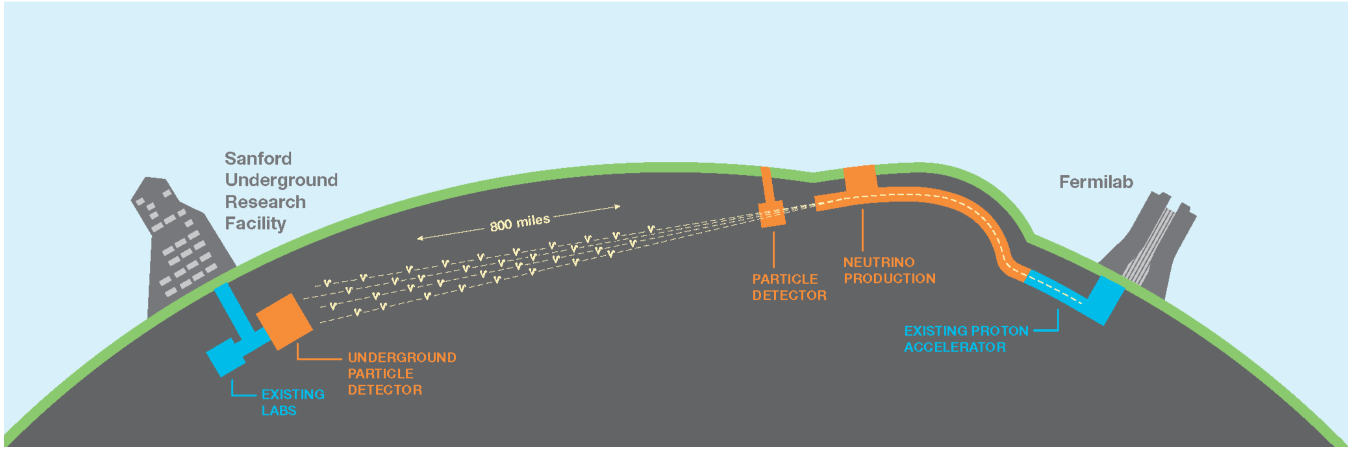


DUNE: Status and Plans

Mark Thomson

On behalf of DUNE-UK

PPAP Meeting, 26th July 2016

UNIVERSITY OF CAMBRIDGE

Overview

- **A lot has happened since the last PPAP meeting…**
  - The Deep Underground Neutrino Experiment formed
  - It will be the flagship project of Fermilab
  - Very strong support from US DOE, CERN, …

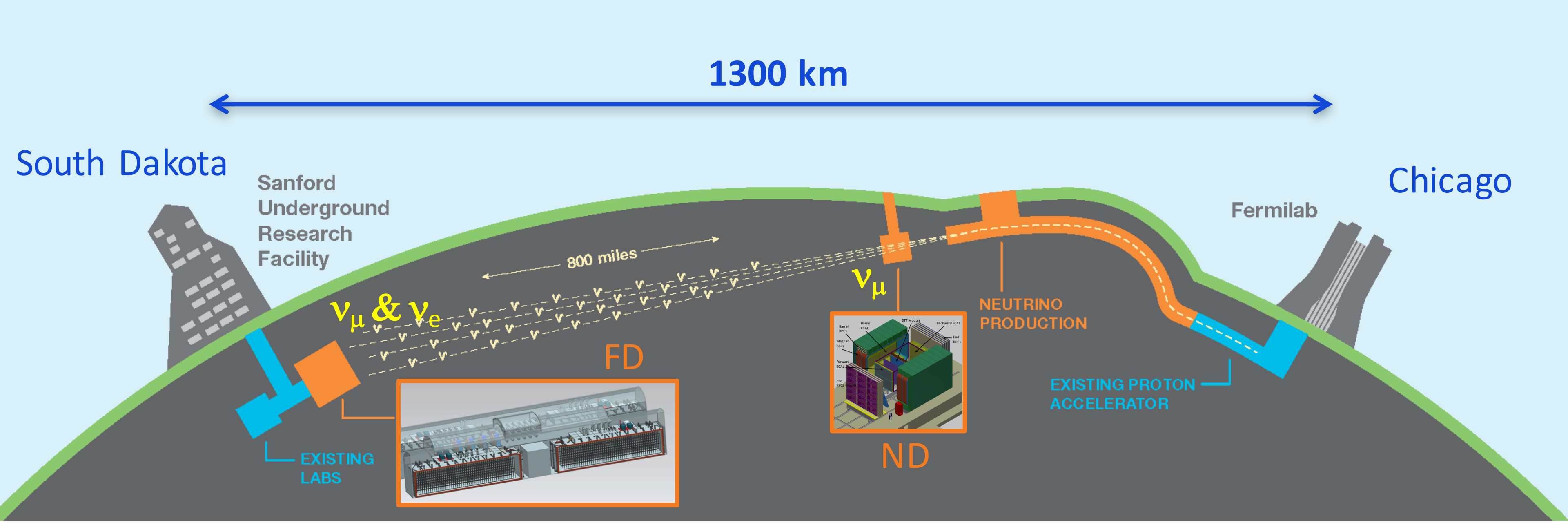
⇨ DUNE is now very much on the real axis

⇨ Anticipate DOE construction funding this Fall

⇨ Construction start in US FY17

1. Introduction: LBNF/DUNE

- **LBNF/DUNE will consist of**
  - **An intense 1.2 MW upgradeable ν beam fired from Fermilab**
  - **A massive (70,000 t) deep underground LAr detector in South Dakota and a large Near Detector at Fermilab**
  - **A large international collaboration**



International from day one

- **US-hosted – but truly international**

- **Model for international partnerships:**
  - LBNF/DUNE developed as an international partnership
  - Governance model follows closely that of the LHC:
    - **Facility:** LHC ↔ LBNF
    - **Experiment:** ATLAS/CMS ↔ DUNE

- **International Funding Model:**
  - LBNF: US-hosted project with international contributions (aim: ~75% US, ~25% international = non US)
  - DUNE: an international science collaboration (aim: ~25% US, ~75% international)

2. DUNE Collaboration

The DUNE Collaboration

Paraphrasing the P5 report (2014)

- **Called for formation of "LBNF":**
  - as an international collaboration
  - ambitious scientific goals:
    - Discovery of Leptonic CP-violation
    - Proton decay
    - Supernova burst neutrinos

Resulted in the formation of the DUNE collaboration with strong representation from:

- LBNE (mostly US)
- LBNO (mostly EU)
- Other interested institutes

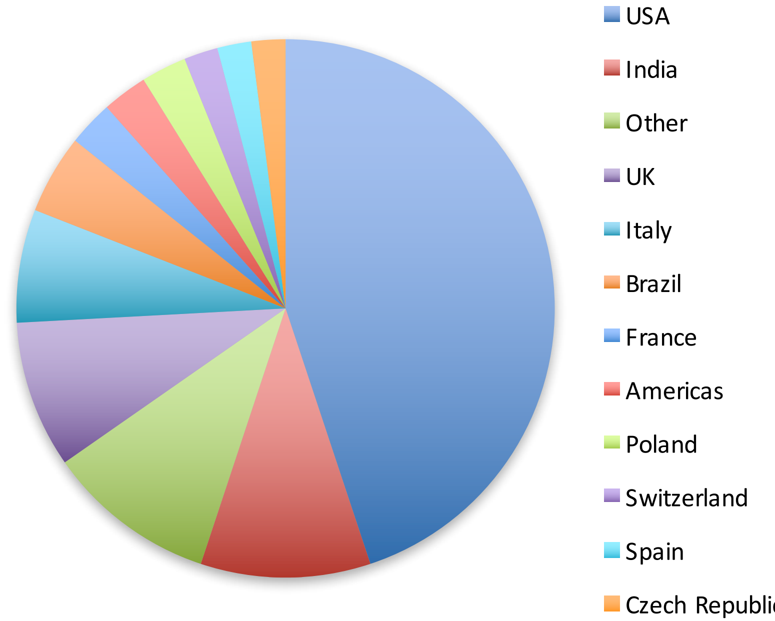
DUNE

The DUNE Collaboration

As of 0500 today from

888 Collaborators 156 Institutes

Armenia, Brazil, Bulgaria, Canada, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, **UK**, Ukraine, USA



DUNE has broad international support and is growing
~80 new collaborators so far this calendar year

DUNE-UK

As of 0500 today **from**

110 Collaborators **13 UK Institutes**

Bristol, Cambridge, Durham, Imperial, Lancaster, Liverpool, Manchester, Oxford, Sheffield, STFC-RAL, Warwick, UCL

+ will soon join: STFC-DL & Birmingham + Edinburgh (?)

DUNE-UK

As of 0500 today **from**

110 Collaborators **13 UK Institutes**

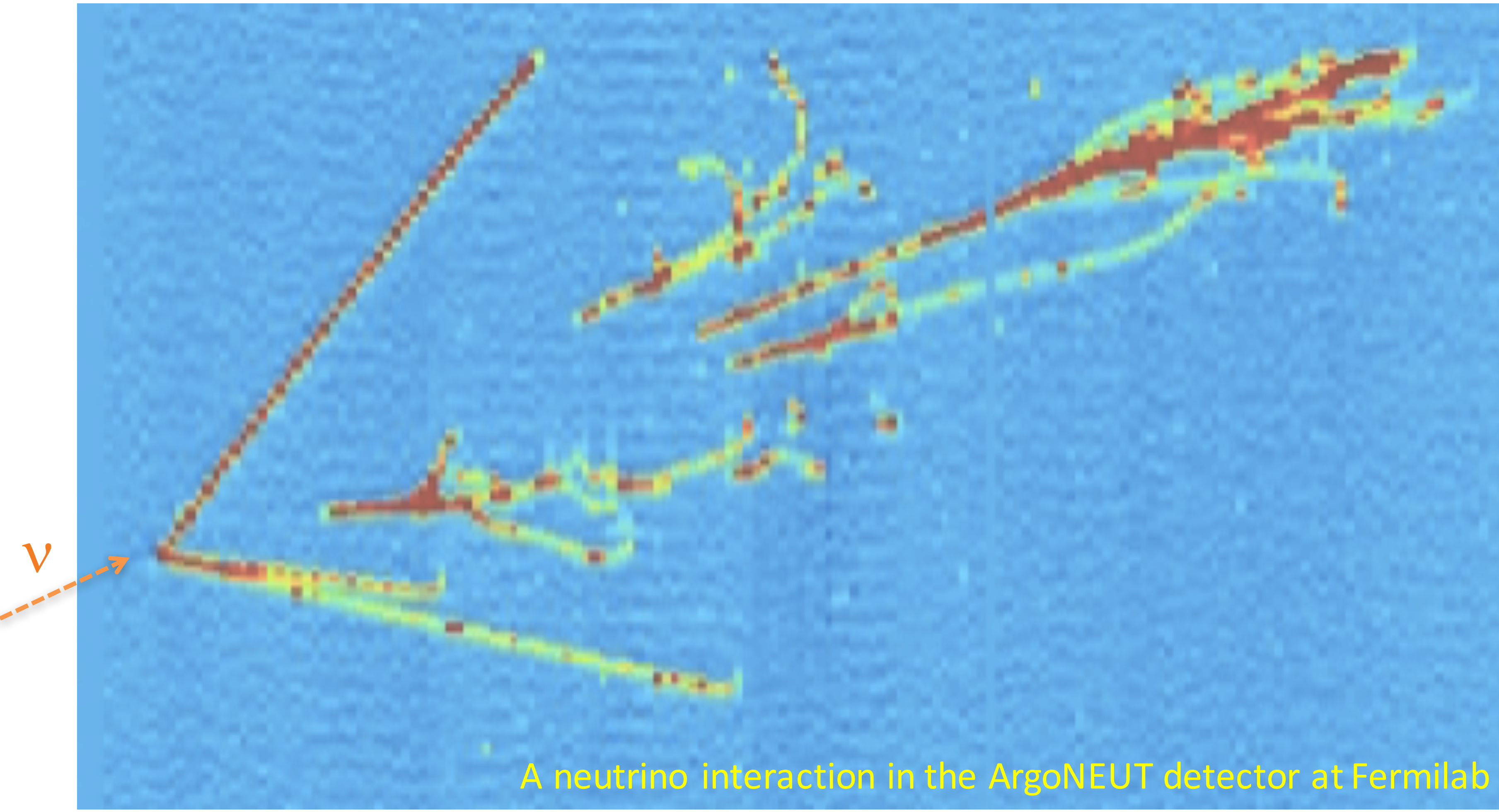
Bristol, Cambridge, Durham, Imperial, Lancaster, Liverpool, Manchester, Oxford, Sheffield, STFC-RAL, Sussex, Warwick, UCL

+ will soon join: STFC-DL, Birmingham & Edinburgh

- **Strong UK Leadership within DUNE:**
  - Co-spokesperson (M. Thomson)
  - Co-coordinator of protoDUNE-SP @ CERN (C. Touramanis)
  - Chair of Speakers Committee (S. Soldner-Rembold)
  - Head of Beam Optimization Group (A. Weber)
  - Coordinator of DUNE DAQ group (G. Barr)
  - + a significant number of WG convenership roles

3. The DUNE Science Program

Unprecedented precision utilizing a massive Liquid Argon TPC

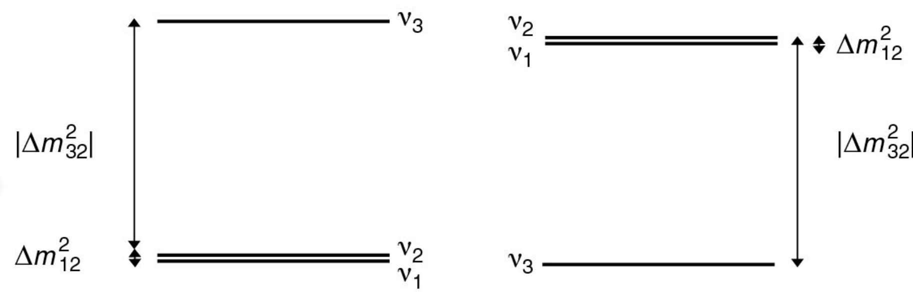


A neutrino interaction in the ArgoNEUT detector at Fermilab

DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astroparticle physics:

- **1) Neutrino Oscillation Physics**
  - **Discover CP Violation** in the leptonic sector
  - Mass Hierarchy
  - Precision Oscillation Physics:
    - e.g. parameter measurement, θ_{23} octant, **testing the 3-flavor paradigm**



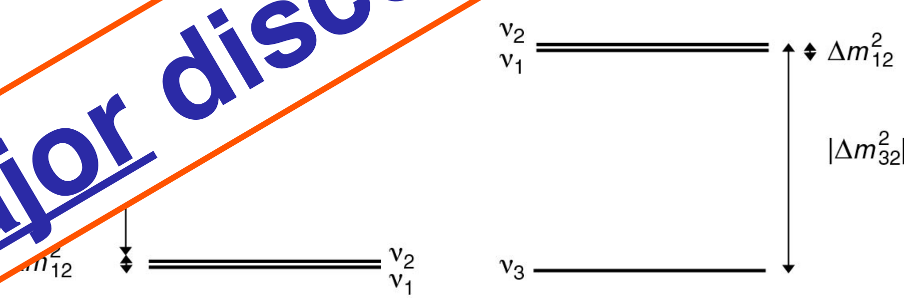
- **2) Nucleon Decay**
  - e.g. targeting SUSY-favored modes, $p \rightarrow K^+\overline{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

DUNE Primary Science Program

Focus on fundamental open questions in partic... physics and astroparticle physics:

All would be ***major*** discoveries

- **1) Neutrino Oscillation Physics**
  - **Discover CP Violation** in the leptonic sector
  - Mass Hierarchy
  - Precision Oscill...
    - e.g. para... ...ment, θ_{23} octant, **testing the 3-flavor paradigm**



- **2) N... ...cay**
  - ...eting SUSY-favored modes, $p \rightarrow K^+\bar{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

3.1 DUNE Oscillation Strategy

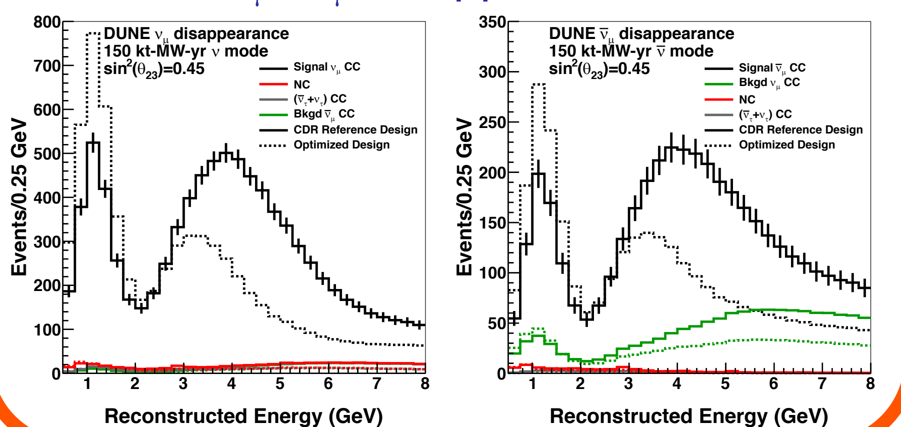
Measure neutrino spectra at 1300 km in a wide-band beam

- Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for BSM effects (e.g. NSI) in a single experiment
  - **Long baseline gives:**
    - Matter effects are large ~ 40%
  - **Wide-band beam:**
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects are separable

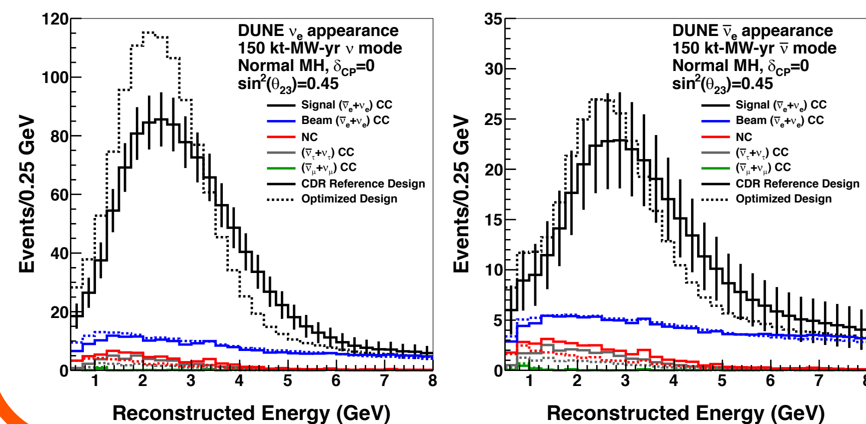
E ~ 1-10 GeV

3+$\overline{3}$ years

ν_μ / $\overline{\nu}_\mu$ disappearance

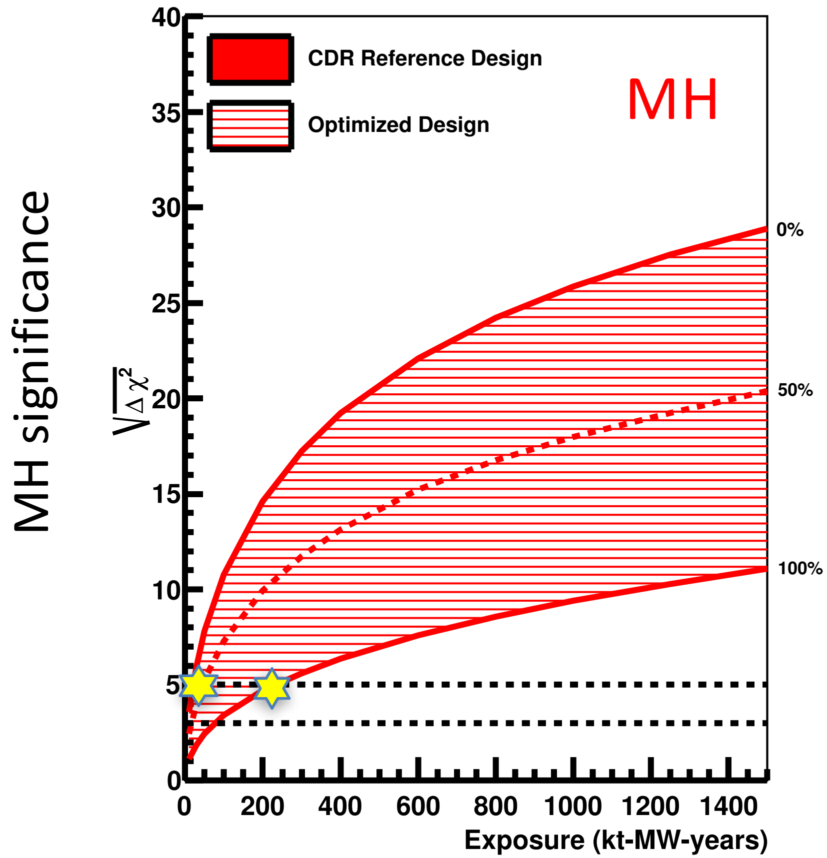


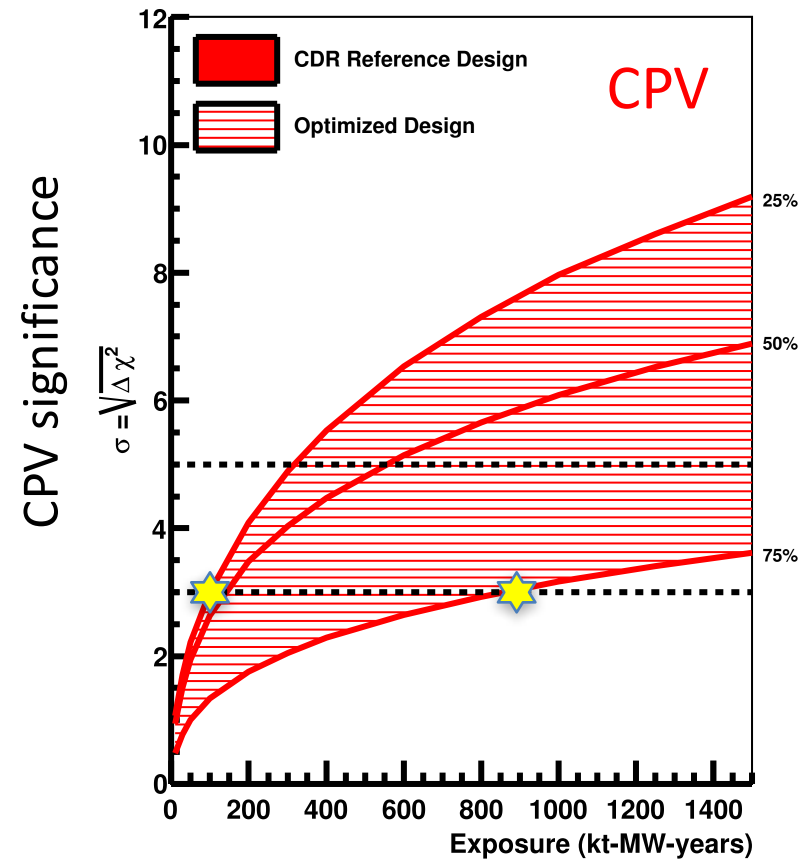
ν_e / $\overline{\nu}_e$ appearance



MH and CPV Sensitivities

★ Sensitivities depend on multiple factors:
- Other parameters, e.g. δ
- Beam spectrum, …





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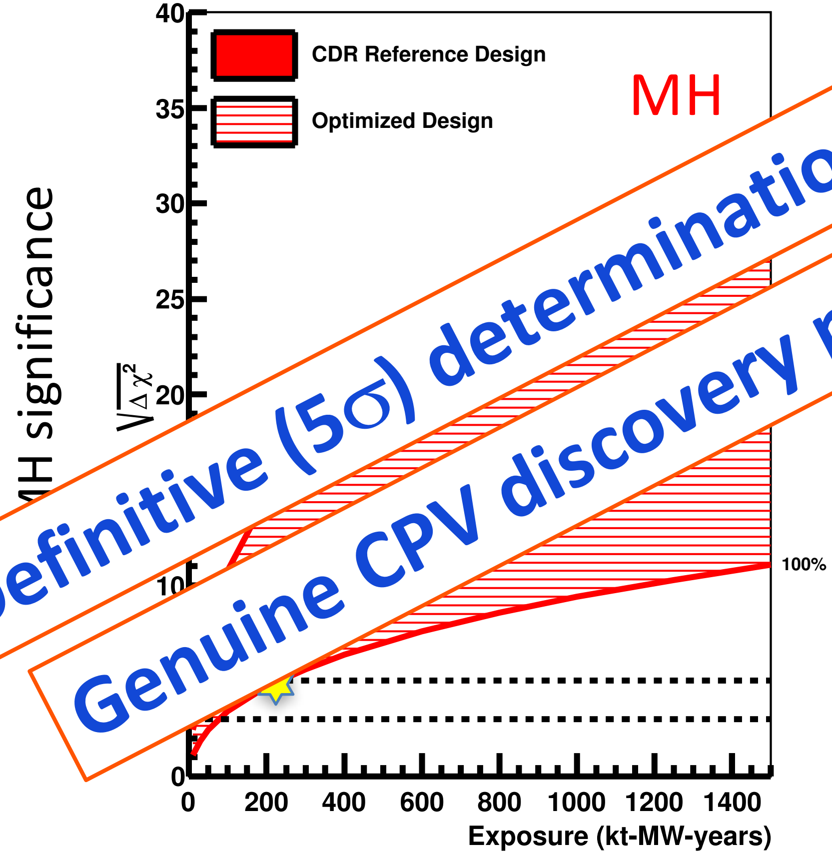
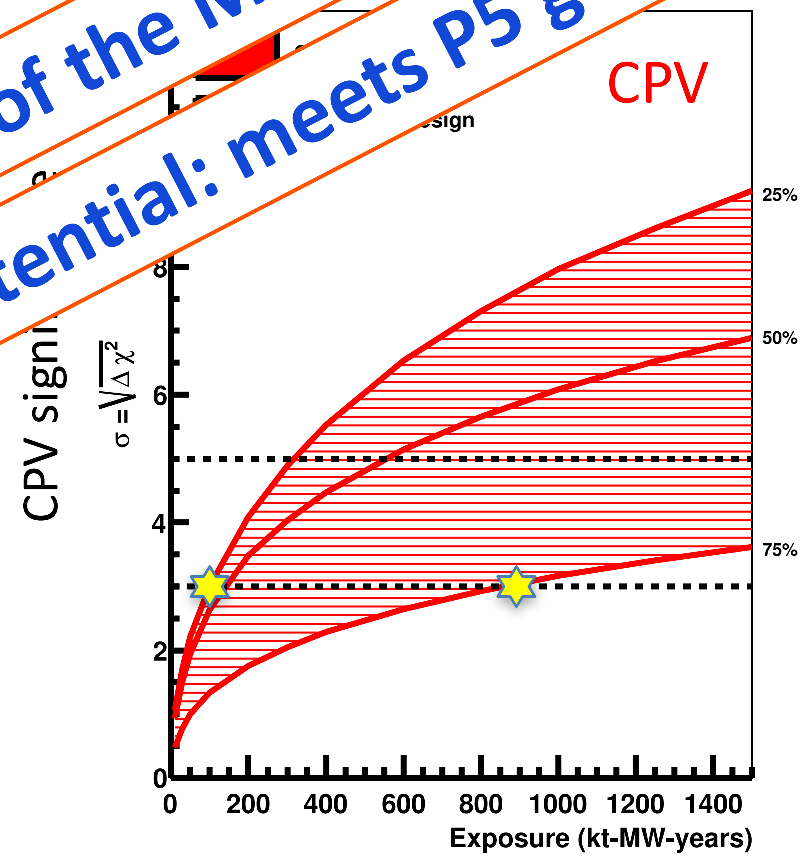


