Update on the code intercomparison and benchmark for muon fluence and absorbed dose induced by an 18 GeV electron beam after massive iron shielding

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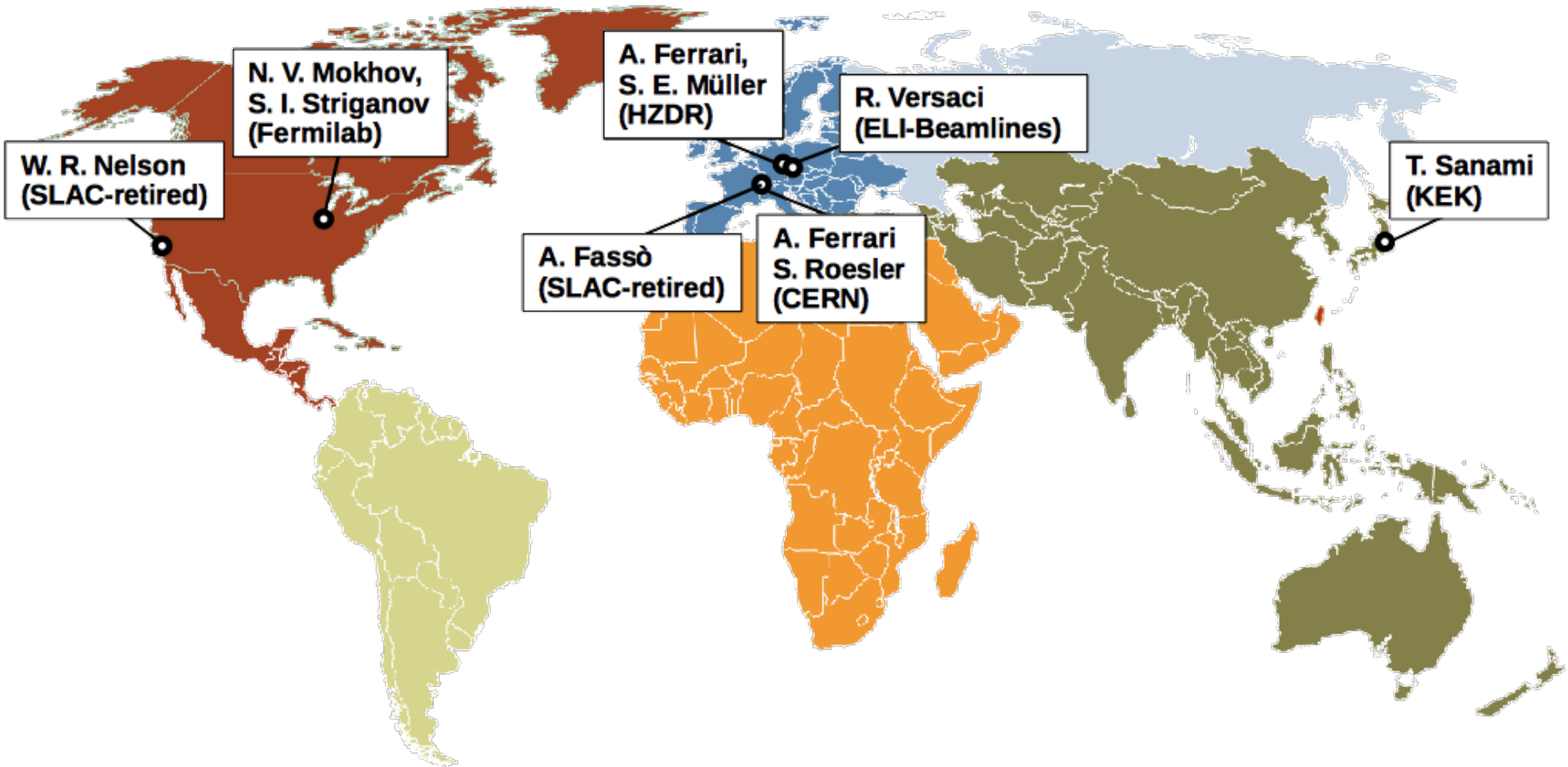
13th Meeting on Shielding Aspects of Accelerators, Targets and Irradiation Facilities (SATIF-13) - Dresden, October 10-12, 2016

HZDR

DRESDEN concept

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Mitglied der Helmholtz-Gemeinschaft

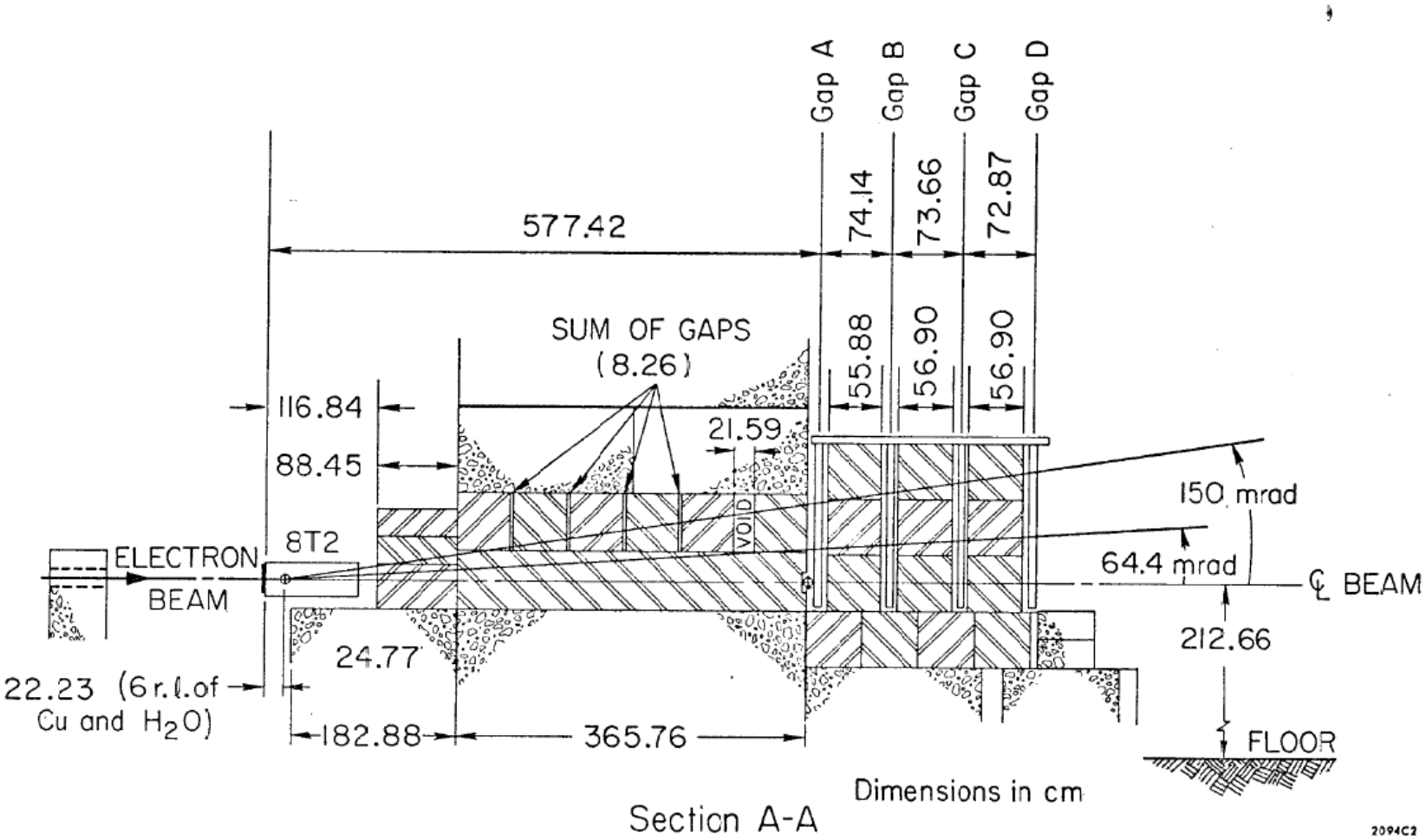

W. R. Nelson
(SLAC-retired)
N. V. Mokhov,
S. I. Striganov
(Fermilab)
A. Ferrari,
S. E. Müller
(HZDR)
R. Versaci
(ELI-Beamlines)
T. Sanami
(KEK)
A. Fassò
(SLAC-retired)
A. Ferrari
S. Roesler
(CERN)

The experiment

- 1974: Nelson, Kase and Svensson publish the results of an experiment performed at SLAC (*NIM 120 (1974) 413*)
- 18 GeV e^- beam hits beamdump-target made of copper and water discs
- massive shielding (*"iron"*) after beamdump
- detectors for muon fluence and dose measurements were placed in 4 gaps of shielding:
  - Nuclear track emulsion plates (400μm thick) to measure muon fluence
  - Thermoluminescent dosimeters (TLD-700 phosphor) to measure dose
- in addition, 2 scintillation counters to determine exposure (and muon fluence)
- Results were compared to theoretical predictions of the time (*NIM 120 (1974) 401*)

The experiment

Vertical view of experimental setup:



The experiment

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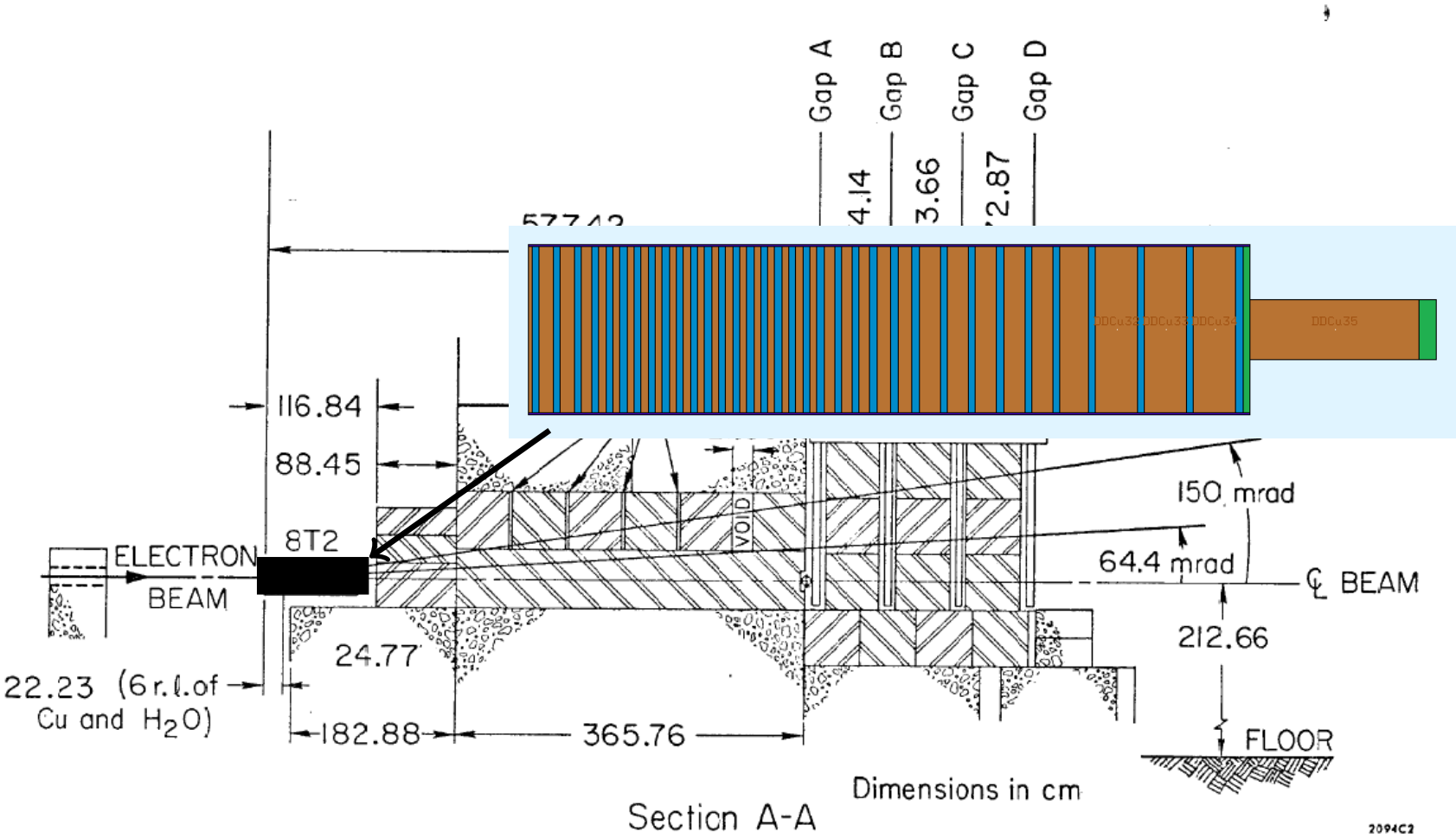

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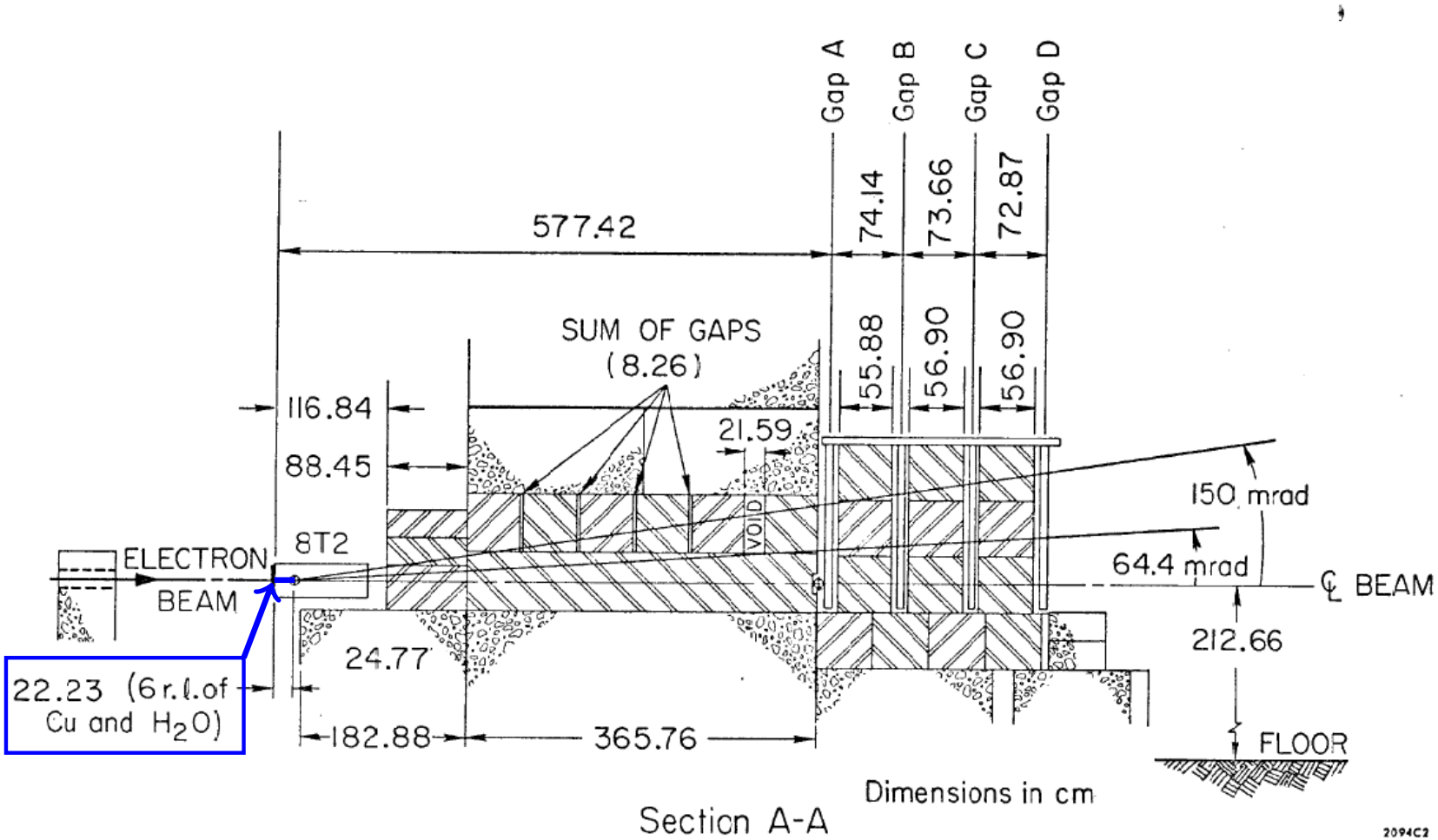

The experiment

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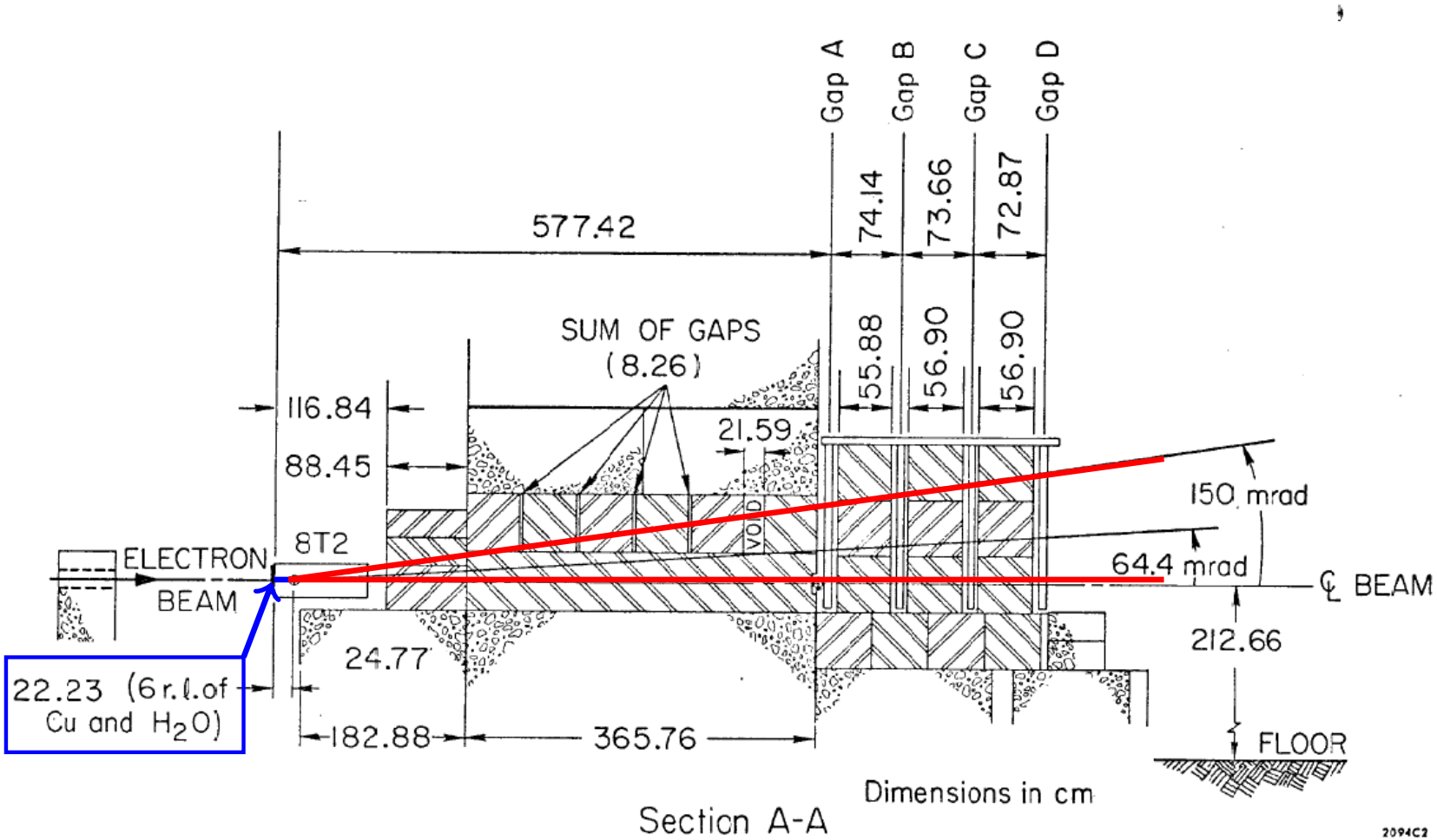

The experiment

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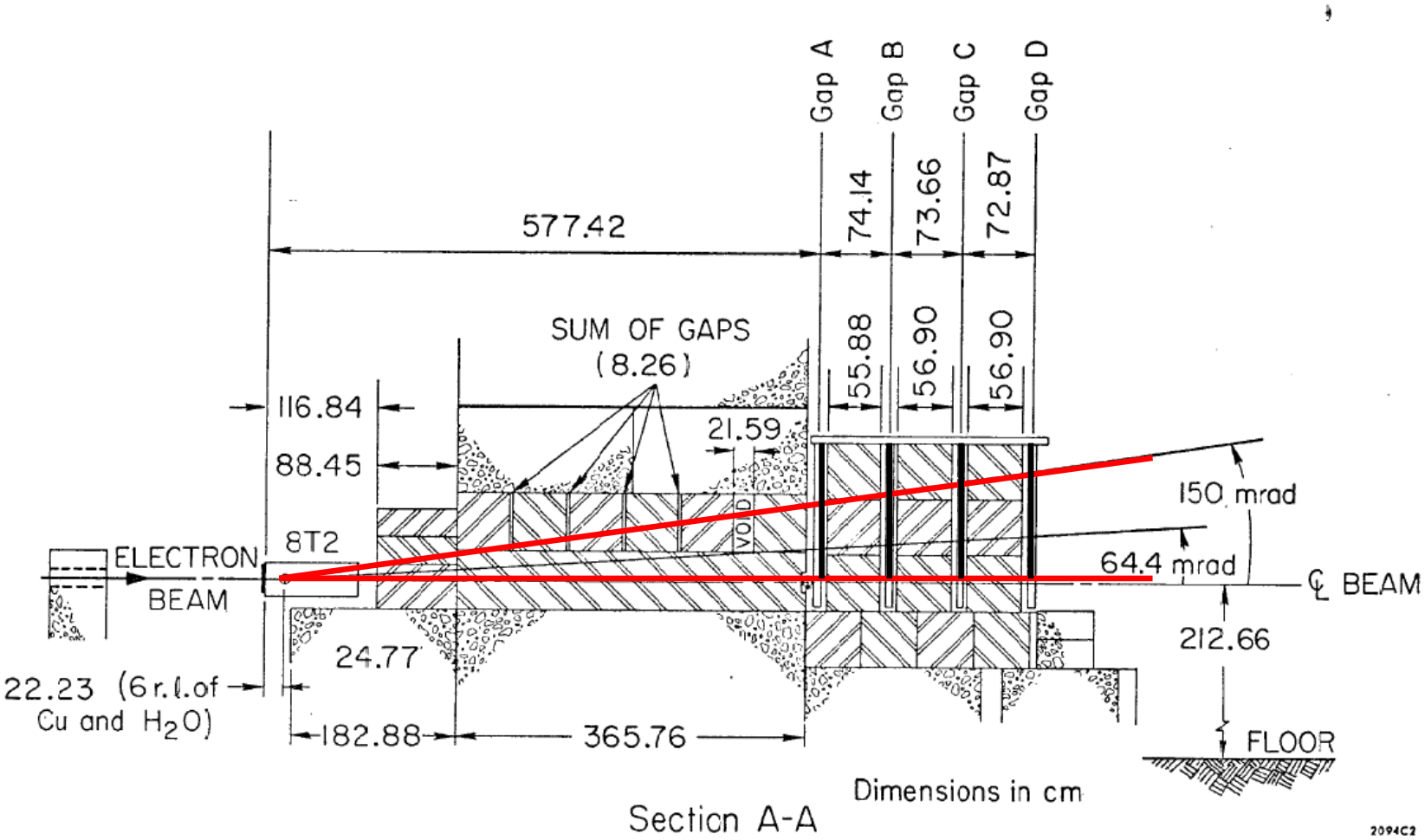
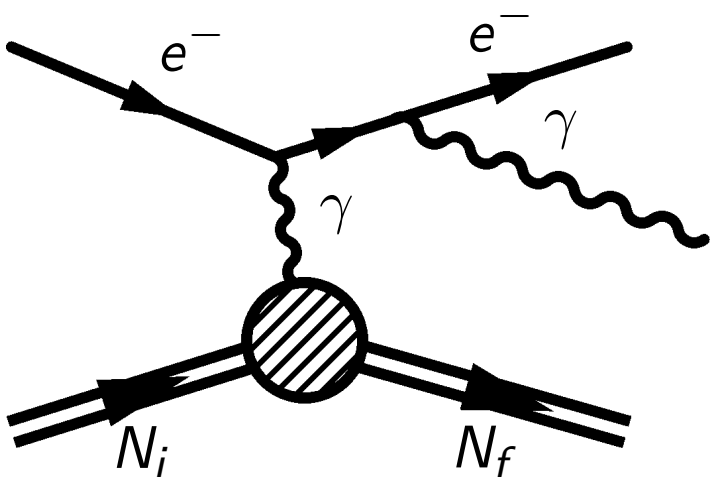


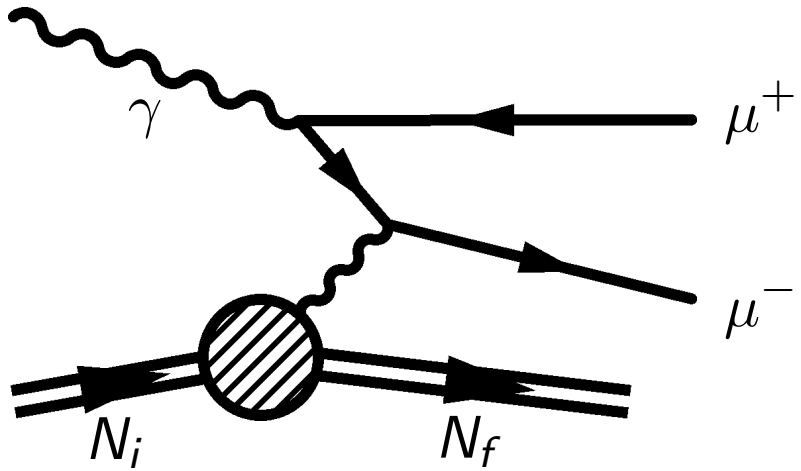
Physics models:

Muon pair production in the field of the nucleus from Bremsstrahlung photons

Bremsstrahlung:



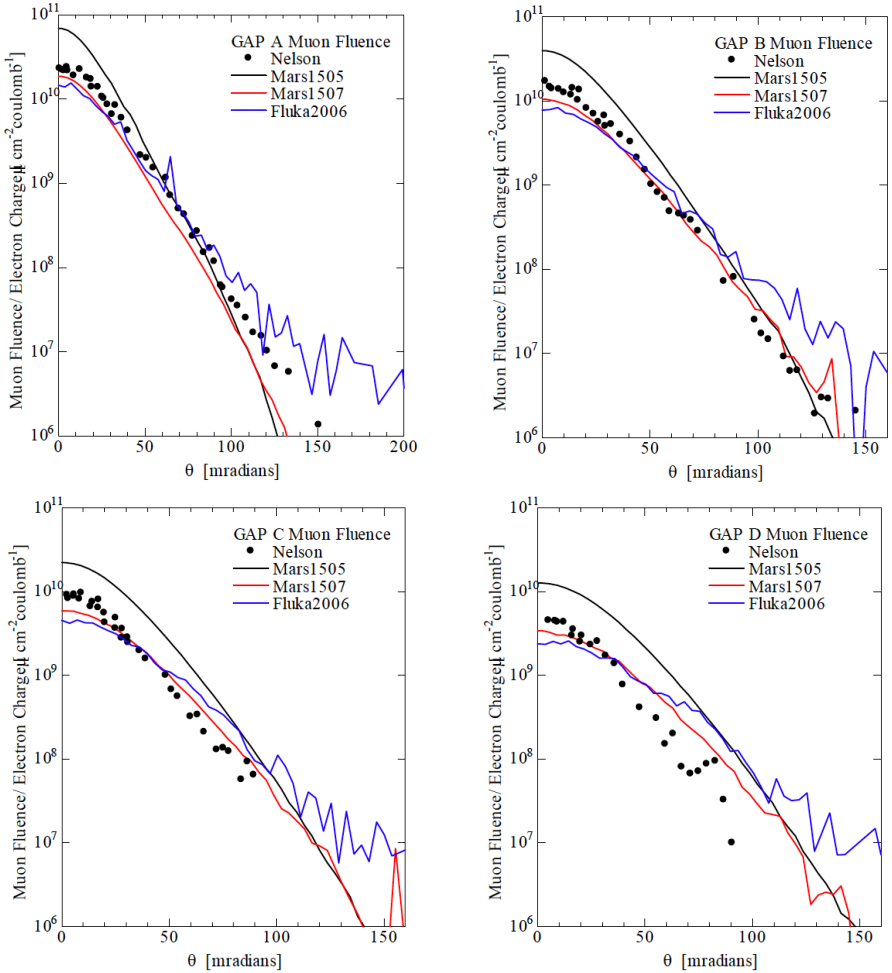
Photomuon production:



Y. S. Tsai: *Pair production and Bremsstrahlung of charged leptons*, Rev. Mod. Phys. 46 (1974) 815, Rev. Mod. Phys. 49 (1977) 421

First comparison with modern transport codes:

2007: N. V. Mokhov, W. R. Nelson and T. Sanami (*SLAC Radiation Physics Note RP-07-15*): Comparison with MARS and FLUKA



The transport codes:

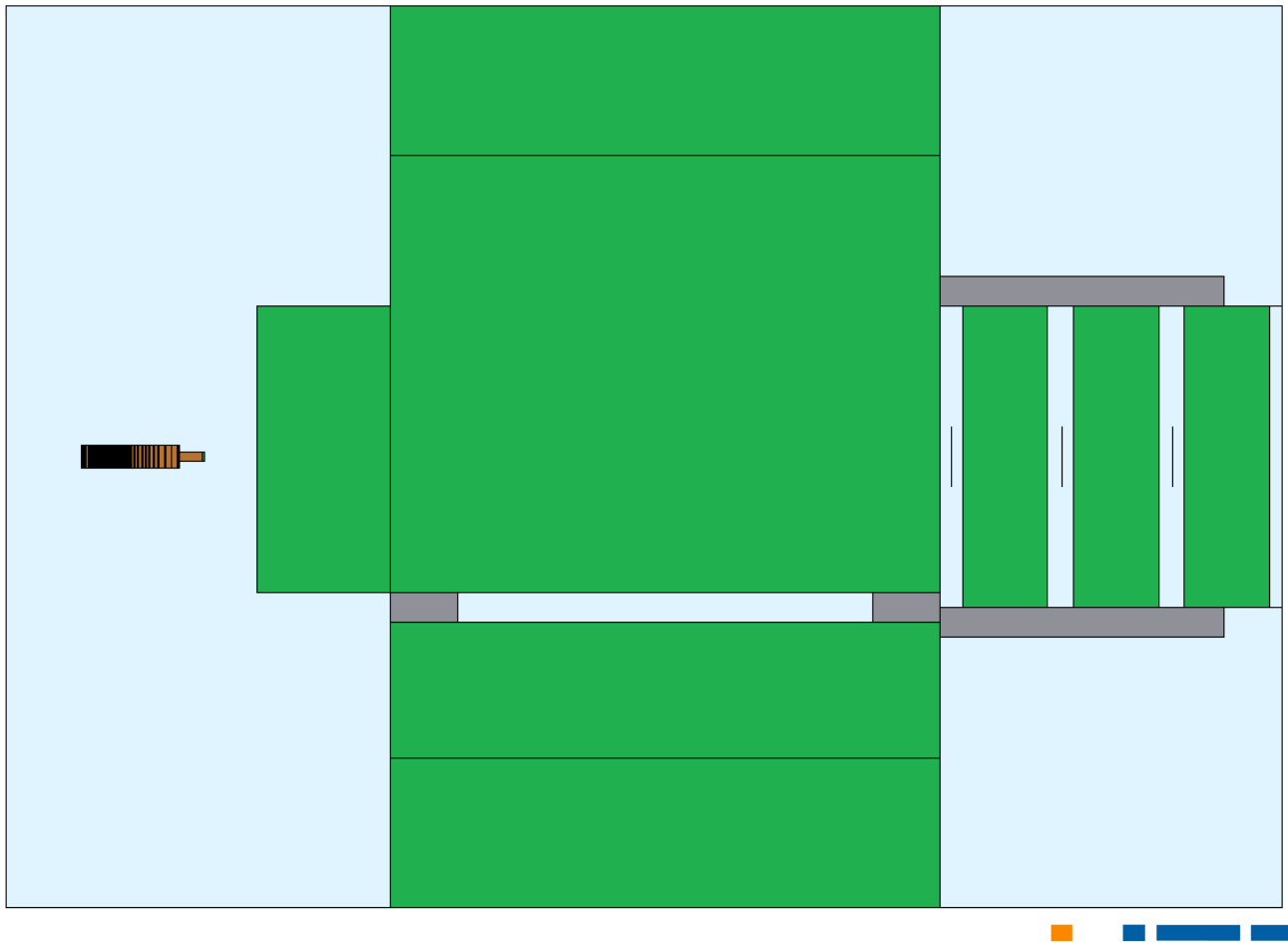
- FLUKA2011
  - www.fluka.org
- MARS15
  - https://mars.fnal.gov
- GEANT4.10
  - geant4.cern.ch/

FLUKA2011

- Historical origin (1970): **FLU**ktuierende **KA**skade (J. Ranft *et al.*, Leipzig)
- Current version: **FLUKA2011.2c.4** (maintained by CERN-INFN)
- Fully integrated particle physics MonteCarlo simulation package
- Driven by "data cards" (minimum of programming knowledge required)
- Linux platform (g77/gfortran)
- Well tested built-in scoring
- Graphical user interface: **FLAIR** (FLUKA Advanced Interface)

