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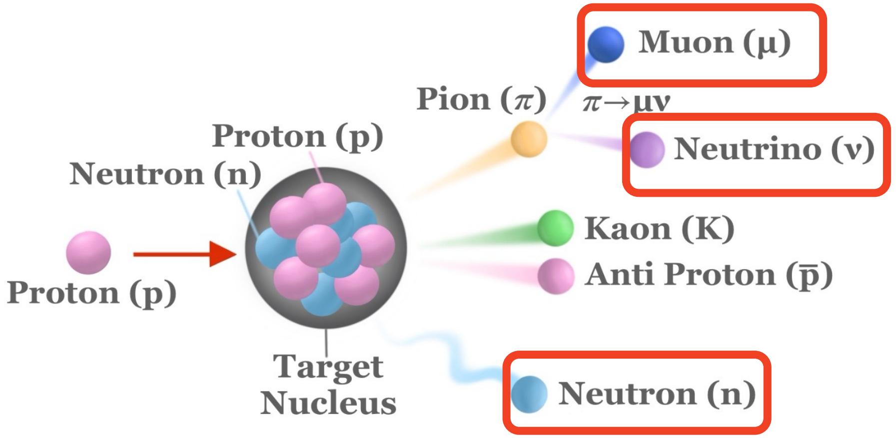
BDX & BEYOND WORKSHOP

Simulation of Secondary Beam Fluxes

Physics with secondary beams

- **Usually produced using proton beams**
  - Generally, they need to be focused and/or re-accelerated
- **Physic interest:**
  - Neutrinos: SM tests, neutrino properties, physics beyond SM, etc
  - Muons: muon scattering, dark matter search, etc.



Neutrinos

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Beam: proton
  - $E_p = 60 - 120$ GeV
- Target: graphite
- $E_\nu = \mathcal{O}(\text{GeV})$
- $I_\nu = \mathcal{O}(10^3)\ \nu/s$

Muons

PAUL SCHERRER INSTITUT PSI

- Beam: proton
  - $E_p = 590$ MeV
- Target: graphite
- $E_\mu = \mathcal{O}(\text{keV} - \text{MeV})$
- $I_\mu = \mathcal{O}(10^3 - 10^8)\ \mu/s$

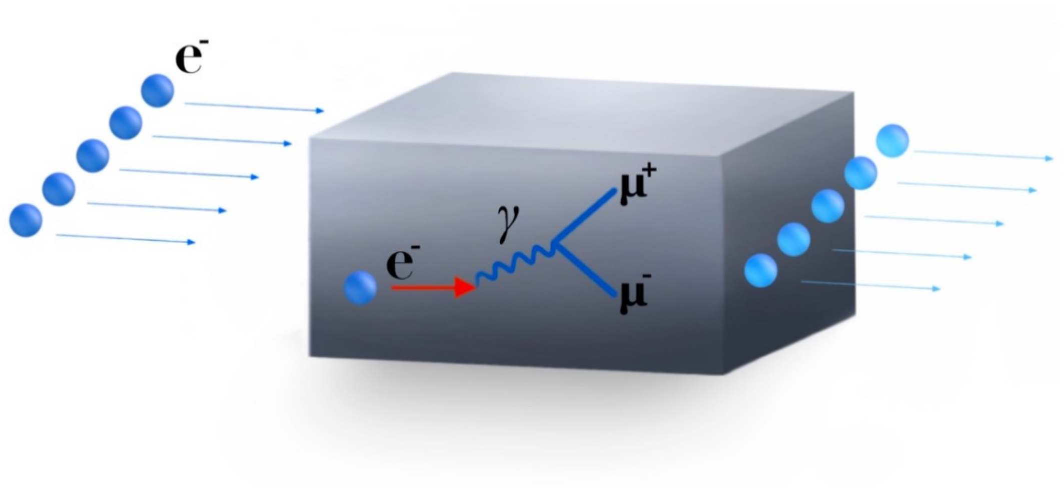
Neutrons

SNS SPALLATION NEUTRON SOURCE

- Beam: proton
  - $E_p = 1$ GeV
- Target: liquid mercury
- $E_n = \mathcal{O}(\text{meV} - \text{keV})$
- $I_n = \mathcal{O}(10^{15} - 10^{16})$ n/s

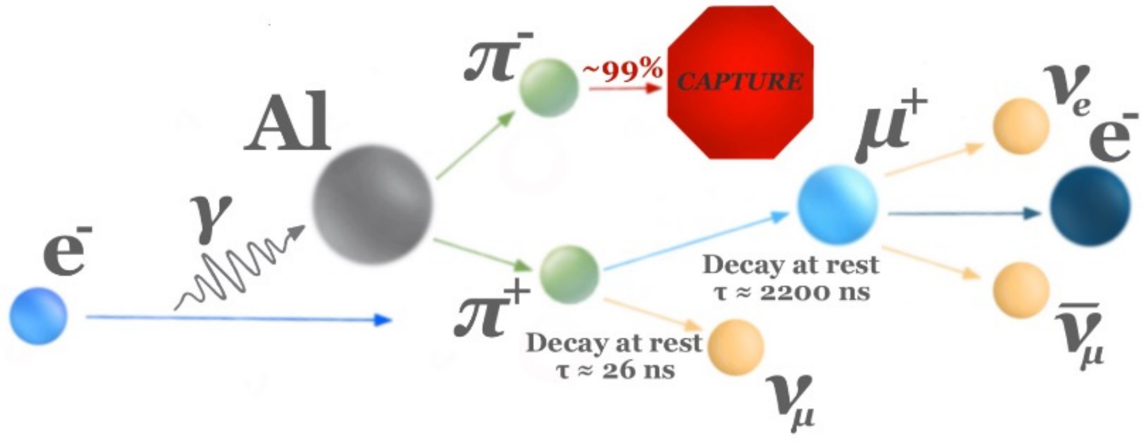
Physics with secondary beams

- Also produced using **high-energy high-intensity e-beams**
  - Thick targets (>4 r.l.)
  - Primary production process:
    1. Electron radiates photons
    2. Photons pair produce secondary particles
       - Muons
       - Pions & Kaons: muons & neutrinos
- ~50 years ago: SLAC muon beam