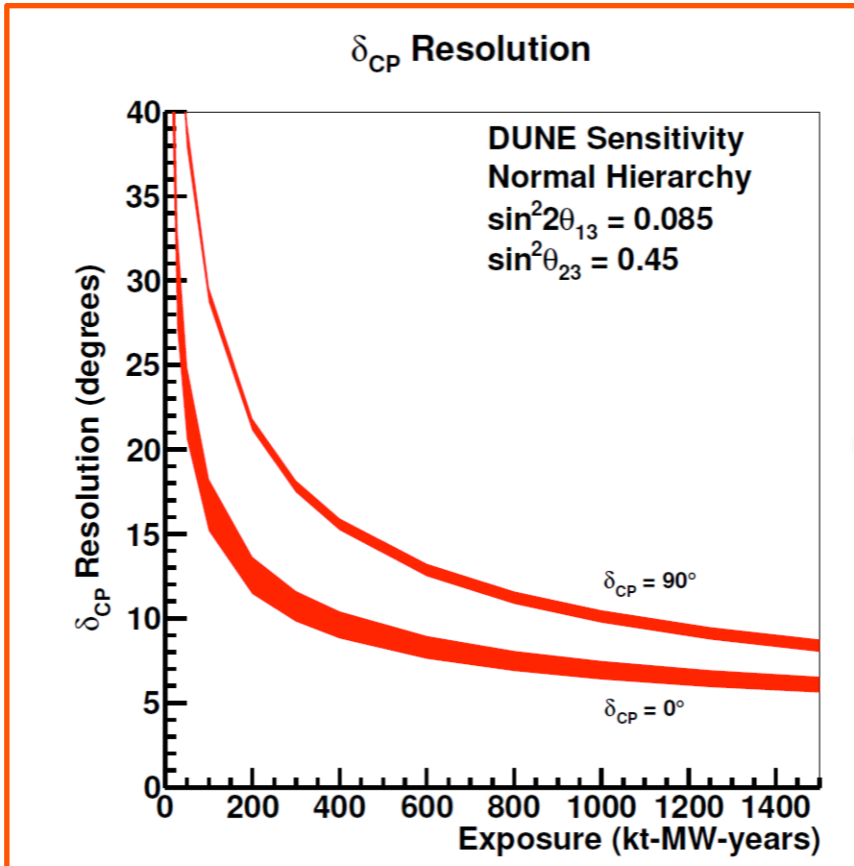


Definitive (5σ) determination of the Mass Hierarchy

Genuine CPV discovery potential: meets P5 goals

Beyond discovery: measurement of δ

- ★ CPV "coverage" is just one way of looking at sensitivity…
- ★ DUNE will **measure** δ_{CP}



Start to ~approach current level of precision on quark-sector CPV phase (although takes time)

Oscillation Über-Summary

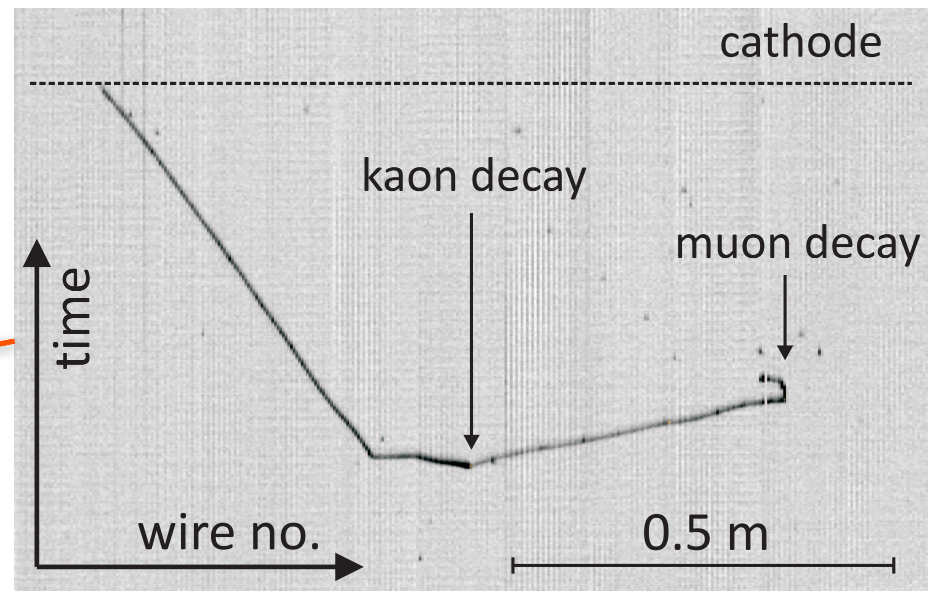
- **Nail the Mass Hierarchy**
  - 5σ in 2 – 5 years
- **75 % coverage for 3σ CPV discovery**
  - although it could take time
- **If "lucky", CPV reach 3σ (5σ) in 3-4 (6-7) years**
- **Wide-band beam provides test of 3-flavour paradigm**
  - Sensitivity to BSνM effects, e.g. NSI, steriles, …
- **On-axis: potential to tune beam spectrum**
  - Study 2nd oscillation maximum
  - Study tau appearance (?)

3.2 Proton Decay

Proton decay is expected in most new physics models

- But lifetime is very long, experimentally $\tau > \sim 10^{33}$ years
- Relative strength of LAr (c.f. water) is for "heavy" particles in final state
  - For example, look for kaons from SUSY-inspired GUT p-decay modes such as $p \to K^{+}\overline{\nu}$

E ~ O(200 MeV)



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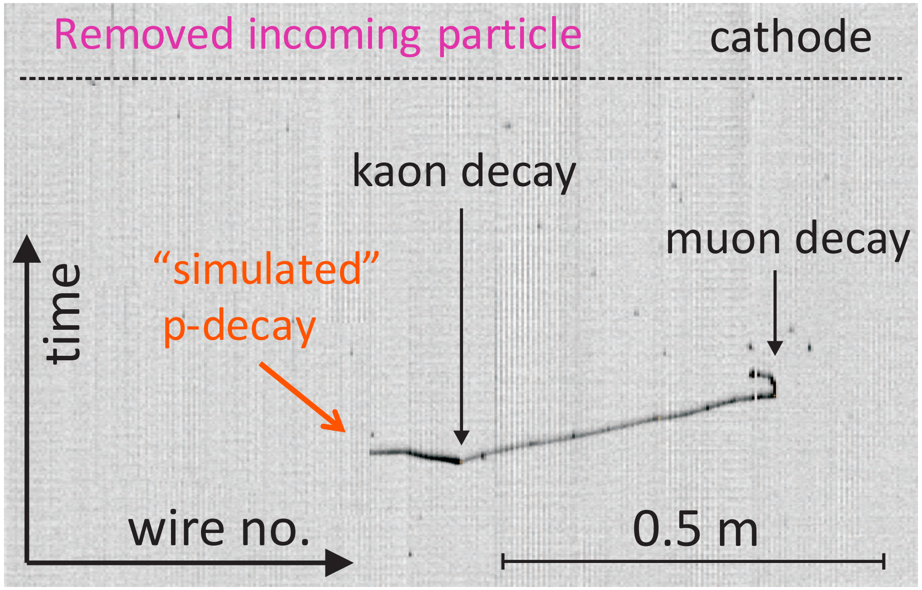
  - For example, look for kaons from SUSY-inspired GUT p-decay modes such as $p \rightarrow K^+ \overline{\nu}$

- **Clean signature**

  ➡ **very low backgrounds**

Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow K^+ \overline{\nu}$	19%	4	97%	1
$p \rightarrow K^0 \mu^+$	10%	8	47%	< 2
$p \rightarrow K^+ \mu^- \pi^+$			97%	1
$n \rightarrow K^+ e^-$	10%	3	96%	< 2
$n \rightarrow e^+ \pi^-$	19%	2	44%	0.8

1 Mt.yr

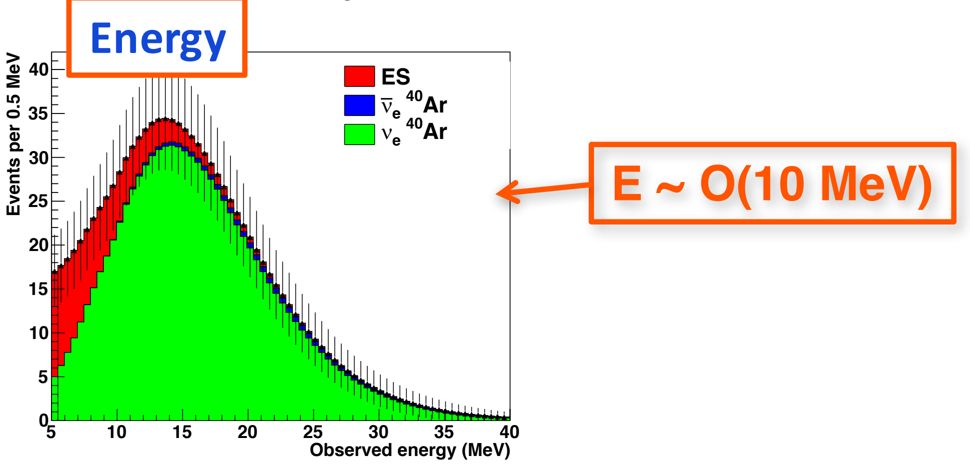


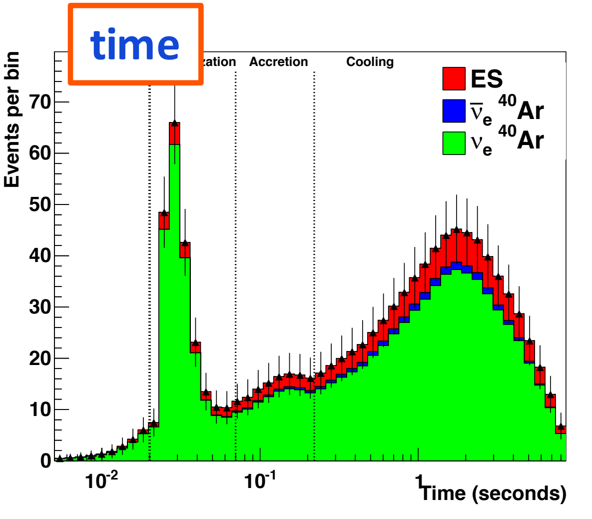
3.3 Supernova νs

A core collapse supernova produces an incredibly intense burst of neutrinos

- Measure energies and times of neutrinos from galactic supernova bursts
  - In argon (uniquely) the largest sensitivity is to ν_e

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$





Physics Highlights include:

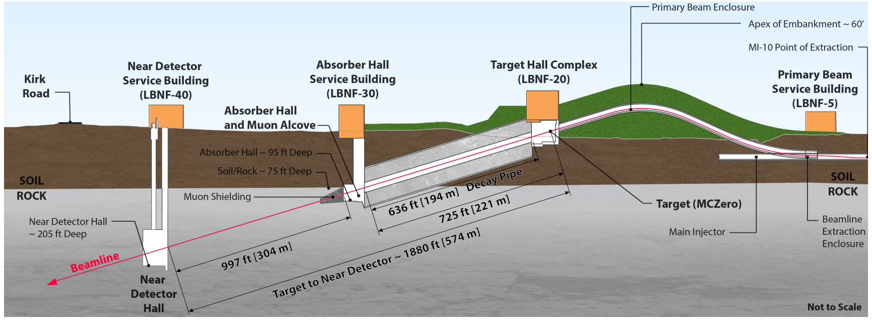
- Possibility to "see" neutron star formation stage
- Even the potential to see black hole formation…

4. LBNF – a MW-scale facility

LBNF and PIP-II

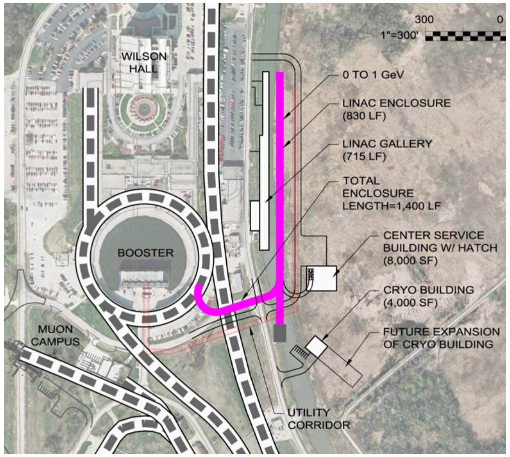
★ **LBNF: the world's most intense multi-GeV ν beam**

- **1.2 MW from day one**
  - NuMI (MINOS) <400 kW
  - NuMI (NOVA) ~700 kW
  - Builds on strong FNAL track record
- **upgradable to 2.4 MW**



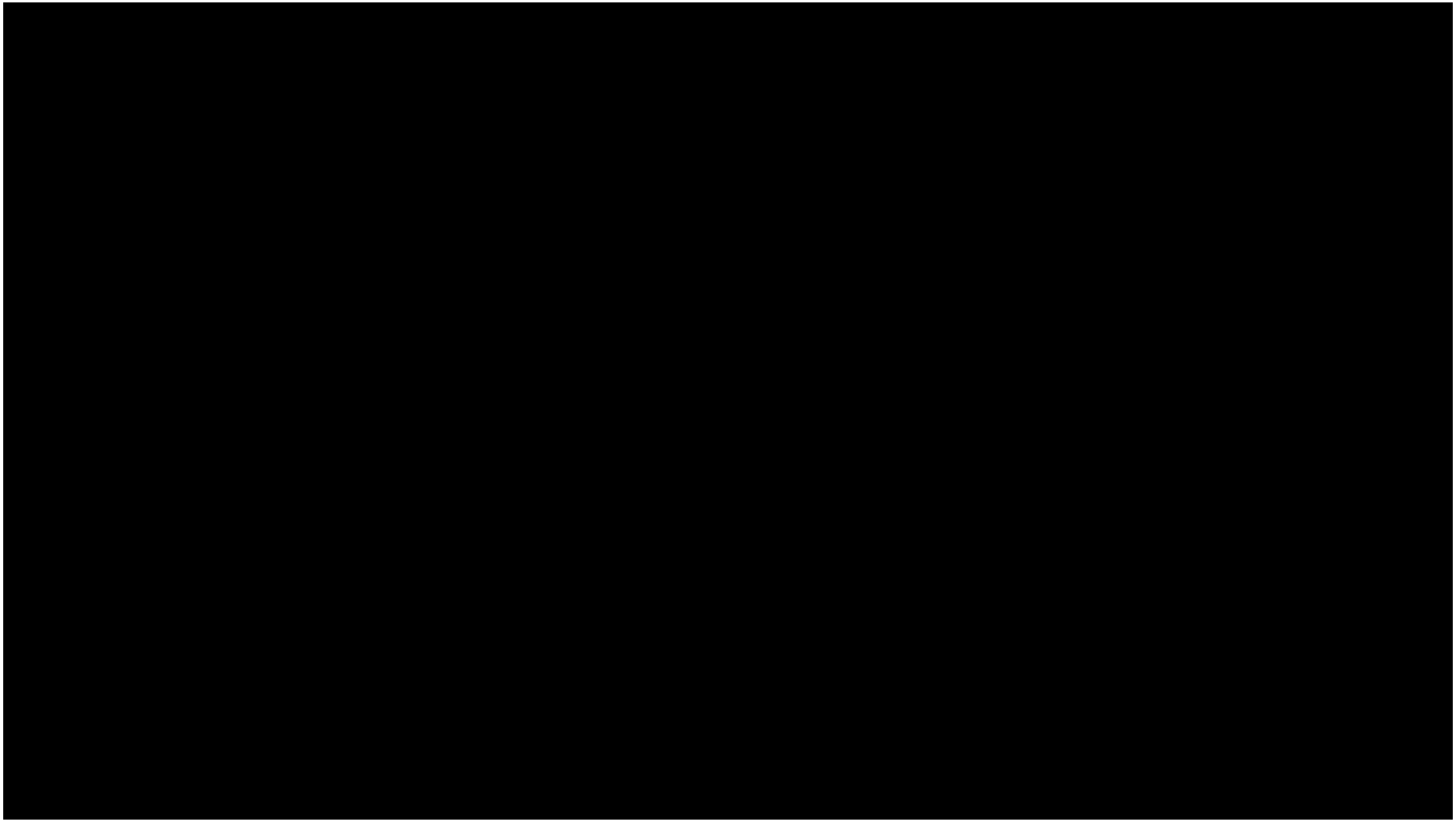
★ **1.2 MW Requires PIP-II**

- **major** ($0.5B) upgrade of FNAL accelerator infrastructure
- Replace existing 400 MeV LINAC with 800 MeV SC LINAC

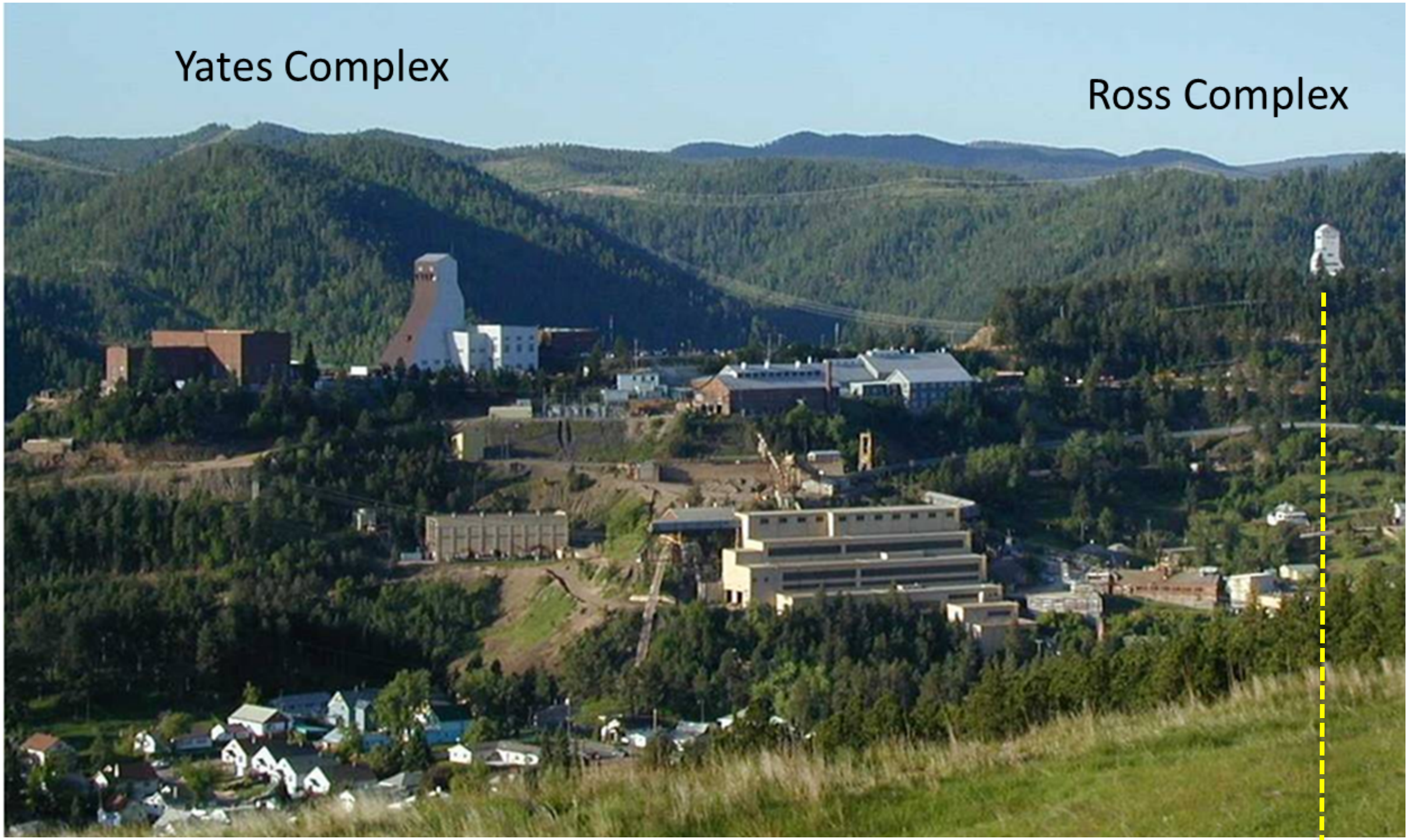


LBNF/DUNE – Fermilab in 2026

LBNF/DUNE – Fermilab in 2025



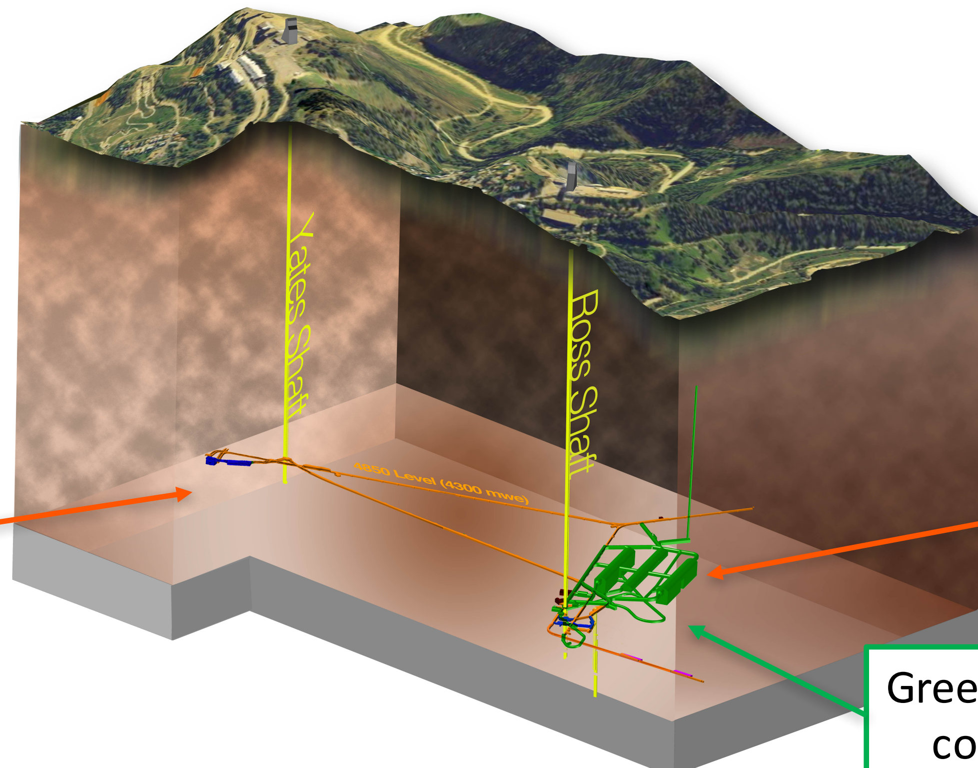
5. DUNE Far Detector



Underground at SURF…

DUNE Far Detector site

- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)



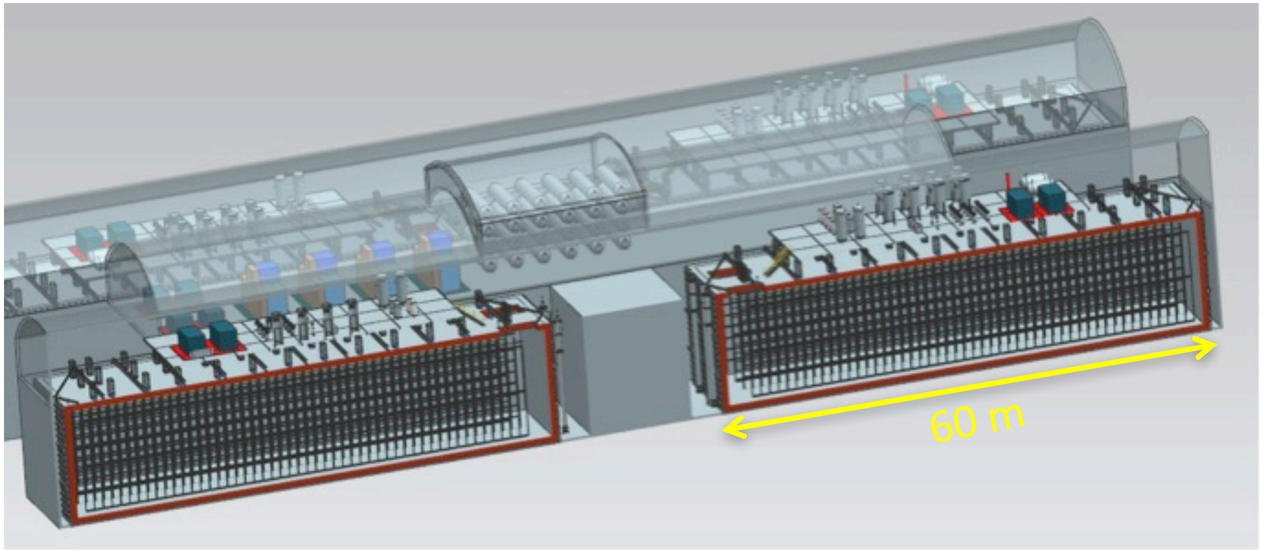
Davis Campus:
- LUX
- Majorana demo.
- …
- **LZ**

Ross Campus:
- CASPAR
- …
- **DUNE**

Green = construction commences in 2017

DUNE Far Detector

- **Four chambers hosting four independent 10-kt FD modules**
  - Gives flexibility for staging & evolution of LAr-TPC technology design
    - Assume four **identical** cryostats: 15.1 (W) x 14.0 (H) x 62 (L) m^3
    - Assume the four 10-kt modules will be similar but **not identical**
    - **Strategy allows for developments in LAr-TPC technology**

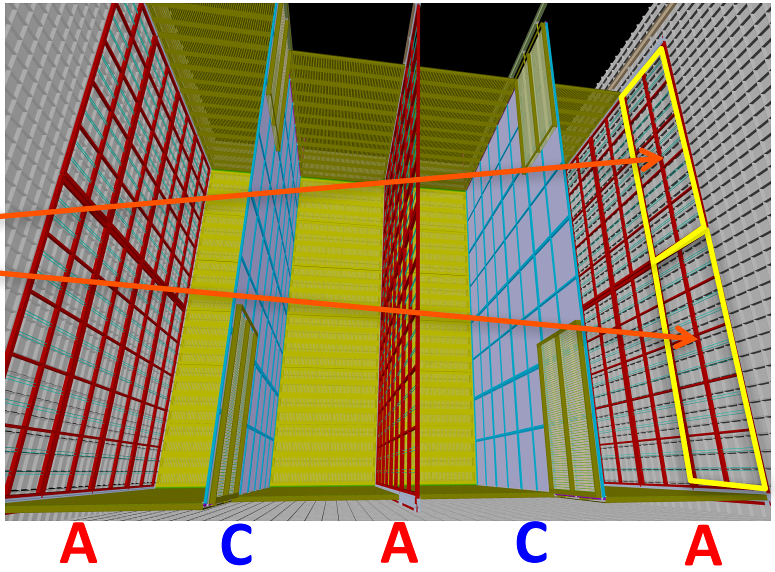


- Civil engineering is well understood (at near final design)
  - Tendering process for excavation contracts before end of year

