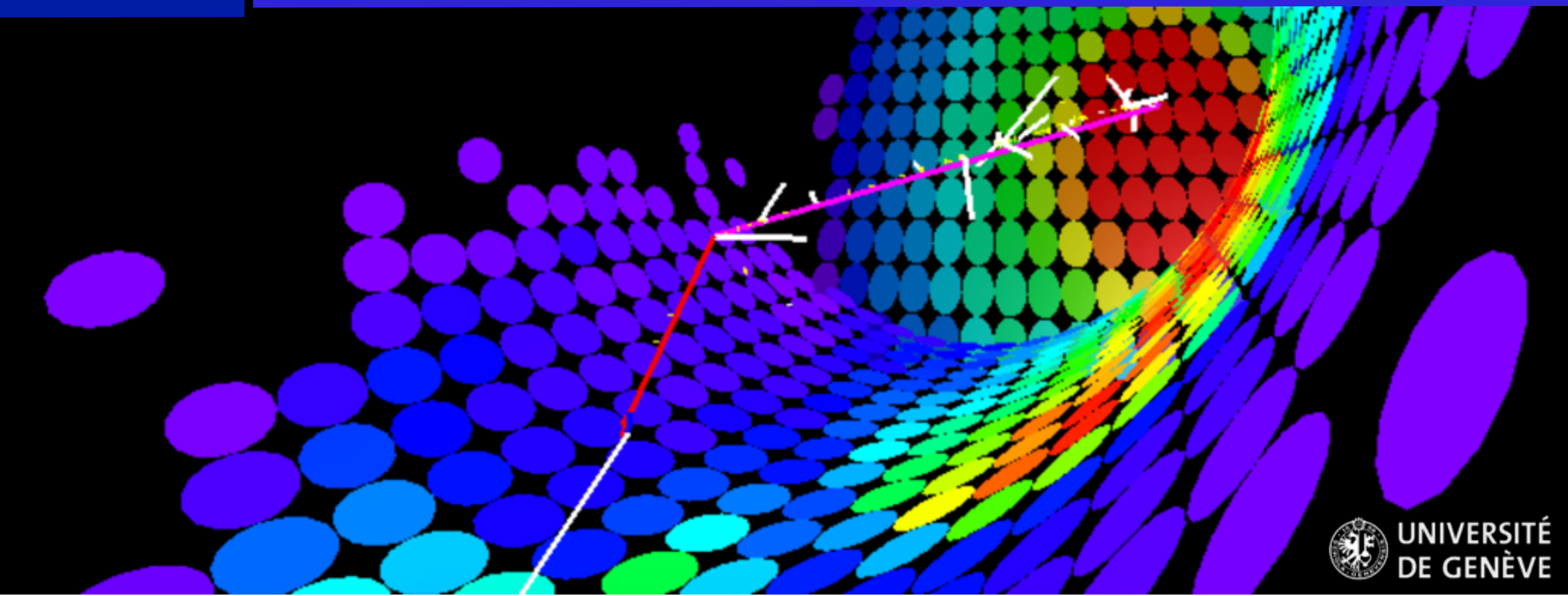
Intermediate Detectors

6 Aug 2015

Mark Rayner, University of Geneva / ND session, Tokai workshop



UNIVERSITÉ DE GENÈVE


octant
sin δ_{CP}
cos δ_{CP}
MH
wikiHow
θ_{13}
θ_{12}


octant
sin δ_{CP}
cos δ_{CP}
MH
RPA
2p2h
M_A
wrong-
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octant
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$\sigma(\nu_e)$
nuSTORM
Hyper-K
ND280
nuPRISM
TITUS
wikiHow
θ_{13}
θ_{12}

Traditional Movitation for an intermediate detector #1

We can reduce systematic error with the same target nucleus

Ichikawa-san, Tuesday

2014 → 2015

		ν_μ sample	ν_e sample	$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
ν flux		16%	11%	7.1%	8%
ν flux and cross section	w/o ND measurement	21.8%	26.0%	9.2%	9.4%
	w/ ND measurement	2.7%	3.1%	3.4%	3.0%
ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%	10%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
total	w/o ND measurement	23.5%	26.8%	14.4%	13.5%
	w/ ND measurement	7.7%	6.8%	11.6%	11.0%

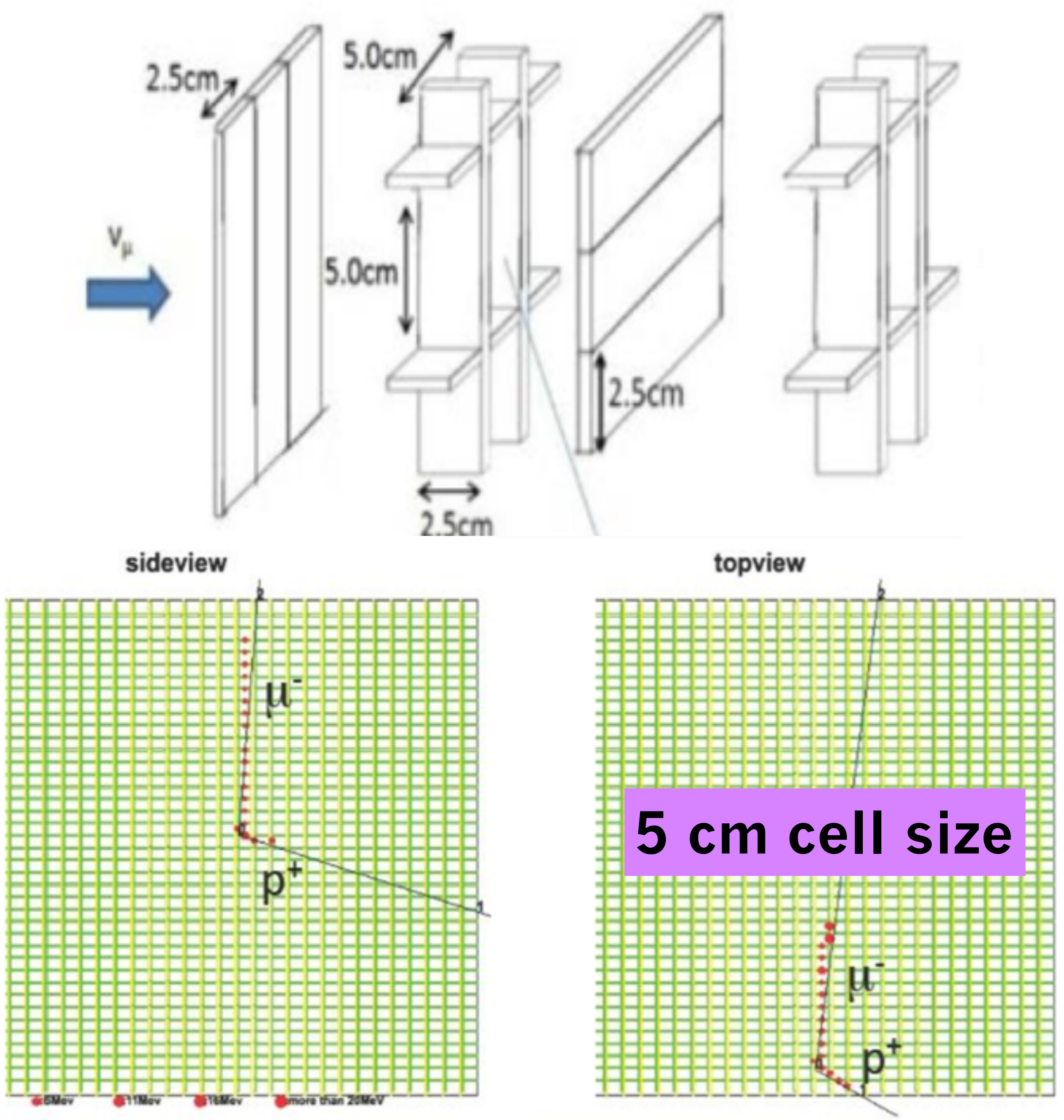
Many improvements

* 2014 error does not include the effect of multi-nucleon at the neutrino-nucleus interaction.

A limitation of the current detector:
FGD2 is only 40% water, short track reconstruction is difficult

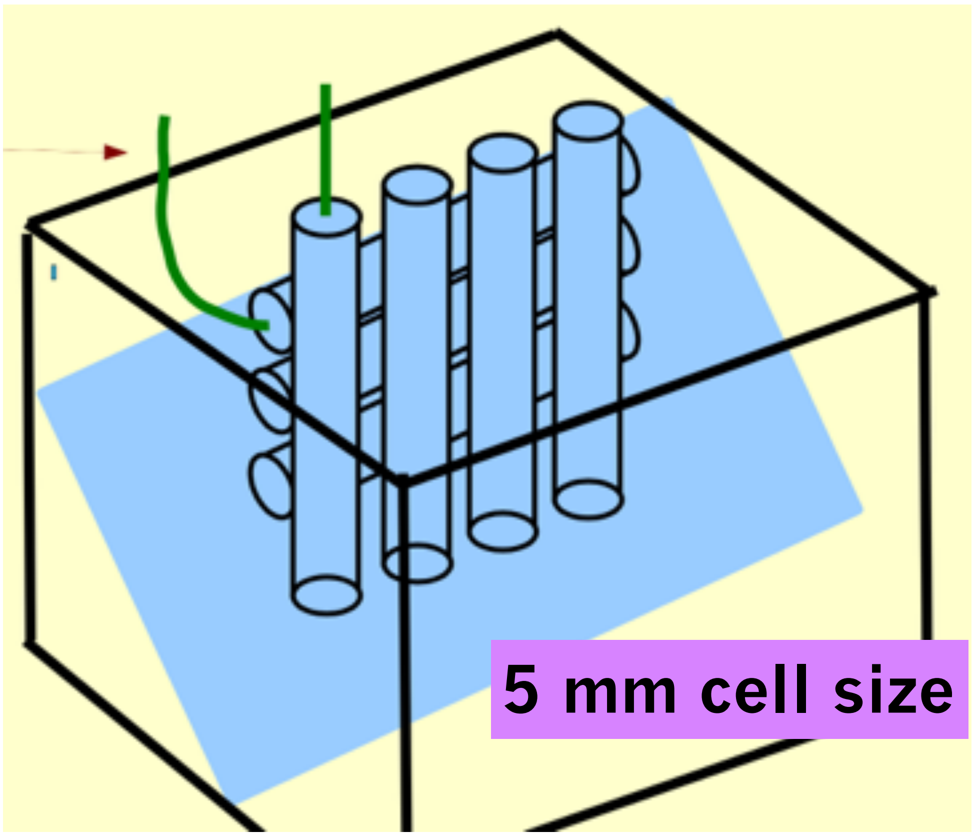
Two solutions have been proposed in an ND280 upgrade…
80% and 70% water respectively, and can reconstruct short 3D tracks

A Wagasci style scintillator grid



Water-based liquid scintillator

Mylar straws painted with reflective paint on the outside, WLS fibres strung inside the straws



Stanley Yen *et al.*, TRIUMF

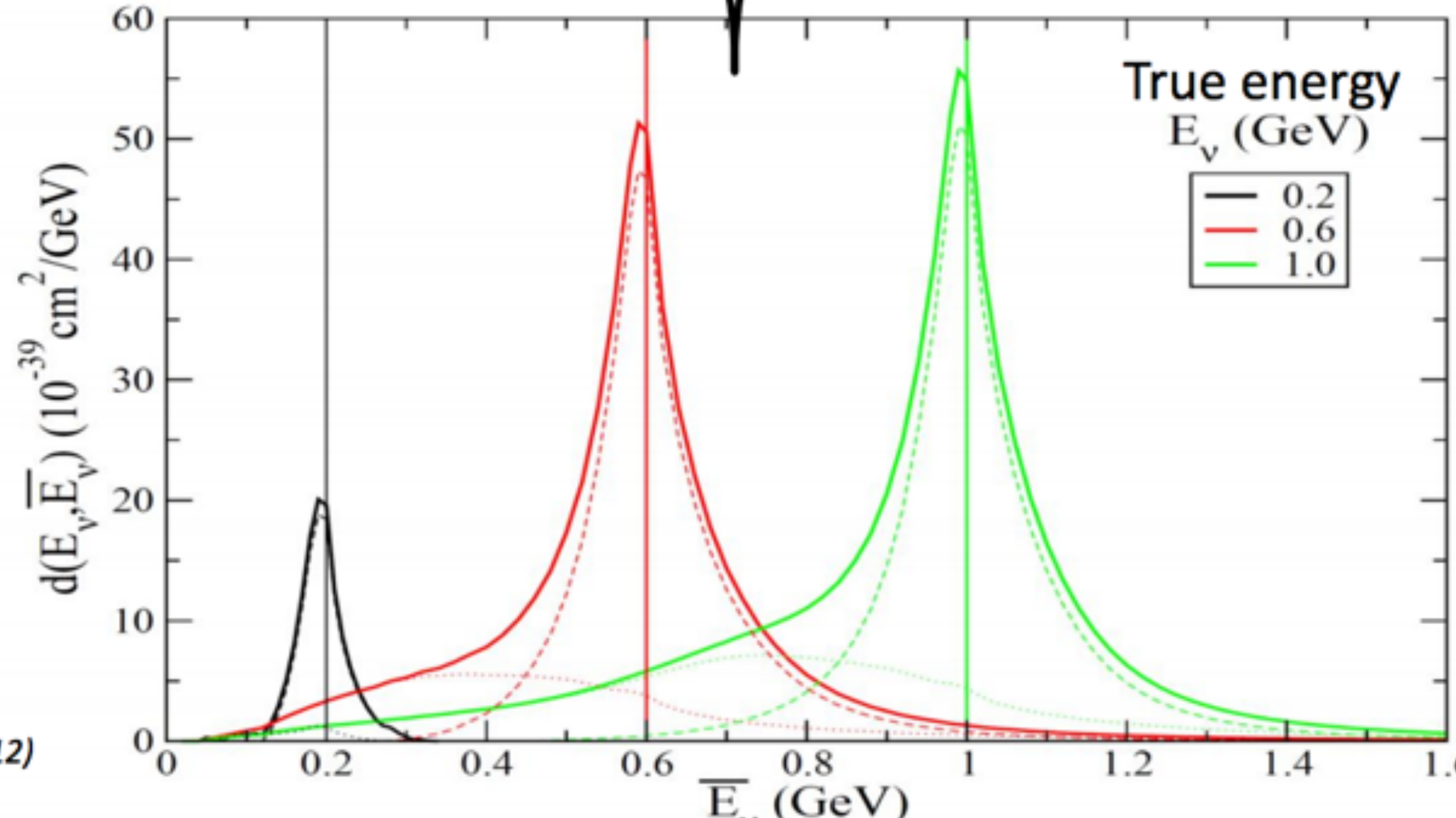
From true neutrino energy to reconstructed neutrino energy

Probability energy distribution $(E_\nu, \bar{E}_\nu)$

$$D_{rec}(\overline{E_\nu}) = \int dE_\nu \Phi(E_\nu) \int_{E_l^{min}}^{E_l^{max}} dE_l \frac{ME_l - m_l^2/2}{\overline{E}_\nu^2 P_l} \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu-E_l,\ \cos\theta=\cos\theta(E_l,\overline{E_\nu})}$$

The quantity $D_{rec}(\overline{E_\nu})$ corresponds to the product $\sigma(E_\nu)\Phi(E_\nu)$ but in terms of reconstructed neutrino energy

M. Martini, M. Ericson, G. Chanfray
- Phys. Rev. D 85 093012 (2012)
- Phys. Rev. D 87 013009 (2013)



Similar results in:
- Nieves, Sanchez, Simo, Vicente Vacas PRD 85 113008 (2012)
- Lalakulich, Mosel, Gallmeister, PRC 86 054606 (2012)

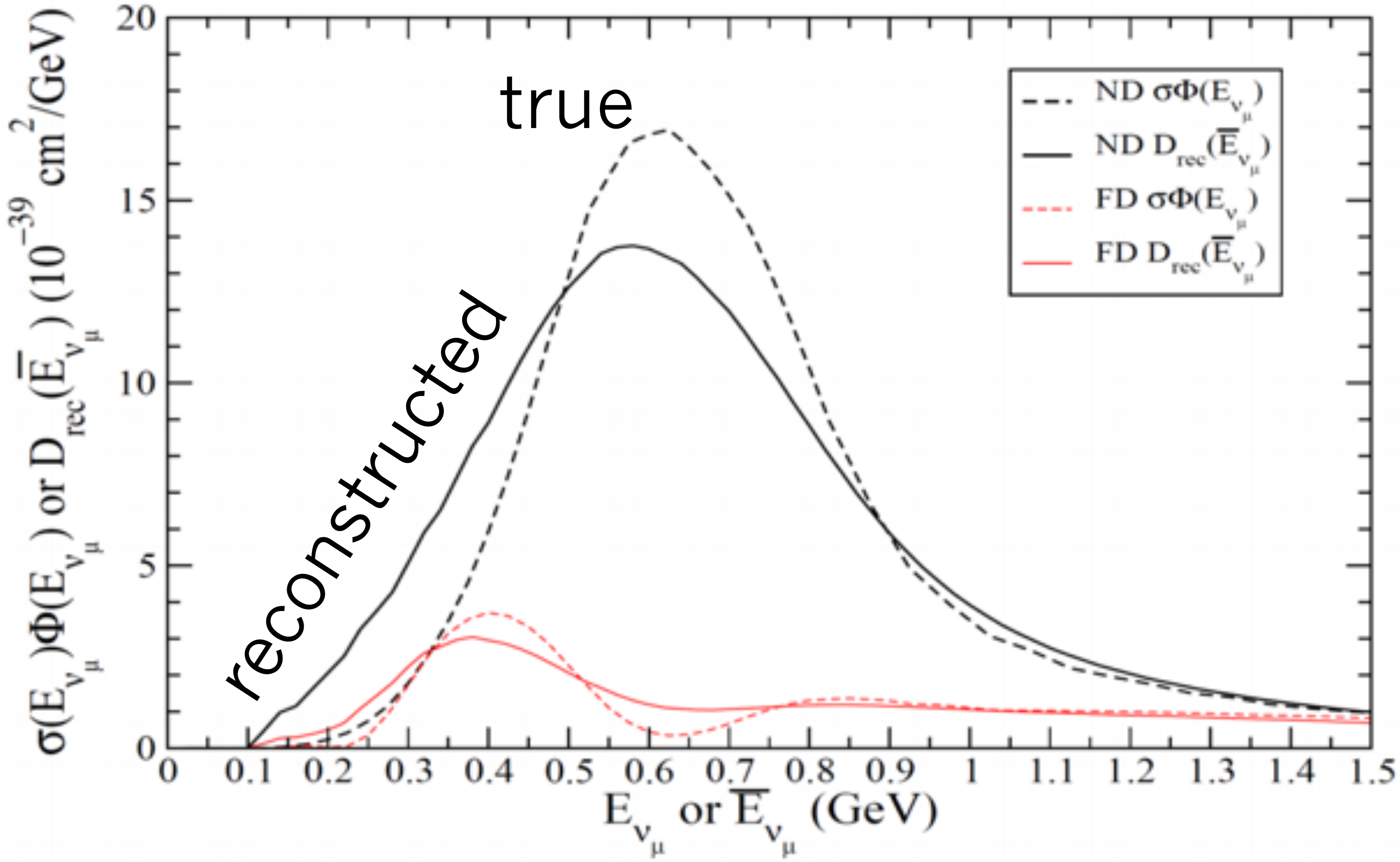
- Distributions not symmetrical around Ev
- Crucial role of np-nh: low energy tail

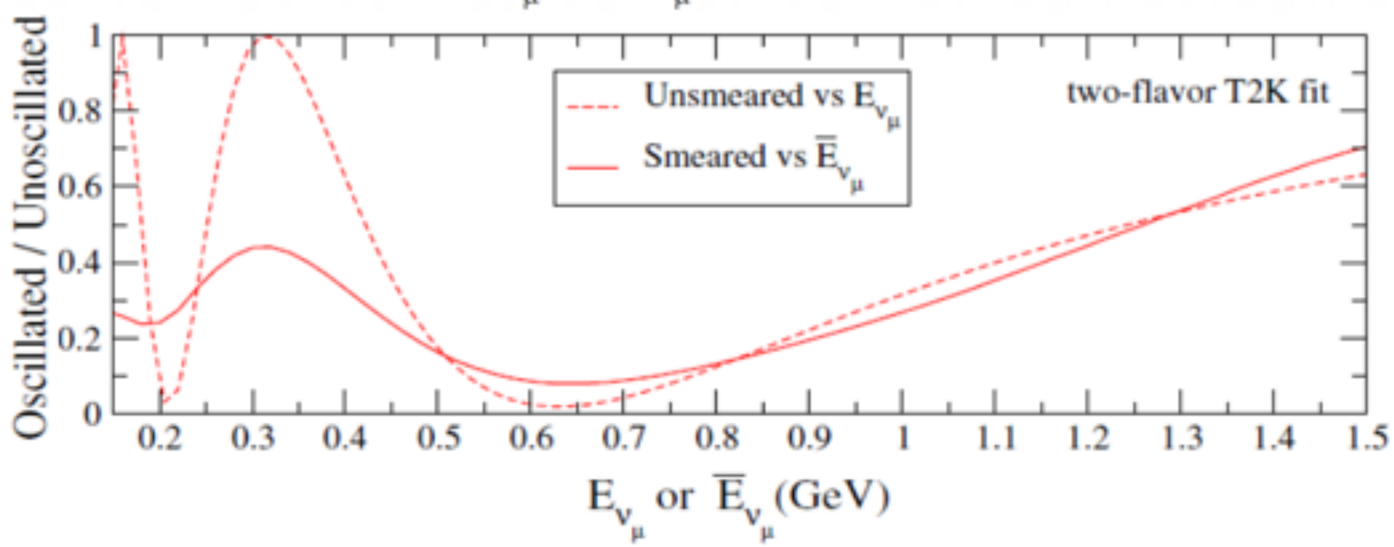
Marco Martini, EPS-HEP

23/7/2015 M. Martini, EPS - HEP 32

νμ disappearance T2K

PRD85 (2012); PRL 111 (2013)





M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

Similar results in: O. Lalakulich, U. Mosel, K. Gallmeister, PRC 86 054606 (2012)

After reconstruction correction:

- Near Detector:
  clear low energy enhancement
- Far Detector:
  low energy tail and
  the middle hole is largely filled

  Effects largely due to np-nh

Recent T2K experimental analysis :

PhysRevD.91.072010 (2015)

"For the present exposure, the effect can be ignored, but future analyses will need to incorporate multi-nucleon effects in their model of neutrino-nucleus interactions."

Marco Martini, EPS-HEP

23/7/2015 M. Martini, EPS - HEP 33

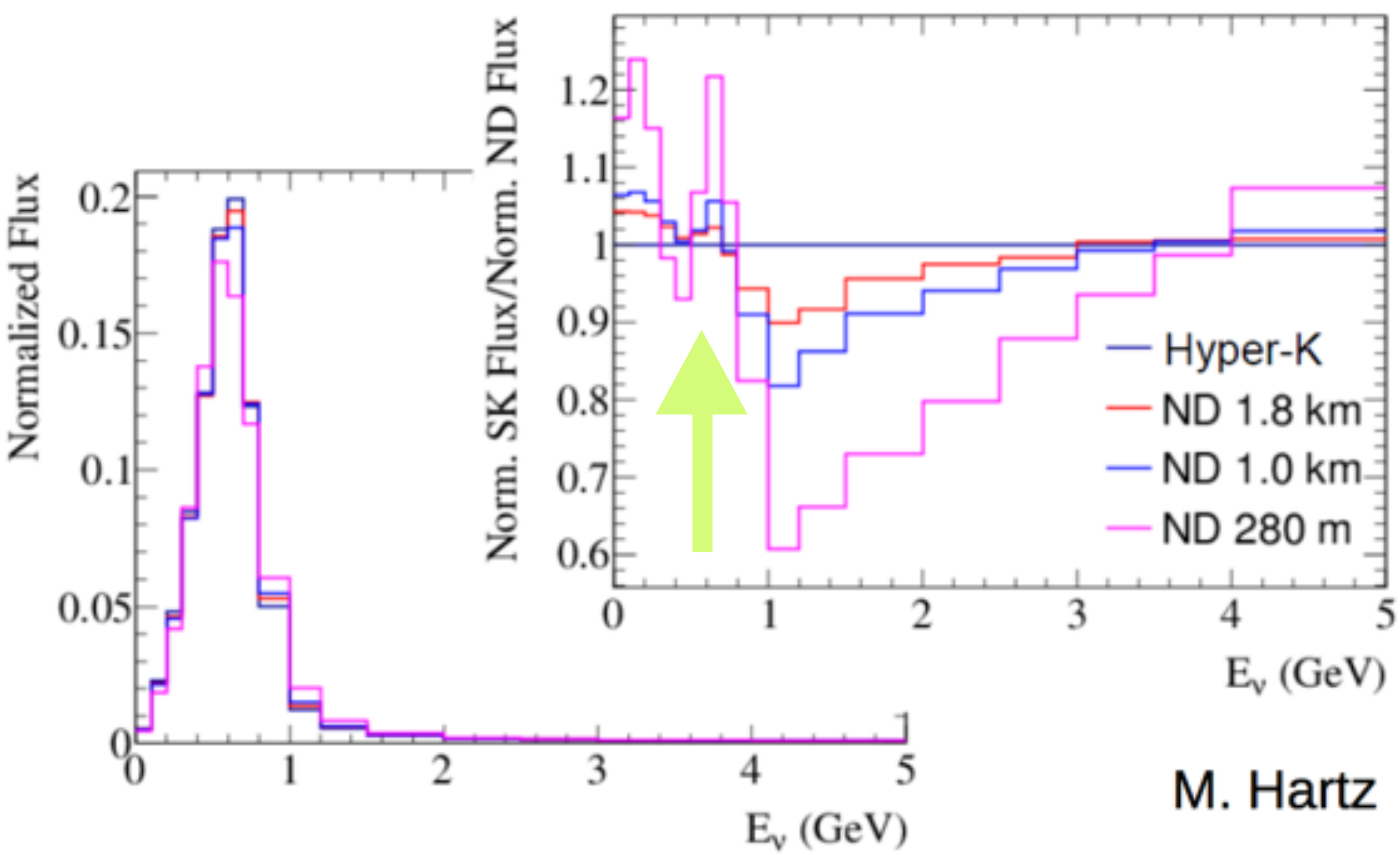
Traditional Movitation for an intermediate detector #2

The flux shape is more similar at ~2 km

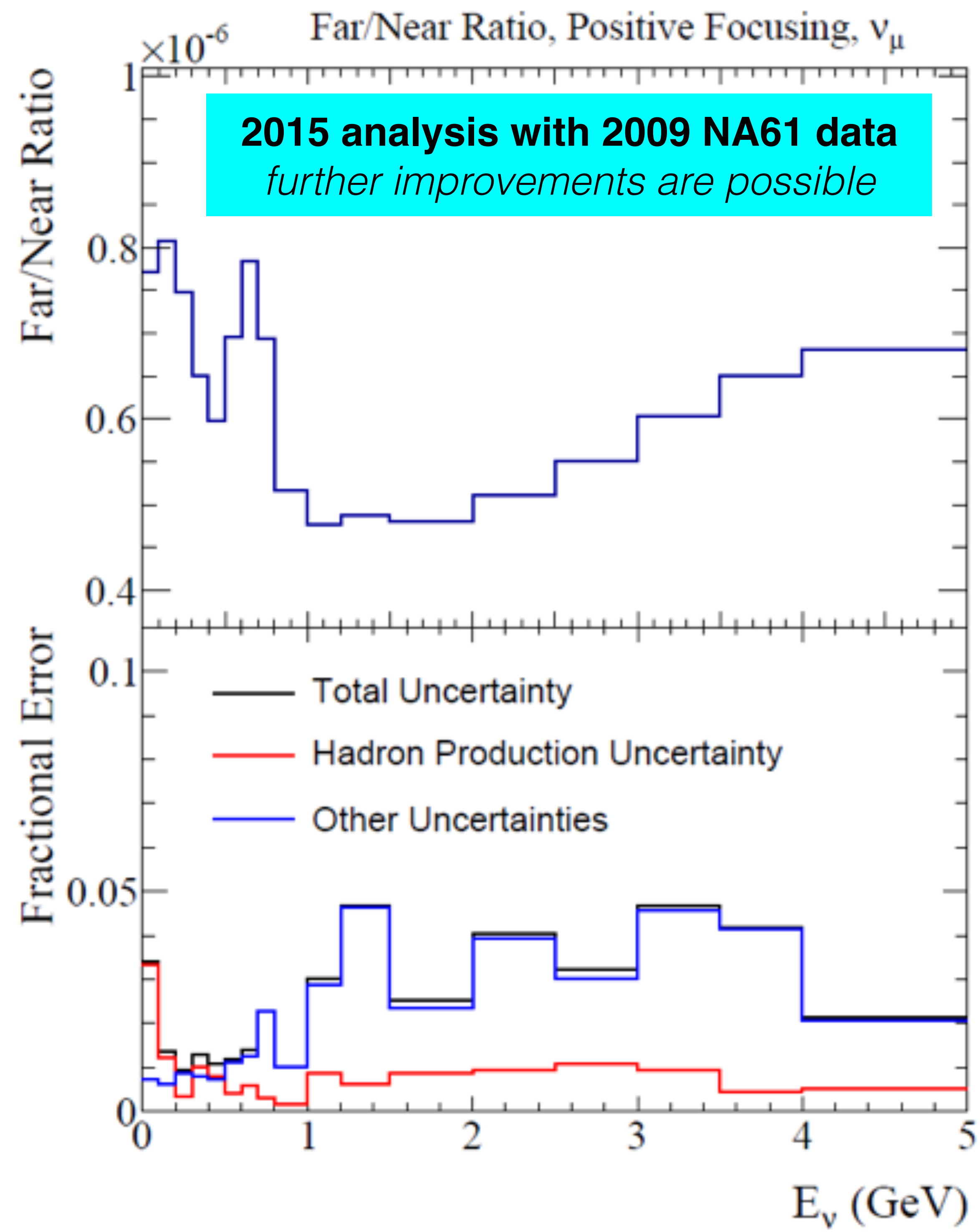
Uncertainty on FD/ND flux is ≲ 2%

The detector being close to the target is probably not a fundamental limitation

(quantitative study is envisaged)



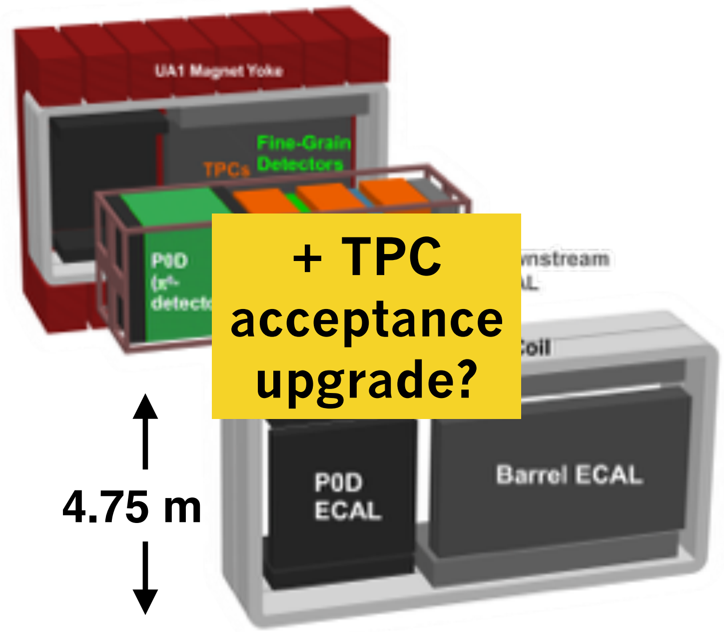
M. Hartz



But, naively, flux extrap. errors should decrease by a factor 4 at 2km?

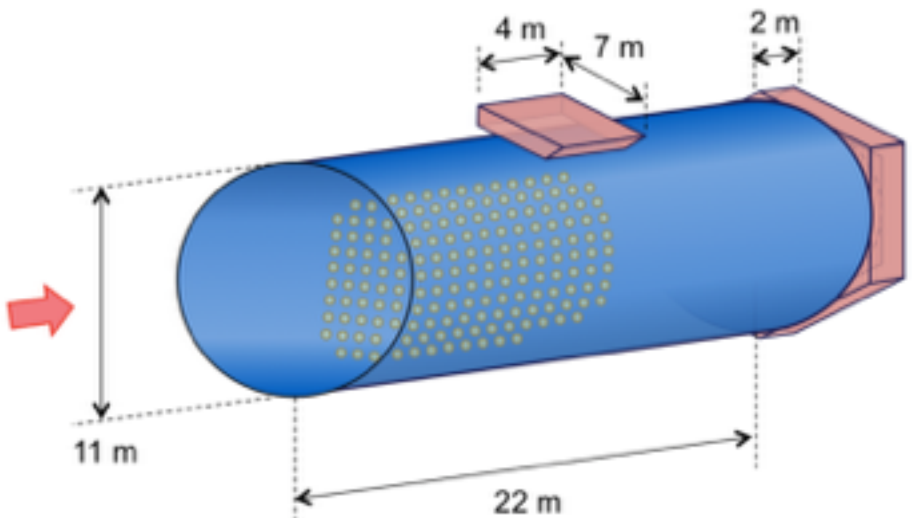
NOT AN EXHAUSTIVE LIST!

✓ already have magnet

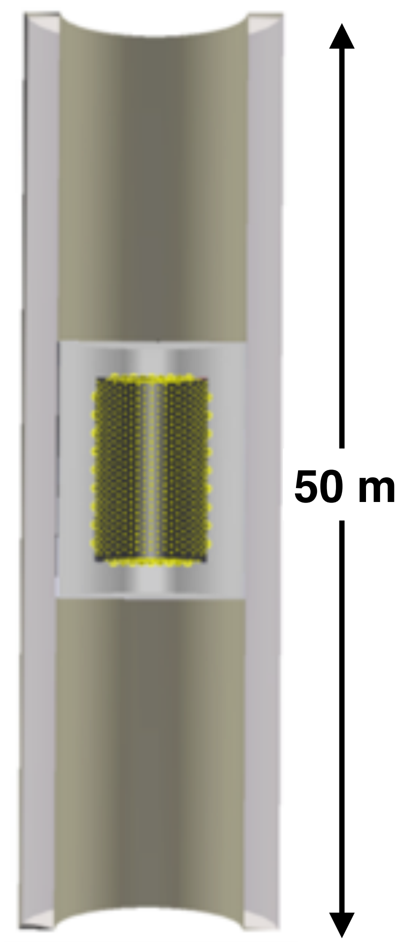


Alain, today

- ☑ **Constrain wrong-sign BG** *(B-field+TPCs)*
- ☑ **High-E constraints***
- ☑ **Wagasci-style water target with short-track resolution**
- **And what about a HP-TPC?**
  - *Do we need a clear measurement of small recoil nuclei?*
  - *Also: ν_e cross section and a constraint on intrinsic ν_e* *(excellent kinematics)*



- ☑ **Constrain wrong-sign BG** *(Gd & magnetized MRD)*
- ☑ **Same detection method**
- ☑ **Higher-E sample with MRD***



- ☑ **Interaction model independence**
- ☑ **Same detection method**
- ☑ **Sterile neutrinos**

Mike, yesterday

seems important for CPV sensitivity, cf. Raj's talk

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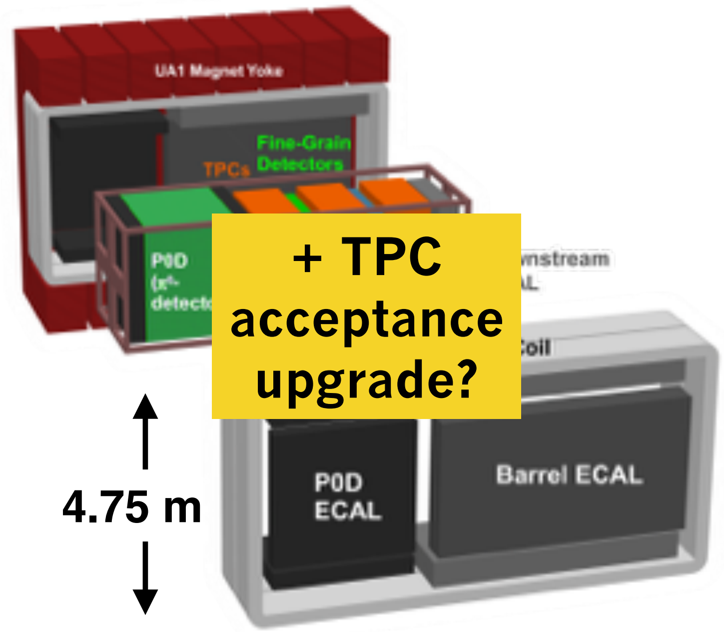

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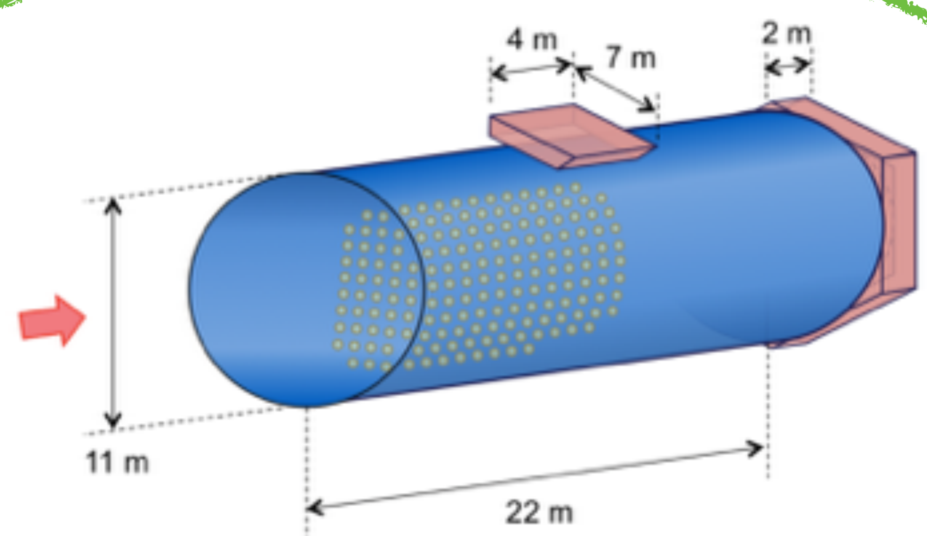
now…



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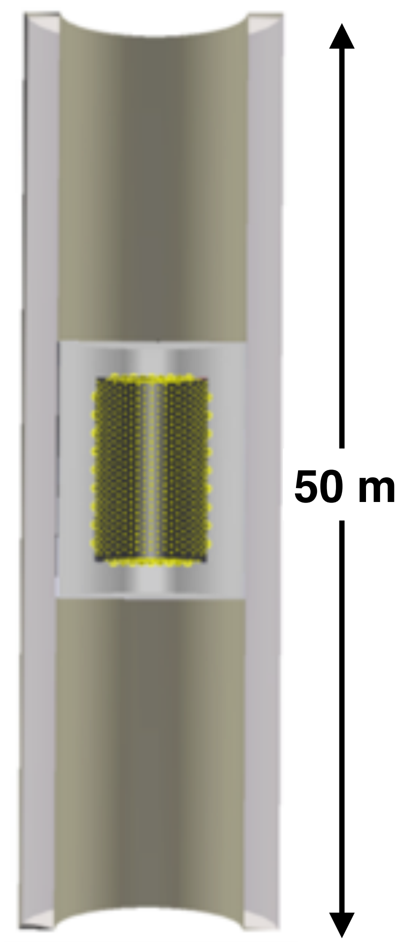

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I shall now bring you up to date on TITUS

The results on the next few slides are shown on behalf of the TITUS working group, and come from the TITUS preprint which will be released soon

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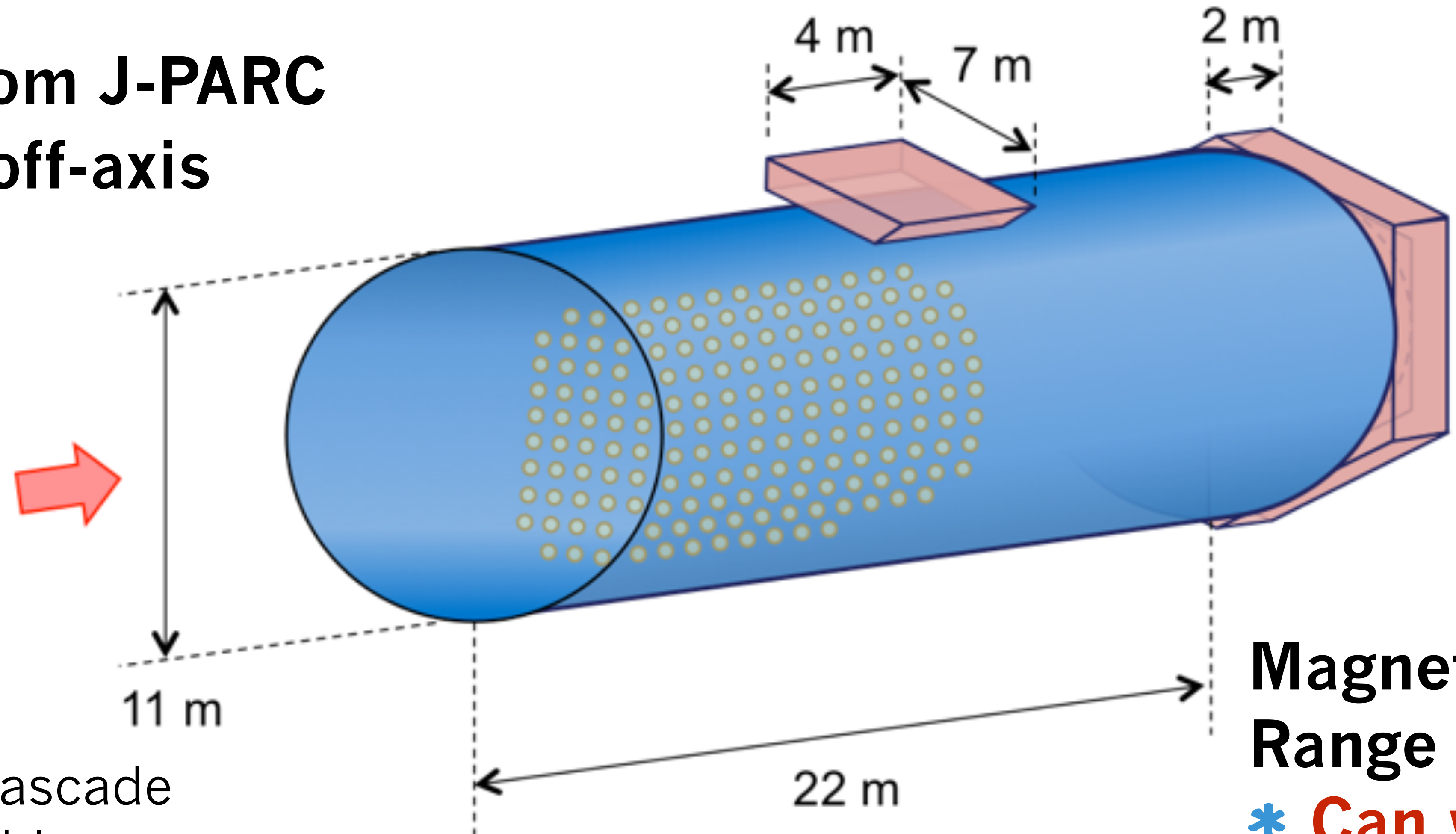
> **A particular shout-out to Nick Prouse, Wing Ma, David Hadley and Raj Shah, who have really motored on with the analysis in recent weeks**