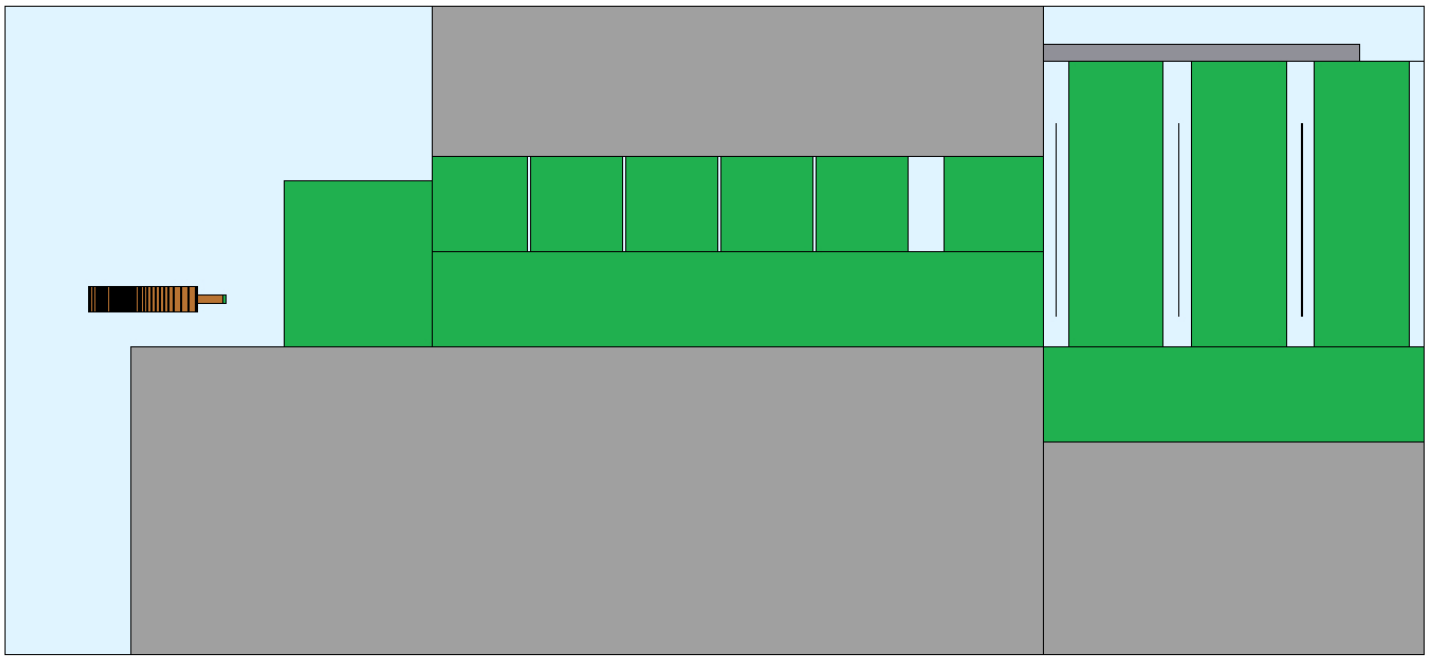
FLUKA2011: Geometrical model

Horizontal view



FLUKA2011: Geometrical model

Vertical view



FLUKA2011: Muons

- Theoretical model:
  - Photomuon production implemented according to Y. S. Tsai (Rev. Mod. Phys. 46 (1974) 815, Rev. Mod. Phys. 49 (1977) 421)
  - Only coherent production of photomuons

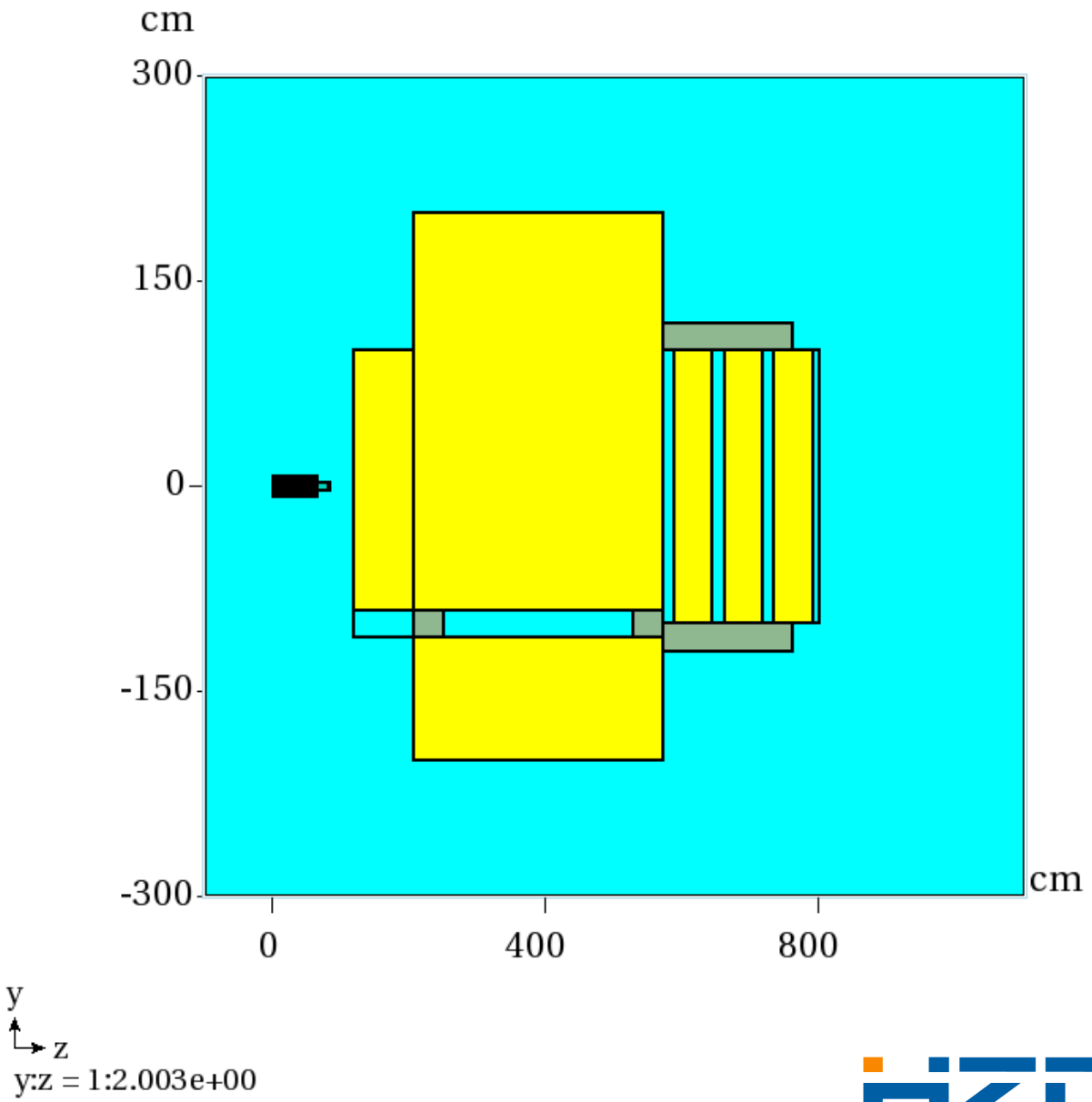
- Simulation parameters:
  - Biasing scale factor on photon interaction length for photomuon production: `2.5E-5`
  - Biasing scale factor for hadronic inelastic interaction length of photons: `0.05`
  - δ-ray production of muons and charged hadrons switched on (1 MeV threshold)
  - full simulation of muon nuclear interactions and production of secondary hadrons switched on
  - $e^{\pm}$ and γ production thresholds set to 100 and 10 keV
  - `DEFAULTS` card is set to `PRECISIO`

MARS15

- General-purpose, all-particle Monte Carlo simulation code
- Current version: **MARS15(2016)**
- Established theoretical models for strong, weak and electromagnetic interactions of hadrons, heavy ions and leptons
- Most processes can be treated either
  - exclusively (analogously)
  - inclusively (with corresponding statistical weights)
  - in a mixed mode
- Variety of geometry options, major ones are
  - "extended"
  - ROOT-based
- Especially powerful in particle production, accelerator lattice, beamline and machine-detector interface applications
- Participant of international benchmarking for more than two decades

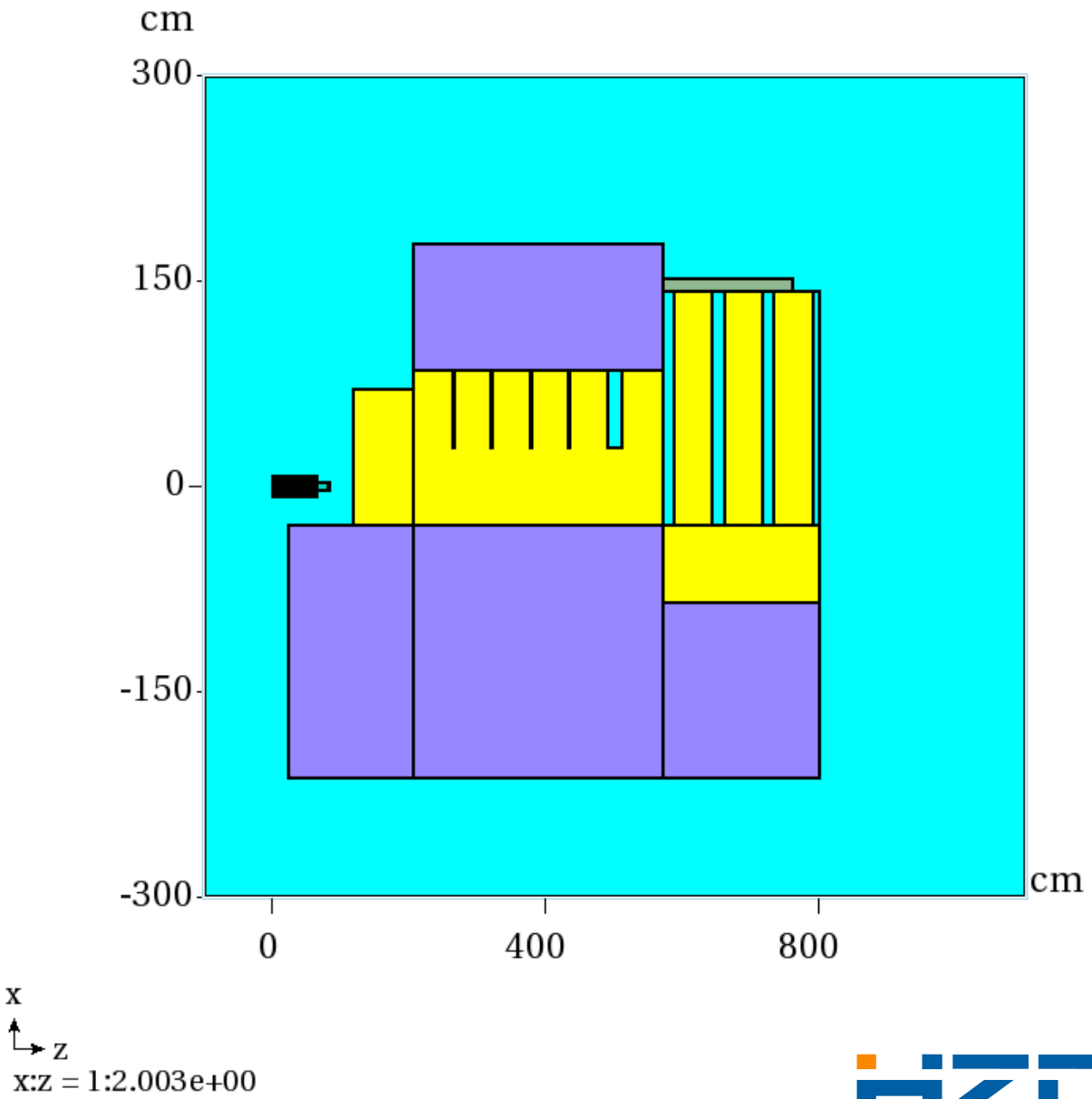
MARS15: Geometrical model

Horizontal view



MARS15: Geometrical model

Vertical view



MARS15: Muons

- Exclusive generator based on Weizsäcker-Williams approximation
  - algorithms based on Burkhardt, Kelner, and Kokoulin (2002)
  - only coherent photomuon production
  - used as default
- Inclusive generator based on Y. S. Tsai (Rev. Mod. Phys. 46 (1974) 815, Rev. Mod. Phys. 49 (1977) 421))
  - calculation in lowest-order Born approximation
  - target of arbitrary mass, spin and form factor
  - arbitrary final state
- Both models give practically identical results for E $>$ 10 GeV photons
- At lower energies, precise description of nuclear form factor is important. MARS supports two options for description of nuclear density:
  - original Tsai power-law mode
  - symmetrized Fermi function

Geant4.10

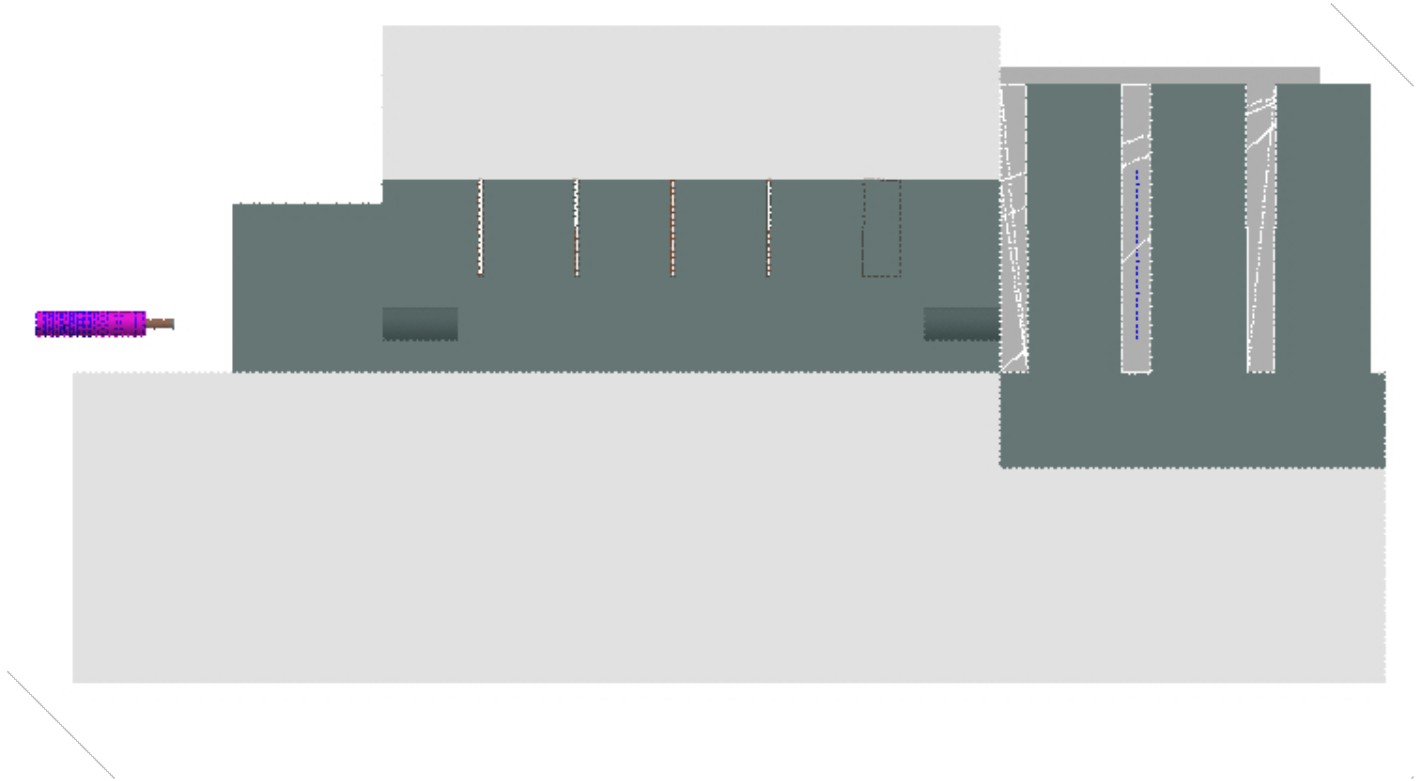
- GEANT4: **Geo**metry **AN**d **T**racking (since 1998)
- Successor of GEANT program developed at CERN
- Current version: **GEANT4.10.2p2**
- Written in C++ (Object Oriented software technology)
- Open source software
- Toolkit - user needs to program an application using GEANT4 tools
- Many examples provided

GEANT4.10: Geometrical model

Horizontal view

GEANT4.10: Geometrical model

Vertical view



GEANT4.10: Muons

- Theoretical model:
  - Photomuon production algorithms based on Kelner, Kokoulin, and Petrukhin (*Moscow Phys. Eng. Inst. 024-95, 1995*)

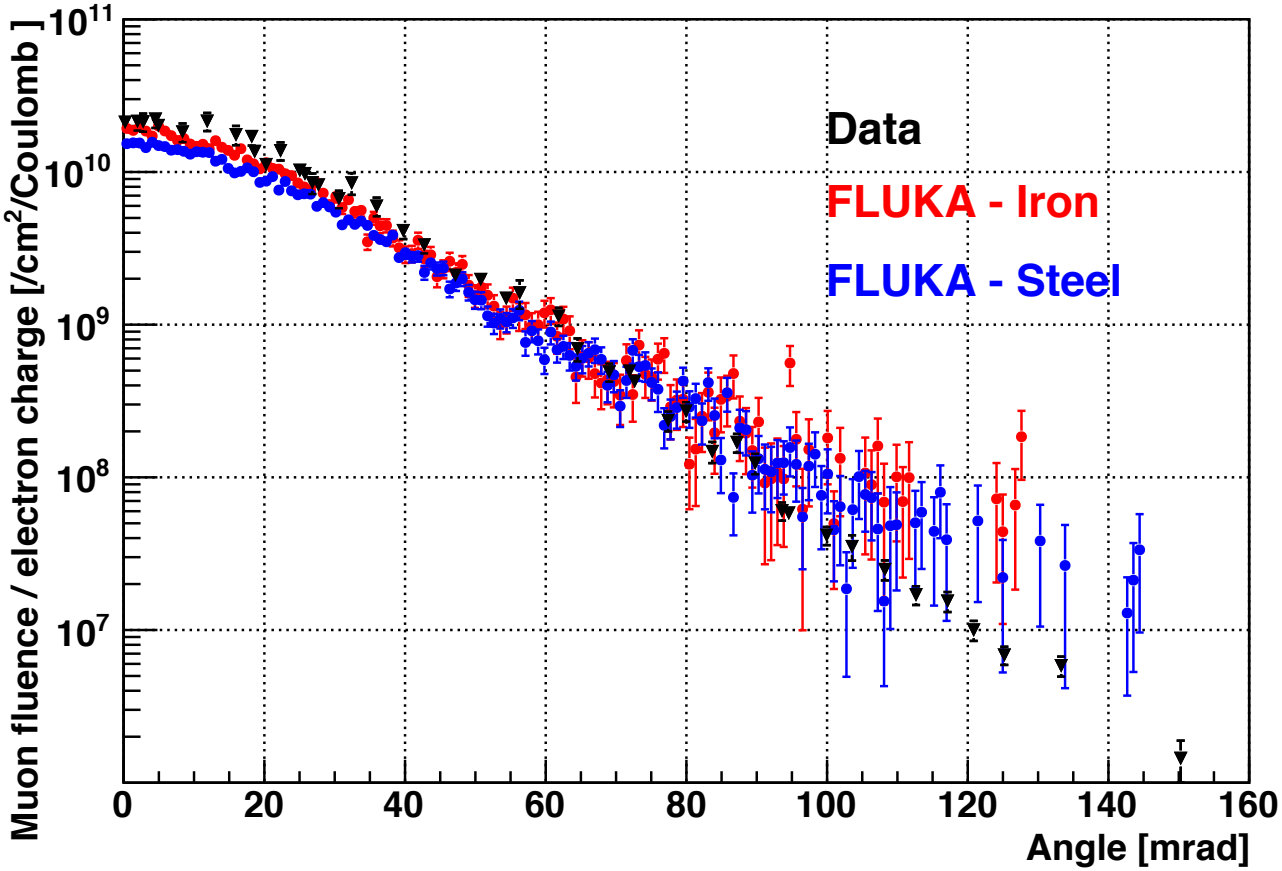
- Simulation parameters:
  - Build customized physics list:
    - Start with `QGSP_BERT_EMZ` list (contains `G4EmStandardPhysics_option4` and `G4EmExtraPhysics`)
    - Register the process `G4GammaConversionToMuons` to the process list for photons
    - Register process `G4MuonNuclearProcess` to process lists for muons (using `G4MuonVDNuclearModel`)
  - Mixture of built-in scoring and `ROOT` histograms

Scoring

- Muon fluence in the 4 gaps
  - normalized to integrated electron charge on beam dump
  - in $\mu/\mathrm{cm}^2/\mathrm{coulomb}$
- Dose in the 4 gaps
  - scored in thin volumes of LiF placed in each gap (to simulate thermoluminescent dosimeters)
  - normalized to integrated electron charge on beam dump
  - in rad/coulomb
- Double-differential scoring in energy and angle for muons crossing copper-water boundaries of target beam dump
  - scored over a target thickness of 6 radiation length

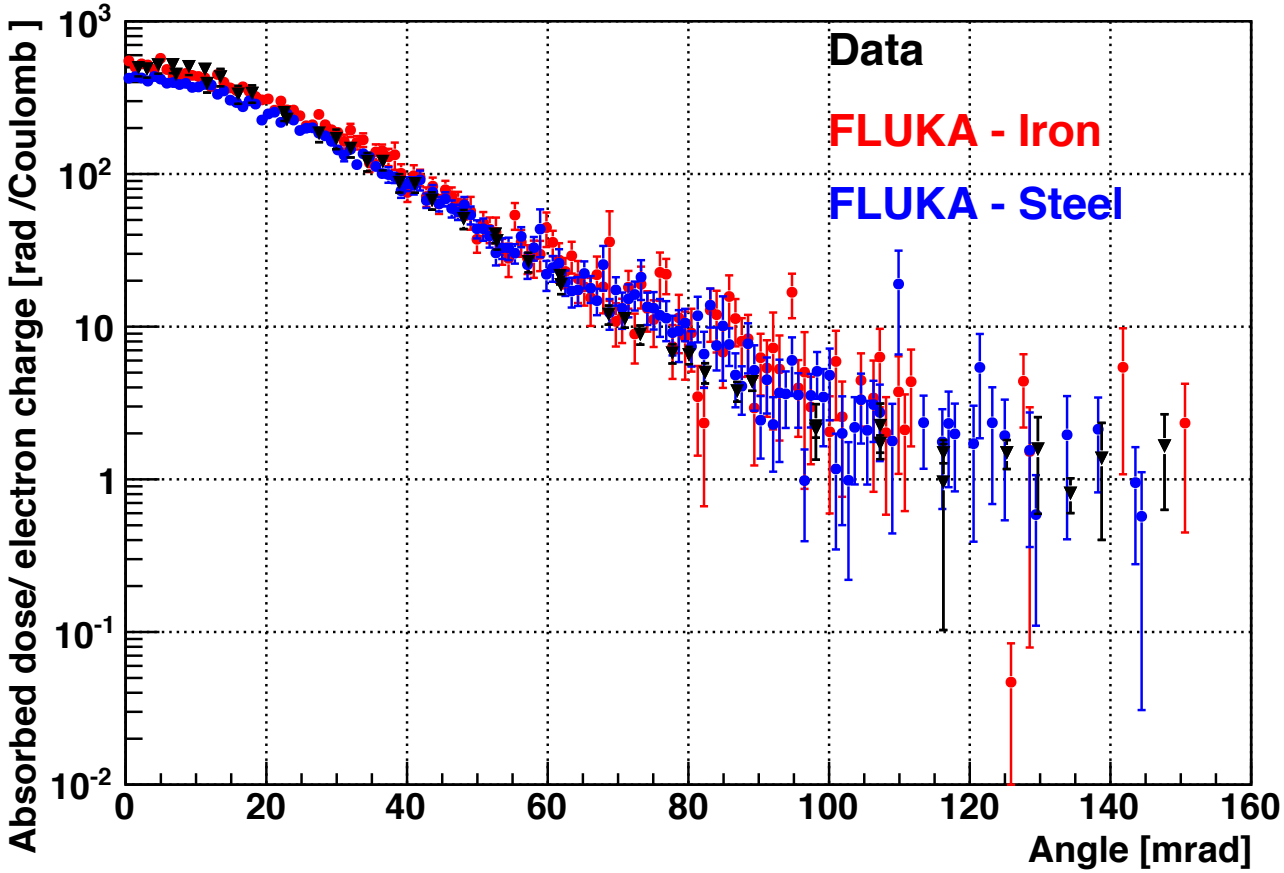
Status at SATIF12

Muon fluence in Gap A (shielding material steel, ρ =7.6 g/cm^3 and cast iron, ρ =7.0 g/cm^3):



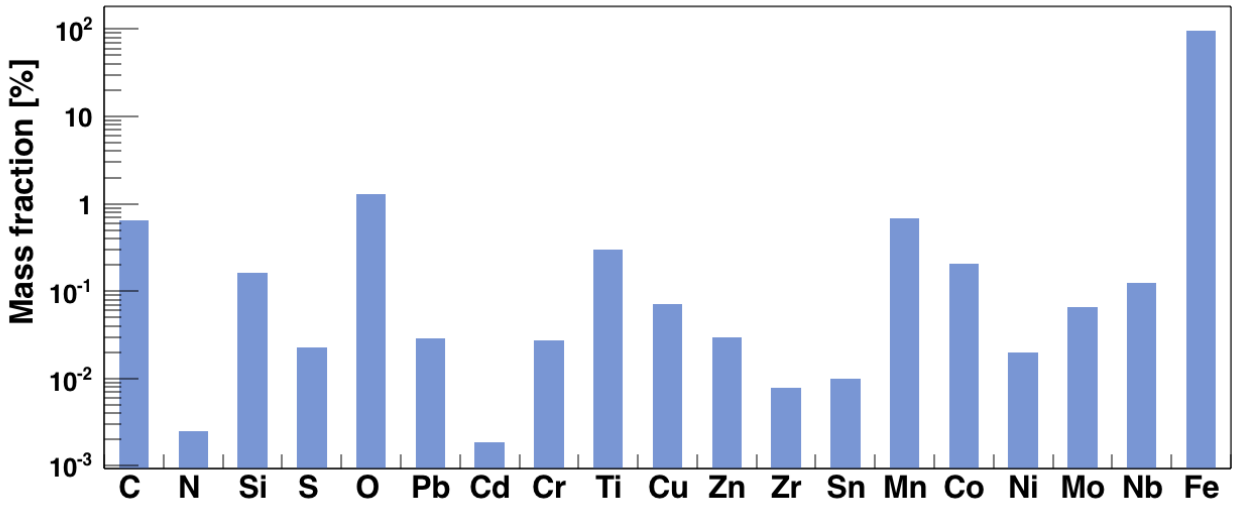
Status at SATIF12

Absorbed dose in Gap A (shielding material steel, ρ =7.6 g/cm^3 and cast iron, ρ =7.0 g/cm^3):



Updates

- Material composition for shielding iron:
  - density 7.6 g/cm^3
  - composition:

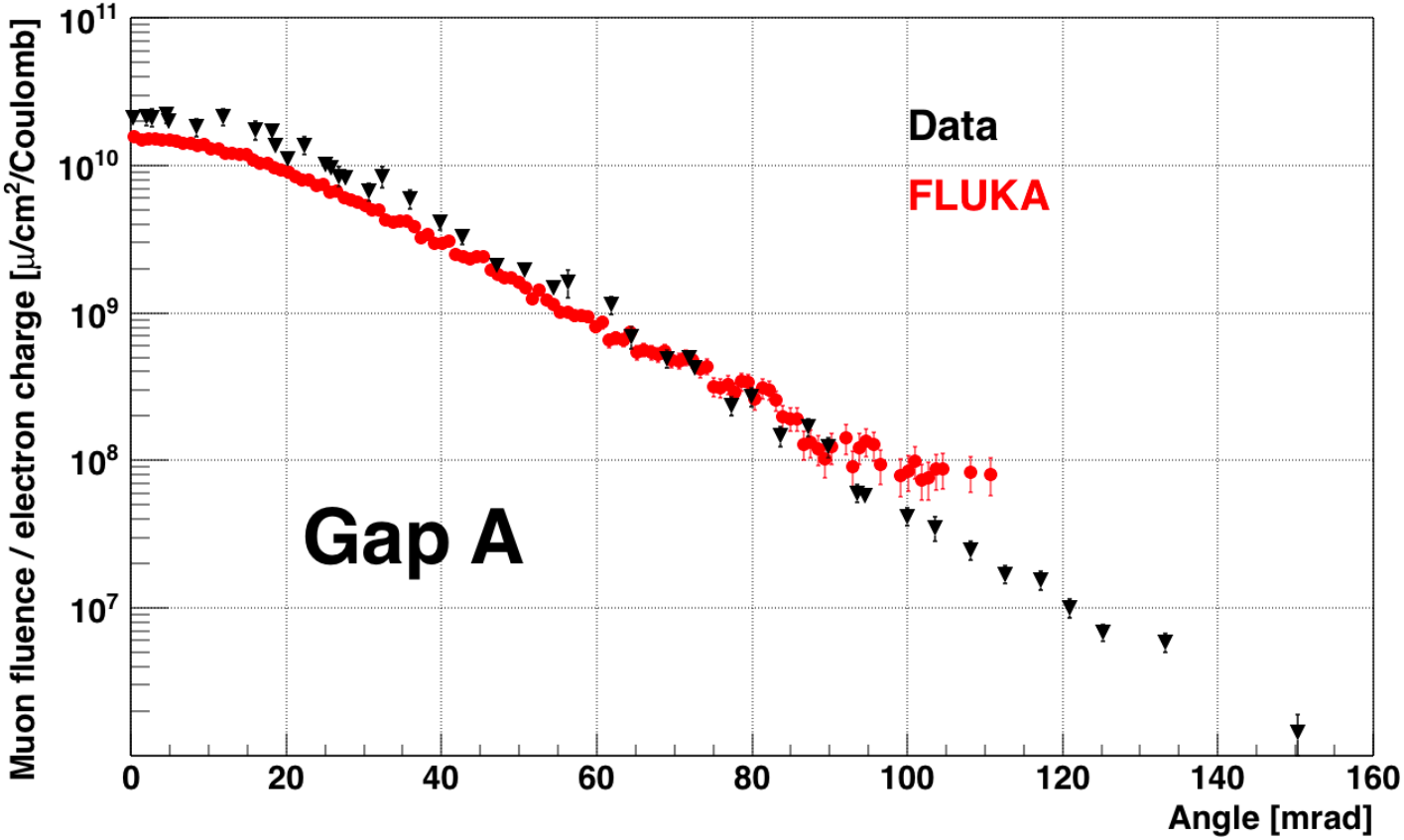


values provided by Ludovic Nicolas (SLAC)

- Minor geometry updates:
  - void for 2. beamline in shielding structure
  - lead shielding around gaps A, B and C

First results

Muon fluence in Gap A (shielding material steel, ρ =7.6 g/cm^3):



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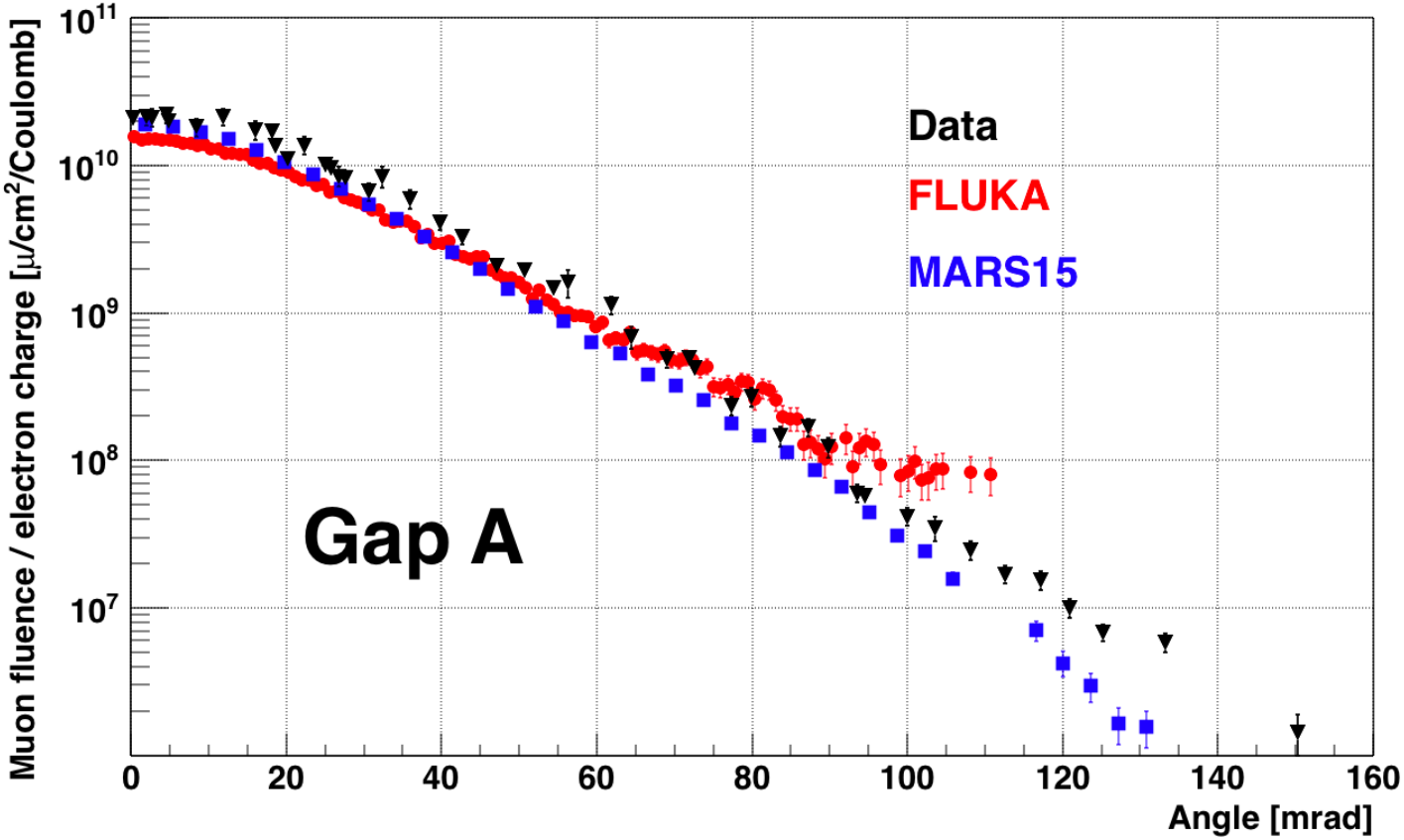