First 17-kt detector

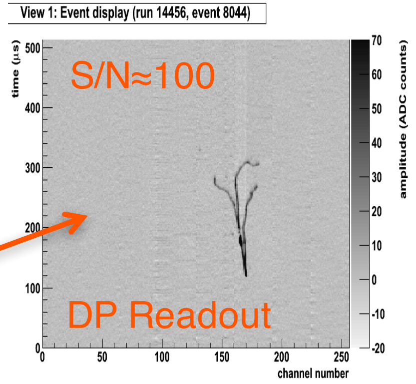
Modular implementation of Single-Phase LAr-TPC

- Active volume: **12m x 14m x 58m**
- 150 Anode Plane Assemblies
  - 6m high x 2.3m wide
- 200 Cathode Plane Assemblies
  - Cathode @ -180 kV for 3.5m drift



Second & subsequent far detector modules

- Not assumed to be exactly the same, could be:
  - Evolution of single-phase design
  - Dual-phase readout – potential benefits

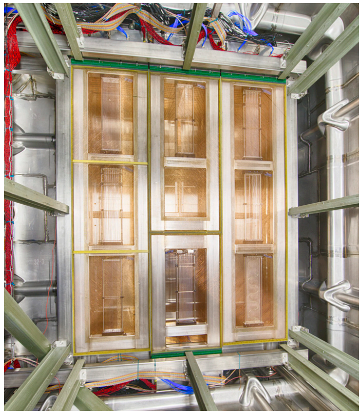


Far Detector Development

Single-phase APA/CPA LAr-TPC:

- Design is well advanced – evolution from ICARUS
- Supported by strong development program at Fermilab
  - 35-t prototype (ran in early 2016)

    tests of basic design



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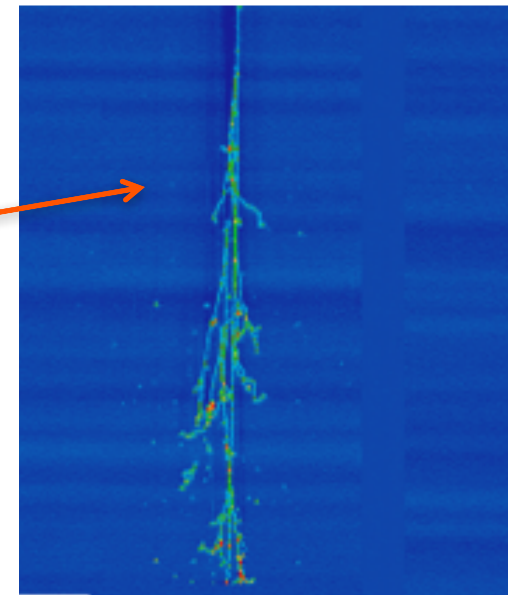

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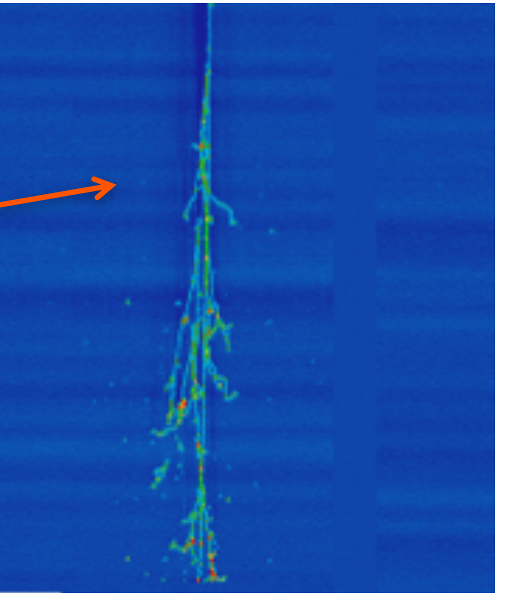

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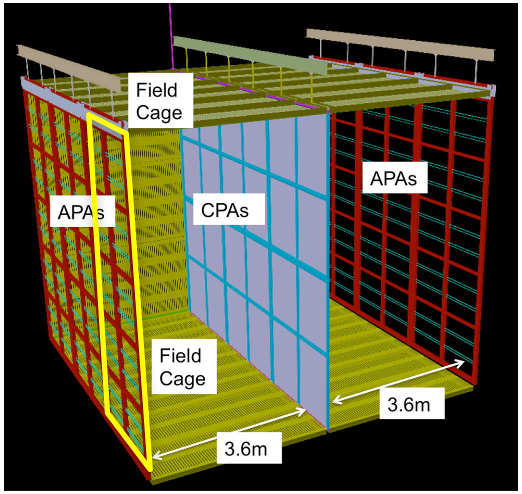
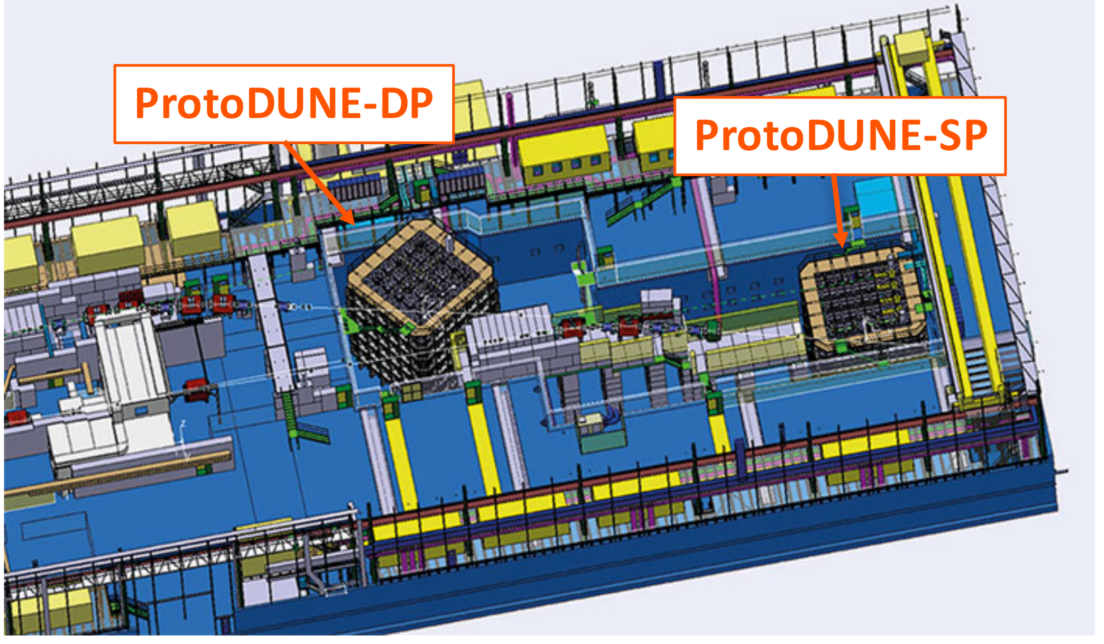
  - 35-t prototype (ran in early 2016)
    tests of basic design
  - MicroBooNE (operational since 2015)
  - SBND (aiming for operation in 2018)
- "Full-scale prototype" with ProtoDUNE
  at the CERN Neutrino Platform
  - **Engineering prototype**
    - 6 full-sized drift cells c.f. 150 in the far det.
  - Approved experiment at CERN
  - Aiming for operation in 2018



CERN Neutrino Platform

CERN support of international neutrino programme

- **Major** infrastructure investment for DUNE:
  - New building: EHN1 extension in the North area
  - Two tertiary charged-particle beam lines
  - Two large ($8x8x8\,m^3$) cryostats & cryogenic systems



Beneficial occupancy later this year

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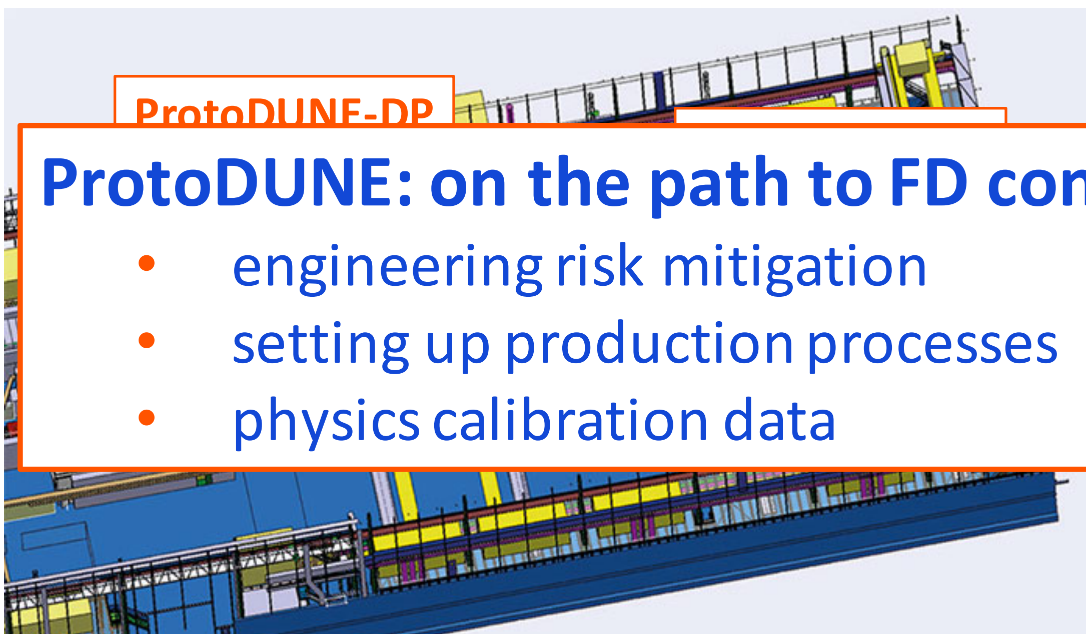

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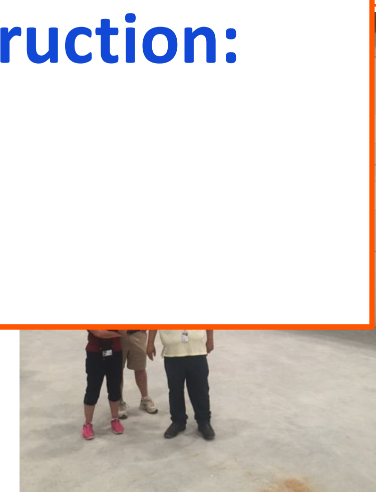


ProtoDUNE: on the path to FD construction:

- engineering risk mitigation
- setting up production processes
- physics calibration data

6. DUNE in the UK

DUNE-UK Aims & Status

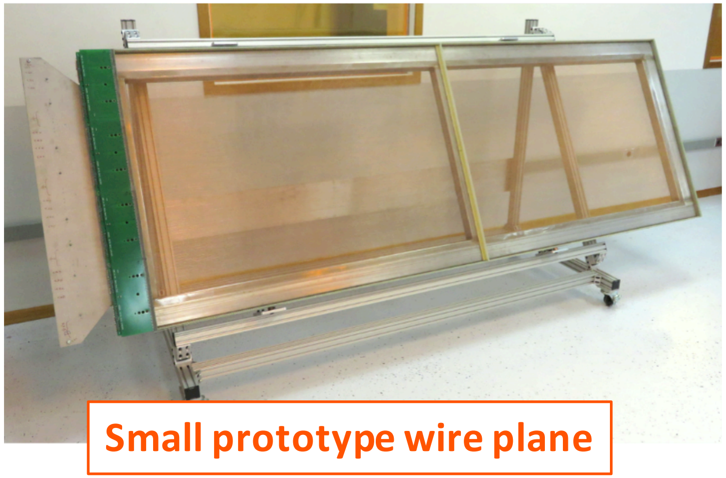
AIMS:

- **Play a leading role in far detector construction:**
  - One of four production sites for the LAr-TPC wire planes (APAs)
  - Major contribution to Far Detector DAQ system
- **Leading role in LAr-TPC reconstruction/DUNE physics**

DUNE-UK Aims & Status

STFC Funding:

- **Existing DUNE-UK grant (Oct 2014 – Sep 2017):**
  - Focuses on these long-term aims
- **Supplemental grant (July 2016 – Mar 2018):**
  - Major UK role in ProtoDUNE-SP construction (APAs & DAQ)



DUNE-UK Activities

- **WP1: Physics**
  - Physics and detector design/optimisation studies
- **WP2: LAr-TPC Reconstruction**
  - Leading development of LAr-TPC automated reconstruction
    - Strong connection to UK MicroBooNE activties
- **WP3: DAQ**
  - Leading design/architecture work for Far Detector
  - Leading role in ProtoDUNE DAQ
- **WP4: 35-t prototype at Fermilab (now complete)**
  - Hands on experience with LAr-TPC data
- **WP5: LAr-TPC construction (capacity building)**
  - Hardware for SBND detector (APAs & Cathode planes)
  - Major contribution to ProtoDUNE-SP (3 of the 6 APAs)

DUNE-UK Activities

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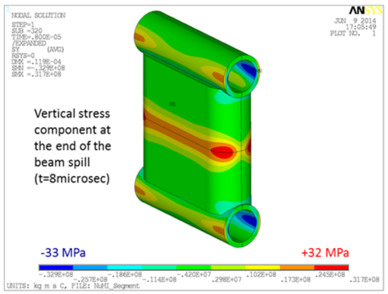
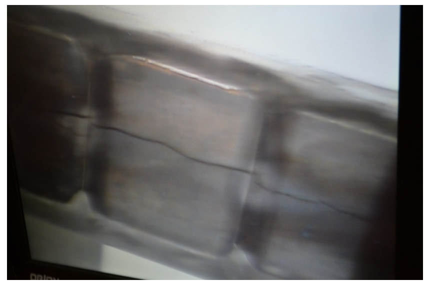
- **...P5: LAr-TPC construction (capacity building)**
  - Hardware for SBND detector (APAs & Cathode planes)
  - Major contribution to ProtoDUNE-SP (3 of the 6 APAs)

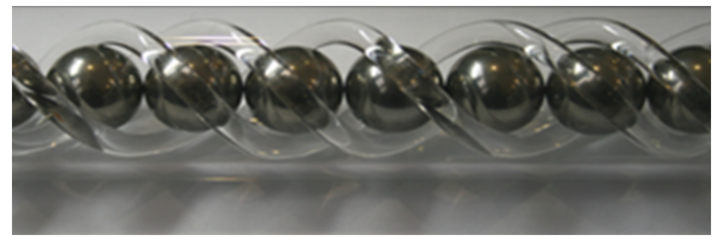
Activities tightly aligned with long-term goals

Beyond DUNE: UK and LBNF

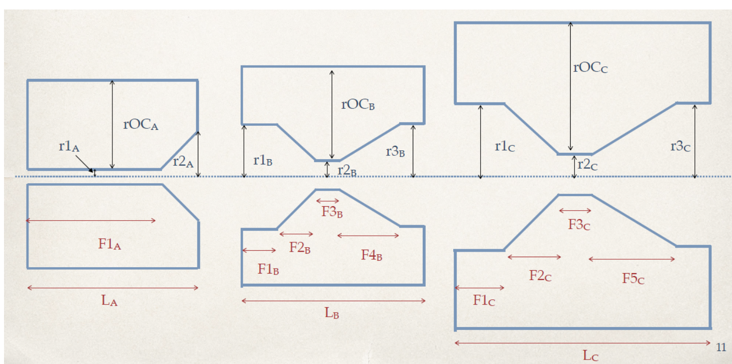
- **Also UK interest and expertise in the facility:**
  - High-power targets (UK is world leading)

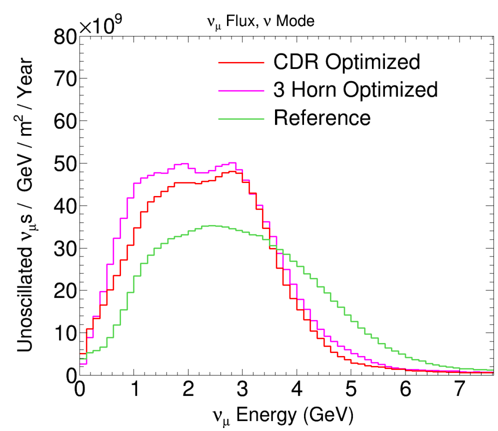






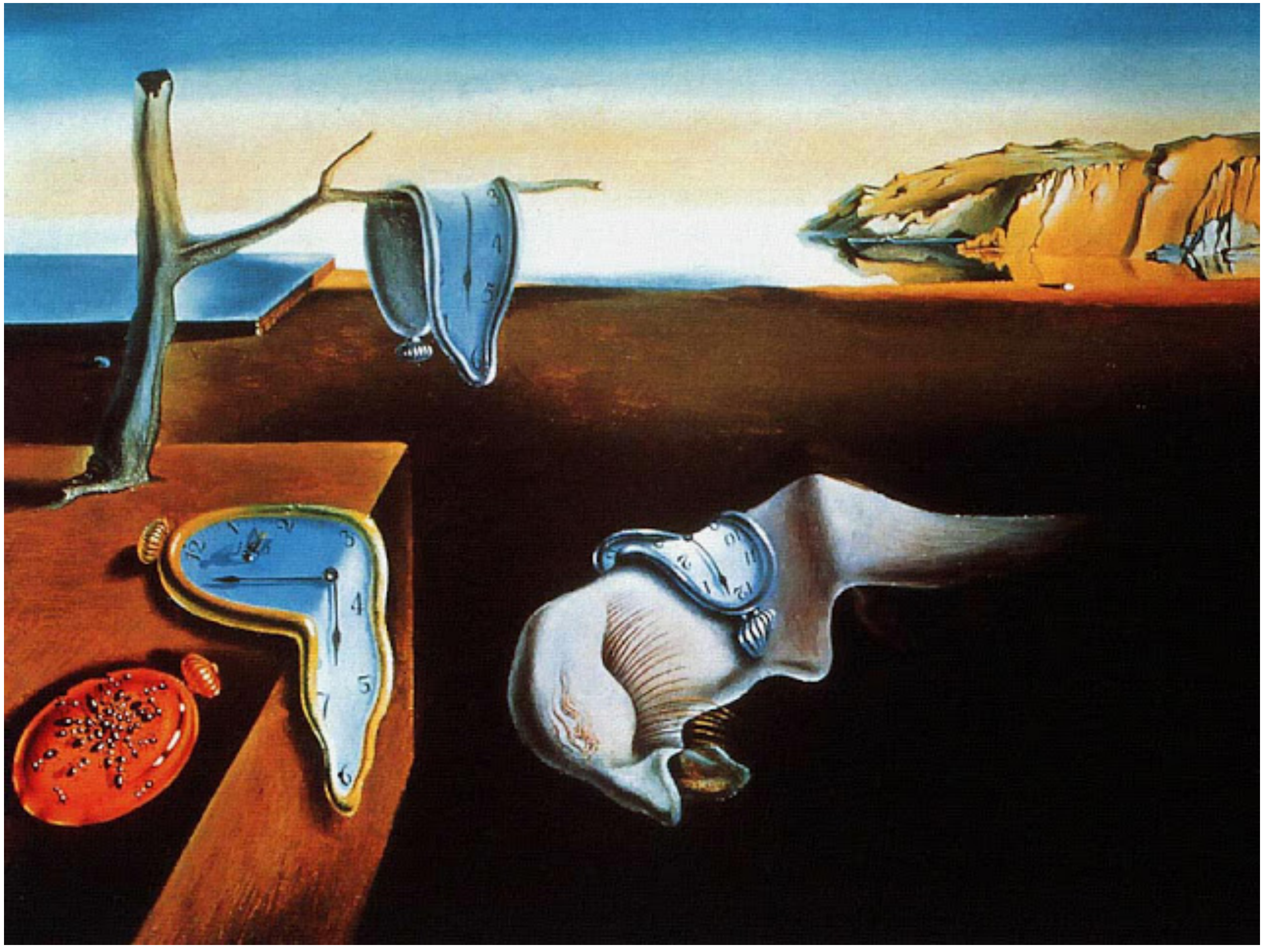
  - Optimization of the neutrino beam line





  - Design of the target hall
  - Potential for UK investment in PIP-II - e.g. SRF

7. Schedule



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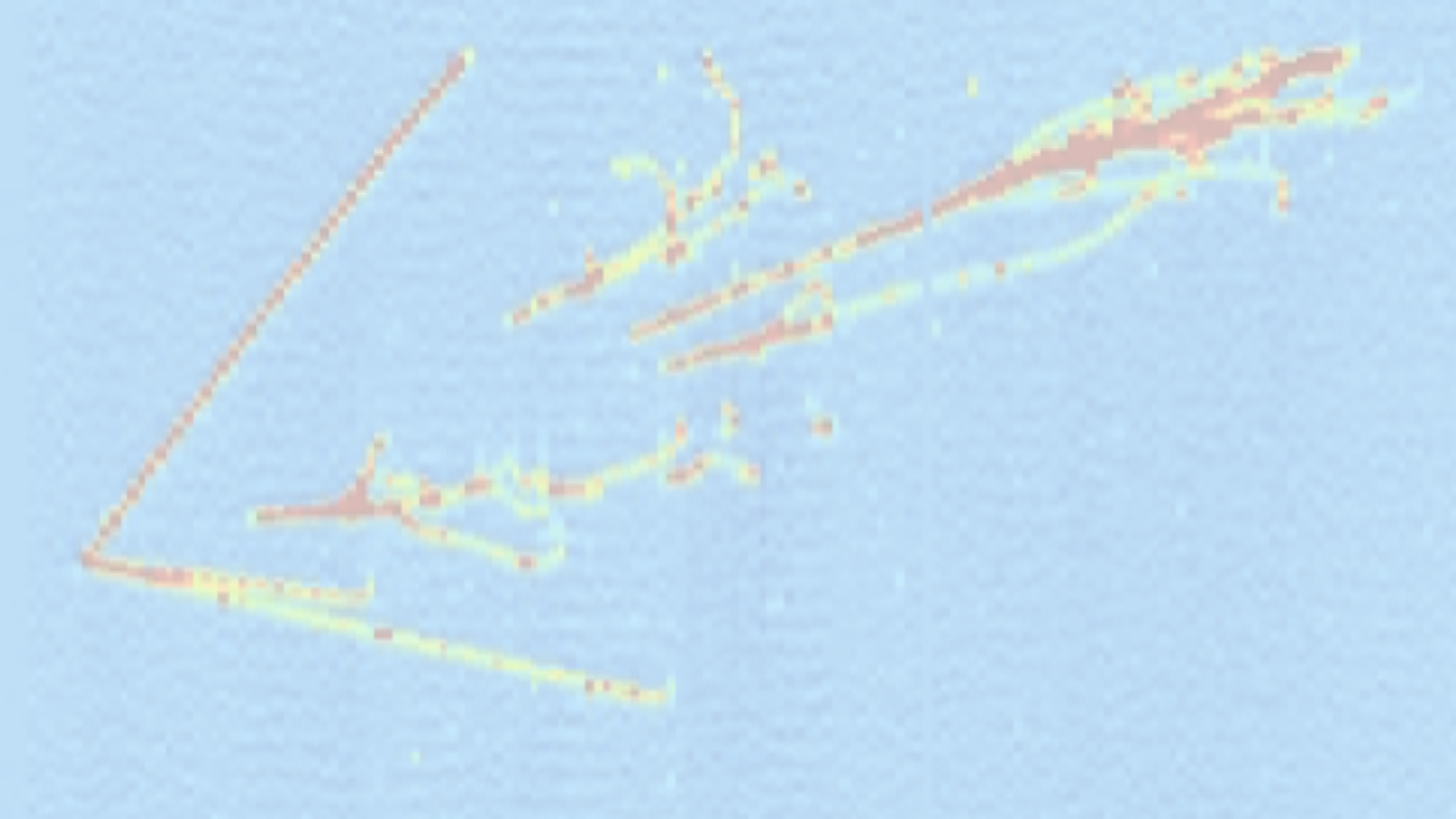

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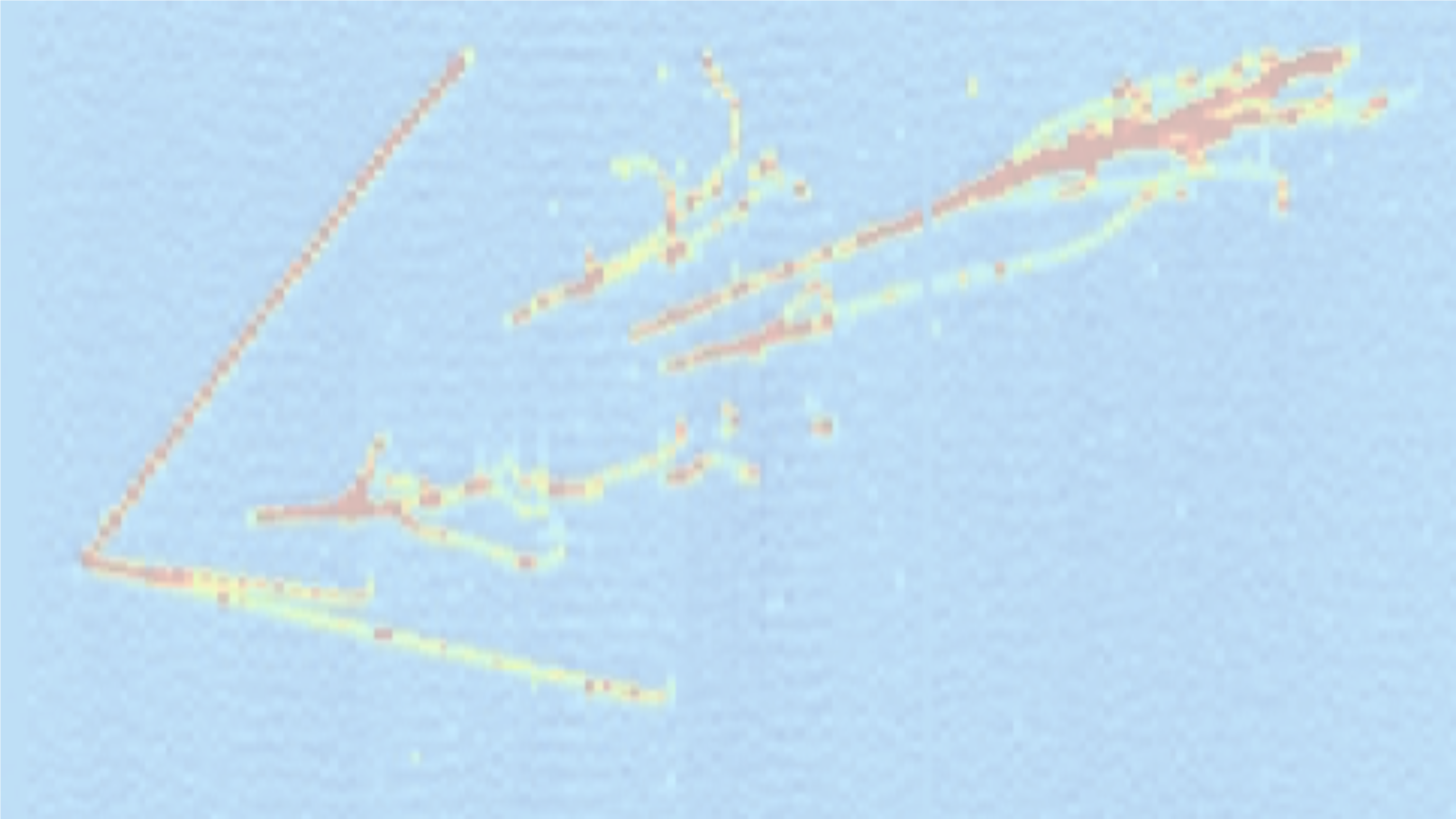

