Physics TDR Assessment

NDK Group

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Part 1: CDR

CDR assumptions

- Signal efficiency and background rates for NDK modes considered promising in DUNE:

Table 4.1: Efficiencies and background rates (events per Mt · year) for nucleon decay channels of interest for a large underground LArTPC [97], and comparison with water Cherenkov detector capabilities. The entries for the water Cherenkov capabilities are based on experience with the Super–Kamiokande detector [99].

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

- Note: assume backgrounds are dominated by atmospheric neutrinos
- Assume systematic uncertainty on signal efficiencies and background rates is negligible

CDR assumptions

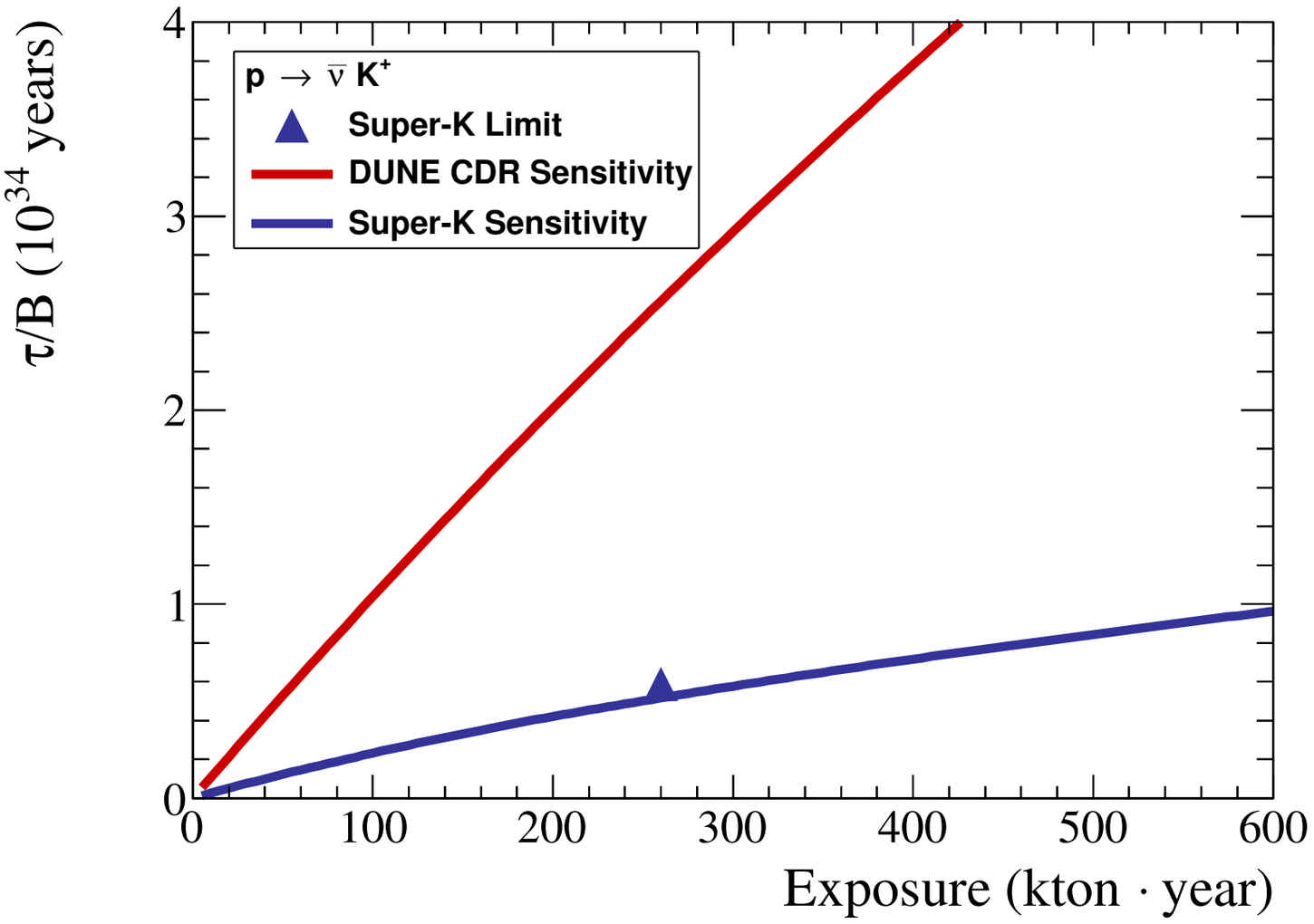
Digging deeper

- CDR efficiencies and backgrounds from Bueno et al. paper, hep-ph/0701101, assuming:
