XVII International Conference on Topics in Astroparticle and Underground Physics

Kaon Quenching Studies to Improve JUNO‘s Sensitivity to Proton Decay

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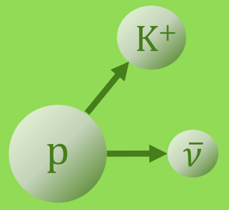
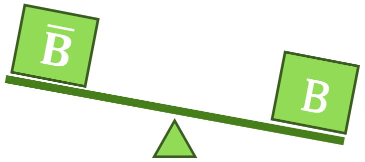


Why do we search for a proton decay?



Baryogenesis under the Sakharov conditions:

- **Baryon number B violation**
- C-symmetry and CP-symmetry violation
- Thermodynamic nonequilibrium

Standard model:
Effectively conserves B

Grand Unified Theories (GUTs):

- Conversion reactions between quarks and leptons become possible
- Gauge coupling unification scale typically at the order of 10^{15} GeV

Test GUT predictions via nucleon decay search

$$\mathbf{p \rightarrow e^{+} + \pi^{0}}$$

- Favored by non-SUSY GUTs
- Current best limit $\tau(p \rightarrow e^{+}\pi^{0}) > 2.4 \times 10^{34}$ yr with 90 % C.L. from Super-Kamiokande

A. Takenaka et al., Phys. Rev. D ***102****, 112011*

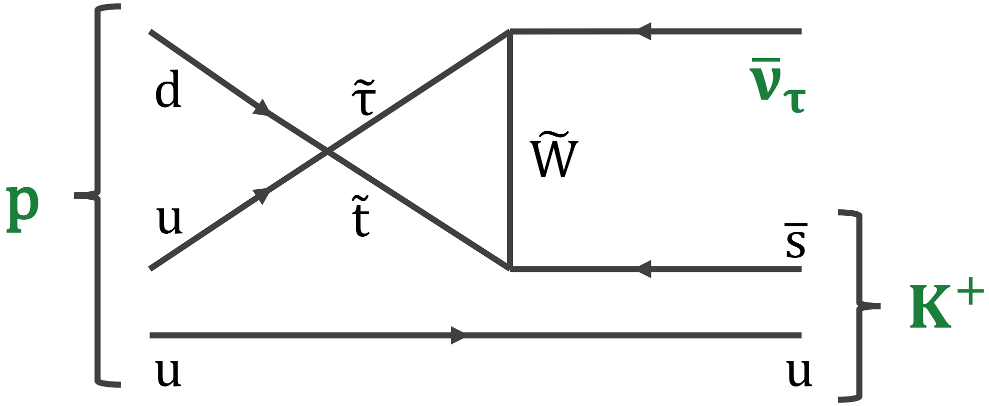
$$\mathbf{p \rightarrow K^{+} + \bar{\nu}}$$

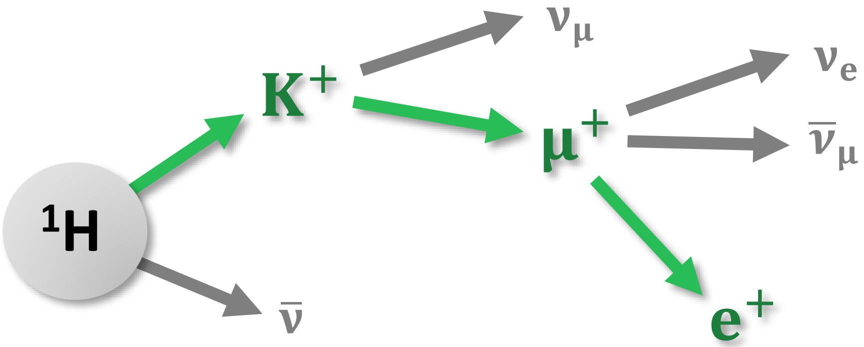
- Favored by SUSY GUTs
- Current best limit $\tau(p \rightarrow K^{+}\bar{\nu}) > 5.9 \times 10^{33}$ yr with 90 % C.L. from Super-Kamiokande

K. Abe et al., Phys. Rev. D ***90****, 072005*

Which proton decay are we searching for?

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





Current best limit from Super-Kamiokande:

$\tau(p \rightarrow K^{+}\overline{\nu}) > 5.9 \times 10^{33}$ yr with 90 % C.L.

