Searching for Proton Decay with JUNO

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Motivation for proton decay search

Standard Model

- Baryon number is a global symmetry

- Observed matter/anti-matter imbalance in our universe
- Impose Baryon number violation

Grand Unified Theories

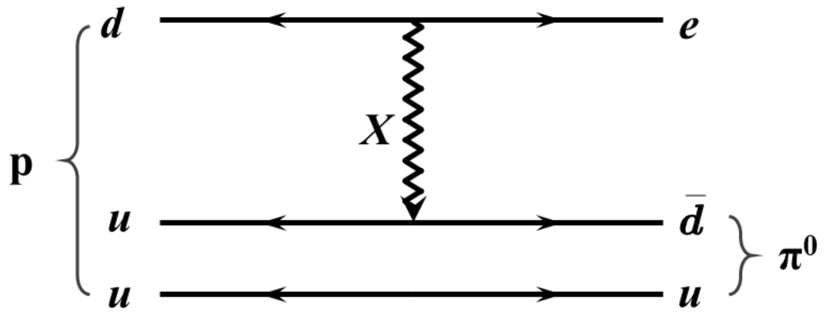
- Conversion reactions between quarks and leptons are possible
- Gauge coupling unification scale of GUTs typically at the order of 10^{16} GeV

-> Test GUTs via Proton Decay studies

Main proton decay channels

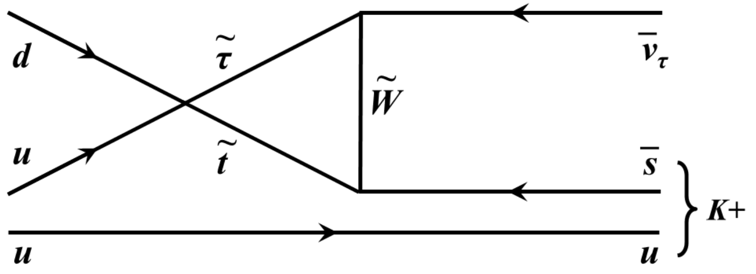
$$p \rightarrow \pi^0 + e^+$$

- Leading mode in many non-SUSY GUTs
- Best current limit by Super-Kamiokande:
  $\tau(p \rightarrow \pi^0 e^+) > 1.4 \times 10^{34}$ years with 90 % C.L.
- Decay mode with best degree of accuracy



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

- Favored in many SUSY-GUTs
- Best current limit by Super-Kamiokande:
  $\tau(p \rightarrow K^+ \bar{\nu}) > 5.9 \times 10^{33}$ years with 90 % C.L.
- More than an order of magnitude from prediction



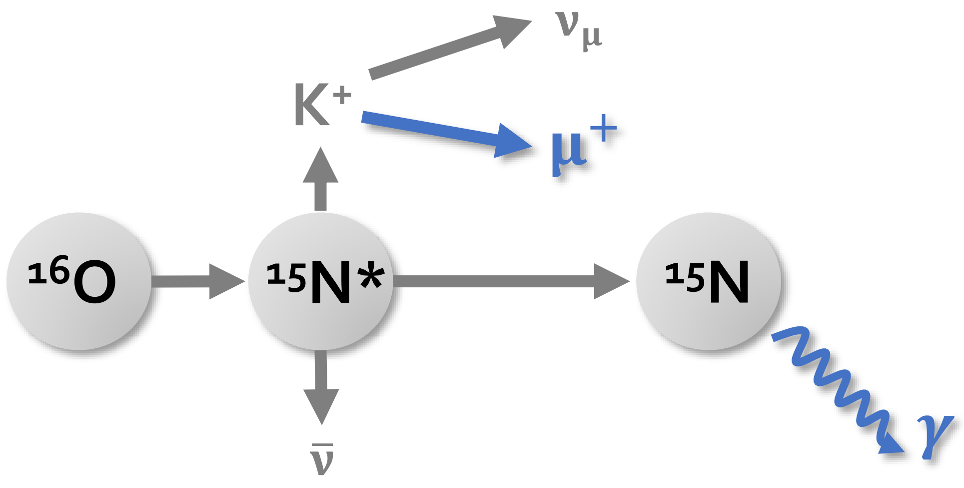
Improving limits by using LS detectors

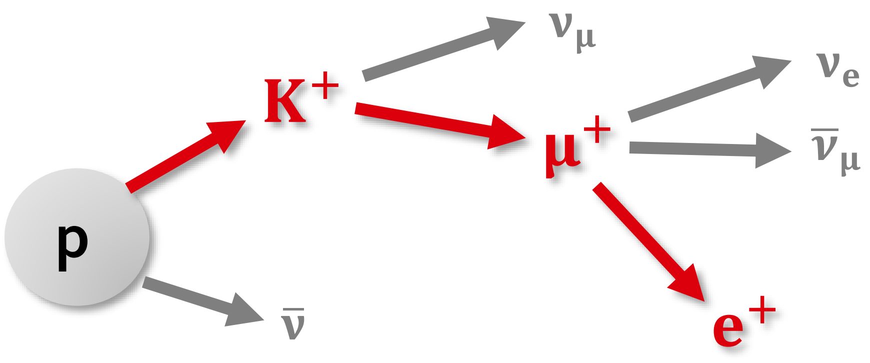
Water-Cherenkov detectors:

- Kaon energies mainly below the Cherenkov limit
  -> decay kaons are invisible
- Reconstruct the kaon's decay products
- Photon tagging technique from de-excitation of ^{15}N

Liquid scintillator detectors:

- Direct measurement of the kaon's scintillation light
- Improved energy resolution
- Loss of directional information