The TITUS detector

2kton Gd-doped (0.1%) water Cherenkov

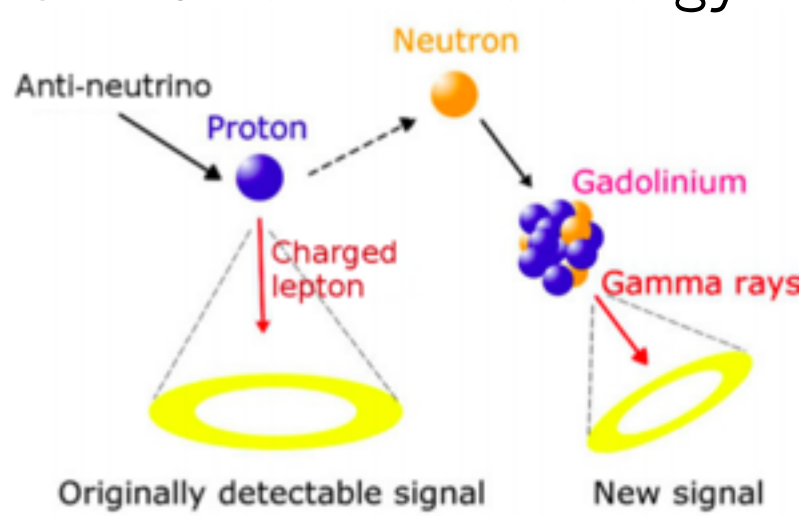
~2km from J-PARC
2.5° off-axis



Magnetized Muon Range Detectors

- **Can validate Gd** (depends on cuts)
- **Enlarges sample**
- **Extra wrong-sign constraint**

8 MeV gamma cascade
with 4-5MeV visible energy



Baby-MIND, the forward Wagasci detector, is a proof of principle for low-E magnetized MRDs

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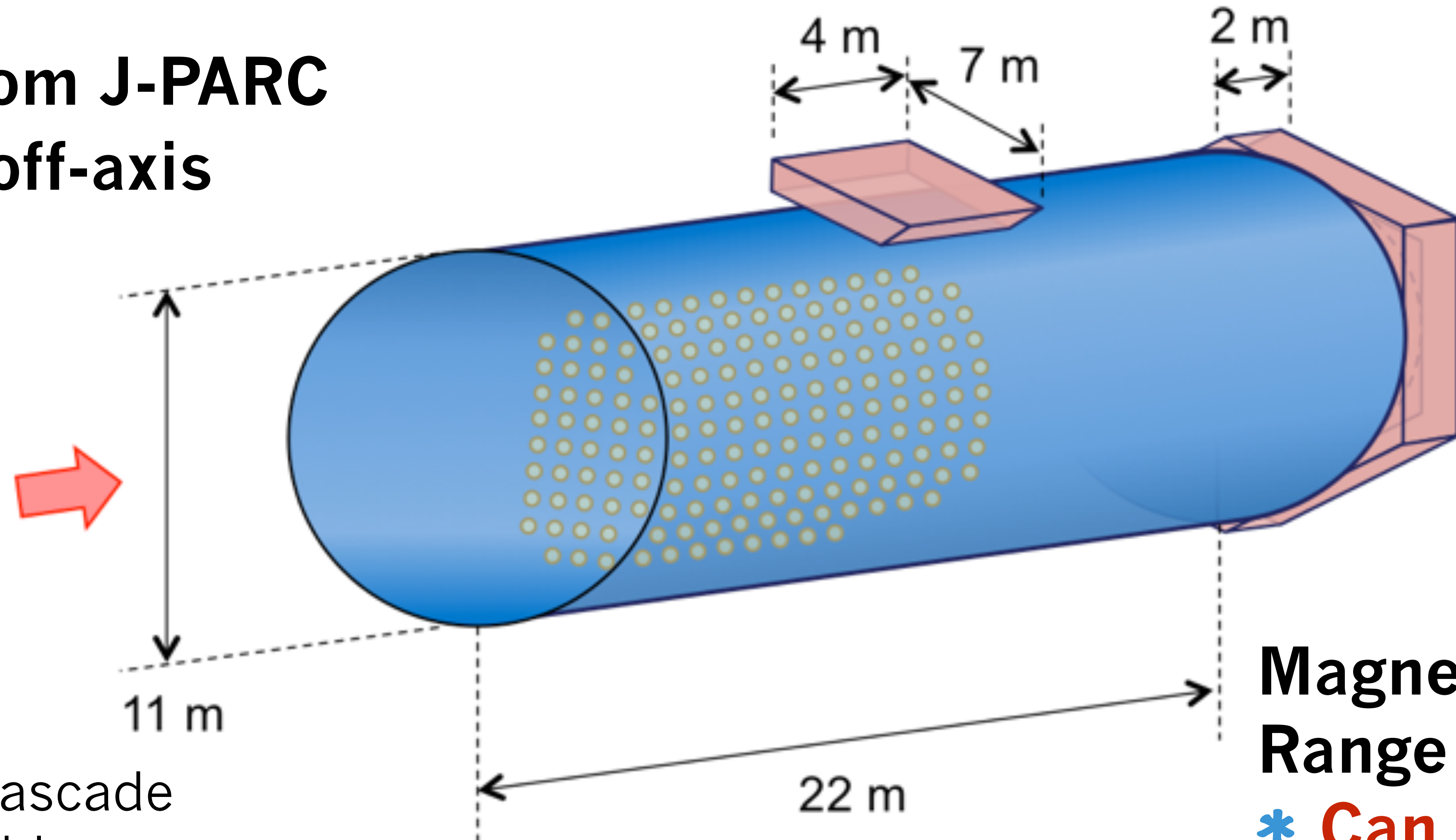

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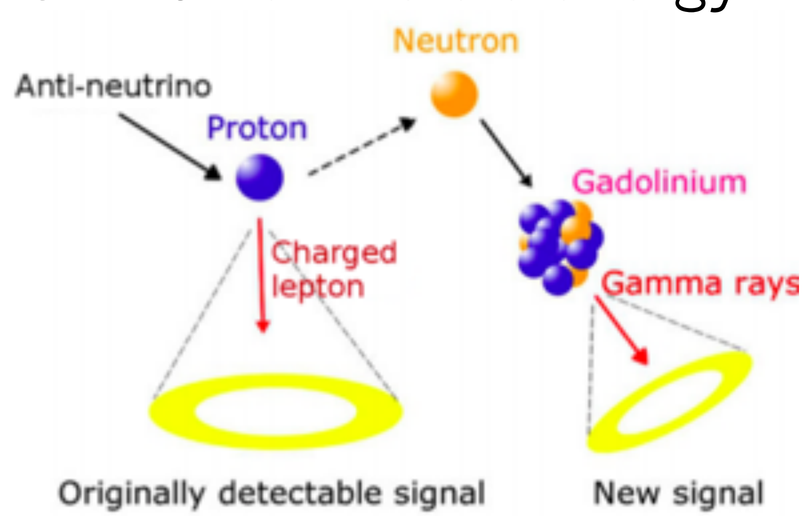
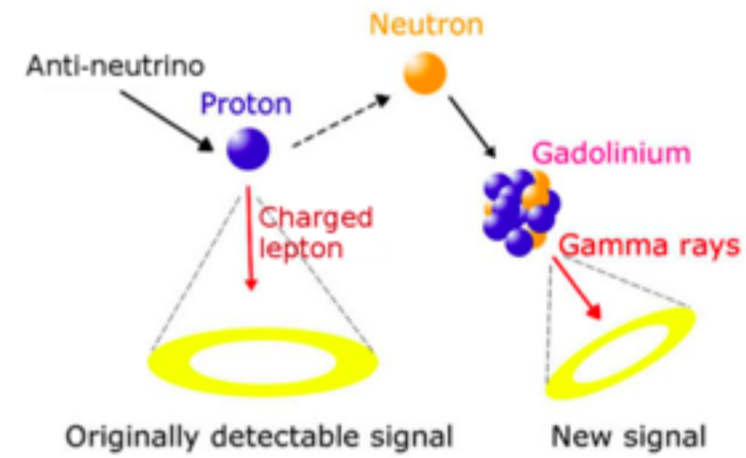


TITUS could be brought to an accelerated schedule, given the T2K*3 motivation

Baby-MIND, the forward Wagasci detector, is a proof of principle for low-E magnetized MRDs

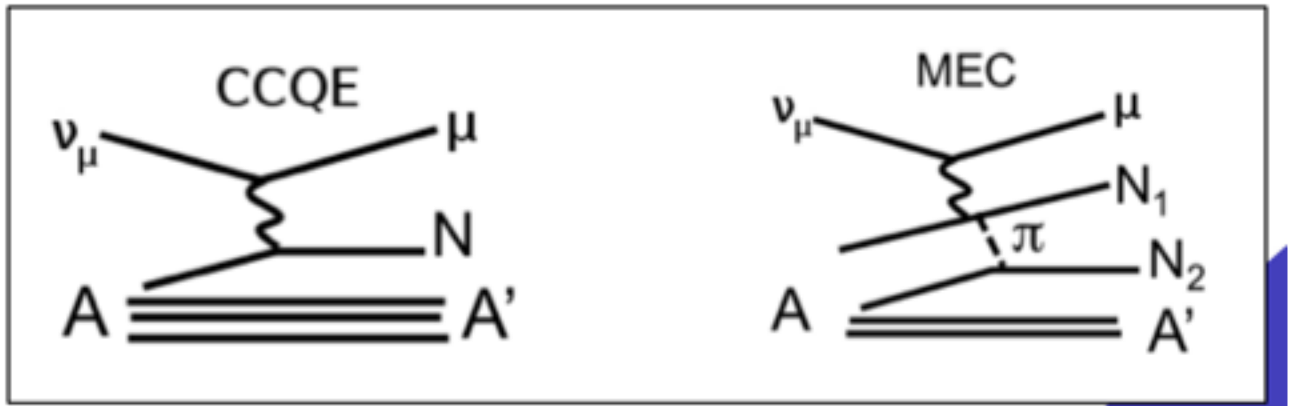
Gadolinium Doping

- Neutron capture on Gadolinium:
  - Cross section of 49,000b compared to 0.3b for H
  - 8MeV gamma cascade with 4-5MeV visible energy
  - 0.1% Gd doping: ~90% of neutrons capture on Gd



- New signal to distinguish ν / $\bar{\nu}$ events and different interaction modes:
  - ν_μ CCQE: $\nu_\mu + n \rightarrow \mu^- + p$ 0 neutrons
  - $\bar{\nu}_\mu$ CCQE: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ 1 neutron
  - ν_μ MEC: $\nu_\mu + (n+n) \rightarrow \mu^- + p + n$ 0.2 neutrons on average
  - $\bar{\nu}_\mu$ MEC: $\bar{\nu}_\mu + (p + p/n) \rightarrow \mu^+ + n + p/n$ 1.8 neutrons on average

- Greatly enhanced sample purities:
  - ν_μ CCQE: 36% $\rightarrow$ 67%
  - $\bar{\nu}_\mu$ CCQE: 63% $\rightarrow$ 88%

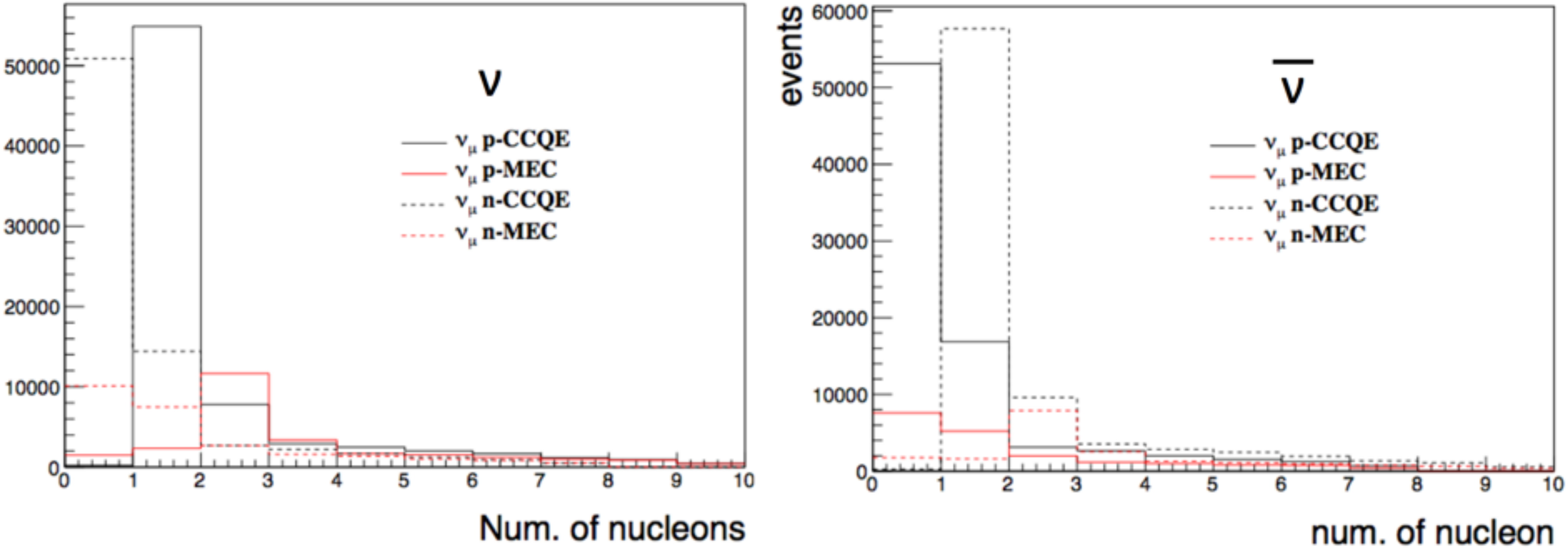


- Feasibility of Gd in water Cherenkov detector being tested in EGADS arXiv: 1201.1017

5

Neutron multiplicity

- Precise neutrino energy reconstruction requires understanding of the hadronic system
- Improve neutrino interaction physics around 1 GeV



- GENIE v2.8.0 simulations of neutrino/antineutrino interactions with carbon target
- Clear n signals can be modified by nuclear effects: re-scattering, charge exchange, and absorption in the nuclear media
- Statistical information remains – powerful approach for H_2O
    - cross section measurements

6

The power to remove wrong-sign BGs

Distinguish 0 tagged neutrons and 1+ tagged neutrons in 1 Rμ samples

		CCQE	CC 2p2h	CC inelastic	NC	nue and nuebar
FHC	ν	**423404**	30150	59404	2301	294
		74274	24321	29651	3175	139
	$\bar{\nu}$	822	55	878	109	10
		5295	952	1179	106	15
RHC	ν	19071	2036	5959	549	58
		3420	1621	4034	663	41
	$\bar{\nu}$	18811	930	11484	548	30
		119717	15744	8575	588	61

SELECTION CUTS
dwall > 1m
towall > 2m
1 mu-like ring
200MeV < E < 1GeV

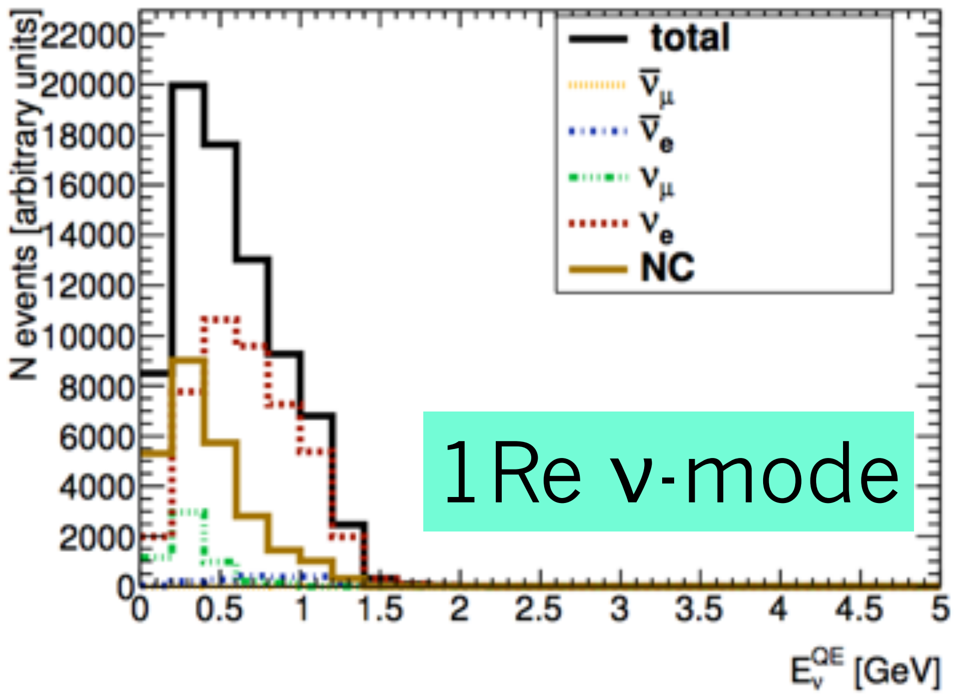
Initial sensitivity studies from the proto-CM

- Smeared MC truth
- Resolution and efficiencies from SK-tables
- Assumes TITUS can achieve the same performance as current SK fitQun
  - Tables are binned by distance from walls so this takes into account the fact that TITUS is smaller
- T2K NIWG **2012** xsec error model
  - with additional errors for **MEC uncertainty** and **neutron FSI**

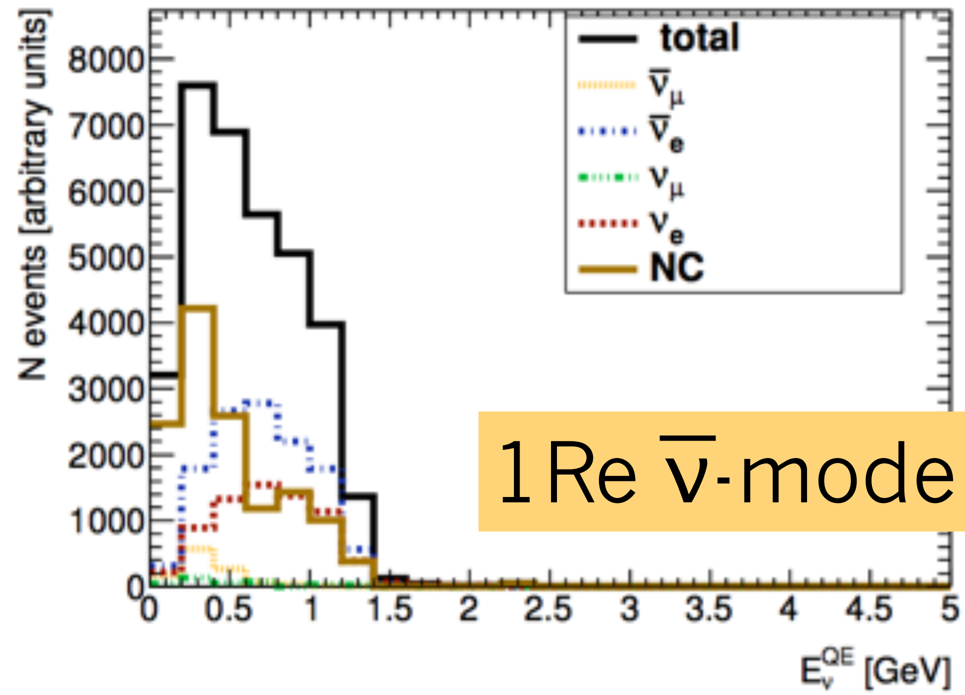
Parameter	Nominal value and Prior Uncertainty
δ_{CP}	0.0, uniform in δ_{CP}
$\sin^2 2\theta_{13}$	0.095, uniform in $\sin^2 2\theta_{13}$
$\sin^2 2\theta_{23}$	1.00 ± 0.03 ($\approx \sin^2 2\theta_{23} > 0.95$ at 90% CL)
$\sin^2 2\theta_{12}$	0.857 ± 0.034
Δm^2_{32}	$2.32 \pm 0.10 \times 10^{-3}$ eV^2
Δm^2_{21}	$7.5 \pm 0.2 \times 10^{-5}$ eV^2

Dave Hadley

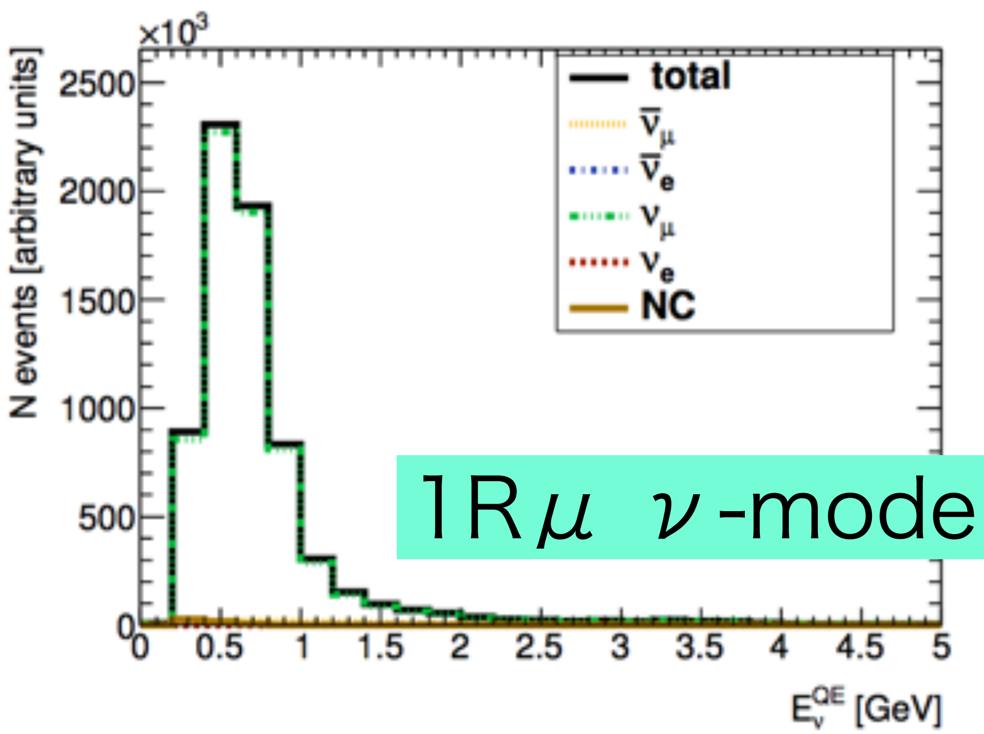
TITUS samples



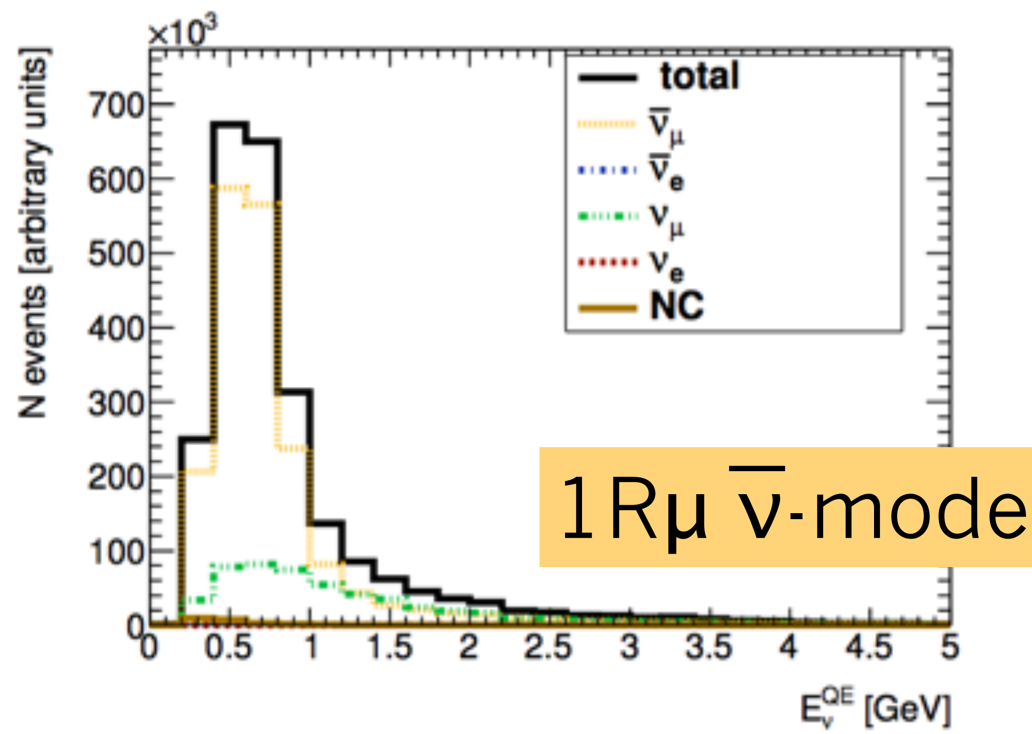
(a) 1Re FHC



(b) 1Re RHC



(c) 1Rmu FHC

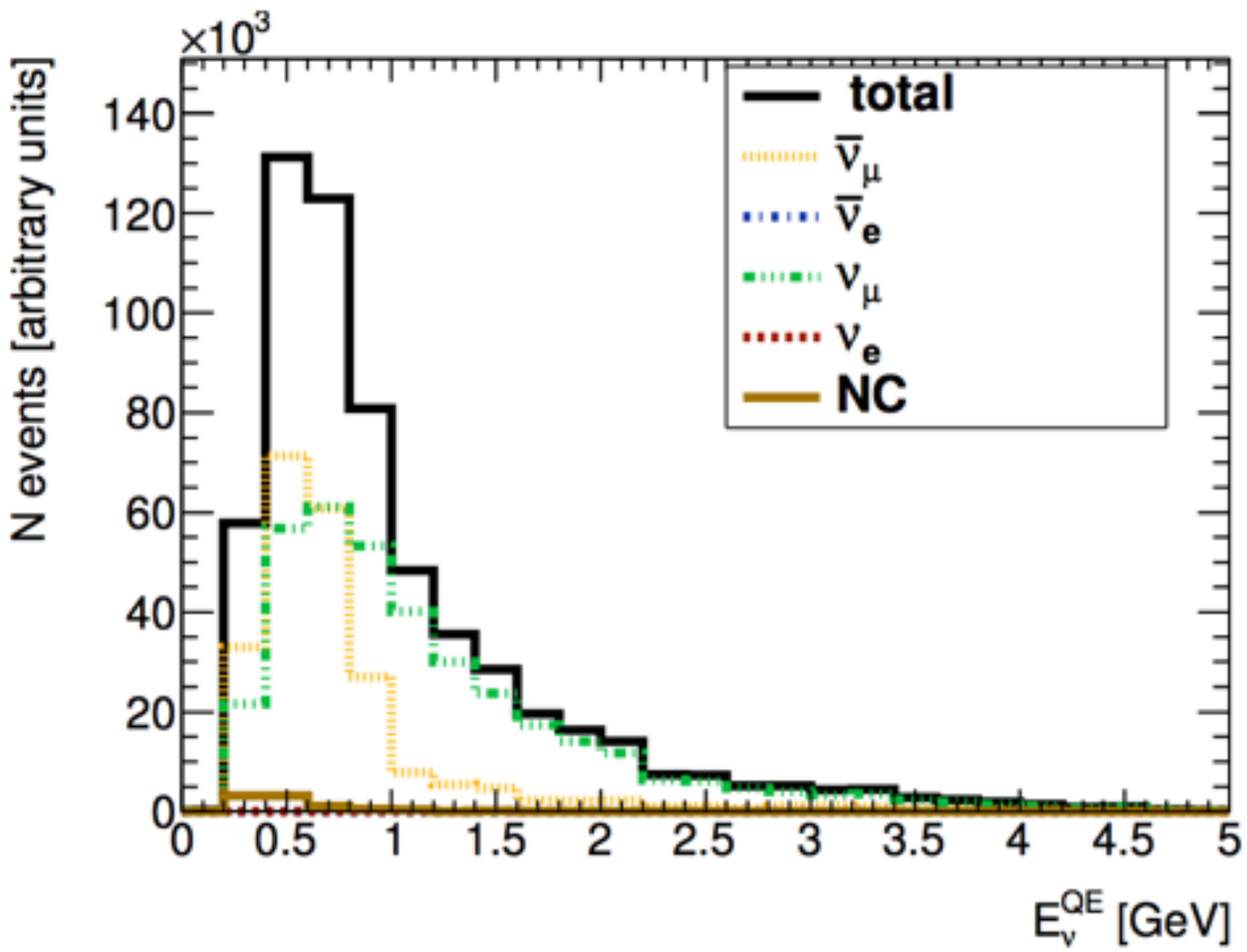


(d) 1Rmu RHC

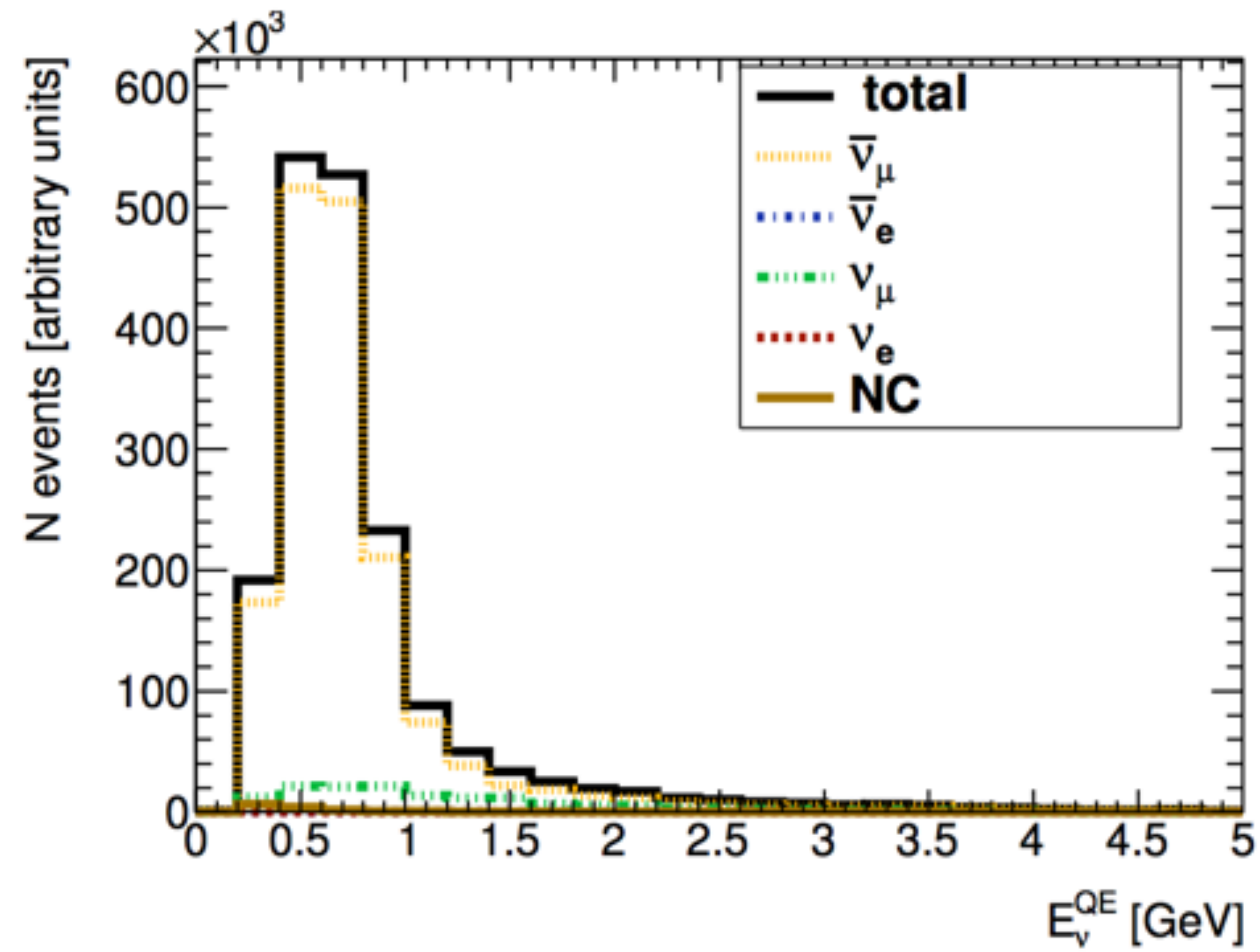
Selection with the addition of neutron tagging:

Anti-neutrino mode

- In RHC, 23% wrong-sign in 1Rμ selection
- Reduce to 8% by requiring ≥1 tagged neutrons
- Signal/BG almost doubles from 1.5 to 2.7



(b) $N_{\mathrm{neutrons}} = 0$

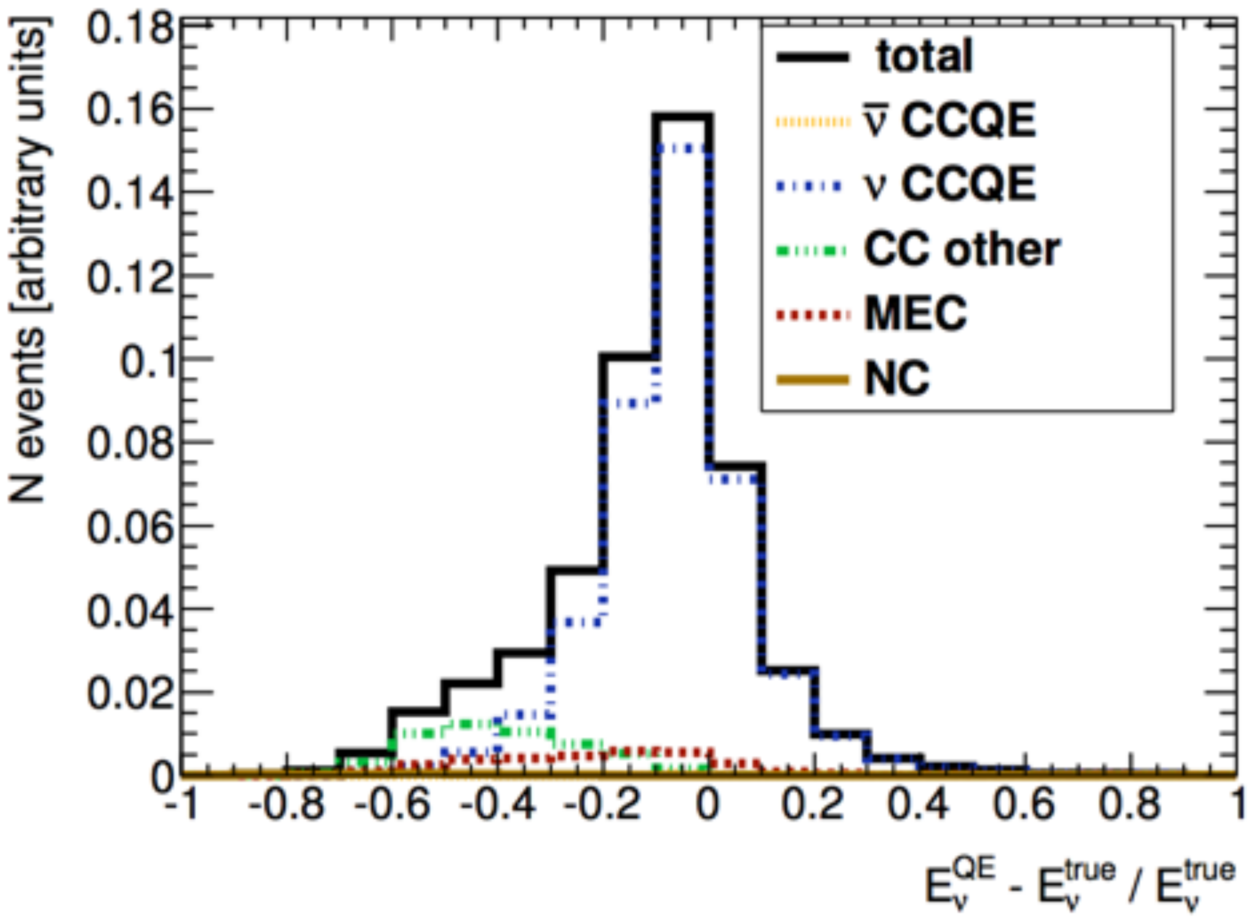


(c) $N_{\mathrm{neutrons}} \geq 1$

Selection with the addition of neutron tagging:

Neutrino mode

- In FHC, 24% CCother in 1Rμ selection
- Reduce background by requiring 0 tagged neutrons
- Signal/BG increases from 2.9 to 4.8
- Improved neutrino energy reconstruction(QE assumption)



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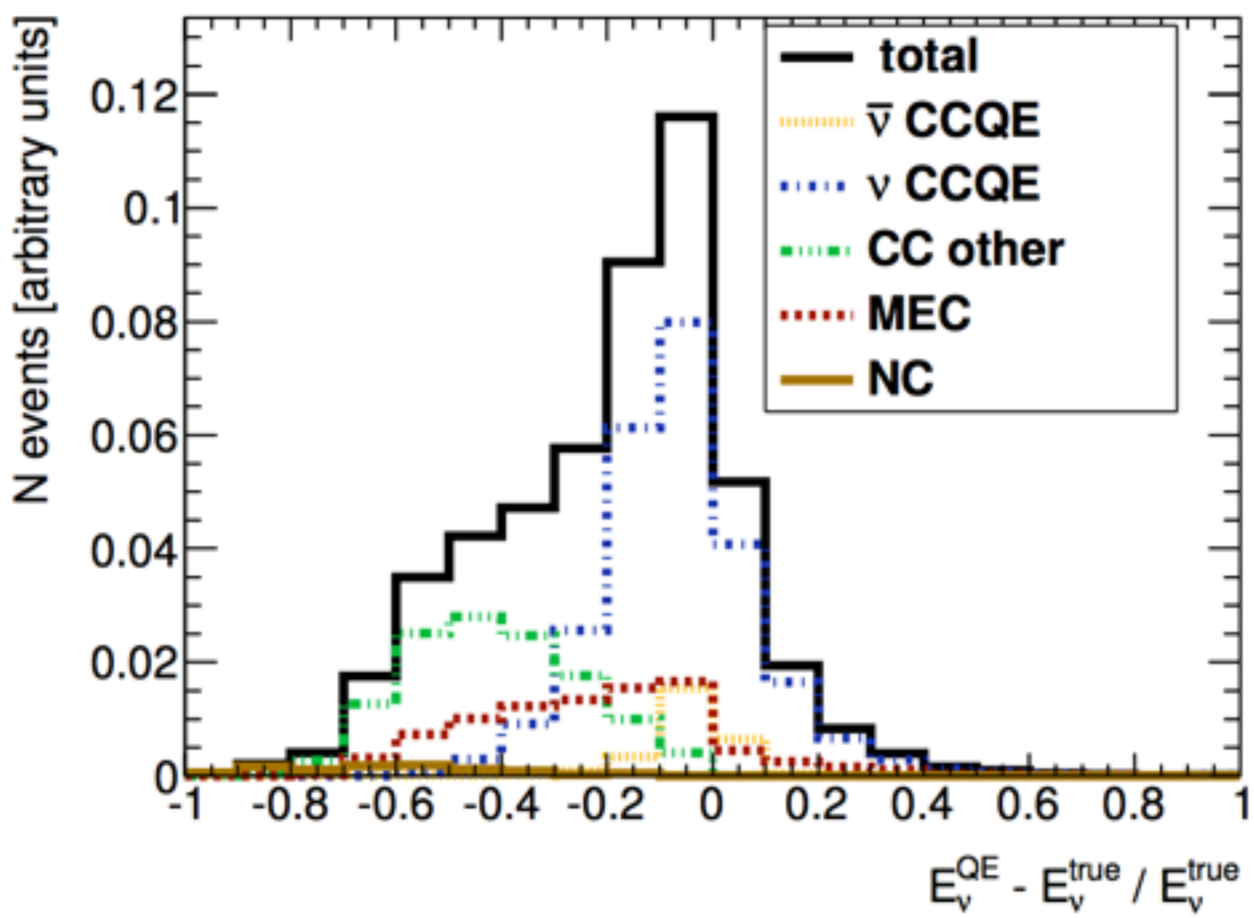

