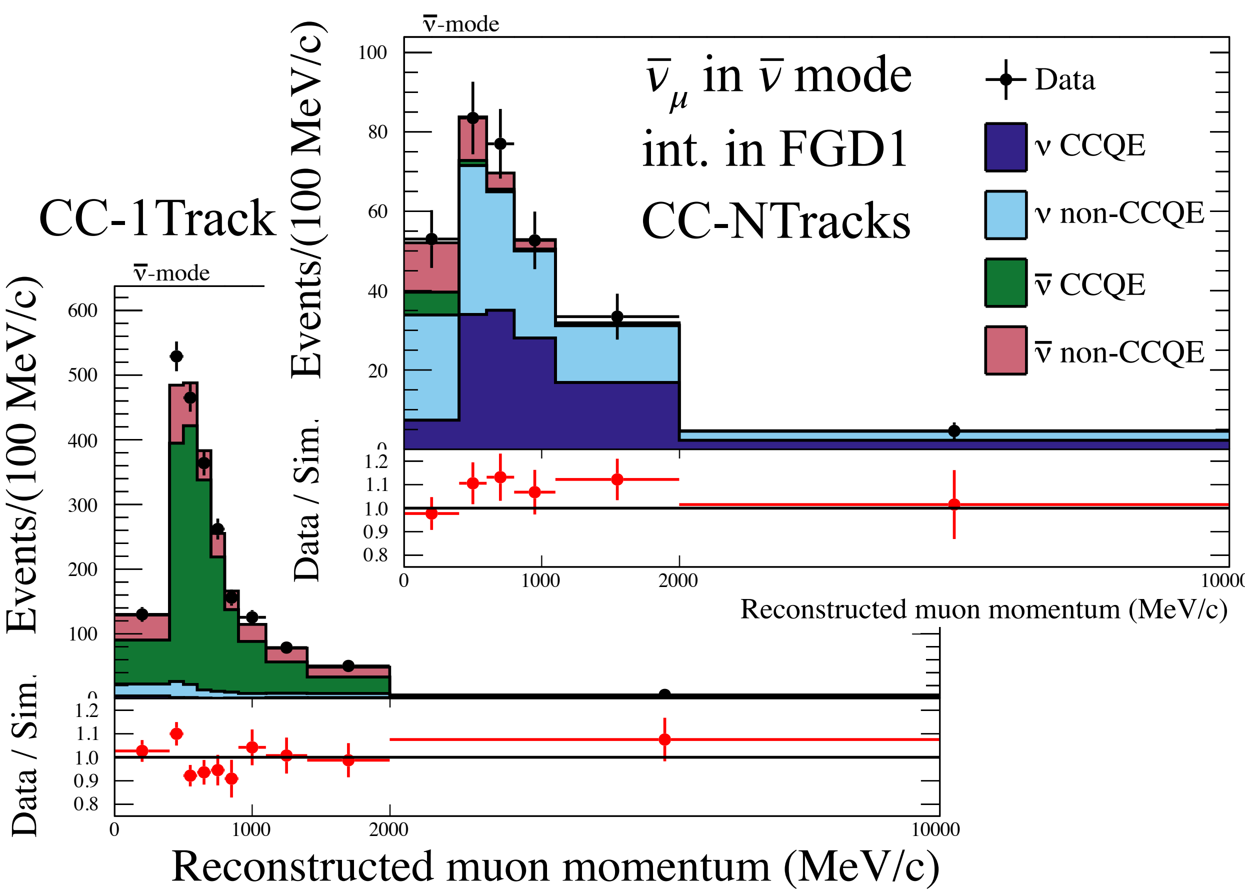


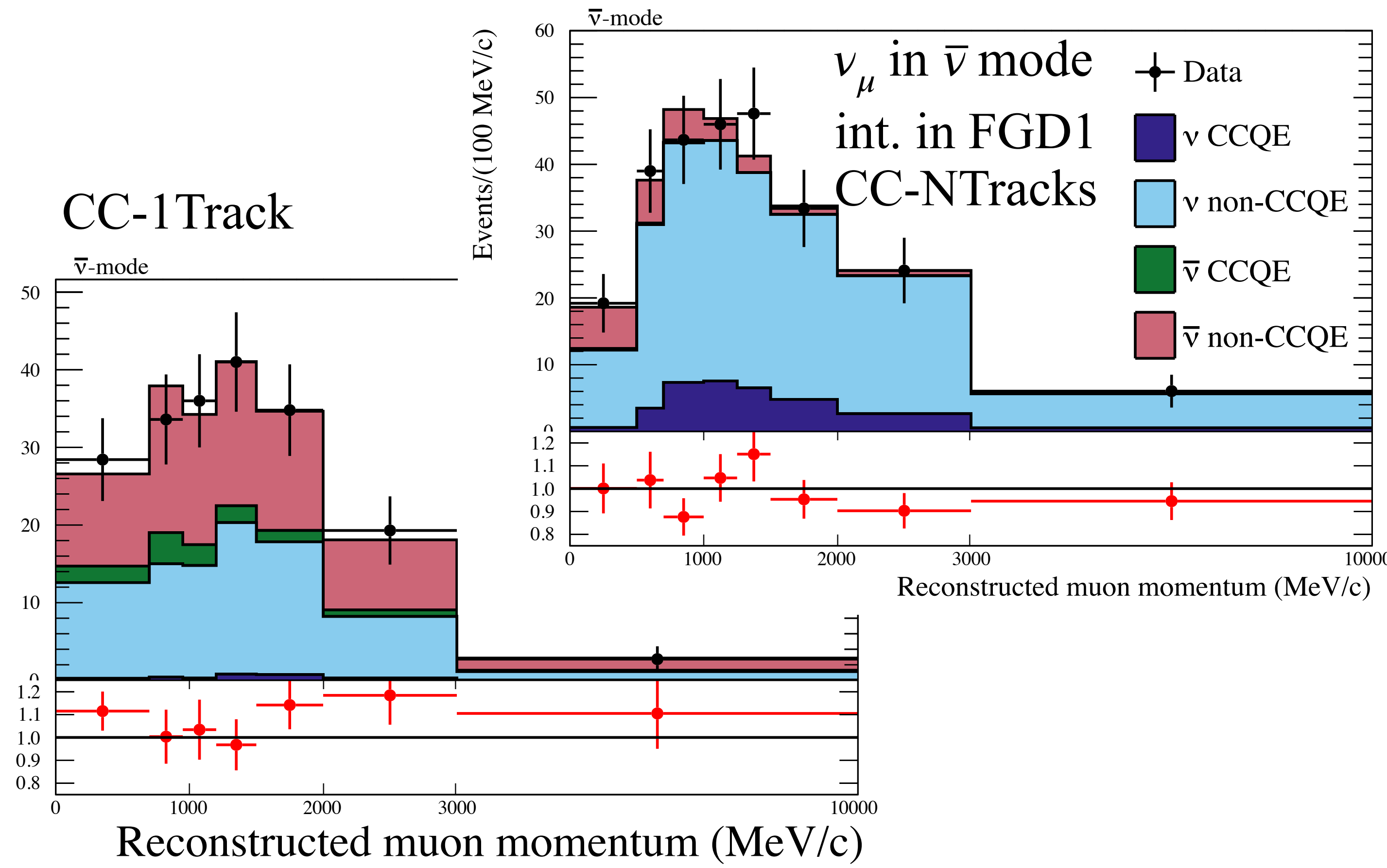


ND280 measurements: $\bar{\nu}$ beam

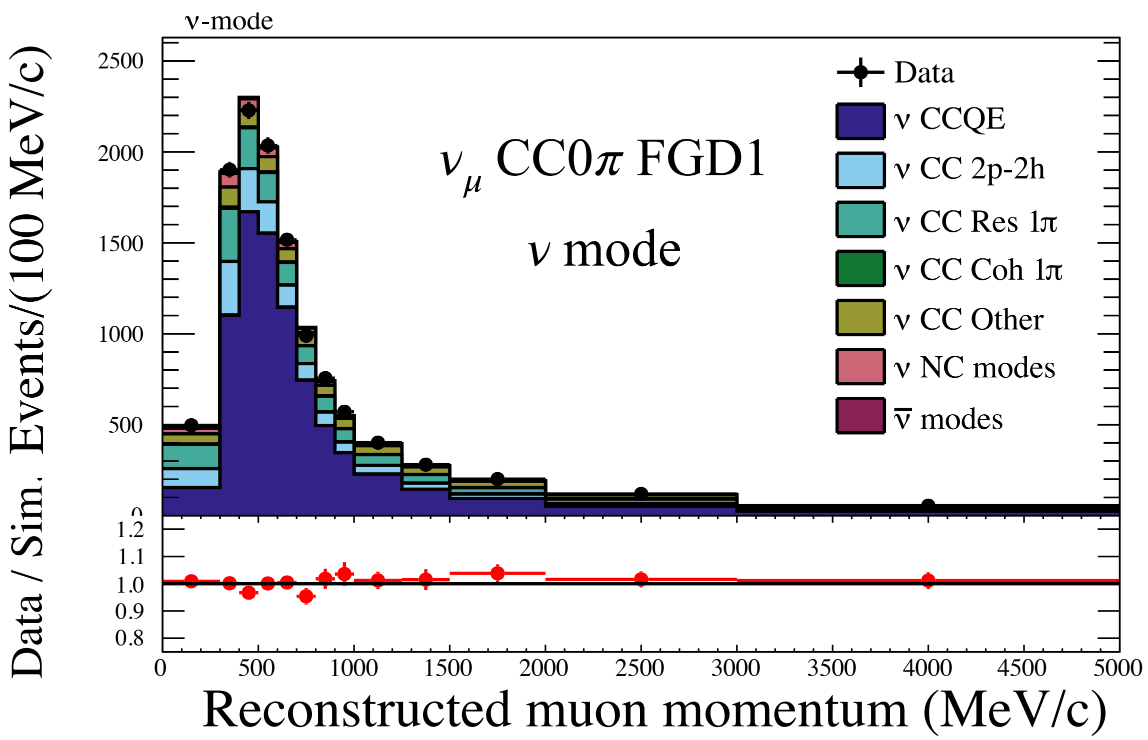
CC-1Track | CC-NTracks

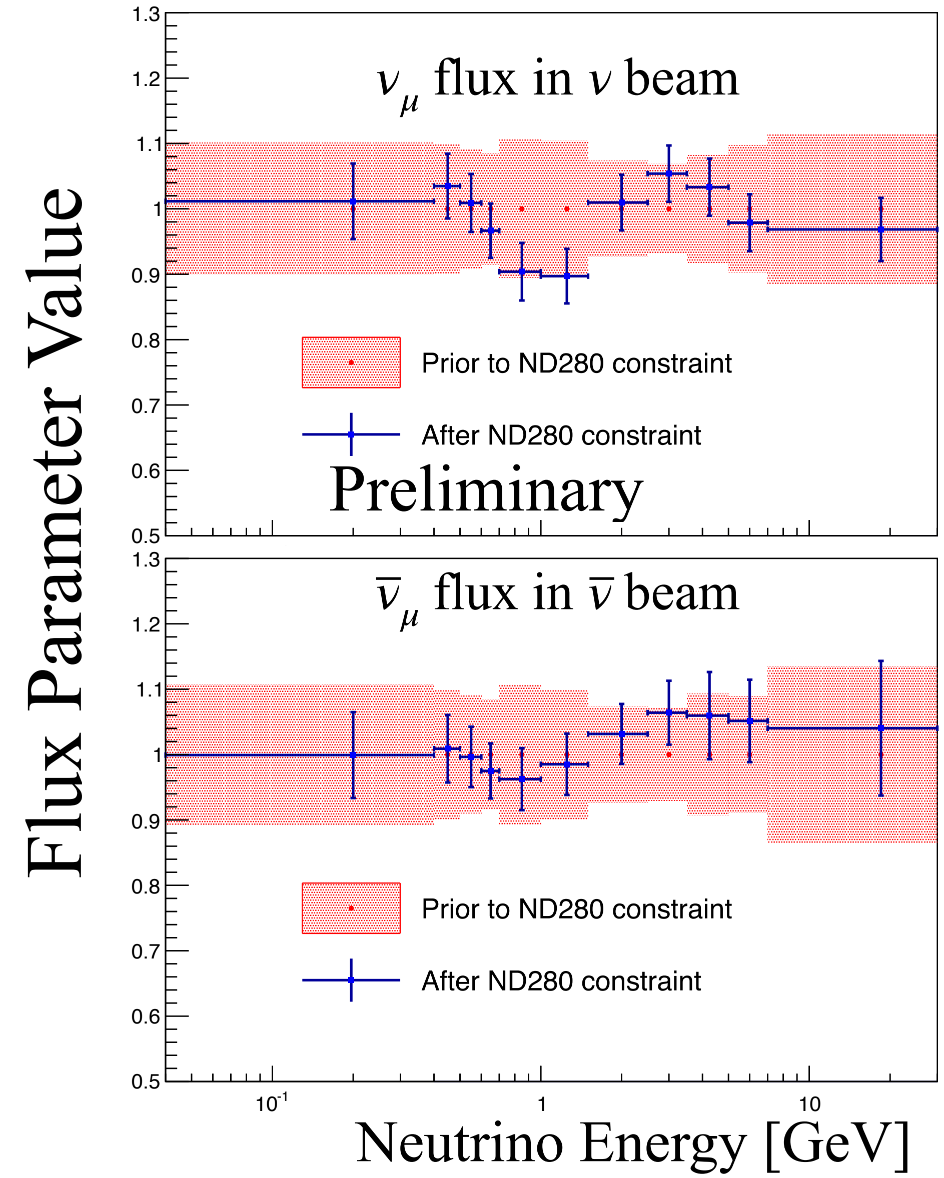






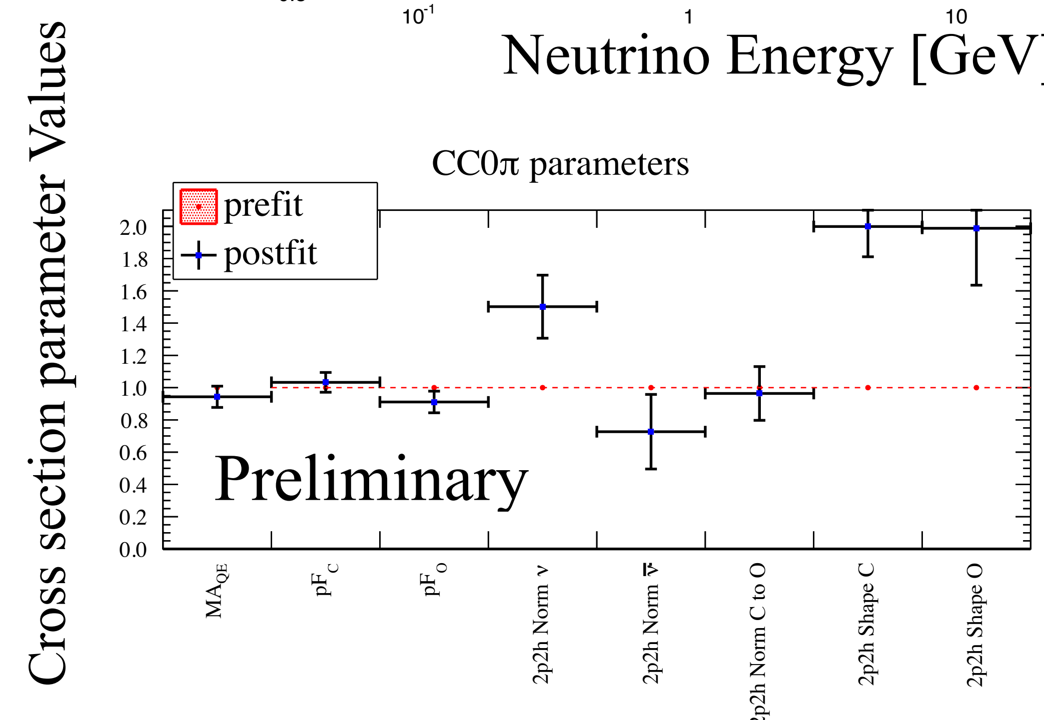
ND280 fit results





Impact on SK:

Sample	w/o ND280	w/ ND280
ν 1Rμ	14,6%	5,1%
$\bar{\nu}$ 1Rμ	12,5%	4,5%
ν 1R*e*	16,9%	8,8%
$\bar{\nu}$ 1R*e*	14,4%	7,1%
ν 1R*e*+1π^+	22,0%	18,7%



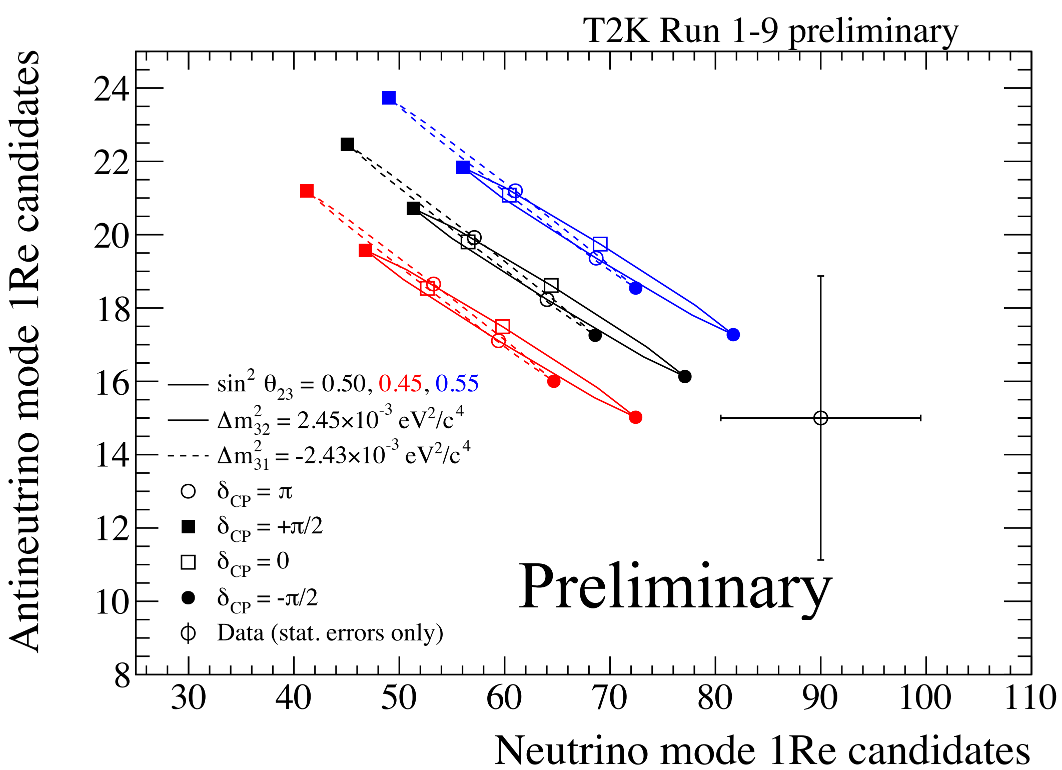
Observed events at SK

	Observed	$\delta = -\pi/2$	$\delta = 0$	$\delta = +\pi/2$	$\delta = \pi$
e-like ν mode	75	74.4	62.2	50.6	62.7
e-like+1π^+ ν mode	15	7.0	6.1	4.9	5.9
e-like $\overline{\nu}$ mode	15	17.1	19.4	21.7	19.3
μ-like ν mode	243	272.4	272.0	272.4	272.8
μ-like $\overline{\nu}$ mode	140	139.2	139.2	139.5	139.9

Observed events at SK

	Observed	$\delta = -\pi/2$	$\delta = 0$	$\delta = +\pi/2$	$\delta = \pi$
***e*-like ν mode**	75	74.4	62.2	50.6	62.7
***e*-like+1π^+ ν mode**	15	7.0	6.1	4.9	5.9
***e*-like $\bar{\nu}$ mode**	15	17.1	19.4	21.7	19.3
μ-like ν mode	243	272.4	272.0	272.4	272.8
μ-like $\bar{\nu}$ mode	140	139.2	139.2	139.5	139.9

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

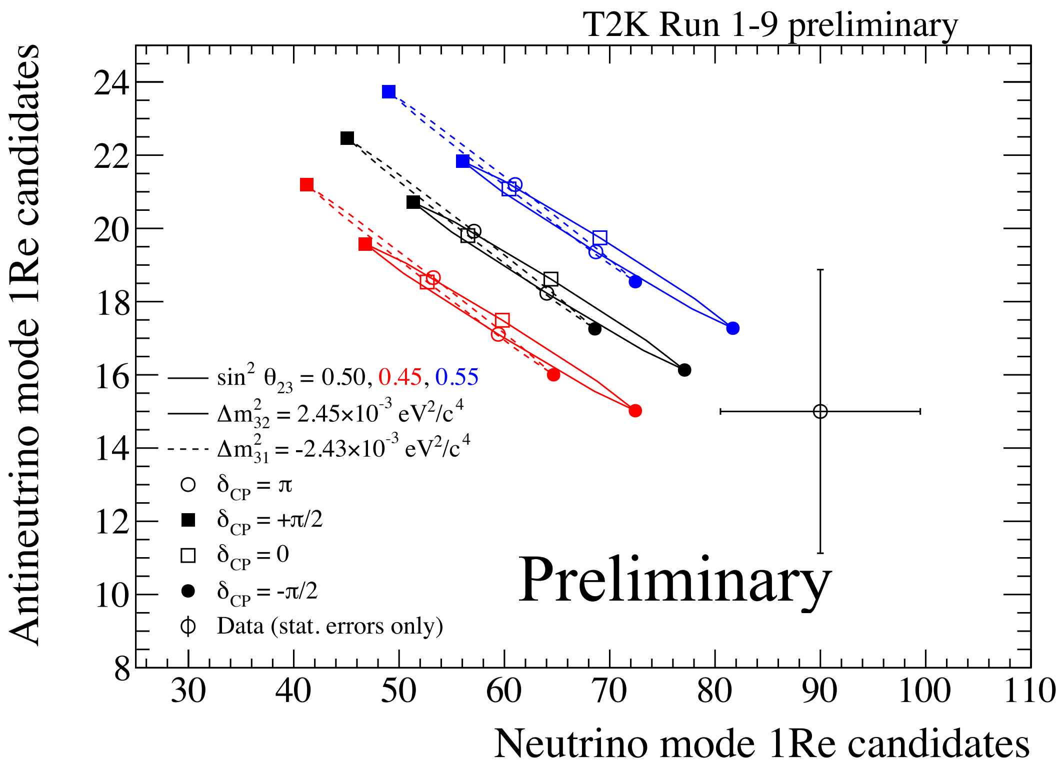


Observed events at SK

	Observed	$\delta = -\pi/2$	$\delta = 0$	$\delta = +\pi/2$	$\delta = \pi$
e-like ν mode	75	74.4	62.2	50.6	62.7
e-like+1π^+ ν mode	15	7.0	6.1	4.9	5.9
e-like $\bar{\nu}$ mode	15	17.1	19.4	21.7	19.3
μ-like ν mode	243	272.4	272.0	272.4	272.8
μ-like $\bar{\nu}$ mode	140	139.2	139.2	139.5	139.9

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

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



T2K oscillation analysis strategy

Flux prediction:
proton beam measurements and external hadron production measurements

Neutrino interactions model:
tuned using external data

ND280 measurements:
select CC ν_μ and $\overline{\nu}_\mu$ interactions
constrain flux and cross sections

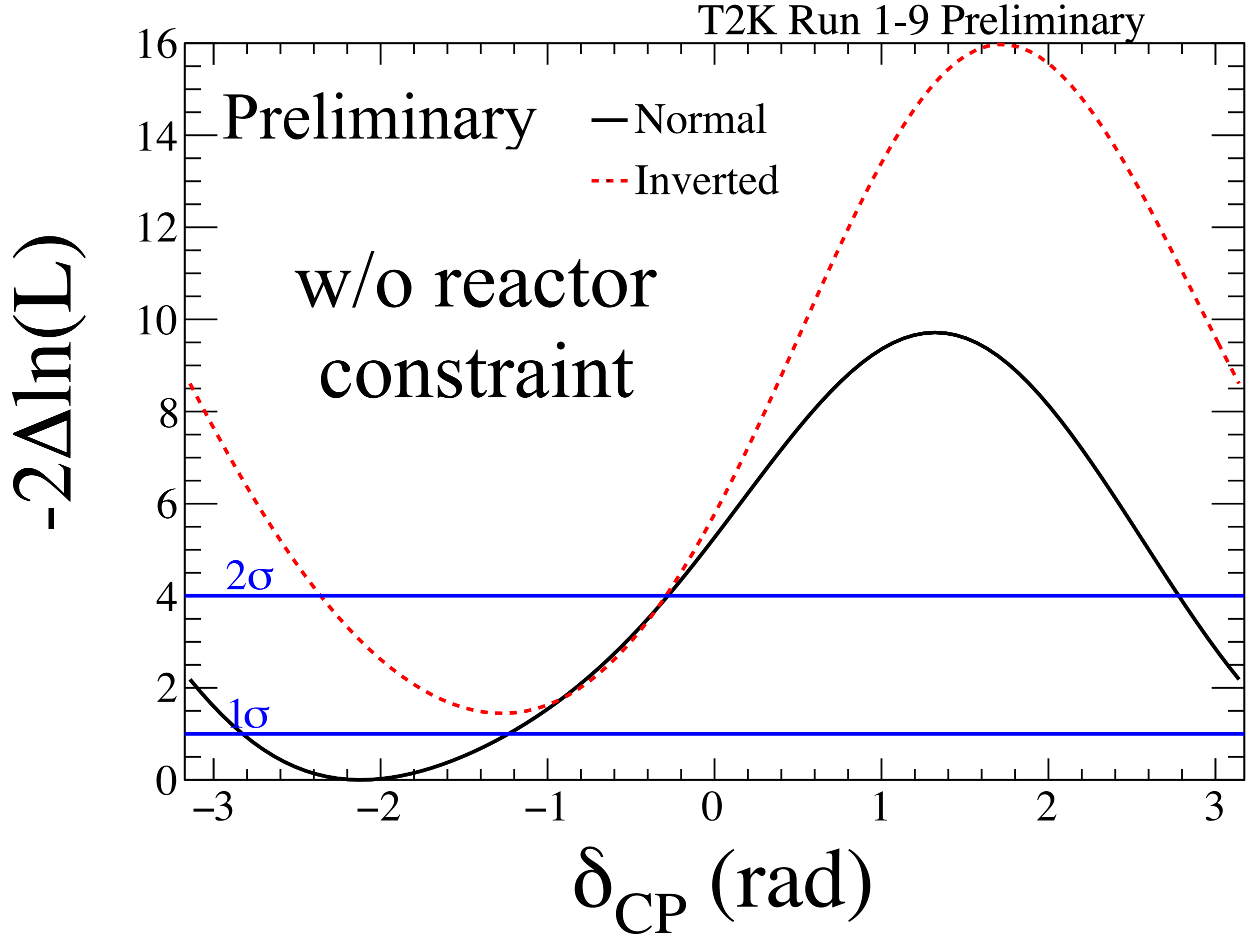
Prediction at the Far Detector:
ND280 measurements predict the expected events at SK