K. Abe et al., Phys. Rev. D ***90****, 072005*

- The kaon is emitted at energies below the Cerenkov threshold

➡ Invisible in a water Cerenkov detector

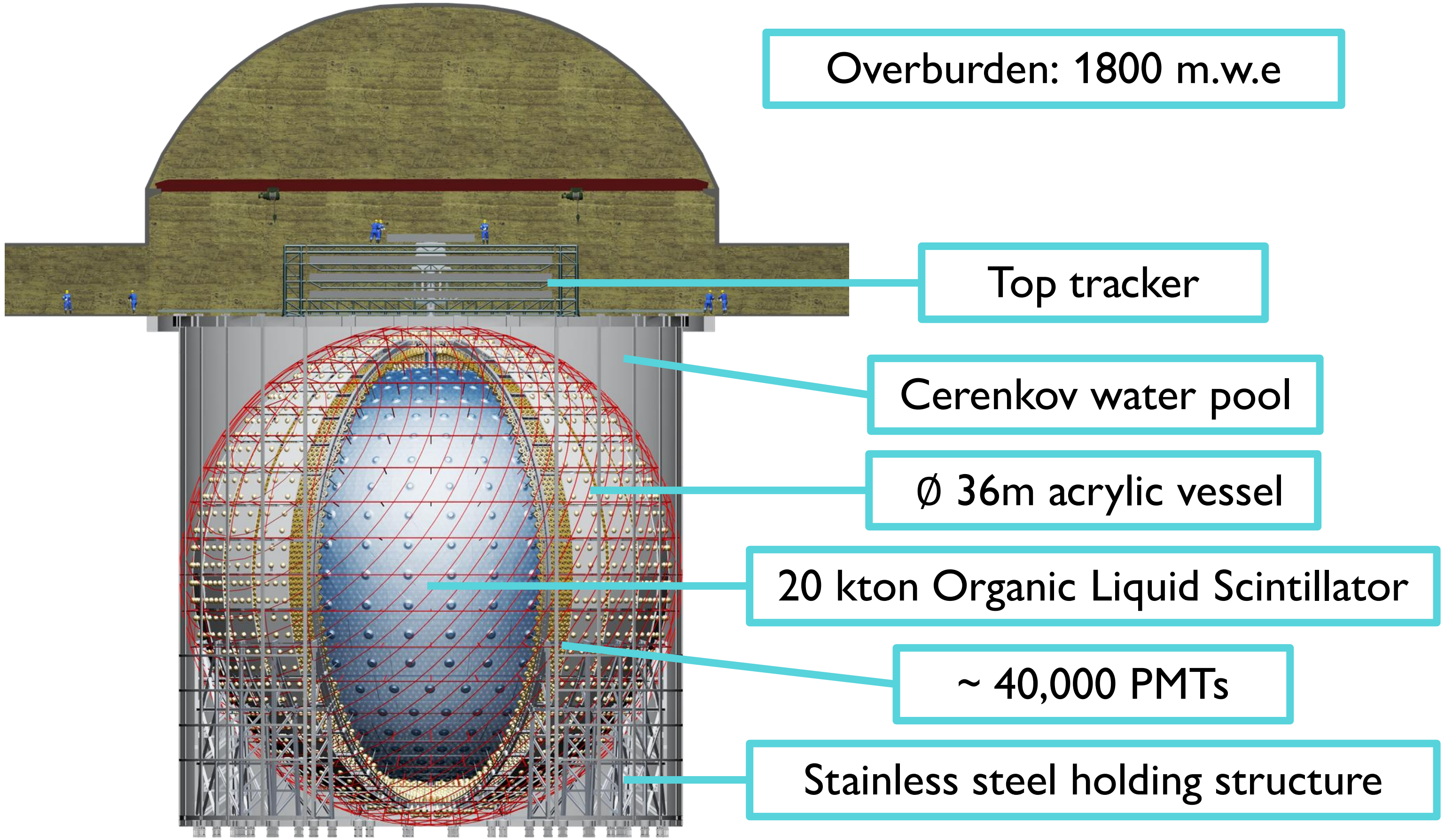
  ➡ Event selection via the kaon daughters and gamma tagging of nuclear deexcitations.

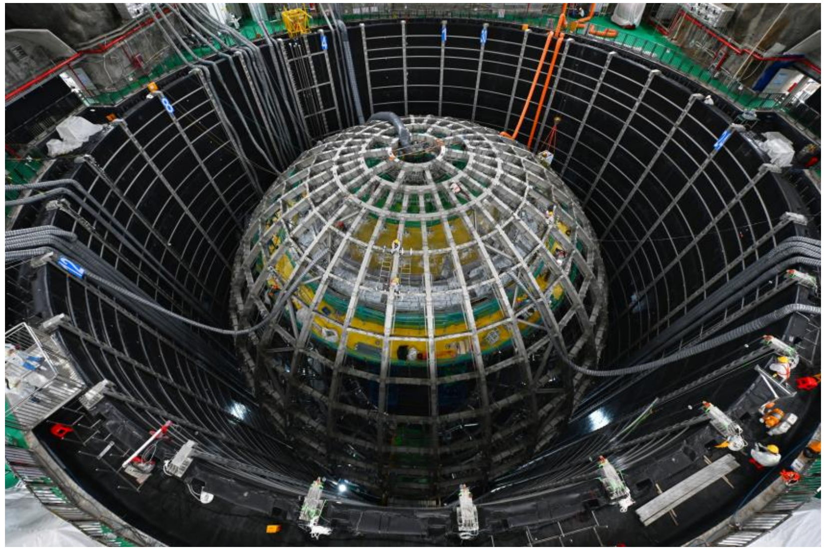
➡ Visible in liquid scintillator

With its large target mass and long runtime, the JUNO experiment is in a great position to search for this decay.

What is JUNO?