  - **100-kt** LAr-TPC detector module
  - Nuclear effects (NDK, ν-A) and atmospheric neutrino interactions with **FLUKA** / PEANUT / NUX
  - **Fast reconstruction** based on energy/angular smearing, and momentum thresholds for particle detection (**30 MeV/c** for K^+, 20 MeV/c for μ)
  - **Perfect particle identification**
- **Essential** to replace these assumptions with DUNE-specific end-to-end simulations
- Straightforward to compute τ/B sensitivity for any exposure once signal efficiency and background rate are estimated

CDR sensitivity

$p \rightarrow \overline{\nu} K^+$

- DUNE CDR sensitivity (90% CL) for p → $\overline{\nu}$ K^+ versus exposure and versus Super-K:



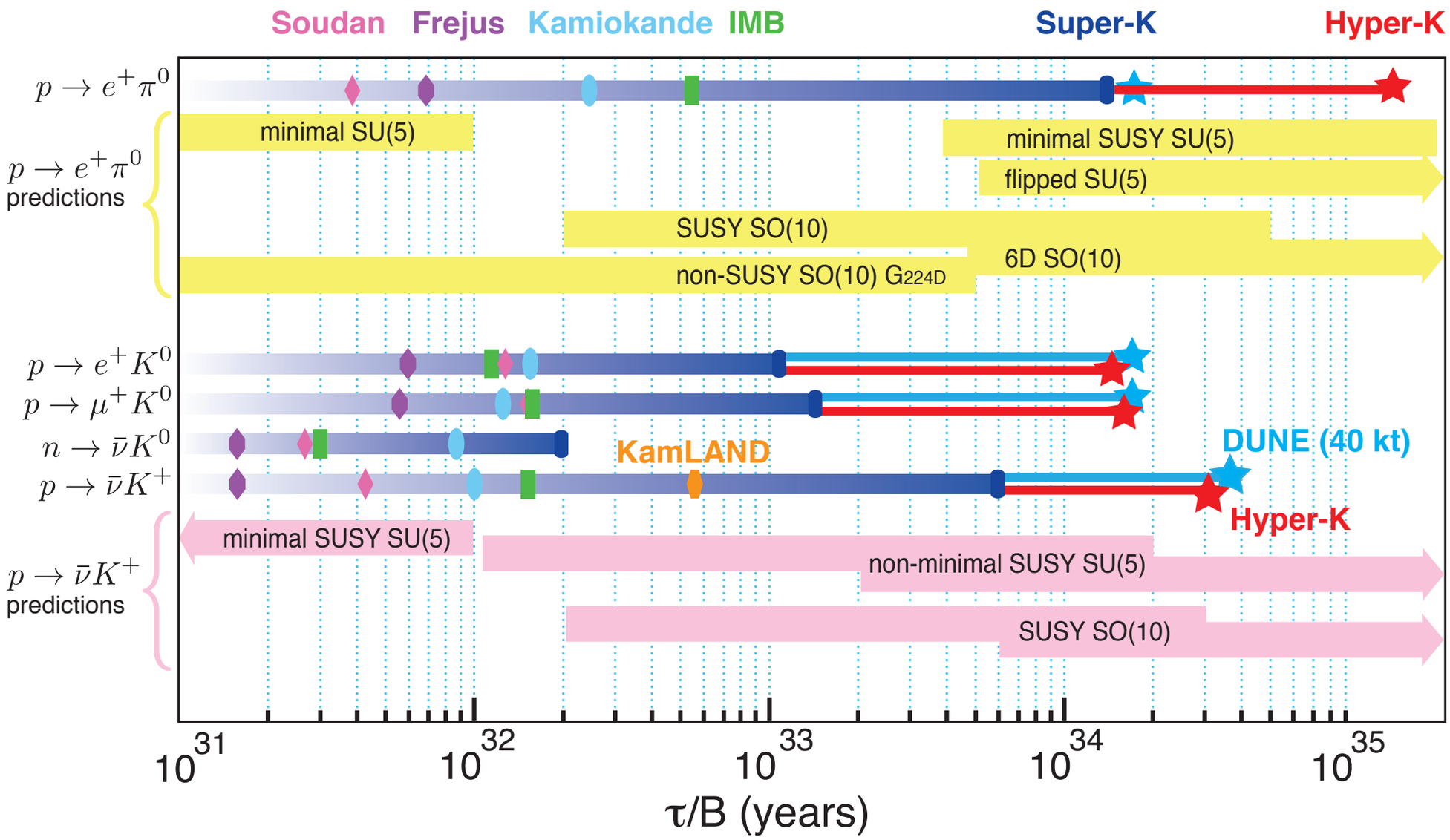
- **DUNE** sensitivity: $\tau/B > 3.8\times10^{34}$ yr for 400 kt·yr
- Compare with **SK** 2014 limit: $\tau/B > 0.59\times10^{34}$ yr for 260 kt·yr