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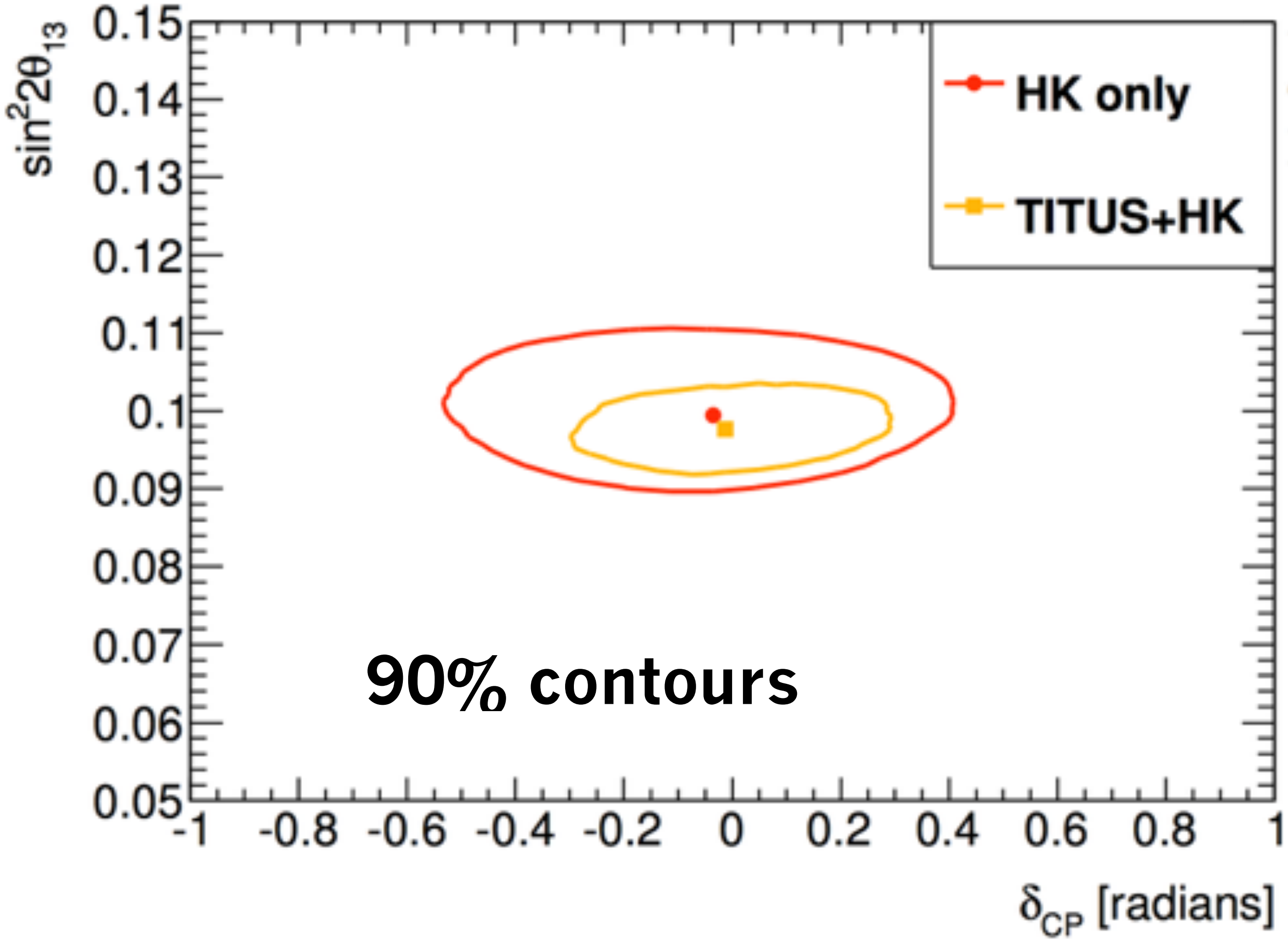
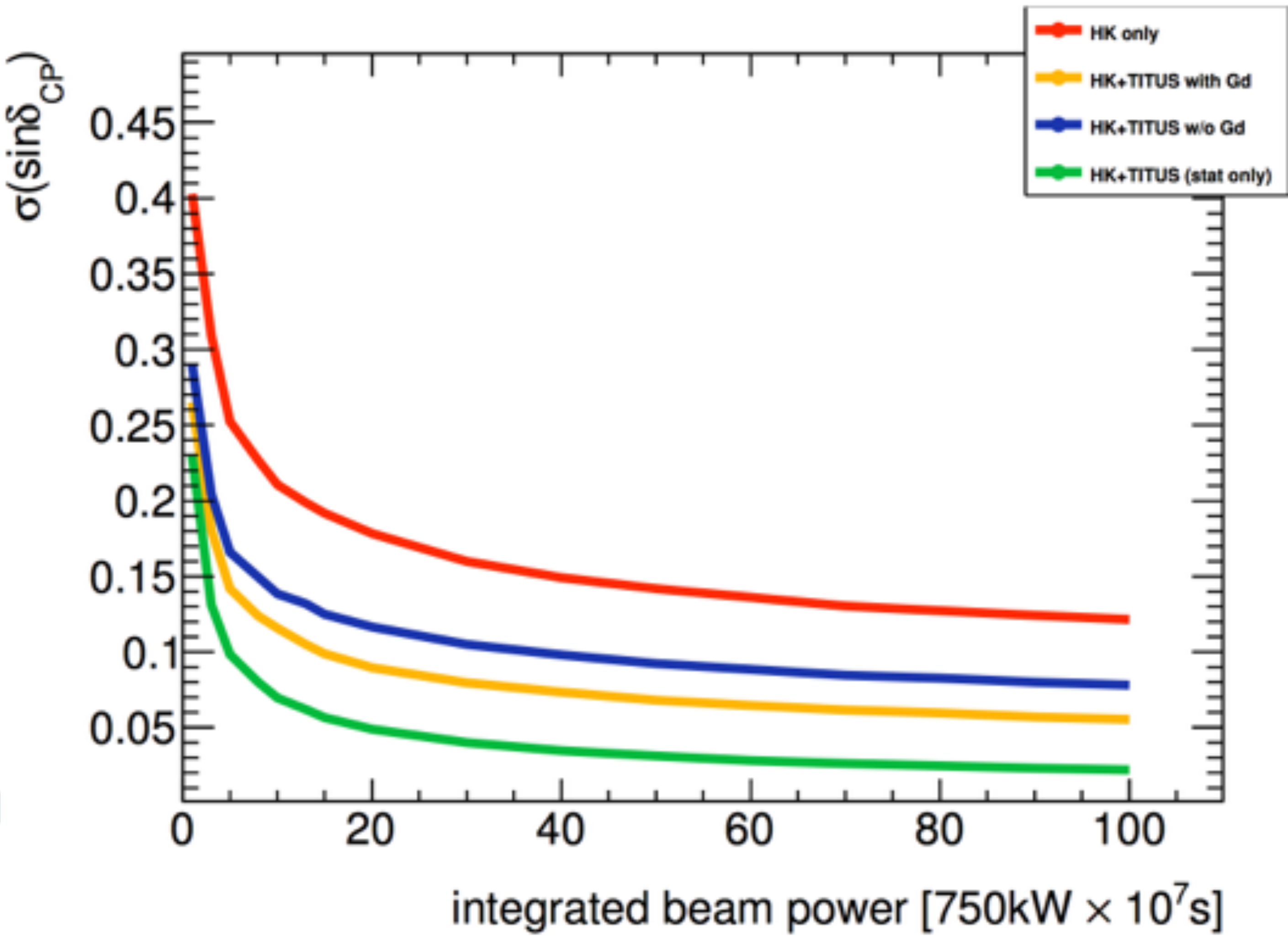
Constraining δ_{CP}





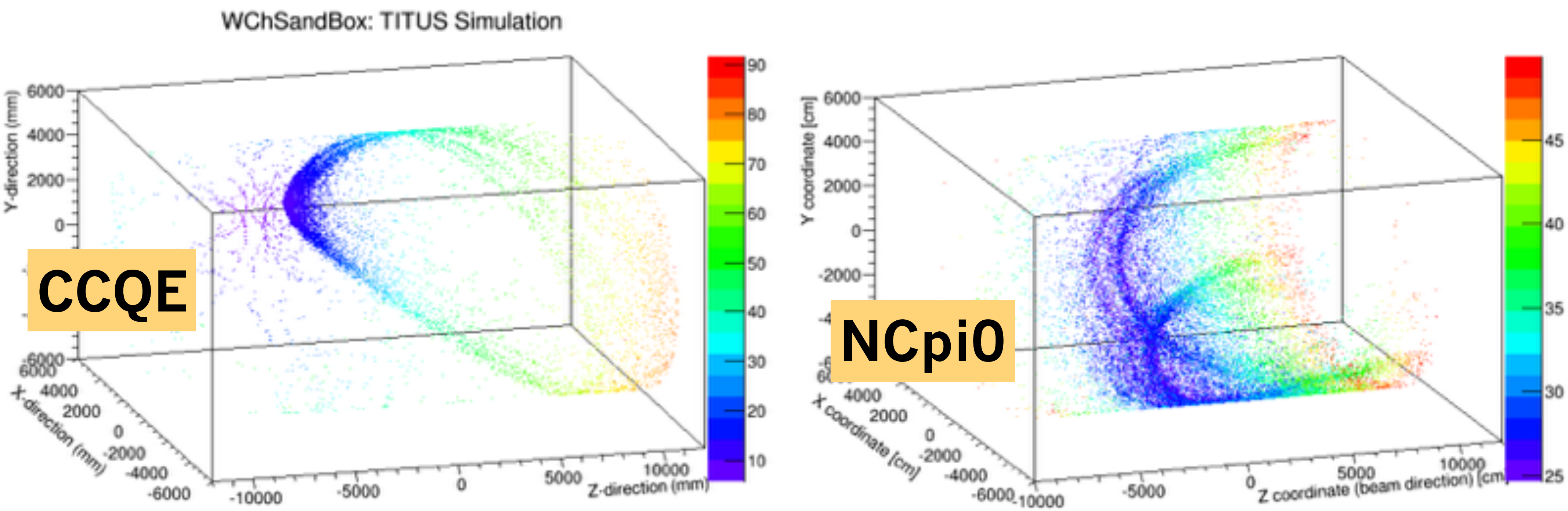
10 years at 750kW
Equal POT FHC:RHC

17% precision improvement due to neutron tagging

For δ_{CP}=0, achieve 0.22 radians precision with HK only
Addition of TITUS gives 0.14 radians precision (36% improvement)

Full TITUS reconstruction

- newly developed full reconstruction developed by TITUS group
- Based on the ANNIE reconstruction code
- new T2K NIWG 2015 model
- Zero correlation between TITUS and HK detector and FSI effects
- 1:3 POT ratio

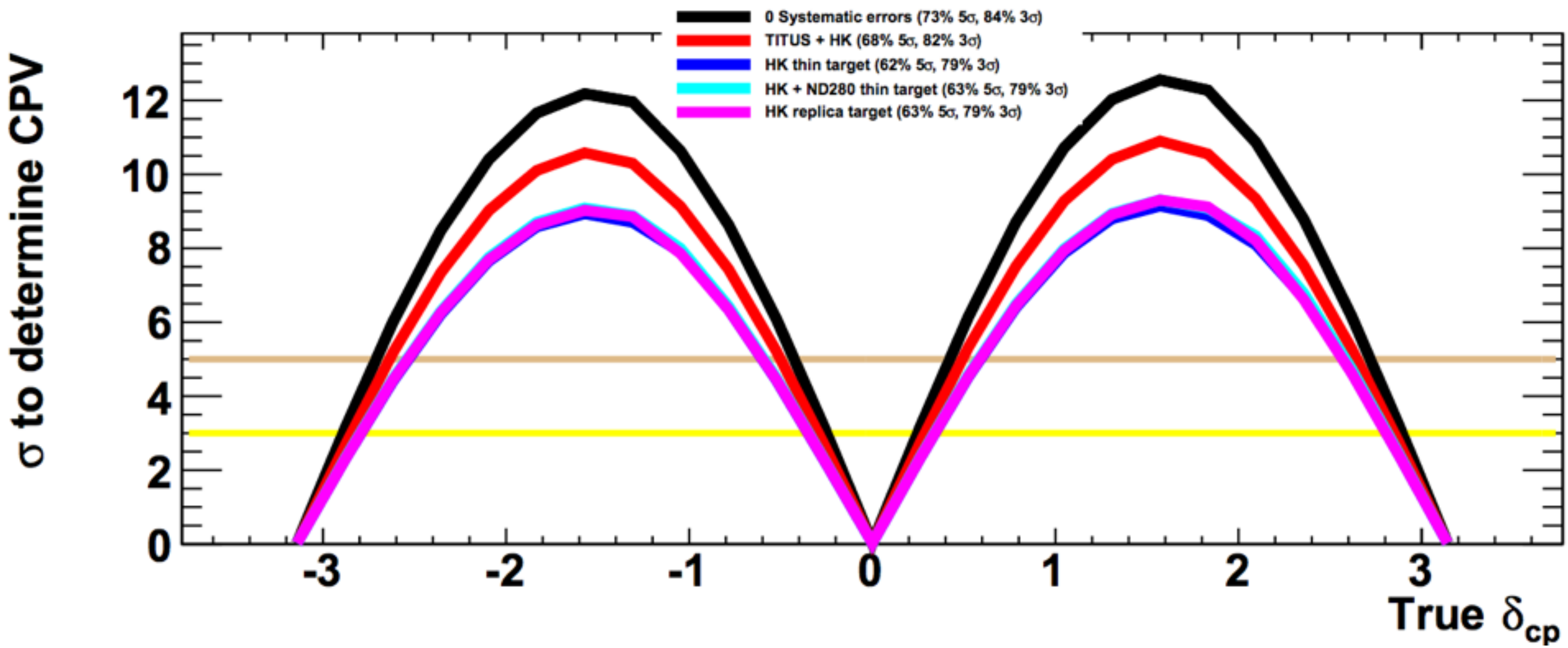


plus photosensor simulations…

Nick Prouse, Wing Ma

Significance to exclude sin $\delta_{CP} = 0$

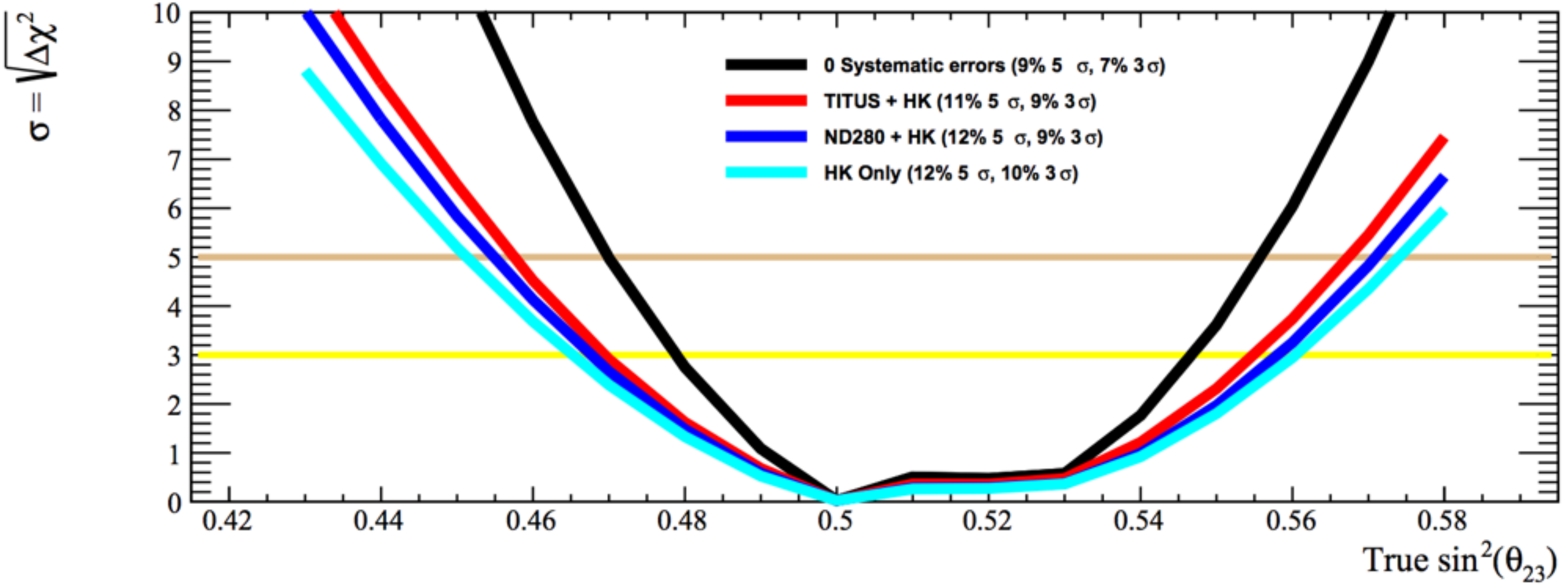
preliminary



These sensitivities will improve with the addition of the outer detector and magnetized MRD to the simulation

Significance to exclude $\sin^2\theta_{23} = 0.5$

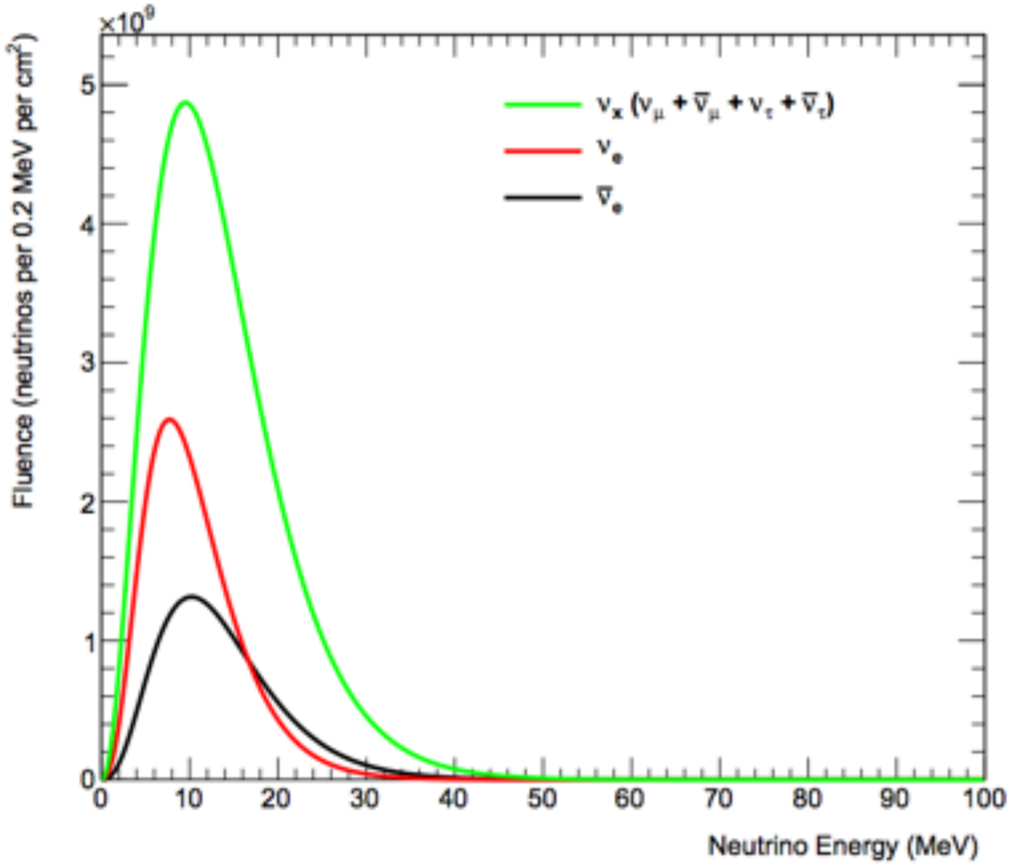
preliminary

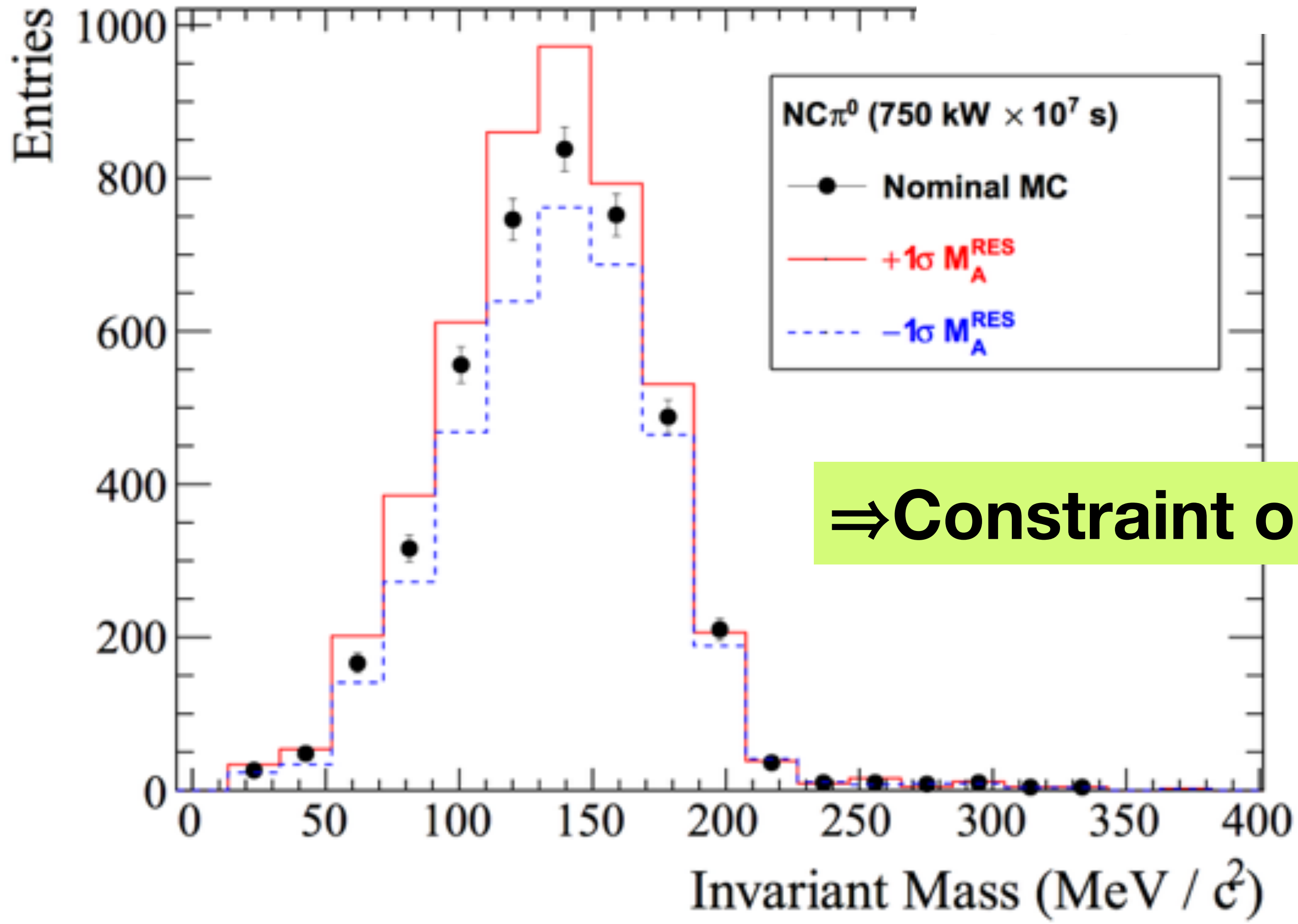


These sensitivities will improve with the addition of the outer detector and magnetized MRD to the simulation

Other TITUS work in progress
all preliminary

Total predicted neutrino flux for 11.2 solar mass progenitor mass star at a distance of 10 kpc





⇒Constraint on M_A

xsections

- TITUS provides a 4π angular acceptance and ability to classify event topologies.
- A statistical separation of interaction types based on neutron multiplicity provides a new way to measure exclusive differential cross-sections by Cherenkov detectors
- It could provide the first measurement of genuine CCQE cross-section by a Cherenkov detector.
- It is also expected that the inelastic channels accompany with nucleon emissions. Detailed measurements of neutron multiplicity also opens a way to study inelastic channels, mainly Delta resonance.
- Work so far concentrated on software/reconstruction tools and beam physics.
- We can start to address xsections, $NC\pi^0$, ratio of ratios $(\nu_e/\nu_\mu)/(\bar{\nu}_e/\bar{\nu}_\mu)$, ratios ν_e/ν_μ, $\bar{\nu}_e/\bar{\nu}_\mu$, CCQE-dominated $CC0\pi$, CCRES, etc.

And let's finish up with some general considerations…

What do the general HK sensitivity studies say?

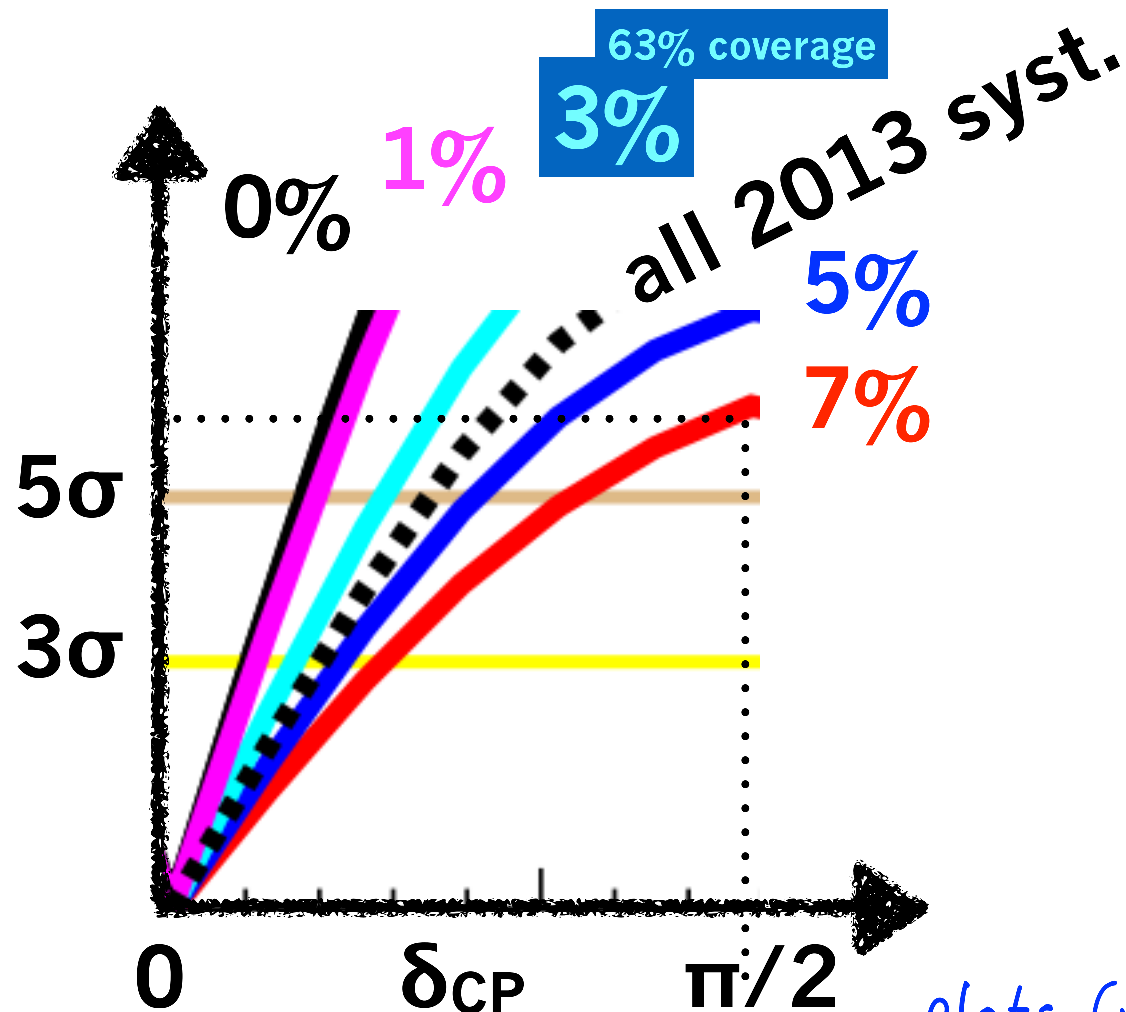
What are the most important things for the near detector(s) to constrain?

- Intrinsic ν_e background has potential to limit sensitivity
- Wrong sign background and High E have equal contribution to sensitivity (at 10% error)
- Intrinsic ν_e - <10% uncertainty required, <5% ideal
- High E (>1GeV) - < 5% would be an improvement
- Wrong sign background - Ideal constraint below 5%, 20%-50% much worse

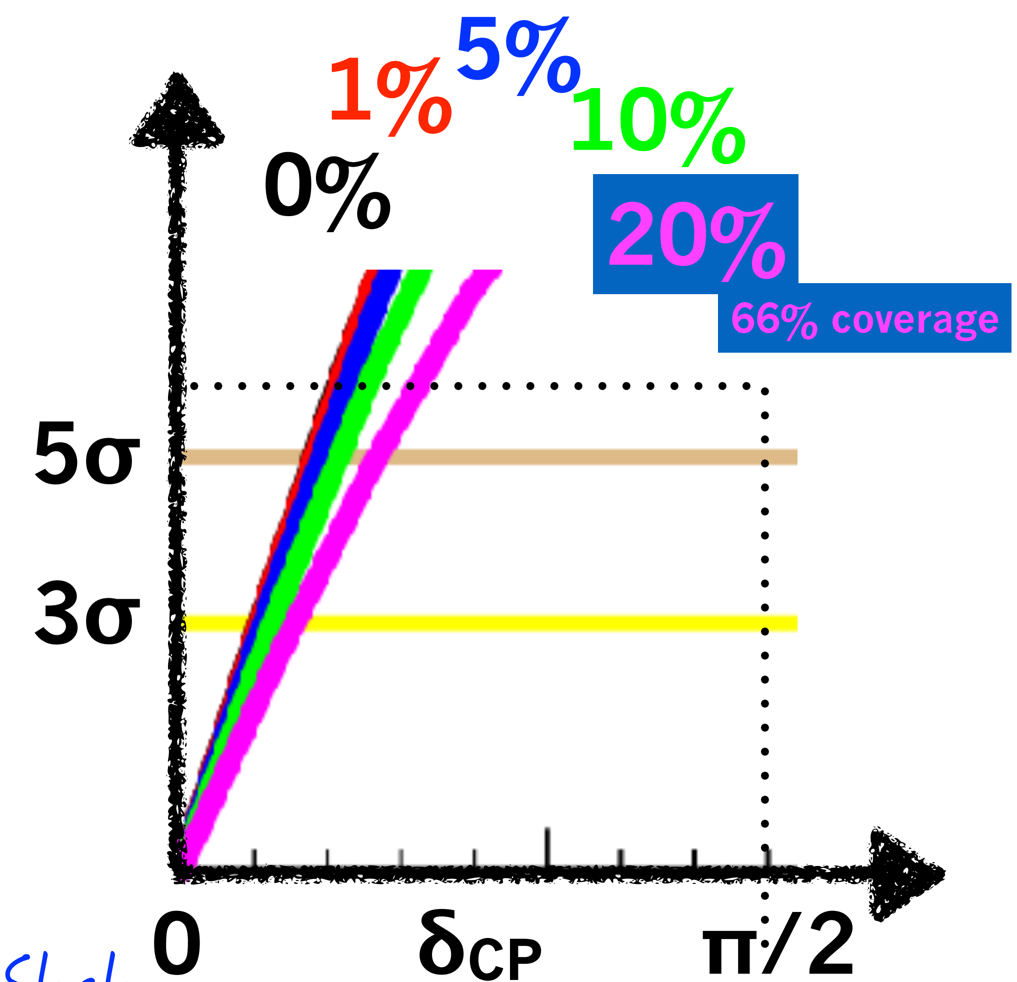
Raj Shah, VALOR sensitivity studies
1st Hyper-Kamiokande Proto Collaboration Meeting

Oscillating and intrinsic ν_e

Effect of prior uncertainty on $\sigma(\nu_e)$ and (independently) $\sigma(\bar{\nu}_e)$



Effect of prior uncertainty on intrinsic ν_e flux below E = 1 GeV

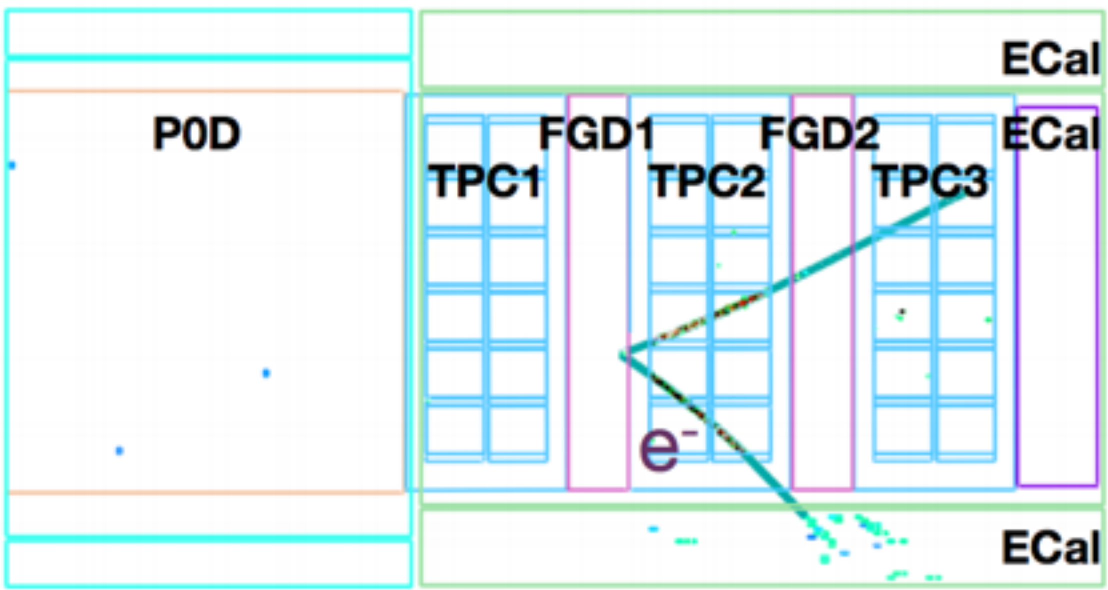


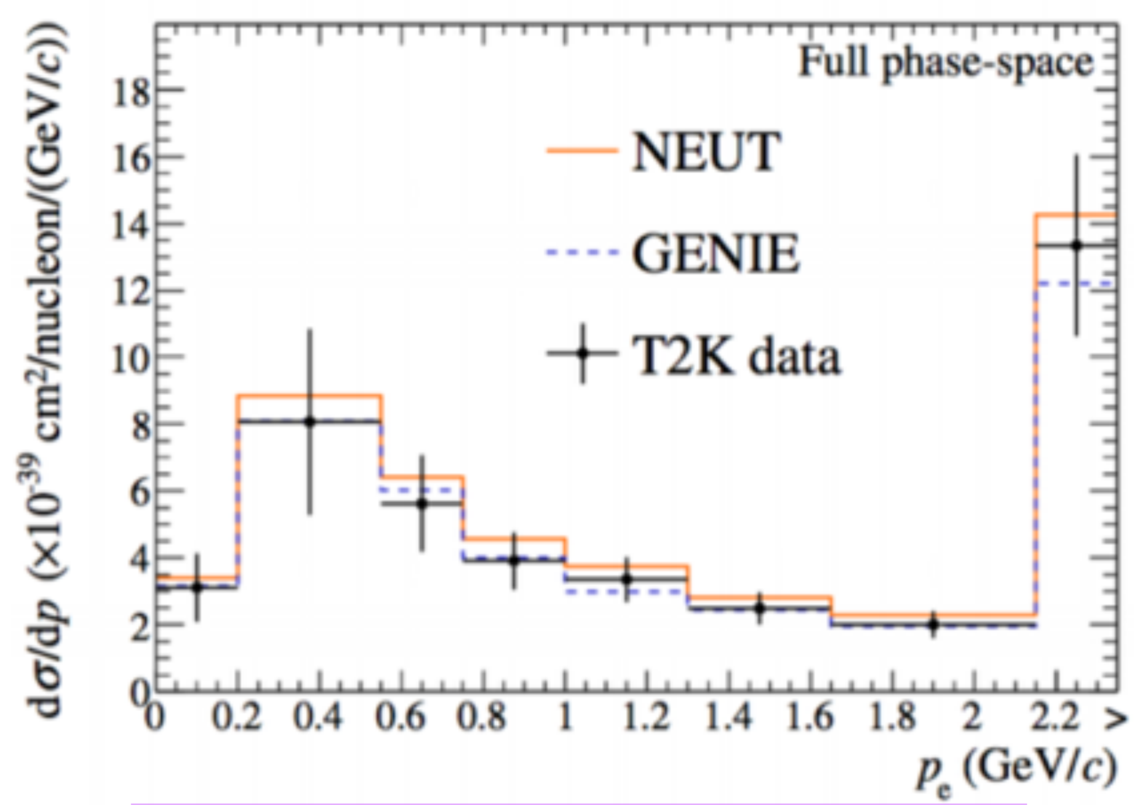
plots from Raj Shah

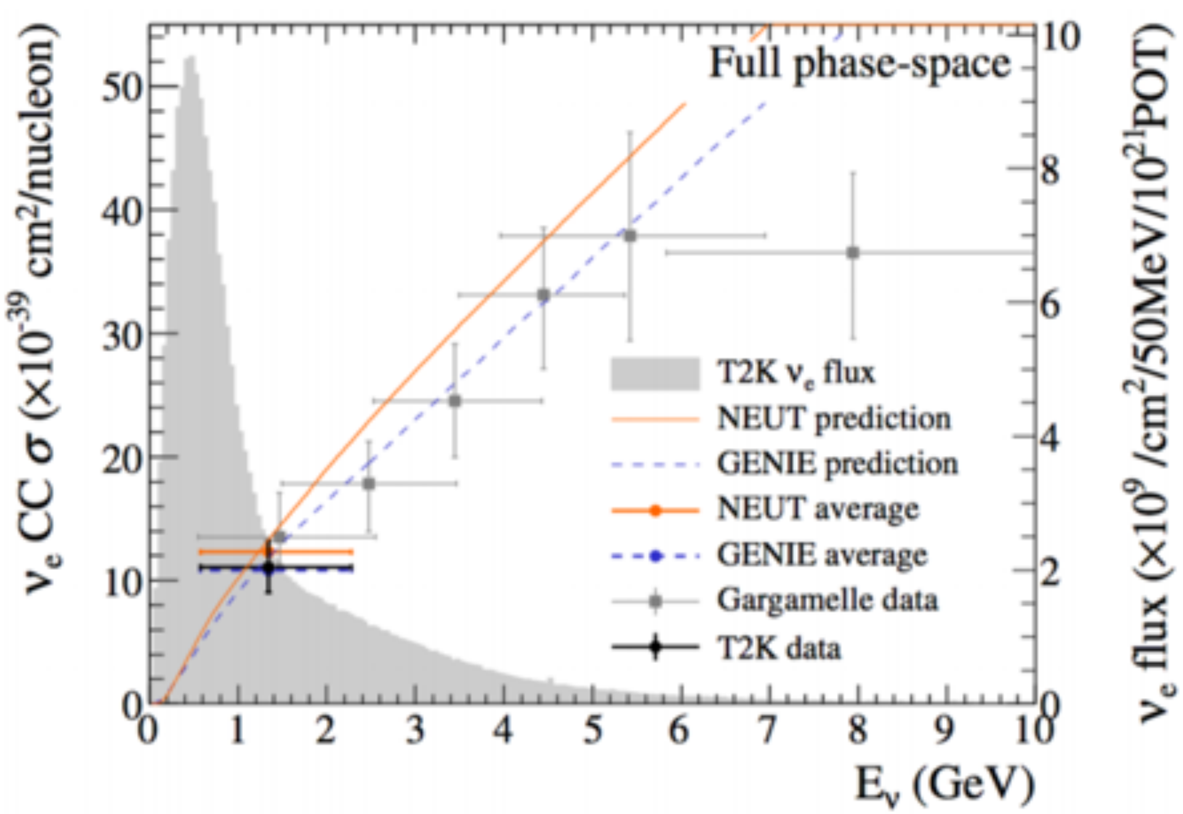
(max [zero systematics] δ_{CP} coverage for 5σ observation of CPV is 77%)

3% prior uncertainty on the cross section does as much damage to CPV sensitivity (~10% coverage of δ_{CP}) **as 20% uncertainty on the intrinsic flux**

Ben Smith has done an ND280 tracker analysis of this







- Sample is 65% pure CC ν_e
- Non-uniform acceptance
- Large BG from $\gamma \rightarrow e^+e^-$
- Largest uncertainties are:
  - *Flux (12.9%)*
  - *Statistics (8.7%)*
  - *Detector (8.4%)*

We need to pin down the intermediate detectors on this analysis!