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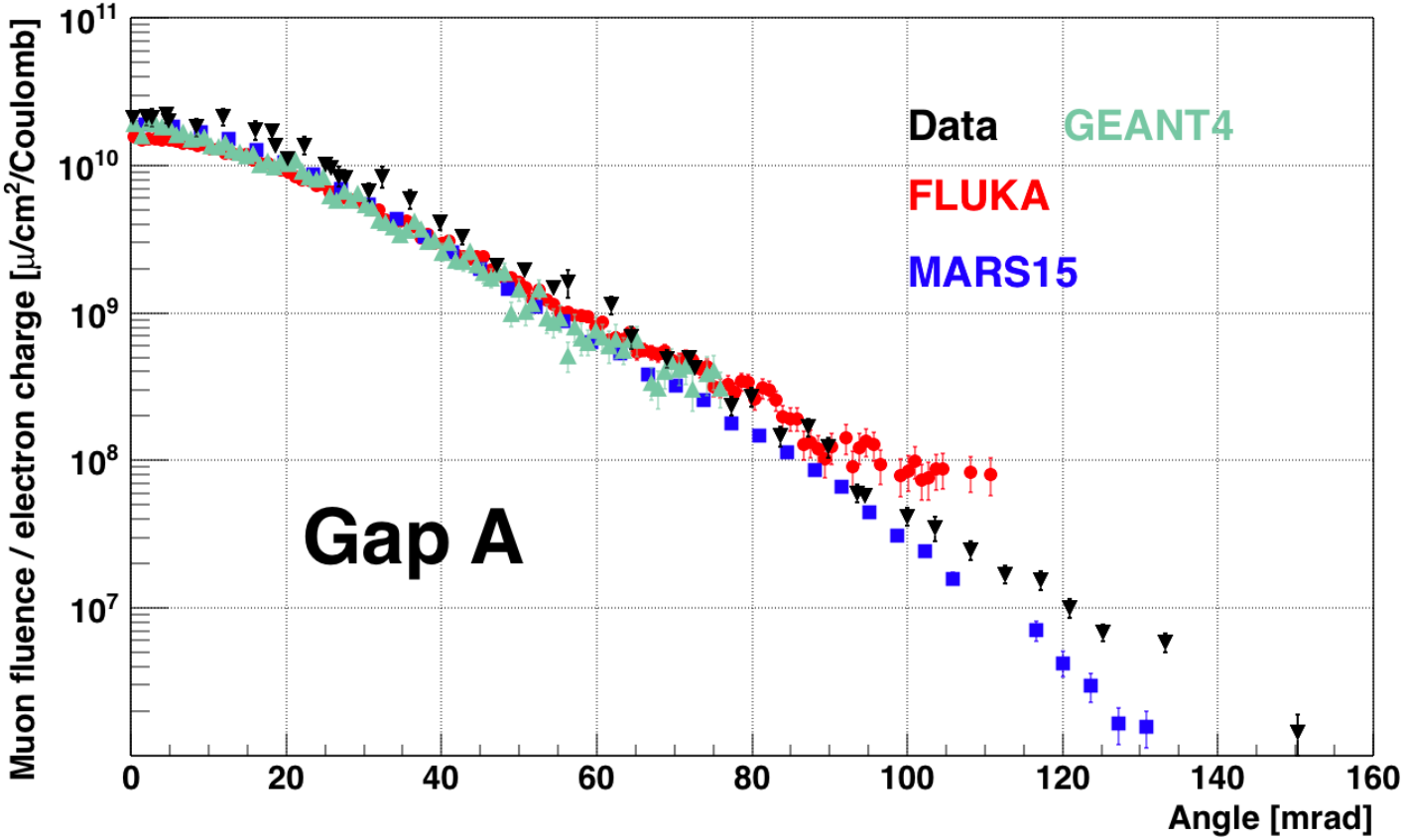
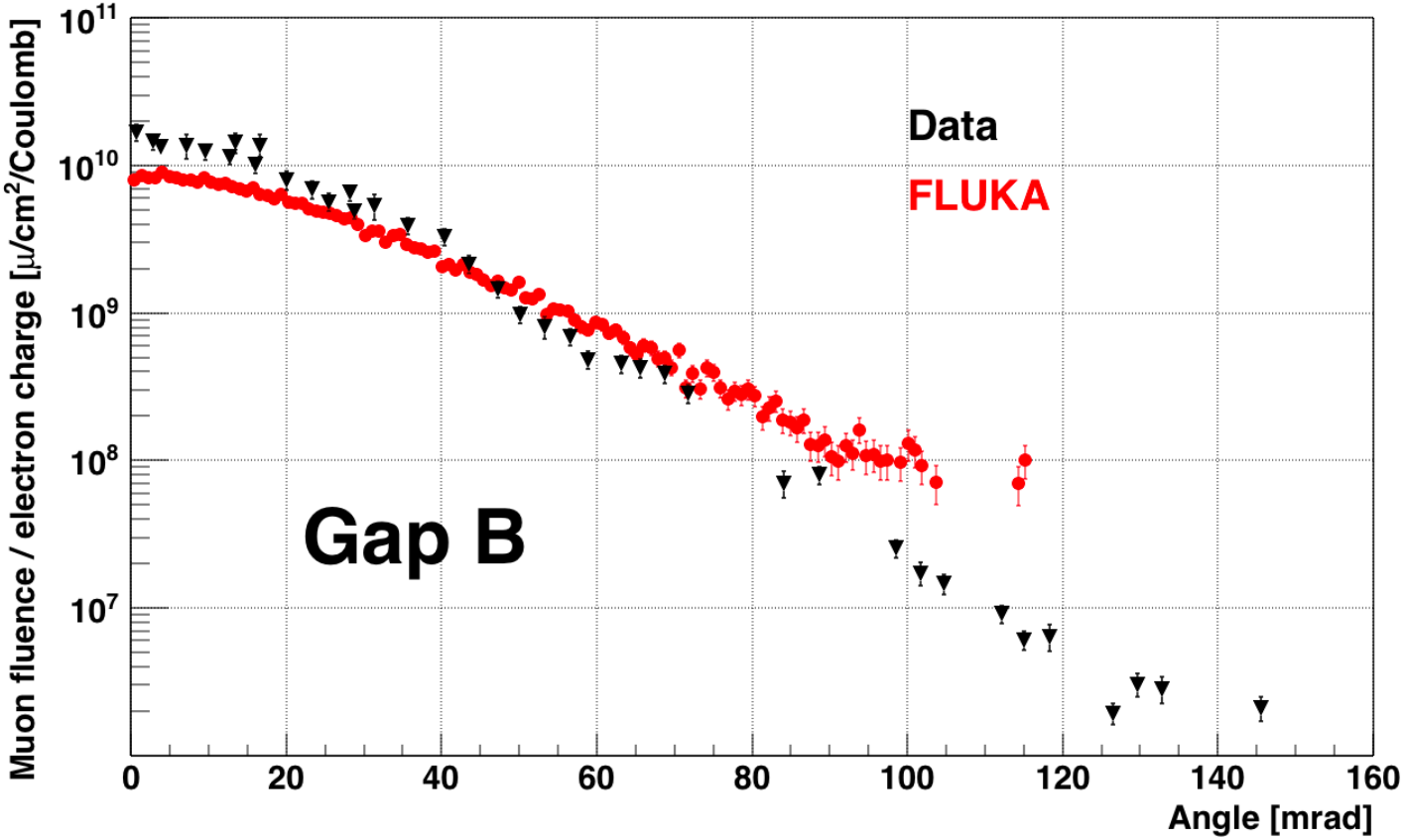


First results

Muon fluence in Gap B (shielding material steel, ρ =7.6 g/cm^3):



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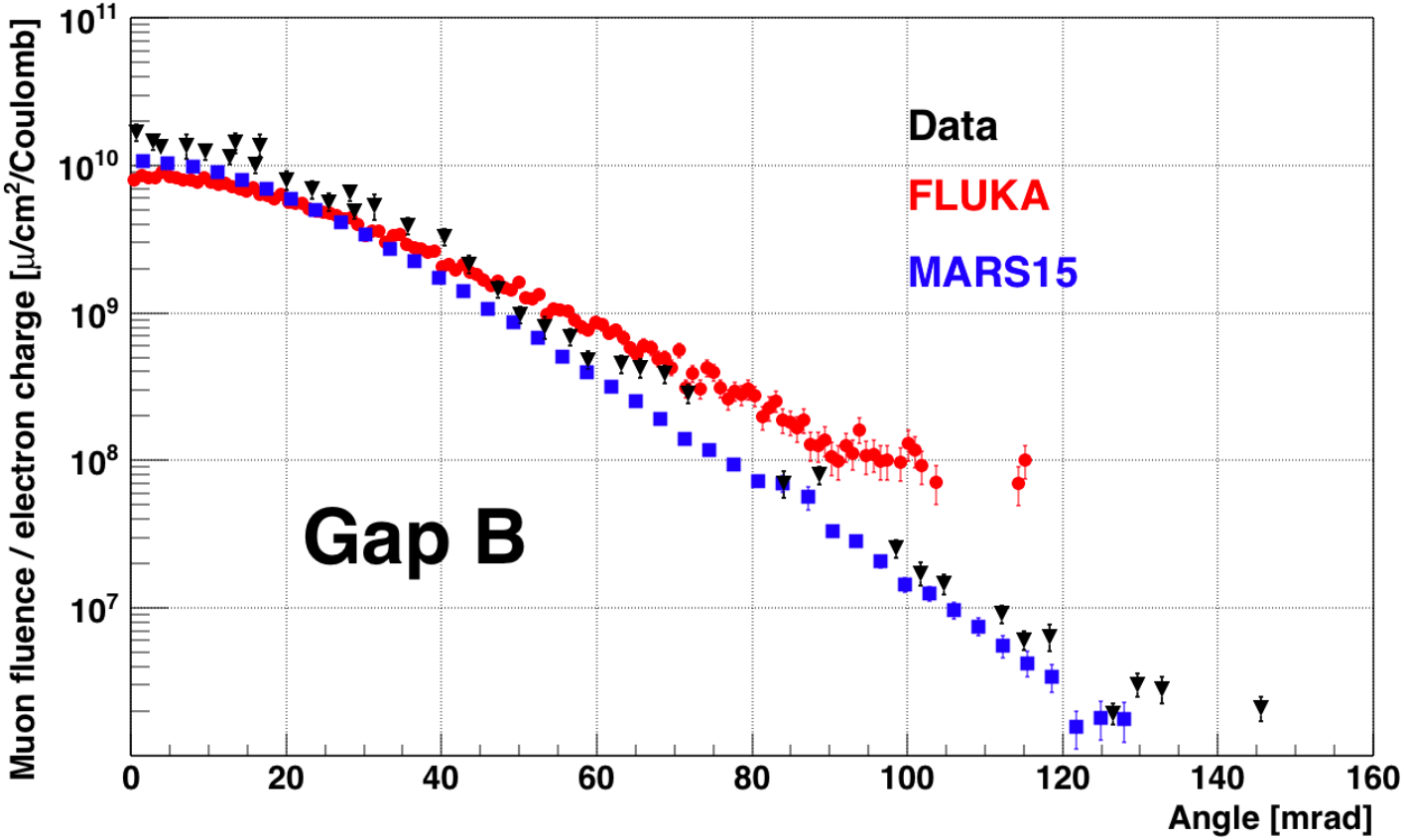

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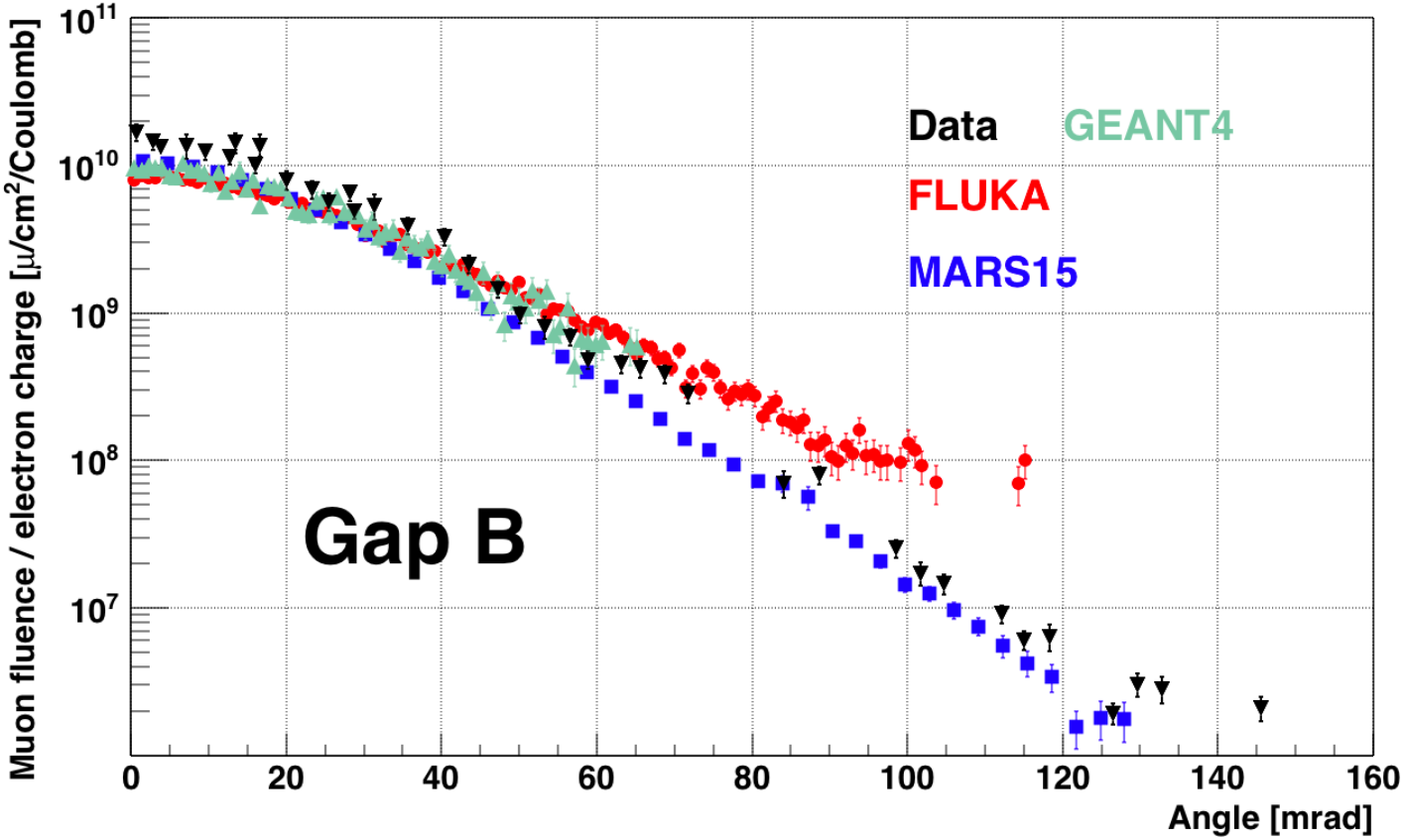

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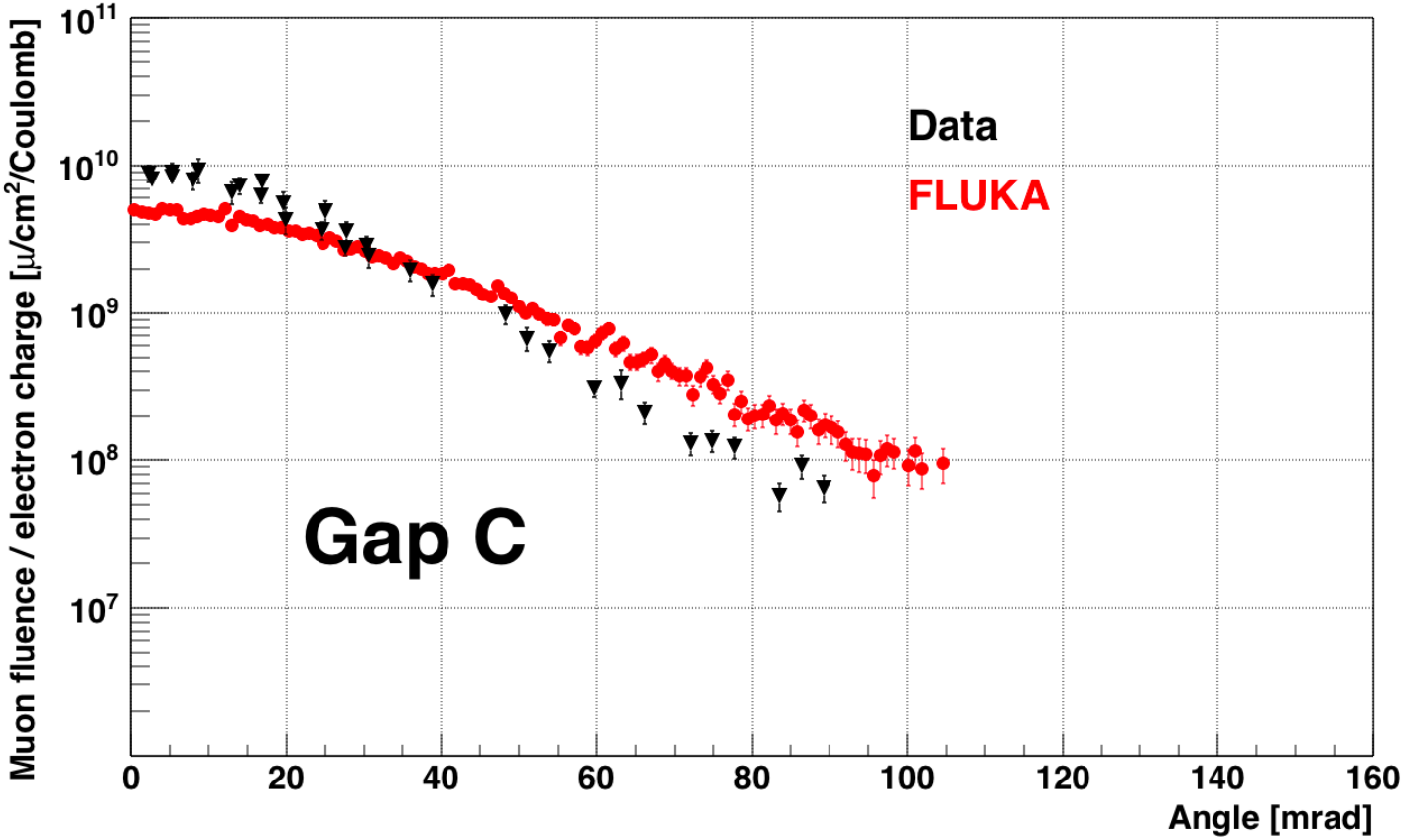
Muon fluence in Gap C (shielding material steel, ρ =7.6 g/cm^3):



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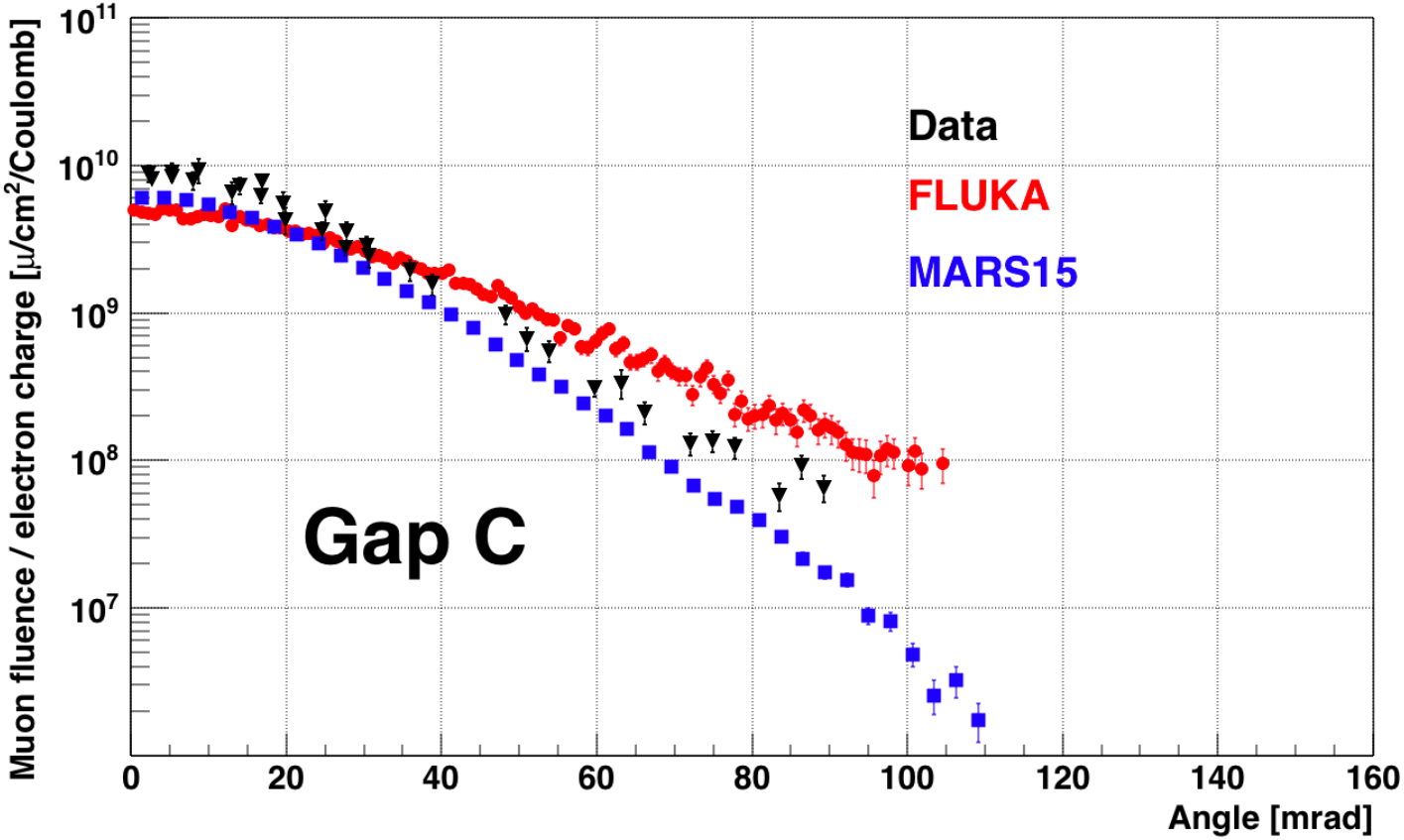

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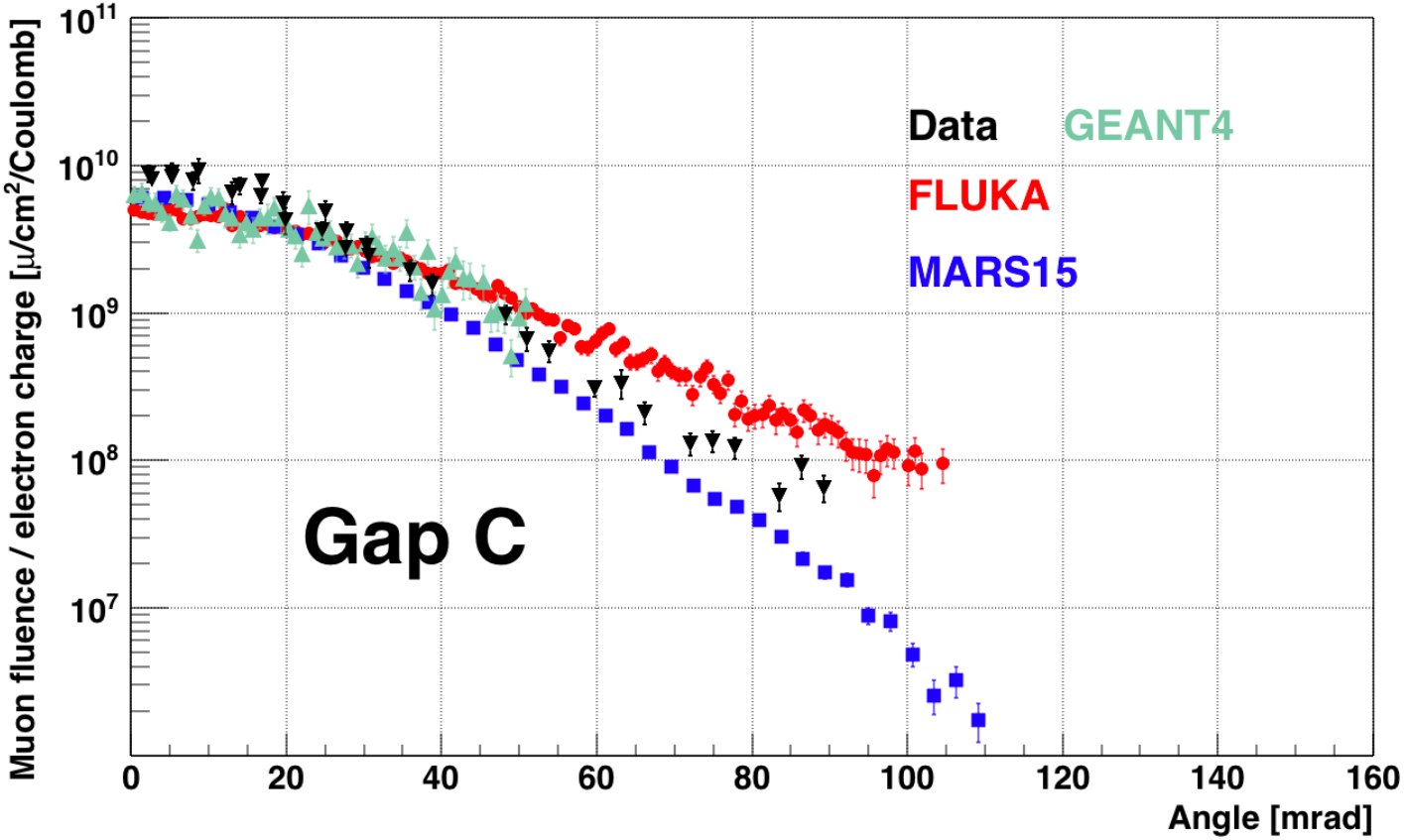
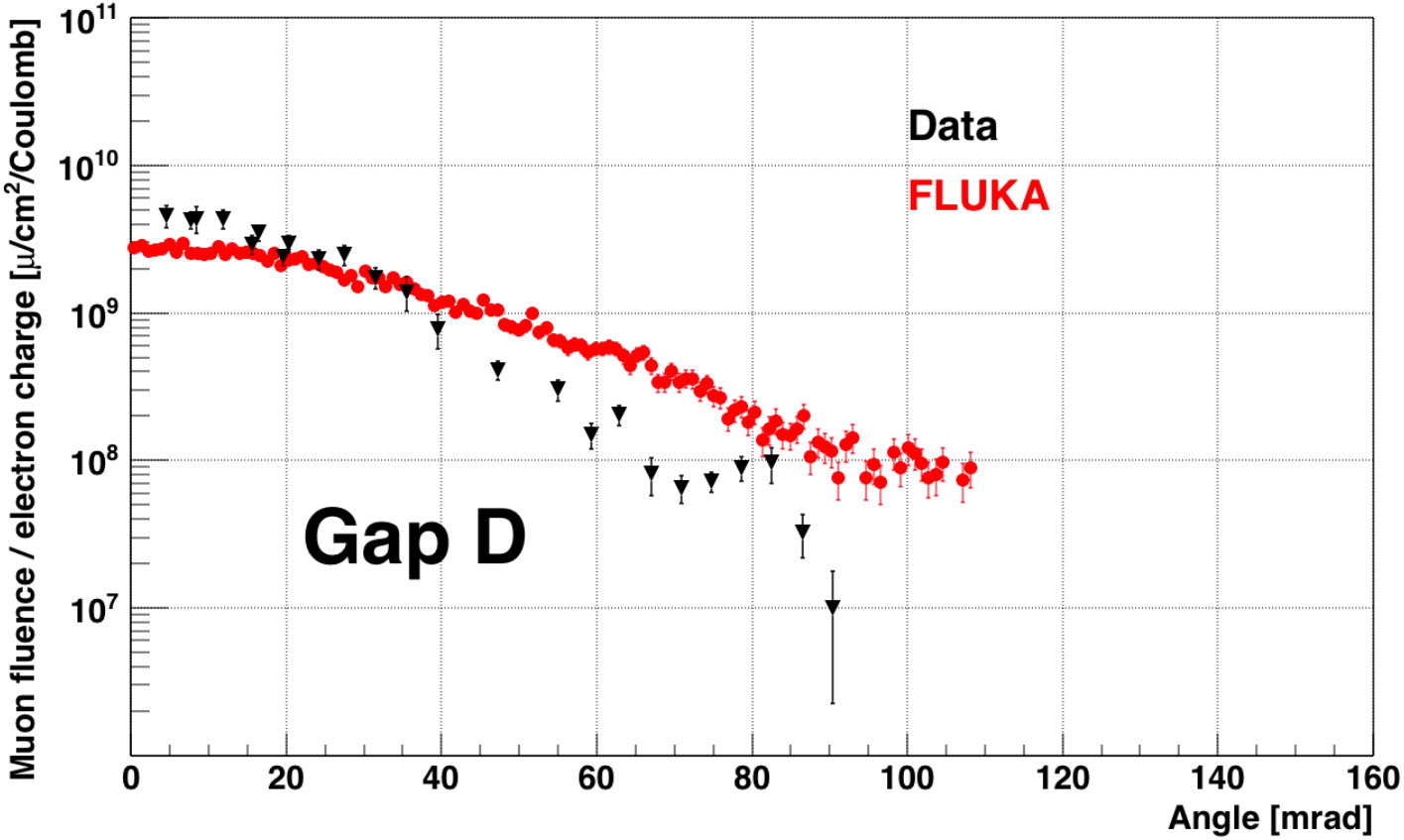


First results

Muon fluence in Gap D (shielding material steel, ρ =7.6 g/cm^3):



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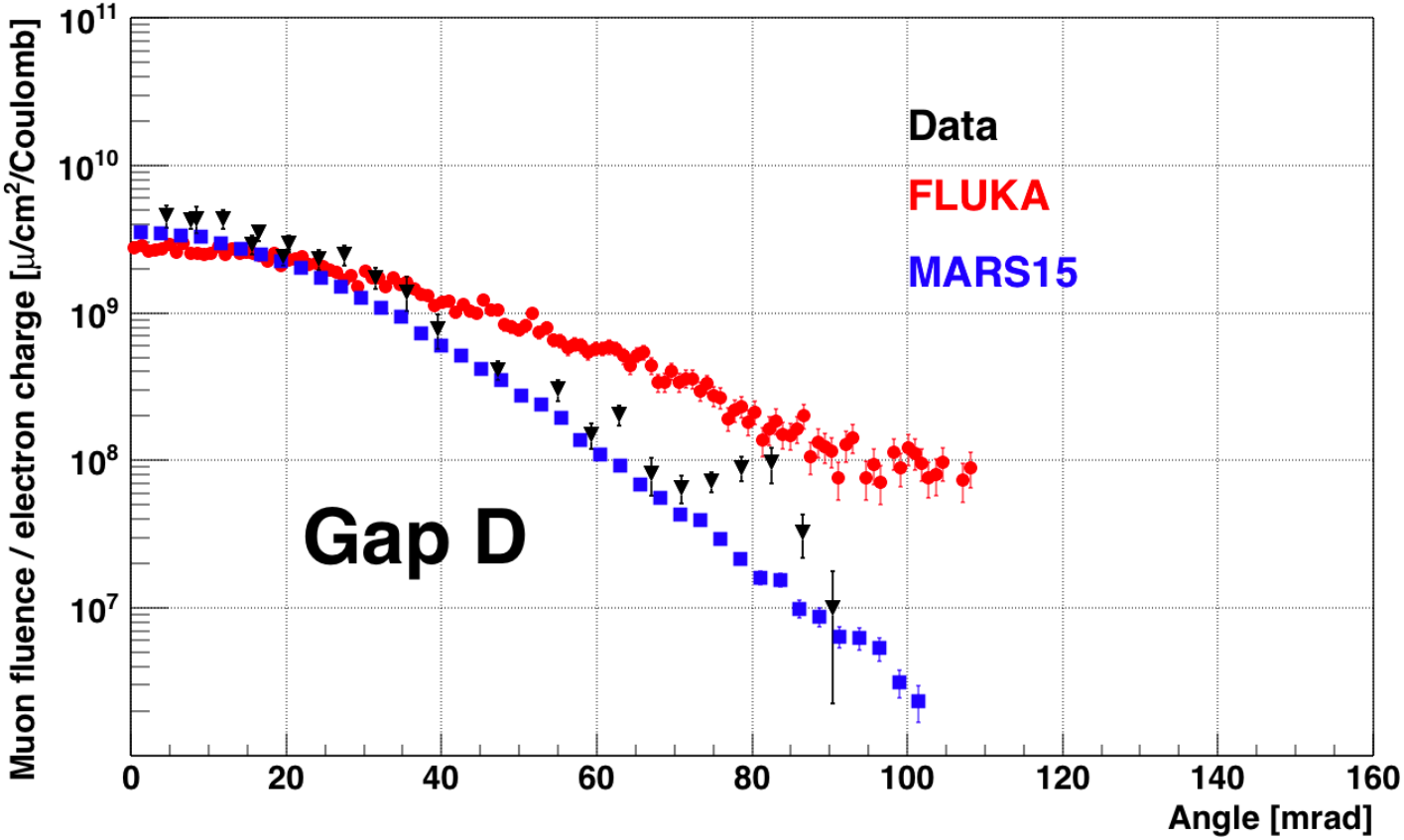

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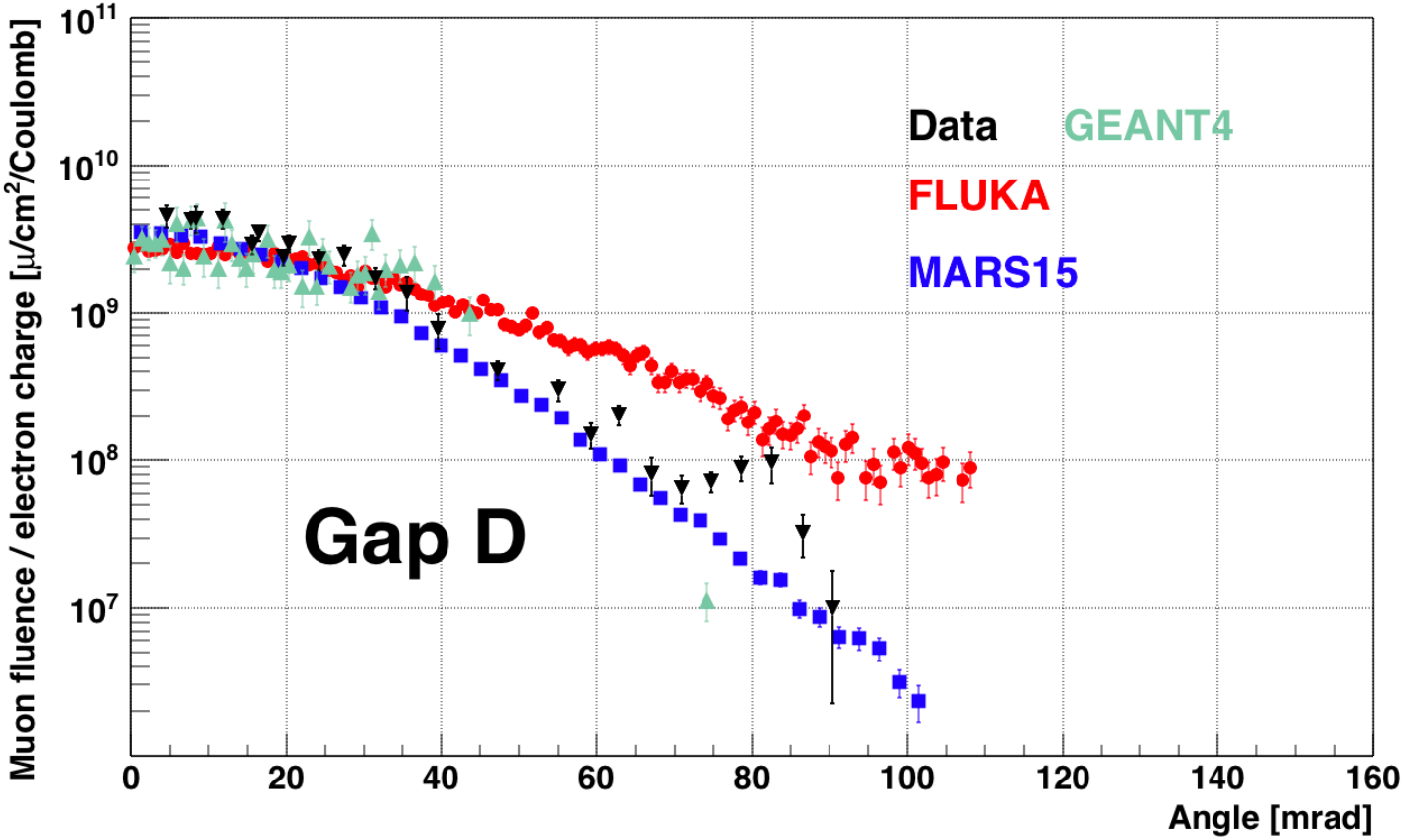

