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MARS Mission:
Monte-Carlo Code and its Applications

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Outline

- Intro
- MARS Code System and Application Classes
- Generic Features and Geometry Description
- Nuclear Cross-sections and Event Generator
- Electromagnetic Interactions, Muons
- DPA, Hydrodynamic Tunneling
- Active Merge with MADX-PTC
- Applications: Fermilab, LHC, Muon Collider and Space
- Computing Aspects
- What's Next

Monte-Carlo Method in Particle Transport in Matter

Nowadays, the **Monte-Carlo method** is the principal, if not the only, method in particle transport applications. In its simplest and at the same time most dependable and common form – ***direct mathematical modeling*** – it involves numerical simulation of the interactions and propagation of particles in matter. All the physics processes are modelled as those take place in the real world, in realistic geometry and fields of accelerators and experimental setups.

The use of various modifications, the so--called ***variance reduction techniques***, makes it possible to greatly simplify the solution of the problem in certain cases, with a very high accuracy reached in a limited phase space volume.

Five Codes Widely Used Around the Globe

The use of **general-purpose particle interaction and transport Monte Carlo codes** is the most accurate and efficient choice for assessing impact and consequences of particle-matter interactions at accelerators. Due to the vast spread of such codes to all areas of particle physics, associated extensive benchmarking with experimental data and related code developments, **the modeling has reached an unprecedented accuracy**.

FLUKA, GEANT4, MARS15, MCNP6 and PHITS

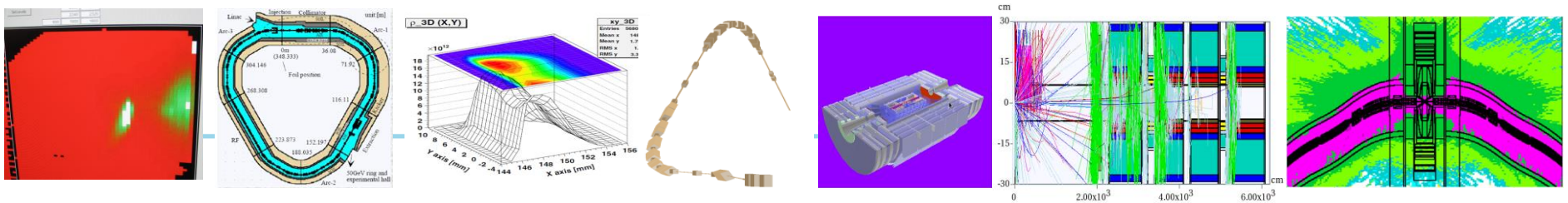
Most of these codes allow the user to simulate all aspects of a high energy particle cascade in one and the same run: from the first interaction of a primary beam (of up to multi-TeV energies) over the transport and re-interactions (hadronic and electromagnetic) of the produced secondaries, to detailed nuclear fragmentation, the calculation of radioactive decays, secondary electromagnetic showers, muon and neutrino generation and their interaction with surroundings.

MARS Code System

The MARS code system is a set of Monte Carlo programs for detailed simulation of hadronic and electromagnetic cascades in an arbitrary geometry of shielding, accelerator, detector and spacecraft components with energy ranging from 10^{-5} electronvolt up to 100 TeV. It was originated by NM in 1974 at MEPhI (Moscow), and developed since at IHEP (Protvino), SSCL (Texas) and Fermilab.

Current MARS15 combines well established theoretical models for strong, weak and electromagnetic interactions of hadrons, heavy ions and leptons with a system which can contain millions of objects, ranging in dimensions from microns to hundreds kilometers in same setup. **Especially powerful in accelerator lattice, beamline and machine-detector interface applications.**

300 official users worldwide, tutorials, https://mars.fnal.gov



Particle yields:
p, n, π, K, μ, Σ, HI

Nuclide inventory

Radiation damage:
DPA, dose, H/He,
soft errors (SEE)

Detector background suppression

Beamline optimization,
beam loss, particle capture
and collimation,
SC magnet quench

Prompt and residual radiation, shielding, impact on environment

Targetry: power dissipation, integrity (shock & buildup), magnetohydrodynamics

MARS Developers over 45 years

- **Current version MARS15(2019):**

N.V. Mokhov, Yu.I. Eidelman, V.S. Pronskikh, I.L. Rakhno, S.I. Striganov and I.S. Tropin

- **Earlier principal contributors:**

P. Aarnio, K.K. Gudima, M.A. Kostin, A.Yu. Konobeev, O.E. Krivosheev, S.G. Mashnik

Plus invaluable feedback from 300 registered/authorized MARS15 users worldwide

MARS15 Generic Features (1)

A setup can be made of up to 500 composite materials, with arbitrary 3-D magnetic and electric fields. Powerful user-friendly GUI is used for visualization of geometry, materials, fields, particle trajectories and results of calculations.

It has 6 geometry options including ROOT and MCNP ones, flexible histograming, can use as an input MAD optics files through a powerful MAD-MARS Beam Line Builder, various tagging, biasing and other variance reduction techniques.

Bilateral geometry model exchange (via GDML files) with Geant4).

It is interfaced with MADX-PTC, EGS5 and DPMJET, can be interfaced with ANSYS (thermal and stress), MESA/SPHINX (hydrodynamics), and FRONTIER (magneto-hydrodynamics).

MARS15 Generic Features (2)

- Customized steppers (with 8th order Runge Kutta solver) for optimal particle tracking in SRF (with time-dependent electromagnetic fields and Dark Current production), quadrupole/dipole magnets and thick shielding
- Variance reduction techniques: multi-stage, splitting/Russian roulette, biasing, weight windows
- Verified set of flux-to-dose (FTD) conversion factors to calculate - in the course of Monte-Carlo - effective prompt dose distributions: ICRP103 + ICRP60+Cossairt(2009)+Pellicioni(2000) + MARS generated for neutrinos
- Nuclide production, decay, transmutation and calculation of the activity distribution is done with the built-in DeTra code
- MARS15 uses ENDF/B-VIII.0(2018) nuclear data to derive the NRT/Stoller/Nordlund DPA x-sections for neutrons from 10^{-11} to 200 MeV

Material Description & Low-Energy Neutrons

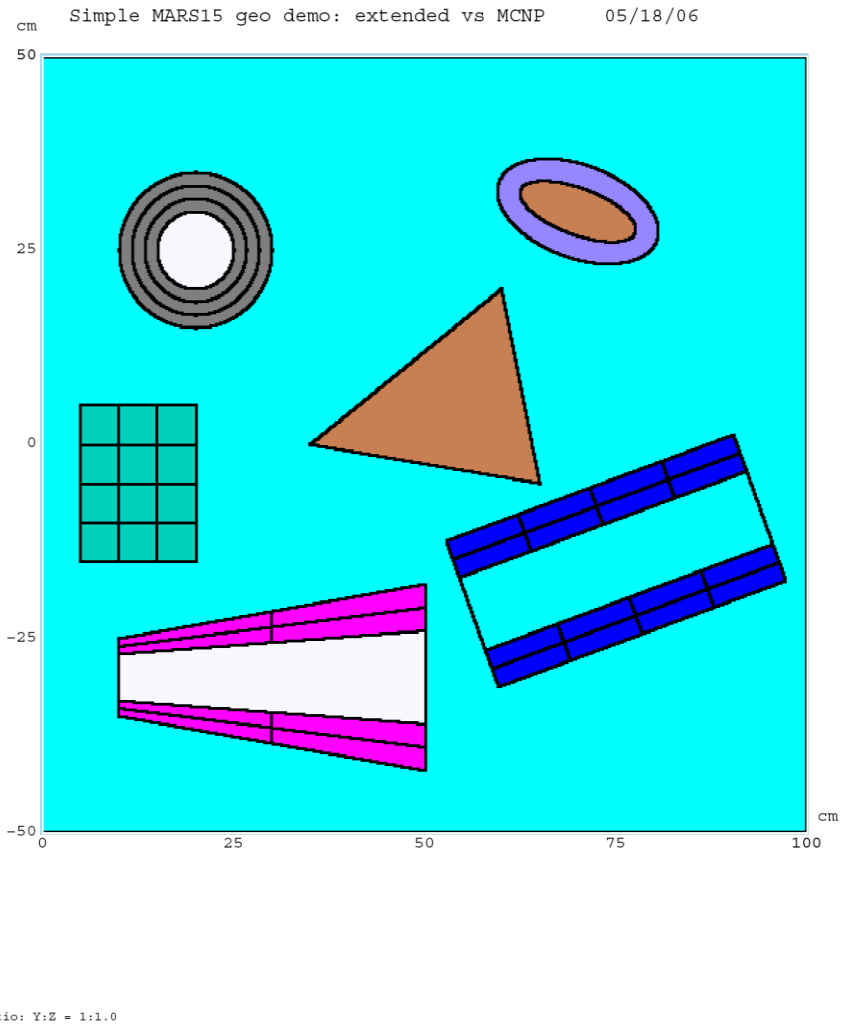
- The code automatically unpacks the elemental distributions into isotope distributions for both user-defined and those from the 172 built-in material definitions for use in the 10^{-11} MeV < E < 100 TeV energy range
- For neutron interactions at $10^{-11} < E_n < 14$ MeV, MARS15(2019) relies on the heavily validated and recently released library of ACE files based on ENDF/B-VIII.0(2018)
- There is no need anymore to add material description in the MCNP format after the STOP card in MARS.INP files: the code does automatically all the required interface work for every single isotope found in the given run
- Accurate treatment of material state (solid, liquid and gaseous); He^3 treatment

Geometry Description and ROOT-based Beamline Builder

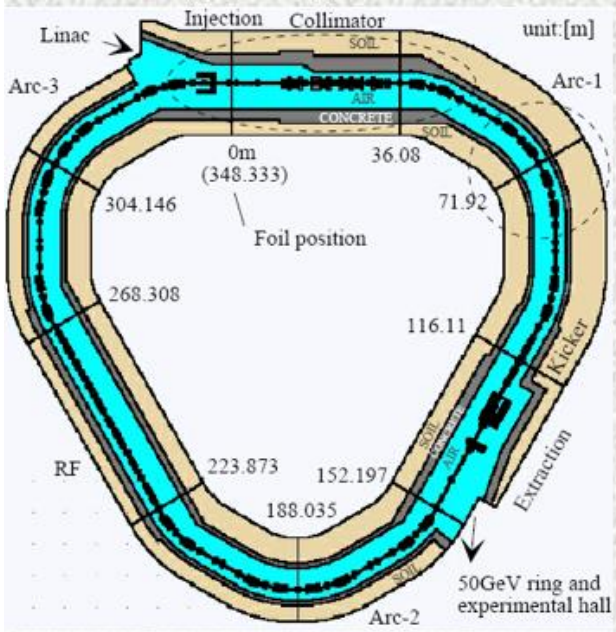
1. User-generated via MARS extended geometry input files
2. User-generated ROOT files: Quantum Leap!
3. GDML files (bilateral exchange with Geant4 teams)
4. G4beamline's BruitDeFond can generate MARS's input files MARS.INP, GEOM.INP and FIELD.INP
5. STEP files from project CAD models used to generate semi-automatically ROOT geometry modules
6. Lattice and beamline components such as dipole and quadrupole magnets, correctors, accelerating cavities, cryomodules and tunnel with all the details available on geometry, materials and electromagnetic fields by means of the advanced ROOT-based Beamline Builder

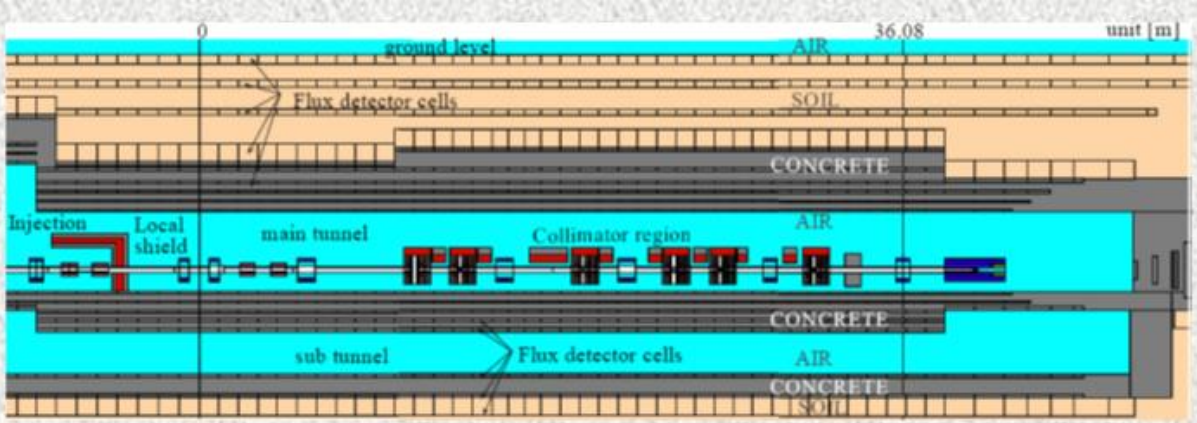
MARS15 Simple GEOM.INP Example

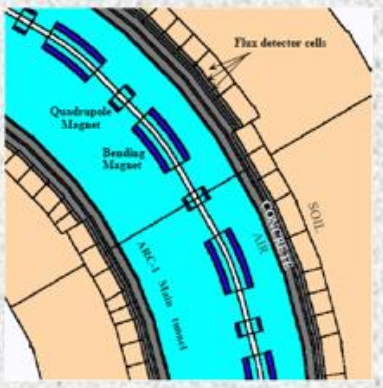
```
Extended Demo  05/17/06
OPT
box-1       1 0 2   0.  -5.   5.  10.  10. 15. 1 4 3
cyl-1a     -2 1 7   0.   0.   0.   0.   5. 20.
cyl-1a     -2 1 1   0.   0.   0.   5.  10. 20. 4 2
ball-a      3 0 8   0.   25. 20.   0.   5.
ball-b      3 0 3   0.   25. 20.   5.  10. 3
cone-in    -4 0 0   0. -30.  30.   0.   3.  0.  6. 20.
cone-out -4 0 4   0. -30.  30.   3.   5.  6. 12. 20. 2 2
th          5 0 6   0. 0. 35. 5. 3. 55. 0. 20. 60. 0. -5. 65.
ell-tub1  -6 2 6   0.   0.   0.   8.   3.  0.  40.
ell-tub2  -6 2 5   0.   0.   0.   8.   3.  3.  40.
TR1  0.  -15. 75. -20.
TR2  0.   30. 70.  20. 90.
stop
```

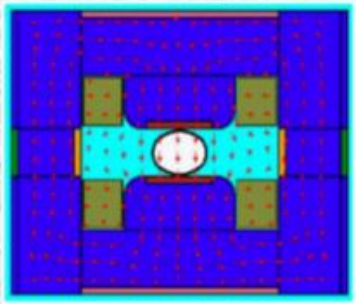


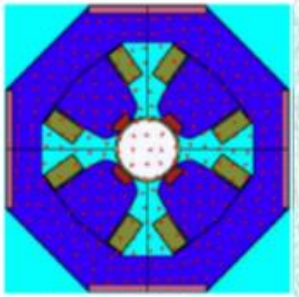
MMBLB Model: J-PARC 3-GeV Ring

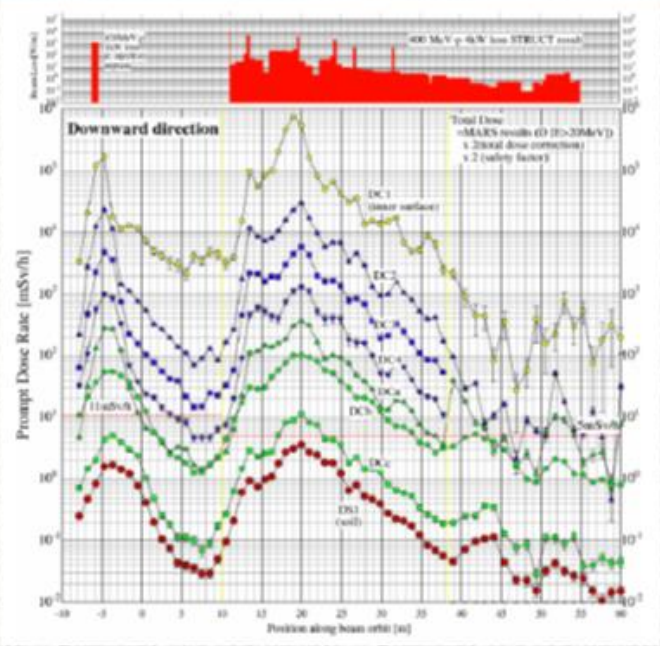




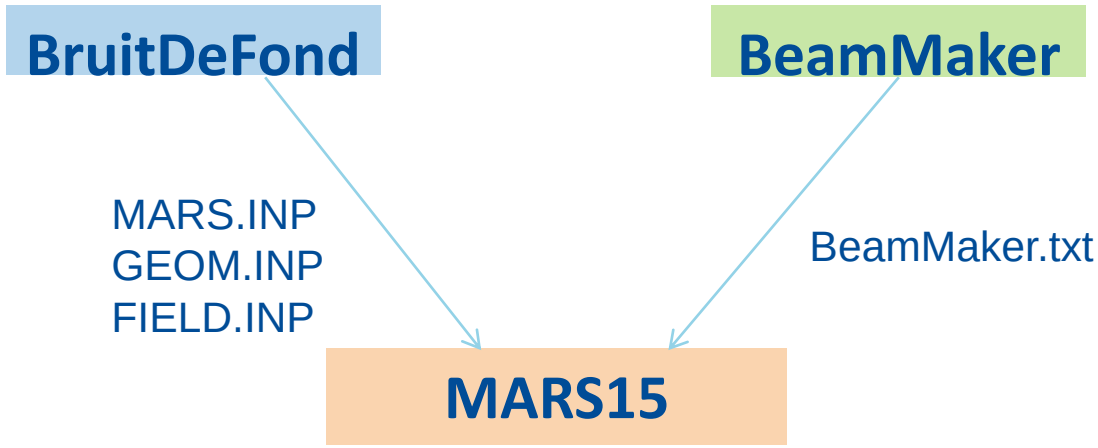




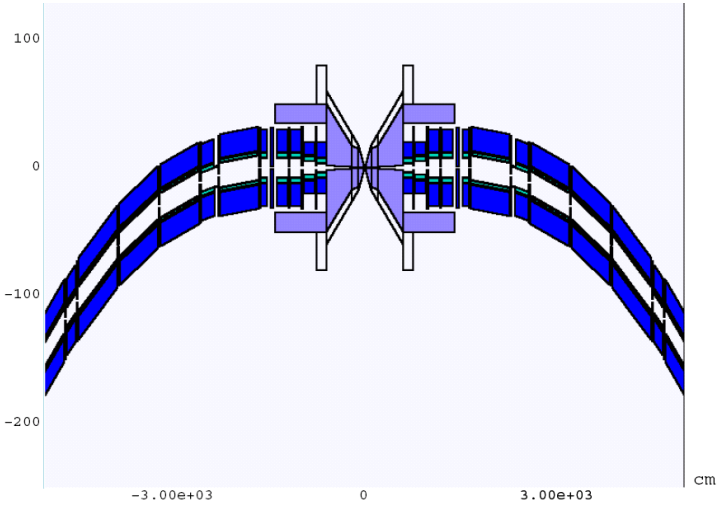




G4beamline's BruitDeFond Can Generate MARS's Input Files

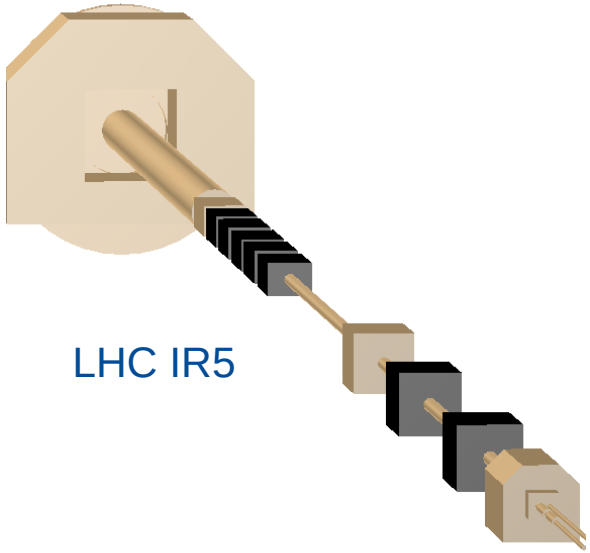


Tom Roberts



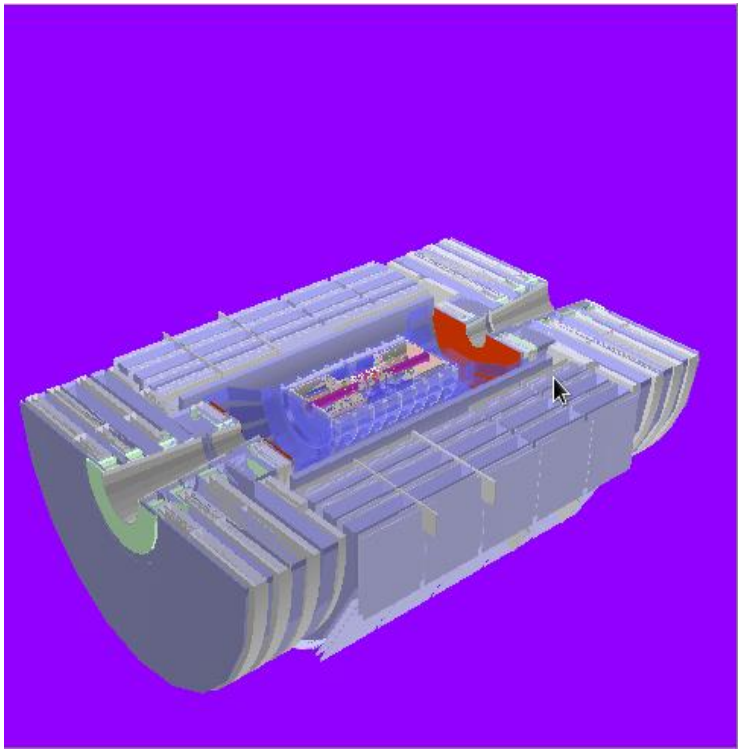
- *BruitDeFond* can generate MARS.INP and GEOM.INP files.
- The *extended* geometry is description is used.
- The field is described by the FIELD.INP file which is read by the MARS user subroutine "field" that we wrote.
- We use the same BeamMaker.txt file for the MARS input.