We need a careful study of backgrounds

Another motivation for an intermediate detector:

ND280 has different energy resolution and acceptance to SK/HK

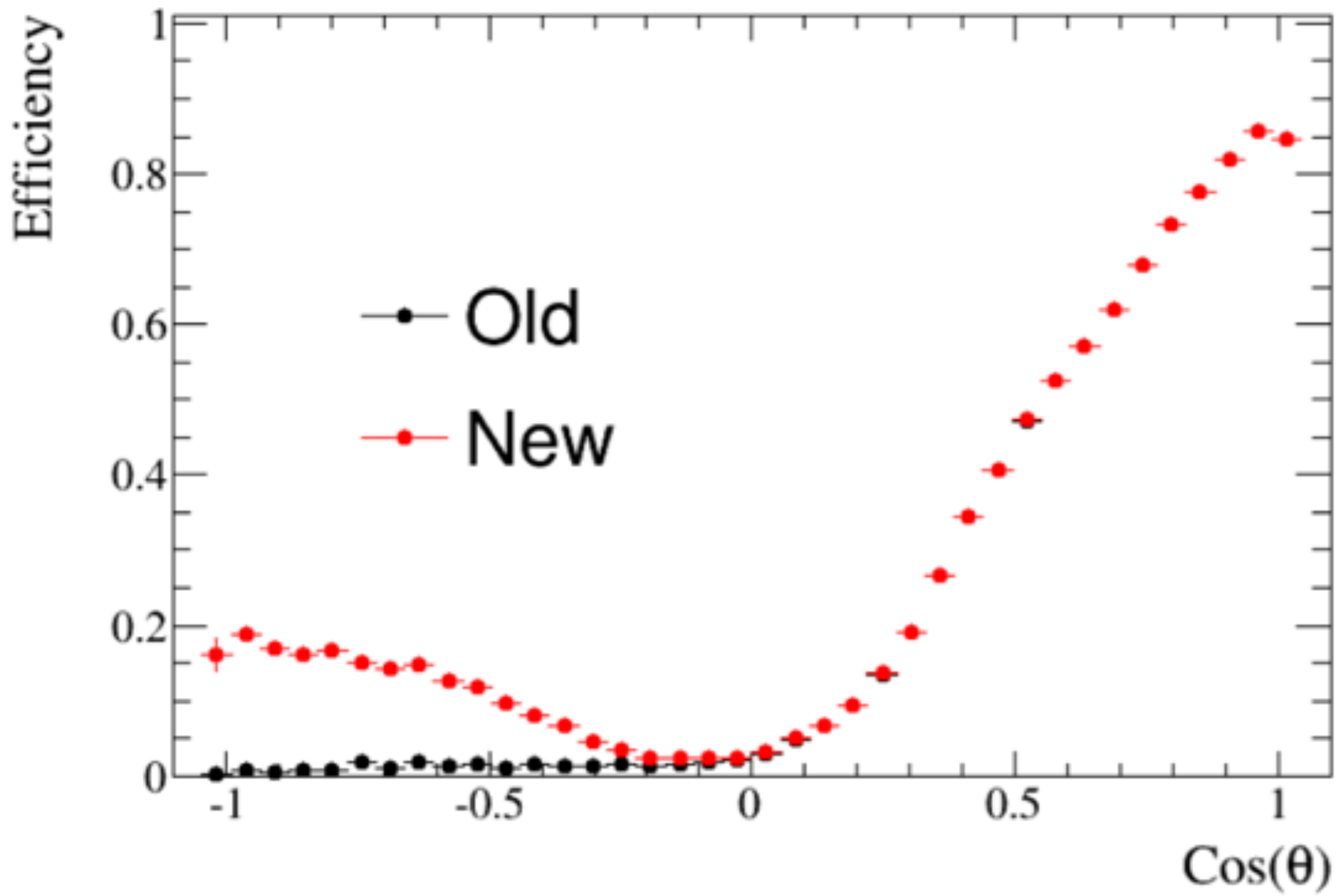
—Acceptance is currently limited to ± 53° (forward) for muons

—Extrapolation leads to model dependent error

—*Needs to be quantified: concerns ~30% of cross-section?*

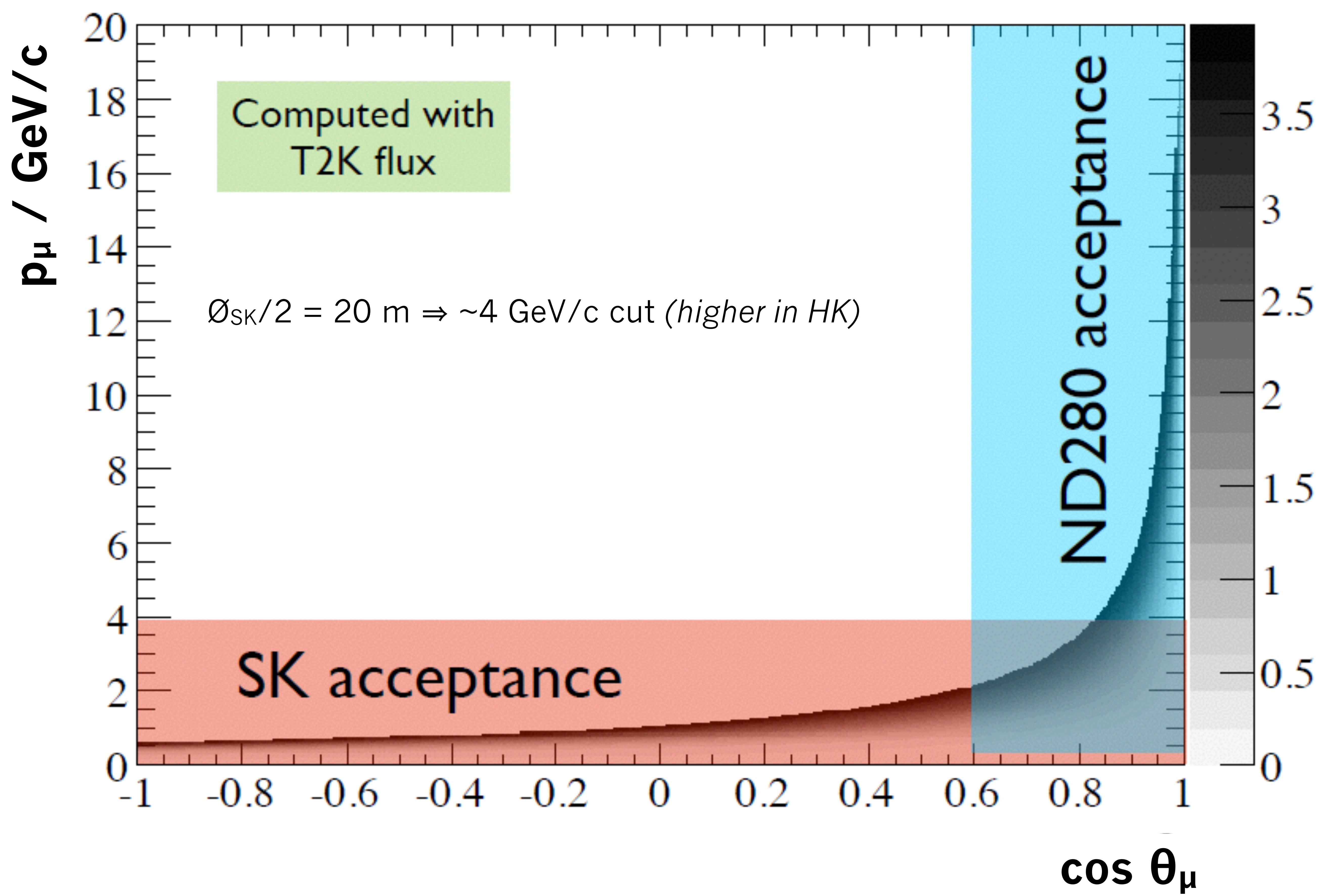
Improvements can only go so far with the present geometry

Momentum and sign determination are unclear



Even with the same detector, ambiguities remain, hence the benefit of nuSTORM or nuPRISM

Original plot from F. Sanchez's talk on RPA at the T2K CM



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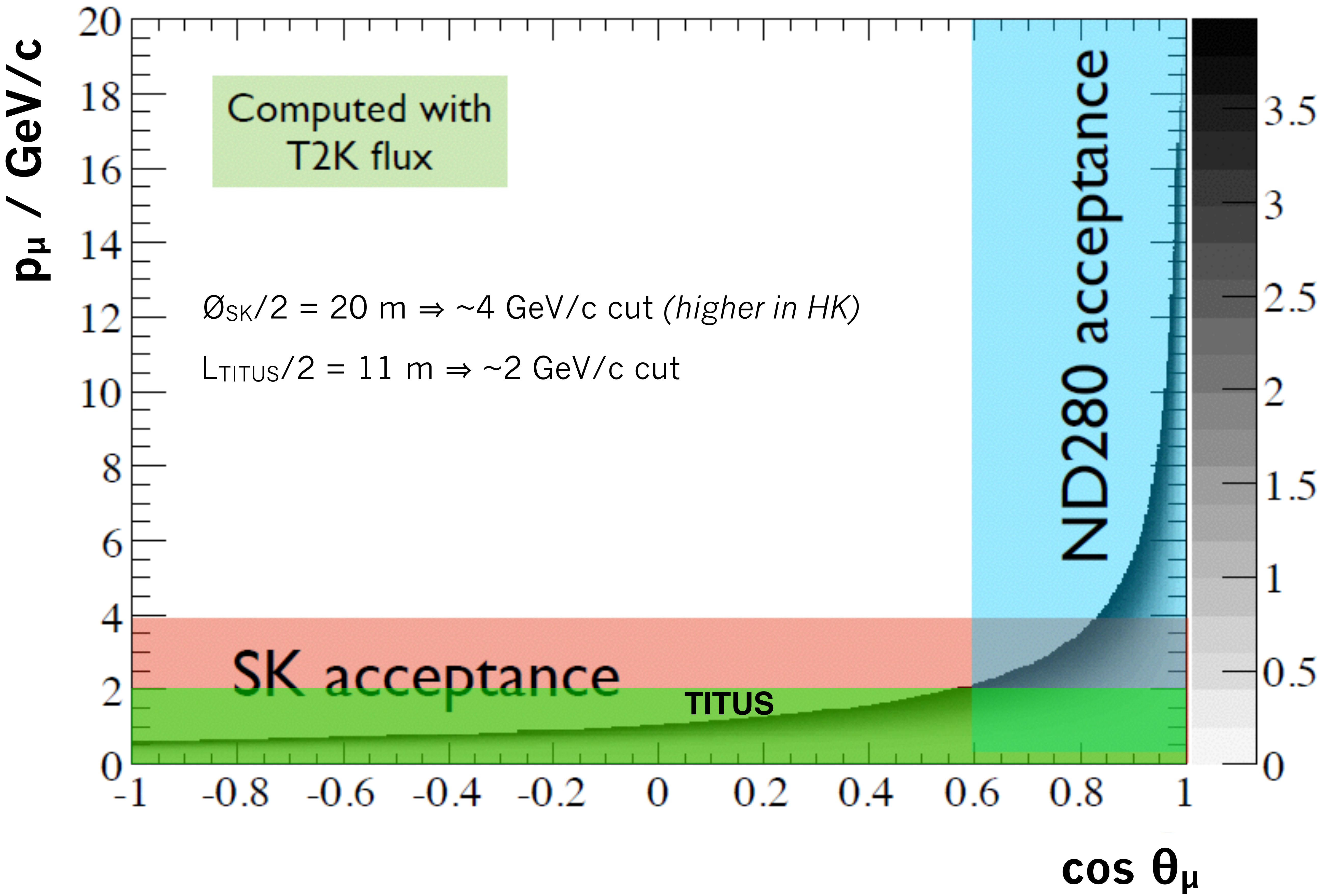

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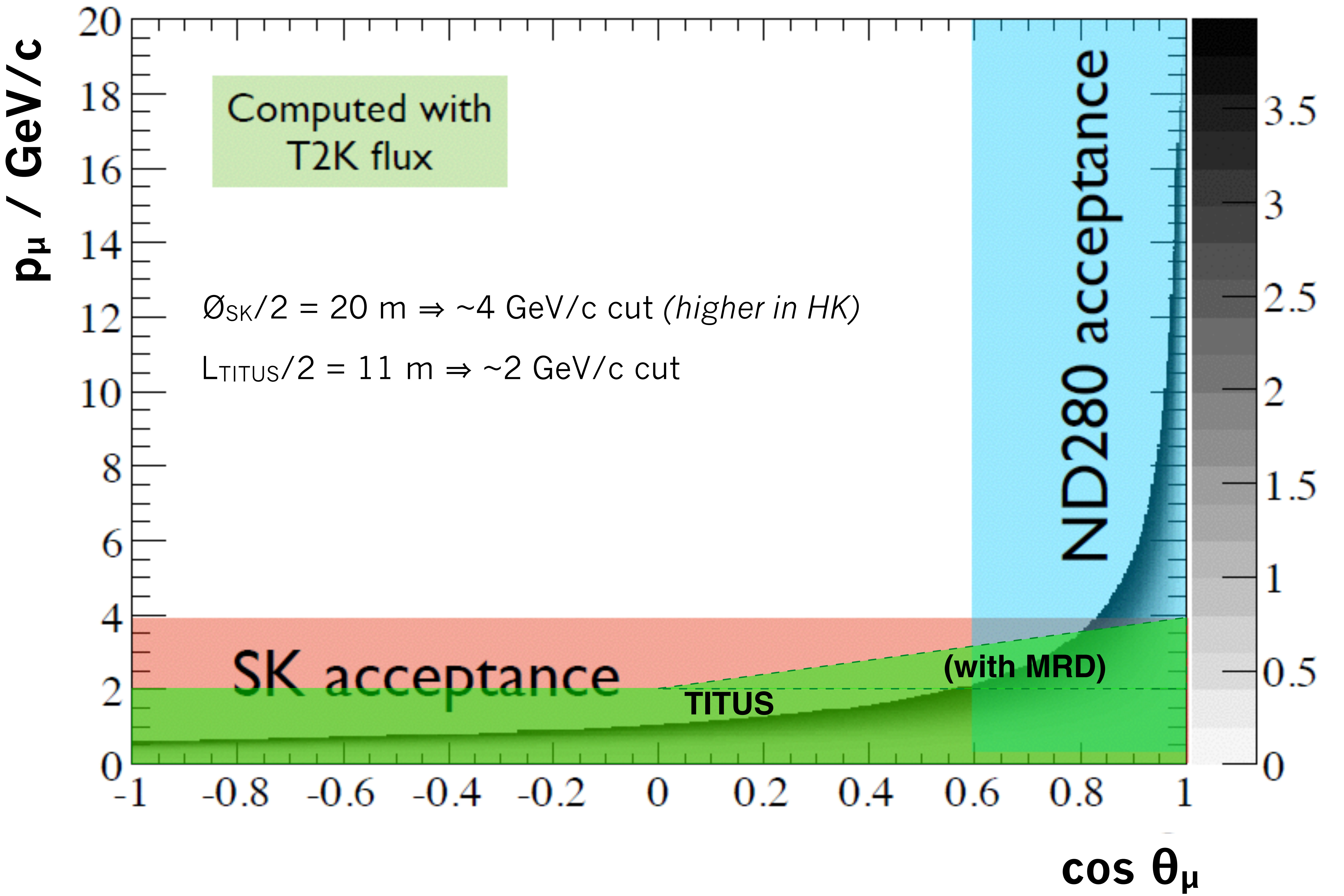

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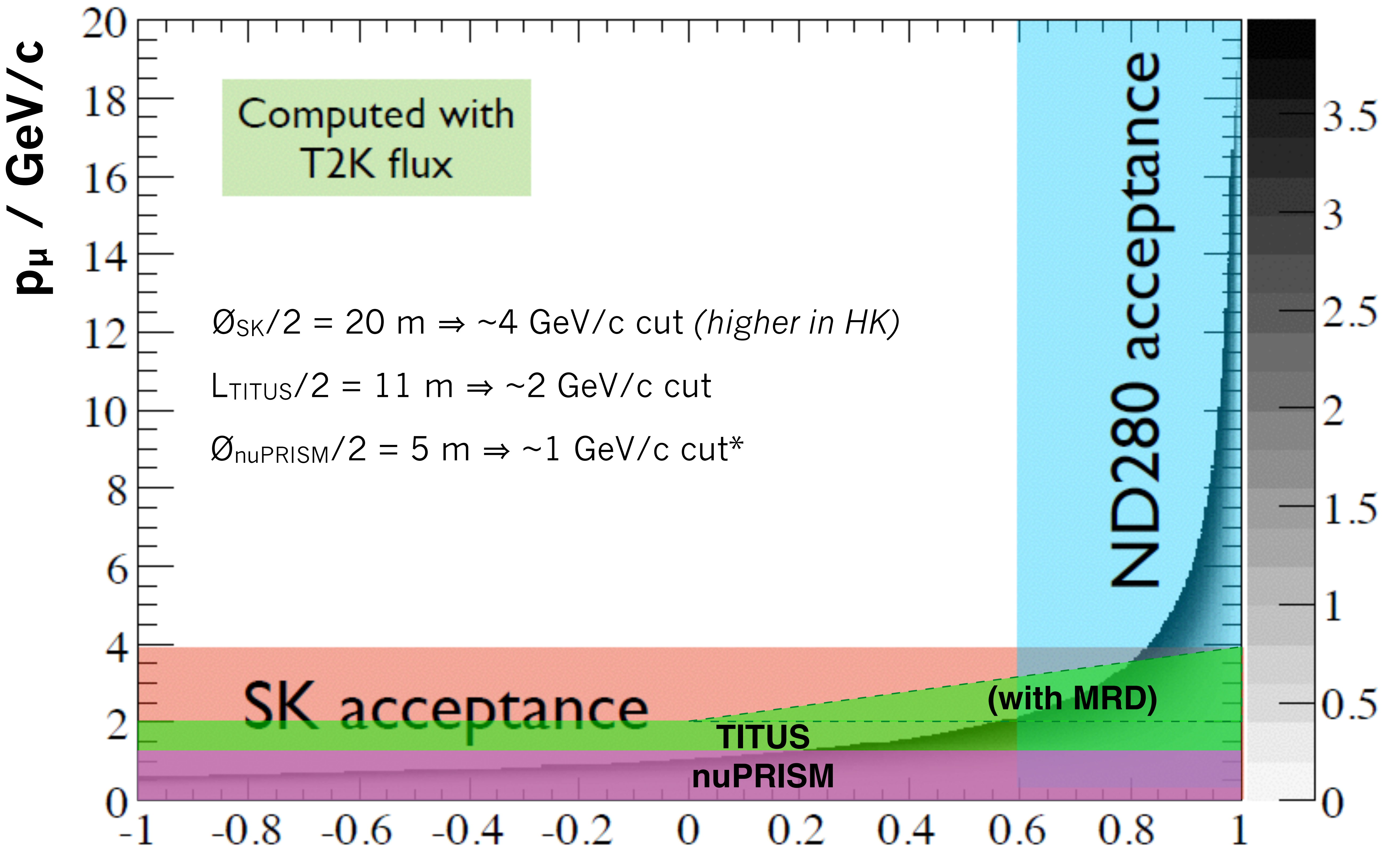

*Mark Hartz: *In the best case scenario where we have a 4 m ID radius and 1 m dWall cut, the maximum distance for forward muons to the to the wall is 7 m which corresponds to 1.4 GeV muons. At 1 GeV, the muon efficiency is pretty high.*

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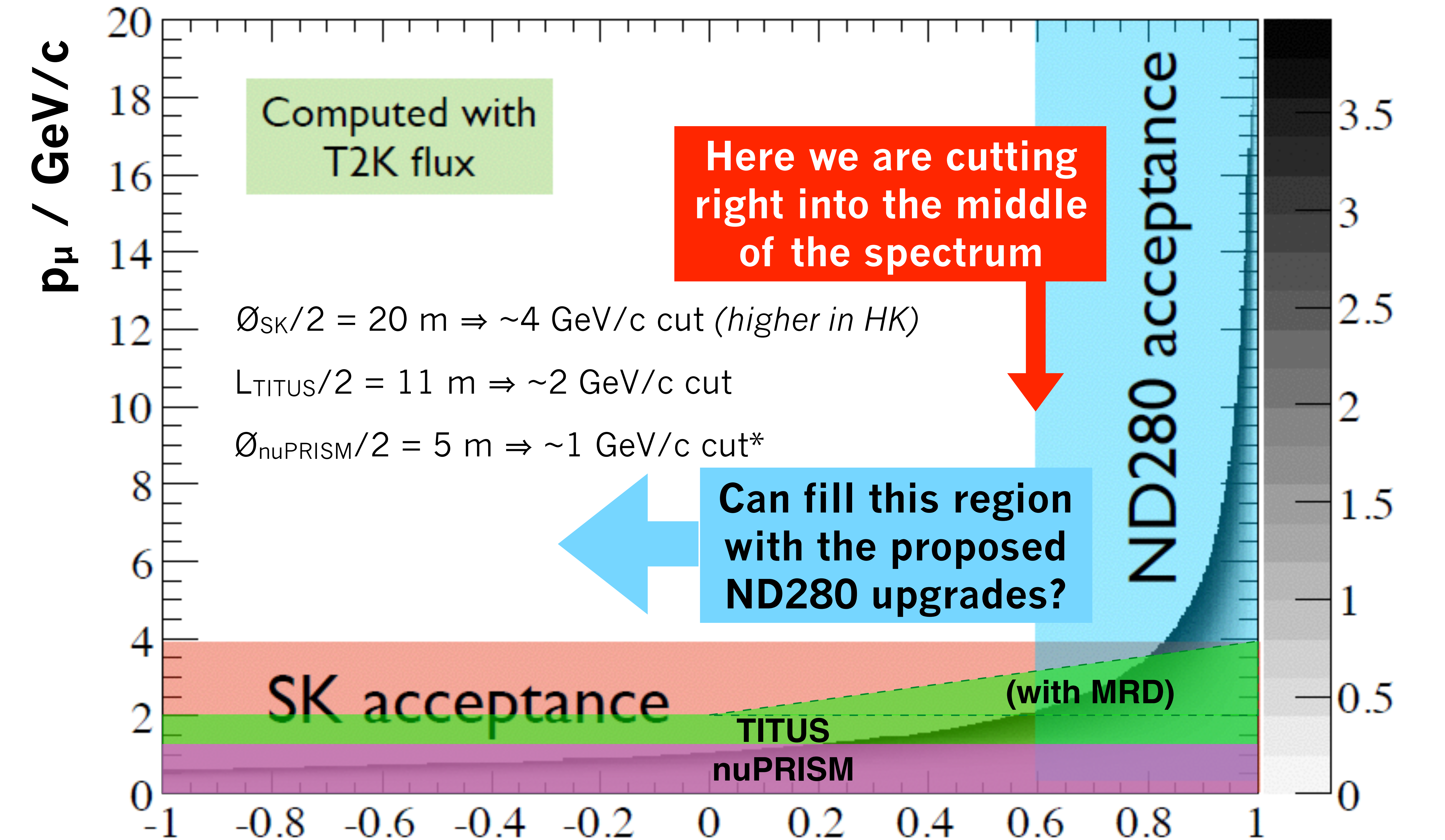

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Broad-brush reasoning, to provoke discussion...

Physics	Systematics	Detectors
sin δ_{CP} $\#\nu_e$	Wrong-sign BG High-E normalization Intrinsic ν_e	ND280 TITUS-like *low area/volume, mag. MRD*
	TITUS has lower OOFV BG $\sigma_{\nu e}/\sigma_{\nu\mu}$?? nuPRISM has more intrinsic ν_e at 4°	*optimization*
cos δ_{CP} *appearance* <E_ν> octant of θ_{23} *disappearance dip*	Interaction model (2p2h, RPA...) ⋮	nuPRISM-like *tall and thin* (nuSTORM)

Broad-brush reasoning, to provoke discussion...

Physics | **Systematics** | **Detectors**

sin δ_{CP}

$\#\nu_e$

cos δ_{CP}

appearance $\langle E_\nu \rangle$

octant of θ_{23}

disappearance dip

Wrong-sign BG

High-E normalization

ND280

Intrinsic ν_e

TITUS-like

low area/volume, mag. MRD

TITUS has lower OOFV BG

$\sigma_{\nu e}/\sigma_{\nu\mu}$??

nuPRISM has more intrinsic ν_e at 4°

optimization

nuPRISM-like

tall and thin

Interaction model (2p2h, RPA...)

(nuSTORM)

⋮

Broad-brush reasoning, to provoke discussion...

Physics | **Systematics** | **Detectors**

sin δ_{CP}

Wrong-sign BG

High-E normalization

ND280

* What is the optimal sythesis of nuPRISM and TITUS?
* Do we need upgraded ND280 <u>and</u> an intermediate detector?

$\sigma_{\nu e}/\sigma_{\nu\mu}$??

nuPRISM has more intrinsic ν_e at 4°

optimization

nuPRISM-like

tall and thin

cos δ_{CP}

appearance $\langle E_\nu \rangle$

octant of θ_{23}

disappearance dip

Interaction model (2p2h, RPA...)

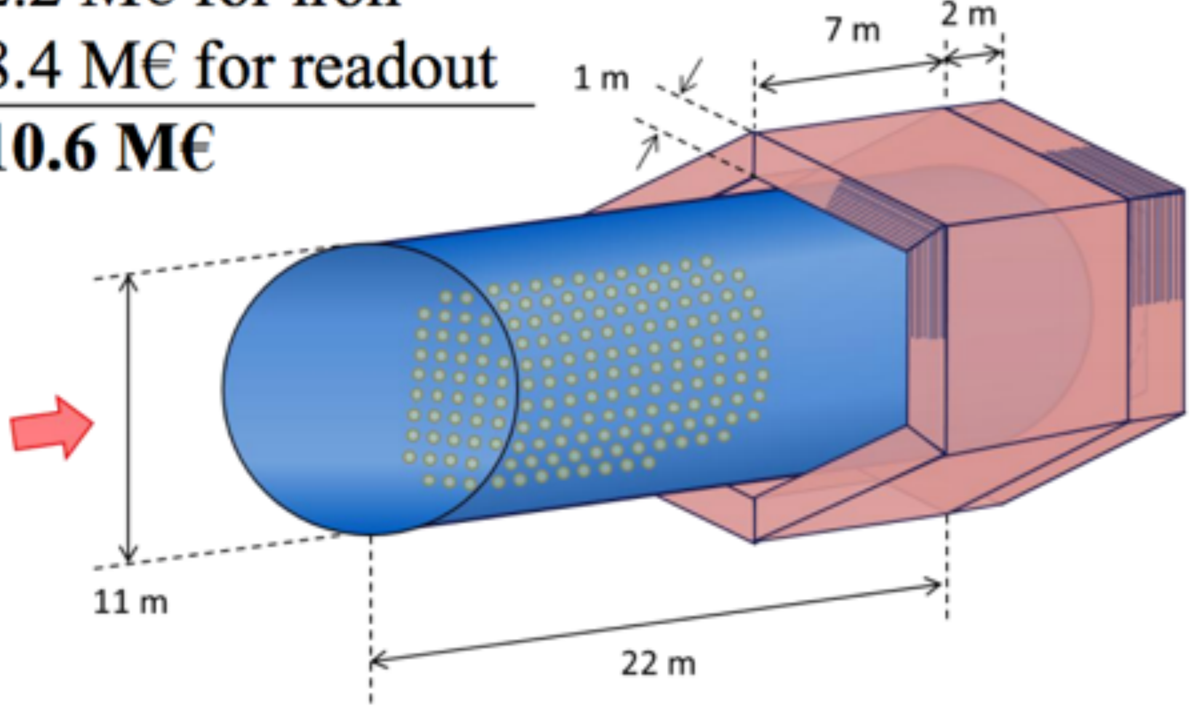
(nuSTORM)

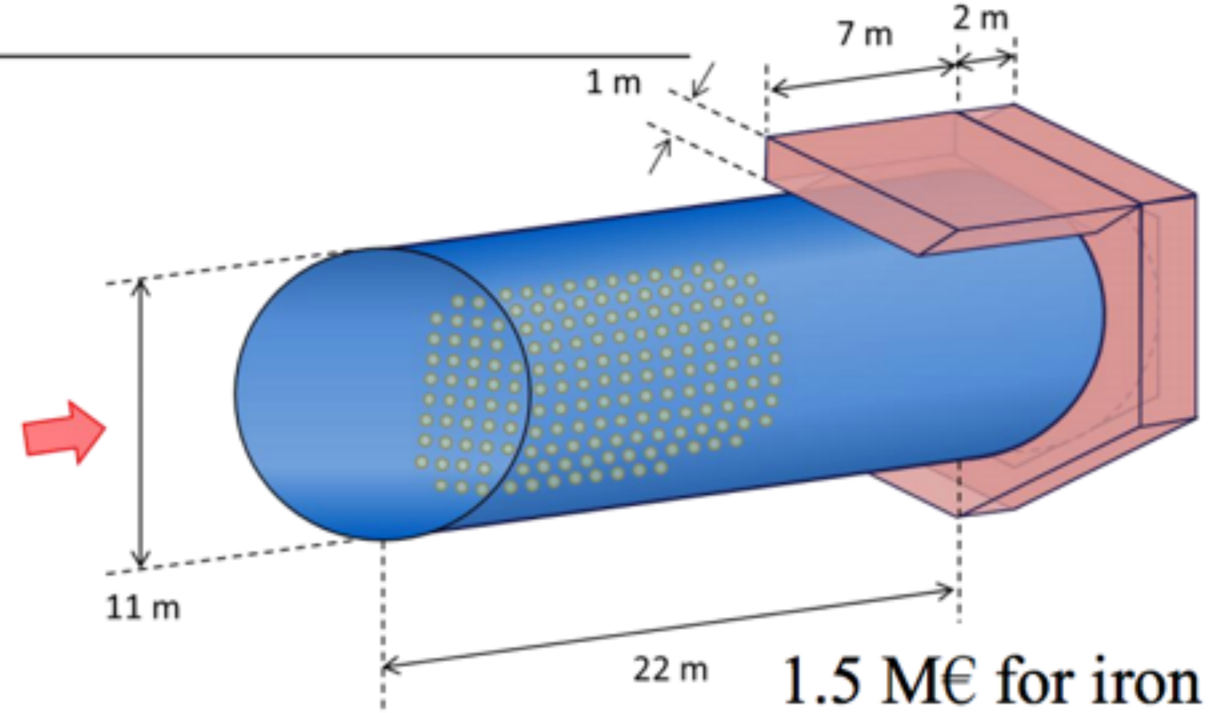
⋮

Backup slides follow

Rough, 'Ballpark' Cost Estimates

2.2 M€ for iron
8.4 M€ for readout
10.6 M€

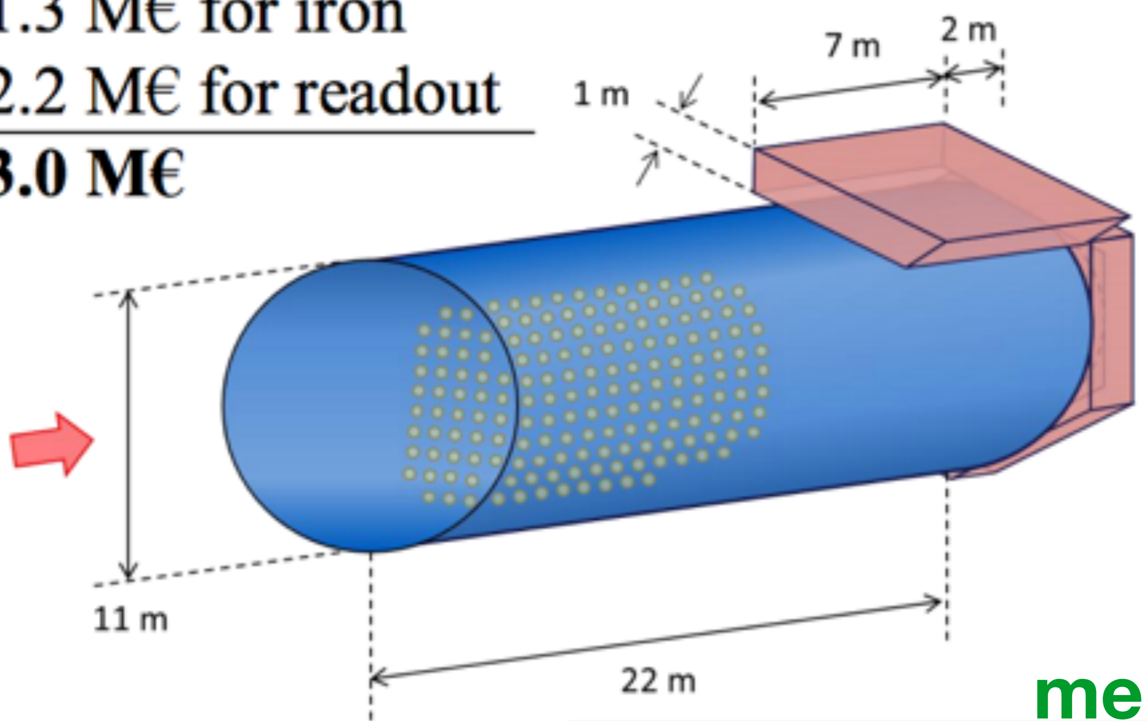


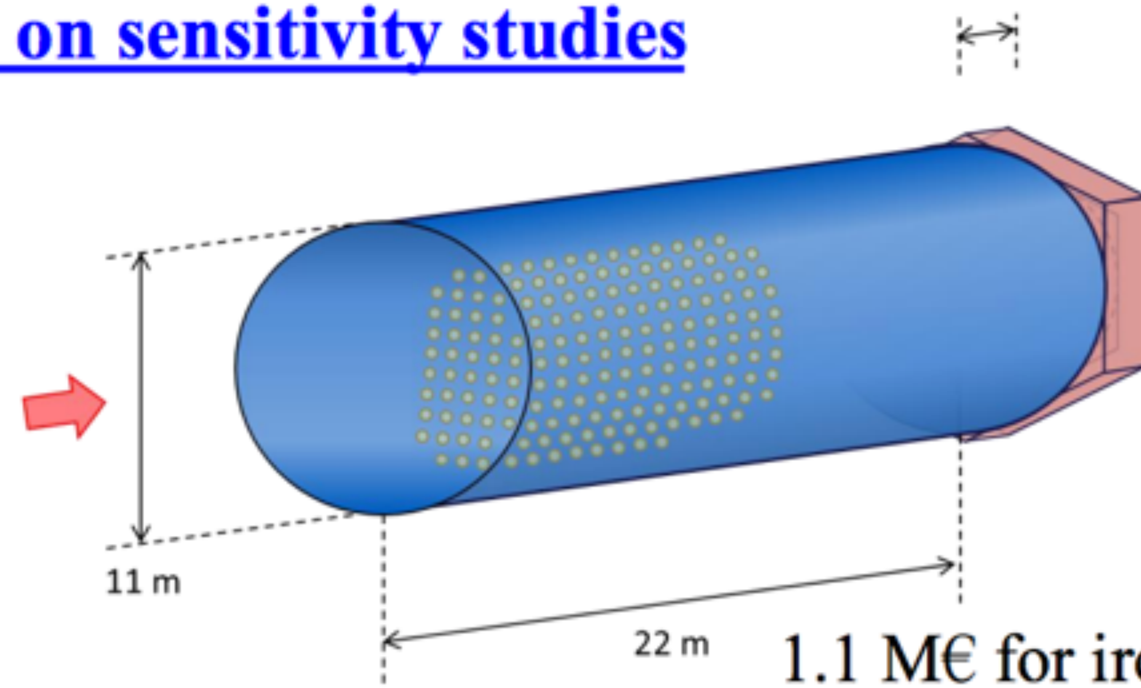


1.5 M€ for iron
2.5 M€ for readout
4.0 M€

We will decide based on sensitivity studies

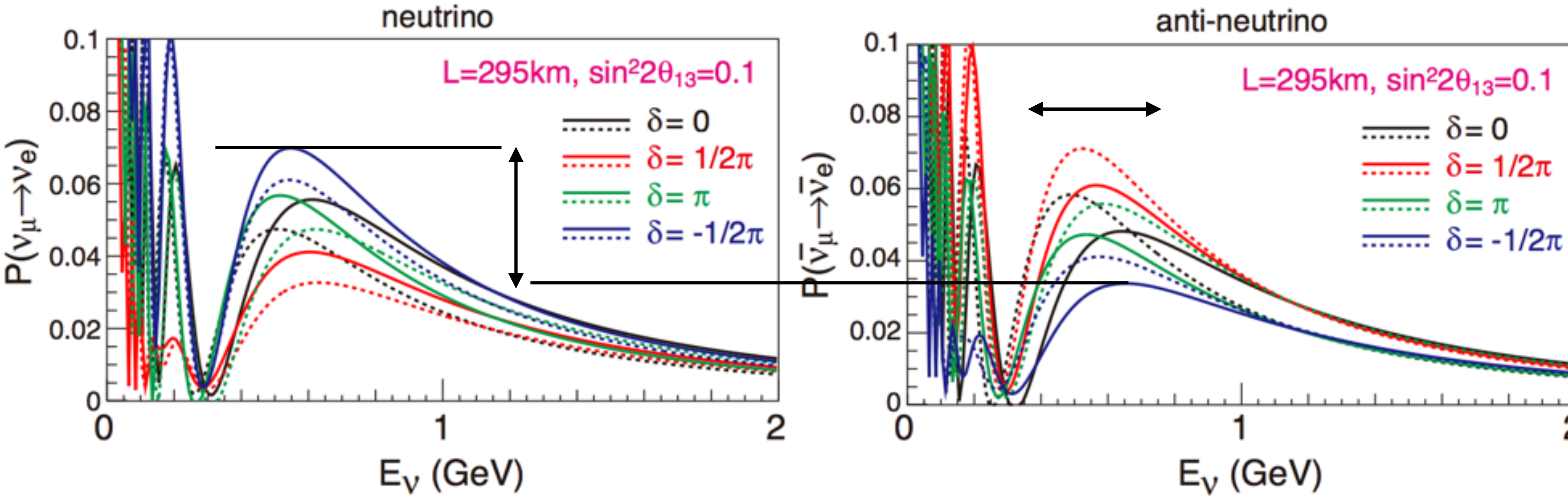
1.3 M€ for iron
2.2 M€ for readout
3.0 M€





1.1 M€ for iron
1.1 M€ for readout
2.2 M€

me, 6th open HK CM

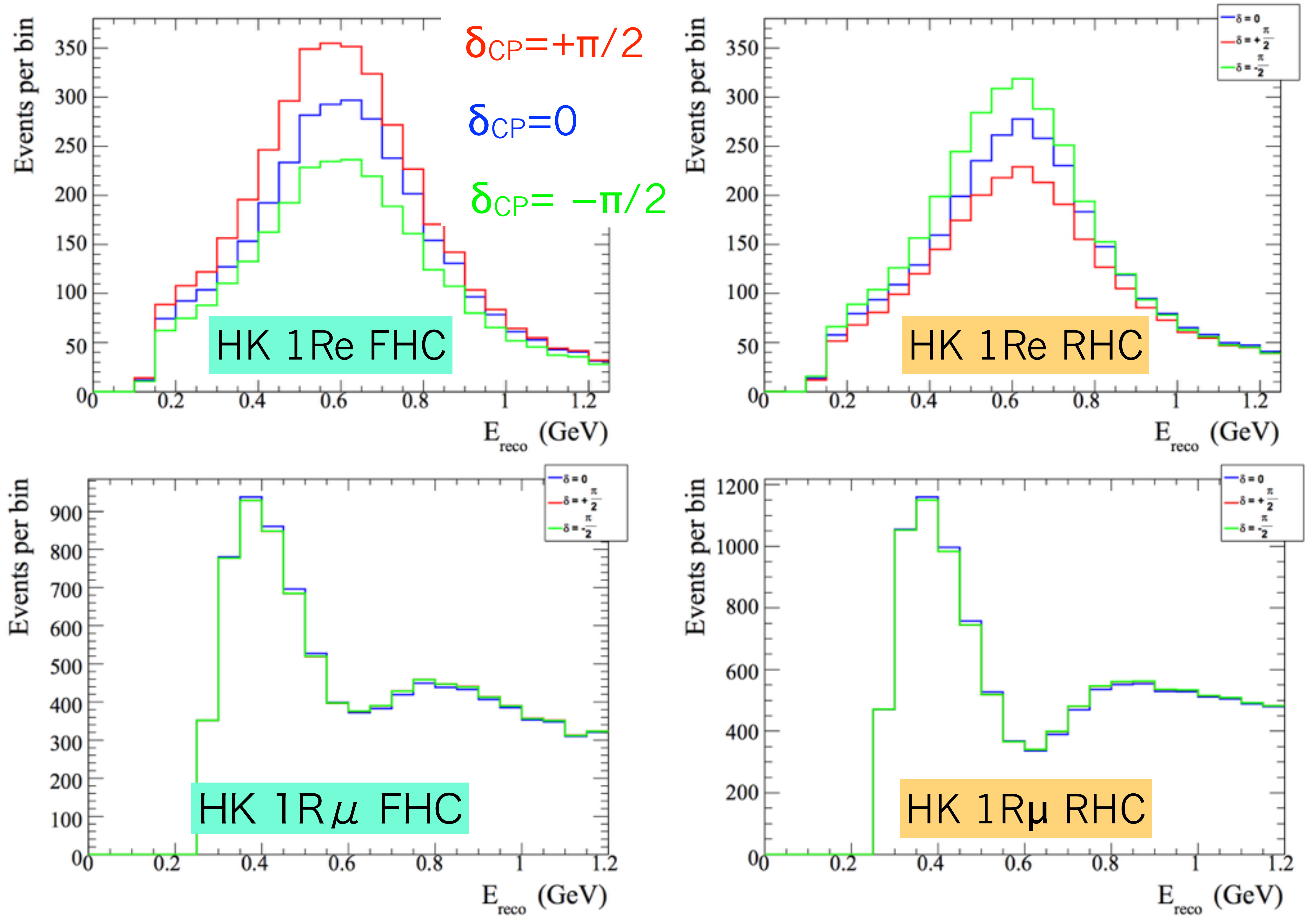


neutrino
L=295km, sin²2θ13=0.1
δ= 0
δ= 1/2π
δ= π
δ= -1/2π
P(νμ→νe)
Eν (GeV)
anti-neutrino
L=295km, sin²2θ13=0.1
δ= 0
δ= 1/2π
δ= π
δ= -1/2π
P(ν̄μ→ν̄e)
Eν (GeV)

Beam Assumptions

- Assume
  - horn current 320kA (ν mode), -320kA (ν mode)
  - 2.2×10^{14} POT /spill
  - Spill window 1.3μs, rep rate 1.3s
  - 8 bunches / spill
  - Bunch width (1σ) = 25ns

- 10 years running:
  - 1.56×10^{22} POT for a 30 GeV proton beam



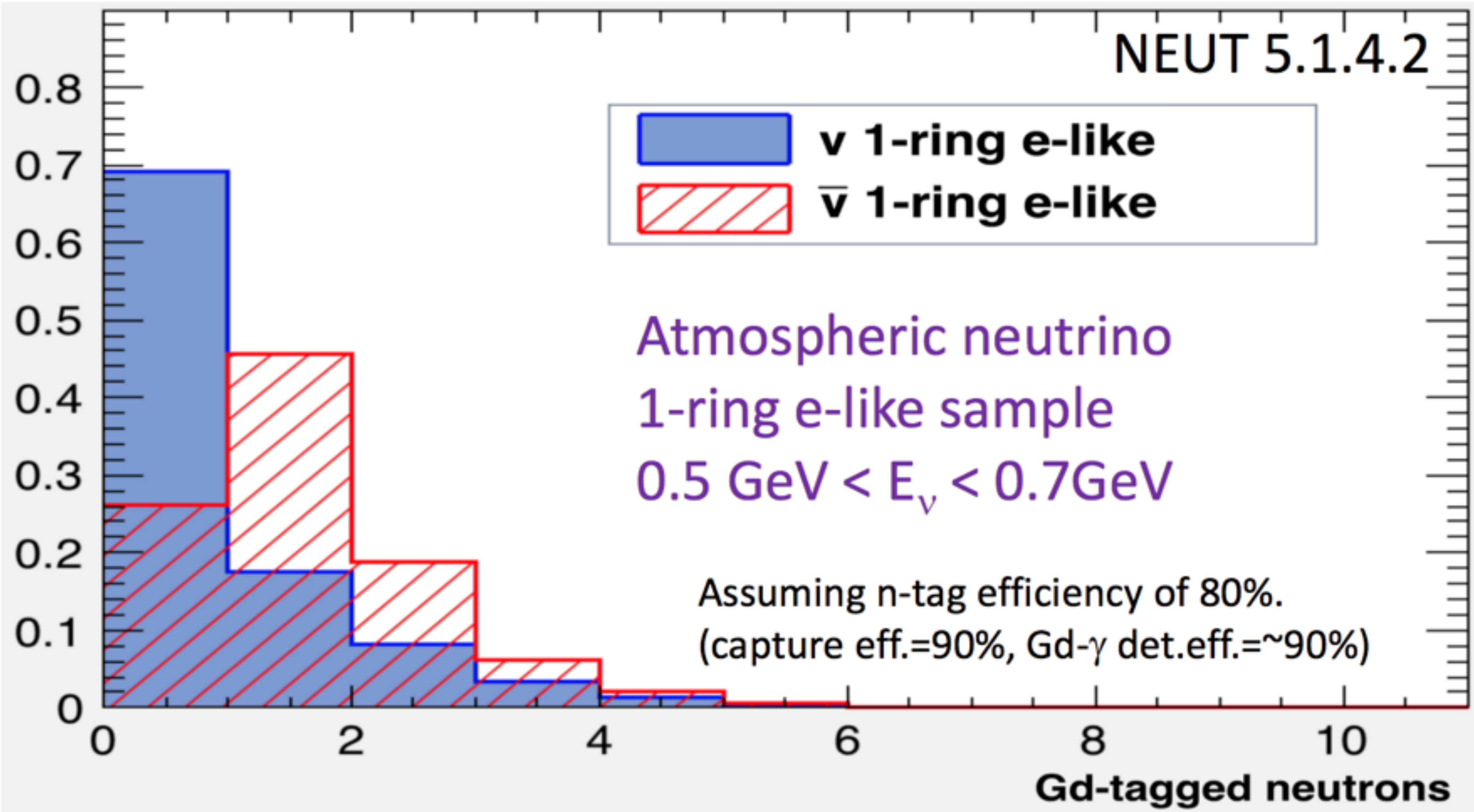
δCP=+π/2
δCP=0
δCP= −π/2
HK 1Re FHC
HK 1Re RHC
HK 1Rμ FHC
HK 1Rμ RHC
Events per bin
E reco (GeV)
δ = 0
δ = +π/2
δ = -π/2

Improvement for T2K

M. Ikeda, Tuesday

By Pablo

Number of tagged neutrons in T2K energy range



Using n-tagging information, $\bar{\nu}_e$ ID (ν_e missID) eff. ~70%(30%)

15

Bibliography

T2K NIM paper
ND280 TPC NIM paper

Alain Blondel, ND280 upgrades, HK-EU meeting
— https://indico.cern.ch/event/378508/contribution/12

Alain and Yokayama-san, Upgrade talks at June T2K CM

Raj Shah and Mark Hartz' talks at this meeting
— http://indico.ipmu.jp/indico/contributionDisplay.py?contribId=29&confId=67
— http://indico.ipmu.jp/indico/contributionDisplay.py?contribId=60&confId=67

Federico's HP-TPC talks at the ND280 upgrade sessions

and thanks to:

Alain, Yordan Karadzhov, Leila Haegel, Lorena Escudero, Jeanne, Mark Hartz, Emilio, Raj Shah and Sandro Bravar for their input

Strong motivation to upgrade ND280

next steps: double rep. rate with new power supplies, fast kickers and higher gradient RF improve loss controls further with more feedbacks

1 MW ???

Hyper-K

750 kW

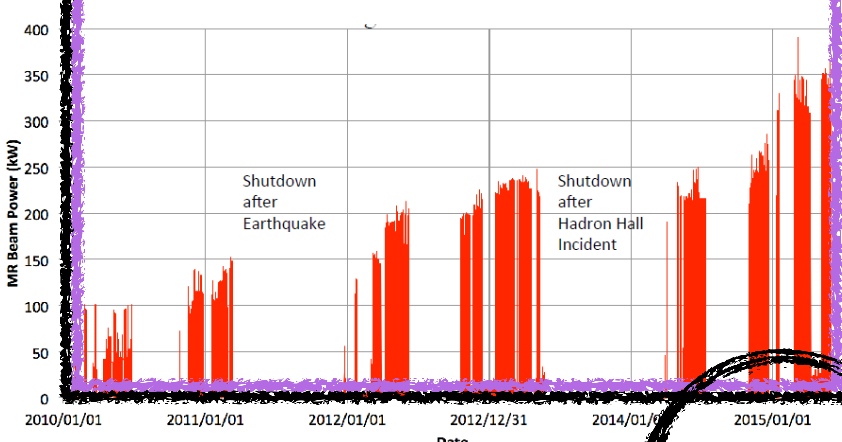
original request

Can achieve 2–3 times the requested T2K POT by 2025 when Hyper-K begins taking data

What's more, we surely want to **keep ND280 for Hyper-K** as it provides unique information.

