Experimental Lecture #3
Sources

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NBIA PhD School: Neutrinos Underground and in the Heavens
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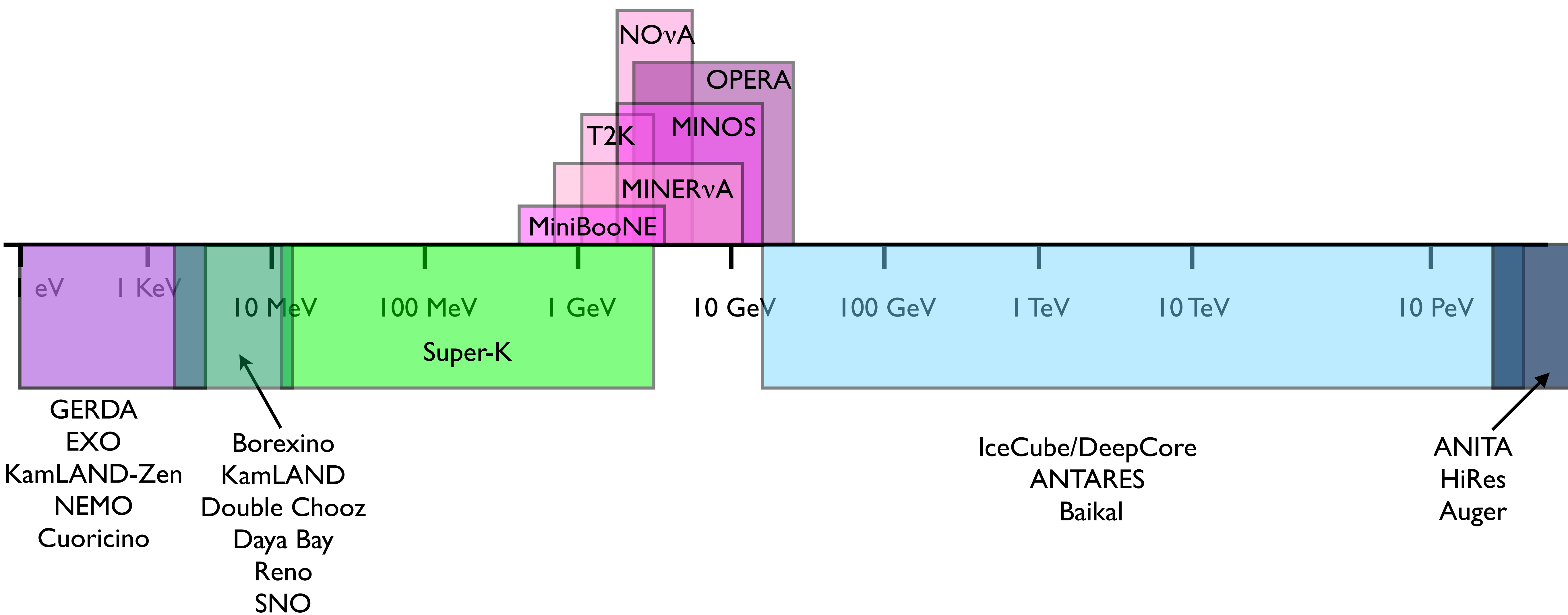
Niels Bohr Institutet
The Niels Bohr International Academy
Discovery centre for particle physics

Experimental Landscape Overview

- Lowest energy experiments focus on neutrino mass and Dirac vs. Majorana
- Reactor/Solar experiments dominate the < 1 GeV non-accelerator region
- Accelerator coupled experiments are mainly probing oscillation physics
- Highest energy experiments are involved with astro-physics and cosmic neutrinos

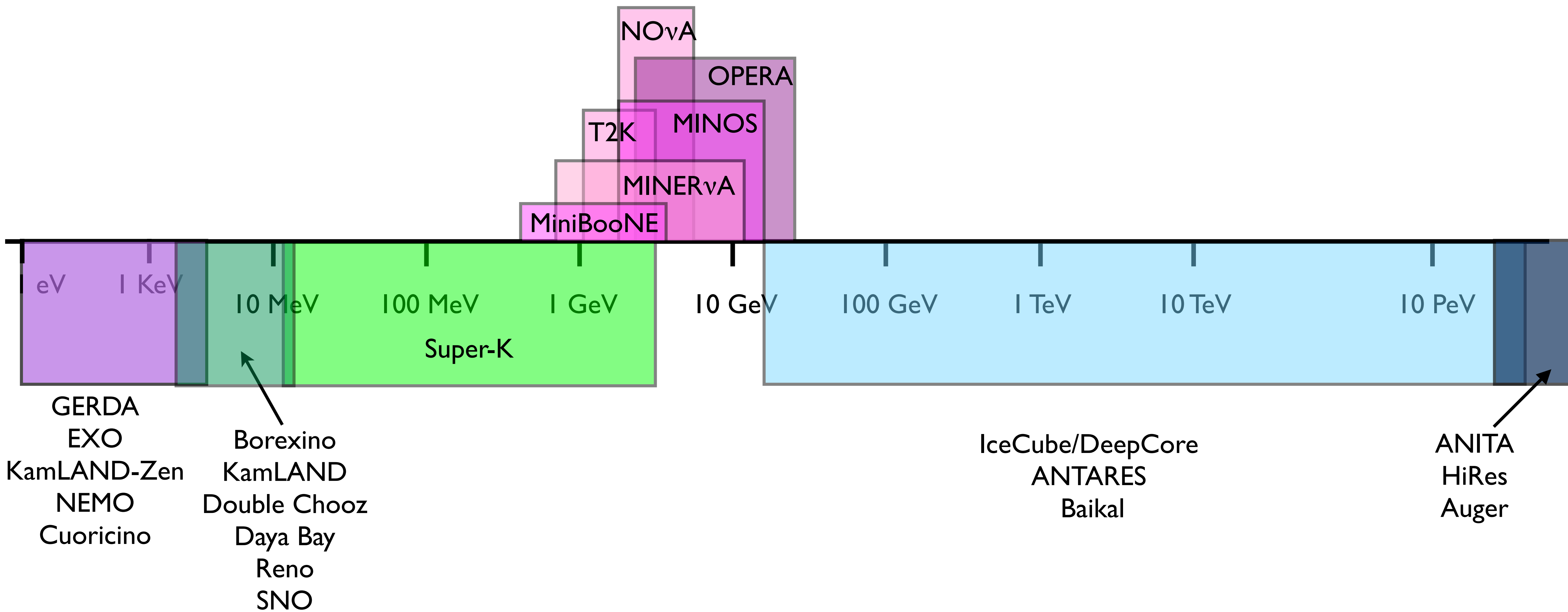


Charged Current Types

- There are different types of Charged Current interactions
  - At high(er) energies Deep-Inelastic Scattering (DIS): Nucleon is destroyed created a shower of secondary hadrons
  - At ~1 GeV neutrino energy Resonance (RES): Nucleon ‘emits’ a low number of secondary mesons or resonant states
  - At lowest energies Quasi-Elastic (QE or QEL): Nucleon stays intact

- Higher energies have higher cross-sections

Sources


NOνA
OPERA
T2K
MINOS
MINERνA
MiniBooNE
1 eV
1 KeV
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
10 PeV
Super-K
GERDA
EXO
KamLAND-Zen
NEMO
Cuoricino
Borexino
KamLAND
Double Chooz
Daya Bay
Reno
SNO
IceCube/DeepCore
ANTARES
Baikal
ANITA
HiRes
Auger

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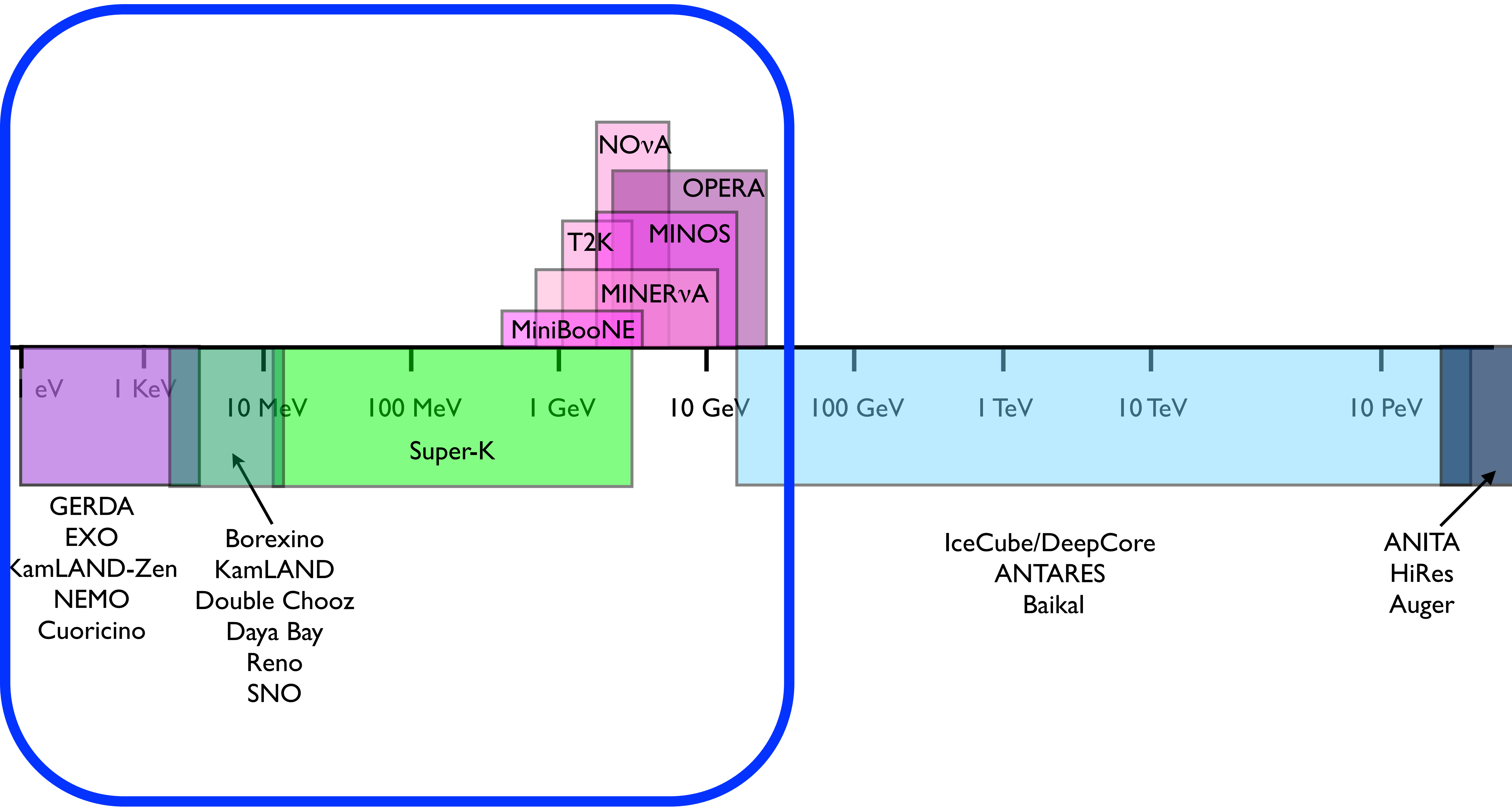

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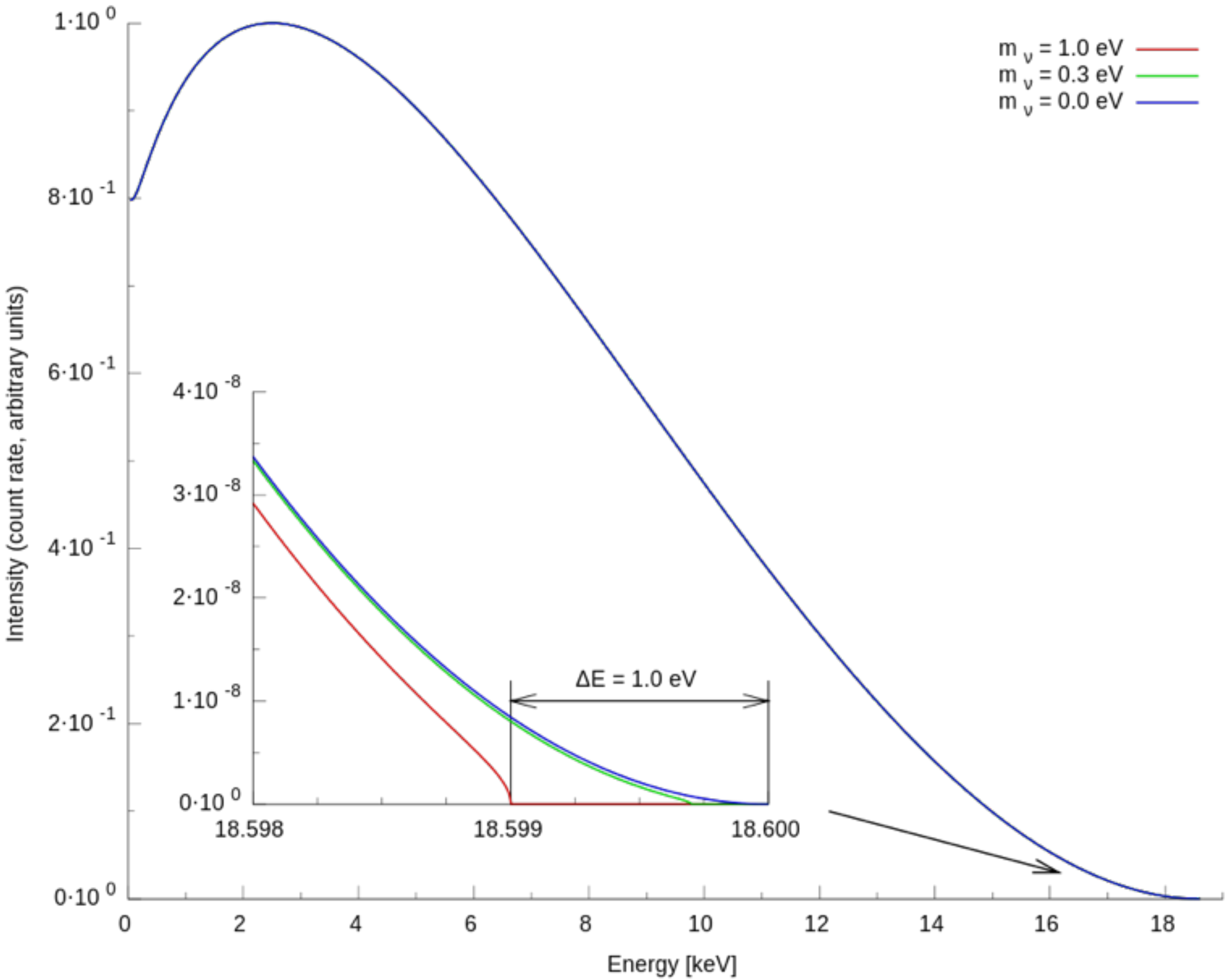
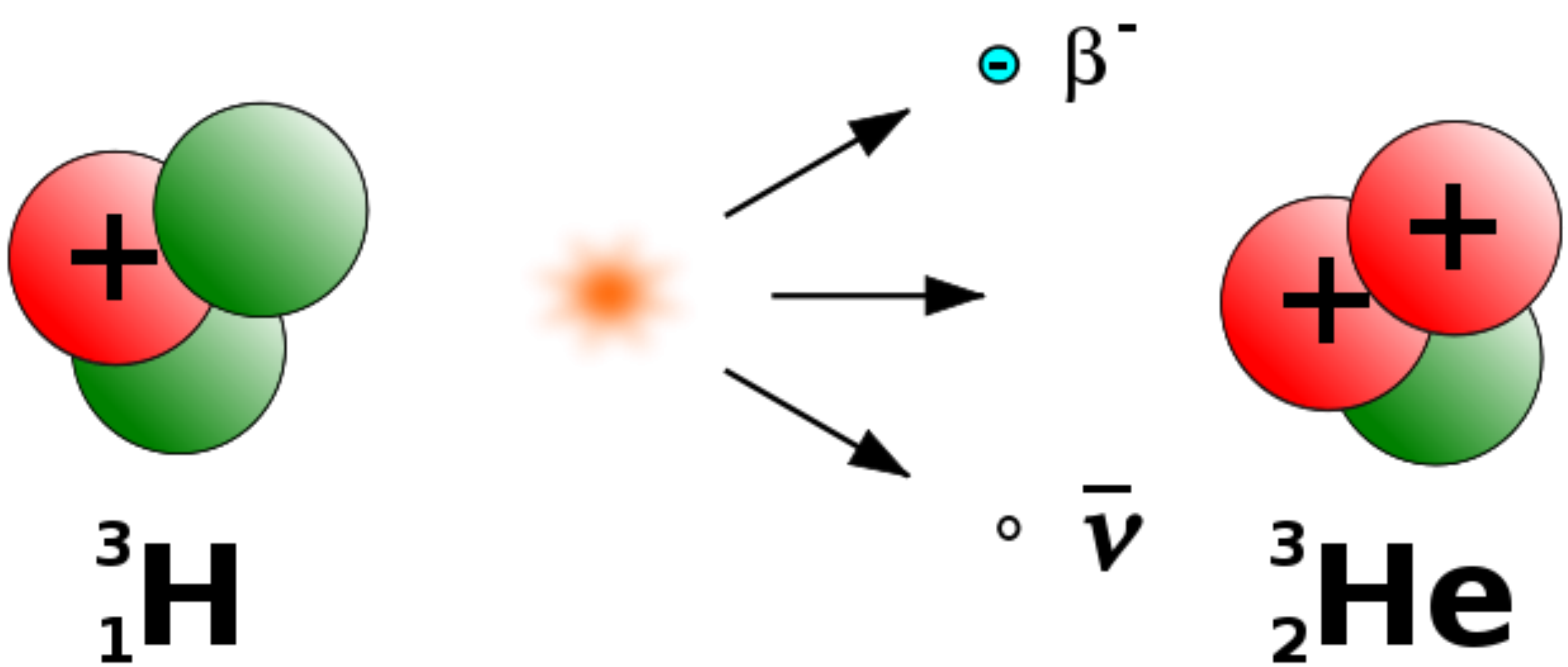
Beta-Decay Endpoint



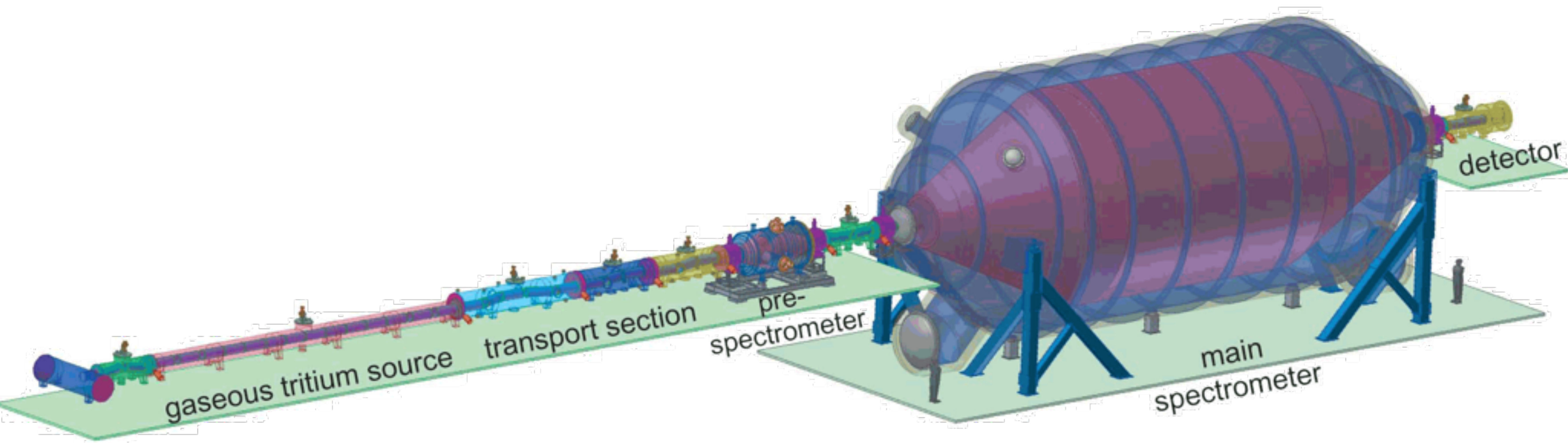
KATRIN Absolute Neutrino Mass

- At rest, the energy of beta-decay is carried by the anti-neutrino and beta (electron)
- Measure the electron from tritium



Tritium

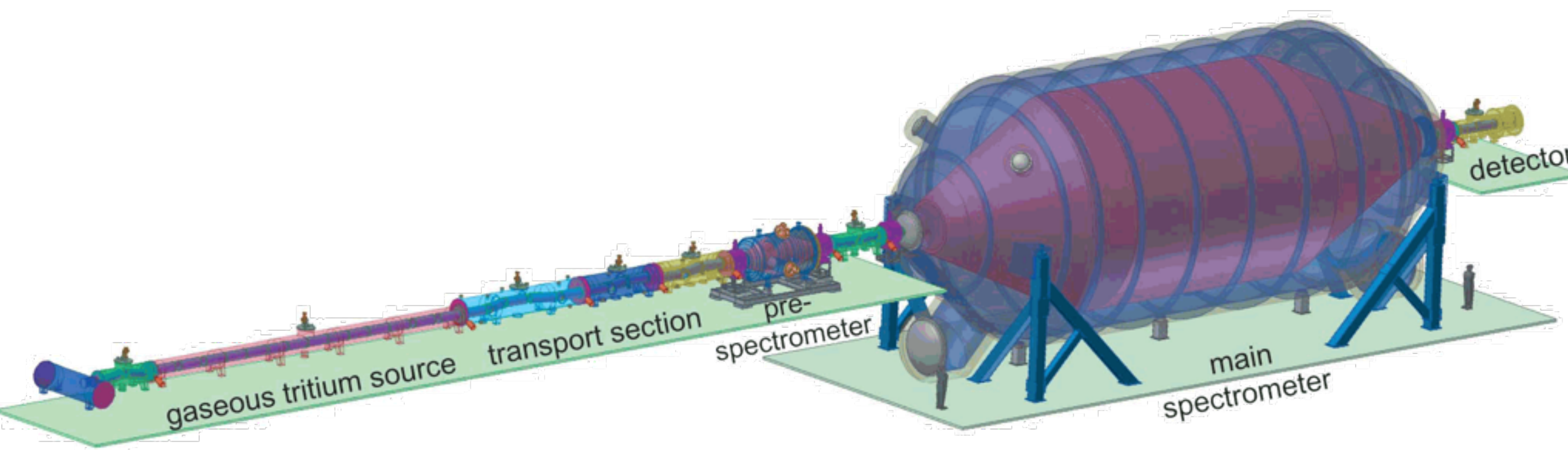
KATRIN



gaseous tritium source
transport section
pre-
spectrometer
main
spectrometer
detector

KATRIN

- Where is the tritium source?



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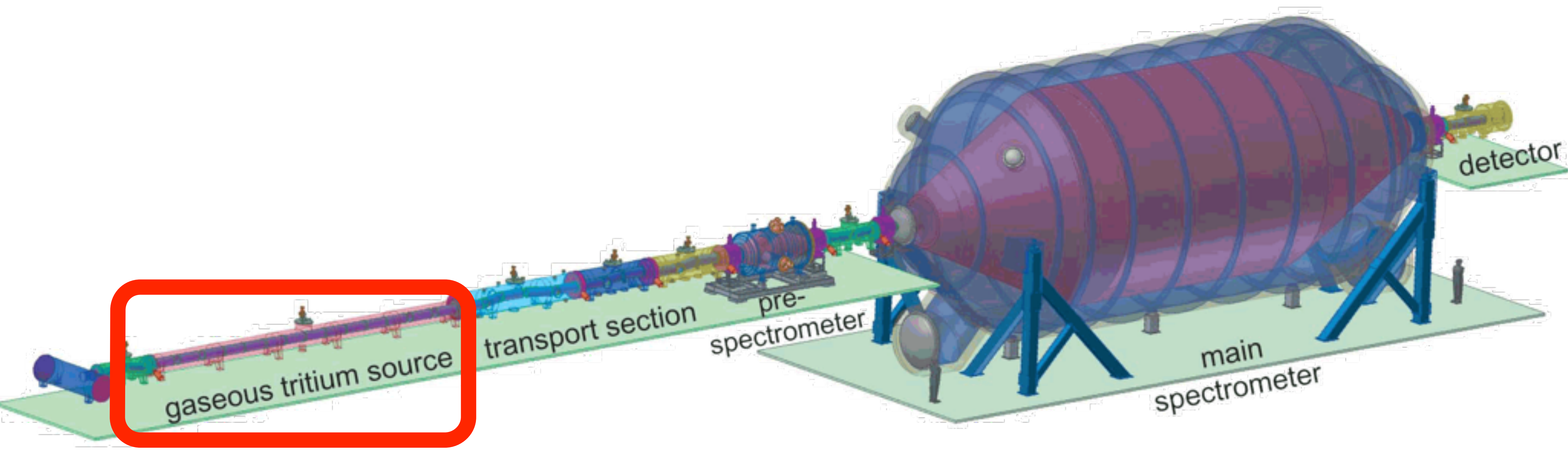
- Where is the tritium source?
  - Easy answer is “Right here. It says so on the diagram.”



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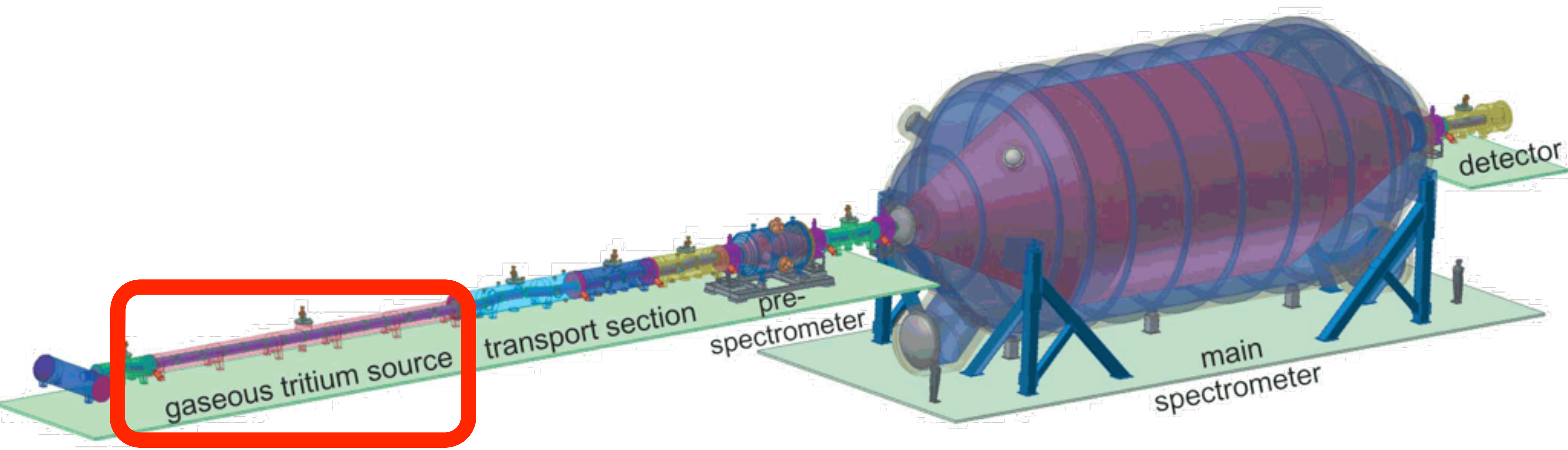

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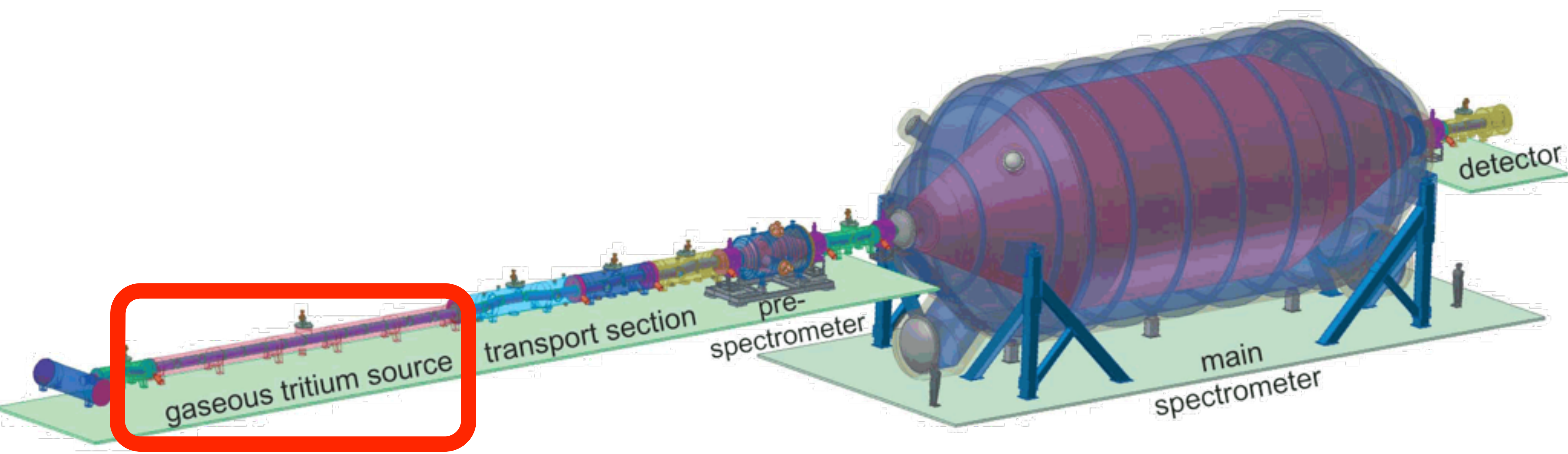

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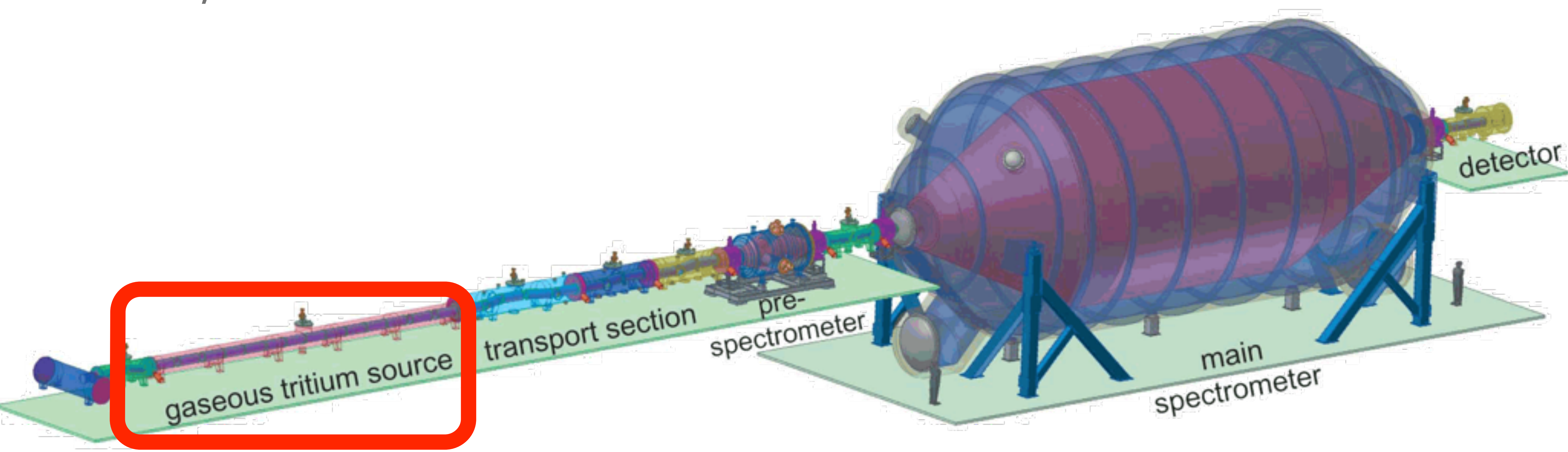
  - But most talks and documents start with “Tritium gas is injected into the Windowless Gas Tritium Source (WGTS)…”
- Tritium comes from the Tritium Laboratory Karlsruhe (TLK)
- But, TLK does not make tritium



KATRIN Tritium Source

- Seriously, where does KATRIN's tritium come from?

