

*XVII International Conference on Topics in Astroparticle and Underground Physics*

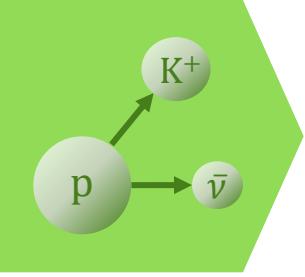
# Kaon Quenching Studies to Improve JUNO's Sensitivity to Proton Decay

ULRIKE FAHRENDHOLZ\* on behalf of the **JUNO collaboration**

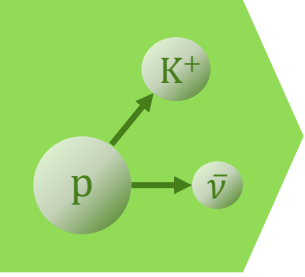
\* Chair for Experimental and Astroparticle Physics E15,  
School of Natural Sciences, TUM  
James-Franck-Str. 1, 85748 Garching, Germany



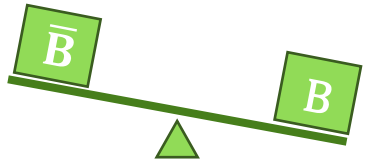
*August 29th 2023  
Neutrino physics and astrophysics 3B*



Why do we search for a proton decay?

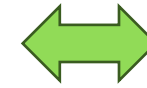


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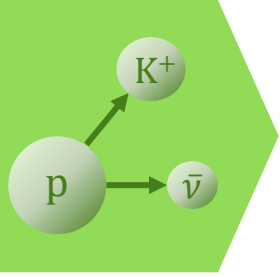
Baryogenesis under the Sakharov conditions:

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



**Standard model:**  
Effectively conserves  $B$

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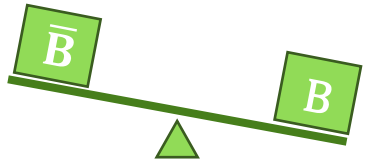


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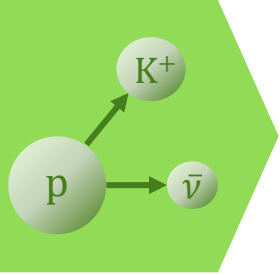
## **Grand Unified Theories (GUTs):**

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



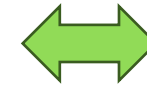
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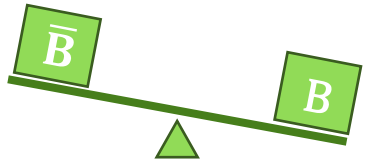


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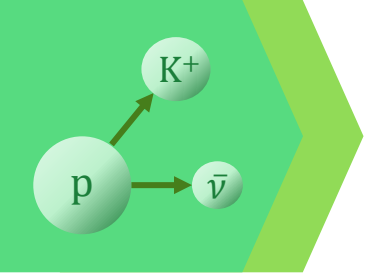
- Favored by non-SUSY GUTs
- Current best limit  $\tau(p \rightarrow e^+ \pi^0) > 2.4 \times 10^{34}$  yr with 90 % C.L. from Super-Kamiokande

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

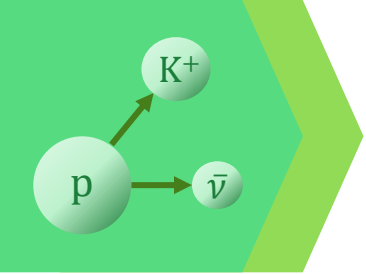


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K. Abe et al., Phys. Rev. D **90**, 072005

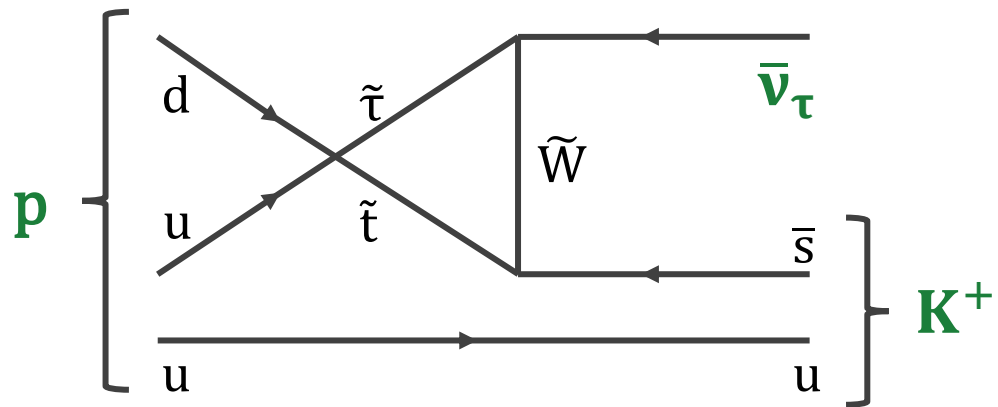


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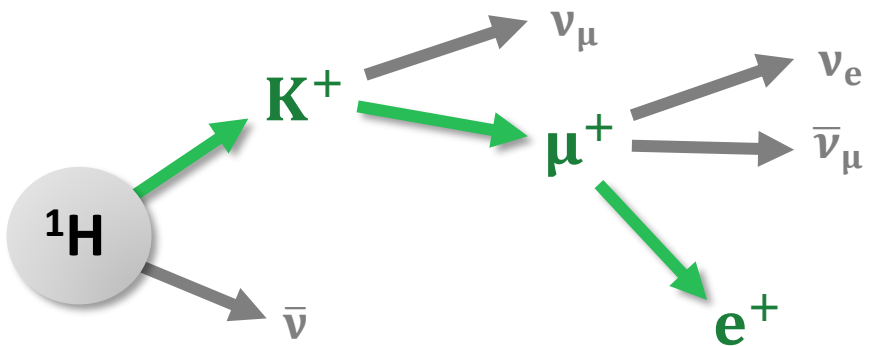
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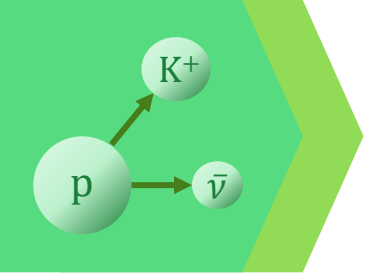


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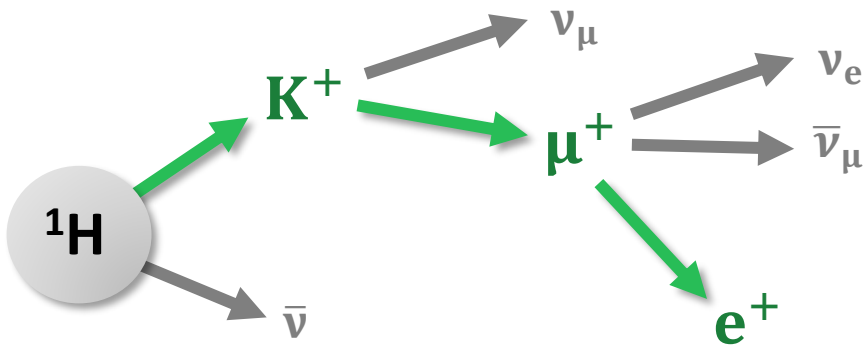
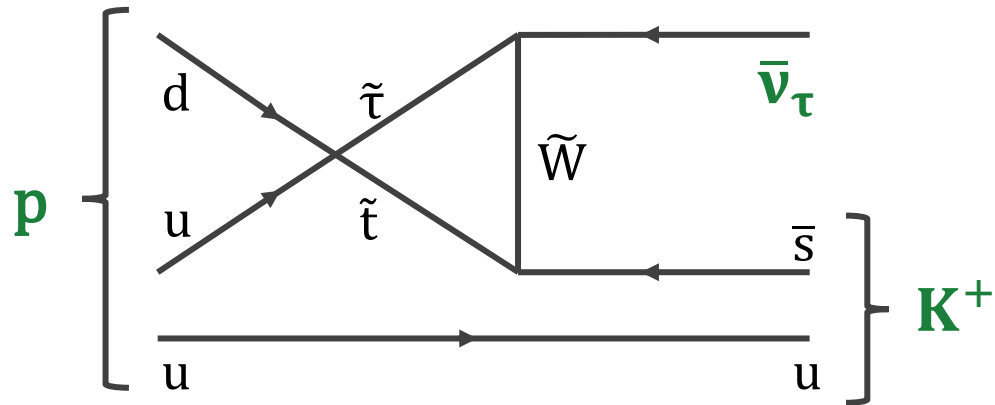
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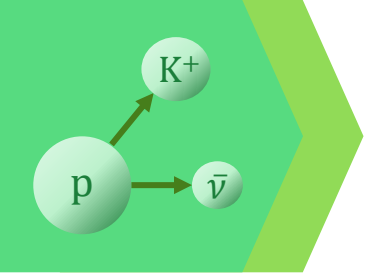
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- The kaon is emitted at energies below the Cerenkov threshold

➡ Invisible in a water Cerenkov detector

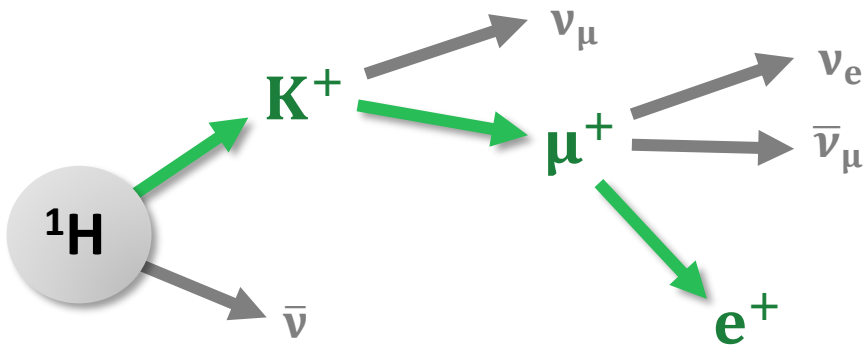
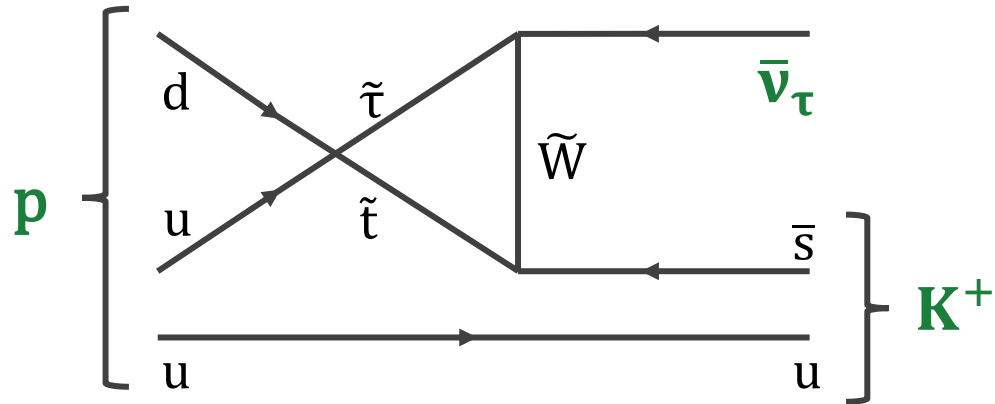
➡ Event selection via the kaon daughters and gamma tagging of nuclear deexcitations.