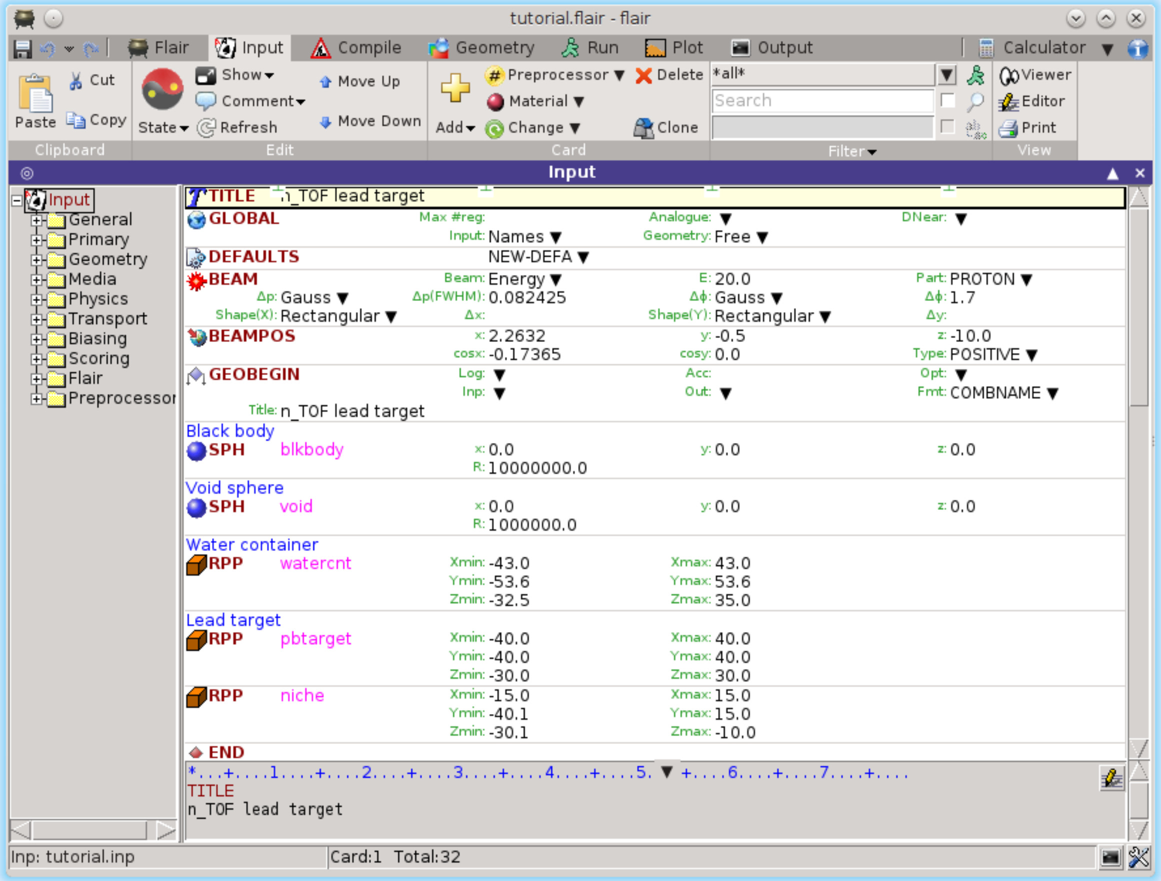
SLAC

- Beam: electron
  - $E_{e^-} = 21$ GeV
- Target: copper
- $E_\mu = 14$ GeV
- $I_\mu = 10^4$ μ/s



Simulation Framework

- **Monte Carlo simulations**
  - Repeated sampling to obtain numerical results
  - Main Monte Carlo software in particle physics:
    - Geant4
    - FLUKA
- **FLUKA**
  - User interface (FLAIR)
  - Ready-to-use biasing technique
    - Importance region sampling, leading particle biasing, interaction length biasing, etc.
- $\boldsymbol{e^- + \mathrm{BD}}$ **simulations needed bias**
  - Rare processes possible thank to the high-intensity
  - **1 year of beam is** $\boldsymbol{\sim 10^{22}\, e^-}$ **@HallA**
    - Standard & custom techniques used



Geometry

BD & Concrete Vault geometry cross-checked with civil drawings
Framework: FLUKA 4-5.0

Beam: e^{-}@11 GeV
Position: on the dump

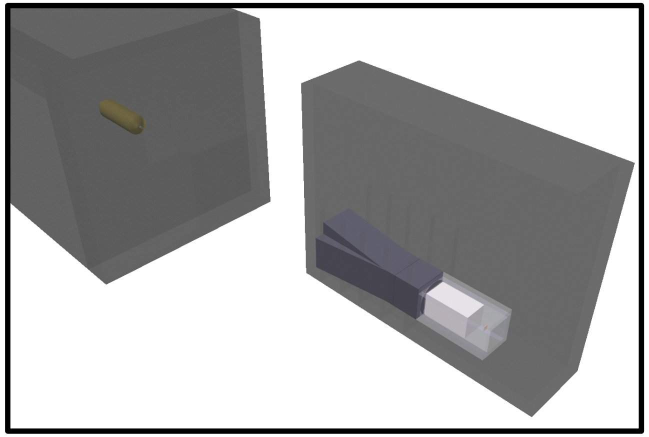
Physics:
- Muon photon nuclear interactions
- Pair production and bremmstrahlung by muons on
- Photo-nuclear interactions on
- Pair production of muons on with bias (x1M)
- Electro-nuclear interactions on
- Decay of $\mu^{\pm}, \pi^{\pm}, K^{\pm}, K^{0}$
- Evaporation model on
- Colaescence model on

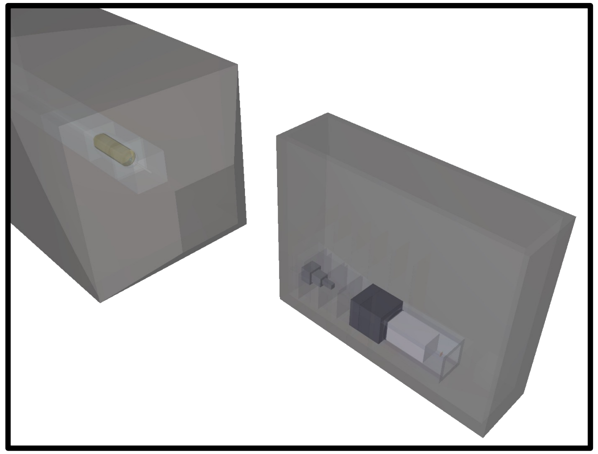
Transport: all particles
- $\mu^{\pm}, \pi^{\pm}, K^{\pm}, K^{0}$ activated decay-at-rest
- $\gamma, e^{\pm}$ cut < 0.1 GeV