JUNO

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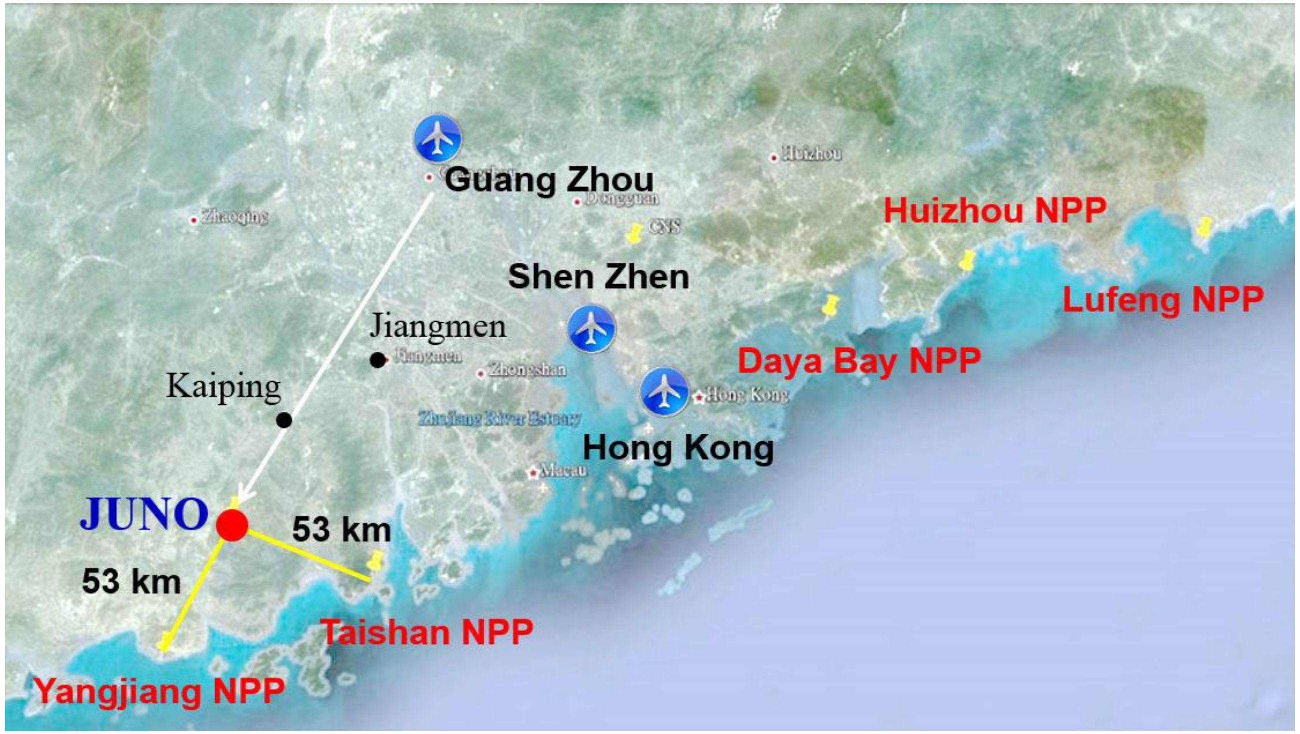
- Multi-purpose neutrino experiment in Southern China
- Excellent energy resolution of 3 % at 1 MeV
- Main goal: determination of the neutrino mass hierarchy
- Other physics goals:
  - Precision measurements on oscillation parameters
  - atmospheric, solar, geo and reactor neutrinos
  - Supernova neutrinos and DSNB

Jiangmen **U**nderground **N**eutrino **O**bservatory



The JUNO detector setup

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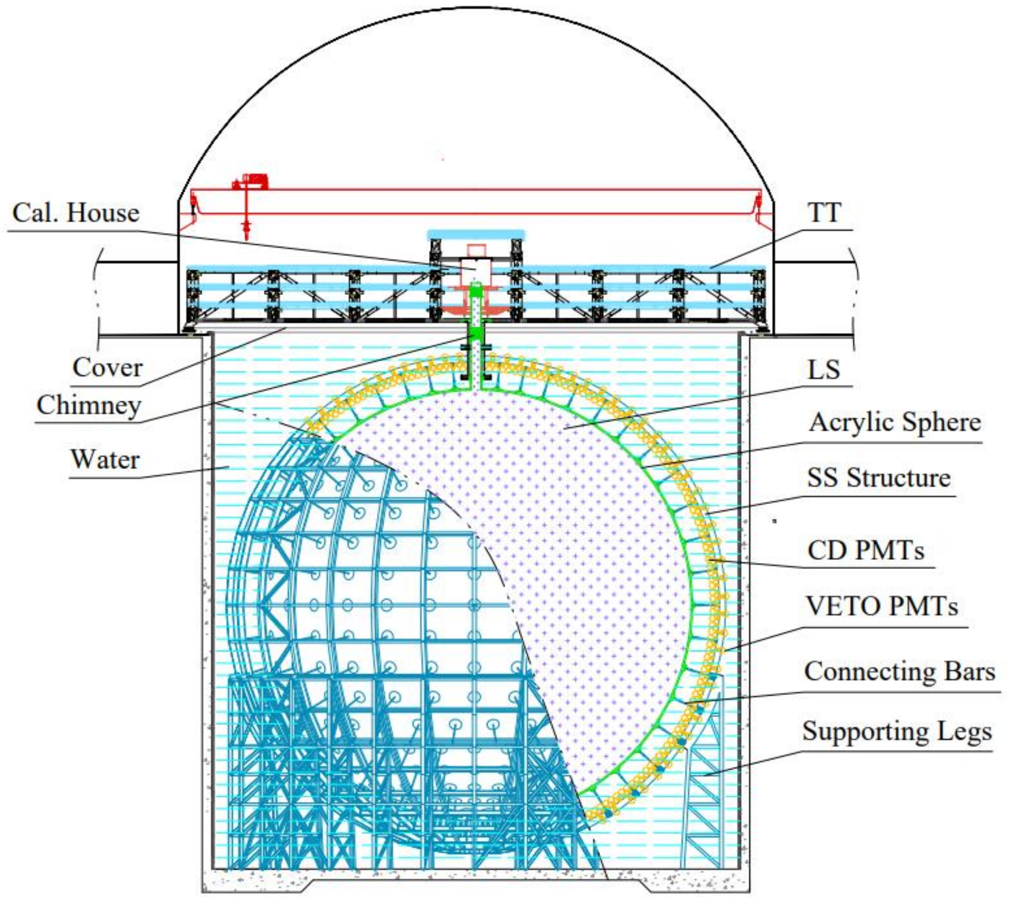