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

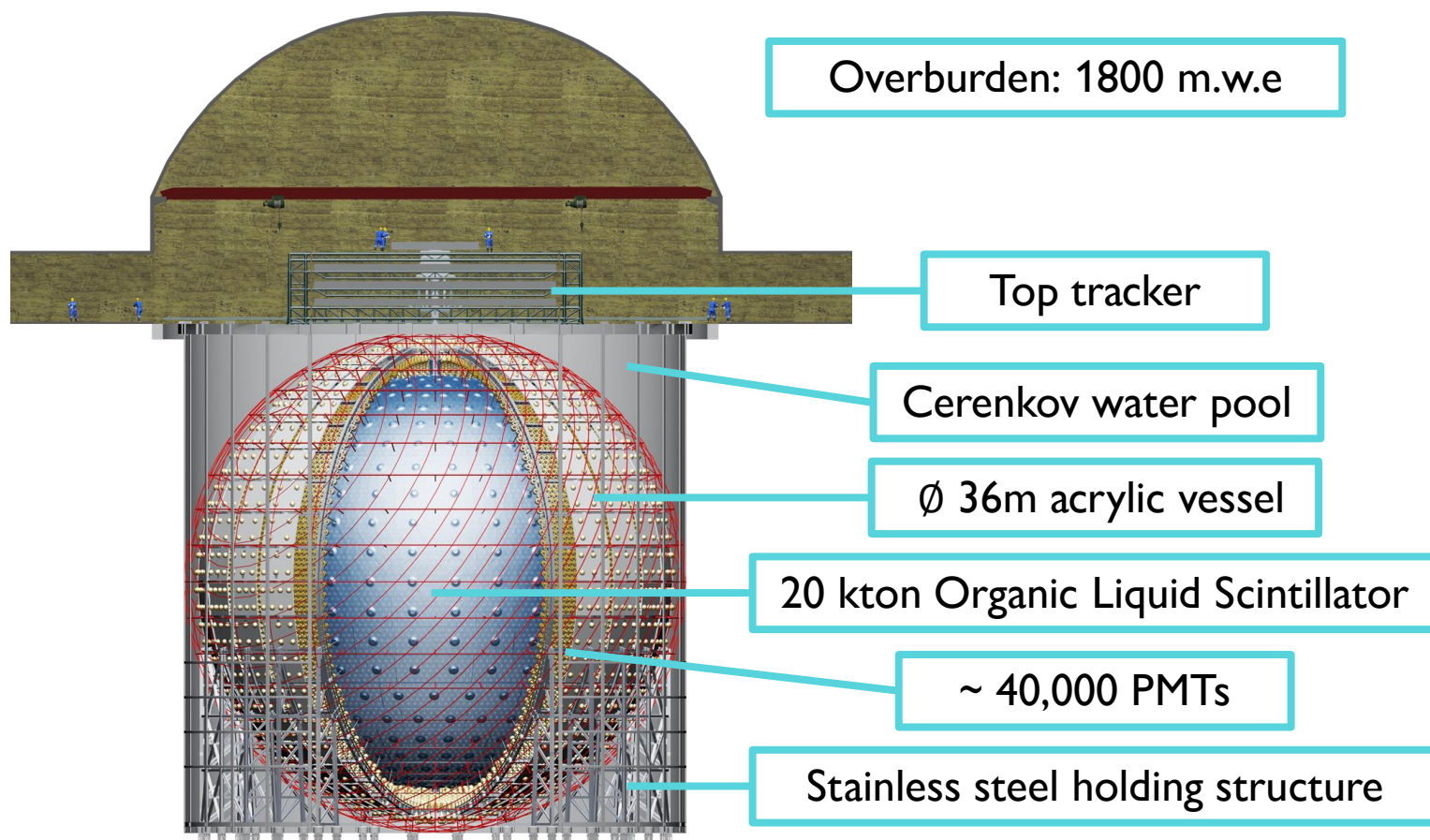


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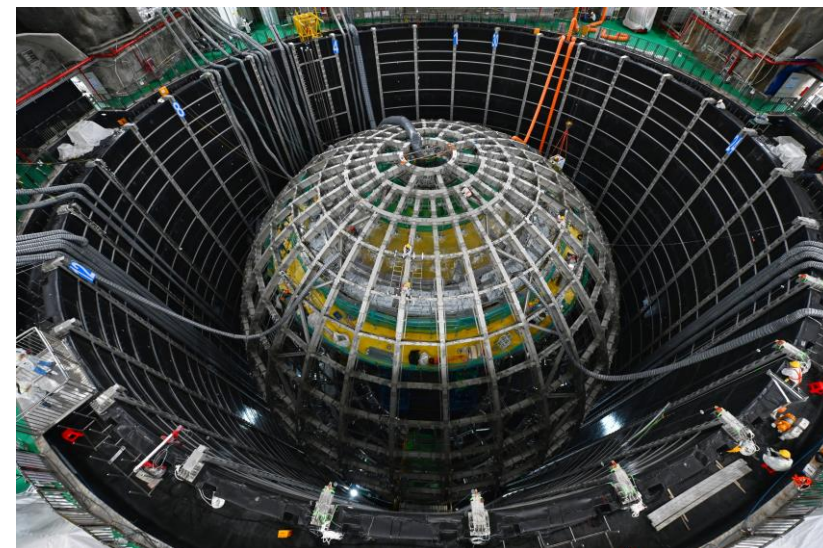
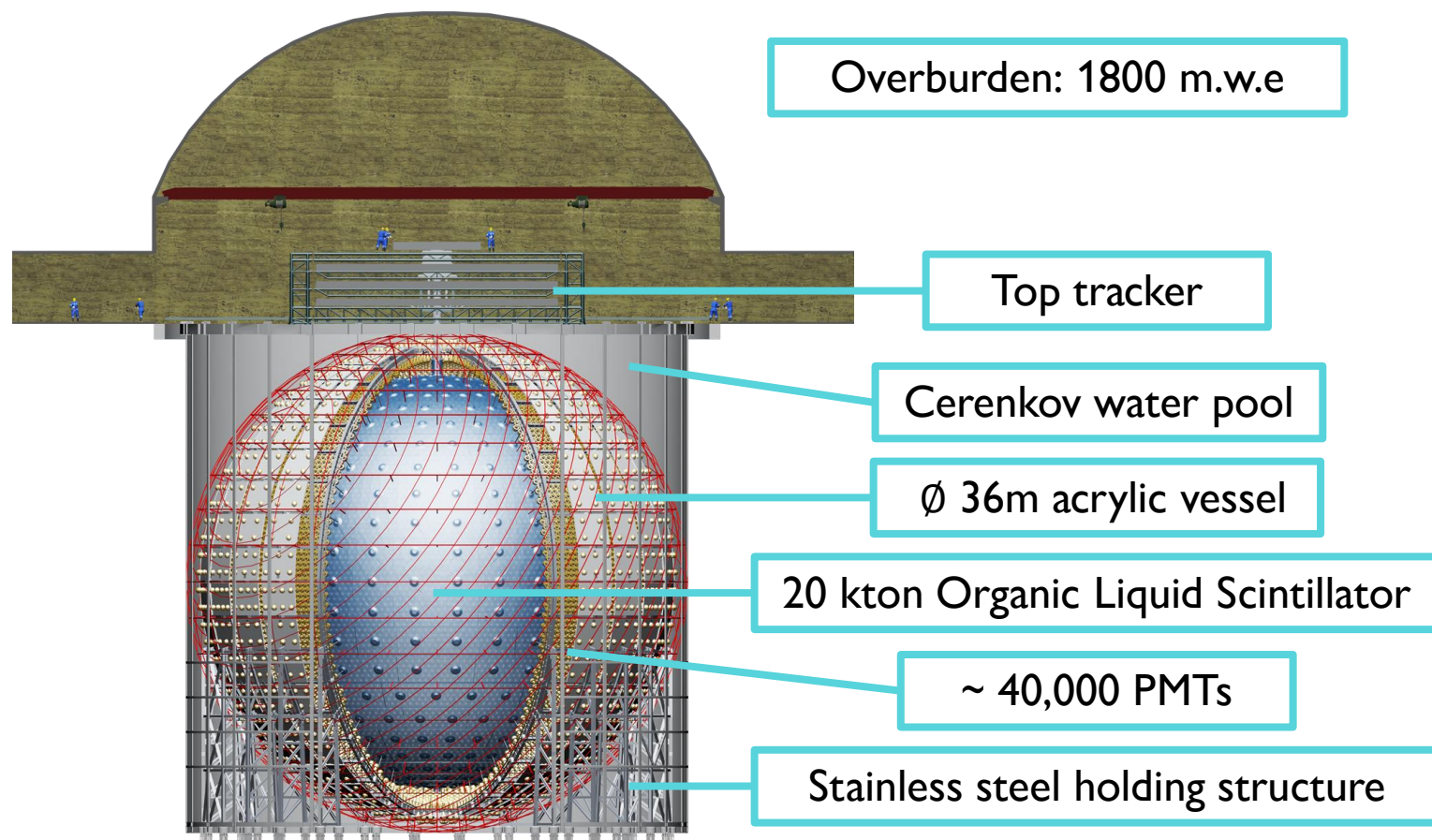
## Jiangmen Underground Neutrino Observatory





# What is JUNO?

## Jiangmen Underground Neutrino Observatory



The physics program also includes:

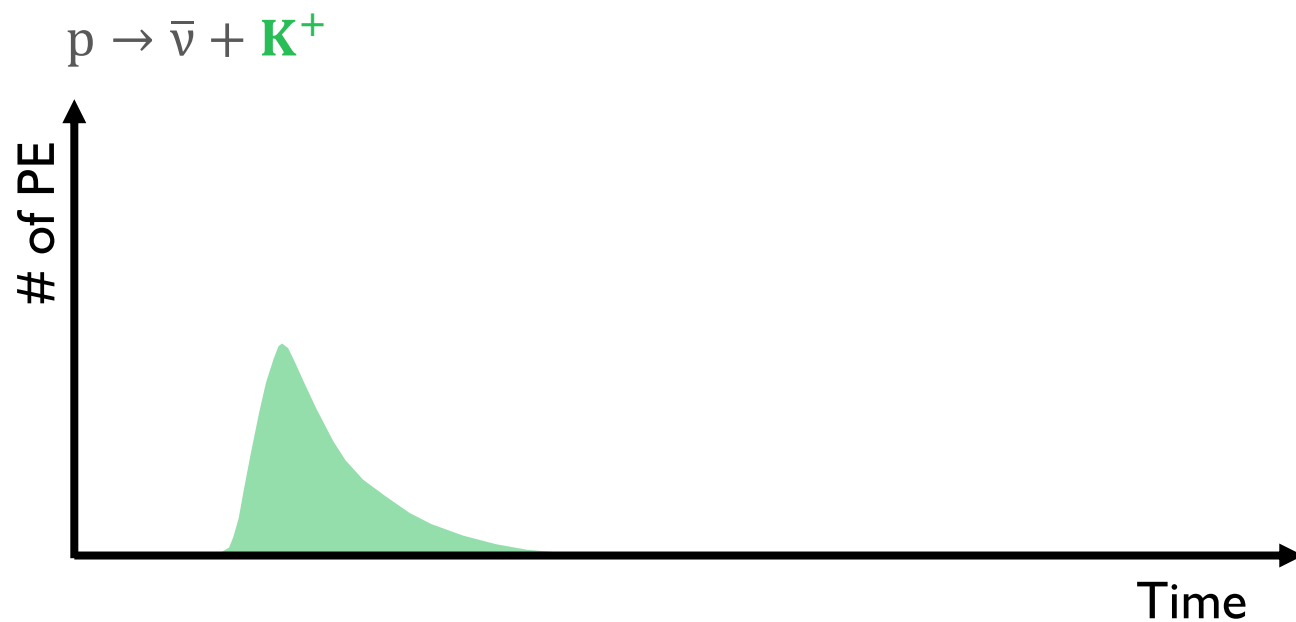
- Determination of the neutrino mass ordering
- High precision oscillation parameters
- Diffuse supernova neutrino background
- Studies on solar, atmospheric, supernova, geo- and reactor-neutrinos



What is the proton decay signal in JUNO?