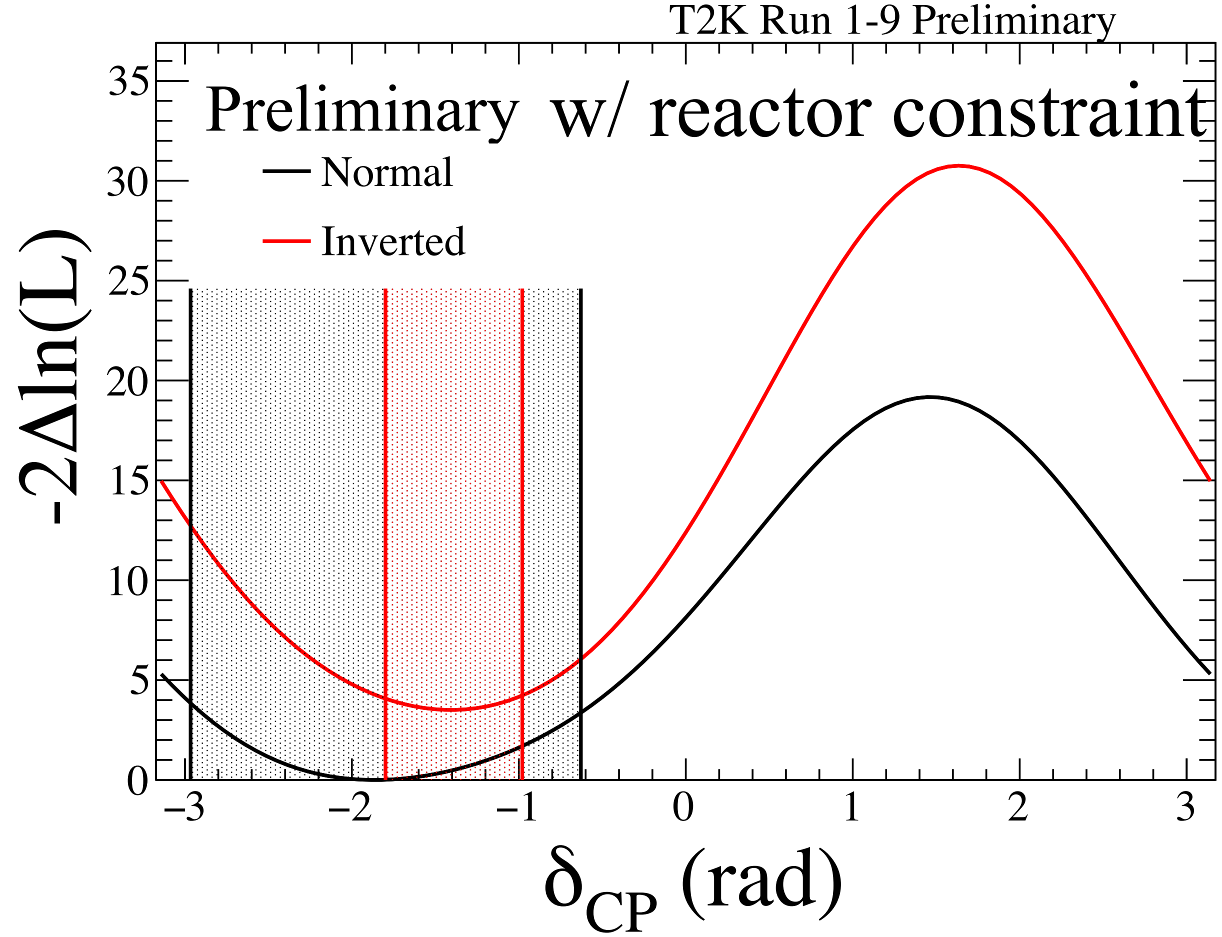
SK measurements:
Select CC $\nu_\mu/\overline{\nu}_\mu$ and $\nu_e/\overline{\nu}_e$ candidates after the oscillations

Extract oscillation parameters

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%	[-2.51, -1.26]	-
90%	[-2.80, -0.84]	-
2σ	[-2.97, -0.63]	[-1.78, -0.98]

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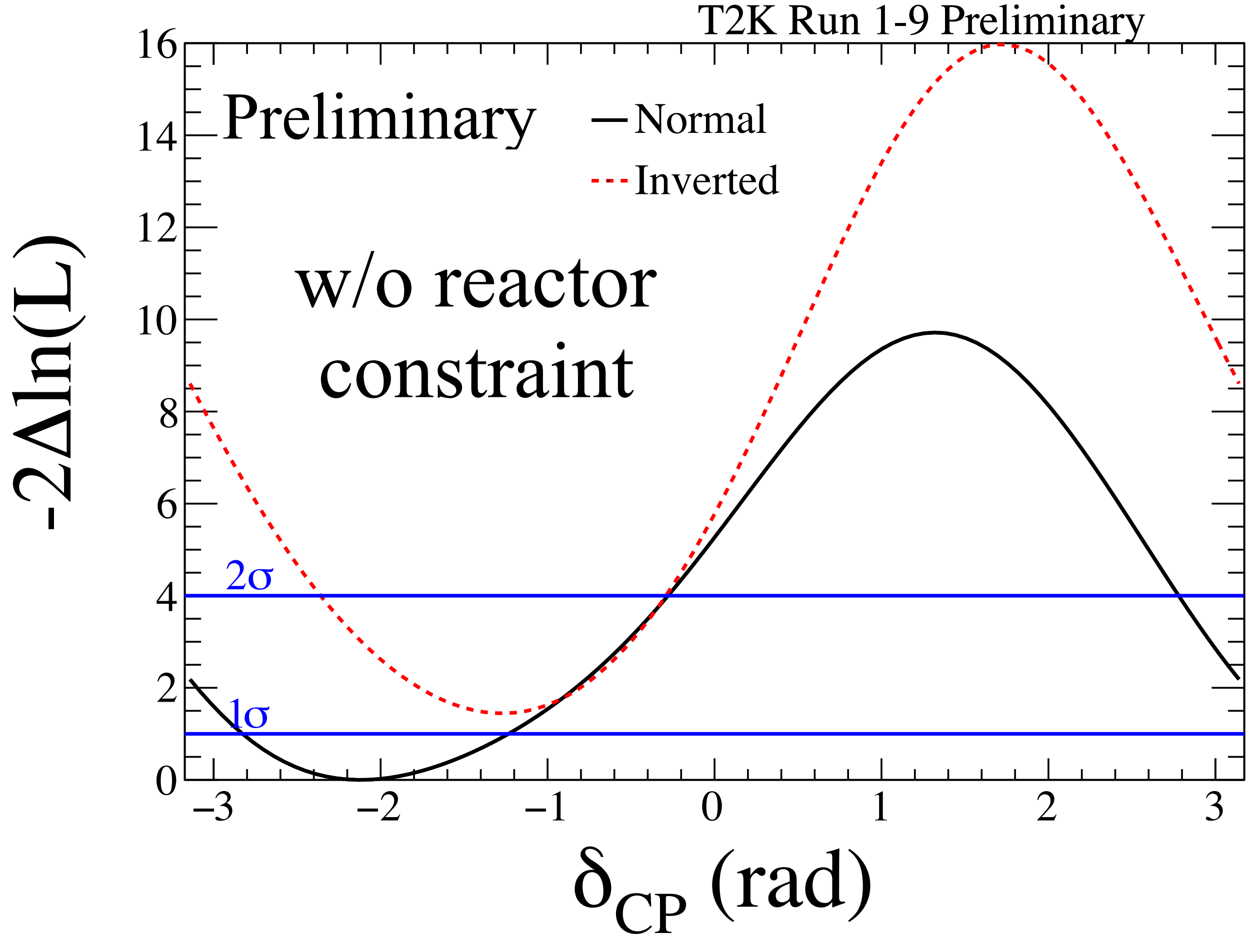
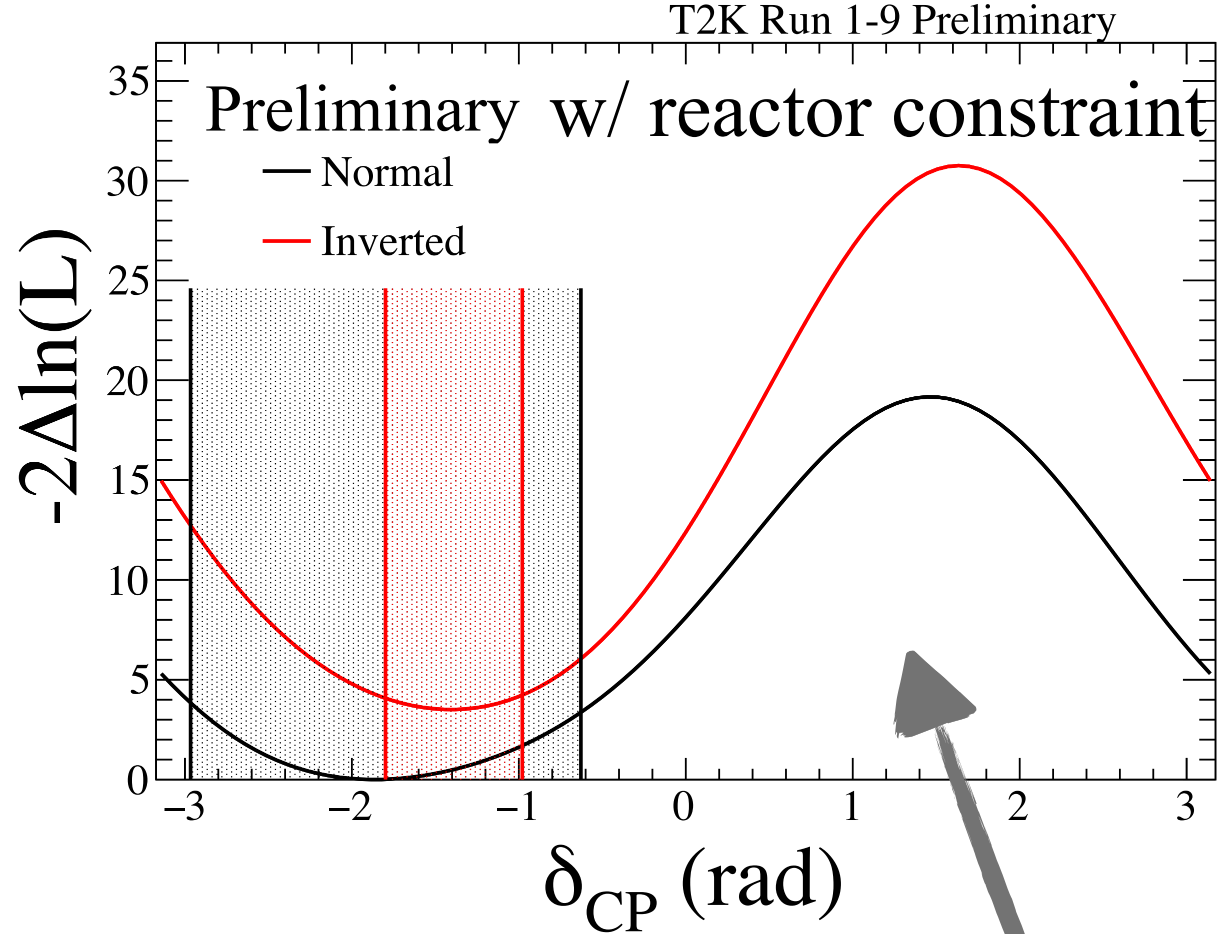
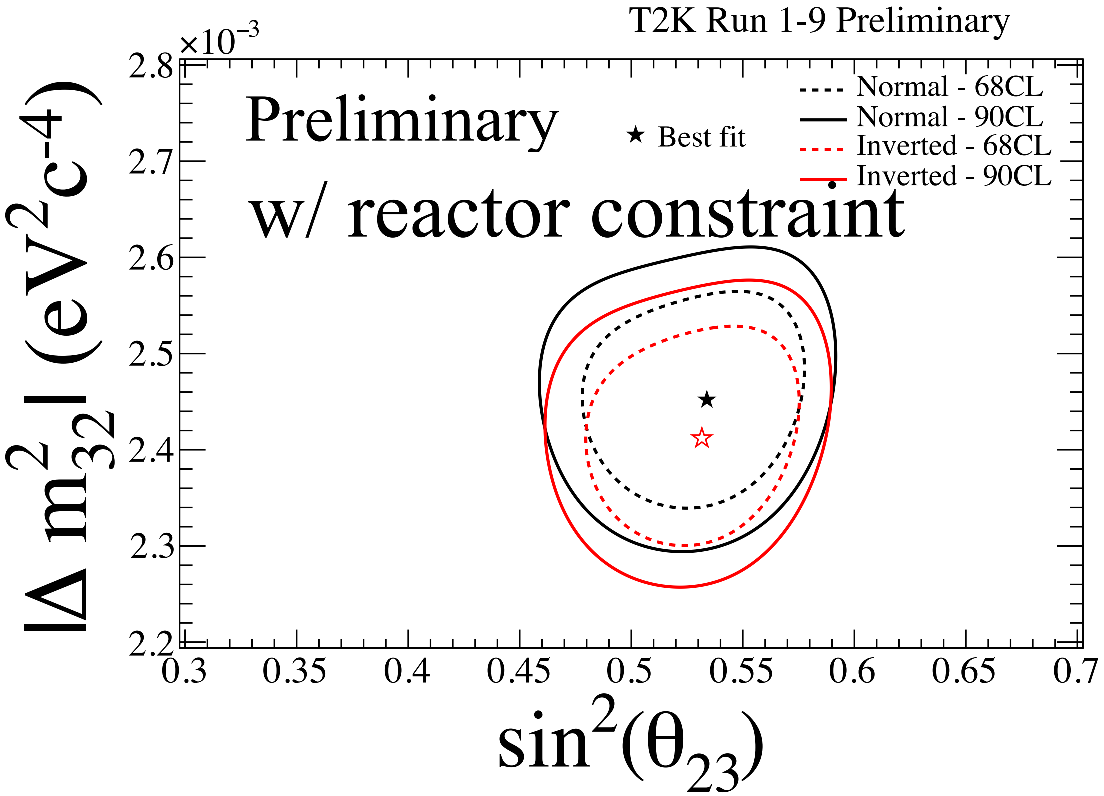




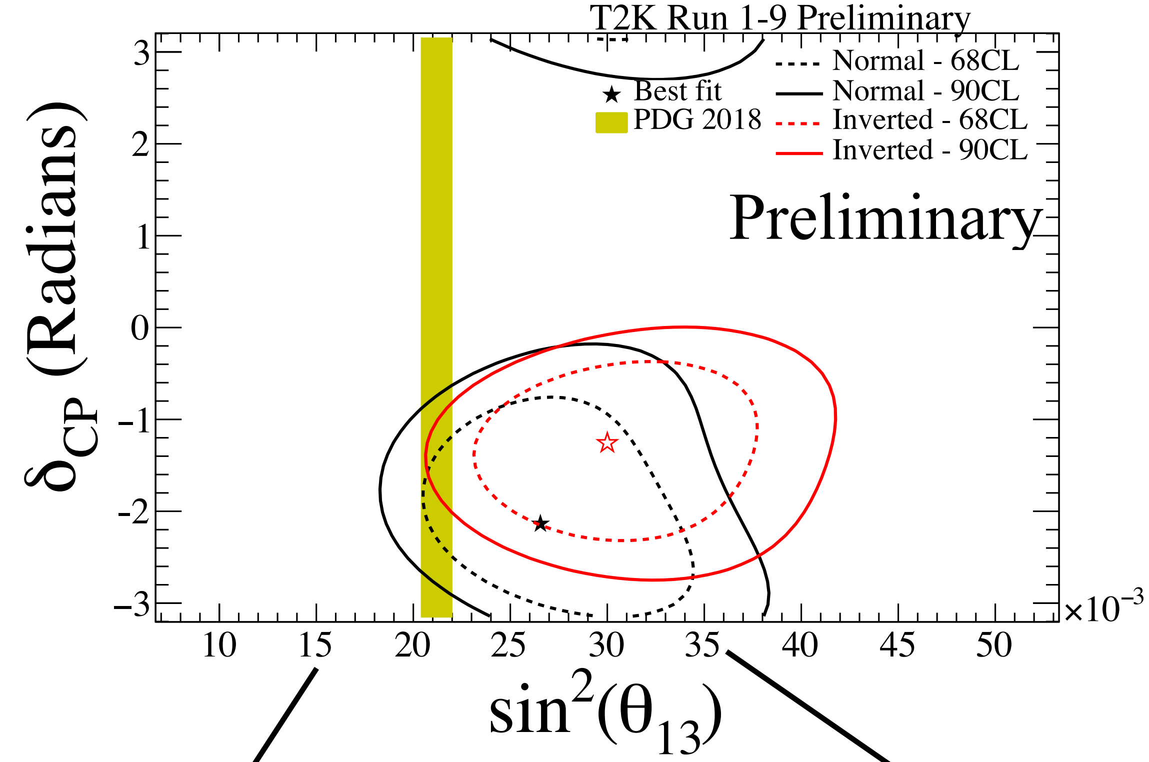
C.L.	Normal hierarchy	Inverted hierarchy
68%	[-2.51, -1.26]	-
90%	[-2.80, -0.84]	-
2σ	[-2.97, -0.63]	[-1.78, -0.98]