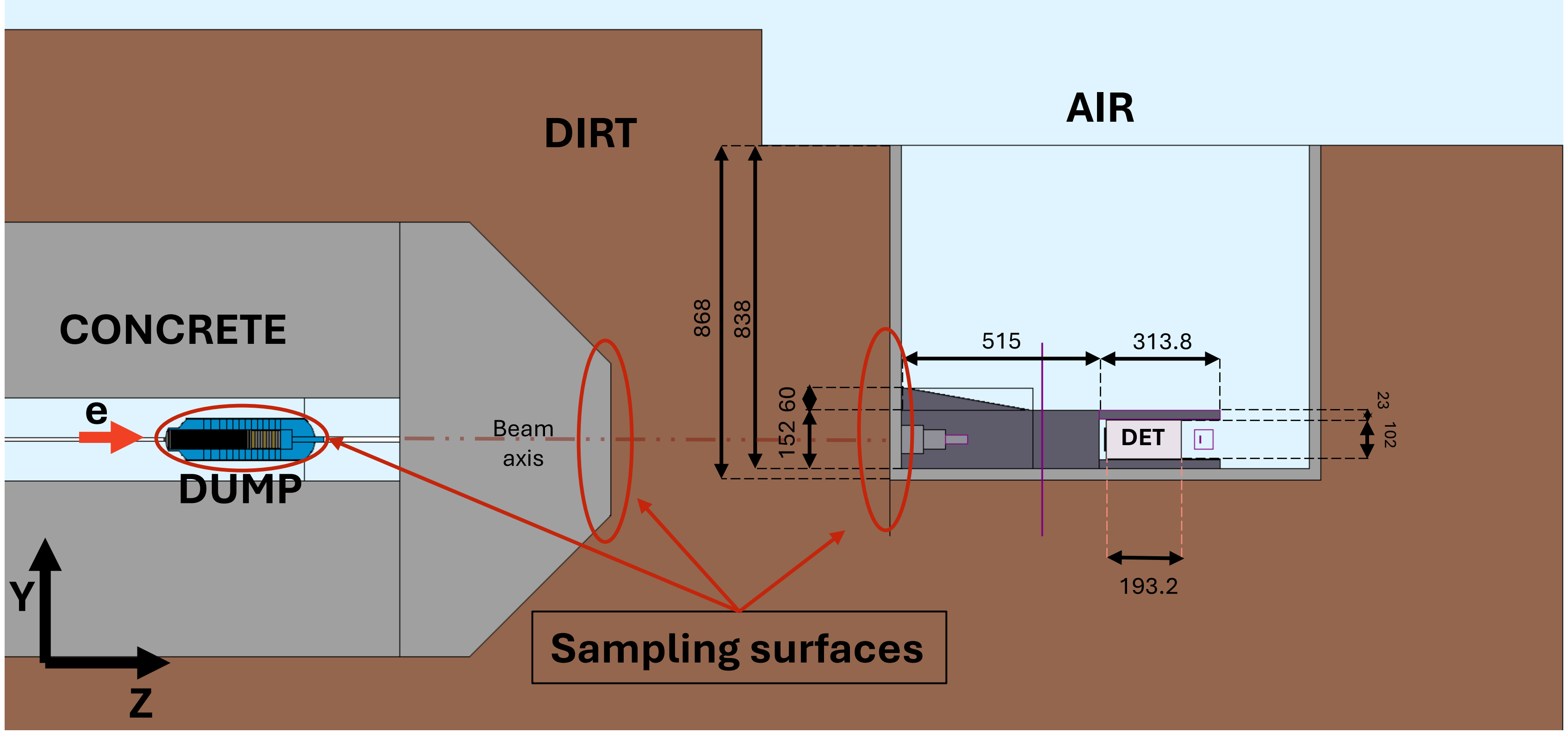
Bias:
- Leading-particle
- Lambda bias inelastic (x100)
- Custom for neutrons

Scoring: boundary crossing with user routines

Results normalized to "Electron On Target" (EOT)



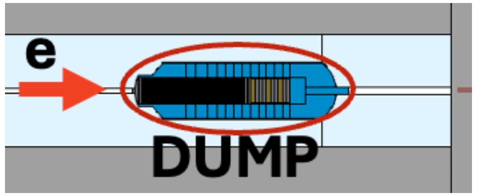




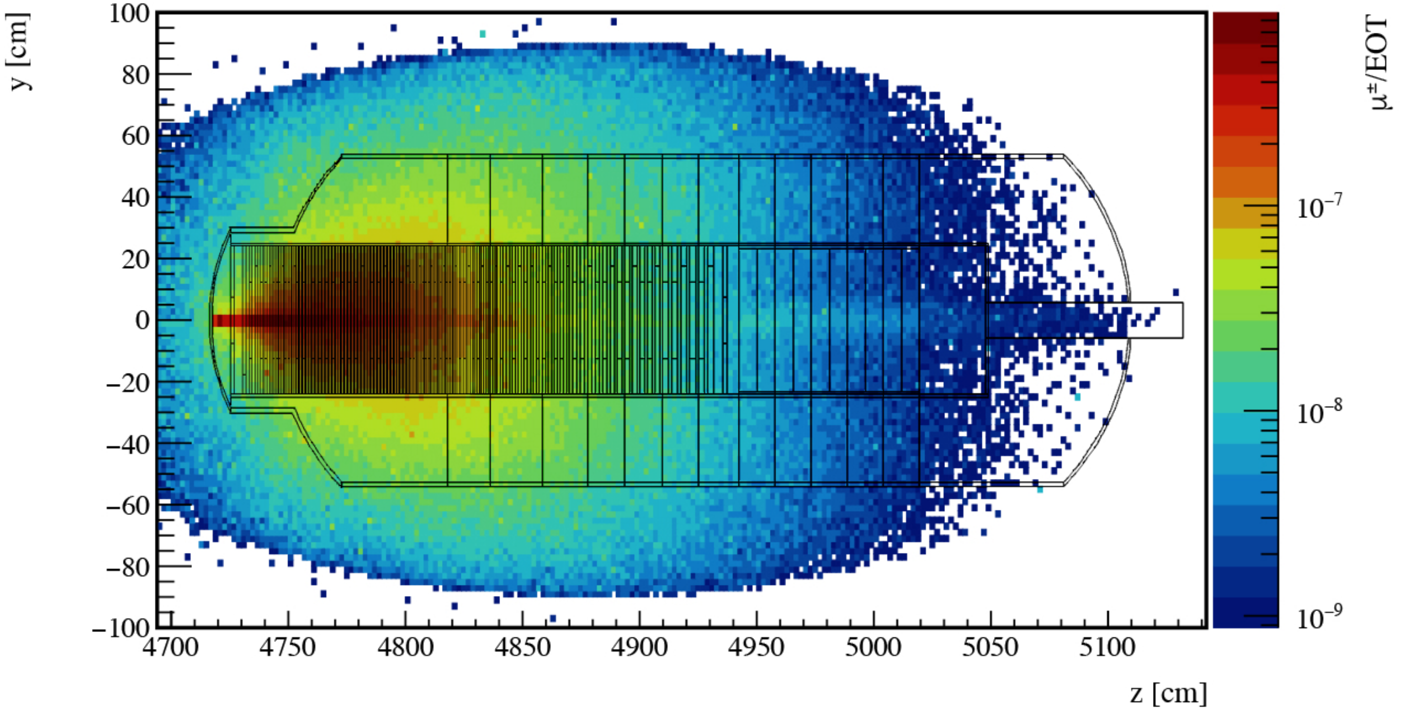
Muon Results

Secondary Muon Beam

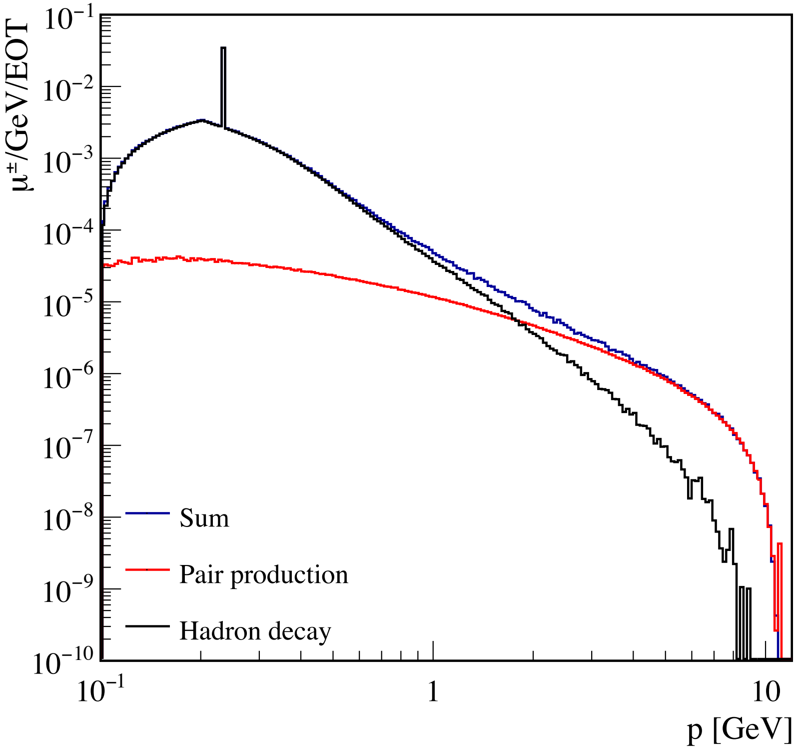
- Muons sampled around the beam-dump
- $\sim$90% of muons produced at the beginning of the beam-dump
- High energy muons: **photoproduction**
- Low energy muons: **hadron decays (pions & kaons)**
  - Peak at 235 MeV: $K \rightarrow \mu + \nu_e$