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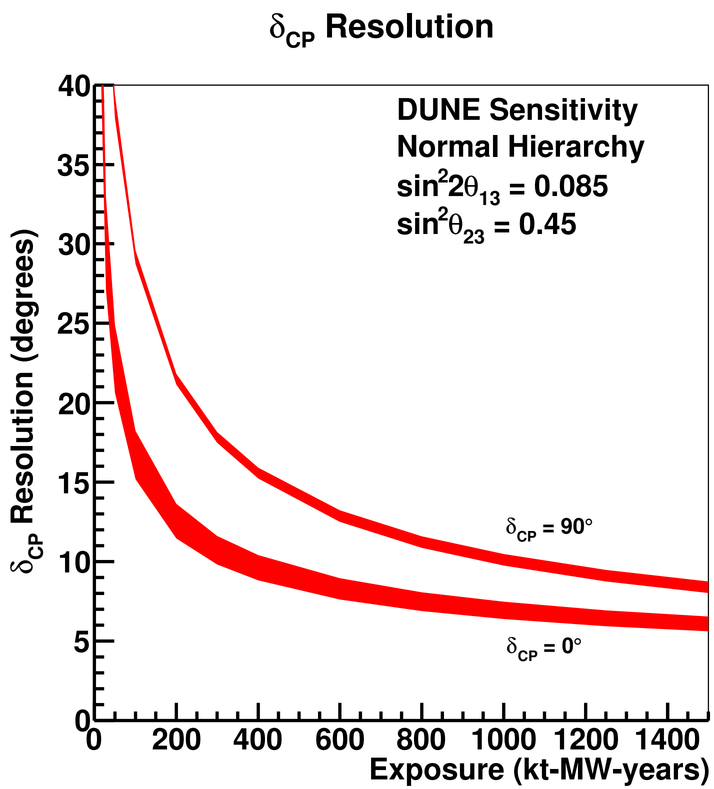

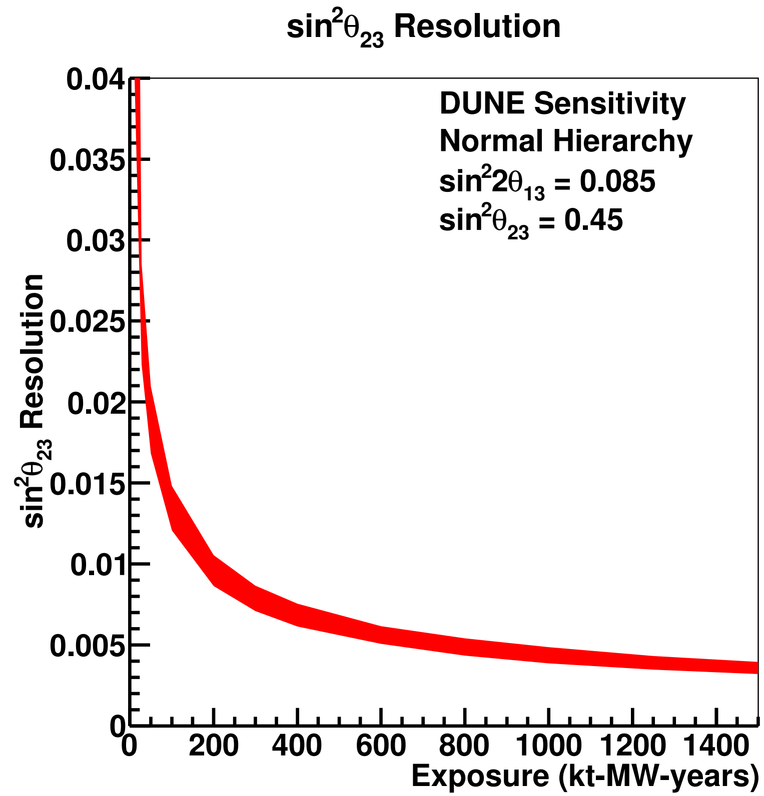

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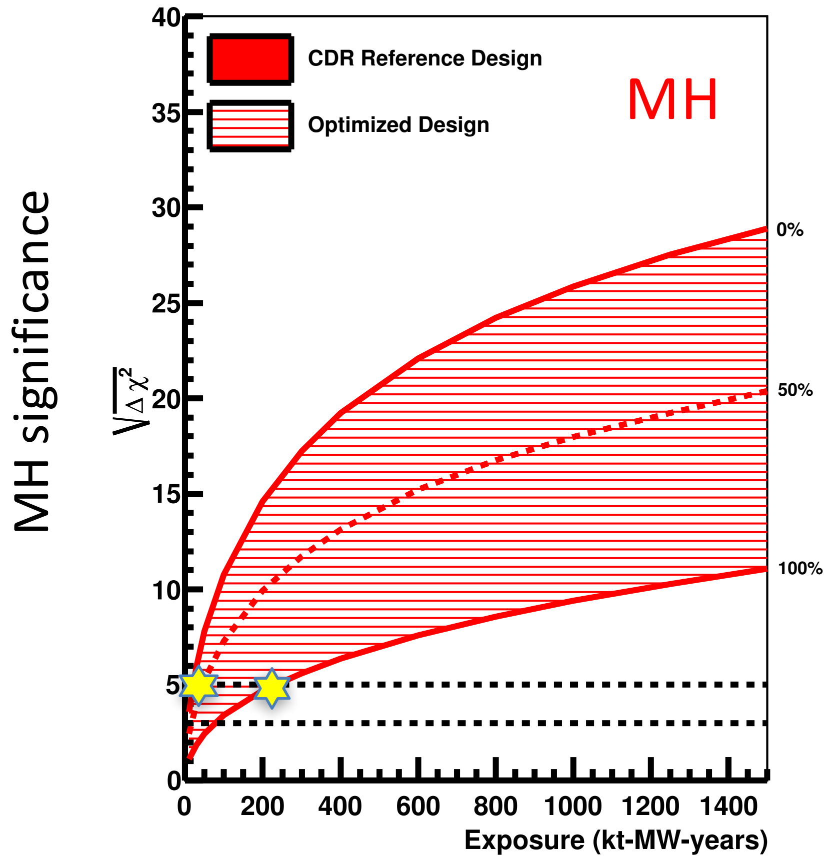
- Beam spectrum, …



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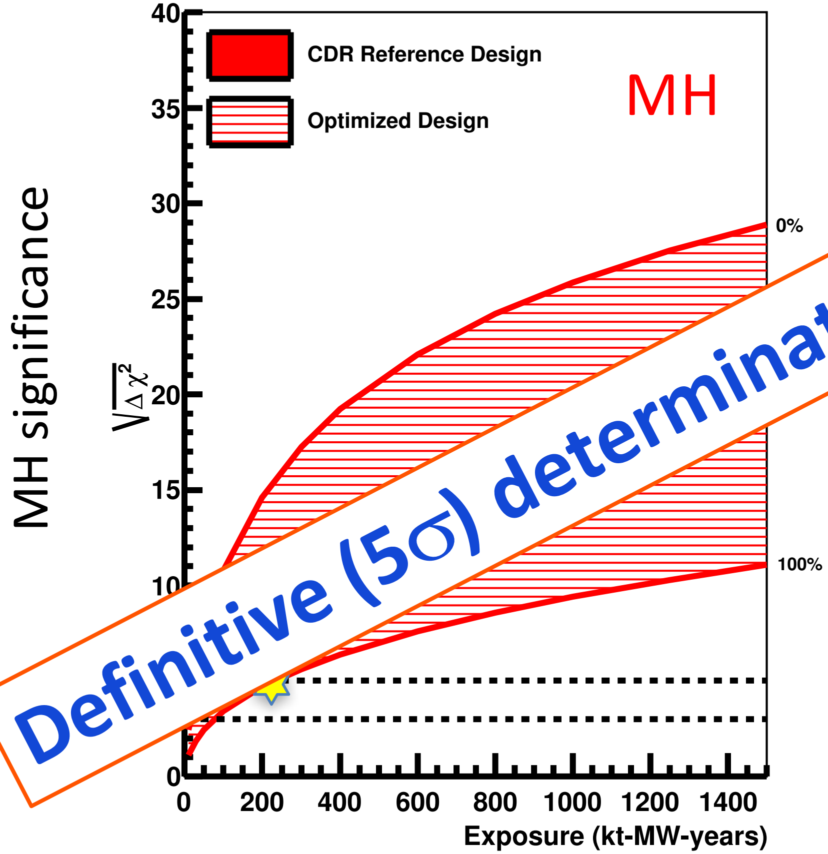

Definitive (5σ) determination of the Mass Hierarchy

MH and CPV Sensitivities

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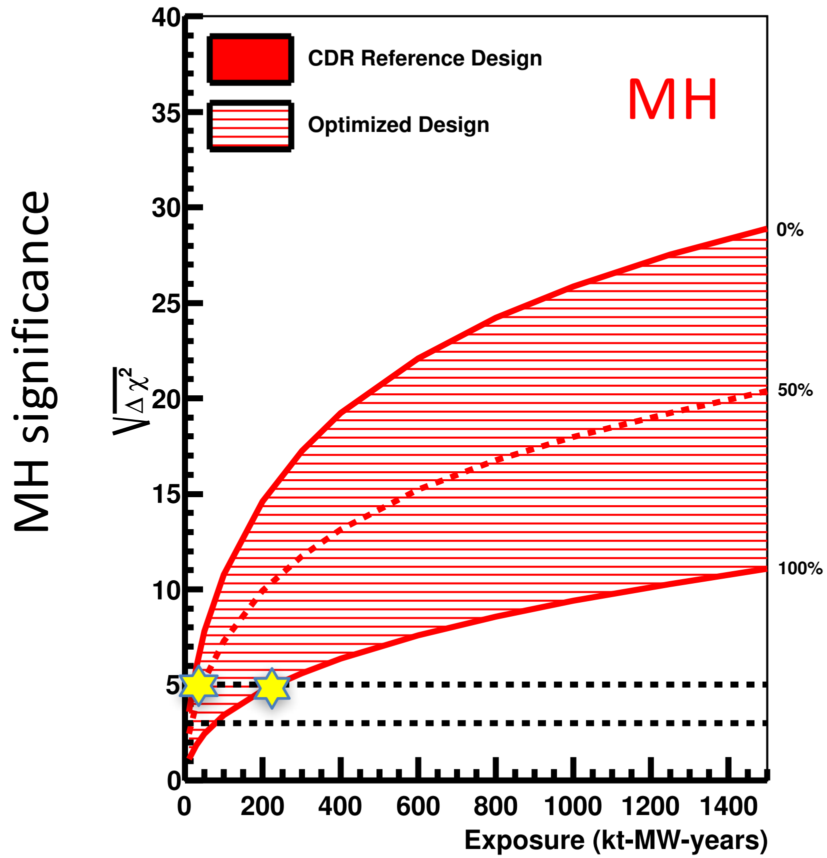

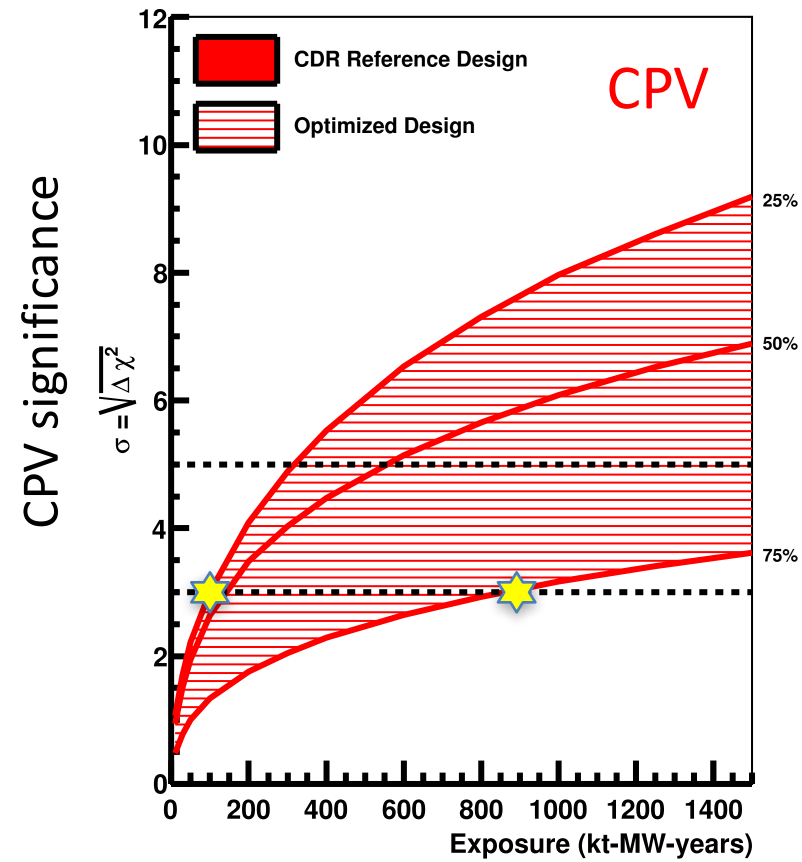

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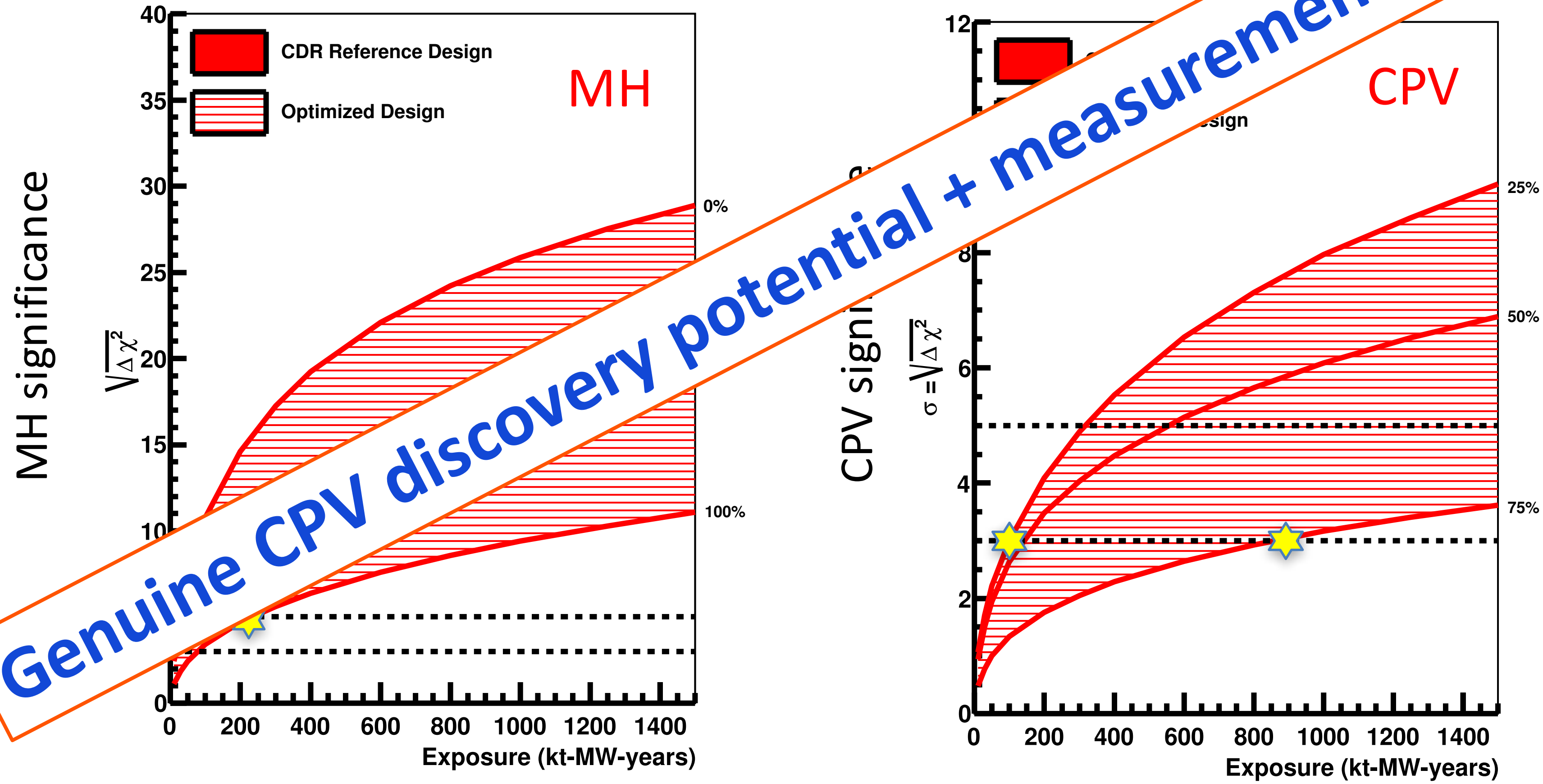
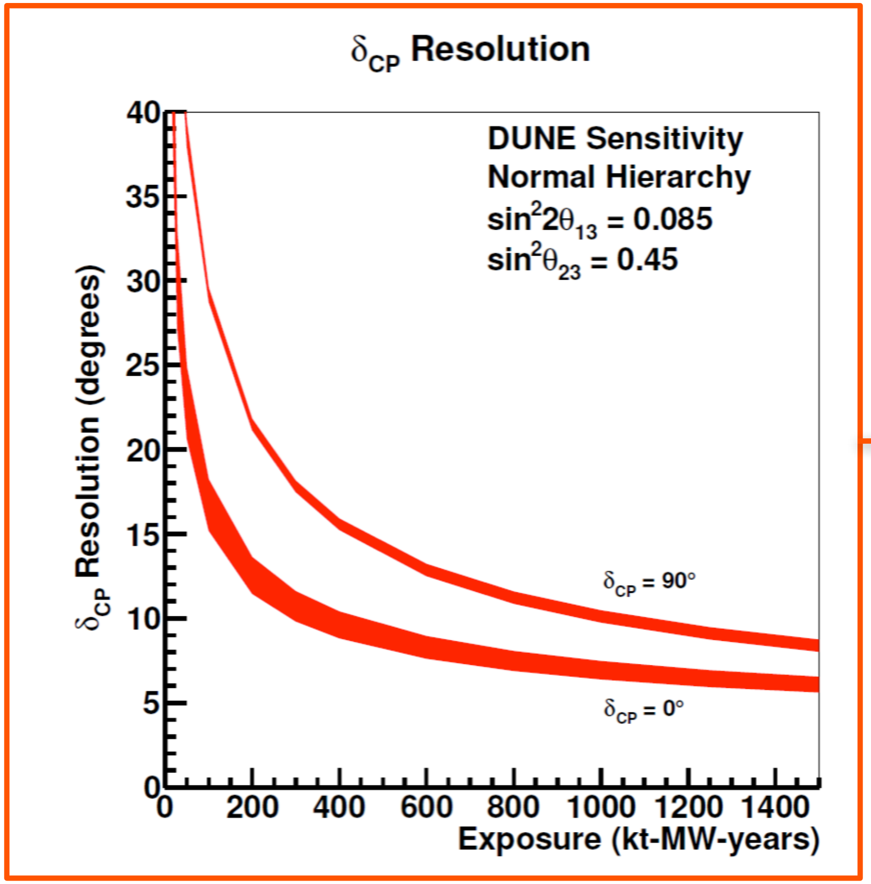


Genuine CPV discovery potential + measurement of δ

Beyond discovery: measurement of δ

- ★ CPV "coverage" is just one way of looking at sensitivity…
- ★ DUNE will **measure** δ_{CP}

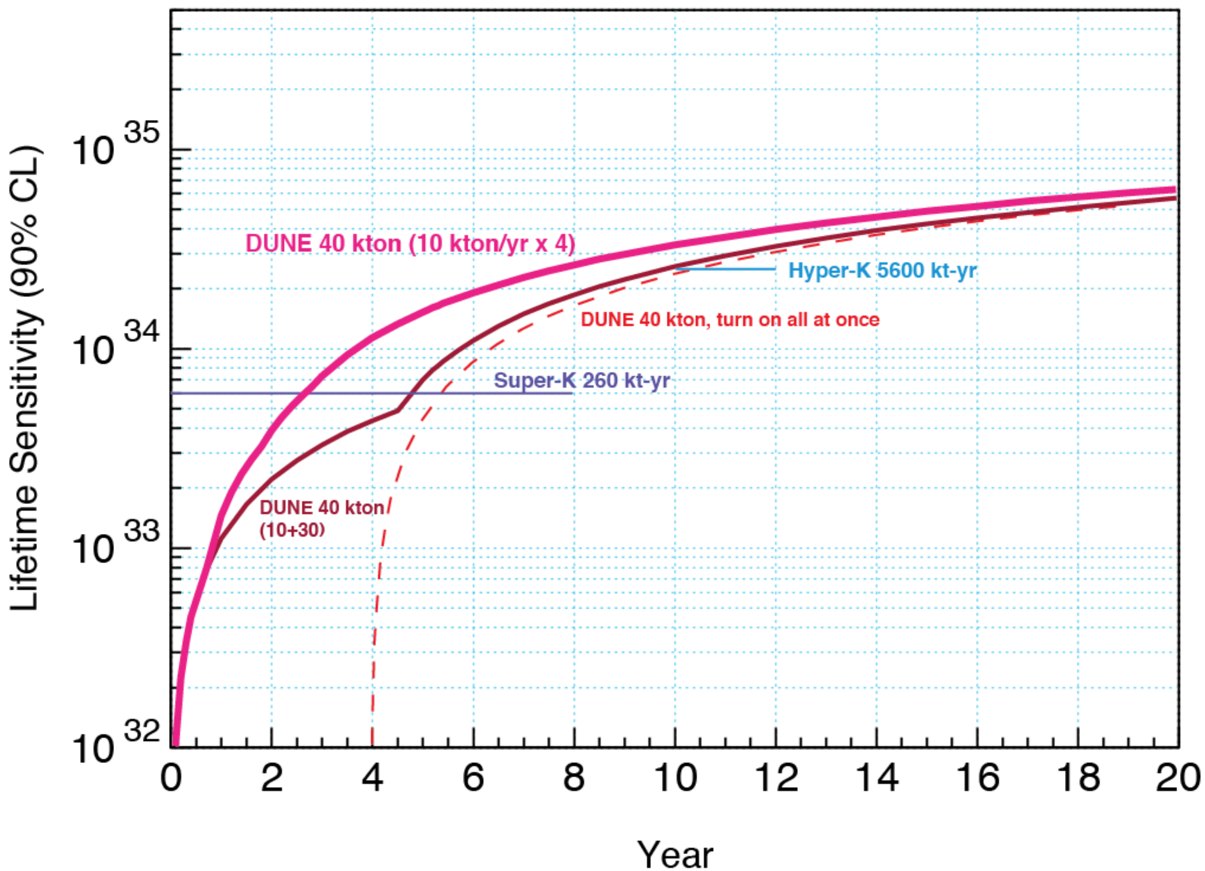


Start to ~approach current level of precision on quark-sector CPV phase (although takes time)

PDK

p → K ν

- DUNE for various staging assumptions



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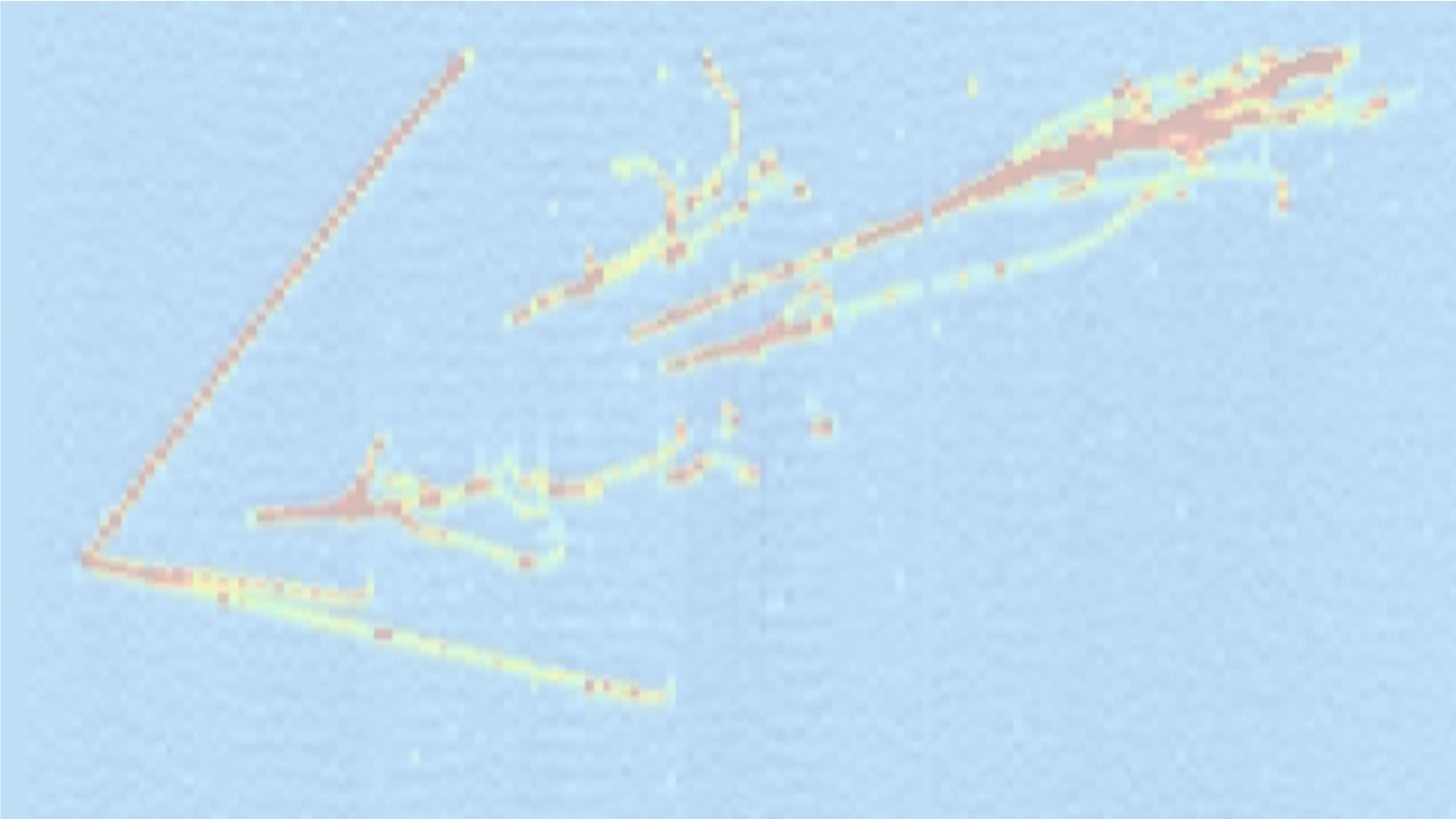

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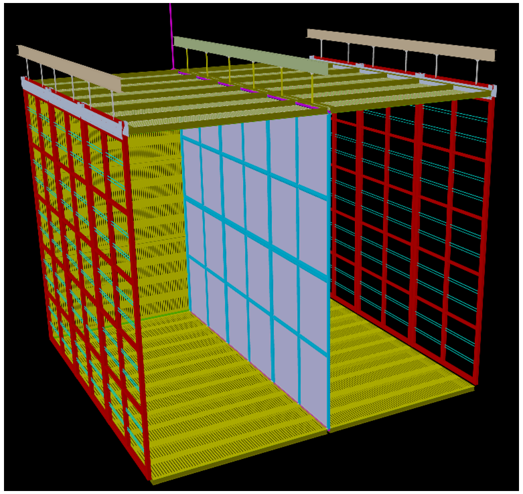