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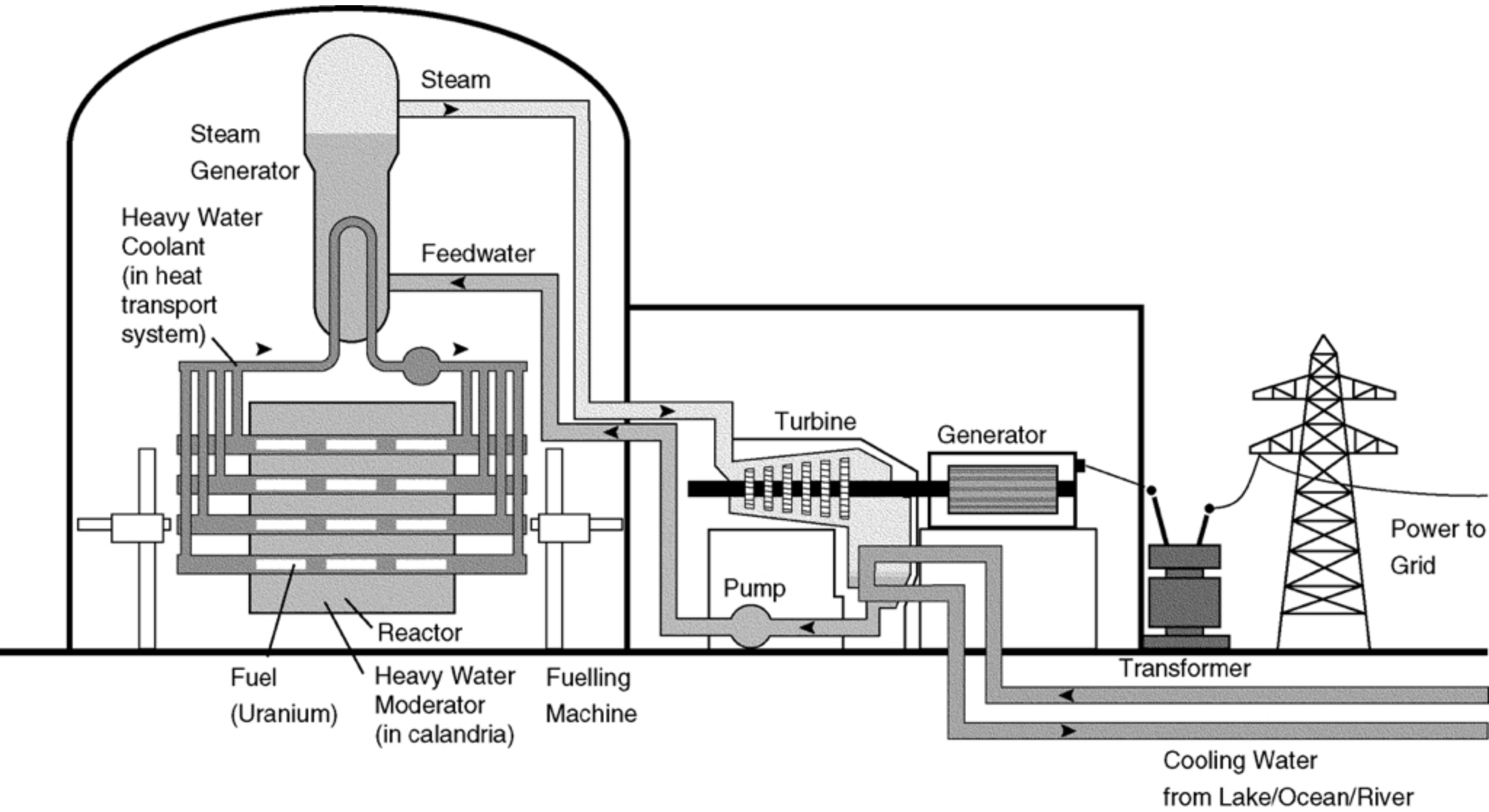
"The tritium at TLK comes from Canada in the form of metal hydride and is essentially a waste product from their natural uranium fuelled, heavy (deuterated) water moderated CANDU reactors."

Tritium Laboratory Karlsruhe (http://www.itep.kit.edu/english/258.php)

CANadian Deutrium Uranium (CANDU)



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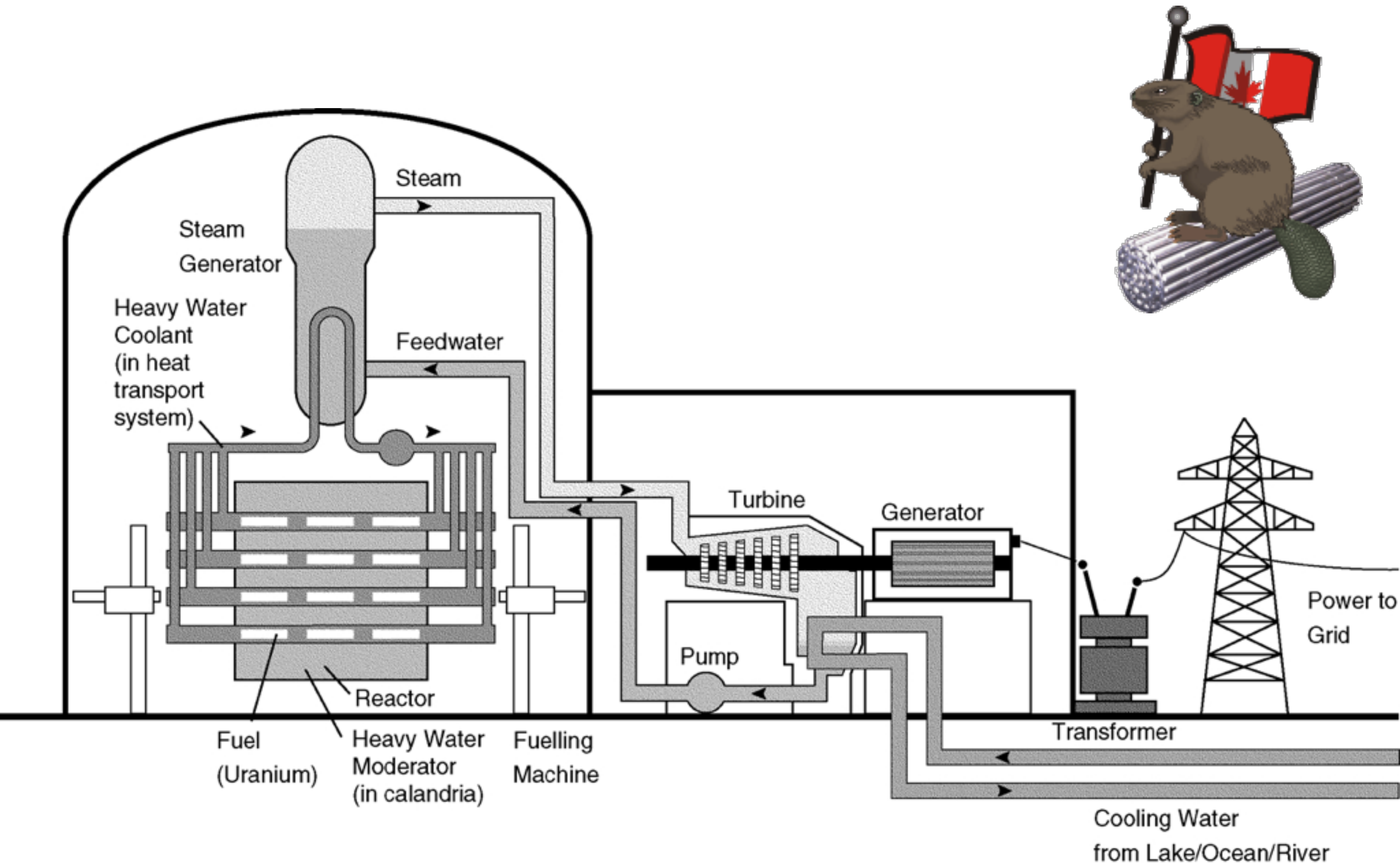
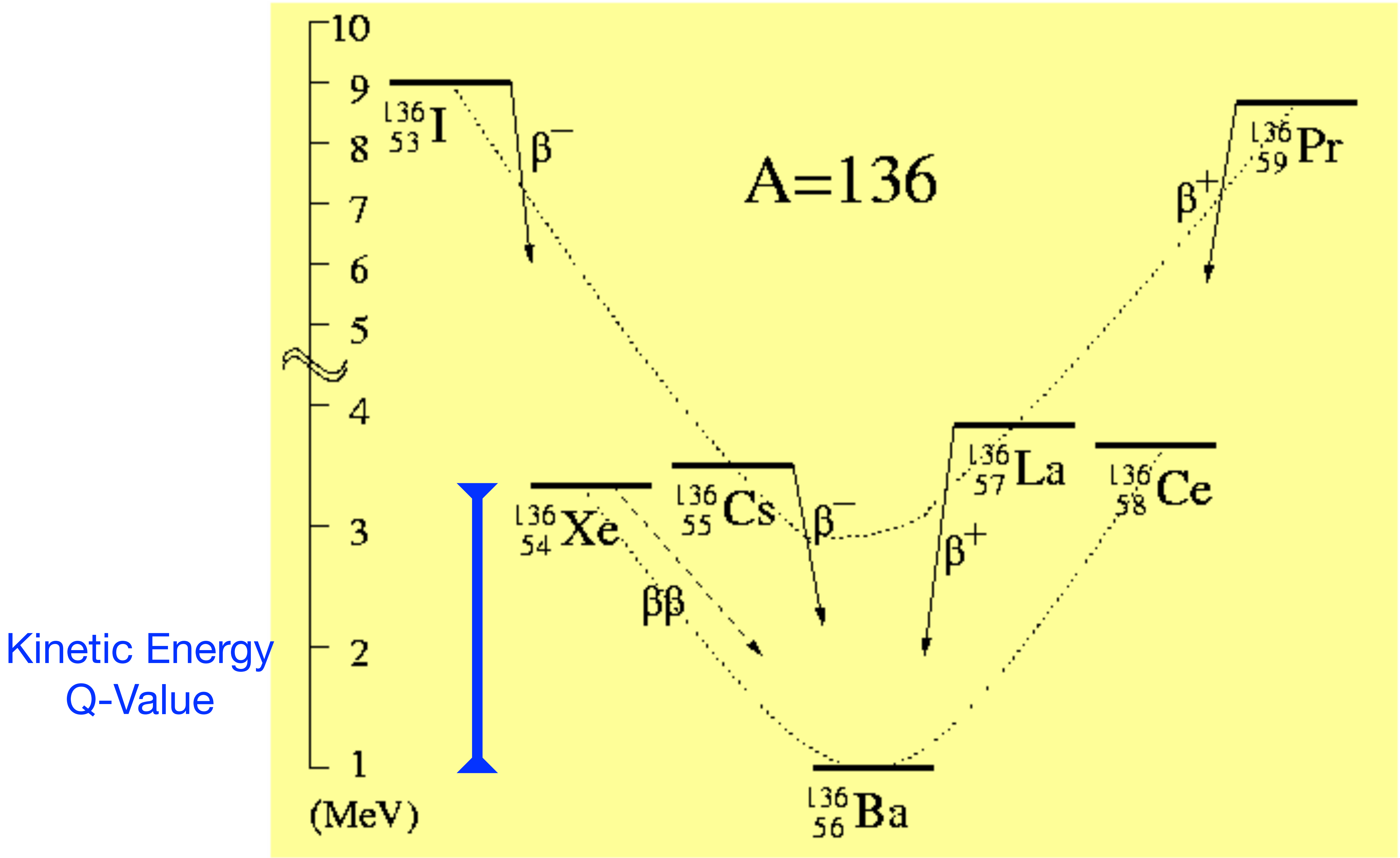
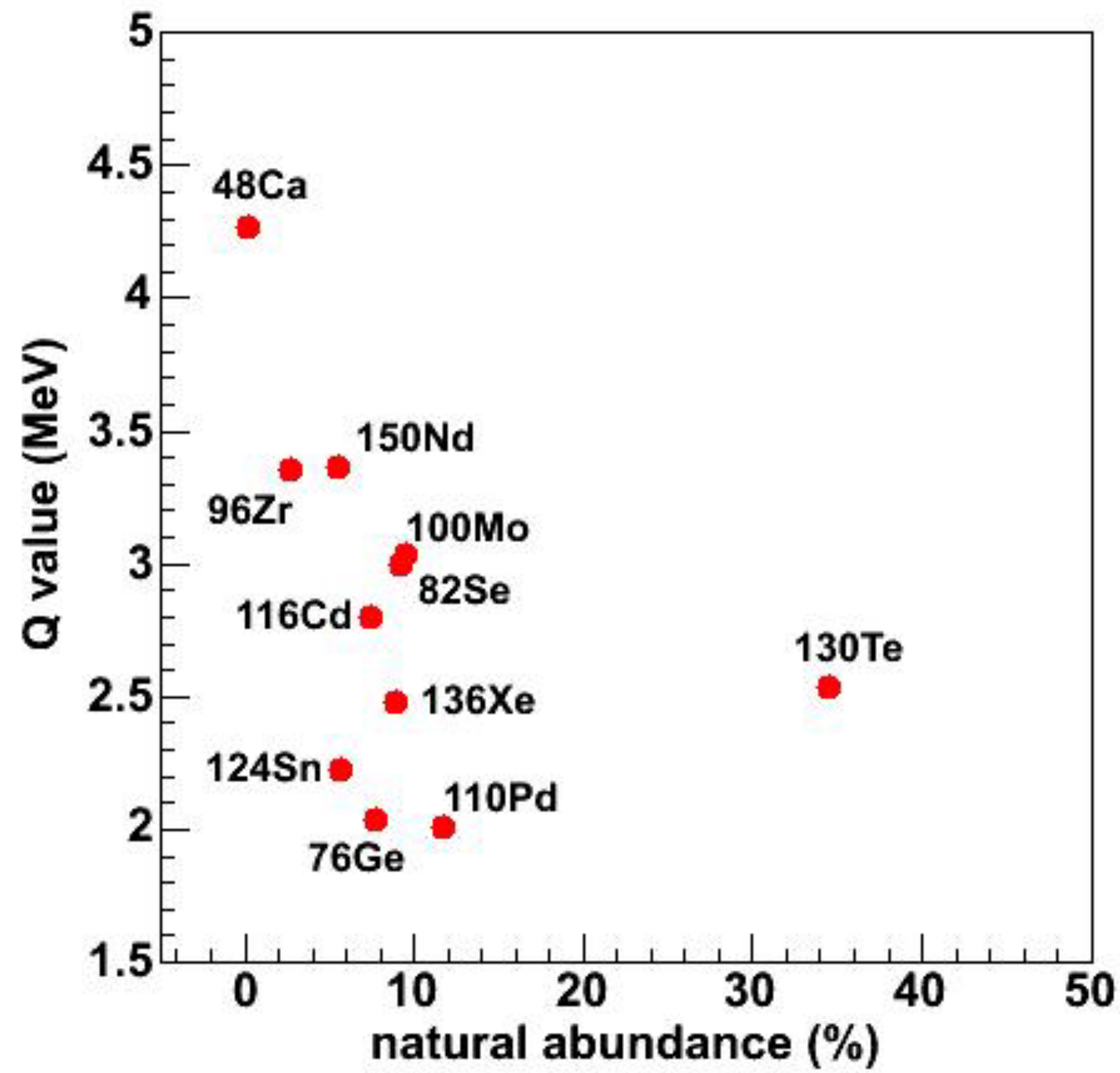


Double Beta-Decay Diagram



Double Beta-Decay Sources

- Higher Q-value is better
    - High decay rate
    - Less radioactive backgrounds
- Larger natural abundance is cheaper



Solar/Reactor

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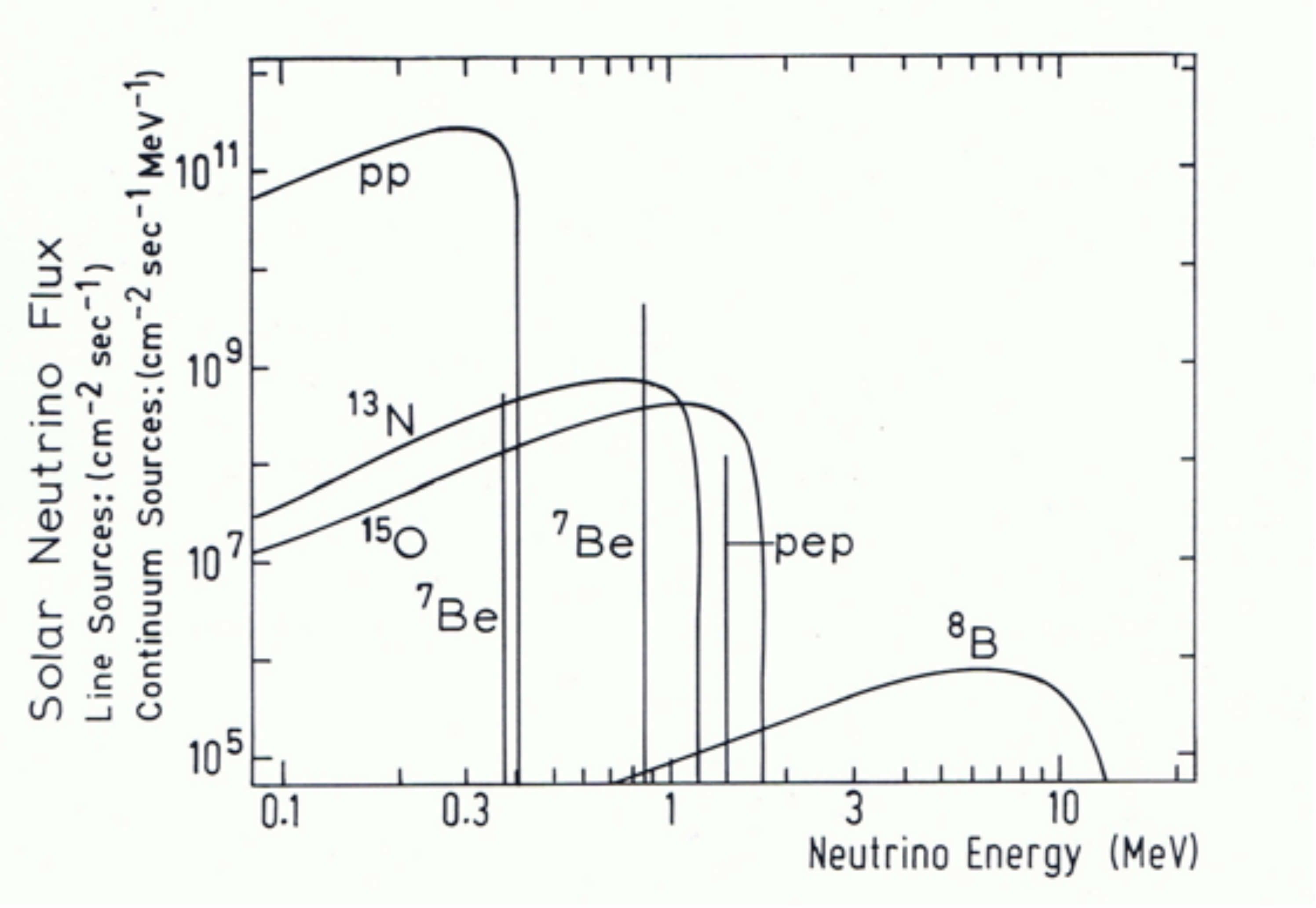
Solar Neutrino Flux



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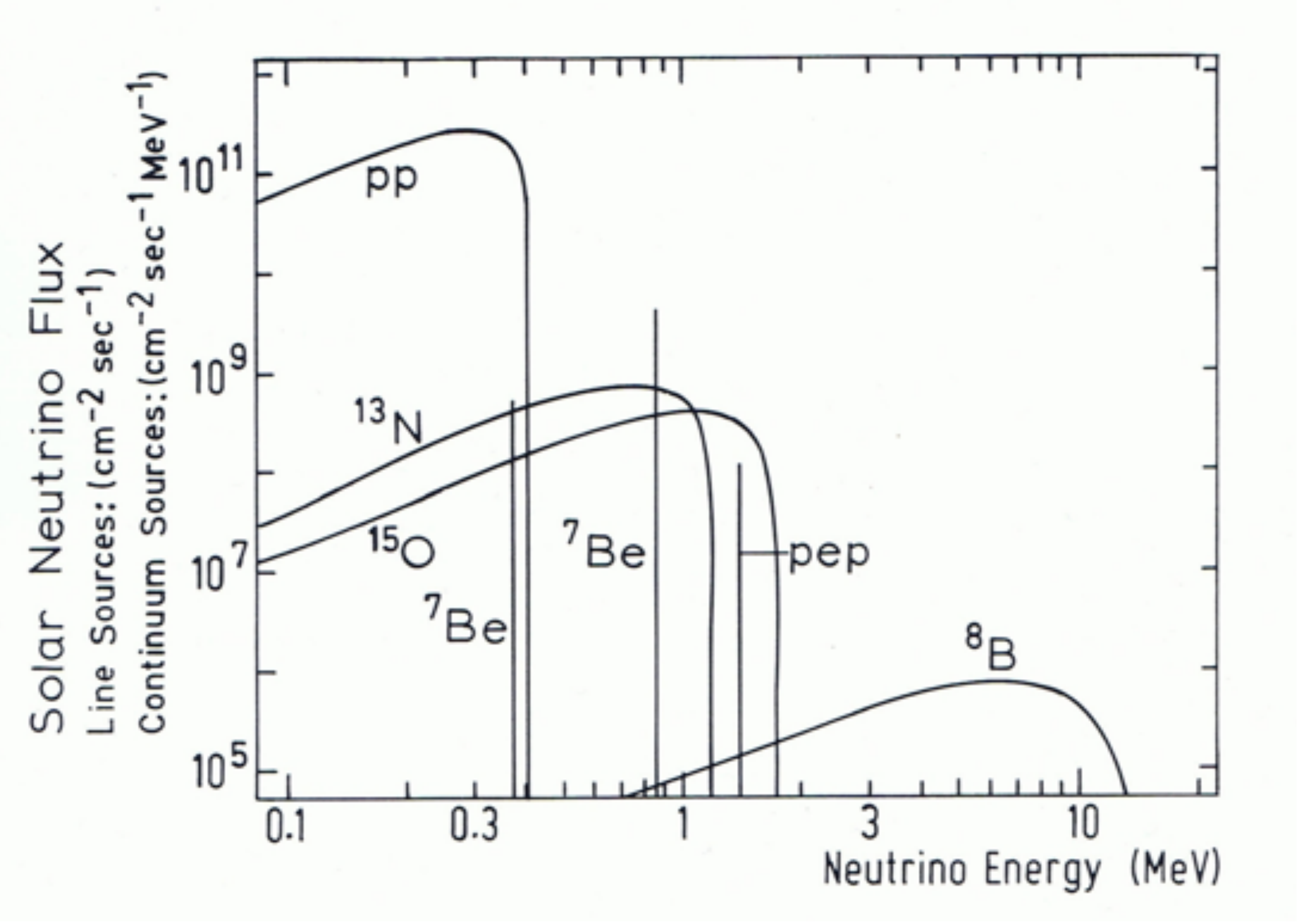
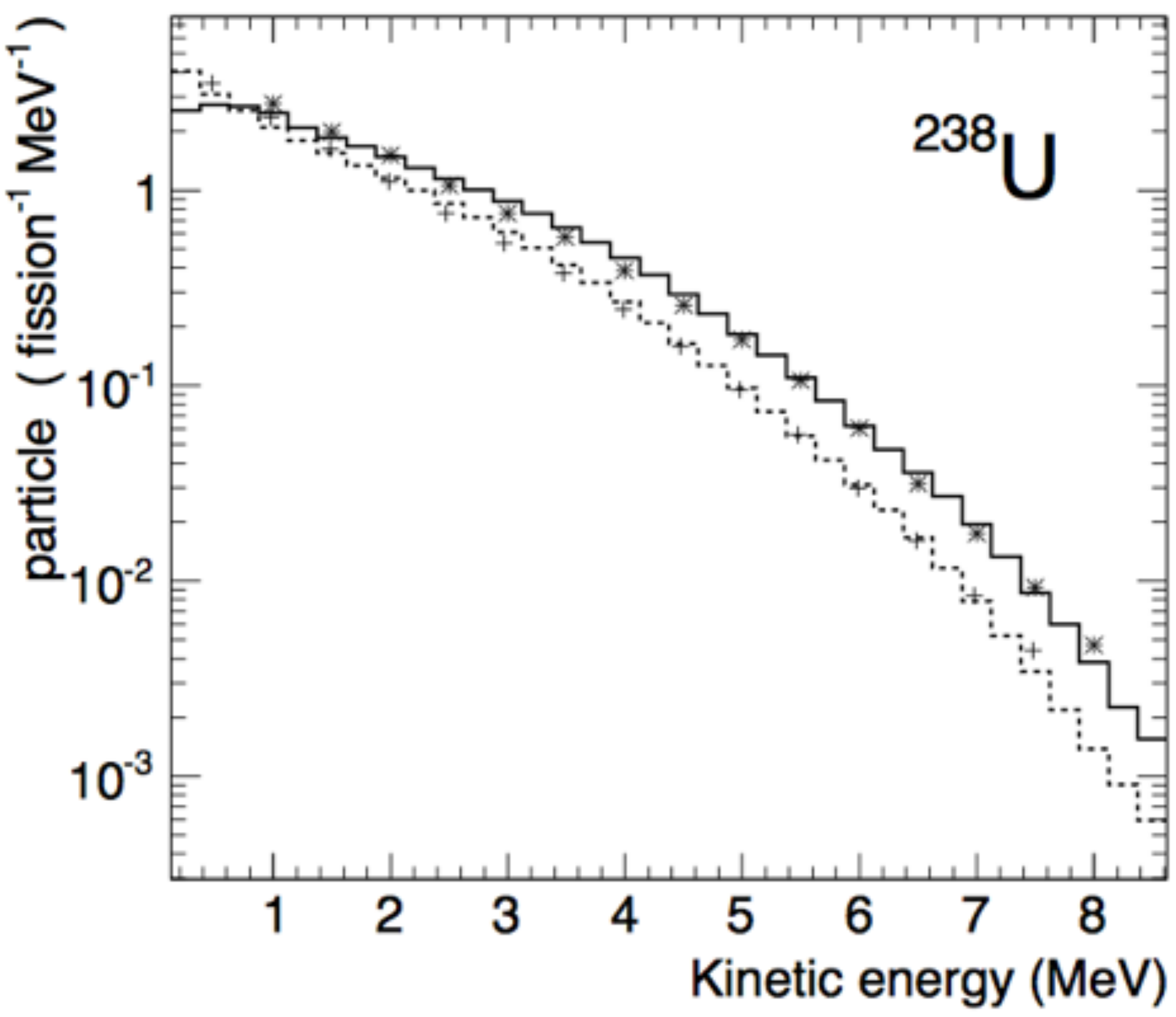


Reactor Neutrino Flux



Low Energy (semi) Natural Sources

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- Tritium: Canada

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- Double Beta-Decay: Radioactive Isotopes

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- Double Beta-Decay: Radioactive Isotopes
- Solar: Sun

Low Energy (semi) Natural Sources

- Tritium: Canada
- Double Beta-Decay: Radioactive Isotopes
- Solar: Sun
- Reactor: Reactors

Scientist Impact

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- Scientists do not control nuclear reactors or the sun

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- Excellent resources can be found online
  - Reactor
    - K. Heeger - http://neutrino.physics.wisc.edu/talks/old/Heeger_reactornu.pdf
  - Double Beta-Decay
    - Carter Hall - http://www-conf.slac.stanford.edu/ssi/2010/Hall080610.pdf

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- Now, a look at man-made neutrinos, i.e. beams

Conventional Neutrino Beam

http://www.symmetrymagazine.org/article/november-2012/how-to-make-a-neutrino-beam http://www.symmetrymagazine.org/article/november-2012/how-to-make-a-neutrino-beam

Where it All Starts (Fermilab)