Jiangmen Undergound Neutrino Observatory

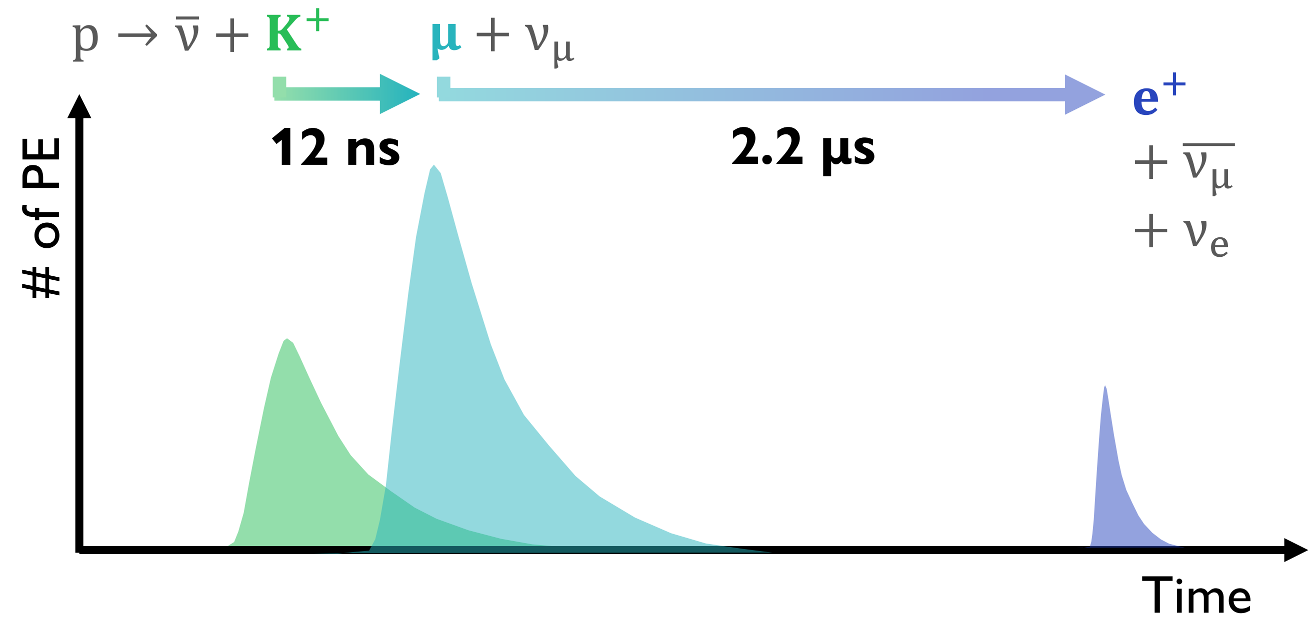




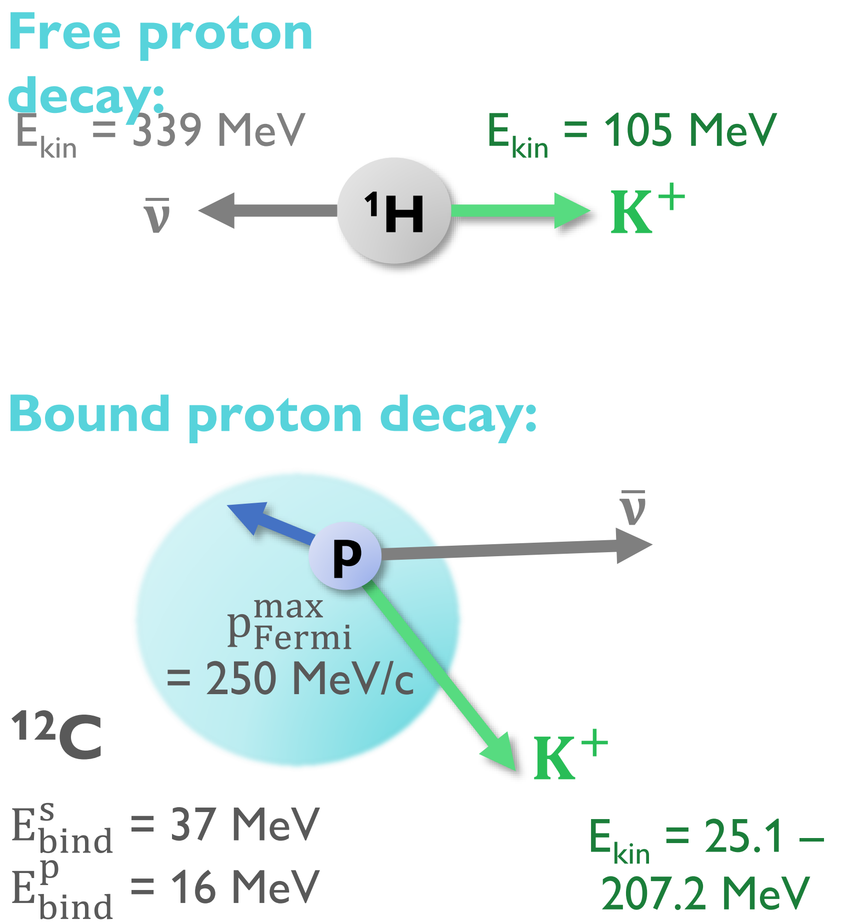
The physics program also includes:

- Determination of the neutrino mass ordering
- High precision oscillation para-meters
- Diffuse supernova neutrino background
- Studies on solar, atmospheric, supernova, geo- and reactor-neutrinos

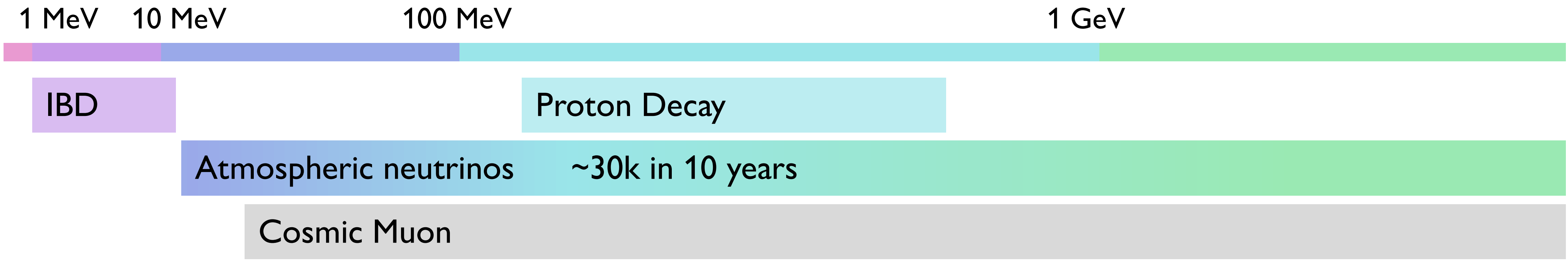
What is the proton decay signal in JUNO?



Well-defined threefold event structure with known emission timing and particle energies!



What are the backgrounds to proton decay?