JUNO LS : LAB + 2.5 g/l PPO + 3 mg/l bisMSB

- 20 kton of liquid scintillator
- PMT array featuring
  - 17600 20 inch PMTs
  - 25600 3 inch PMTs
- Acrylic vessel with thickness of 12 cm and 35.4 m diameter
- Stainless steel holding structure
- Muon veto via top tracker
- 44 m deep water-Cherenkov pool with ~35 kton ultra-pure water
- Water pool instrumented with additional 2400 20 inch PMTs

Decay kinematics

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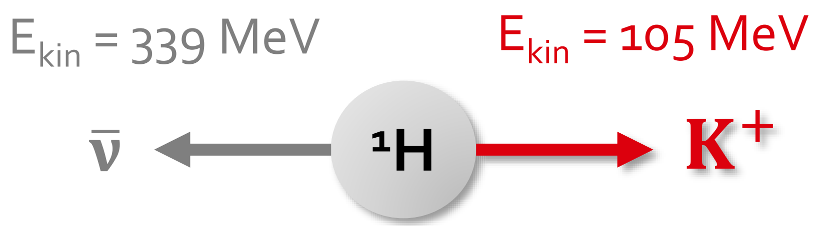
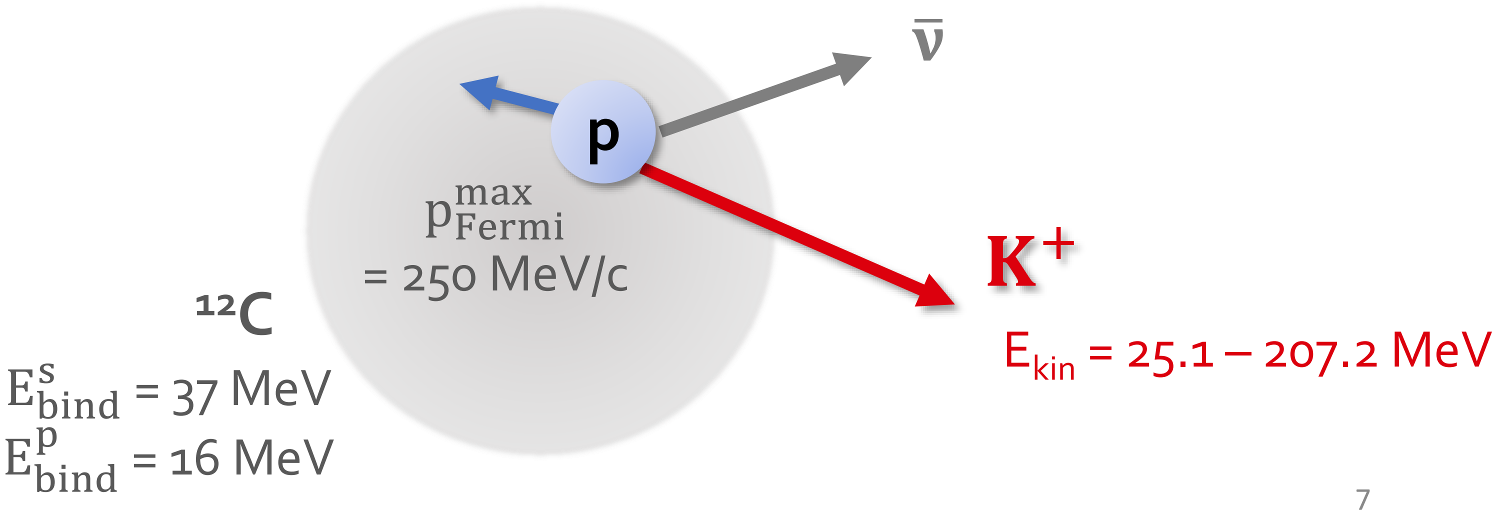
Free proton decay	Bound proton decay



Kaon momentum for bound protons influenced by:

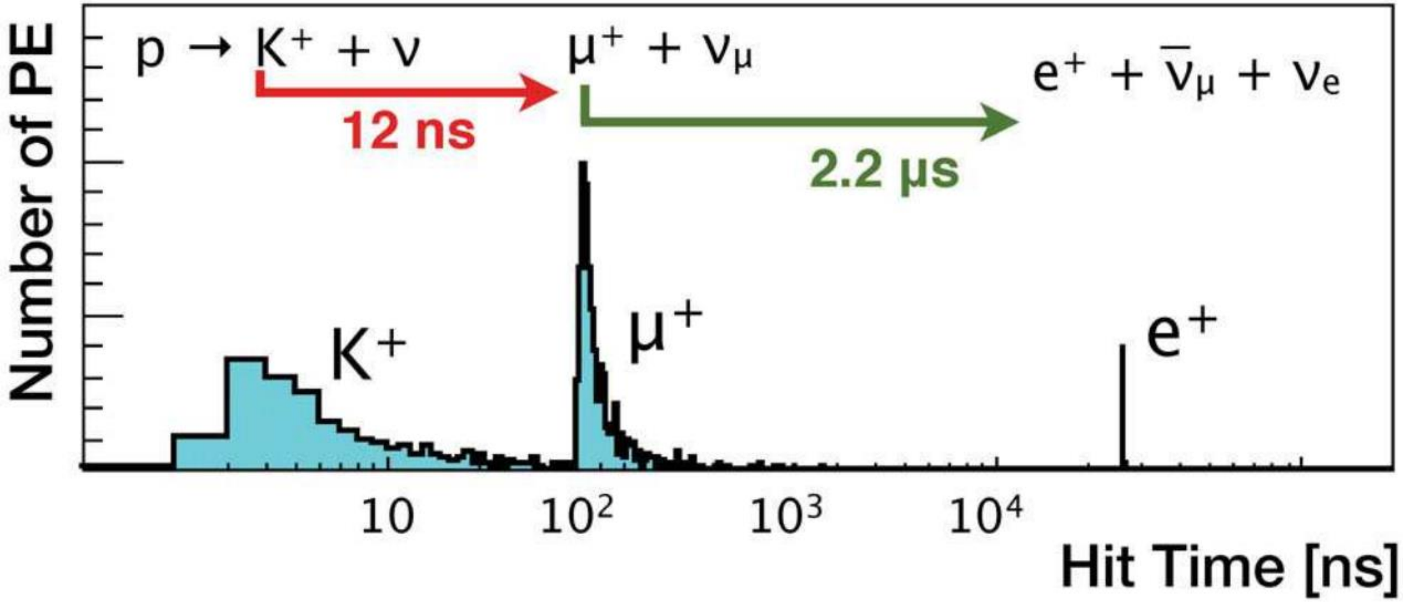
- Binding energy
- Fermi momentum
- Interactions with remaining nucleus



Detection principle in JUNO

Main kaon decay channels:

- $K^+ \rightarrow \mu^+ + \nu_\mu$ (63.43 %)
- $K^+ \rightarrow \pi^+ + \pi^0$ (21.13 %)

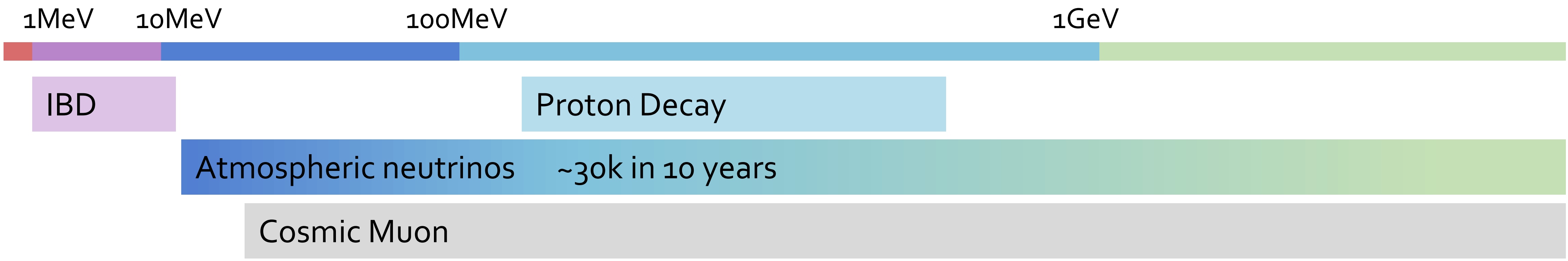


Proton decay event signature in JUNO:

- Prompt K^+ scintillation signal with well-defined energy
- delayed scintillation signal from K^+ daughters with 12 ns time coincidence and well-defined energy
- One and only one decay positron with time coincidence of 2.2 μs to prompt signals

-> Triple-coincidence with well-defined energies!

Backgrounds



- Most cosmic particle backgrounds shielded by overburden
- Muon veto excluding cosmic muons
- Strong energy, pulse shape and timing cuts can reduce most backgrounds efficiently

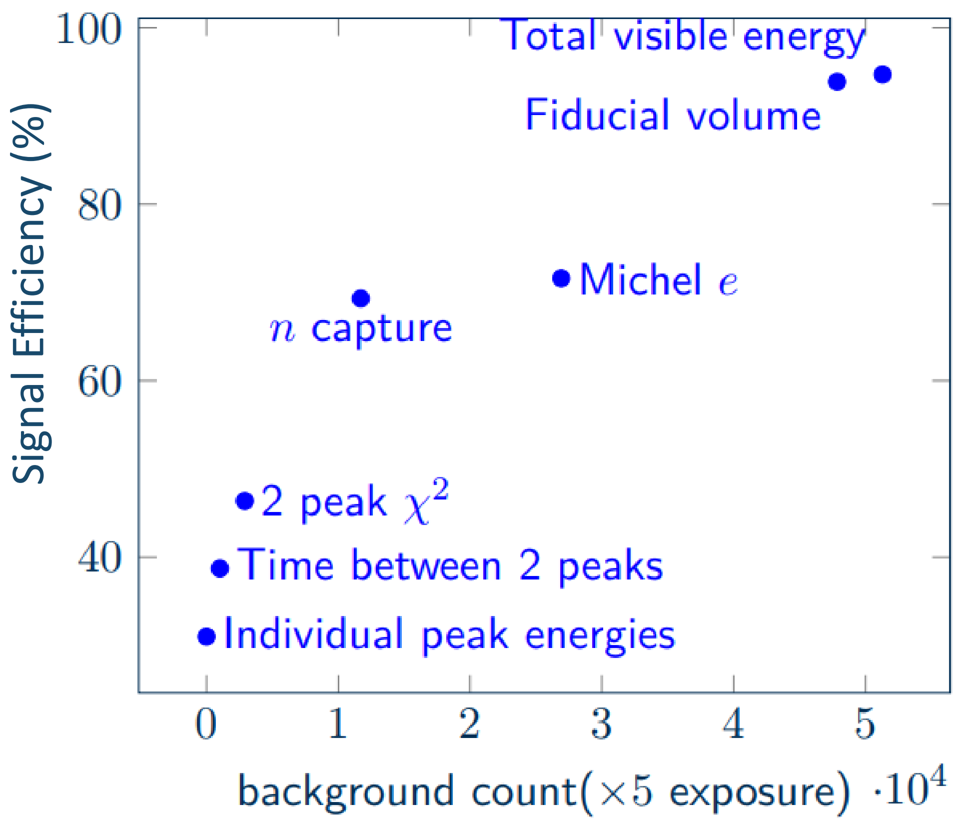
-> Main background left: **atmospheric neutrinos**