Pretty good!

CDR sensitivity

Other modes

- Other modes (partial overlap with Tab.4.1 modes in slide 2):



- DUNE numbers for 400 kt·yr, Hyper-K numbers for 5.6 Mt·yr? → Pretty good!

Part 2: FDTF Final Report

First update to CDR: FDTF Final Report

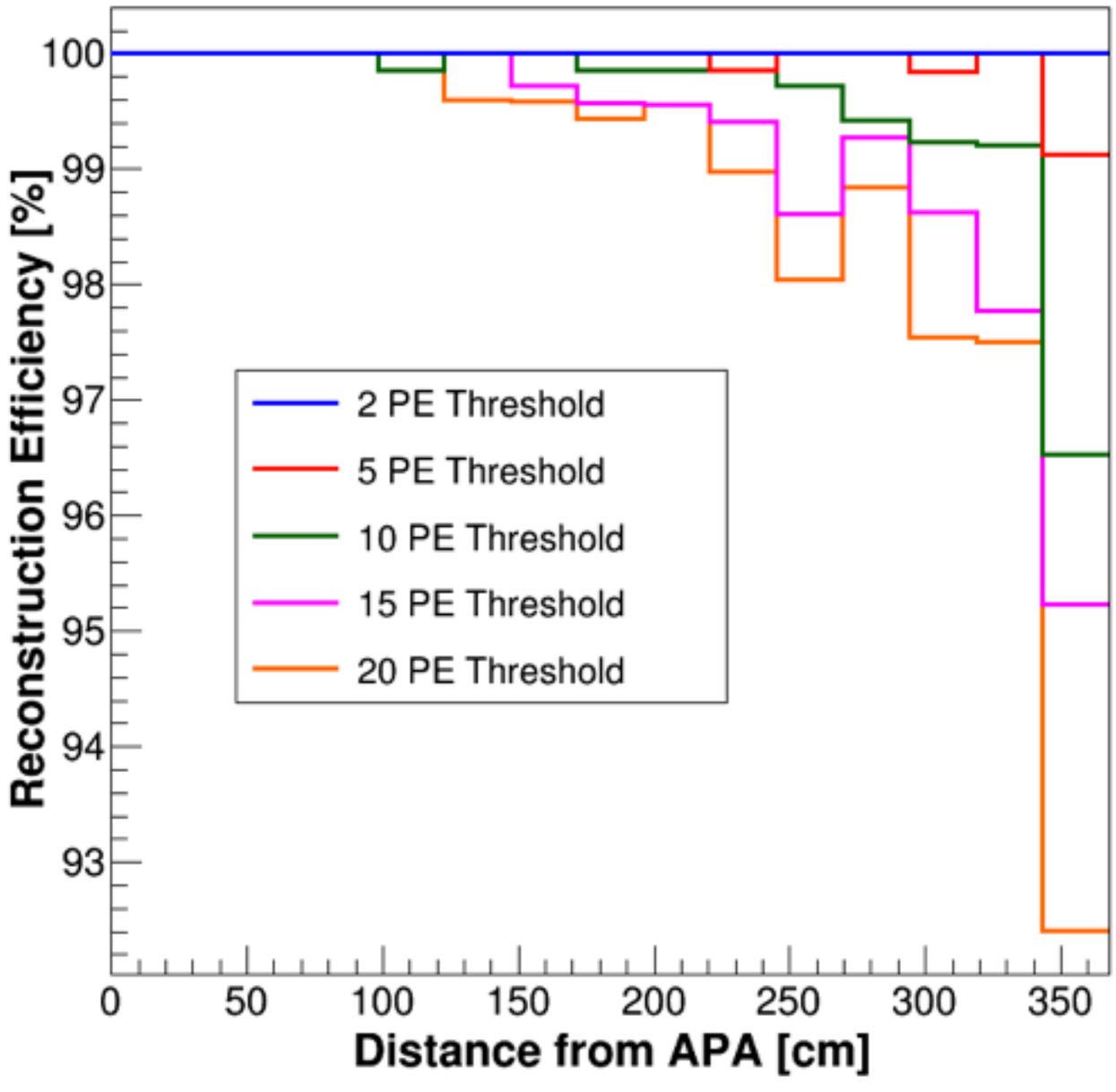
March 2017

- Goal for FDTF Final Report: NDK sensitivity with DUNE's estimate of signal efficiency and background rate. From end-to-end simulation/reconstruction/analysis chain
  - Do this for $p \rightarrow \overline{\nu} K^+$. Unlikely for other modes on March 2017 timescale
  - In sensitivity calculations, assume atmospheric neutrino backgrounds dominate
    - But try to run cosmogenic events through full reconstruction by March 2017
    - Keep assuming, without motivating, that systematic errors are negligible
- Where are we now (Dec 2016) for $p \rightarrow \overline{\nu} K^+$? Next four slides

Current state-of-the-art

Signal efficiency for $p \rightarrow \overline{\nu} K^+$

- Trigger efficiency from photon detector system close to 100% (Kevin Wood):