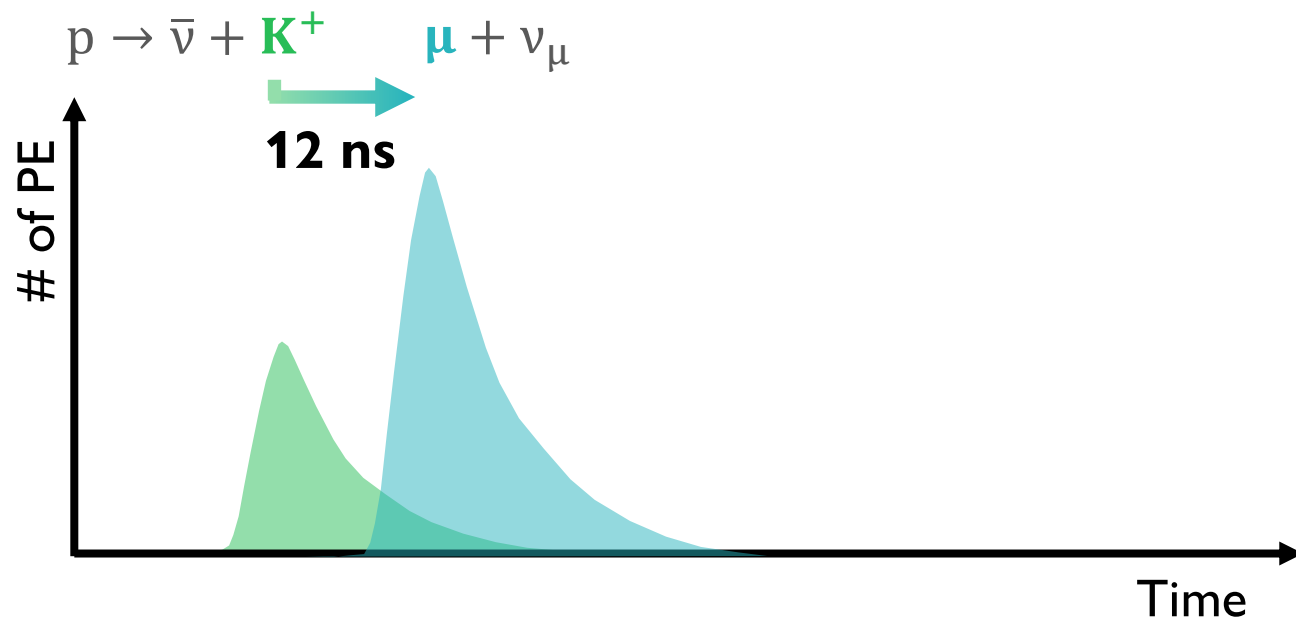


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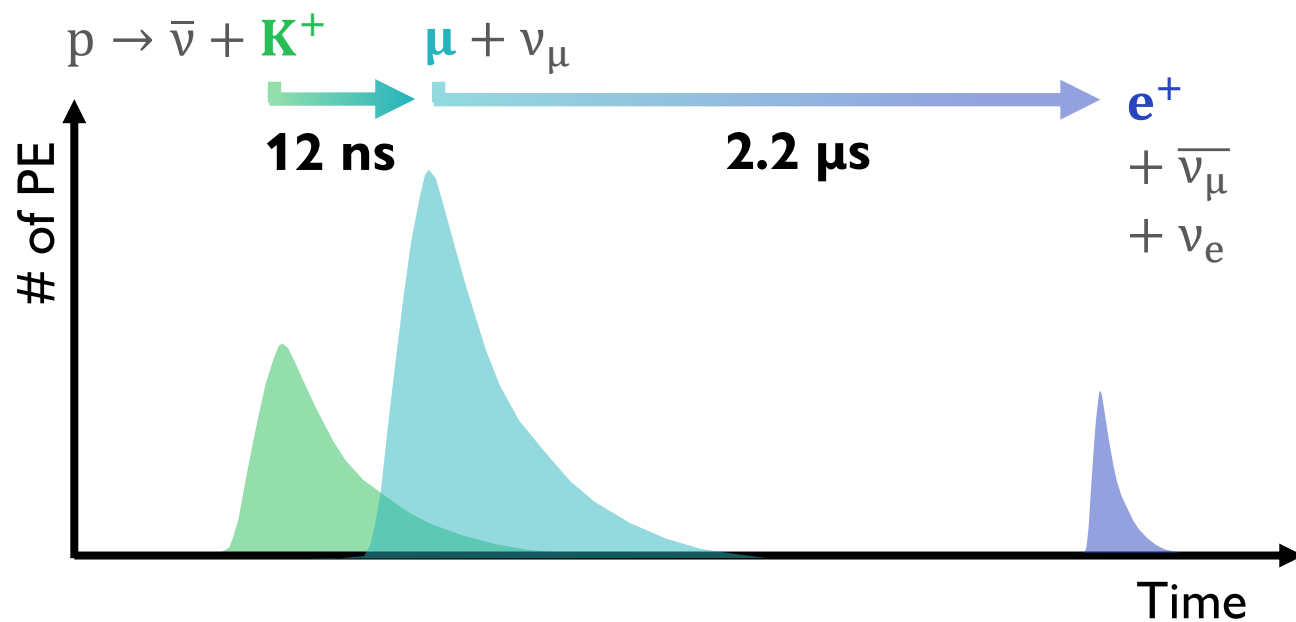


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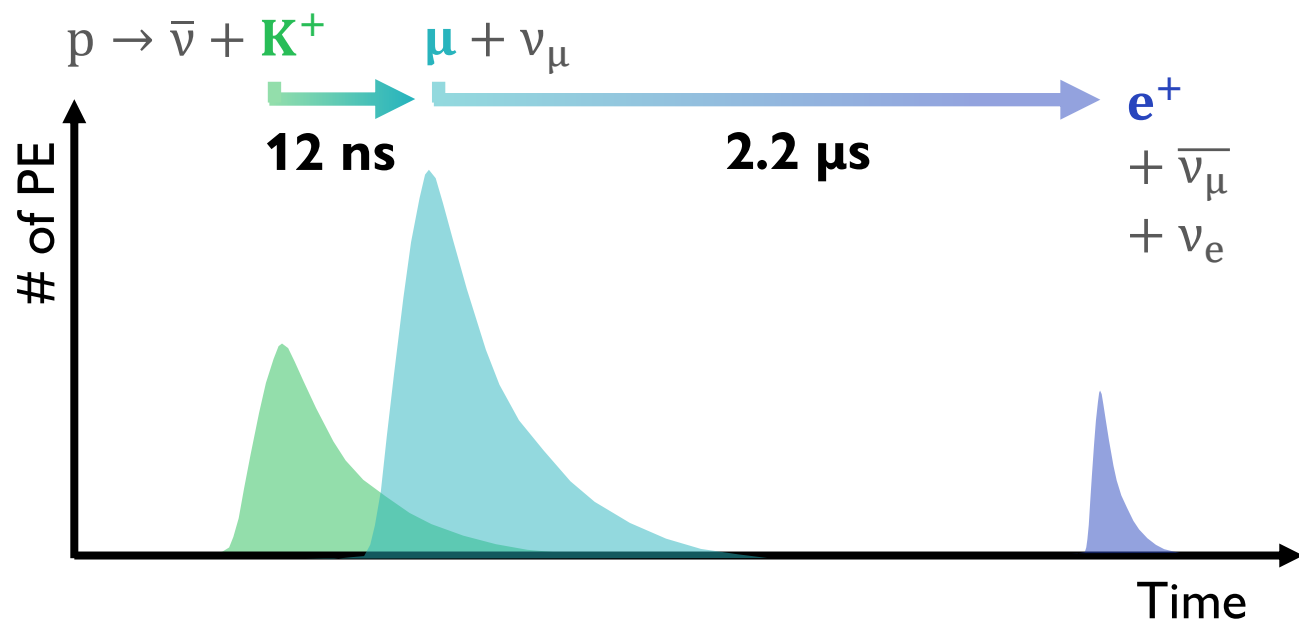


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## Free proton decay:

$$E_{\text{kin}} = 339 \text{ MeV} \quad E_{\text{kin}} = 105 \text{ MeV}$$

$\bar{\nu} \leftarrow {}^1\text{H} \rightarrow K^+$

## Bound proton decay:

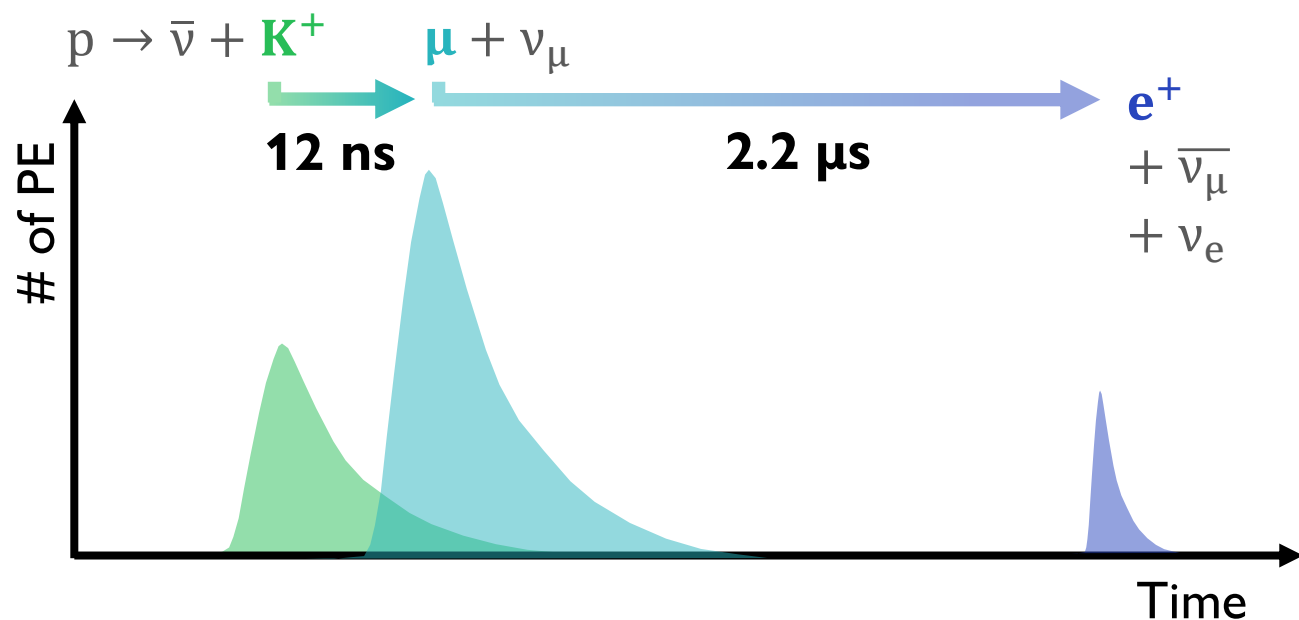
${}^{12}\text{C}$   
 $p_{\text{Fermi}}^{\text{max}} = 250 \text{ MeV}/c$