Cosmic muons:

- Exclude 99 % of cosmic muon events with VETO systems

➡ Require a triple coincidence among the visible energy and volume selection for last 1 %

Atmospheric neutrino events:

- Possible interactions: CCQE, NCES, pion and kaon production
- CCQE and NCES produce single pulses
  ➡ excluded by requiring triple event structure
- Pion production results in an approximate single pulse
  ➡ energetic neutron production could mimic double peak
  ➡ exclude large numbers of neutron capture events
- Kaon production leads to a double-peak structure
  ➡ very unlikely in relevant energy range

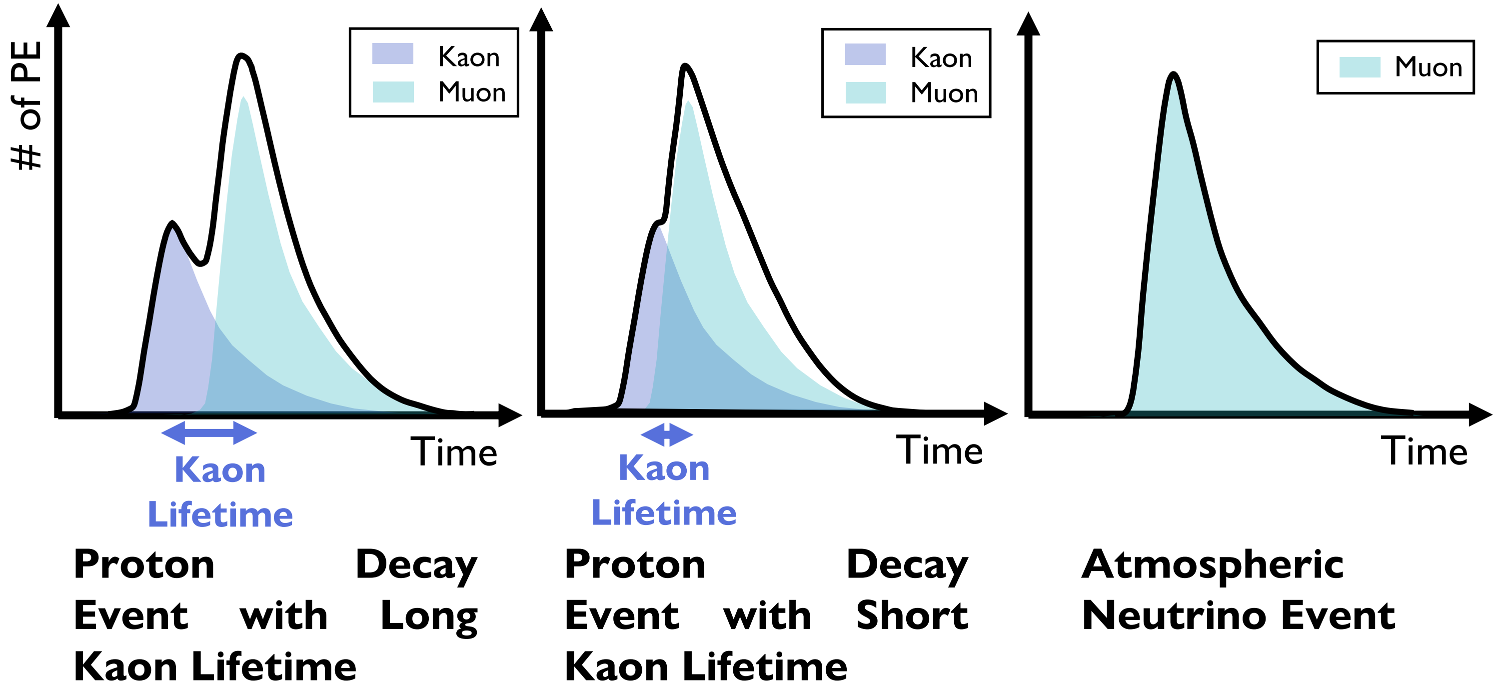
How are events in JUNO selected?

Basic event selection:

- Visible energy cut
- Time window for VETO system
- Volume selection

Other:

- One/two Michel electron(s)
- Tagged neutron number
- Distances from decay position



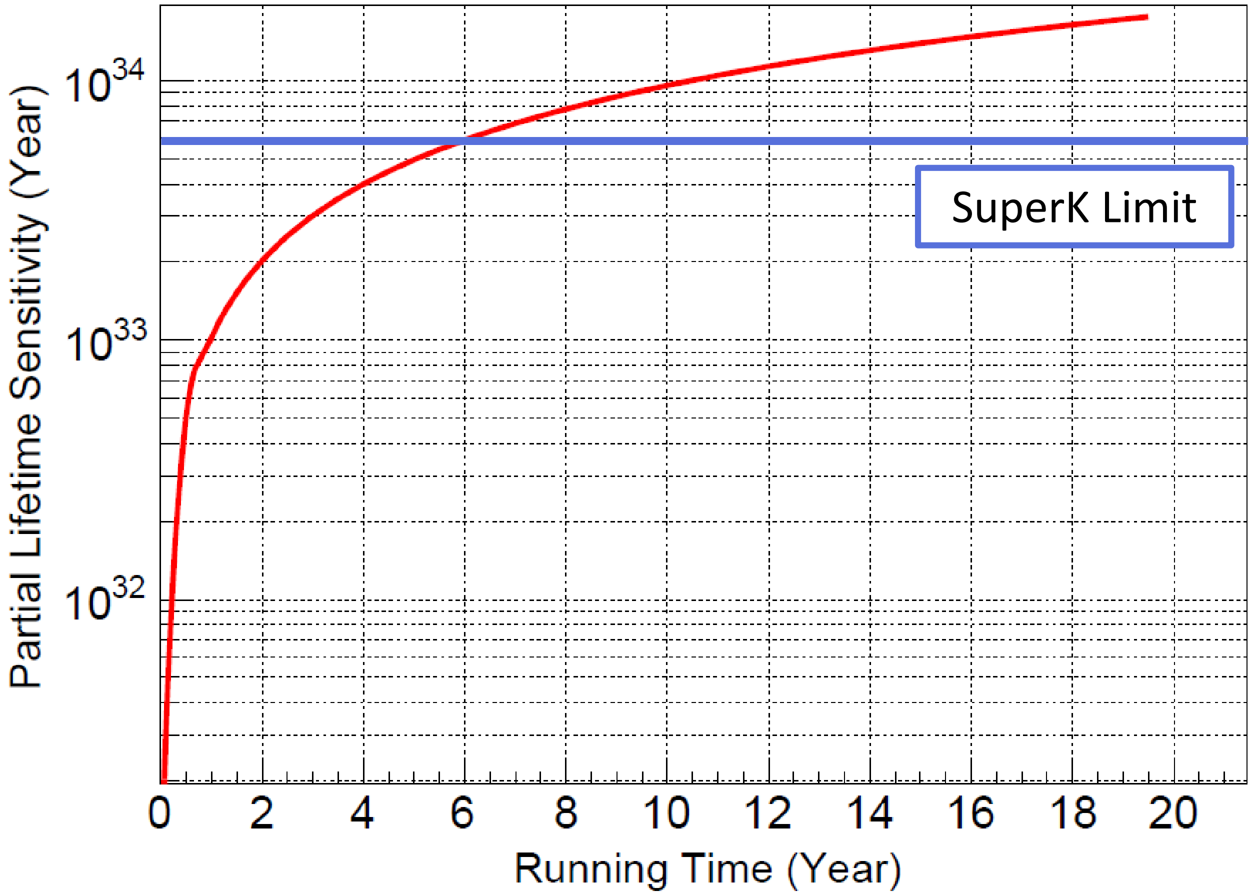
Multi-pulse:

- Correlated time difference
- ➡ Fit with a double-peak and a single-peak model
- Ratio of the obtained χ^2
- Reconstructed energy of the double-peak components

What is JUNO's sensitivity currently?

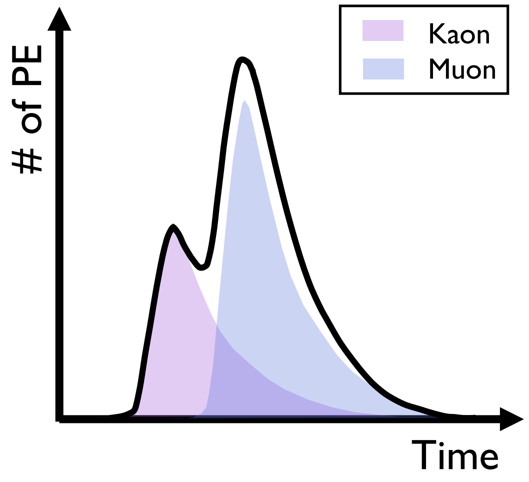
- The expected detection efficiency is 36.9 % with a background level of 0.2 in ten years of data taking.
- For no observed decays and an exposure of 200 kton • years, JUNO's estimated sensitivity is 9.6×10^{33} years at 90 % C.L.

More information in
The JUNO Collaboration (2023)
Juno Sensitivity on Proton Decay p2Kv Searches



How does quenching influence the signal?

The proton decay event selection relies strongly on the shape of the kaon-daughter signal, including the reconstructed energies of both particles.



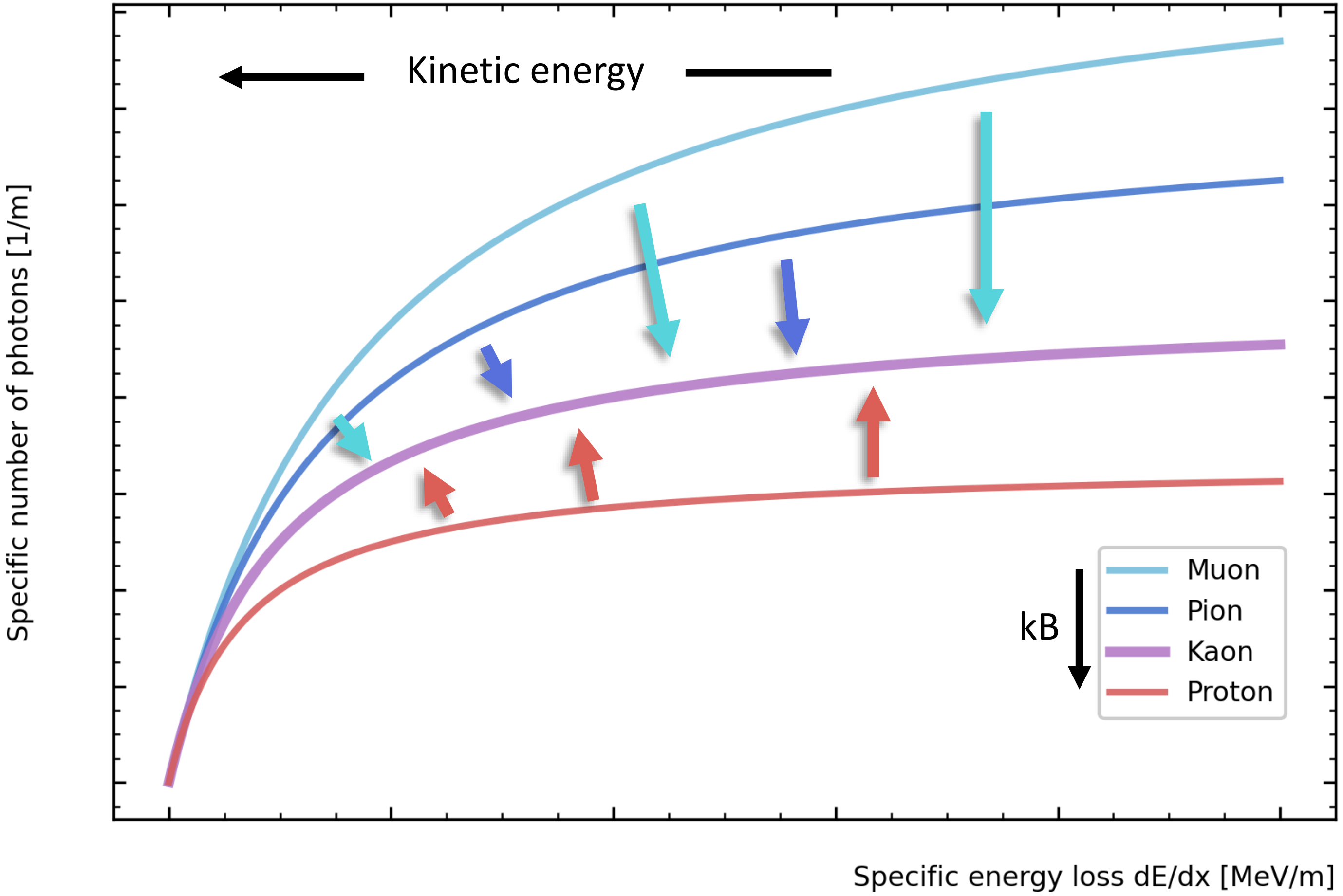
Birks‘ law:

$$\frac{dY}{dx} = LY \cdot \frac{dE/dx}{1 + kB \cdot dE/dx}$$

Relates the deposited energy to the emitted light yield via the Birks‘ constant kB and a prefactor LY.