Discriminate muons created from atmospheric ν_μ from proton decay daughter events!

Event selection and efficiency

Proposed cuts on proton decay data set:

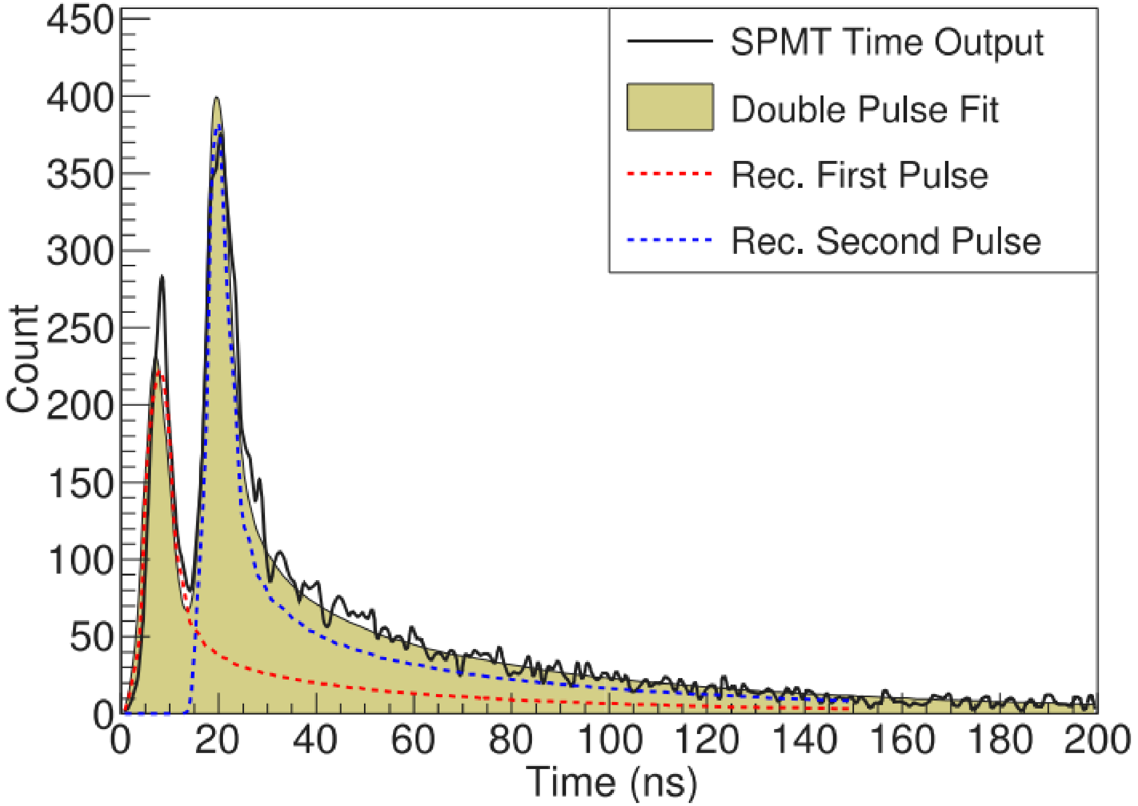
- Cut on overall visible energy
- Muon veto
- Michel electron selection
- Neutron capture veto



Event selection and efficiency

Proposed cuts on proton decay data set:

- Cut on overall visible energy
- Muon veto
- Michel electron selection
- Neutron capture veto
- Analysis of event's time structure



[arXiv:2203.08771]