$E_{\text{bind}}^{\text{s}} = 37 \text{ MeV}$   
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$E_{\text{kin}} = 25.1 - 207.2 \text{ MeV}$



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

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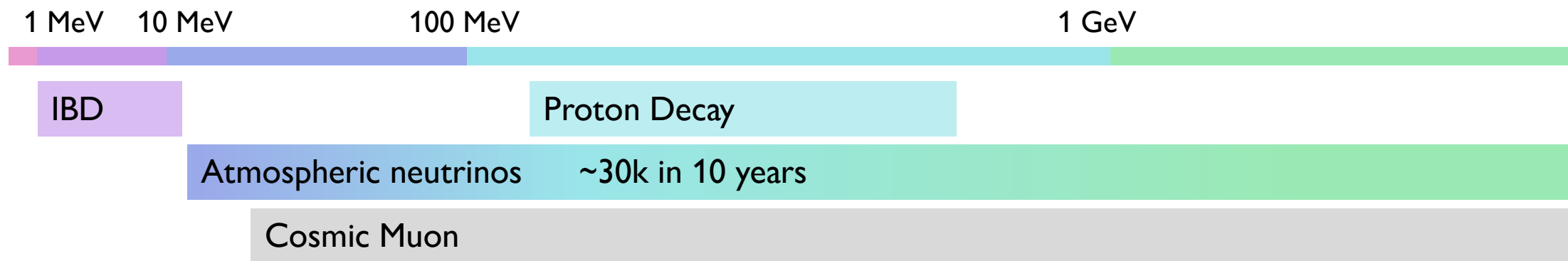
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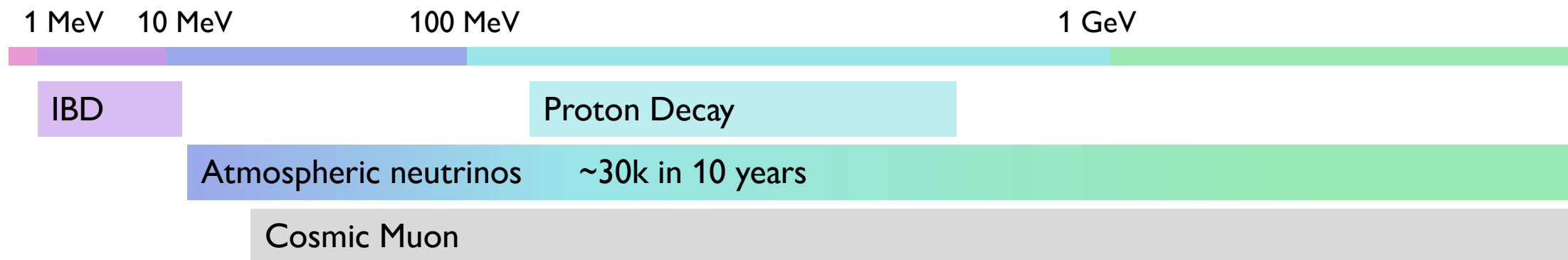


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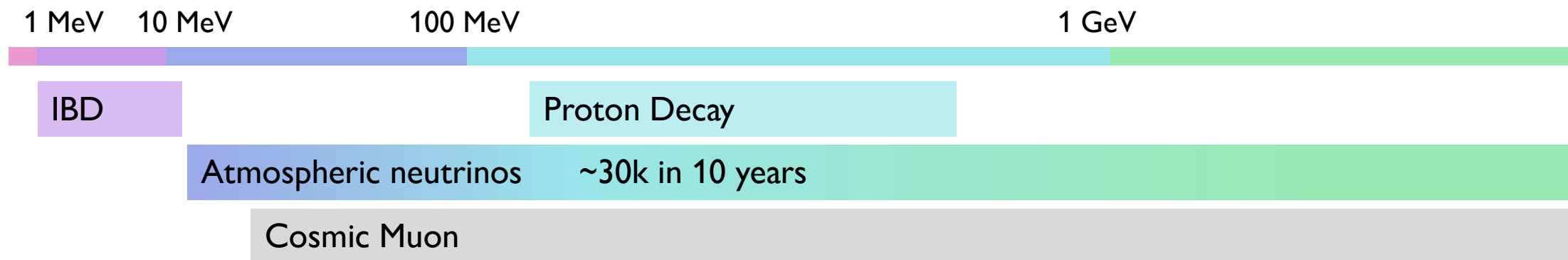


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## Atmospheric neutrino events:

- 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



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## Basic event selection:

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## Other:

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



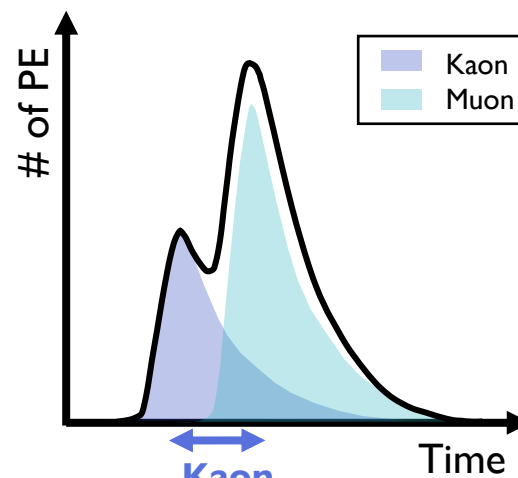
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**Proton Decay Event  
with Long Kaon  
Lifetime**



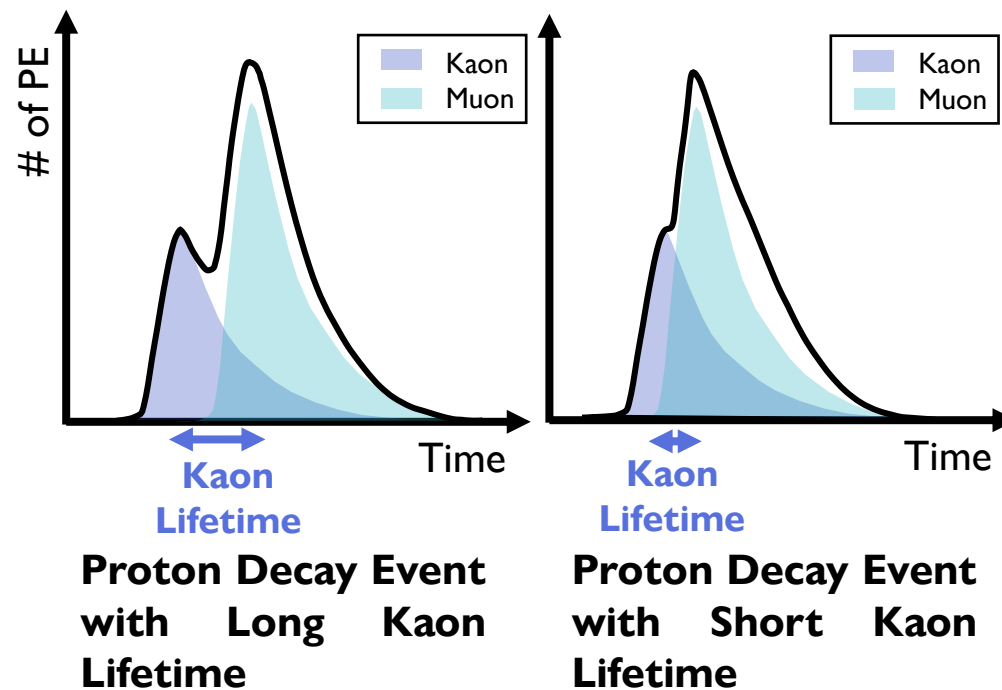
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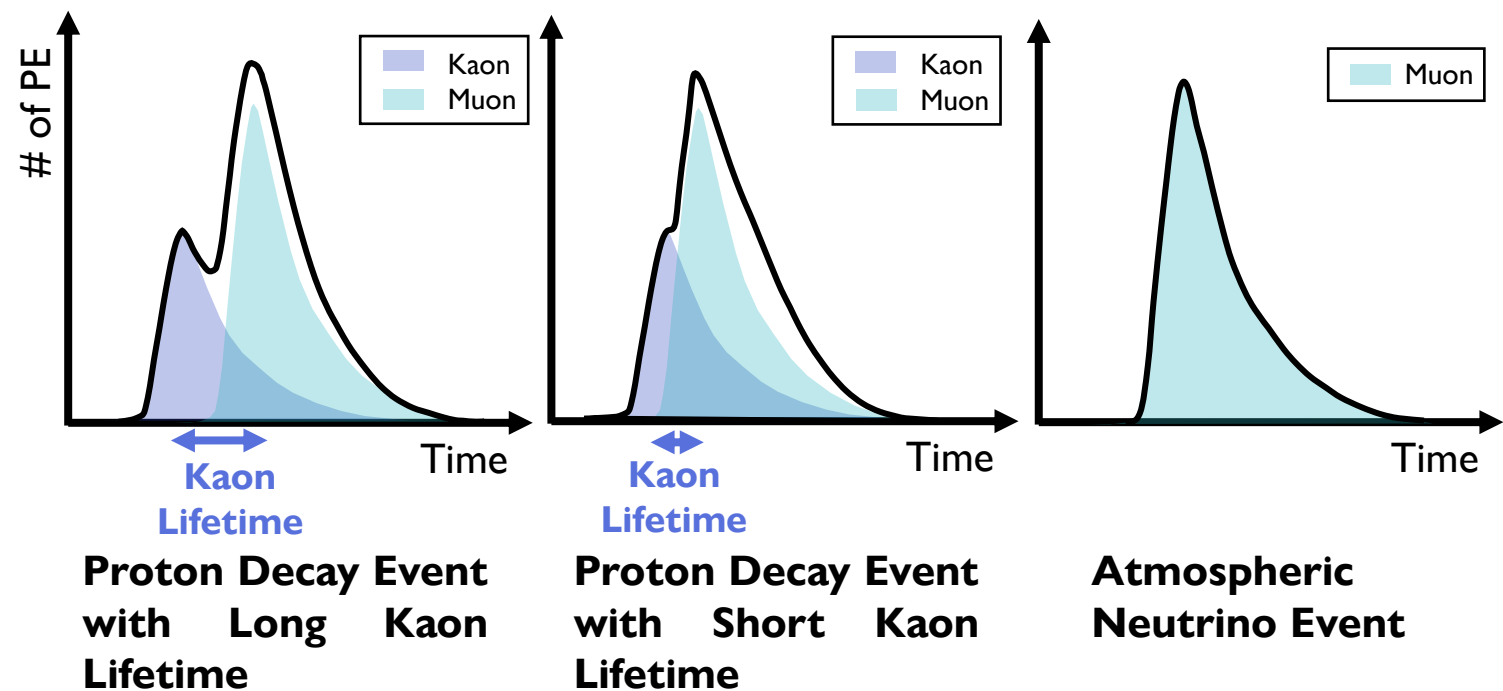
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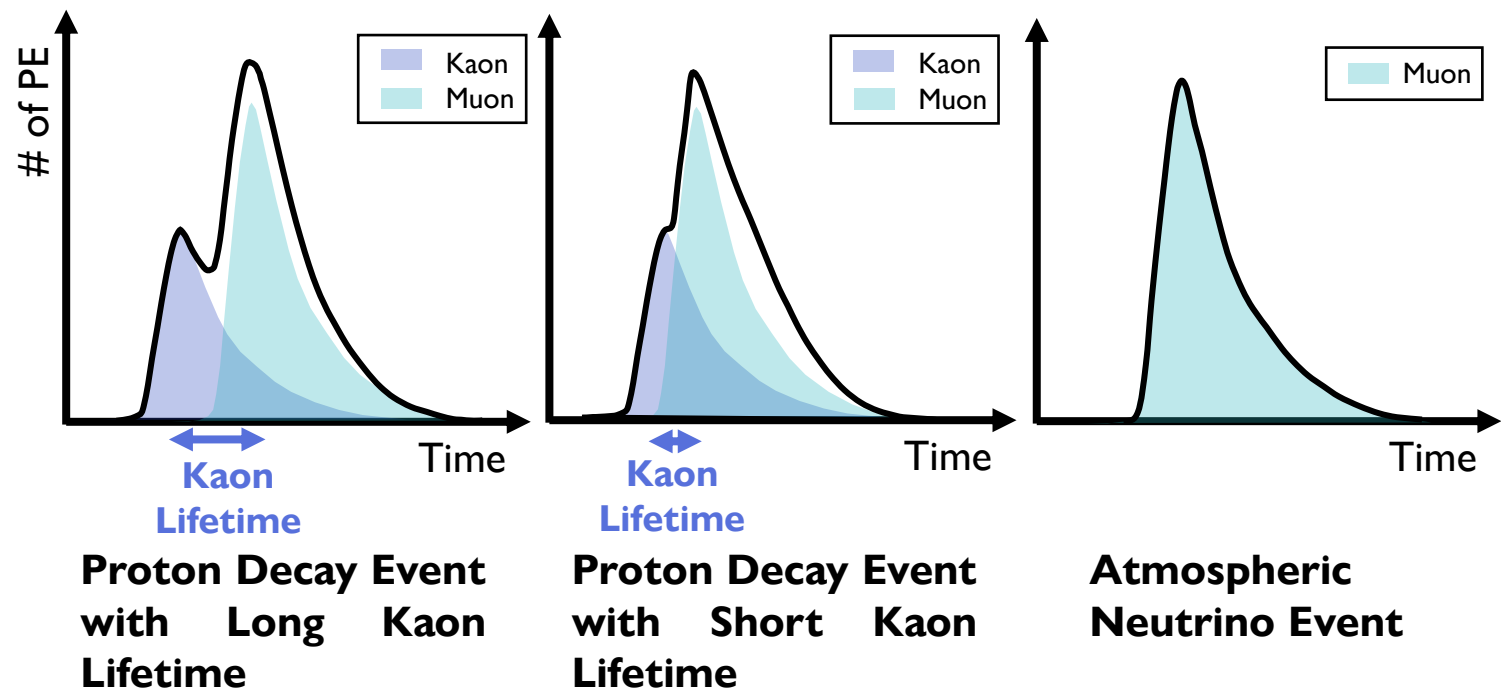
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## Multi-pulse:

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

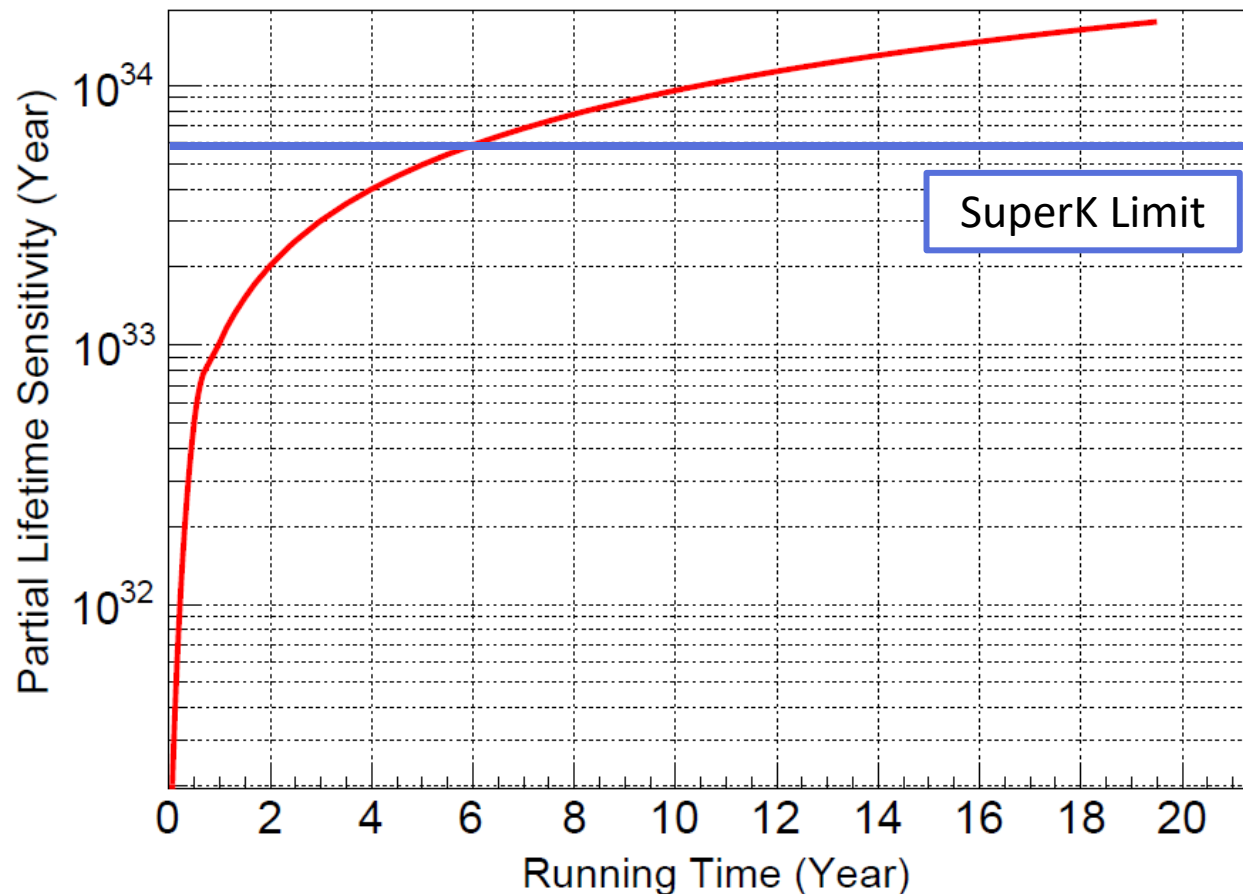


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- The expected detection efficiency is 36.9 % with a background level of 0.2 in ten years of data taking.
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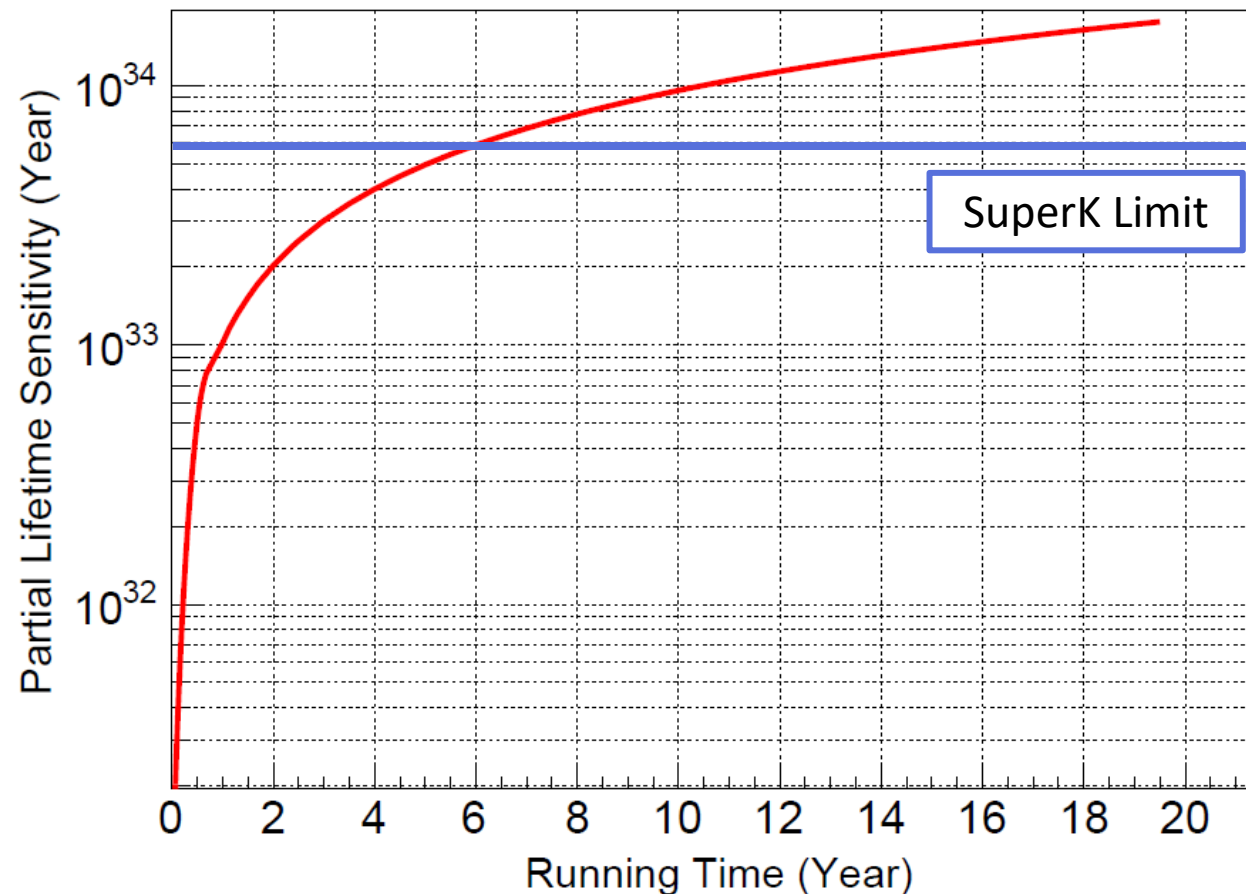
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## More information in

The JUNO Collaboration (2023)  
*Juno Sensitivity on Proton Decay  
 $p2K\nu$  Searches*



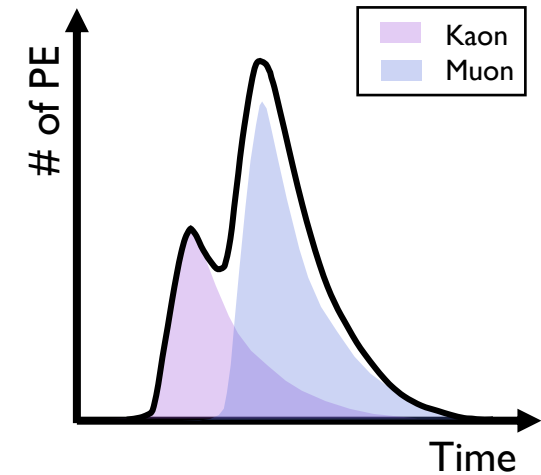


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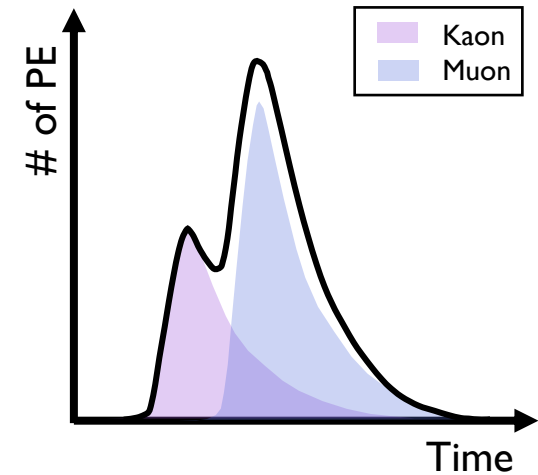
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$$\frac{dY}{dx} = LY \cdot \frac{dE/dx}{1 + kB \cdot dE/dx}$$