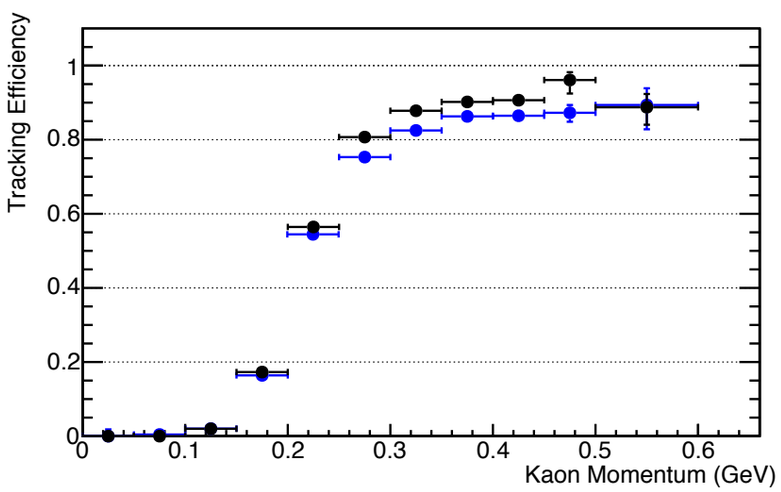


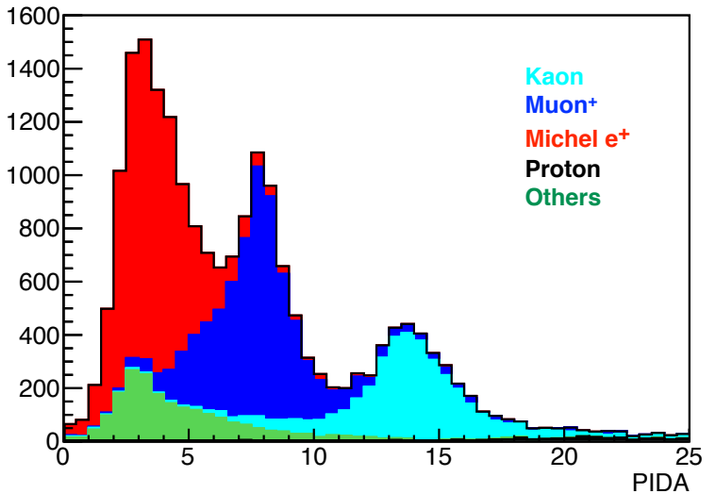
Current state-of-the-art

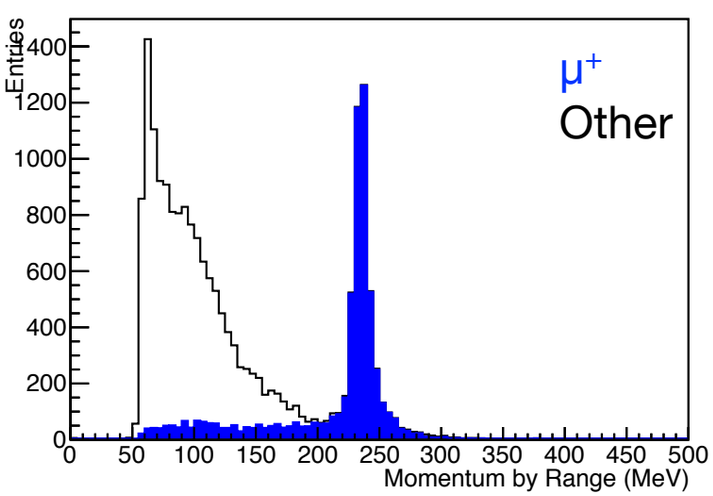
Signal efficiency for $p \rightarrow \overline{\nu} K^+$

- Event selection efficiency with current full reco/analysis chain, $p \rightarrow \overline{\nu} K^+$ & $K^+ \rightarrow \mu^+ \nu_\mu$ events (Aaron Higuera):

Category	Description	Signal Efficiency (%)
Golden	Pass K^+ PIDA criterion & Stopping μ^+ candidate (range)	38.3