Muons sampled around the beam-dump



Muon production vertexes with beam-dump outline

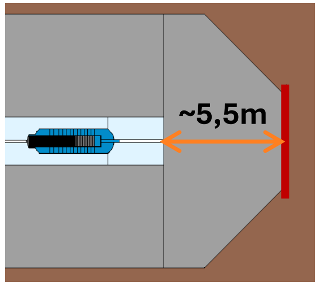


Muon production

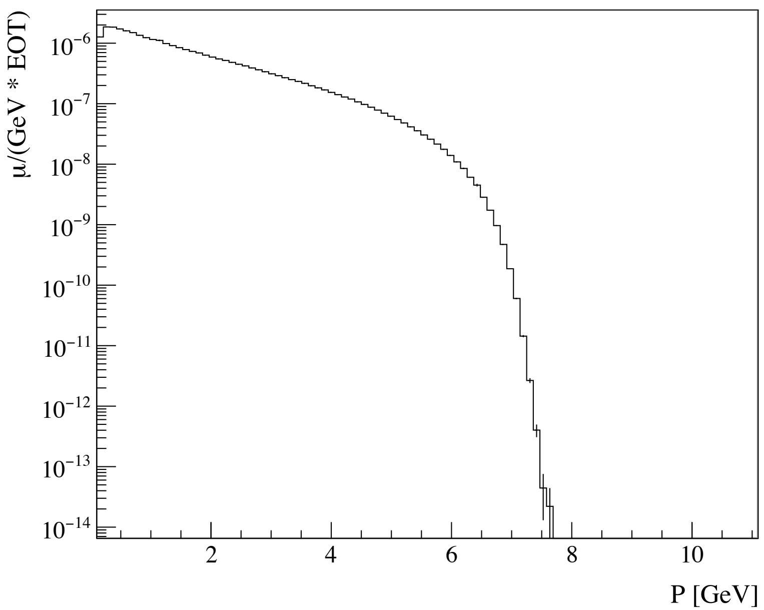
Secondary Muon Beam

- **Muons sampled at the end of the BD's concrete vault**
- **Main features:**
  - Typical of bremsstrahlung
    - Cut $E_{\mathrm{kin}} > 100$ MeV
  - Beam partially focused
  - $\sim$50% are contained within $r \approx 25\ cm$
  - Higher energy muons produced at small angles

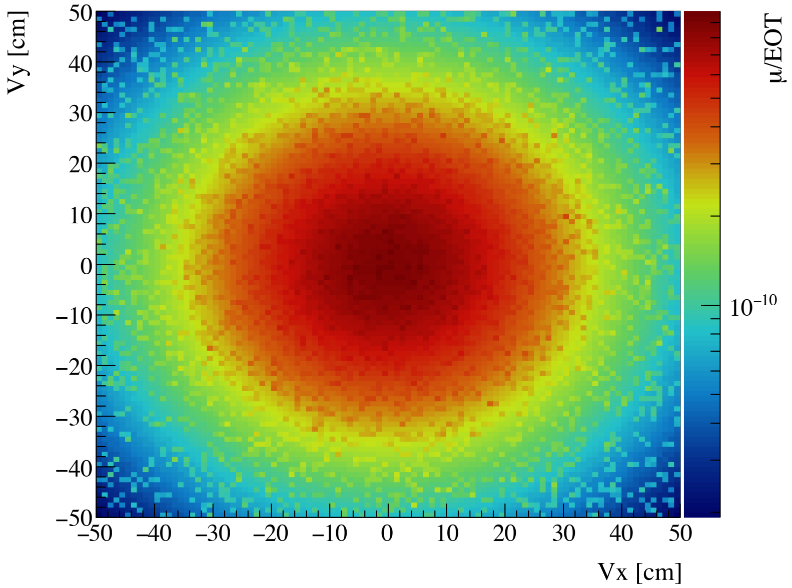
- **Estimated flux:**
  - $100 \times 100\ cm^2$: $\mathbf{2.5 \times 10^{-6}\ \mu^{\pm}/EOT}$
- **Spatial distribution:**
  - $\sigma_x \approx \sigma_y \approx 24\ cm$
- **Distance from the BD's tunnel end: $\sim 5.5m$**



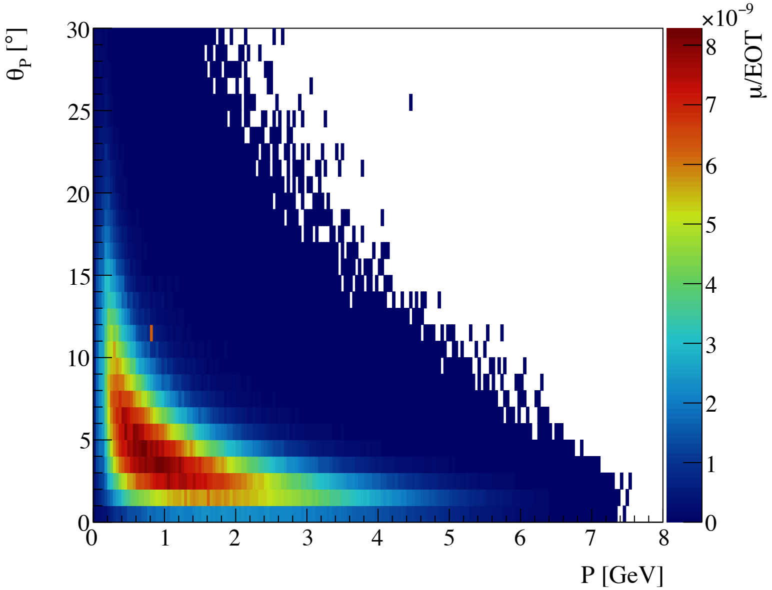
Muons sampled at the end of the beam-dump's concrete vault ($1m^2$)



