Radiation Effect Modeling: Status, Uncertainties and Benchmarking Needs

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Workshop on Radiation Effects
in Superconducting Magnet Materials
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Outline

- Subject and Issues
- Particle and Nuclide Production
- Electromagnetic Interactions
- Energy Deposition
- DPA and Radiation Damage
- Radiation Shielding

Subject and Issues

What? Primarily, production solenoids of Mu2e, COMET and Muon Collider (E_p = 1-15 GeV), but also other superconducting setups in radiation fields

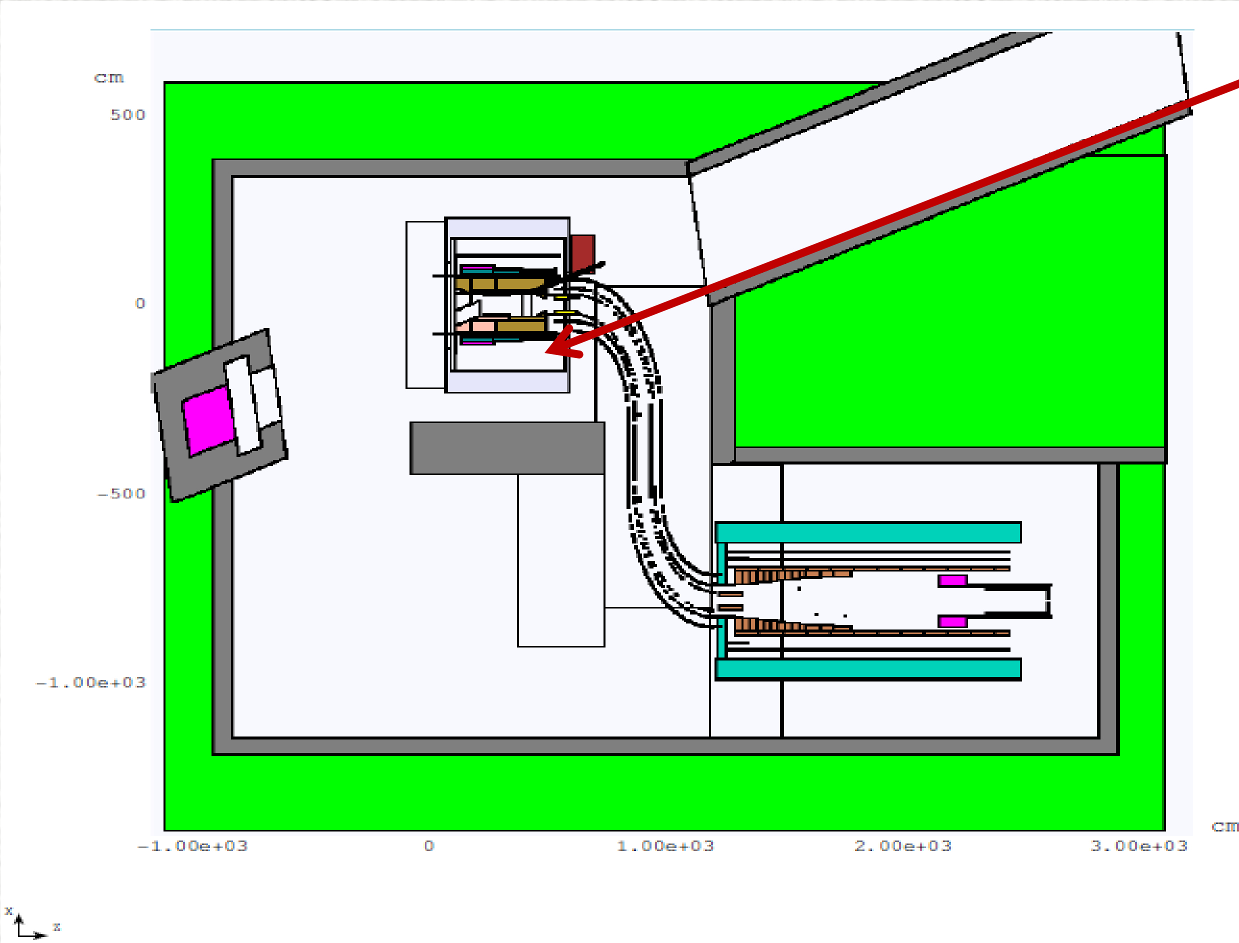
Issues:

- Maximize useful particle & minimize background particle yields (also a primary source of all radiation effects considered here)
- Quench, integrity & lifetime: power density and integrated dose in critical components, e.g., SC coils, organic materials etc.
- Radiation damage to superconducting and stabilizing materials: DPA, helium gas production, integrated particle flux
- ES&H aspects: shielding, nuclide production, residual dose, impact on environment. Not forget electronics (SEU etc.)

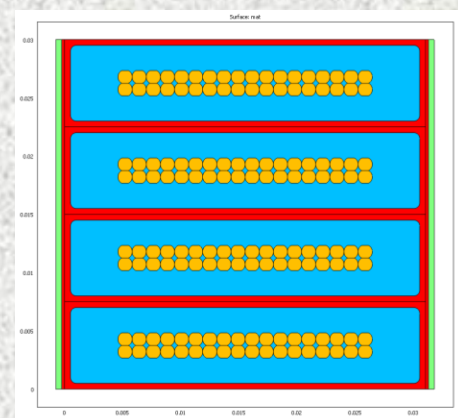
Attacked via thorough simulations.

How reliable are they?

RRR Degradation: DPA limit for SC coils = 2.5E-5 /yr



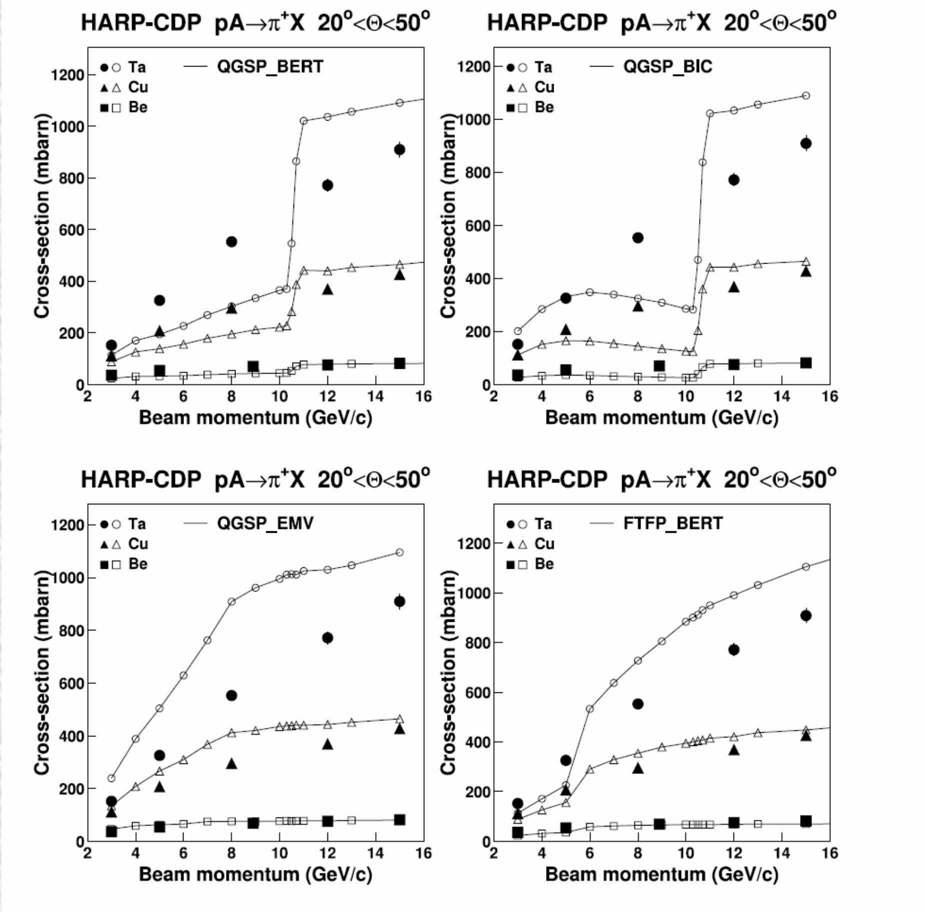
8-GeV p, 25 kW
2.e13 p/s
$\sigma_x = \sigma_y = 1mm$
Gold water-cooled target (r=3mm, L=160mm)

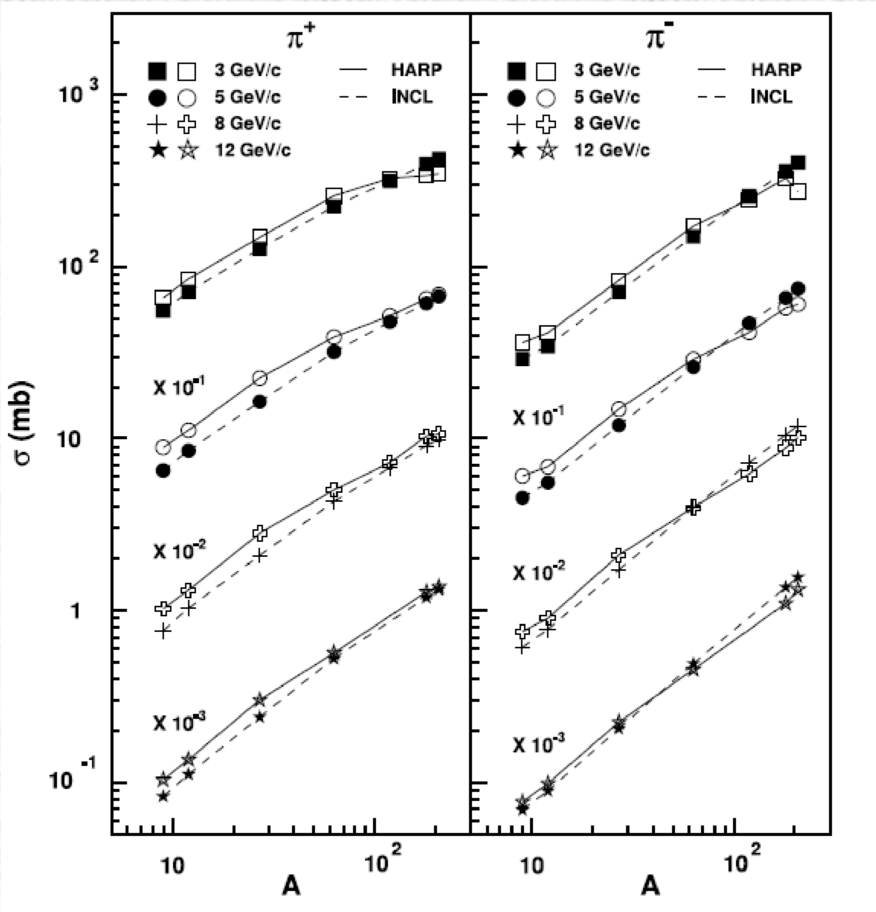


Coil materials:
8.35% NbTi
8.35% Cu
17.33% G10
65.97% Al

Bottleneck: degradation of Residual Resistivity Ratio (RRR) of **stabilizer** (ratio of electric resistivity of a conductor at room temperature to that at the liquid He one).