Silver	Pass K^+ PIDA criterion	11.1
Bronze	Stopping μ^+ candidate (range)	39.8
All		**89.2**







Current state-of-the-art

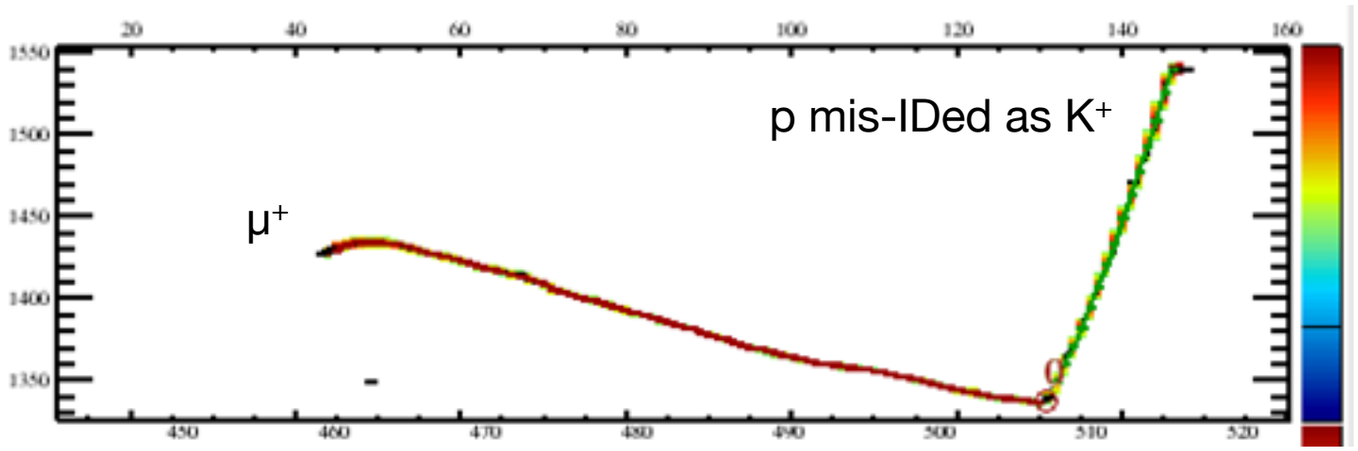
Background rate for $p \rightarrow \bar{\nu} K^+$

Atmospheric neutrino backgrounds

- Very preliminary estimate for golden-like NDK selection (Aaron Higuera, Sept 2016 CM):

  B ≃ 500 / (Mt·yr) 

- Mostly ν_μ CC interactions
- Let's not worry too much (yet), still early days for NDK analysis based on full sim/reco