Quenching:
Different particle types with the same specific energy deposition produce **different amounts of scintillation light** due to ionization effects. The **Birks’ constant kB** accounts for the quenching probability and the local density of ionized molecules and needs to be determined **experimentally**.

How to measure kaon quenching?

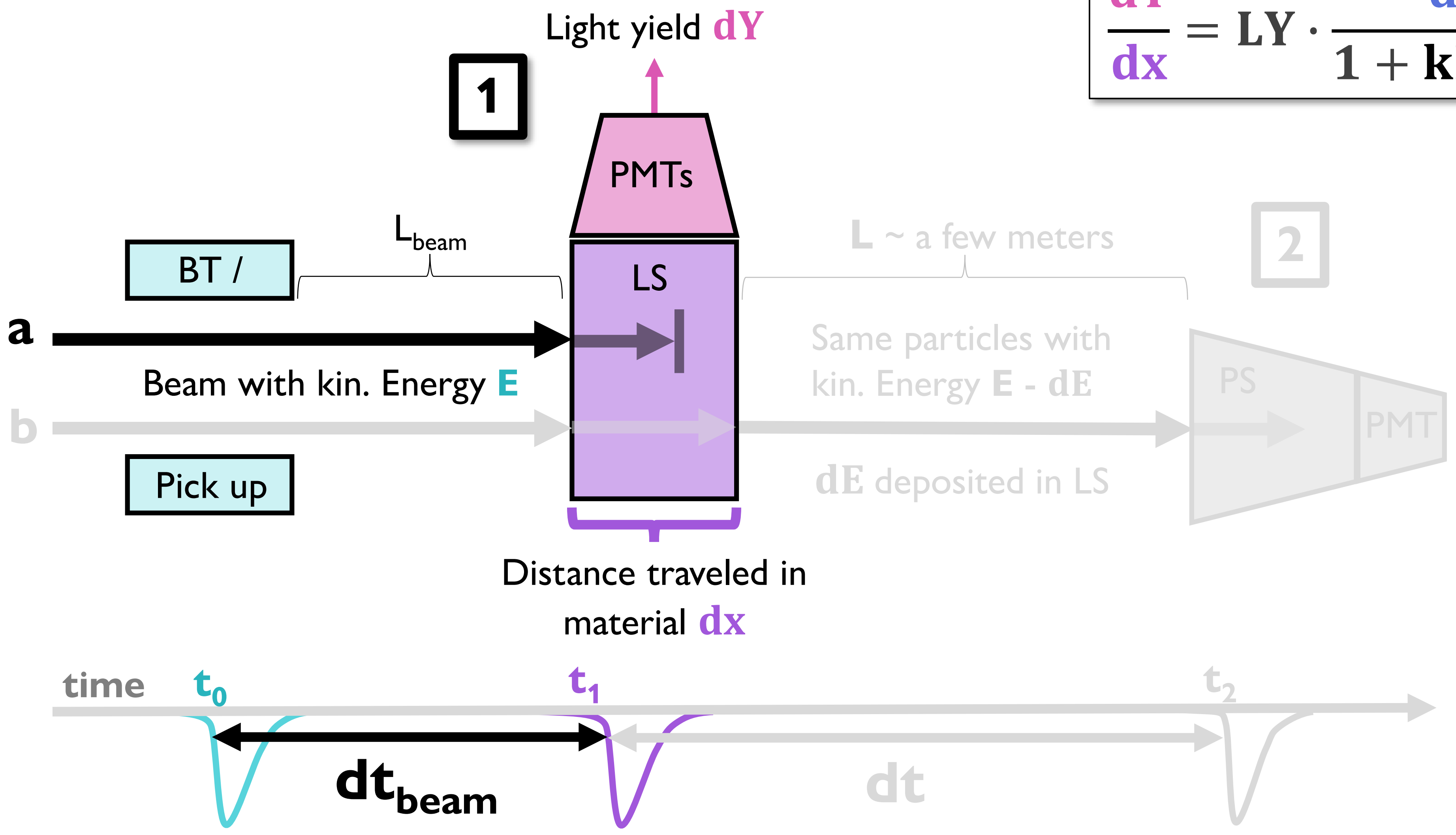


Illustrational plot with exaggerated Birks‘ factors for the different particle species

- Measure light output and deposited energy independently
  ➡ The measured results then correspond to the integral of the Birks‘ curve.
- Reconstruct Birks‘ curve by using different inertial energies and energy depositions
- Too short kaon lifetime for beams
  ➡ Use muon, pion and proton beams
- Extrapolate kaon light emission behavior

What is the working principle of UniKaon?