MARS15 ROOT-based Models



LHC IR5

Fermilab Booster by ROOT-based BeamlineBuilder



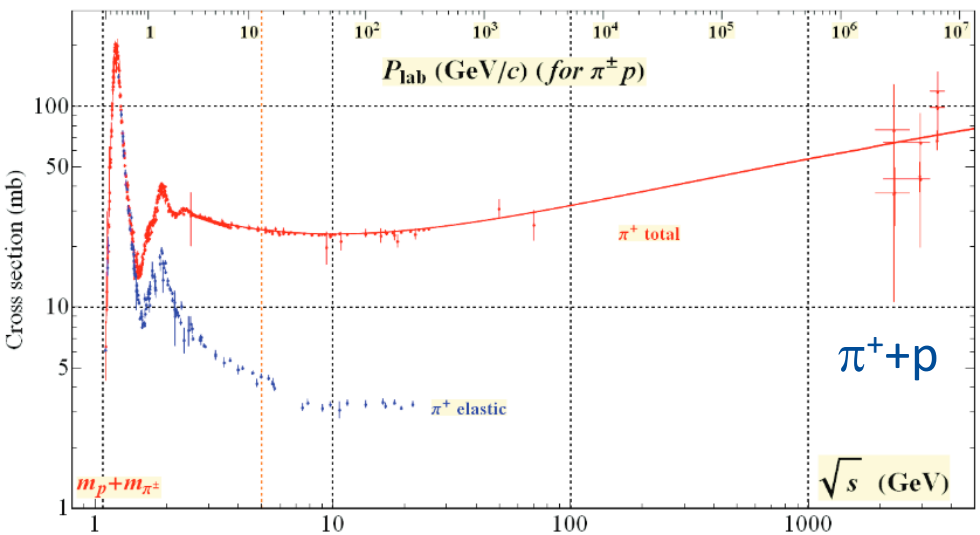
LHC CMS detector

MARS Nuclear Interaction Cross-Sections

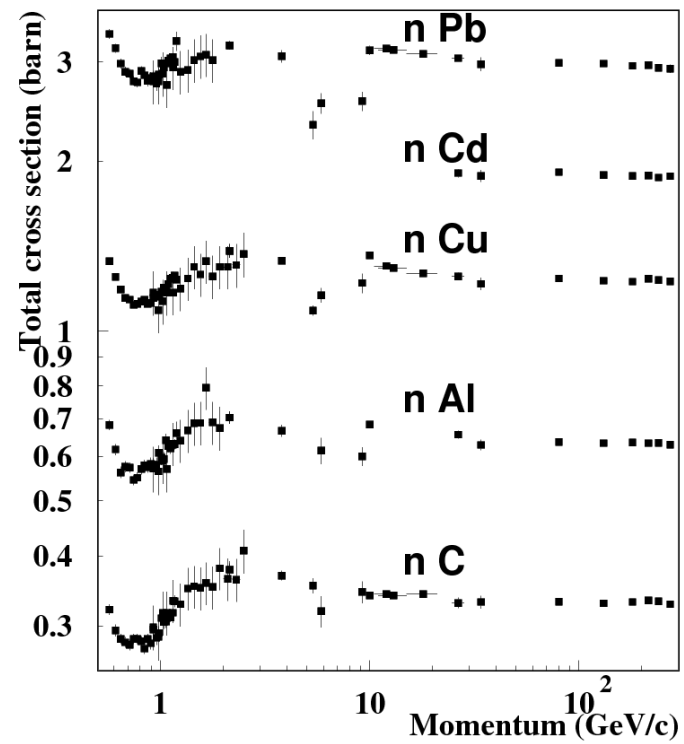
The **first most important quantity** to simulate particle transport by Monte-Carlo method

$$\Sigma(i,A,E) = \frac{\sigma(i,A,E) N_A 10^{-27} \rho}{A}, \text{ cm}^{-1}$$

where σ is a microscopic x-section (mb) for a given interaction type of a particle of *i*-type with a chosen absorber nucleus with atomic mass A; N_A is Avogadro number (=6.022× 10^{23} mol^{-1}), ρ is density (g/cm^3)

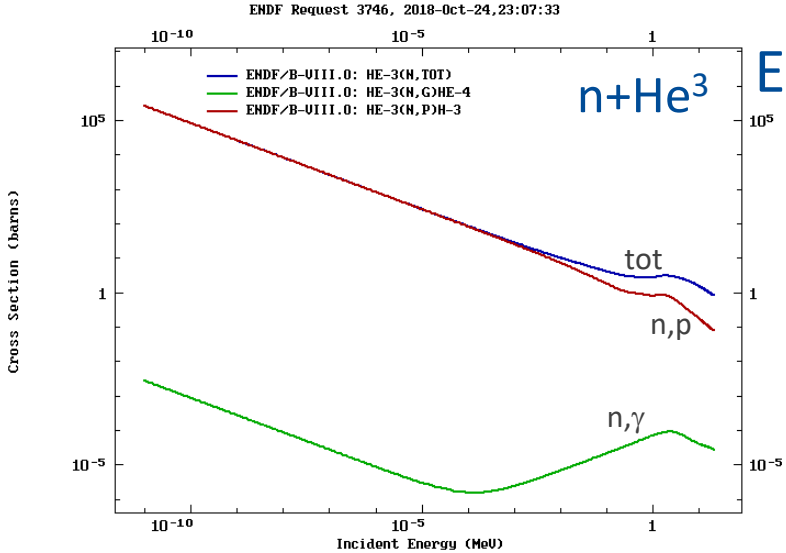


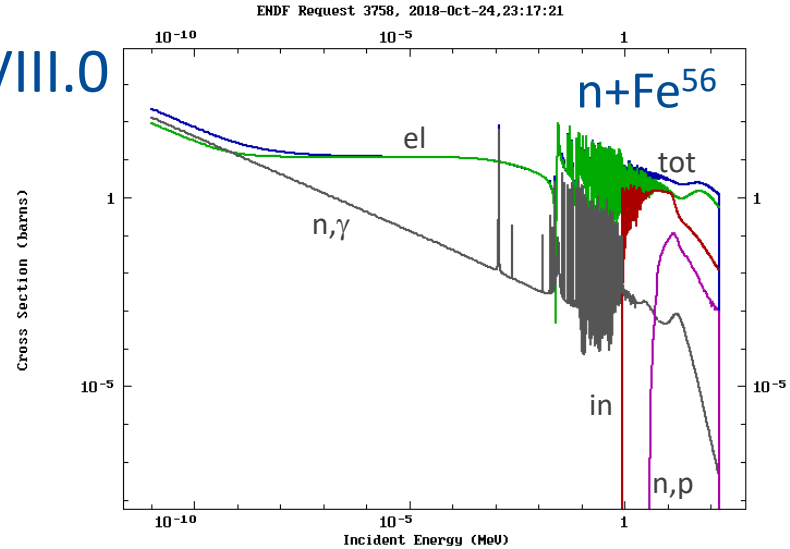
$$s = m_1^2 + m_2^2 + 2E_{1lab}m_2$$

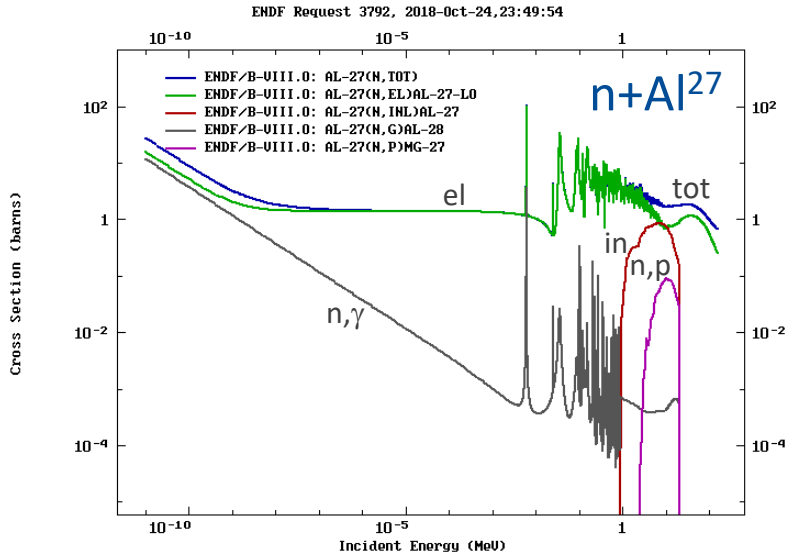


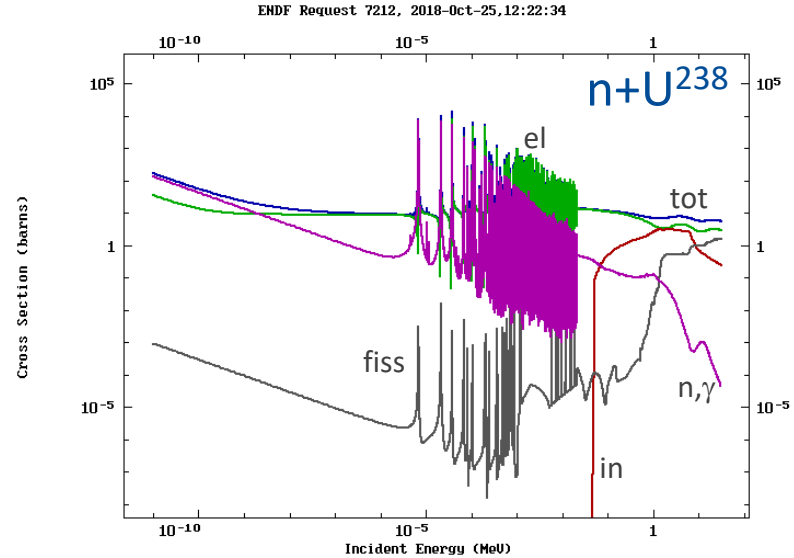
Low-Energy Neutron-Nucleus Cross-Sections

ENDF/B-VIII.0









Double-Differential X-Section or Particle Production Models

The **second most important quantity** to simulate particle transport by Monte-Carlo method is a double-differential cross-section:

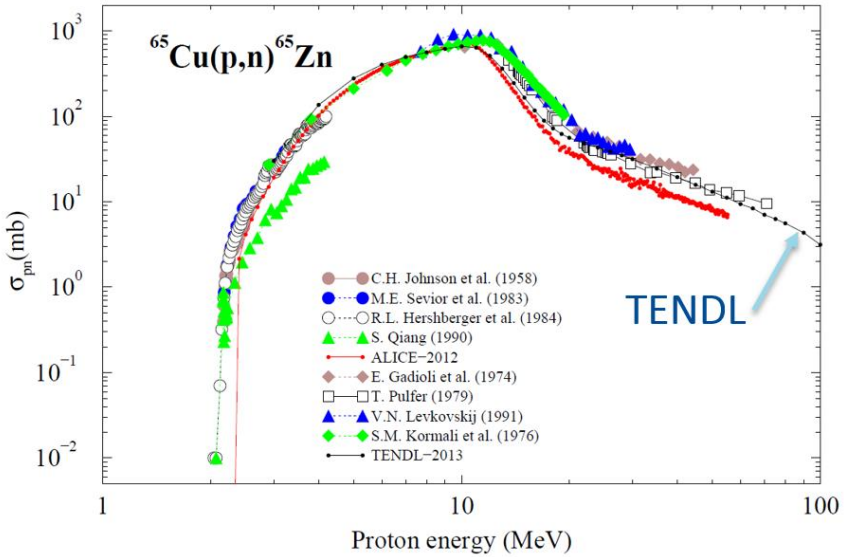
$$\Sigma(\vec{r}, \Omega' \rightarrow \Omega, E' \rightarrow E) = \frac{d^2\sigma(i,j,A,E',E,\Omega',\Omega)}{dEd\Omega} \times \frac{N_A 10^{-27}\,\rho}{A}$$

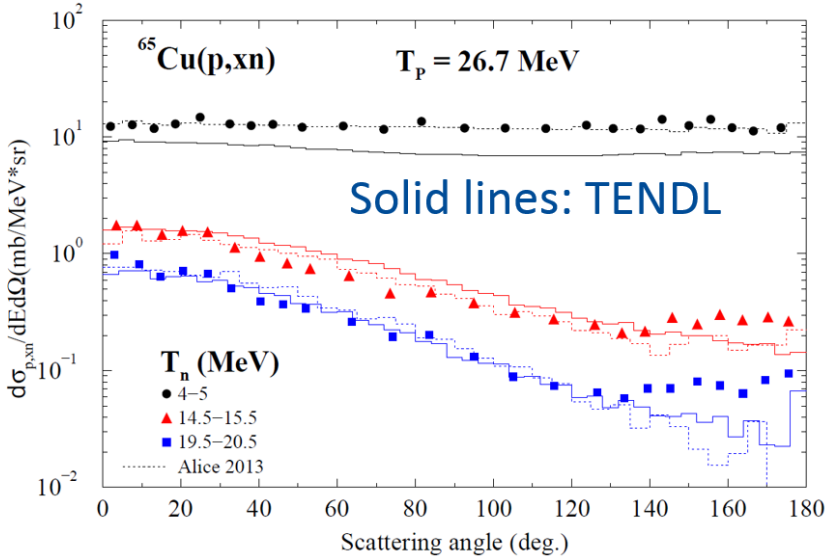
It can be taken from pre-calculated databases (e.g., ENDF for low-energy neutrons with their x-section resonant structure), or some theoretical forms

At high-energies, a standard approach is to use ***event generators***, performing Monte-Carlo simulation through all the stages of particle interactions inside a nucleus like a quark-gluon cascade, hadron intranuclear cascade, preequilibrium stage, evaporation/fragmentation and gamma-deexcitation. This is realized in DPMJET (Dual Parton Model), FRITIOF (string model), LAQGSM (quark-gluon string model), QMD (Quantum Molecular Dynamics model) and other theoretical models and codes.

MARS15 Nuclear Event Generator Set

- Projectile E_0 < 0.12 GeV down to 1 MeV (charged particles) and 14 MeV (neutrons): a combination of extended TENDL-2016 (inclusive, semi-inclusive or exclusive mode – user's choice) and LAQGSM
- 0.12 < E_0 < 0.5 GeV: a combination of CEM-2018 and LAQGSM-2018
- 0.5 < E_0 < 10 GeV: LAQGSM or inclusive (at E_0 > 3 GeV) -> user's choice
- 10 GeV < E_0 < 100 TeV: LAQGSM or inclusive -> user's choice





MARS15: Exclusive, Inclusive and Hybrid

Most of the processes in MARS15, such as electromagnetic showers, hadron-nucleus interactions, decays of unstable particles, emission of synchrotron photons, photo-hadron production and muon pair production, can be treated exclusively (analogously), inclusively (with corresponding statistical weights), or in a mixed mode.

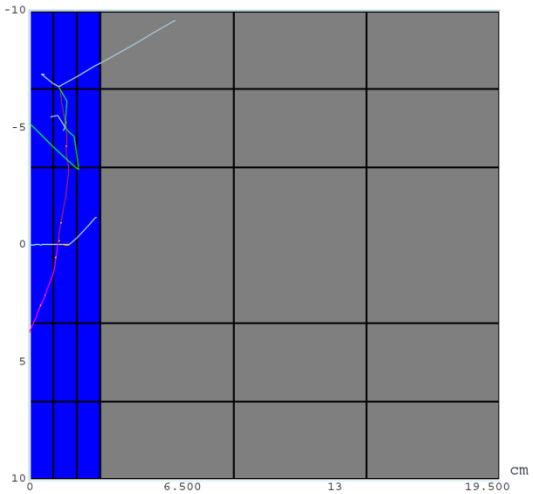
The choice of the mode is left for the user to decide, via the input settings.

<u>Goal:</u> Maximize computing efficiency $\varepsilon = t_0/t$, where t is CPU time needed to get a RMS error σ equal to the one in the reference method with CPU time t_0 provided $\sigma < 20\%$.

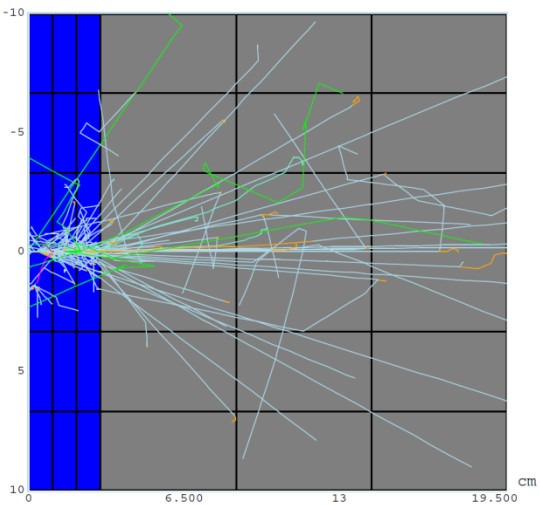
Inclusive, Exclusive and Hybrid EMS Simulations

One 10-GeV e^+ on 3cm W + 17cm concrete

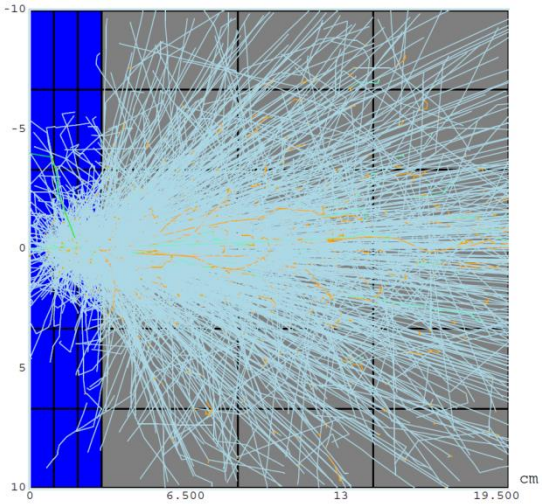
Inclusive



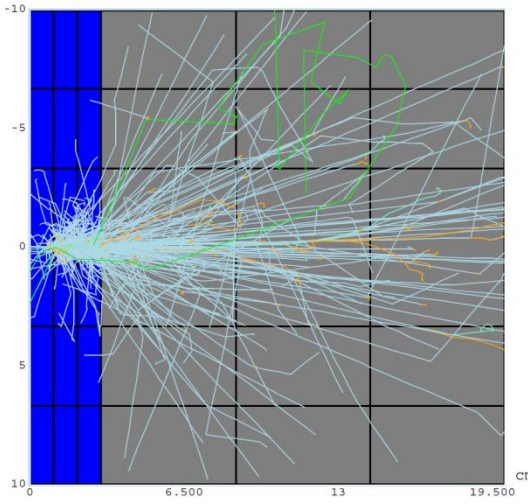
Hybrid-10



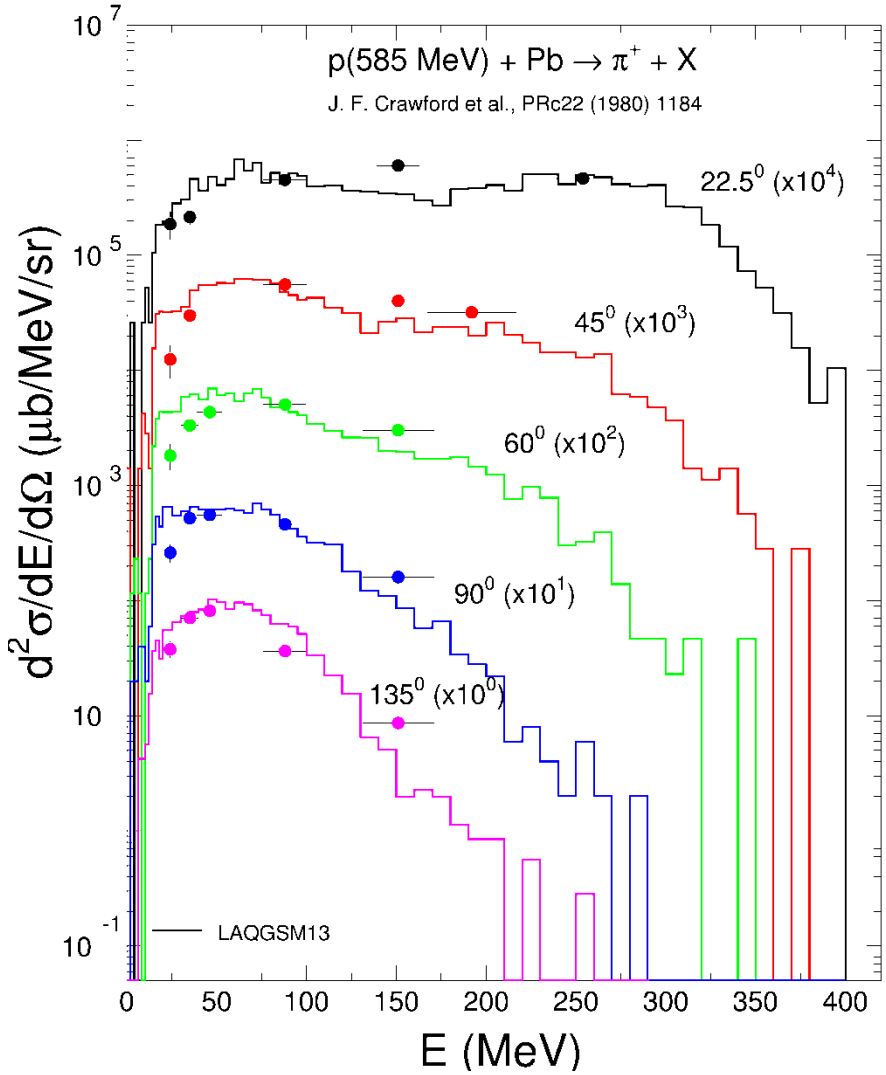
Exclusive

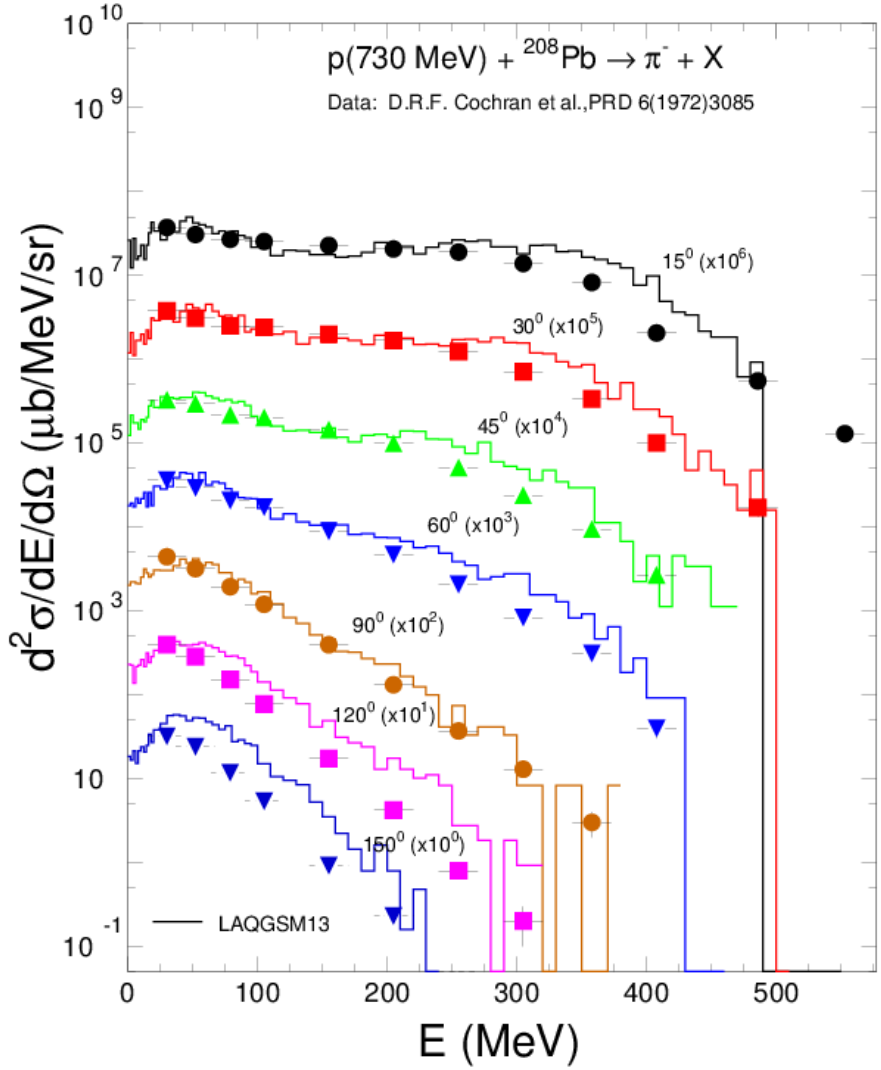


Hybrid-20

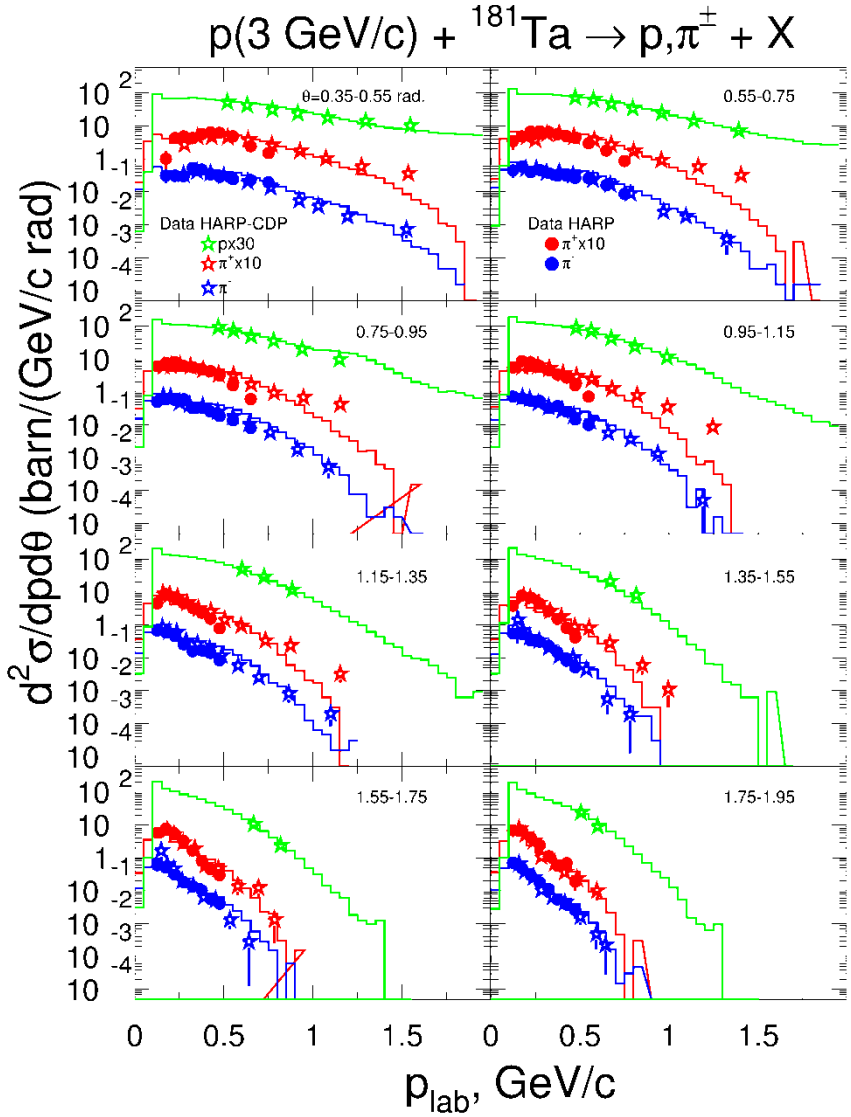


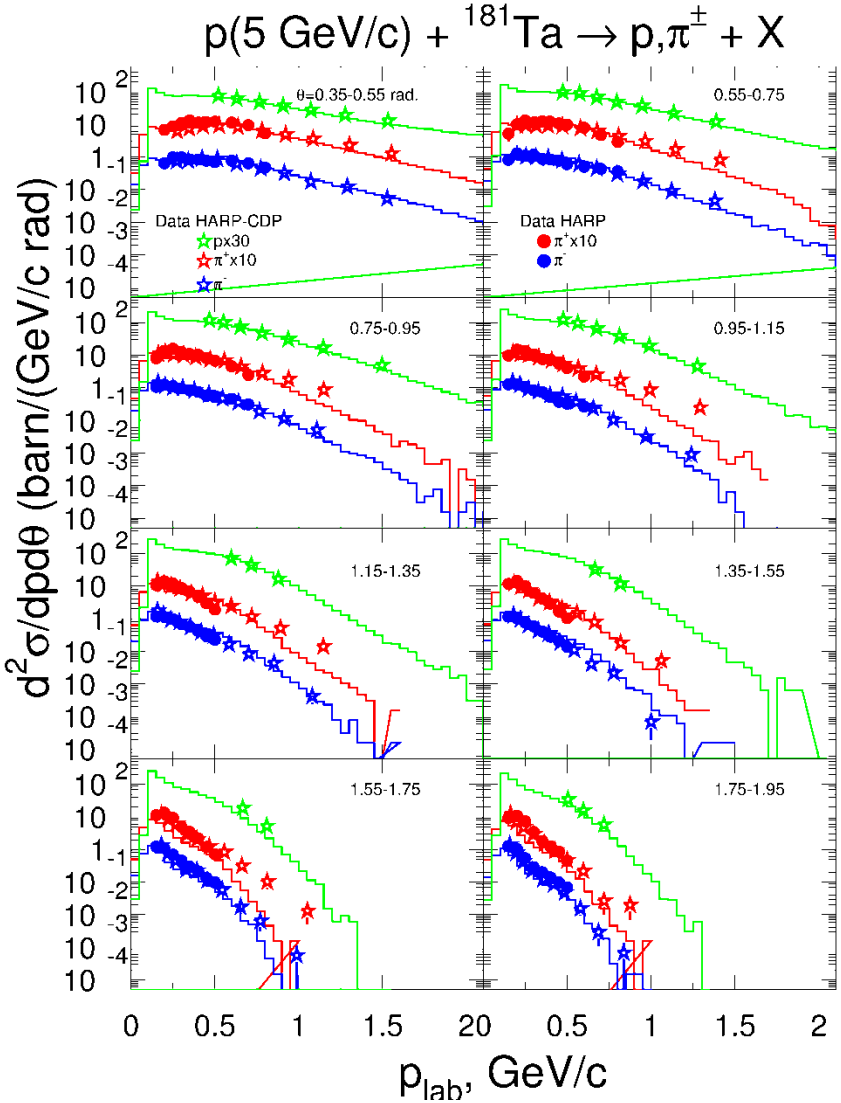
MARS-LAQGSM Performance at 585 and 730 MeV