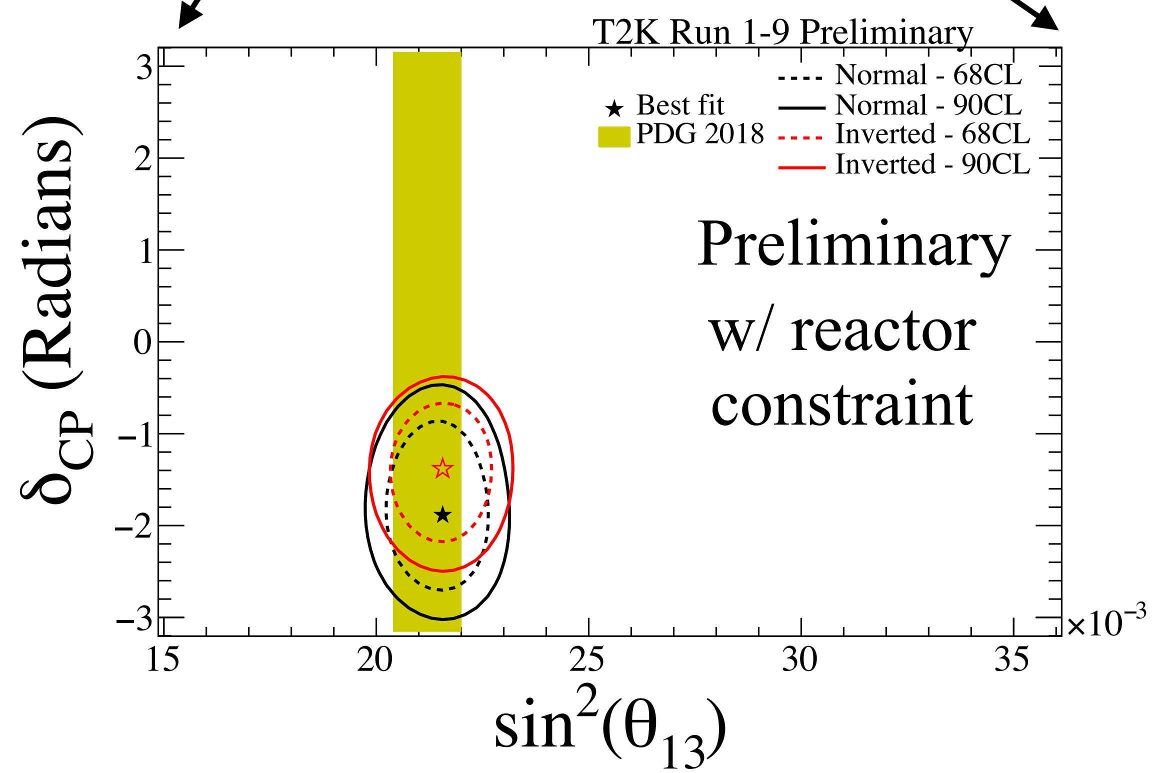
$\delta_{CP} = 0, \pi$ fall outside 2σ interval

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



w/o reactor constraint





T2K data compatible with maximal mixing

Parameter	Best Fit NH (HI)	±1σ NH (IH)
$\sin^2\theta_{32}$	0.54 (0.53)	[0.490,0.558] ([0.496,0.560])
$|\Delta m^2_{32}|$ ($10^{-3}eV^2/c^4$)	2.46 (2.43)	[2.370,2.498] ([2.362,2.502])
$\sin^2\theta_{13}$	0.0268 (0.0305)	[0.0222,0.0319] ([0.0253,0.0369])

Conclusions

- T2K released results with 3.1×10^{21} POT (50% ν-mode, 50% $\bar{\nu}$-mode)
- With these data CP conserving values are excluded at more than 2σ
- T2K data prefers maximal mixing
- Future improvements:
  - More data will come with many improvement in the analysis;
  - New antineutrino samples at the near detector;

Stay tuned!!!

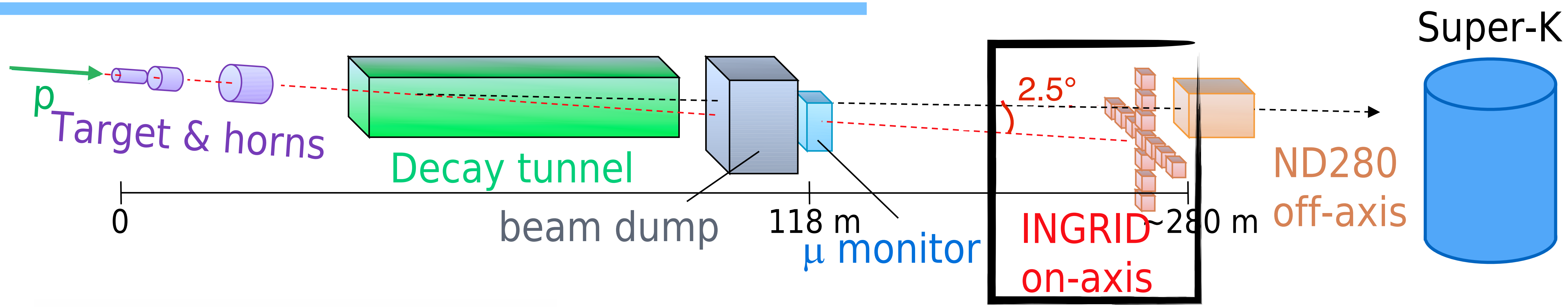
Thank you for your attention

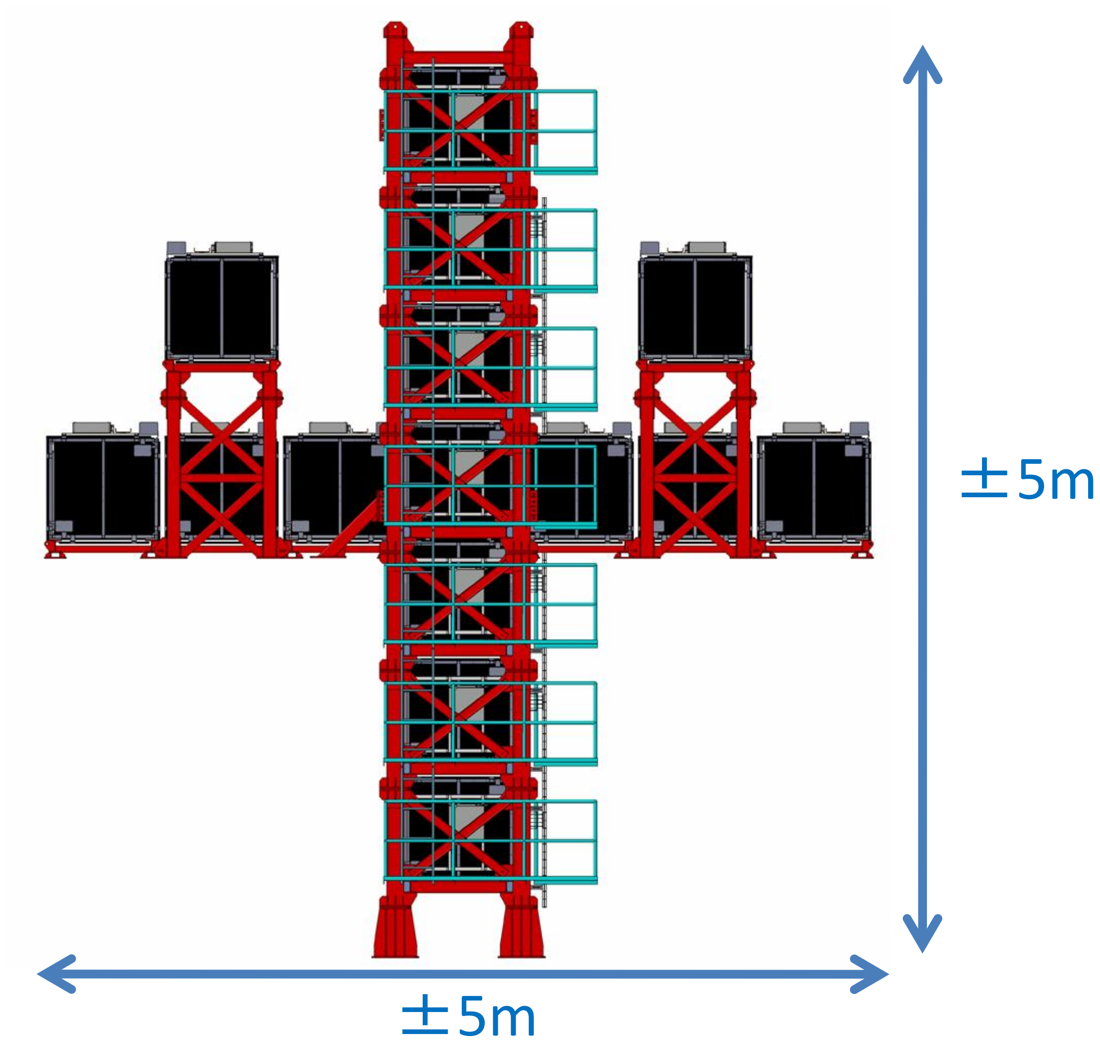
T2K Breakthrough Prize Party

January 28th, 2016 at Kuji Sunpia Hitachi

Backup

The on-axis near detector (INGRID)



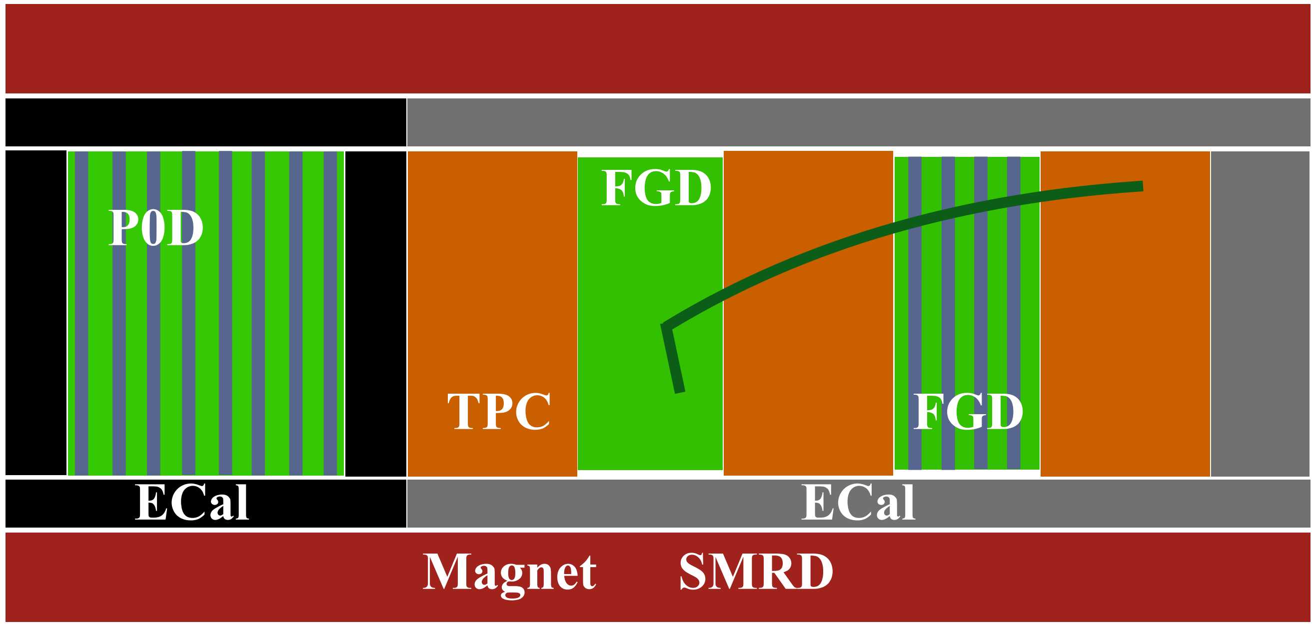


Monitor the beam stability and direction day-by-day looking at ν ($\overline{\nu}$) interactions