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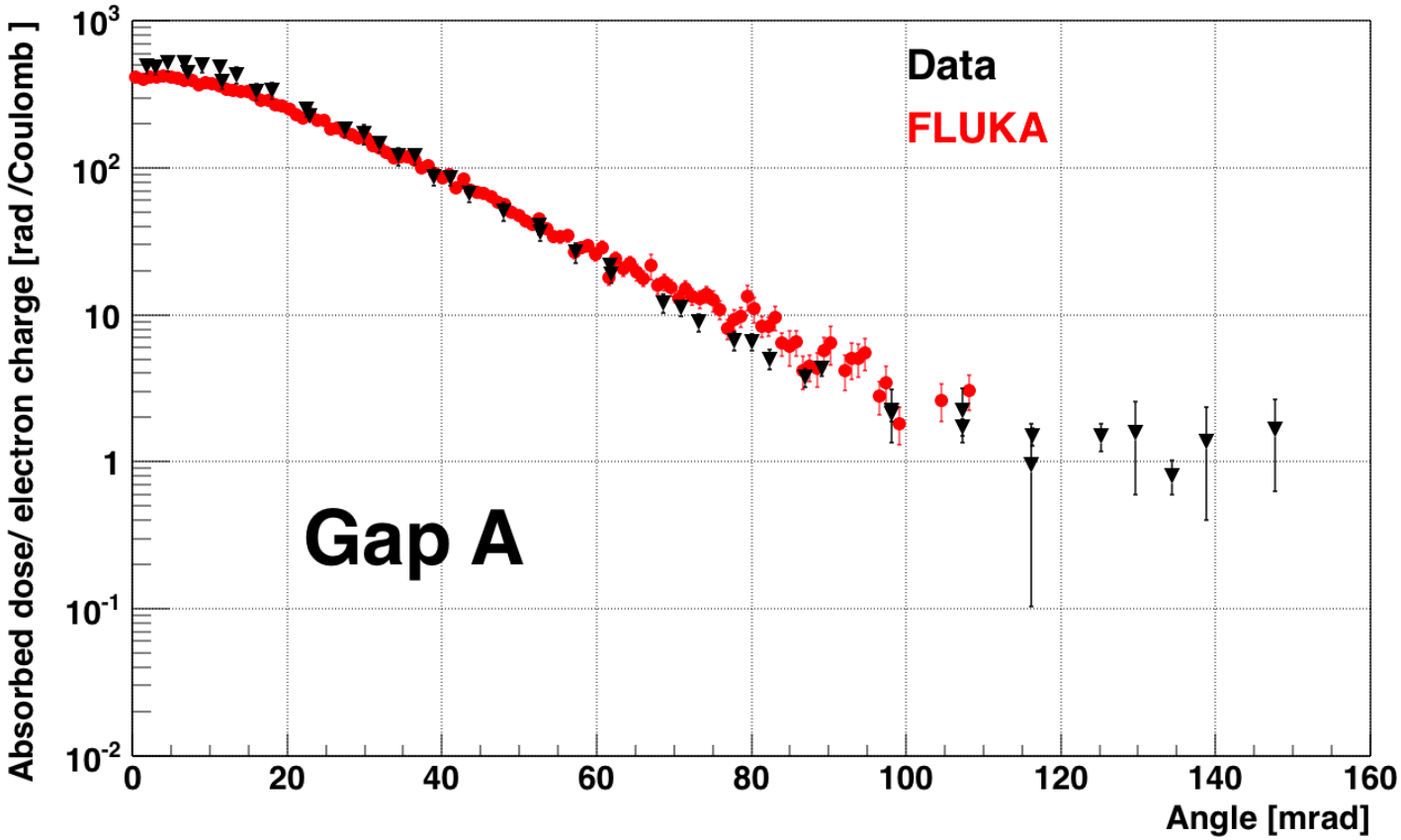

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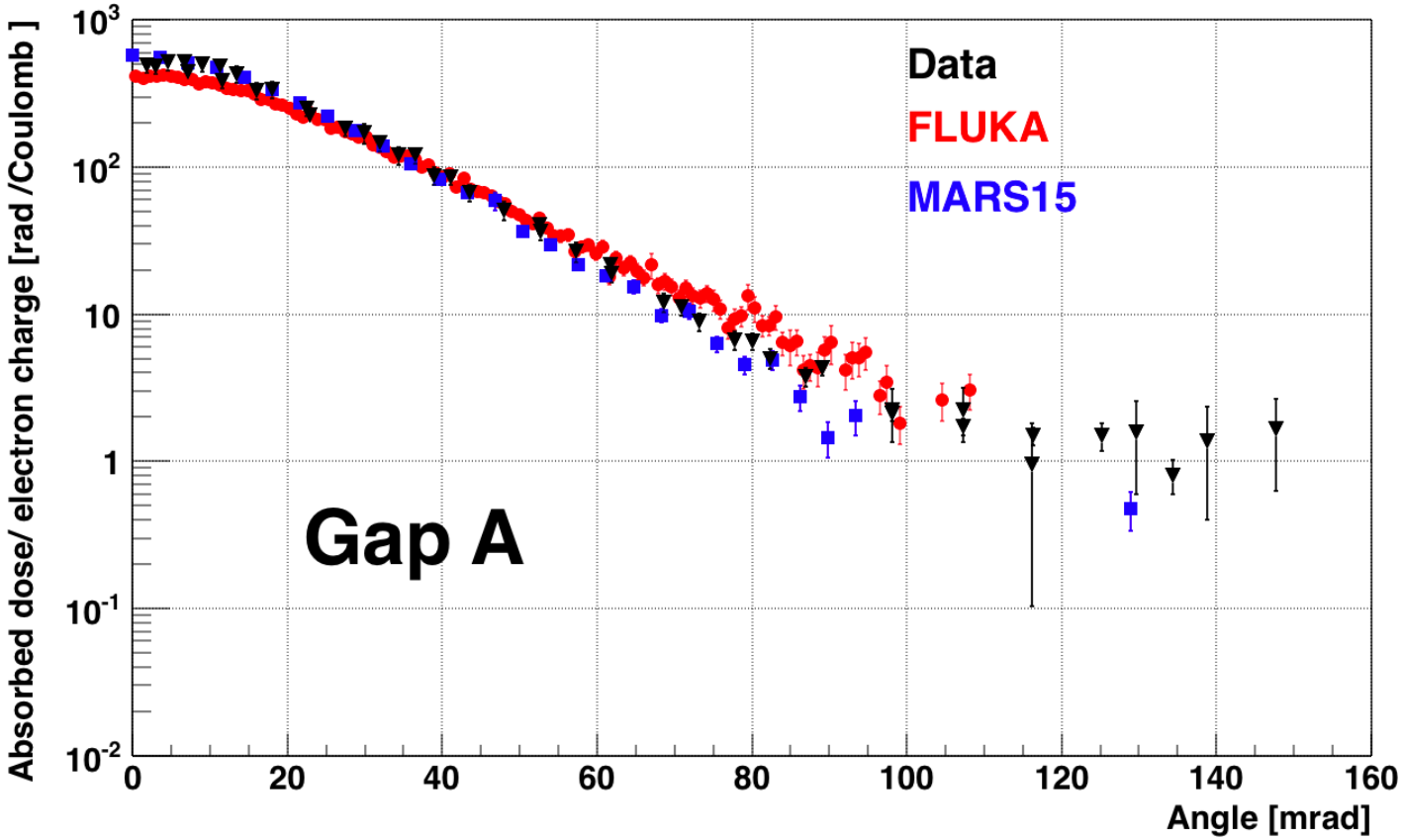

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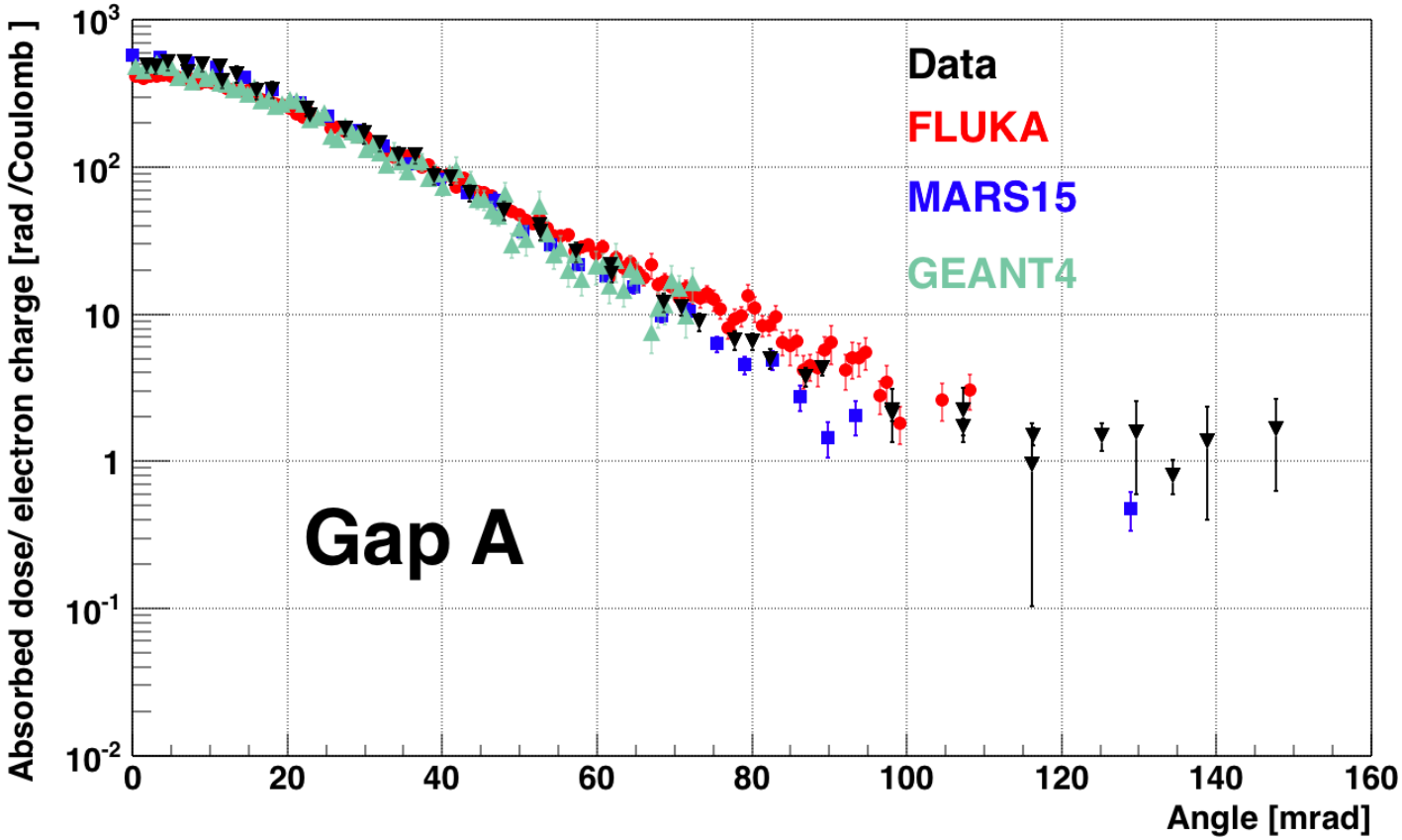

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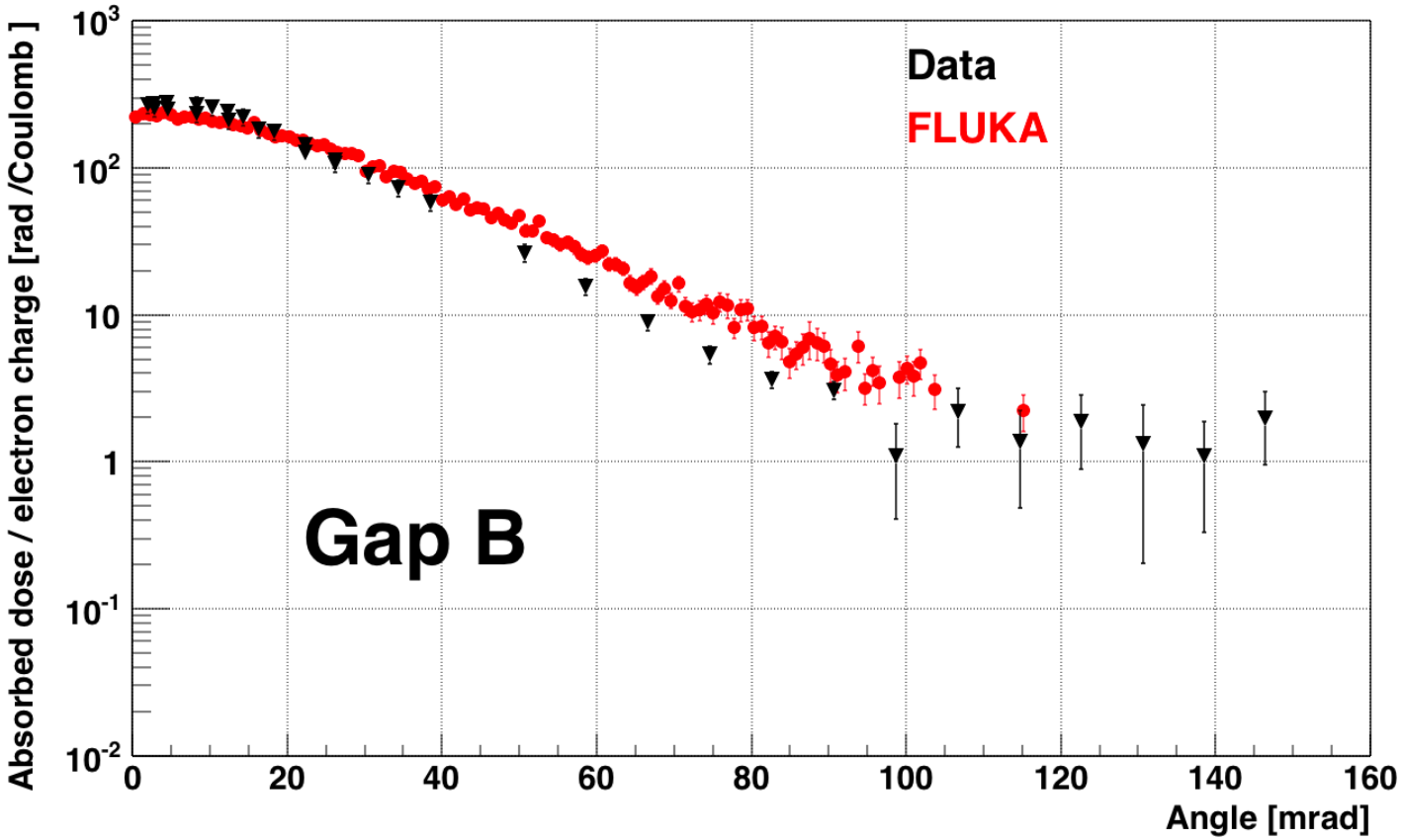

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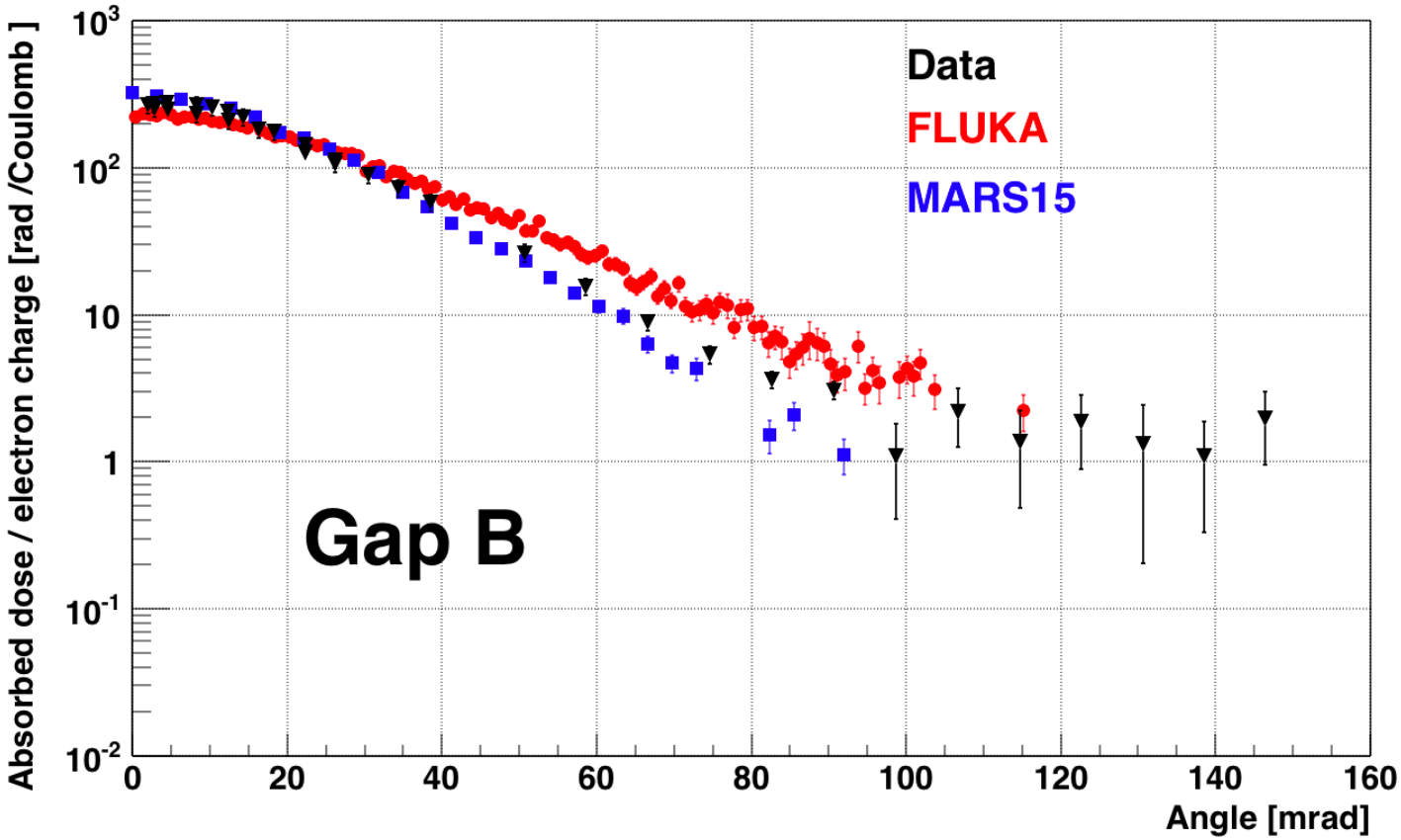

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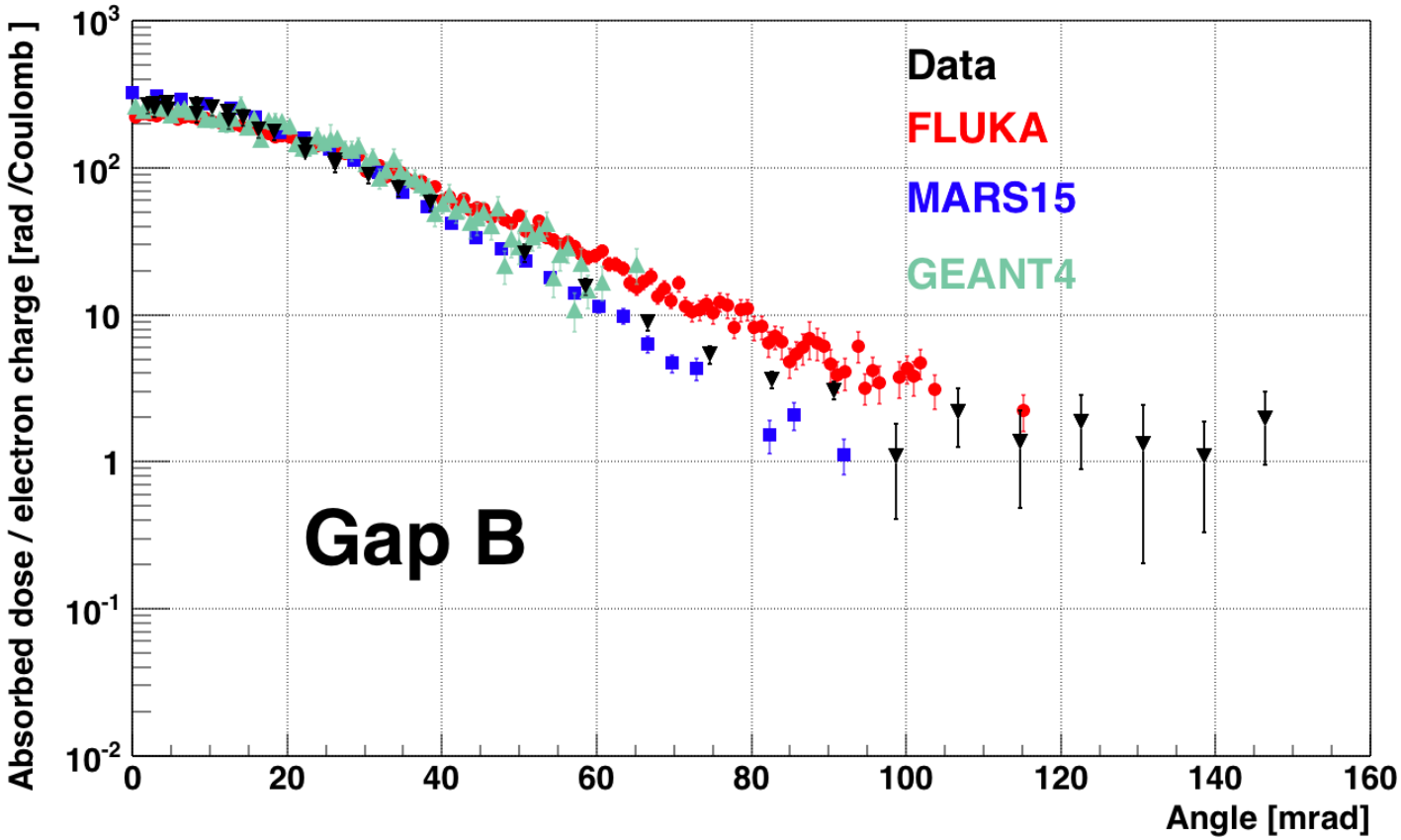

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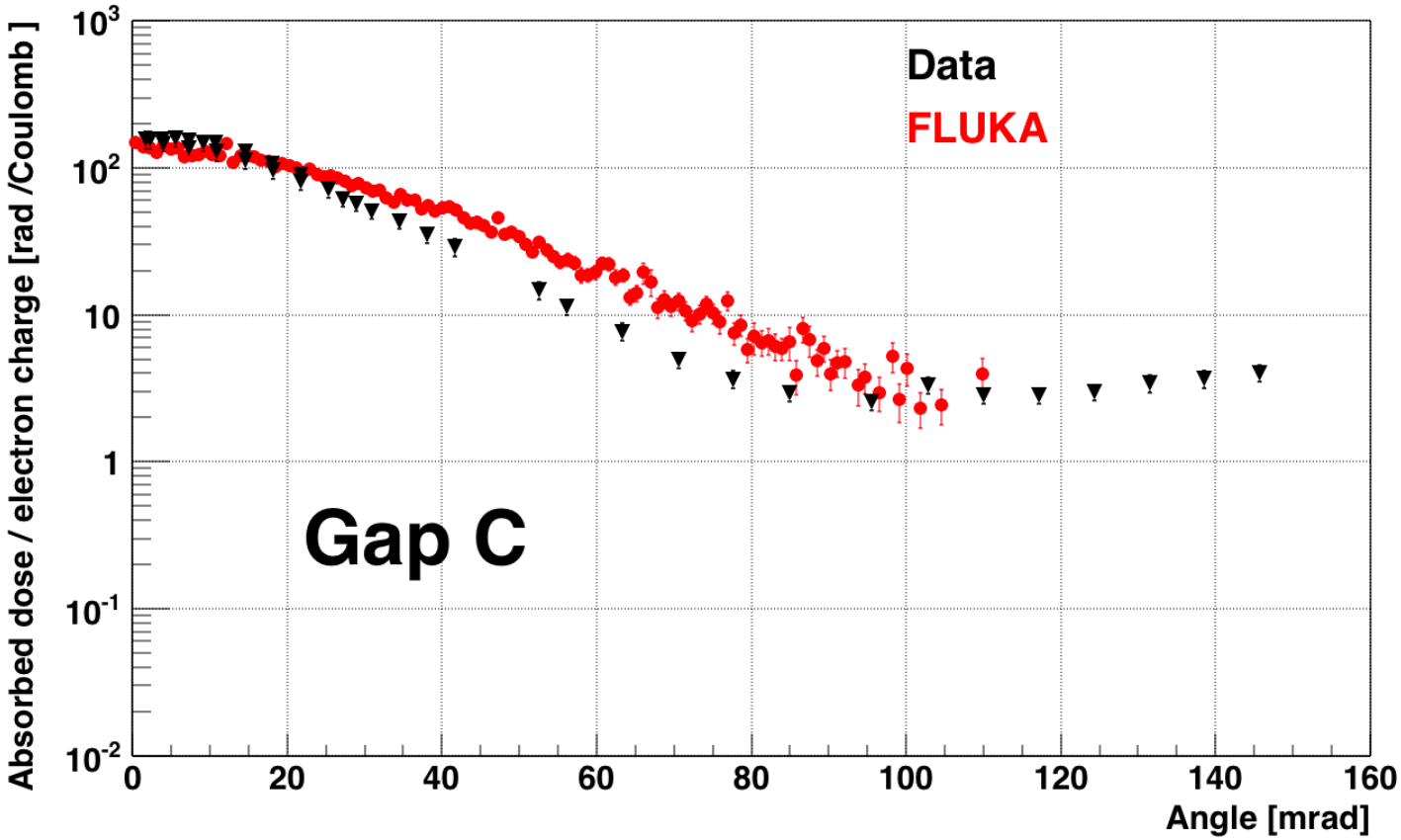

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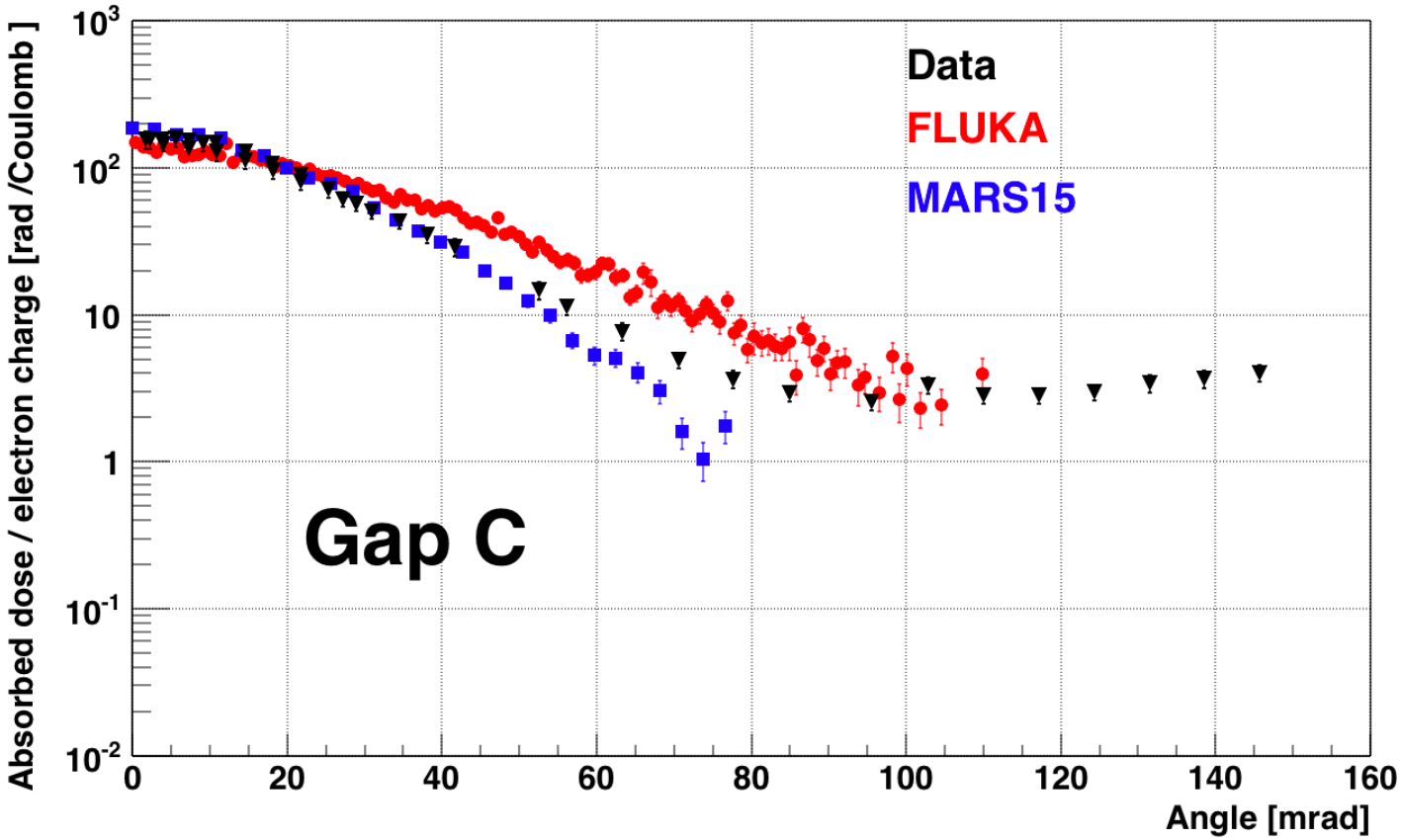

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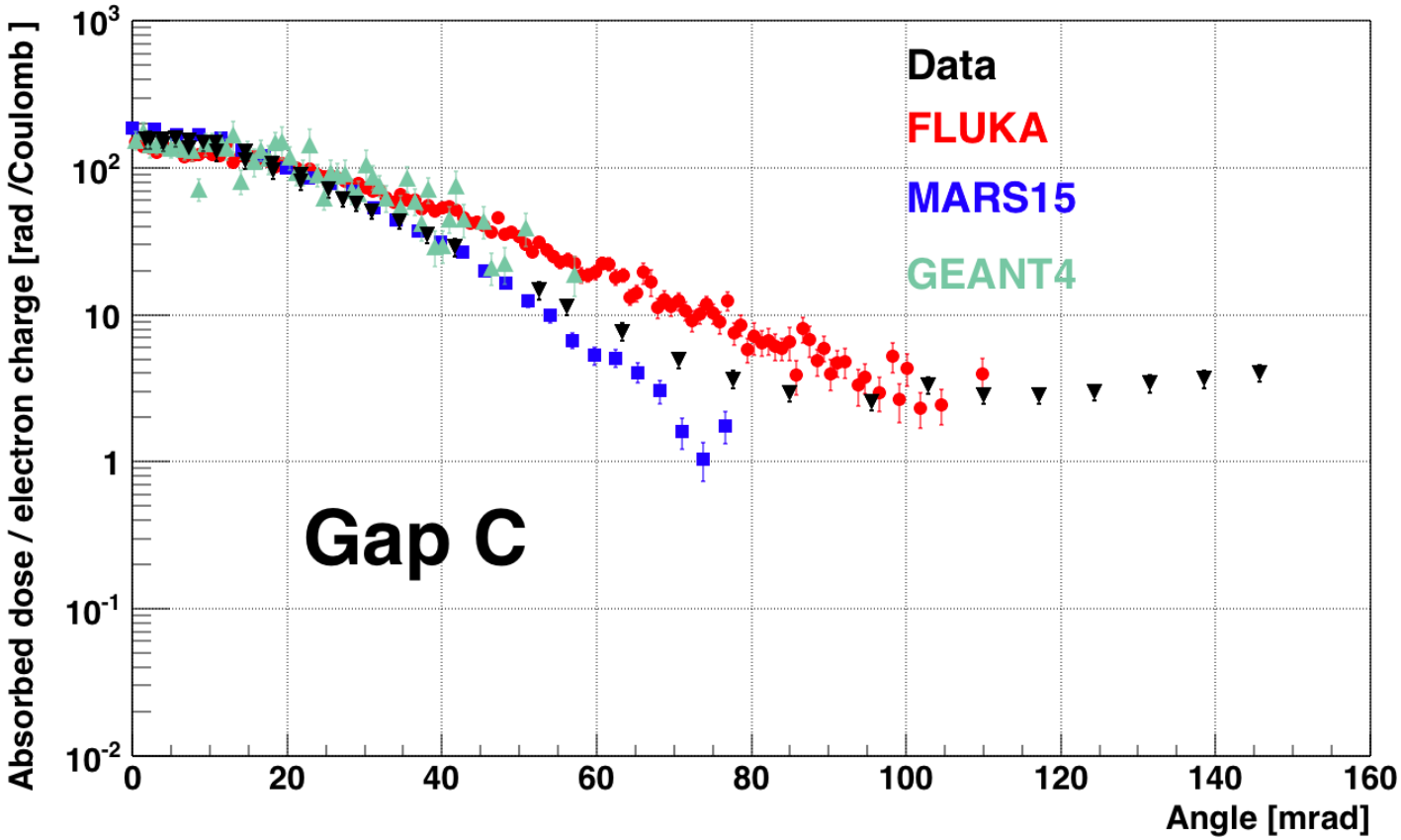