$$\frac{dY}{dx} = LY \cdot \frac{dE/dx}{1 + kB \cdot dE/dx}$$



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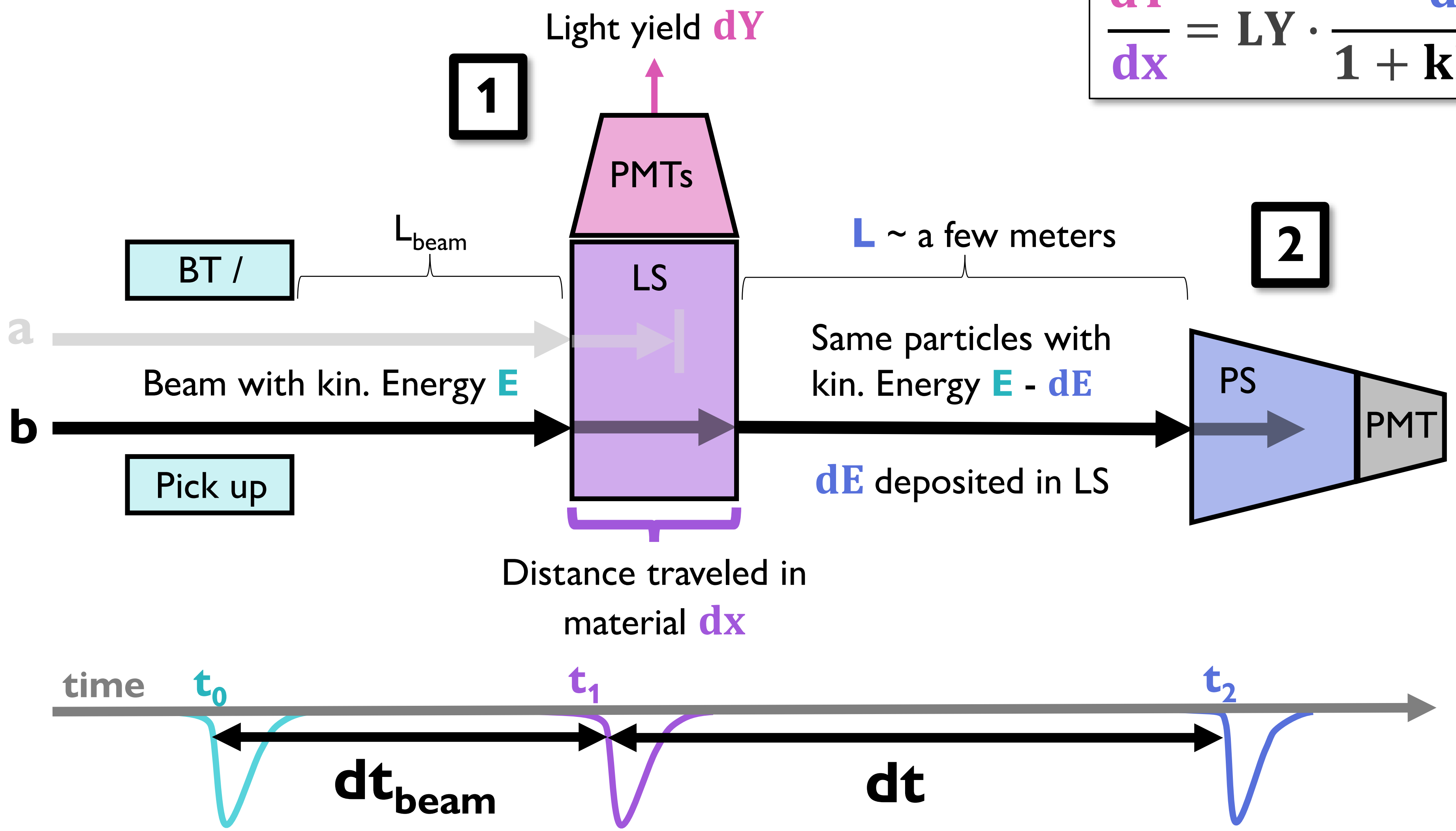
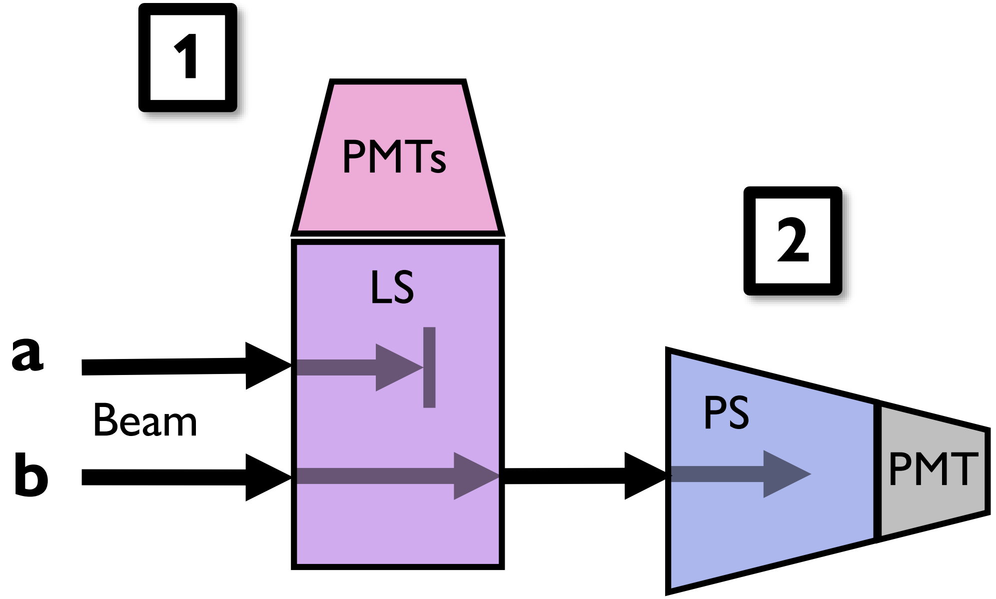


How is the setup designed?