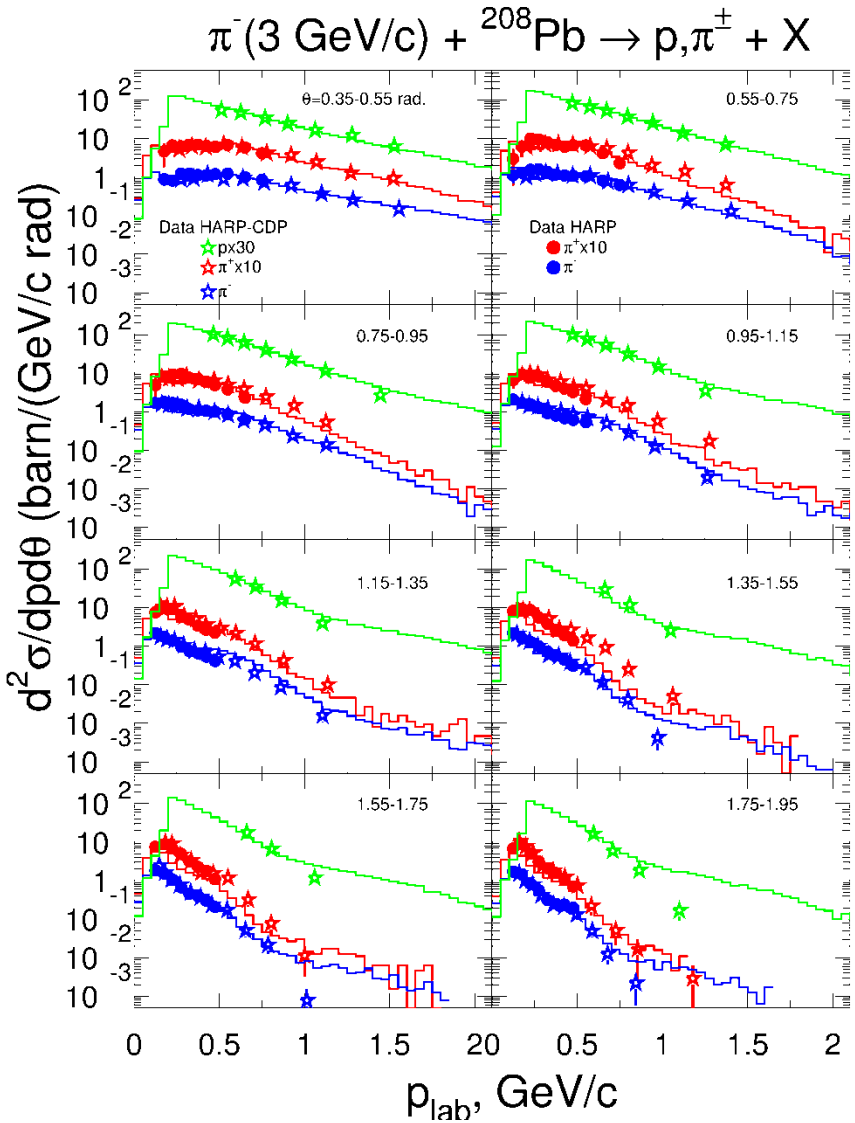


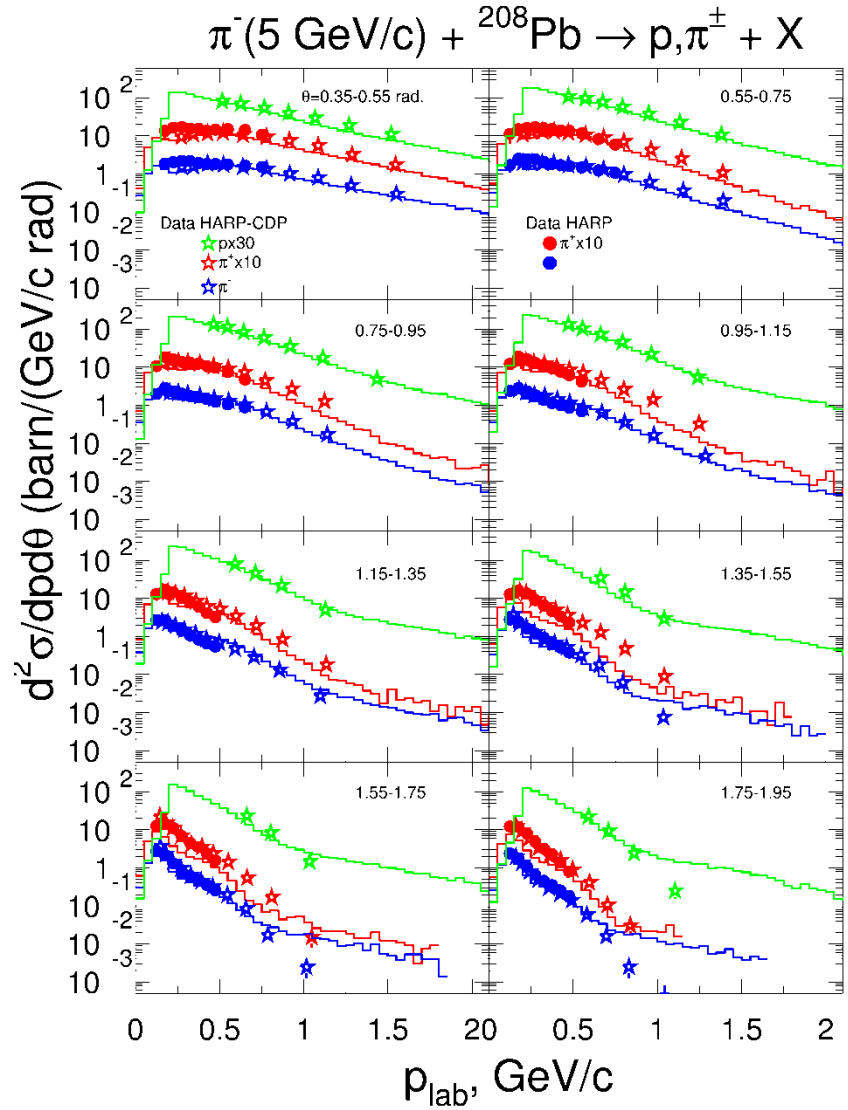
MARS-LAQGSM *vs* HARP Data: p+Ta ⟶ p, $\pi^{\pm}$ + X at 3 and 5 GeV/c



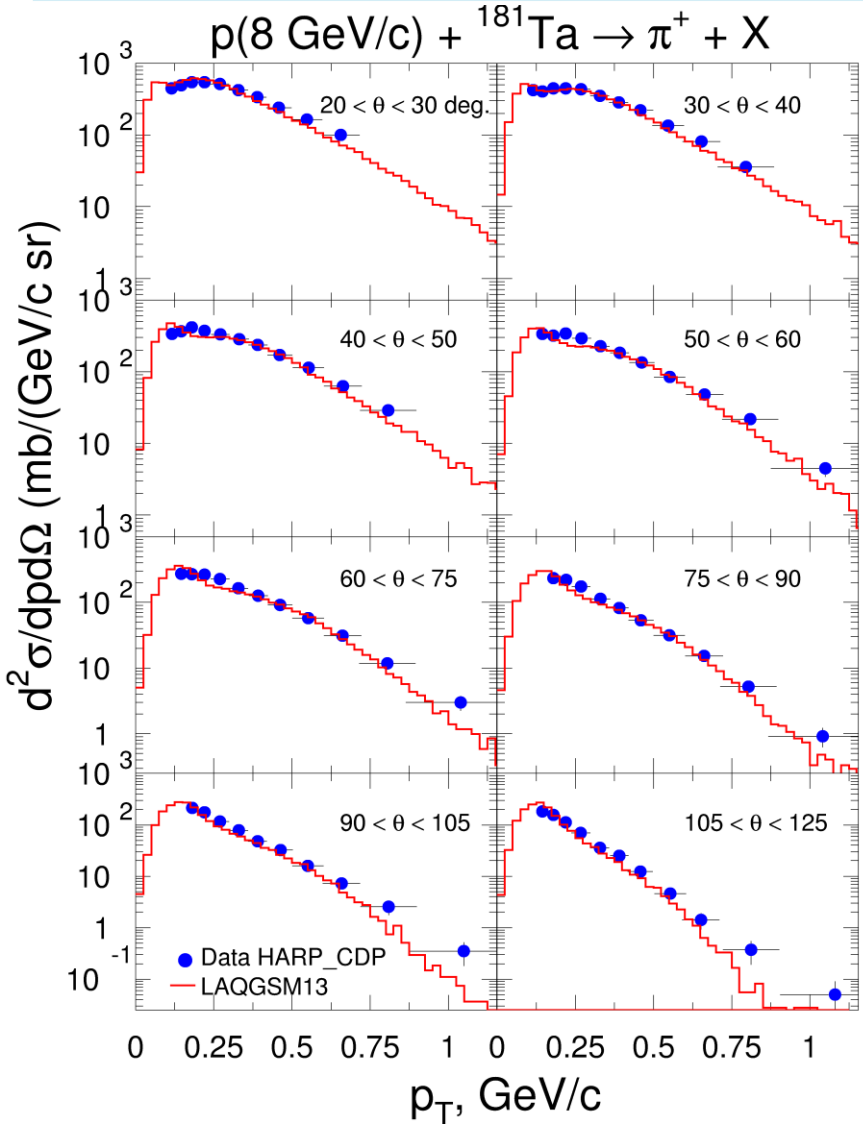


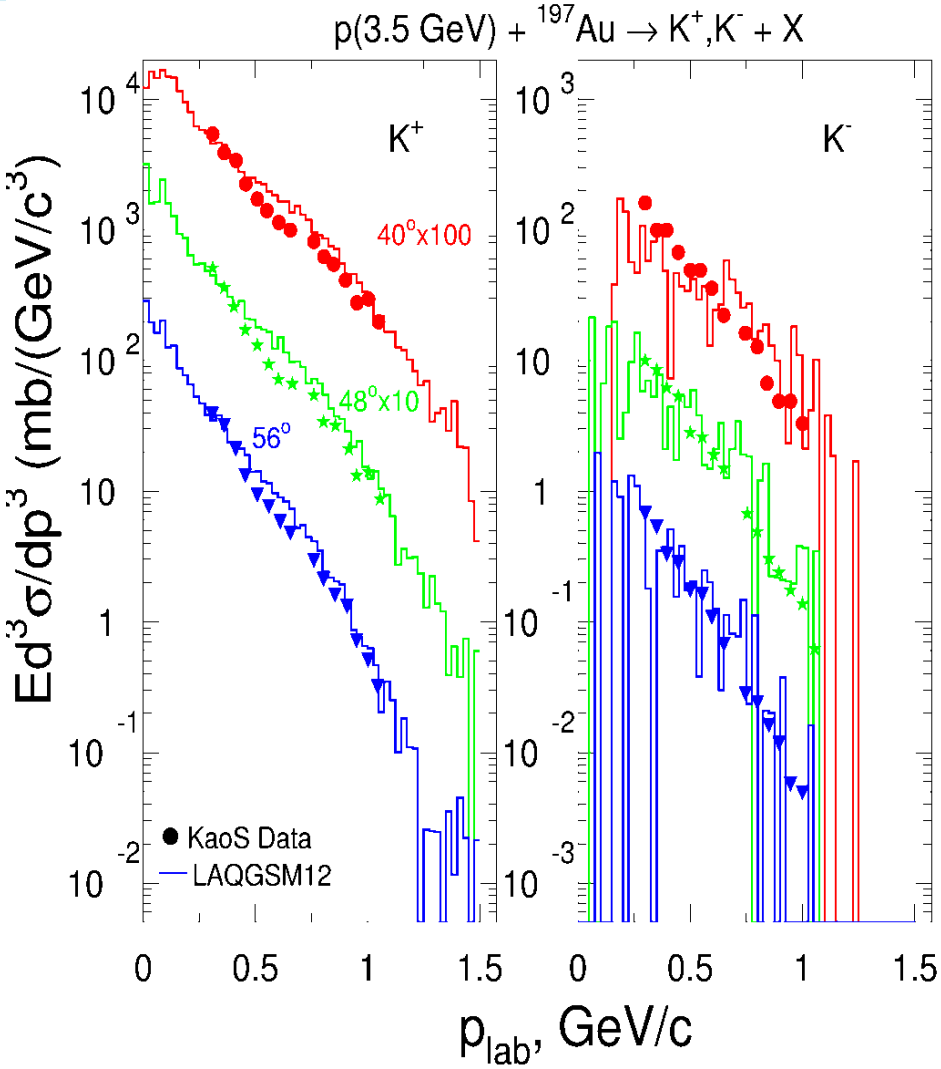
MARS-LAQGSM *vs* HARP Data: π^- +Pb ⟶ p, $\pi^\pm$ + X at 3 and 5 GeV/c