Muon beam spectrum



Muon beam spatial distribution

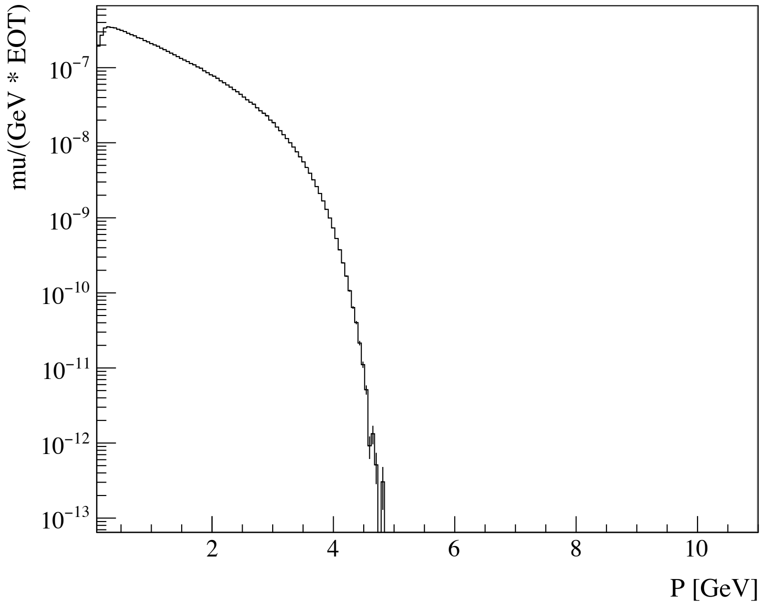


Muon beam energy-angle distribution

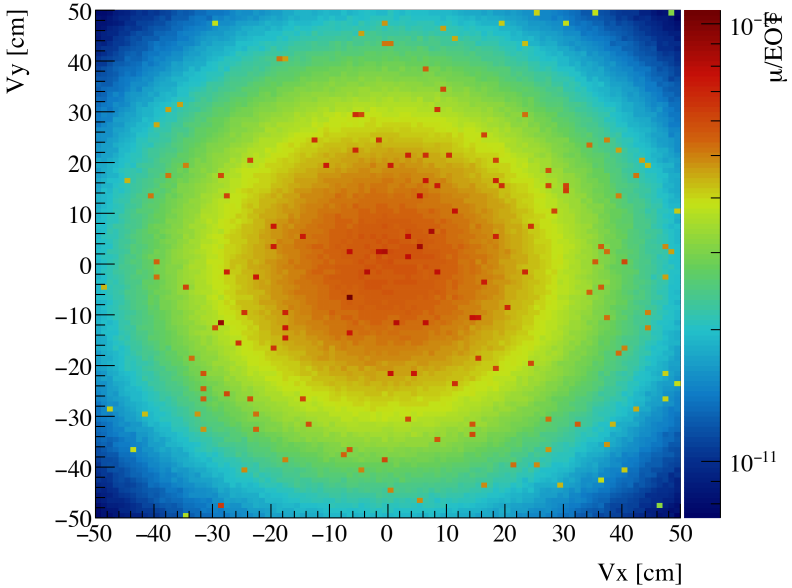
Secondary Muon Beam

- **Muons sampled at the beginning of the BDX pit**
- **Estimated flux:**
  - $100 \times 100\ cm^2$: $\mathbf{3.0 \times 10^{-7}\ \mu^{\pm}/EOT}$
- **Spatial distribution:**
  - $\sigma_x \approx \sigma_y \approx 35\ cm$
- **Distance from the BD's tunnel end: $\sim 13m$**

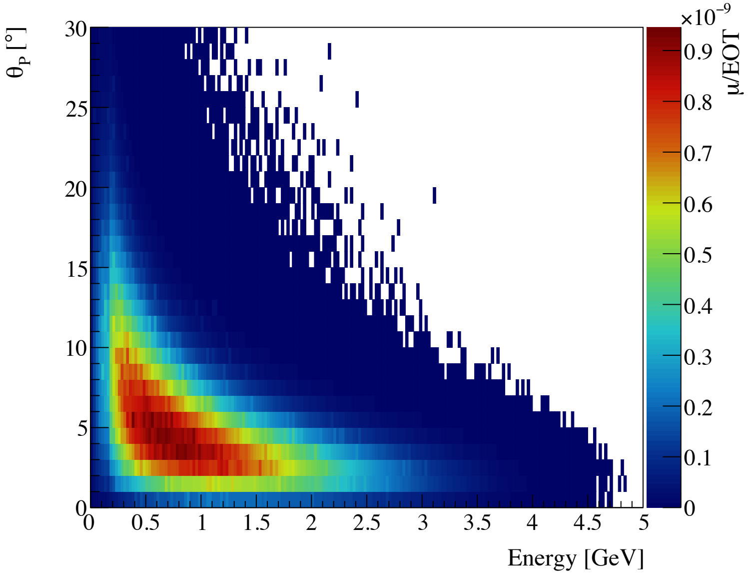
Muons sampled at the beginning of the BDX pit ($1m^2$)



