Neutrino Factory: Interim Design Report (IDR) Yield Calculations

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Figure of Merit (MARS only)

- Method:
  - from a MARS simulation of a given proton beam on target, count the number of $\pi^{\pm} + K^{\pm} + \mu^{\pm}$ at $z = 50$ m with $40 \leq E_{kin} \leq 180$ MeV.
  - normalize the total yield by the number of protons on target and by the energy (~yield per beam power).
- Validation:
  - difference in muons yield for runs produced using different starting seeds (over 50 runs @CERN) is about 2% for 10^5 protons on target.
  - difference in muons yield for different MARS versions (e.g., BNL and CERN MARS1507 versions) can be up to 10%.
  - difference in muons yield for different field maps (ST2 at 1.25 T or ST2a at 1.75 T tapering) within 2-3% (slight increase with ST2).
- Purpose:
  - good to optimize target or compare code.
  - does not provide the effective number of muons captured.

Yield including the front-end acceptance (1/3)

- MARS+ICOOL+ECALC9F:
  - take the MARS $\pi^{\pm}$ + $K^{\pm}$ + $\mu^{\pm}$ at z=0 m (37.5 cm after the beam/Hg crossing point).
  - apply a 0-3 ns gaussian smearing to the particle time (gasdev numerical recipe).
  - send the particles through the ICOOL front-end lattice.
  - at the end of the cooling channel, use ECALC9F to compute the acceptance using the cuts $100 \leq p_z \leq 400$ MeV/c - $A_{//}$ = 150 mm – $A_{\perp}$ = 30 mm.
  - normalize the total yield by the number of protons on target and by the energy (~ yield by beam power).

- FLUKA+ ACCEPTANCE MAP:
  - simulate a 0-3 ns proton beam on a Hg target in FLUKA.
  - take the FLUKA $\pi^{\pm}$ + $K^{\pm}$ + $\mu^{\pm}$ at z=0 m.
  - apply an acceptance map (derived from ICOOL+ECALC9F) to the particles to compute the yield (averaged over $\pi/K/\mu$ and charge) in p_z, p_t.
  - normalize the total yield by the number of protons on target and by the energy (~yield per beam power).

Yield including the front-end acceptance (2/3)

- Verification:
  - difference in muon yield between MARS+ICOOL+ECALC9F run at CERN and run at BNL up to 29%.

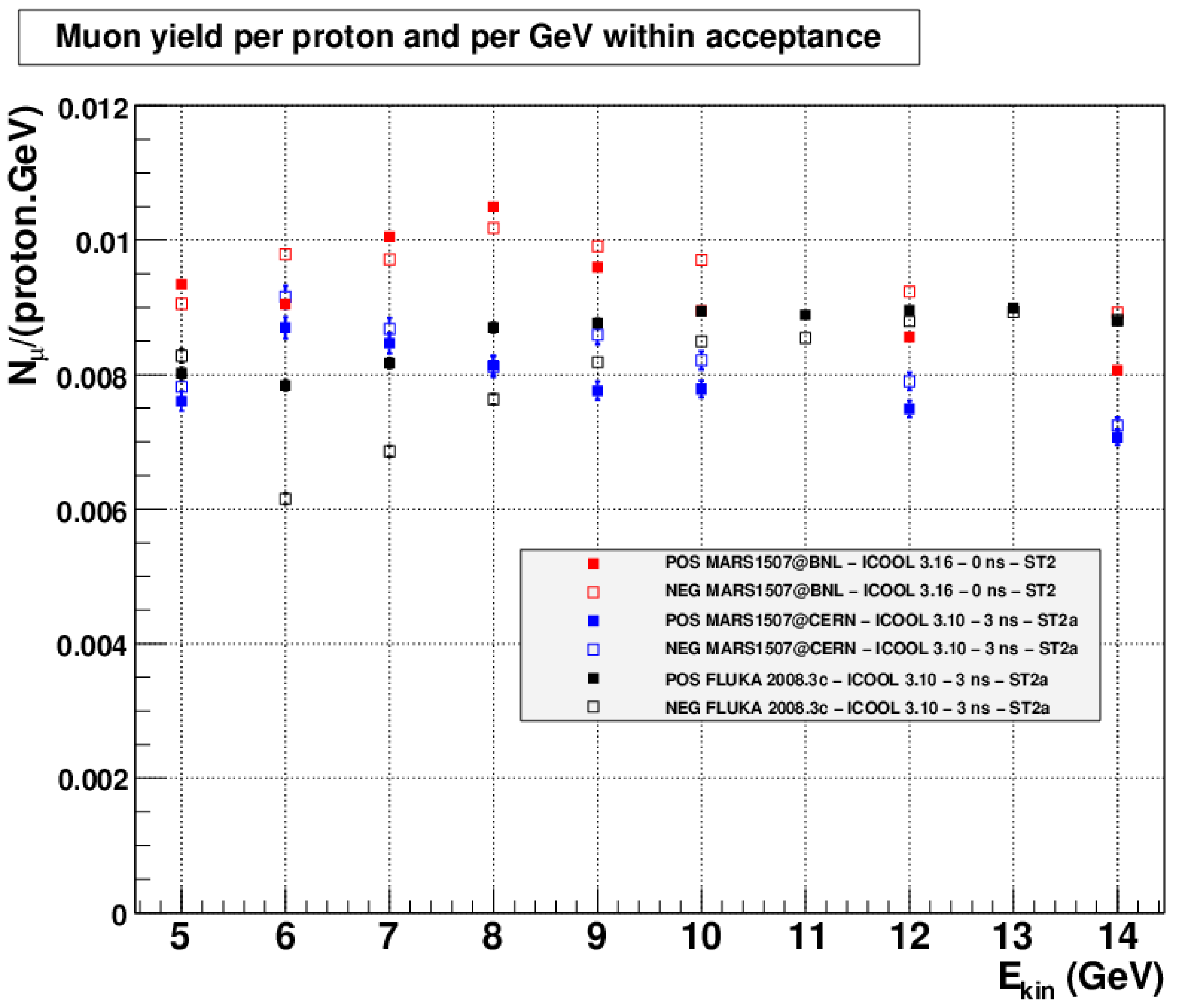
    ⇒ convoluted with time-spread & code versions (MARS/ICOOL) difference.