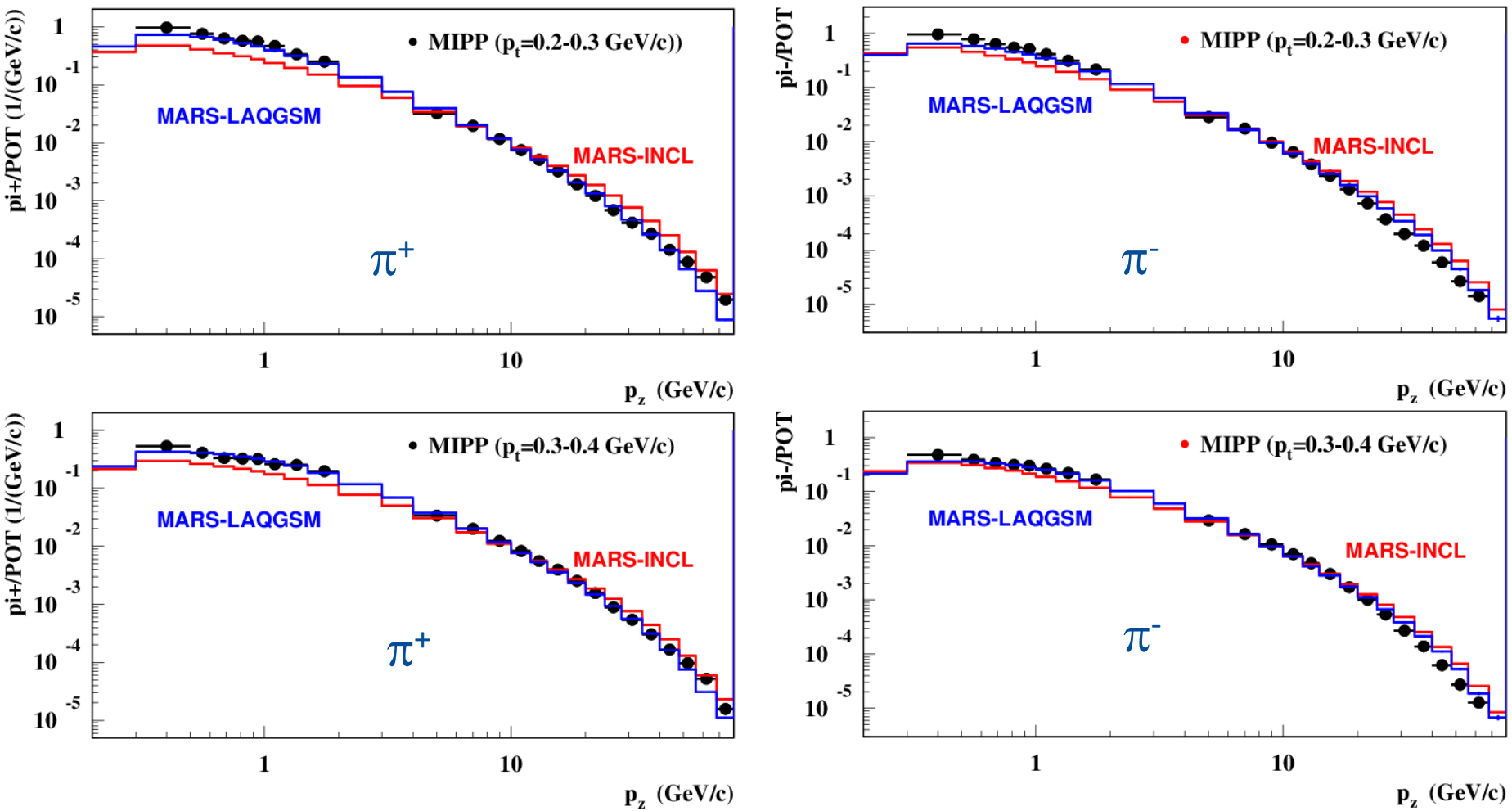


MARS-LAQGSM *vs* HARP-CDP at 8 GeV/c and KaoS at 3.5GeV

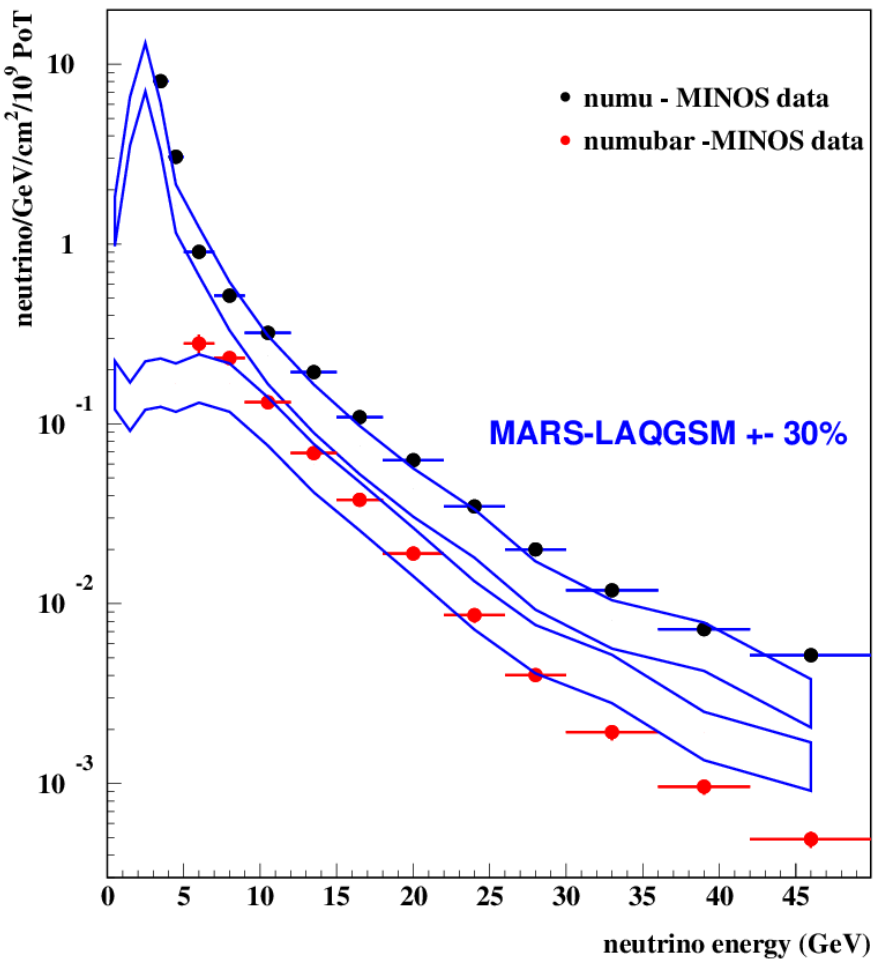


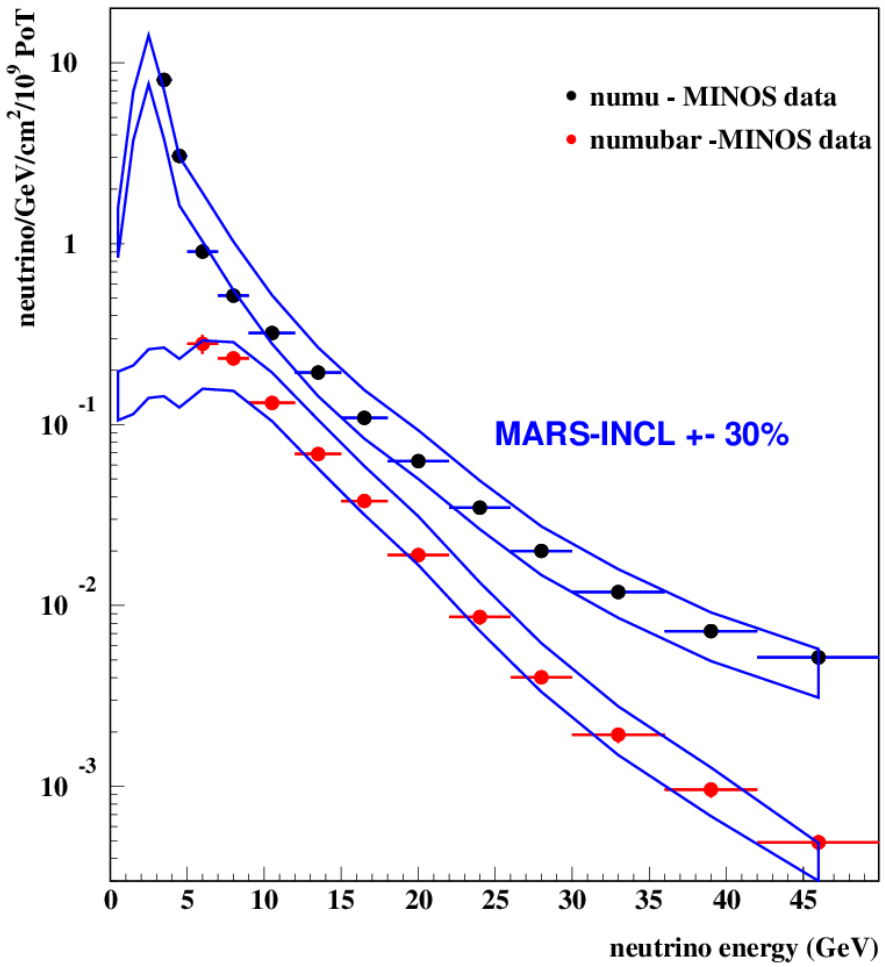


MARS Pion Spectra *vs* MIPP Data at 120 GeV

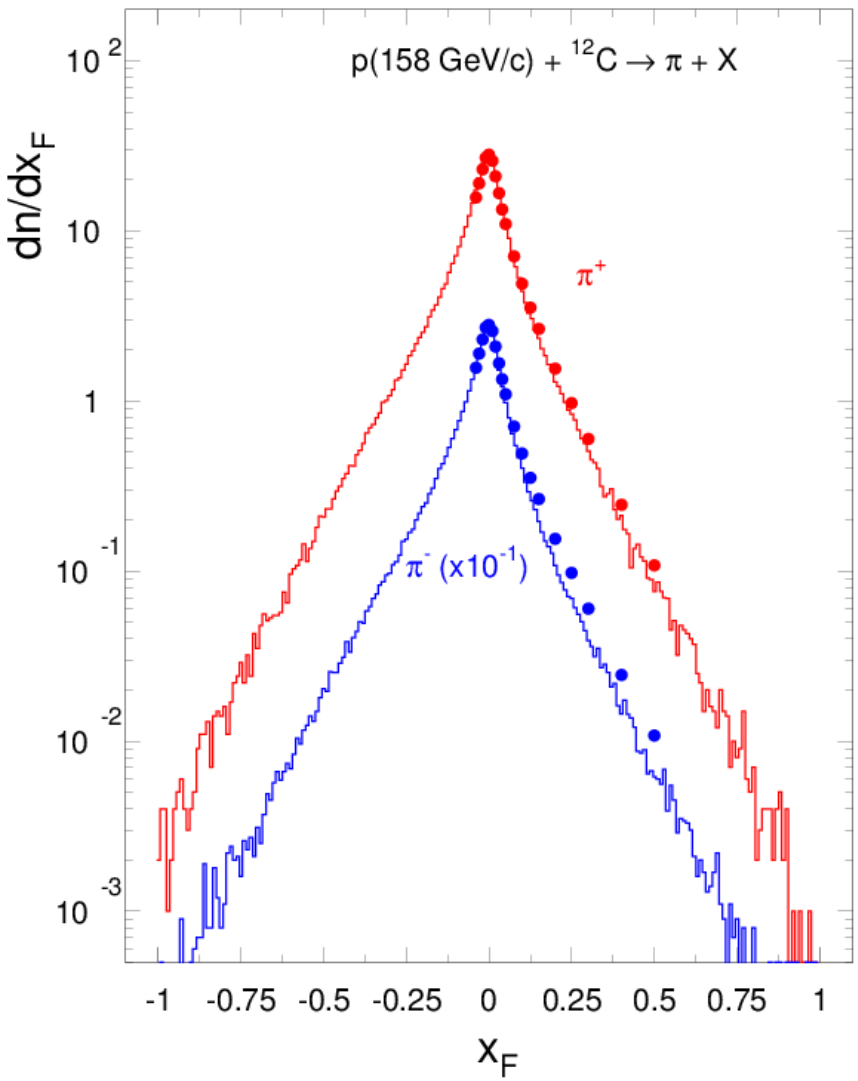


MARS *vs* MINOS-Measured Neutrino Spectra at ND





MARS-LAQGSM *vs* NA49 Data



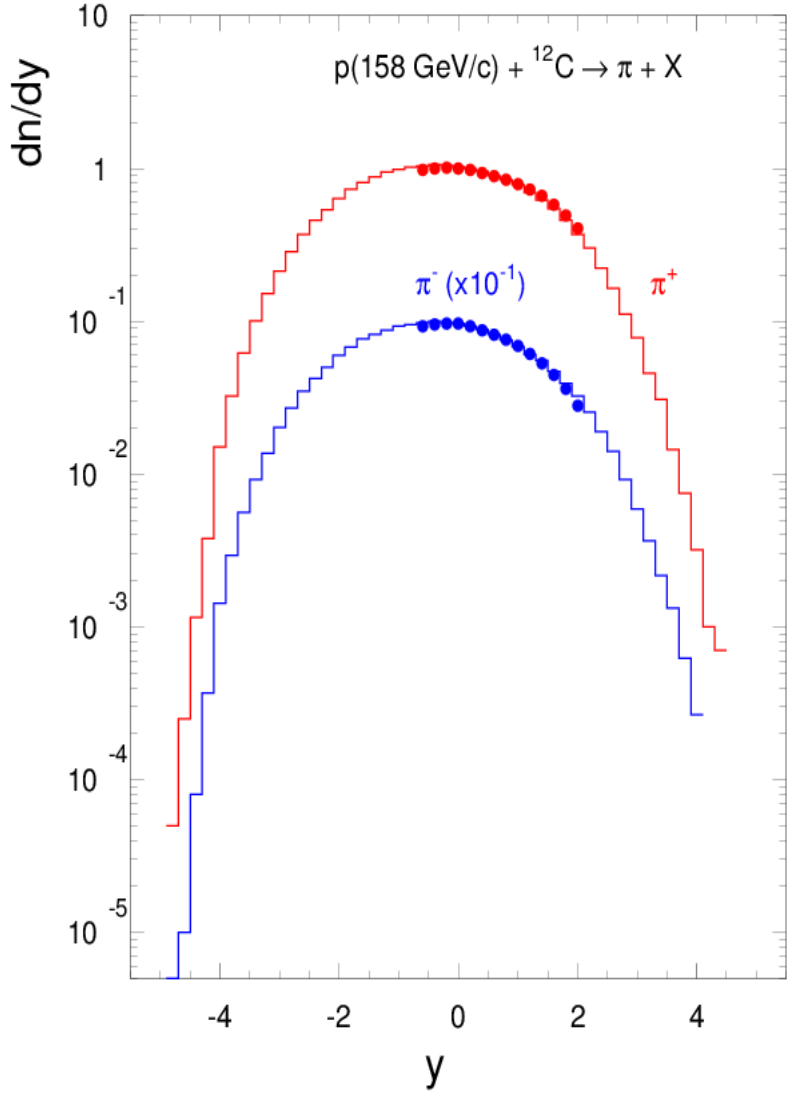
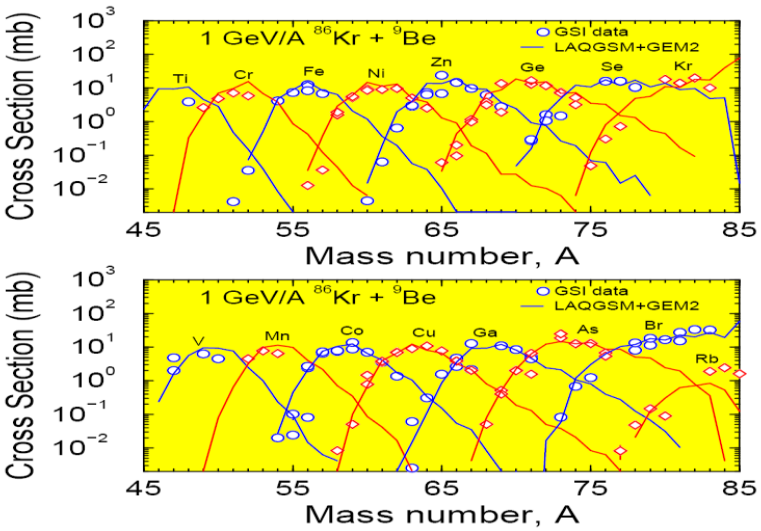
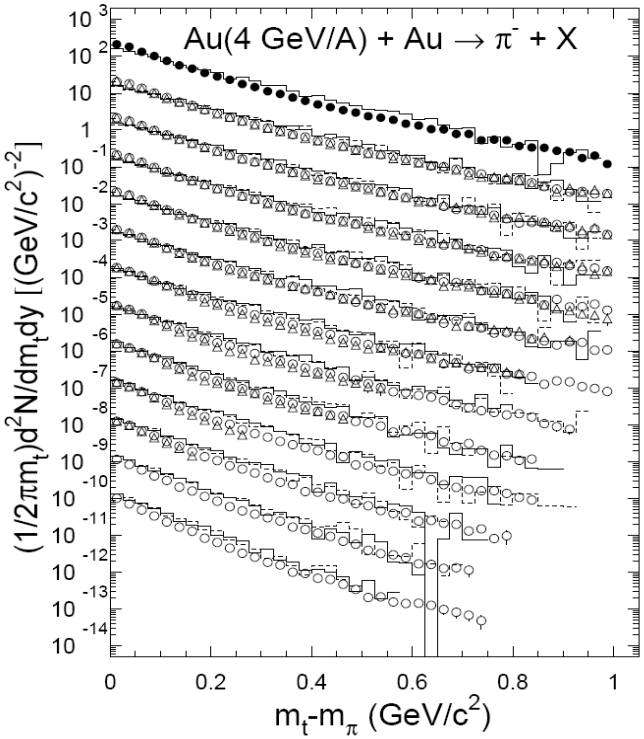
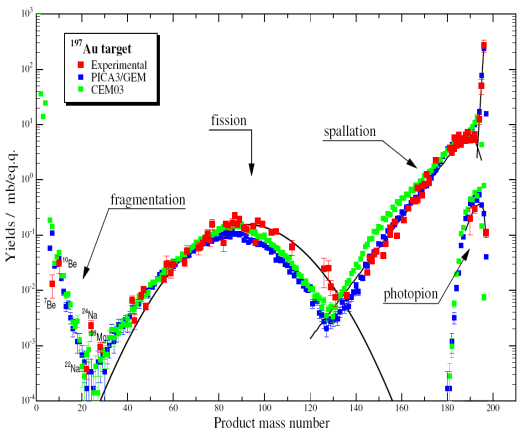


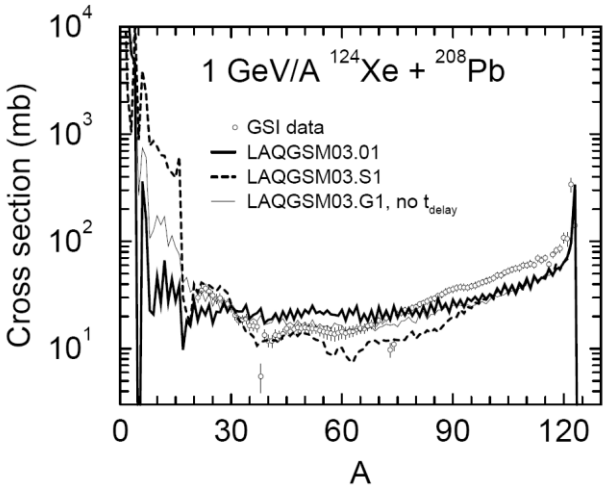
Photo-Nucleus and Nucleus-Nucleus





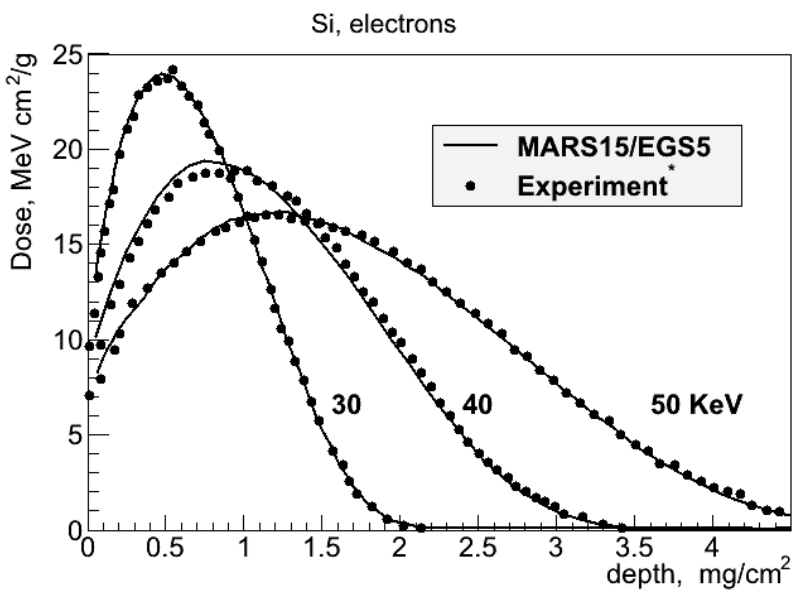
Bremsstrahlung (Emax=1 GeV) on gold





Energy Loss and Energy Deposition Modeling

1. The CSDA dE/dx is widely used in quick estimations of energy loss by particle beams and in simplified simulations of energy loss and energy deposition along the charged particle tracks in hadronic and electromagnetic cascades.
2. In MARS15, precise modeling of knock-on electron production with energy-angle correlations taken into account is done for electronic losses.

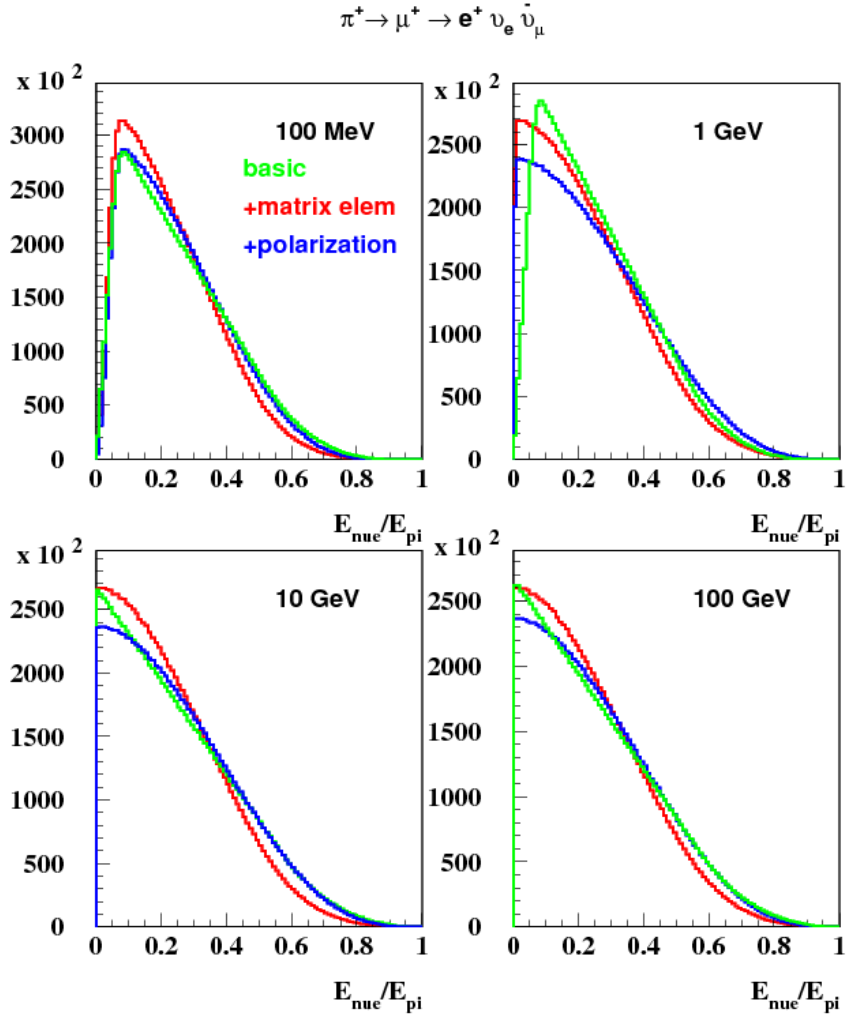


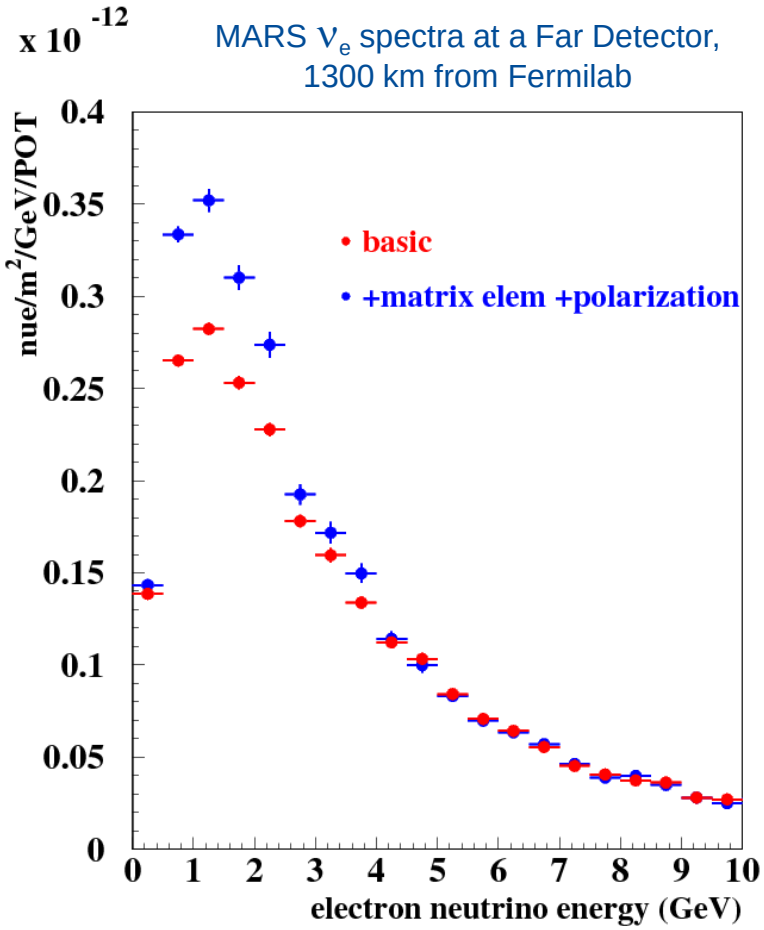
3. Radiative processes – e^+e^- pair production, bremsstrahlung, and inelastic nuclear interactions (via virtual photon) – for muons and high-energy hadrons - are modelled exclusively using pointwise x-sections.

Items (2) and (3) allow precise calculation of 3D energy deposition maps induced by high energy cascades.

Three-Body Decays

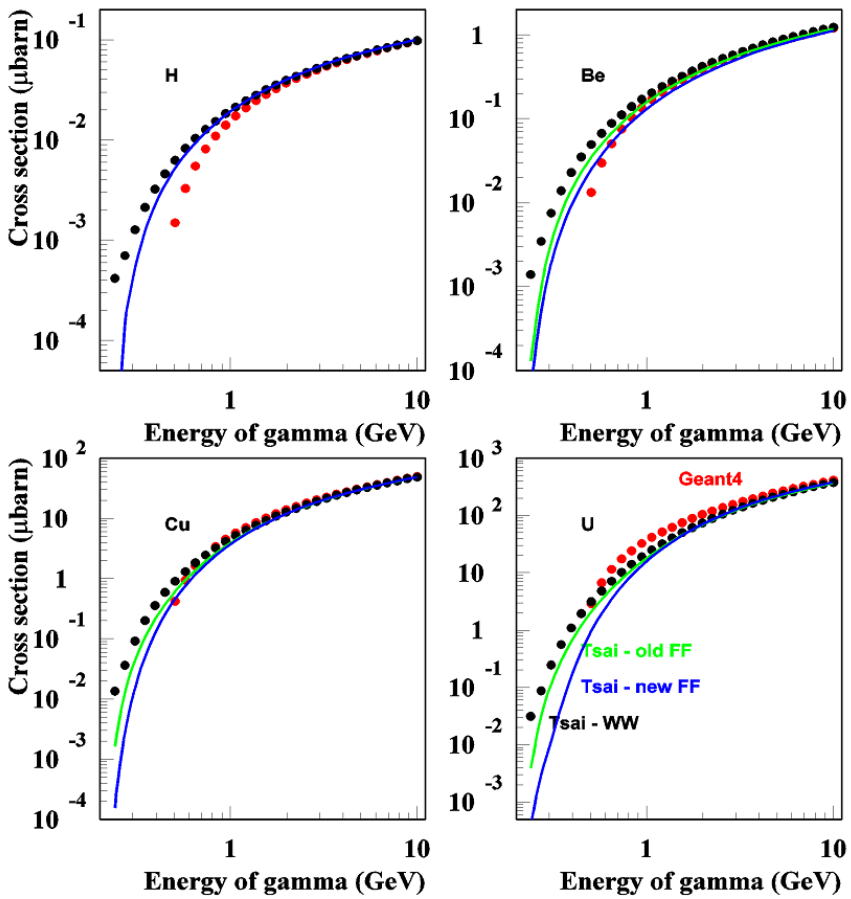
Lorentz-invariant matrix element & polarization added to basic decay kinematics of kaons and muons



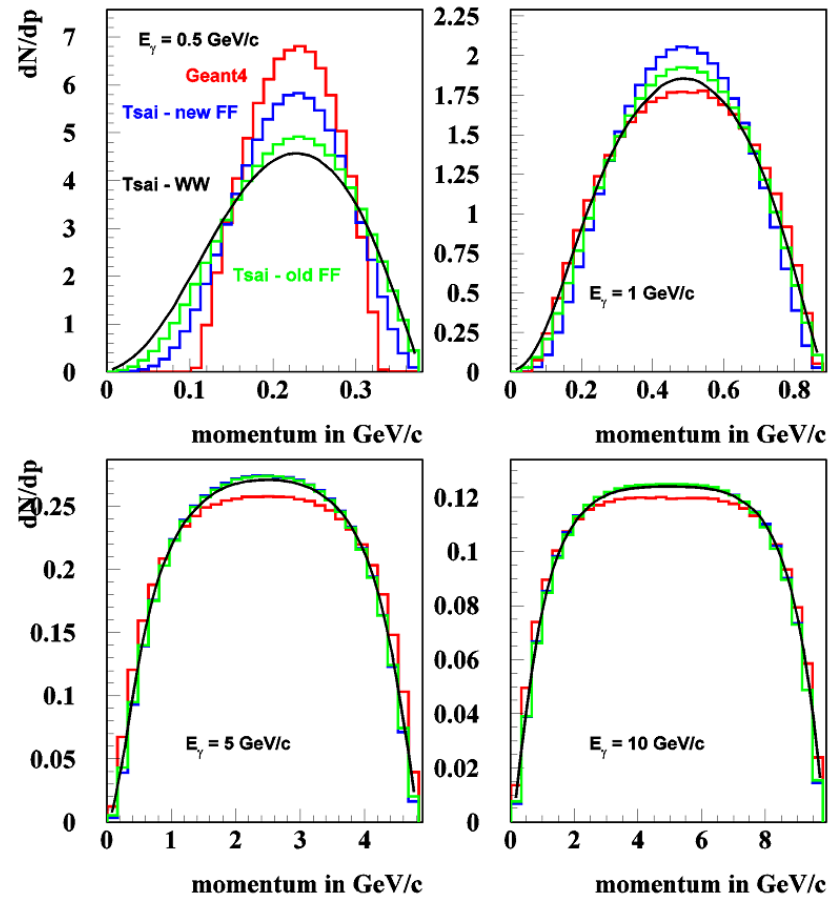


Muon Pair Production in Coherent Low-E γA

Generalized MARS15 model for arbitrary target mass and form-factor with extension at 0.2 to a few GeV photons where Bethe-Heitler model fails



Muon production in coherent gamma nucleus collisions



Muon production in coherent gamma uranium collisions

MARS15 (blue lines) labeled "Tsai – new FF"

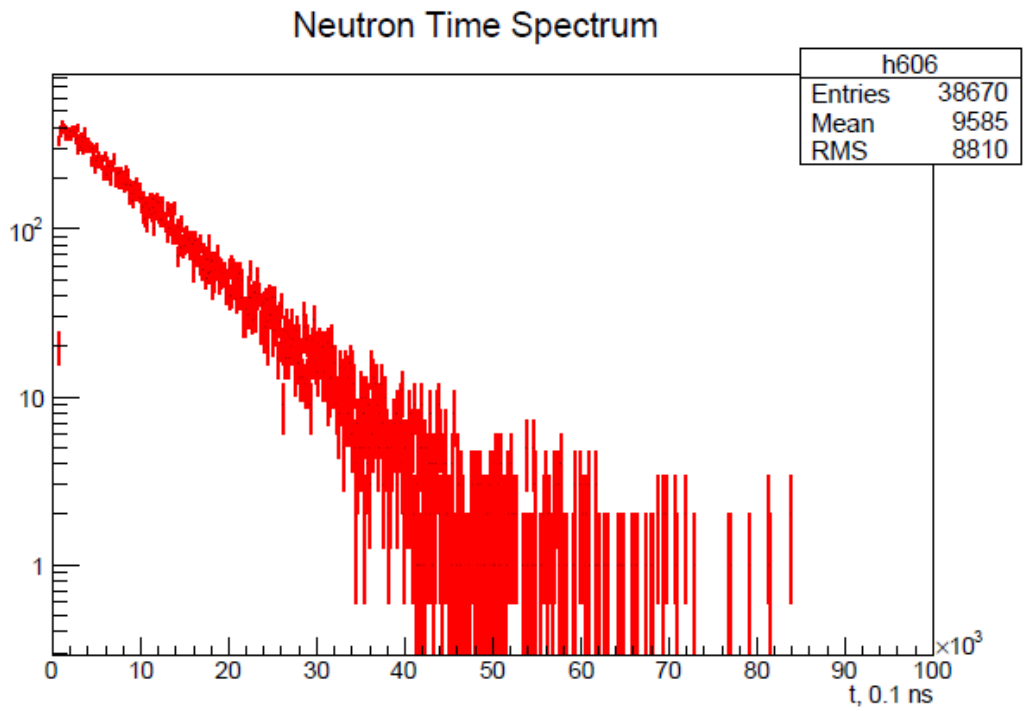
Electro-Nuclear Reactions and Vector Mesons in MARS15

- Production of hadrons in electro-nuclear interactions implemented via Equivalent-Photon Approximation: important for CLIC, ILC (thin objects), and various high energy electron beam applications.