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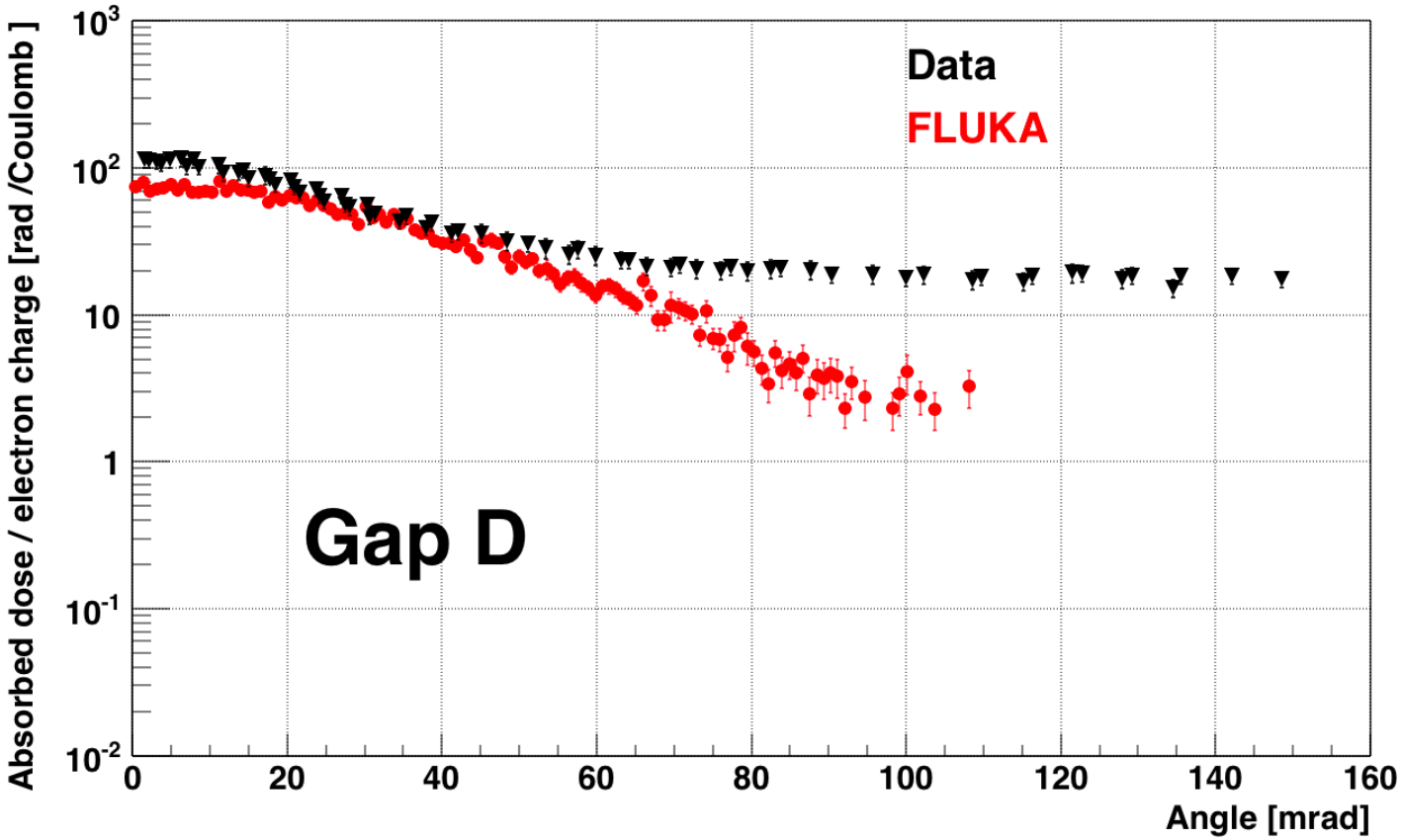

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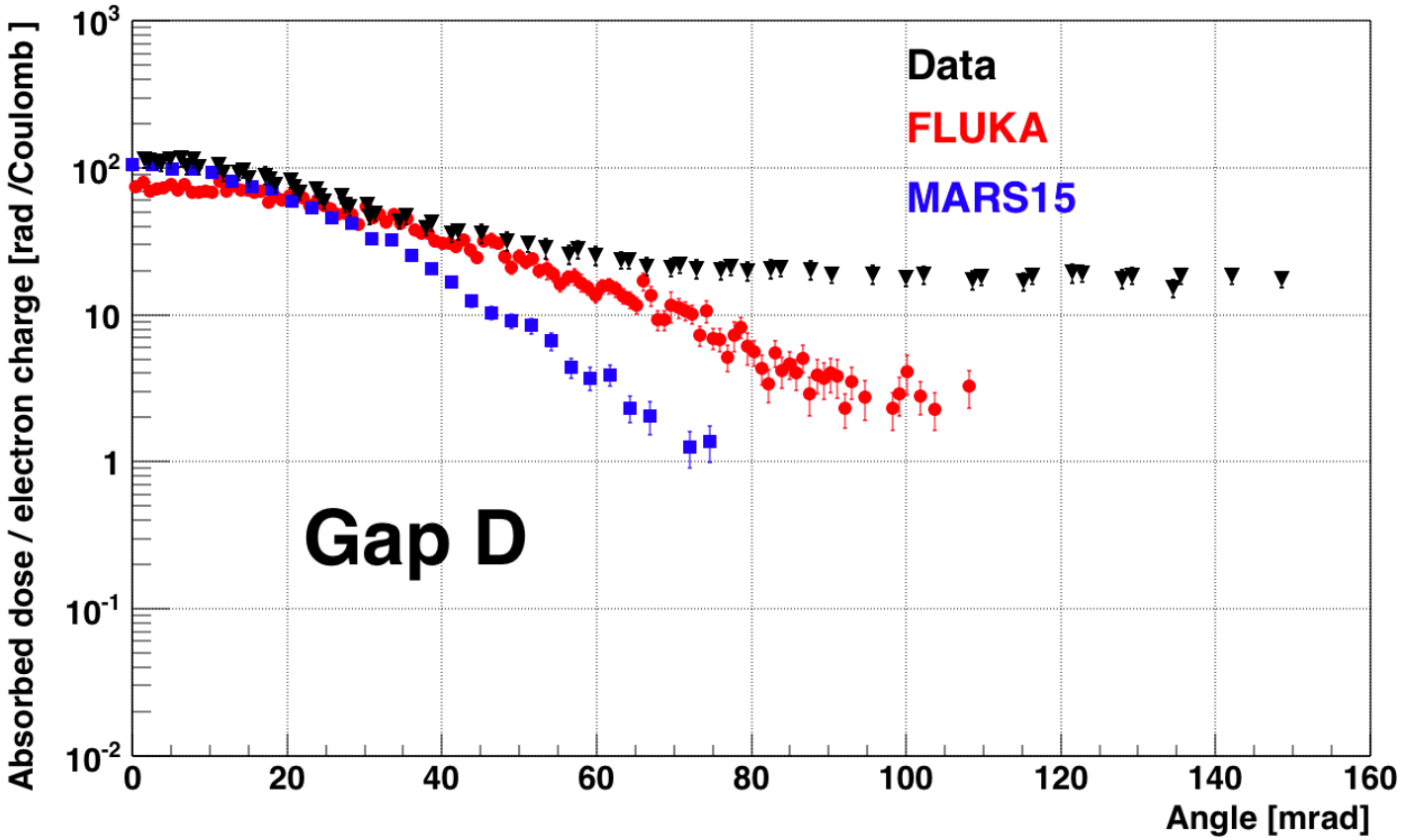
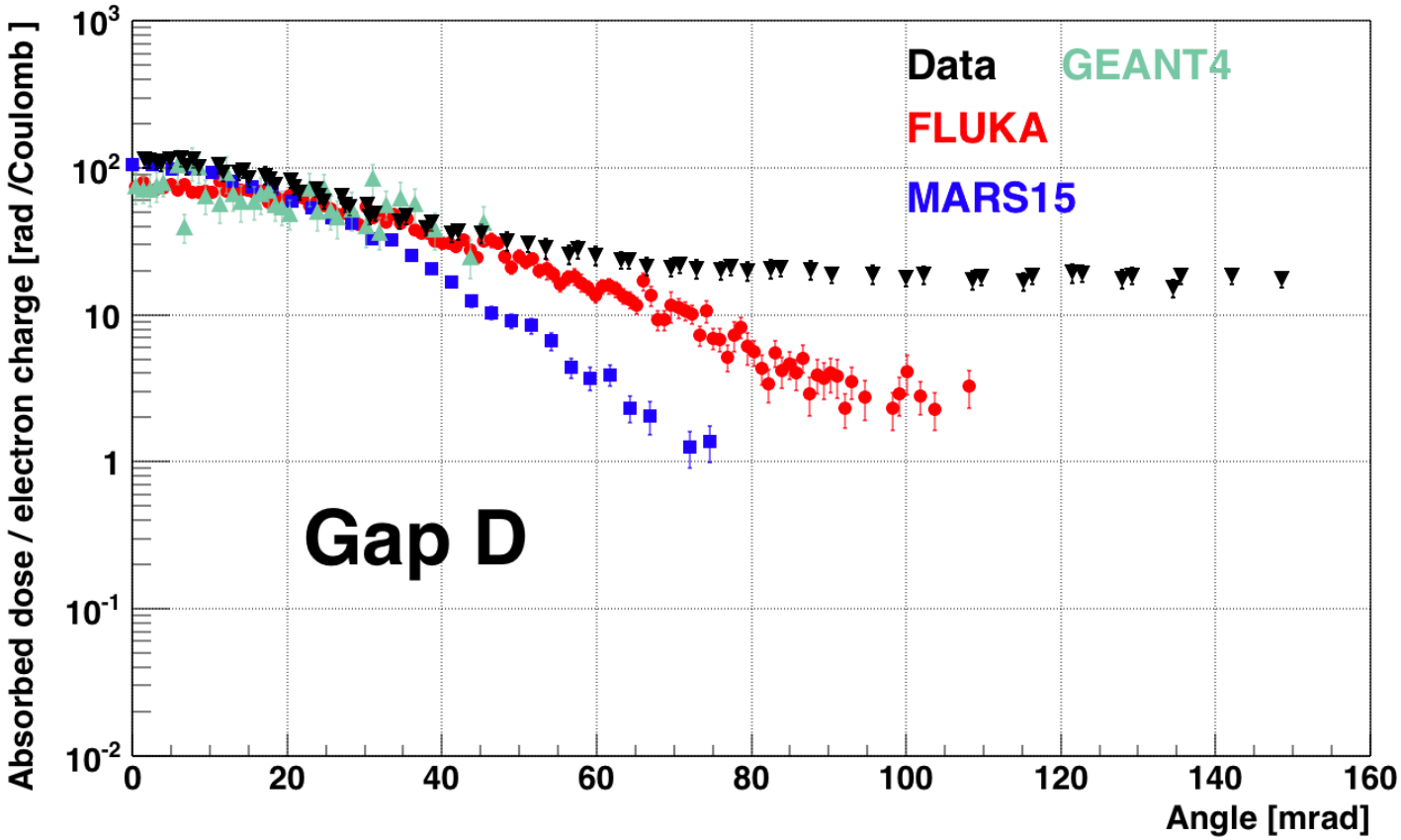


First results

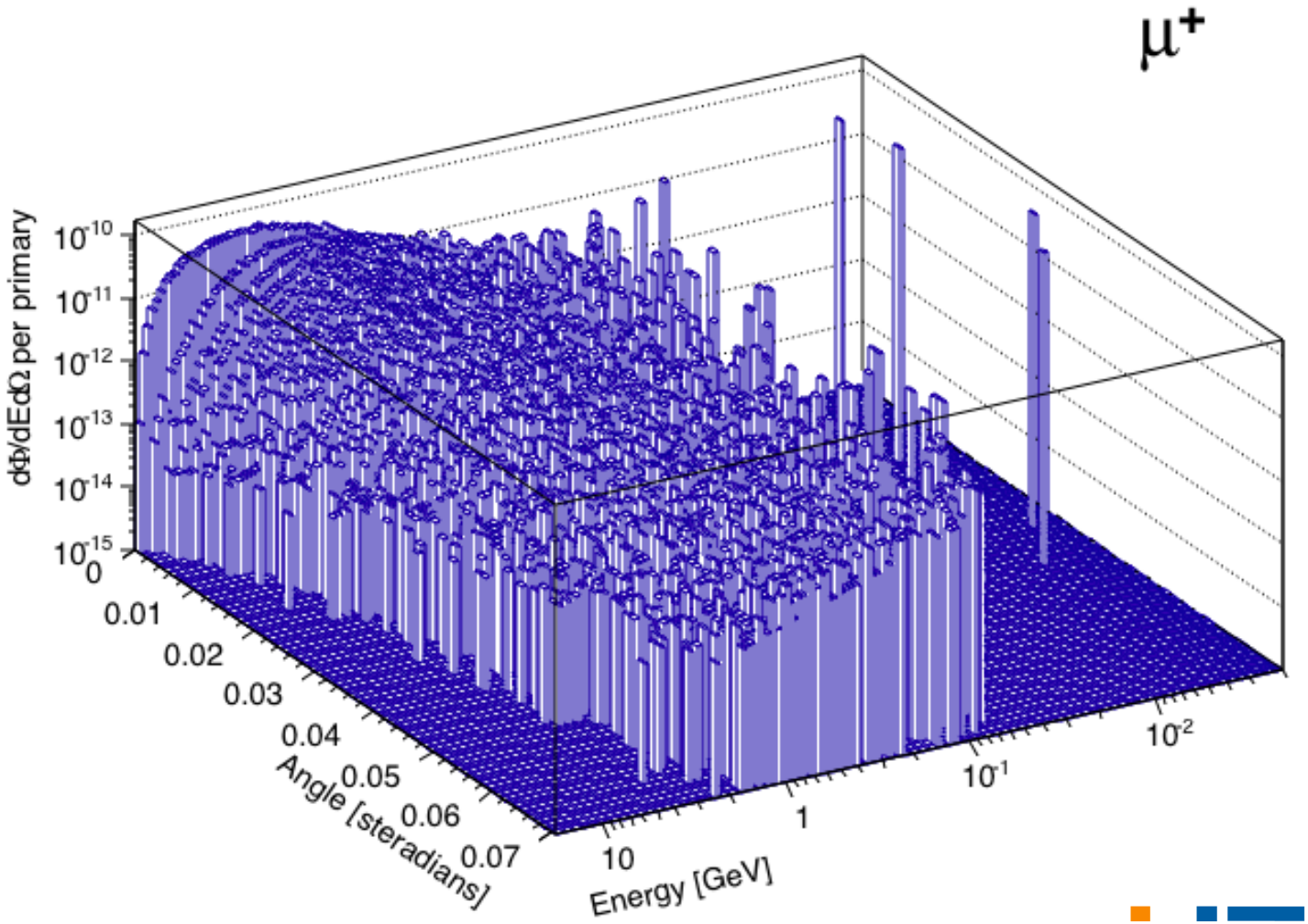
Absorbed dose in Gap D (shielding material steel, ρ =7.6 g/cm^3):



Double diff. distributions

$d\Phi/dEd\Omega$ per primary for muons in the target (obtained with FLUKA)

$0 < E < 18GeV \qquad 0 < \theta < 150\text{mrad}$



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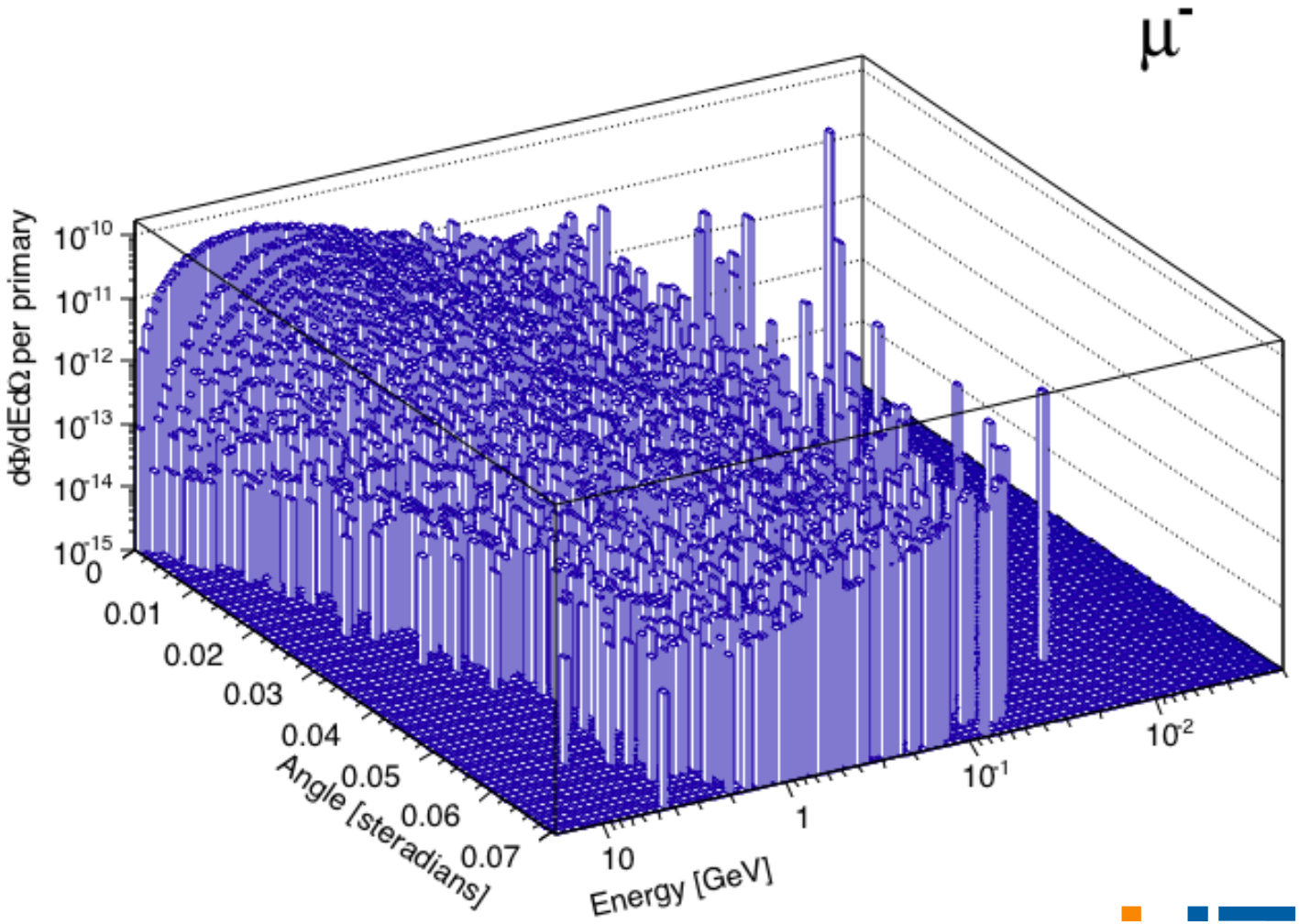


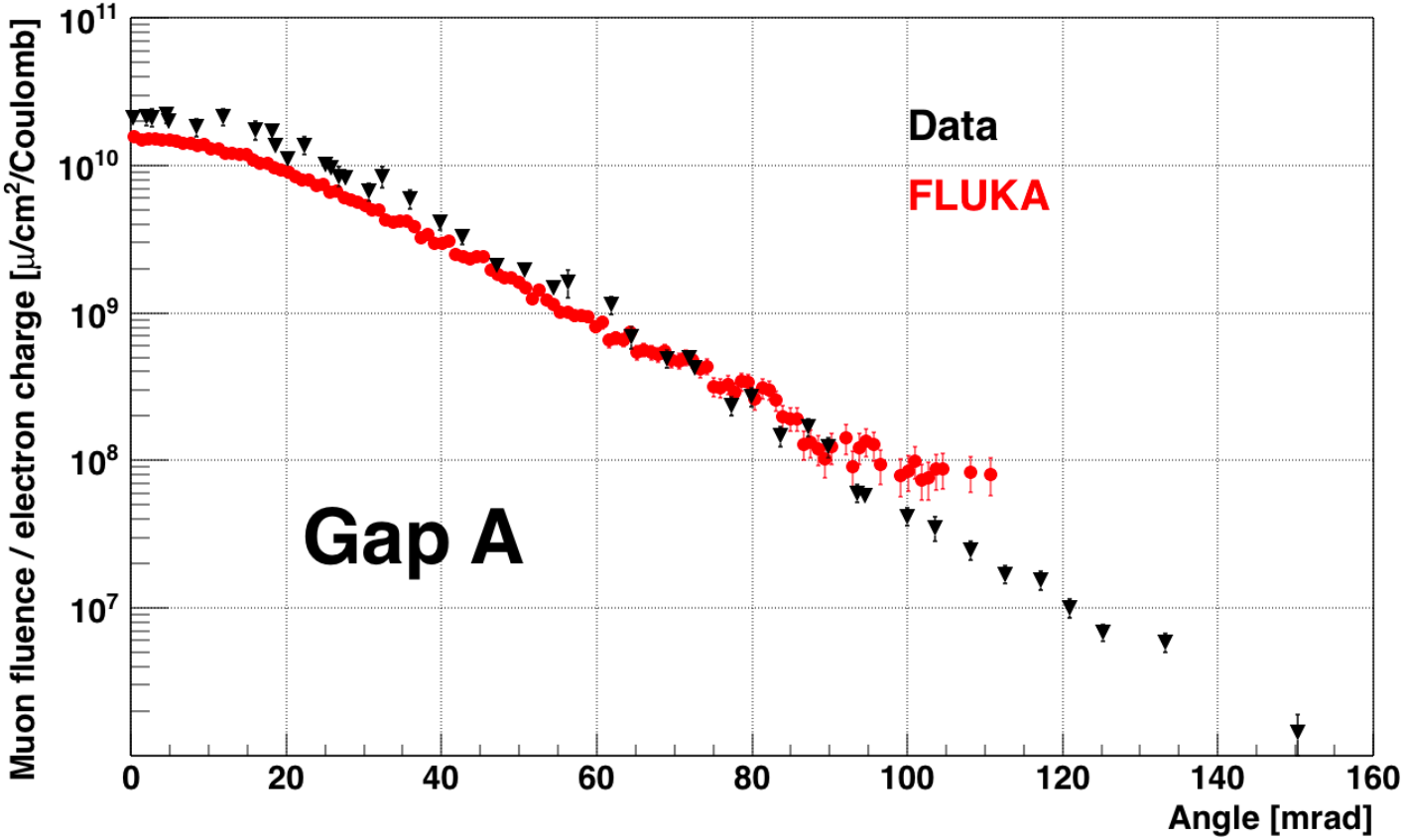
Conclusions:

- Based on the experimental results on muon production by an 18 GeV e^- beam hitting a copper-water target reported by Nelson, Kase, and Svensson, the Monte Carlo transport codes FLUKA, MARS and GEANT4 have been used to model the experimental conditions
- First results on muon fluence and absorbed dose simulations have been produced. The agreement between the simulated results and the experimental values is quite promising
- Differences between the codes as well as the codes and the data need to be understood
  - due to implementation of theoretical model or transport?
- Further refinement of the simulations together with consistency checks will allow to compare and optimize the implementation of muon production and transport in the different transport codes

SPARE SLIDES

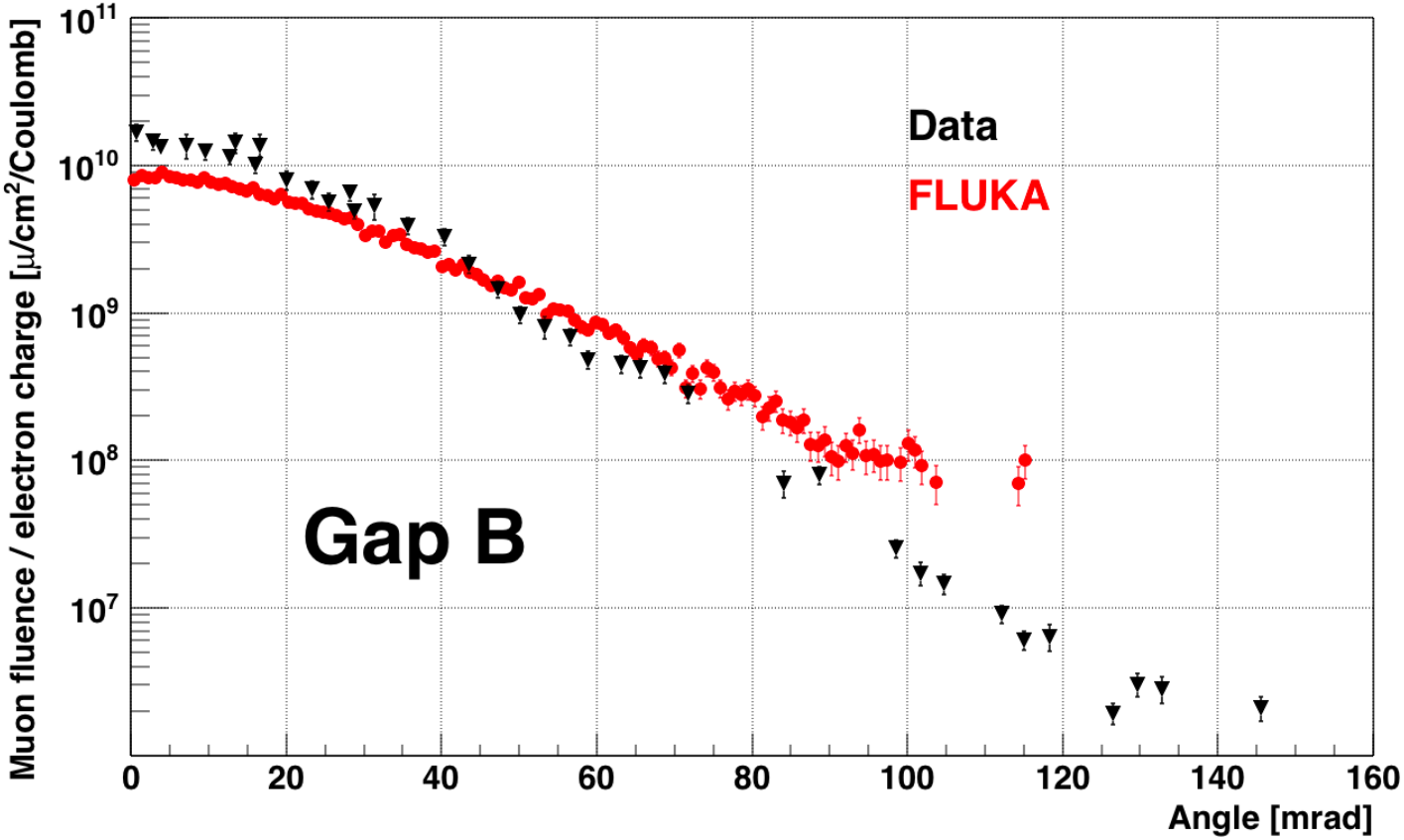
FLUKA: First results

Muon fluence in Gap A (shielding material steel, ρ =7.6 g/cm^3):



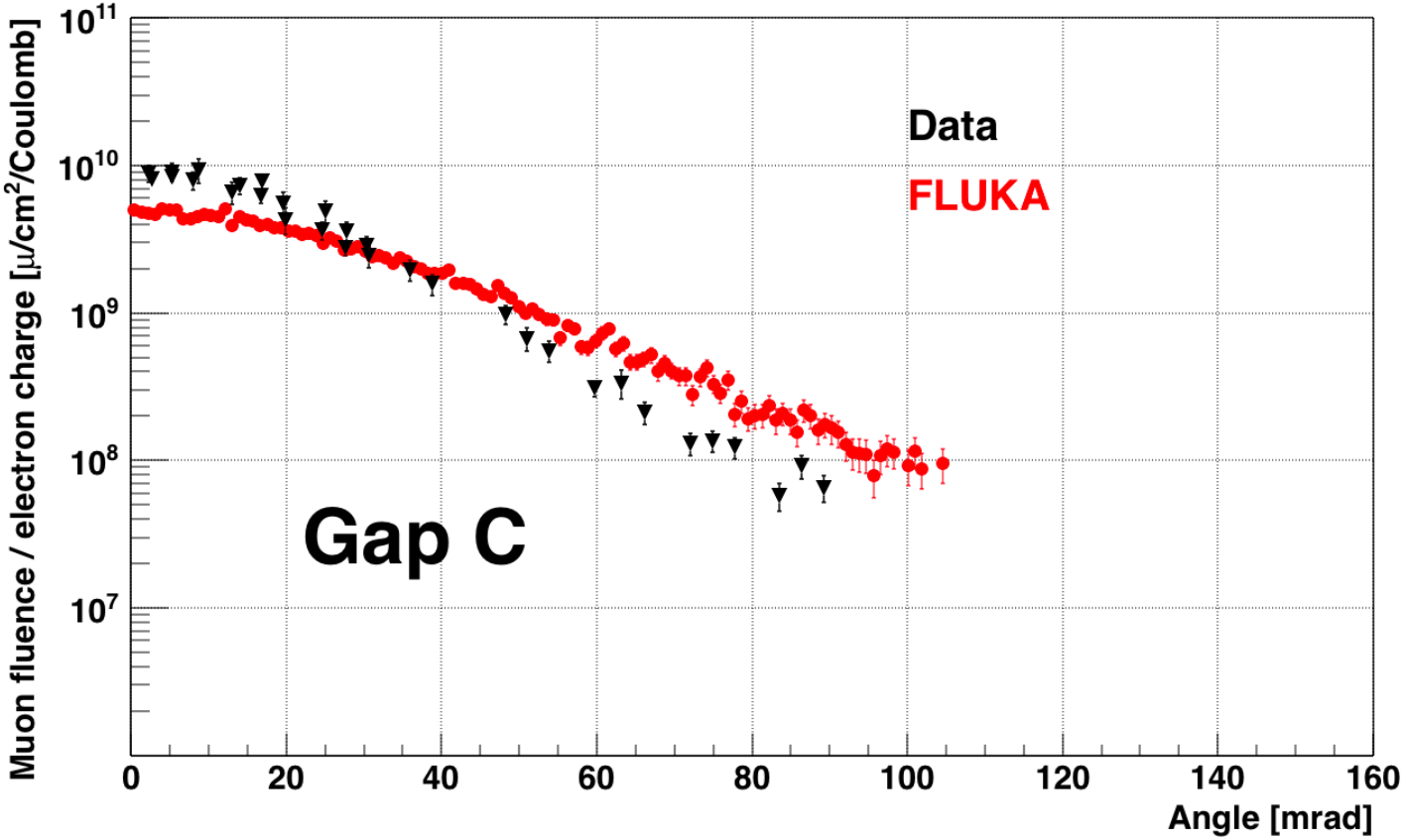
FLUKA: First results

Muon fluence in Gap B (shielding material steel, ρ =7.6 g/cm^3):



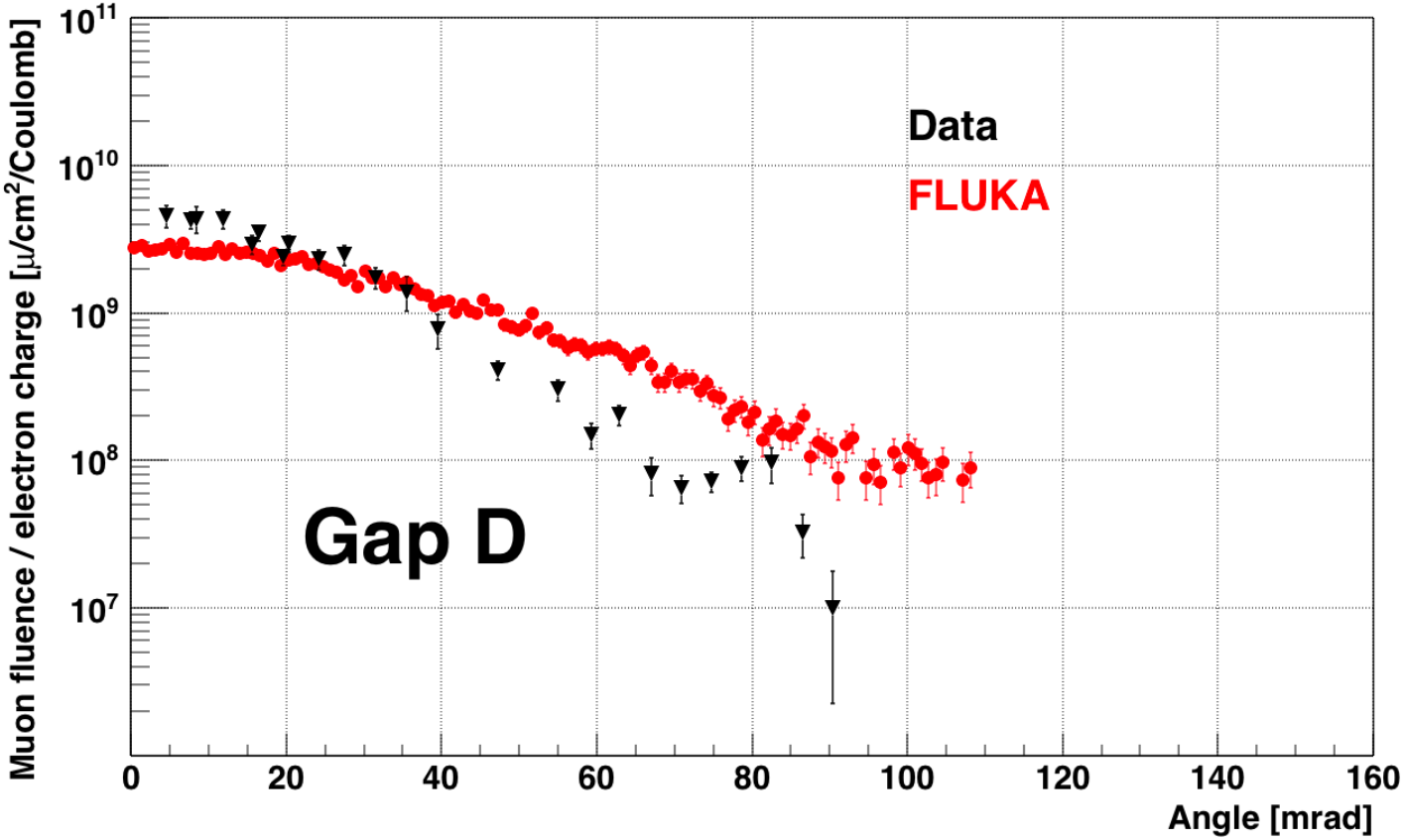
FLUKA: First results

Muon fluence in Gap C (shielding material steel, ρ =7.6 g/cm^3):