  - difference in muon yield between MARS+ICOOL+ECALC9F (@CERN) and FLUKA+ACCEPTANCE MAP up to 27% (μ^+) and 49%(μ^-).

    ⇒ convoluted with differences in acceptance assumptions.

  - dependence of the muon yield on the version of ICOOL (on-going).
  - dependence of the muon yield on the beam spread (on-going).
- Purpose:
  - provides the effective (accepted) muons yield.
  - acceptance map avoids long (time consuming) tracking in ICOOL.

Yield including the front-end acceptance (3/3)



Yield using HARP data (1/2)

- MARS + reweighting method:
  - simulation in MARS of the muons (pions) acceptance, defined as a fraction of the number of pions produced at the target that reach the end of the 50m-long tapered solenoid channel.

    ⇒ MARS version more recent than MARS1507 but not released yet.

    ⇒ simplified geometry in comparison with other MARS simulation.

  - convolution with the HARP measured double differential cross-section of pions production from a Ta target (close in atomic weight to Hg).
  - integration over the measured phase-space and divided by the beam kinetic energy.
  - correction for the phase-space not covered by HARP.
  - correction for hadronic showers effects in thick target (HARP only published 5% Λ_{int} data but measured also 100%Λ_{int}).
- Conclusion:
  - for constant beam power, the yield is within 10% of his maximum (at 7 GeV beam kinetic energy) for $4 \leq E_{kin} \leq 11$ GeV.
  - the results from HARP and HARP-CDP corrected for the difference in the phase space considered and taken to the neutrino factory acceptance are in agreement within 5-6% ($2 < E_{kin} < 7$ GeV) and 15% ($E_{kin} = 11$ GeV).

J. Strait *et al.*, PRSTAB 13, 111001 (2010).

Yield using HARP data (2/3)

- G4Beamline + reweighting method:
  - simulation in G4Beamline with different models and target materials for 5% and 1% Λ_{int} of the HARP setup.
  - extrapolate 5% and 1% Λ_{int} results to 0% Λ_{int} to remove re-absorption effects in target.
  - perform ratio of HARP to simulation for each target at each proton energy and bin of phase-space.
  - perform empirical fit to reweighting functions for phase-space not covered by HARP.
  - run new simulations using reweighting functions and compare to HARP data to determine the error of the method.
  - extract final muons yield for each target material and energy by adding up all reweighted pions functions multiplied by the neutrino factory acceptance.

$\Rightarrow$ thick target effects not taken into account.

- Conclusion:
  - for Al, Be, C (low-Z) targets, the yield decreases linearly as the beam energy increases.
  - for Ta, Pb (high-Z) targets, the yield is flat for beam energy between 5-8 GeV and dropping for beam energy below 5 GeV or above 8 GeV.

P. Soler, NUFACT'10 Conf. Proc. (to appear in AIP).

Conclusion (for the IDR)

- Yield simulations including the front-end acceptance either running through ICOOL or with an acceptance map is THE method to compute the muons yield.
  - ⇒ difference in code (MARS to MARS) + beam size + tracking code version (ICOOL to ICOOL) can lead to up to 30% difference in yield.
  - ⇒ difference in code (MARS to FLUKA) can lead up to 30% difference in yield for positive and 50% for negative.

- Yield simulations folded with HARP data shows:
  - ⇒ distribution in yield for 4-11 GeV beam within 10% of the maximum (at 7 GeV).
  - ⇒ difference in HARP and HARP-CDP results does not matter once taken to the same phase-space and to the neutrino factory acceptance.
  - ⇒ low-Z material favors low-energy beam and depends strongly on the energy.
  - ⇒ high-Z materials flat for 5-8 GeV beam and drops under 5 GeV and above 8 GeV.

Next step (IDR to RDR)

- Update on yield simulations including the front-end acceptance:
  - need new MARS 20 T to 1.5 T input files (all the simulations were performed assuming ST2 or ST2a geometry and field map).
  - need the latest release of MARS (MARS1509 awaited since July 2009).
  - continue the beam size dependence study.
  - continue the tracking code version dependence study.
  - produce new FLUKA simulations with 20 T to 1.5 T input files.
  - tracking study in the IDR lattice (so far was the ISS one).
  - acceptance map for the IDR lattice.
  - fine tuning of the acceptance map depending on PID, charge.
  - hands-off of MARS/FLUKA at $z > 6$ m (after target window to take into account all interactions in target surrounding material).

- Update on yield simulations folded with HARP data:
  - re-run simulations with thick target results from HARP (when paper published) included.