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





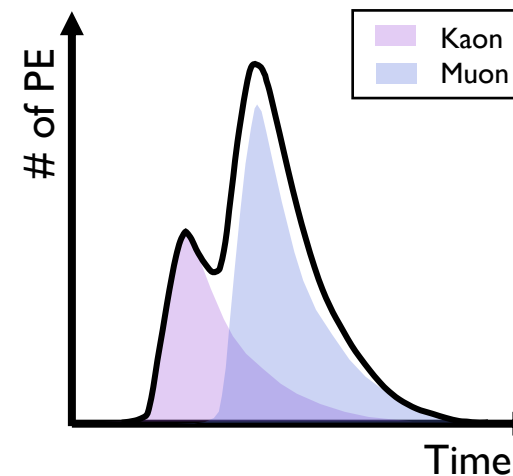
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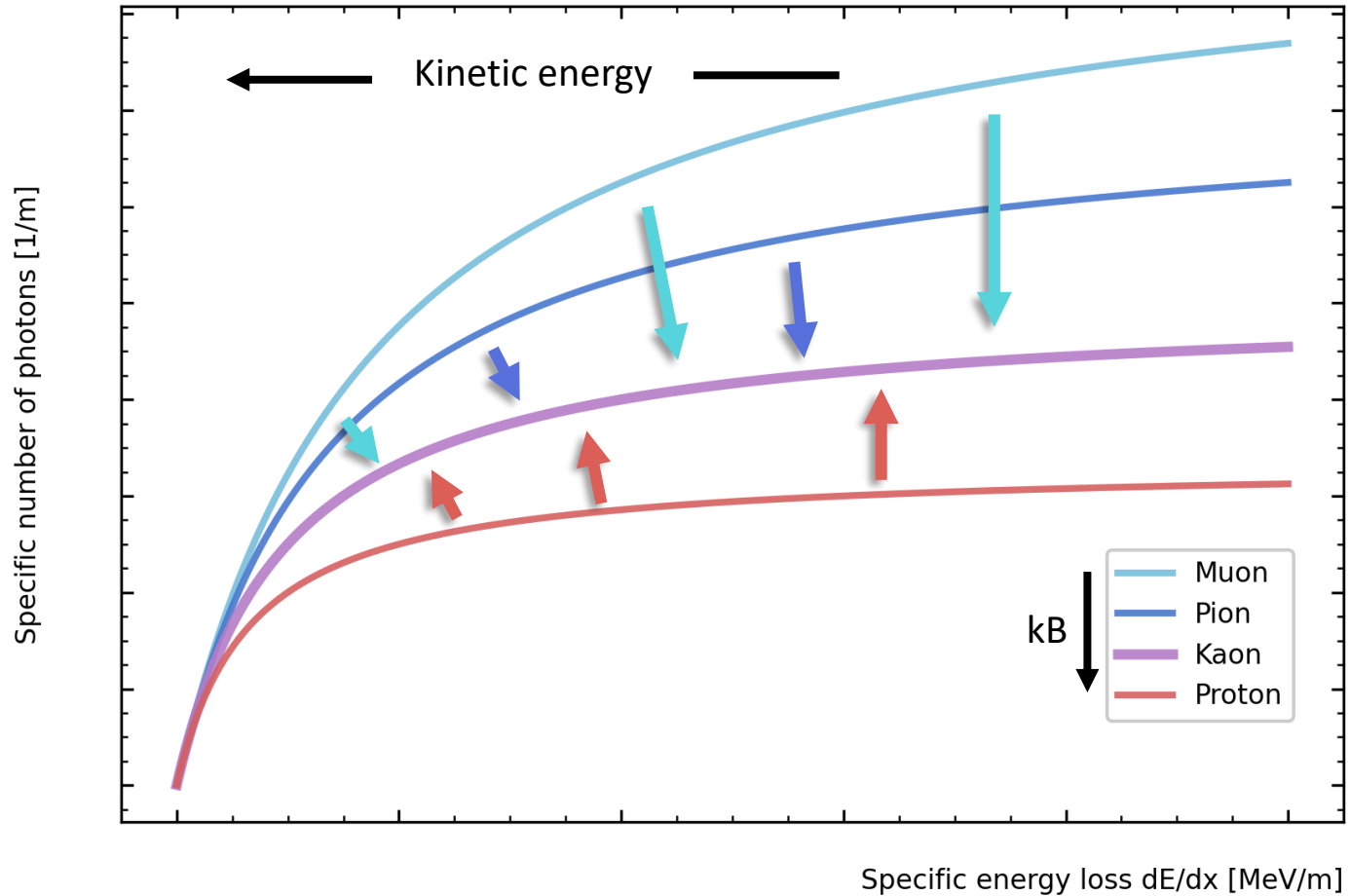
**Different particle types** with the same specific energy deposition produce **different amounts of scintillation light** due to ionization effects. The **Birks' constant  $kB$**  accounts for the quenching probability and the local density of ionized molecules and needs to be determined **experimentally**.



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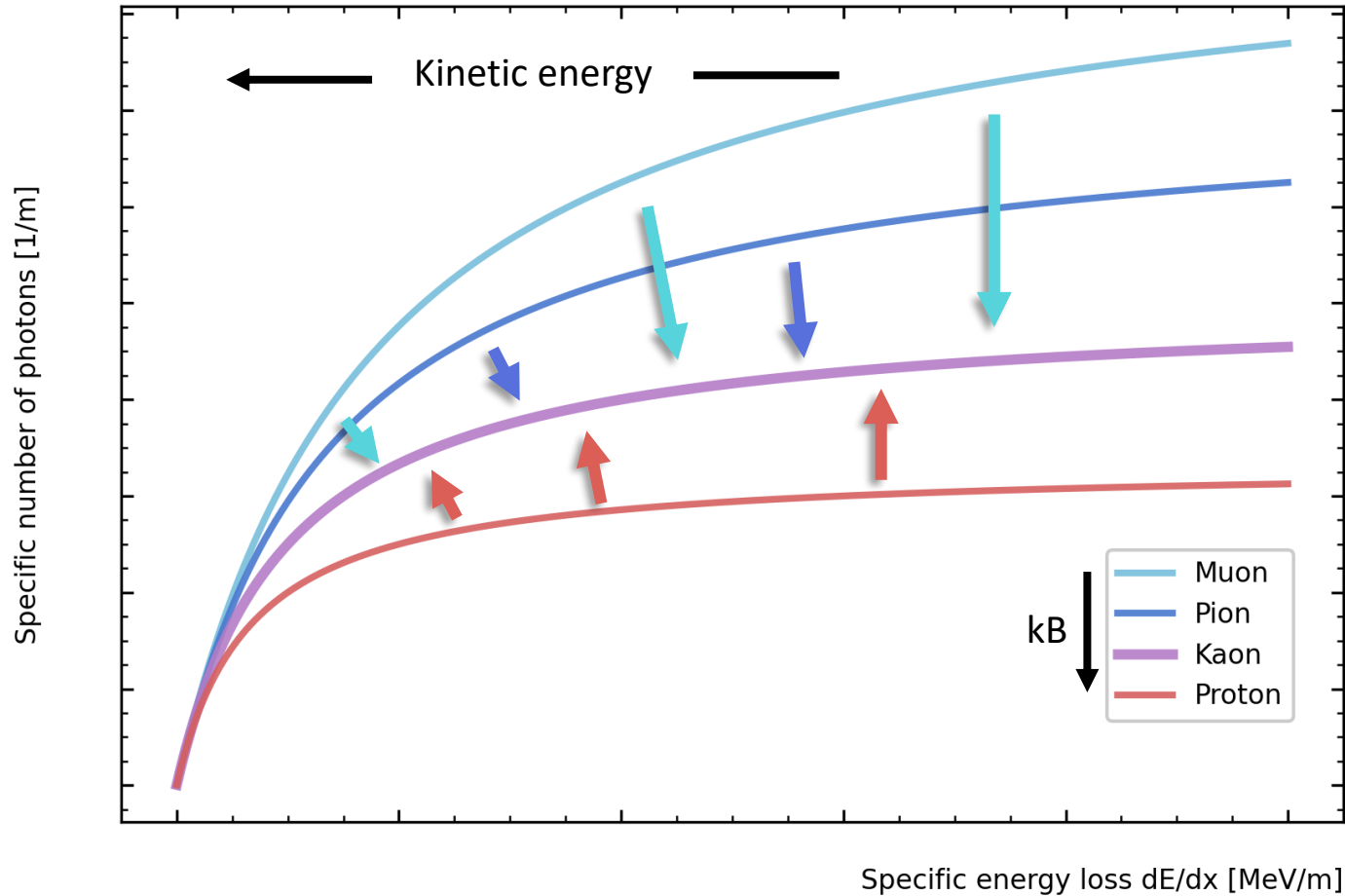


*Illustrational plot with exaggerated Birks' factors for the different particle species*

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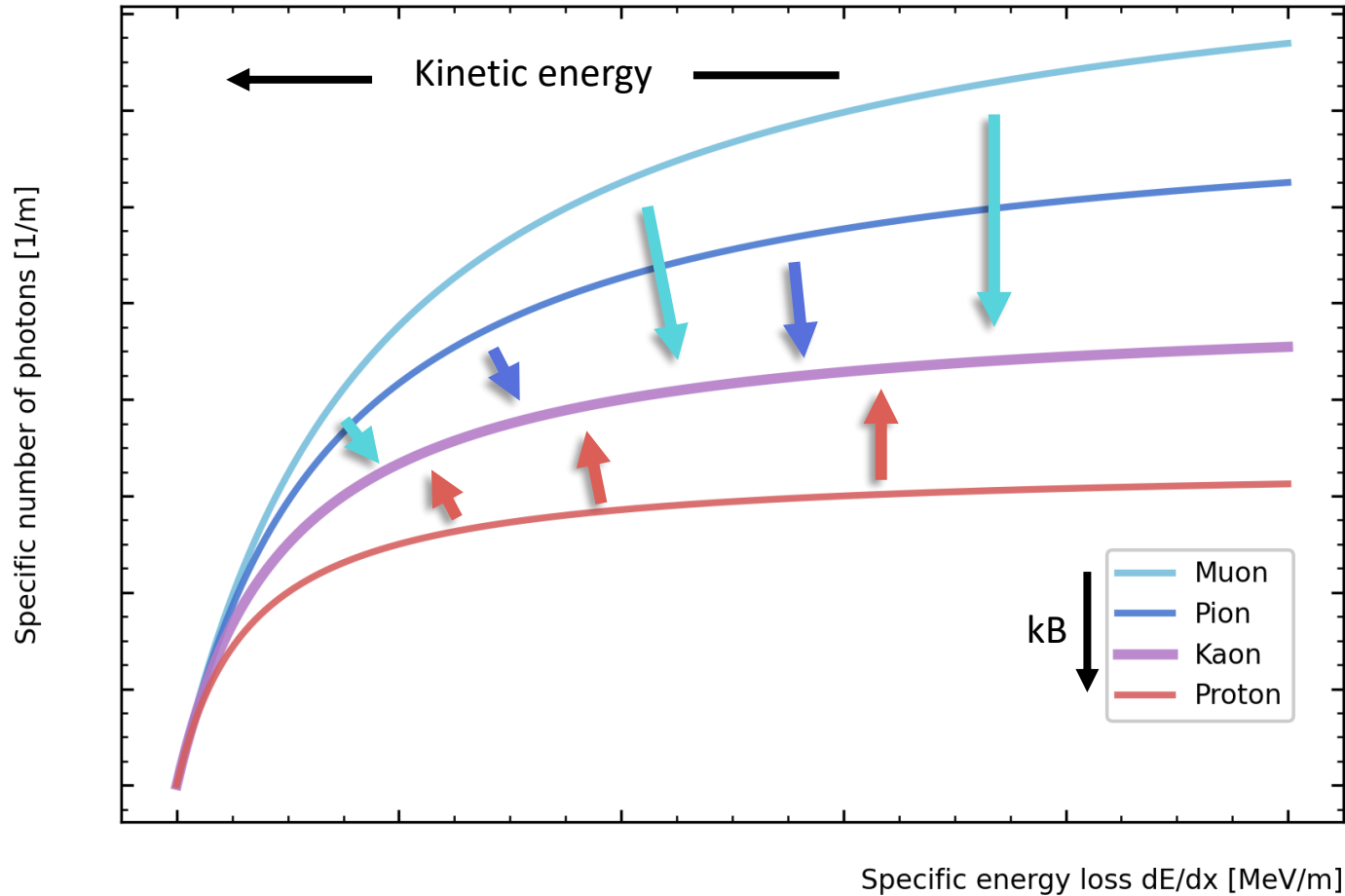