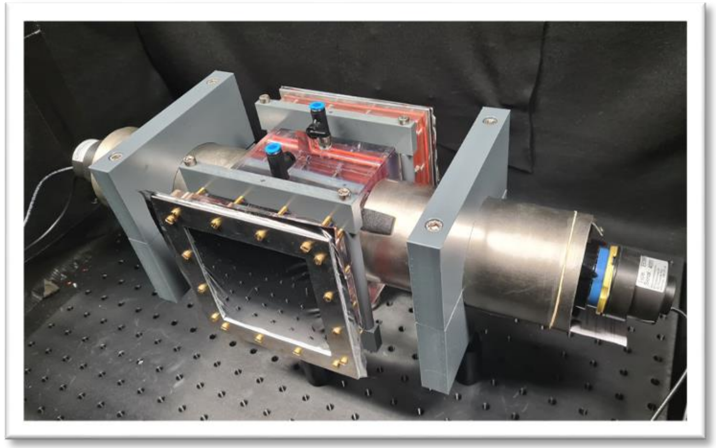


Particle beams:

- Proton beams around 200 MeV
- Muon beams around 25 MeV
- If available: Pion beams around 30 MeV

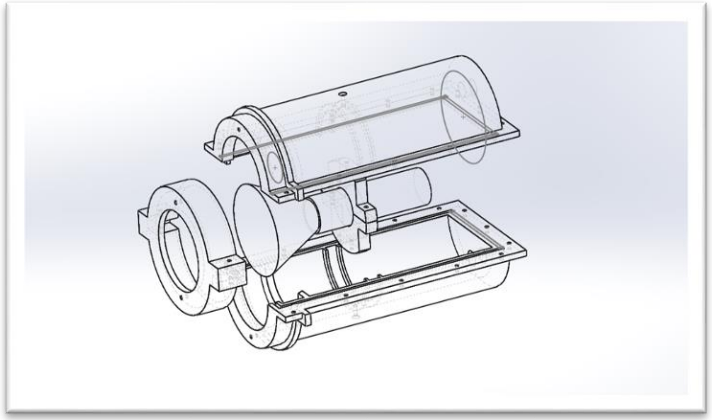
1 LS vessel

- Lengths from 10 cm to 30 cm
- Ultra-thin beam entry windows
- Low gain PMTs



2 ToF detector

- Conic fast-timing plastic scintillator
- Fast-timing PMT
- Lightproof housing
- Ultra-thin beam entry window

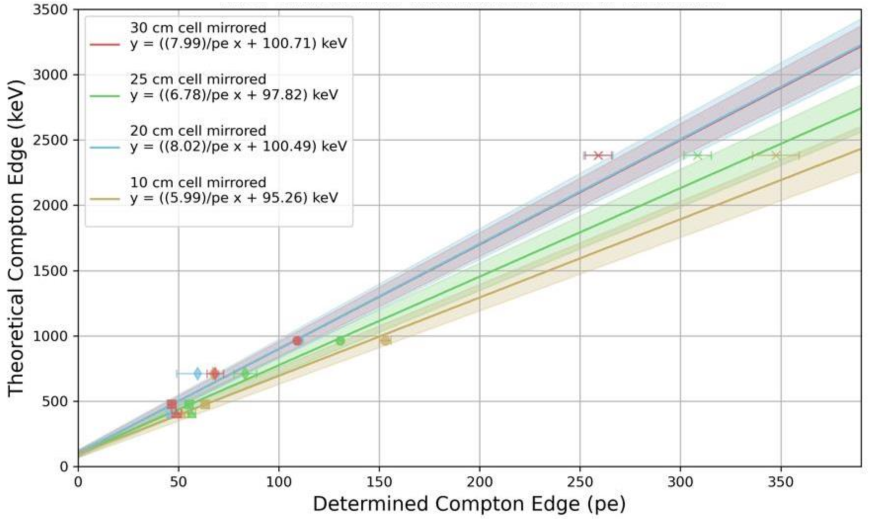


What is the status of UniKaon?

A 20 cm prototype was successfully operated at a neutron beamtime in Legnaro, Italy.

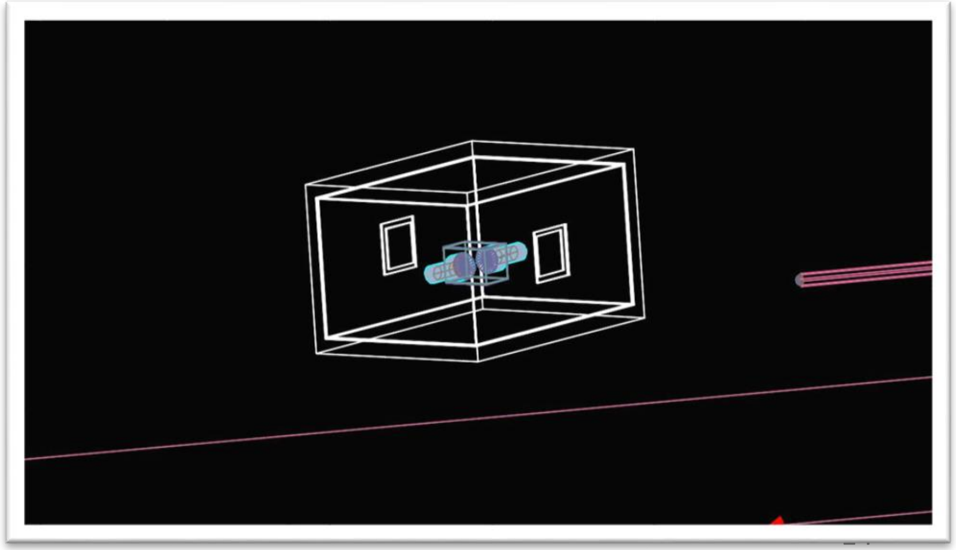
Laboratory:

- New liquid tight vessel construction
- First PMT gain calibration completed
- All liquid scintillator vessels are calibrated with different configurations of applied mirror foil and changing PMT positions as input to the simulation



Simulation:

- First simulation of the prototype under beamtime conditions
- Full light propagation simulation to account for geometry effects in work



What happens next?

JUNO:

- Acrylic vessel and PMT arrays under construction
- First data taking expected in 2024
- Ongoing efforts to enhance event selection for proton decay

Kaon Quenching Influence on Event Selection:

- Ongoing Master thesis on proton decay backgrounds
- Studies on the influence of the kaon quenching on the signal shape in JUNO

UniKaon:

- Ongoing LS detector characterization to study light propagation behavior
- Input results to simulation
- Gain calibration of PMTs at high photon yields
- Proton beamtime expected in winter

Thank you for your attention!