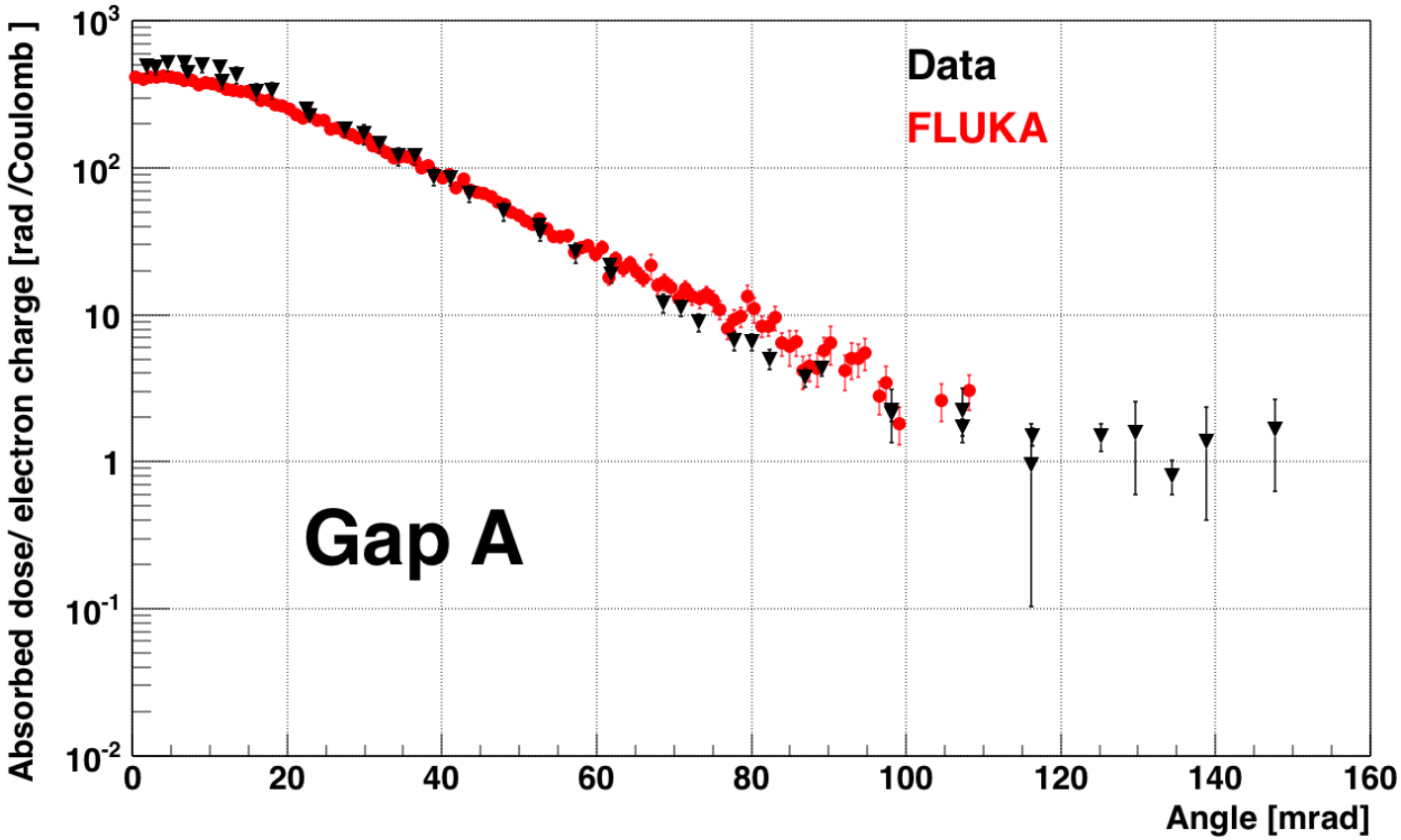
FLUKA: First results

Muon fluence in Gap D (shielding material steel, ρ =7.6 g/cm^3):



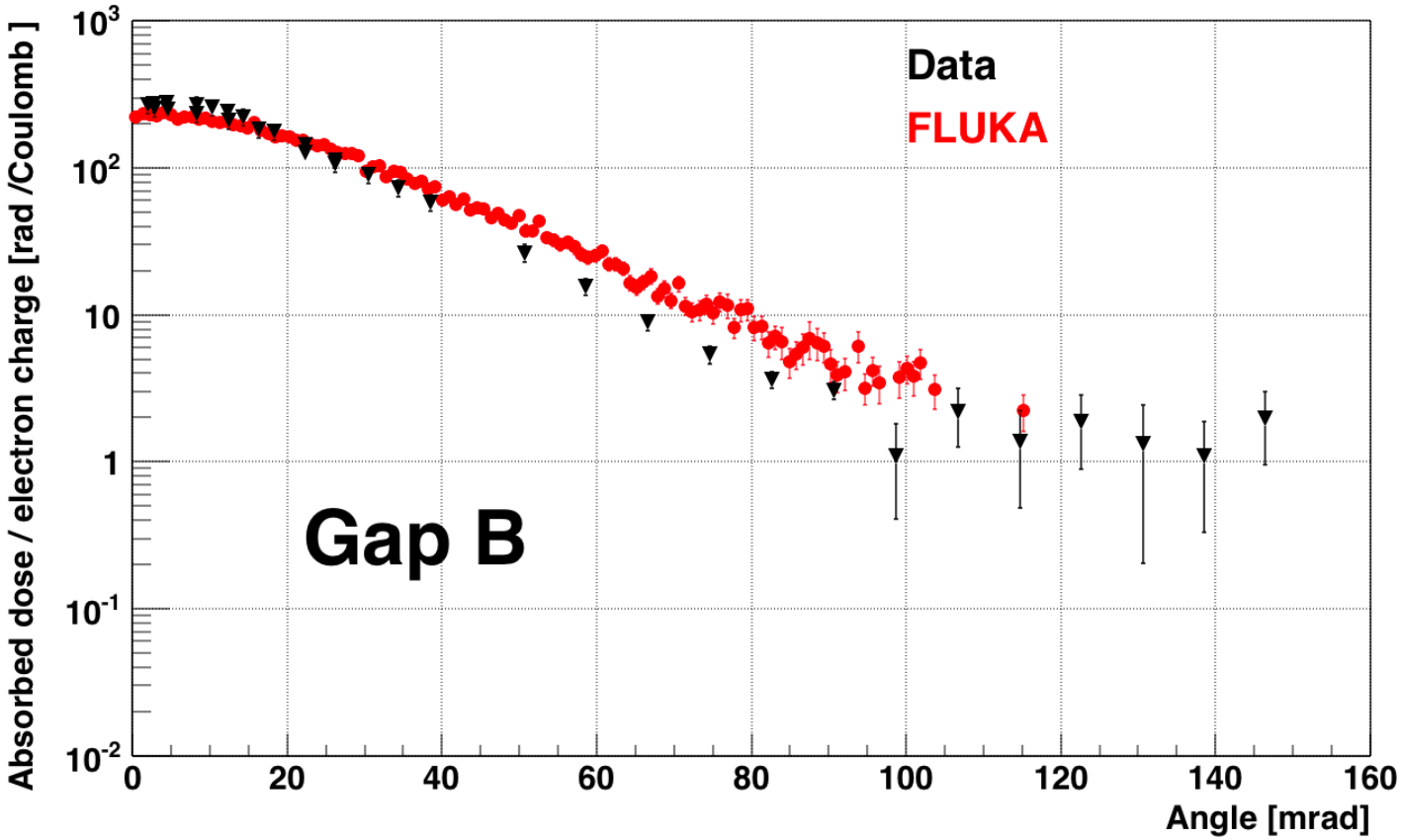
FLUKA: First results

Absorbed dose in Gap A (shielding material steel, ρ =7.6 g/cm^3):



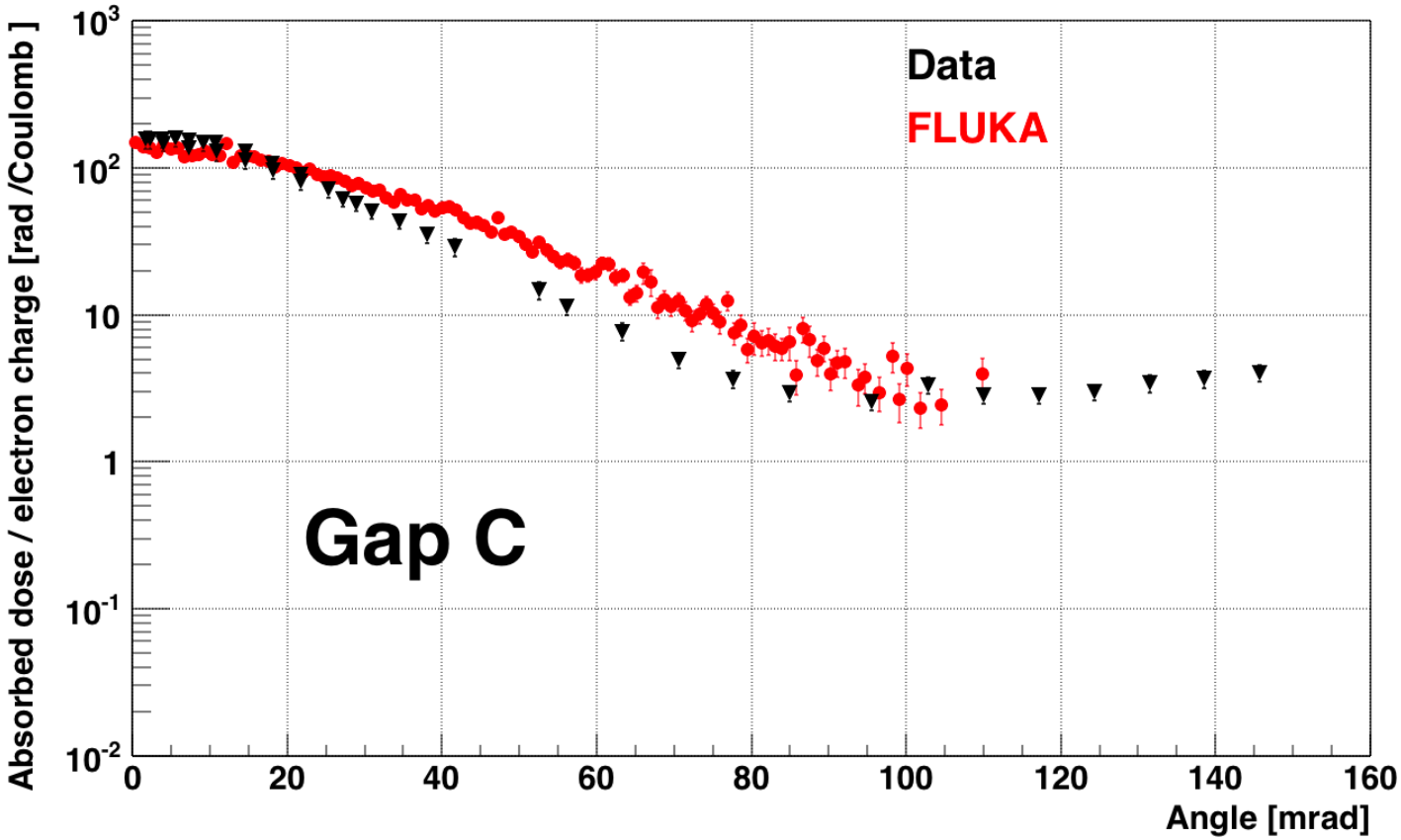
FLUKA: First results

Absorbed dose in Gap B (shielding material steel, ρ =7.6 g/cm^3):



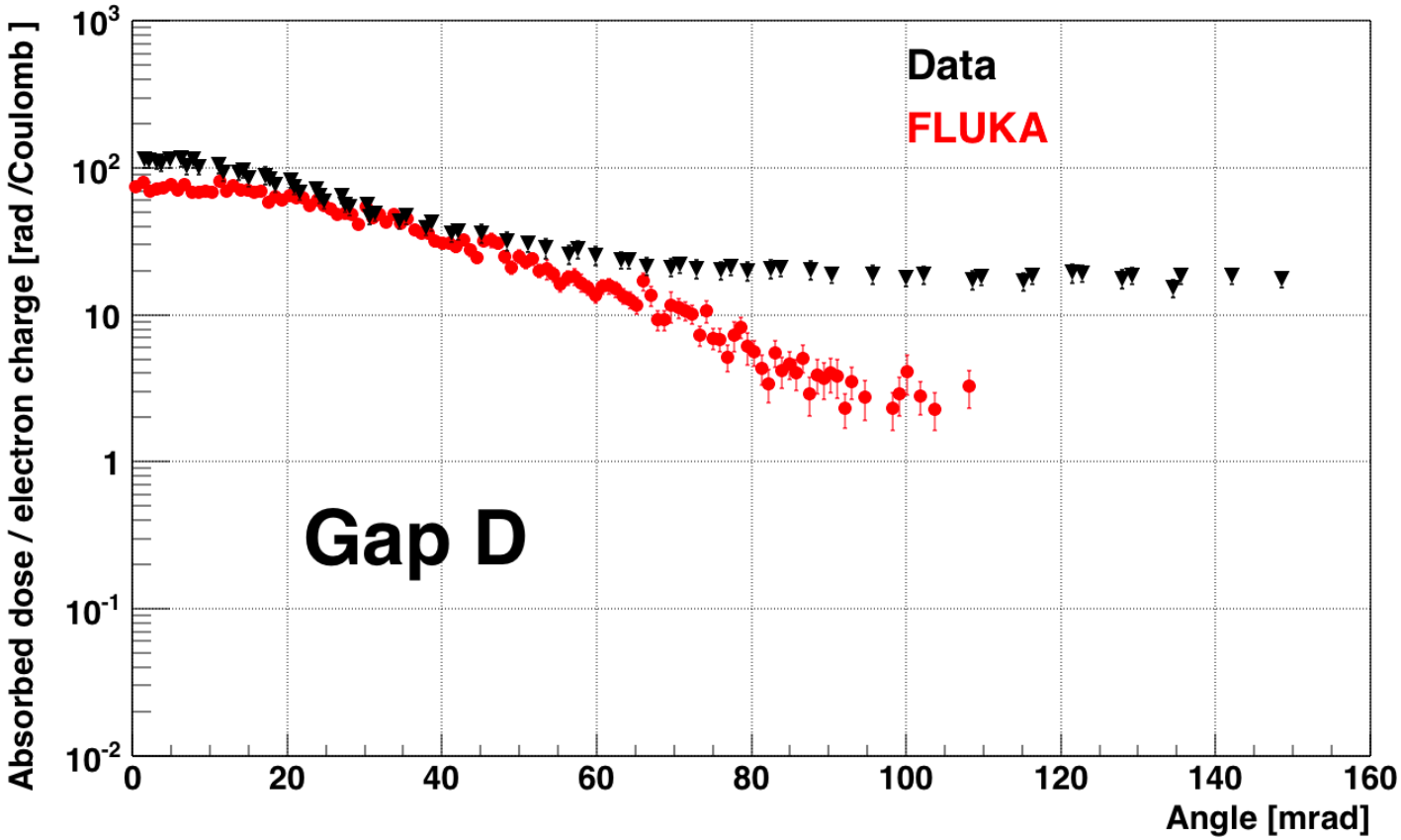
FLUKA: First results

Absorbed dose in Gap C (shielding material steel, ρ =7.6 g/cm^3):



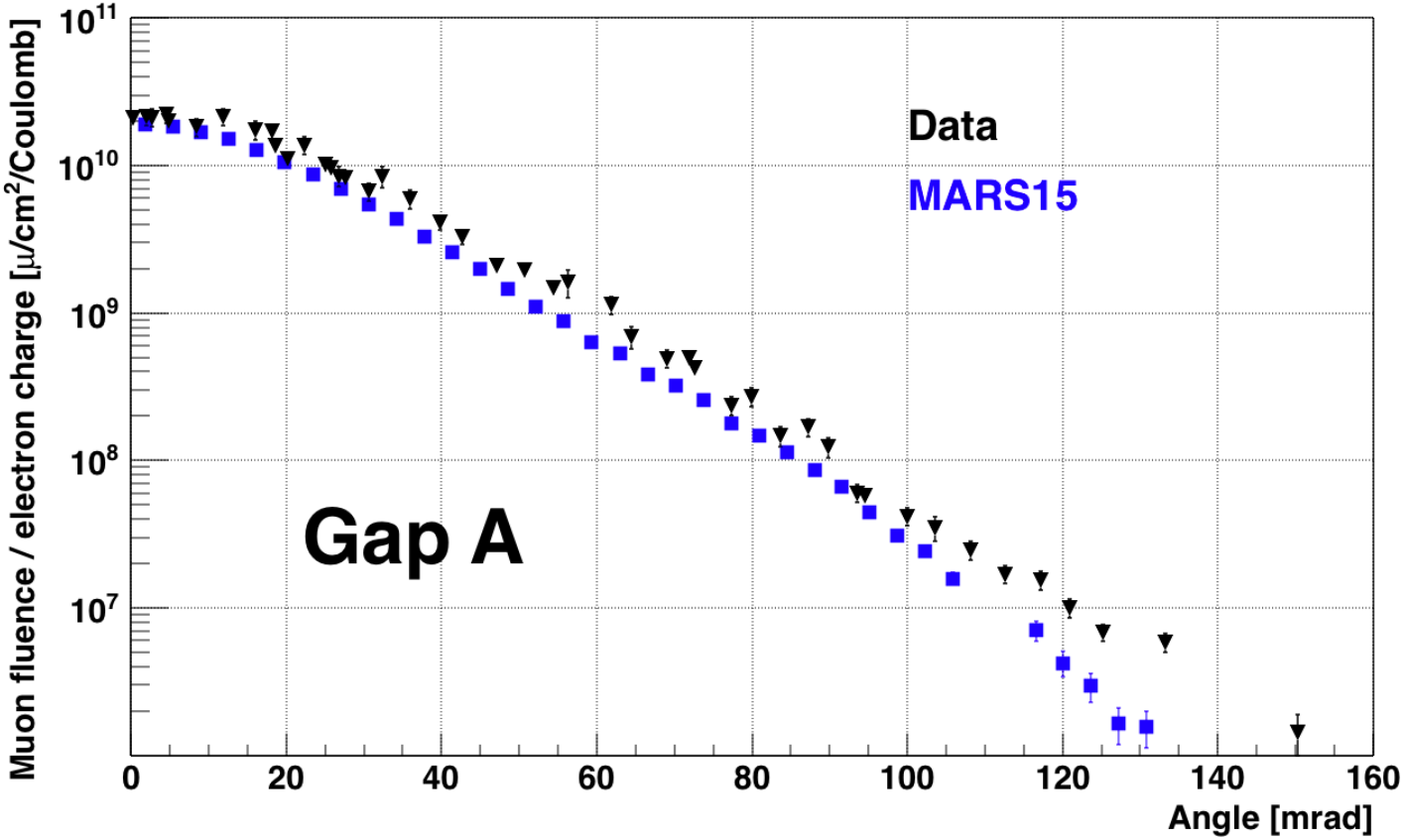
FLUKA: First results

Absorbed dose in Gap D (shielding material steel, ρ =7.6 g/cm^3):



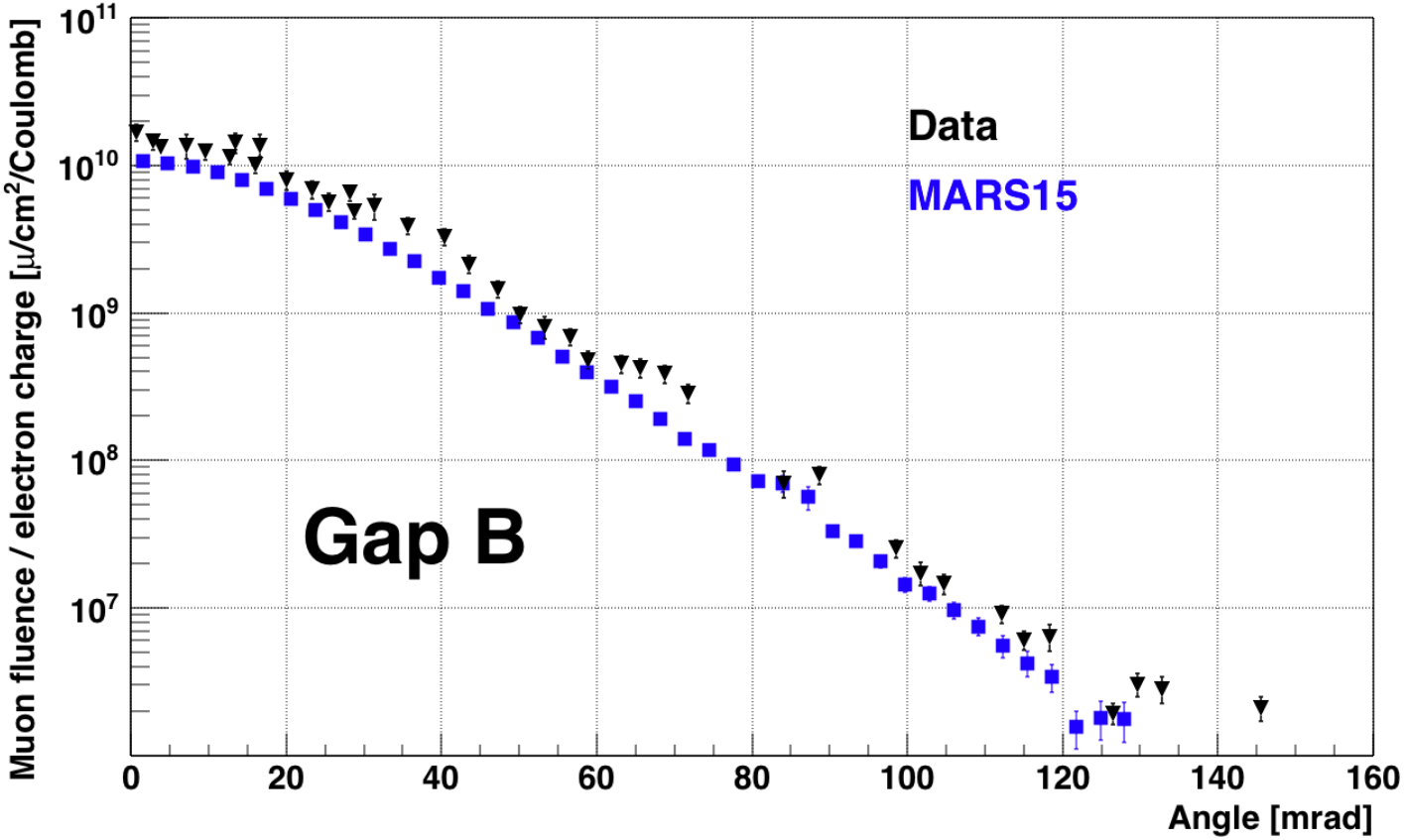
MARS15: First results

Muon fluence in Gap A (shielding material steel, ρ =7.6 g/cm^3):



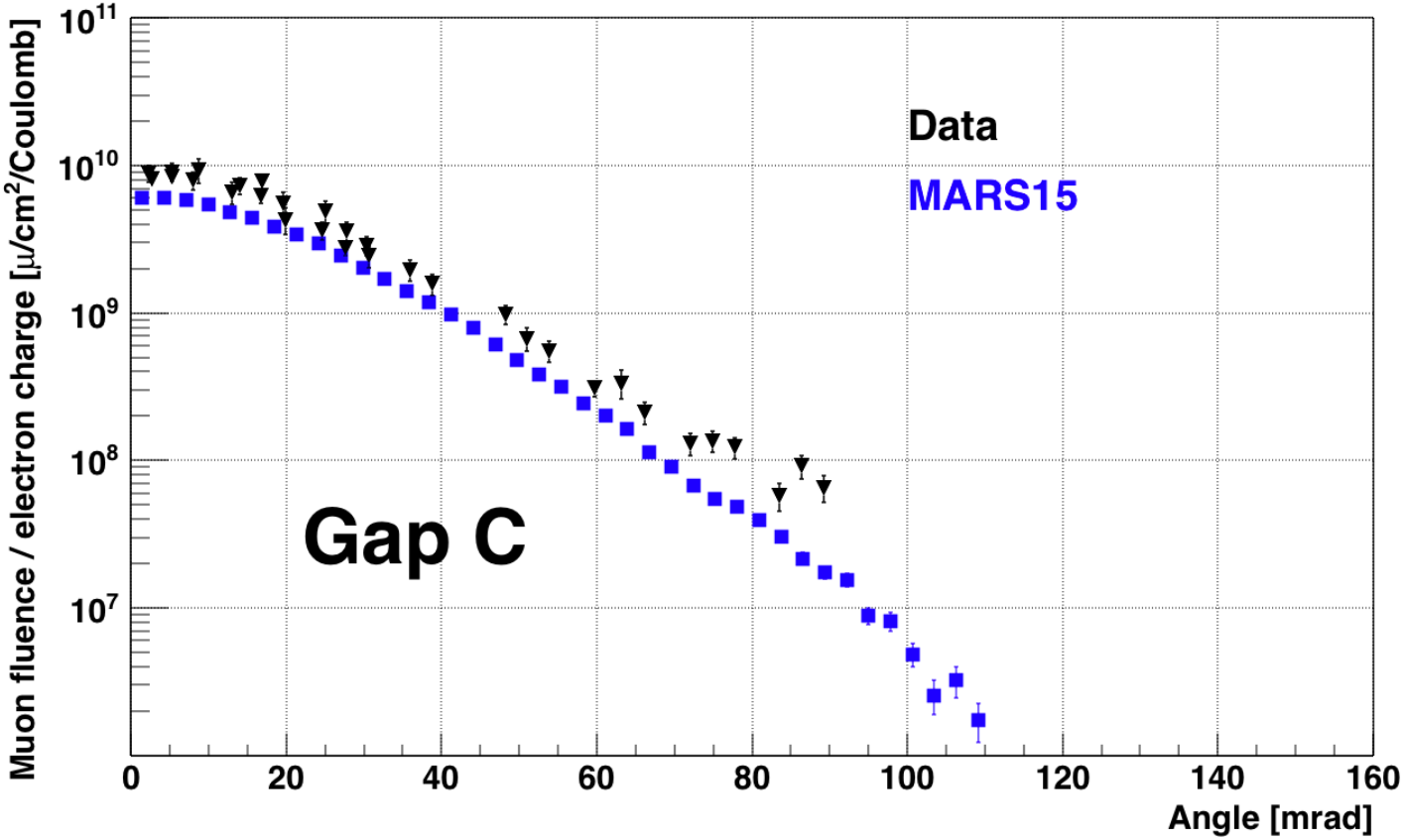
MARS15: First results

Muon fluence in Gap B (shielding material steel, ρ =7.6 g/cm^3):



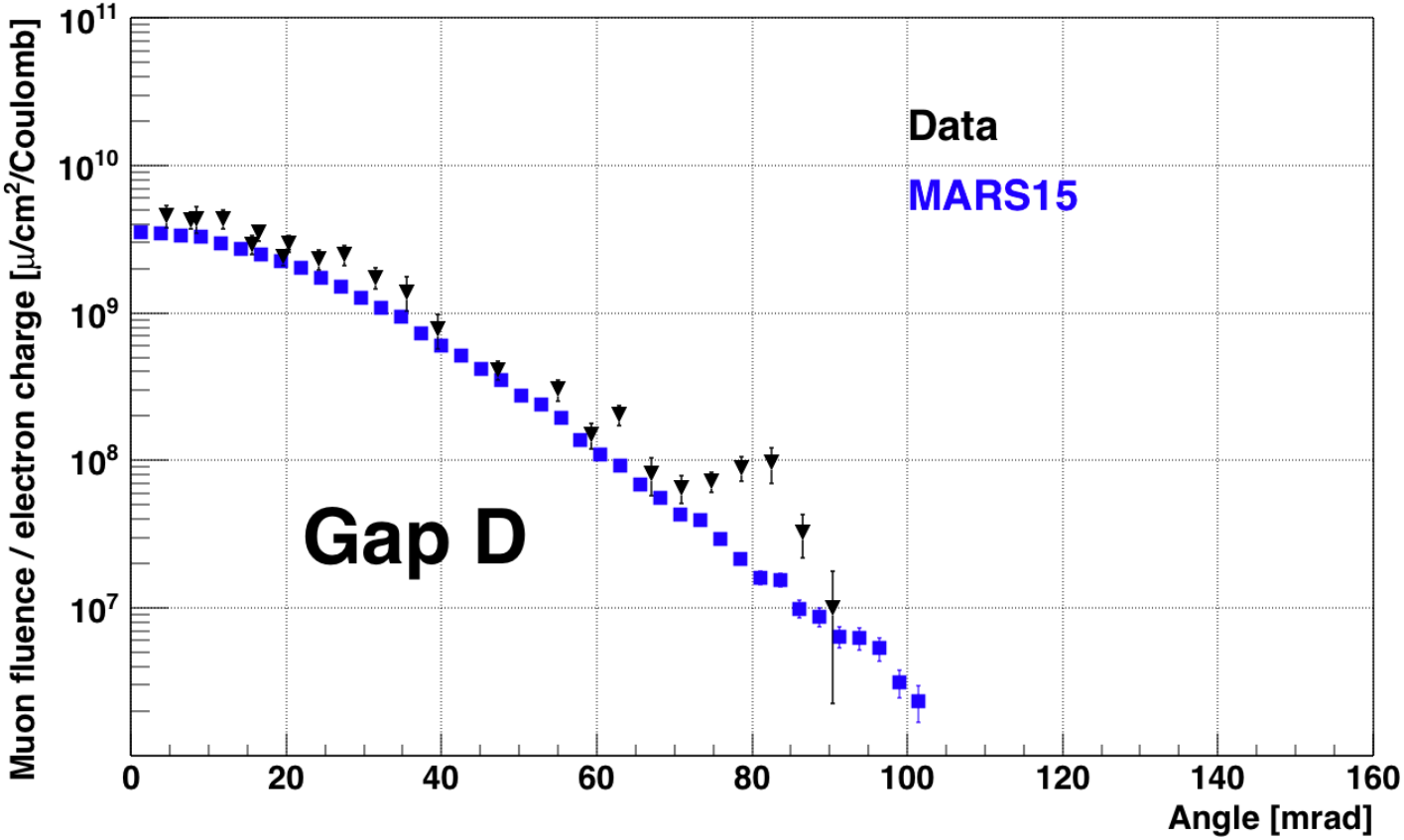
MARS15: First results

Muon fluence in Gap C (shielding material steel, ρ =7.6 g/cm^3):



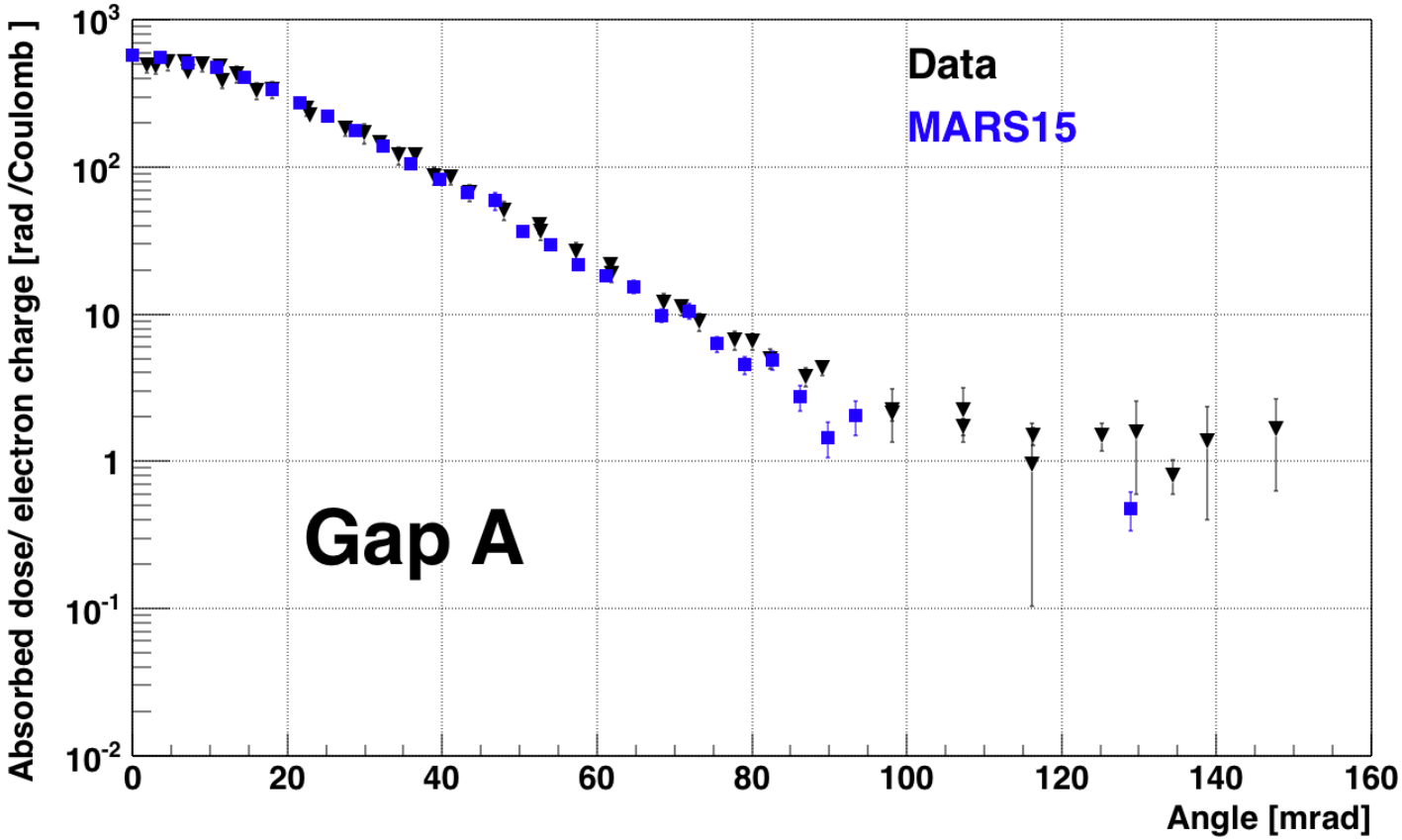
MARS15: First results

Muon fluence in Gap D (shielding material steel, ρ =7.6 g/cm^3):