Pion Production Cross-Sections at 3-15 GeV/c



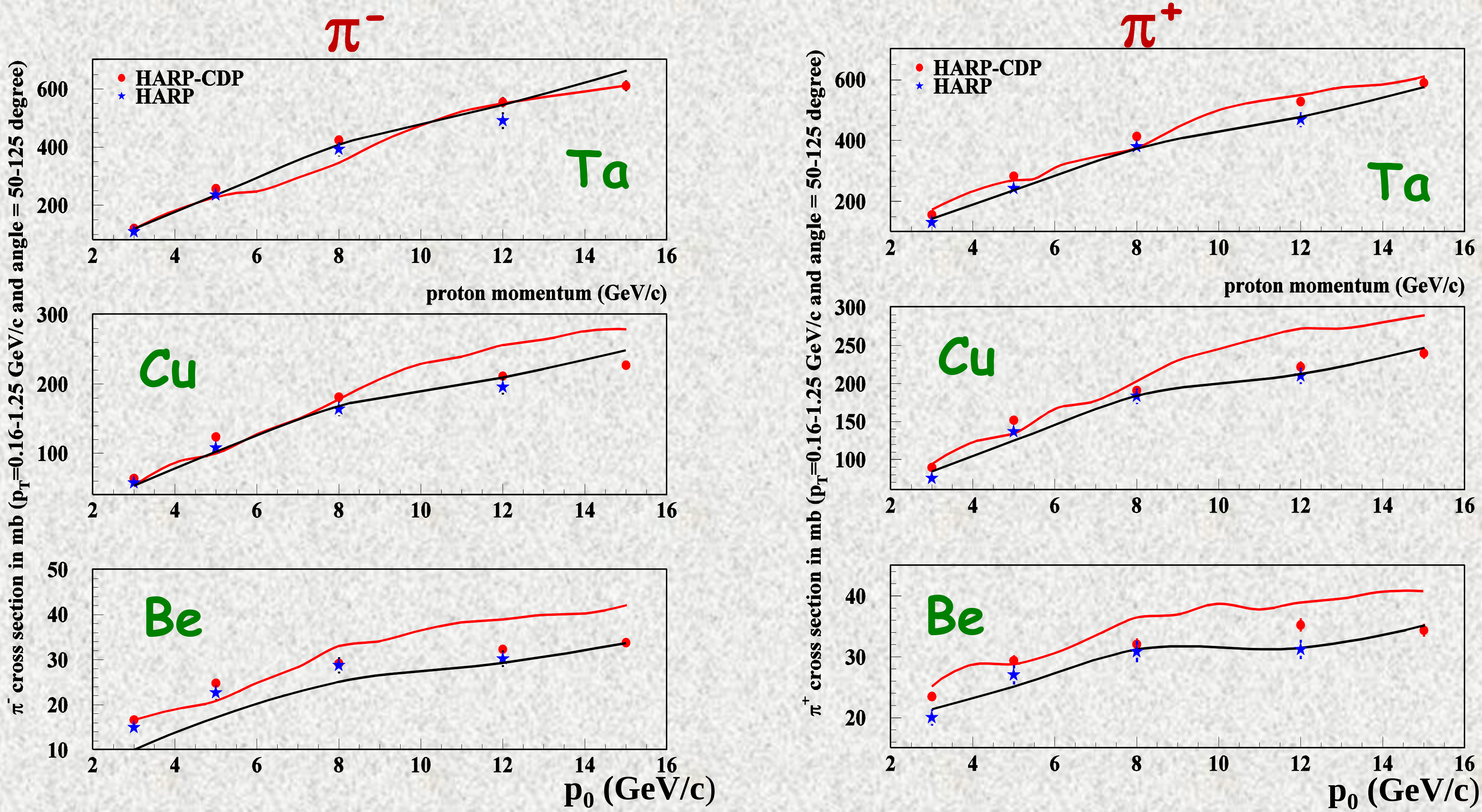


3-15 GeV/c p on Be, Cu and Ta:
GEANT4 models vs HARP

INCL-HE vs HARP

Pion Production Cross-Sections at 3-15 GeV/c

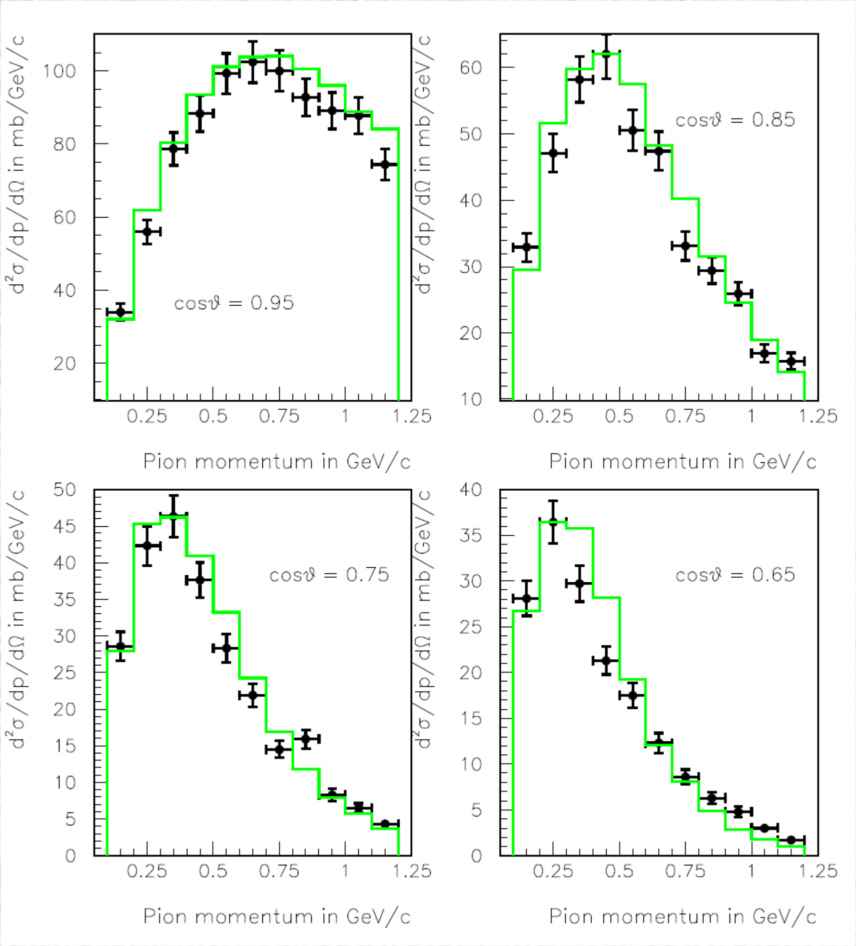
Protons on Be, Cu and Ta: FLUKA and MARS15/LAQGSM vs HARP



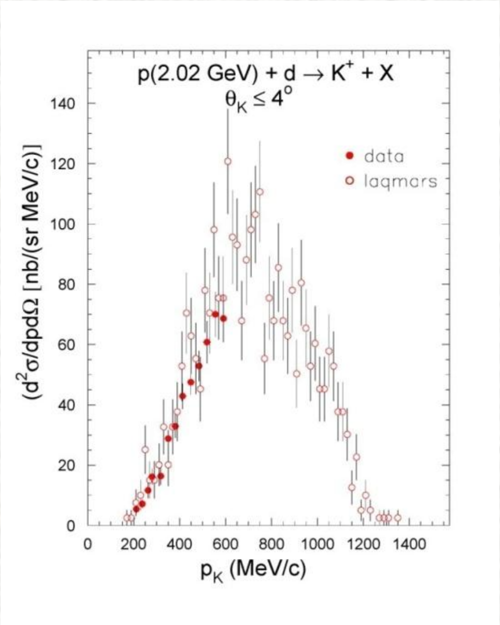
Red lines - FLUKA, black lines - LAQGSM

Red lines - FLUKA, black lines - LAQGSM

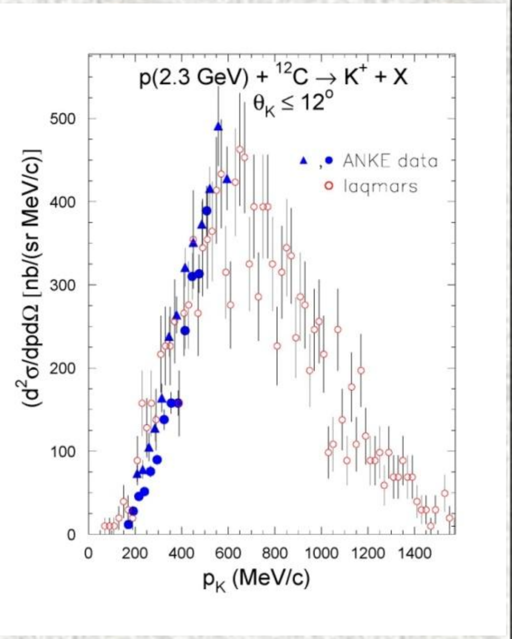
Pion and Kaon Production in MARS15/LAQGSM