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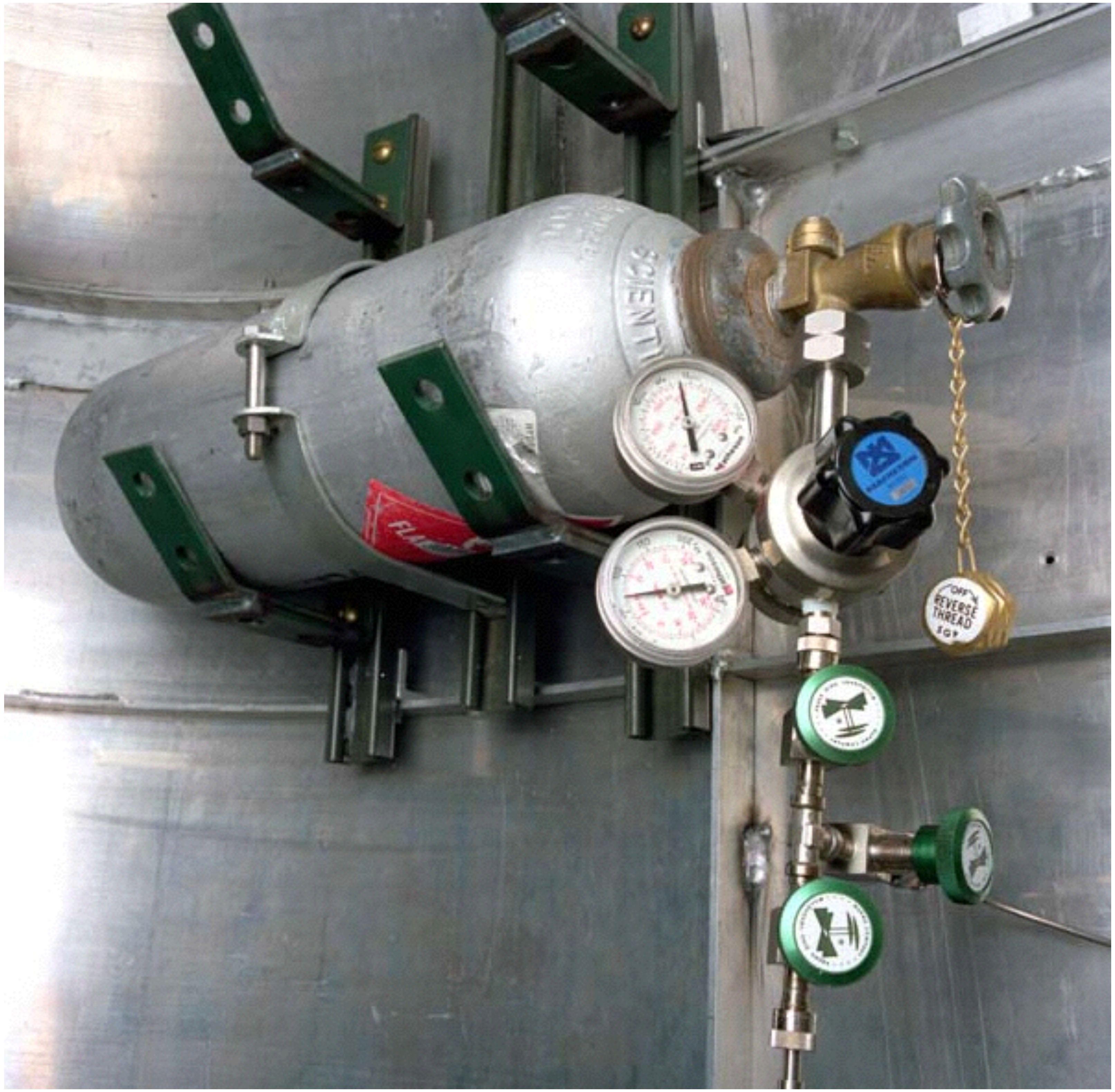
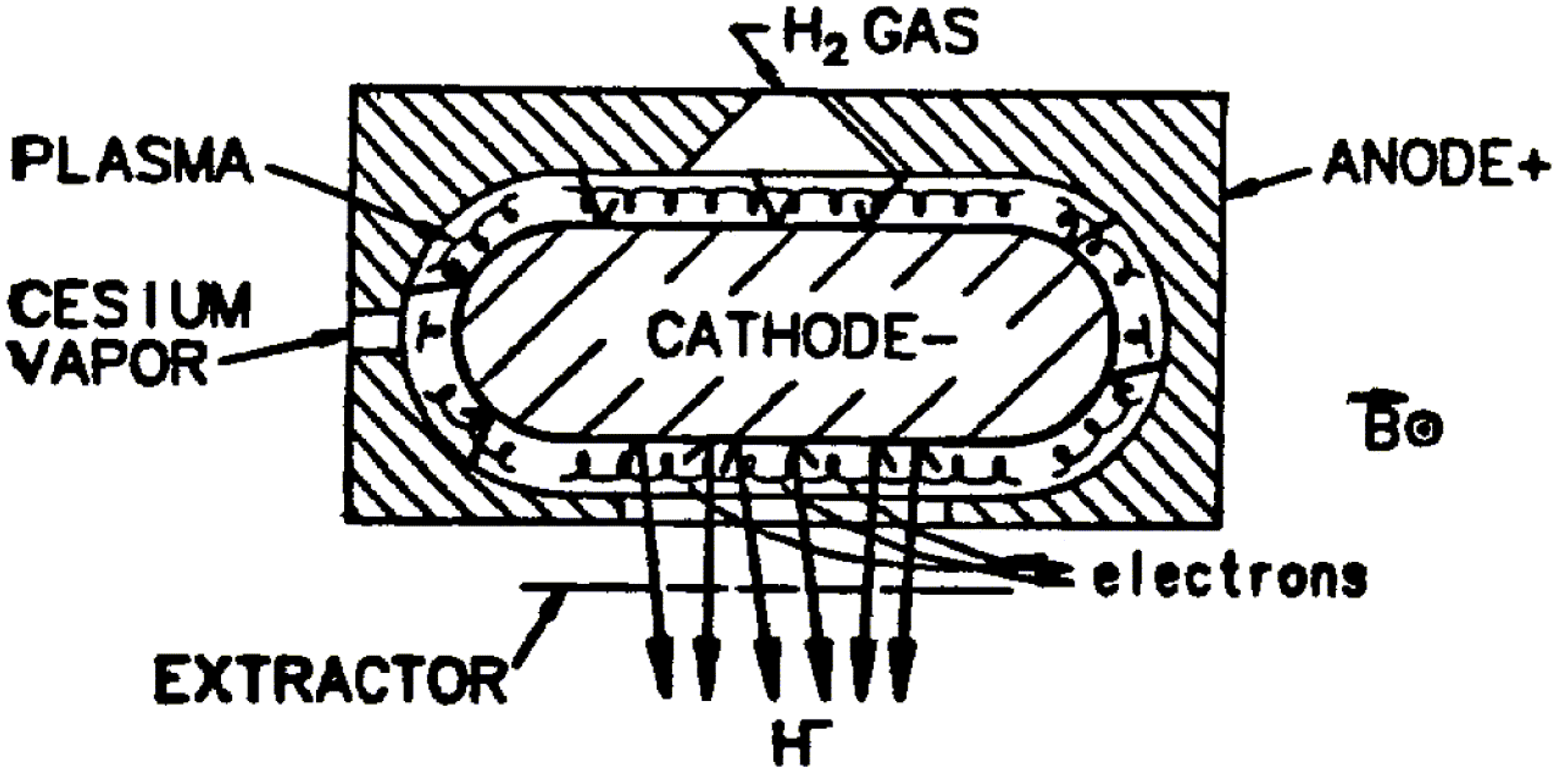


A canister of hydrogen gas

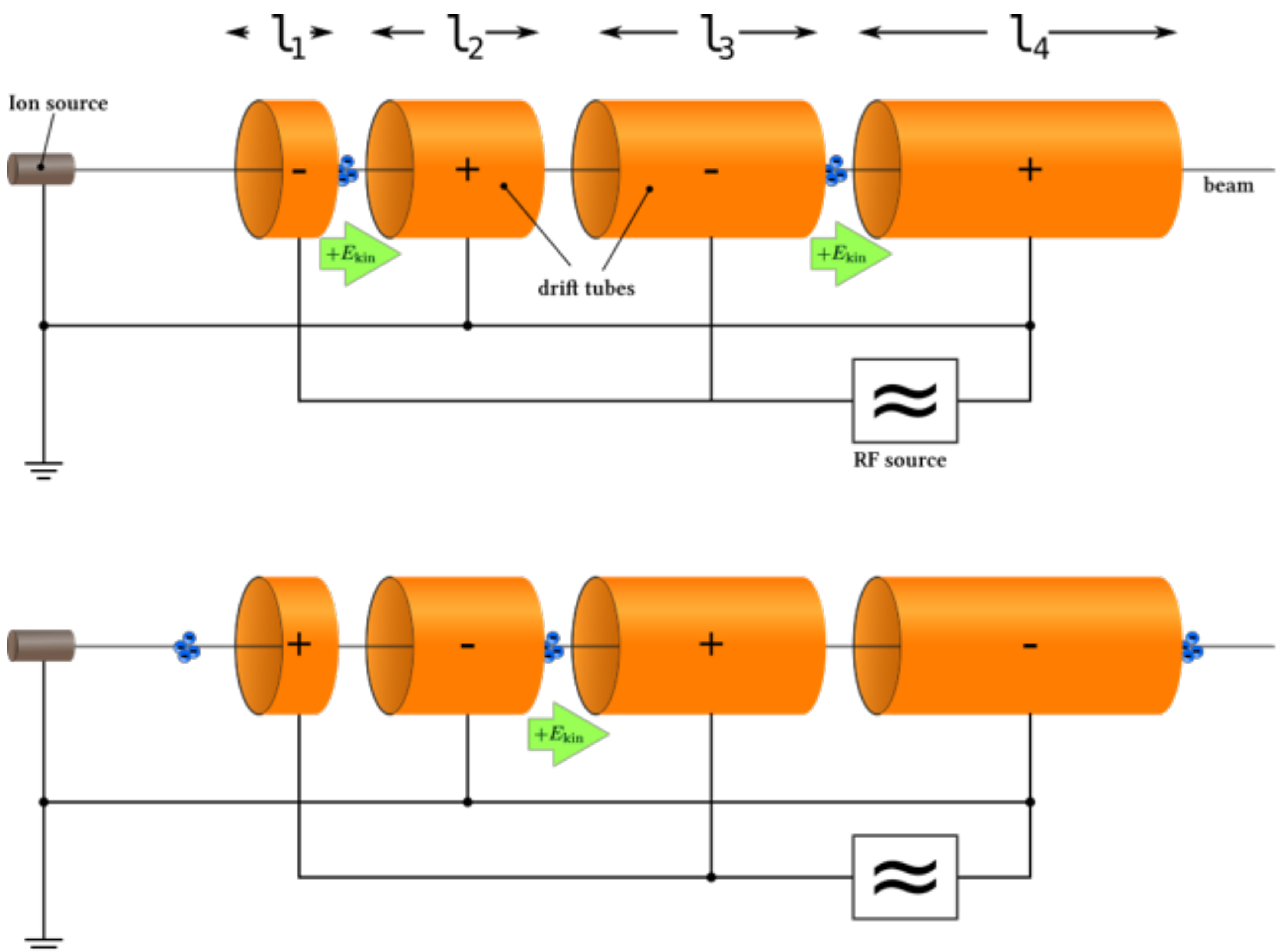
Ions

- Hydrogen gas is fed into H^- ion creator
  - In this case a plasma magnetron
  - Continuous feed

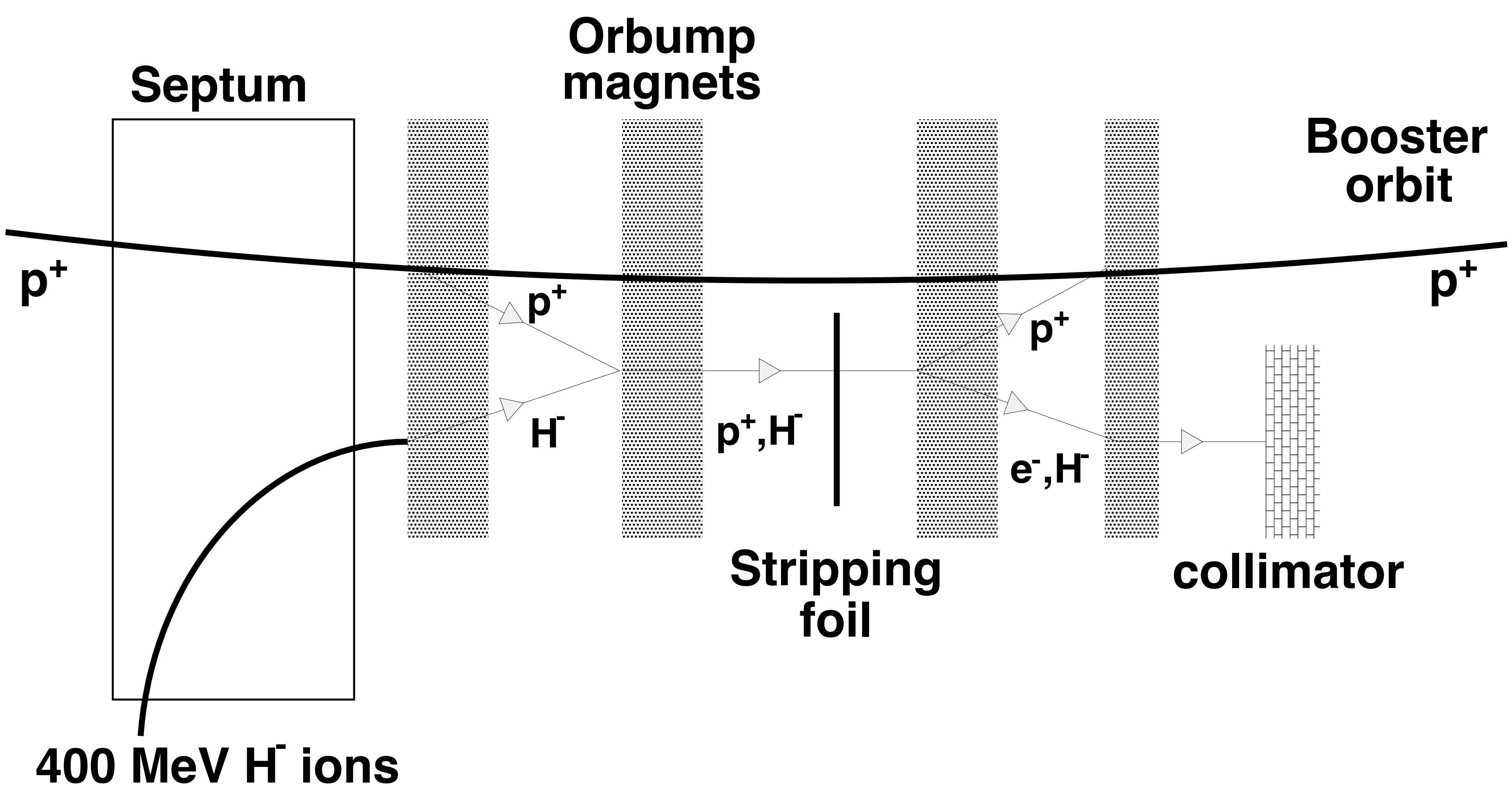


Linear Accelerator

- Ions are continuously fed into a linear accelerator (linac)
- Accelerated to MeV energies and slightly ‘bunched’

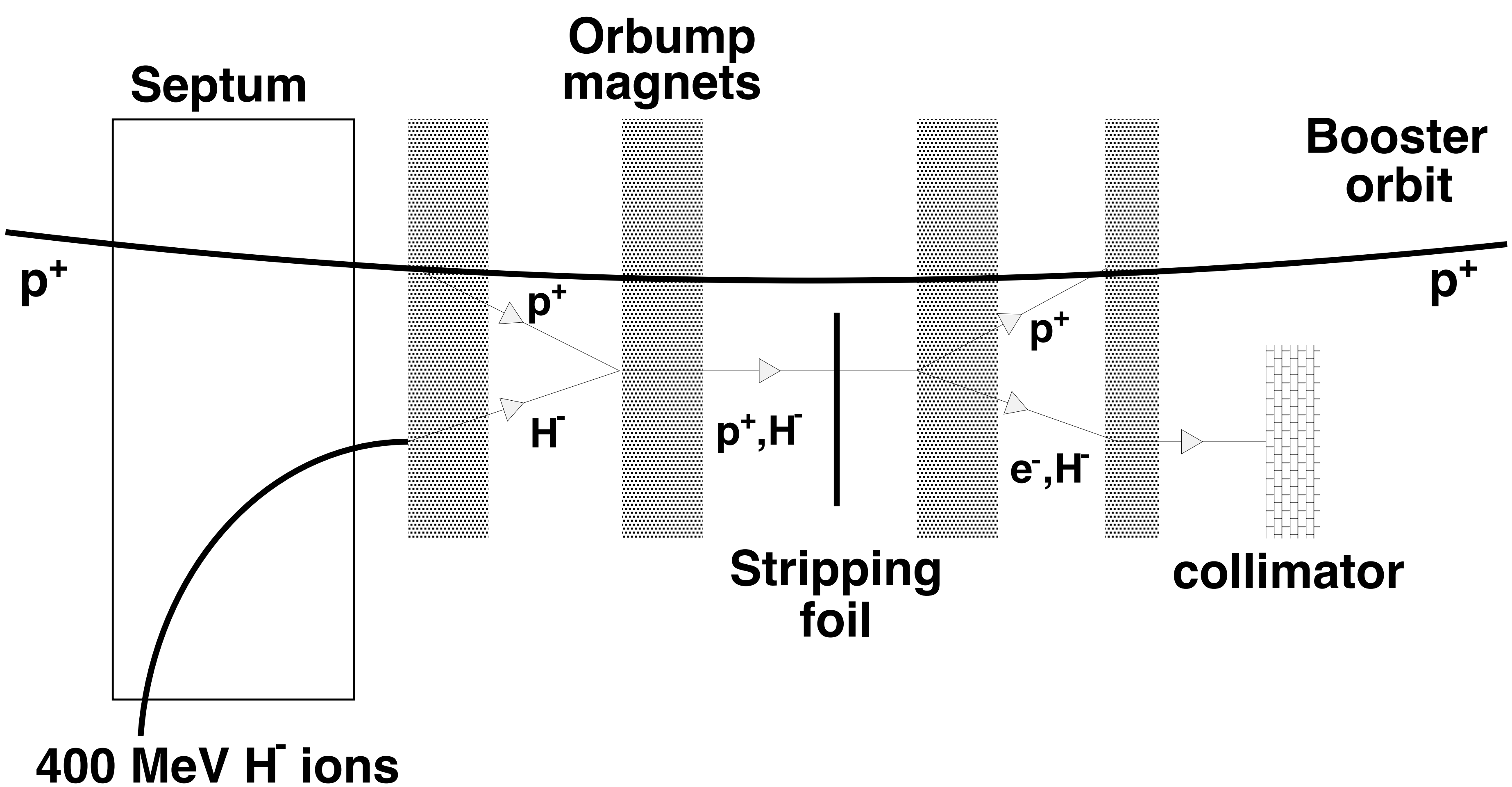


Ions to Protons



Ions to Protons

- After the linear accelerator the ions are at ~400 MeV



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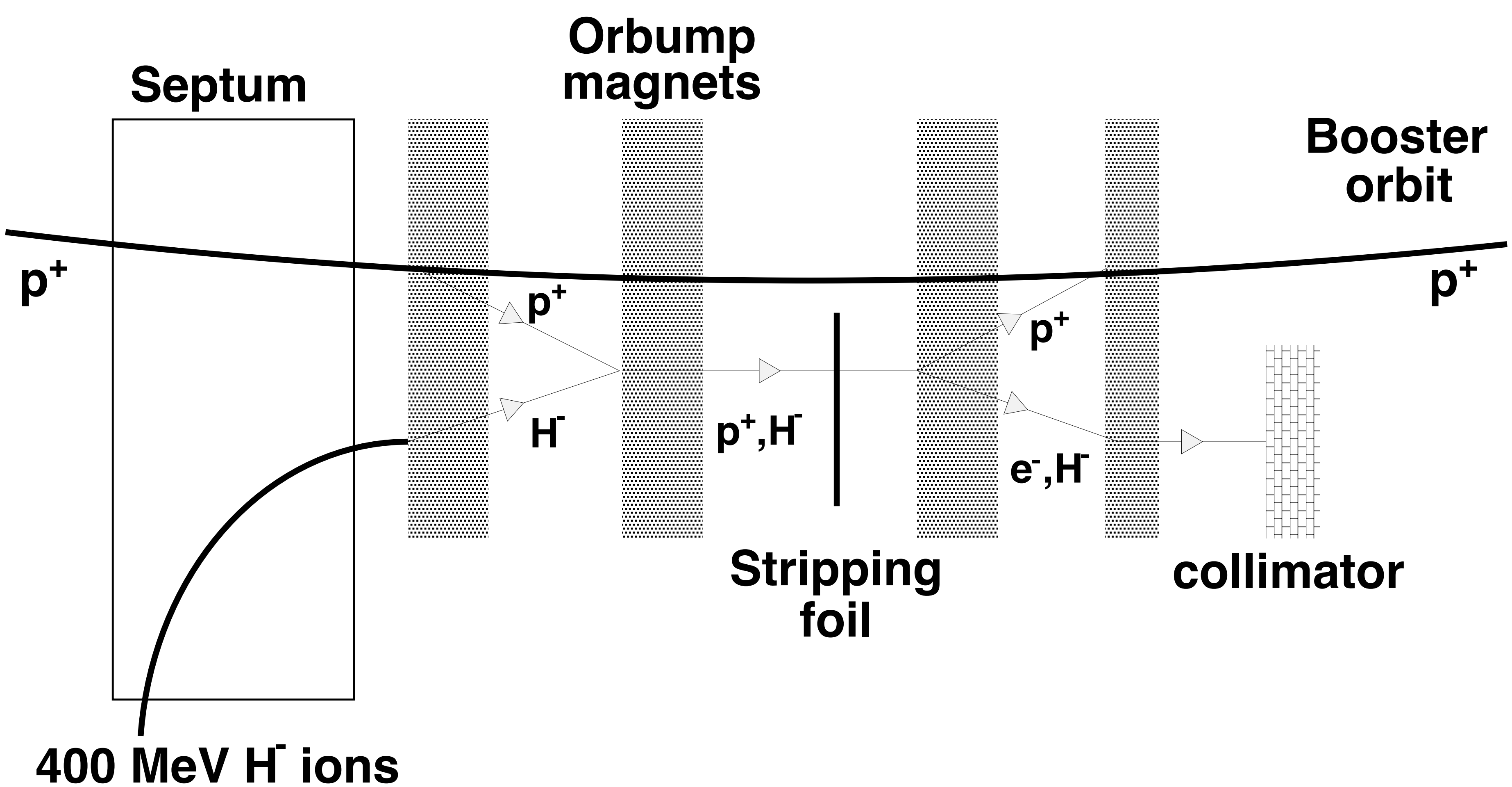
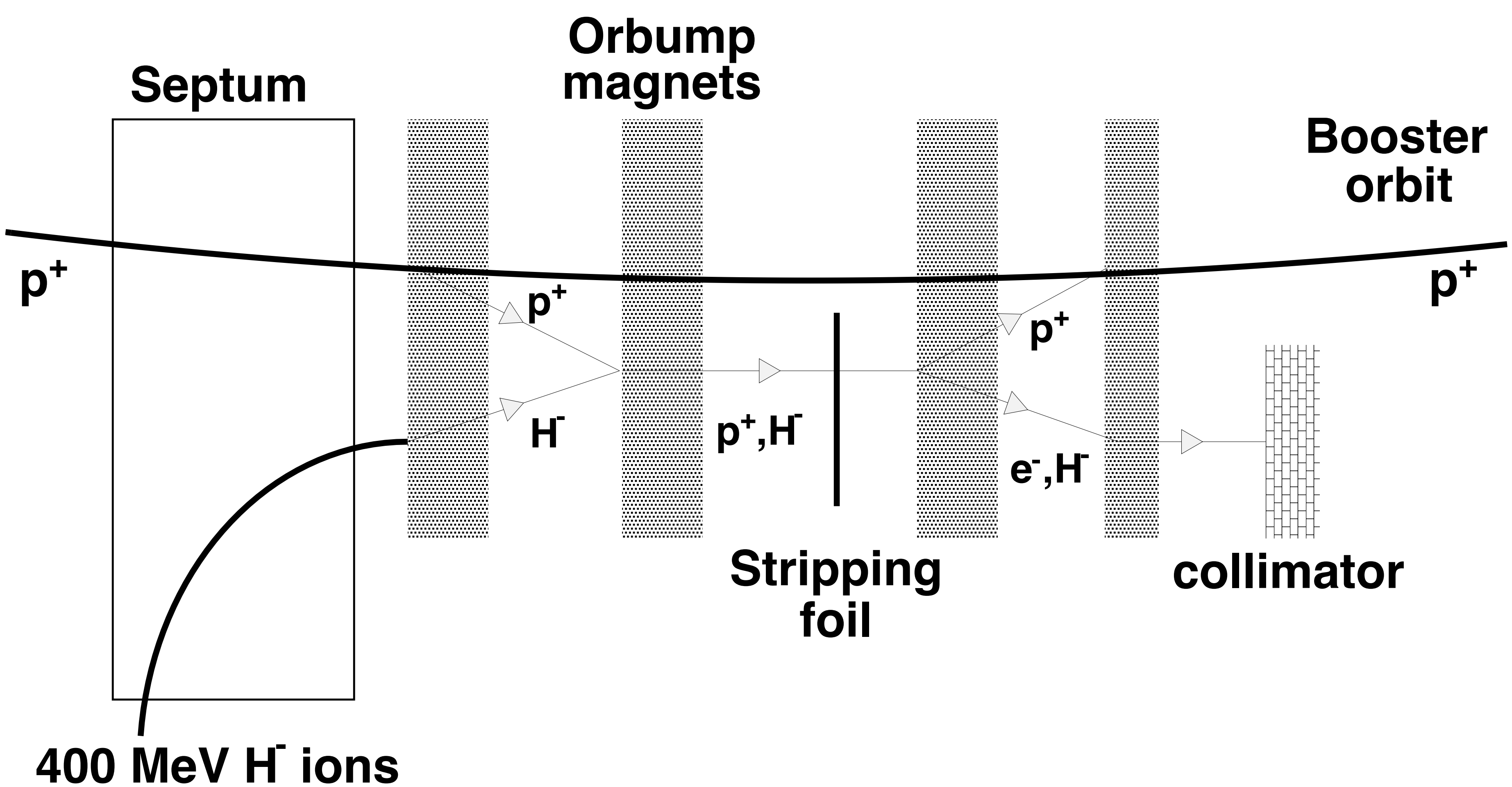
- After the linear accelerator the ions are at ~400 MeV
- Take the ions and put them into a proton accelerator



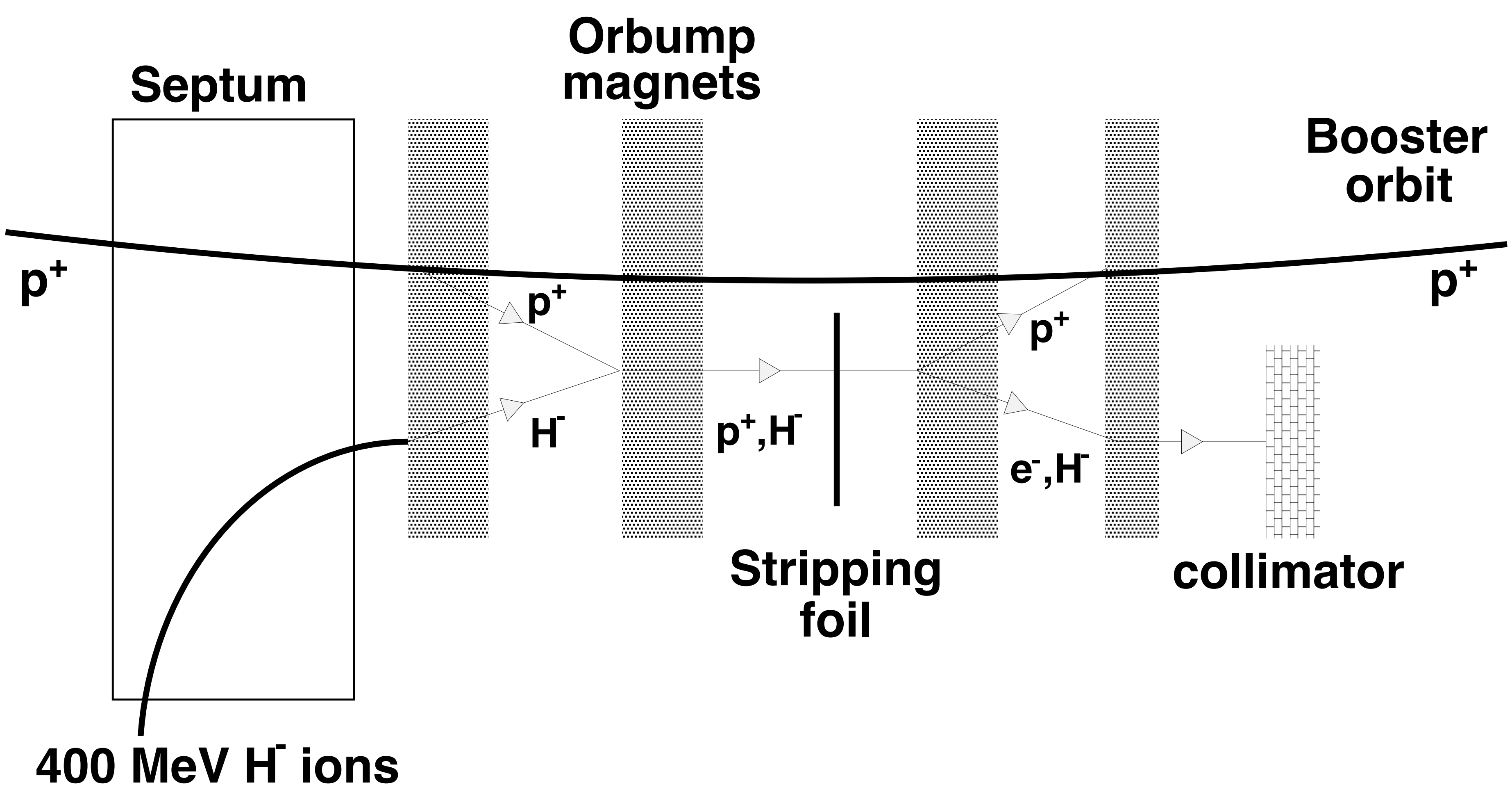
Ions to Protons

- After the linear accelerator the ions are at ~400 MeV
- Take the ions and put them into a proton accelerator
  - Strip off the electron