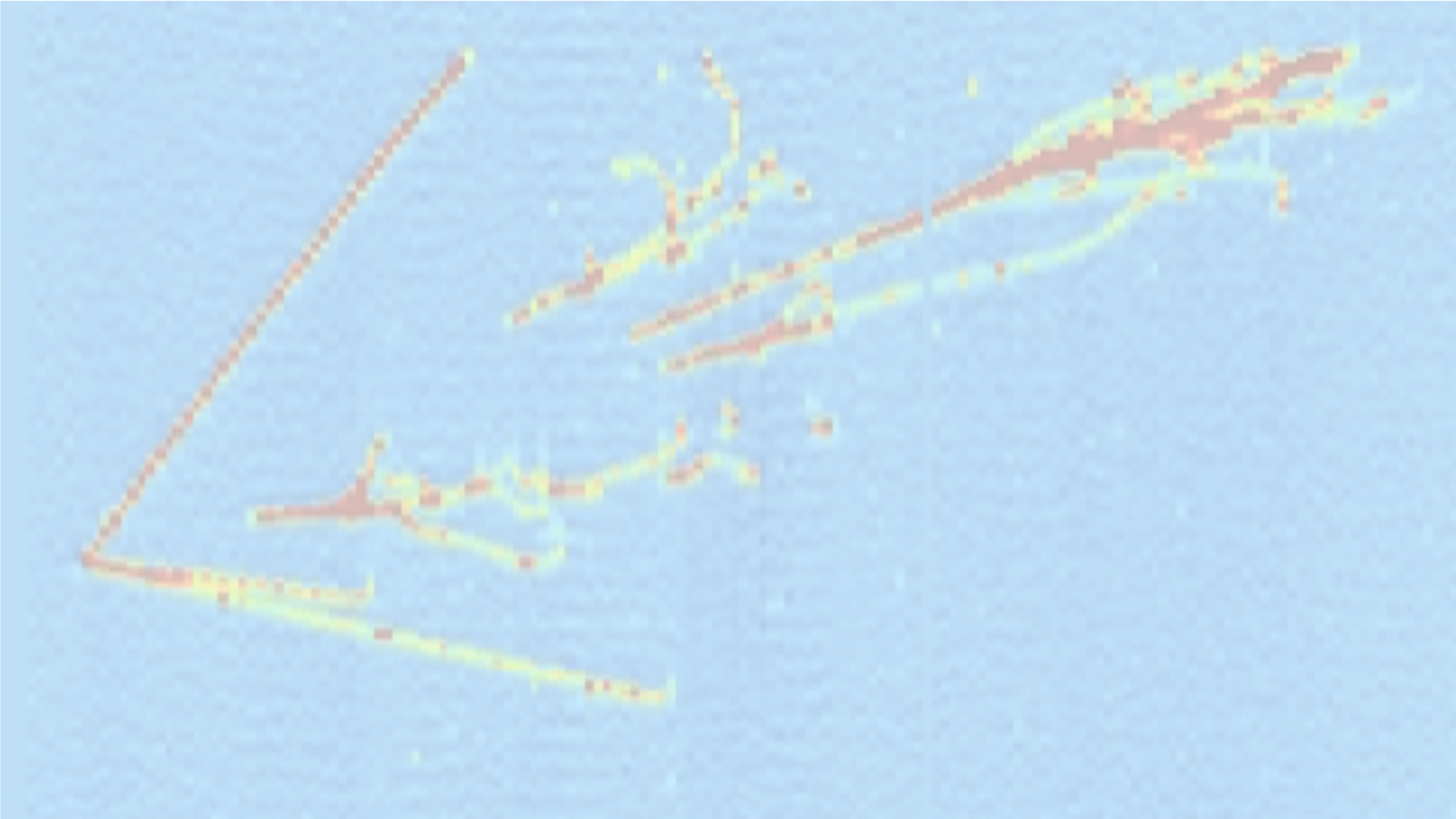
DUNE is moving rapidly

- Excavation starts in 2017
- ProtoDUNE @ CERN in 2018
- Far Detector construction in 2019
- Far Detector installation in 2021

DUNE: the next large global Particle Physics project

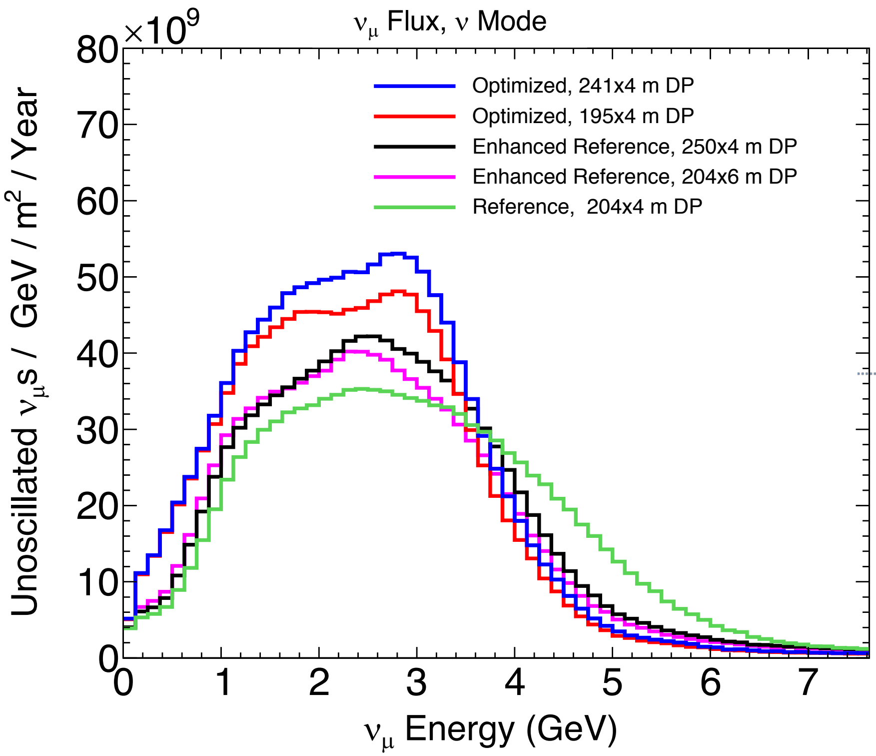
- Actively seeking new collaborators
  - many synergies with collider experiments
- Immediate Focus in Europe will be ProtoDUNE @ CERN
- Many Opportunities:
  - Hardware: e.g. photon detection system (scintillator + SiPMs)
  - DAQ/Computing: continuous readout = high-data rates
  - Software: LAr-TPC reconstruction

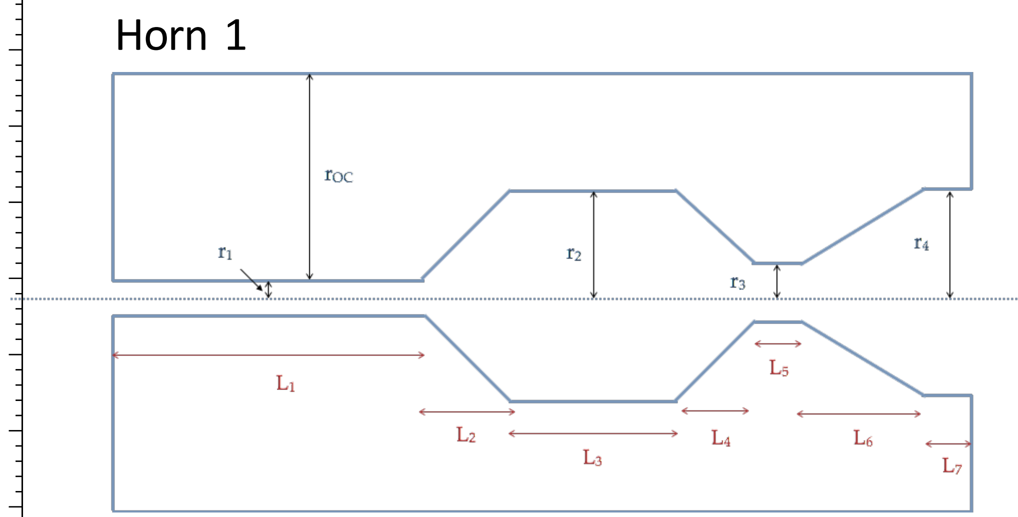
Beam Optimization



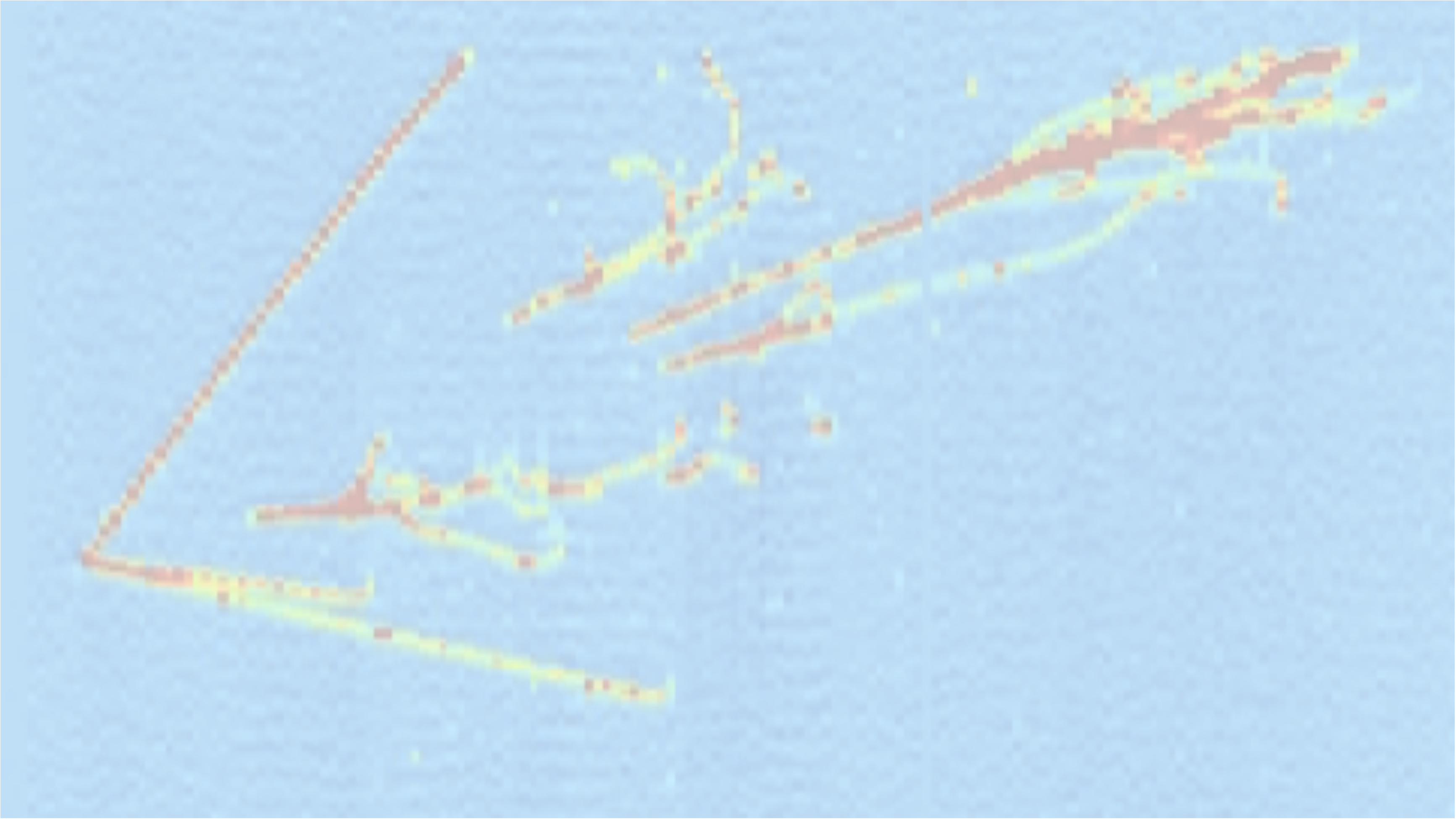
Beam Optimization

Following LBNO approach, genetic algorithm used to optimize horn design – increase neutrino flux at lower energies





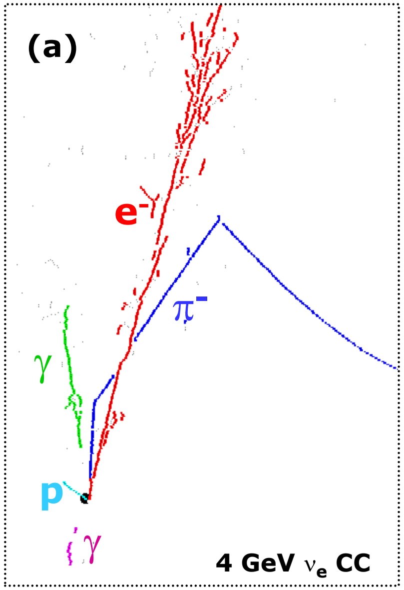
Reconstruction

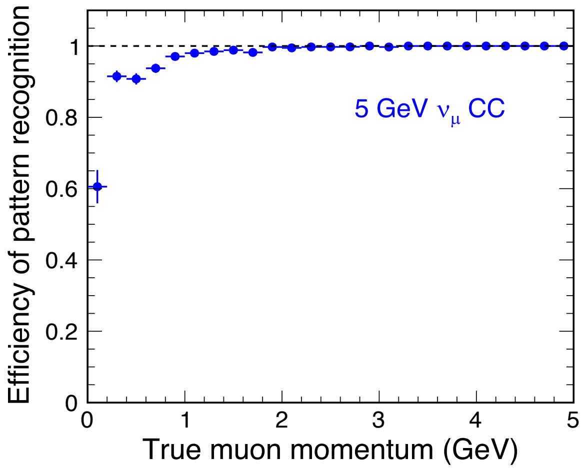


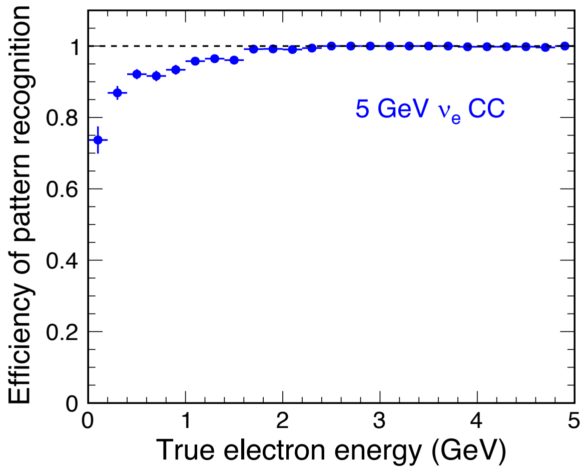
LAr-TPC Reconstruction

Real progress in last year – driven by 35-t & MicroBooNE

- Full DUNE simulation/reconstruction now in reach







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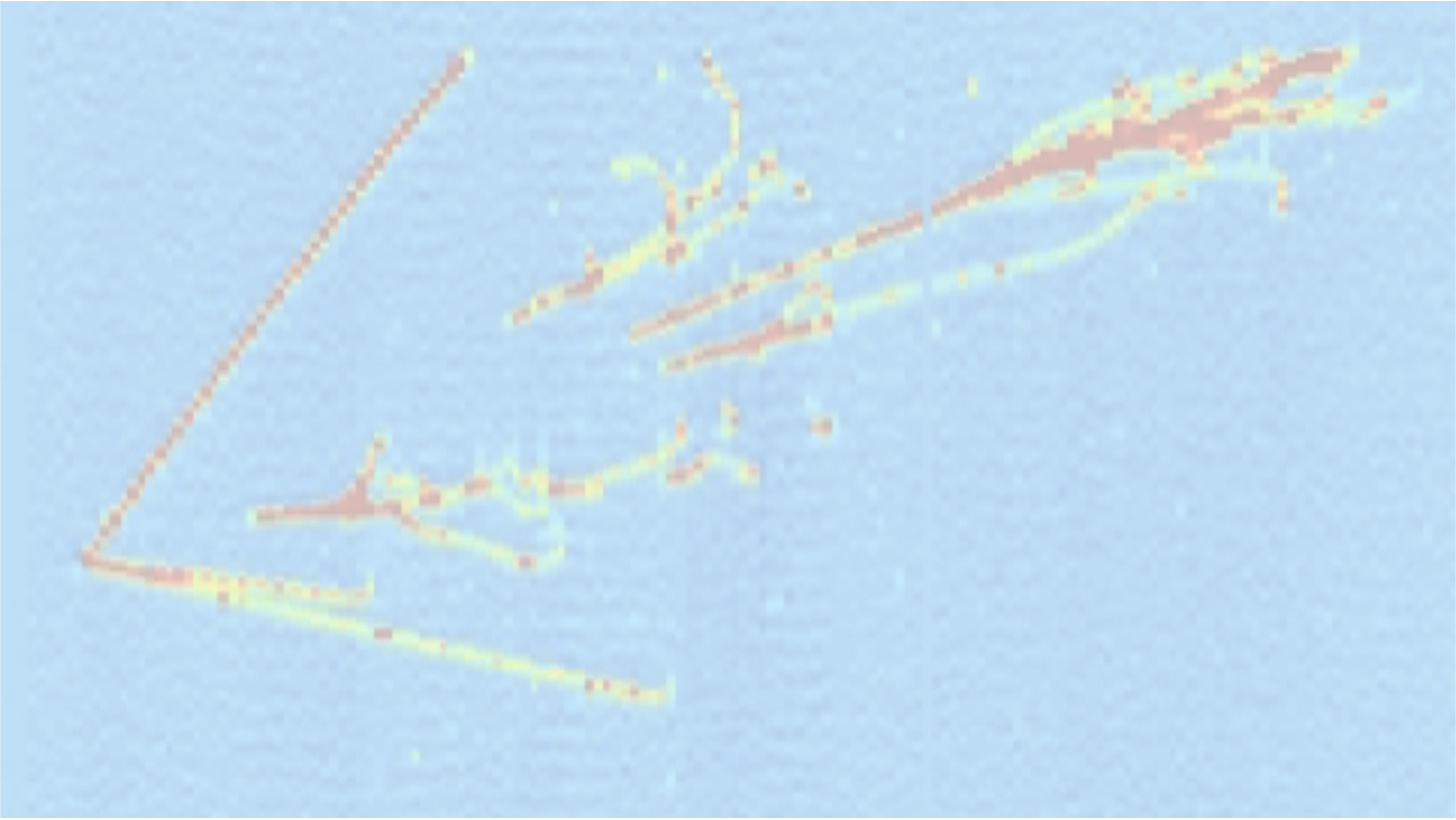

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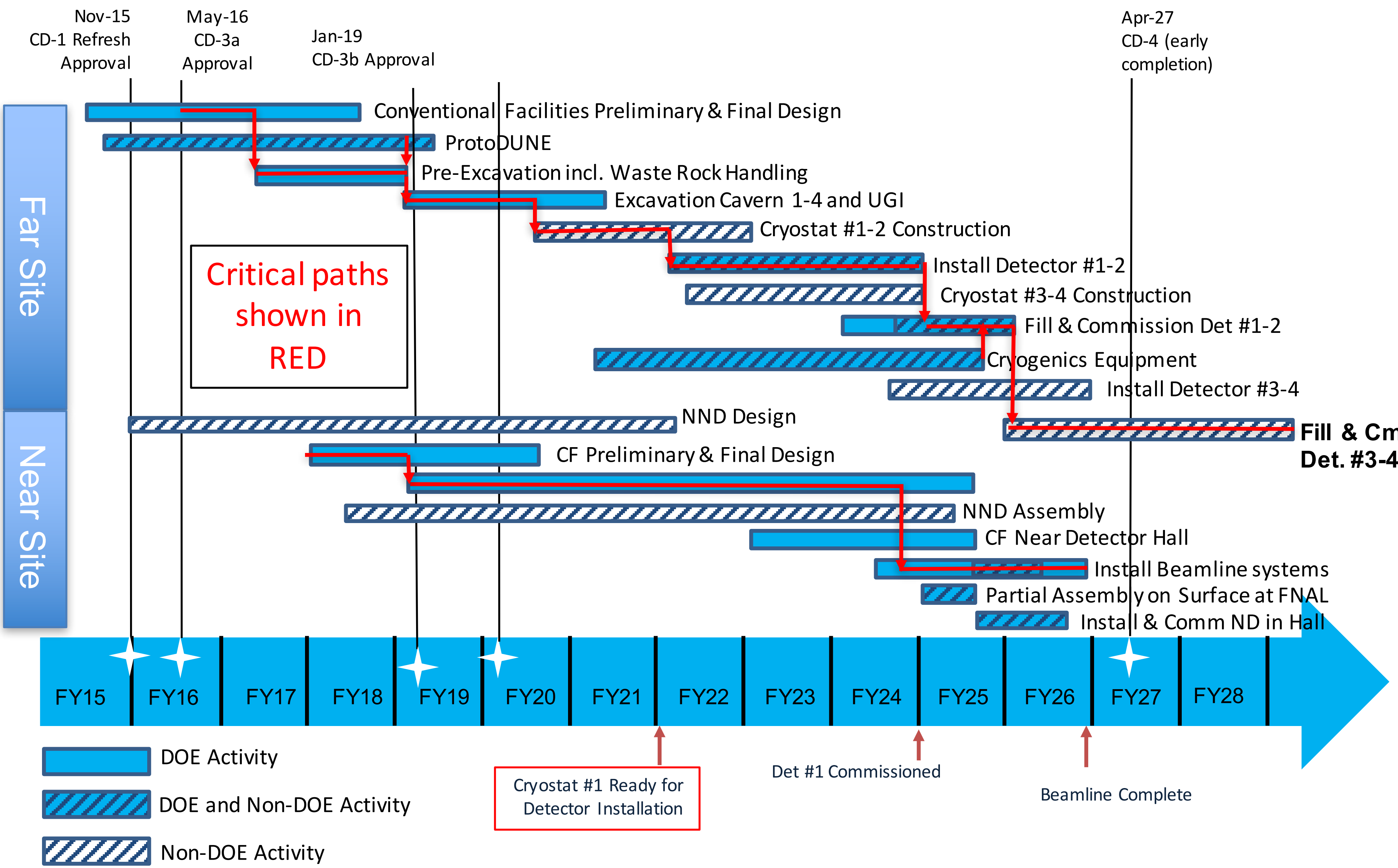
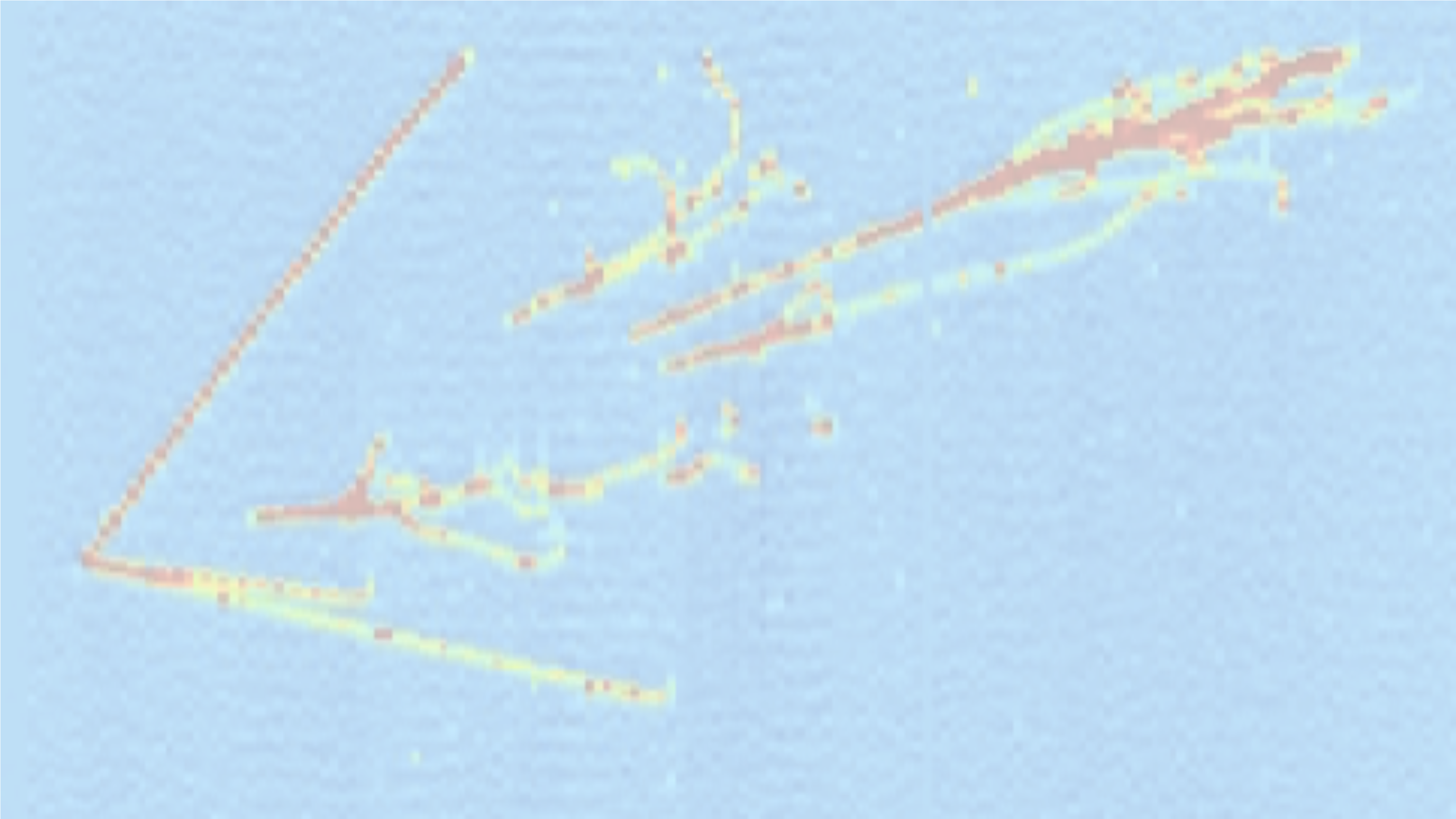


Nov-15
CD-1 Refresh
Approval
May-16
CD-3a
Approval
Jan-19
CD-3b Approval
Apr-27
CD-4 (early
completion)
Far Site
Near Site
Conventional Facilities Preliminary & Final Design
ProtoDUNE
Pre-Excavation incl. Waste Rock Handling
Excavation Cavern 1-4 and UGI
Cryostat #1-2 Construction
Install Detector #1-2
Cryostat #3-4 Construction
Fill & Commission Det #1-2
Cryogenics Equipment
Install Detector #3-4
Fill & Cm
Det. #3-4
Critical paths
shown in
RED
NND Design
CF Preliminary & Final Design
NND Assembly
CF Near Detector Hall
Install Beamline systems
Partial Assembly on Surface at FNAL
Install & Comm ND in Hall
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
FY23
FY24
FY25
FY26
FY27
FY28
DOE Activity
DOE and Non-DOE Activity
Non-DOE Activity
Cryostat #1 Ready for
Detector Installation
Det #1 Commissioned
Beamline Complete