12.3 GeV/c p+Be -> π^- vs BNL E910

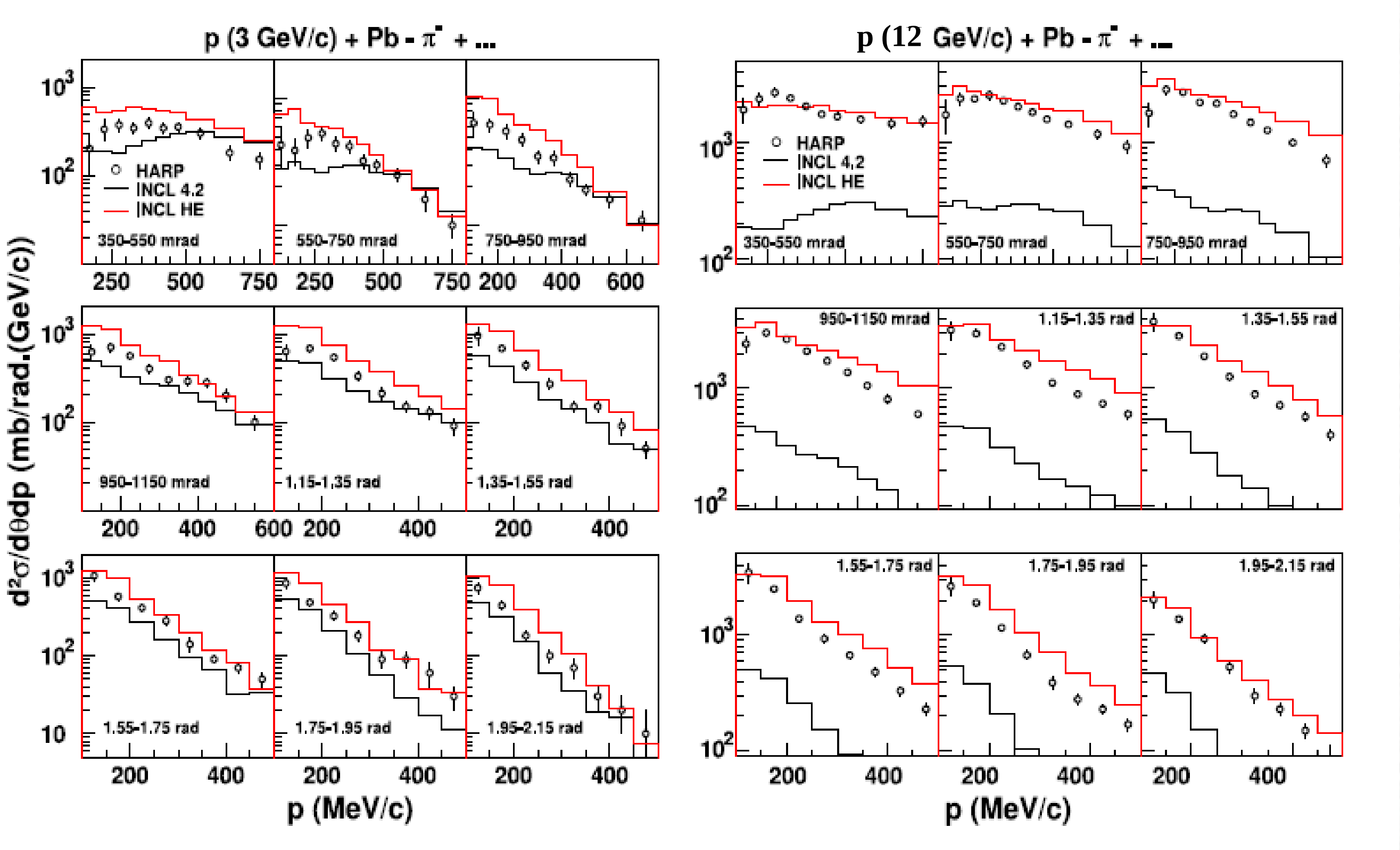


2.02 GeV p+d -> K^+



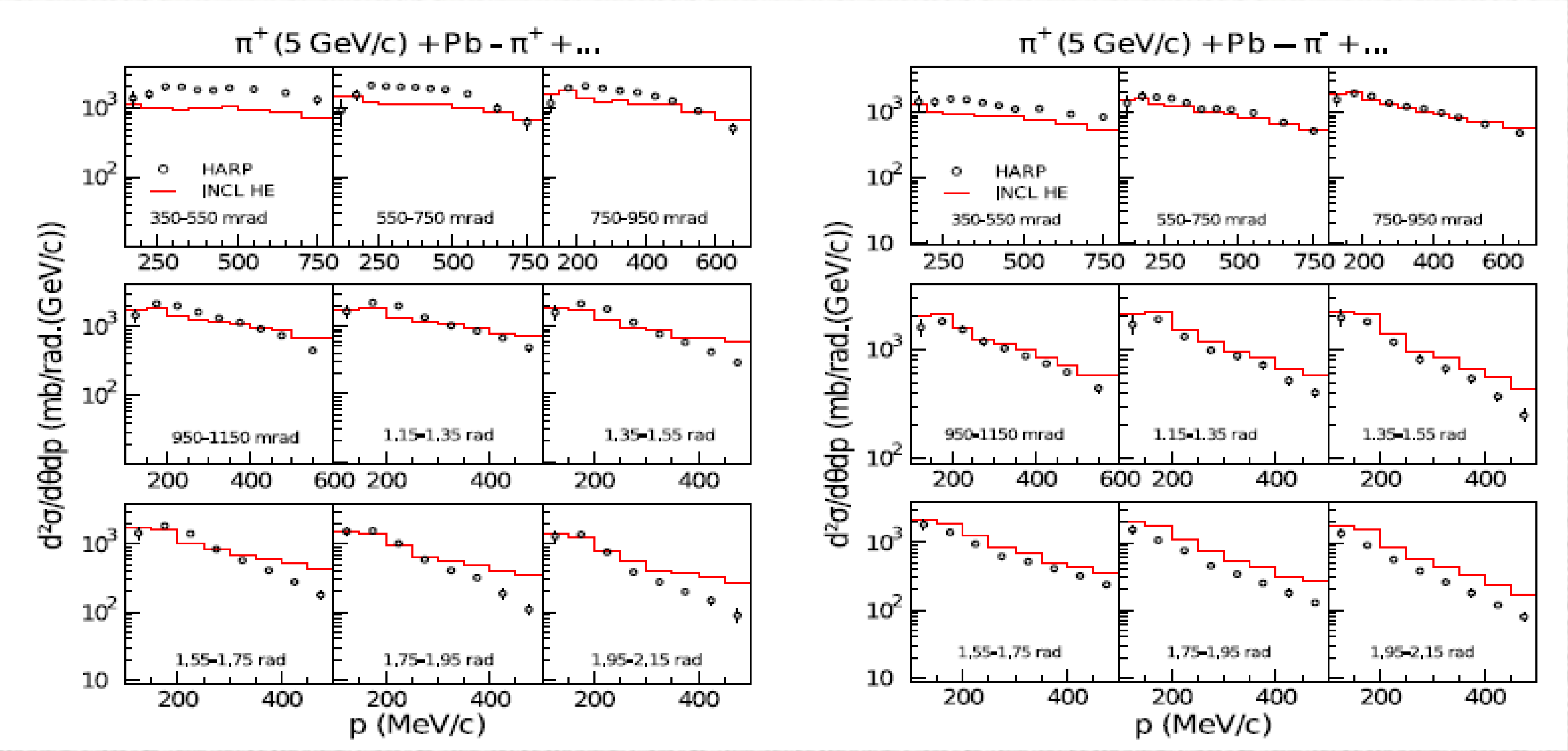
2.3 GeV p+C -> K^+

p+Pb →π^-X Differential x-sections at 3 and 12 GeV/c



Old INCL-4.2 (black) and new INCL-HE (red) vs HARP

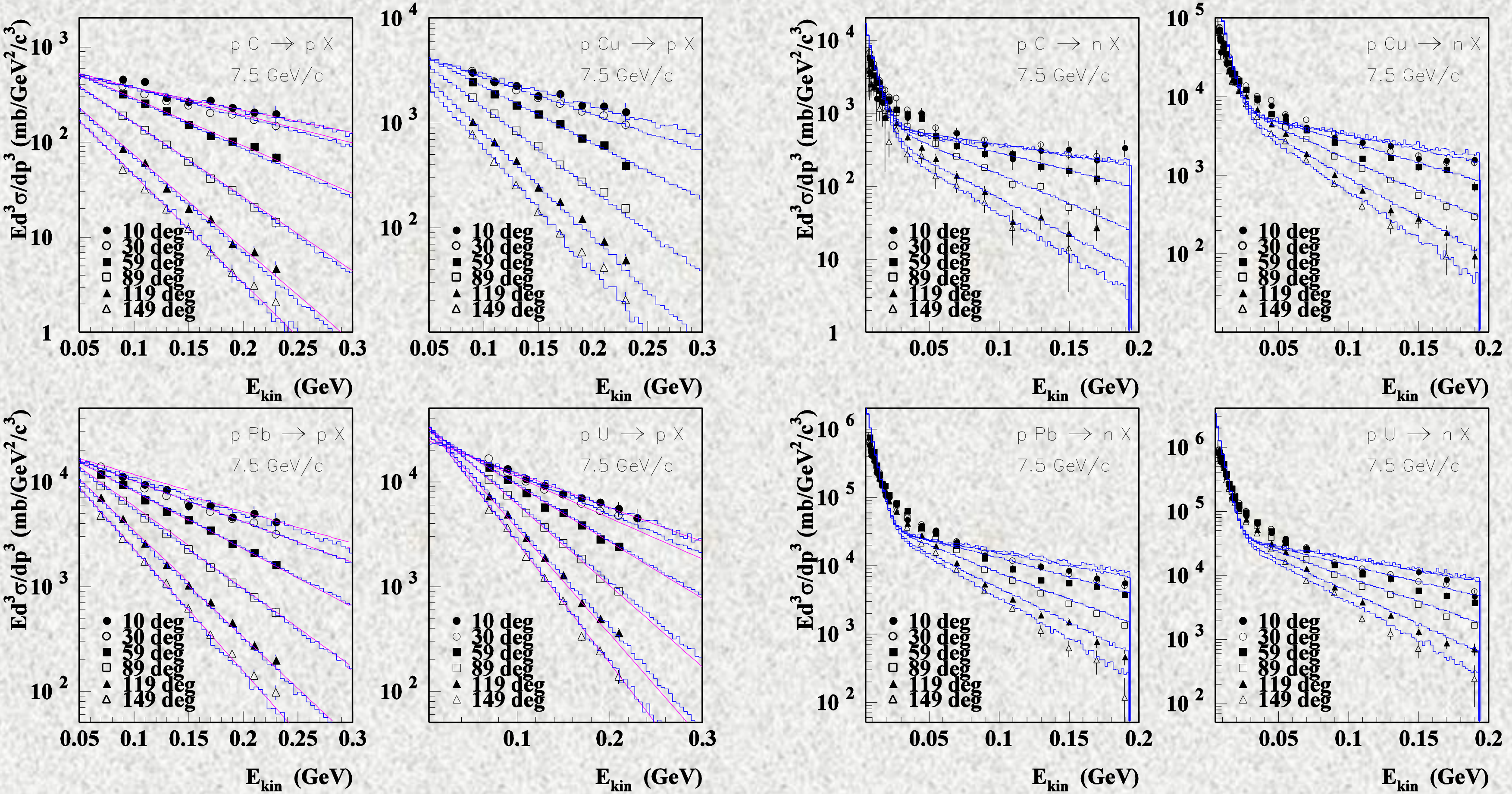
Pion Production in 5 GeV/c π^+Pb Interactions



INCL-HE vs HARP

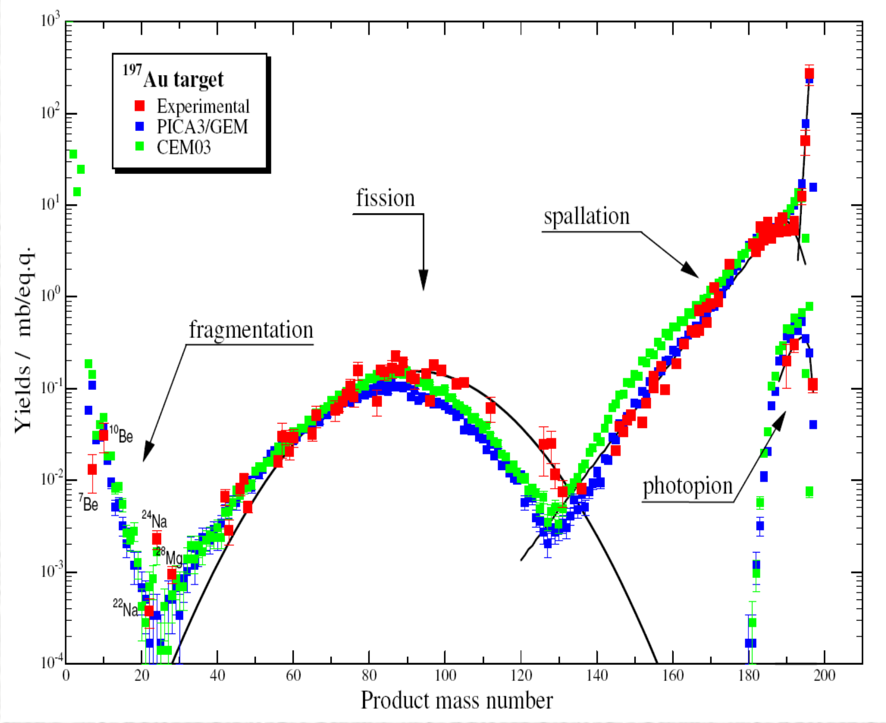
Low-Energy Nucleon Production in MARS15

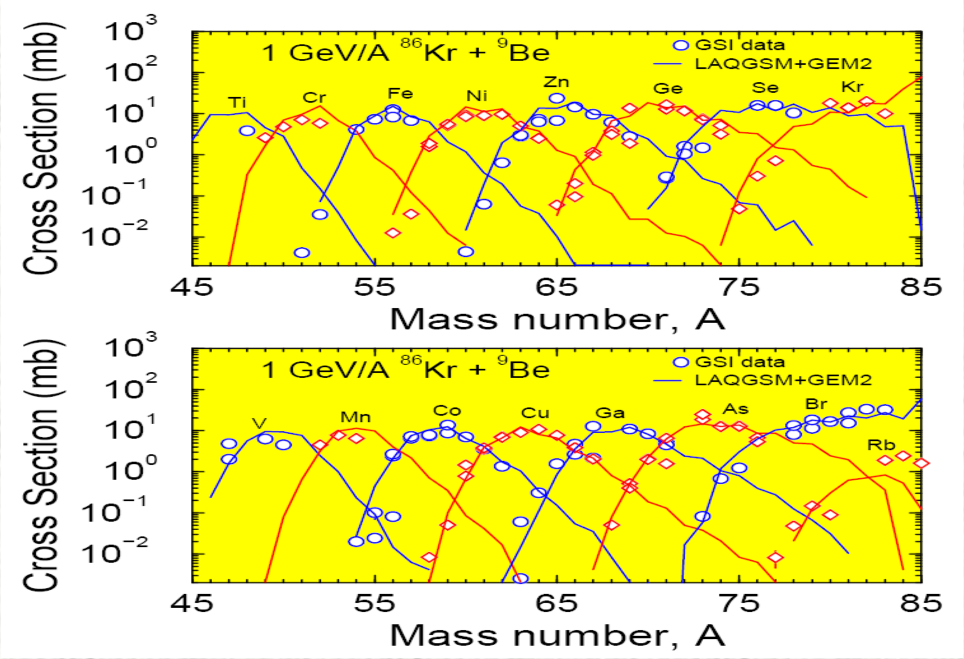
7.5 GeV/c protons on C, Cu, Pb and U



Nuclide Production

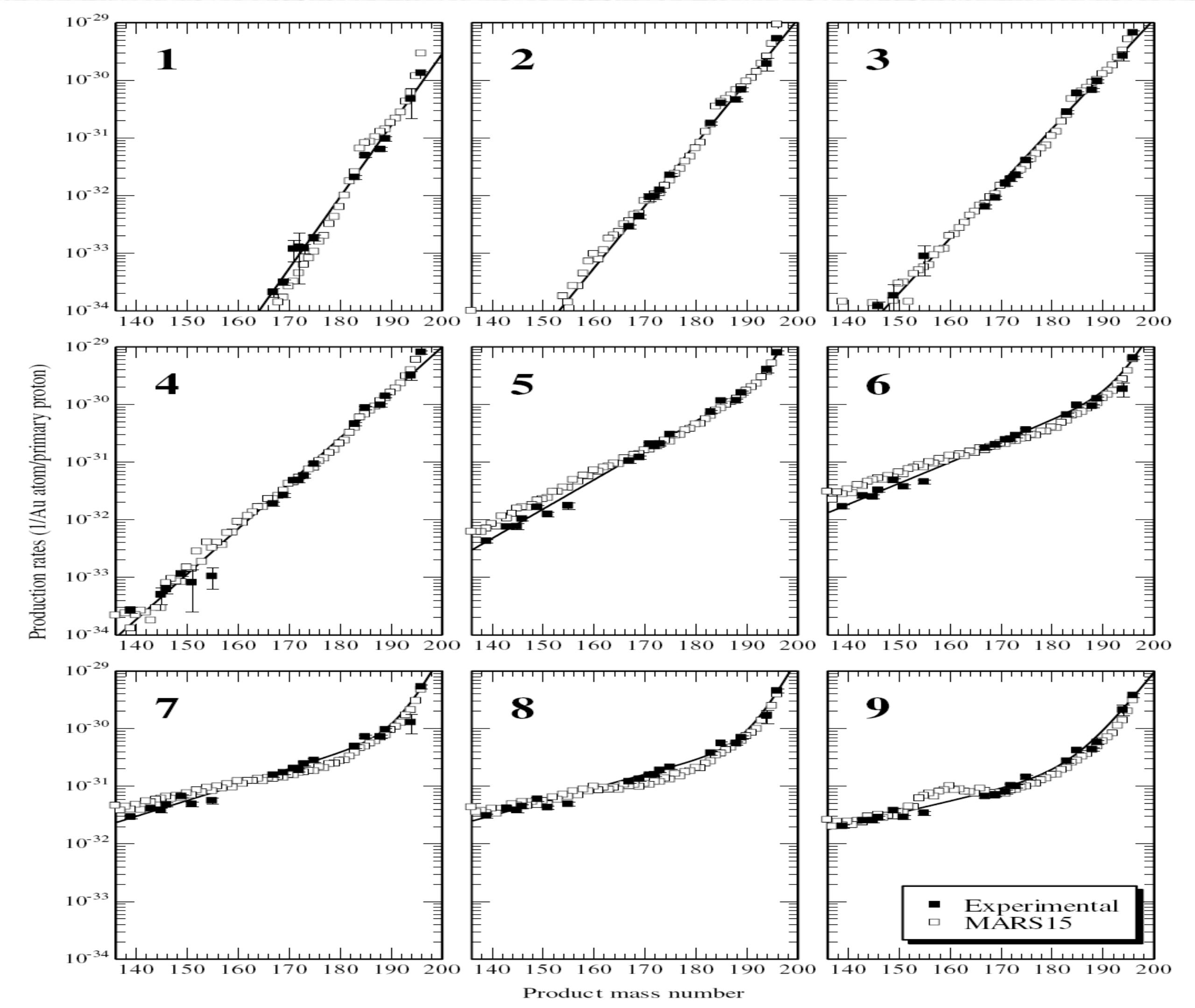
Bremsstrahlung (E_{max}=1 GeV) on gold

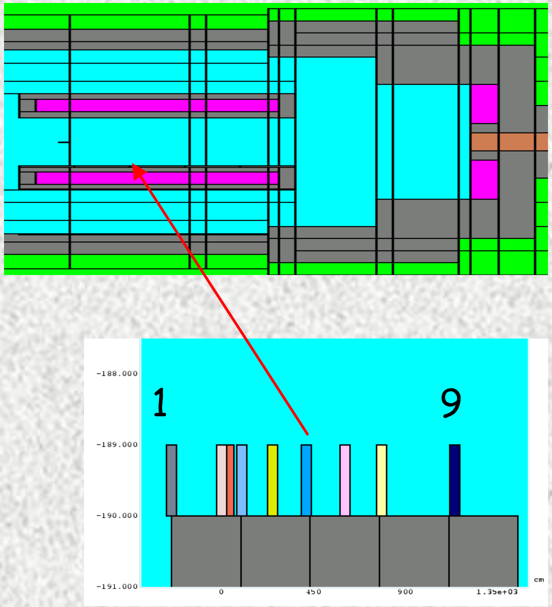




1 GeV/A ^{86}Kr + ^{9}Be

Nuclide Production at 12-GeV K2K Target Station





Nine gold foil samples over 12 meters

Courtesy: T. Suzuki and H. Matsumura

Particle and Nuclide Production at 1-15 GeV: Status and Needs

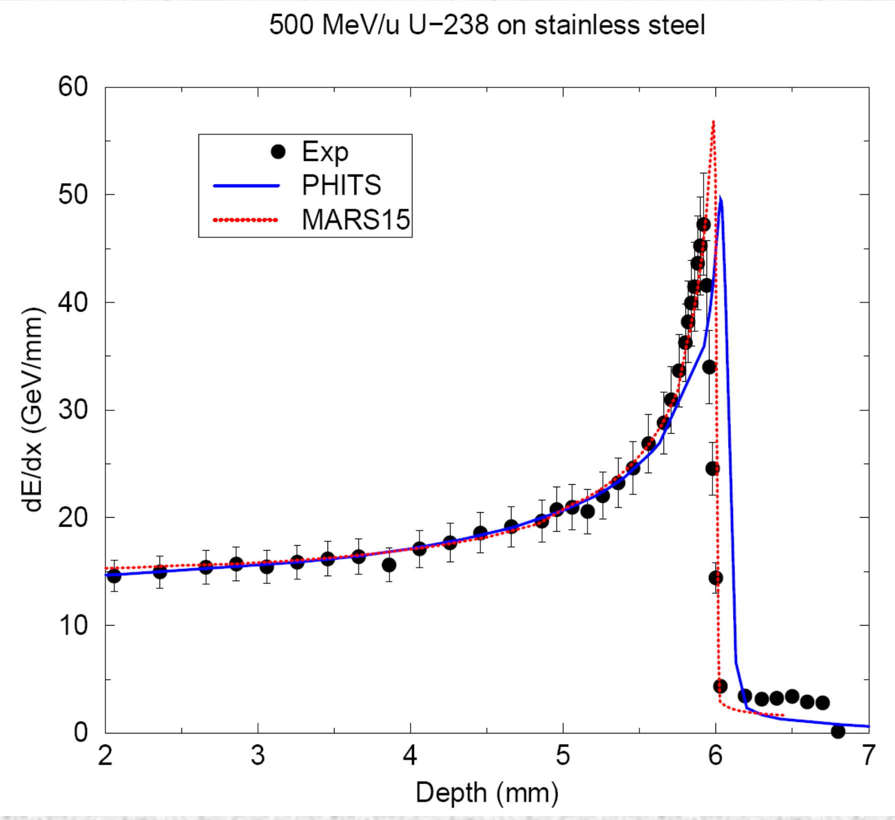
- Production x-sections (total particle yields) modeled with the current versions of MARS15, FLUKA and INCL-HE agree within 10% with data. These code's event generators (for MARS15: CEM, LAQGSM and inclusive) predict general features of double differential x-sections, but can disagree with data up to a factor of 2 to 3 in some phase space regions. There are noticeably larger problems with GEANT4 models.