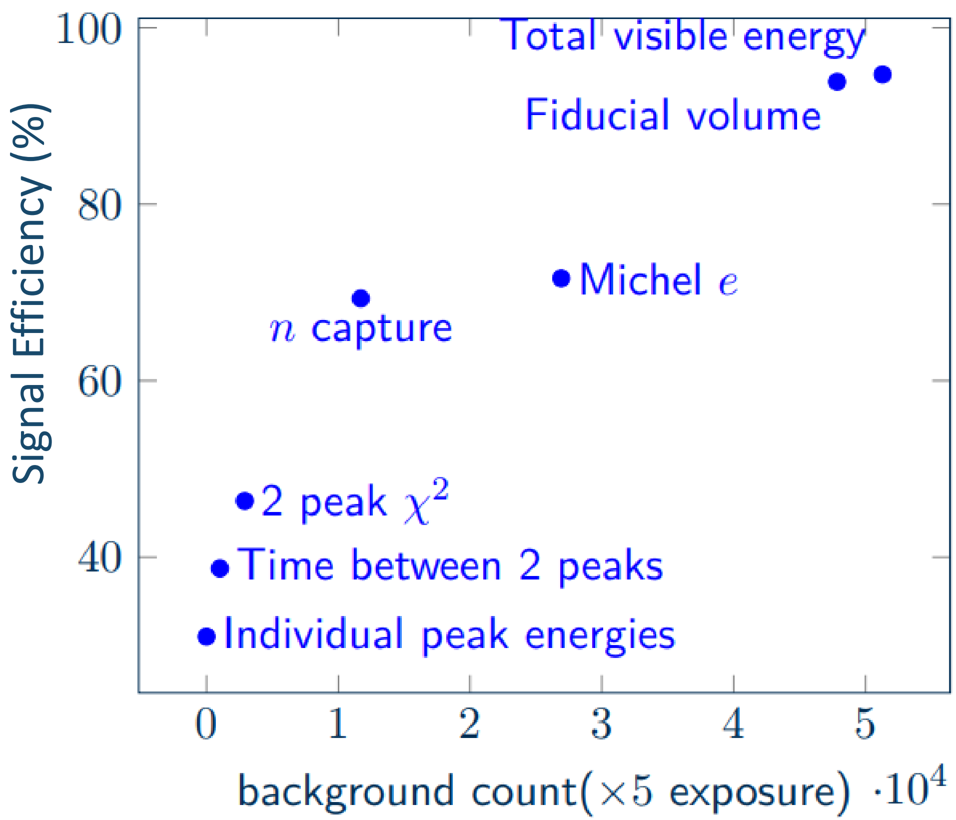
Event selection and efficiency

Proposed cuts on proton decay data set:

- Cut on overall visible energy
- Muon veto
- Michel electron selection
- Neutron capture veto
- Analysis of event's time structure

Total signal efficiency: 31 %
-> Development of analysis improvement ongoing

JUNO's 10 year sensitivity:
$\tau(p \rightarrow K^+ + \bar{\nu}) > 8.34 \times 10^{33}$ years at 90 % C.L.



Birk‘s law and kaon quenching

$$\frac{dy}{dx} = \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}$$

- relates a particle‘s specific energy loss dE/dx to the amount of visible energy from scintillation light dy/dx
- Birk‘s constant k_B includes the quenching probability and the local density of ionized molecules for the traversing particle

Quenching = The share of deposited energy, which is not converted into scintillation light due to the particle type

Event selection for $\boldsymbol{p \rightarrow K^+ + \bar{\nu}}$ relies strongly on the kaon and its energy