If we want to keep ND280 alive, we should **update/upgrade**

Main ring beam power



365 kW

2010 2015 2020 2025 time

Foreseen ND280 tracker TPC statuses in 2025

Must refurbish gas system

—Drives operation cost, not negligible

Must upgrade the DCC back end readout electronics

—However the rate of channel failures is small so Micromegas and front end electronics would not need major work

Possible upgrades

—Reduce the DCC front end readout latency

—Increase robustness against high occupancy events

TPCs look sustainable

Foreseen P0D/FGD detector statuses in 2025

Likely degradation of scintillator light output

— ~5% / year in MINOS, MINERVA

—*Serious problem over the long term*

Big question mark over scintillator detectors

Expect all DAQ components to fail at some level over the next 5–15 years

—Continuing backend board connector availability?

—The electronics is obsolete: impossible to build spares

<1% of TRIPt frontend board have failed: *>10% spares*

5% of the backend board have failed: *20% spares*

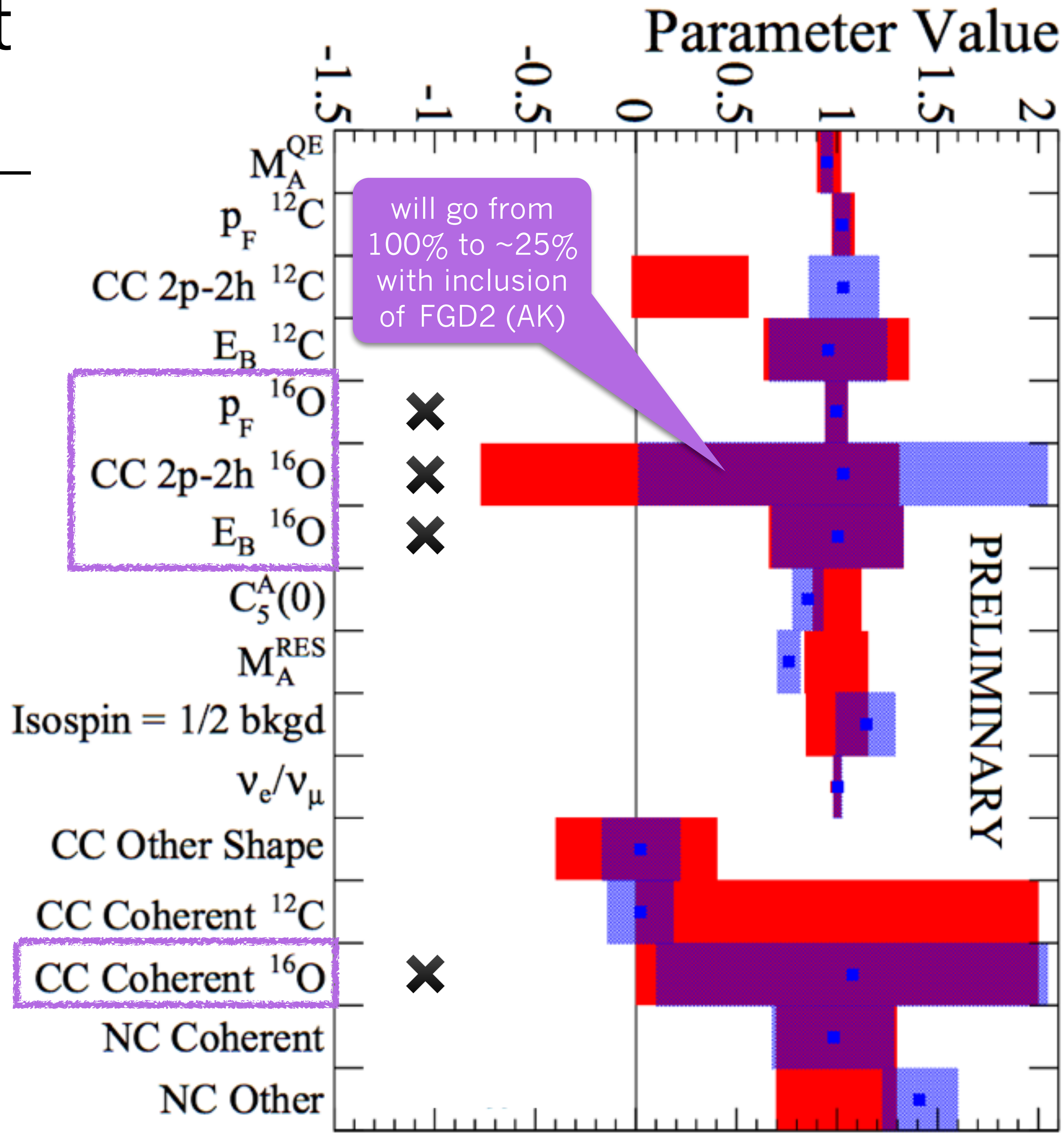
Is a water target a key feature?

J. Myslik, BANFF report, June 2015 T2K meeting

Prior to ND280 Constraint

After ND280 Constraint

✖ **not constrained**



Oxygen parameters require a fit to a water target

FGD2 has water layers, however…

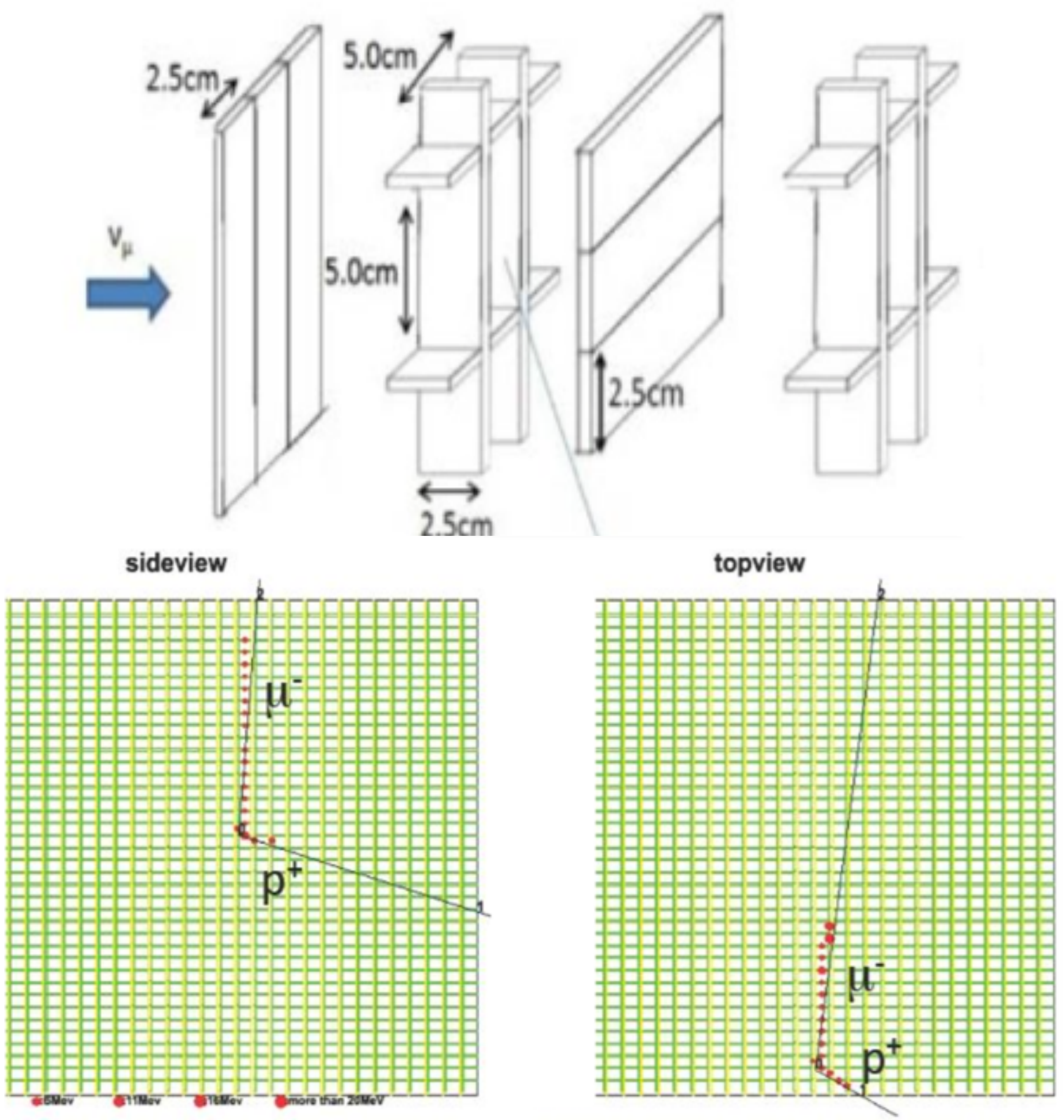
A limitation of the current detector:

FGD2 is only 40% water, short track reconstruction is difficult

Two solutions have been proposed…

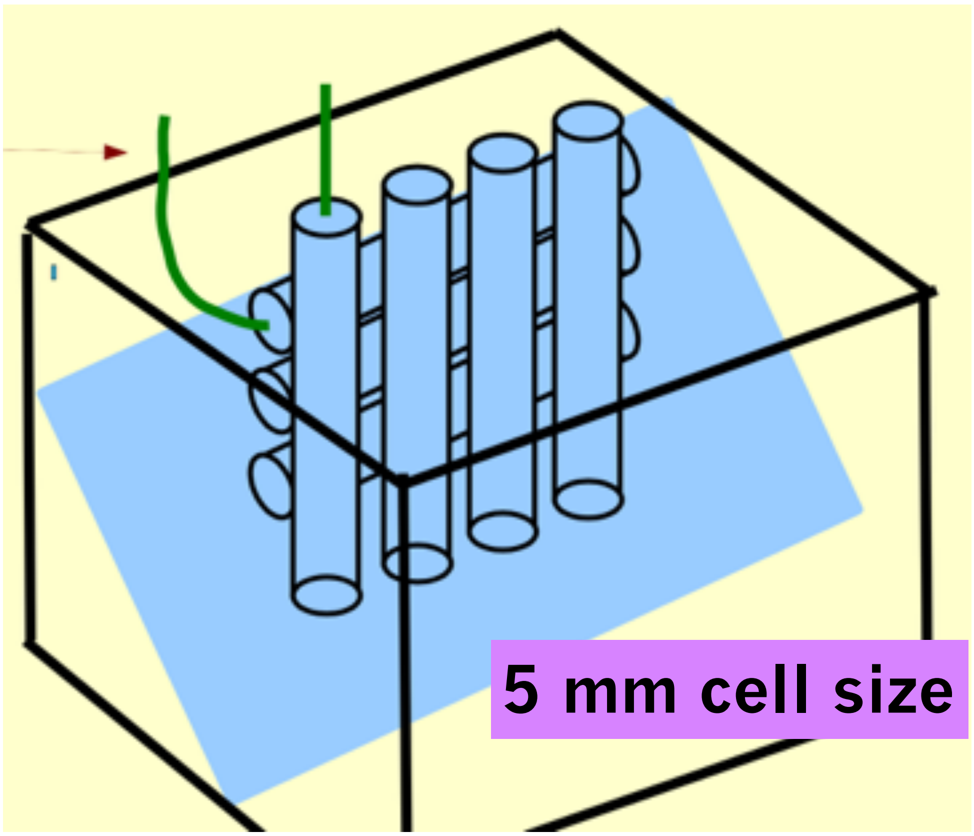
80% and 70% water respectively, and can reconstruct short 3D tracks

A Wagasci style scintillator grid



Water-based liquid scintillator

Mylar straws painted with reflective paint on the outside, WLS fibres strung inside the straws



Stanley Yen *et al.*, TRIUMF

Aside: Can such a target be big enough?

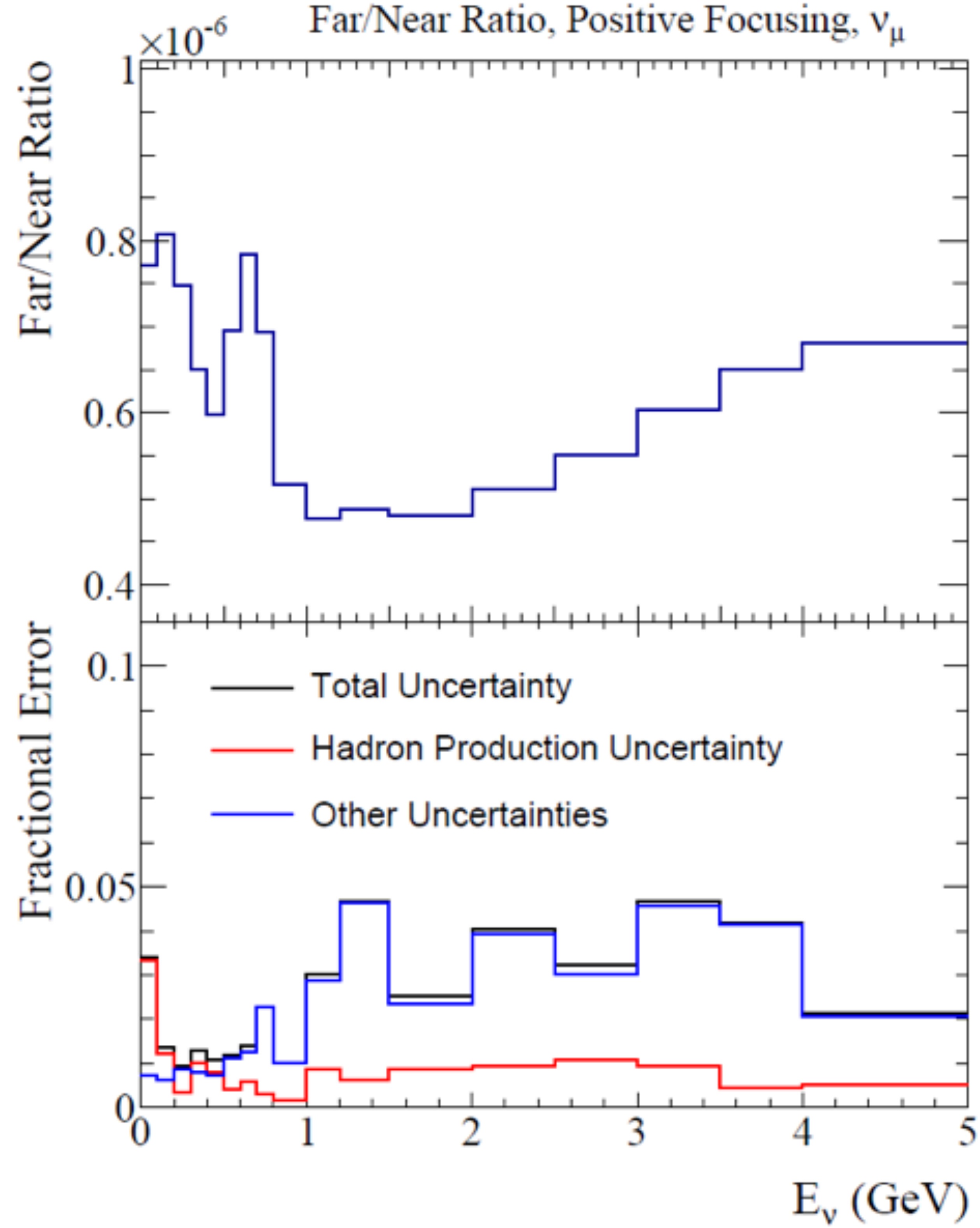
FGD1 is 1.07m^3 or ~1 ton

far/near flux ~ 0.6 — 0.8 x 10^{-6}

→statistics at 280 m in 1 ton is equivalent to ~1.4 Mton at HK

More than enough for HK

(particularly as the disappearance is almost complete and appearance is small)



Aside: Is L = 280 m << 1 km limiting?

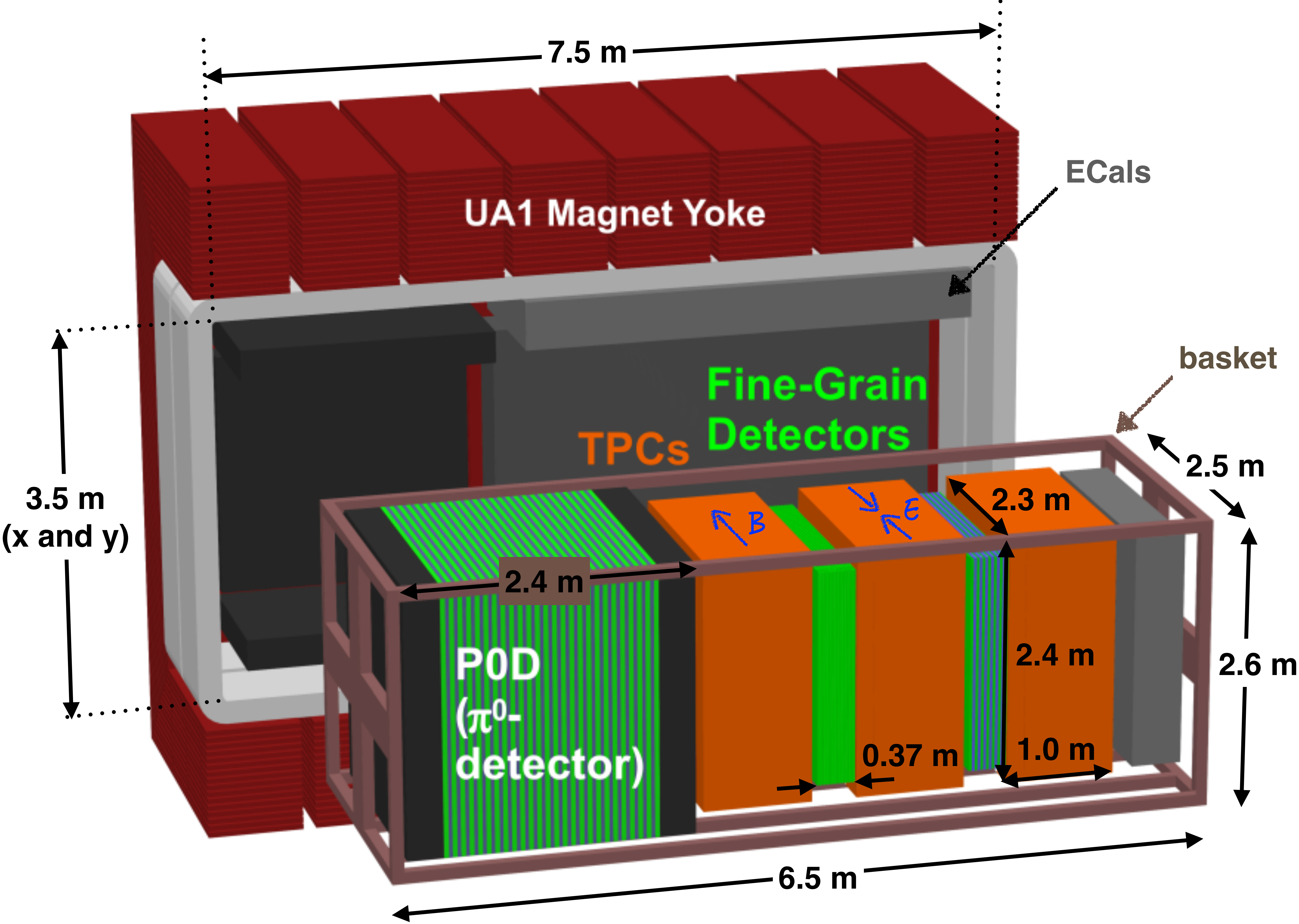
Uncertainty on FD/ND flux is ≤ 2%

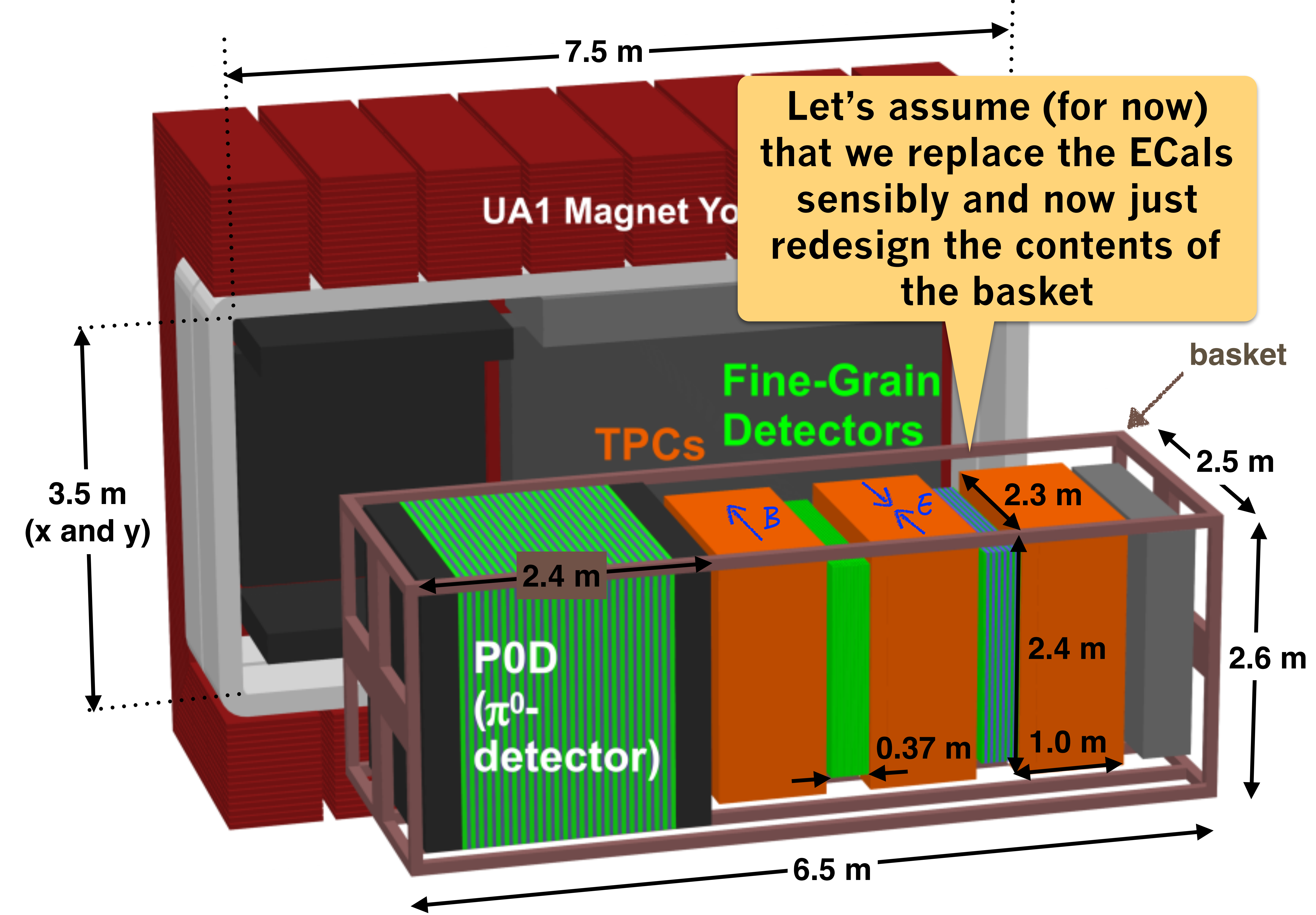
The detector being close to the target is probably not a fundamental limitation

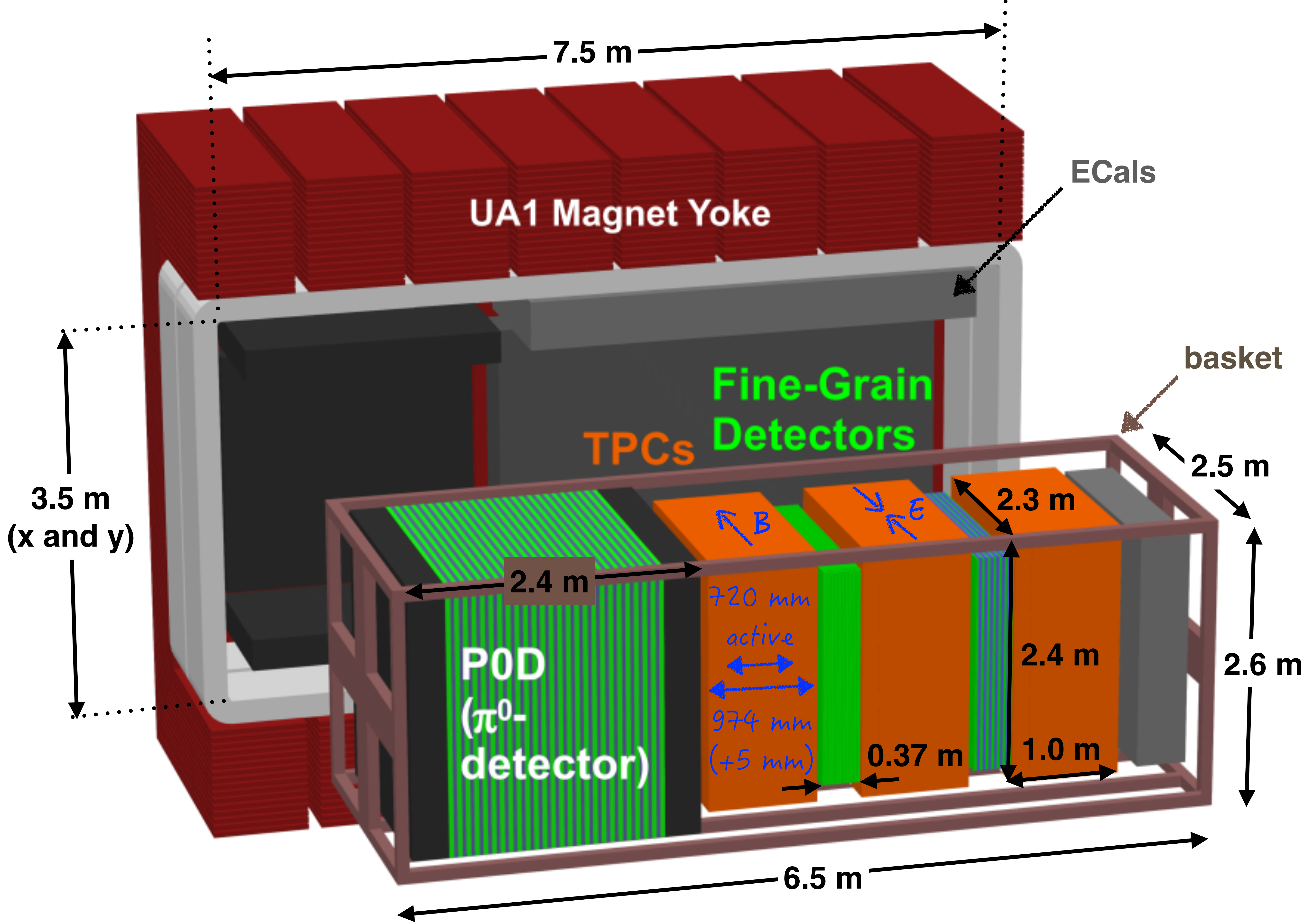
(quantitative study is envisaged)

2015 analysis with 2009 NA61 data

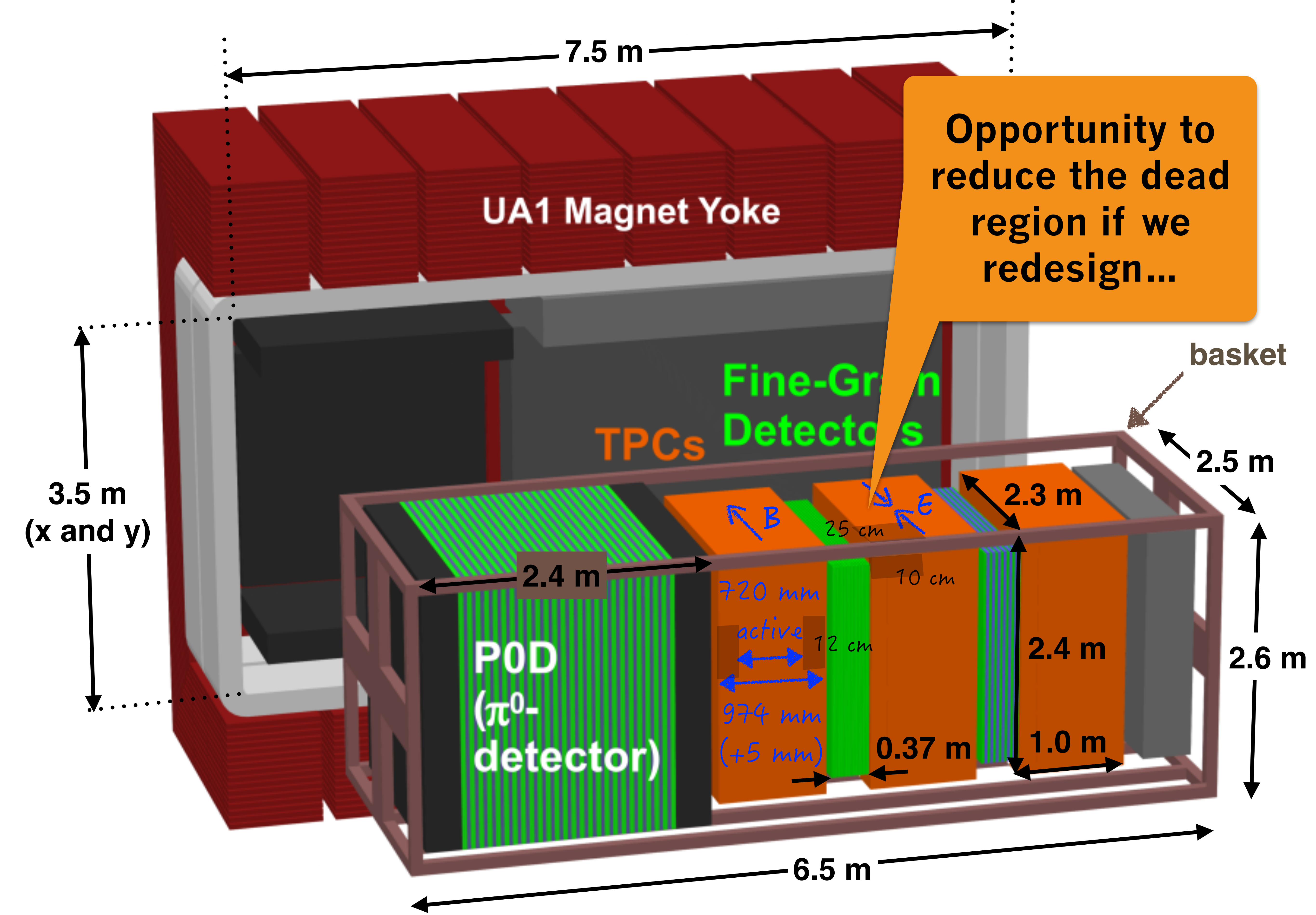
further improvements are possible

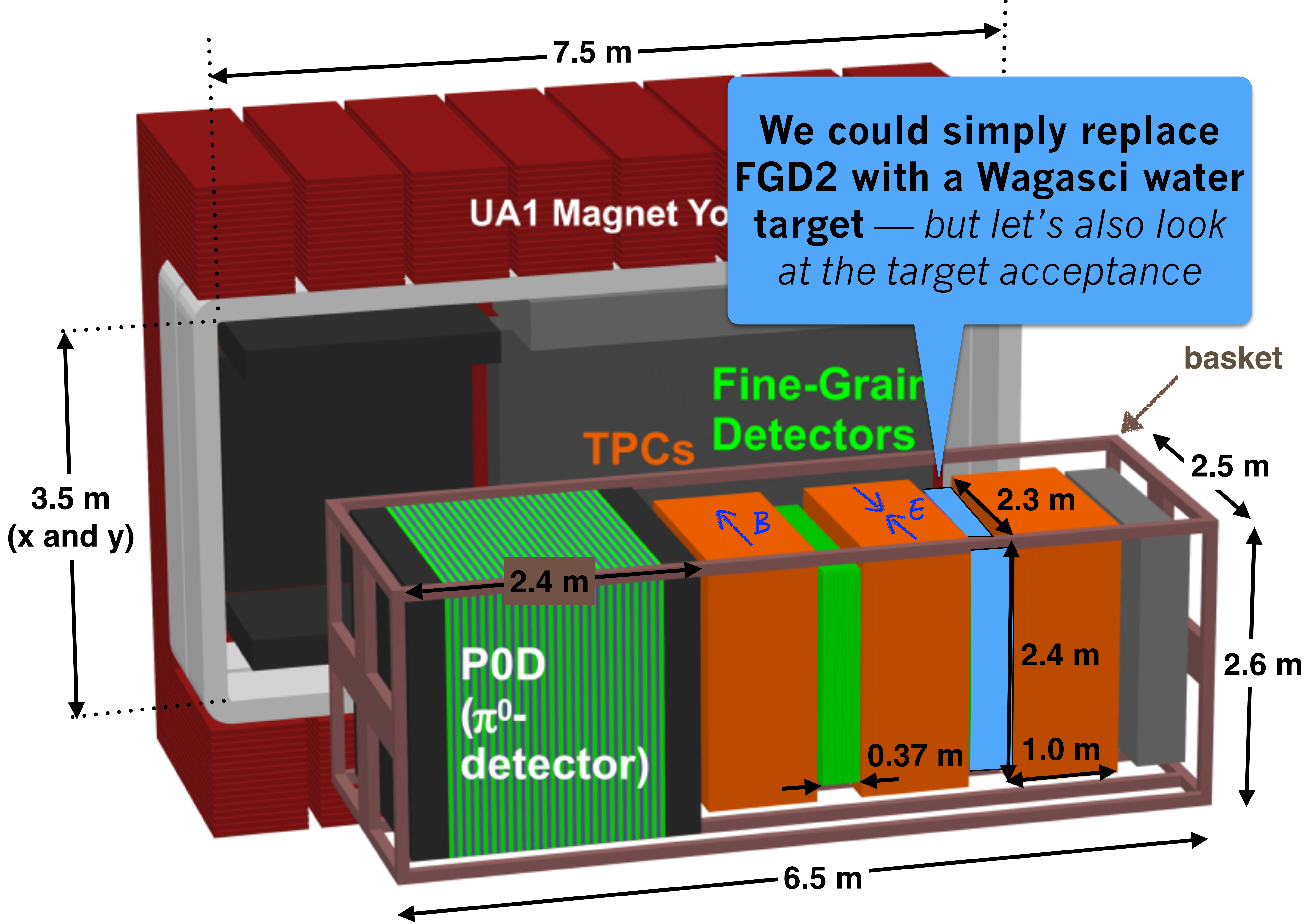

7.5 m
UA1 Magnet Yoke
ECals
basket
Fine-Grain
Detectors
TPCs
3.5 m
(x and y)
2.5 m
2.3 m
B
E
2.4 m
P0D
(π0-
detector)
2.4 m
2.6 m
0.37 m
1.0 m
6.5 m


7.5 m
UA1 Magnet Yo
Let's assume (for now) that we replace the ECals sensibly and now just redesign the contents of the basket
basket
Fine-Grain Detectors
TPCs
3.5 m (x and y)
2.5 m
2.3 m
B
E
2.4 m
P0D (π^0-detector)
2.4 m
2.6 m
0.37 m
1.0 m
6.5 m



7.5 m
UA1 Magnet Yoke
ECals
basket
Fine-Grain
Detectors
TPCs
3.5 m
(x and y)
2.5 m
2.3 m
B
E
2.4 m
720 mm
active
974 mm
(+5 mm)
P0D
(π⁰-
detector)
2.4 m
2.6 m
0.37 m
1.0 m
6.5 m


7.5 m
UA1 Magnet Yoke
Opportunity to reduce the dead region if we redesign...
basket
Fine-Grain Detectors
TPCs
3.5 m (x and y)
2.5 m
2.3 m
B
E
25 cm
10 cm
2.4 m
720 mm active
12 cm
974 mm (+5 mm)
P0D (π^0-detector)
2.4 m
2.6 m
0.37 m
1.0 m
6.5 m



We could simply replace FGD2 with a Wagasci water target — *but let's also look at the target acceptance*

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Different energy resolution and acceptance to Hyper-K

- Acceptance is currently limited to ± 53° (forward) for muons
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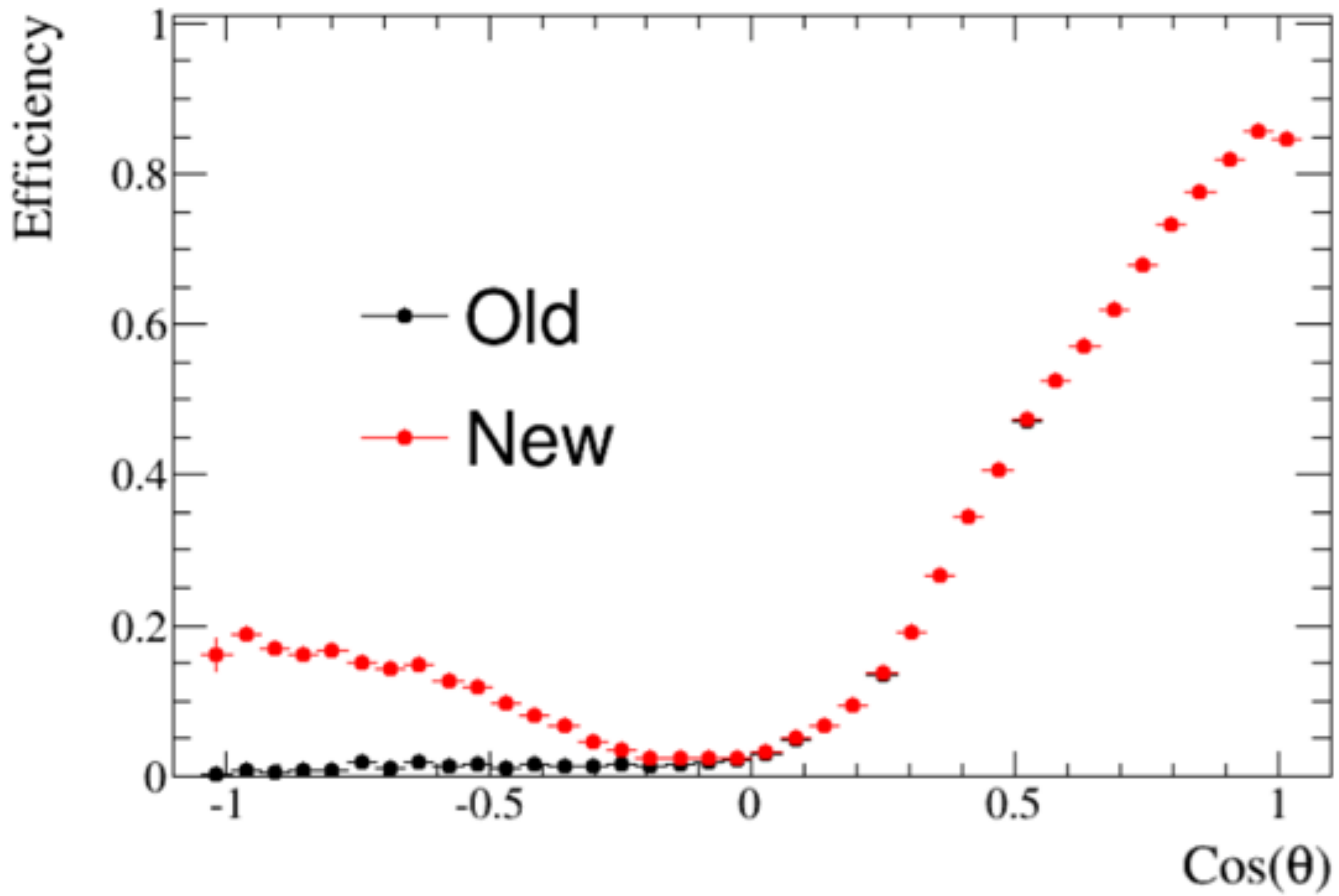