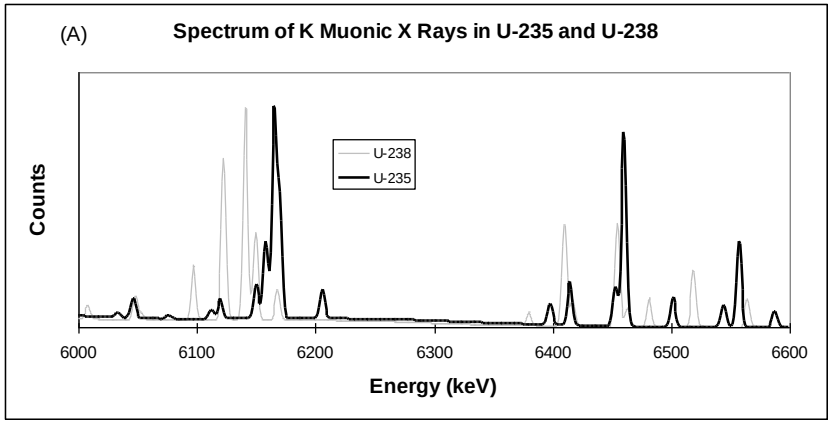
- Vector meson production and their decays implemented for γA reactions (CLIC, ILC, LCLS, LHC etc).

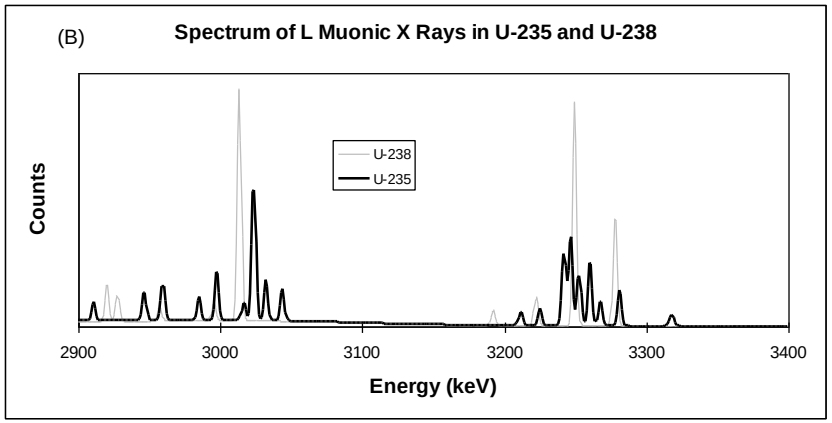
Neutron Time Spectrum from Stopped 5-keV μ^- in Al

Neutron and neutrino spectra are MARS15-calculated on the basis of a comprehensive database for muon lifetime at capture and nuclear capture fraction



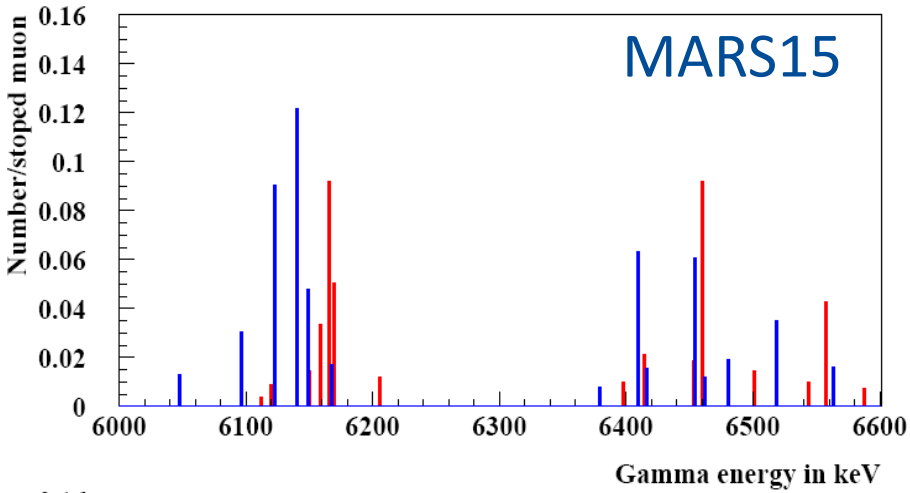
Stopped Muons in Uranium: exp *vs* MARS15

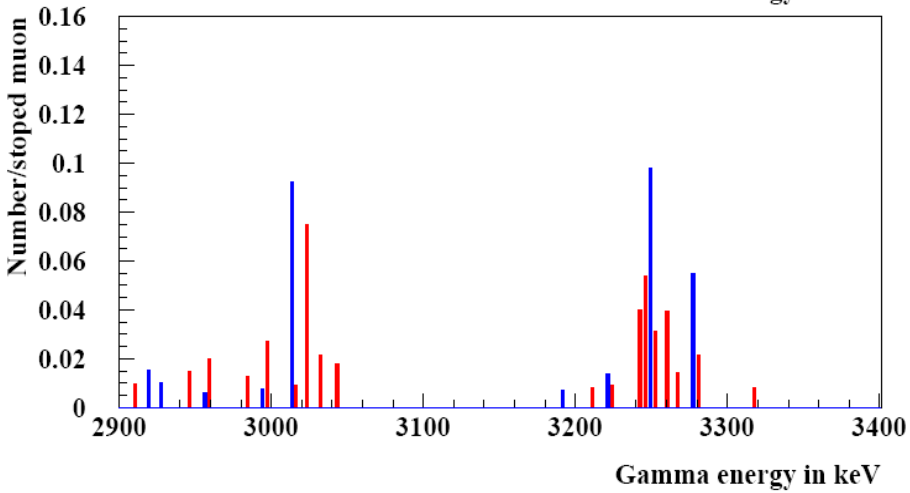




Simulation from experimental data on μ^- cascade in U238 an U235

Homeland Security



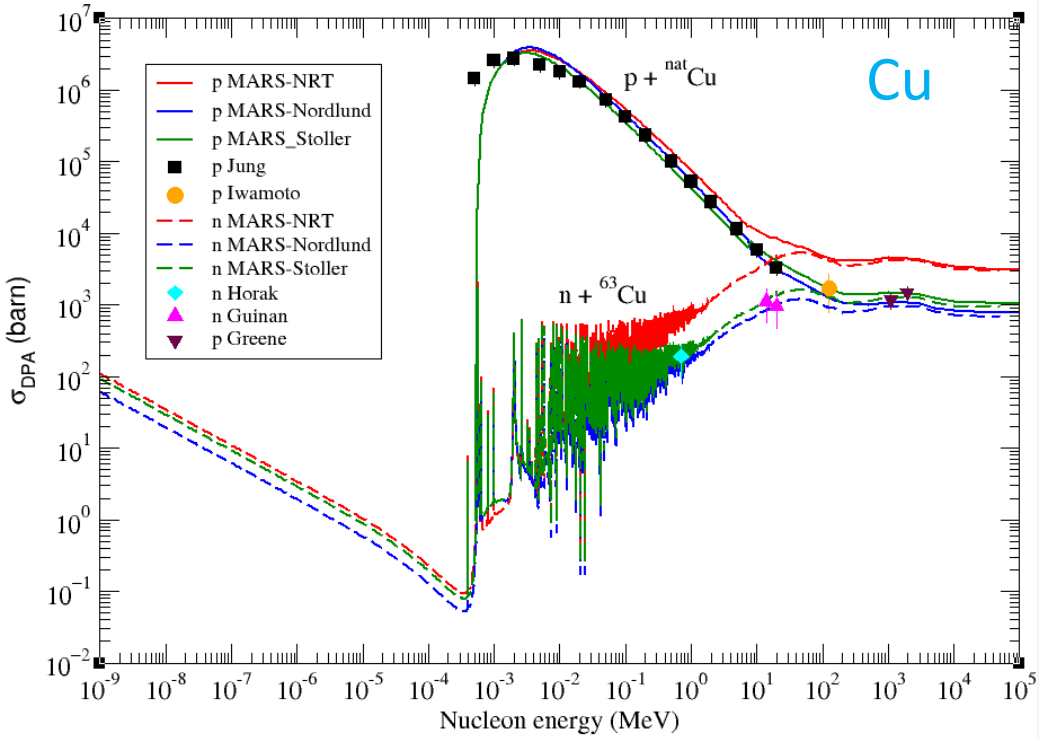


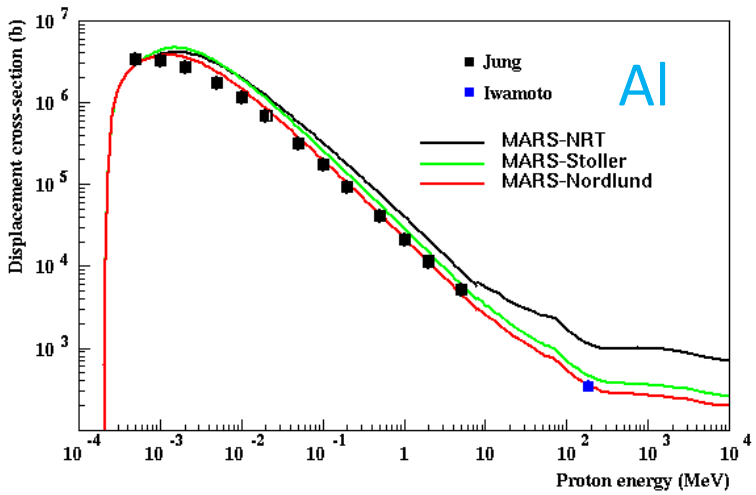
X-rays at muon stop. Red - U^{235}. Blue - U^{238}.

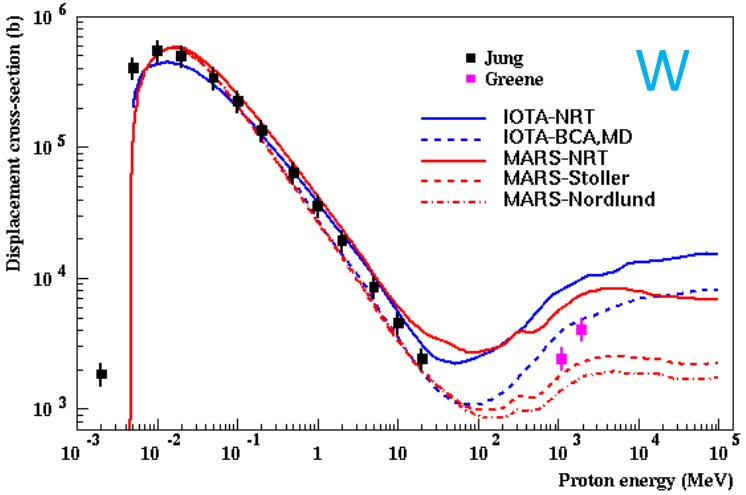
Atomic Displacements (DPA) in MARS15

- Atomic displacement cross-section σ_{DPA} is a reference way to characterize the radiation damage induced by neutrons and charged particles in crystalline materials. To evaluate a number of displaced atoms, Norget, Torrens and Robinson proposed in 1975 a standard (so-called, NRT-DPA), which has been widely used since.
- Energy of recoil fragments and charged particles in (elastic and inelastic) nuclear interactions is used to calculate atomic displacement cross sections σ_{DPA} for the NRT model – w/o or with Nordlund/Stoller damage efficiency $\xi(T)$ – for a number of stable defects
- Atomic screening parameters are calculated using the Hartree-Fock form-factors and recently suggested corrections to the Born approximation
- NJOY2016+ENDF/B-VIII.0(2018) is used to generate an NRT/Nordlund/Stoller database for 490 nuclides for neutrons from 10^{-5} eV to 200 MeV; DPA in neutron-nuclear interactions above 200 MeV are treated the same way as described in the second bullet

Proton and Neutron DPA Verification







MARS15 Generic Features (3)

- A **tagging module** allows one to tag the origin of a given signal for source term or sensitivity analyses. Several variance reduction techniques, such as weight windows, particle splitting, and Russian roulette are possible.

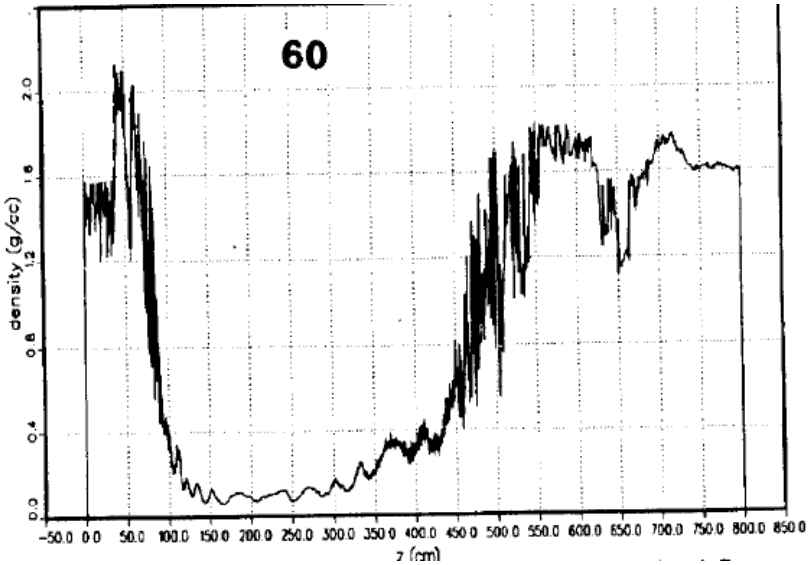
- Beam-induced bulk damage in silicon detectors and electronics (via 1-MeV equivalent neutron fluence) and coming algorithm to model Single-Event Upset (SEU) or soft errors.

- ***The powerful capabilities of MARS15 for simulation in accelerator environment*** with the MARS-MAD Beamline Builder (**MMBLB**) working in concert with an accelerator tracking code (since almost 20 years ago) and with a recent active merge with MADX-PTC for a convenient creation of accelerator models and multi-turn tracking and cascade simulation in accelerator and beamline lattices.

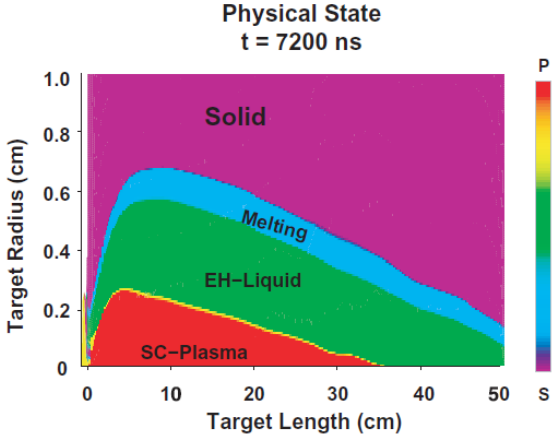
- MARS15 is routinely used in concert with ANSYS for iterative studies of thermo-mechanical problems and can be interfaced to a hydrodynamic code to study phase transition and "**hydrodynamic tunneling**" – first done by SSC-LANL collaboration for a 20-TeV proton beam in 1993.

Hydrodynamic Tunneling in Solid Materials

Pulses with EDD >15 kJ/g: hydrodynamic regime.
First done for the 300-μs, 400-MJ, 20-TeV proton beams for the SSC graphite beam dump, steel collimators and tunnel-surrounding Austin Chalk by SSC-LANL Collaboration (D. Wilson, …, N. Mokhov, PAC93, p. 3090). Combining MARS ED calculations at each time step for a fresh material state and MESA/SPHINX hydrodynamics codes.



The hole was drilled at the 7 cm/μs penetration rate. Shown is axial density of graphite beam dump in 60 μs after the spill start

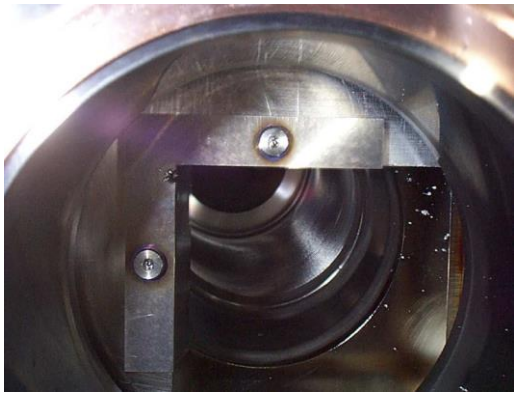


Later, studies by N. Tahir et al with FLUKA+BIG2 codes for SPS & LHC

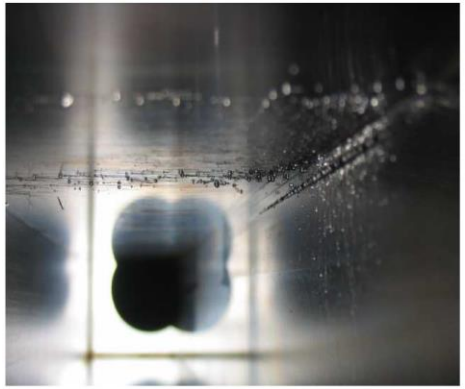
We also used MARS+FRONTIER

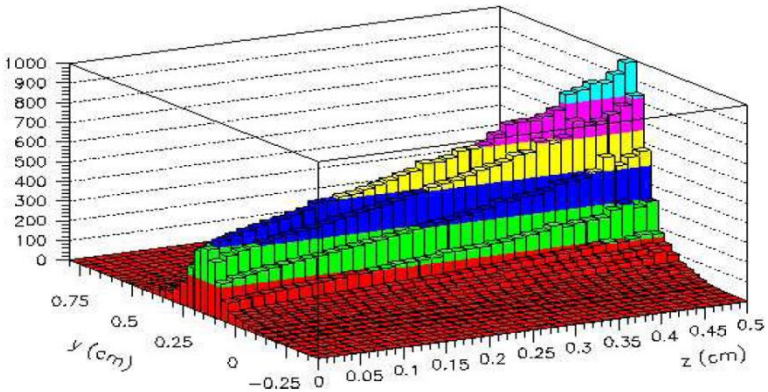
Tevatron Tungsten Collimator Ablation

Hole in 5-mm W



25-cm groove in SS





Detailed modeling of dynamics of beam loss (STRUCT), energy deposition (MARS15) as high as 1 kJ/g, and time evolution over 1.6 ms of the tungsten collimator ablation, fully explained what happened

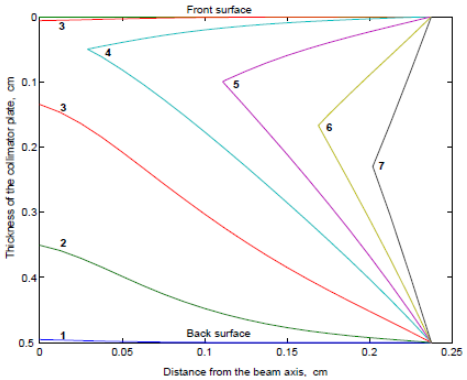
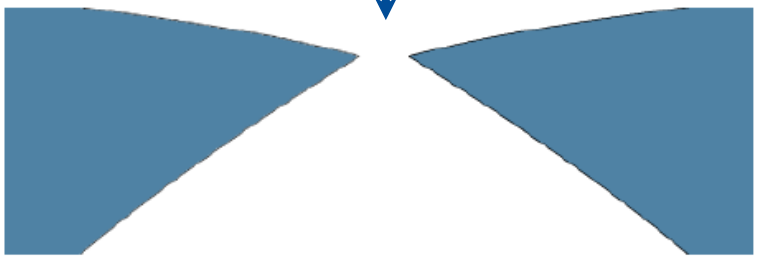


Figure 7: Evolution of the front and back surfaces of the collimator plate at $t = 0.4_{[1]} - 1.6_{[7]}\ ms$ with Δt=0.2 ms.

980-GeV p-beam



MARS15-MADX-PTC Integration (1)

Basic integration outline:

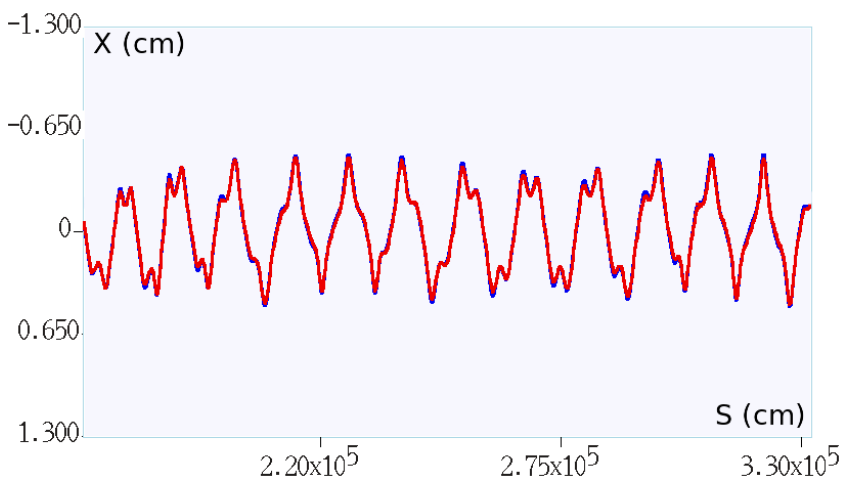
1. A library containing functions and C++ classes which interfaces MARS with MADX is now packed with the MARS15 distribution. The library allows to

- Create a 3-D TGeo ROOT geometry model for the sequence described in a MADX-PTC input file. Alignment of elements is performed by means of the MAD-X survey table.
- Define transformation for each point in the phase space used in the PTC module to the phase space used in MARS15 and vice-versa.
- Inject particles transported by MARS15 to MADX-PTC module using a formulated acceptance for the accelerator code model.
- For particles transported in PTC, perform check of boundary crossing against the ROOT geometry in MARS15; the particle is forwarded to the MARS15 stack.

MARS15-MADX-PTC Integration (2)

2. The PTC module of MADX was modified in order to

- Allow a particle to start from the upstream end of an arbitrary element in the sequence. Originally, it always started from S=0.
- Check the aperture crossing against the MARS15 geometry not only at the entrance and exit of the element, but also all along a curved track (e.g., in dipoles).



Beam orbits in the Fermilab 8-GeV Recycler calculated with MAD-X PTC module (blue) and MARS15 native stepper (red)

MARS15 Applications at Fermilab over 40 Years

- **Tevatron** complex (since 1979): beam abort and beam collimation systems; superconducting magnets (e.g., R. Dixon, N.V. Mokhov and A. Van Ginneken, Beam Induced Quench Study of Tevatron Dipoles, Fermilab-FN-0327 (1980)); backgrounds & MDI for the CDF and D0 collider detectors; Booster, Main Injector and Recycler chain; beam instrumentation; numerous radiation problems (e.g., JASMIN T-972, T-993, T-994); E-853 and T-980 crystal extraction and collimation experiments; PIP-II; fixed target experiments: neutrino (NuMI/MINOS, NoVA, MiniBoone, DONUT (E-872), LBNF/DUNE), mu2e, g-2, kaons, SeaQuest etc.

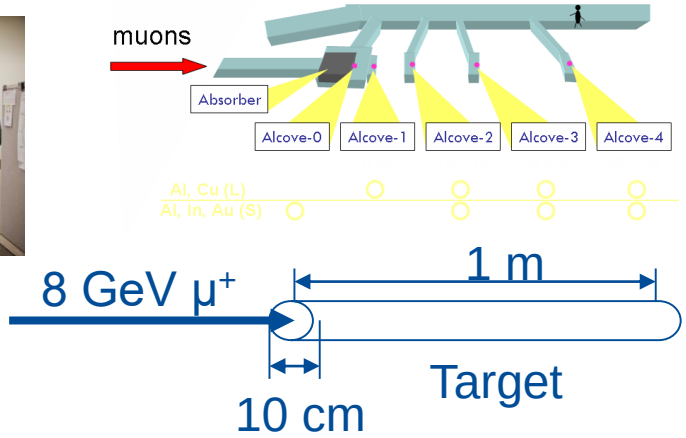
- **Muon collider and Higgs Factory** (since 1994): targetry, machine-detector interface, machine protection, neutrino-induced hazard etc.