Muon beam spectrum



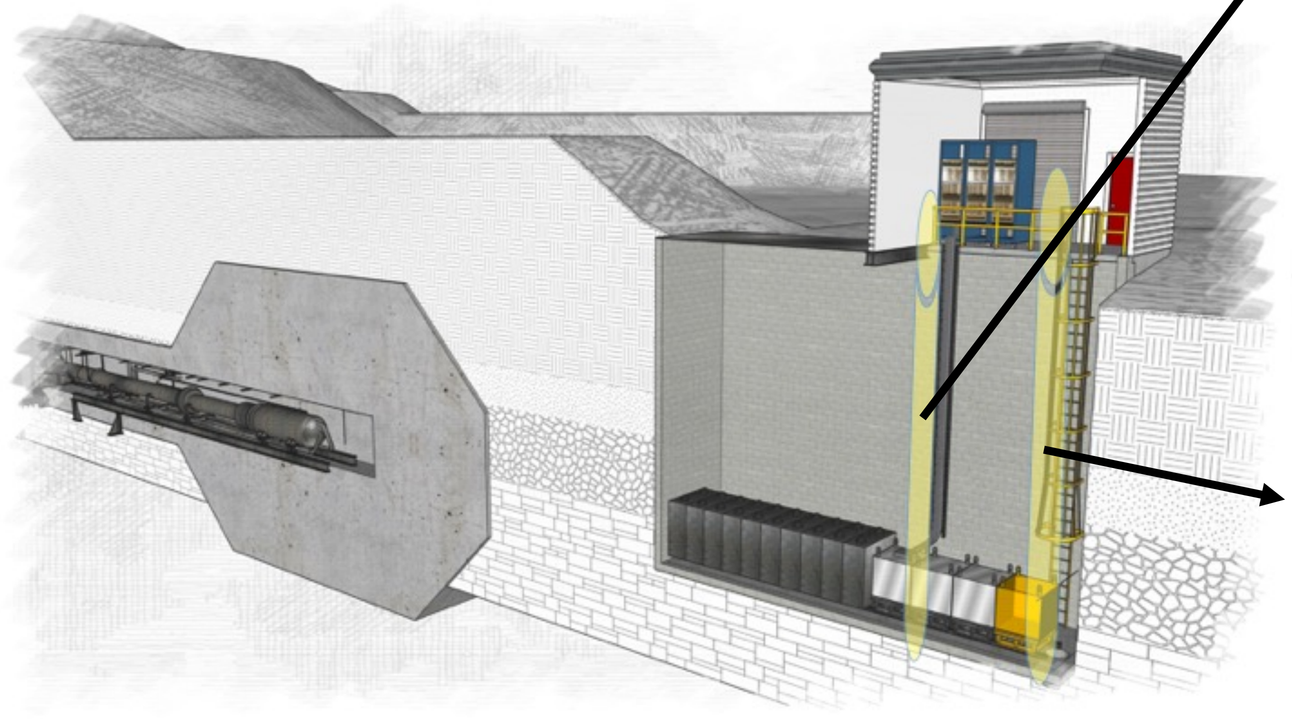
Muon beam spatial distribution

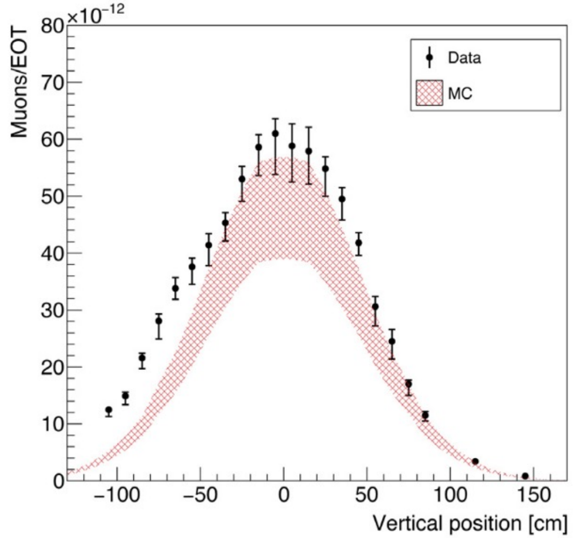


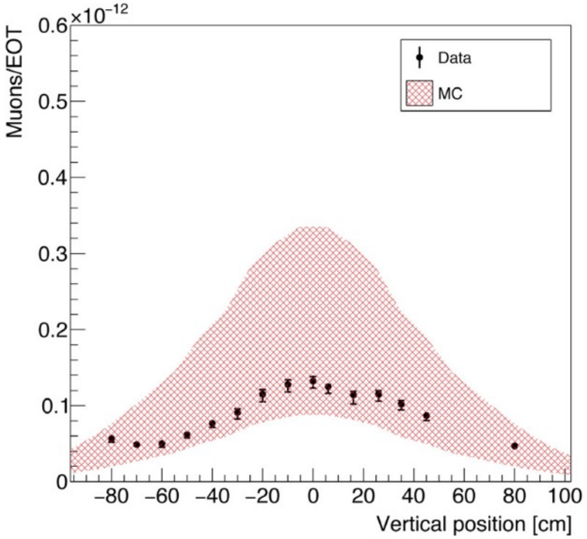
Muon beam energy-angle distribution

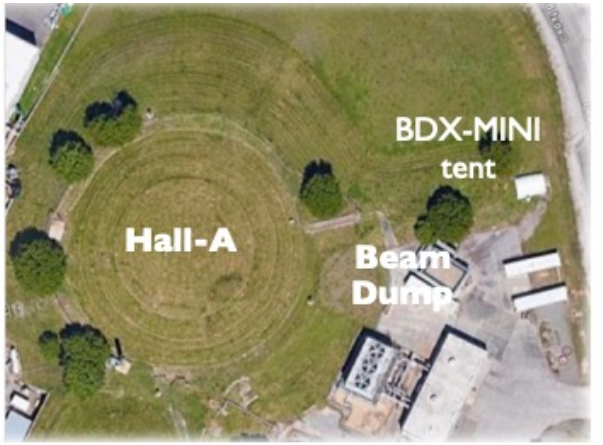
Simulation framework validation with μBDX experiment

- Comparison between simulated and measured muon rates as a function of vertical height
  - Flux dependant on density variation
  - Simulation ran with $\rho_{dirt} = 1.93\ g/cm^3$ and $\rho_{concrete} = 2.3\ g/cm^3$





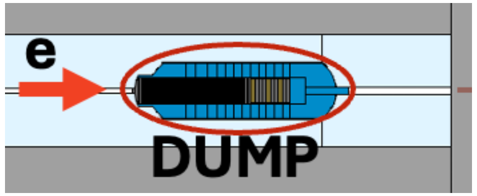




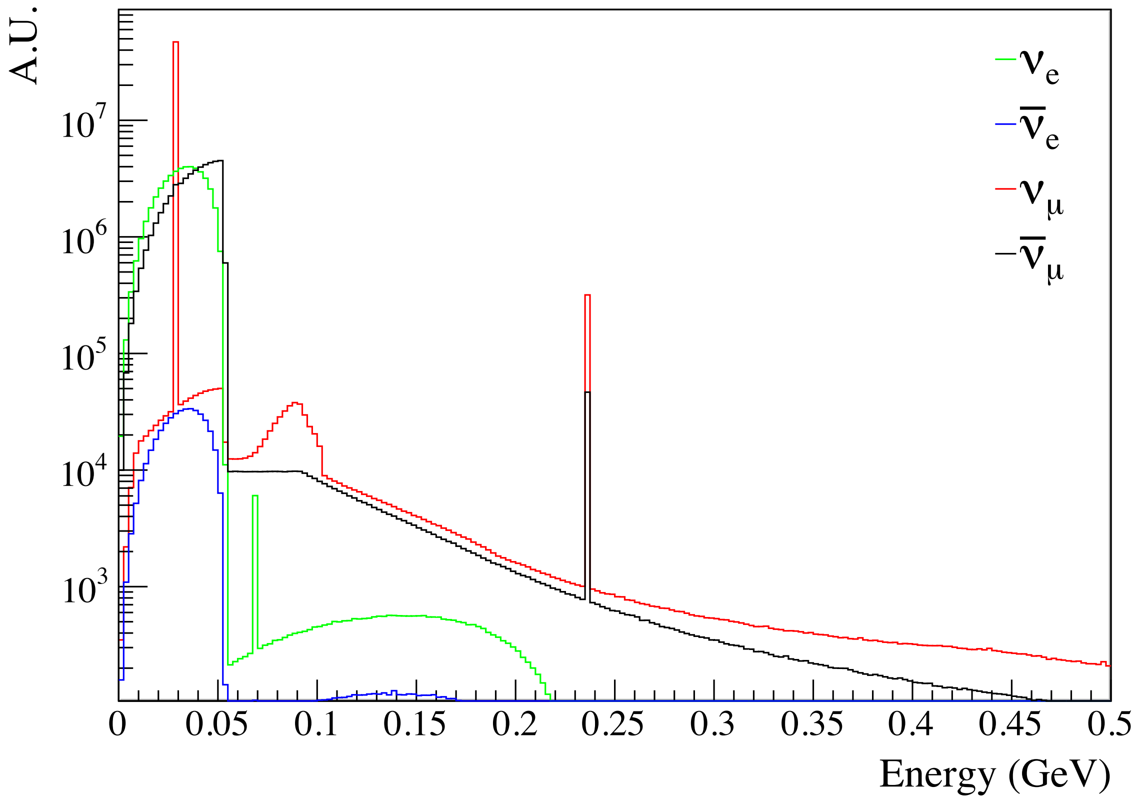
Neutrino Results

Secondary Neutrino Beam

- **Main features:**
  - Isotropic distribution
  - Peak at 29.8 MeV: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Neutrinos from $0 < E_\nu < 52.8$ MeV: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
  - Peak at 236 MeV: $K^+ \rightarrow \mu^+ + \nu_\mu$
  - Peak at 70 MeV (suppressed): $\pi^+ \rightarrow e^+ + \nu_e$