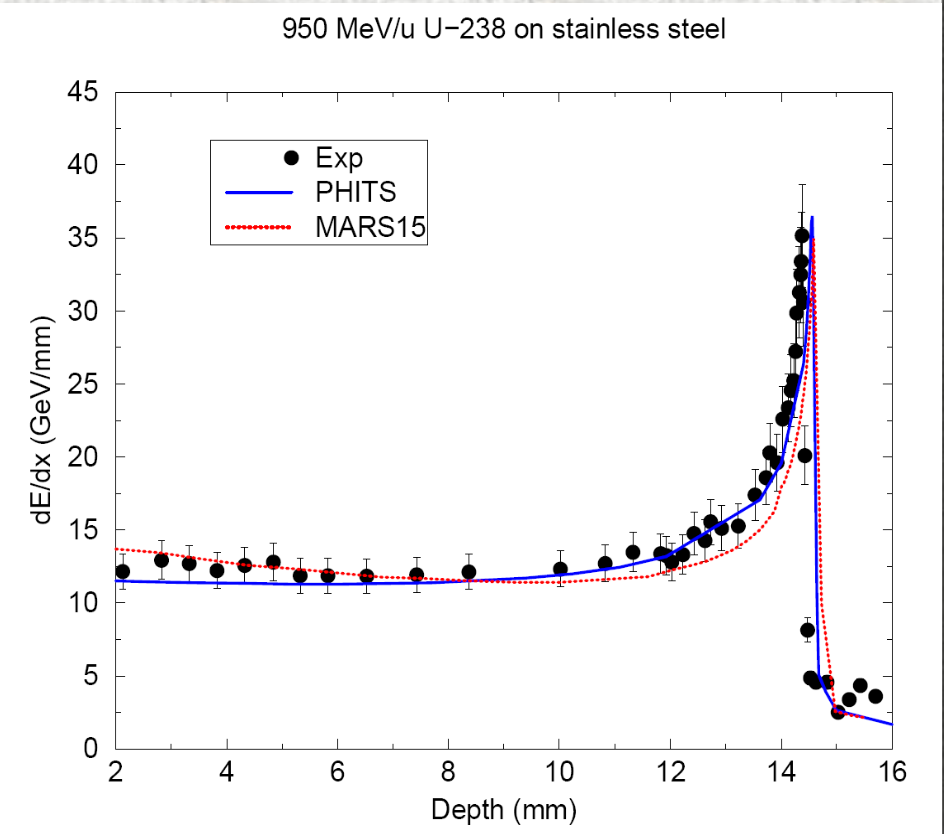
- Nuclide production is described quite reliably by the event generators of the above three codes, although there are issues with some channels.

- **Models/Codes:** model developments in transition region (2-7 GeV) and at E_p=1-30 MeV; add PHITS predictions to the above benchmarking; more work on GEANT4.

- **Data needs:** low-energy pion/kaon/pbar spectra at E_p=2-7 GeV; neutrons in fragmentation region; light fragment yields; nuclide yields for difficult cases; more ion and photon induced reactions.

500 and 950 MeV/u U-238 on Stainless Steel





MARS15 and PHITS vs GSI data

120-GeV Muon Range-out Distance (meters) in LBNE Dolomite

	All dolomite	Dolomite after absorber
MARS15	223.7	214.5
FLUKA	223	218

Notes:

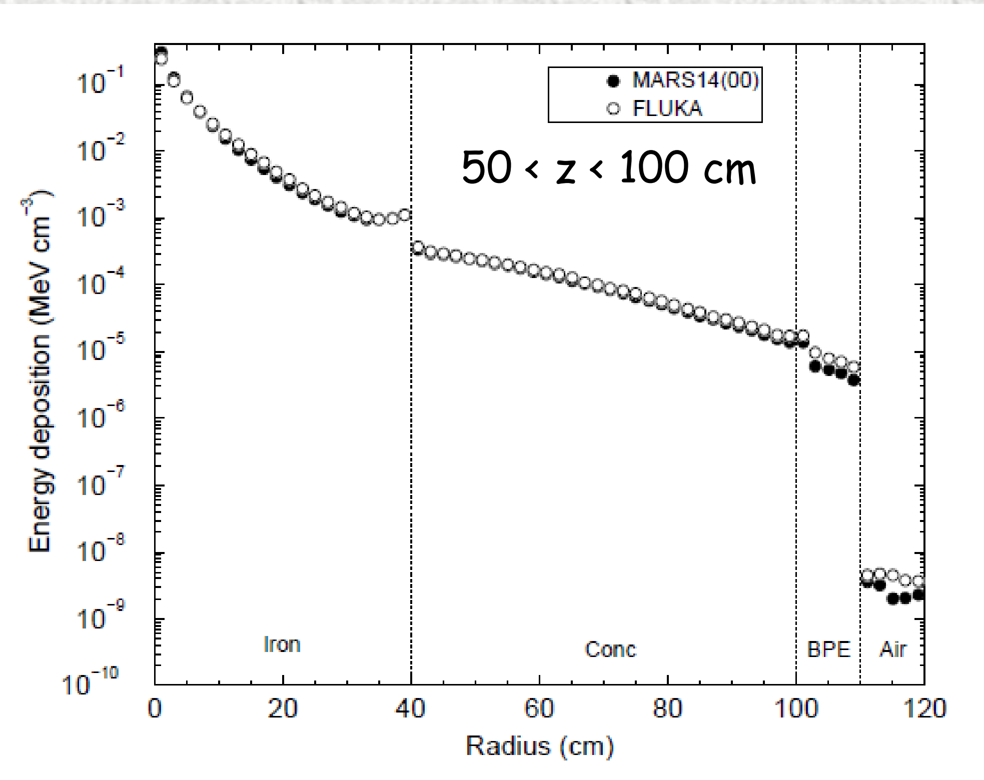
1. All-dolomite FLUKA and MARS results are in a **perfect agreement over 9 decades** of muon survival distribution.
2. Absorbers were slightly different in two models, resulting in a ~2% difference for the second case.

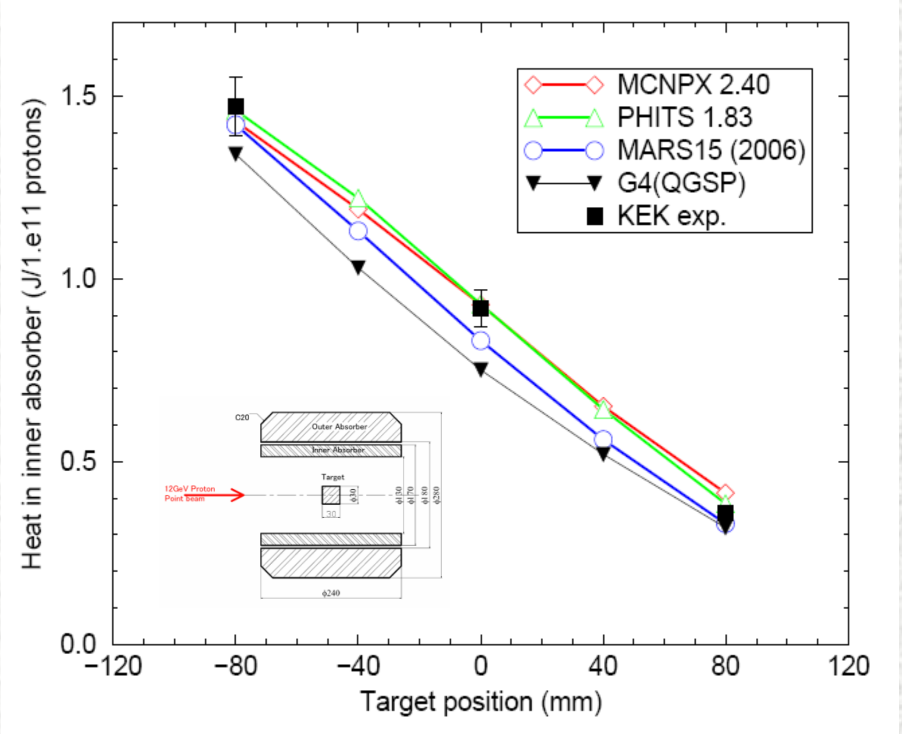
Electromagnetic Interactions: Status and Needs

- Coulomb scattering and ionization and radiative energy losses are described with a percent level accuracy in the considered codes at both CSDA and (in many cases) differential levels.
- **Models/codes:** Accurate description of particle and heavy-ion dE/dx down to ~1 keV in mixtures is mandatory; precise algorithms for Coulomb scattering especially for heavy ions.
- **Data needs:** Whatever possible to help with the previous bullet.

Energy Deposition

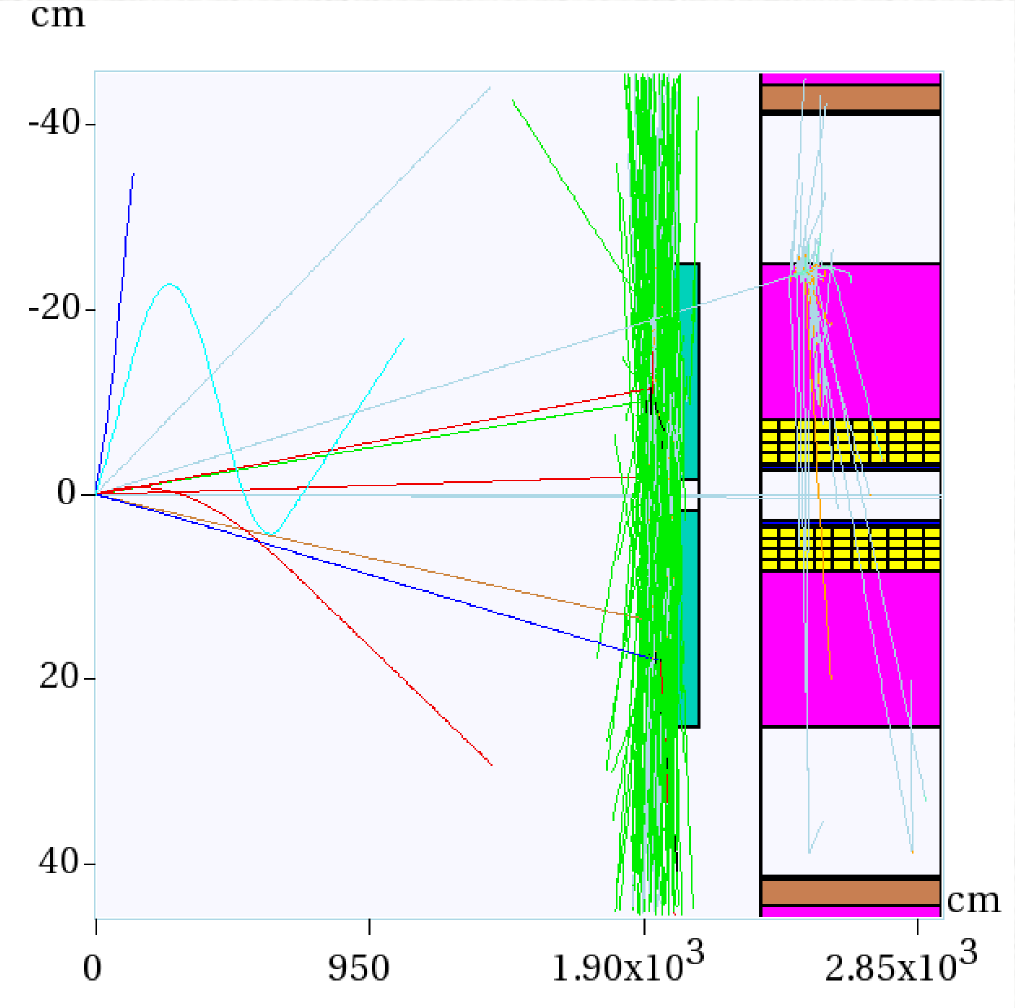
10 GeV/c p on 2-m long radial sandwich cylinder