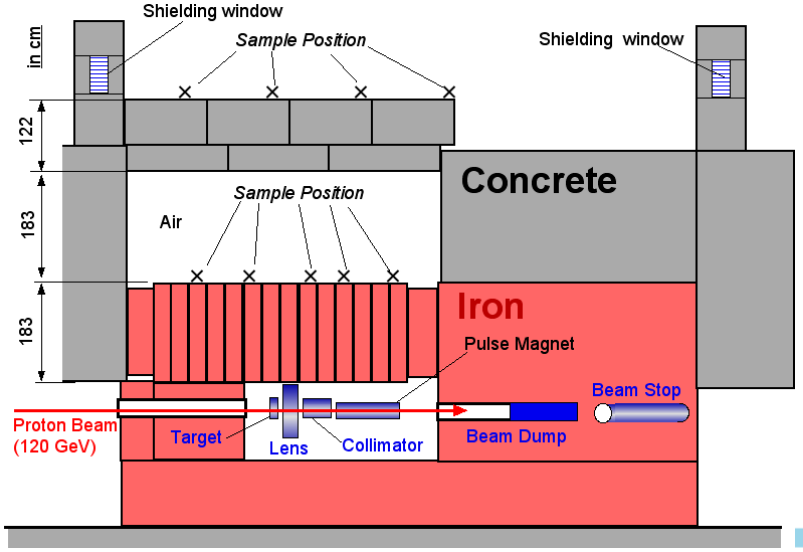
- **SSC, LHC and ILC**

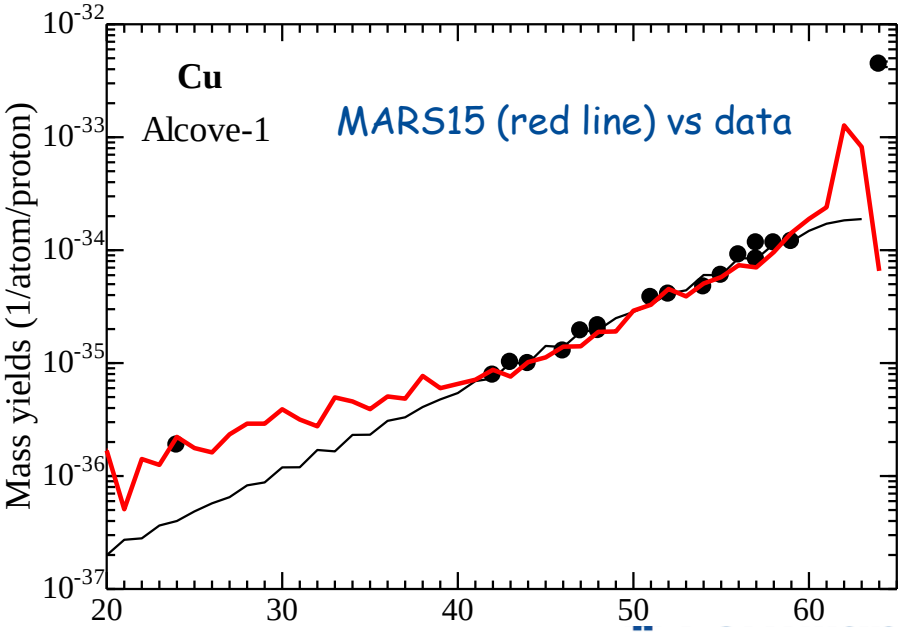
JASMIN: Shielding and Radiation Effect Experiment

JASMIN Japan-FNAL Collaboration:
<u>Shielding and Radiation Effect Experiments at FNAL</u>
T-972 (2007-2009)
T-993 and T-994 (2009-2012)
Shielding data and code benchmarking; targets, collimators and thick shields; radiation effects on instruments and materials. **A dozen of journal papers**

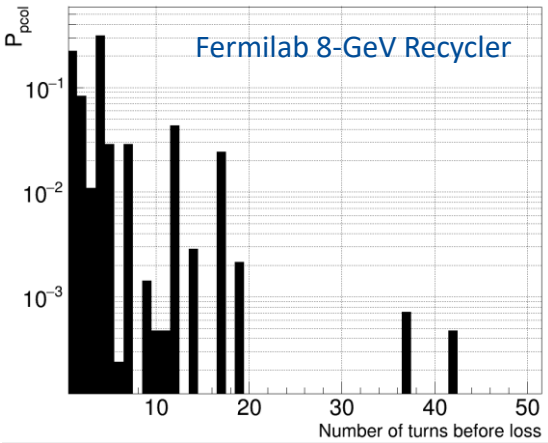
Example: Muon-induced nuclide production



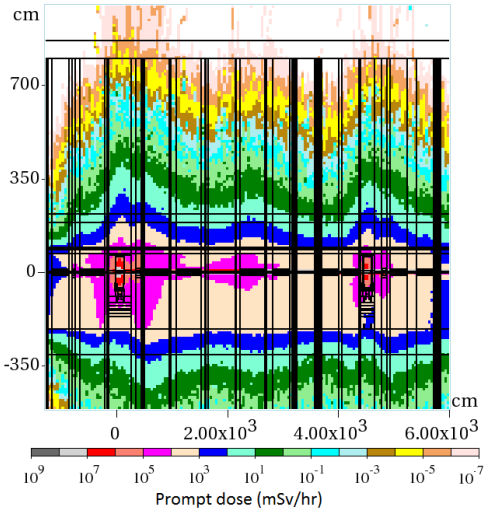




MARS-MADX-PTC: Fermilab Recycler and ILC

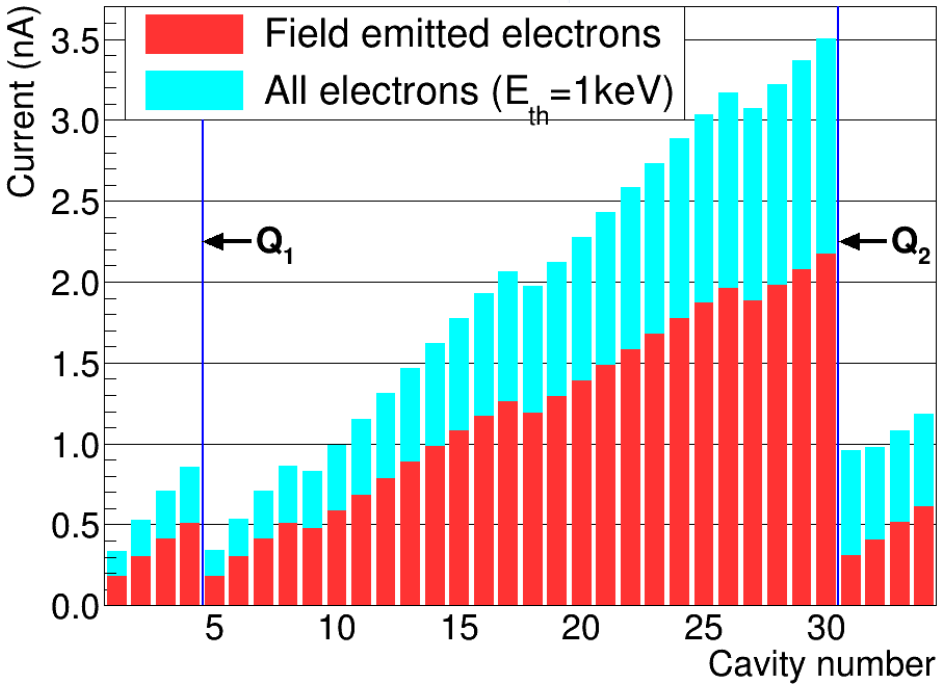


Probability to be lost for beam halo protons passed through the primary collimator vs #turns



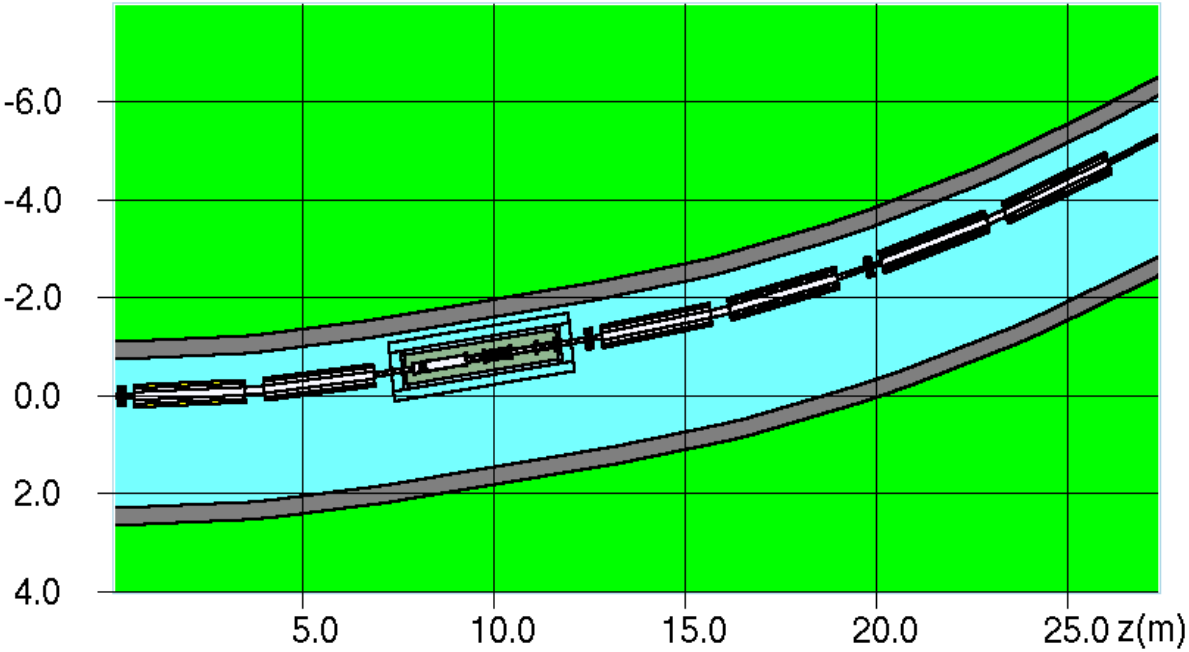
Prompt dose in collimation region

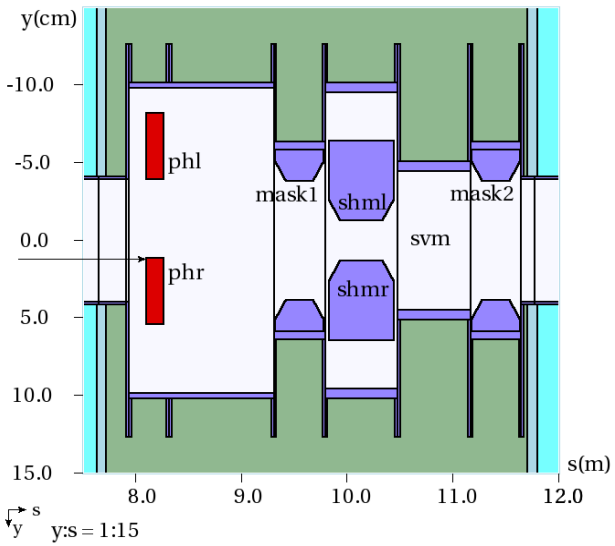
MARS15 SRF model (ILC & LCLS-II)

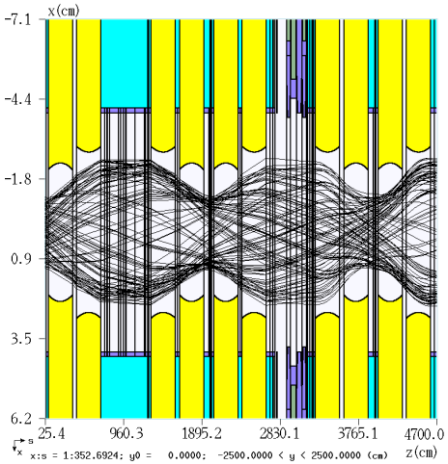


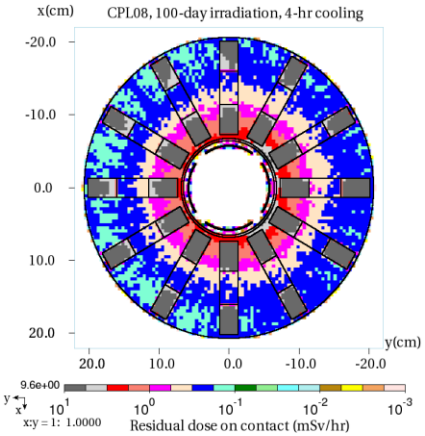
Dark current electrons and EMS electrons in ILC aperture with their loss responsible for radiation load to components and radiation field in ILC tunnel

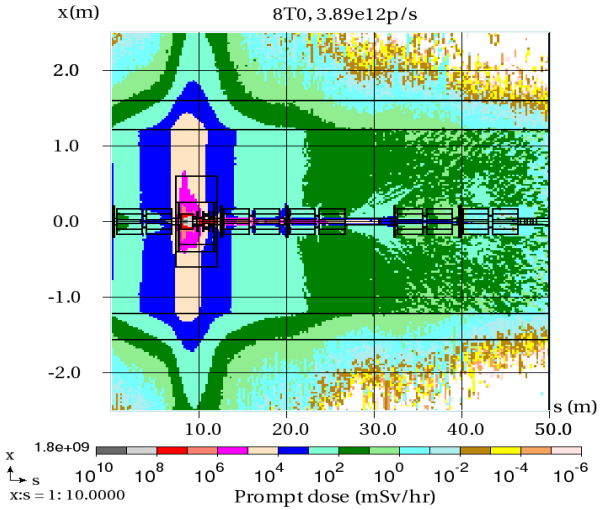
Booster New Collimation System



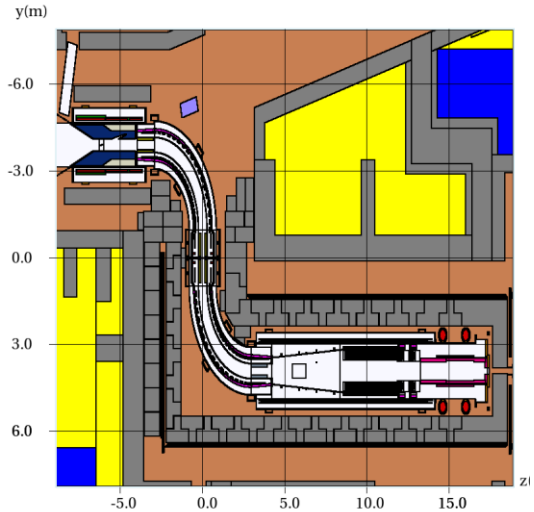




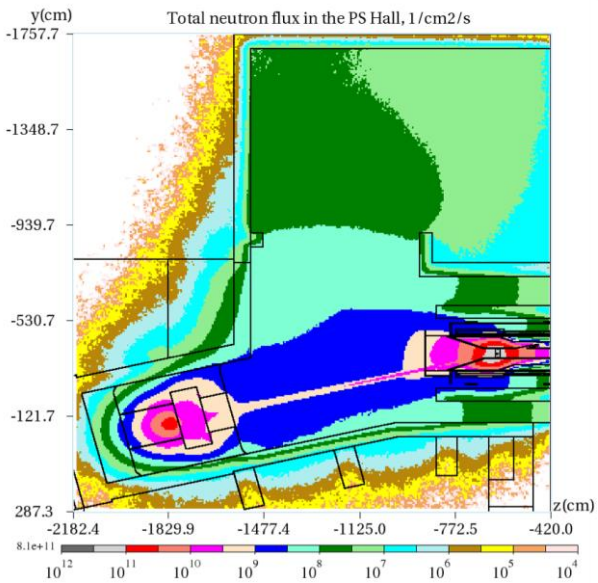


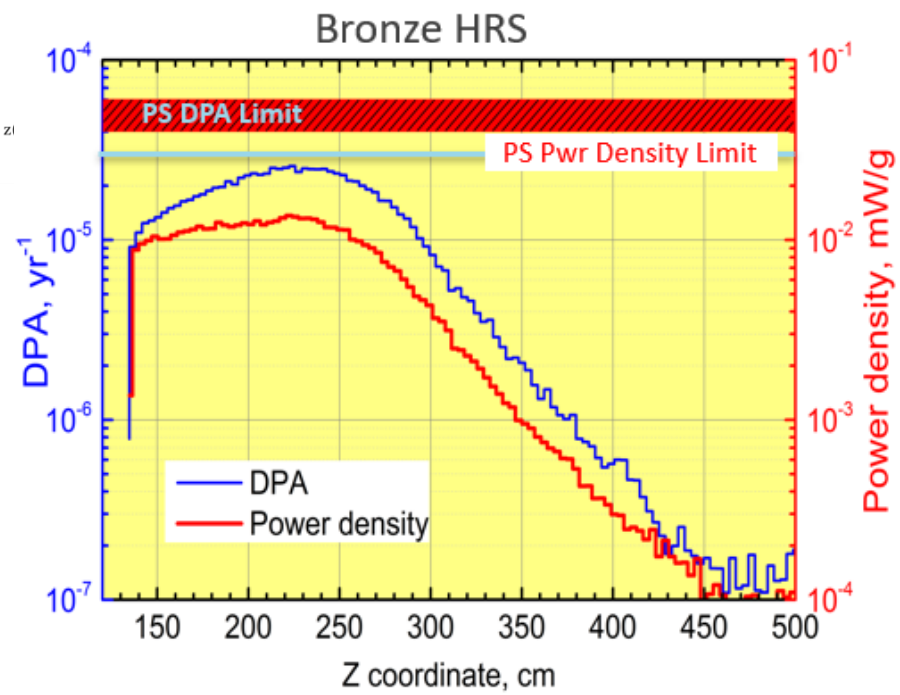


Mu2e: from Design to Construction

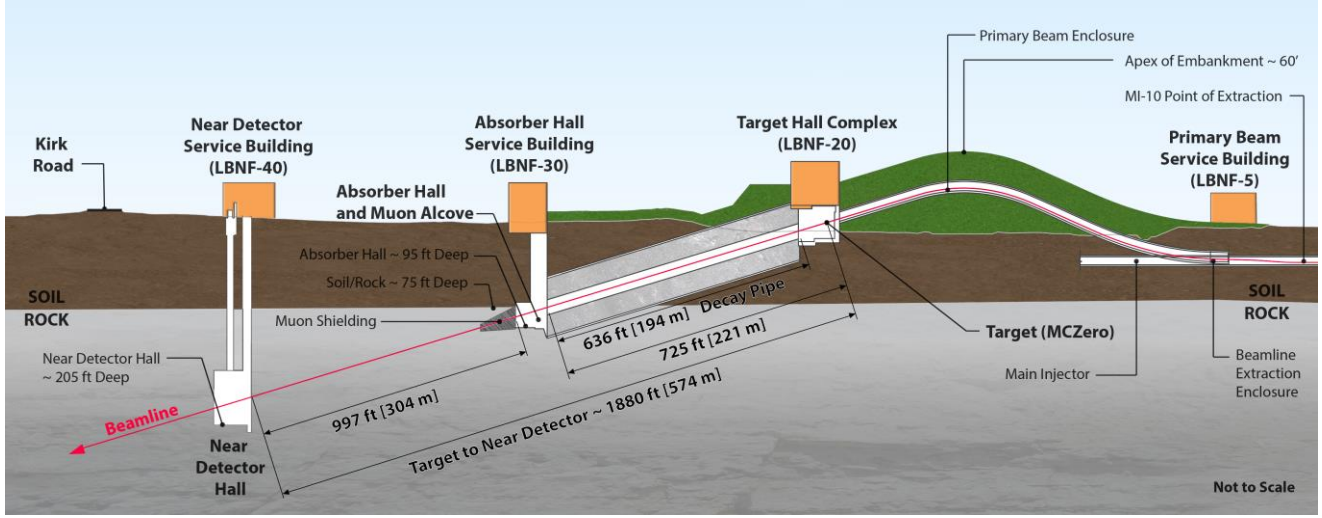


Several years of efforts to optimize with MARS15 the Mu2e Production, Transport and Detector solenoid systems w.r.t. their performance, lifetime, shielding and cost

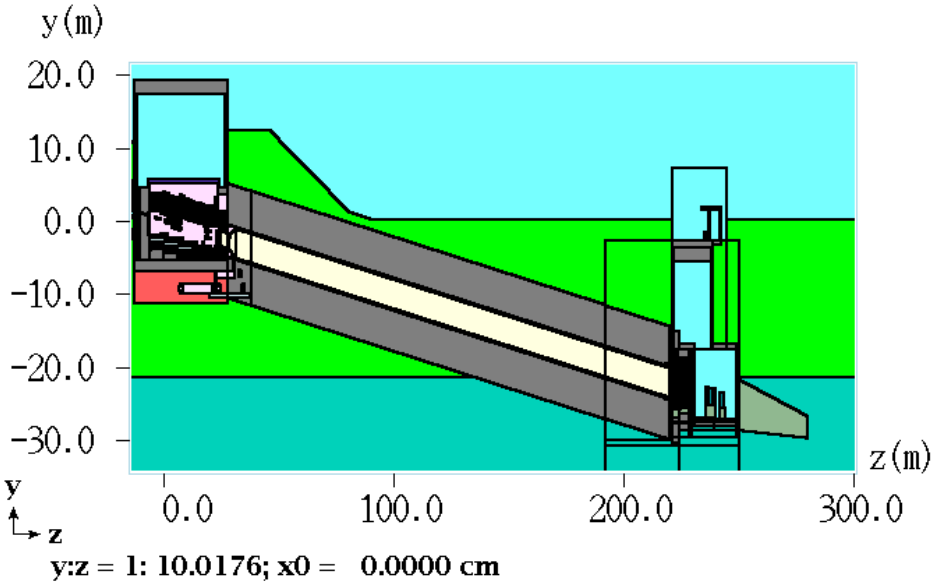




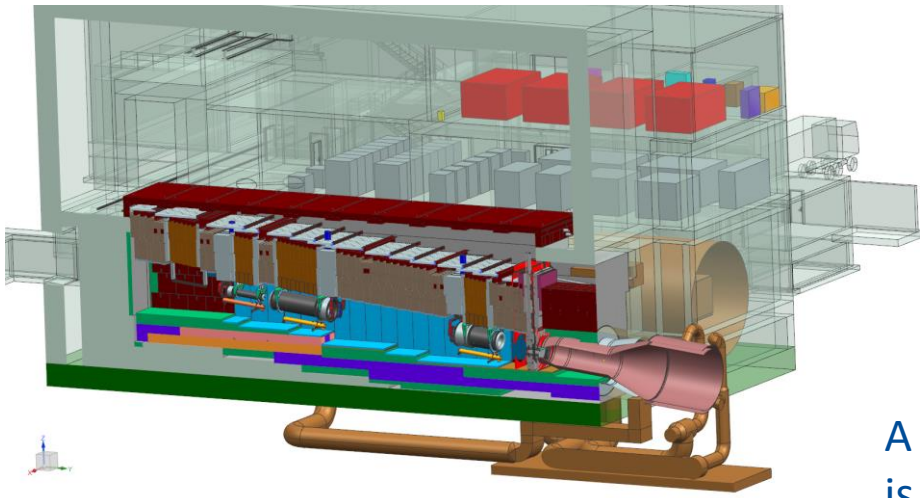
LBNF Beamline: Schematic & MARS Model



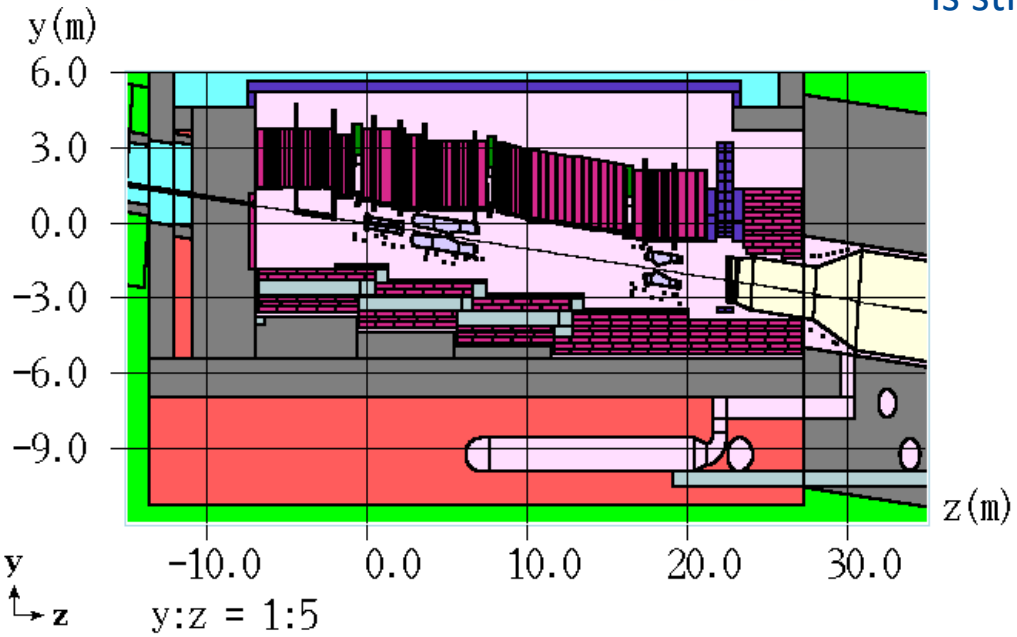
- LBNF and DUNE
- Neutrinos from 60 to 120 GeV proton beam
- **1.2 MW from day one**; upgradeable to 2.4 MW
- **Near detector** to characterize the beam
- Massive underground LAr TP Chambers
- **4 x 17 kton** (fiducial mass of more than 40 kton)



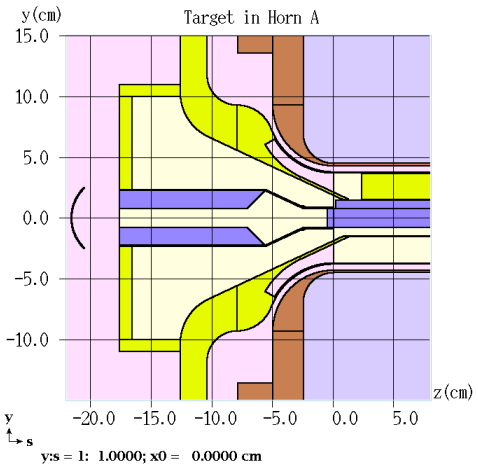
Target Station (TS): CAD & MARS15 Models