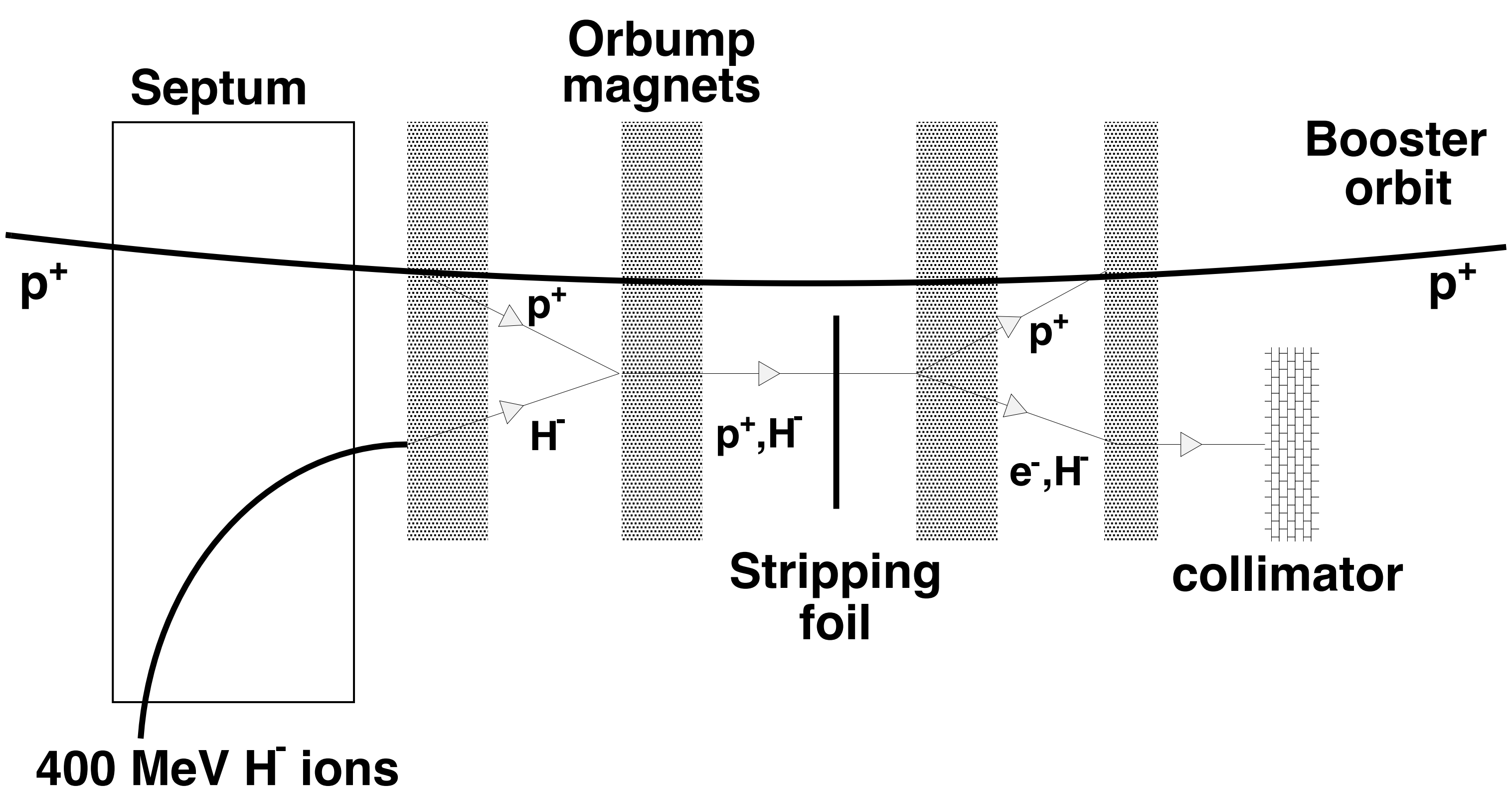
Ions to Protons

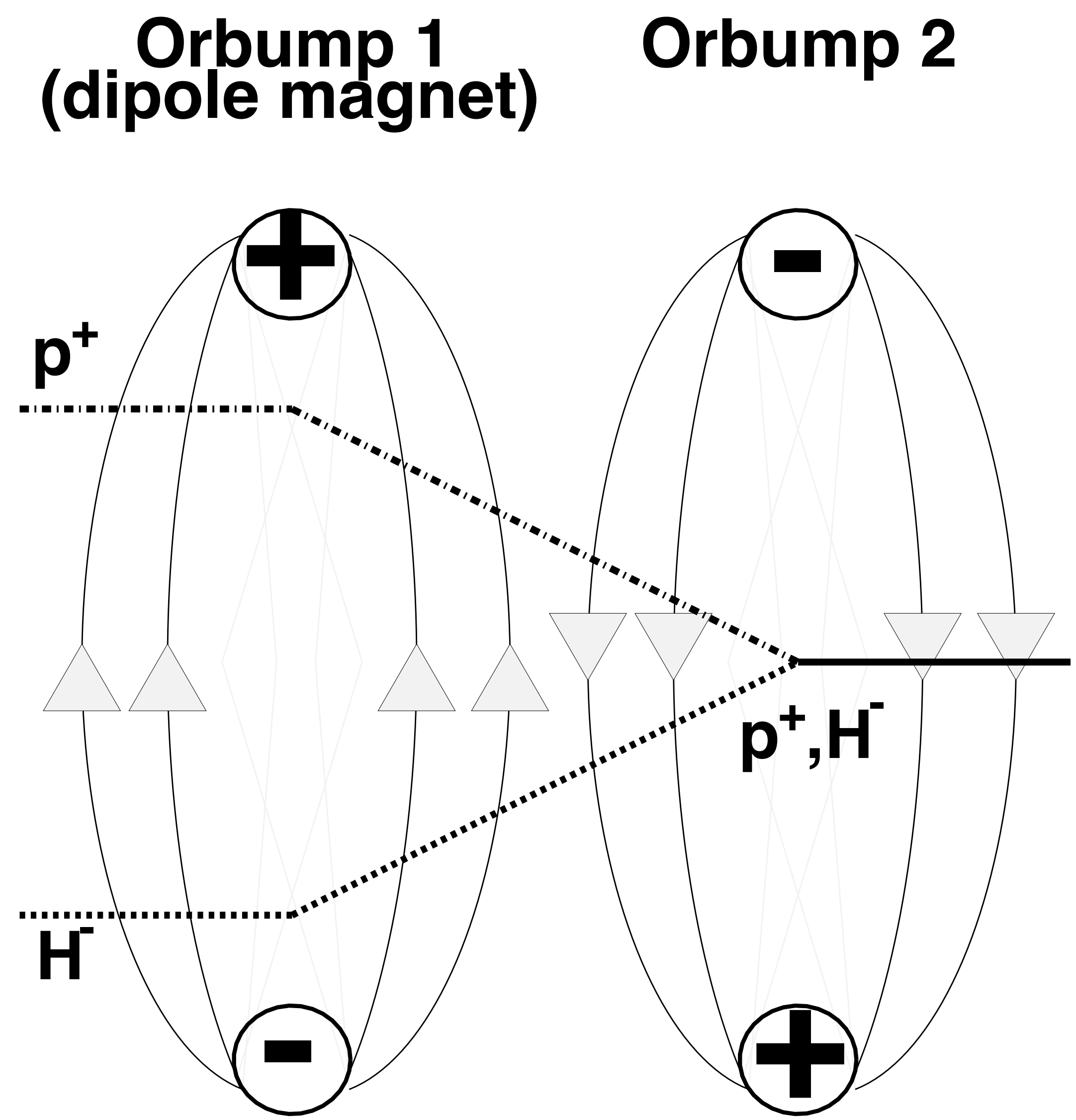
- After the linear accelerator the ions are at ~400 MeV
- Take the ions and put them into a proton accelerator
  - Strip off the electron
  - Combine with a circulating proton beam (FNAL Booster)



Ions to Protons

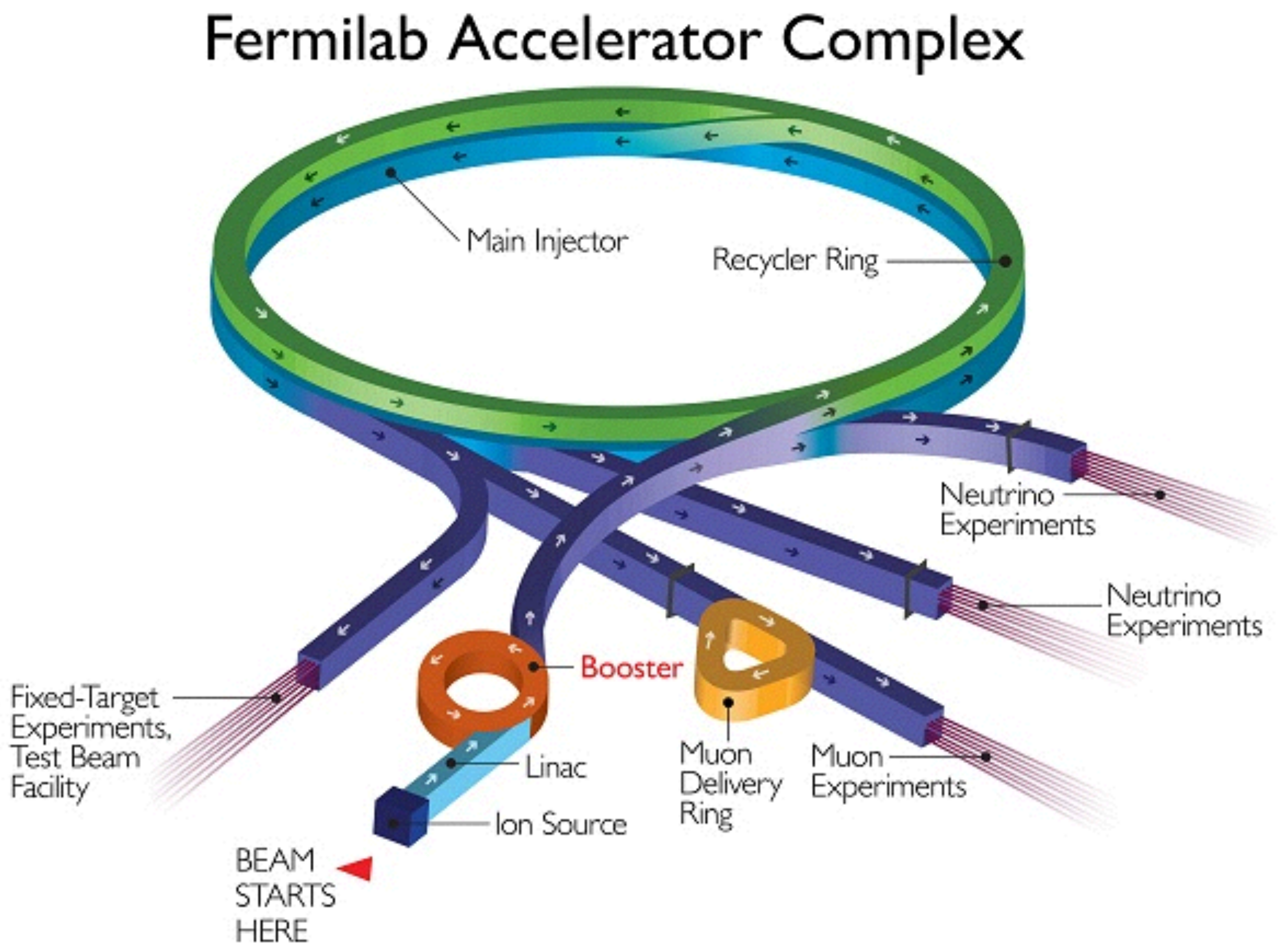
- Use the same magnets for (de)focusing the p+ and H- because of the opposite sign





Proton Acceleration

- Accelerate protons in Booster to 8 GeV
  - Extract for fixed target experiments (rare particle and MiniBooNE)
  - Extract for further acceleration for (MINOS, NOvA)



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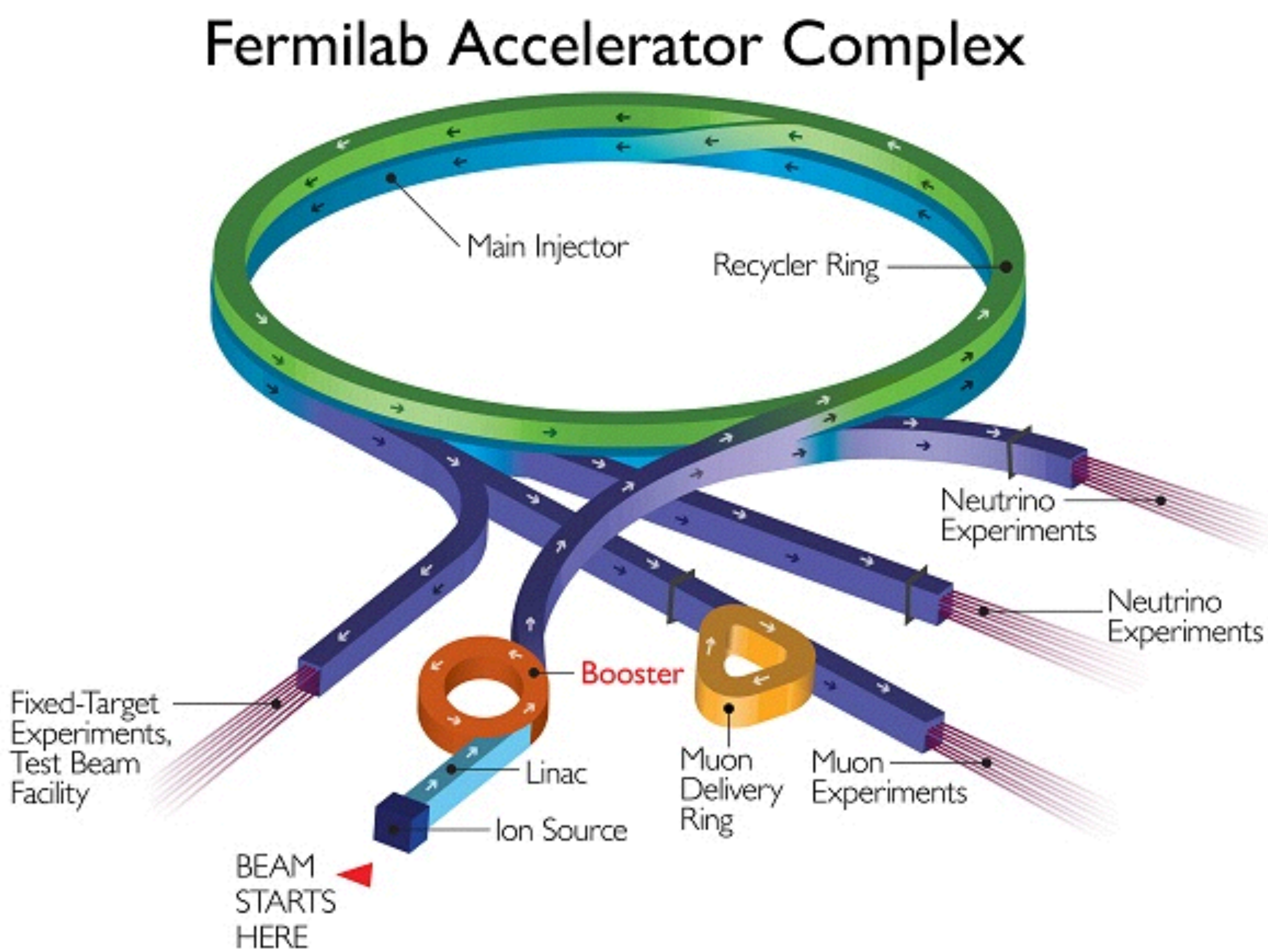
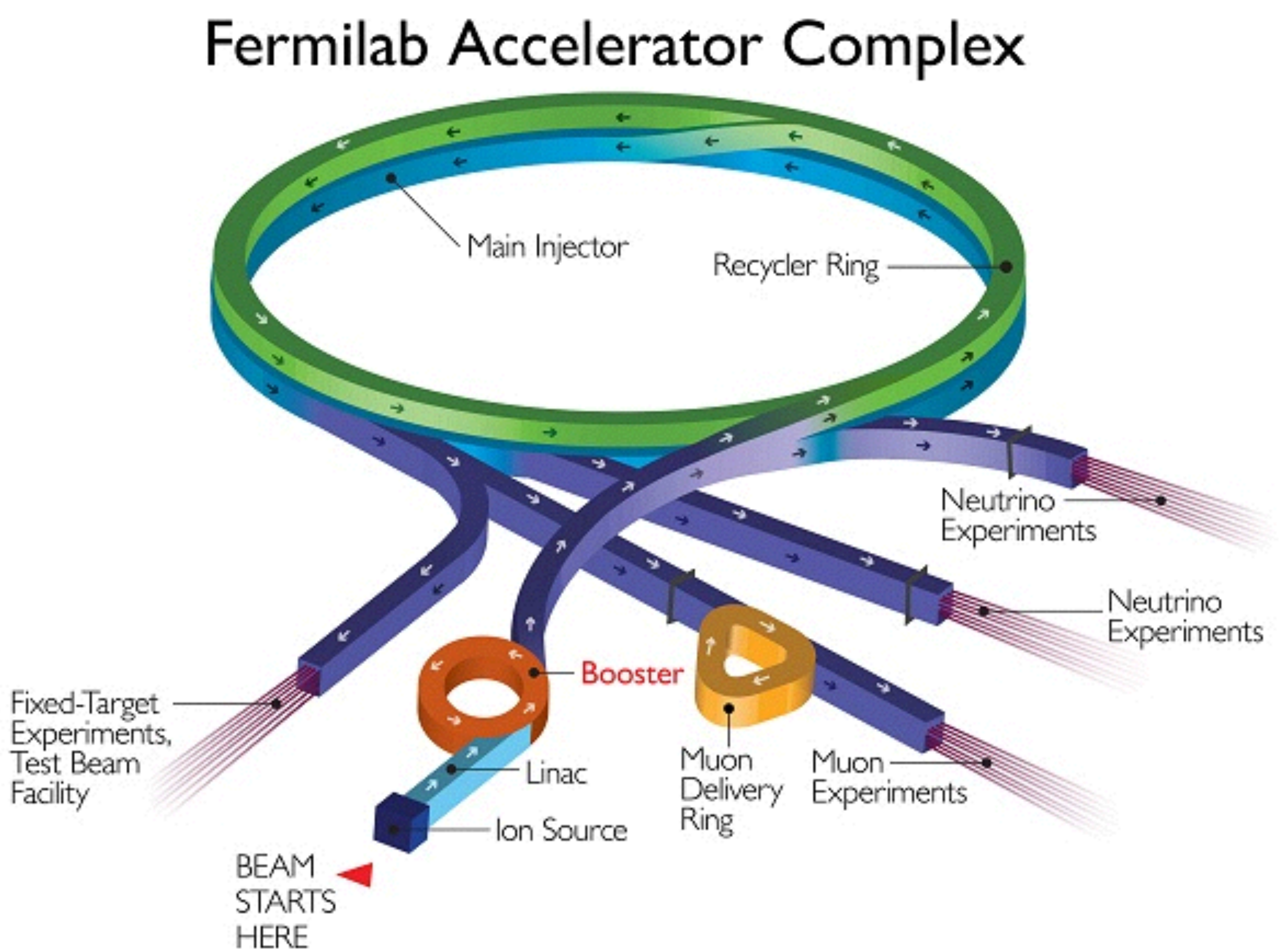


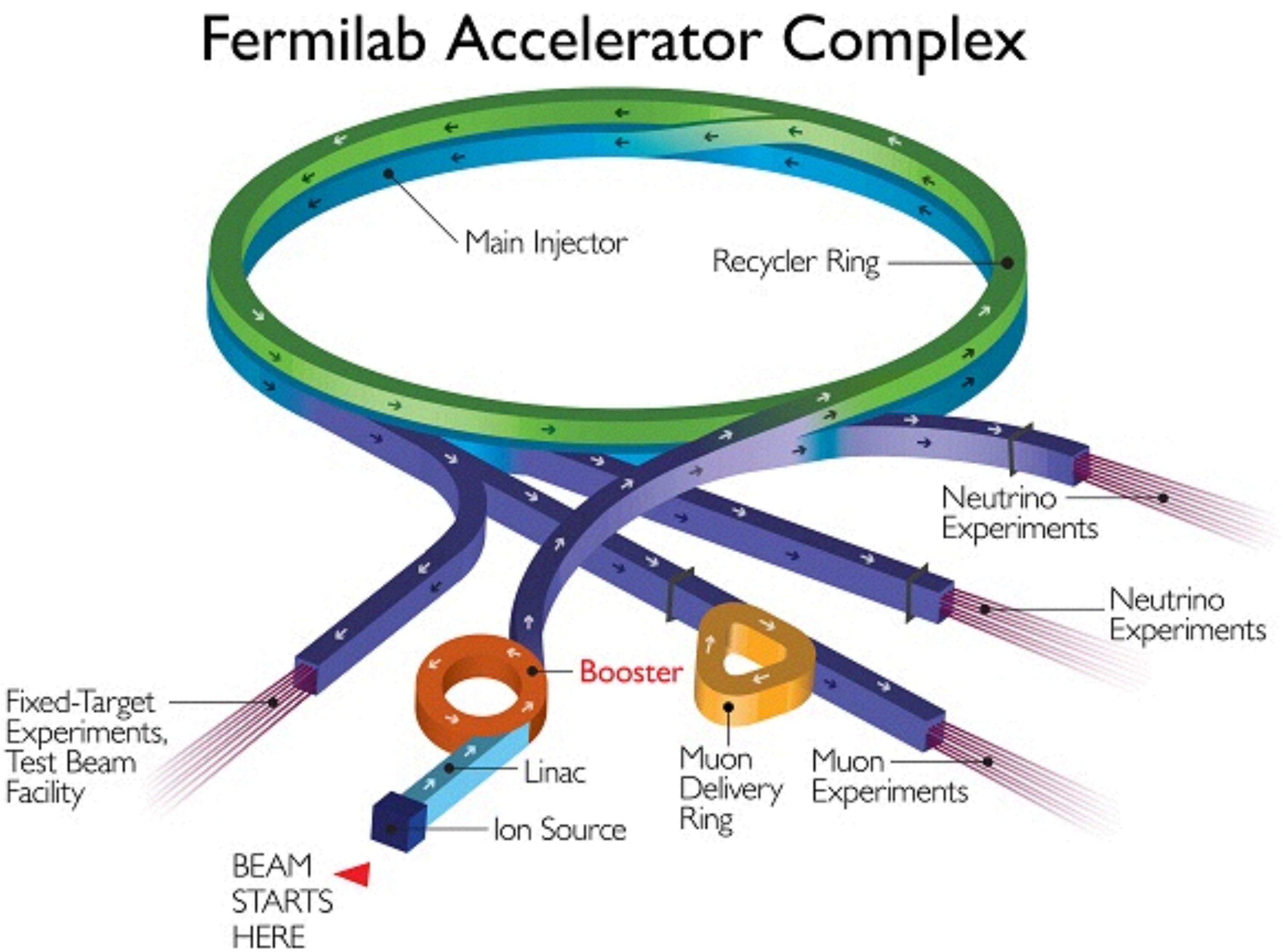
Proton Acceleration

- 2nd accelerator (Main Injector) with is 7x the circumference of Booster

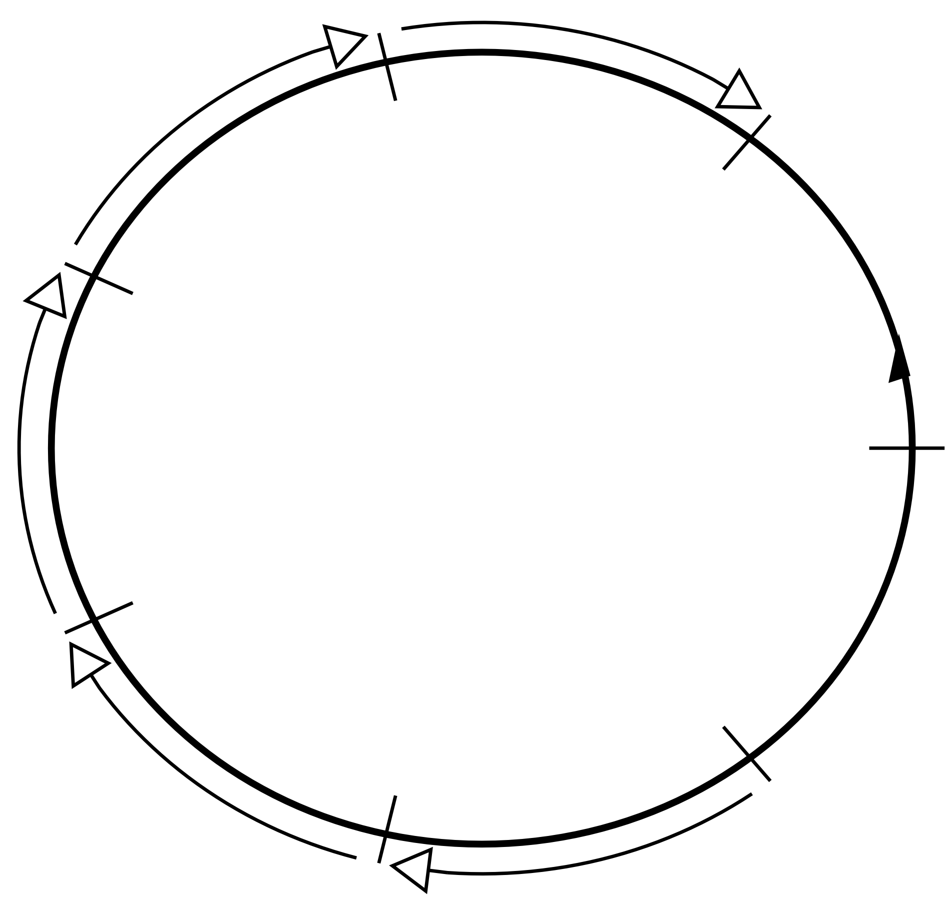


Proton Acceleration

- 2nd accelerator (Main Injector) with is 7x the circumference of Booster
- Can load 6 Booster 'batches'

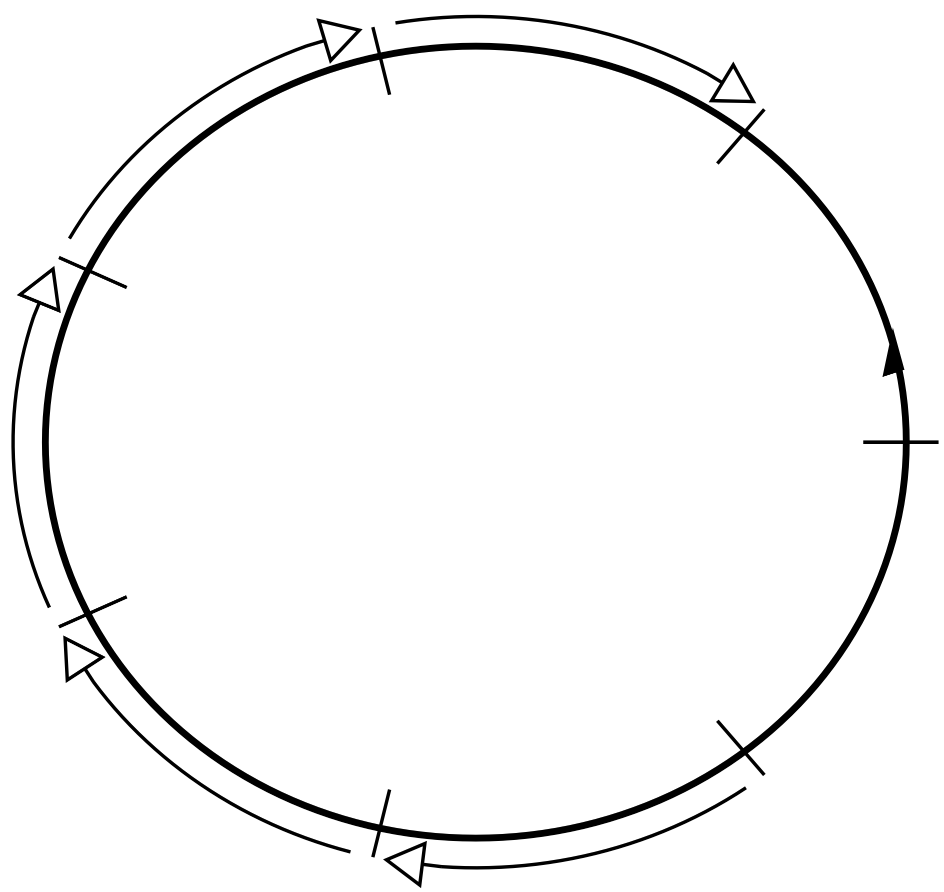


Main Injector



Main Injector

- Why only 6 batches if there are 7 total?



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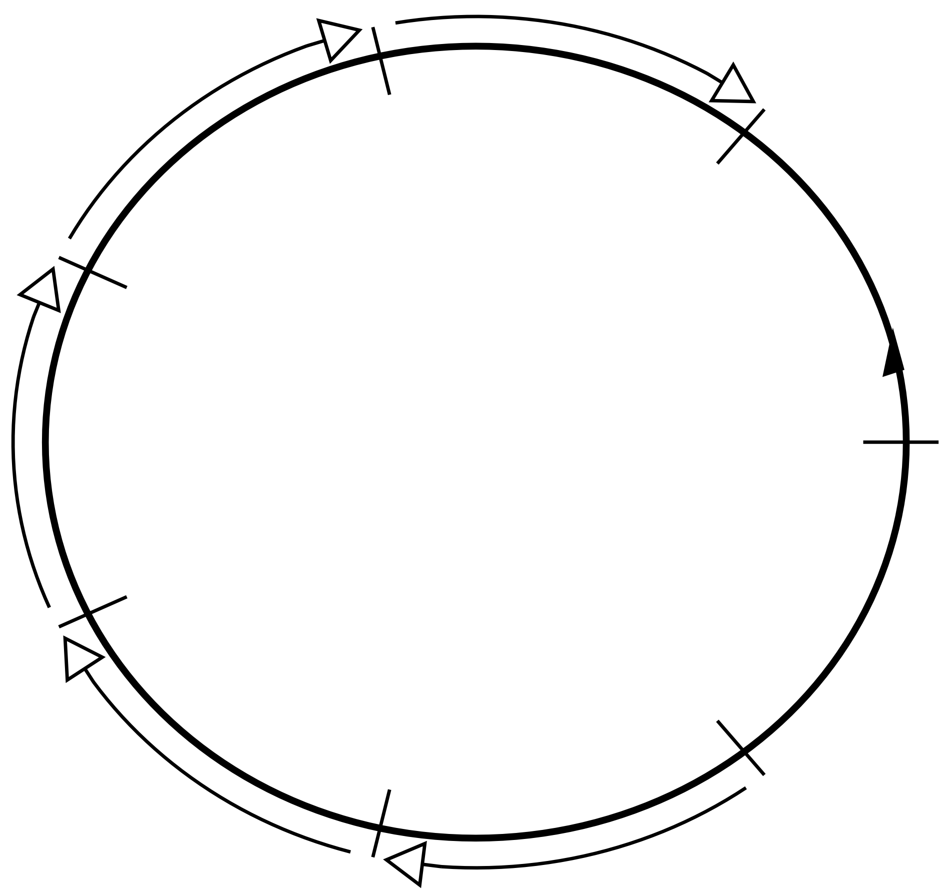