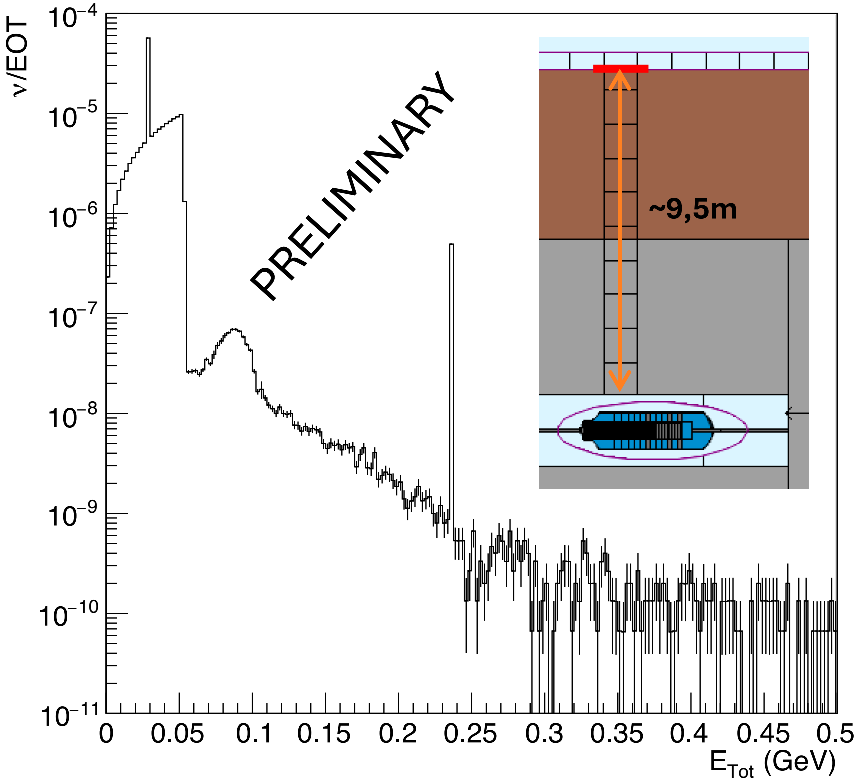
Neutrino sampled around the beam-dump



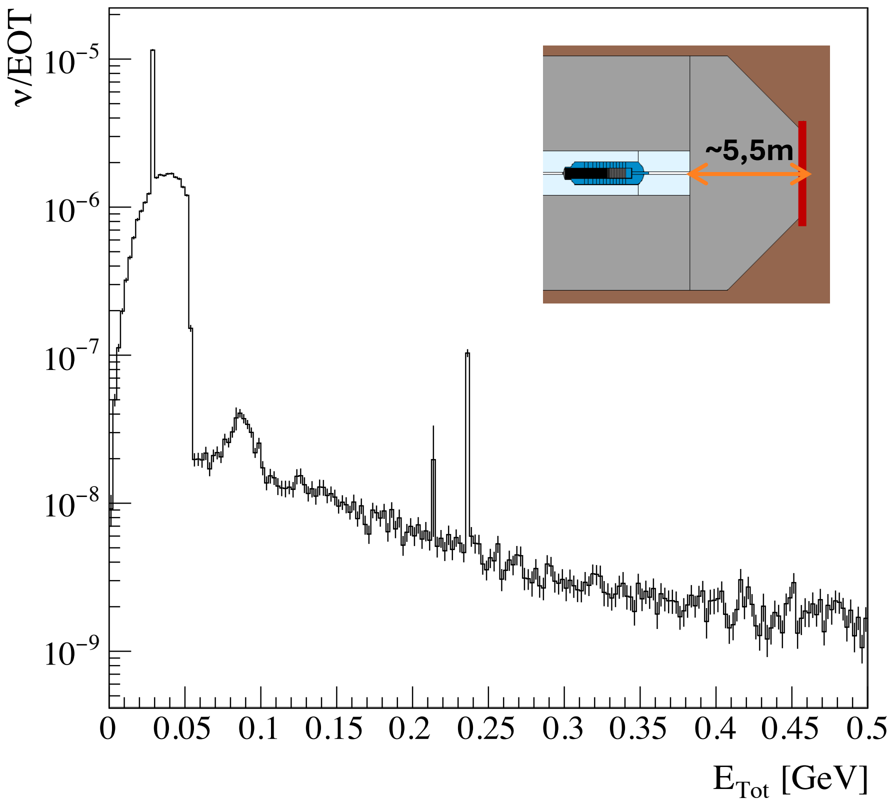
On/Off axis neutrino flux

- **Estimated flux:**
  - **On-Axis:** $\sim 3.0 \times 10^{-5}\ \nu/EOT$ **@ 11 GeV e^- beam**
  - **Off-Axis:** $\sim 6.7 \times 10^{-5}\ \nu/EOT$ **@ 11 GeV e^- beam**