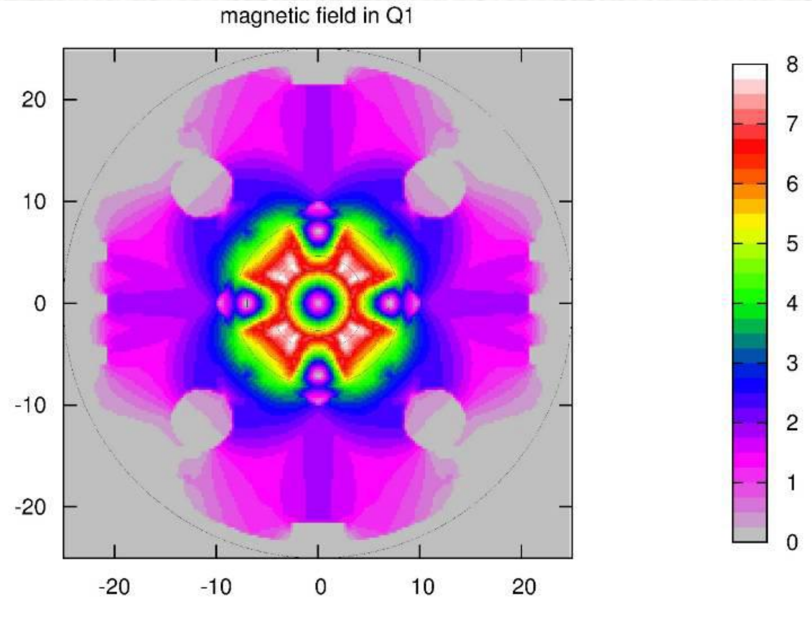




12 GeV p on KEK Copper target

IR5 Inner Triplet Simplifed Model





Running FLUKA and MARS for $\sqrt{S}$ = 14 TeV and L=10^{35} (2008)

FLUKA 2006.3 and MARS15 (2008) Intercomparison

Total heat loads in the insertion region elements (W) for upgrade luminosity L=10*L0

	FLUKA	+/- (%)	MARS	+/- (%)	Ratio FLUKA/MARS
TAS	1853.7	0.5	1827.3	0.1	1.01
Beam pipe	89.1	1.0	97.9	0.4	0.91
Q1 cable	158.0	0.6	159.1	0.2	0.99
yoke	96.3	0.9	78.5	0.4	1.23
aluminium layer	2.3	0.6	2.4	0.5	0.98
mylar insulation	19.5	0.8	20.4	0.3	0.96
stainless steel vessel	16.8	0.8	17.3	0.3	0.97

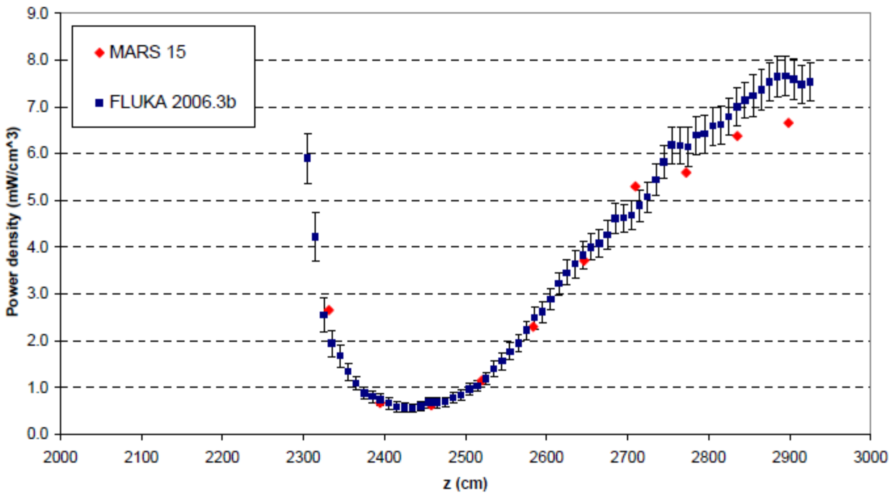


Figure 8: Azimuthal averaged power density in cable1 along Q1

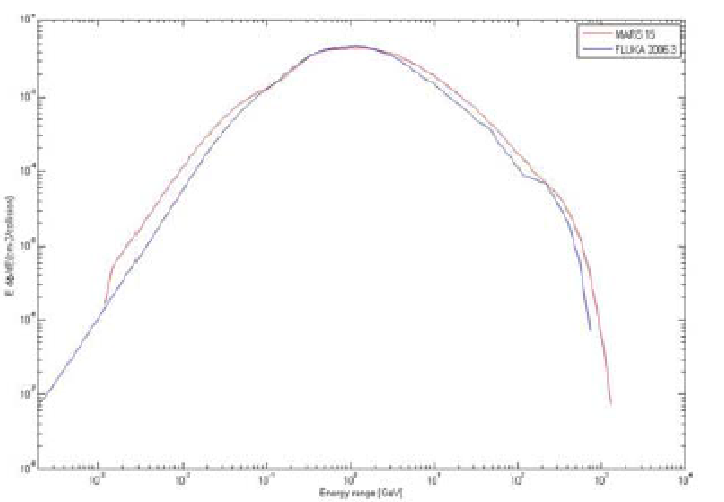
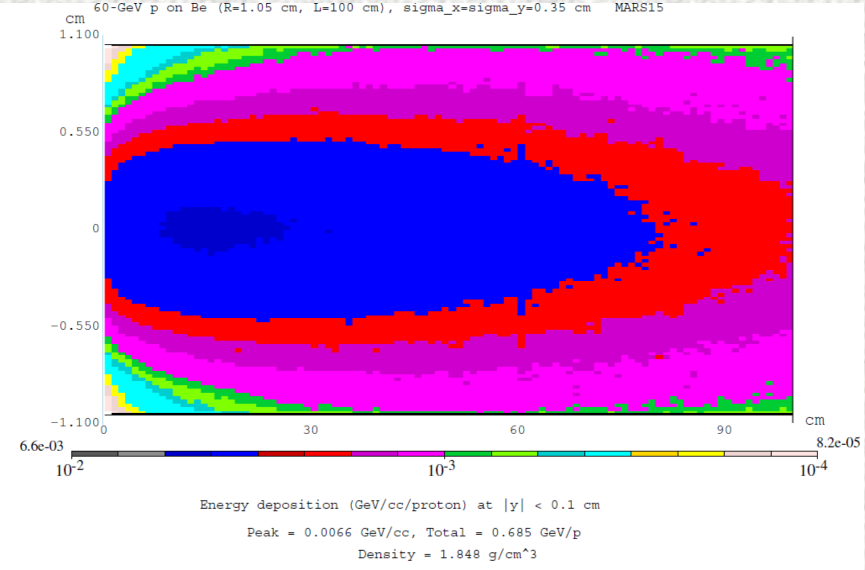


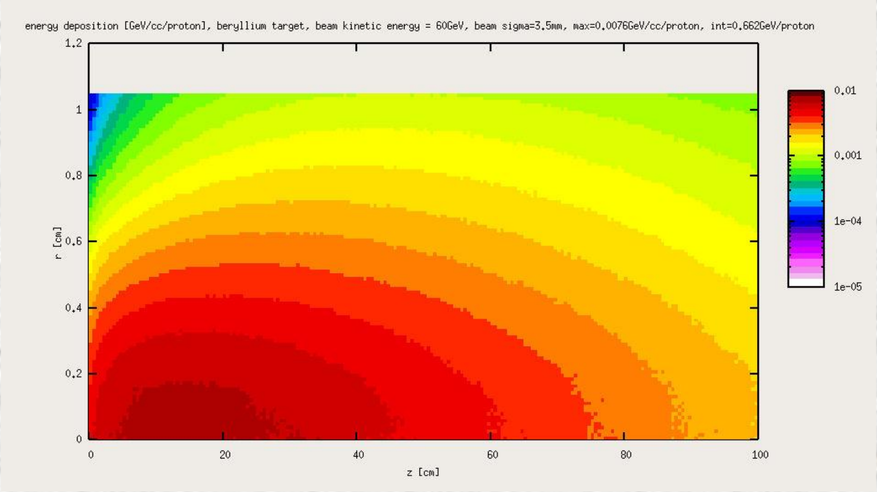
Figure 12: Pion and kaon spectra in cable1

LBNE Target: MARS15/FLUKA Intercomparison

60-GeV protons (σ_x=σ_y=0.35 cm)
on Be target (R=1.05 cm, L=100 cm)

	MARS15	FLUKA
Peak (GeV/cc)	0.0066	0.0076
Total (GeV)	0.685	0.662





Energy Deposition: Status and Needs

- Comparison to data and FLUKA/MARS (and recently PHITS) intercomparison reveal ~10% accuracy in majority of cases.
- **Models/codes:** All of the above on nuclear and electromagnetic modeling; the key is precise description of material properties, geometries, magnetic fields and source terms.
- **Data needs:** Longitudinal and lateral energy deposition profiles in fine-segmented setups with combination of low-Z and high-Z composite materials for primary beam (heavy ions), hadron, electron and low-energy neutron dominated cases.

Consequences of High DPA in SC Coils

1. Higher electrical resistivity at 4.5K/lower RRR:
   - Higher peak temperature during quench
   - Higher resistive voltage across the coil during quench
   - Reduced stability against heat pulses

2. Lower thermal conductivity at 4.5K:
   - Increased temperature increment across the coil
   - Reduced thermal margin
   - Reduced stability against heat pulses

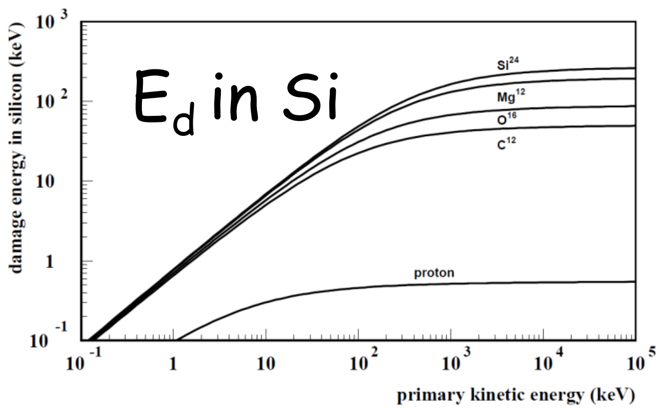
RRR change by a factor of 2 leads to the temperature change by ~50 mK

DPA Model in MARS15 (in one slide)

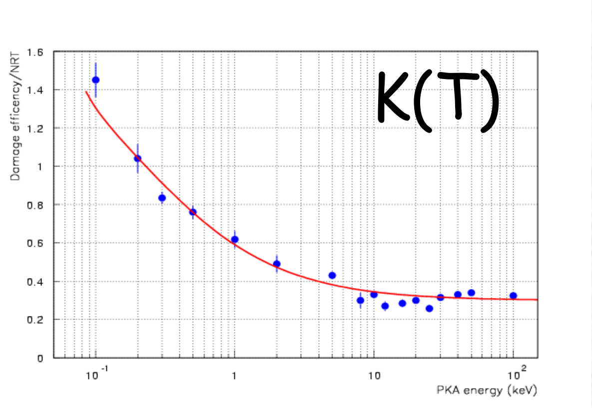
Norgett, Robinson, Torrens (NRT) model for atomic displacements per target atom (DPA) caused by primary knock-on atoms (PKA), created in elastic particle-nucleus collisions, with sequent cascades of atomic displacements (via modified Kinchin-Pease damage function ν**(T)**), displacement energy T_d (irregular function of atomic number) and displacement efficiency **K(T)**.

$$\sigma_d(E) = \int_{T_d}^{T_{\max}} \frac{d\sigma(E,T)}{dT}\nu(T)dT$$

$$\nu(T) = \begin{cases} 0 & T < T_d \\ 1 & T_d \le T < 2.5T_d \\ k(T)E_d/2T_d & 2.5T_d \le T \end{cases}$$



M. Robinson (1970)

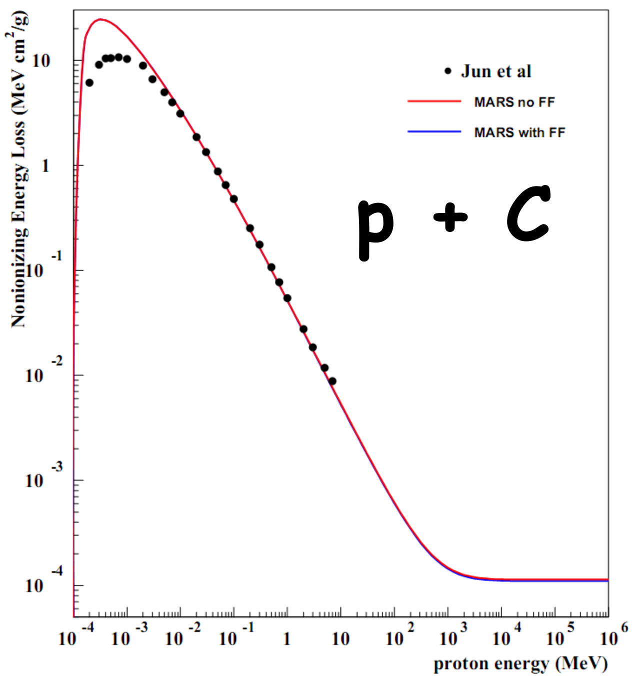


R. Stoller (2000), G. Smirnov

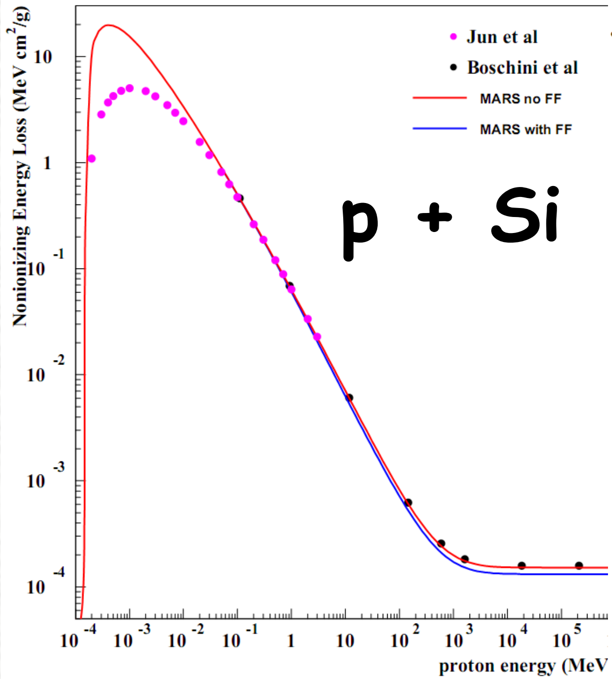
All products of elastic and inelastic nuclear interactions as well as Coulomb elastic scattering of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV. Coulomb scattering: Rutherford cross-section with Mott corrections and **nuclear form factors for projectile and target** (important for high-Z projectiles and targets, see next two slides).