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

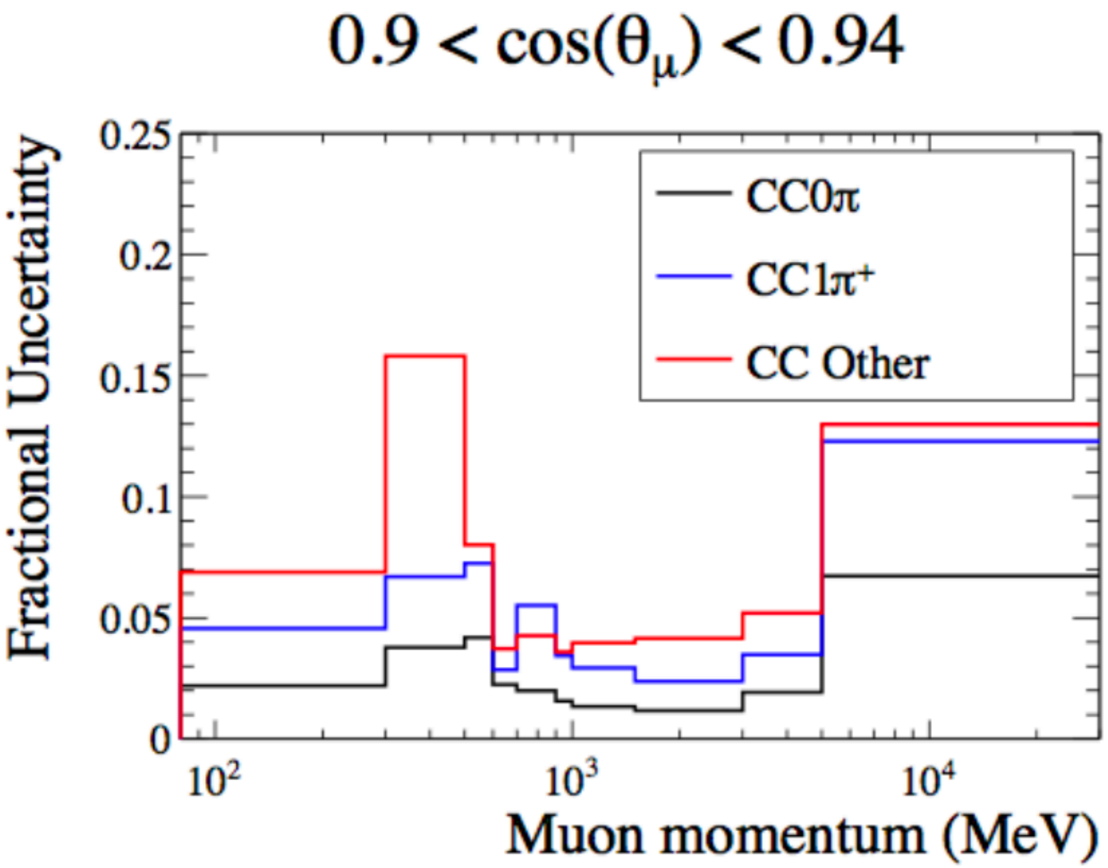
1 extra module made of scintillators and water at the center of the cross

ND280 Detector modeling



As far as possible, use data to constrain systematics; e.g. use cosmic samples to evaluate inter-detector matching

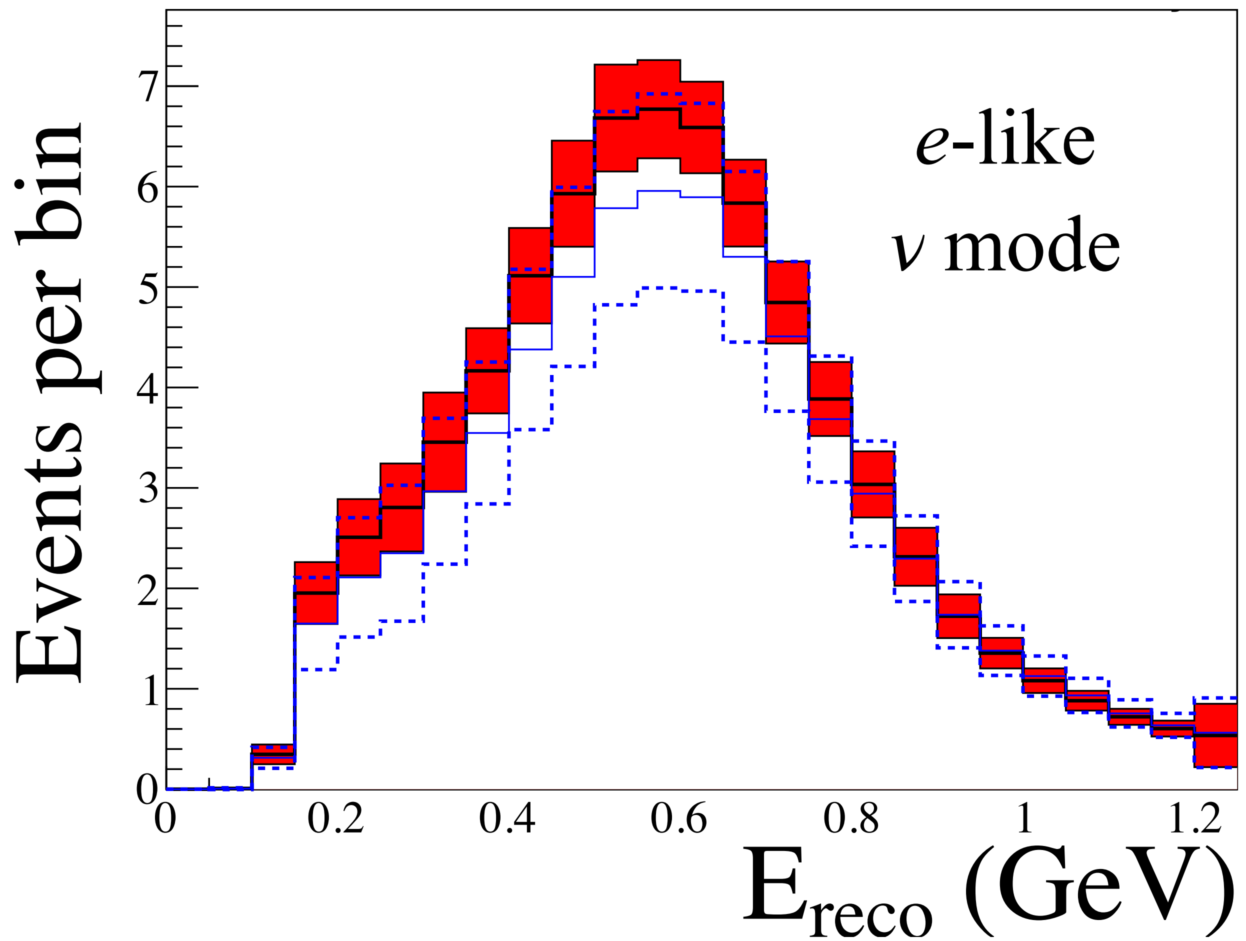
Dominant systematics are pion secondary interactions and out of fiducial volume events

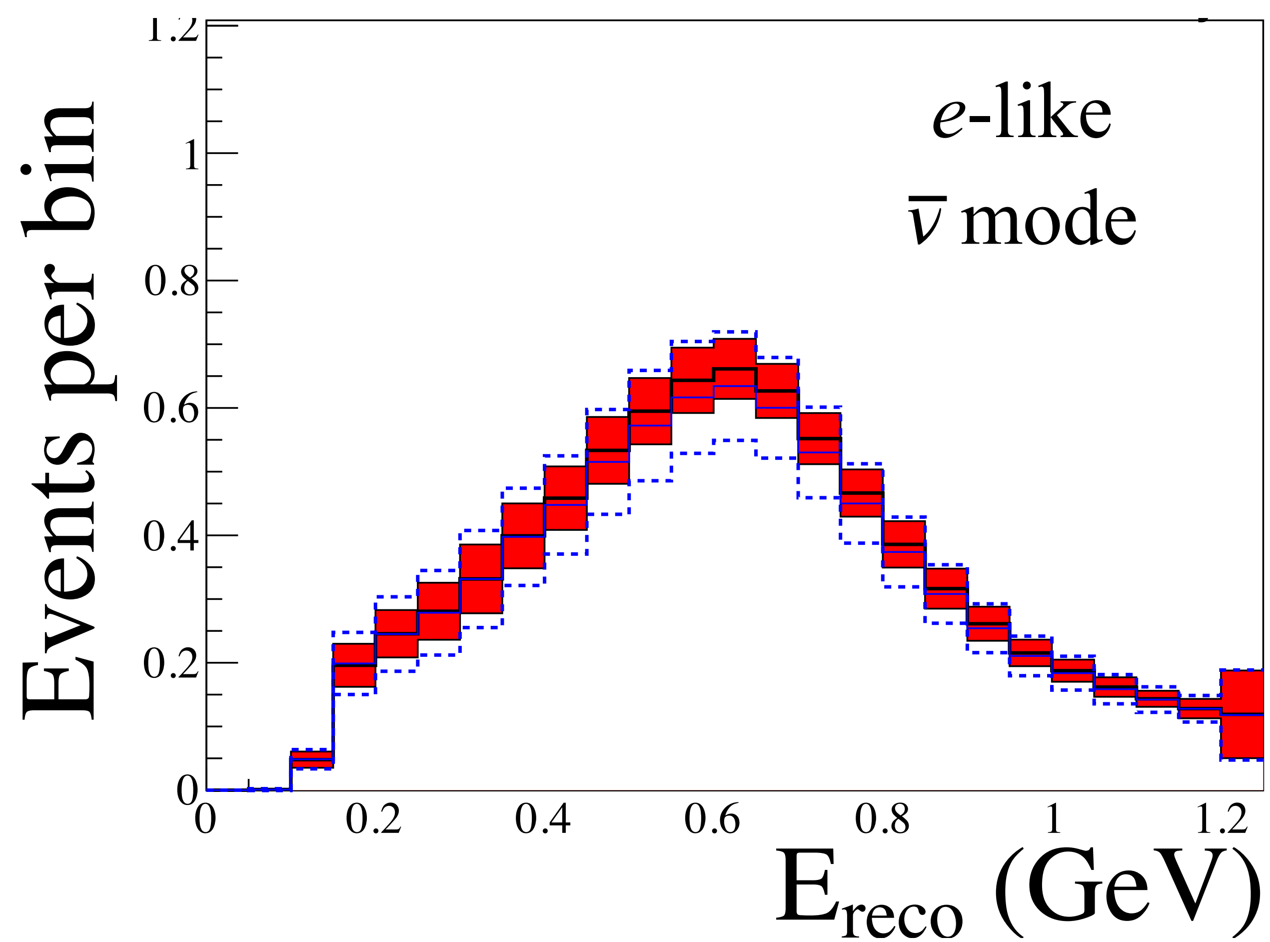


Event generators: details

	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)

Expectation at SK



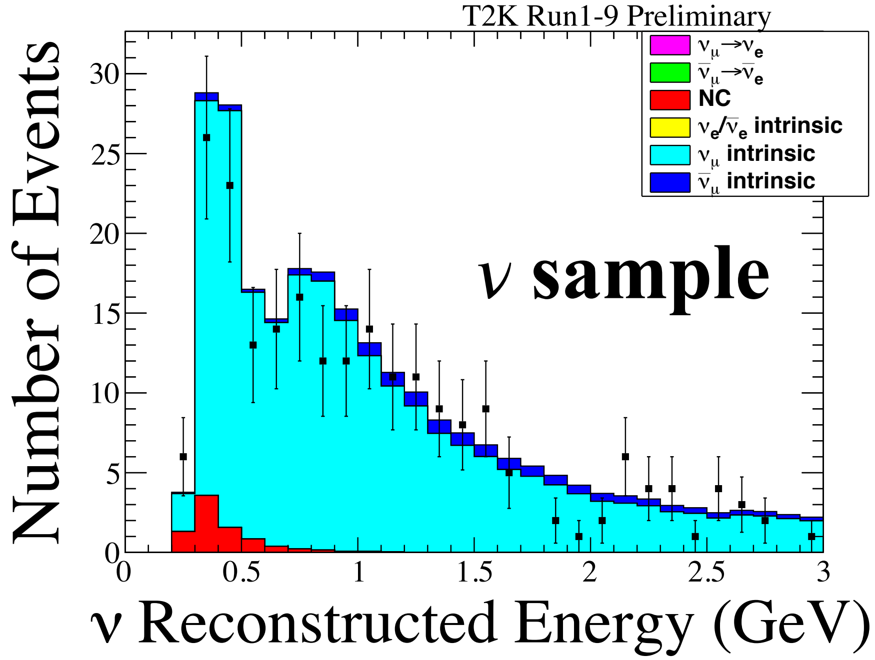


ND280 constraints are crucial for oscillation analysis precision

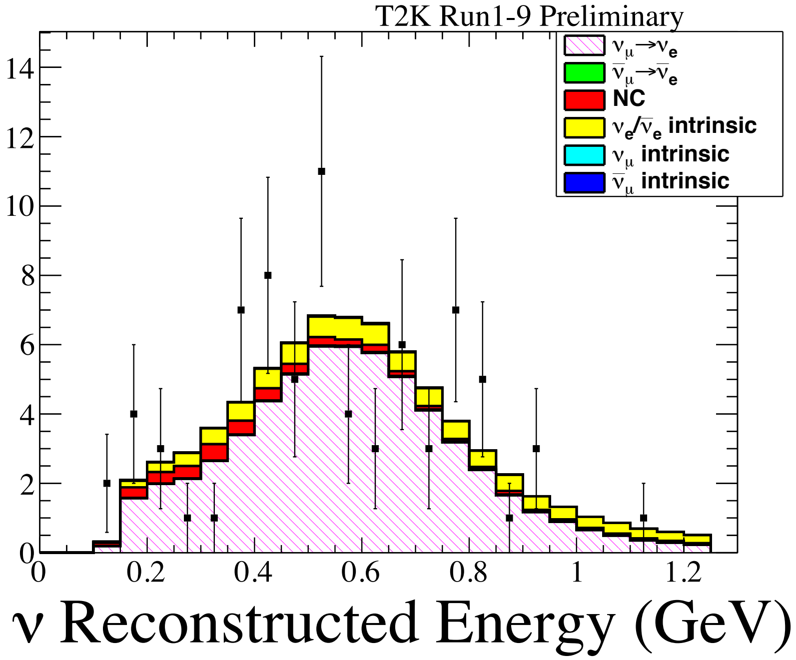
	ν mode			$\bar{\nu}$ mode	
	μ-like	e-like	e-like+1π^+	μ-like	e-like
Total w/o ND280	14.6%	16.9%	22.0%	12.5%	14.4%
Total w/ ND280	5.1%	8.8%	18.7%	4.5.%	7.1%