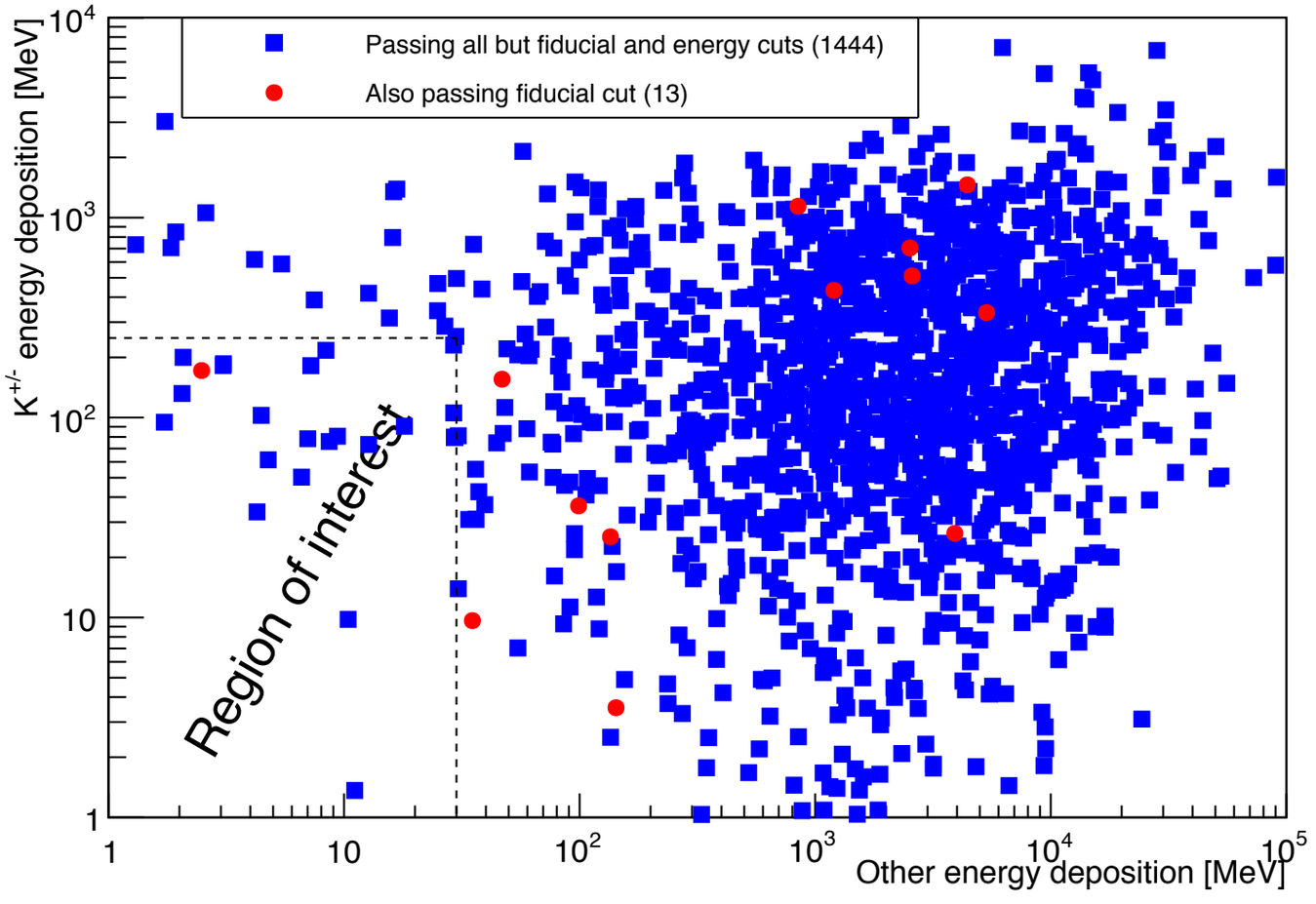
Background	Efficiency
Kaon ID	33.3%
Stopping Muon	23.0%
210<p<250 MeV	1.5%
no shower-like	0.18%

Current state-of-the-art

Background rate for $p \rightarrow \overline{\nu} K^+$

Cosmogenic backgrounds

- Very preliminary estimate based on MC truth (Matt Robinson): **B ≃ 0.5 / (Mt · yr)**
- One event passing all cuts in 10-kt FV out of 10^9 simulated muons (200-yr exposure)
- This would be tolerable rate if confirmed with full sim/reco



Part 3: TDR

TDR assessment goal 1

Risk no.1 and direction changes

- **Risk no.1: LAr-TPC event reconstruction performance for p → $\bar{\nu}$ K^+ events is far worse than what was assumed in the CDR**
  - Far worse in terms of signal efficiency, background rate, or both
  - Assessment of "standard" reconstruction performance on p → $\overline{\nu}$ K^+ in FDTF Final Report
  - **Possible direction change**: start exploring alternative reconstruction around March 2017 if standard performance not satisfactory
  - Options include reconstruction tailored on specific NDK topologies, or other sophistications (eg, machine learning)

TDR assessment goal 1

Risk no.2 and direction changes

- **Risk no.2: systematic uncertainty on signal/background expectations is large, having a big hit on NDK sensitivities**
  - Unable to quantify this risk at the moment. **Direction change**: start addressing NDK systematic uncertainties during 2017
  - Level of sophistication may not need be ultra-high, e.g. at the level of systematic uncertainty studies for LBL CDR sensitivities?