Comparing MARS15 with Most Recent Models

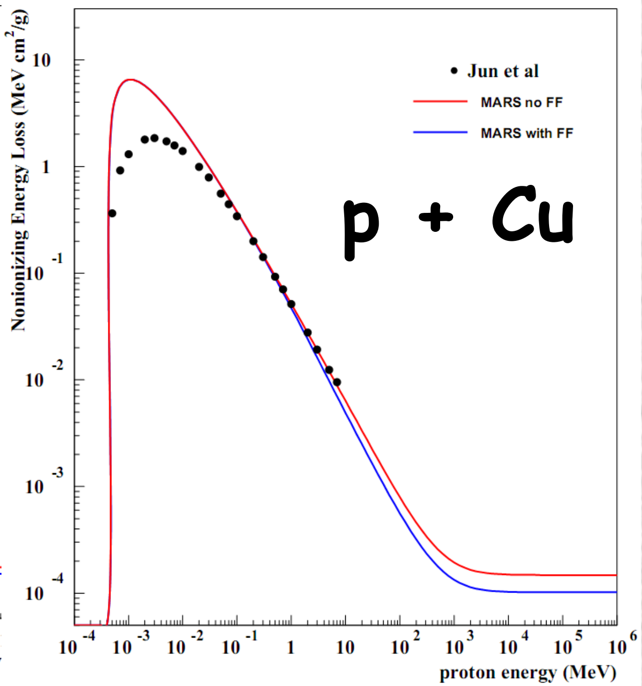
I.Jun, "Electron Nonionizing Energy Loss for Device Applications",
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 6, DECEMBER 2009



Proton NIEL for carbon due the Coulomb scattering



Proton NIEL for silicon due the Coulomb scattering

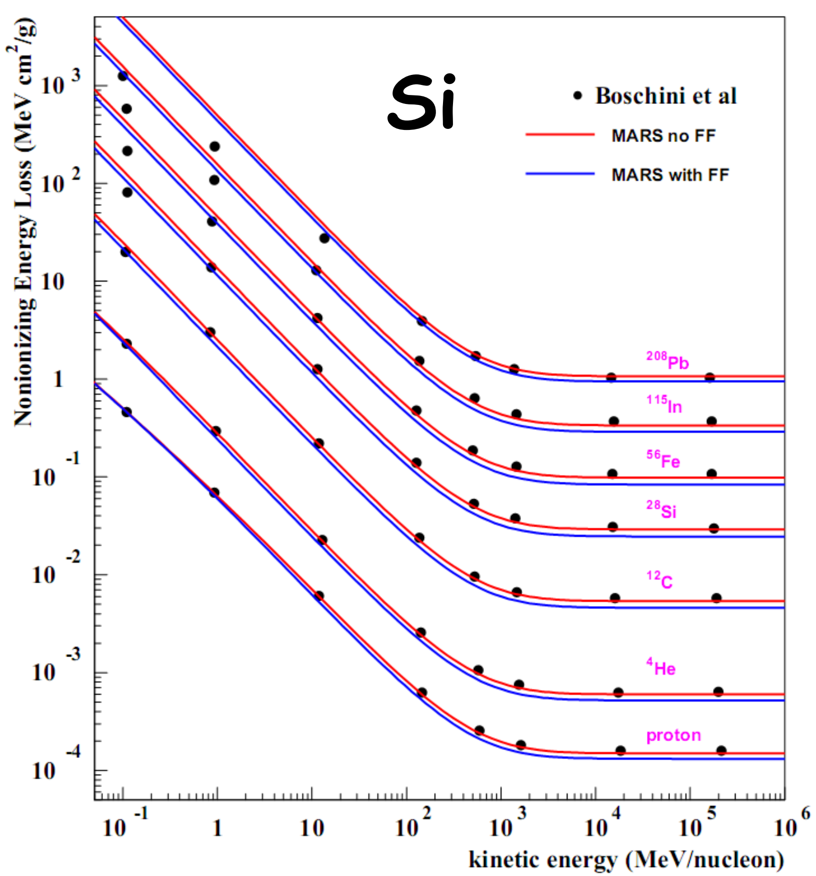


Proton NIEL for copper due the Coulomb scattering

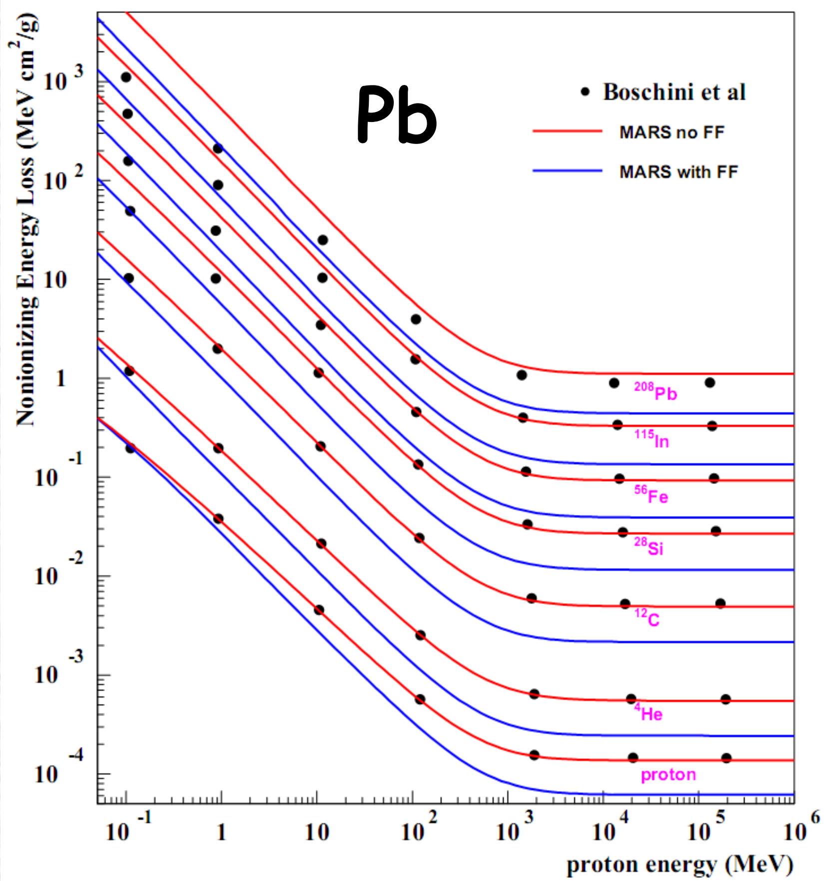
- Minimal proton transport cutoff energy in MARS is 1 keV

Comparing MARS15 with Most Recent Models

M.J. Boschini et al., "Nuclear and Non-Ionizing Energy-Loss for Coulomb Scattered Particles from Low Energy up to Relativistic Regime in Space Radiation Environment", arXiv:1011.4822v6 [physics.space-ph] 10 Jan 2011



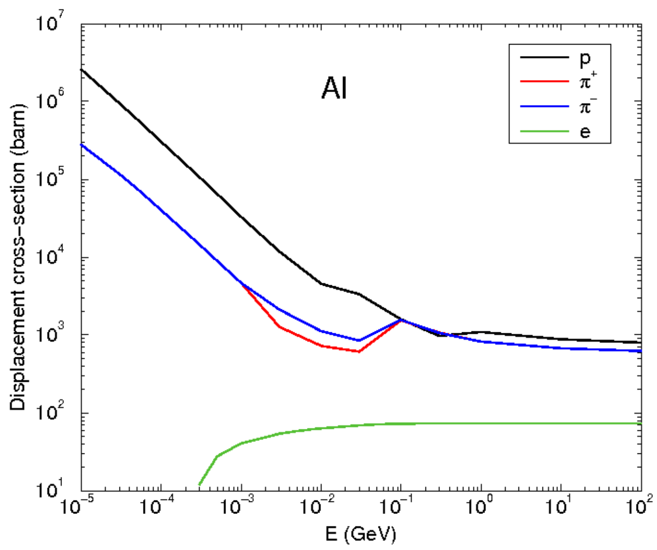
NIEL for silicon due the Coulomb scattering

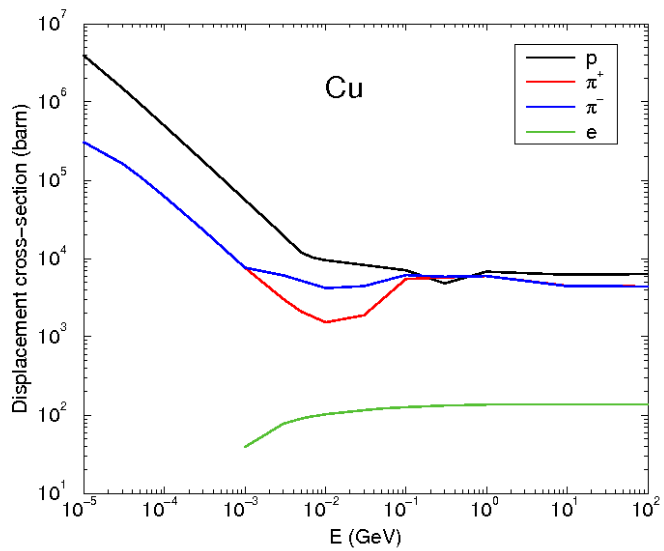


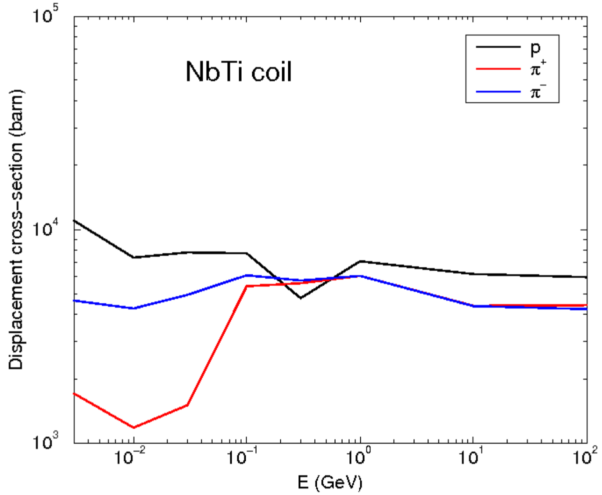
Proton NIEL for lead due the Coulomb scattering

MJB et al. do not include form factors of target and projectile (default in MARS15), which are substantial for high Z

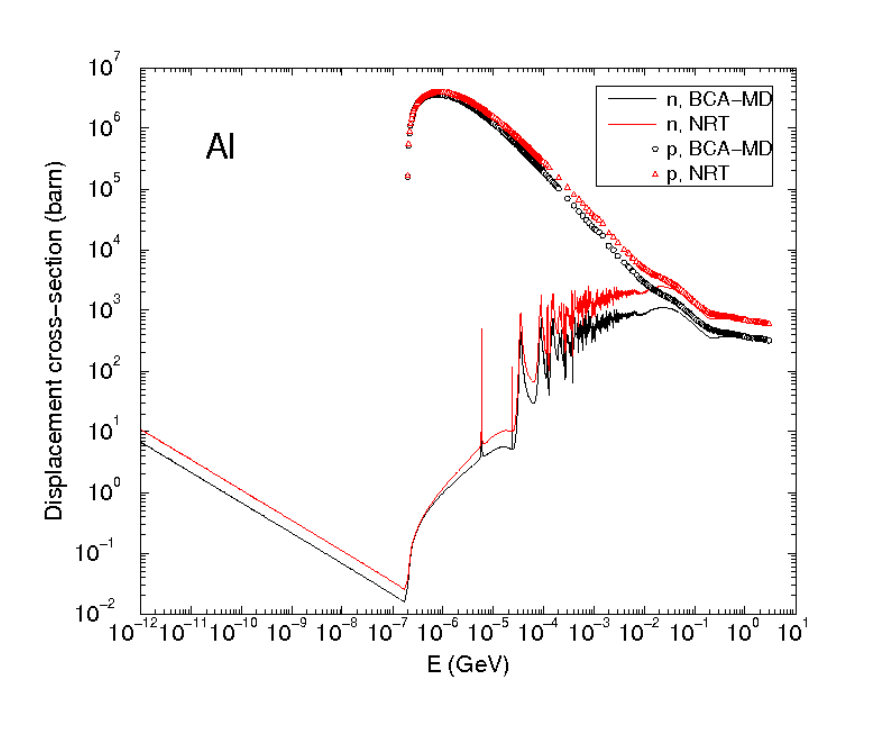
p, π, e Displacement x-sect. in Al, Cu and NbTi Coil