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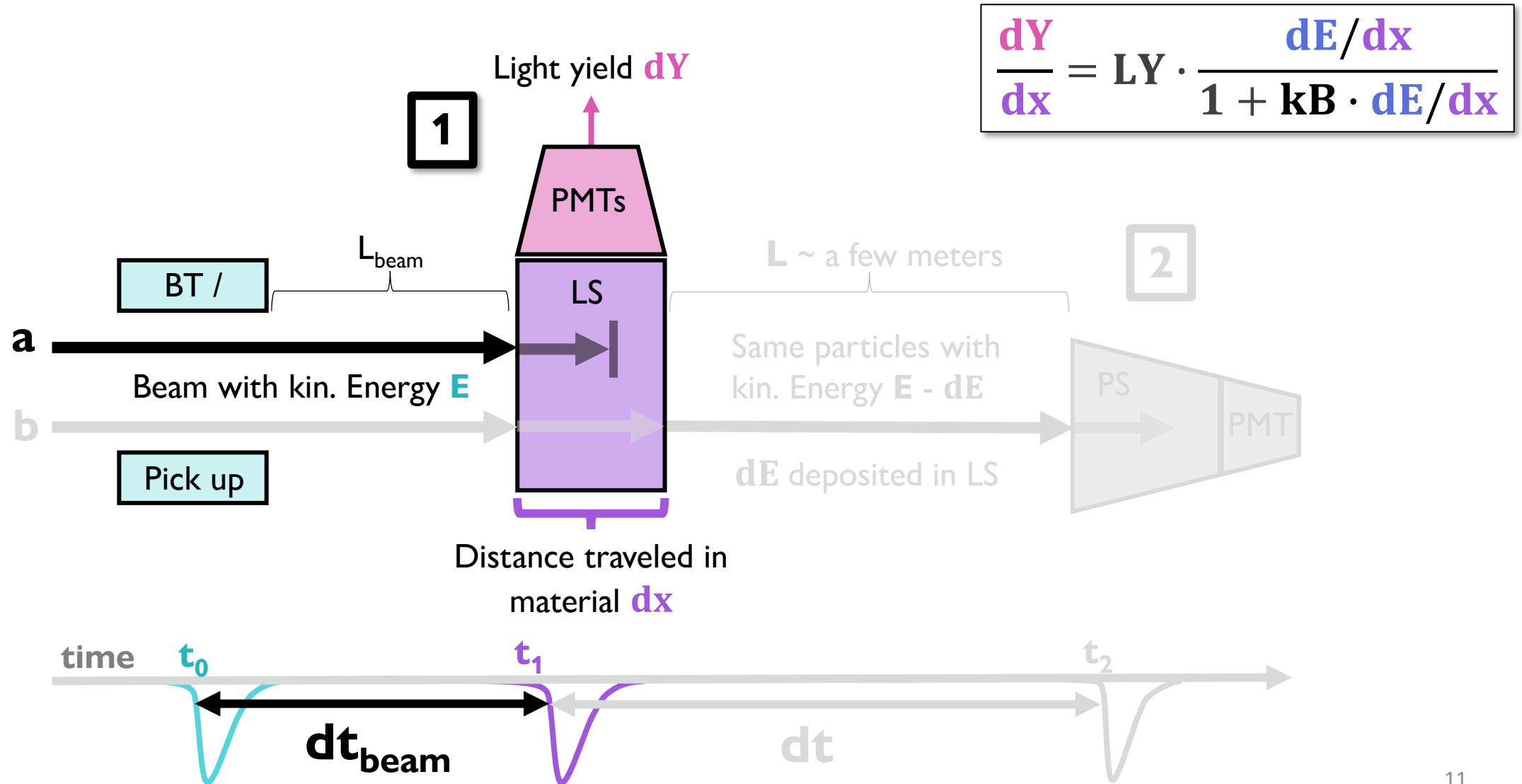


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- Measure light output and deposited energy independently  
 ➡ The measured results then correspond to the integral of the Birks' curve.
- Reconstruct Birks' curve by using different inertial energies and energy depositions
- Too short kaon lifetime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

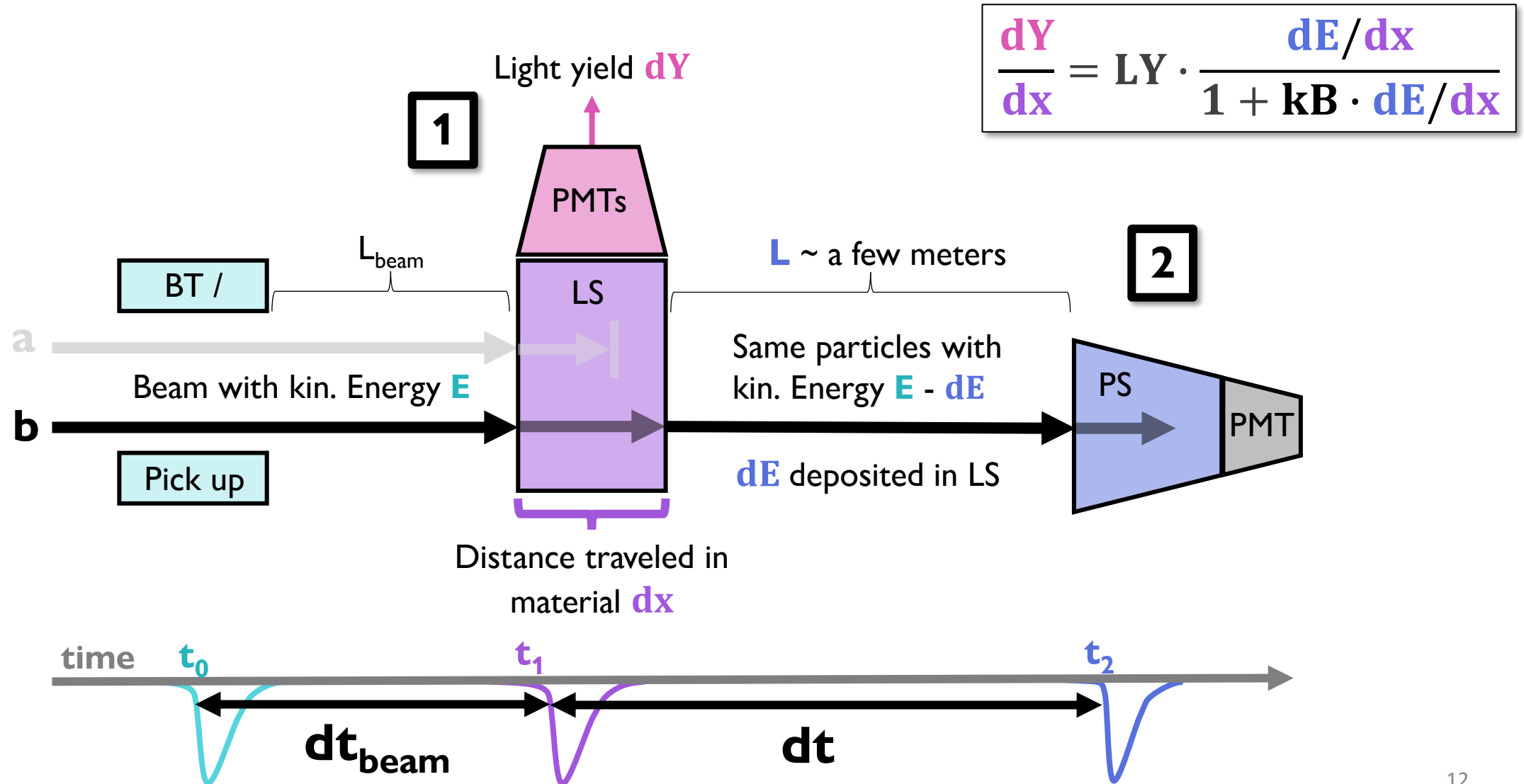


# What is the working principle of UniKaon?



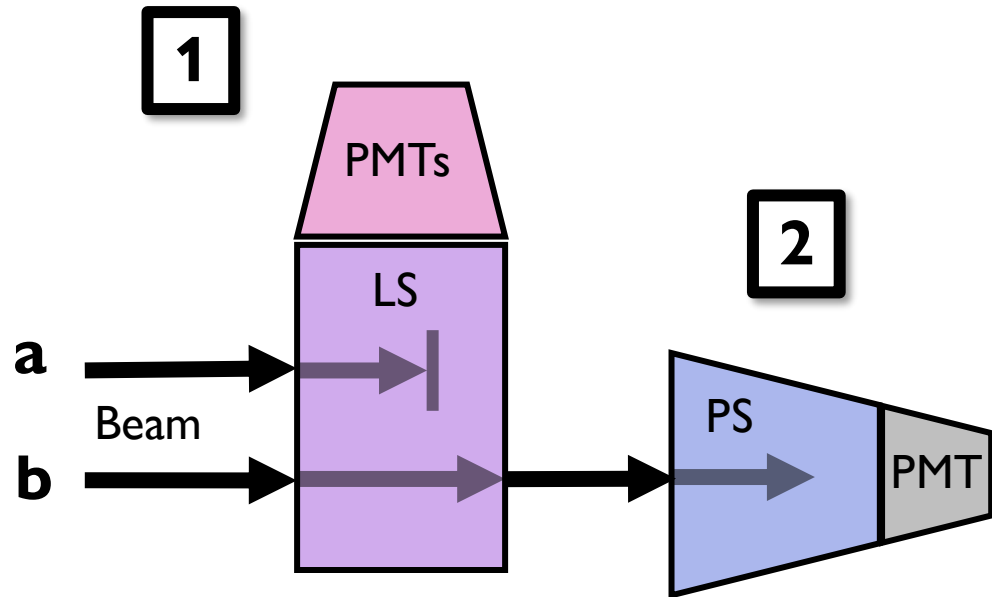


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# How is the setup designed?