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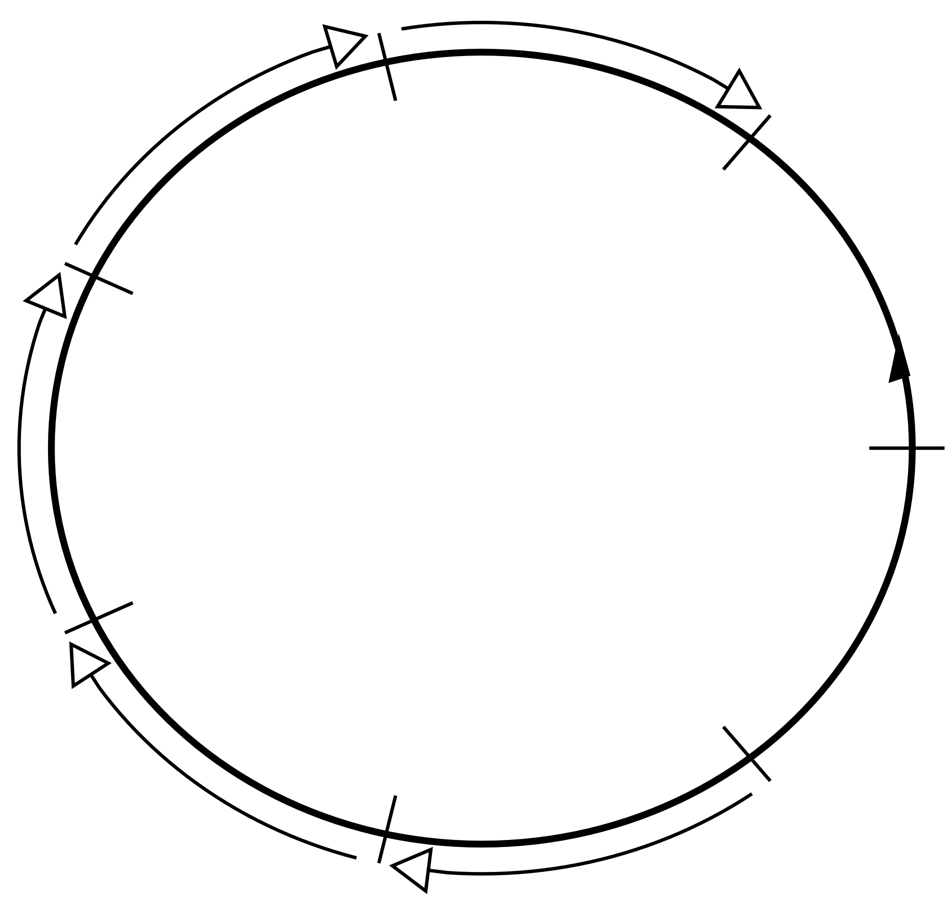
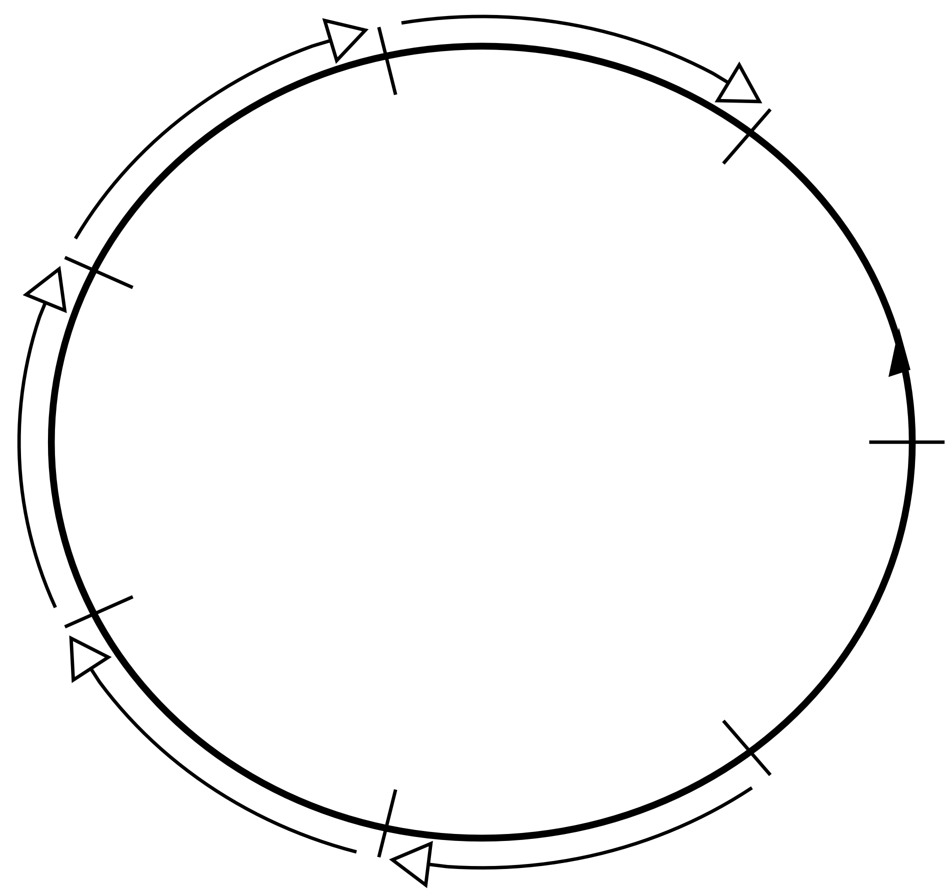
  - In diagram below only 5 batches filled



Main Injector

- Why only 6 batches if there are 7 total?
  - Need empty space, ‘notch’, to extract beam
  - In diagram below only 5 batches filled
  - The reason is due to a process called Slip Stacking



Slip Stacking

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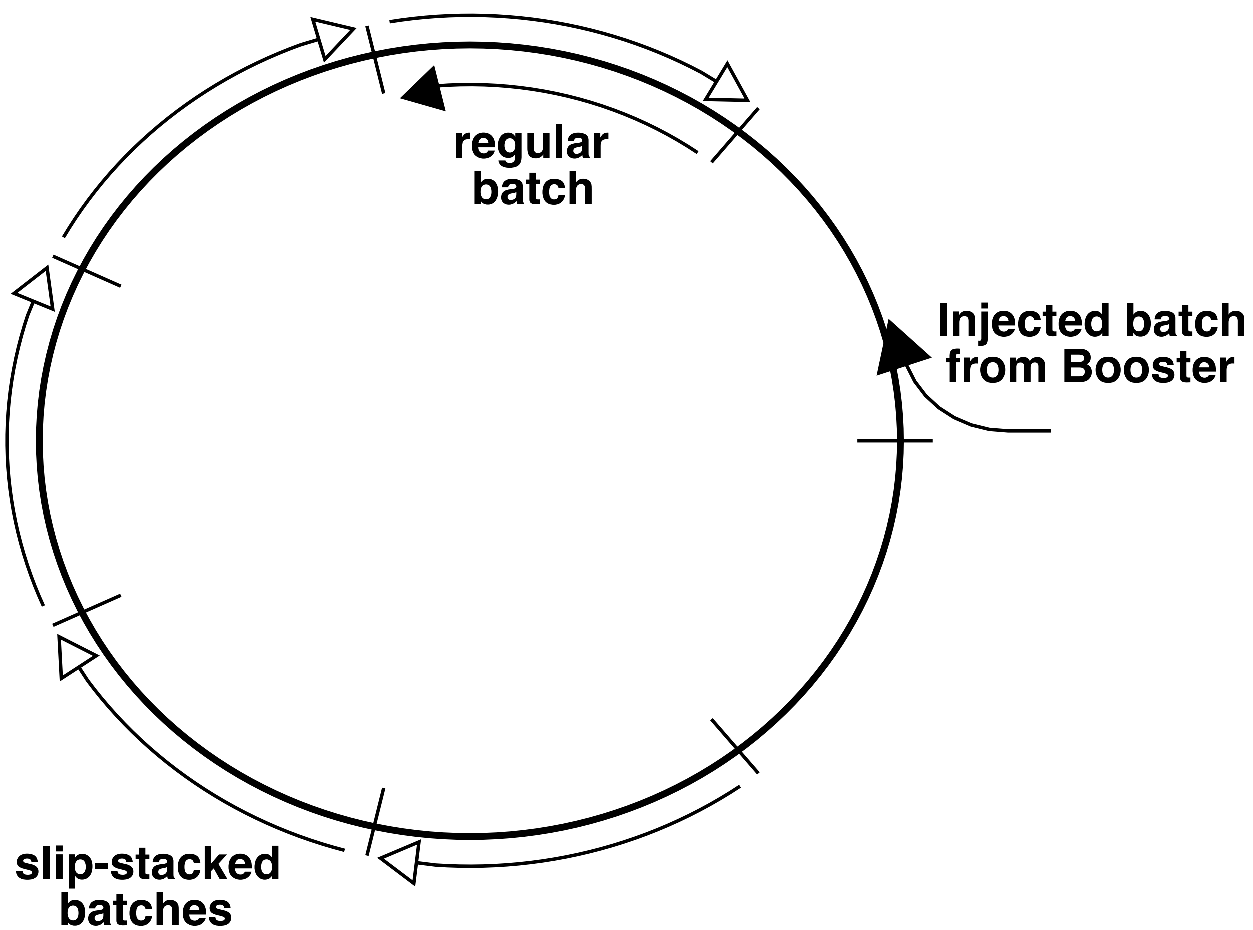
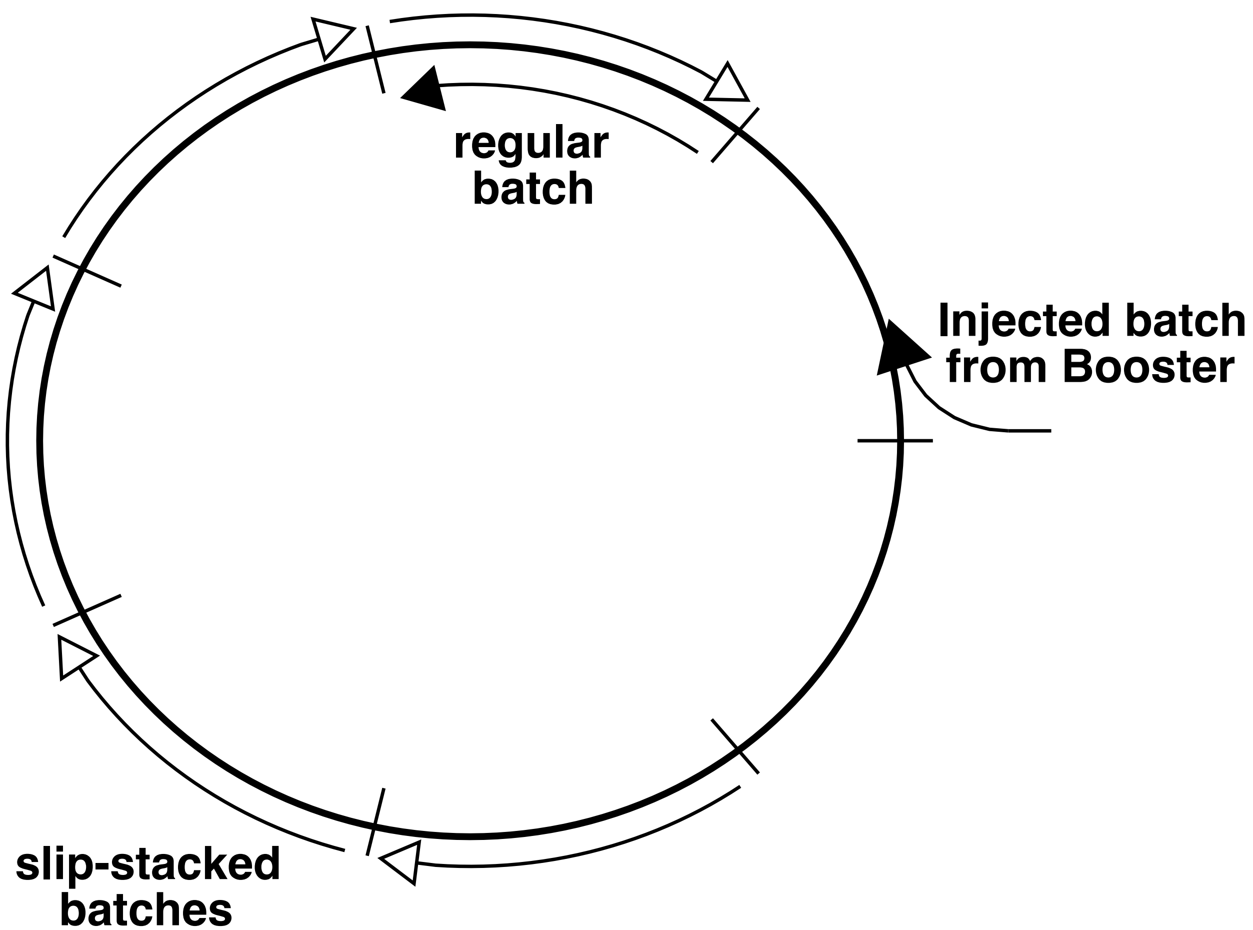
- Inject 5 slipped stacked batches with a slight frequency offset followed by 6 regular batches



Arrows are illustrative. Batches are not actually counter-rotating

Slip Stacking

- Add more protons into the accelerator by radio-frequency manipulation
- Inject 5 slipped stacked batches with a slight frequency offset followed by 6 regular batches
- Frequency offset makes them drift in time



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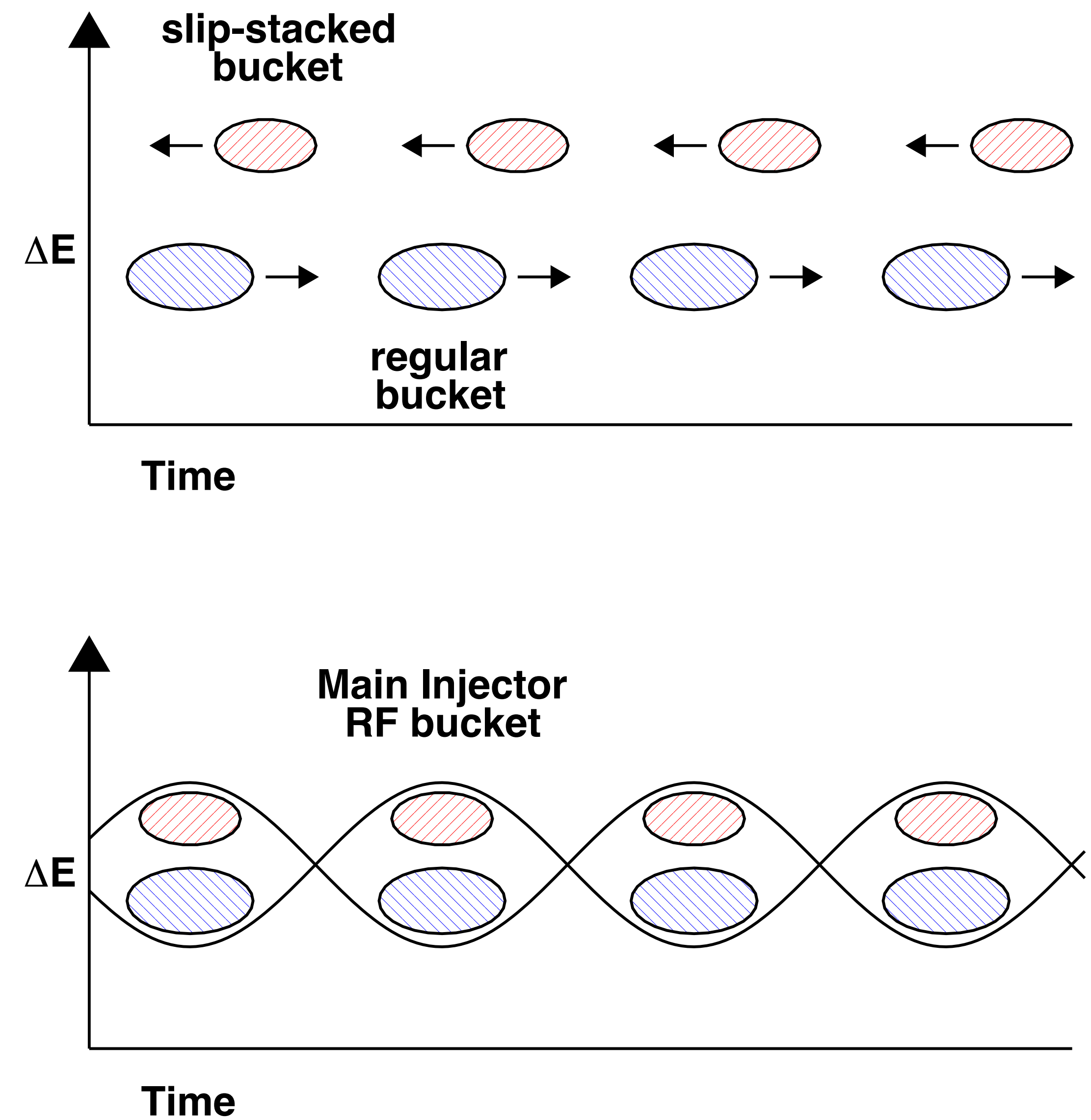

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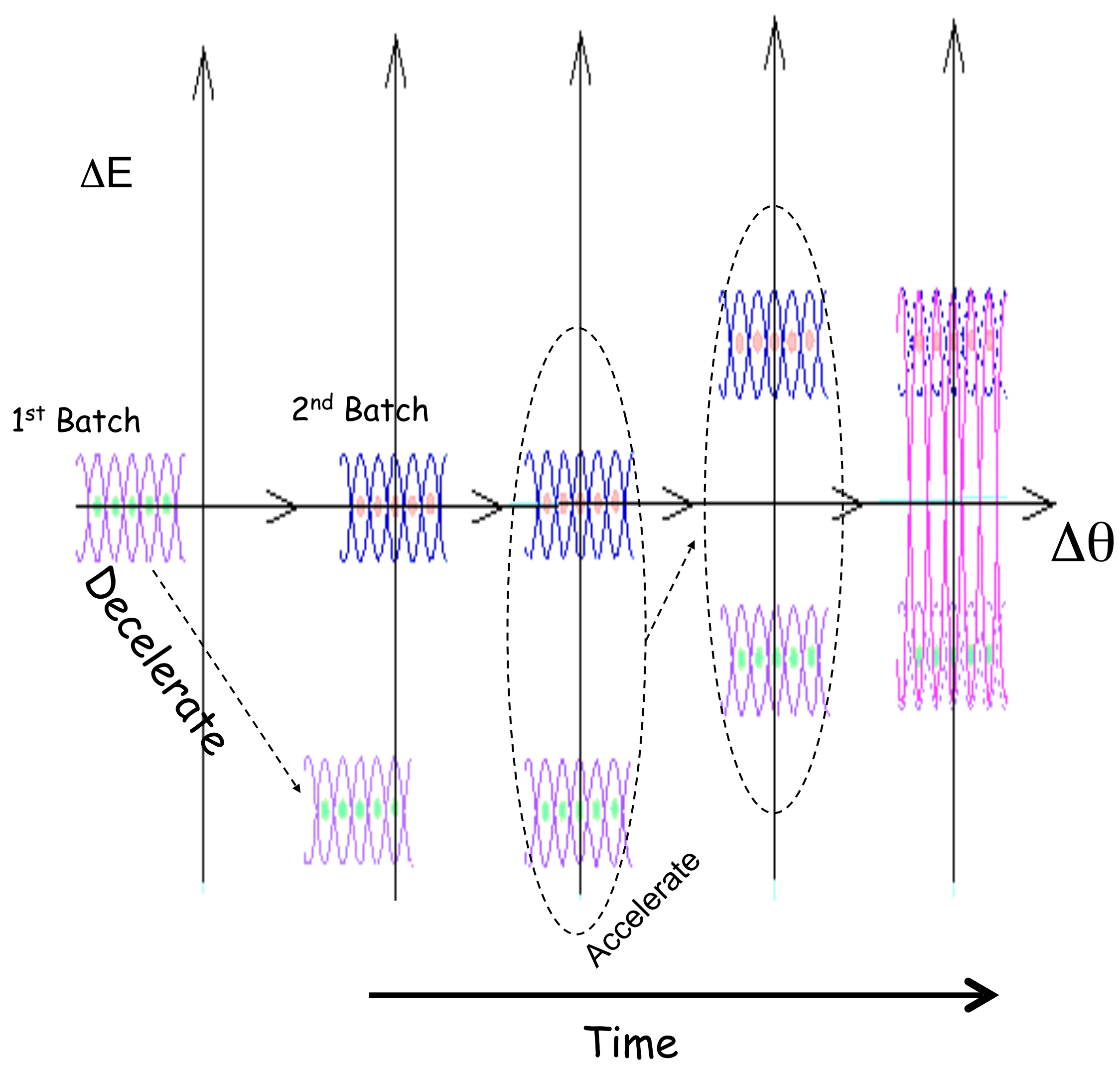

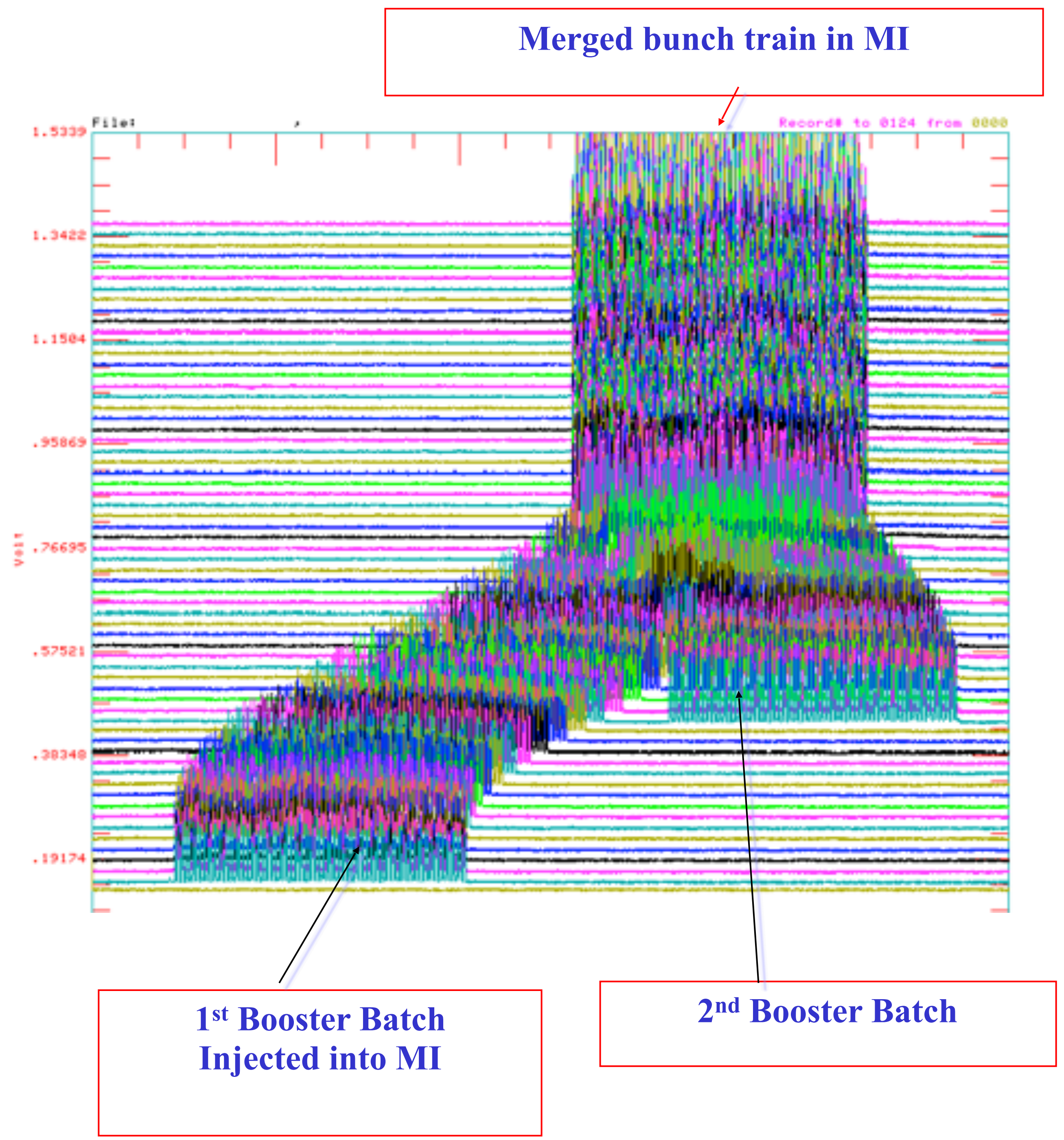

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  - Two separate out-of-phase proton 'beams' in the same pipe

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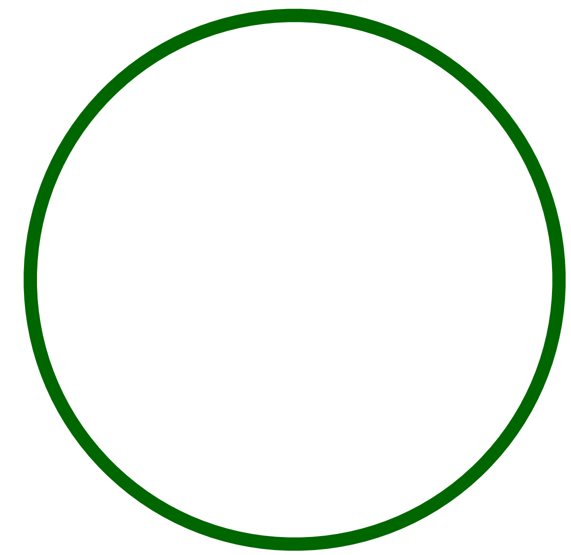
- Requires impressive accelerator expertise
  - Proton bunches are not well defined
  - Two separate out-of-phase proton ‘beams’ in the same pipe

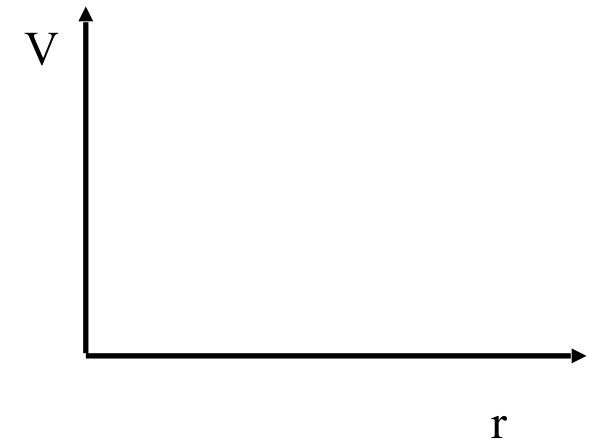
- More protons means more neutrinos

- Are there downsides to more protons?

Electron Cloud Model in Proton Machines

- Considering the Main Injector beam
  - ➢1-8 ns long bunches every 19 ns
  - ➢1-5 mm transverse sigma
  - ➢Bunch intensities of ~10^{11} protons





*Bob Zwaska, FNAL

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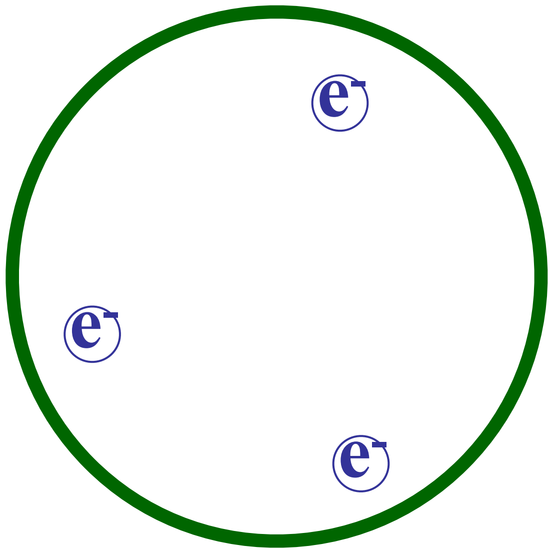
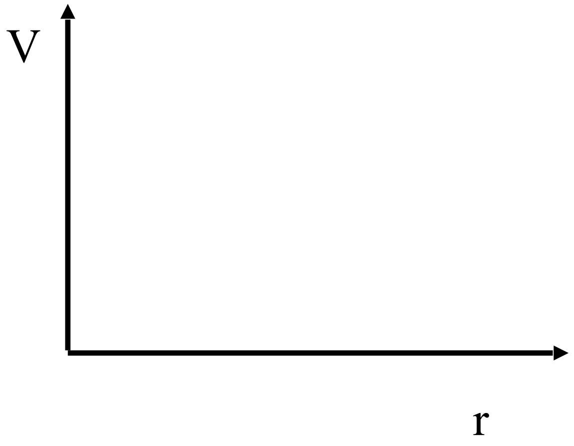
  - ➢1-8 ns long bunches every 19 ns
  - ➢1-5 mm transverse sigma
  - ➢Bunch intensities of ~10^{11} protons

- Produce a few initial/primary electrons
  - ➢Residual gas ionization
    - *O*(e^- / m / torr / proton)
  - ➢Lost protons





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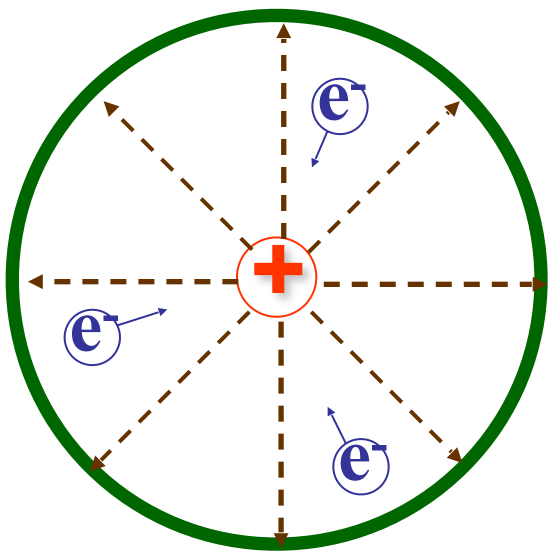

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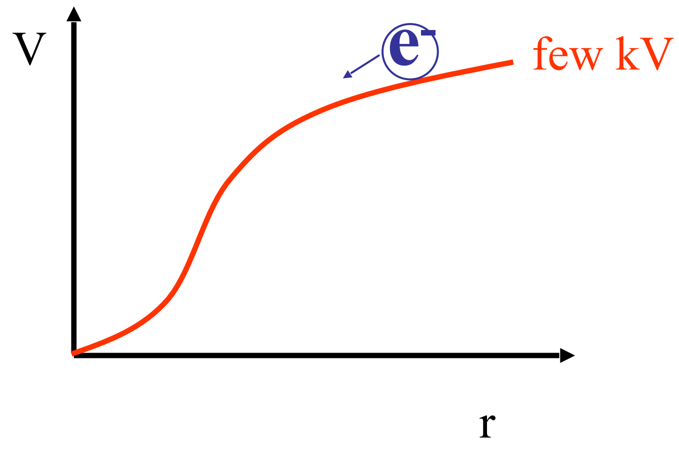
  - ➢Lost protons
    - Can produce 100’s in beam pipe



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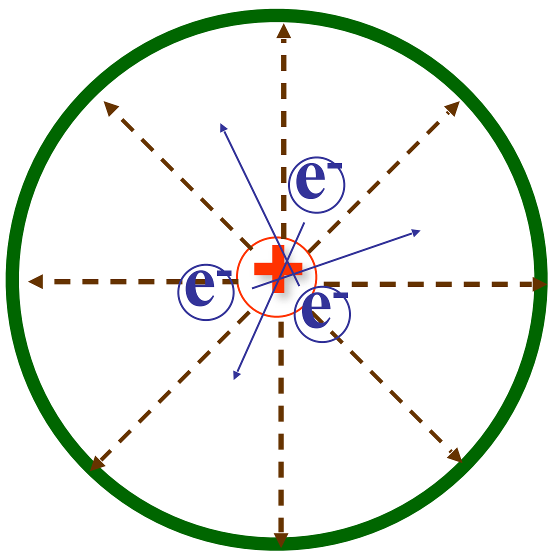
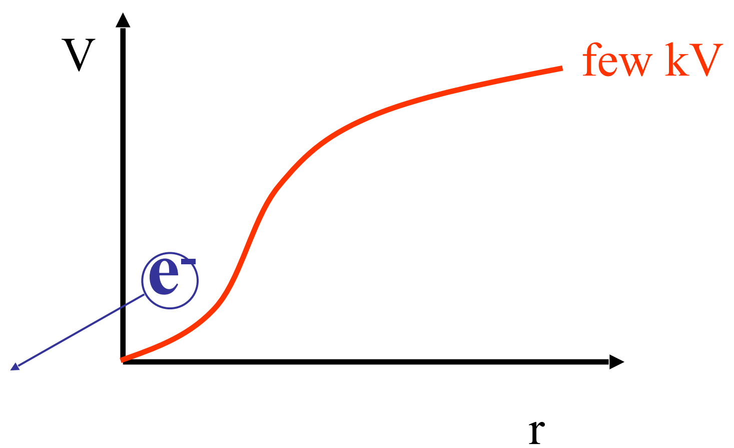
Electron Cloud Model in Proton Machines

- Considering the Main Injector beam
  - ➢1-8 ns long bunches every 19 ns
  - ➢1-5 mm transverse sigma
  - ➢Bunch intensities of $\sim 10^{11}$ protons