-> The kaon‘s k_B is an important value for particle discrimination

Development of a kaon quenching measurement setup at TUM

Quenching measurement: Detector concept

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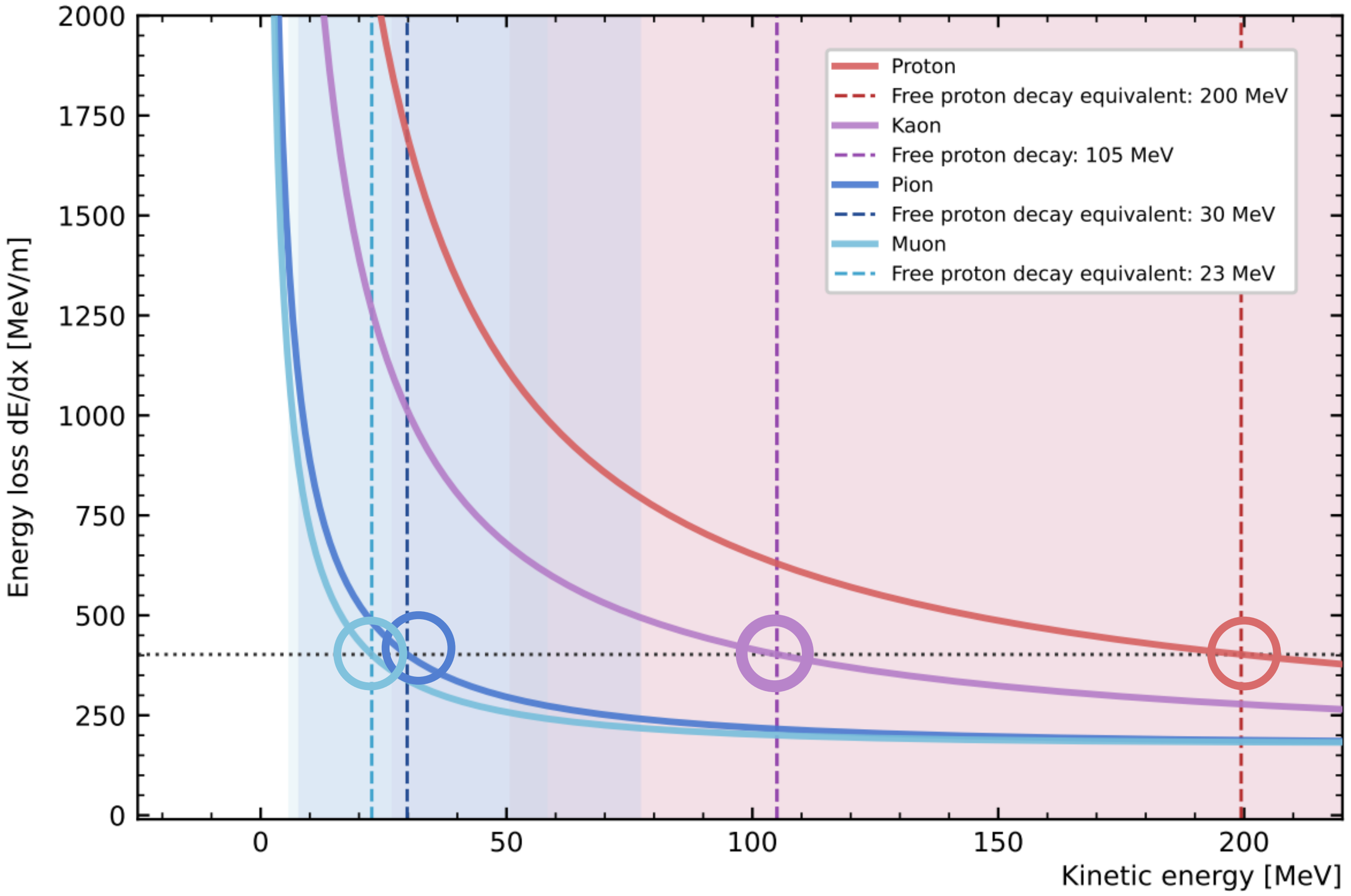
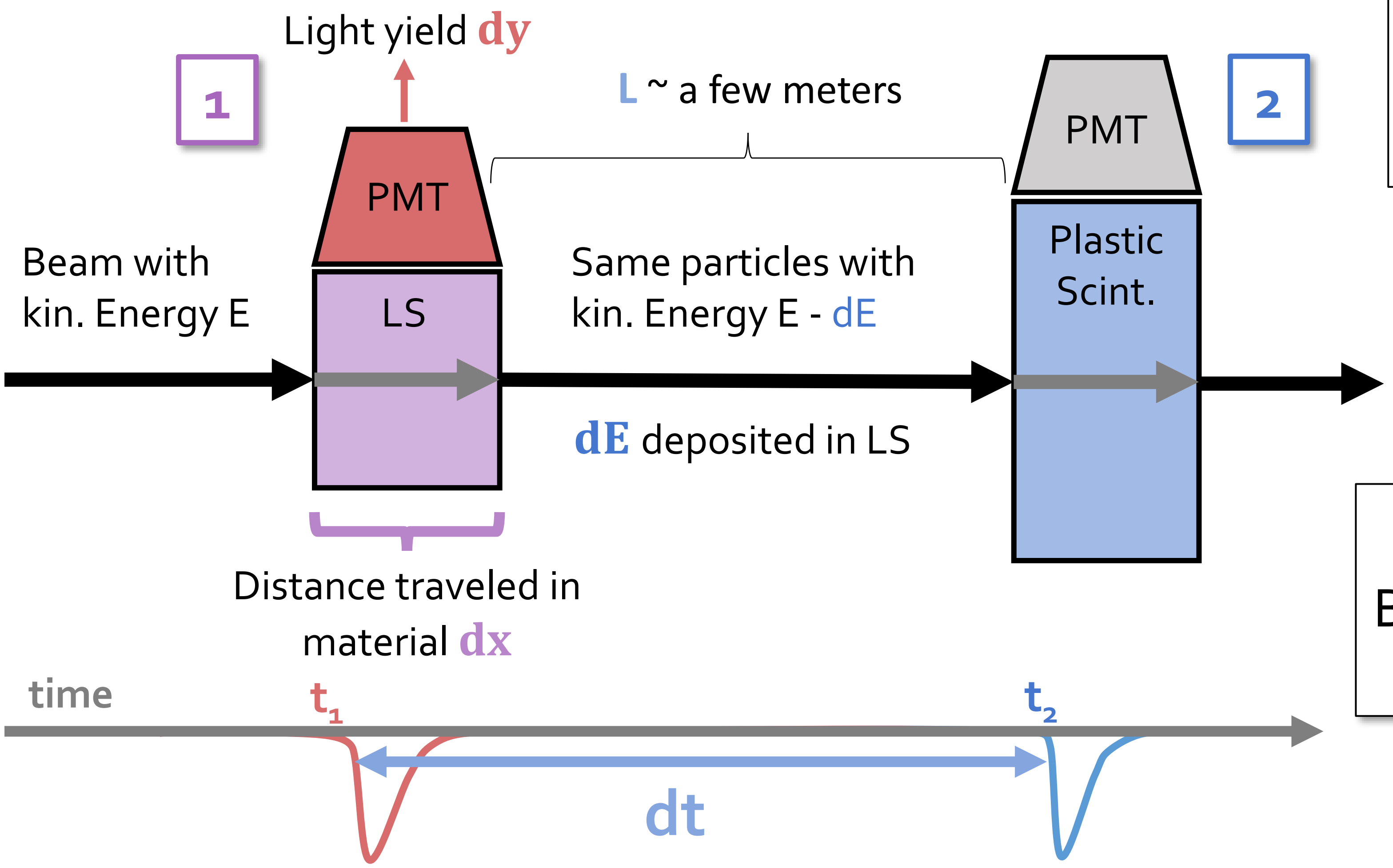
- Due to its short lifetime and the comparably low energy region of interest, producing a fitting kaon beam for quenching measurements remains difficult.

Solution: measure k_B for particles with lower (μ & π) and higher (p) mass and extrapolate Birk's curve for kaons.

- Calculate particle energies refering to kaons dE/dx
- Create data points for different inertial energies and energy losses



Quenching measurement: protons



Planning proton beam time at the Proton Irridiation Facility (PIF) of the Paul-Scherrer-Institute in Switzerland.