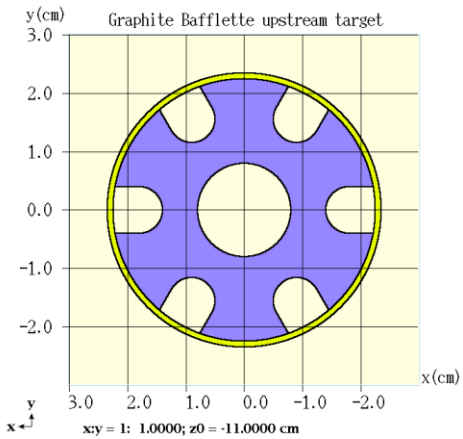


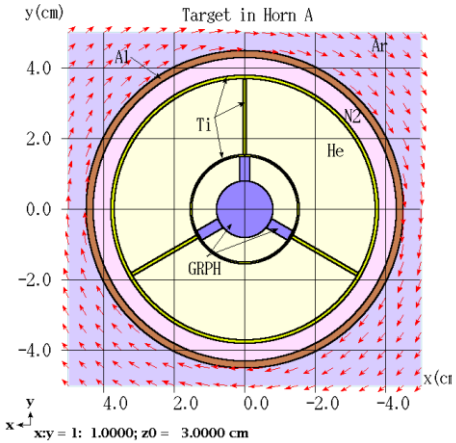
A replaceable target design is still in a preliminary stage

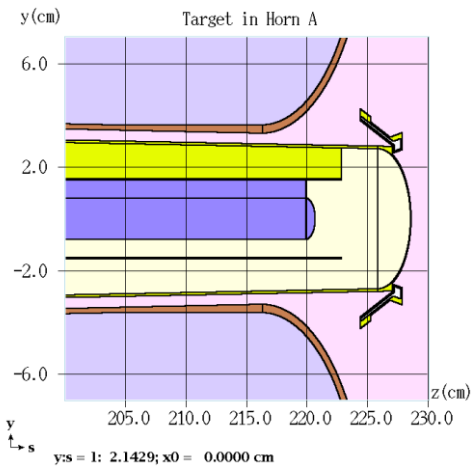


Details of the LBNF-MARS TS Model

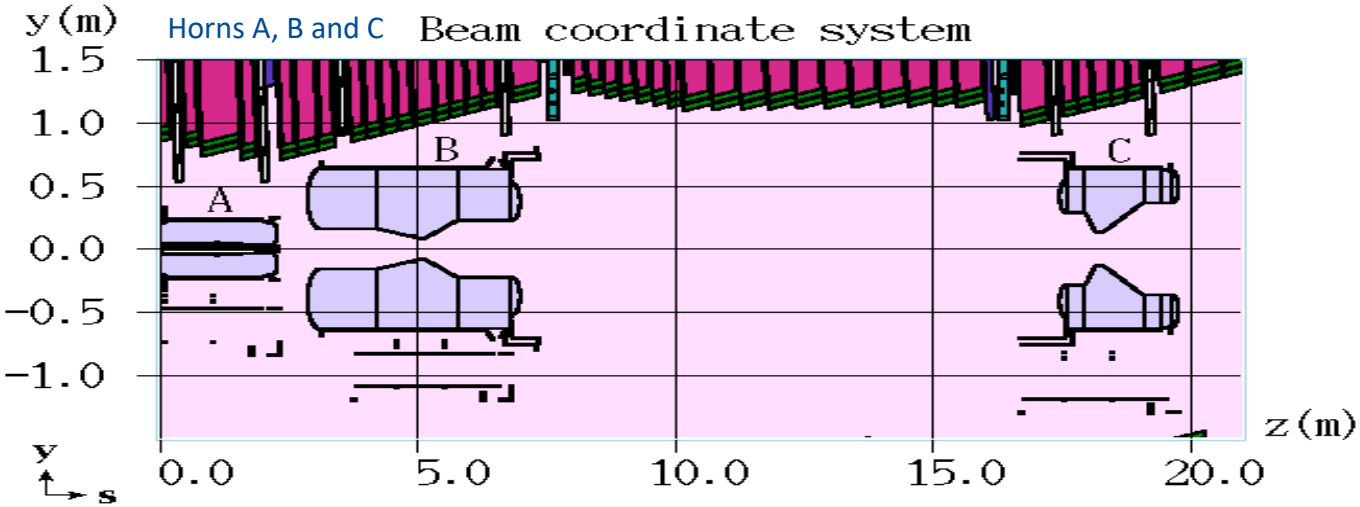




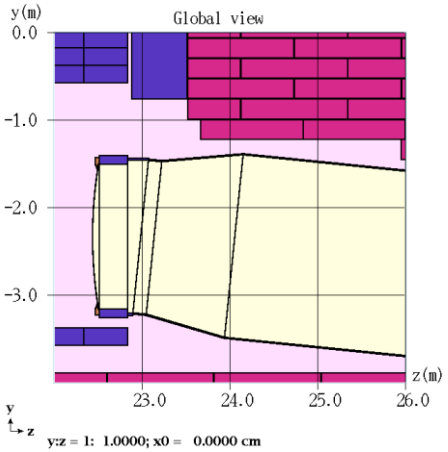




Horns A, B and C

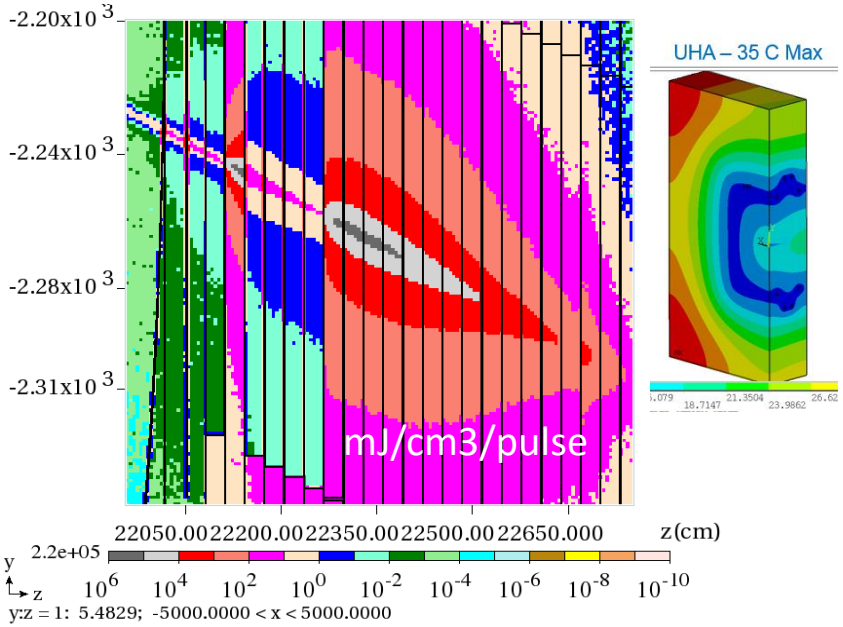


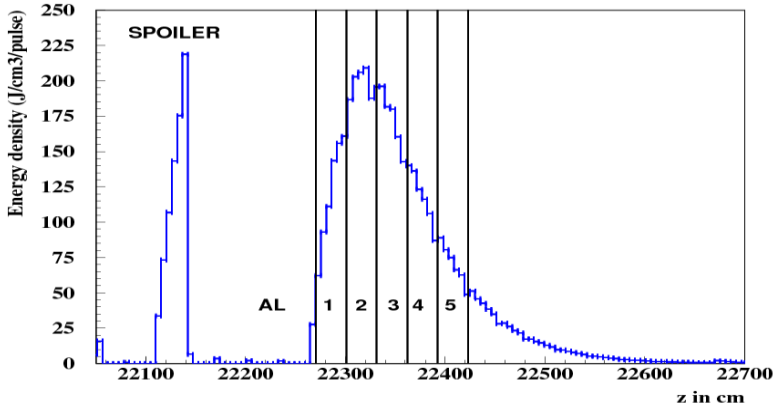
Upstream of DK pipe



Hadron Absorber Complex: EDEP & Prompt Dose

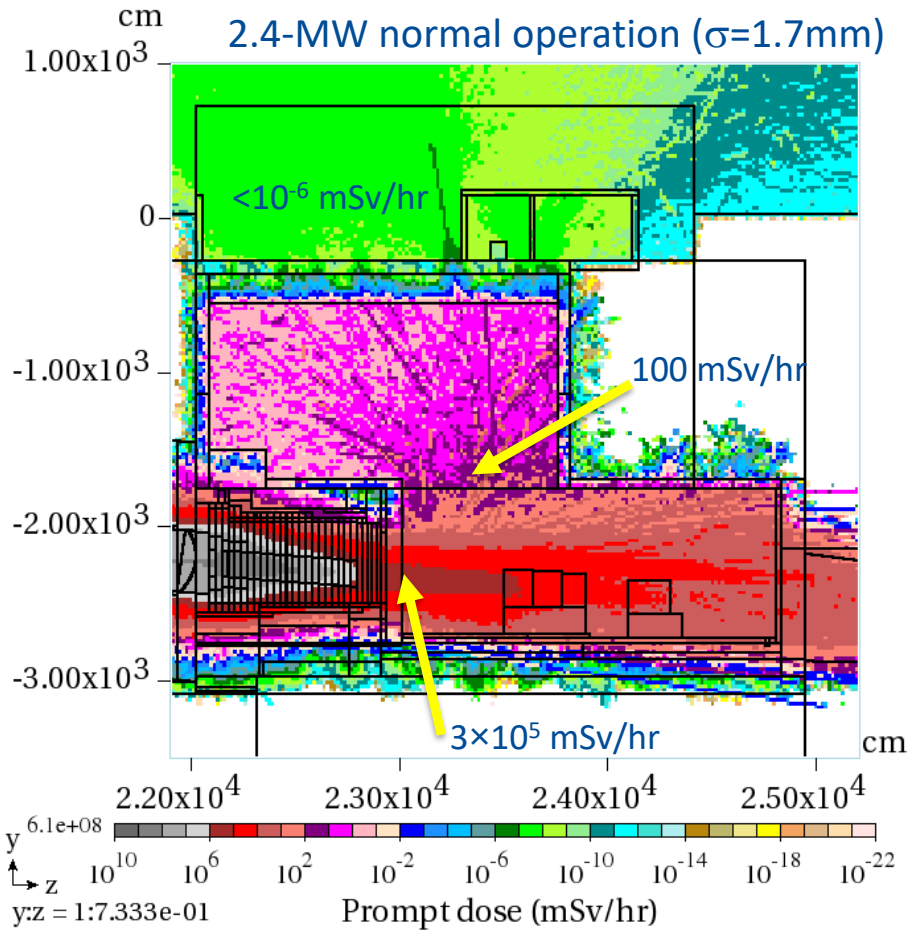
No-target beam accident (σ=2.4mm)





Temperature and stresses below the limits

2.4-MW normal operation (σ=1.7mm)

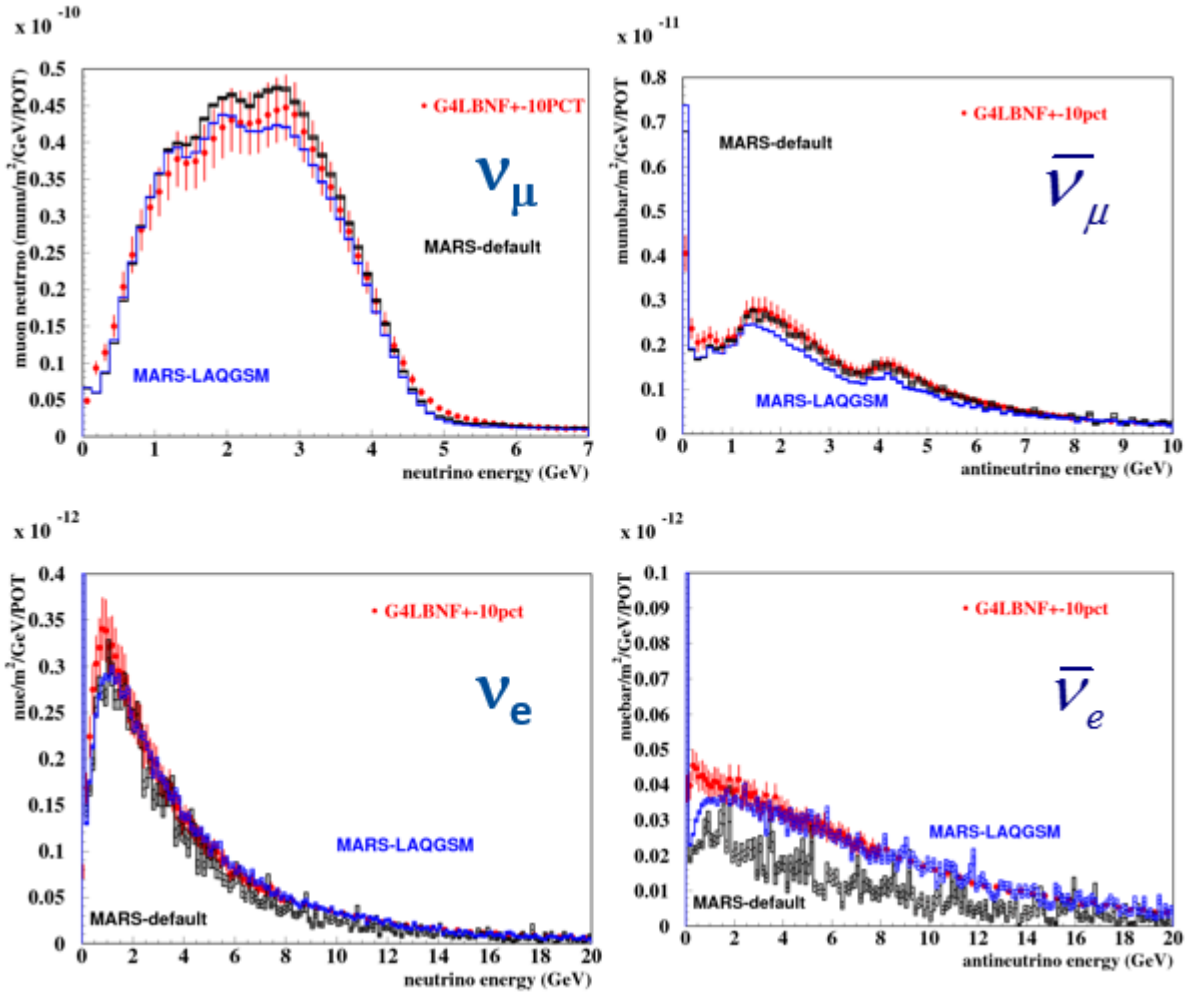


Carefully designed shielding guarantees prompt and residual dose, air and cooling water activation as well as radiation load on ground water to be below the administrative limits with corresponding safety margins

Neutrino Fluxes at Far Detector (1300 km)

Thorough search and elimination of differences in MARS15LBNF and G4LBNF models were performed on geometry, materials, magnetic fields etc.

Optimized ν-fluxes at the Far Detector calculated with MARS15 and Geant4 now agree within 10%. The code related uncertainties were reduced to the differences in the event generators, especially for K^- and K^0 mesons (need data!)



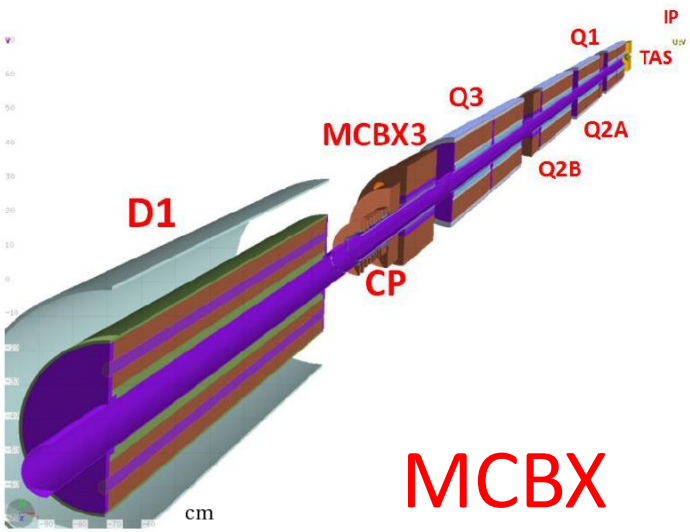
MARS for LHC and HiLumi LHC

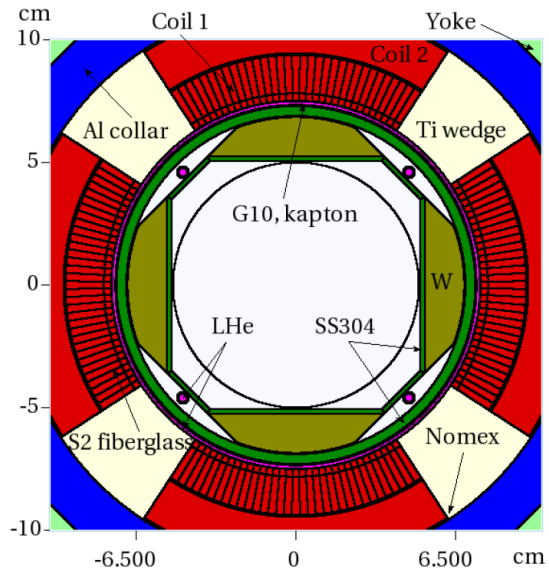
- MARS simulations since 1998 helped design the optimal high-luminosity Interaction Regions IR1 and IR5 of LHC, including their TAS, TASB and TAN absorbers, and predict superconducting magnet short-term (quench stability) and long-term (lifetime) performances (e.g., N.V. Mokhov et al., Protecting LHC IP1/IP5 Components Against Radiation Resulting from Colliding Beam Interactions, Fermilab-FN-732 (2003), LHC Project Report 633, CERN (2003))

- "MARS predictions of 16 years ago of energy deposition in the low-beta quads agree within 20% with recent measurements in the real LHC machine. No beam-induced quench has been observed at LHC". Lucio Rossi, talk at Fermilab, February 2014.

- Note that two decades ago there was no collider experimental data above 1 TeV to verify the code's physics models. These days – working on the HiLumi LHC upgrade - we have a luxury of coherent studies with the FLUKA and MARS codes benchmarked in the TeV energy region.

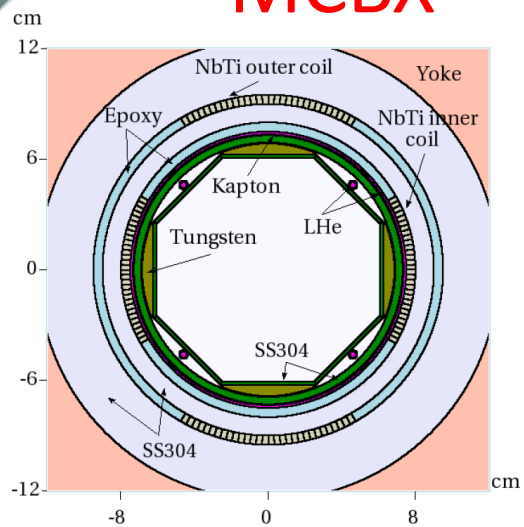
HL-LHC IT FLUKA-MARS Study and Intercomparison (1)



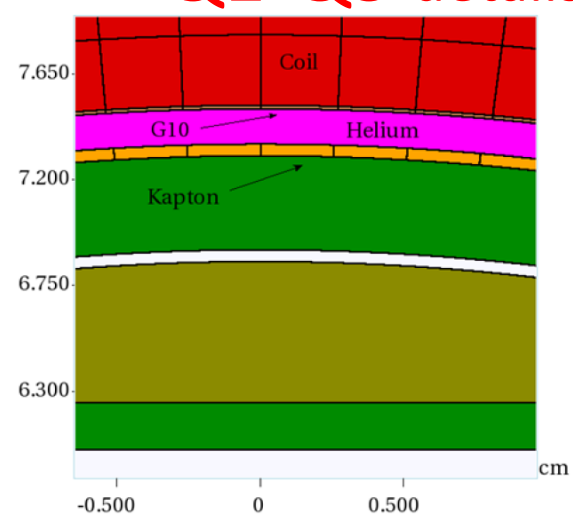


Q1

MCBX



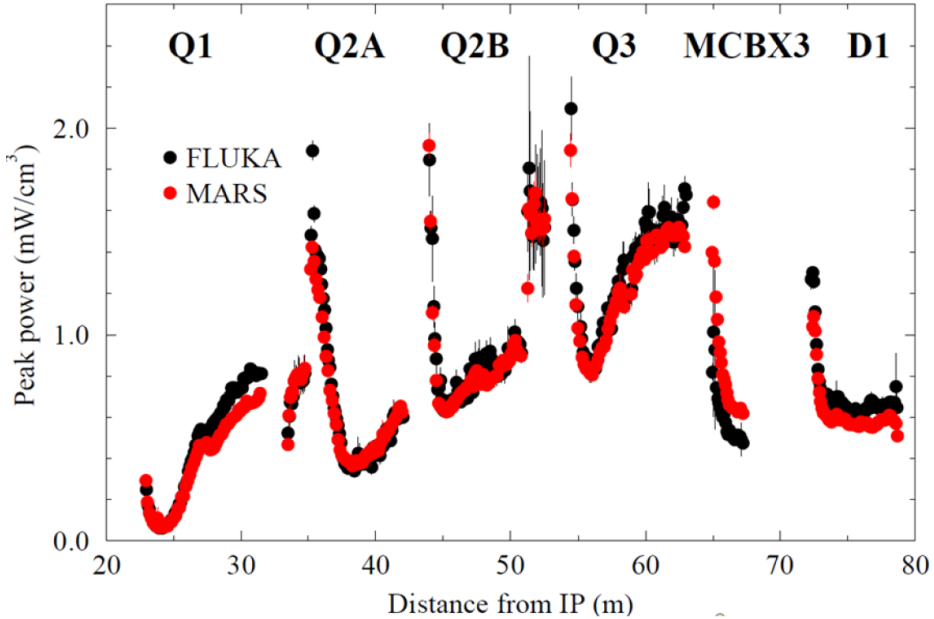
Q1-Q3 details



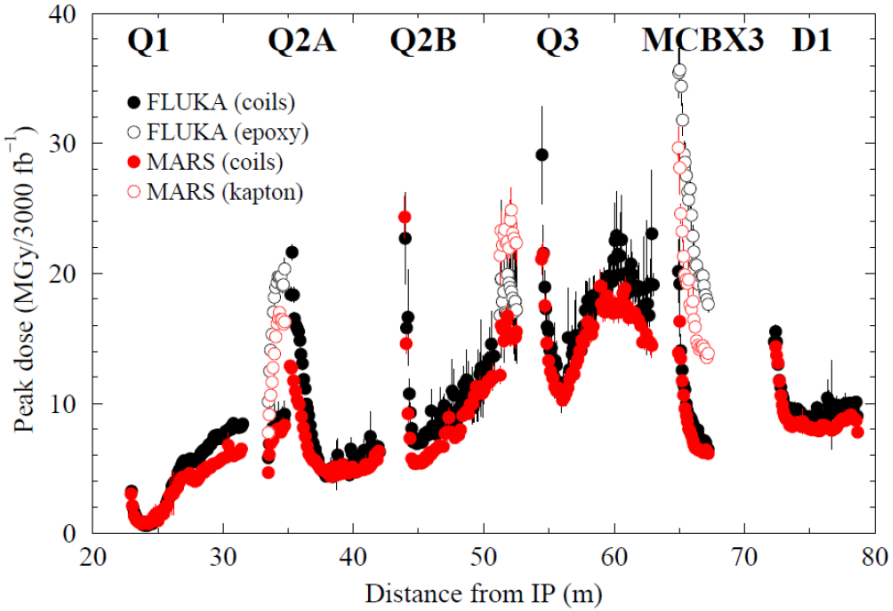
Phys. Rev. ST Accel. Beams **18** 051001 (2015)

HL-LHC IT FLUKA-MARS Study and Intercomparison (2)

Peak power density in SC coils (mW/cm^3)



Peak dose in critical components 20 to 35 MGy/3000 fb^{-1}, close to the accepted limits



Quench limit at I_{op}/I_c=0.8 in Nb_3Sn quad coils is 40 mW/cm^3, and 13 mW/cm^3 in NbTi MCB and D1. The peaks are respectively 20 and 10 times below the limits