- Produce a few initial/primary electrons
  - ➢Residual gas ionization
    - *O*(e^- / m / torr / proton)
  - ➢Lost protons
    - Can produce 100's in beam pipe

- Beam produces strong potential



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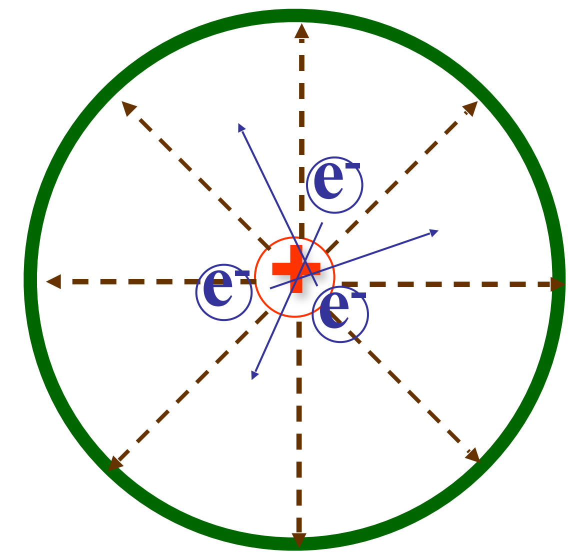

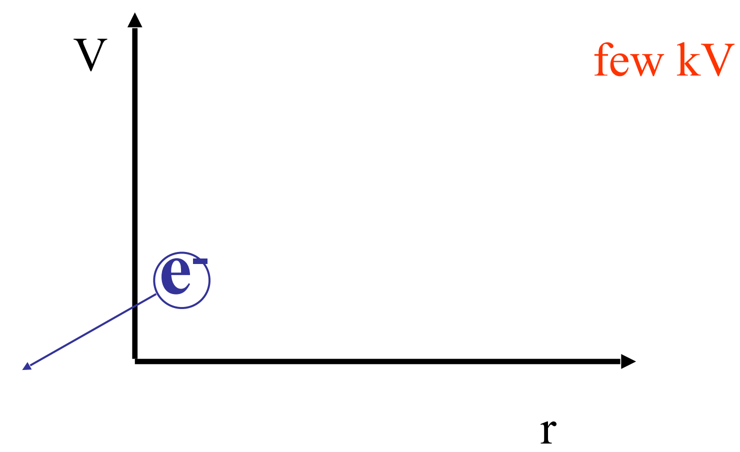

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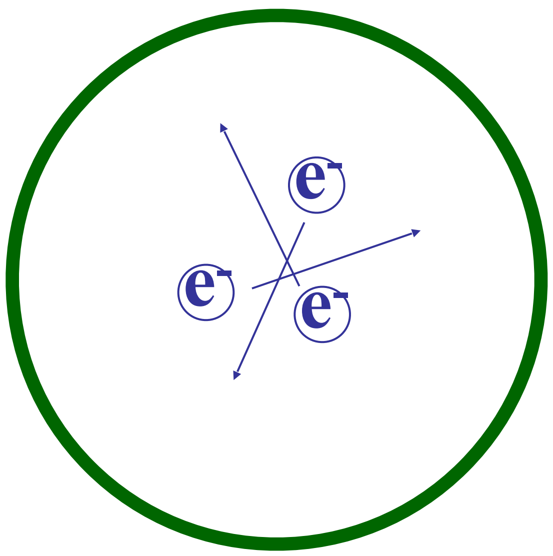

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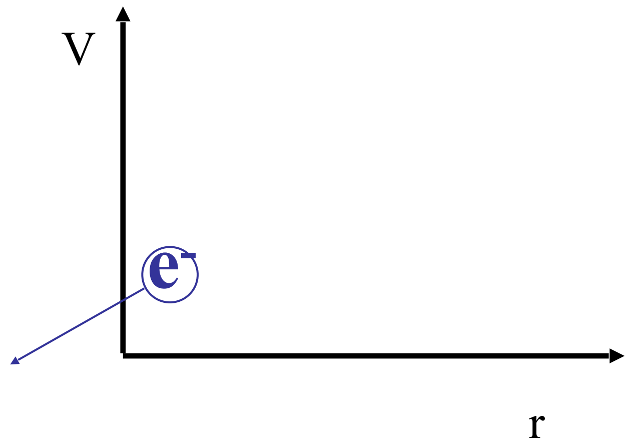
  - ➢Nonadiabatic appearance
  - ➢Electrons Accelerate



- Beam disappears
  - ➢Electrons collide with wall
  - ➢Produce more electrons through secondary emission

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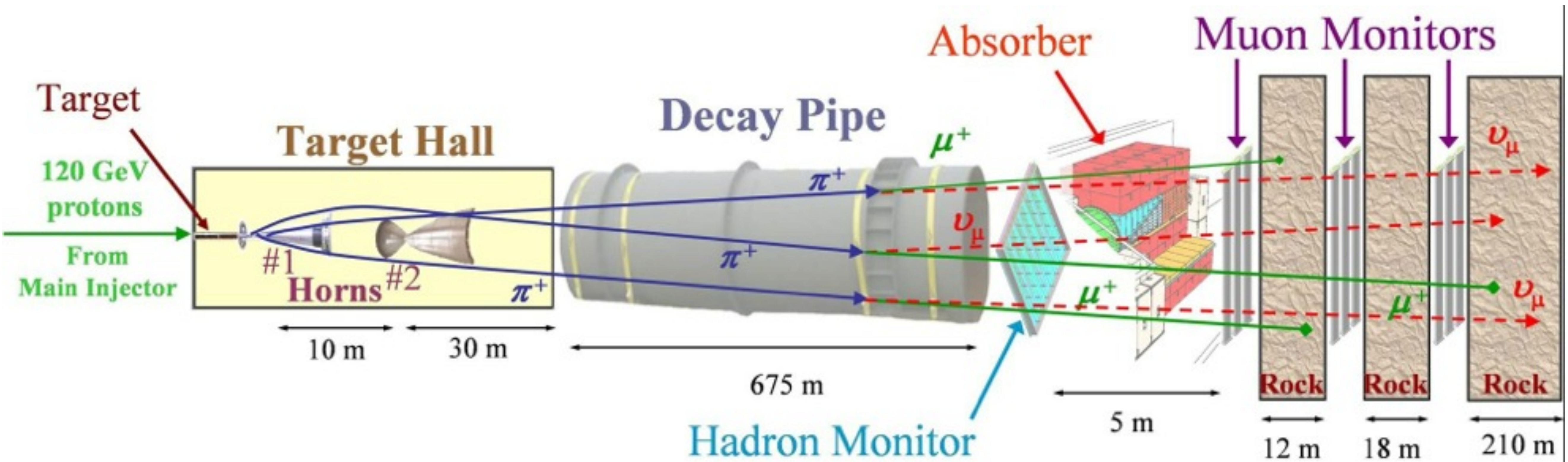
Neutrino Beamline (NuMI)



Proton Target for Neutrino Beam

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- Must be tough
  - Will be struck repeatedly by 100s or 1,000s of kilowatts or protons every few seconds
  - Should not warp, crack, shatter, or quickly degrade
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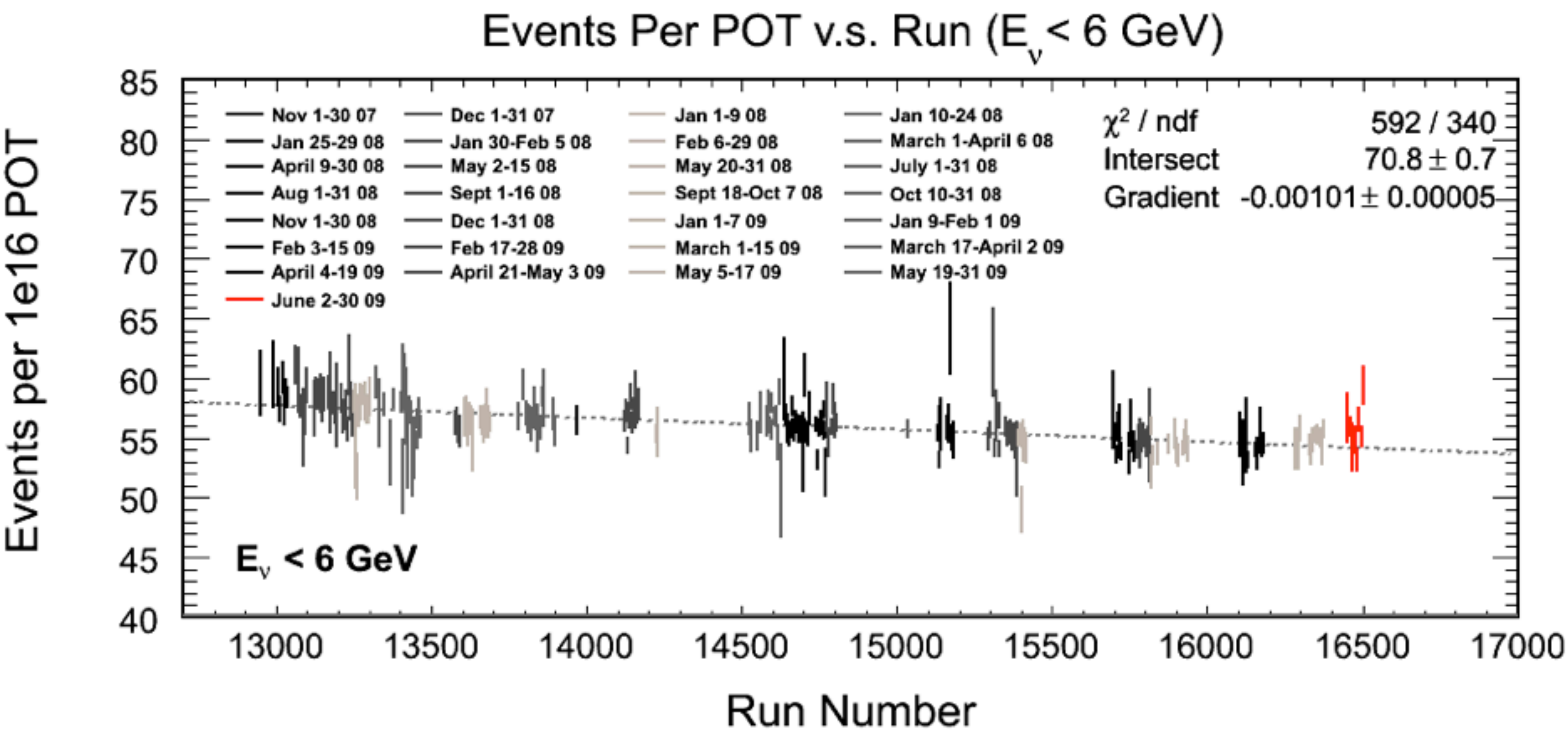
  - Should not warp, crack, shatter, or quickly degrade
  - Carbon (graphite) and Beryllium
- Produces charged hadrons (pions, kaons)
- Optimize target mass and design
  - More mass: produces more mesons and therefore more neutrinos
  - More mass: higher chance of meson absorption within the target

NuMI Target Degradation

- Neutrino yield from the NuMI target degraded by ~5% over an exposure of ~ 6e20 protons



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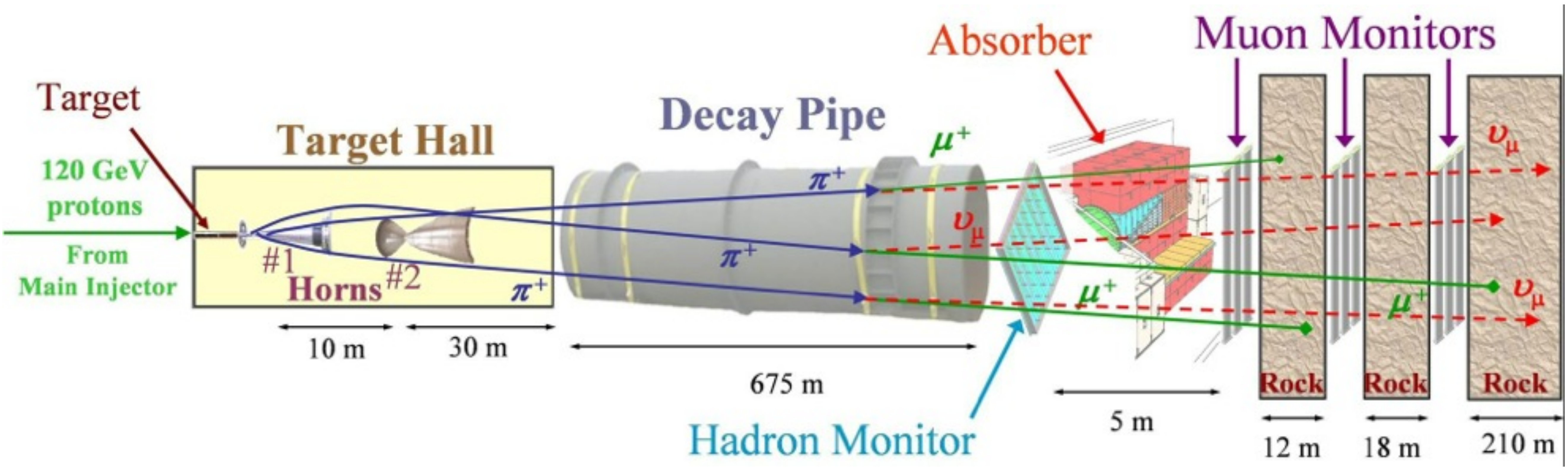
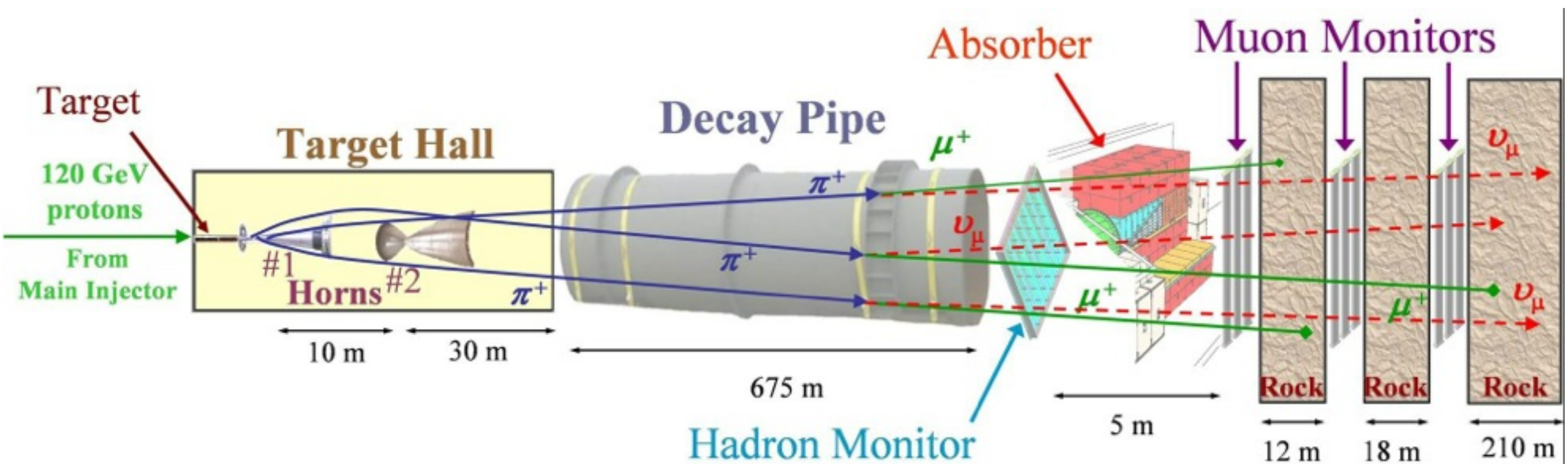
Magnetic Horns



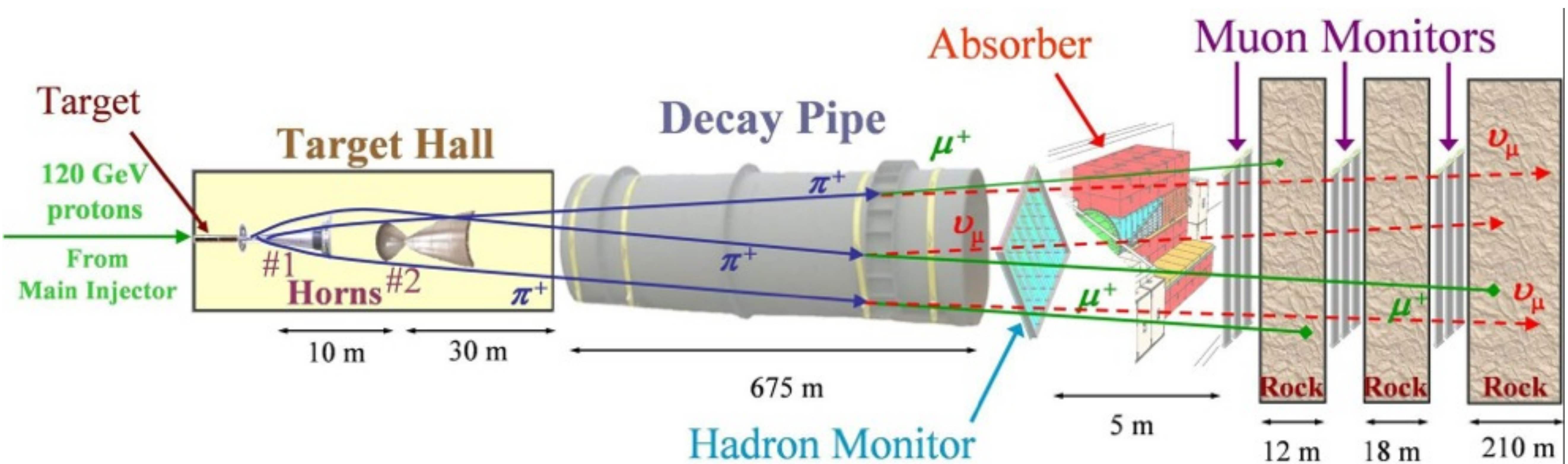
Magnetic Horns

- Must bend energetic particles over short distances (1-10m) with minimal material

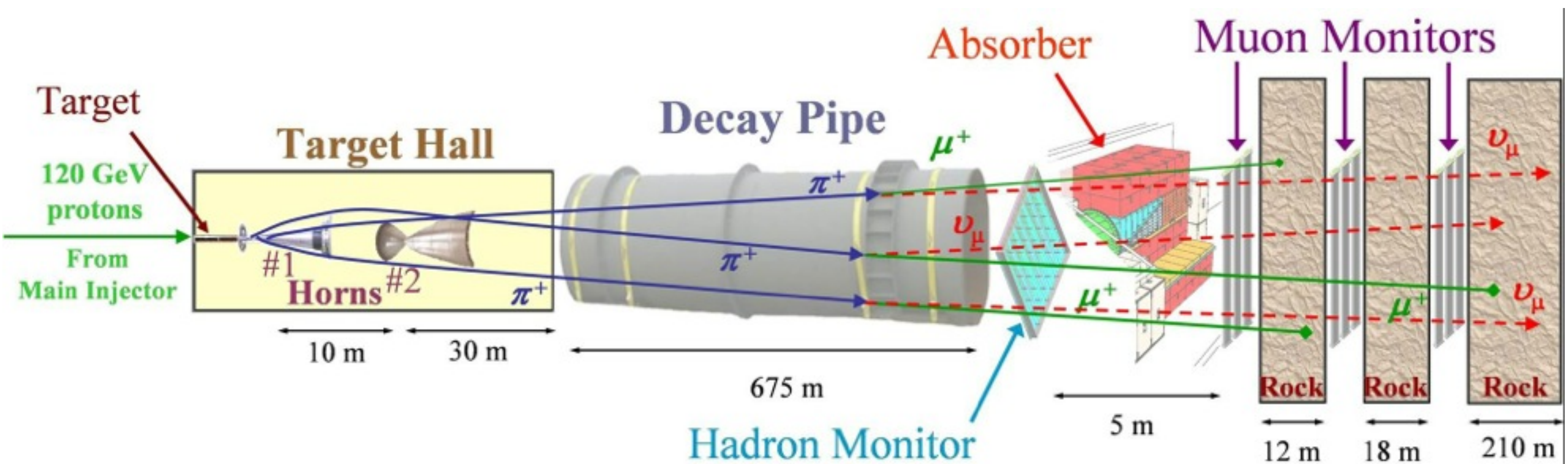


Magnetic Horns

- Must bend energetic particles over short distances (1-10m) with minimal material
- Pulsed focusing horns produce magnetic field
  - Momentum selects mesons
  - Directionally focuses selected mesons down decay pipe



Decay Pipe and Absorber



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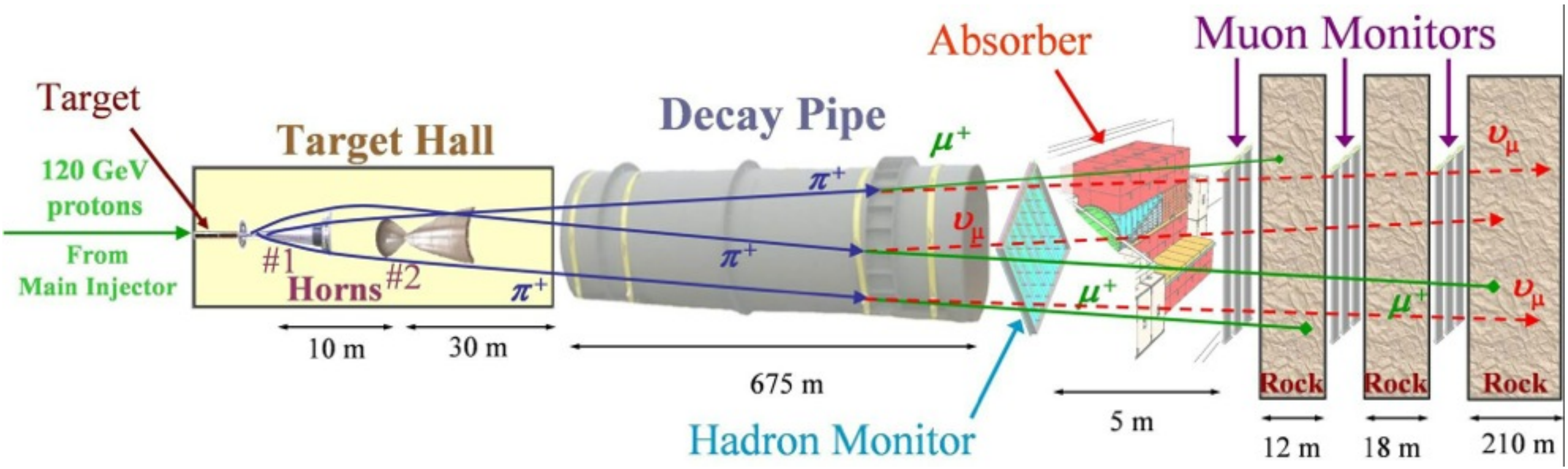
- Decay pipe allows mesons to decay into neutrinos
  - Low pressure
  - Length is governed by funding



Decay Pipe and Absorber

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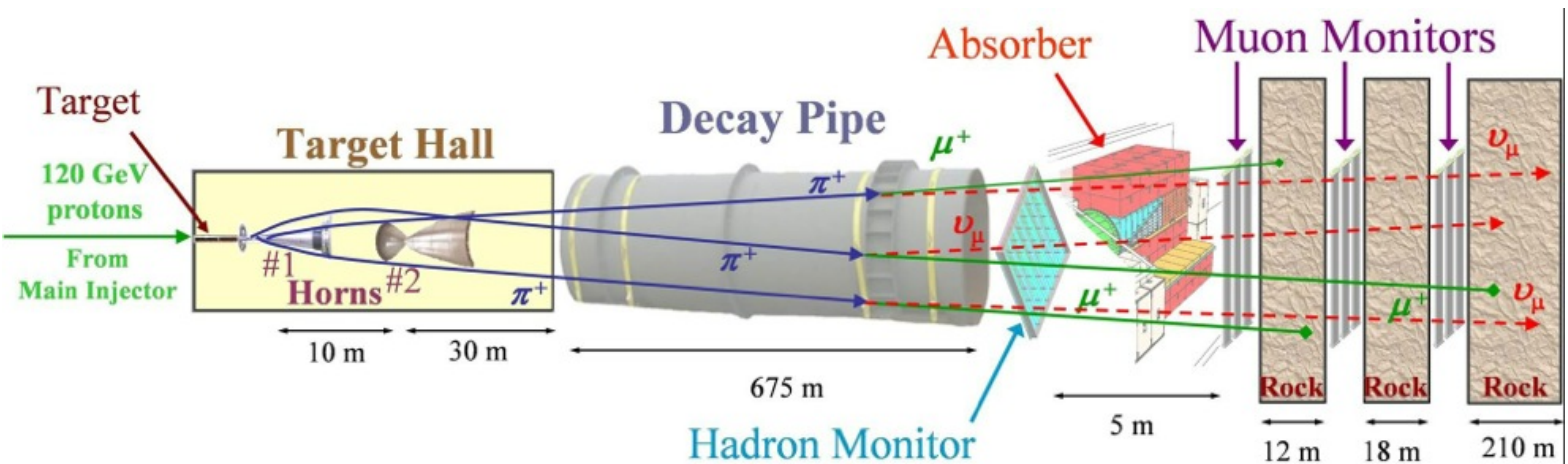
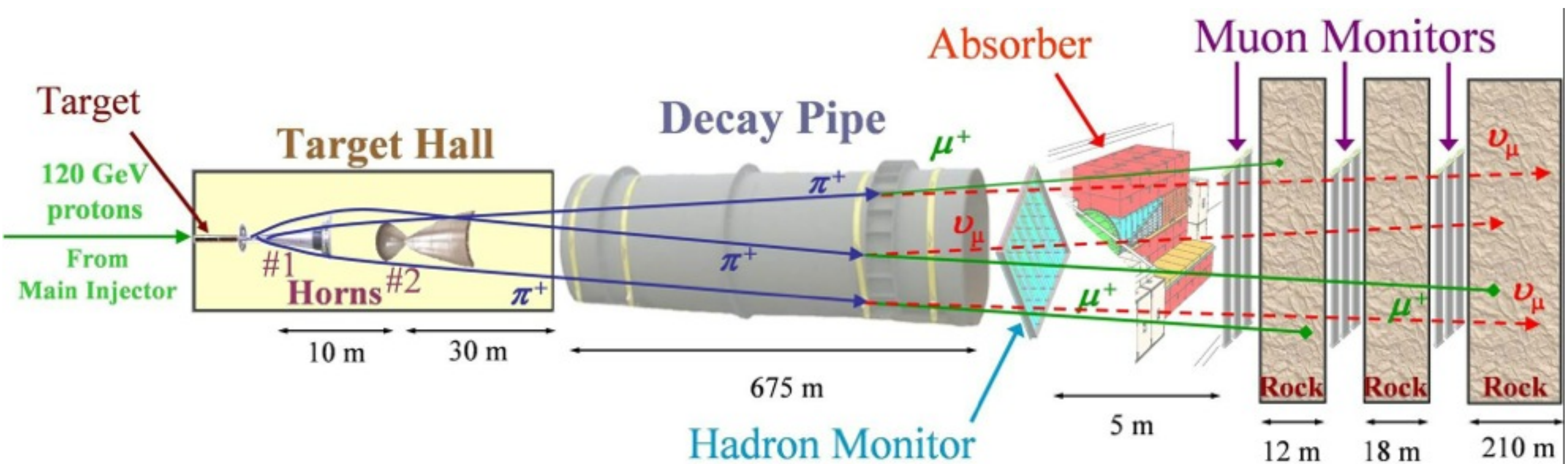
  - Length is governed by funding
- Absorber stops un-decayed mesons



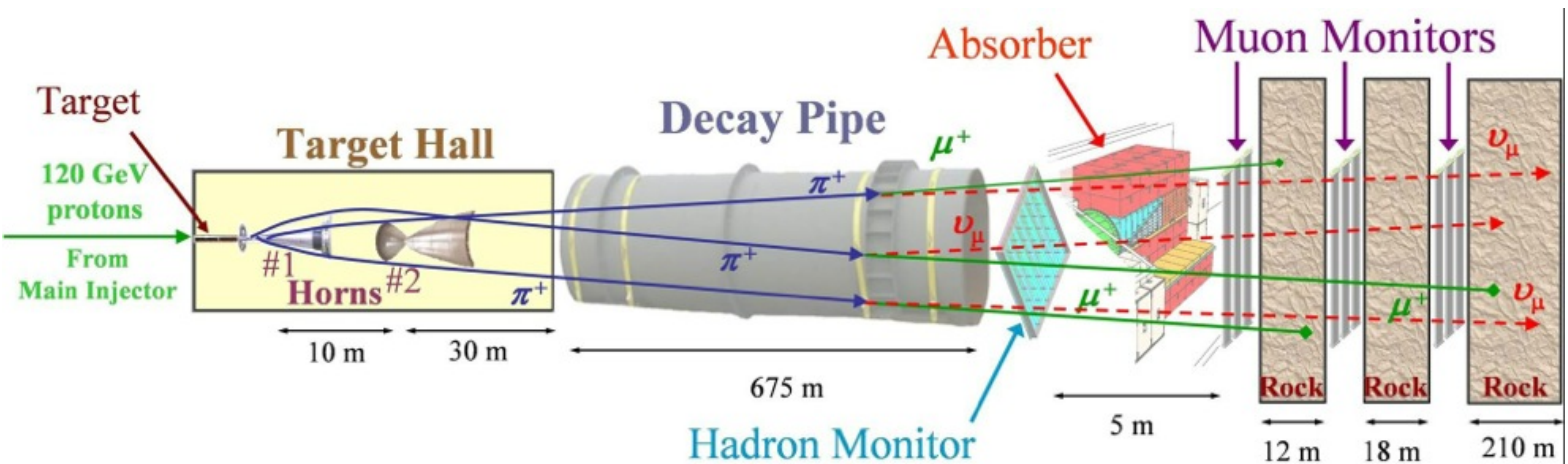
Monitors



Target
120 GeV
protons
From
Main Injector
Target Hall
#1
Horns
#2
Decay Pipe
Absorber
Muon Monitors
Hadron Monitor
Rock
Rock
Rock
10 m
30 m
675 m
5 m
12 m
18 m
210 m

Monitors

- Hadrons are the neutrino parent particles and muons are the ‘siblings’