Calculating Sensitivities



Determining Physics Sensitivities

For Conceptual Design Report

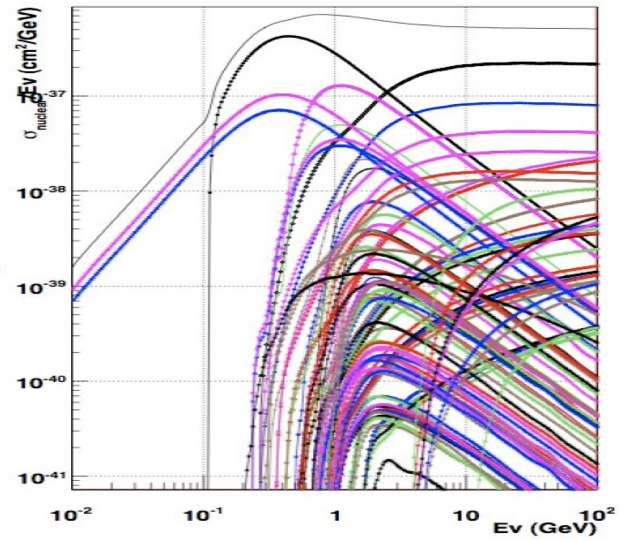
- **Full detector simulation/reconstruction not available**
  - See later in talk for plans
- **For Far Detector response**
  - Use parameterized single-particle response based on achieved/expected performance (with ICARUS and elsewhere)
- **Systematic constraints from Near Detector + …**
  - Based on current understanding of cross section/hadro-production uncertainties
  - \+ Expected constraints from near detector
    - in part, evaluated using fast Monte Carlo

Evaluating DUNE Sensitivities I

Many inputs calculation (implemented in GLoBeS):

- **Reference Beam Flux**
  - 80 GeV protons
  - 204m x 4m He-filled decay pipe
  - 1.07 MW
  - NuMI-style two horn system
- **Optimized Beam Flux**
  - Horn system optimized for lower energies
- **Expected Detector Performance**
  - Based on previous experience (ICARUS, ArgoNEUT, …)
- **Cross sections**
  - GENIE 2.8.4
  - CC & NC
  - all (anti)neutrino flavors

Exclusive ν-nucleon cross sections



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Evaluating DUNE Sensitivities II

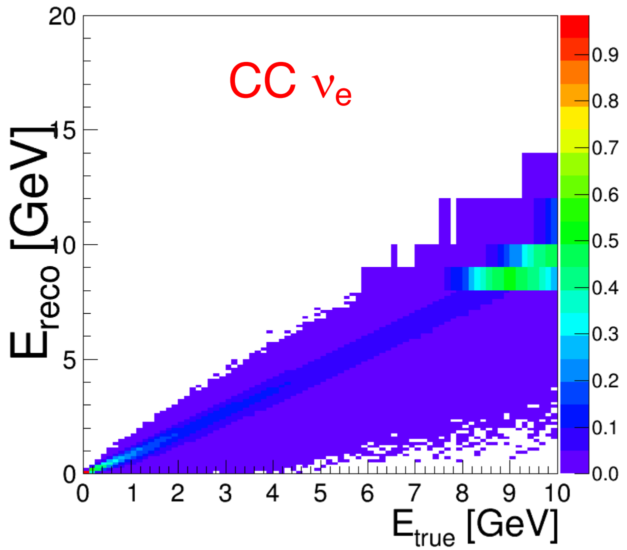
- **Assumed* Particle response/thresholds**
  - Parameterized detector response for individual final-state particles

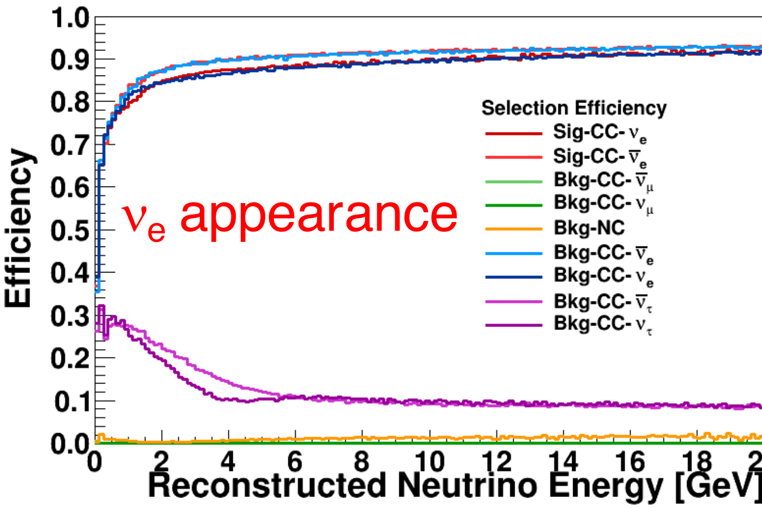
Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained: from track length Exiting: 30 %	1^{o}
$\pi^{\pm}$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1^{o}
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{(E/GeV)}$	1^{o}
p	50 MeV	p < 400 MeV: 10 % p > 400 MeV: $5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^{o}
n	50 MeV	$440\%/\sqrt{(E/GeV)}$	5^{o}
other	50 MeV	$5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^{o}

*current assumptions to be addressed by FD Task Force

Evaluating DUNE Sensitivities III

- **Efficiencies & Energy Reconstruction**
  - Generate neutrino interactions using GENIE
  - **Fast MC** smears response at generated final-state particle level
    - "Reconstructed" neutrino energy
    - kNN-based MV technique used for ν_e "event selection", parameterized as efficiencies
  - Used as inputs to GLoBES





Evaluating DUNE Sensitivities IV

- **Systematic Uncertainties**
  - Anticipated uncertainties based on MINOS/T2K experience
  - Supported by preliminary fast simulation studies of ND

Source	MINOS ν_e	T2K ν_e	DUNE ν_e
Flux after N/F extrapolation	0.3 %	3.2 %	2 %
Interaction Model	2.7 %	5.3 %	~ 2 %
Energy Scale (ν_μ)	3.5 %	Inc. above	(2 %)
Energy Scale (ν_e)	2.7 %	2 %	2 %
Fiducial Volume	2.4 %	1 %	1 %
Total	**5.7 %**	**6.8 %**	**3.6 %**

- **DUNE goal for ν_e appearance < 4 %**
  - For sensitivities used: 5 % $\oplus$ 2 %
    - where 5 % is correlated with ν_μ & 2 % is uncorrelated ν_e only

DUNE-UK Activities

- **WP1: Physics**
  - Physics and detector design/optimisation studies
- **WP2: LAr-TPC Reconstruction**
  - Leading development of LAr-TPC automated reconstruction
    - Strong connection to UK MicroBooNE activties
- **WP3: DAQ**
  - Leading design/architecture work for Far Detector
  - Leading role in ProtoDUNE DAQ
- **WP4: 35-t prototype at Fermilab (now complete)**
  - Hands on experience with LAr-TPC data
- **WP5: LAr-TPC construction (capacity building)**
  - Hardware for SBND detector (APAs & Cathode planes)
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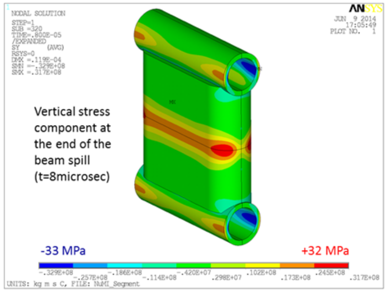
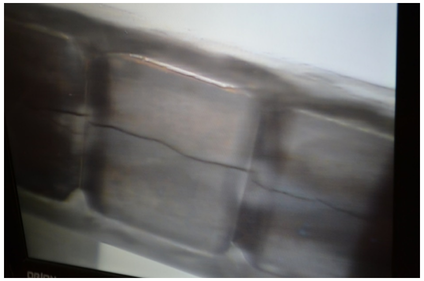
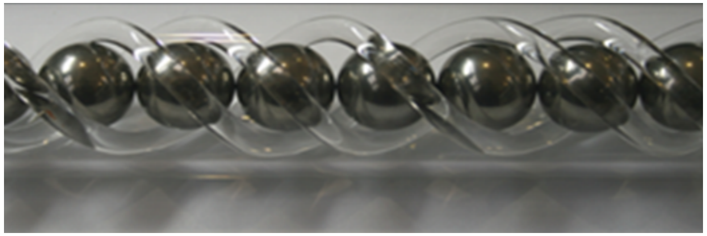
Activities tightly aligned with long-term goals

Beyond DUNE: UK and LBNF

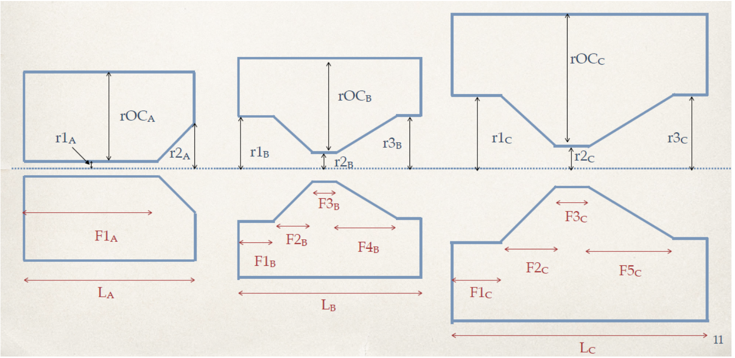
- **Also UK interest and expertise in the facility:**
  - High-power targets (UK is world leading)

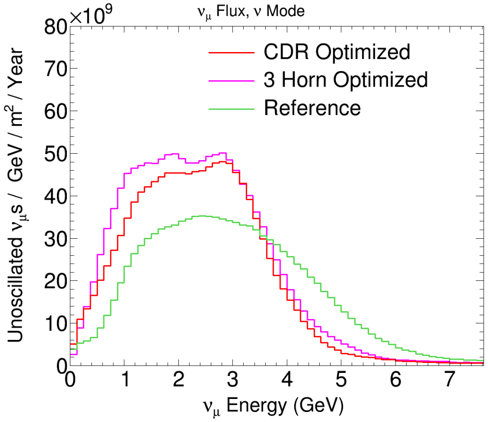






  - Optimization of the neutrino beam line





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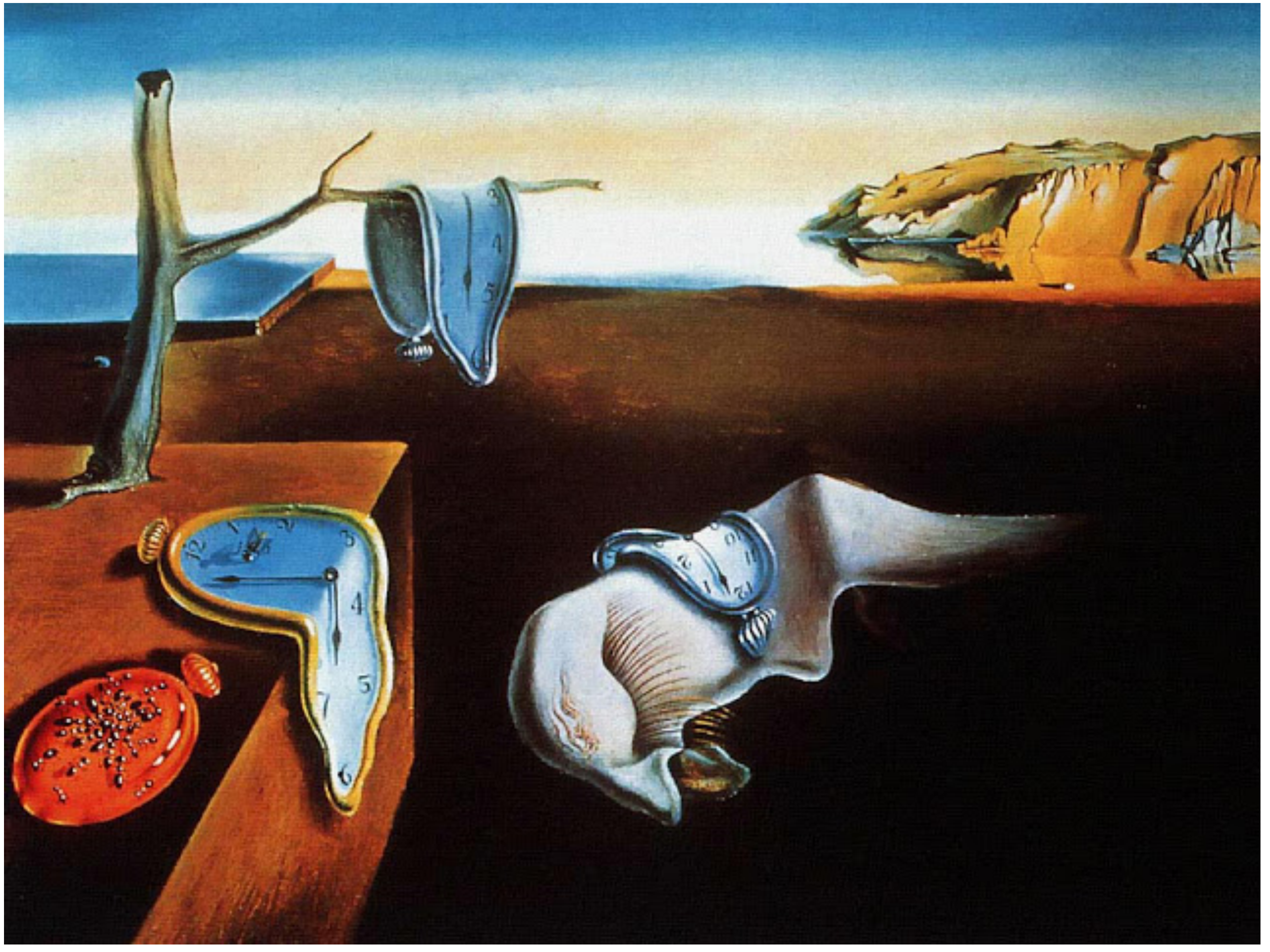

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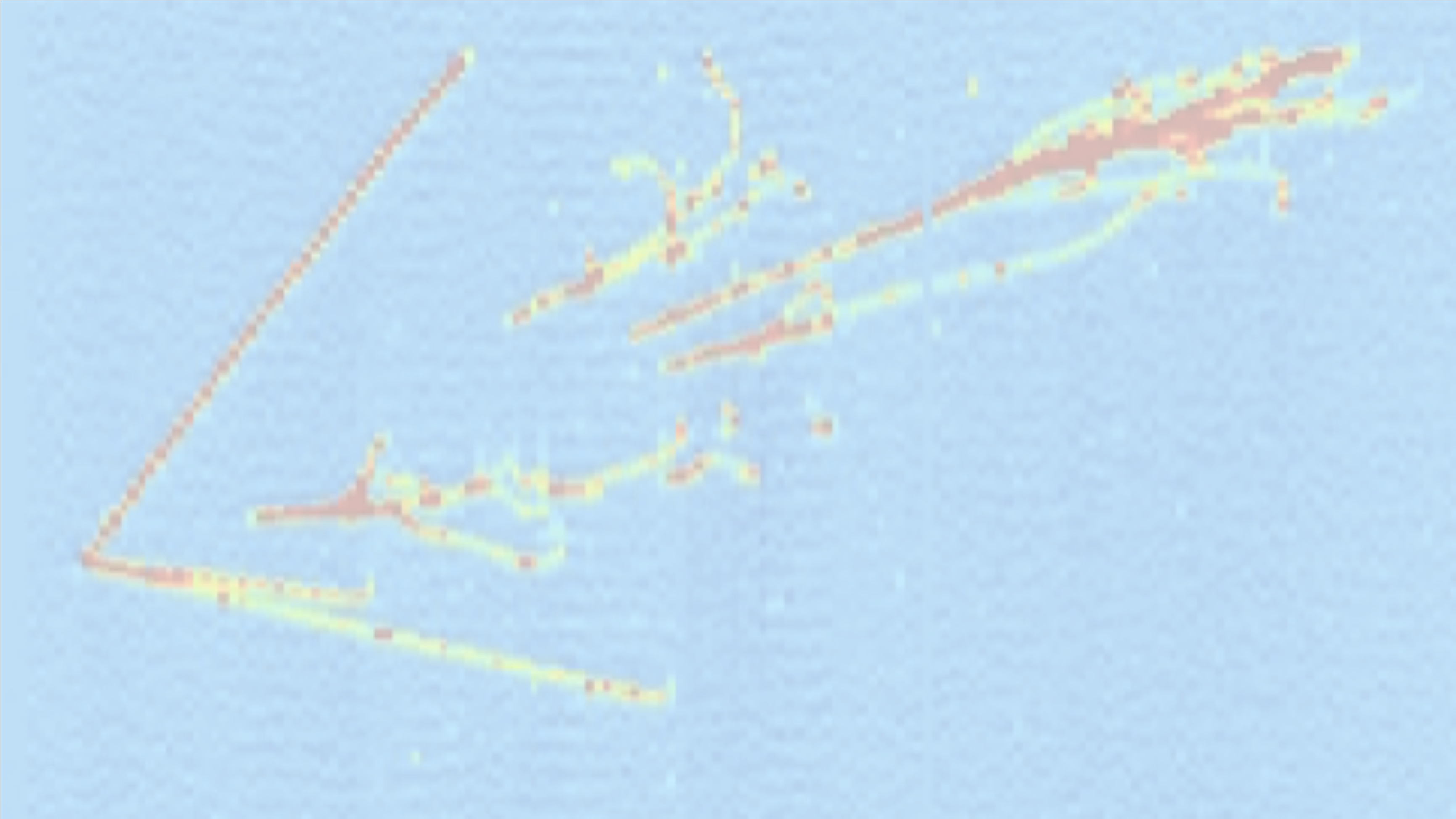

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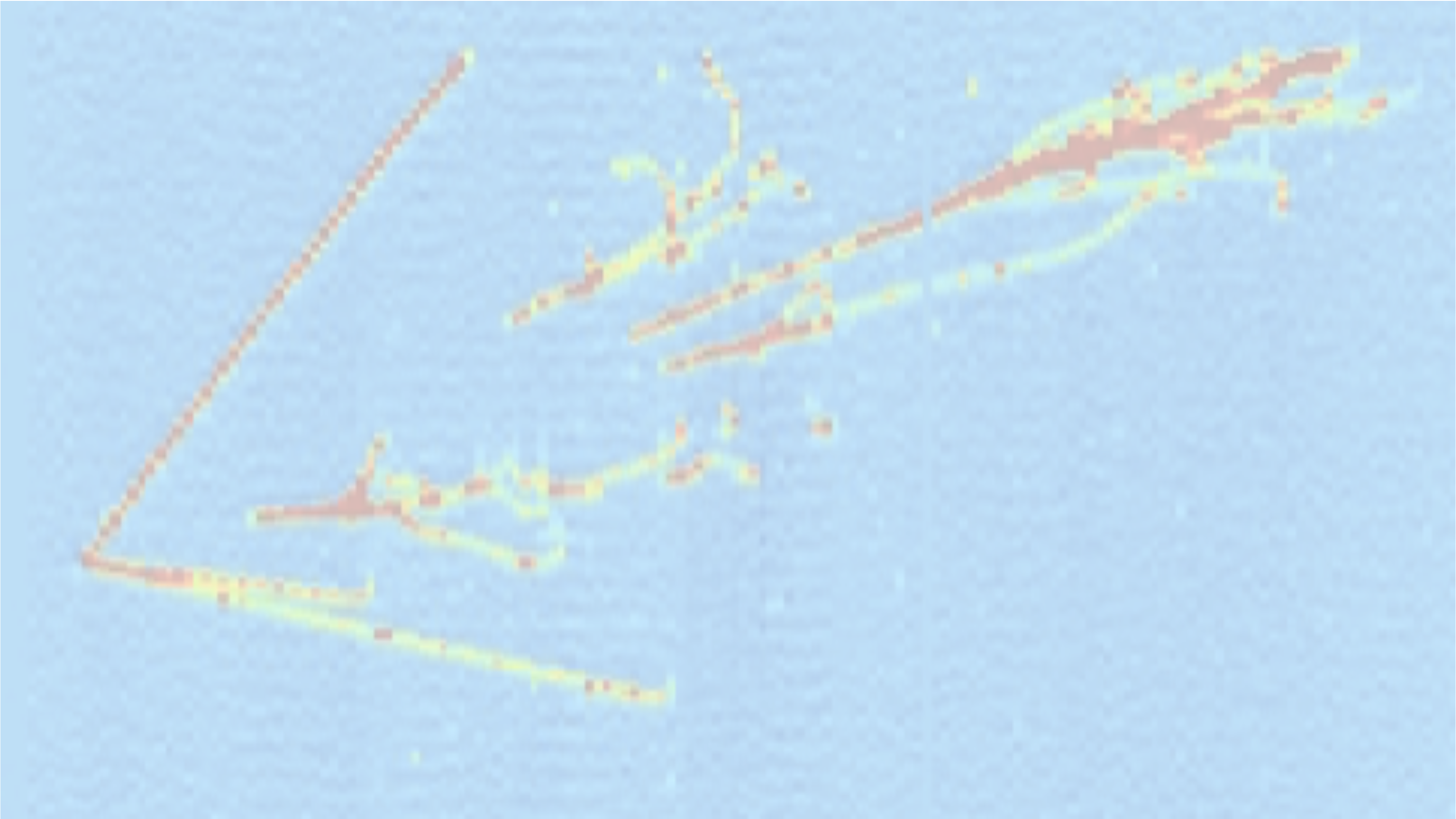

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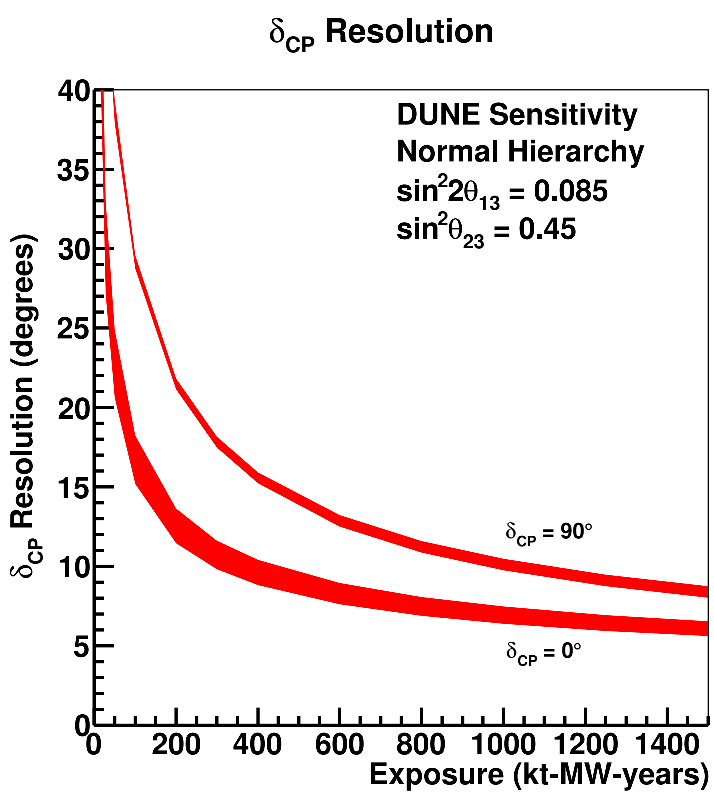

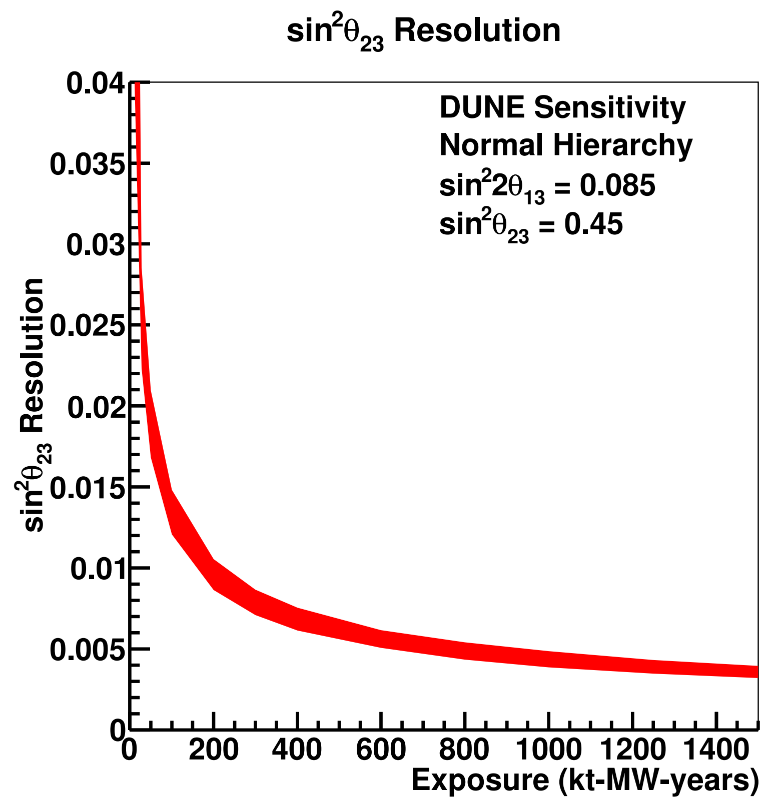

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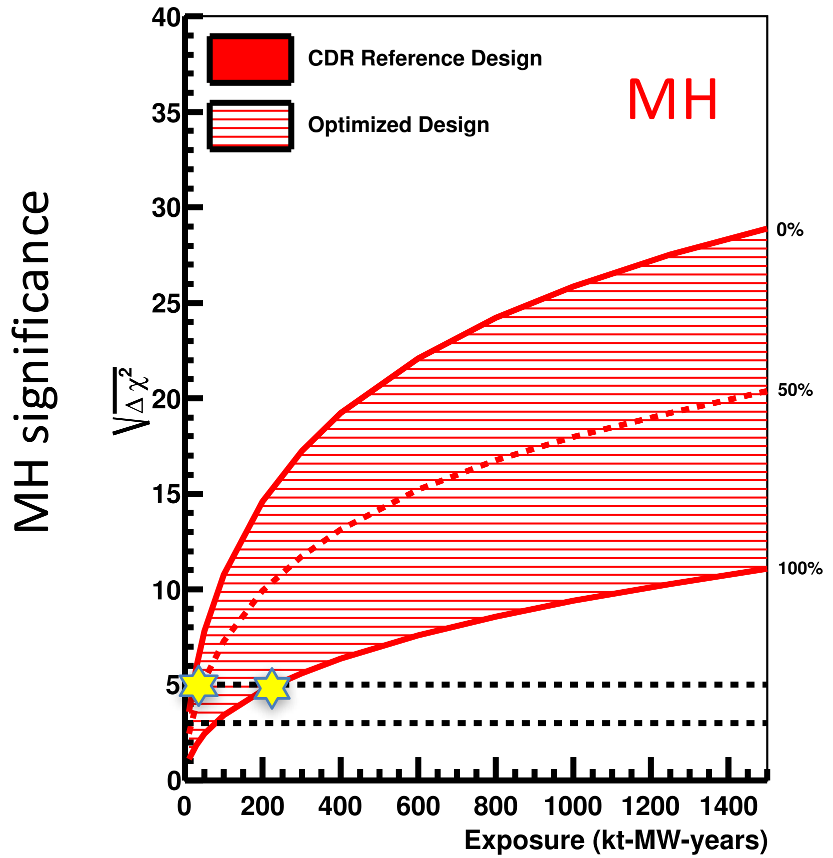