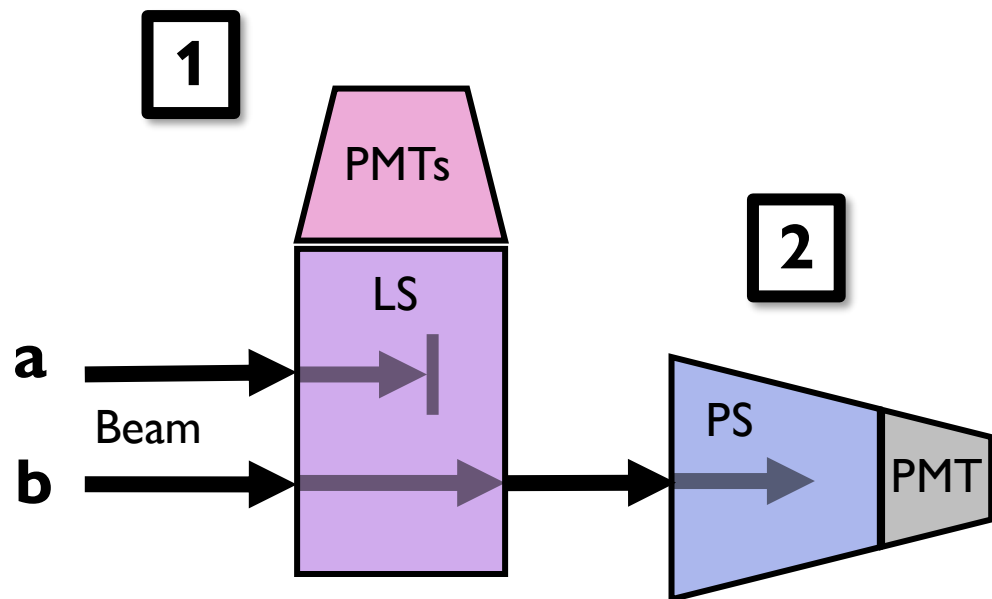


## Particle beams:

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

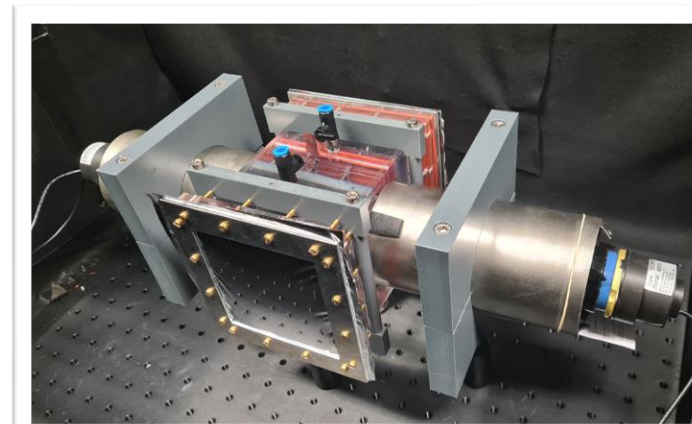


# How is the setup designed?



## 1 LS vessel

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

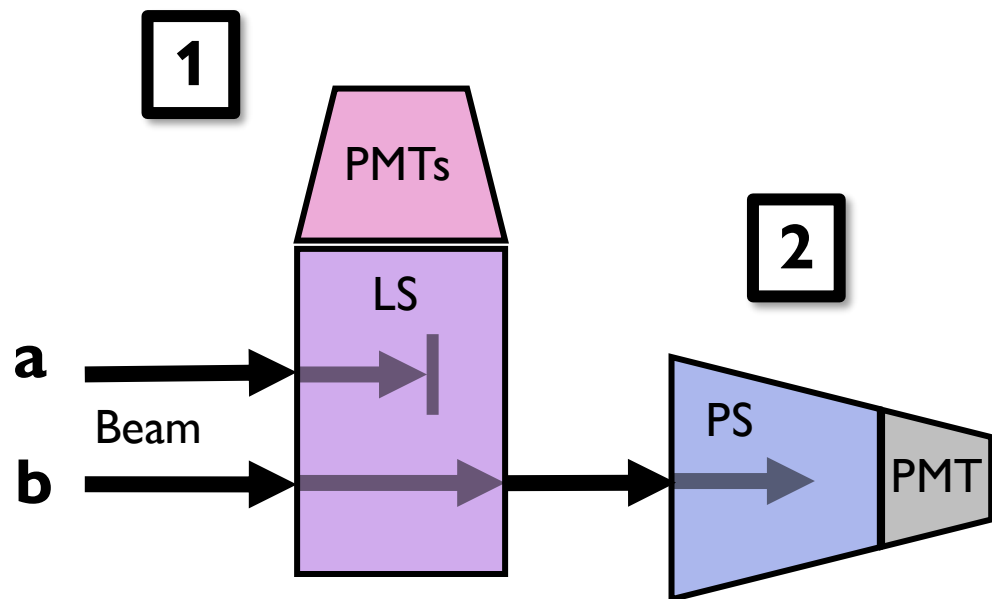


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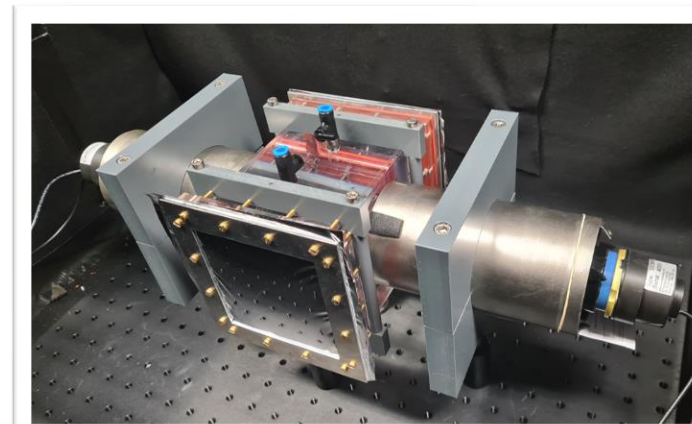
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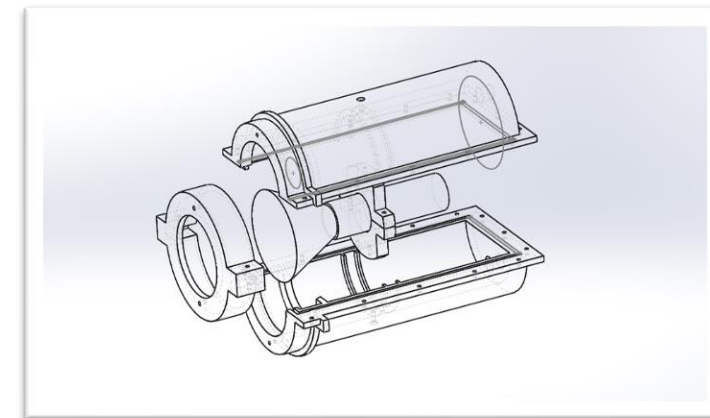
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2

## ToF detector

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





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



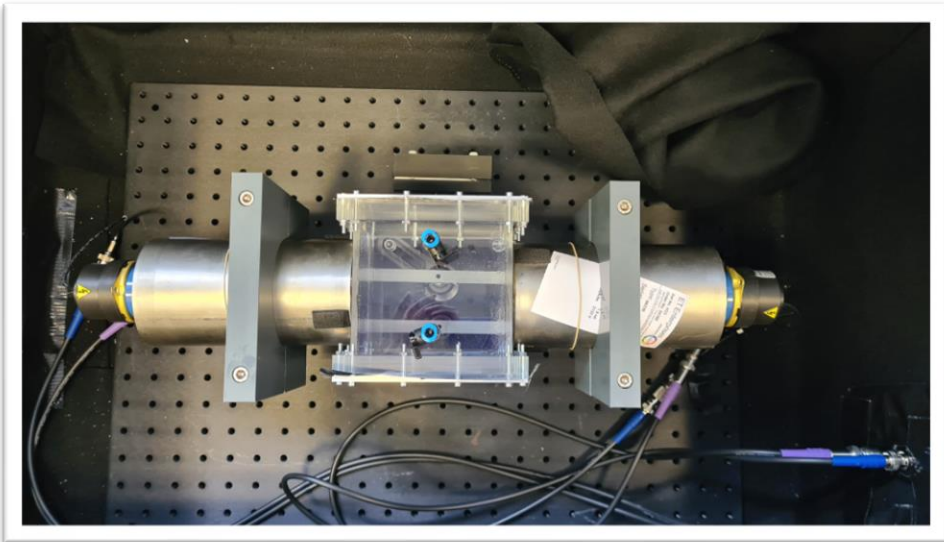
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## Laboratory:

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- First PMT gain calibration completed
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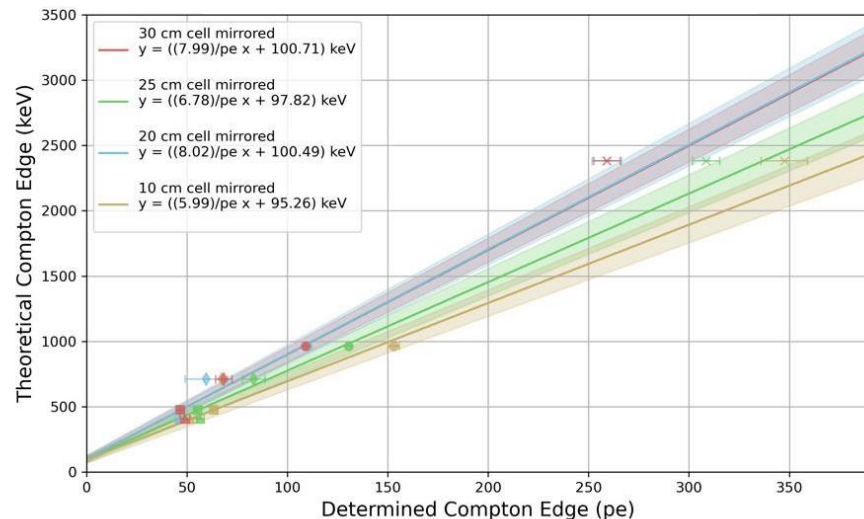
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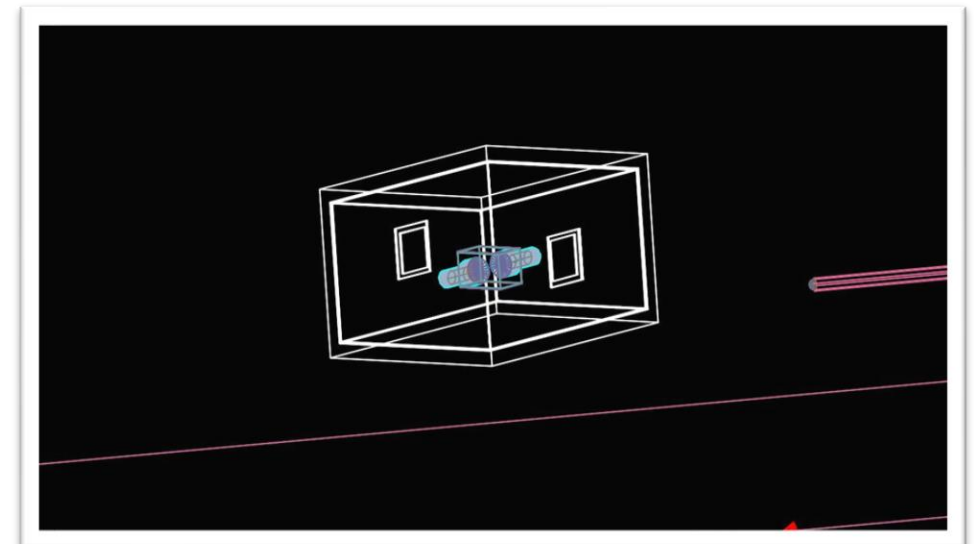
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## Simulation:

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





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## JUNO:

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



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**Thank you for your attention!**