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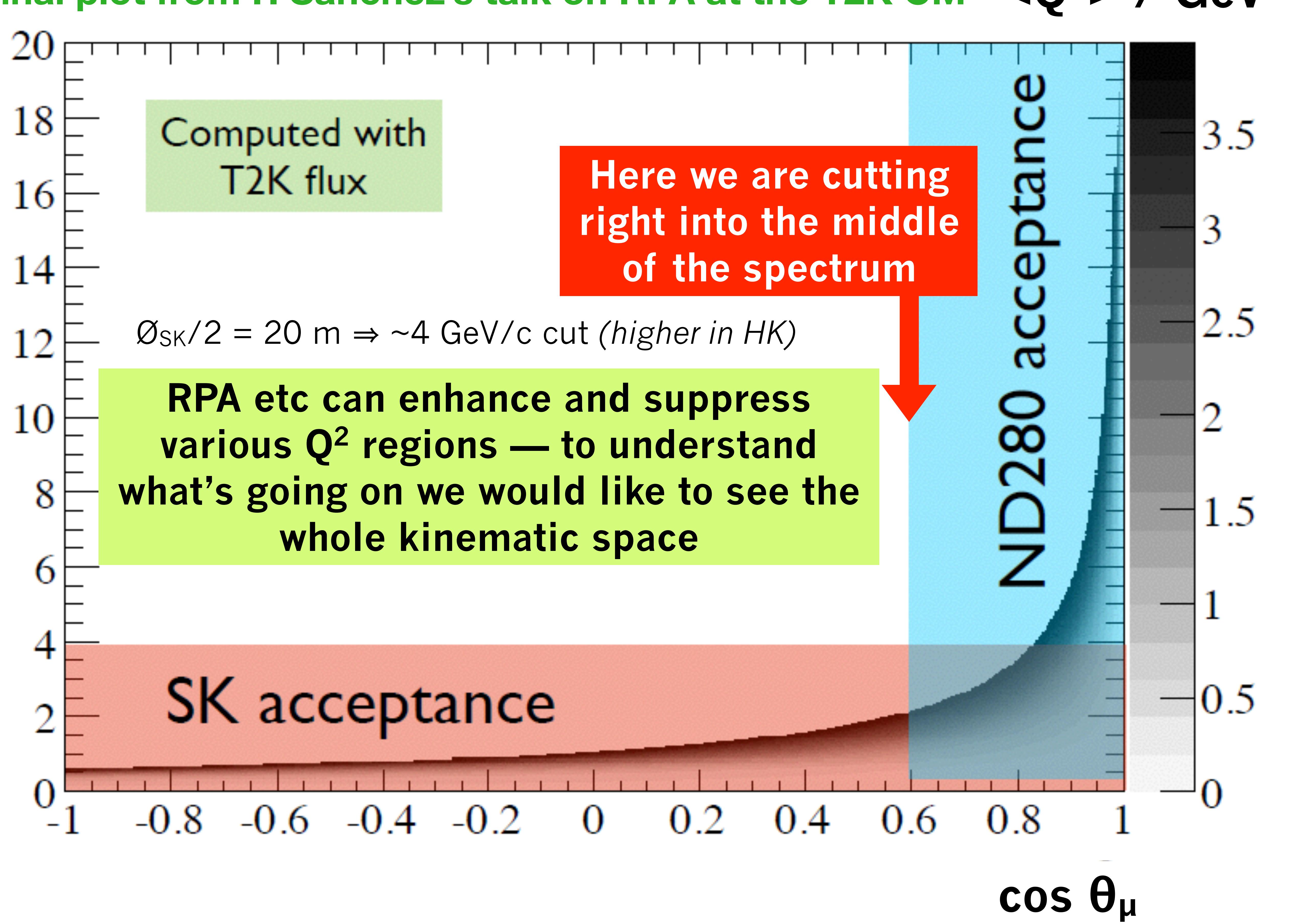

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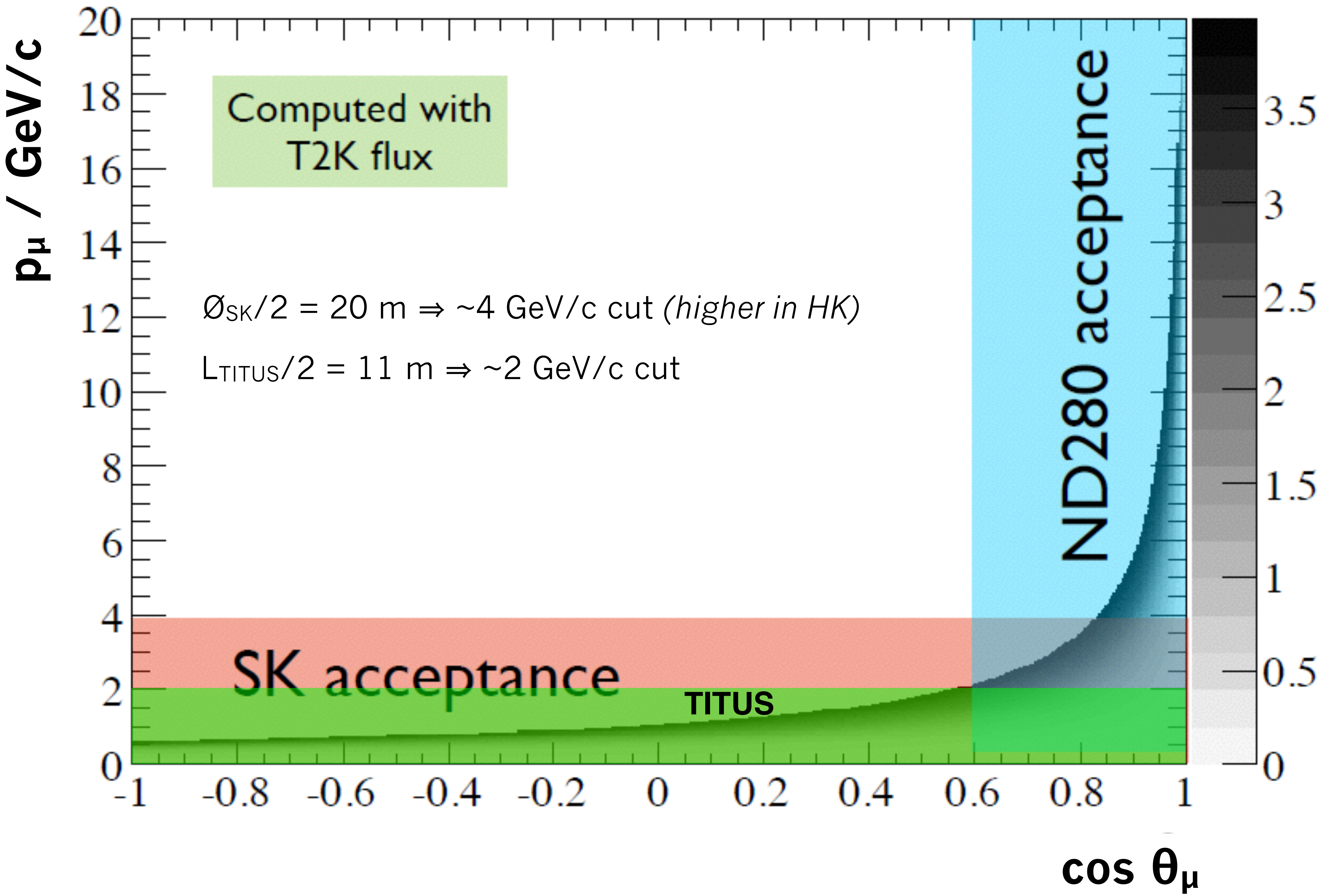

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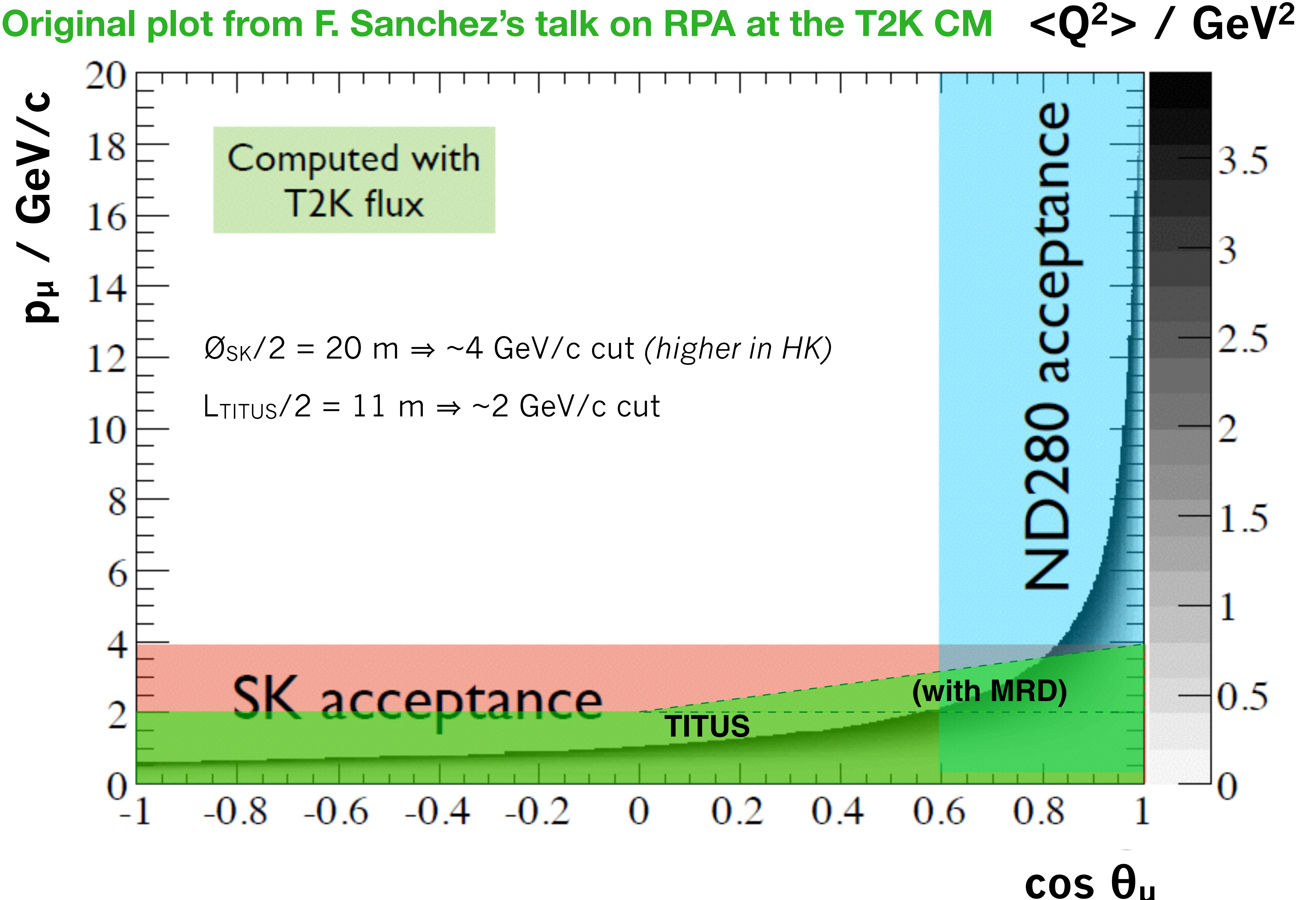

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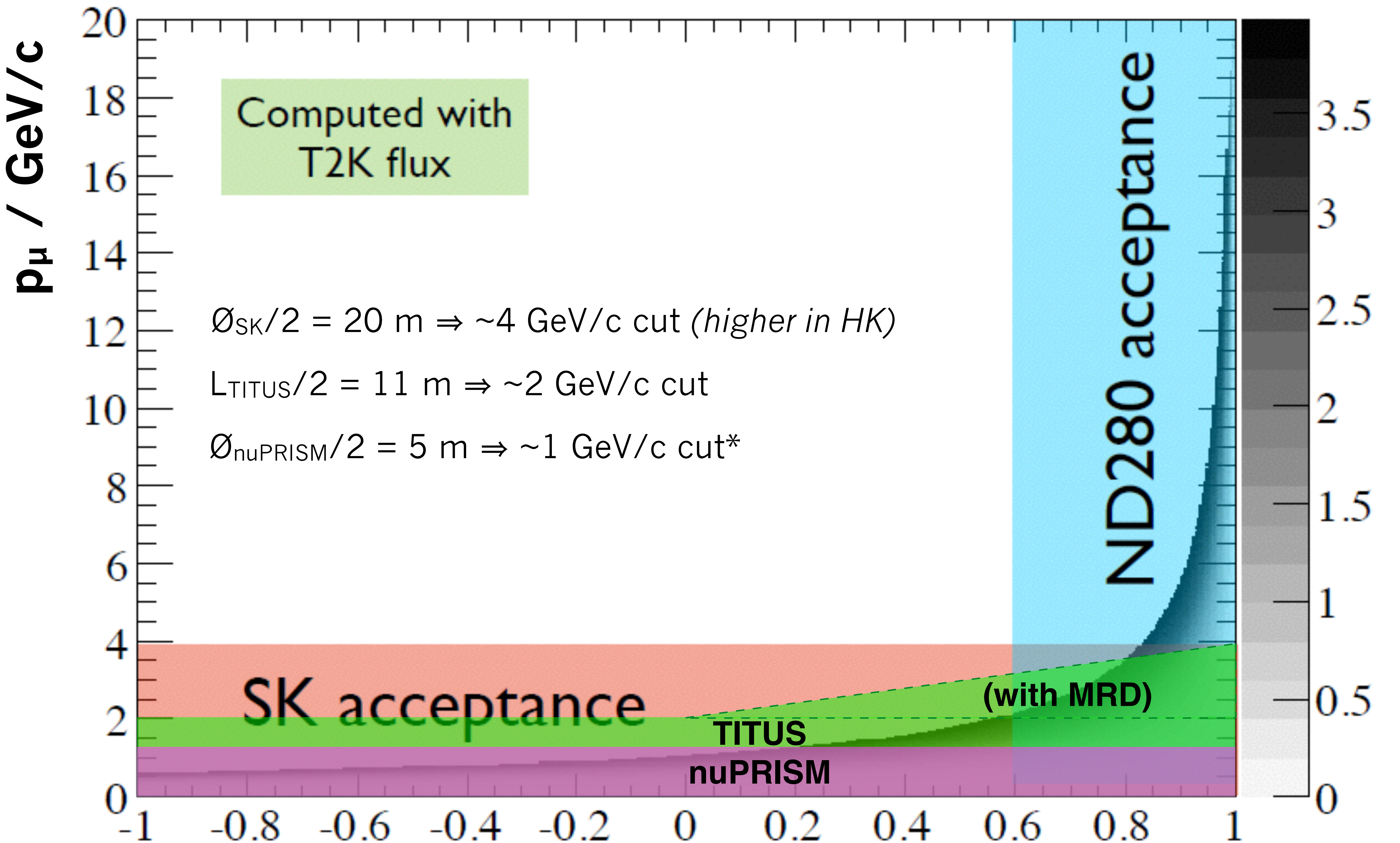

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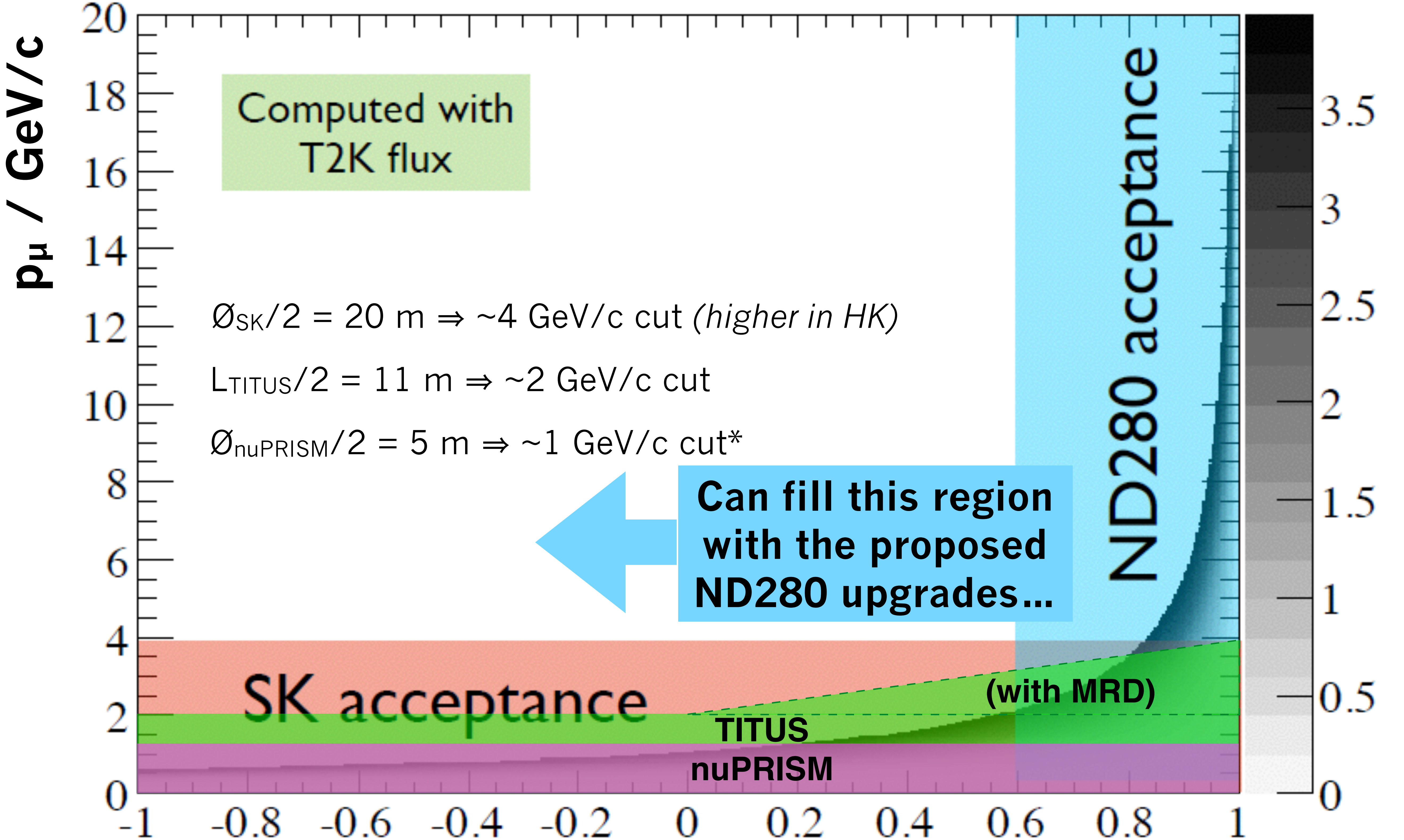

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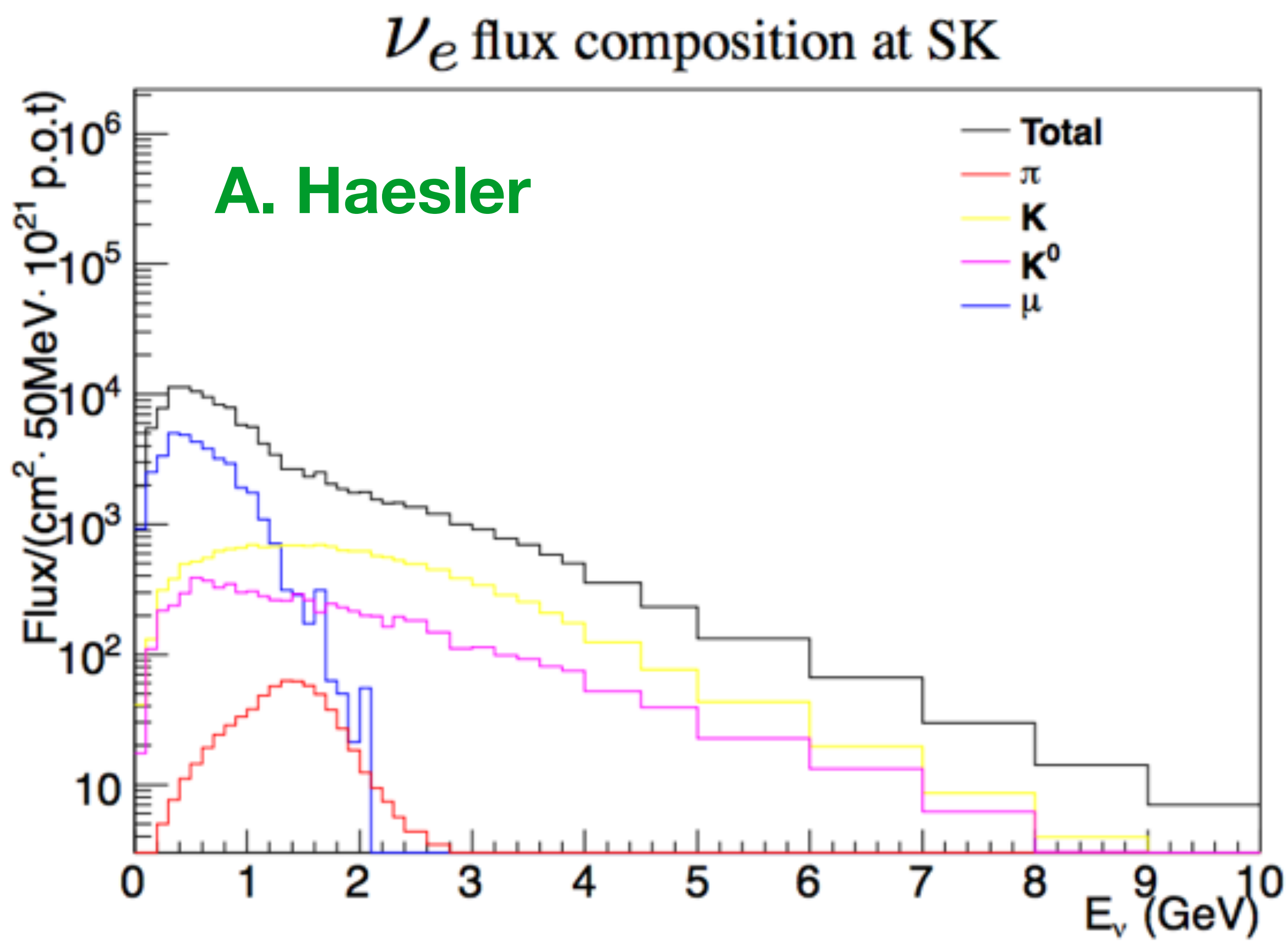
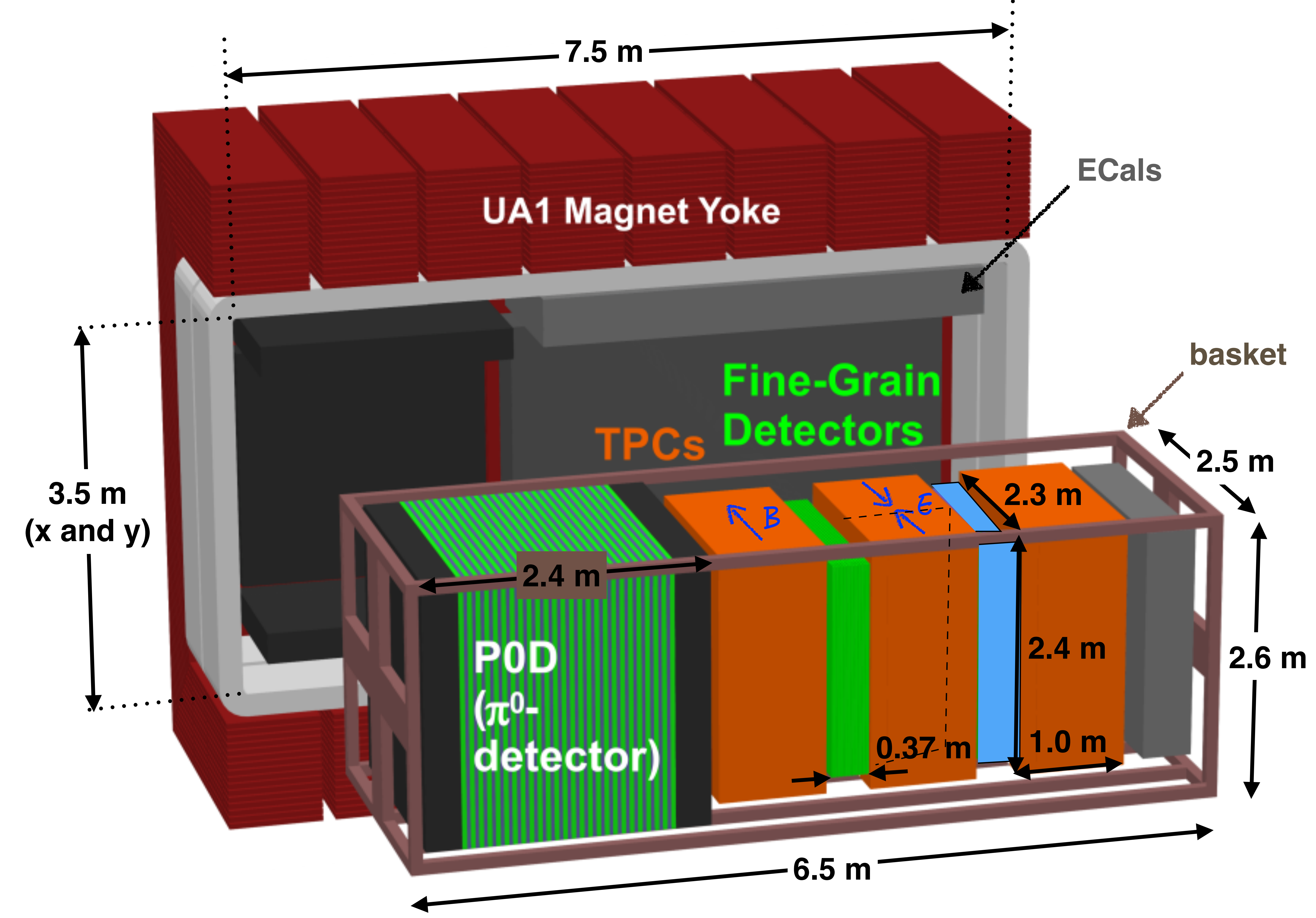
It is good to measure the full kinematic space for muons and even better to do it for electrons

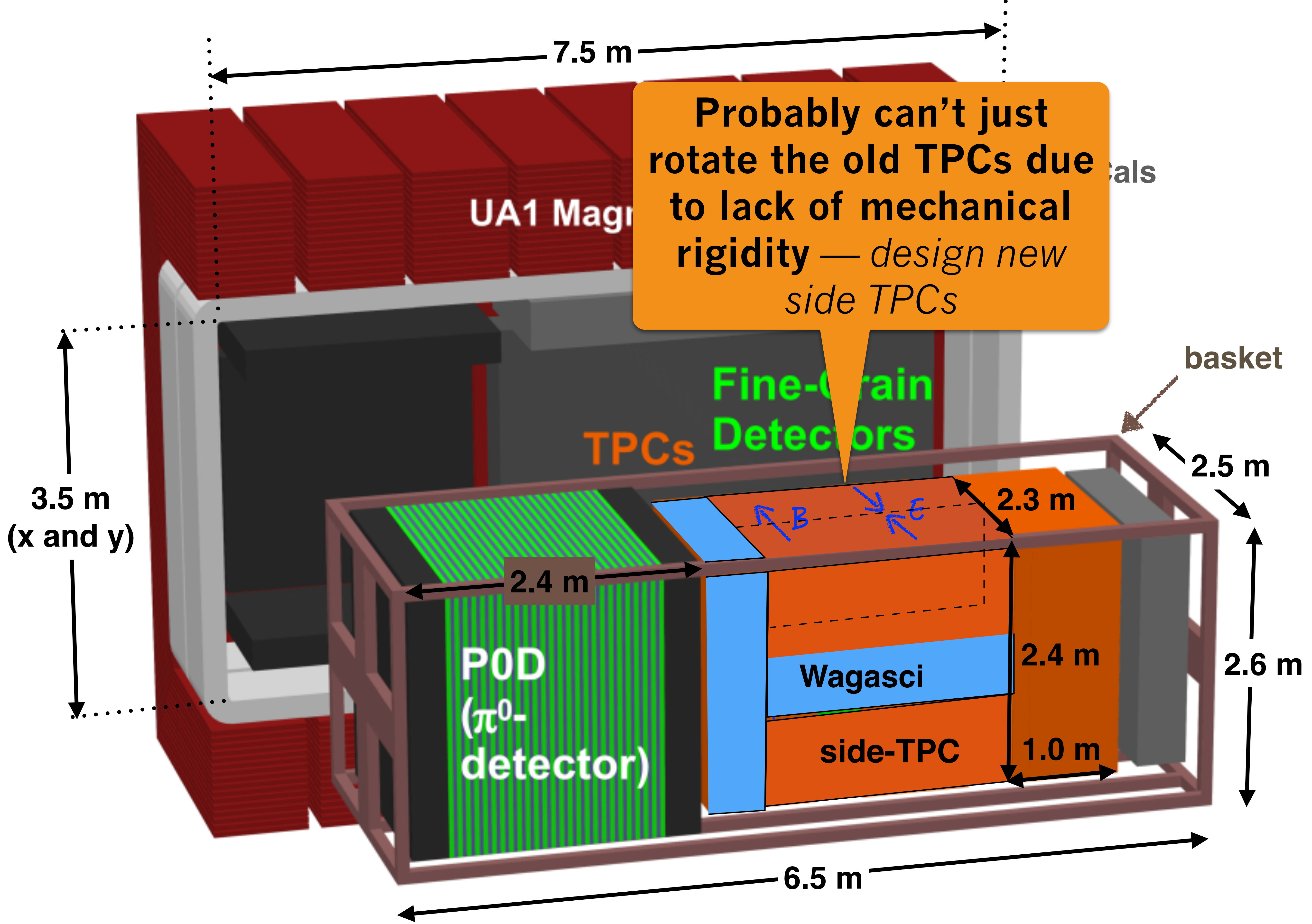
Upgraded ND280 is the only proposed solution to have this ability

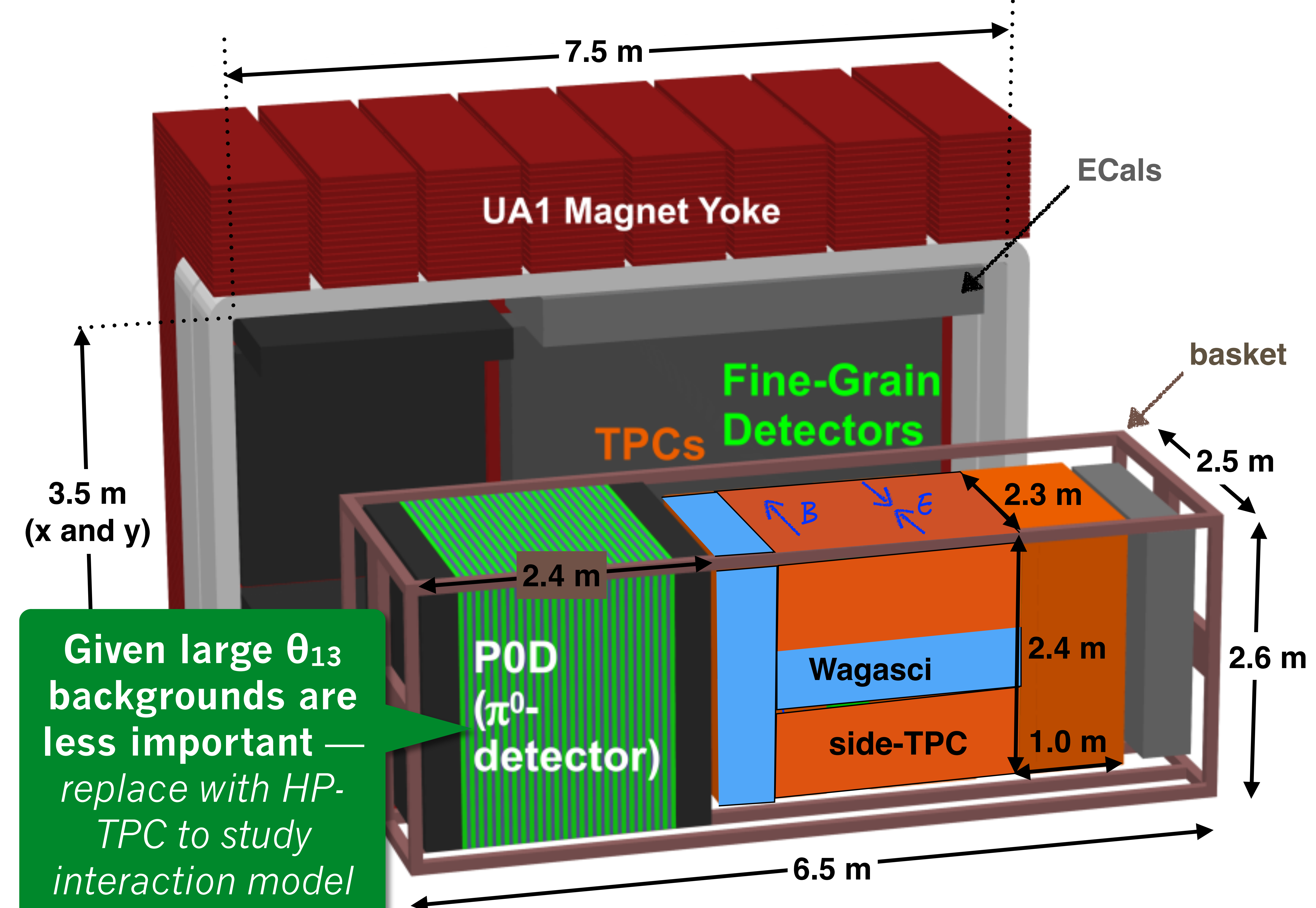
High energy electrons and muons can be well measured in the ND280 magnetic field, we should quantify the precision needed and achievable — it is only a matter of the space we leave in the forward direction for TPCs.

The ν_e flux in the low energy (E<1GeV) region is intimately tied with that of the ν_μ, as it is produced by muon decays, the muons being themselves being produced by the decays of pions which produce the same low-energy part of the neutrino spectrum

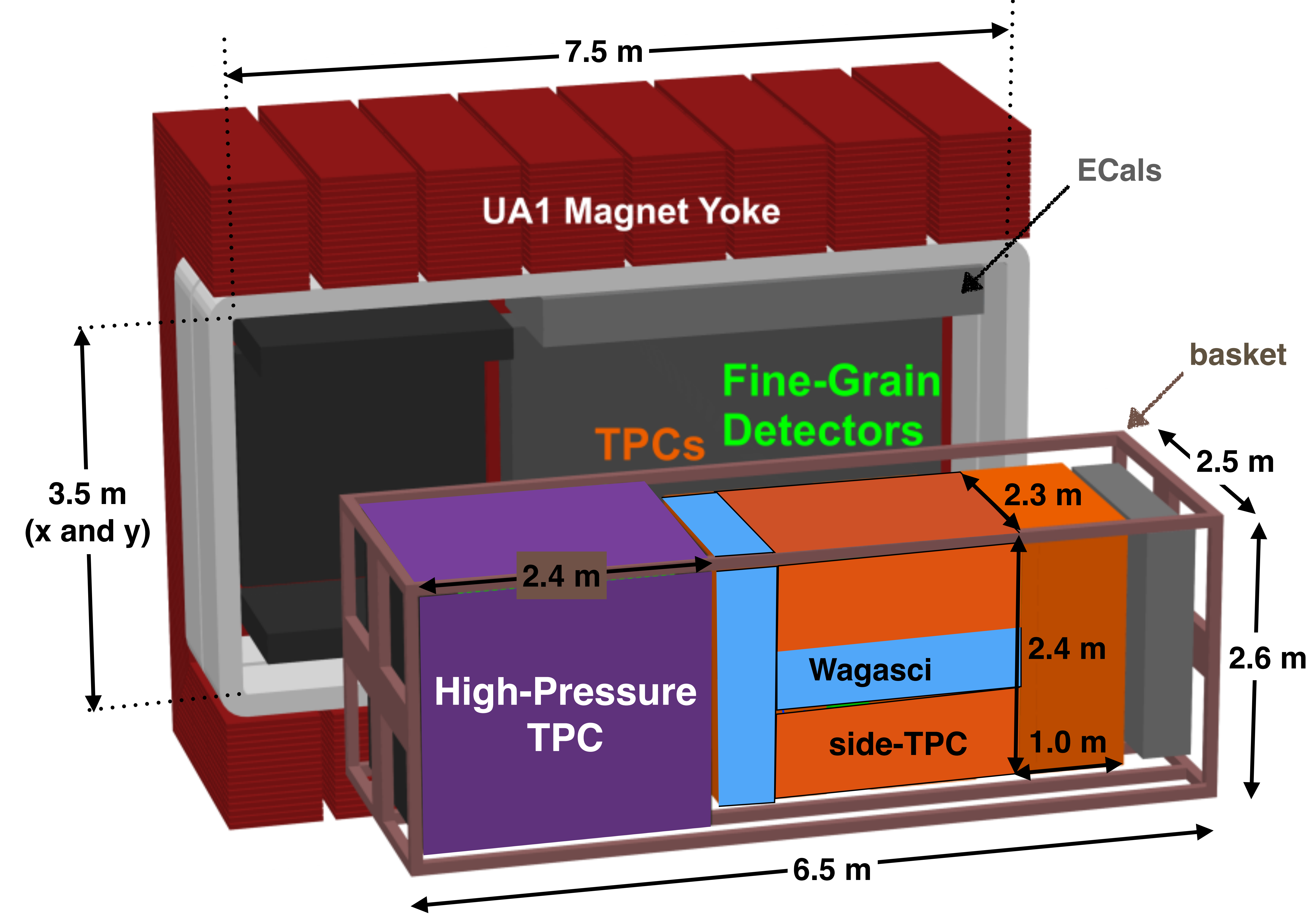



7.5 m
UA1 Magnet Yoke
ECals
basket
Fine-Grain Detectors
TPCs
3.5 m (x and y)
2.5 m
2.3 m
2.4 m
2.4 m
2.6 m
P0D (π^0-detector)
0.37 m
1.0 m
6.5 m
B
E


7.5 m
UA1 Magn
als
Probably can't just rotate the old TPCs due to lack of mechanical rigidity — *design new side TPCs*
basket
Fine-Grain Detectors
TPCs
3.5 m (x and y)
2.5 m
2.3 m
B
E
2.4 m
P0D (π^0-detector)
Wagasci
2.4 m
2.6 m
side-TPC
1.0 m
6.5 m



Given large θ_{13} backgrounds are less important — *replace with HP-TPC to study interaction model*


7.5 m
UA1 Magnet Yoke
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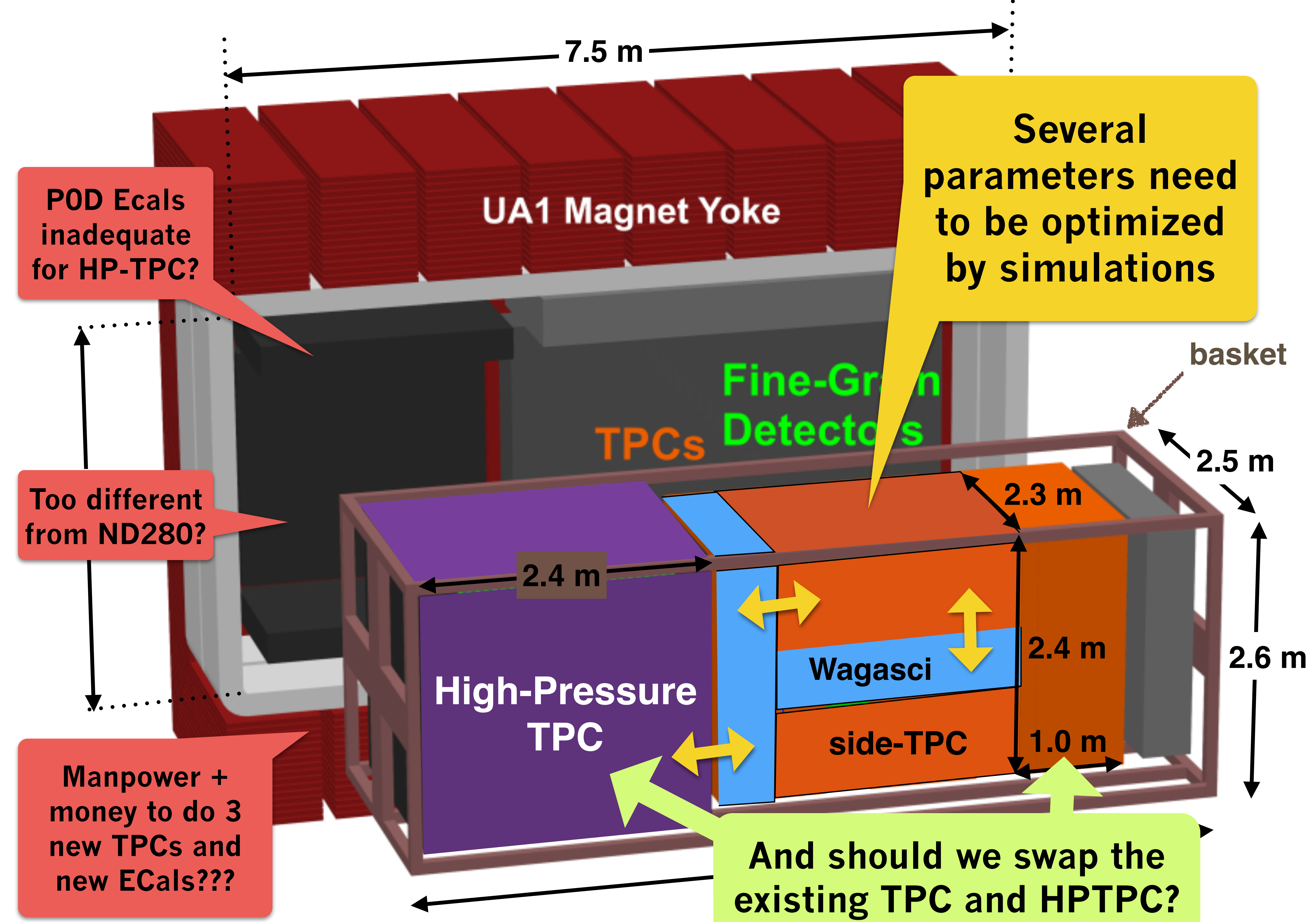
basket
Fine-Grain
Detectors
TPCs
3.5 m
(x and y)
2.5 m
2.3 m
2.4 m
2.4 m
2.6 m
Wagasci
High-Pressure
TPC
side-TPC
1.0 m
6.5 m

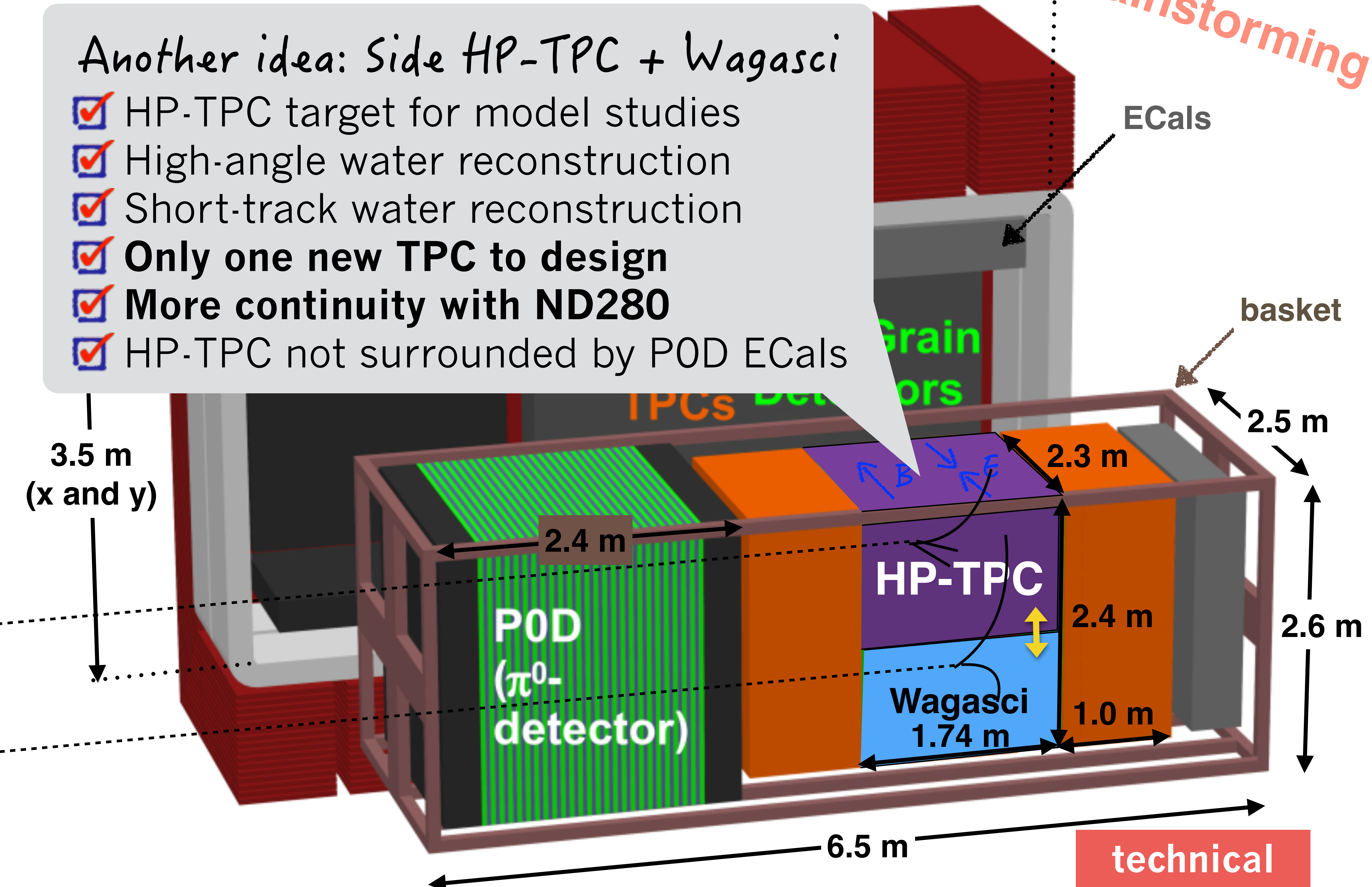

7.5 m
UA1 Magnet Yoke
Several parameters need to be optimized by simulations
P0D Ecals inadequate for HP-TPC?
basket
Fine-Grain Detectors
TPCs
2.5 m
2.3 m
Too different from ND280?
2.4 m
2.4 m
2.6 m
Wagasci
High-Pressure TPC
side-TPC
1.0 m
Manpower + money to do 3 new TPCs and new ECals???
And should we swap the existing TPC and HPTPC?