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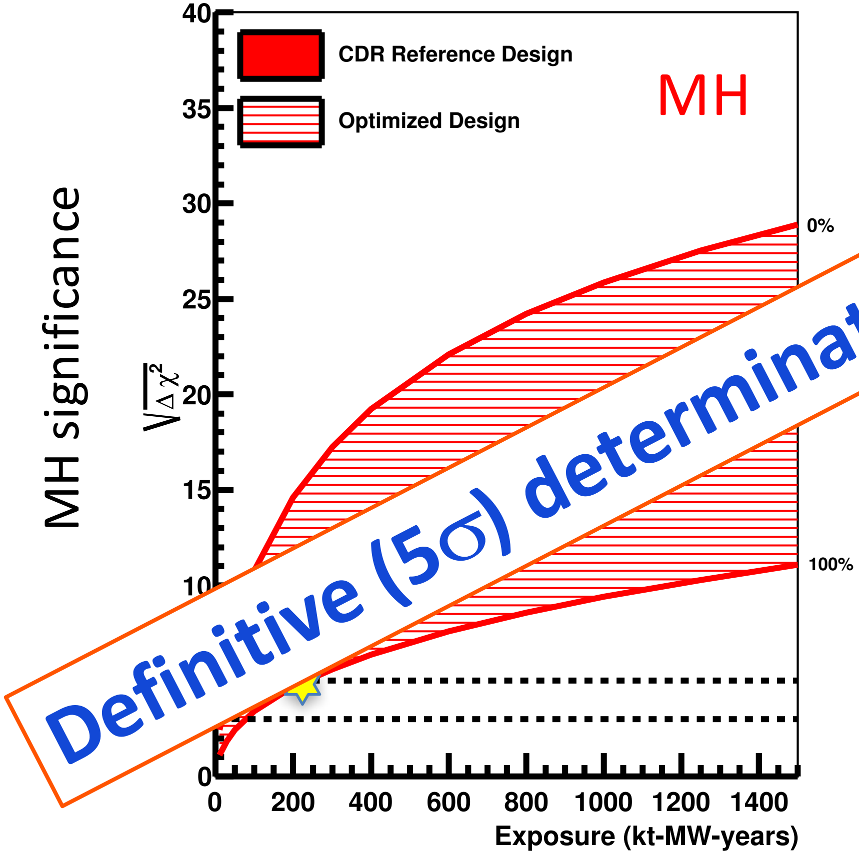

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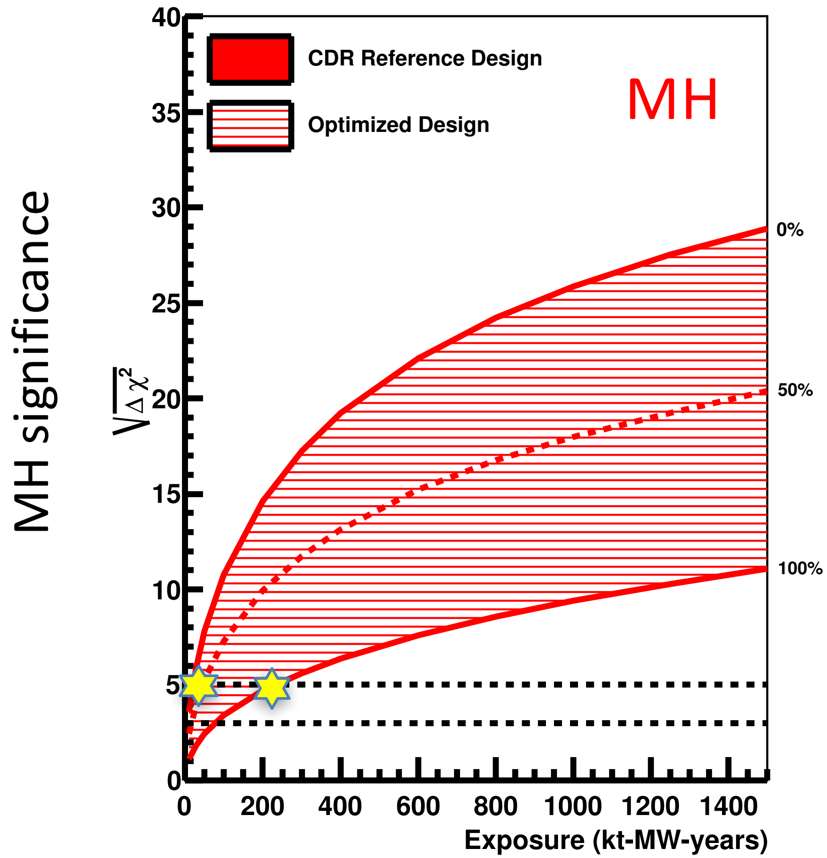

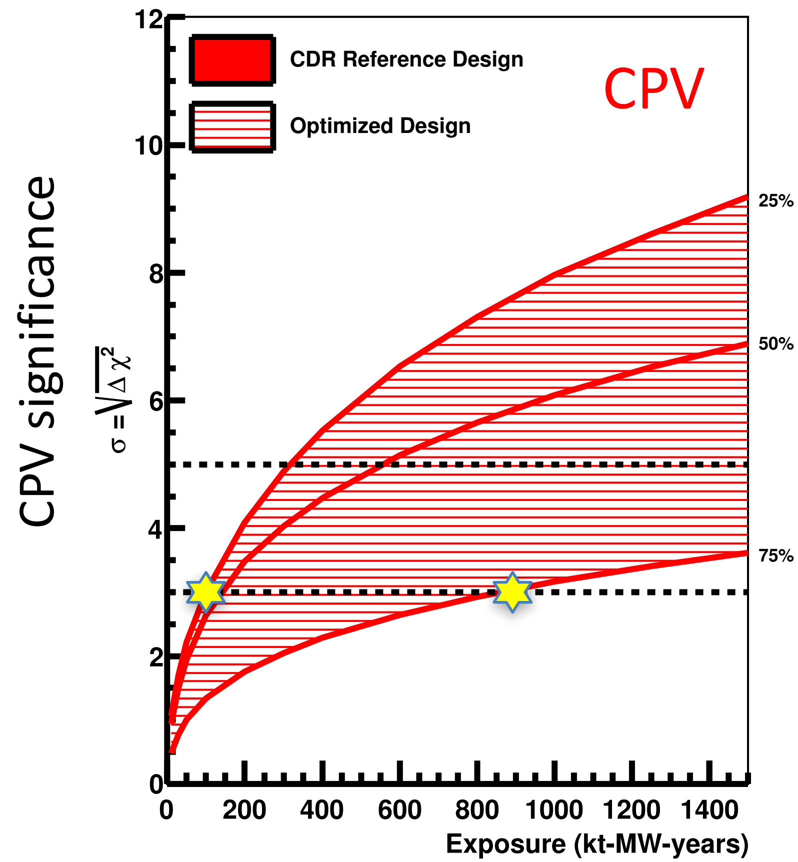

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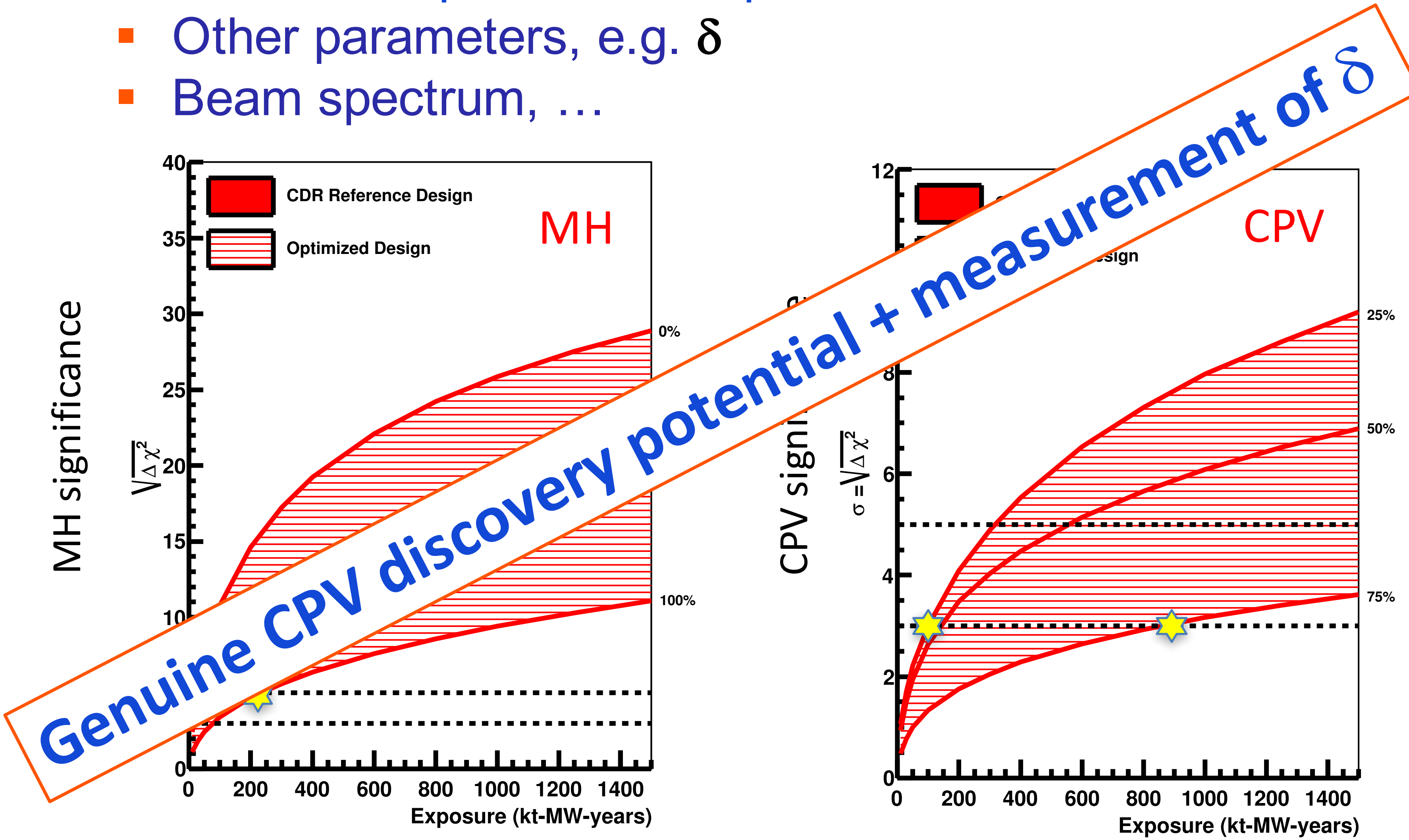
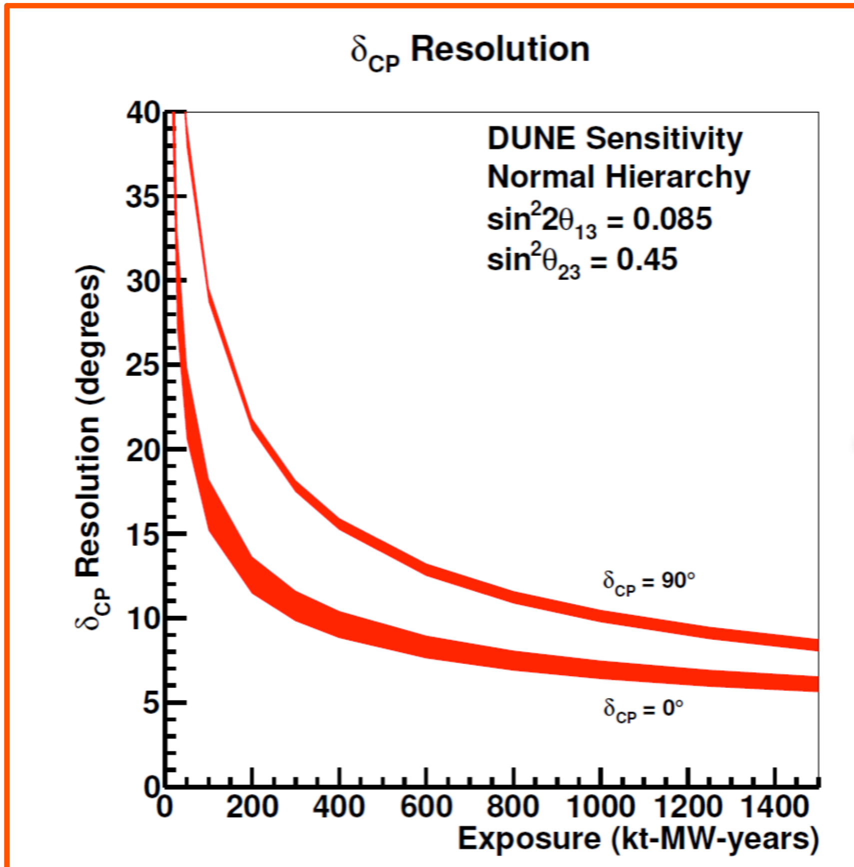
- Other parameters, e.g. δ
- Beam spectrum, …



Beyond discovery: measurement of δ

- ★ CPV "coverage" is just one way of looking at sensitivity…
- ★ DUNE will **measure** δ_{CP}

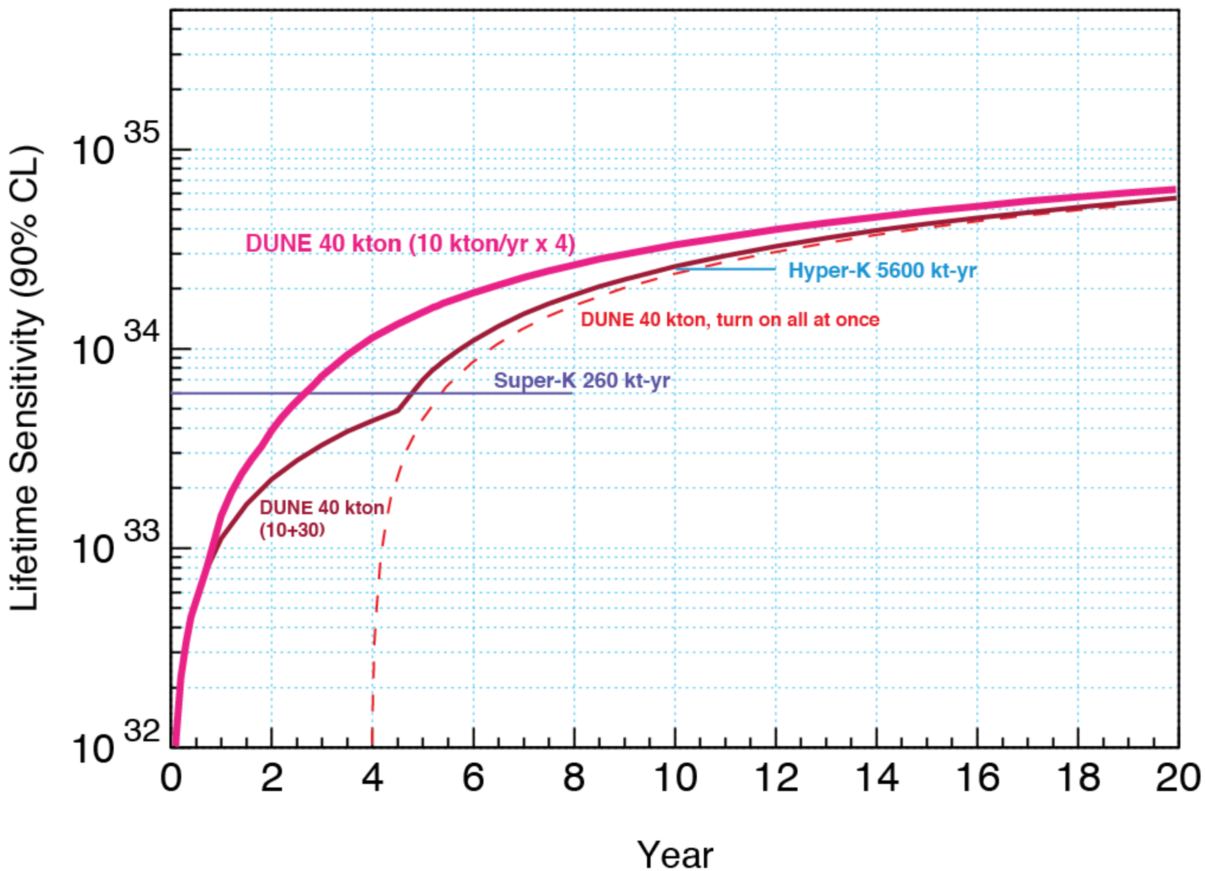


Start to ~approach current level of precision on quark-sector CPV phase (although takes time)

PDK

p → K ν

- DUNE for various staging assumptions



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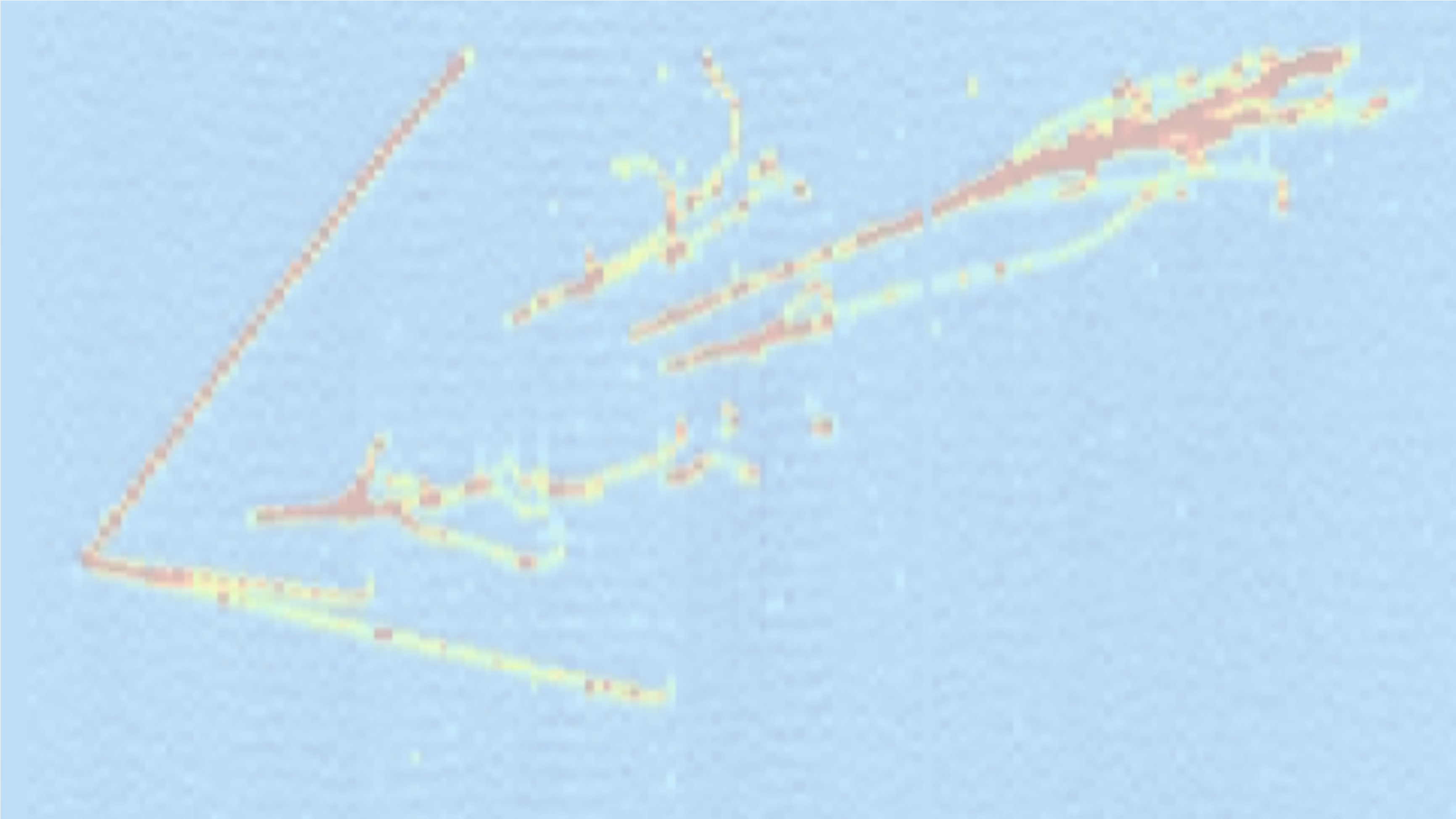
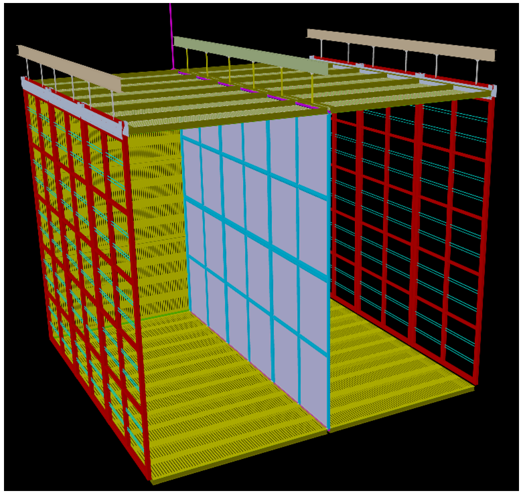
11. Opportunities on DUNE



Opportunities in DUNE



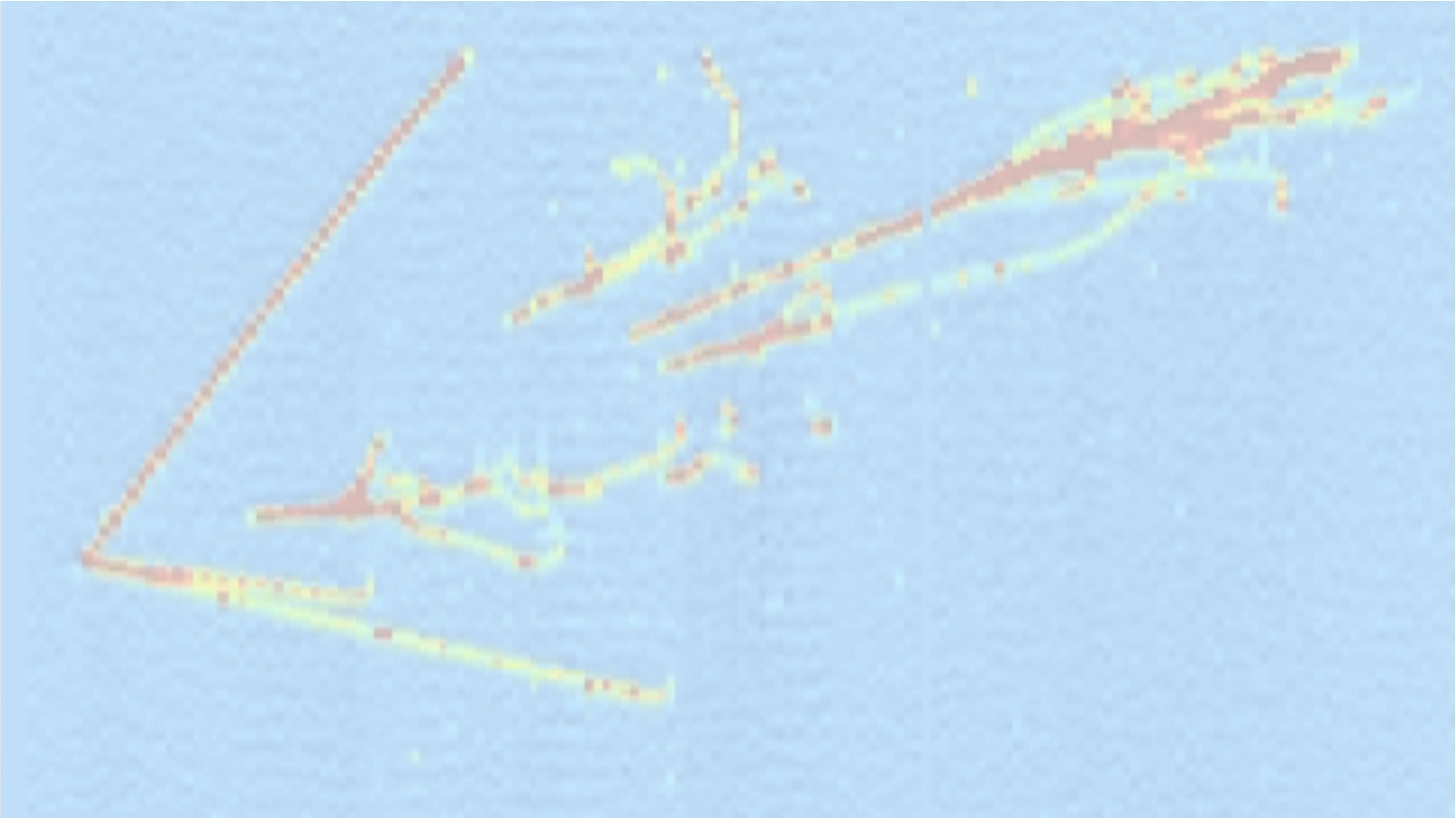
DUNE is moving rapidly

- Excavation starts in 2017
- ProtoDUNE @ CERN in 2018
- Far Detector construction in 2019
- Far Detector installation in 2021

DUNE: the next large global Particle Physics project

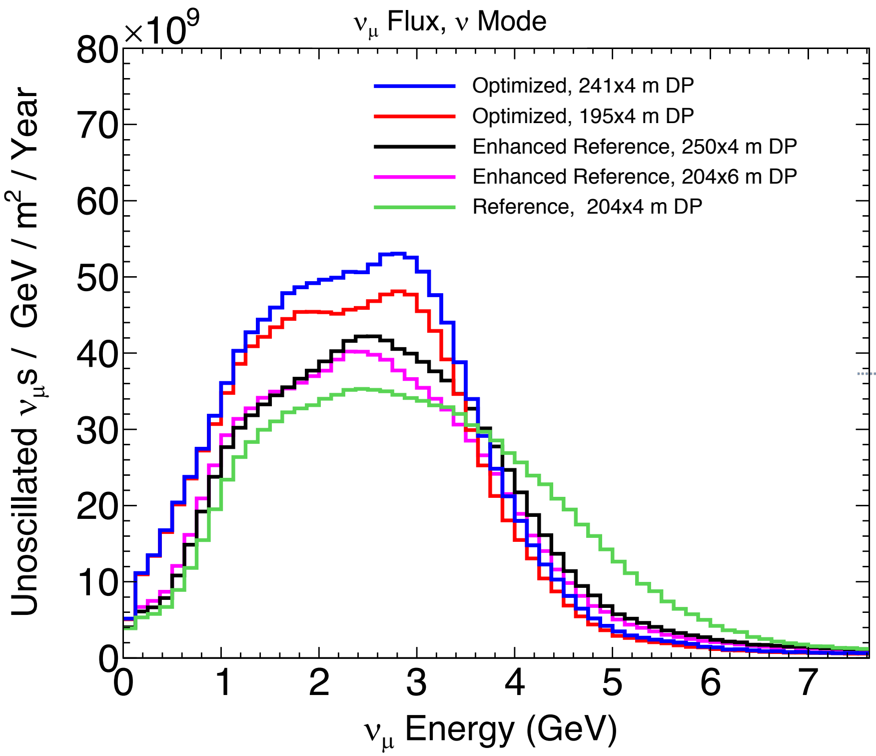
- Actively seeking new collaborators
  - many synergies with collider experiments
- Immediate Focus in Europe will be ProtoDUNE @ CERN
- Many Opportunities:
  - Hardware: e.g. photon detection system (scintillator + SiPMs)
  - DAQ/Computing: continuous readout = high-data rates
  - Software: LAr-TPC reconstruction