SK Samples

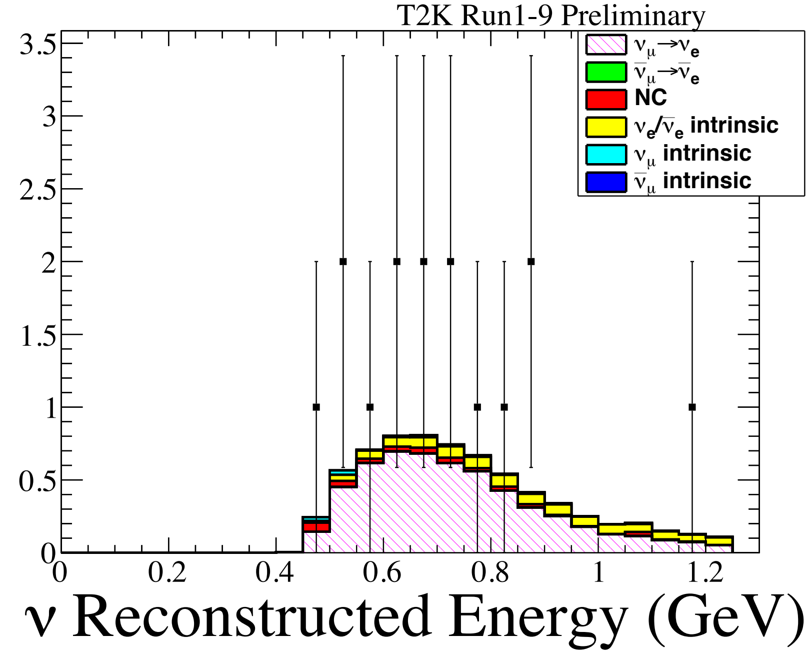
1 μ-like ring



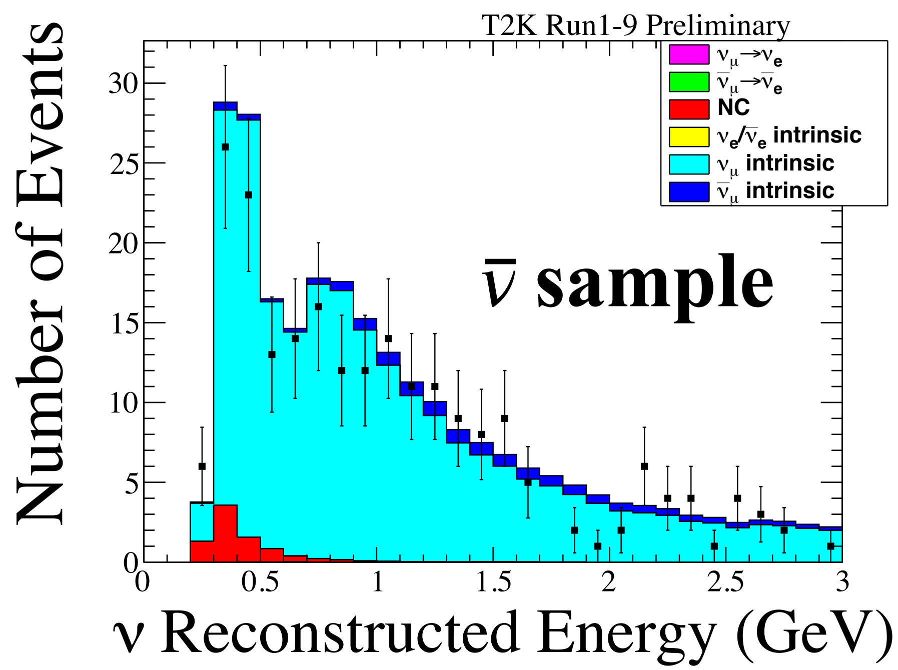
1 *e*-like ring



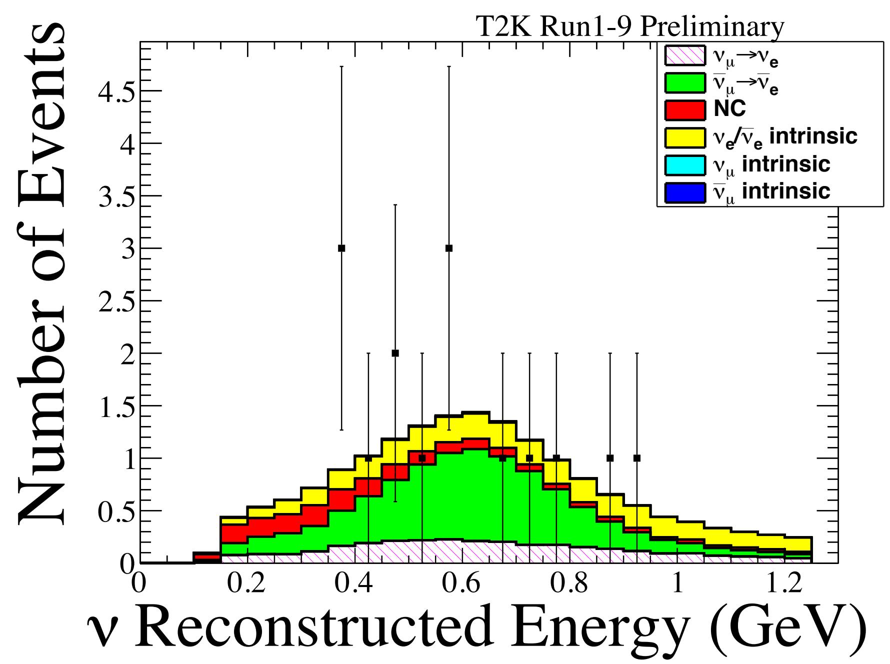
1 *e*-like + 1 Michel-*e*-like ring



1 μ-like ring

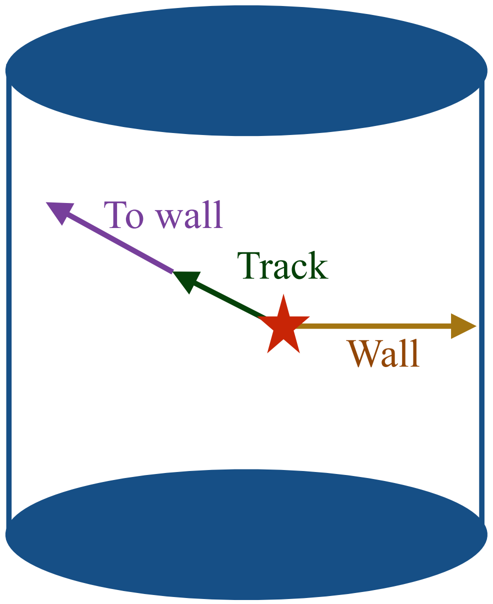


1 *e*-like ring



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



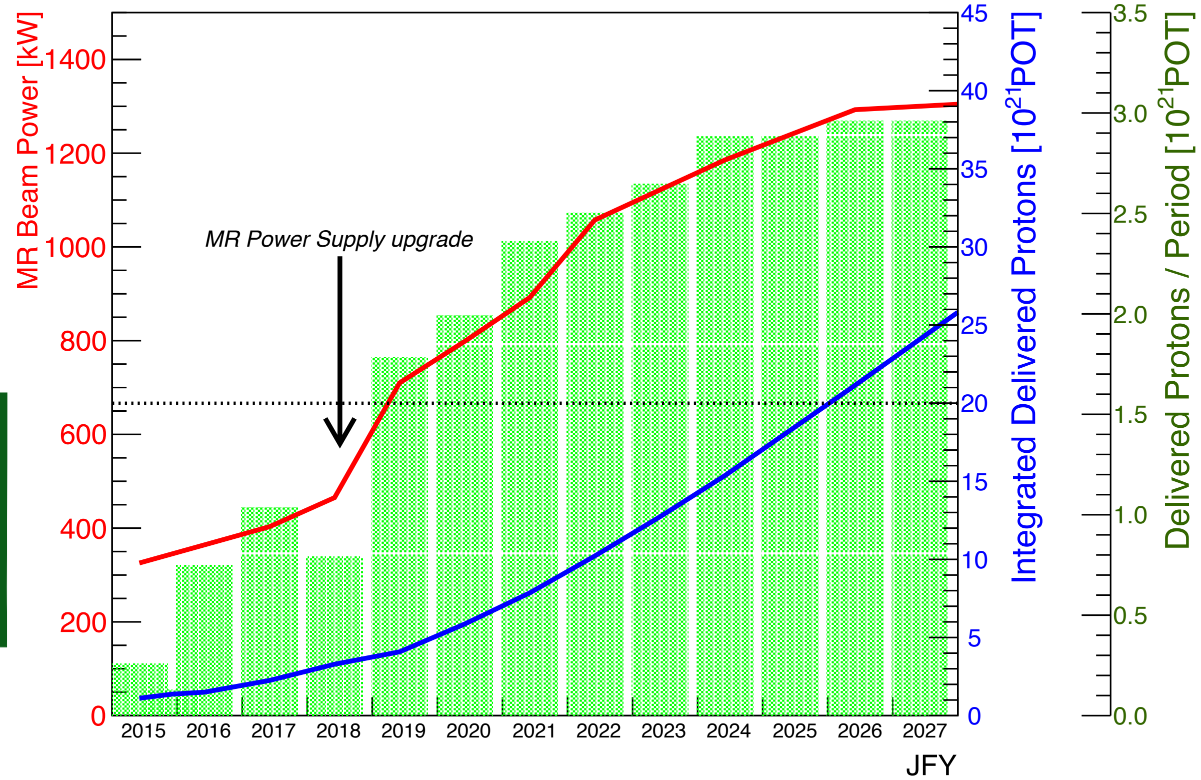
Samples	New SK selection	Old SK selection
	Purity	Purity
μ-like ν mode	80%	68%
e-like ν mode	81%	81%
e-like+1π^+ ν mode	79%	72%
μ-like $\bar{\nu}$ mode	80%	71%
e-like $\bar{\nu}$ mode	62%	64%

Future prospects: T2K-II

T2K was originally approved to collect 7.8×10^{21} POT driven by sensitivity to θ_{13}

Proposal for an extended to collect 20×10^{21} POT

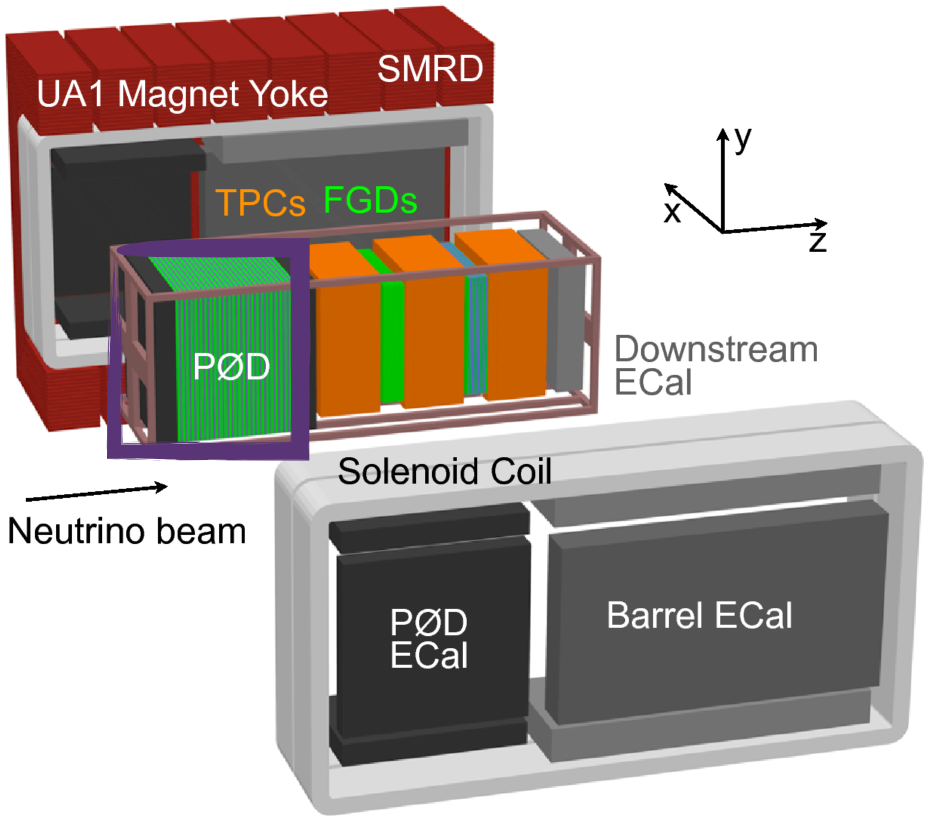
Increase beam power up to 1.3 MW and horn current up to ±320 kA

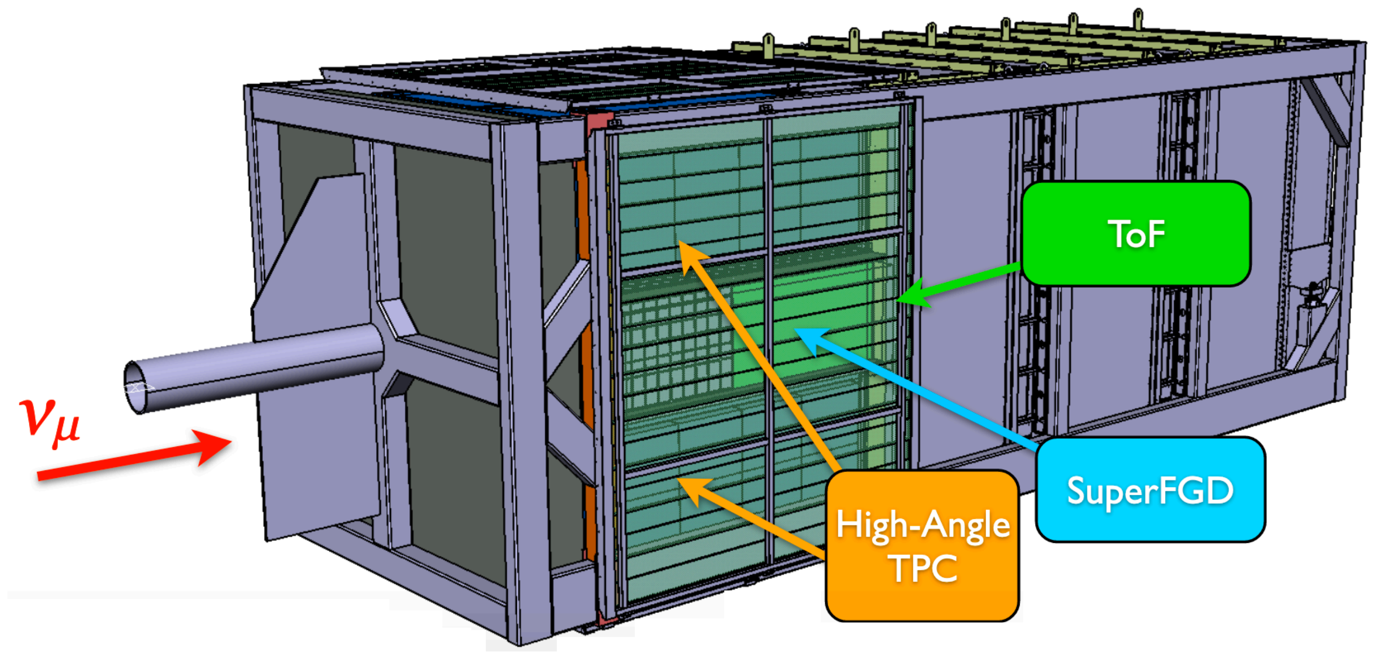


SK plan to start to dope water with Gadolinium from next year:

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

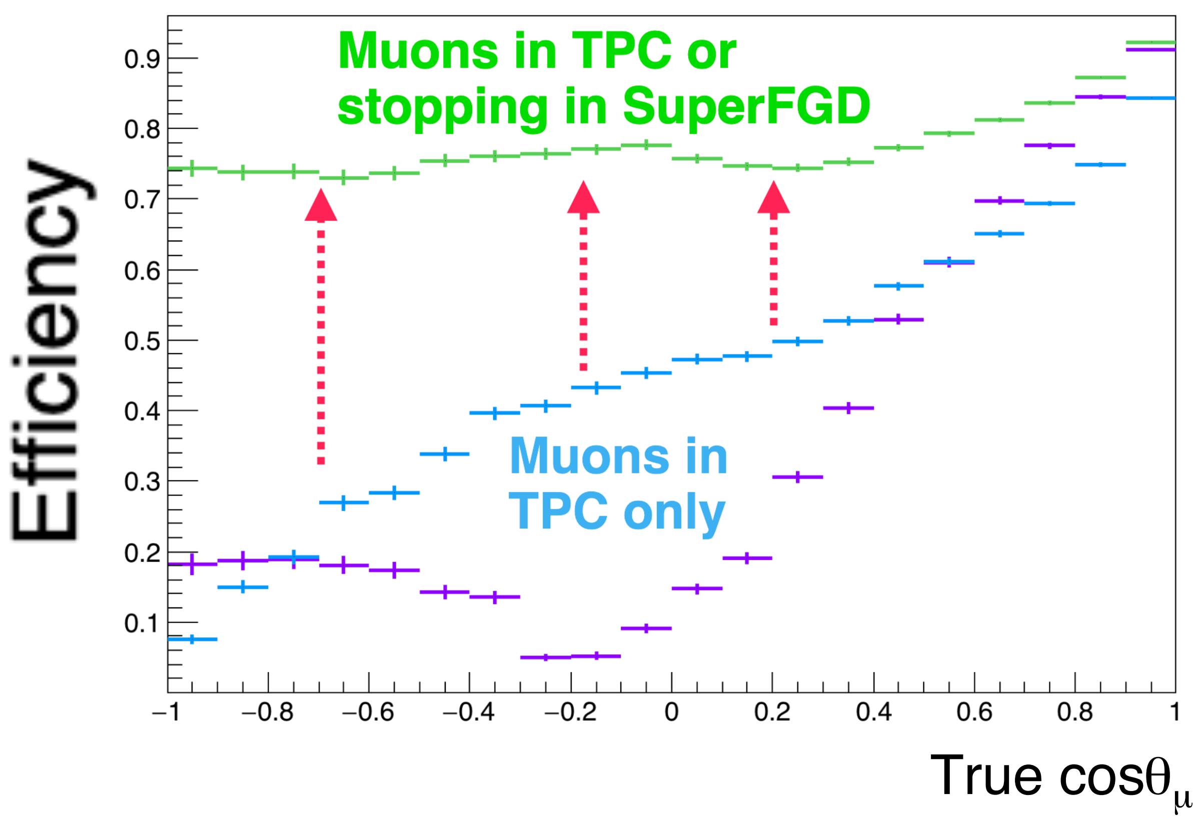
T2K-II: ND280 upgrade



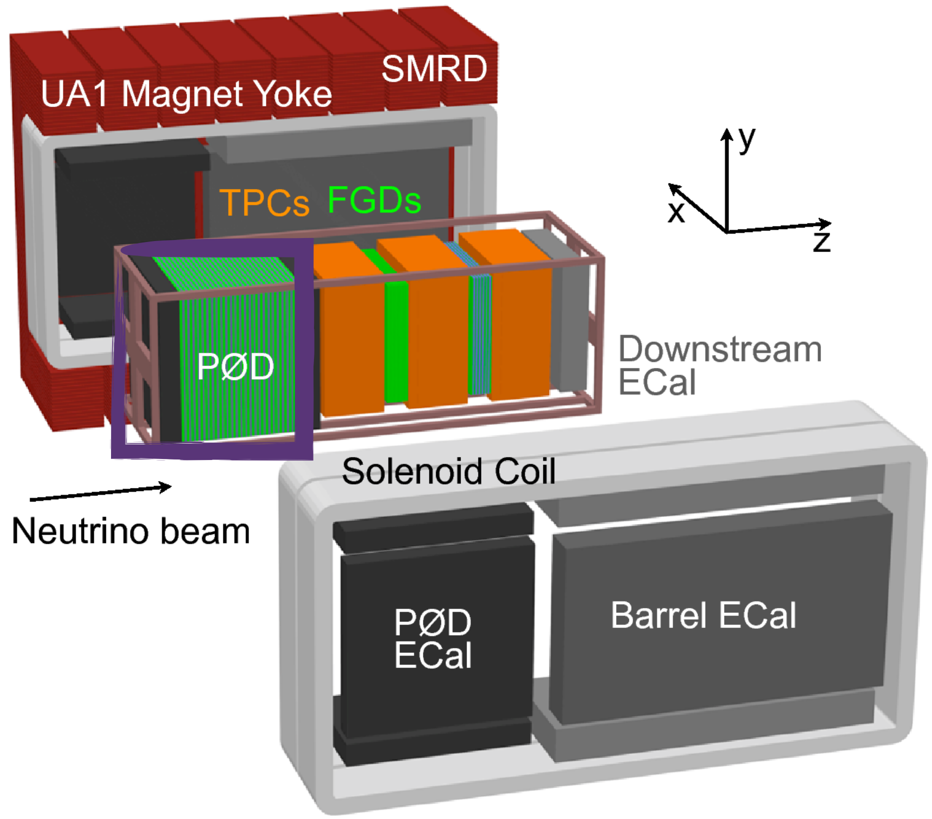


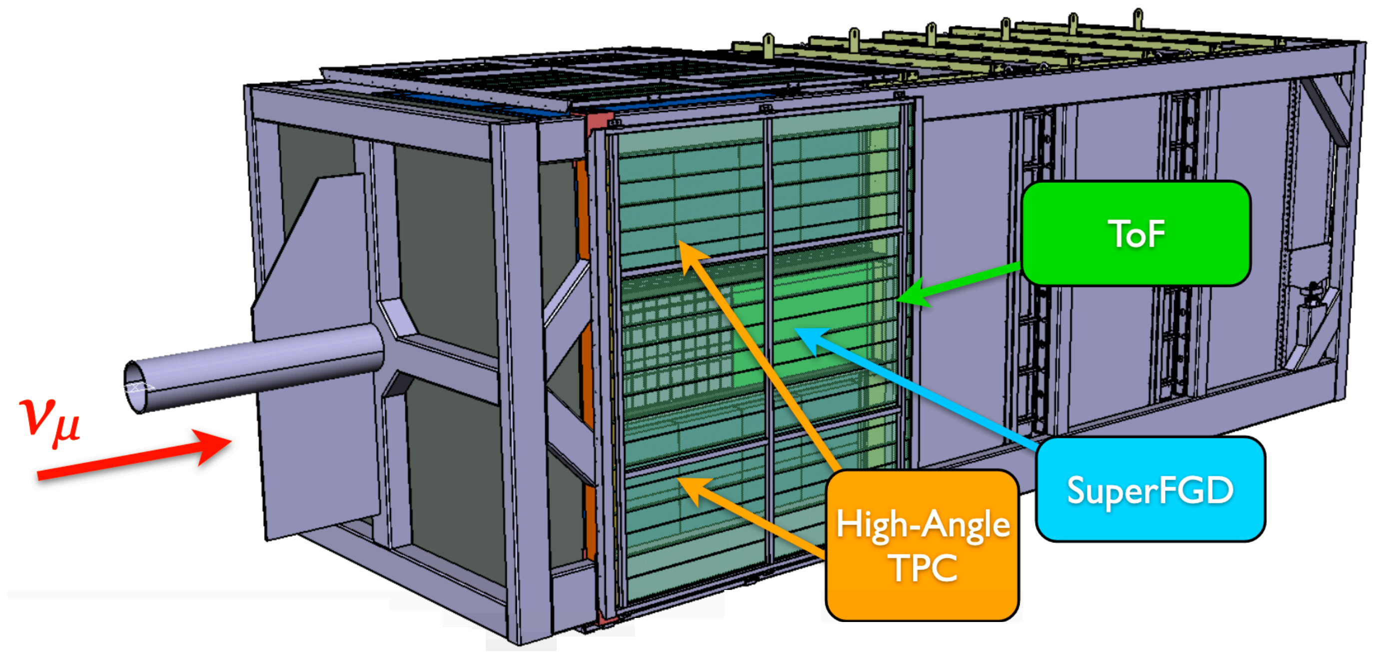
Main ND280 limitations:

- Low efficiency in the "high-angle" region
- Reduced sensitivity to cross section models
- Low threshold for protons



T2K-II: ND280 upgrade





Main ND280 limitations:

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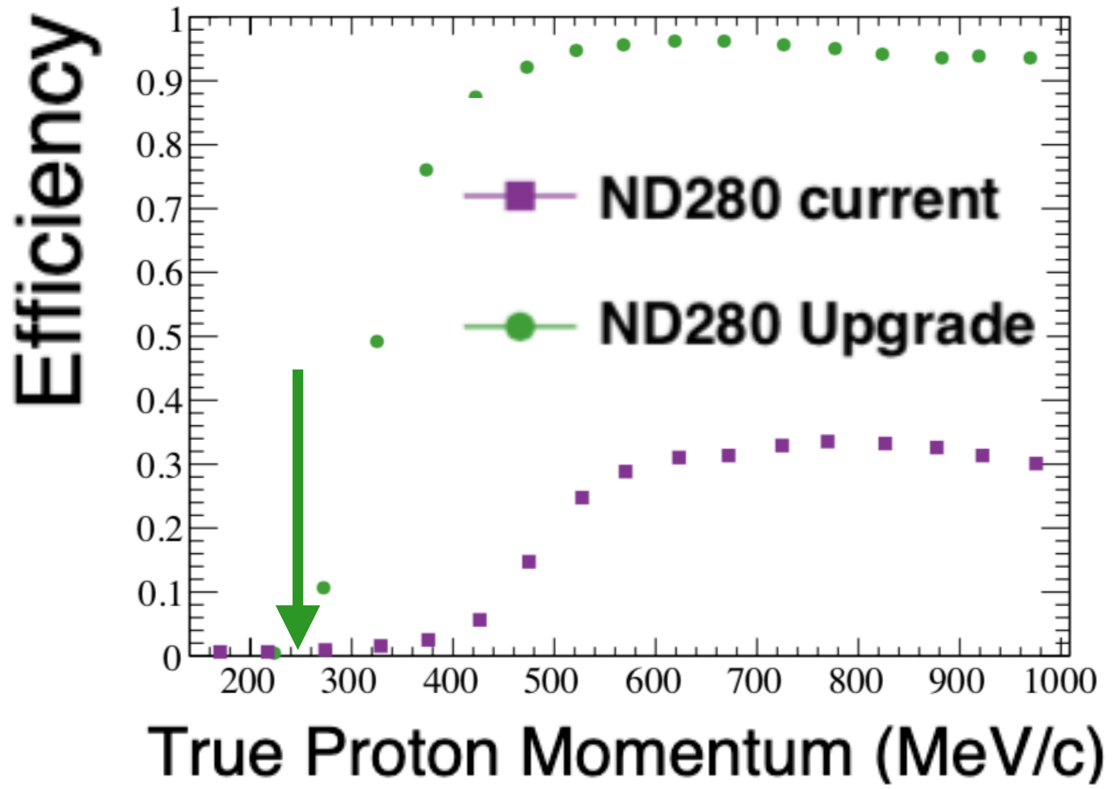
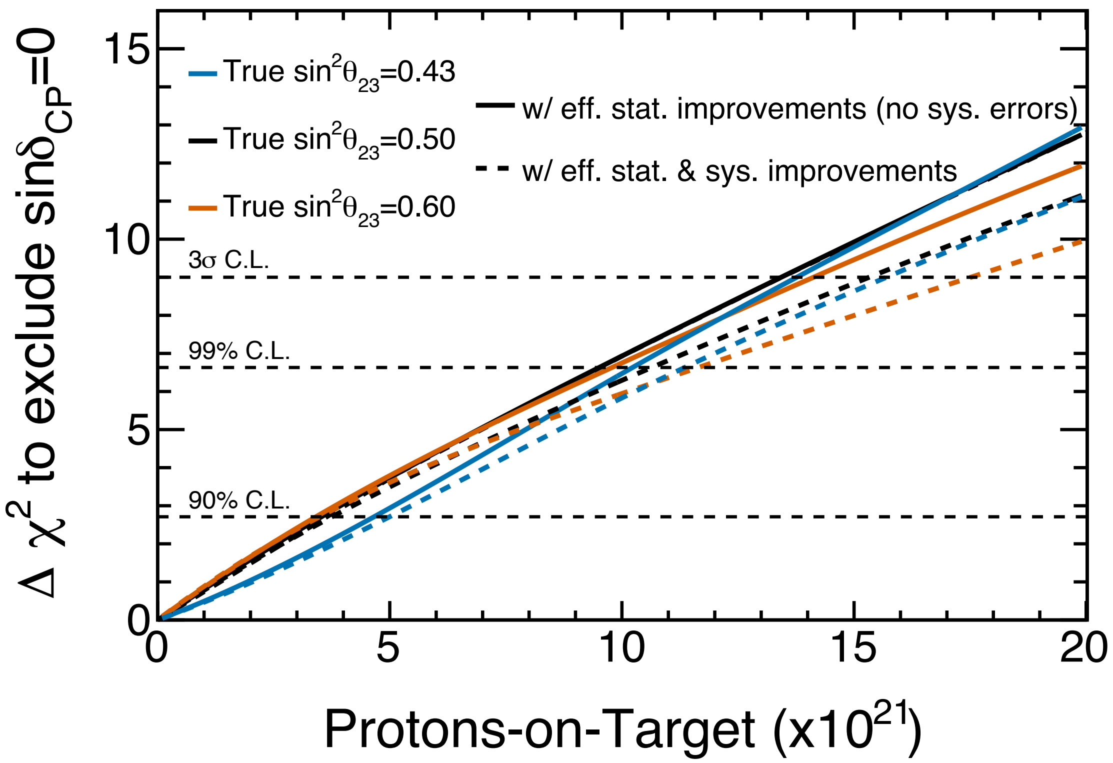
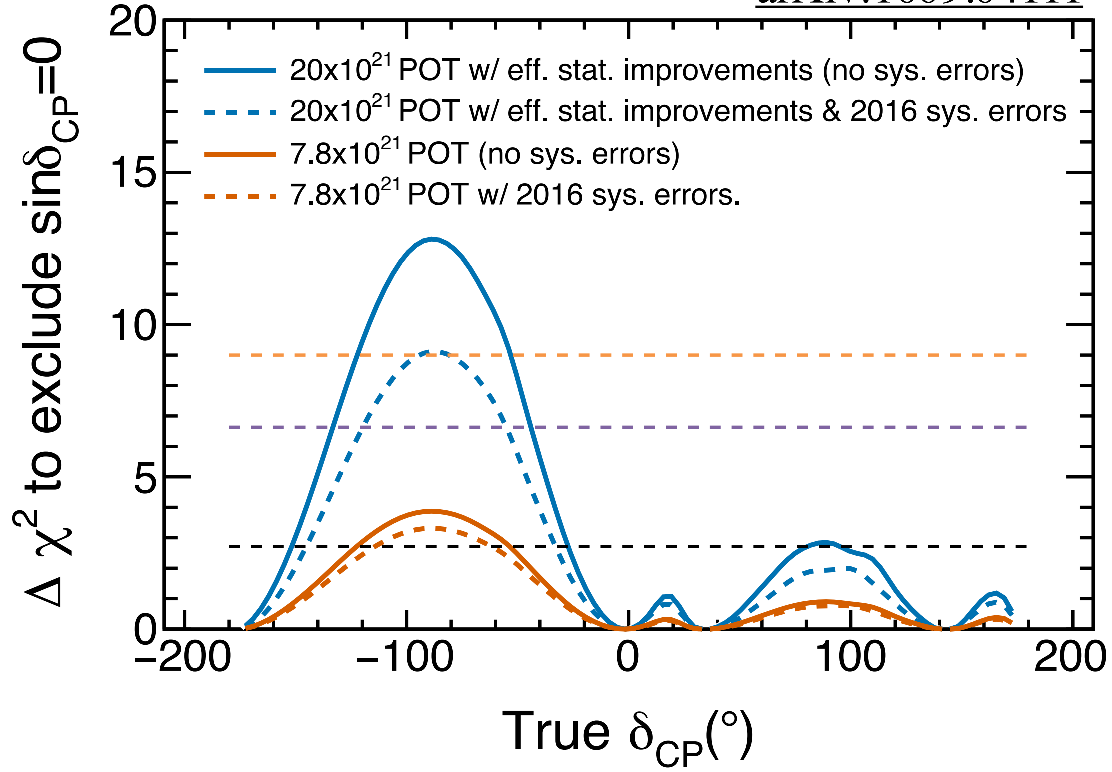