Get **dE** from time of flight **dt**

-> plug into Birk's formula

Birk's law: $$\frac{dy}{dx} = \frac{\frac{dE}{dx}}{1+k_B\frac{dE}{dx}}$$

Quenching measurement: muons and pions

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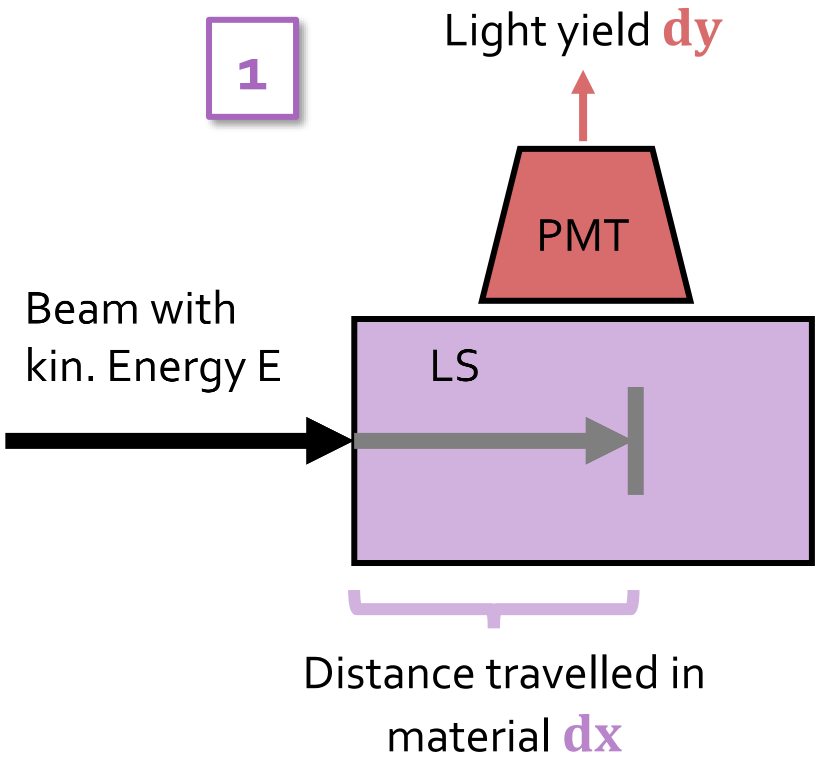


Planning muon and pion beam time at the secondary beamlines of the Paul-Scherrer-Institute in Switzerland.

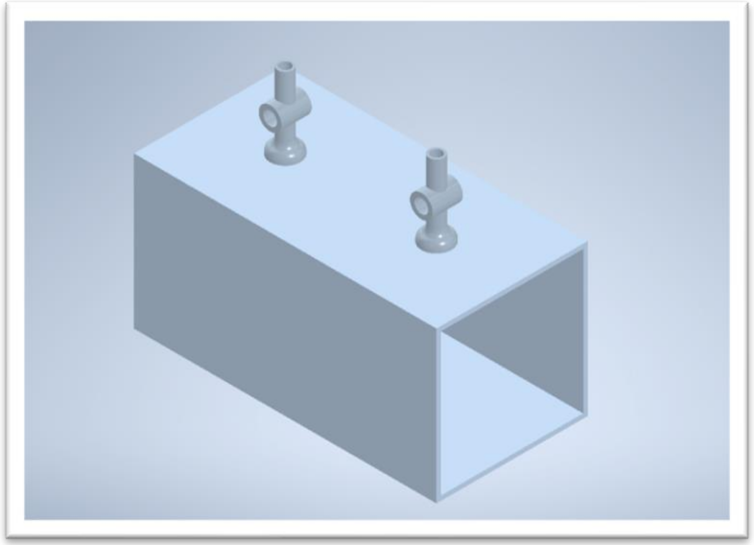
- Due to low respective energies, the muons and pions will be stopped after short distances in the LS

-> dE = kinetic beam energy E_{beam}

-> dx from simulations

Birk's law: $$\frac{dy}{dx} = \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}$$

Outlook: Kaon quenching setup



Simulations on light collection and detection efficiency as well as of expected timing properties ongoing.

3D-drawing of LS cell

- Final sizes to be determined
- In production

Material compatibility test

- Change of scintillation properties due to contact with foil?
- Change in foil's material properties due to LS?

BSc Thesis: Onur Yonar

Outlook: JUNO construction status

- Stainless steel structure finished
- PMT production and testing finished
- Most parts of acrylic vessel ready
- LS purification plants under onsite construction

Data taking is expected to start in the end of 2023

Conclusion and References

- JUNO aims to exceed SuperKamiokande‘s limit on the proton decay channel $p \rightarrow K^{+} + \bar{\nu}$ within 10 years of data taking
- The kaon‘s quenching factor is a crucial factor in proton decay event selection
- Research on LS characteristics and further improved analysis methods is ongoing

More information on Proton Decay Search with JUNO:

- JUNO Yellow Book: An et al. [JUNO], „Neutrino Physics with JUNO“: arXiv:1507.05613
- Dev et al., “Searches for Baryon Number Violation in Neutrino Experiments: A White Paper“ : arXiv:2203.08771
- To be published: Abusleme et al. [JUNO], “Monte Carlo Simulation of Searching for Proton Decay $p \rightarrow \bar{\nu} K$ in JUNO”

Detector design

1: LS detector

- Borosilicate glass cells for LS of different sizes for different energy depositions
- Vacuum-coating with aluminium for higher reflectiveness
- Two low-gain, fast-timing PMTs optically coupled to glass windows
- Front and back enclosed with aluminium coated PET foil to reduce energy loss in walls
- Setup enclosed in a dark box with foil windows for the particle beam

2: TOF detector

- Placed at a few meters distance to LS detector
- Plastic scintillator for fast timing purposes
- Fast timing PMT

Electronics

- Staged coincidence between LS PMTs and TOF PMT for protons
- Double coincidence in LS for muons and pions