Can we eliminate side-TPC = HP-TPC?

Brainstorming

Another idea: Side HP-TPC + Wagasci

- ☑ HP-TPC target for model studies
- ☑ High-angle water reconstruction
- ☑ Short-track water reconstruction
- ☑ **Only one new TPC to design**
- ☑ **More continuity with ND280**
- ☑ HP-TPC not surrounded by P0D ECals



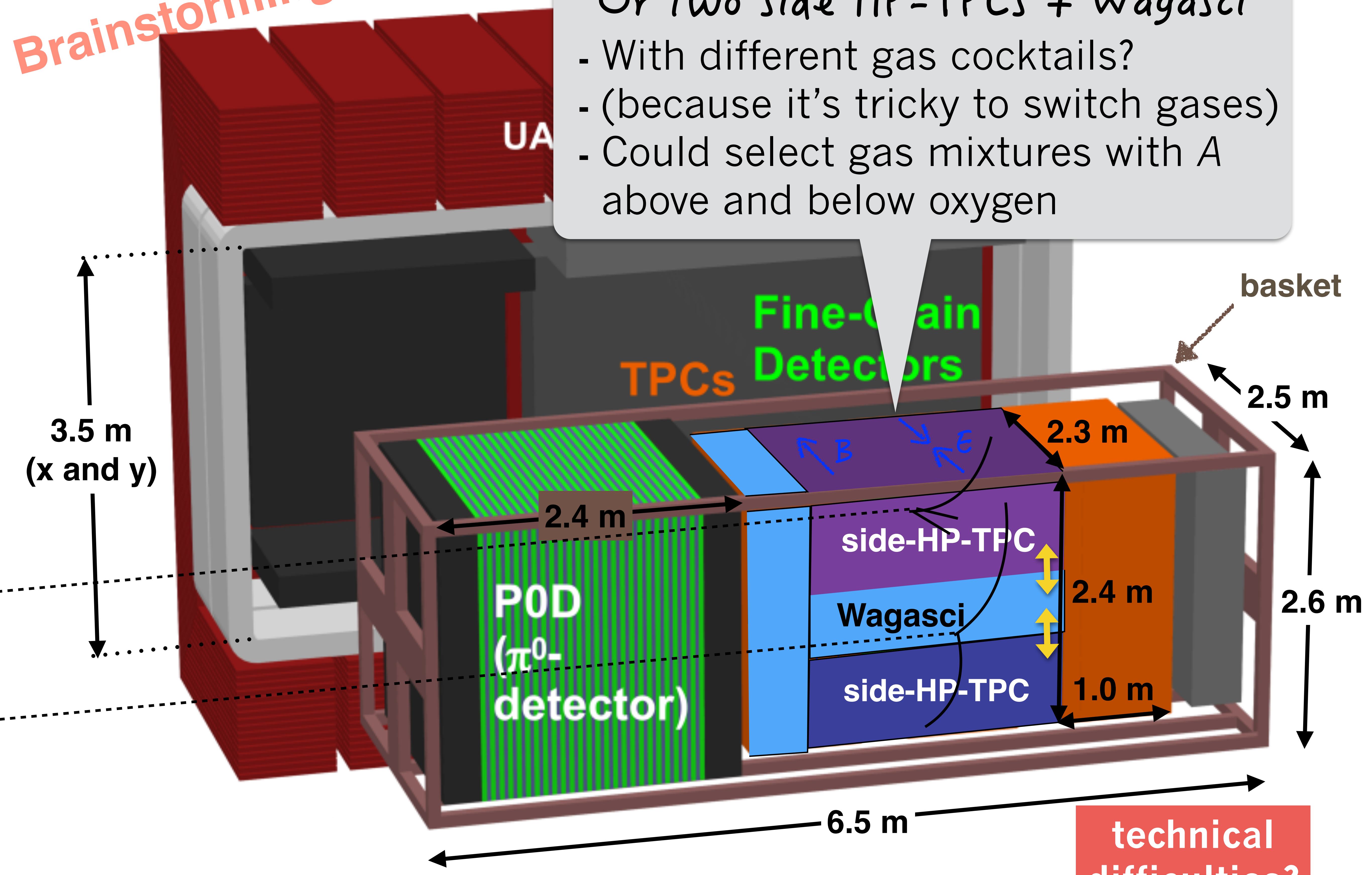
technical difficulties?

Can we eliminate side-TPC = HP-TPC?

Brainstorming

Or two side HP-TPCs + Wagasci

- With different gas cocktails?
- (because it's tricky to switch gases)
- Could select gas mixtures with *A* above and below oxygen



technical difficulties?

F. Sanchez, M. Ravonel

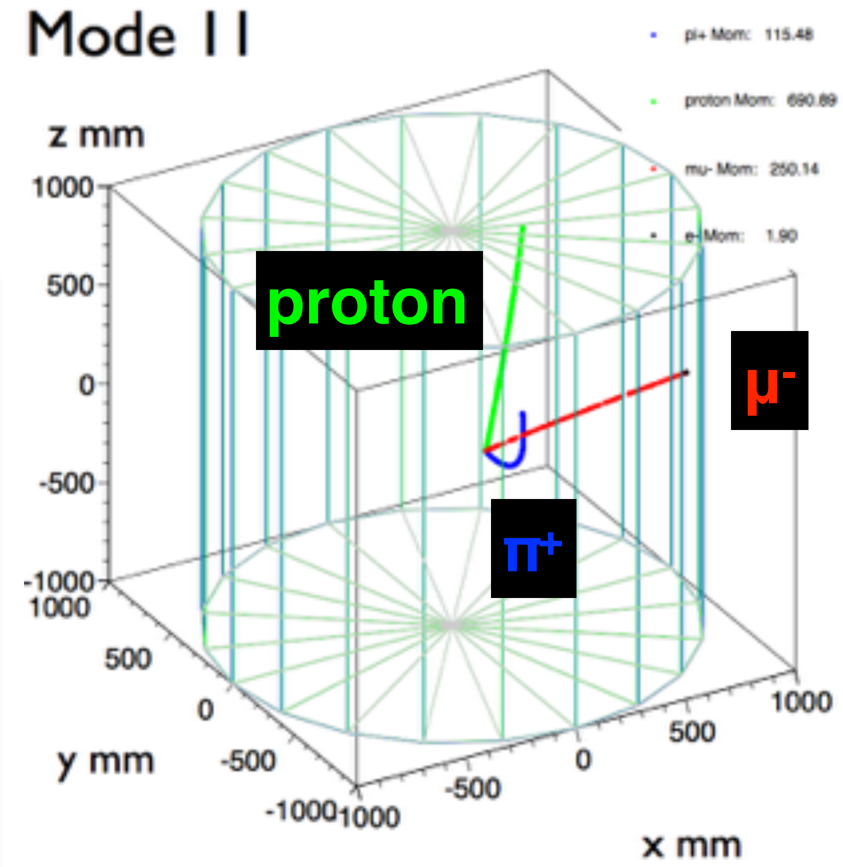
Low threshold detector to pin down nuclear model

High Pressure Time Projection Chamber

Advantages

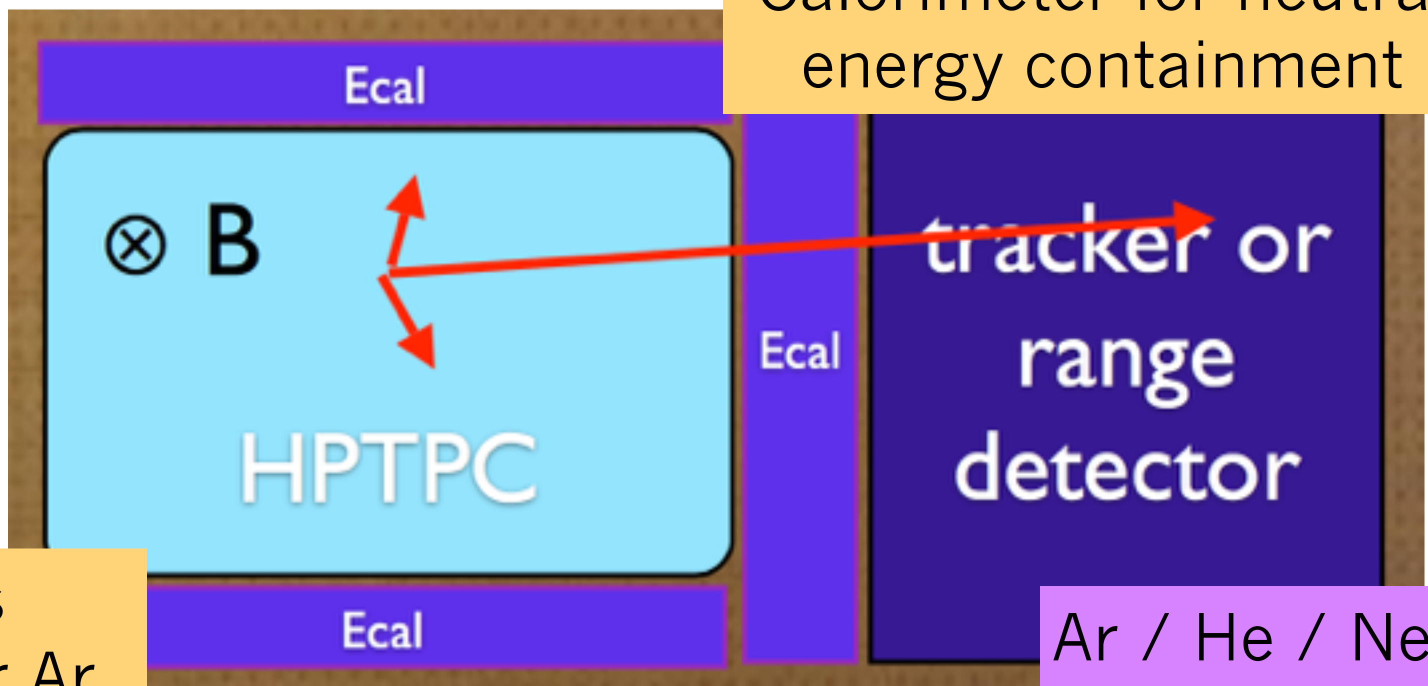
- Target = detector.
- 3D reconstruction capabilities
- Possibility to exchange targets
- low density → low thresholds
- excellent PID capabilities
- Almost uniform 4π acceptance

Key point: these proposed basket HP-TPCs are big enough to get a good number of events



Disadvantages

- low number of interactions → requires high pressure and large volume
- requires in addition a magnet or range detectors to measure momentum



Calorimeter for neutral energy containment

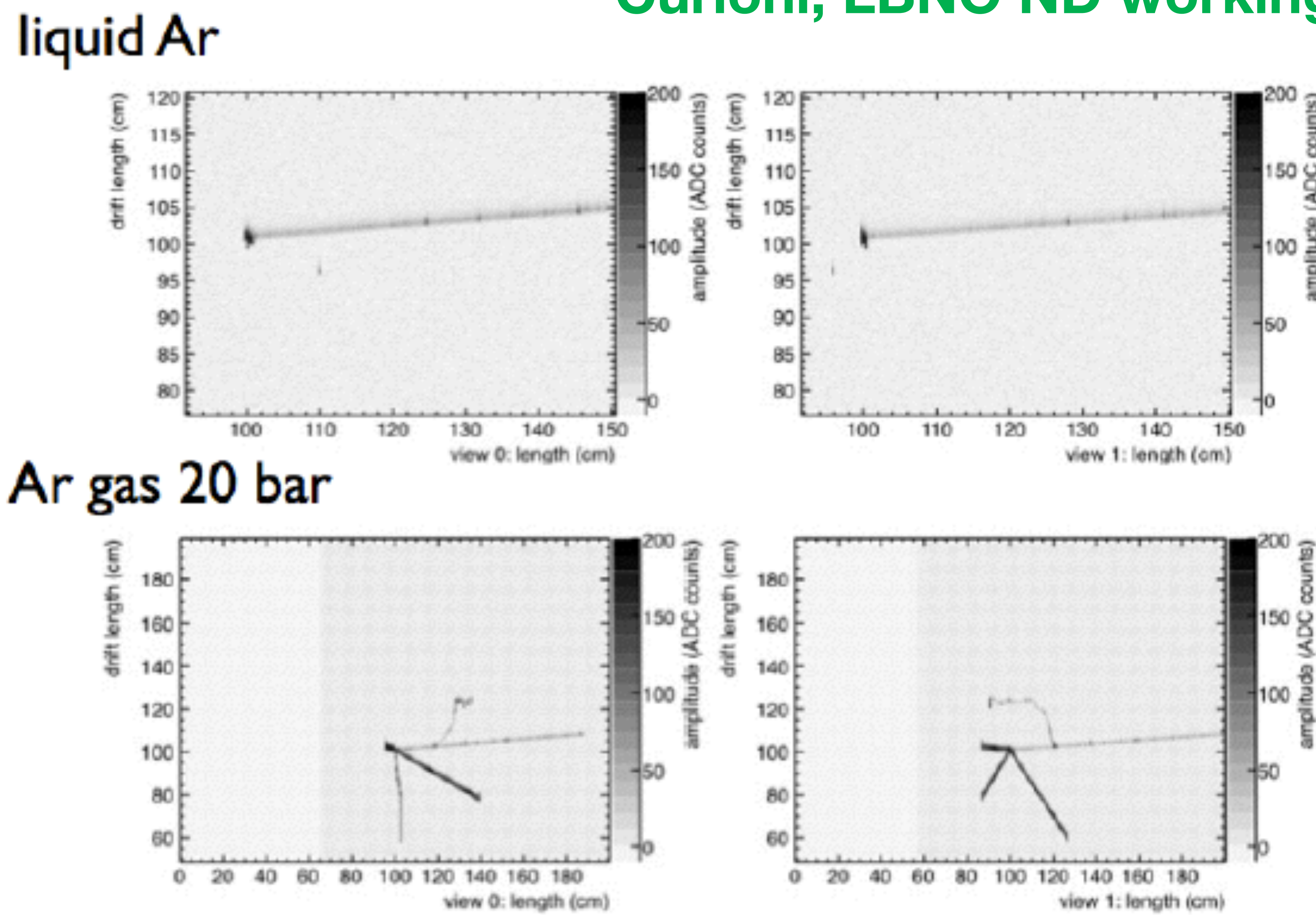
Ar / He / Ne target

~30,000 CC events in He at 5 bars
A factor x5 for Ne and a factor x10 for Ar
($8 m^3$ detector, 4 years, 1.6×10^{21} POT/ year)

http://www.t2k.org/meet/nd280/meet/NDupgrade/ NDWS-Jan14/NDWS

Comparing liquid vs gas argon

Curioni, LBNO ND working group, 2012



Beautiful and interesting, but how would we use these short tracks?

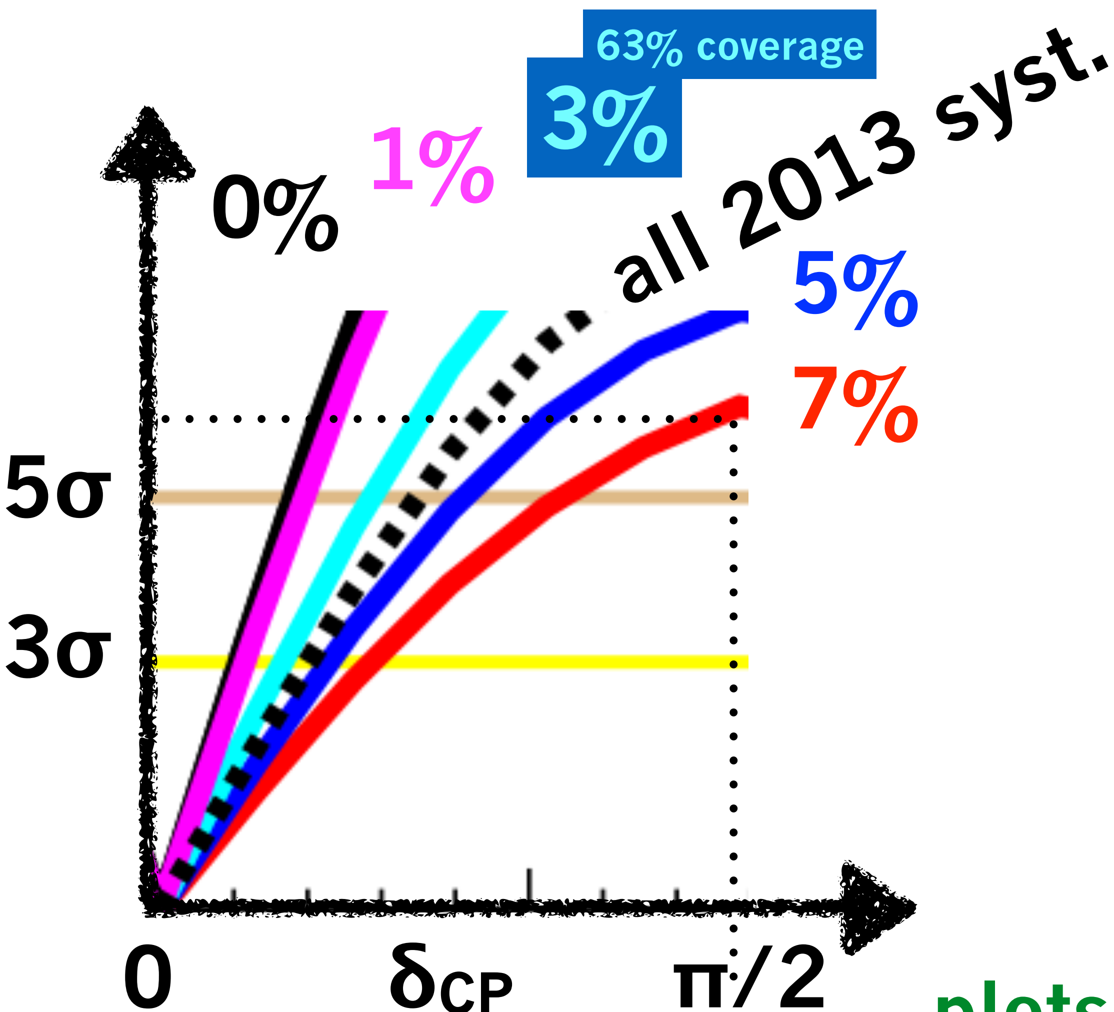
(If the MC is perfect, we don't need to fret about energy reconstruction…)

something must be done!

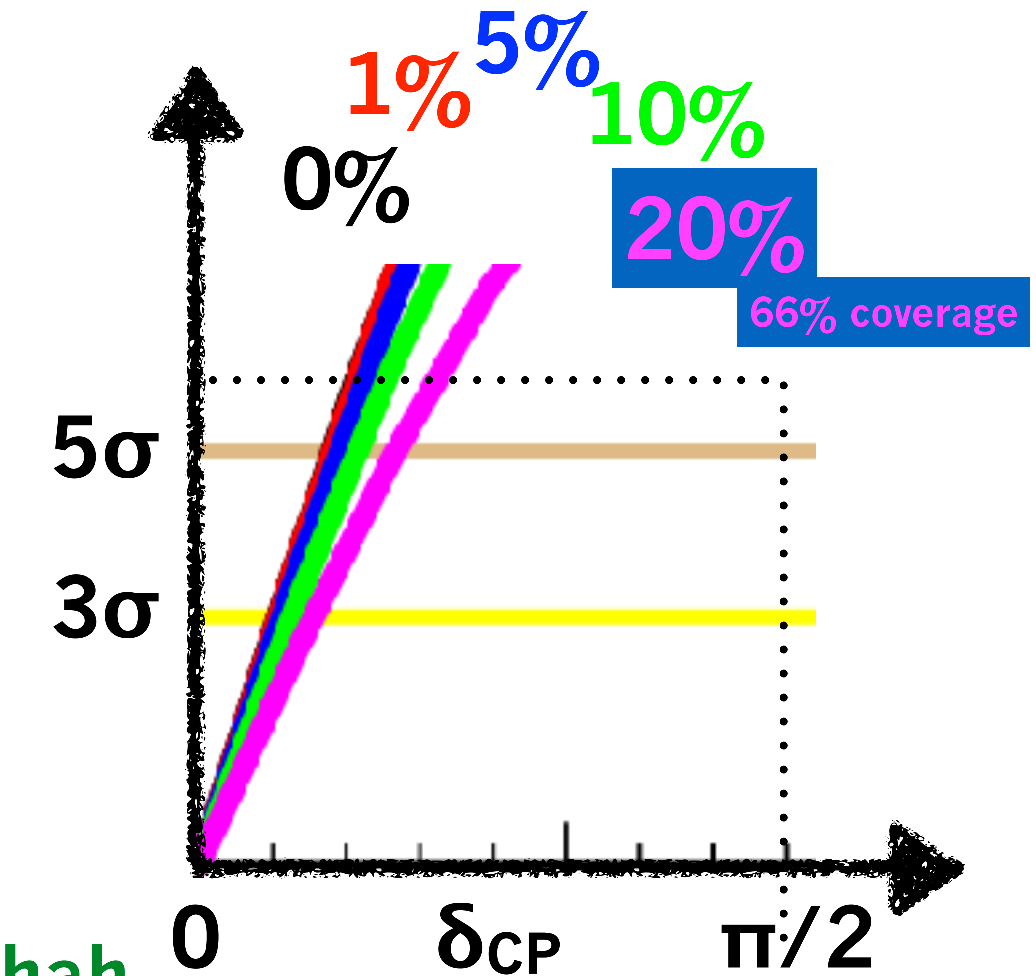
Two tricky issues with big sensitivity ramifications:

Oscillating ν_e and intrinsic ν_e

Effect of prior uncertainty on $\sigma(\nu_e)$ and (independently) $\sigma(\bar{\nu}_e)$



Effect of prior uncertainty on intrinsic ν_e flux below E = 1 GeV

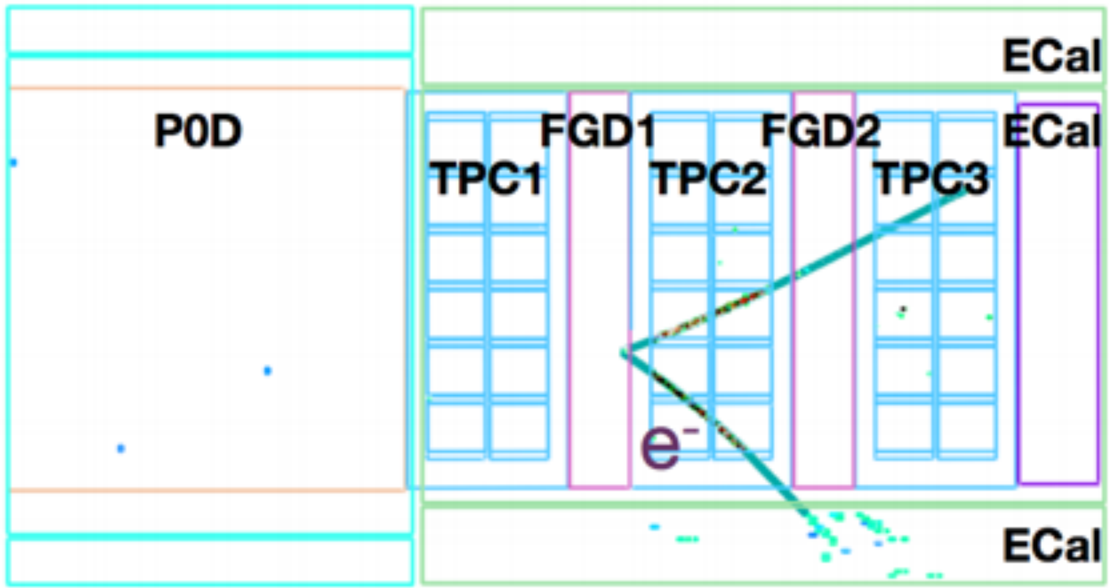


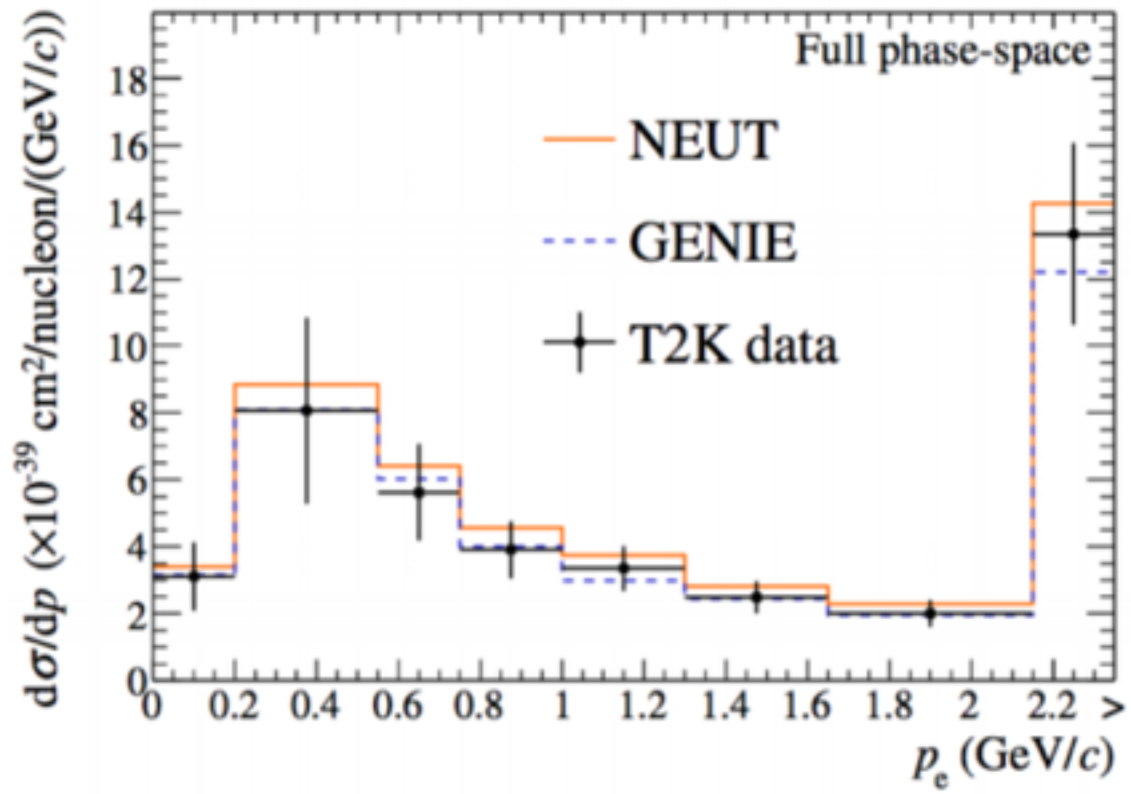
plots: Raj Shah

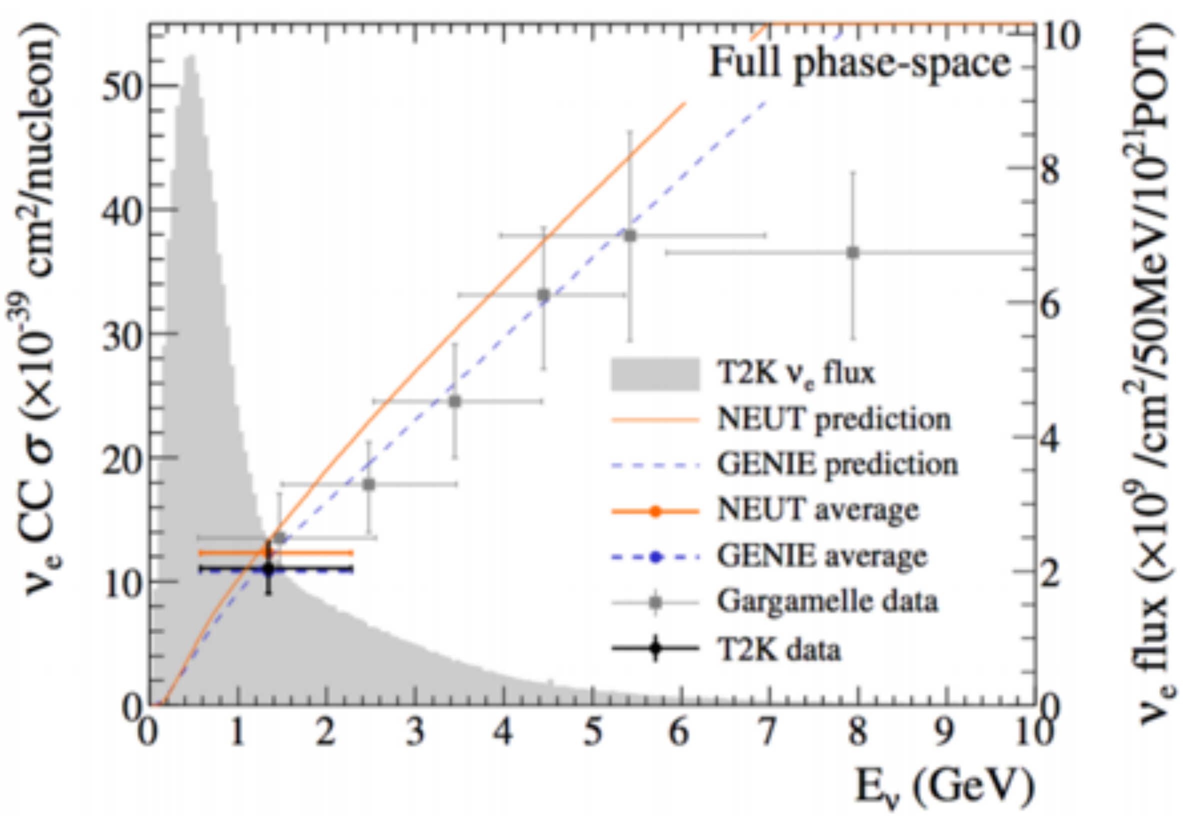
(max [zero systematics] δ_{CP} coverage for 5σ observation of CPV is 77%)

3% prior uncertainty on the cross section does as much damage to CPV sensitivity (~10% coverage of δ_{CP}) **as 20% uncertainty on the intrinsic flux**

Ben Smith has already done an ND280 tracker analysis of the nue x-sect.







- Sample is 65% pure CC ν_e
- Non-uniform acceptance
- Large BG from $\gamma \rightarrow e^+e^-$
- Largest uncertainties are:
  - *Flux (12.9%)*
  - *Statistics (8.7%)*
  - *Detector (8.4%)*

Also cf. Mark H's talk from the HK proto CM for a nice discussion

How might we best improve on this in an ND280 upgrade?

The importance of the ν_e / ν_μ x-section ratio

Theoretically, the CP asymmetry is : $A_{CP}^{th} = \frac{P_{\nu_\mu \to \nu_e} - P_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_e}} \propto \frac{\sin \delta_{CP}}{\cos \delta_{CP}}$

What we measure is : $A_{CP}^{meas} = \frac{N_{\bar{e}} - N_e}{N_{\bar{e}} + N_e} = \frac{1-r}{1+r}$

where $N_e = \frac{\varphi_\mu}{L_{SK}^2} P_{\nu_\mu \to \nu_e} N_{target}^{SK} \sigma_e \epsilon_e^{SK} = N_\mu^{ND} \frac{L_{ND}^2}{L_{SK}^2} \frac{N_{target}^{ND}}{N_{target}^{SK}} \frac{\sigma_e}{\sigma_\mu} \frac{\epsilon_e^{SK}}{\epsilon_\mu^{ND}} P_{\nu_\mu \to \nu_e}$

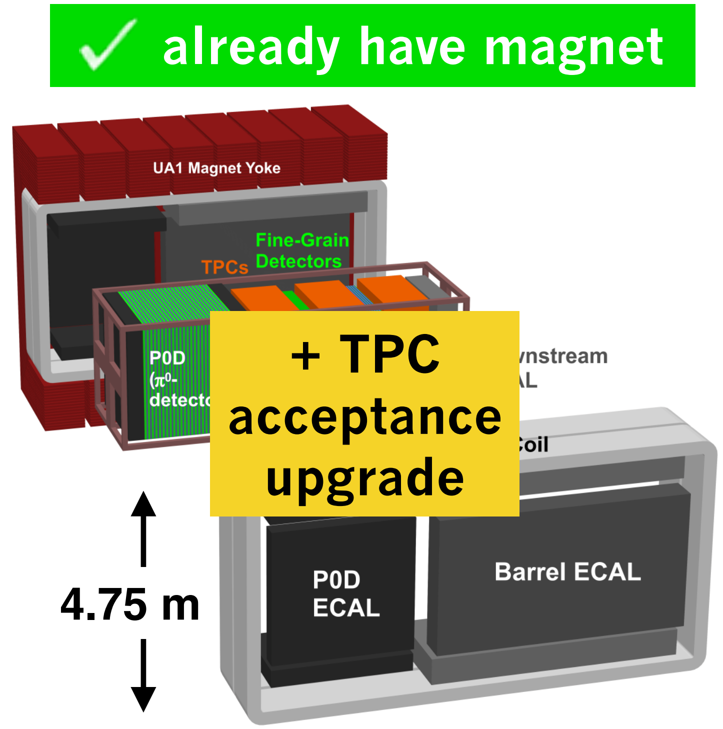
so : $r\,(P_{\nu_\mu \to \nu_e}, P_{\bar{\nu}_\mu \to \bar{\nu}_e}, N_\mu, N_{\bar{\mu}}, R_\sigma) = \frac{N_\mu^{ND}}{N_{\bar{\mu}}^{ND}} \frac{\epsilon_{\bar{\mu}}}{\epsilon_\mu} \frac{\epsilon_e}{\epsilon_{\bar{e}}} \frac{P_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e}} R_\sigma$

with : $R_\sigma = \frac{\left(\frac{\sigma_e}{\sigma_\mu}\right)}{\left(\frac{\sigma_{\bar{e}}}{\sigma_{\bar{\mu}}}\right)}$

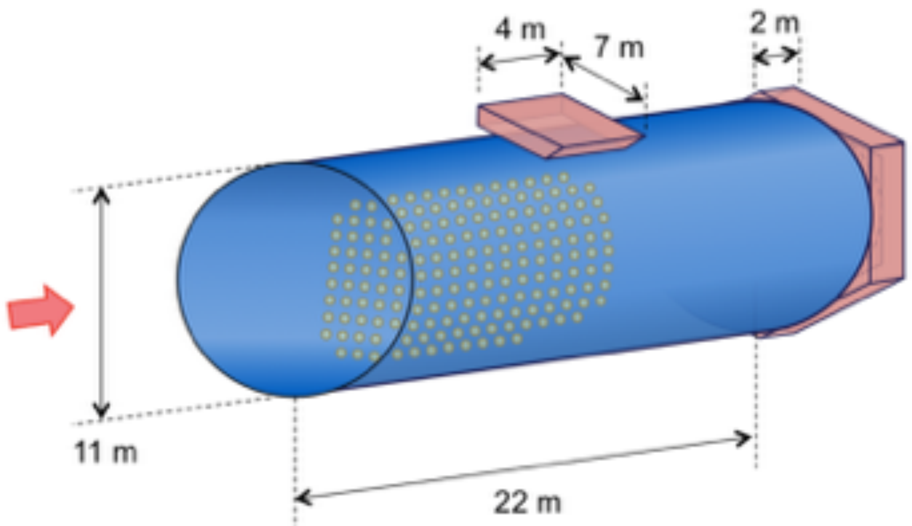
L. Haegel

NOT AN EXHAUSTIVE LIST!

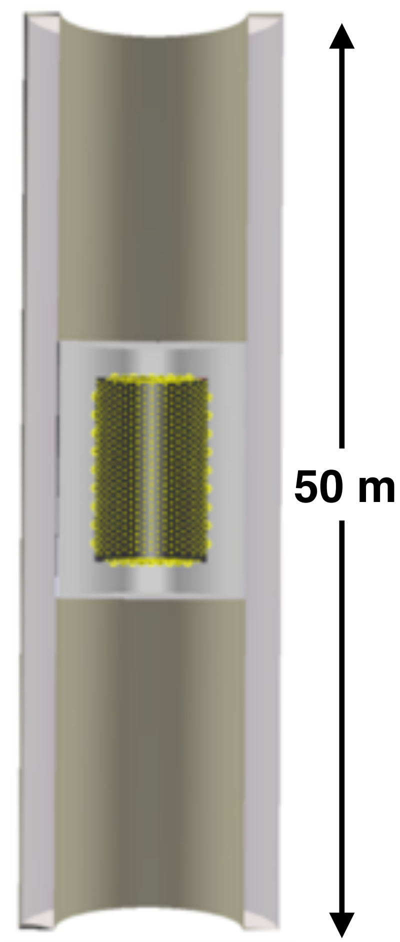
naively favour TITUS or ND280+nuPRISM?



- ☑ **Constrain wrong-sign BG** *(B-field+TPCs)*
- ☑ **High-E constraints***
- ☑ **Wagasci-style water target with short-track resolution**



- ☑ **Constrain wrong-sign BG** *(Gd & magnetized MRD)*
- ☑ **Same detection method**
- ☑ **Higher-E sample with MRD***



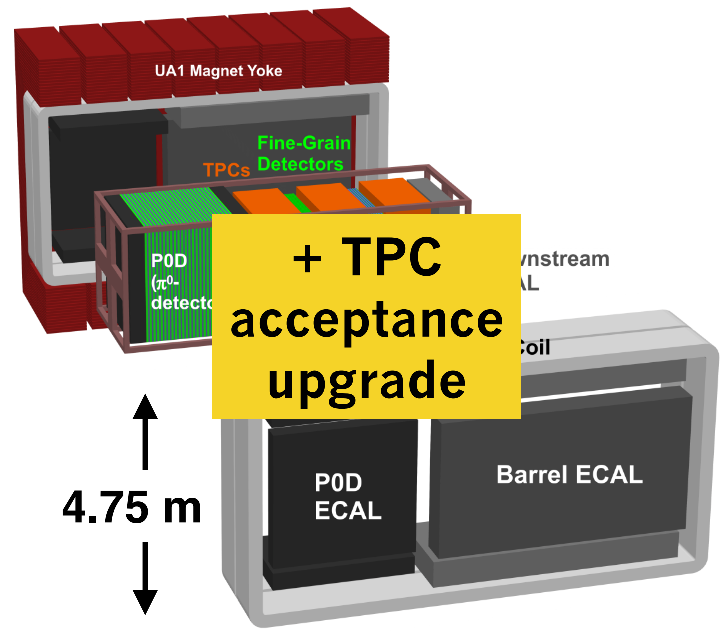
- ☑ **Interaction model independence**
- ☑ **Same detection method**
- ☑ **Sterile neutrinos**

**seems important for CPV sensitivity, cf. Raj's talk*

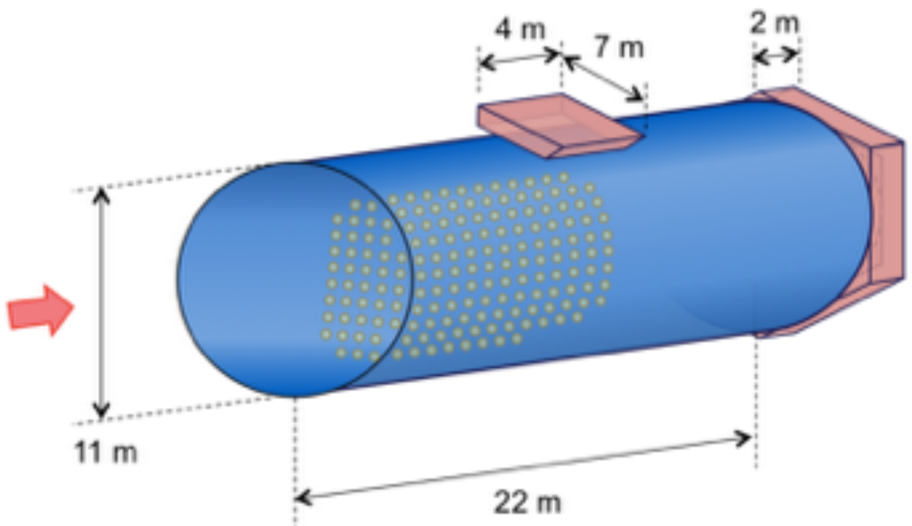
NOT AN EXHAUSTIVE LIST!

naively favour TITUS or ND280+nuPRISM?