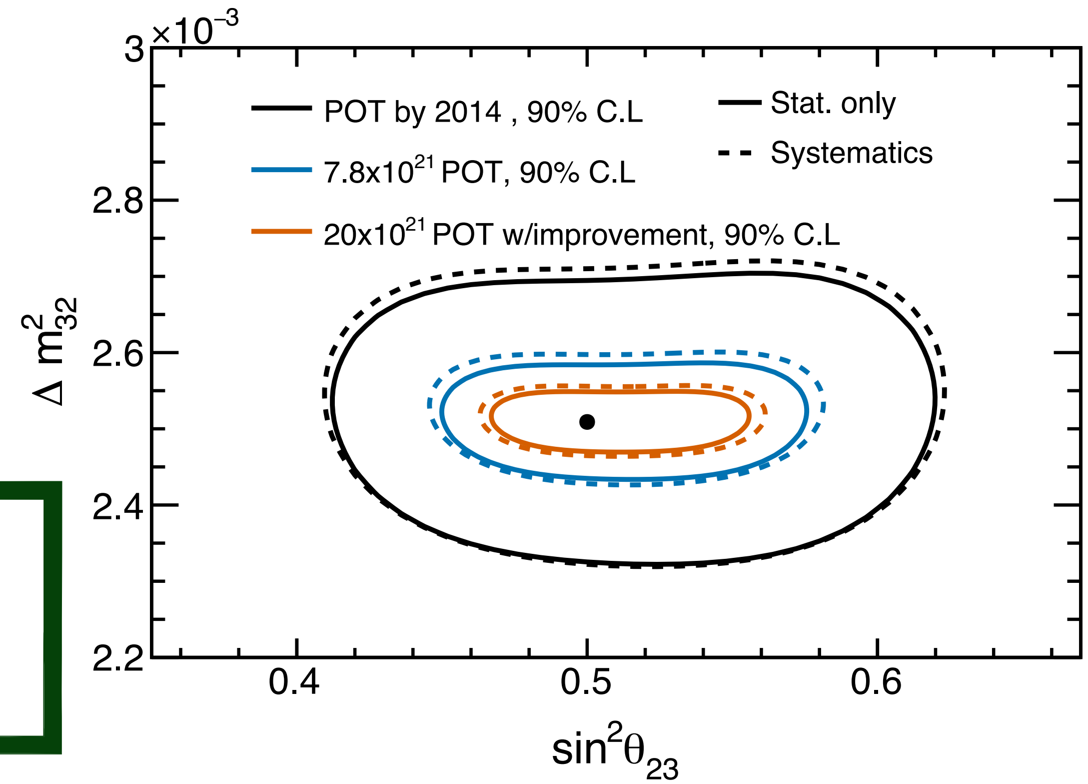
T2K-II physics case



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

T2K-II

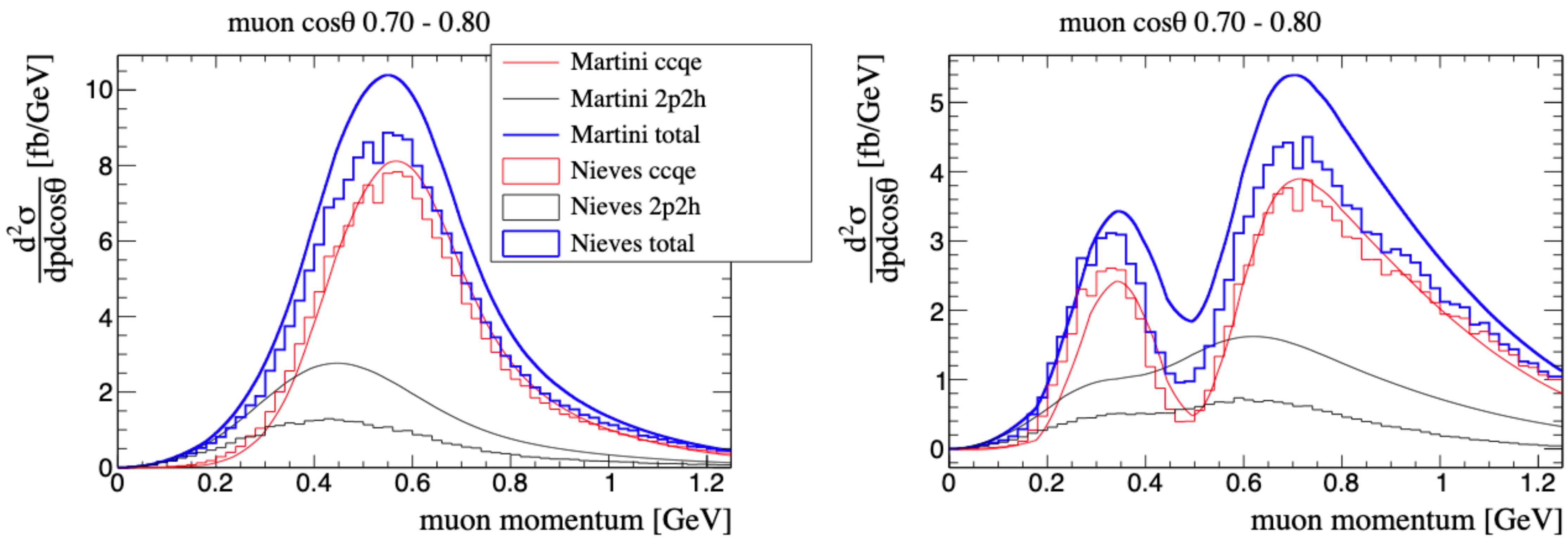
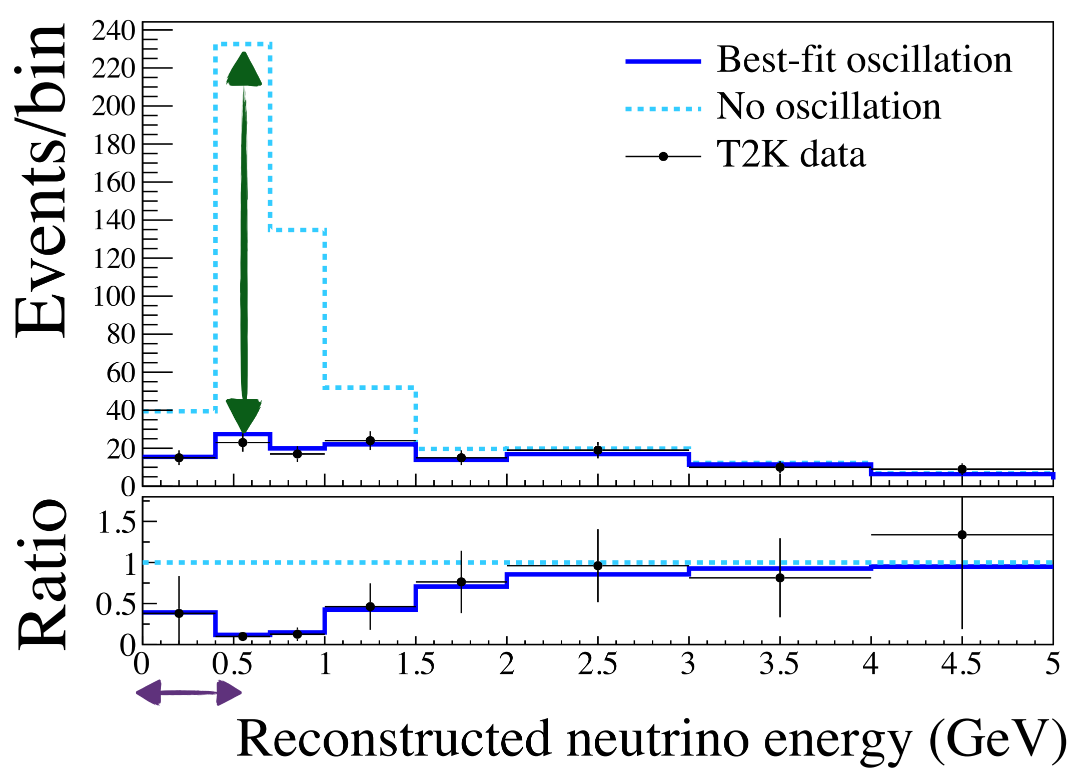


FIG. 18: Distribution of CCQE and 2p2h contributions as a function of muon momentum in the angular range $\cos\theta = [0.7, 0.8]$ at ND280 (left) and Super-K (right) as predicted in the models of Martini *et al.*[68] (continuous line) and Nieves *et al.*[69, 70] (histogram).

T2K oscillation (θ_{23}, $|\Delta m^2_{23}|$)

- Atmospheric parameters (θ_{23}, $\Delta m_{32}{}^2$) through ν_μ disappearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



$\sin^2 2\theta_{23}$ proportional to the depth of the dip (oscillation minimum)

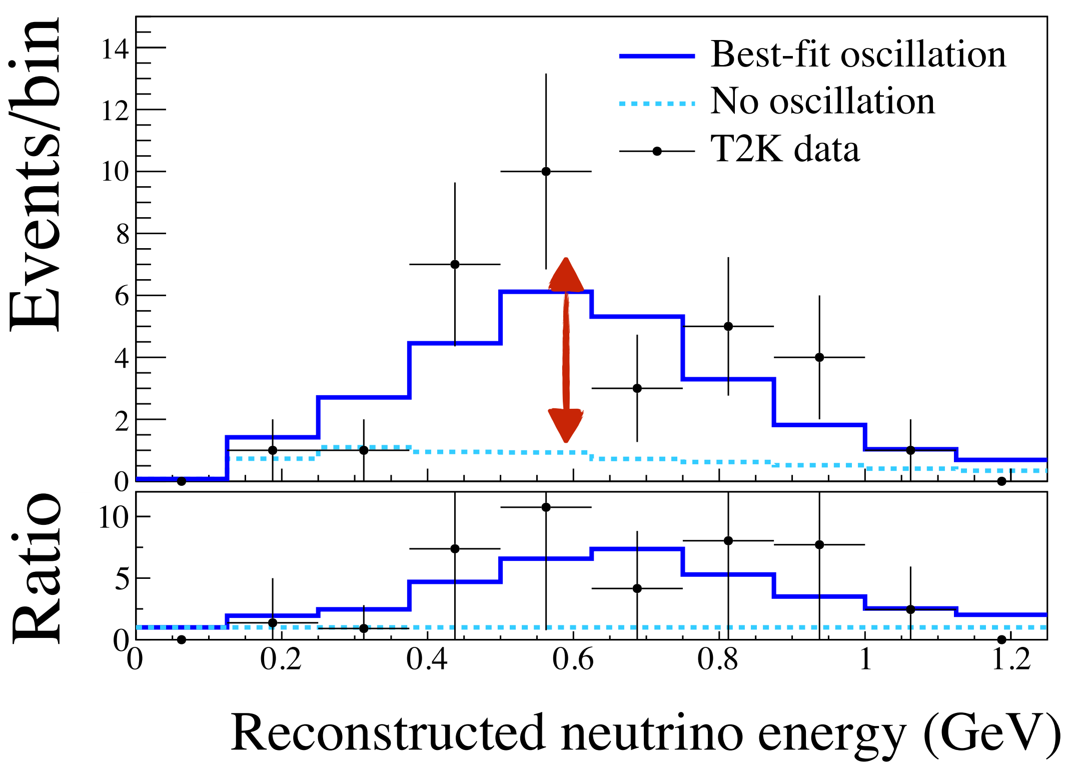
Δm^2_{23} proportional to the position of the dip

T2K oscillation (θ_{13}, δ_{CP})

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

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

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



$\sin^2 2\theta_{13}$ proportional to the oscillation maximum

θ_{13} compatible with the one measured by experiments at reactors.