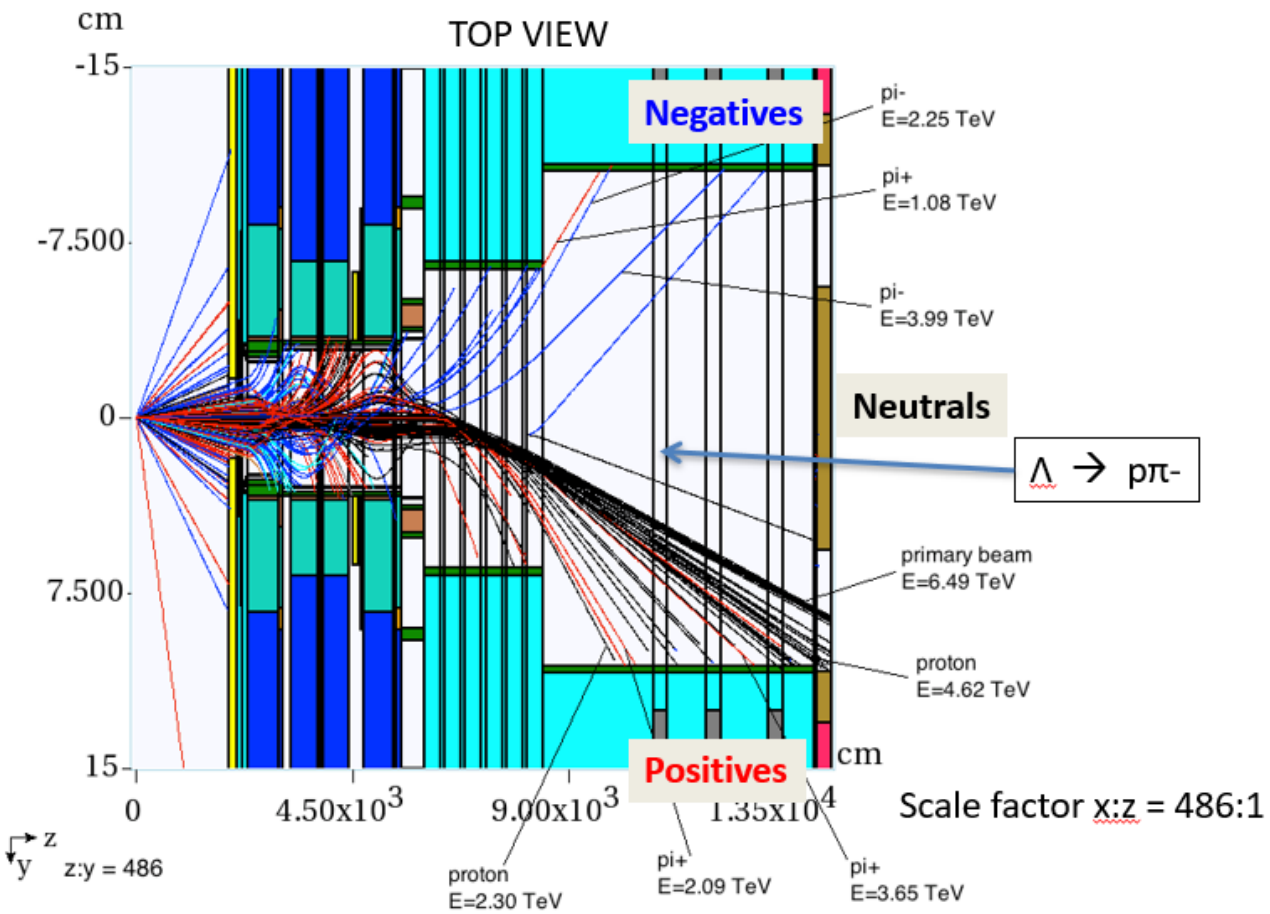
Phys. Rev. ST Accel. Beams **18** 051001 (2015)

Very Forward Hadron Spectrometer at LHC

200 inelastic collisions at Pt 5 (13 TeV, β* = 0.55 m): MARS15

If μ = 1 this is 200 bunch crossings = 6 μs

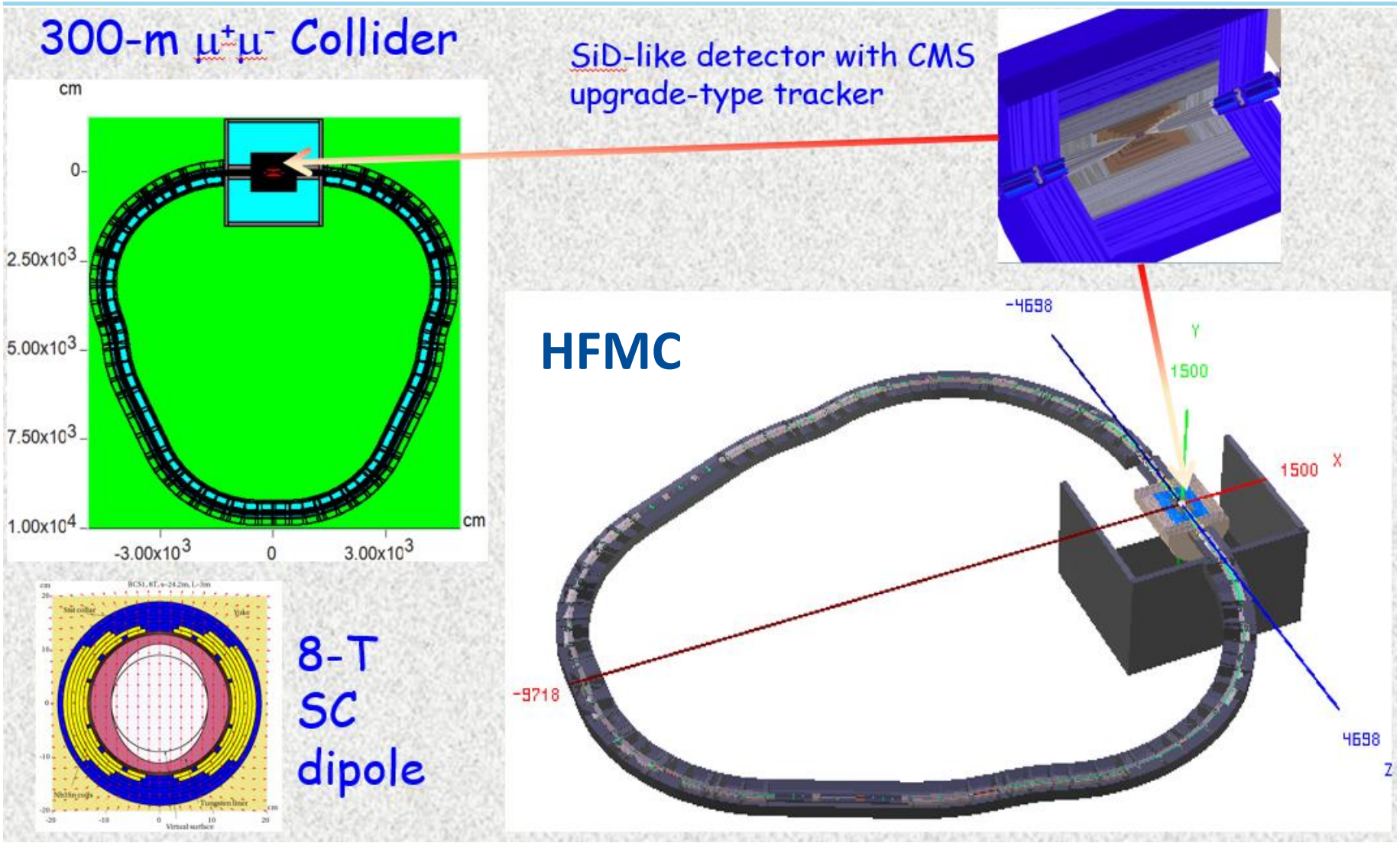
Mike Albrow



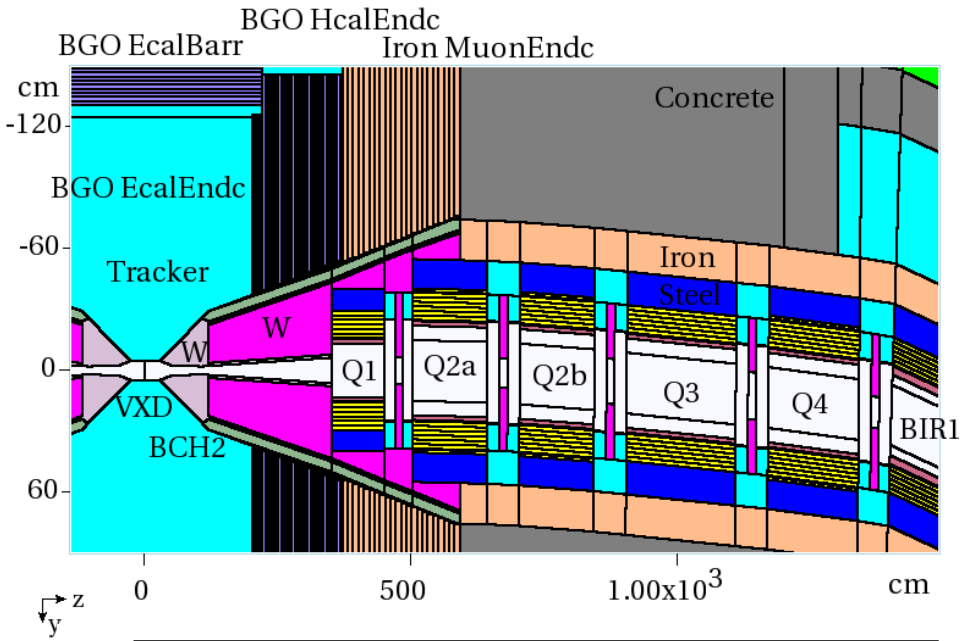
Scale factor x:z = 486:1

Hitting pipe: 2 π- and 4 π+ and about 8 protons / 200 collisions. Near horizontal plane

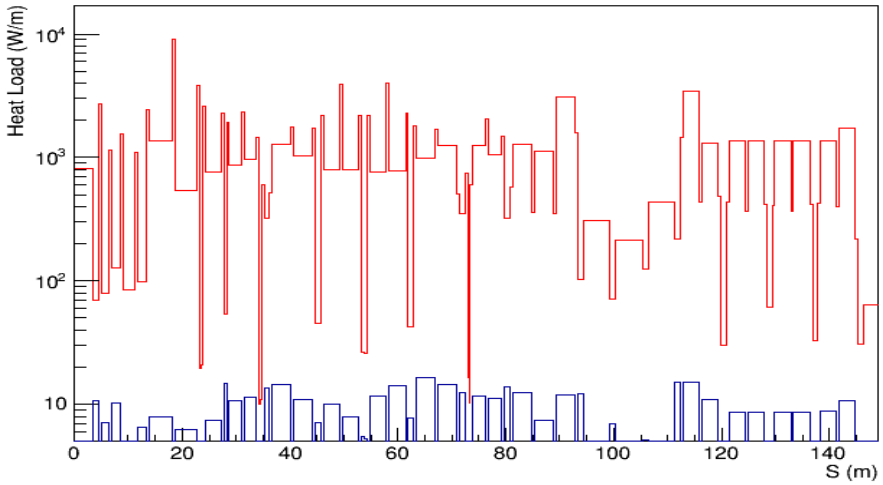
MARS15 Model of the Higgs Factory Muon Collider



HFMC: Protection of SC magnets and Detector



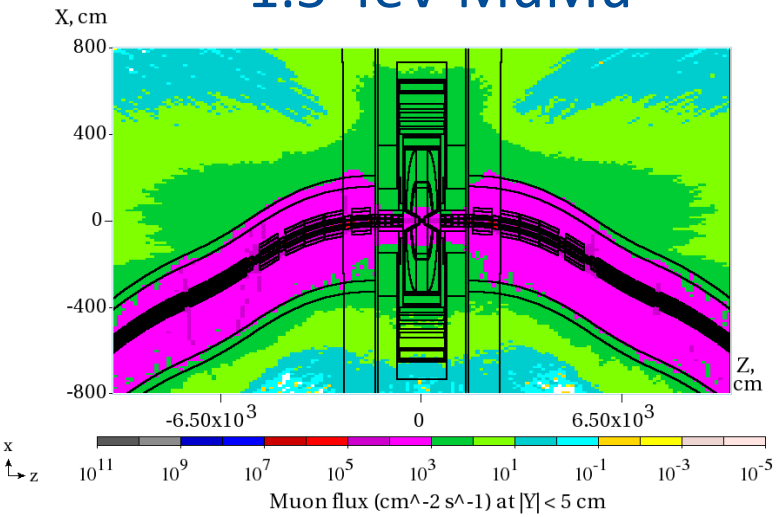
MARS15 model of the HFMC Machine-Detector Interface with a sophisticated tungsten nozzle near IP, collimators in interconnect regions and liners inside SC magnets – all resulted in **reduction of detector backgrounds** to the design limits.

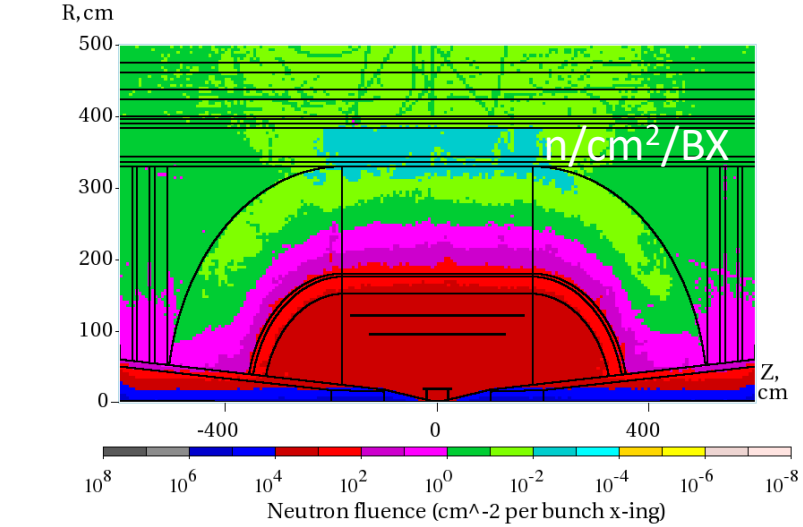


Collimators in interconnect regions and liners inside magnets in the ring have resulted in **x100 reduction of dynamic heat loads in the magnet superconducting coils**.

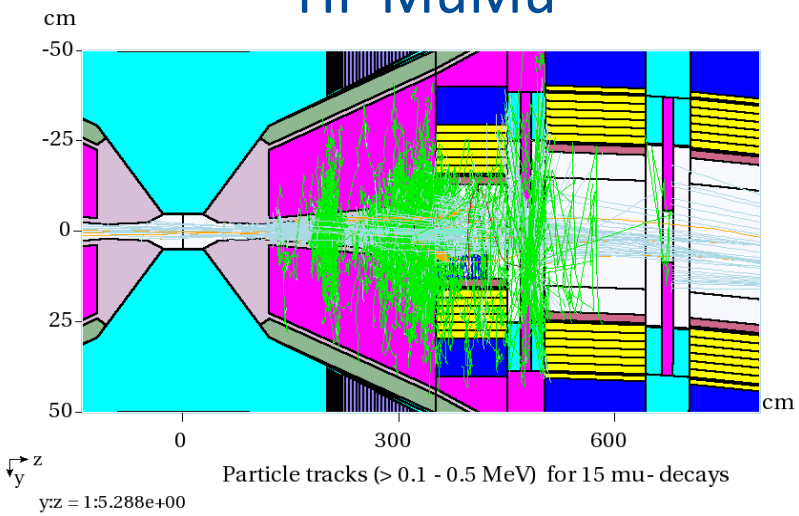
1.5-TeV and 125-GeV c.o.m. Muon Colliders

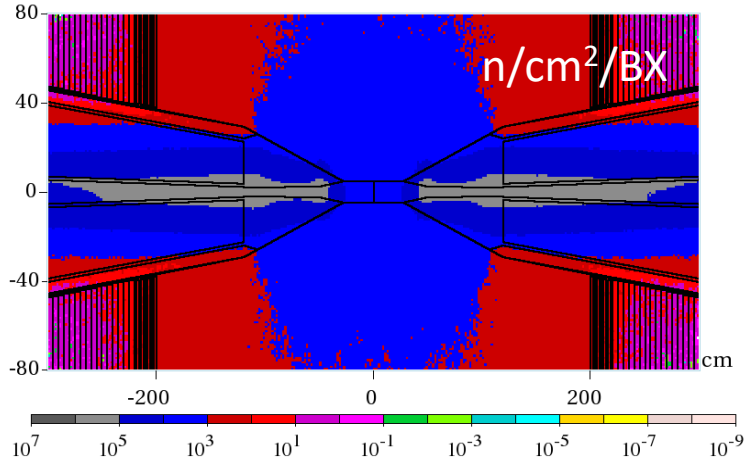
1.5-TeV MuMu





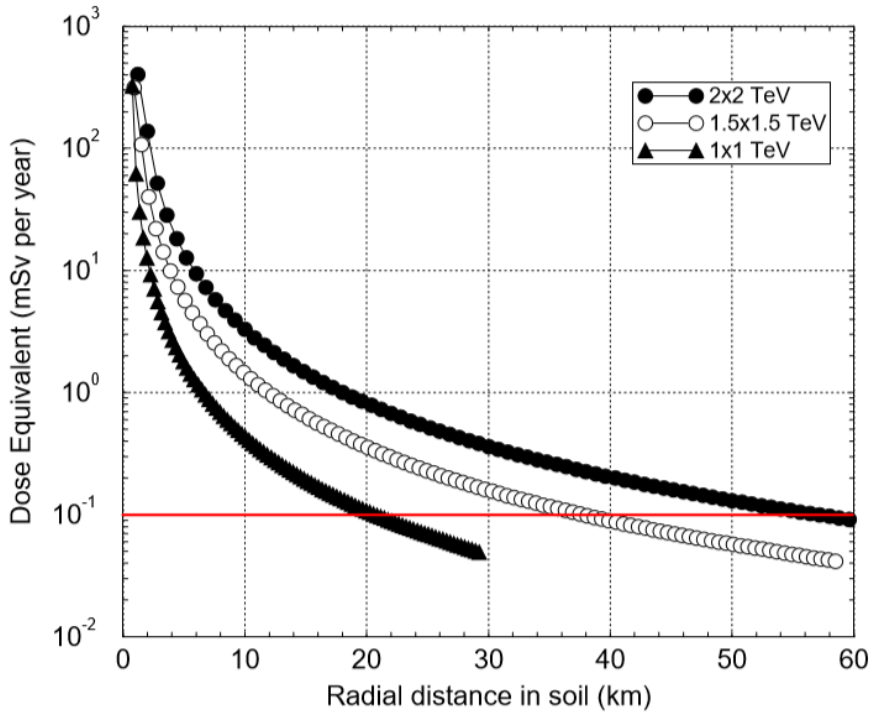
HF MuMu

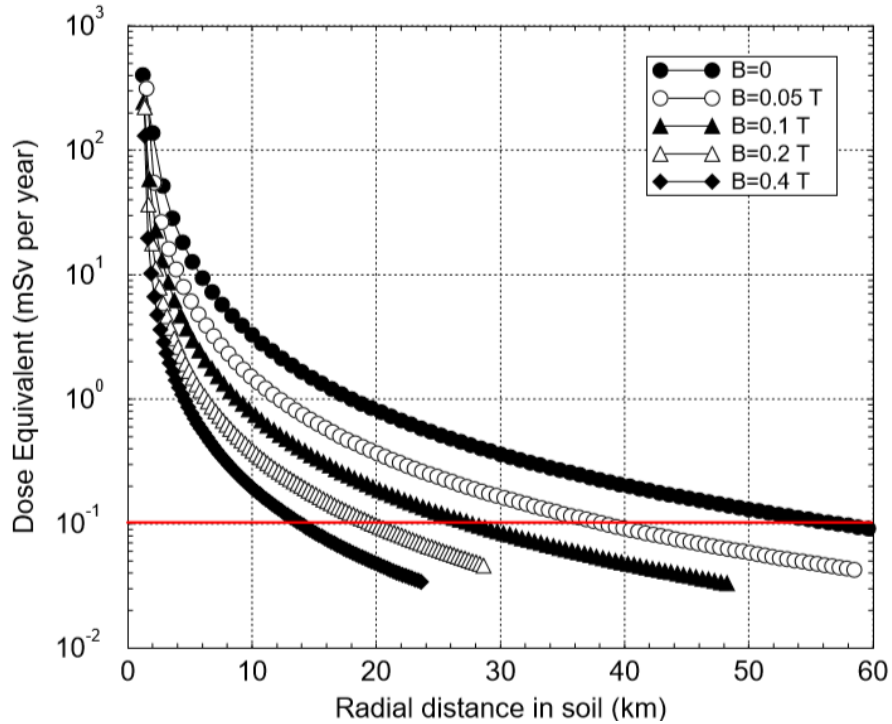




Neutrino-Induced Rad. Hazard at High-Energy Muon Colliders

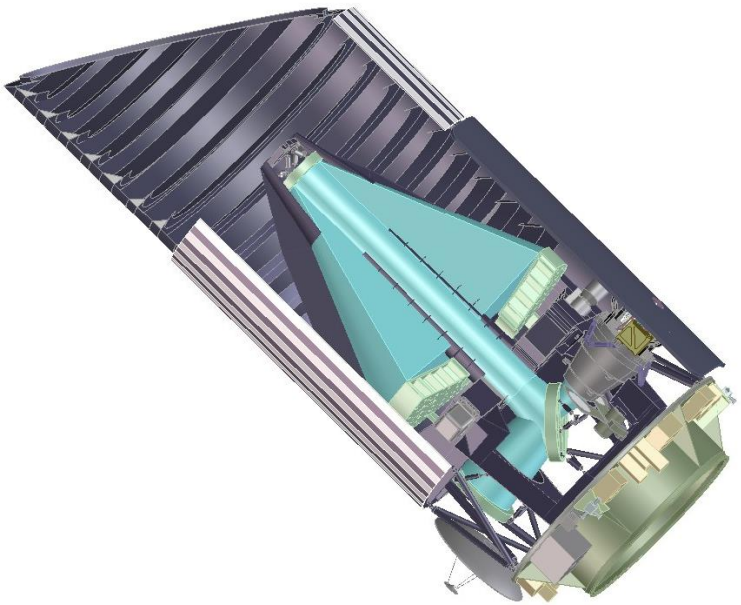
Maximum dose equivalent in muon collider orbit plane *vs* distance from ring center

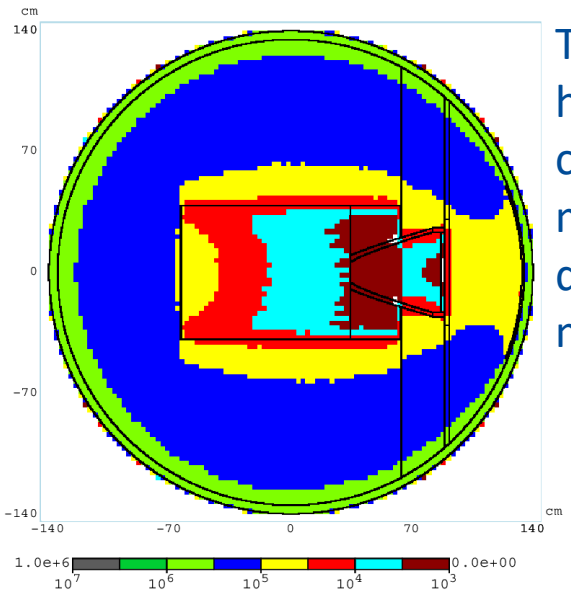




N.V. Mokhov and A. Van Ginneken, Neutrino Radiation at Muon Colliders and Storage Rings, J.Nucl.Sci.Tech. **37** (2000) 172-179

MARS Code for Space Exploration Missions and Acoustic Detection of Ultra-high Energy Neutrino (DUMAND)





Trapped-proton induced hadron flux in SNAP critical components. 40% performance degradation in photo detectors over a 4-year space mission

1. Supernova Acceleration project (SNAP): degradation of photo-detectors due to radiation induced by trapped protons. N.V. Mokhov, I.L. Rakhno, S.I. Striganov and T.J. Peterson, Fermilab-Conf-04/-55-AD (2004)
2. Active shielding of astronauts in long missions – conceptual possibilities (2019)
3. Acoustic detection of showers produced in ocean by ultra-high energy neutrino (DUMAND experiment) G.A. Askarian, B.A. Dolgoshein, A.N. Kalinovsky and N.V. Mokhov, Acoustic Detection of High-energy Particle Showers in Water, NIM **164** (1979) 267-278

MARS15 Computing Aspects

- Linux ≥ gcc-8.2 on 64 bit architectures which is ideal for modern c++ codes
- C++11 standard; gsl-2.5; ISO standard Fortran ⇔ C interface
- ROOT-6.16
- Many-core jobs (standard for decade); 10^2 to 10^5 cores routinely; improved submission scripts and built-in averaging
- Genuine MPI mode is now used more and more often; to eliminate discovered scalability bottleneck, common physics data (x-sections etc.) are accessed via a shared memory window (MPI-3 feature)
- At Fermilab, run on heimdall/heimdallr and - for 8 years - on Fermigrid in four MARS groups - marslbne, marsmu2e, marsgm2, and marsaccel - with an excellent support from Scientific Computing Division. New marspip2 group was recently created
- Also, theta of ALCF with its 11.69 petaflops peak performance

What's Next

- Complete implementation of ROOT histograming to MARS
- Complete development of an exclusive modeling in the TENDL module of the MARS event generator
- Complete development of a module for user-friendly calculation of 3D residual dose maps around accelerator equipment
- Put further efforts on CAD -> ROOT -> CAD user-friendly geometry converters
- Minimize a loss in scalability with # of MPI ranks > 4×10^4 on the current petaflop platform and prepare to the exascale computing era
- Put further efforts on update of the MARS User's Guide
- Perform new developments in MARS related to the PIP-II project, complete tests as needed and launch production runs