- For comparison, table shows Super-K sensitivities for various NDK modes assuming:
  - Negligible syst uncertainties: numbers in ( )
  - Realistic syst uncertainties: numbers outside ( )
    - 20-30% errors on signal efficiencies
    - 40-70% errors on background rates

τ/Br (10^{33}yrs)	This Thesis	
$p \to e^+\pi^0$	8.2	(9.1)
$p \to \mu^+\pi^0$	6.6	(7.3)
$p \to e^+\eta$	4.2	(5.4)
$p \to \mu^+\eta$	1.3	(1.8)
$p \to e^+\rho^0$	0.71	(0.96)
$p \to \mu^+\rho^0$	0.16	(0.23)
$p \to e^+\omega$	0.32	(0.63)
$p \to \mu^+\omega$	0.78	(1.1)
$n \to e^+\pi^-$	2.0	(3.2)
$n \to \mu^+\pi^-$	1.0	(1.7)
$n \to e^+\rho^-$	0.070	(0.18)
$n \to \mu^+\rho^-$	0.036	(0.16)

TDR assessment goal 1

Risk no.3 and direction changes

- **Risk no.3: DUNE is unable to perform the broad, sensitive, searches for baryon number violation we have been advertising**
  - Broad program in DUNE implies sensitive searches in several/tens of NDK modes, not just $p \to \overline{\nu} K^+$. And also n-nbar oscillation searches
  - Unable to quantify this risk at the moment. **Direction change**: need to bring few other analyses to the level of maturity of $p \to \overline{\nu} K^+$ during 2017
  - Favour analyses relying on different experimental strategies in DUNE and/or different theory motivation, compared to $p \to \overline{\nu} K^+$
  - Priorities toward full analysis, in addition to $p \to \overline{\nu} K^+$:

Analysis	Motivation
$p \to l^+ K^0$ (l = e, μ)	Different exp strategy (+ DUNE should do well)
$p \to e^+ \pi^0$	Different theory motivation (non-SUSY GUTs), different exp strategy
n-nbar	Different theory motivation (new physics at 10^3-10^5 GeV), different exp strategy

TDR assessment goal 2

Effort allocation and priorities

- Prioritise by addressing first three above-mentioned risks, namely:
  - poor reconstruction performance, systematics-dominated sensitivities, overly narrow searches
- Risk no.3: easy to adjust to available resources the max number of full analyses that can be explored in parallel
  - **Philosophy**: better to have few (1-4?) full analyses in TDR rather than lots of "half-cooked" analyses
- There should be synergies in systematic uncertainty evaluation across different analyses. Perhaps also in alternative reconstruction. If so, exploit those.
  - **Example**: dominant systematics on Super-K signal efficiency for most NDK modes is nuclear effects → one "GENIE expert" may provide this knowledge for all DUNE analyses?

TDR assessment goal 3

TDR goalposts

- TDR initial goalpost should include **demonstration** (with full MC) of "quasi-background-free" searches for some key NDK modes discussed above
  - This is an important "DUNE CDR selling point" that we should try to maintain
  - Quasi-background-free = **<1 background event per 400 kt·yr**
- TDR should also include **demonstration** (with full MC) that quasi-background-free regime can be reached with signal efficiency that is significantly better (eg, **factor 2-4**) than Water Cherenkov efficiency for at least some modes
  - Example: 80% signal efficiency for $p \rightarrow \overline{\nu} K^+$, 40% for $p \rightarrow l^+ K^0$ (l = e, μ)
- TDR should also include a first, simplified, **justification** (not quite demonstration) of systematic uncertainty assumptions on efficiency/background for key modes
  - Initial goal: systematic uncertainties have "little" effect on τ/B sensitivities (eg, **<20-50% change?**)