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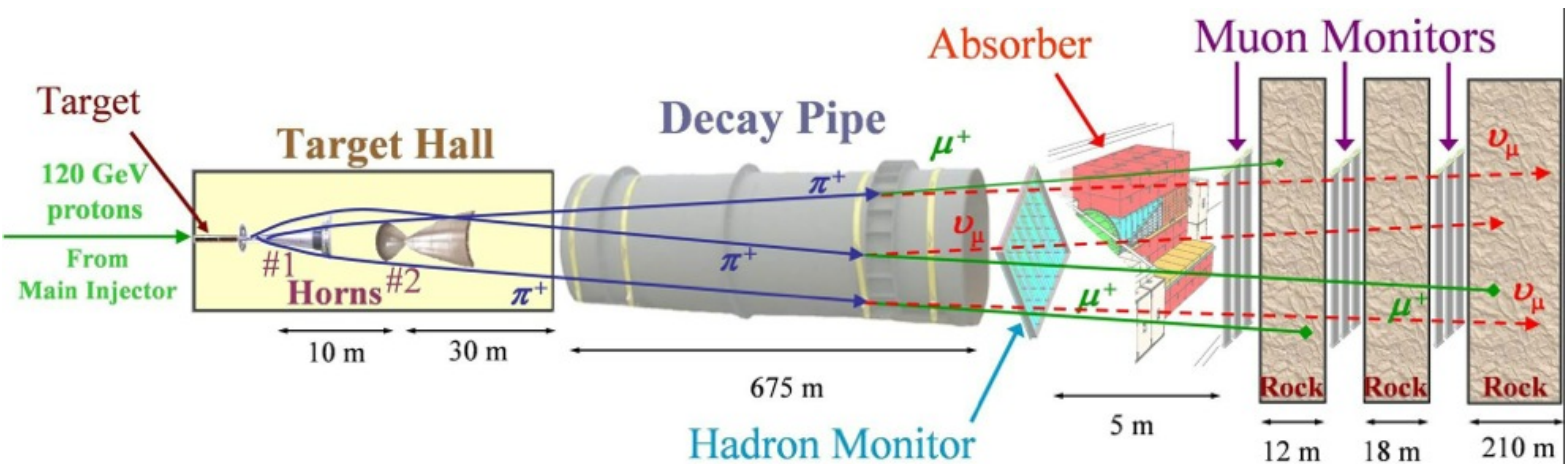

Monitors

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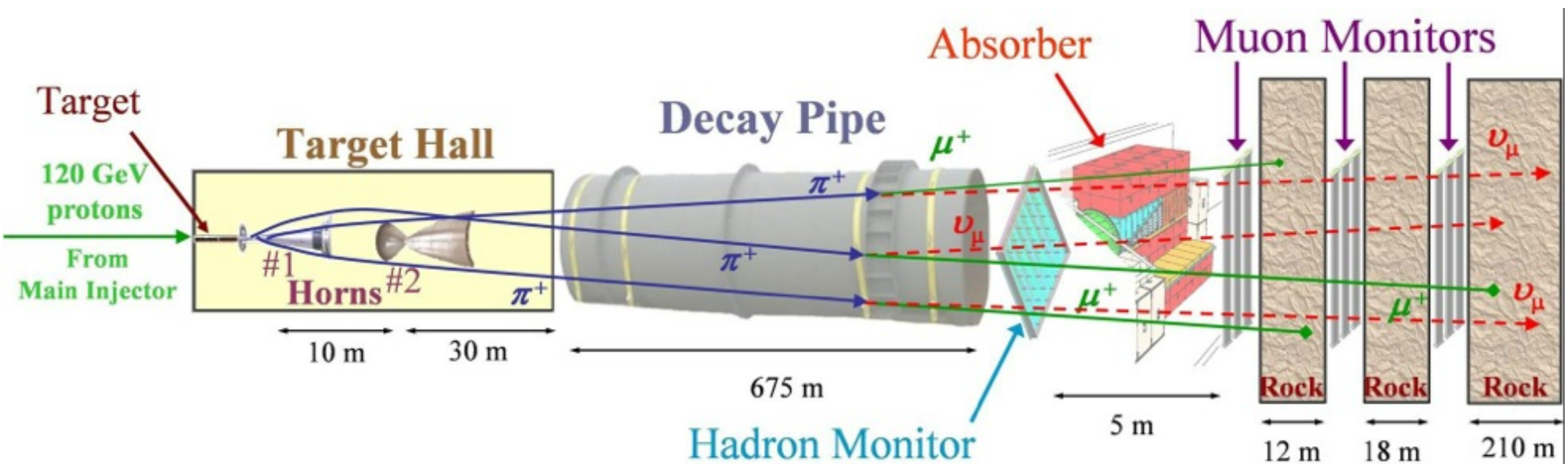
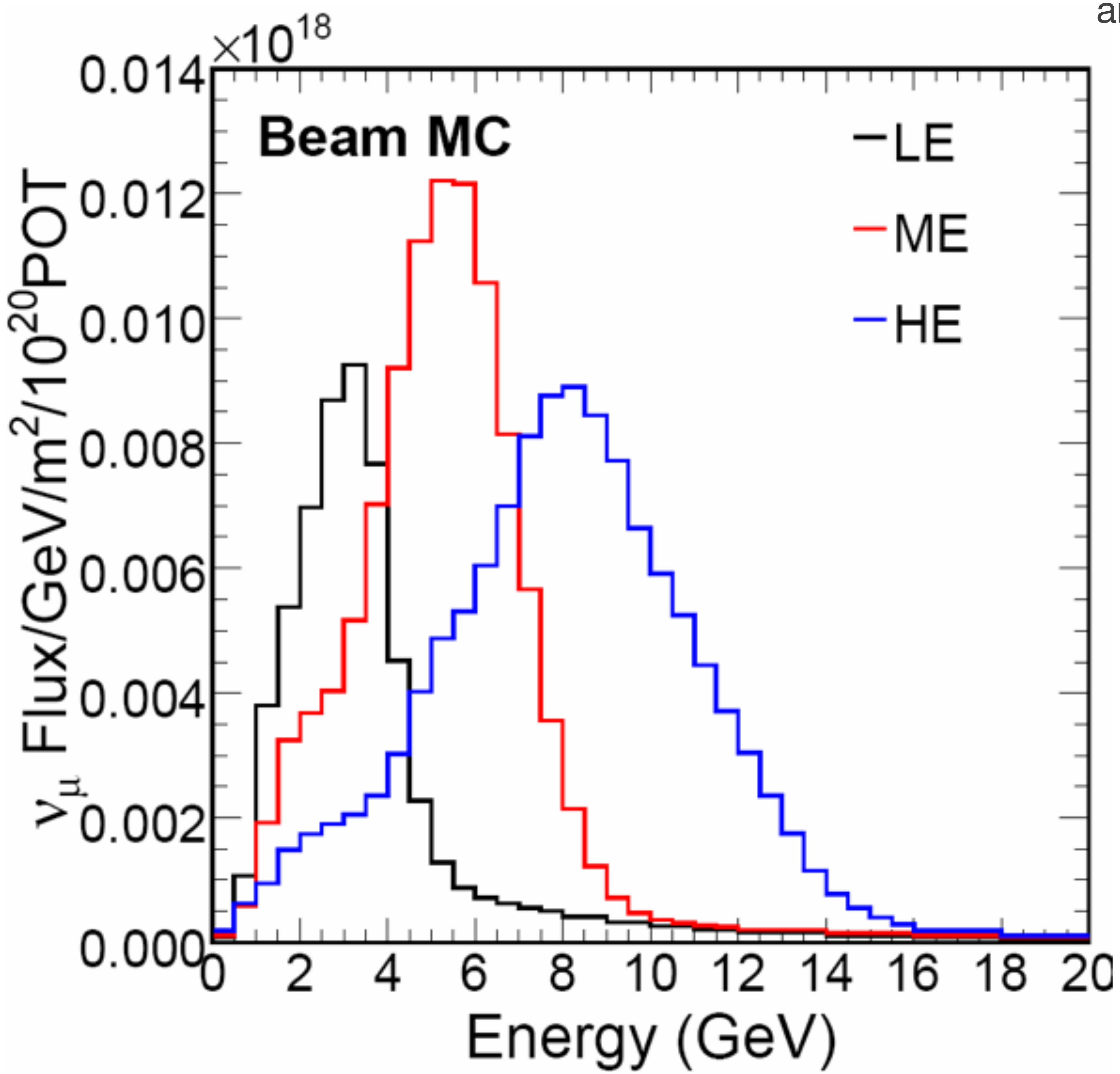
  - Beam issues will show up much sooner in hadrons and muons than neutrinos
  - Additional constraints on the neutrino beam intensity, energy, and direction



What is at the End?

arXiv:0709.2737



Neutrino Flux Koan

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- How do we know neutrino flux?

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    - Rate

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- Accelerators: Initial estimate uses simulations of protons on a target and downstream physics

MiniBooNE

- Predicted MiniBooNE flux using different hadron interaction models in Geant4

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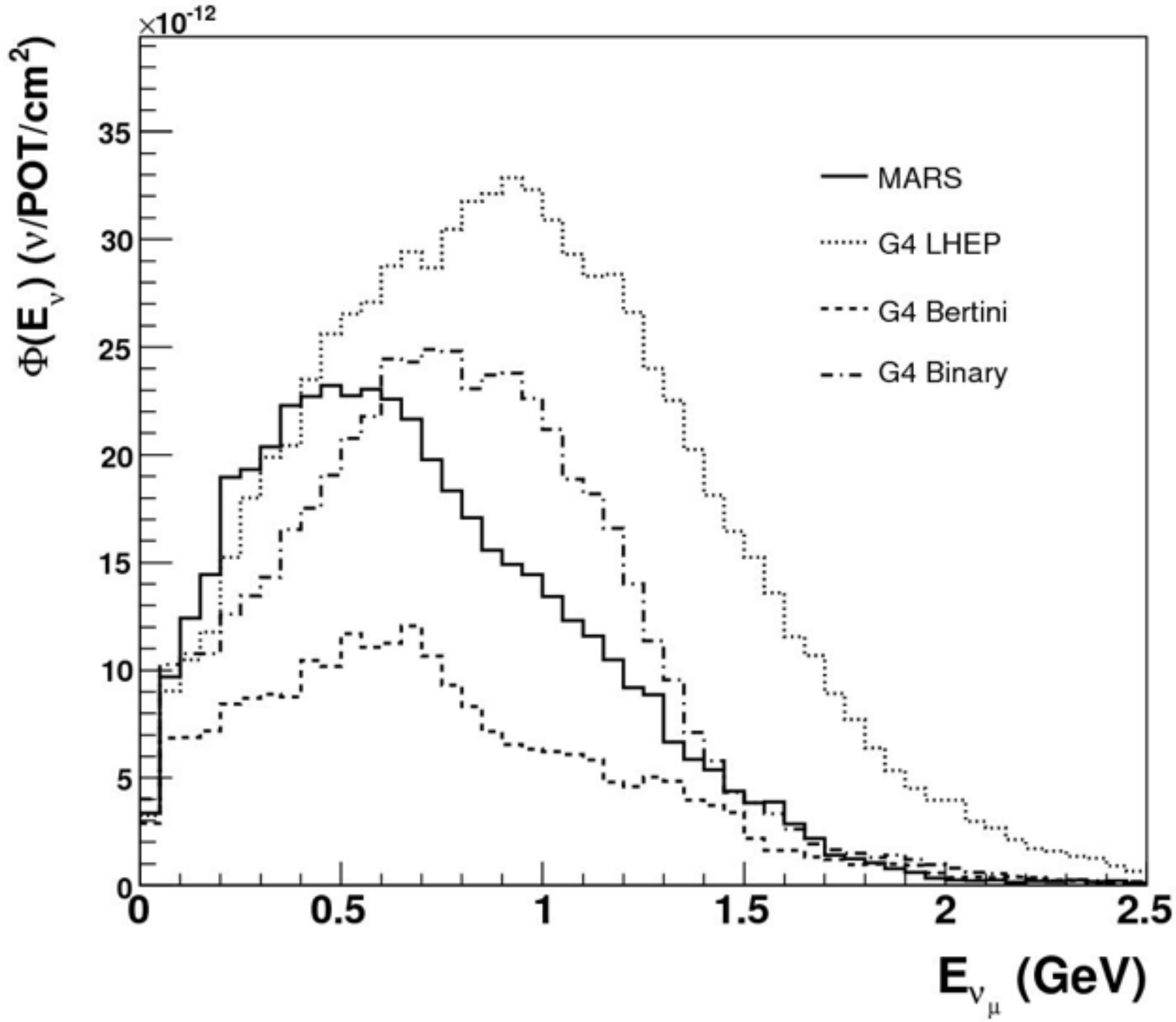
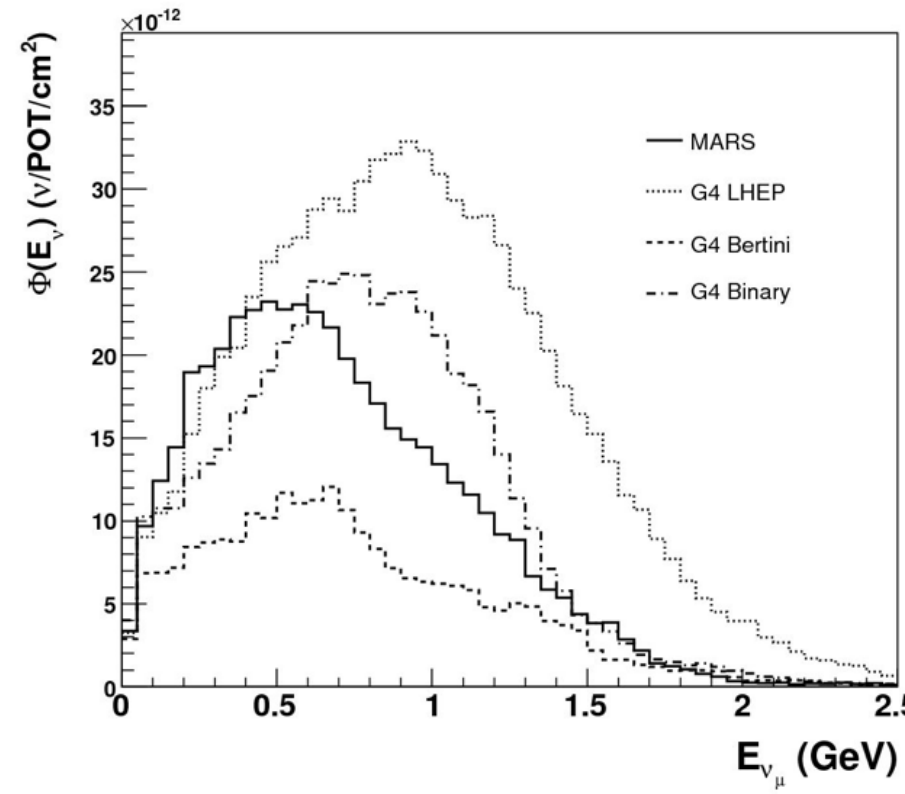
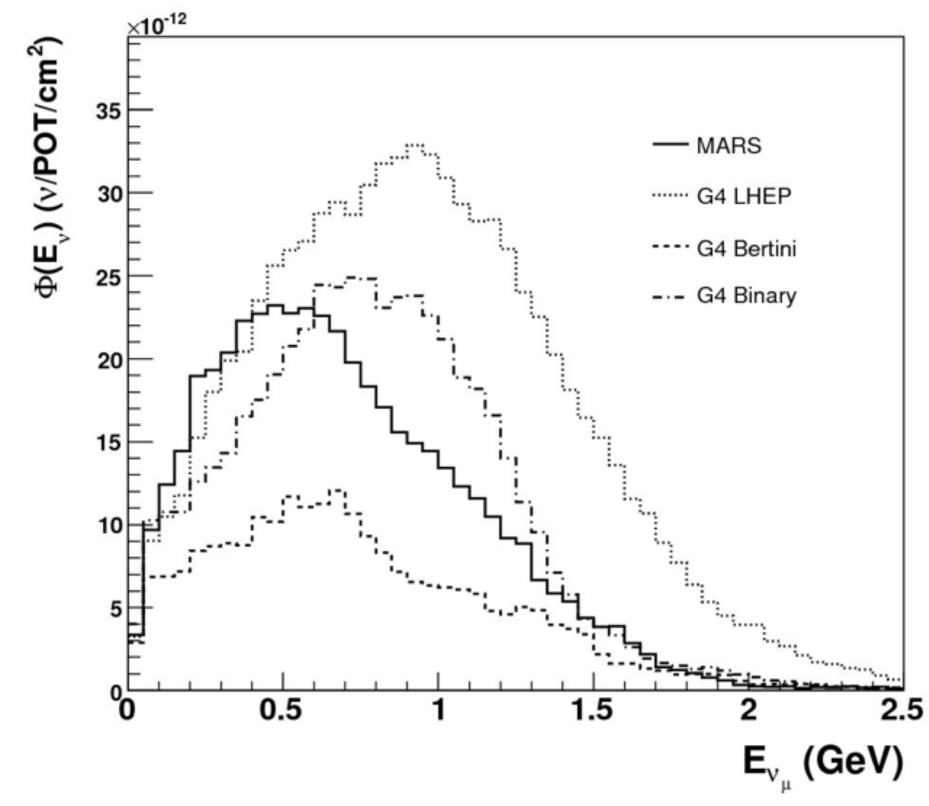


Neutrino Beam Simulation



Neutrino Beam Simulation

- Measure the energy and intensity of protons onto the target



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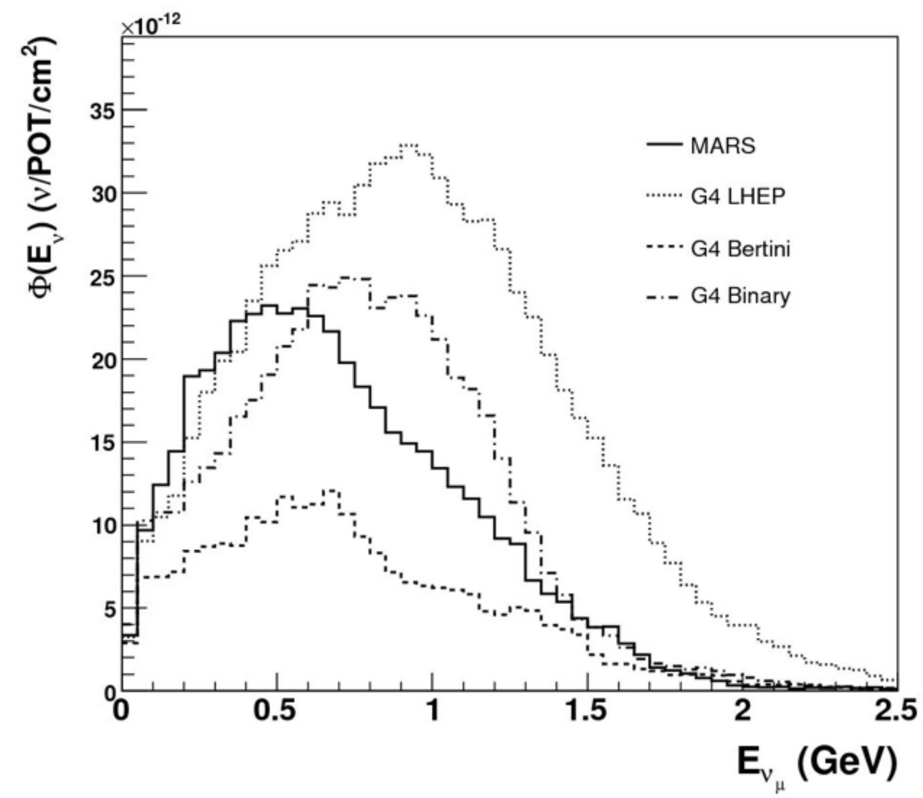

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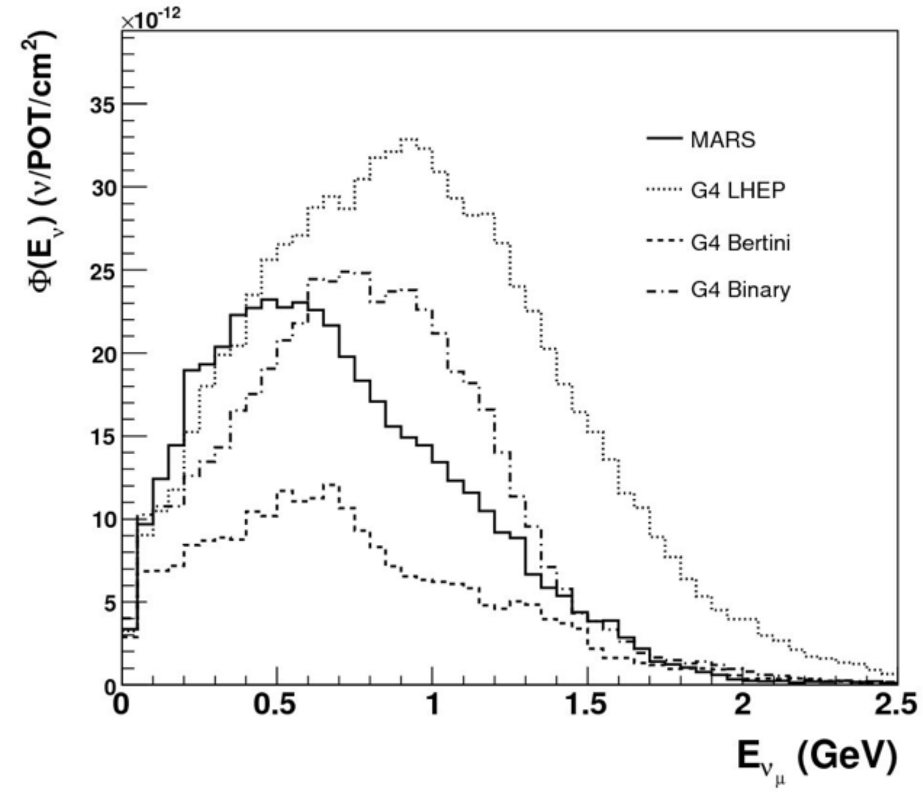

Neutrino Beam Simulation

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- Use simulation for secondary hadron creation (pions/kaons)
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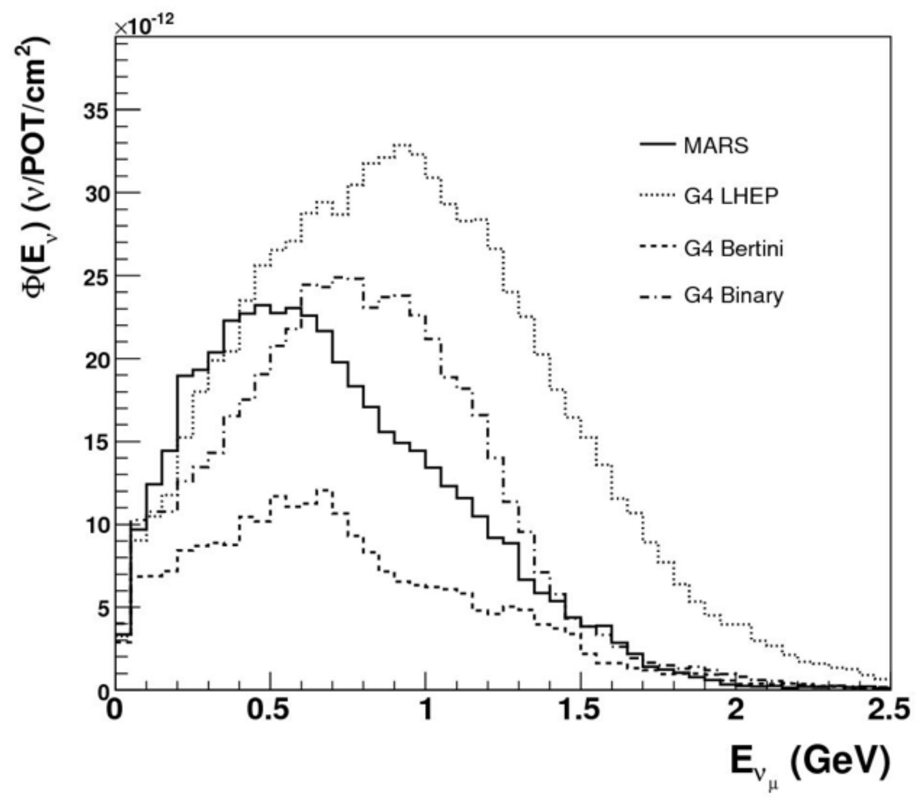
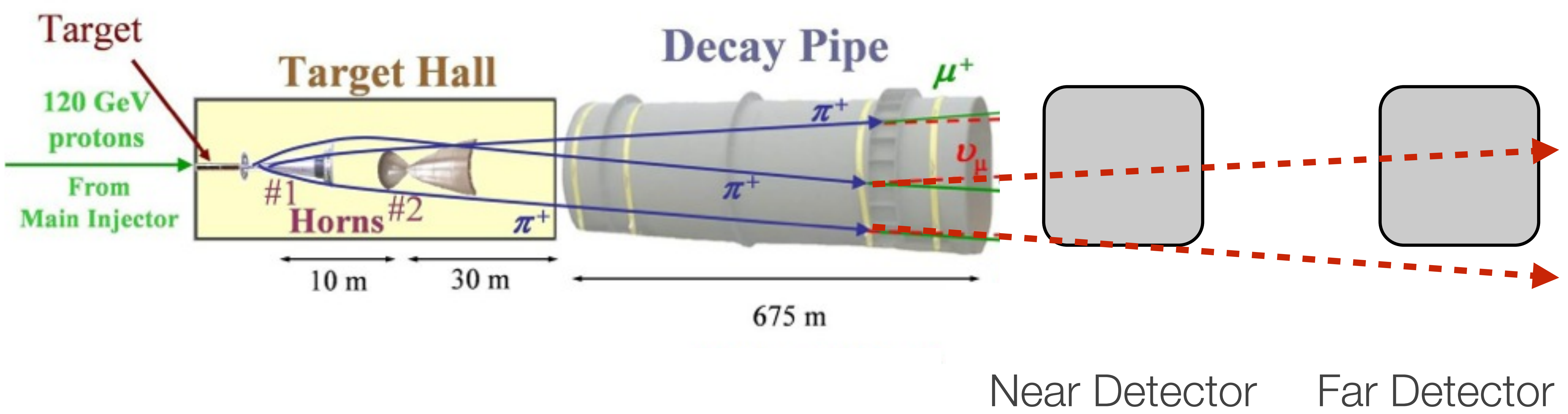
- Transport hadrons through magnetic field, magnetic horns, into decay pipe, and decay to produce neutrinos
- Large contribution from pion production from the target



Near Detector

- Near Detectors are wonderful ways to constrain neutrino flux uncertainties
  - Measure unoscillated spectrum and use Monte Carlo to extrapolate to Far Detector
  - Many uncertainties or mis-modeling in Near Detector neutrinos map to Far Detector neutrinos
  - High neutrino statistics

Near Detector



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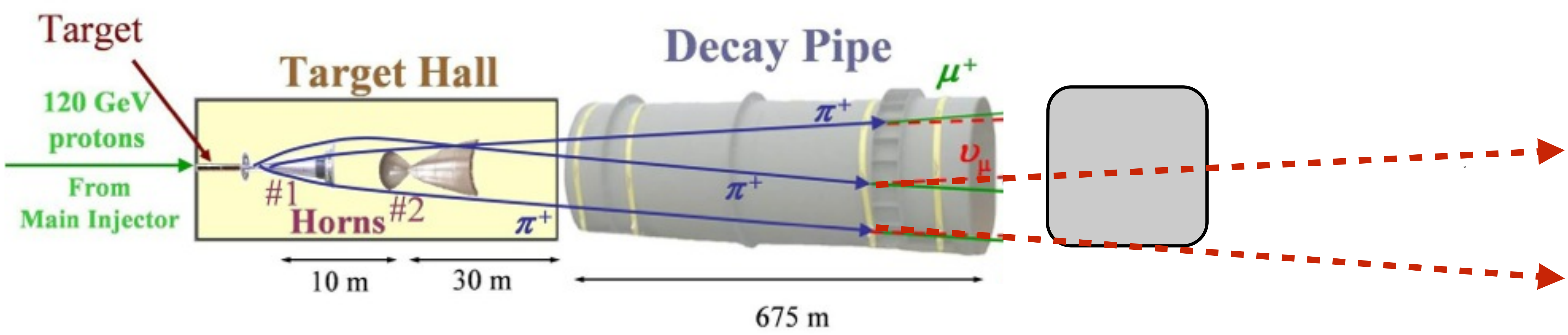

Near Detector Far Detector

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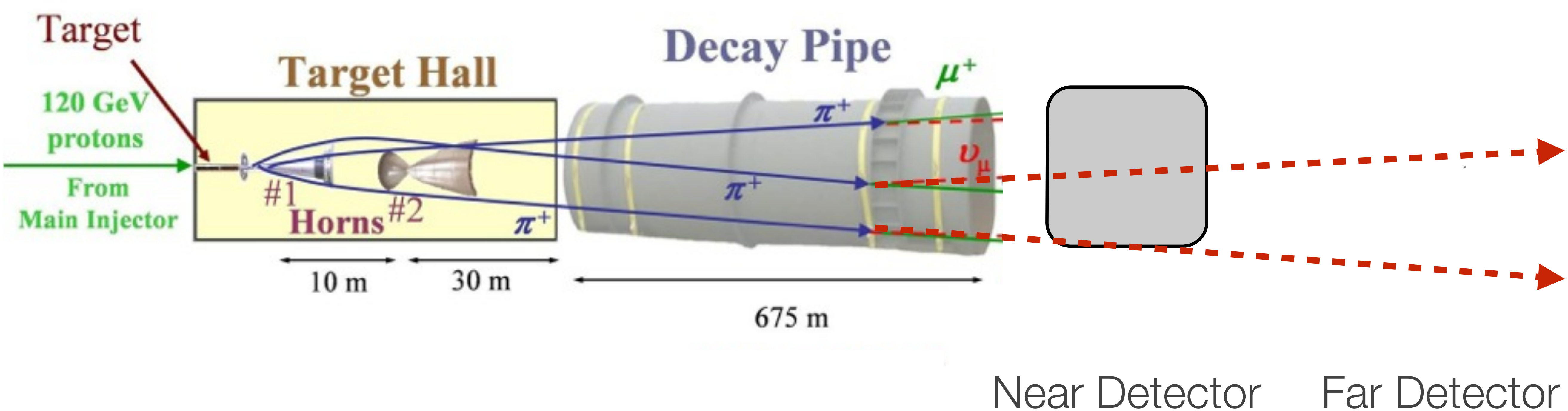
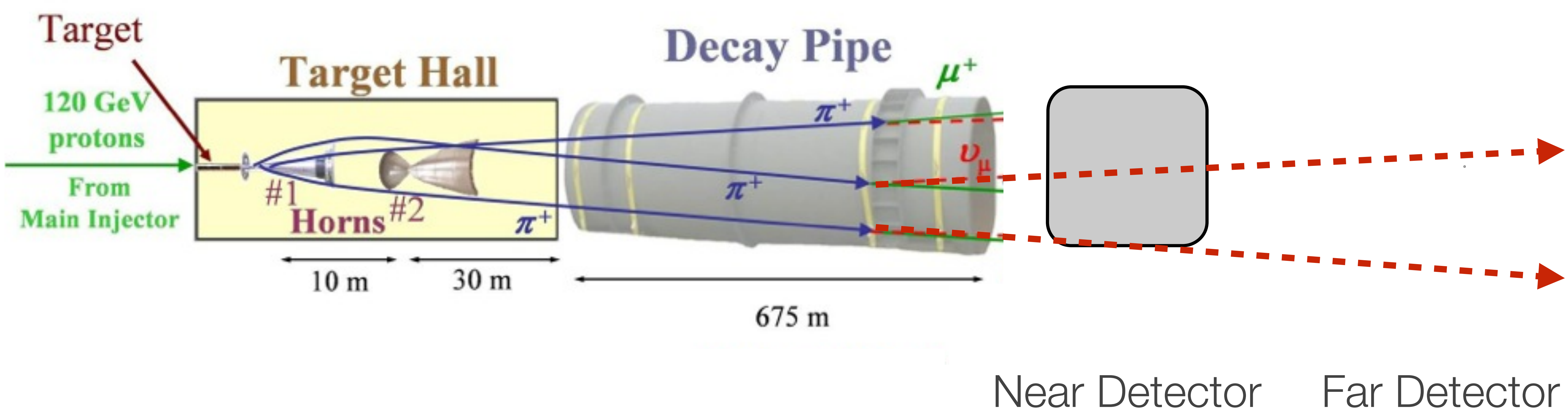
- The neutrinos observed at the Near Detector are not guaranteed to be similar in kinematics to those at the Far Detector