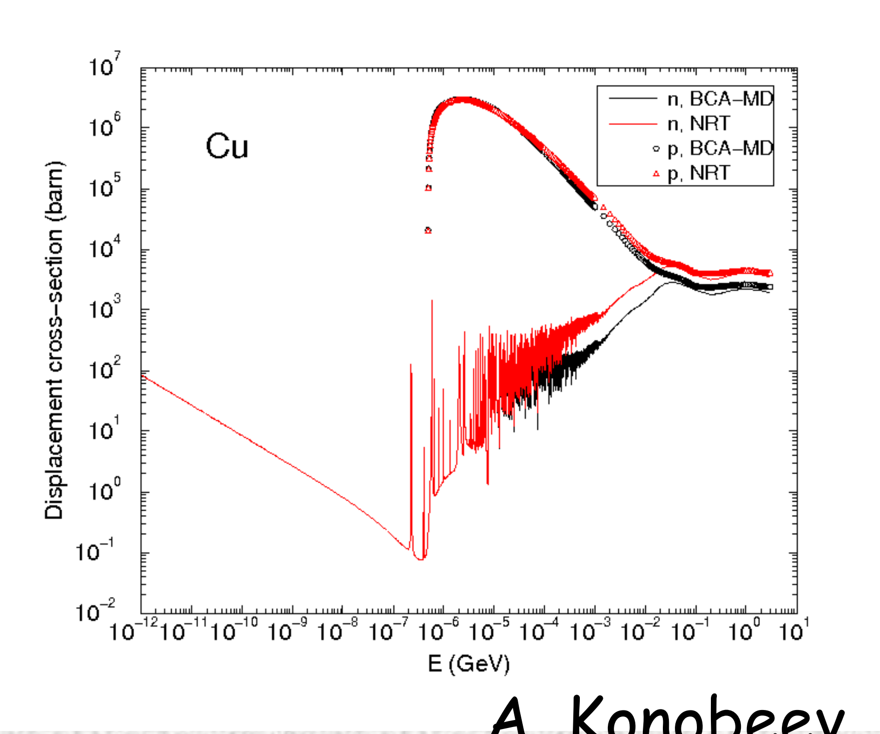






Nucleon Displacement x-section in Al and Cu

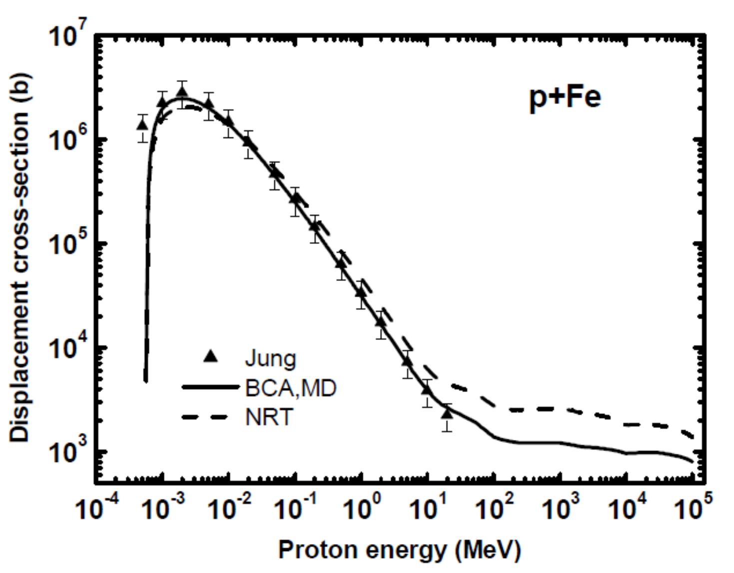


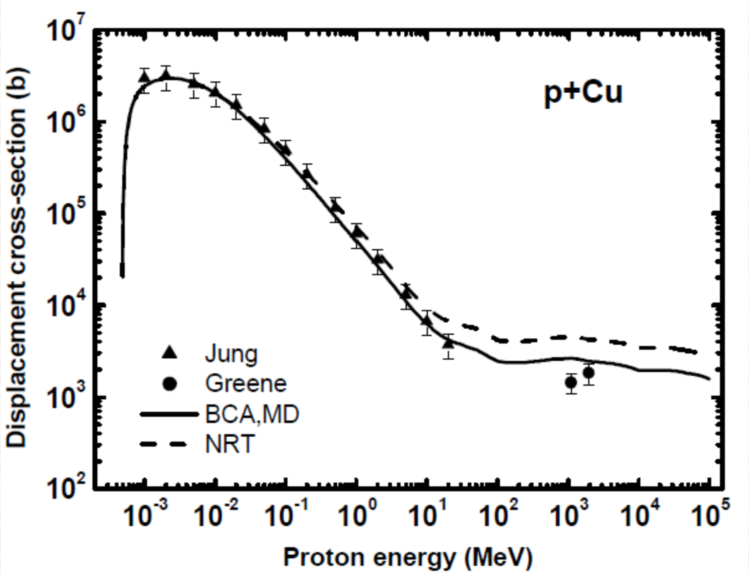


A. Konobeev

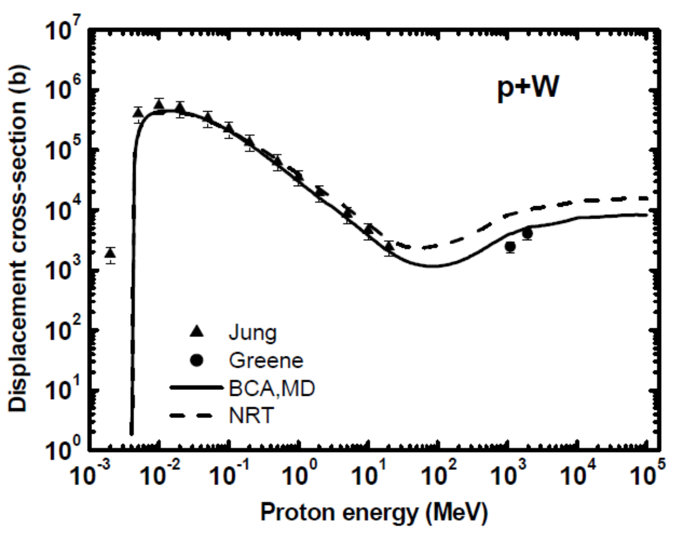
BCA-MD and pure NRT models can differ by a factor of two

BCA-MD vs NRT vs Data for p+Fe, p+Cu, p+W

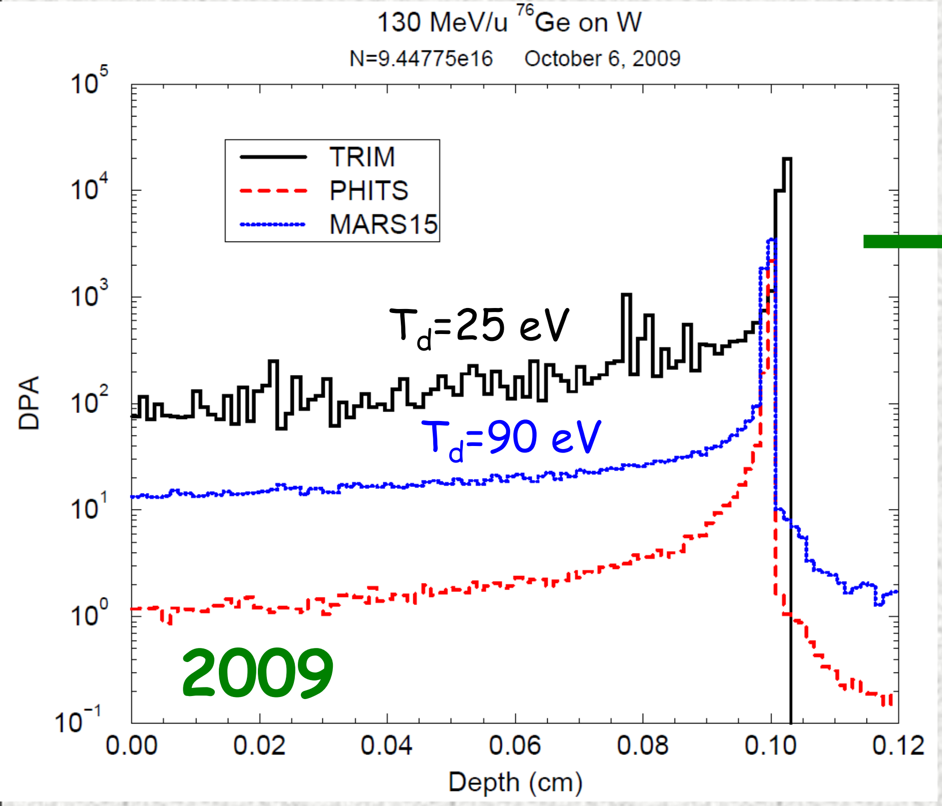


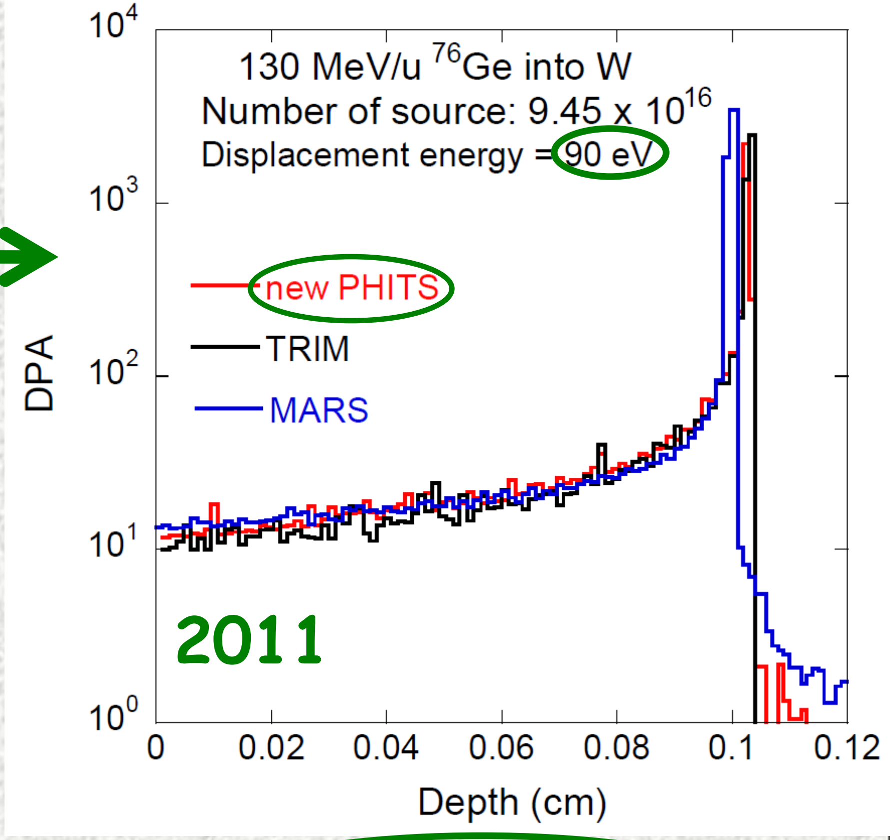


Jung data derived from resistivity degradation



DPA Comparison: 130 MeV/u ^{76}Ge on W





Pencil beam, uniform in R=0.03568 cm disc.
Target W_{nat}, cylinder with R=0.03568 cm, L=0.12 cm

Old PHITS: T_d=90 eV, no Coulomb elastic

Include all processes, use correct parameters

TRIM and PHITS results: Courtesy Yosuke Iwamoto

DPA Calculation Comparisons (1)

0.32-GeV/u ^{238}U on 1-mm Be, 9 cm^2 beam

* Courtesy Susana Reyes (2009)

Code	SRIM*	PHITS*	MARS15
DPA/pot	2.97e-20	5.02e-22	2.13e-20

6.50e-20, new PHITS by Yosuke Iwamoto (2011)

Dominant for high-Z projectiles in thin targets

MARS15: Physics process (%)

Nucl. Inel.	EM elastic	L.E. neutron	$e^{\pm}$
0.3	99.06	0.02	0.62

DPA Calculation Comparisons (2)

1-GeV p on 3-mm Fe, 1 cm^2 beam

* Courtesy Susana Reyes (2009)

Code	SRIM*	PHITS*	MCNPX*	MARS15
DPA/pot	1.18e-22	2.96e-21	3.35e-21	8.73e-21

7.79e-21, new PHITS by Yosuke Iwamoto (2011)

MARS15: Physics process (%)

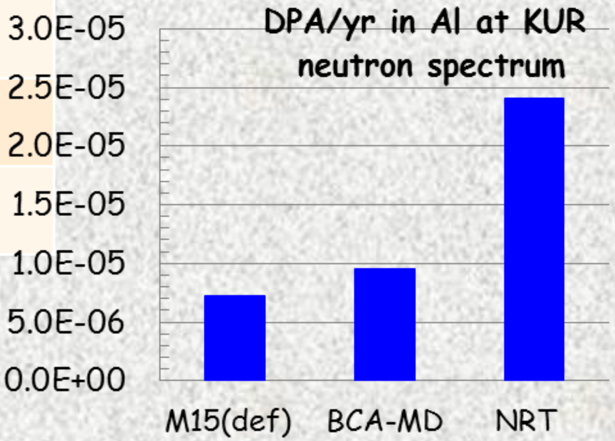
Nucl. Inel. & Coulomb	Nucl. Elastic	L.E. neutron	$e^{\pm}$
78.25	16	5.5	0.25

Tests at Reactors and Low Temperatures

Ratio of number of single interstitial atom vacancy pairs produced in material to number of defects calculated by NRT model

Material	Theo (MD)	Exp
Fe	0.32 ± 0.1	0.32 ± 0.05
Cu	0.27 ± 0.03	0.32 ± 0.03
	Ratios exp/MD	
Ti	2	
Zr	2	
W	2	