✓ already have magnet



- ☑ **Constrain wrong-sign BG** *(B-field+TPCs)*
- ☑ **High-E constraints***
- ☑ **Wagasci-style water target with short-track resolution**
- **And what about a HP-TPC?**
  - *Do we need a clear measurement of small recoil nuclei?*
  - *<u>Also</u>: ν_e cross section and a constraint on intrinsic ν_e (excellent kinematics)*



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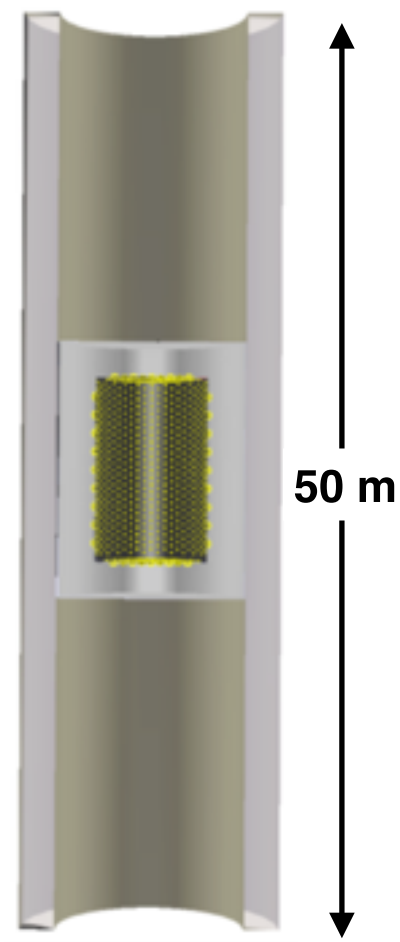

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Conclusion

Do we need a water target?

80% water, 5cm-grid 3D-tracking *Wagasci target*

After taking 10% or our original POT request in 5 years, we can achieve 2-3 times our request by 2025 — and then follows Hyper-K

It may be advantageous to *upgrade the acceptance* of the target to match Super-K/Hyper-K's by introducing *new side-TPCs*

POD is less strongly motivated given large θ_{13}

—There is space for a *High Pressure TPC*

—What better tool to study interaction model effects in detail?

Other issues

—Probably need to replace ECAL — expensive

—Introduce a range detector in the basket?

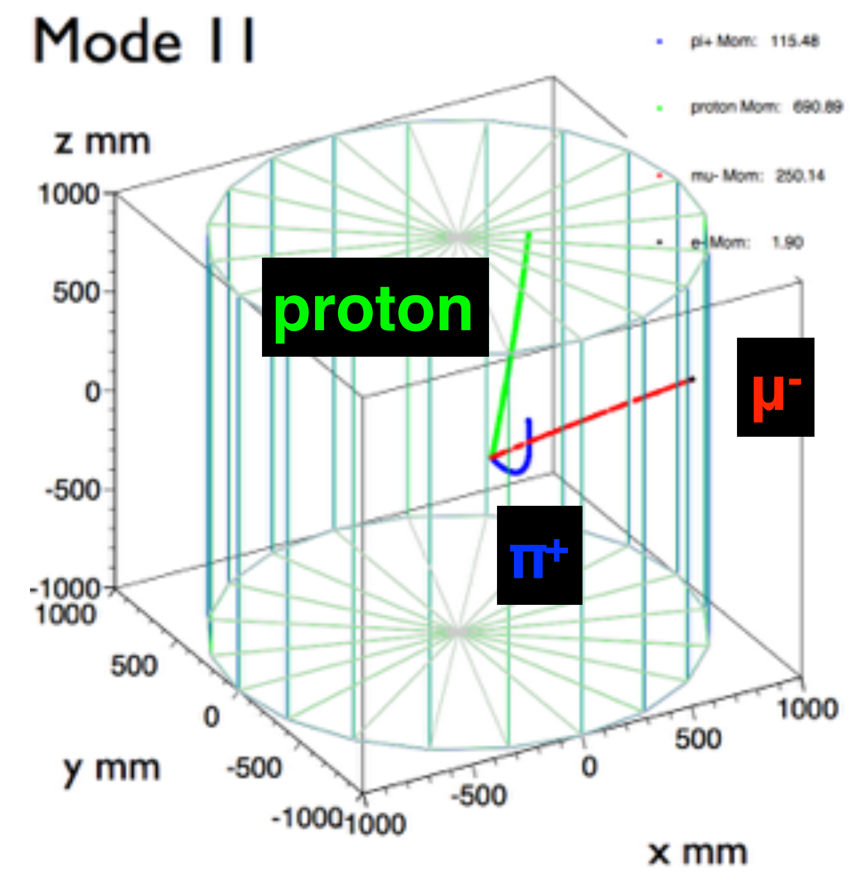
Simulations and quantitative predictions are underway

Backup slides follow

F. Sanchez, M. Ravonel

Low threshold detector to pin down nuclear model

High Pressure Time Projection Chamber



Advantages

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- Possibility to exchange targets
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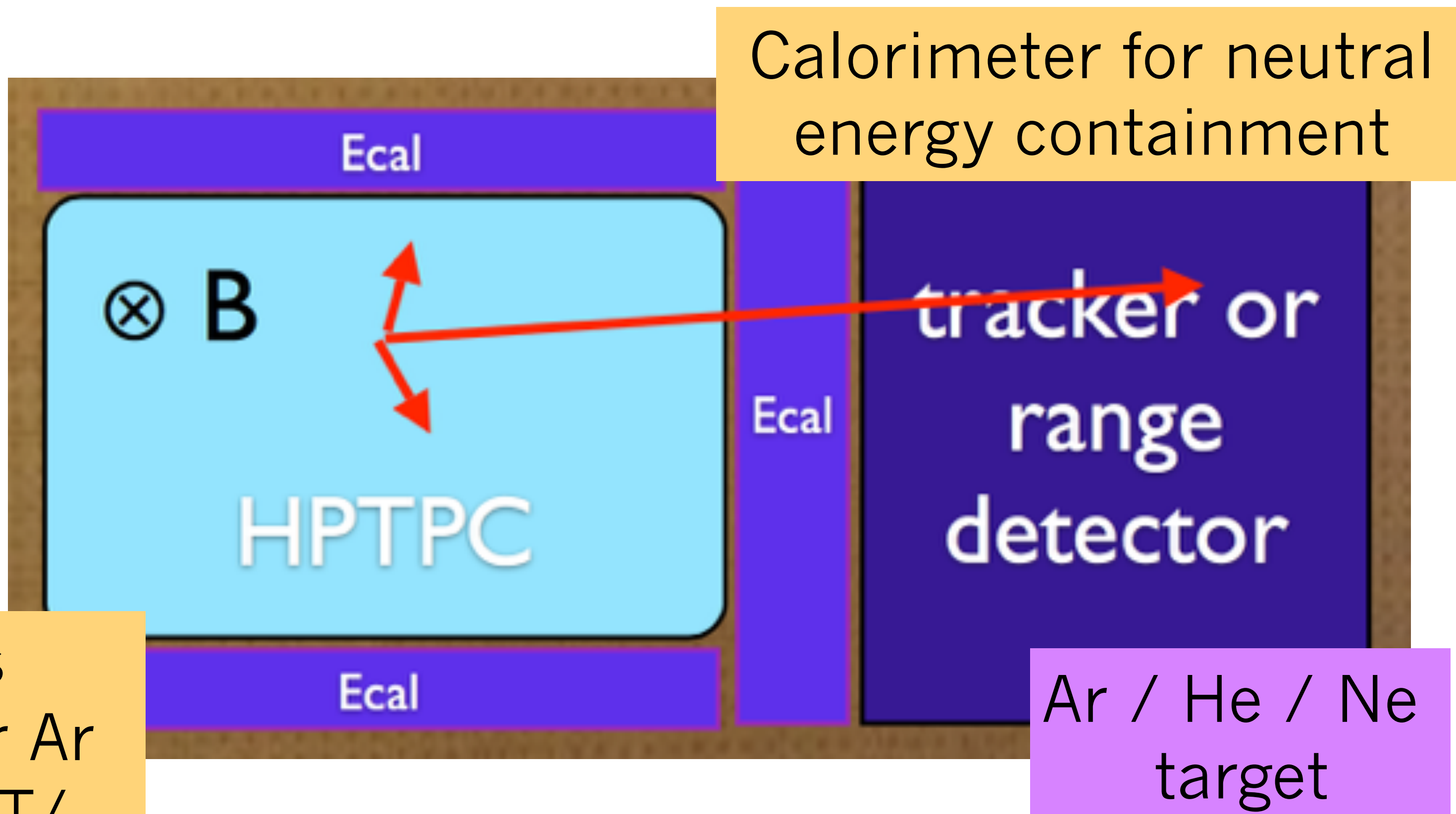

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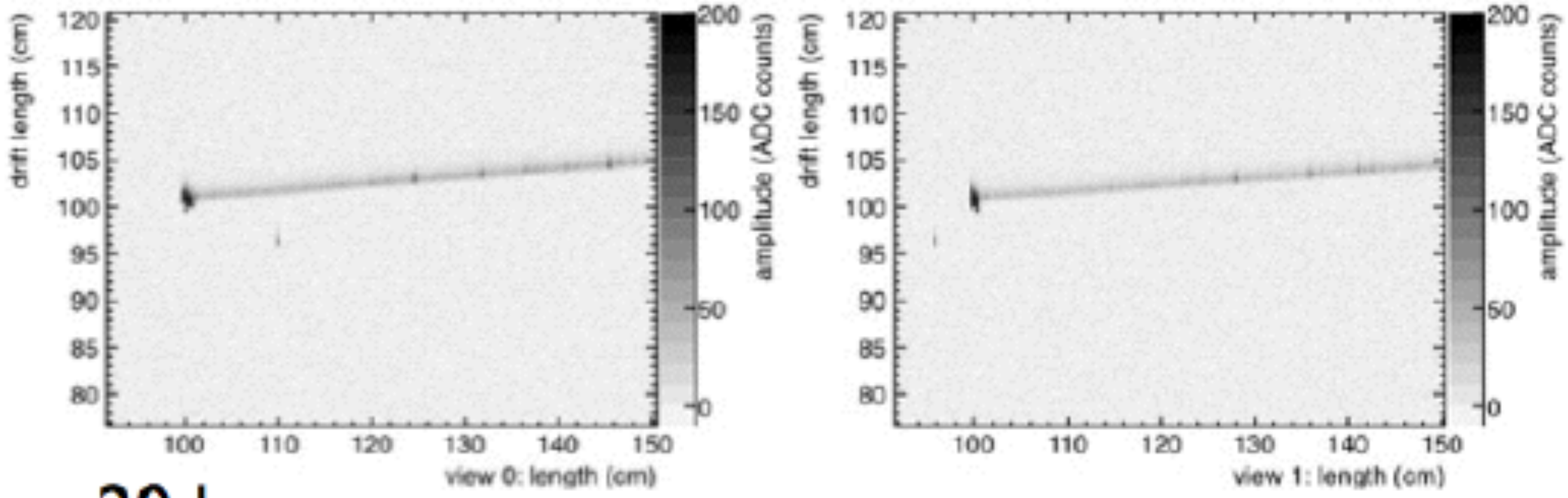
($8 m^3$ detector, 4 years, 1.6×10^{21} POT/ year)

http://www.t2k.org/meet/nd280/meet/NDupgrade/ NDWS-Jan14/NDWS

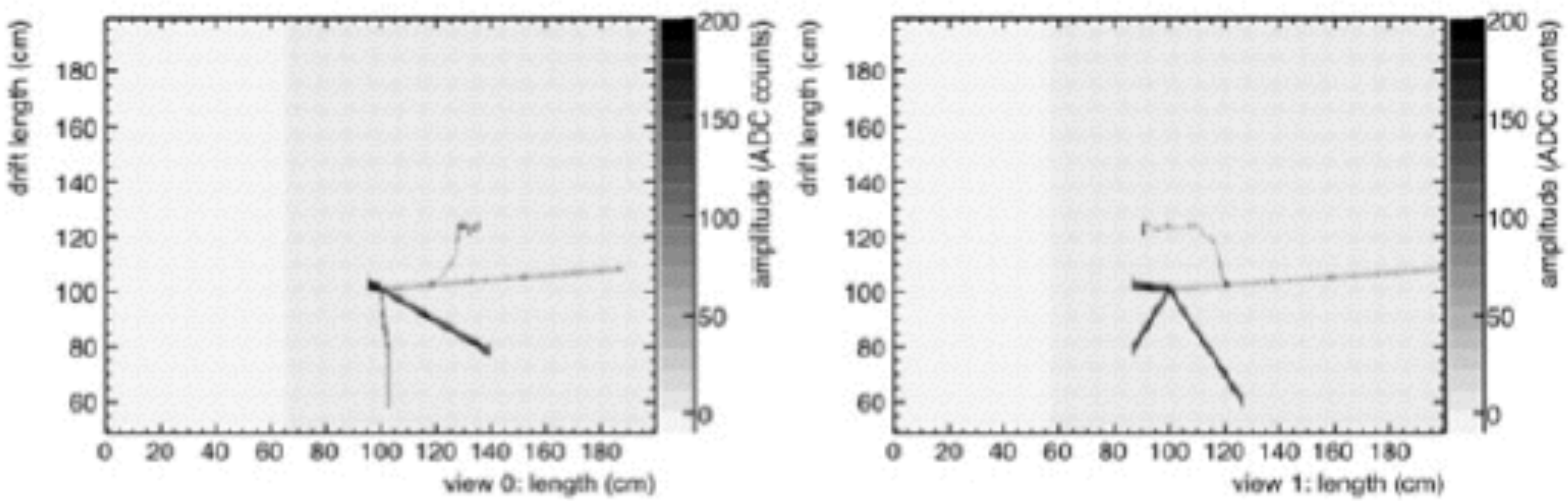
Comparing liquid vs gas argon

Curioni, LBNO ND working group, 2012

liquid Ar



Ar gas 20 bar



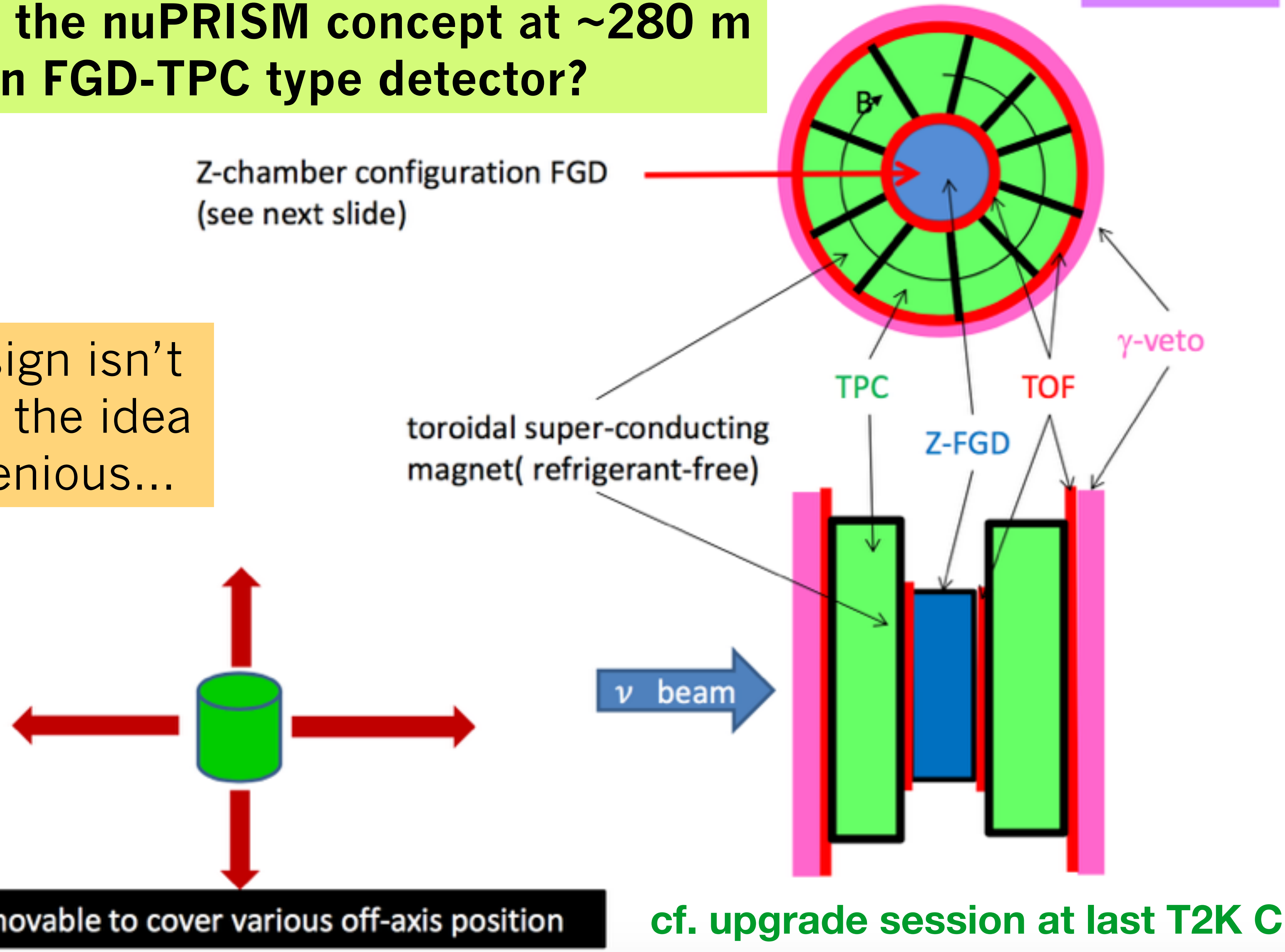
Beautiful and interesting, but how would we use these short tracks?

“a toy to have a brainstorm for the future”

Could we use the nuPRISM concept at ~280 m with an FGD-TPC type detector?

A.Ichikawa

This TPC design isn’t practical, but the idea is rather ingenious…

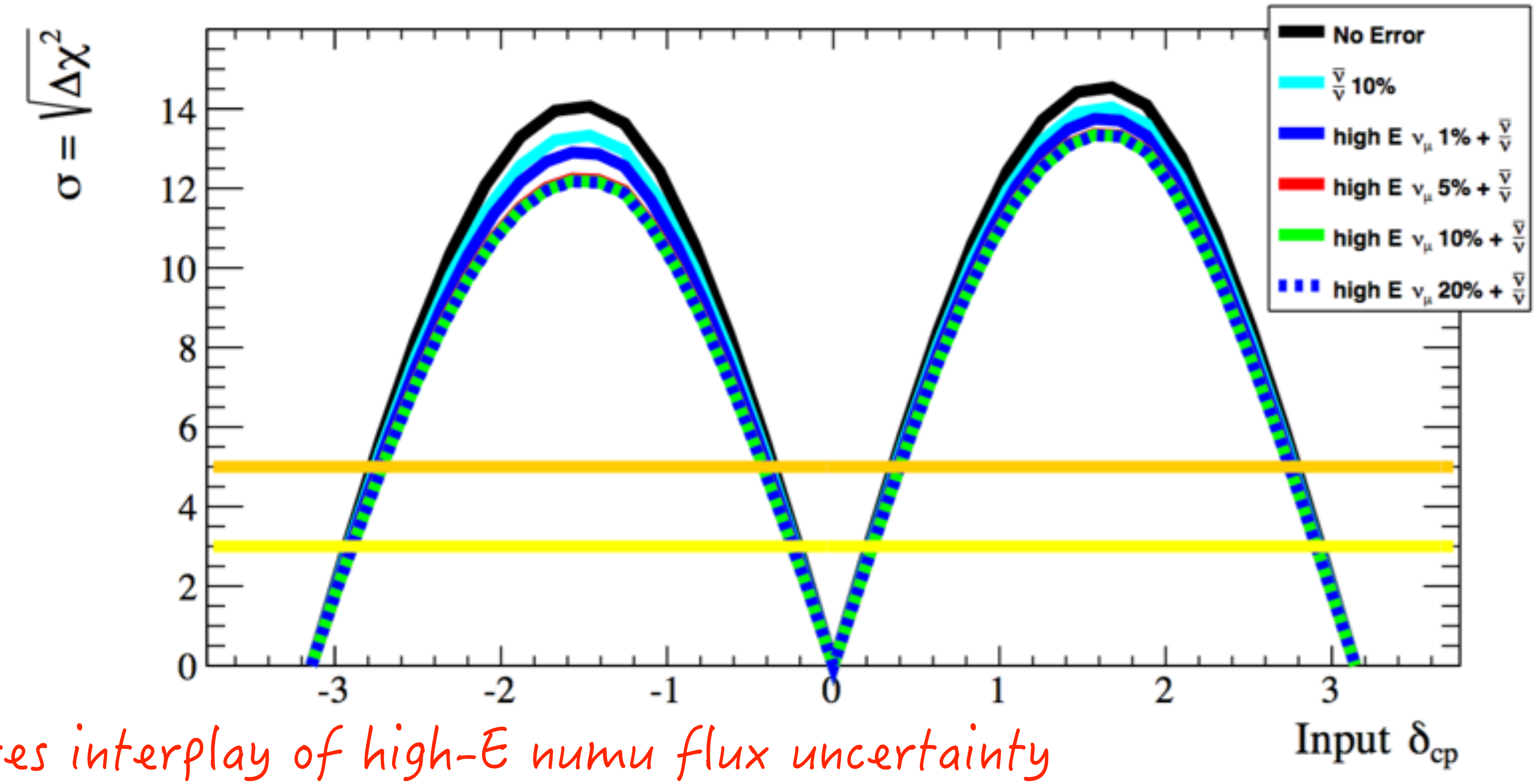


cf. upgrade session at last T2K CM

Or more simply, a magnetized MRD behind a Wagasci/PM-style target?

informal chat, MH

Additional effect of High E($>$ 1GeV) uncertainty



Illustrates interplay of high-E numu flux uncertainty
and antineutrino cross-section unceratinty on CPV sensitivity

Up to 2x reduction in sensitivity when high E error considered with $\frac{\bar{\nu}}{\nu}$

Increase error beyond 5% makes no difference

Constraint between 1%-5% necessary to improve sensitivity

Raj Shah, VALOR sensitivity studies, this meeting

Raj Shah (Oxford) R HyperK Studies June 30, 2015 8 / 68

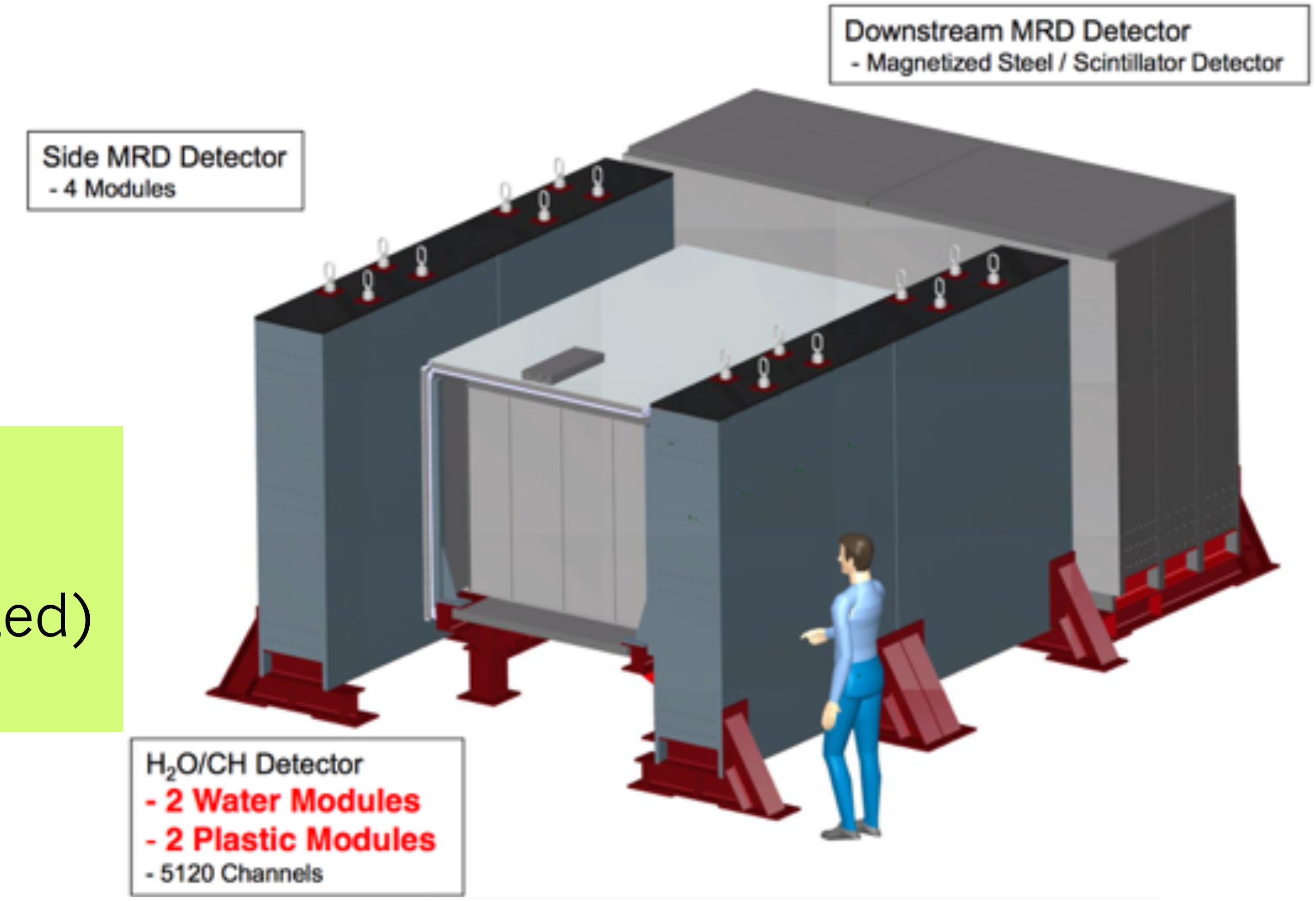
Notes

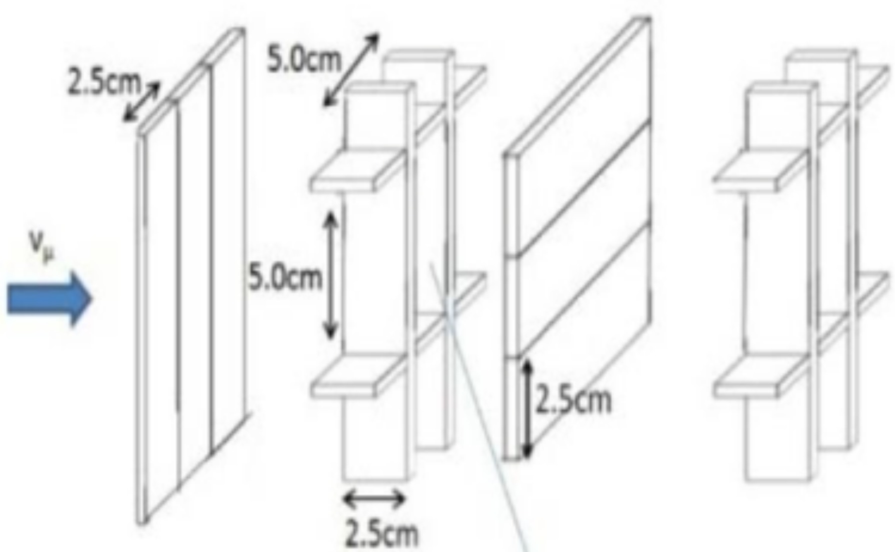
3% precision H_2O / CH x-section ratio

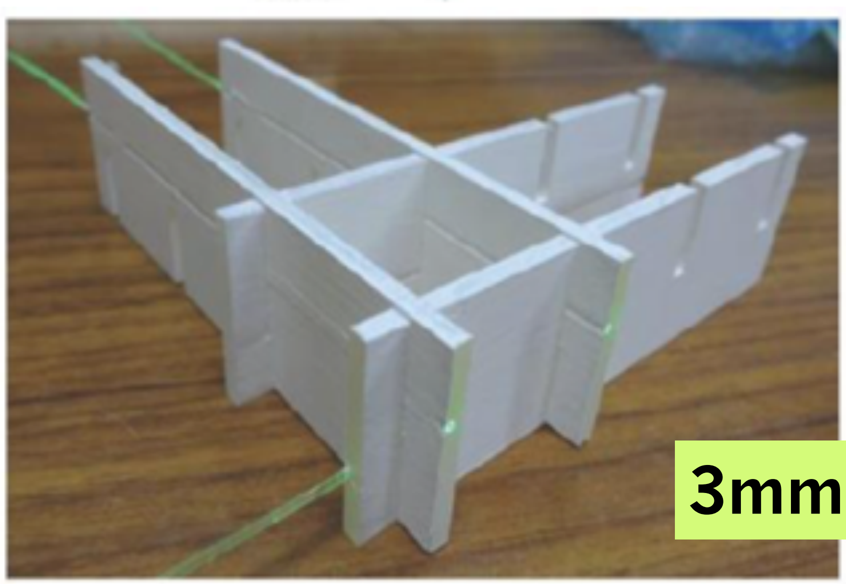
Wagasci

Wagasci collaboration

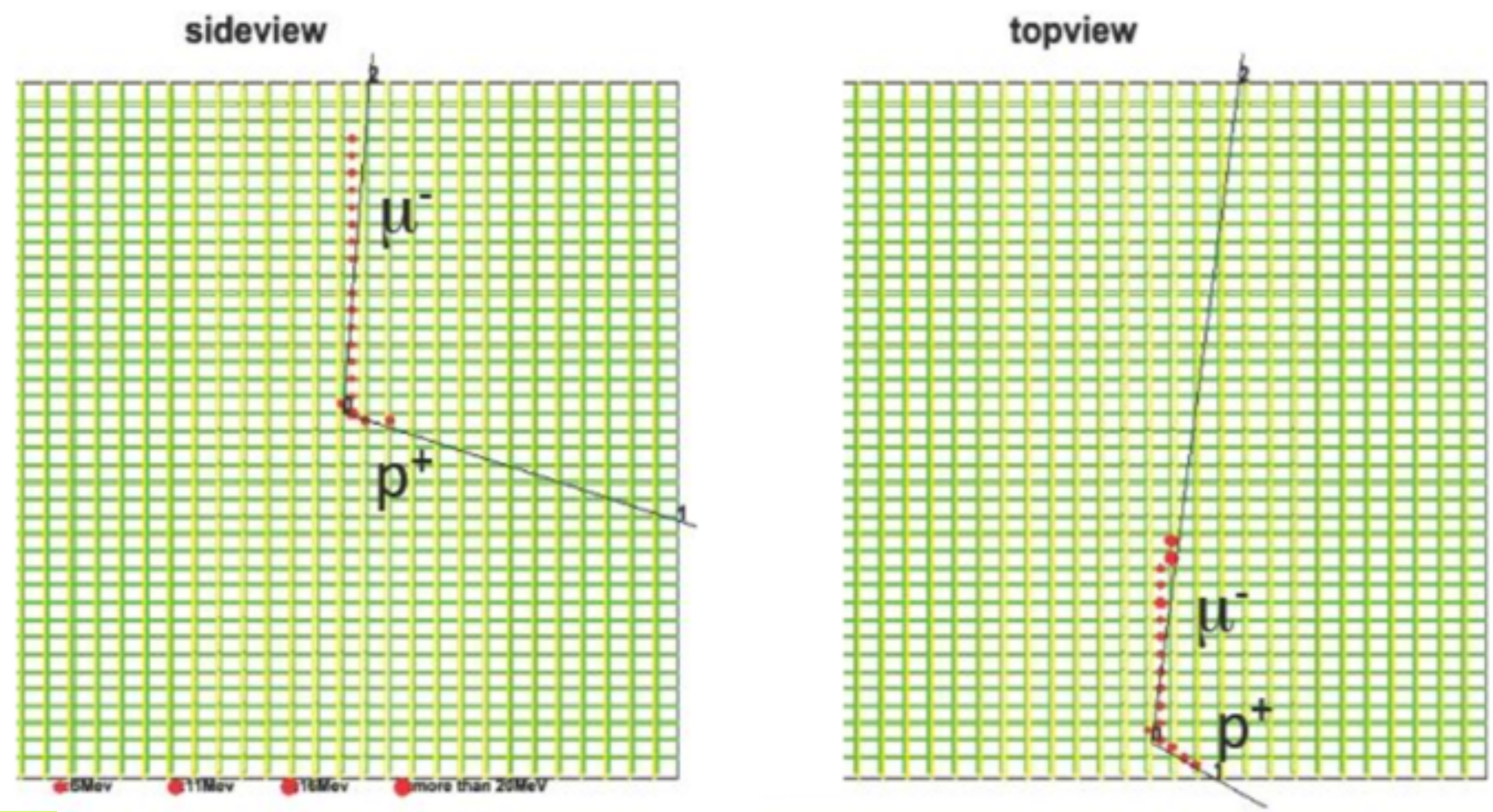
'The B2 experiment'
- 3D scintillator grid filled with water
- Side MRDs and end MRD (magnetized)
- Excellent phase space coverage







3mm thick



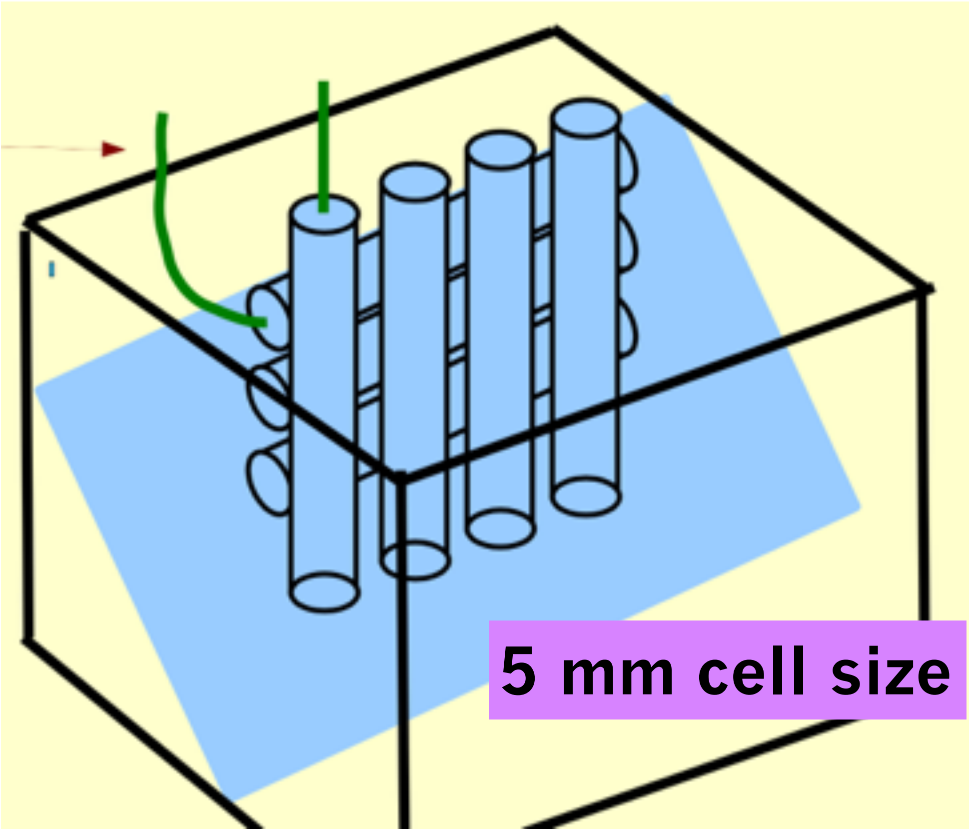
Straws and WBLS - a better target for ND280?

Water-based liquid scintillator

Stanley Yen, TRIUMF

Current FGD2

- Dead regions
- Low energy recoil protons produce no signal in passive water



mylar straws painted with reflective paint on the outside, WLS fibres strung inside the straws

Water-Based Liquid Scintillator (WbLS) at Brookhaven National Lab

- WbLS-1 70% water **1000** optical photons/MeV
- WbLS-2 70% water **1500** optical photons/MeV

compared with pure liquid scintillator (BC408) **10,000** photons/MeV

Currently measuring light output using TRIUMF cyclotron

http://www.t2k.org/ndup/ general/meetings/ 20150203/

Stop water vertices migrating between p0dules - two methods with WBLS

http://www.t2k.org/meet/ndup/general/meetings/ 20141005/NDup-20141005

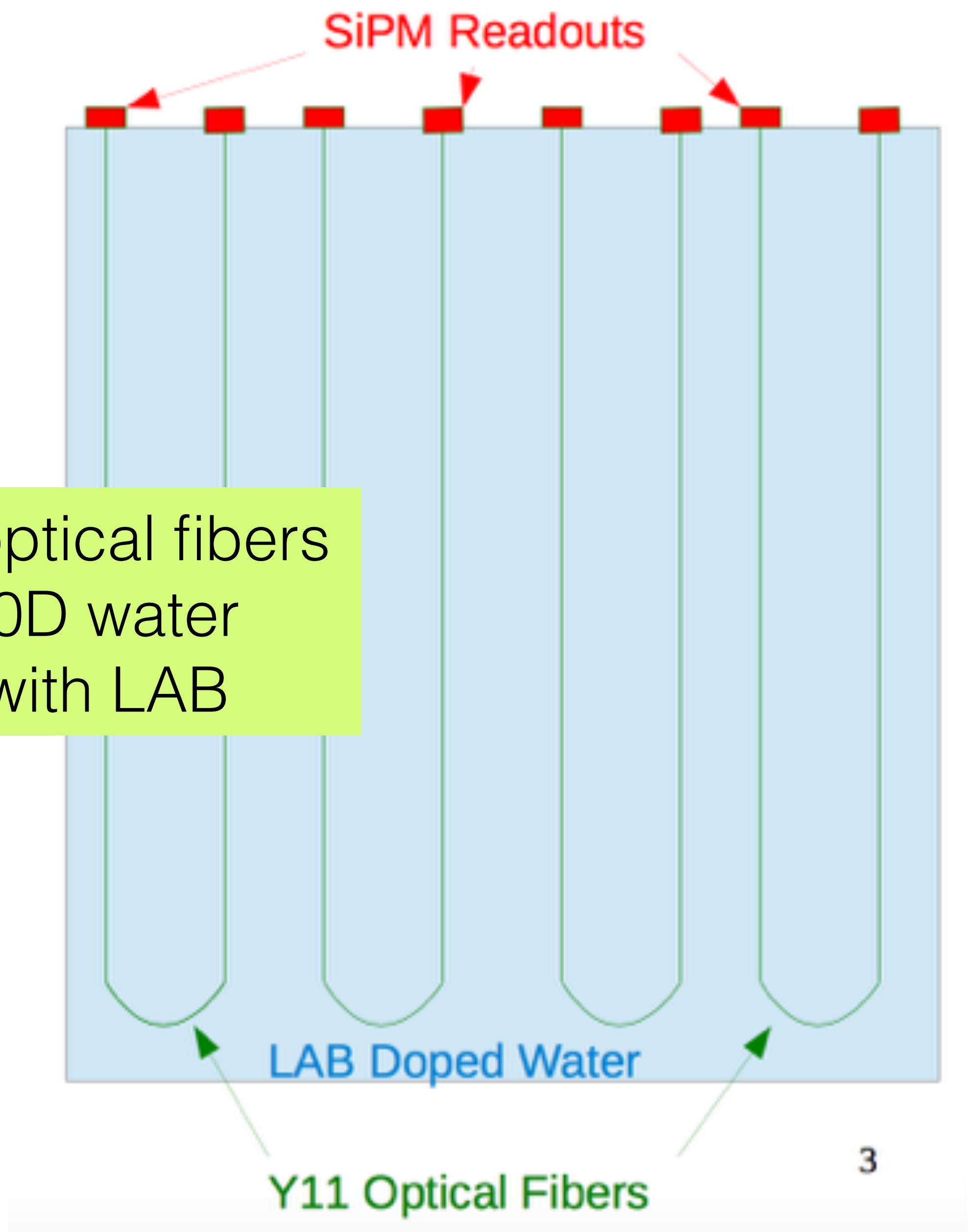
P0D Water Bag Upgrades

Ryan Wasserman, Norm Buchanan, Walter Toki, Colorado State University

liquid scintillator linear alkylbenzene (LAB)

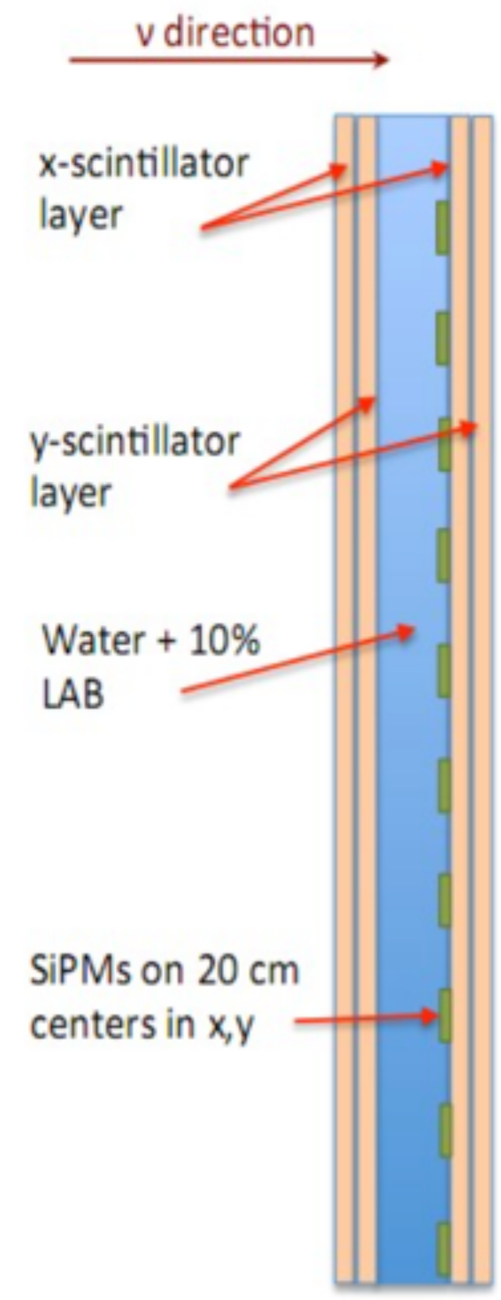
option 1

Curved Y11 optical fibers placed into P0D water bags doped with LAB



option 2

SiPMs and LAB inside P0D water modules



Plans to create a 1m x 1m scale prototype detector in HEP lab at CSU

Neutrino beam mode $\nu_\mu \to \nu_e$ uncertainties:

Error source [%]	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0$
Beam flux and near detector	2.9	4.8
(w/o ND280 constraint)	(25.9)	(21.7)
ν interaction (external data)	7.5	6.8
Far detector and FSI+SI+PN	3.5	7.3
Total	8.8	11.1

What are the limitations?

<u>A. Near detector and far detector are different</u>

A quantitative re-projection of these causes of errors is necessary in order to understand better what to improve.

A0. flux at near detector and far detector are different.

The FD/ND ratio is however quite well known

A1. Near dector is scintillator not water

However cross-sections on water are being measured using FGD2 (40% water) , by subtraction from FGD1 with proper weighting, or by identification of events in water

➔ it would be better to have fractionally more water in target.

A2. Near detector has different E_ν resolution and acceptance than far detector.

Acceptance is presently limited to ± 53° (forward) for muons, extrapolation leads to model dependent error. *Needs to be quantified -- concerns 30% of cross-section?*

We can now get larger angle muons but momentum and sign determination are unclear.

Efficiency for photons is different? (is it sufficient to estimate correction?)