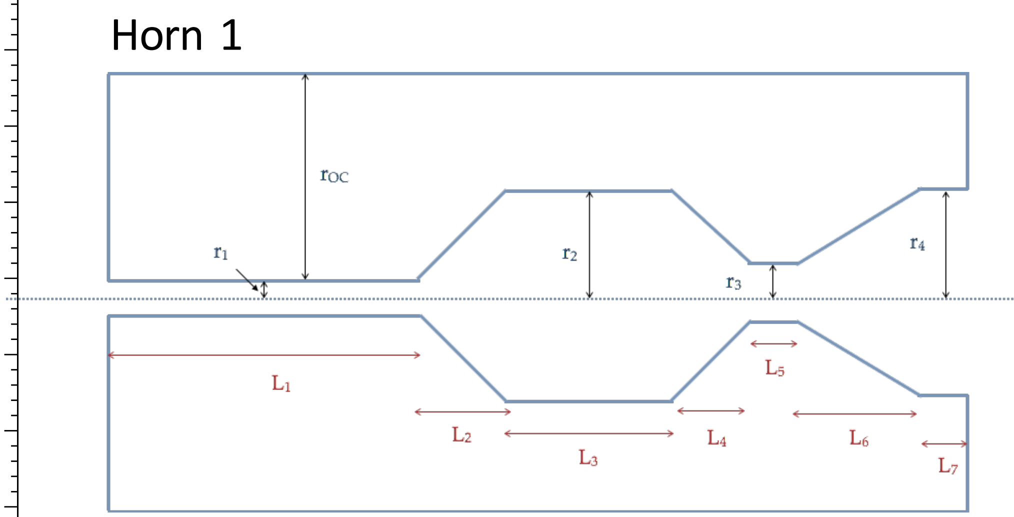
Beam Optimization



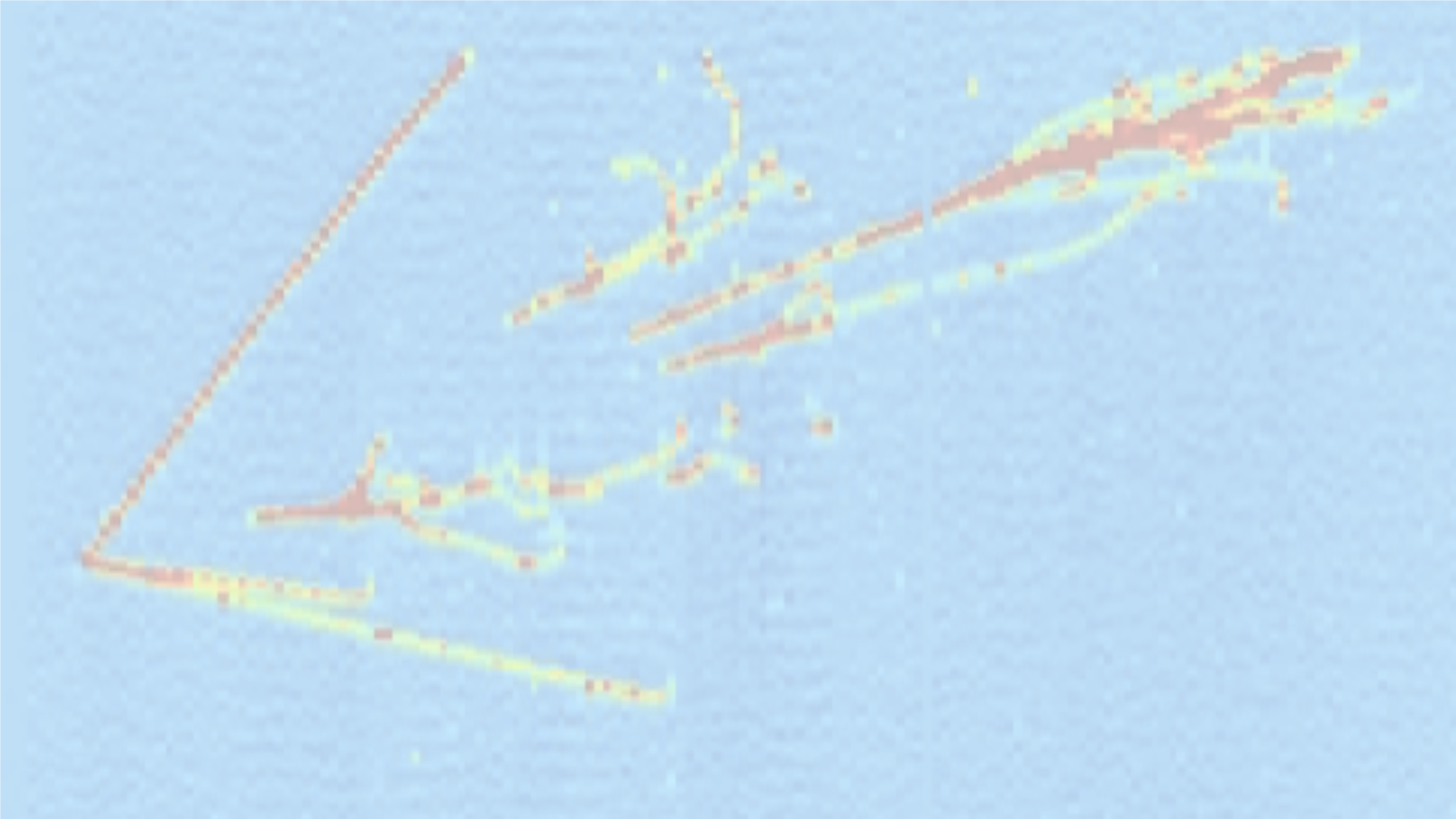
Beam Optimization

Following LBNO approach, genetic algorithm used to optimize horn design – increase neutrino flux at lower energies





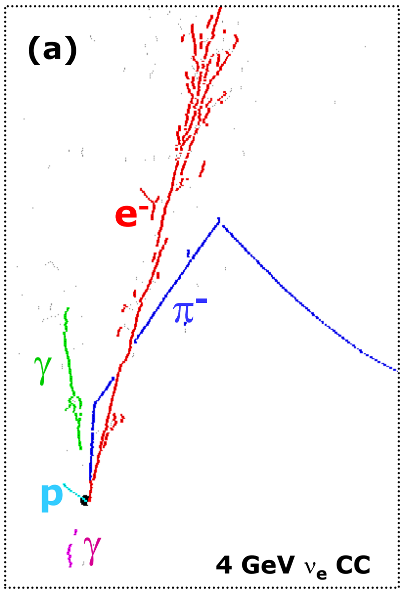
Reconstruction

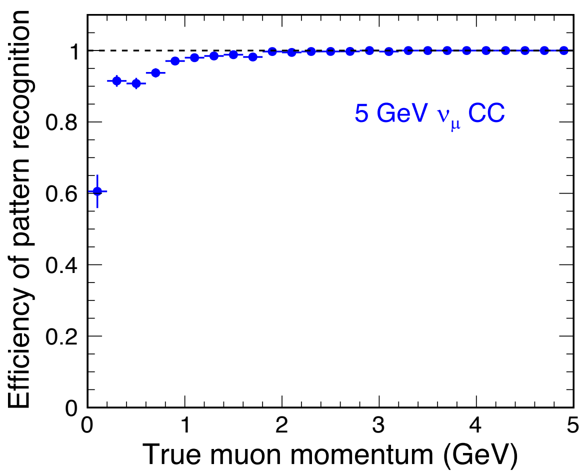


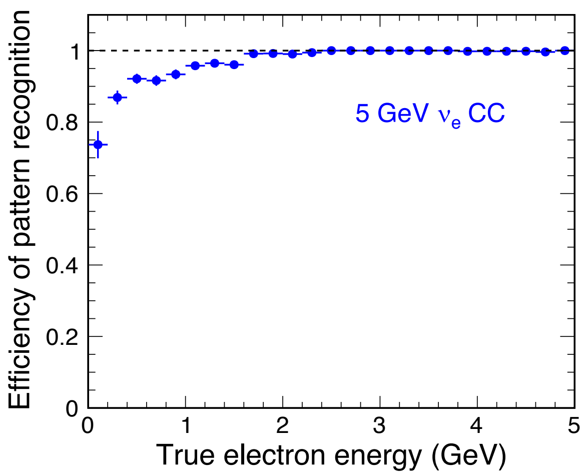
LAr-TPC Reconstruction

Real progress in last year – driven by 35-t & MicroBooNE

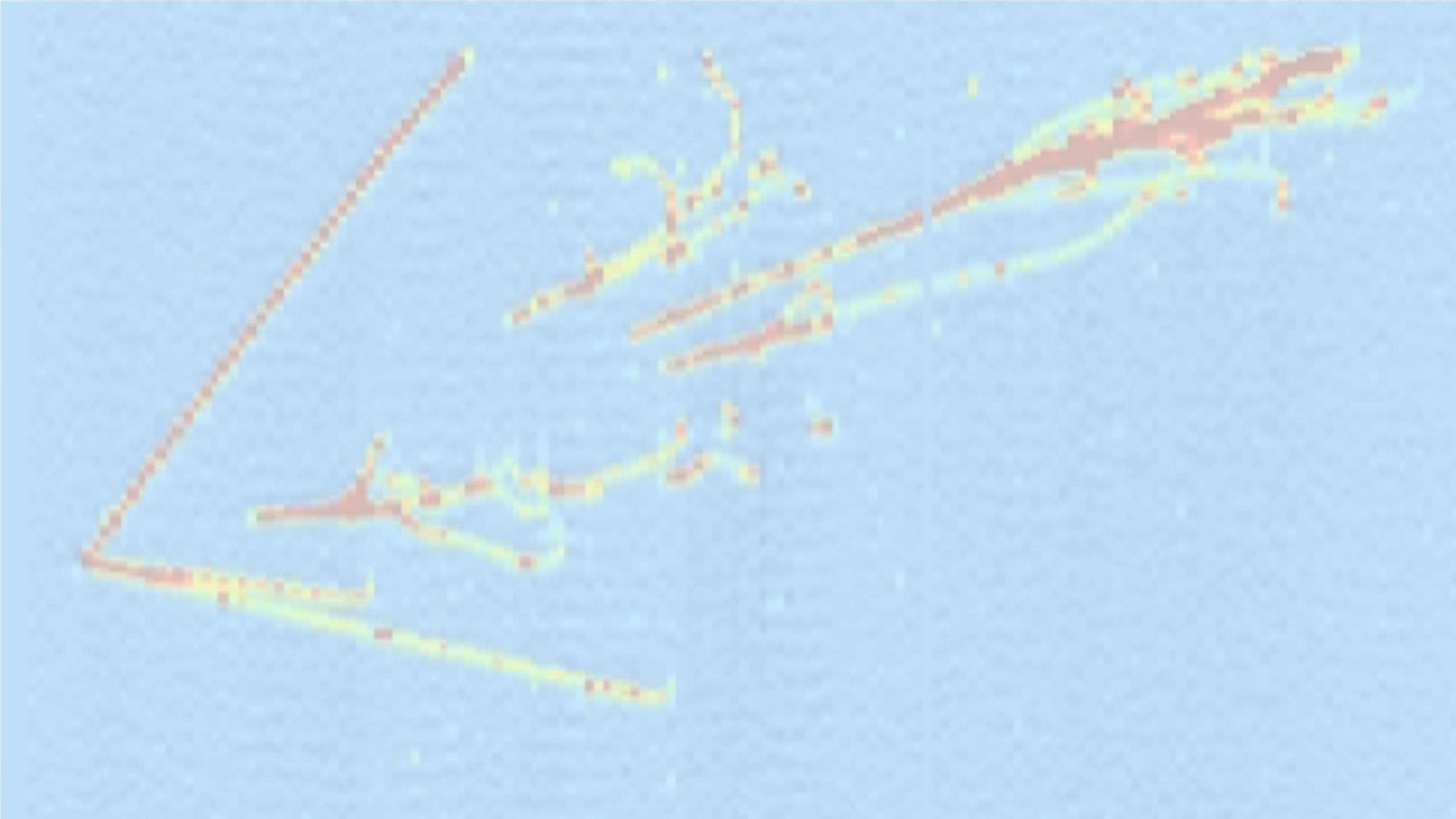
- Full DUNE simulation/reconstruction now in reach



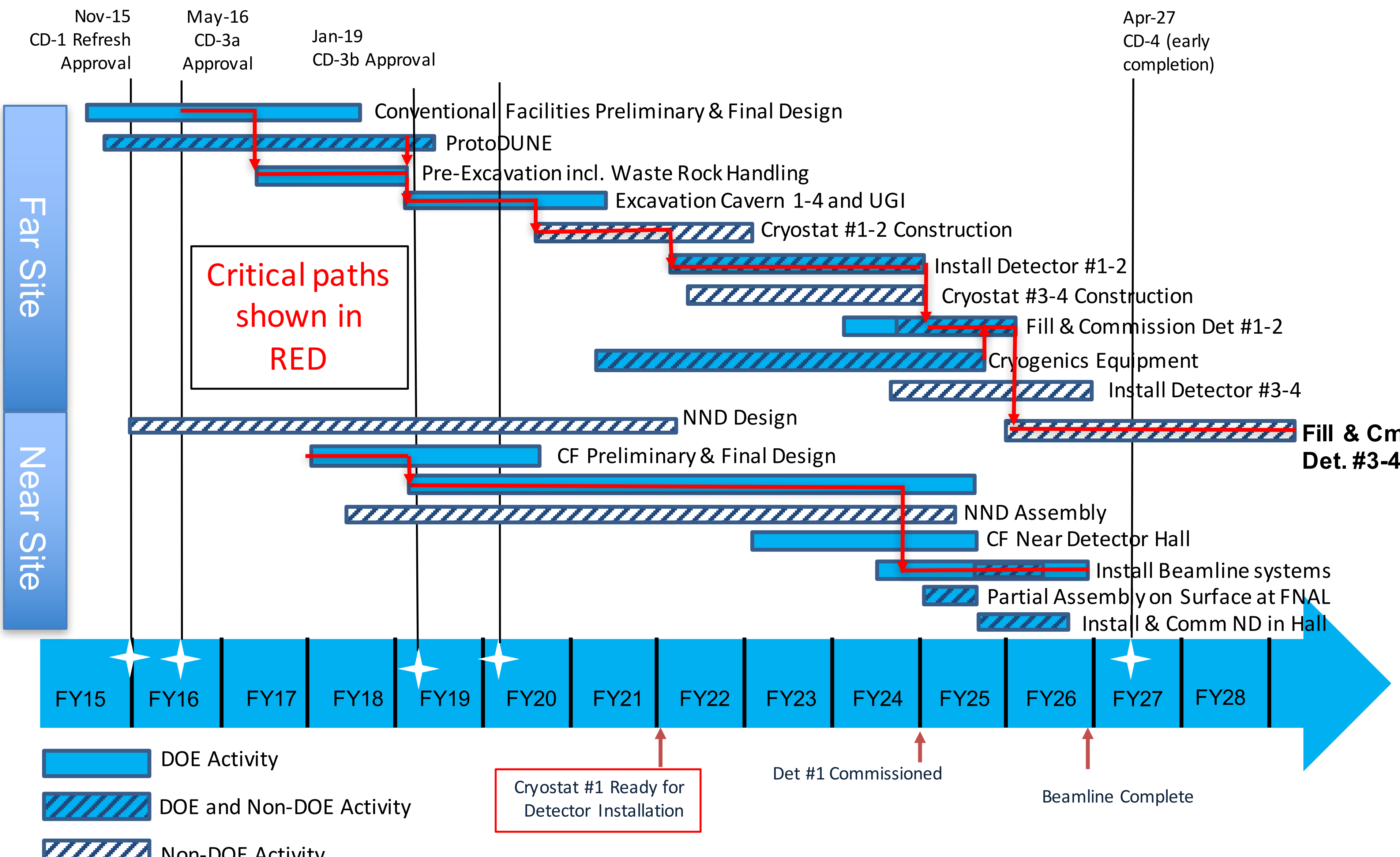




Schedule

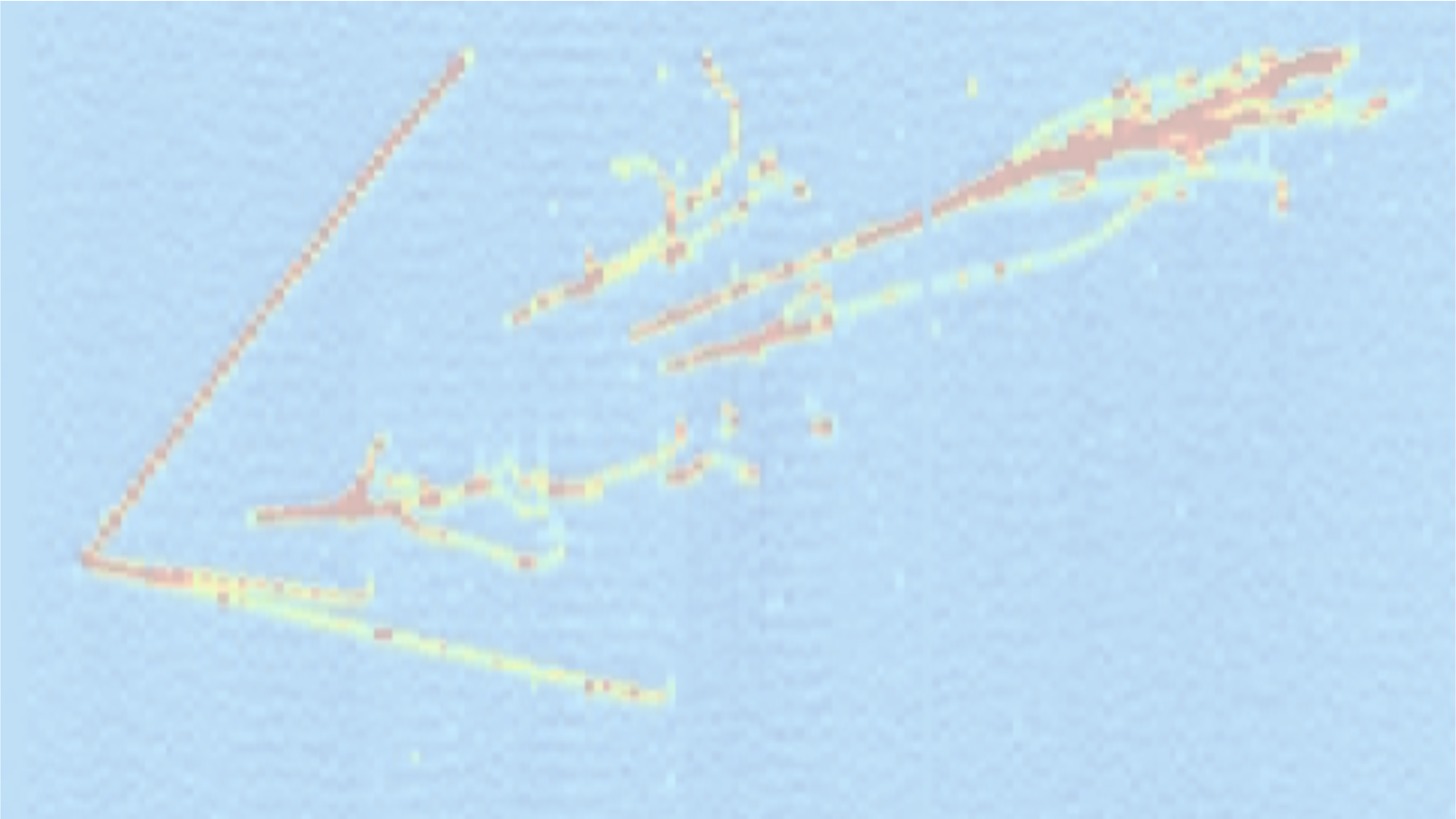


Schedule



Nov-15
CD-1 Refresh
Approval
May-16
CD-3a
Approval
Jan-19
CD-3b Approval
Apr-27
CD-4 (early
completion)
Far Site
Near Site
Conventional Facilities Preliminary & Final Design
ProtoDUNE
Pre-Excavation incl. Waste Rock Handling
Excavation Cavern 1-4 and UGI
Cryostat #1-2 Construction
Install Detector #1-2
Cryostat #3-4 Construction
Fill & Commission Det #1-2
Cryogenics Equipment
Install Detector #3-4
Fill & Cm
Det. #3-4
Critical paths shown in RED
NND Design
CF Preliminary & Final Design
NND Assembly
CF Near Detector Hall
Install Beamline systems
Partial Assembly on Surface at FNAL
Install & Comm ND in Hall
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
FY23
FY24
FY25
FY26
FY27
FY28
DOE Activity
DOE and Non-DOE Activity
Non-DOE Activity
Cryostat #1 Ready for Detector Installation
Det #1 Commissioned
Beamline Complete

Calculating Sensitivities



Determining Physics Sensitivities

For Conceptual Design Report

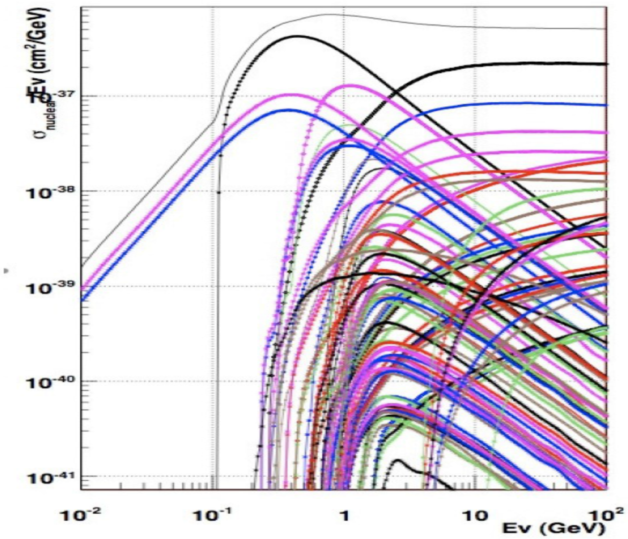
- **Full detector simulation/reconstruction not available**
  - See later in talk for plans
- **For Far Detector response**
  - Use parameterized single-particle response based on achieved/expected performance (with ICARUS and elsewhere)
- **Systematic constraints from Near Detector + …**
  - Based on current understanding of cross section/hadro-production uncertainties
  - \+ Expected constraints from near detector
    - in part, evaluated using fast Monte Carlo

Evaluating DUNE Sensitivities I

Many inputs calculation (implemented in GLoBeS):

- **Reference Beam Flux**
  - 80 GeV protons
  - 204m x 4m He-filled decay pipe
  - 1.07 MW
  - NuMI-style two horn system
- **Optimized Beam Flux**
  - Horn system optimized for lower energies
- **Expected Detector Performance**
  - Based on previous experience (ICARUS, ArgoNEUT, …)
- **Cross sections**
  - GENIE 2.8.4
  - CC & NC
  - all (anti)neutrino flavors

Exclusive ν-nucleon cross sections



Evaluating DUNE Sensitivities II

- **Assumed* Particle response/thresholds**
  - Parameterized detector response for individual final-state particles

Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained: from track length Exiting: 30 %	1^{o}
$\pi^{\pm}$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1^{o}
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{(E/GeV)}$	1^{o}
p	50 MeV	$p < 400$ MeV: 10 % $p > 400$ MeV: $5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^{o}
n	50 MeV	$440\%/\sqrt{(E/GeV)}$	5^{o}
other	50 MeV	$5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^{o}

*current assumptions to be addressed by FD Task Force

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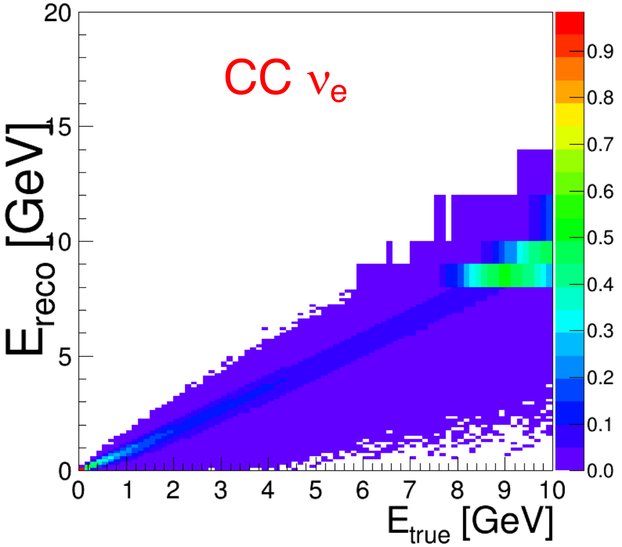
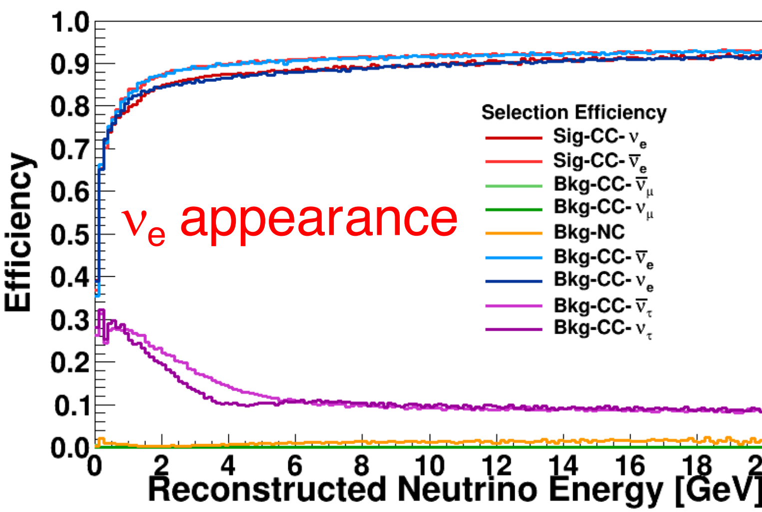
Evaluating DUNE Sensitivities III

- **Efficiencies & Energy Reconstruction**
  - Generate neutrino interactions using GENIE
  - **Fast MC** smears response at generated final-state particle level
    - "Reconstructed" neutrino energy
    - kNN-based MV technique used for ν_e "event selection", parameterized as efficiencies
  - Used as inputs to GLoBES





Evaluating DUNE Sensitivities IV

- **Systematic Uncertainties**
  - Anticipated uncertainties based on MINOS/T2K experience
  - Supported by preliminary fast simulation studies of ND

Source	MINOS ν_e	T2K ν_e	DUNE ν_e
Flux after N/F extrapolation	0.3 %	3.2 %	2 %
Interaction Model	2.7 %	5.3 %	~ 2 %
Energy Scale (ν_μ)	3.5 %	Inc. above	(2 %)
Energy Scale (ν_e)	2.7 %	2 %	2 %
Fiducial Volume	2.4 %	1 %	1 %
Total	**5.7 %**	**6.8 %**	**3.6 %**

- **DUNE goal for ν_e appearance < 4 %**
  - For sensitivities used: 5 % $\oplus$ 2 %
    - where 5 % is correlated with ν_μ & 2 % is uncorrelated ν_e only