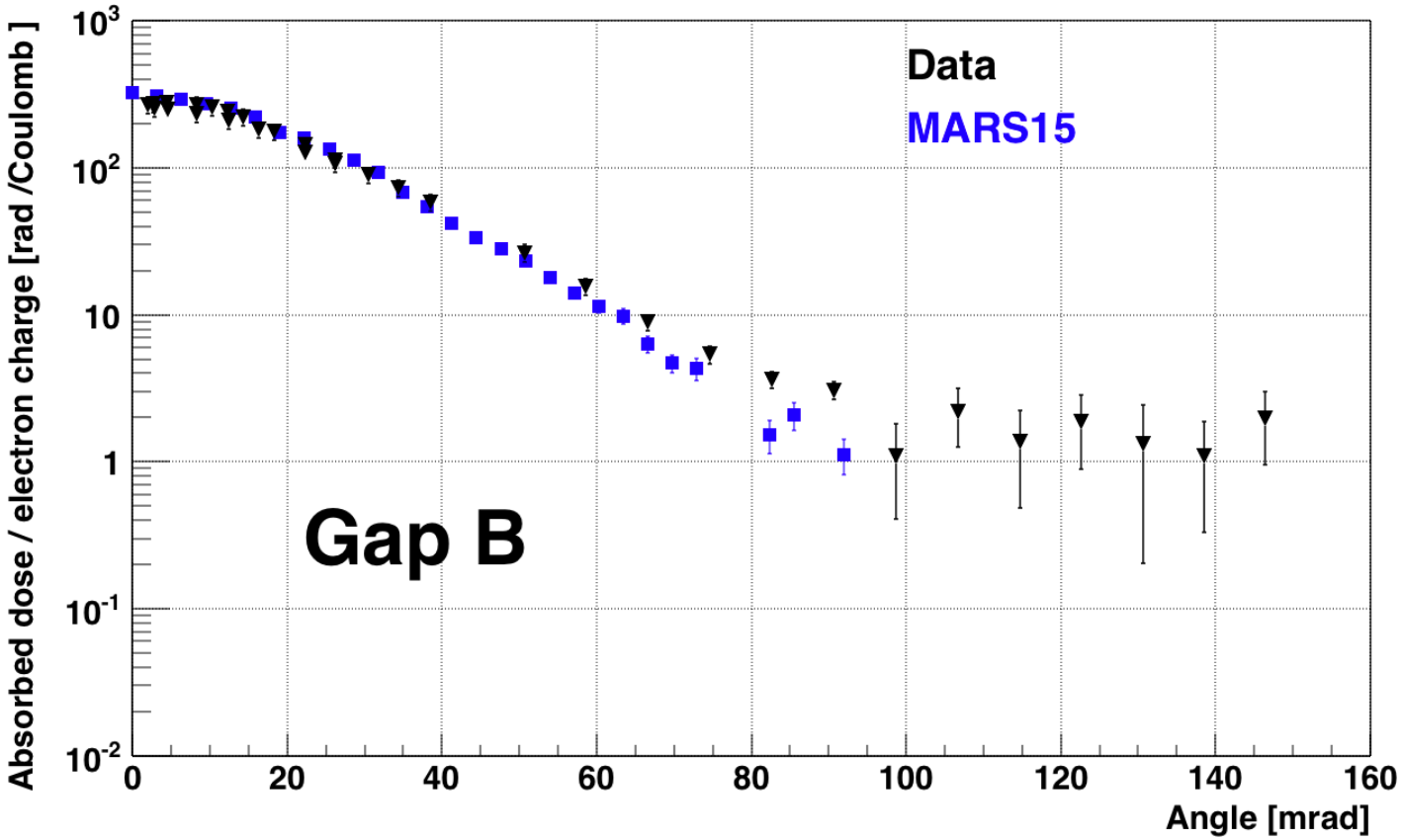
MARS15: First results

Absorbed dose in Gap A (shielding material steel, ρ =7.6 g/cm^3):



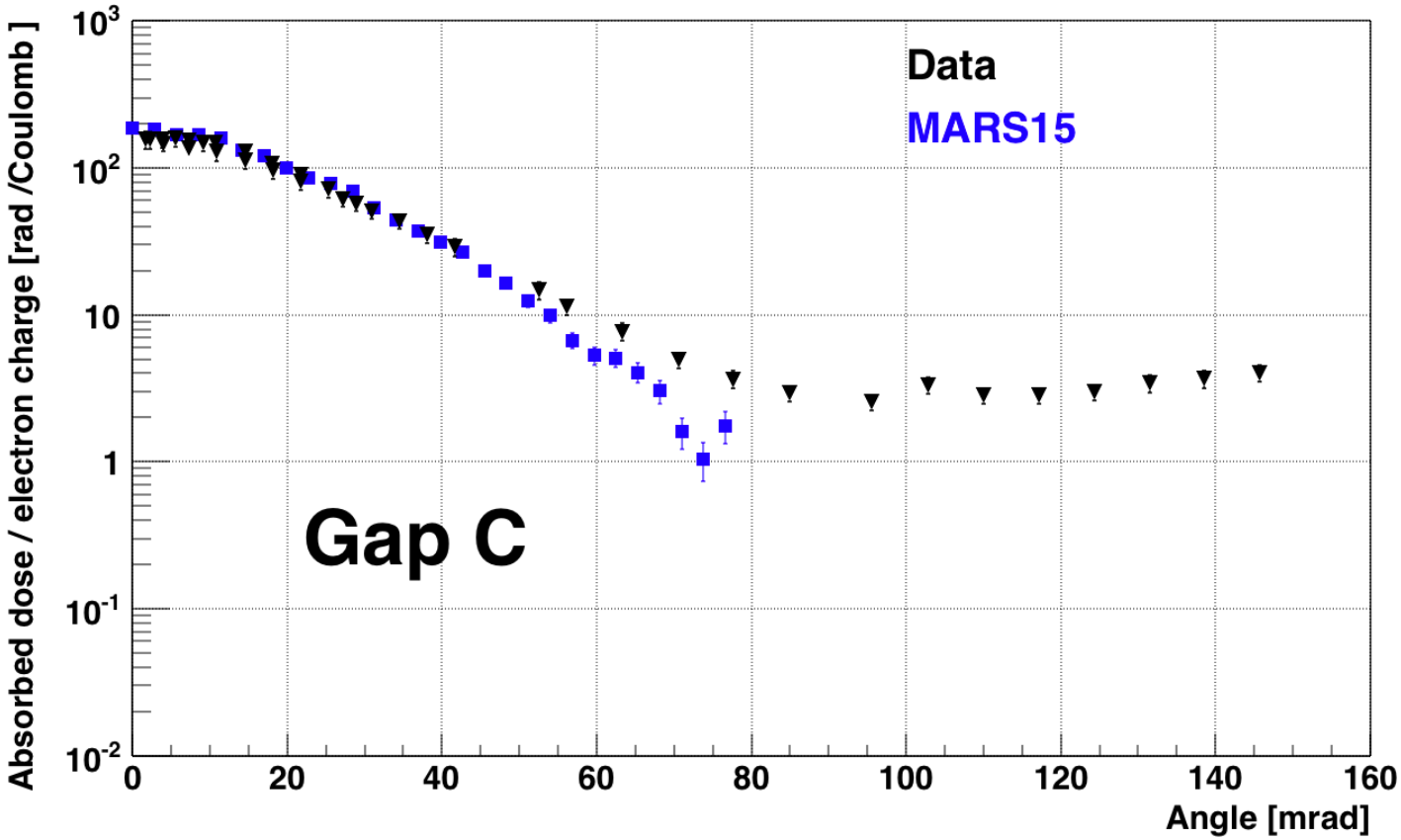
MARS15: First results

Absorbed dose in Gap B (shielding material steel, ρ =7.6 g/cm^3):



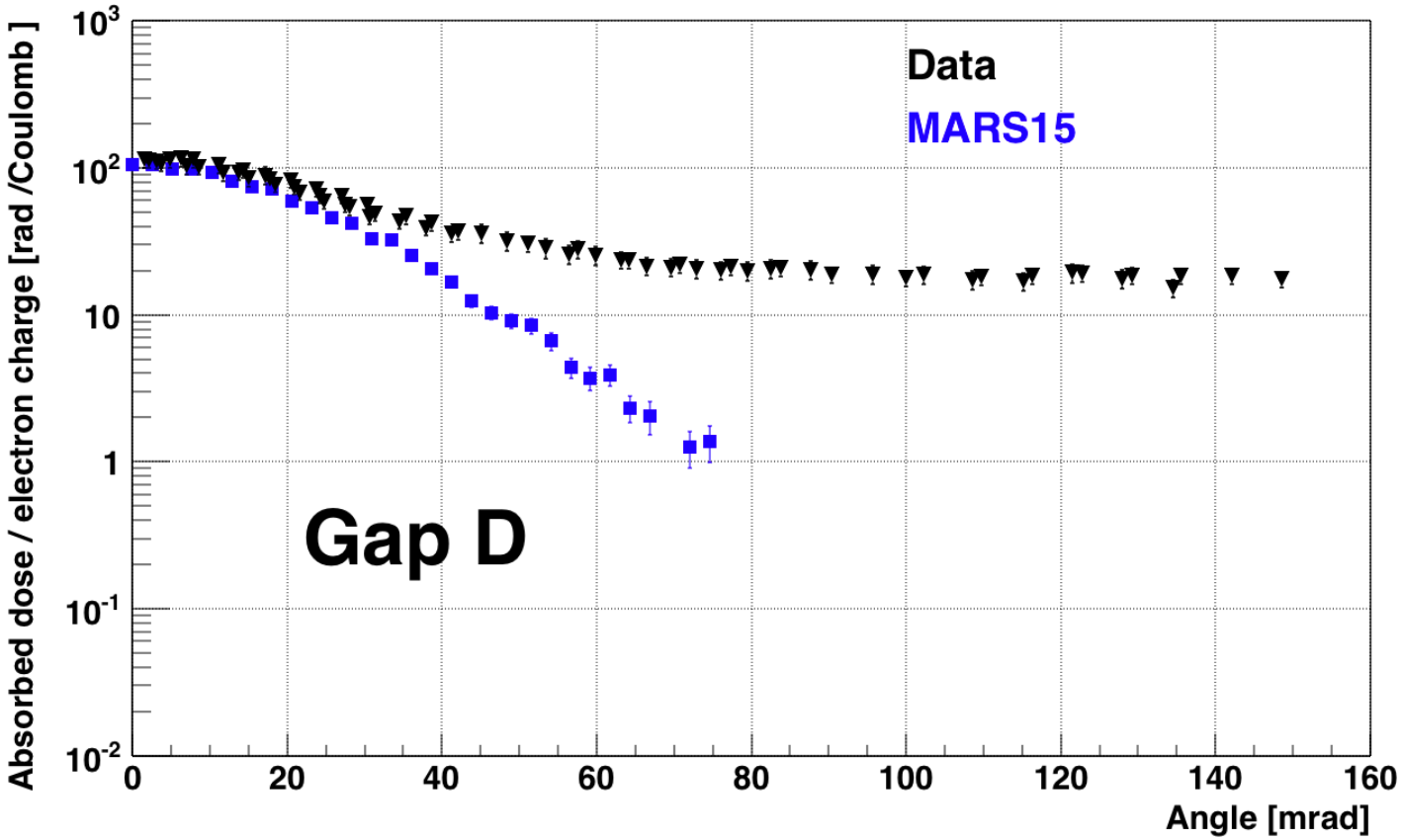
MARS15: First results

Absorbed dose in Gap C (shielding material steel, ρ =7.6 g/cm^3):



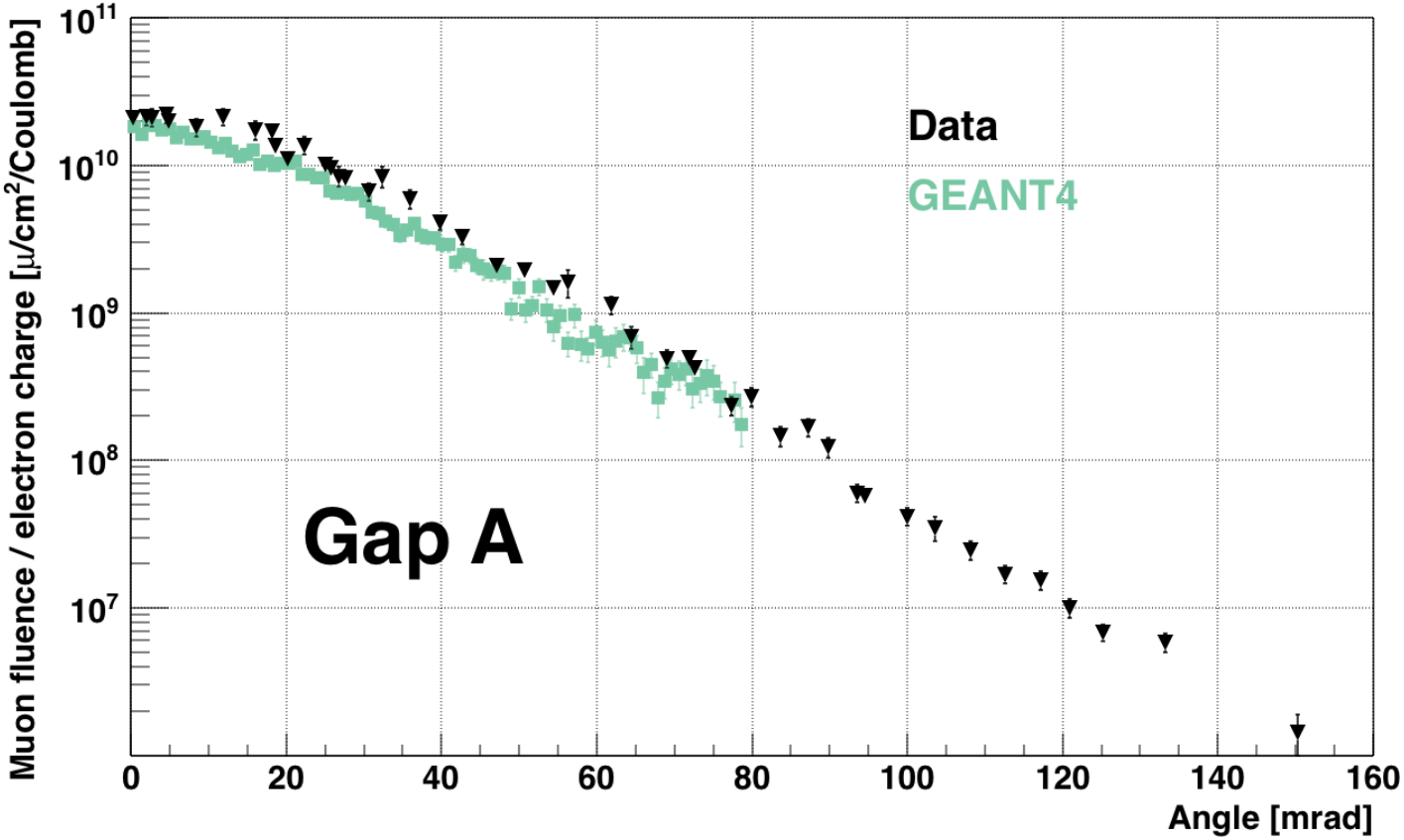
MARS15: First results

Absorbed dose in Gap D (shielding material steel, ρ =7.6 g/cm^3):



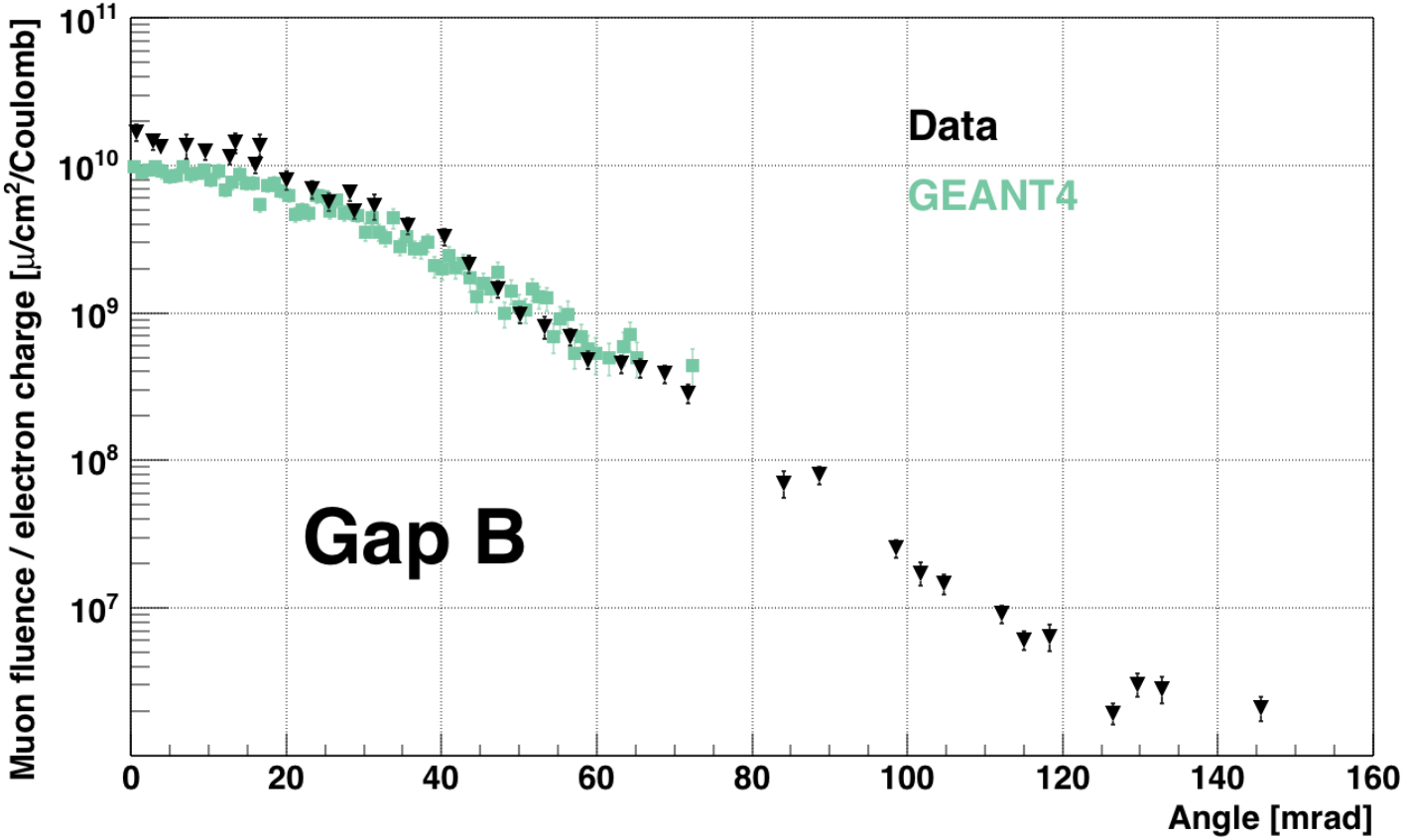
GEANT4: First results

Muon fluence in Gap A (shielding material steel, ρ =7.6 g/cm^3):



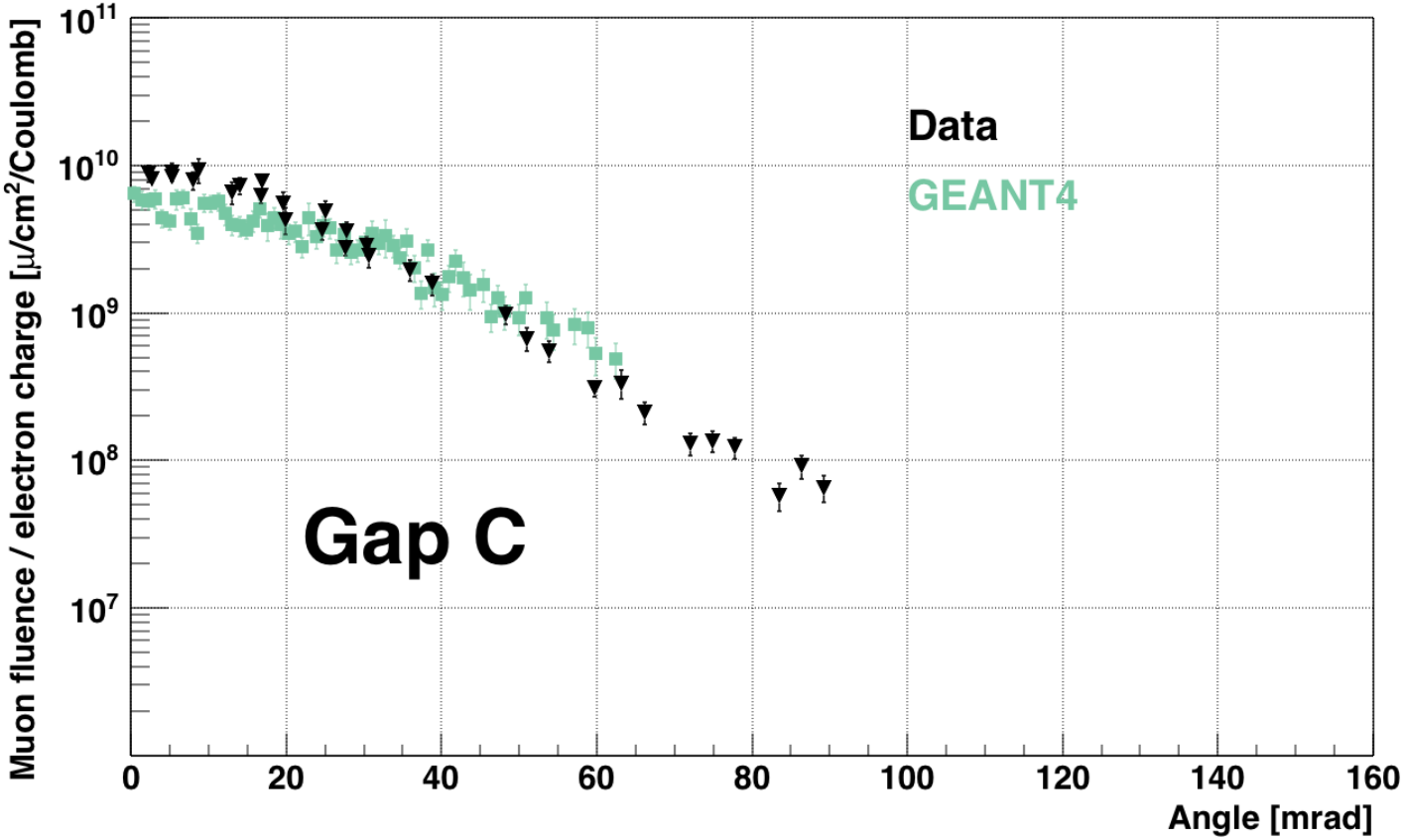
GEANT4: First results

Muon fluence in Gap B (shielding material steel, ρ =7.6 g/cm^3):



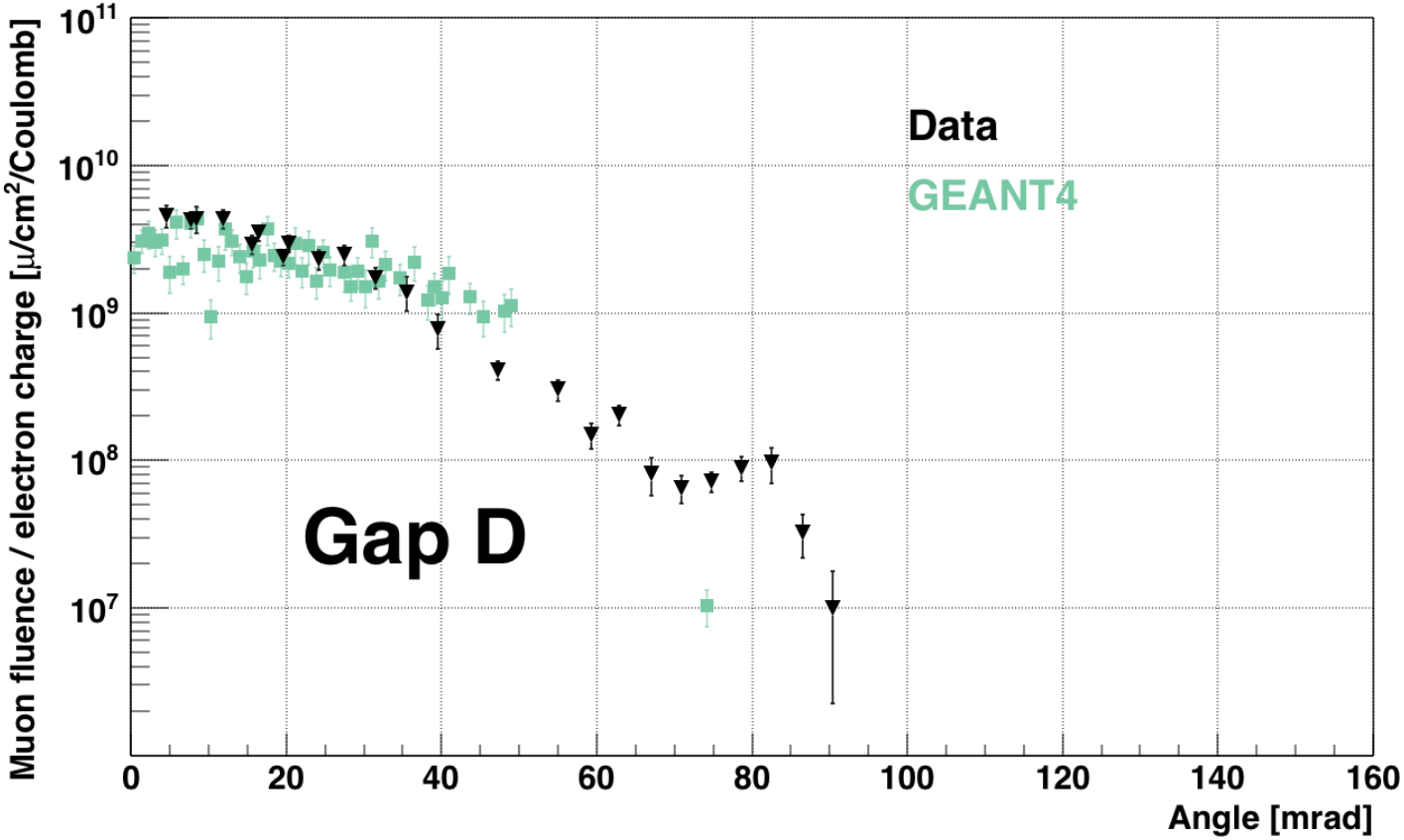
GEANT4: First results

Muon fluence in Gap C (shielding material steel, ρ =7.6 g/cm^3):



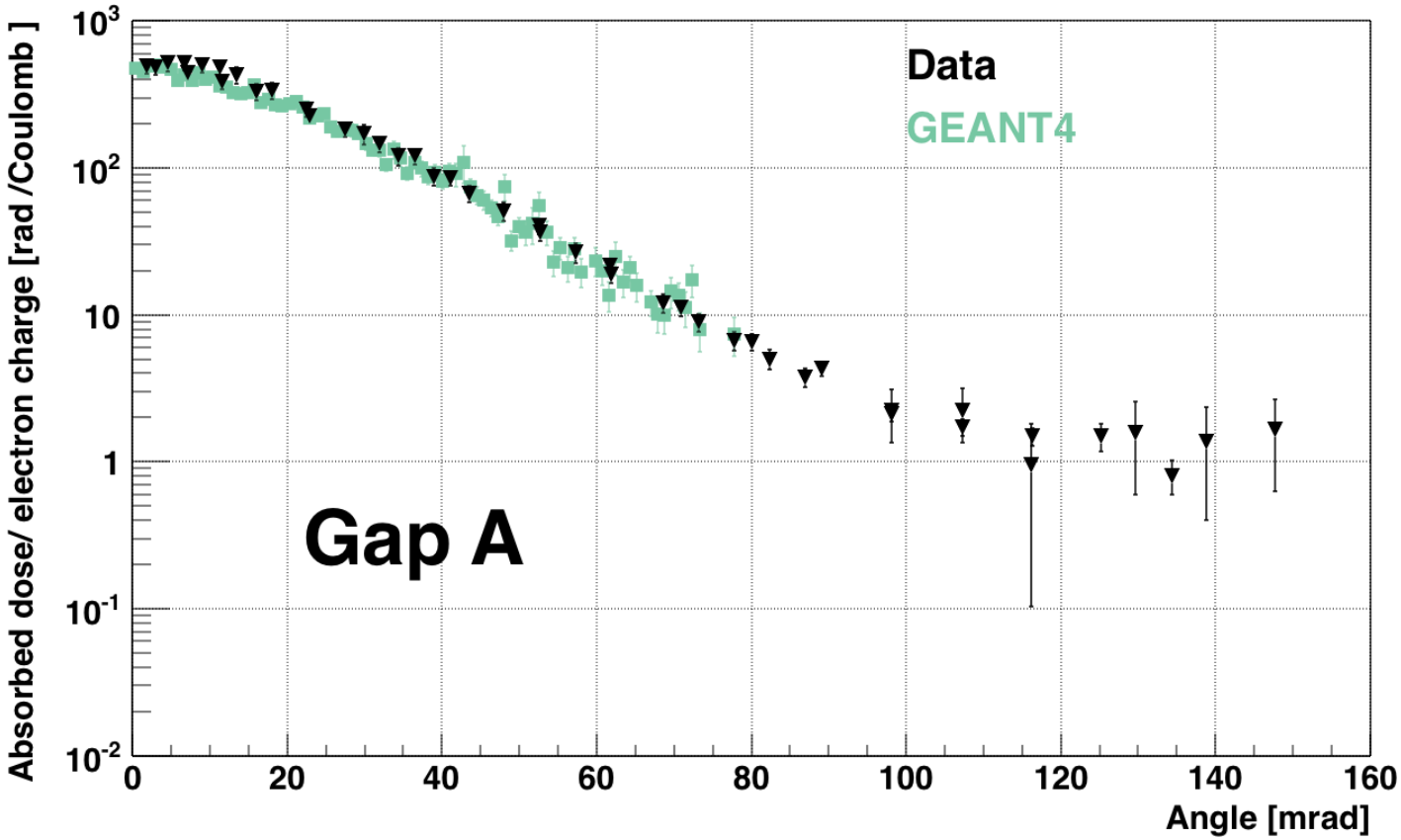
GEANT4: First results

Muon fluence in Gap D (shielding material steel, ρ =7.6 g/cm^3):



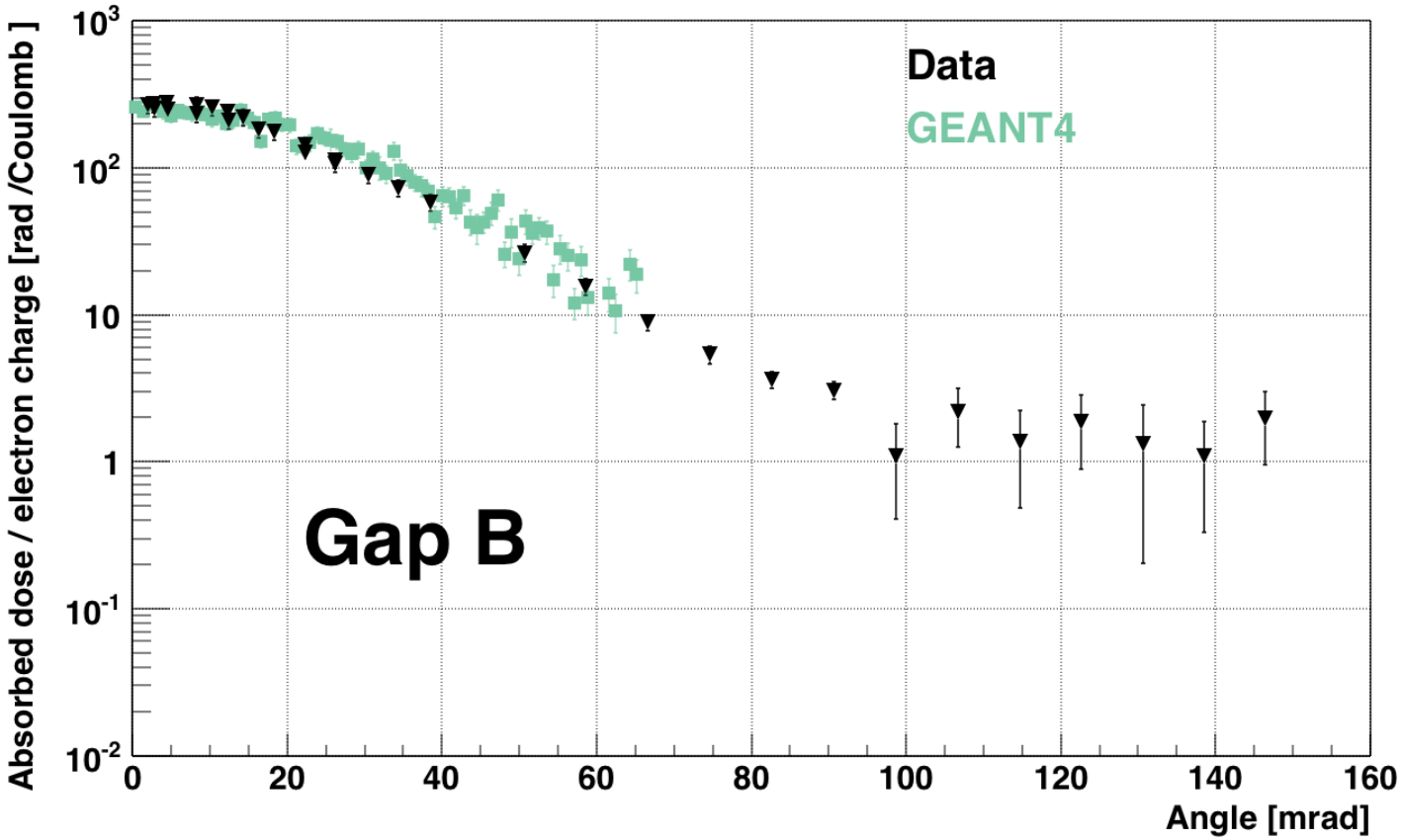
GEANT4: First results

Absorbed dose in Gap A (shielding material steel, ρ =7.6 g/cm^3):