Off-Axis

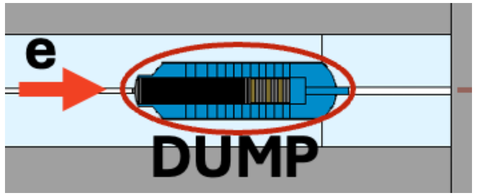


On-Axis



NEUTRON RESULTS

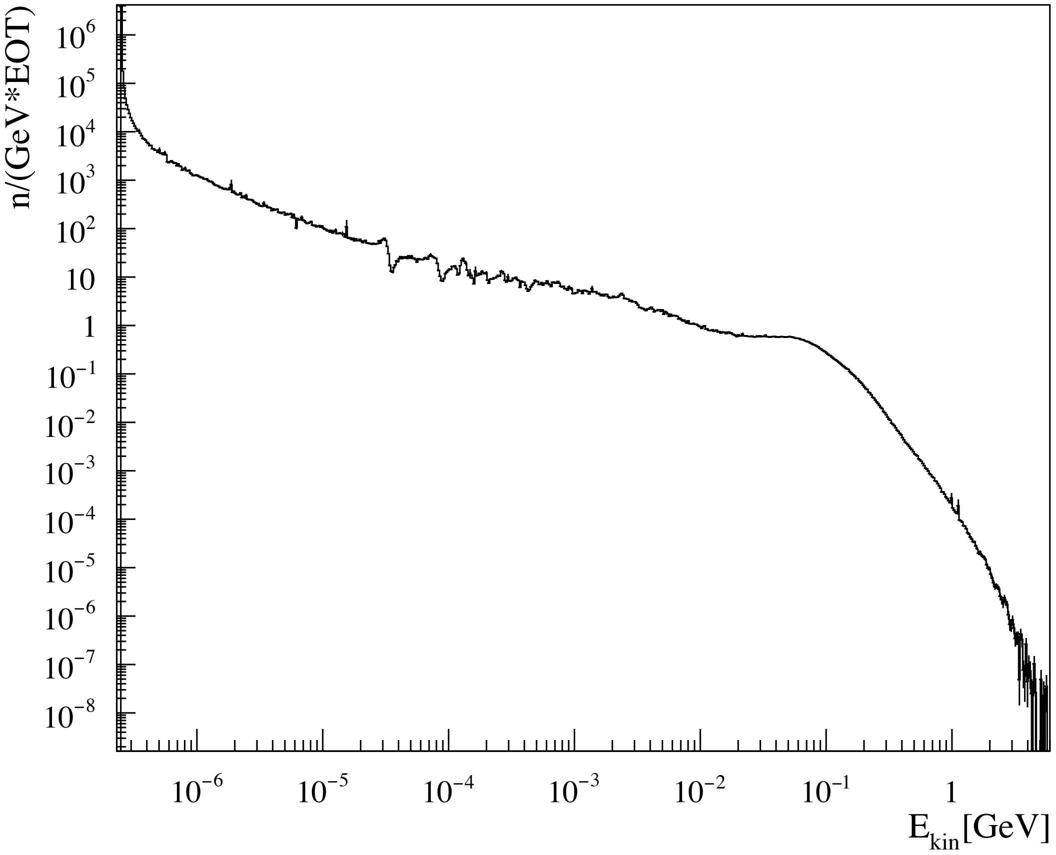
Secondary Neutron production



Neutrons sampled around the beam-dump

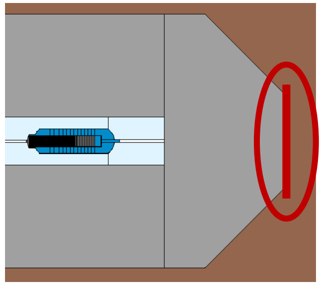
Energy Range	n/EOT
0 - 6GeV	1.26e-01
0.1eV - 100.0eV	0.00e+00
100.0eV - 100.0keV	3.42e-02
100.0keV - 1.0MeV	7.23e-03
1.0MeV - 100.0MeV	6.66e-02
100.0MeV - 2.0GeV	1.82e-02
2.0GeV - 6.0GeV	3.31e-06

$0.1\ eV < E_{kin} < 6$ GeV

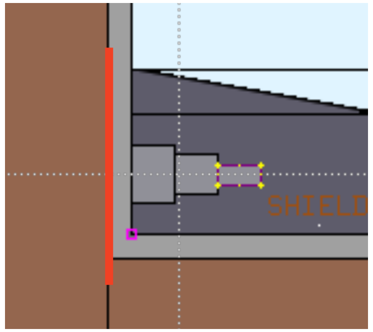


Neutron propagation

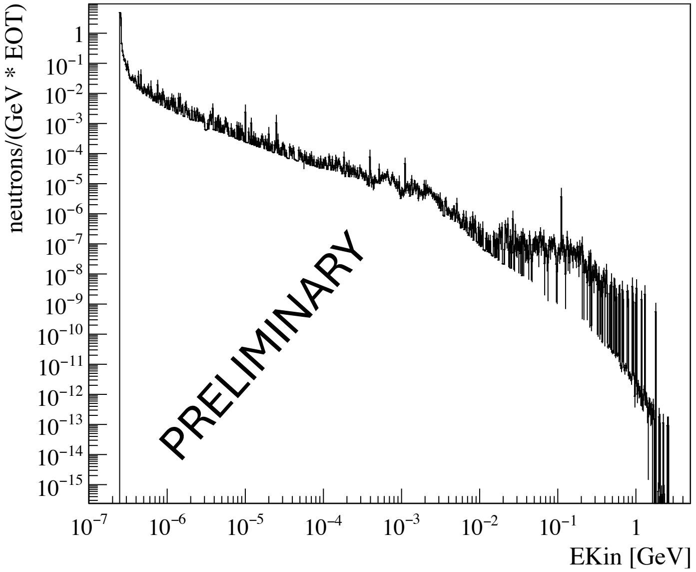
- Low statistics simulations
  - Right now implementing ad hoc biasing techniques



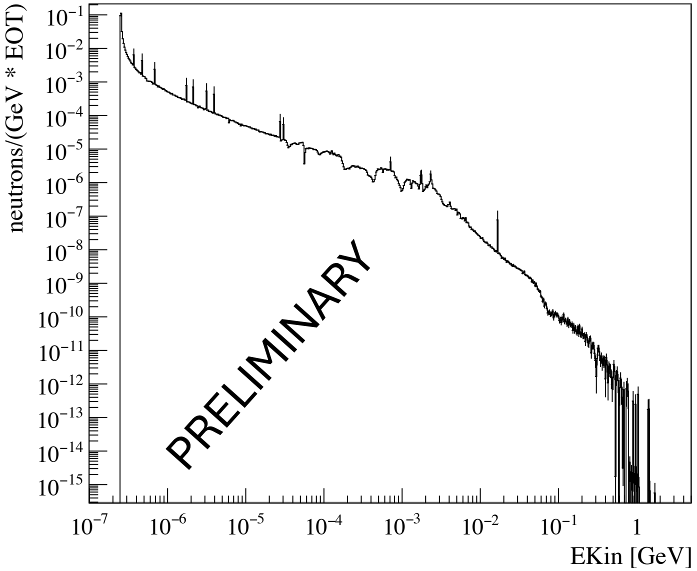
Neutrons sampled at the end of the beam-dump’s concrete vault
500x500cm^2



Neutrons sampled at the start of the BDX pit
500x500cm^2



Energy Range	n/EOT
0 - 6GeV	3.87E-08
0.1eV - 100.0eV	0
100.0eV - 100.0keV	2.25E-08
100.0keV - 1.0MeV	4.31E-09
1.0MeV - 100.0MeV	6.9E-09
100.0MeV - 2.0GeV	5.03E-09
2.0GeV - 6.0GeV	5.87E-15



Energy Range	n/EOT
0 - 6GeV	2.63E-09
0.1eV - 100.0eV	0
100.0eV - 100.0keV	1.40E-09
100.0keV - 1.0MeV	5.55E-10
1.0MeV - 100.0MeV	6.78E-10
100.0MeV - 2.0GeV	2.23E-12
2.0GeV - 6.0GeV	0

THANK YOU!

Neutrons Jlab - Propagation

The neutrons are then propagated to the BDX room.
In doing this a custom biasis is used in order to give more importante to the neutrons moving towards the CCD.
This is doing by implementing a custom directional biasing using a FLUKA Fortran user routine (usimbs.f)

The implements **importance biasing** for neutrons to improve simulation efficiency by "steering" neutrons toward a detector region.

Directional Biasing Algorithm

Calculates distance from current neutron position to target
Computes cosine of angle between neutron direction and target direction
Adjusts particle importance based on this angle:

cos = 1: Neutron heading directly toward target → no change
cos = 0: Neutron perpendicular to target → importance reset to 1
cos < 0: Neutron heading away from target → Russian Roulette applied

Importance Modification

Weigth = Weigth ** cos_direc

Increases survival probability for neutrons heading toward detector
Decreases survival probability for neutrons heading away

EXAMPLE:

If a neutron has FIMP = 0.1:

- 90% chance the particle is killed
- 10% chance it survives with 10× higher weight

Result: Same expected contribution, but 90% fewer particles to track

PROs:

Eliminates neutrons unlikely to reach the detector
Focuses computing power on important particles
Expected values remain unchanged
Variance may actually decrease
FLUKA automatically applies Russian Roulette when FIMP < 1.0
No additional coding required