Derived from resistivity degradation



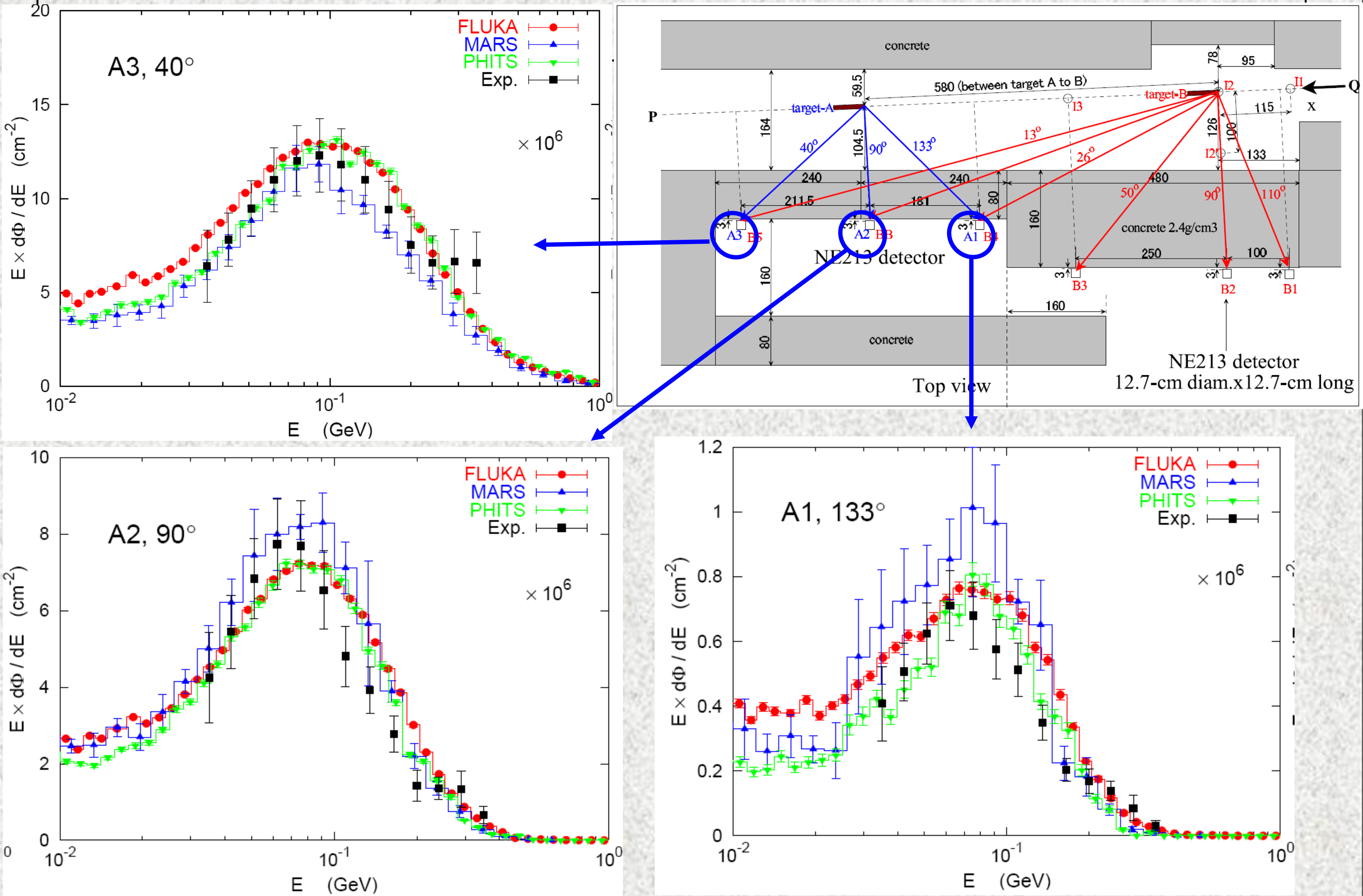
DPA and Radiation Damage: Status and Needs

- Modern models/codes which include Coulomb elastic scattering (crucial for high-Z projectiles), nuclear interactions, and same DPA model parameters agree quite well between each other and with (indirect) data. At the same time, industry standard NRT and state-of-the-art BCA-MD differ by a factor of 2 to 3 in some cases

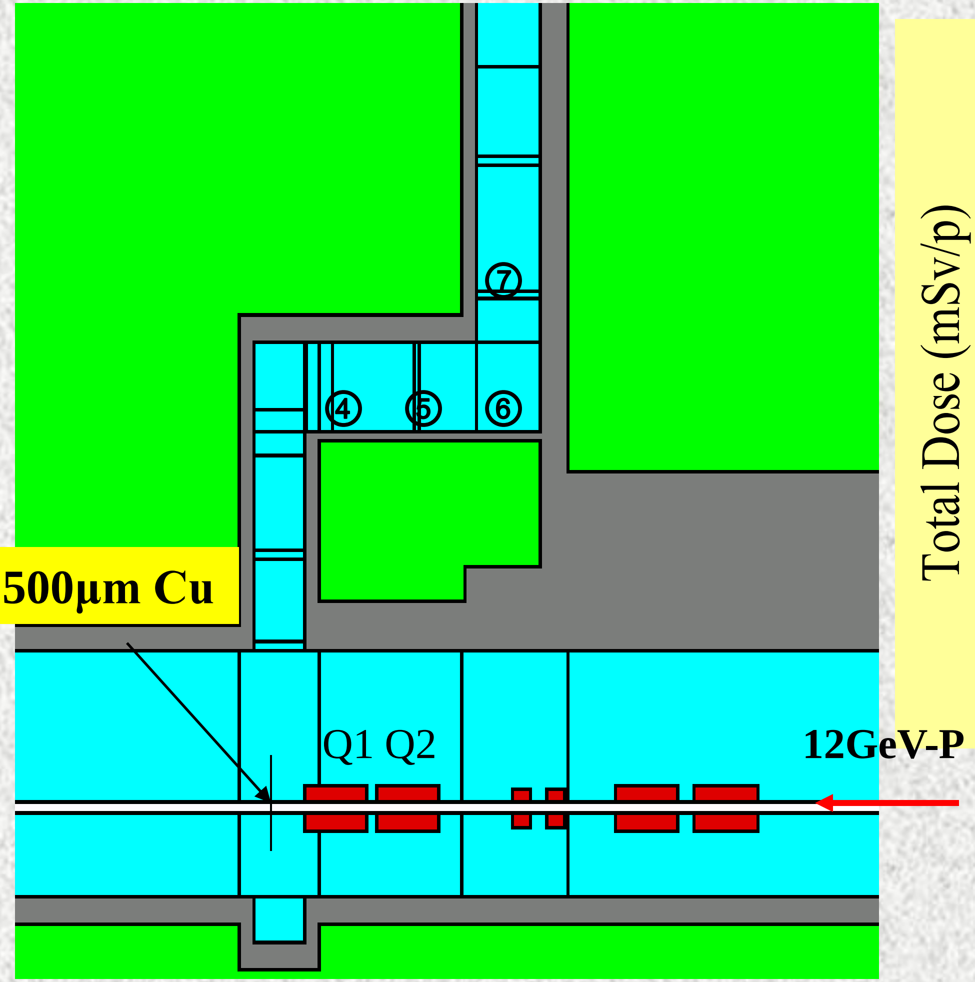
- **<u>Models/codes:</u>** Strong dependencies on projectile type and energy (1 keV to a few GeV), projectile/target charge and nuclear form-factor and material properties to be further studied; work in progress in MARS on better low-energy neutron model; link DPA to changes in material properties

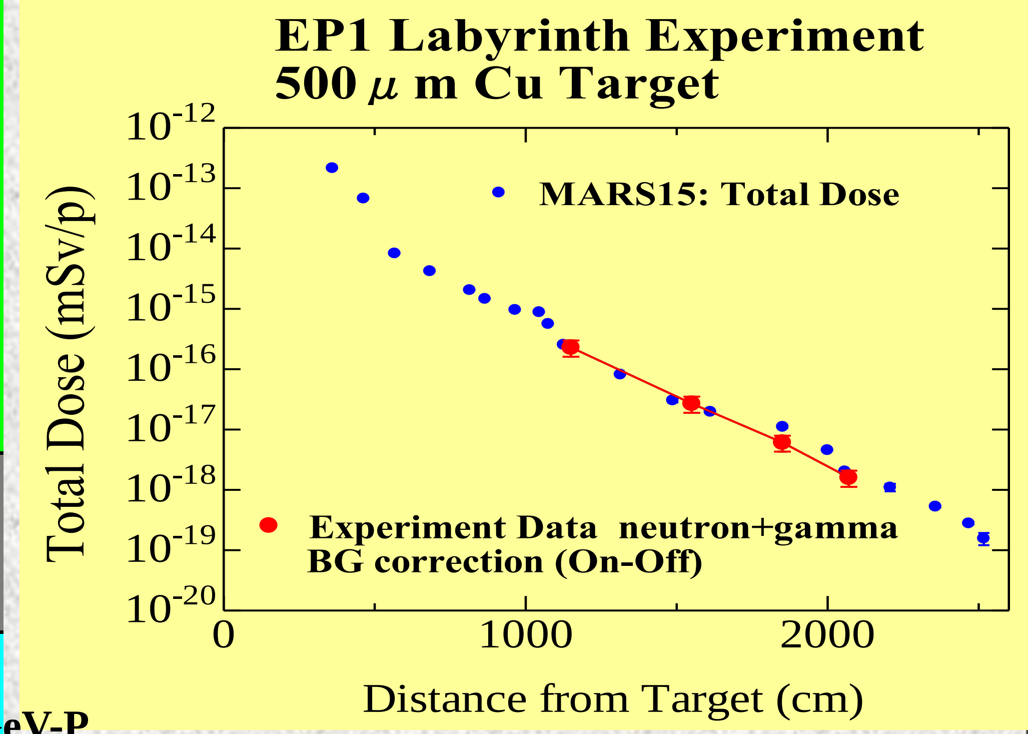
- **<u>Data needs:</u>** Annealed vs non-annealed defects; cryo temperatures!

120-GeV p/π on CERF Cu-Target: Concrete, 80cm



KEK: EP1 Labyrinth

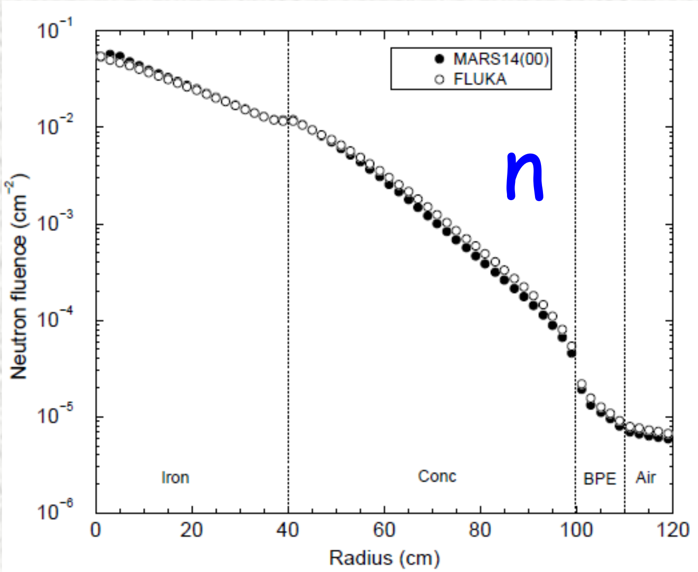




Courtesy: Takenori Suzuki

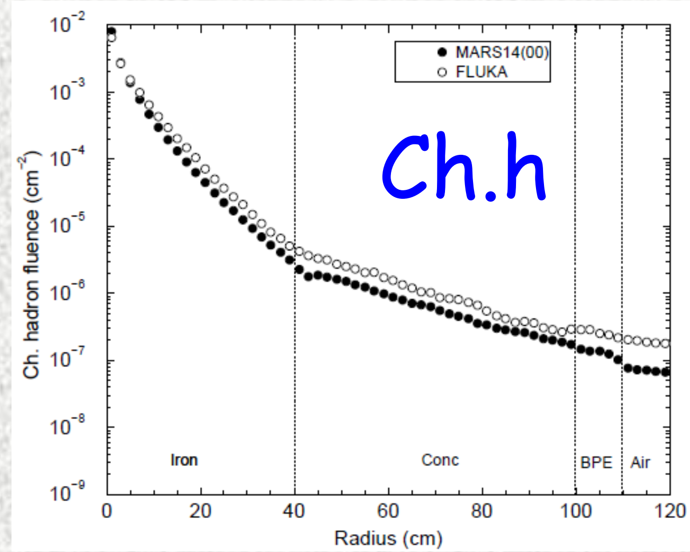
MCNP x-sections, thermal energy cutoff for neutrons and two-step techniques

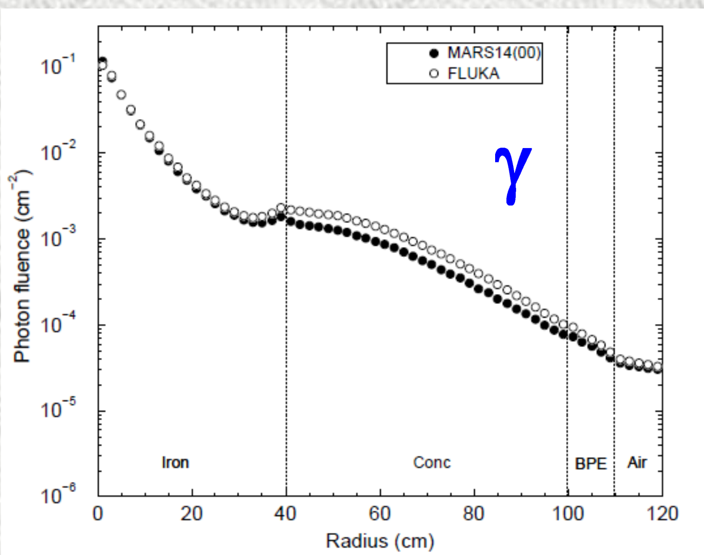
MARS vs FLUKA for 10 GeV/c p on Beam Dump

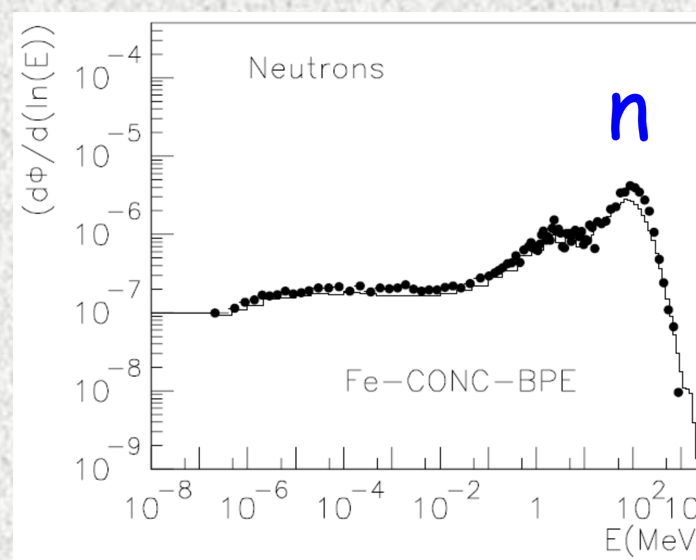


2-m long radial sandwich cylinder

50 < z < 100 cm







Radiation Shielding: Status and Needs

- Current FLUKA, MARS and PHITS agree with each other and data within a factor of 2 for most radiation values, **IF** all details of geometry, materials composition and source term are taken into account.
- **Models/codes:** Further intensification of variance reduction technique use, especially for thick shielding ("deep penetration problem"), growing computation power is not a panacea.
- **Data needs:** JASMIN is on the right track!

SHIELDING AND RADIATION EFFECT EXPERIMENT

JASMIN Japan-FNAL Collaboration:
[Shielding and Radiation Effect Experiments at FNAL]
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

Example: Muon-induced nuclide production