Near Detector

- The neutrinos observed at the Near Detector are not guaranteed to be similar in kinematics to those at the Far Detector
- Near Detector cannot solve everything



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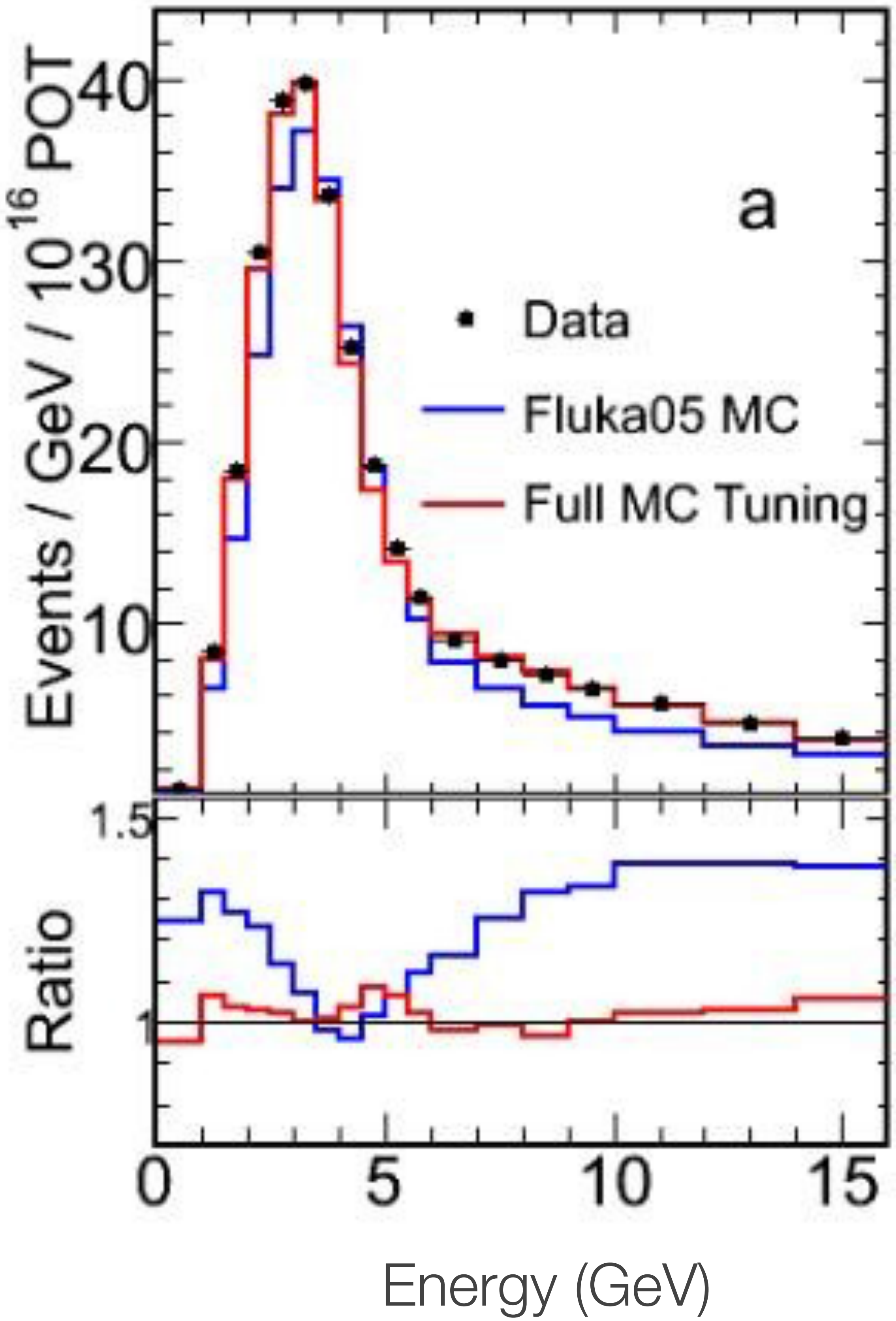
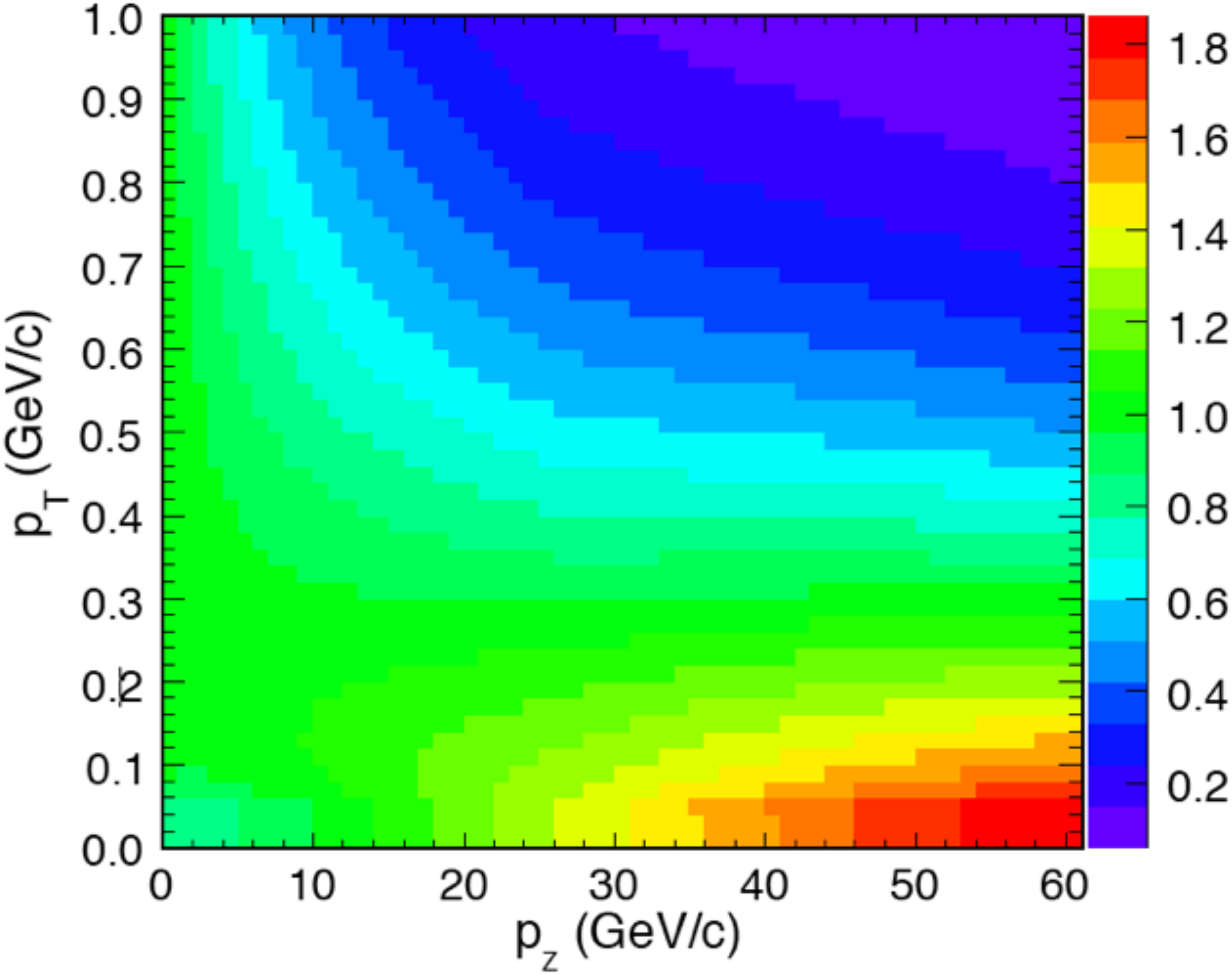


Hadron Tuning

- Reweight pions in terms of transverse and longitudinal momentum

arXiv:0711.0769



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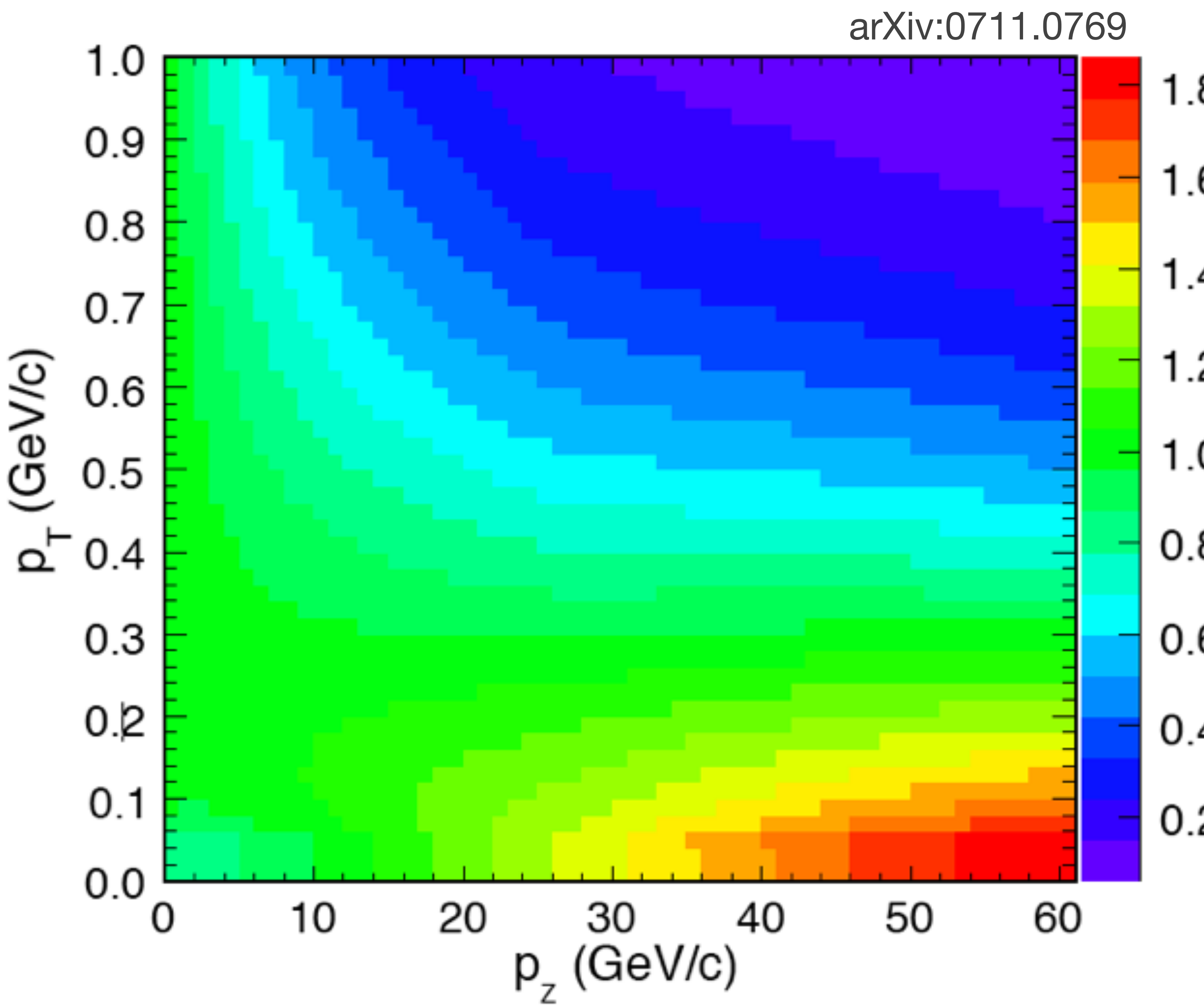
All animals are equal

-Animal Farm



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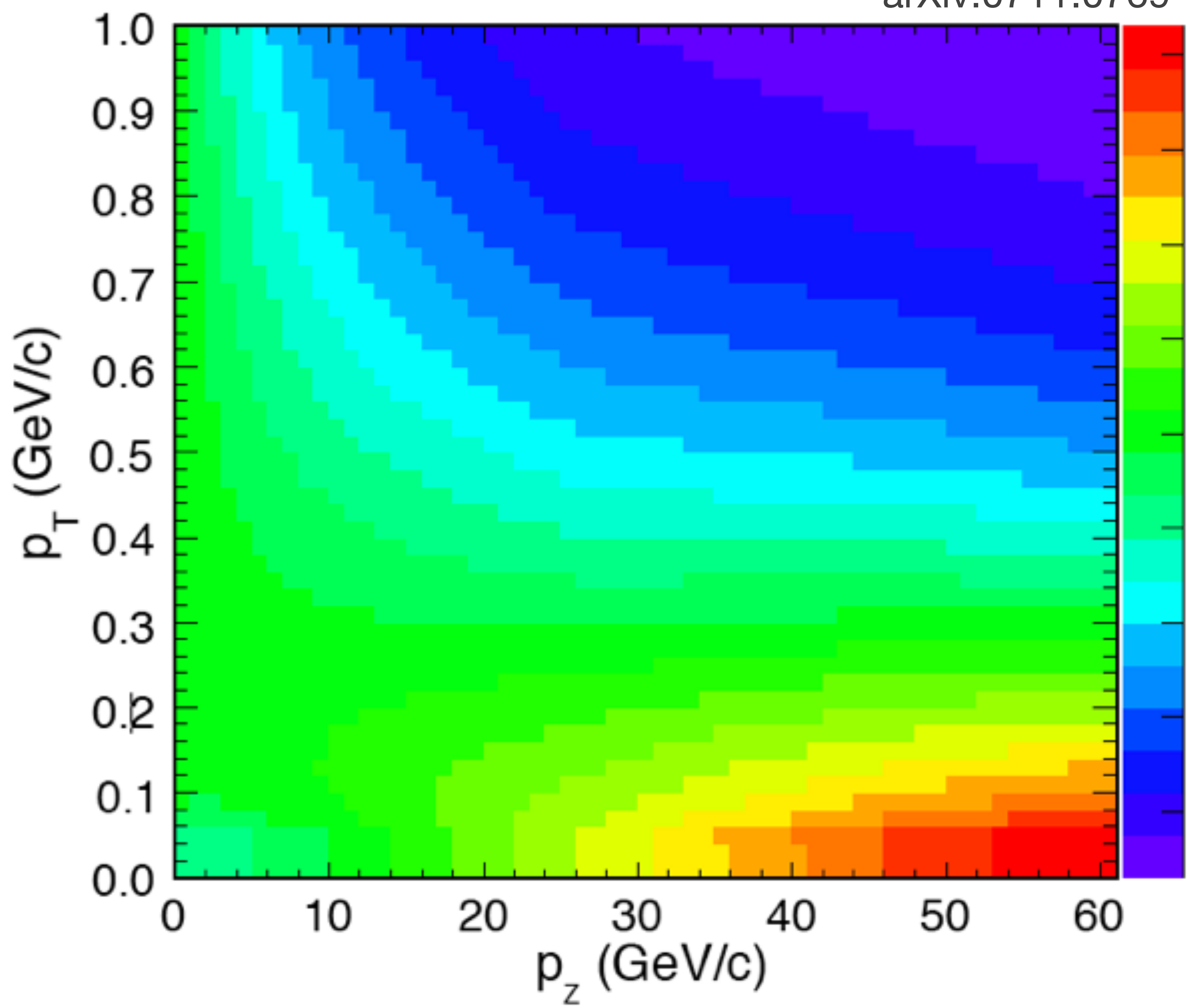

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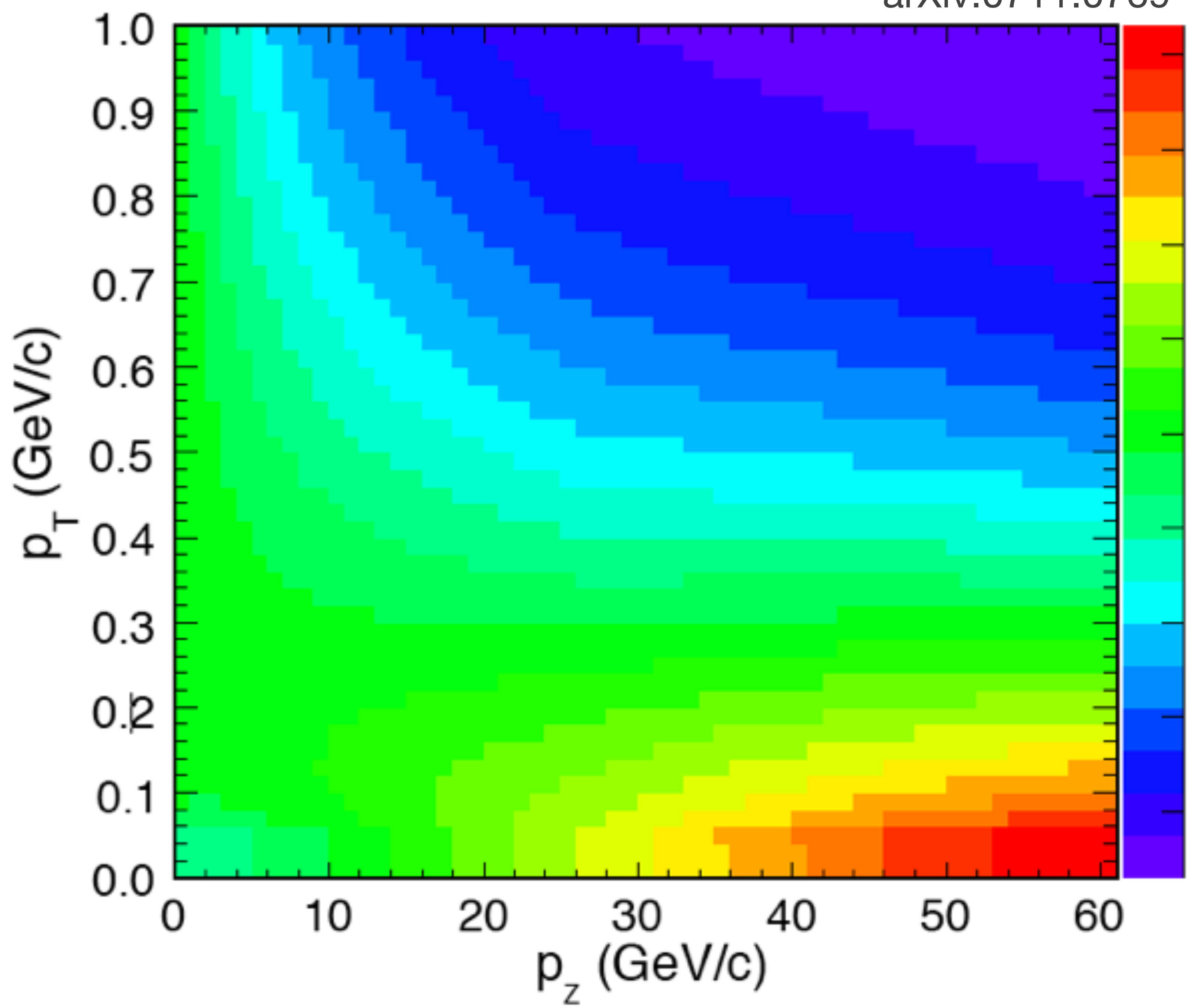
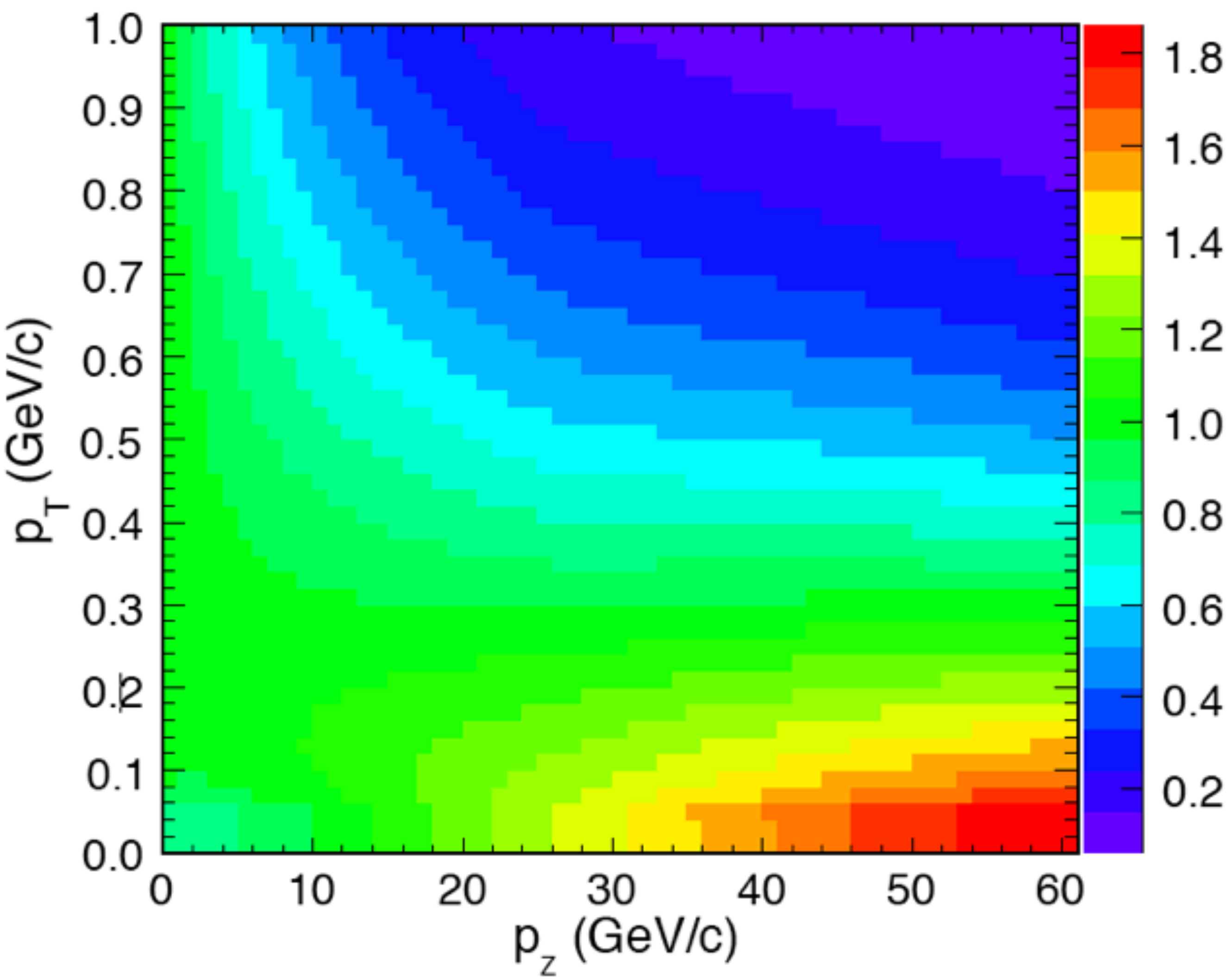
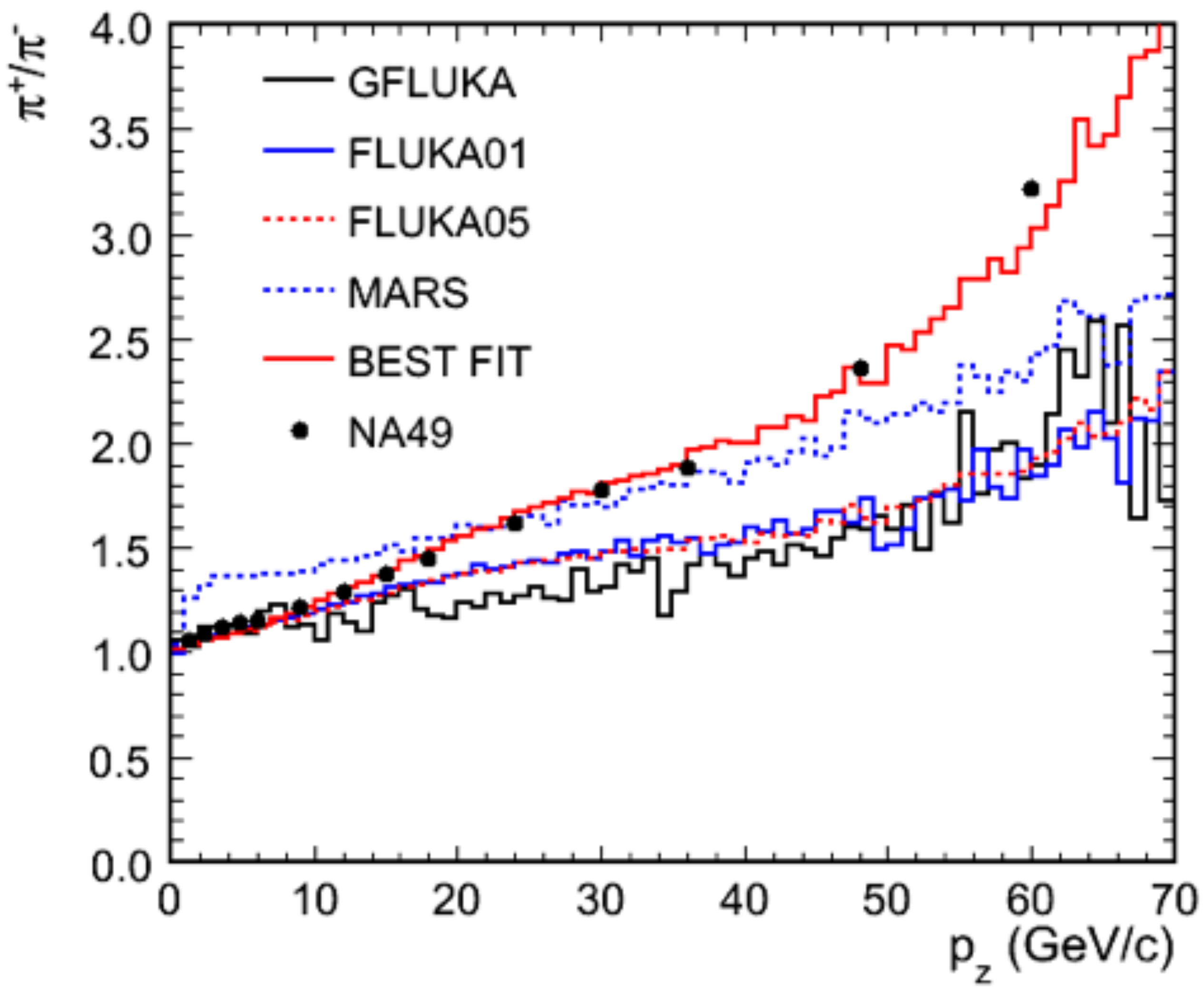


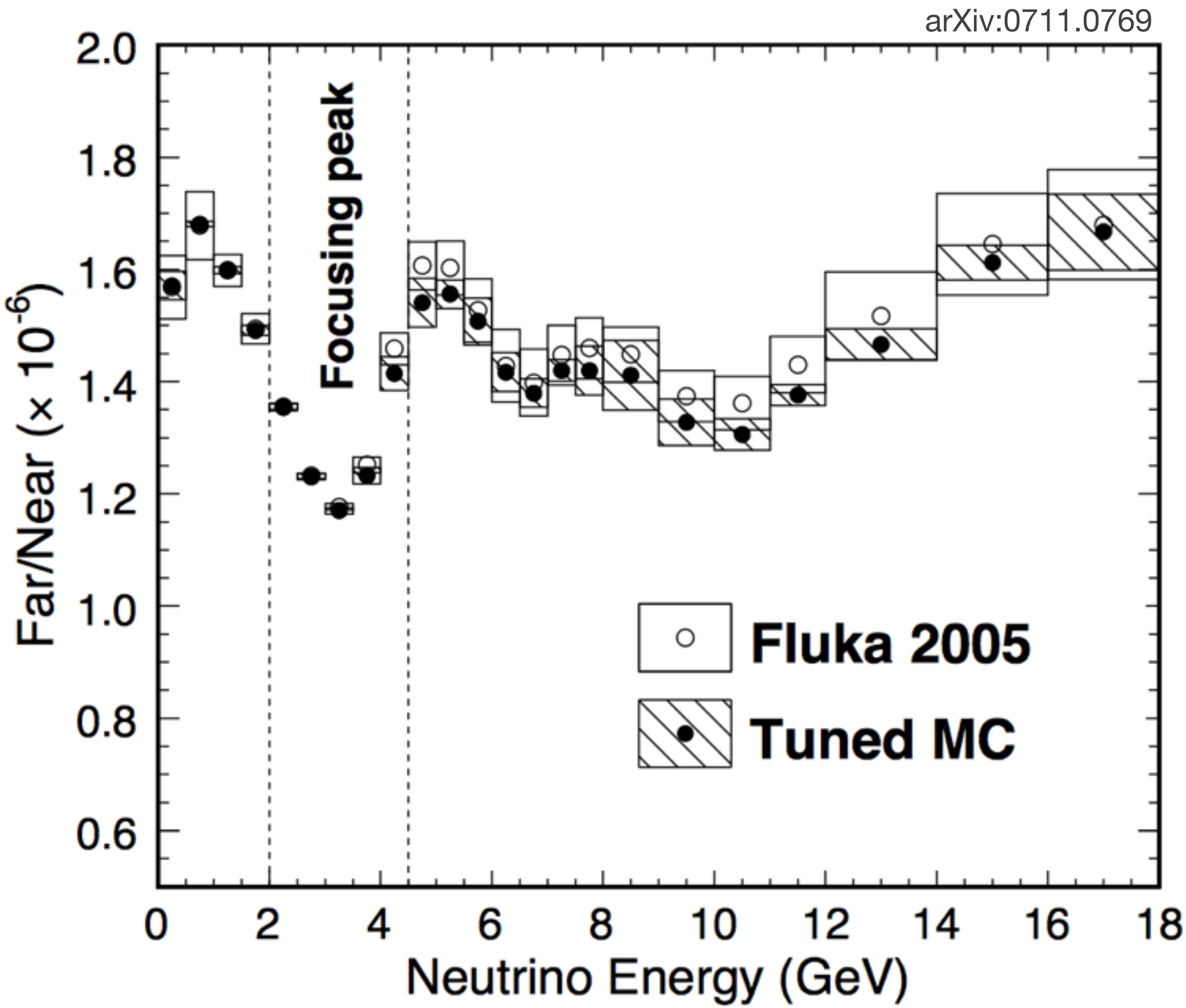
Hadron Tuning

- Reweight pions in terms of transverse and longitudinal momentum
- Produces agreement with dedicated hadroproduction data
  - Experiments explicitly measuring p+target meson production





Beam Effects on Data



Wrap-Up

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- Conventional neutrino beams require many parts
- Near detector is very helpful, but cannot solve all ills
- Future *precision* neutrino physics goals utilizing neutrino beams (CP-violation) must tackle accelerator challenges
  - Target construction
  - Electron cloud
  - Hadroproduction
  - etc