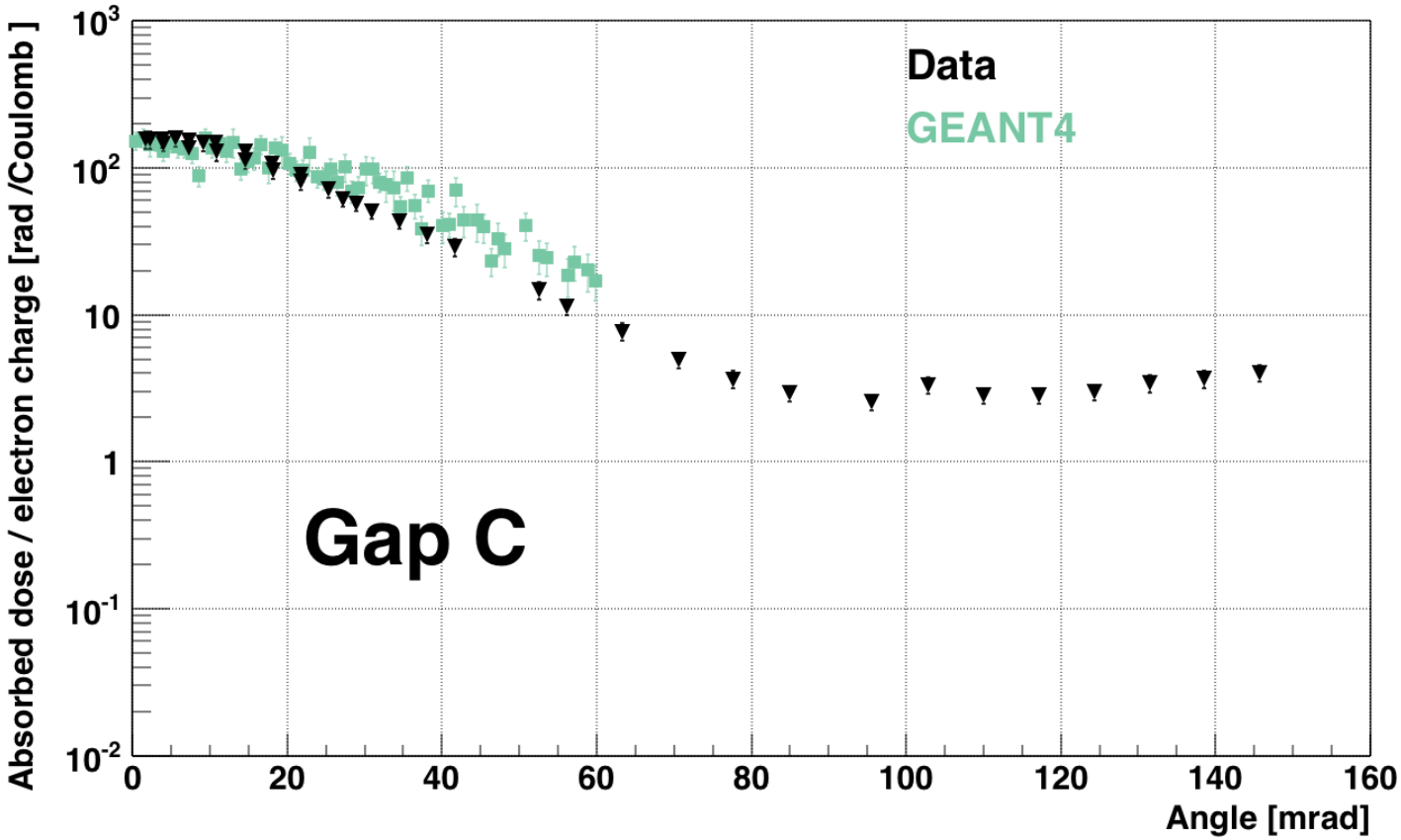
GEANT4: First results

Absorbed dose in Gap B (shielding material steel, ρ =7.6 g/cm^3):



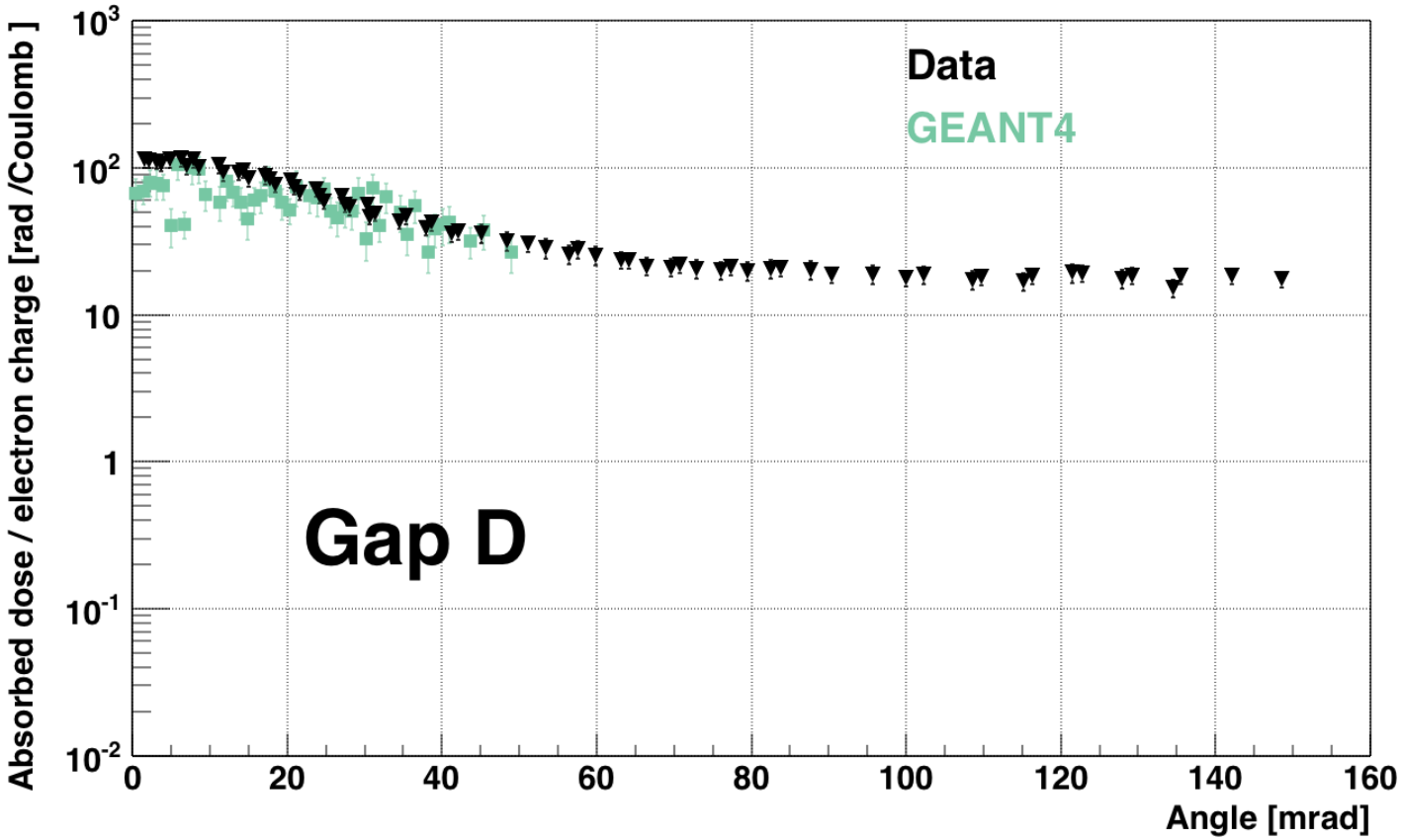
GEANT4: First results

Absorbed dose in Gap C (shielding material steel, ρ =7.6 g/cm^3):



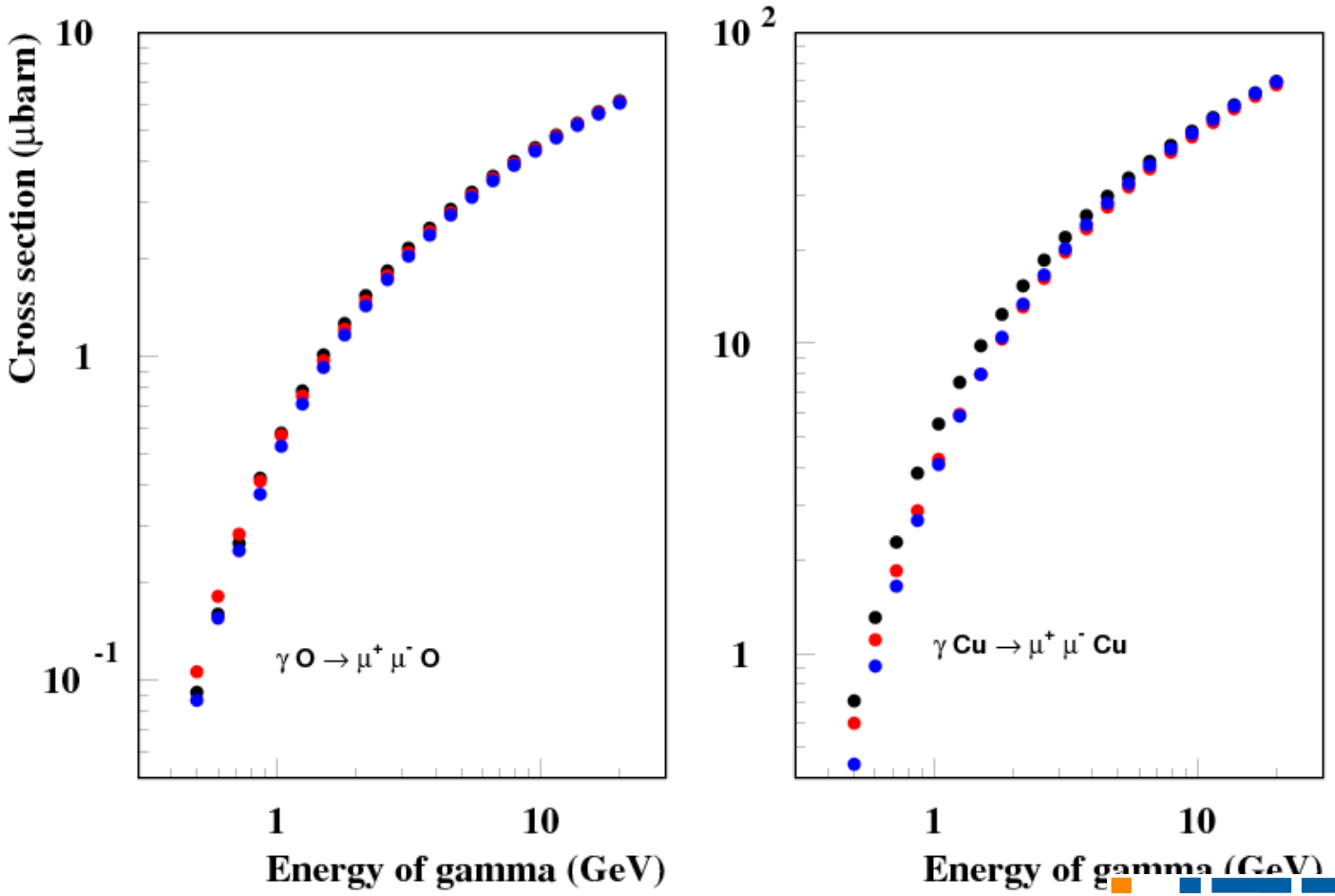
GEANT4: First results

Absorbed dose in Gap D (shielding material steel, ρ =7.6 g/cm^3):



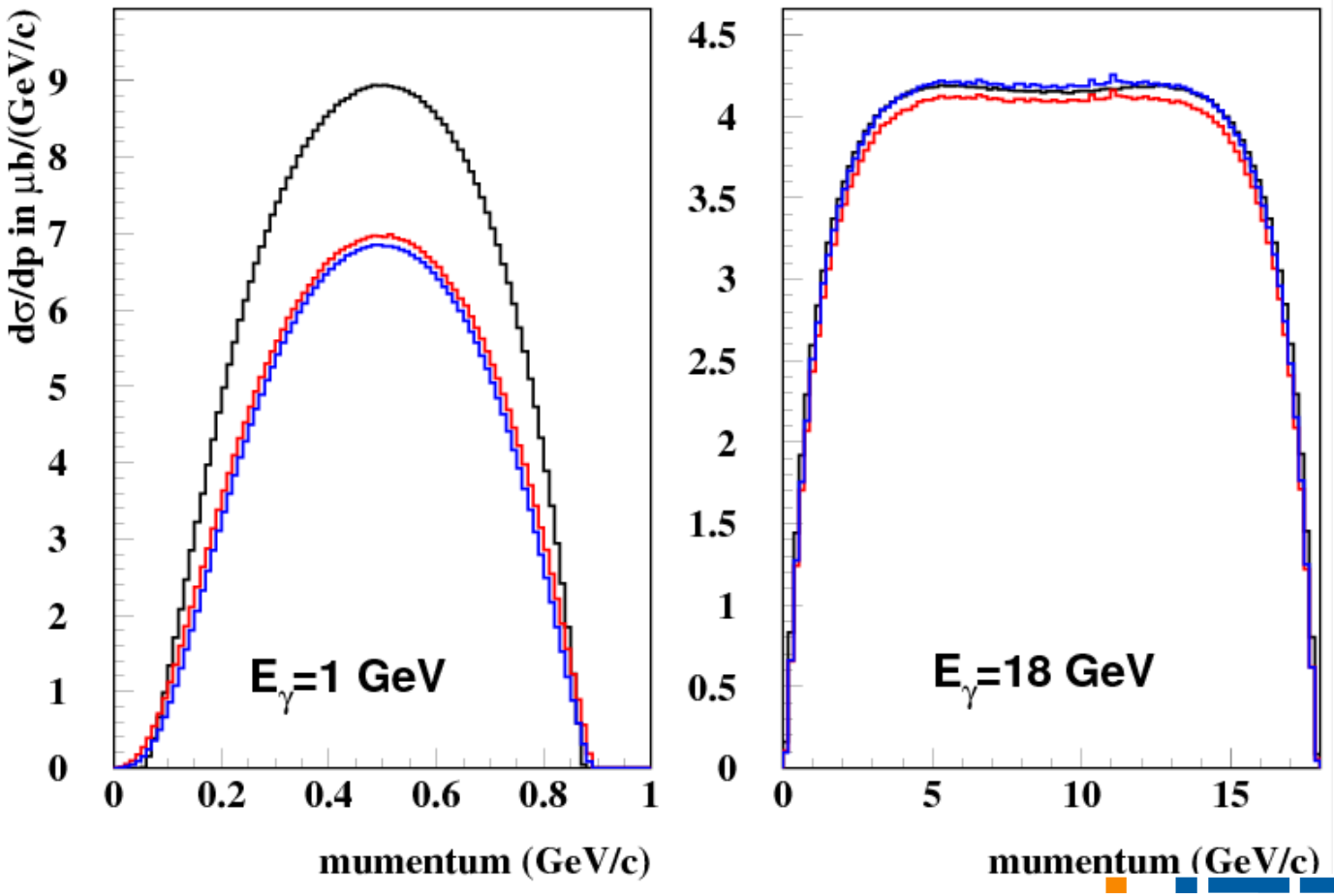
MARS15: Cross sections of muon production in γO and γCu

BKK-model, Tsai original FF, Tsai Fermi FF



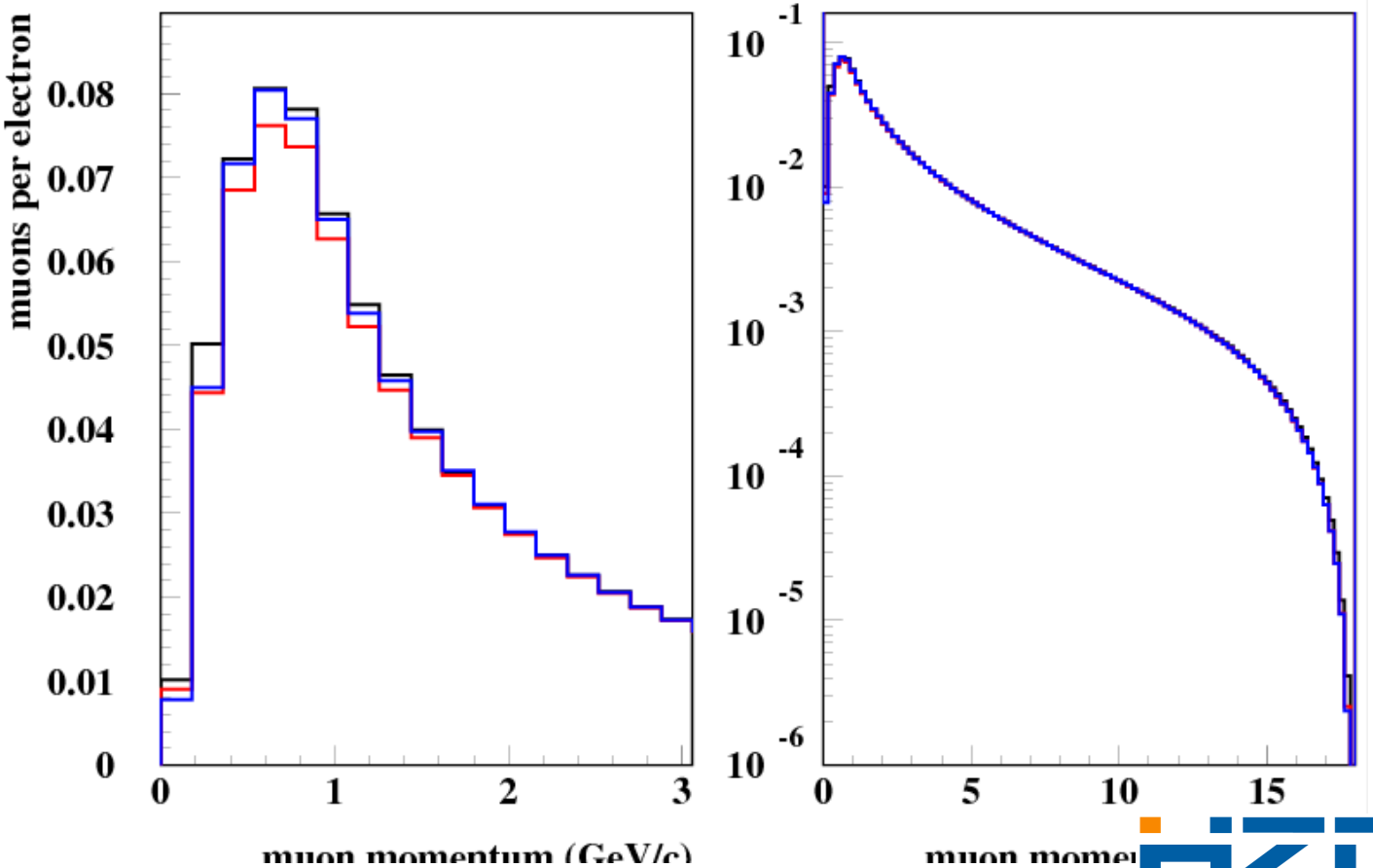
MARS15: Momentum distributions of muons produced in γCu

BKK-model, Tsai original FF, Tsai Fermi FF



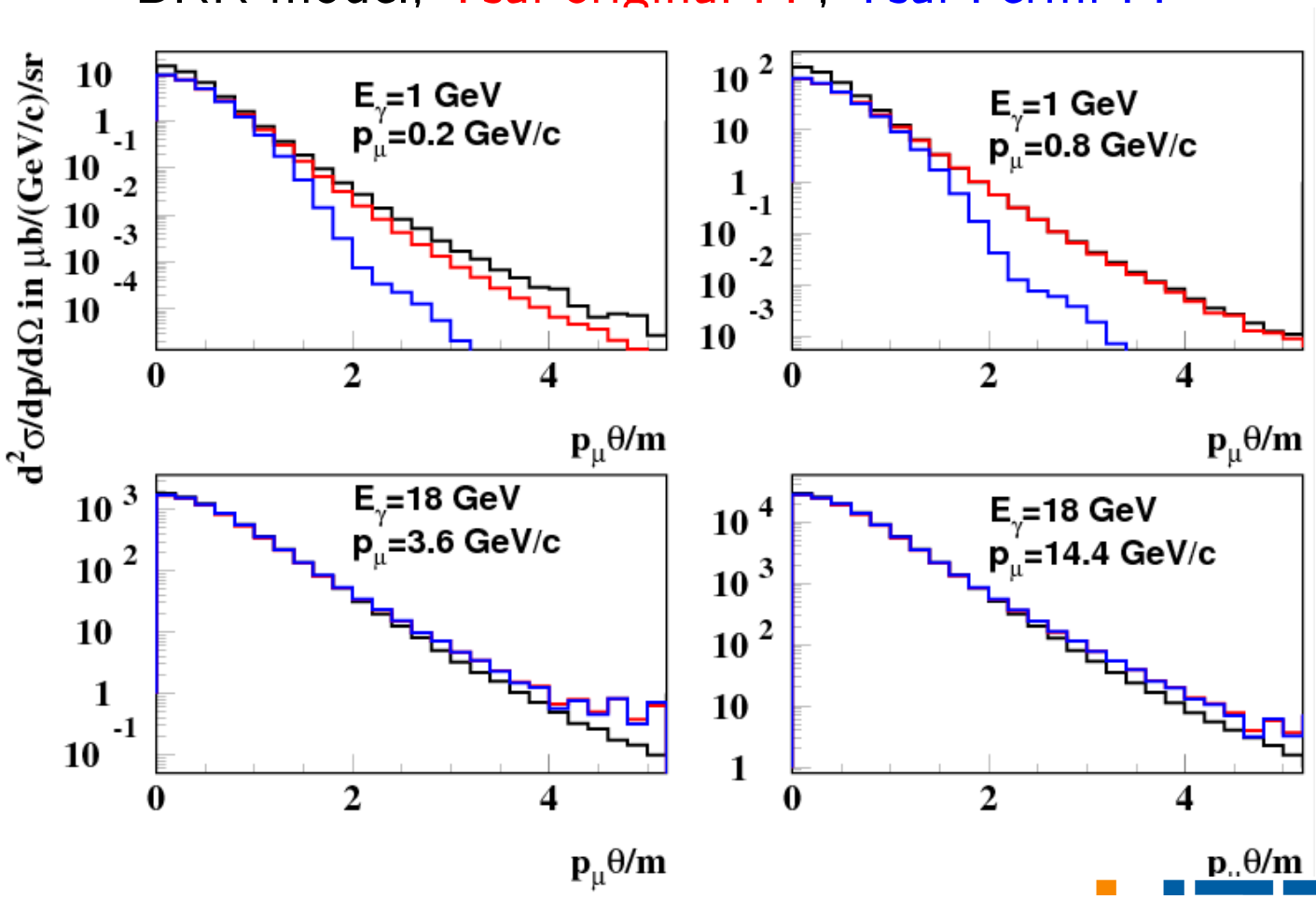
MARS15: Momentum distributions of muons produced by bremsstrahlung of 18 GeV electrons in copper

BKK-model, Tsai original FF, Tsai Fermi FF



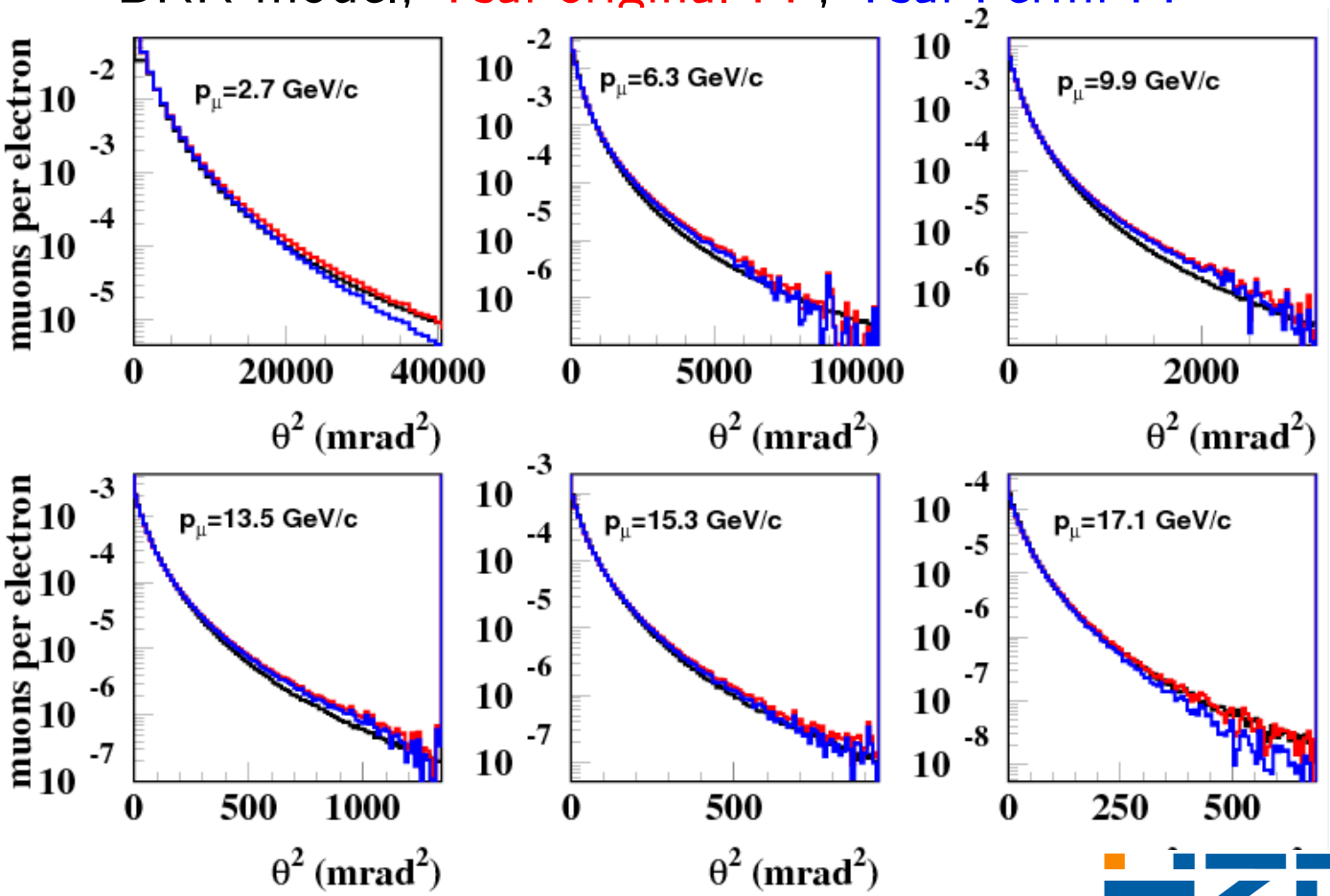
MARS15: Angular distributions of muons produced in γCu

BKK-model, Tsai original FF, Tsai Fermi FF



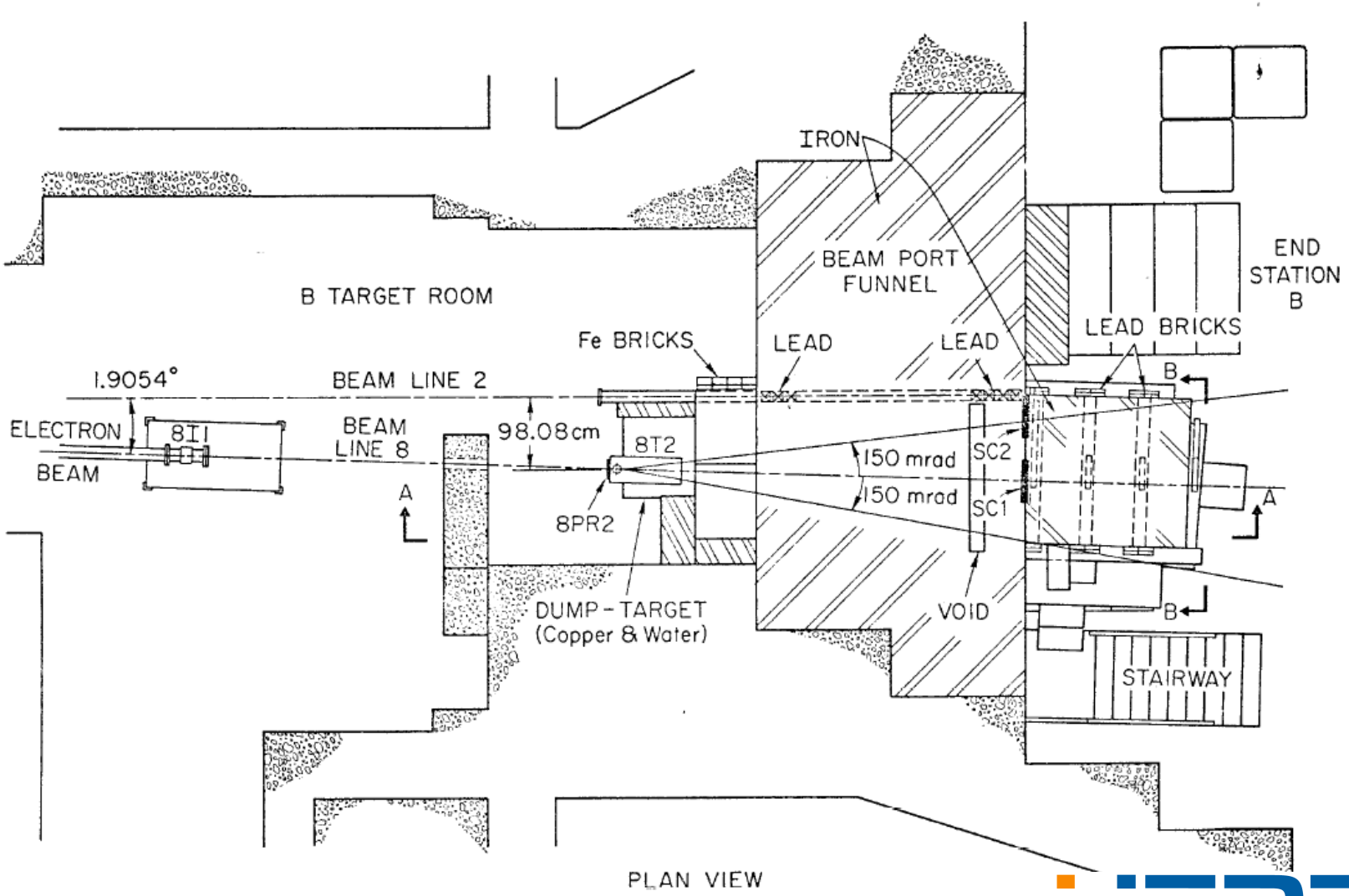
MARS15: Angular distributions of muons produced by bremsstrahlung of 18 GeV electrons in copper

BKK-model, Tsai original FF, Tsai Fermi FF

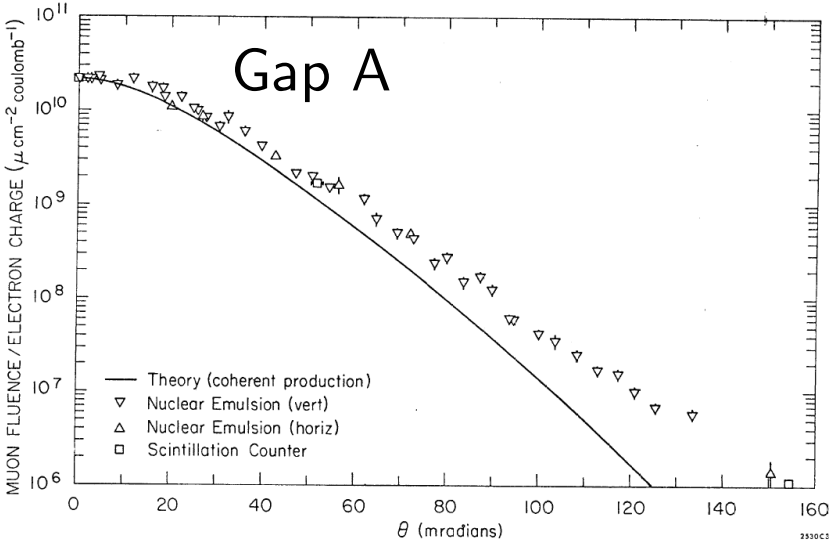


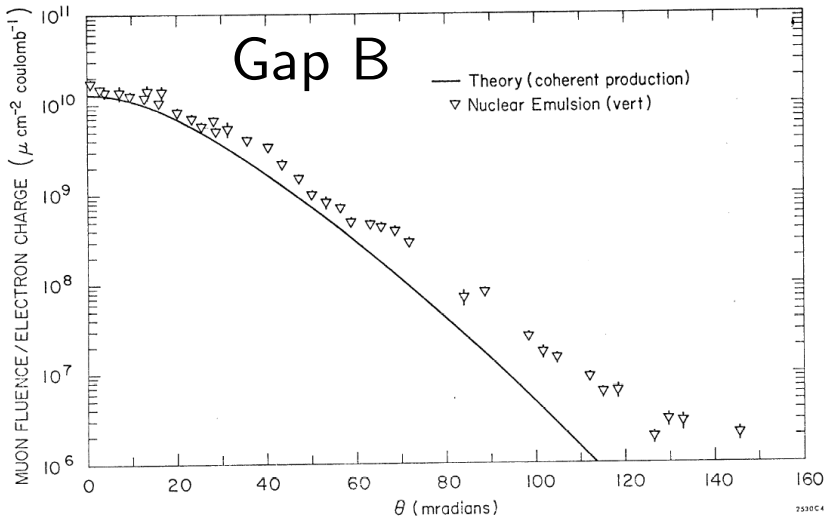
The experiment

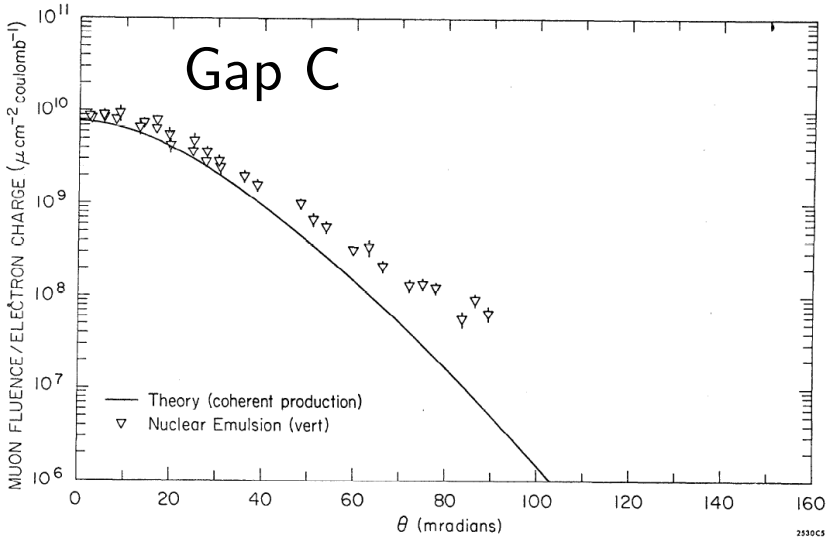
Horizontal view of the experimental setup:

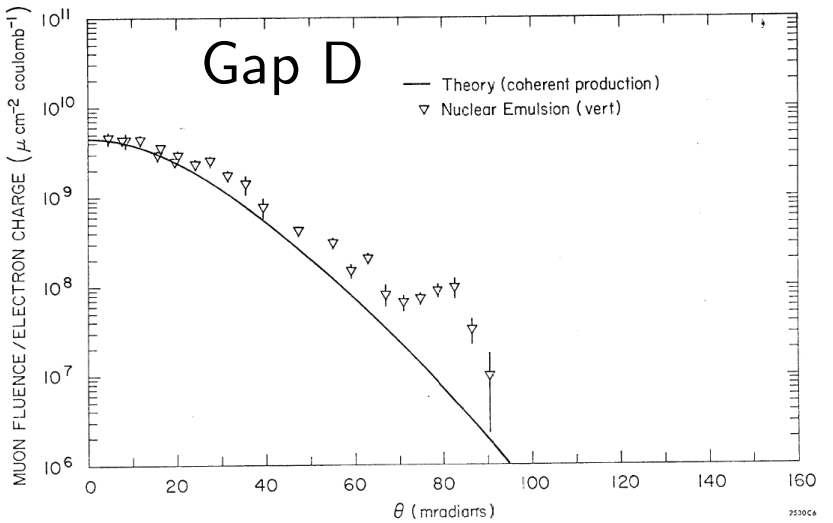


Experiment: Results on muon fluence









Experiment: Results on dose measurements