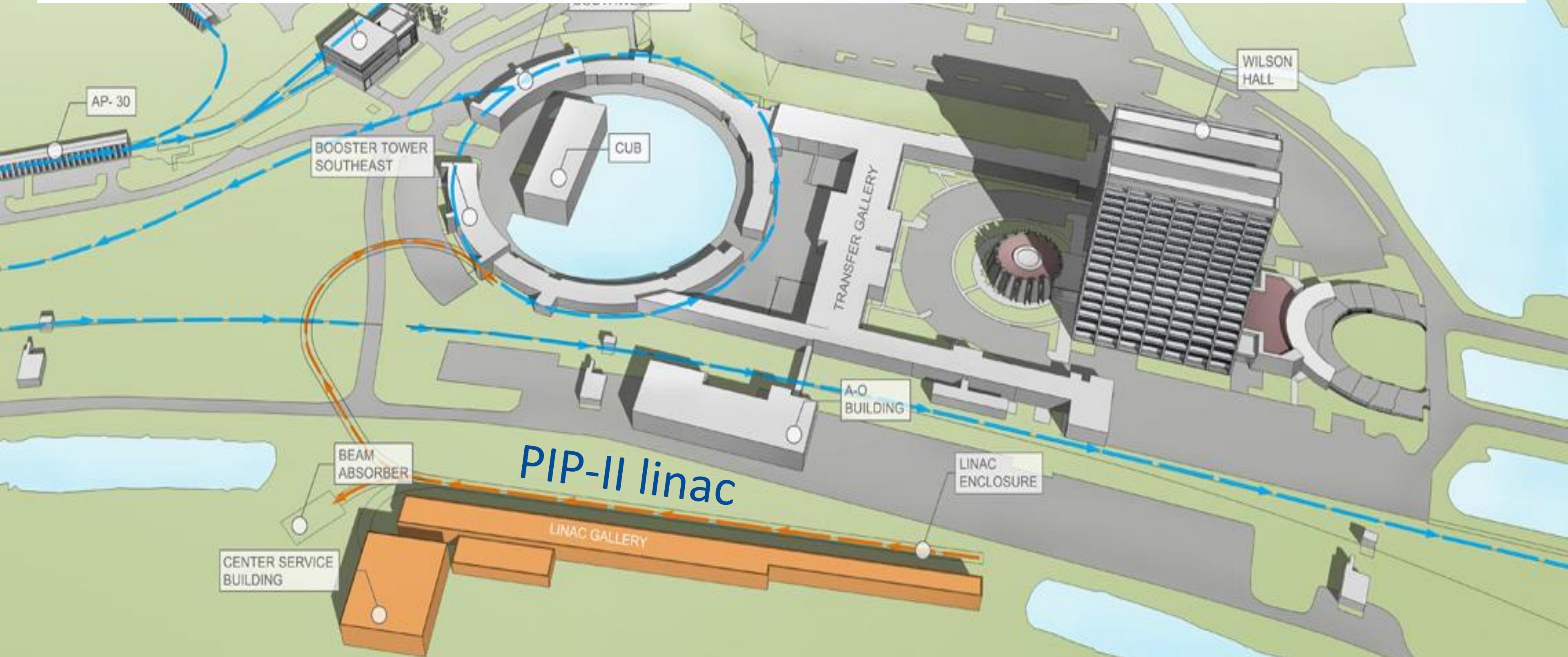
# Mu2e upgrade physics reach optimization studies for the PIP-II era





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On behalf of the Mu2e Collaboration



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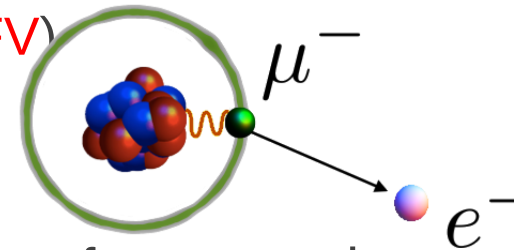
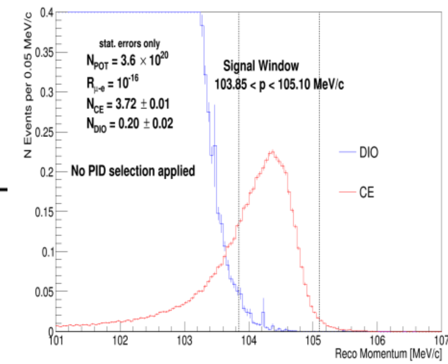
# What is Mu2e about ?

Charged Lepton Flavor Violation (CLFV)




- A BSM process
- Background: SM Decay In Orbit
- Single effect experiment: conversion of muon to electron
- Will be sought in the field of nucleus (remains intact).
- Signature: monoenergetic electron (105 MeV in Al stopping target).
- Produce muonic atoms (~$10^{19}$) by stopping negative muons in Al foils. The muons are produced by an intense 8-GeV proton beam (~1μA) impinging on the production target.



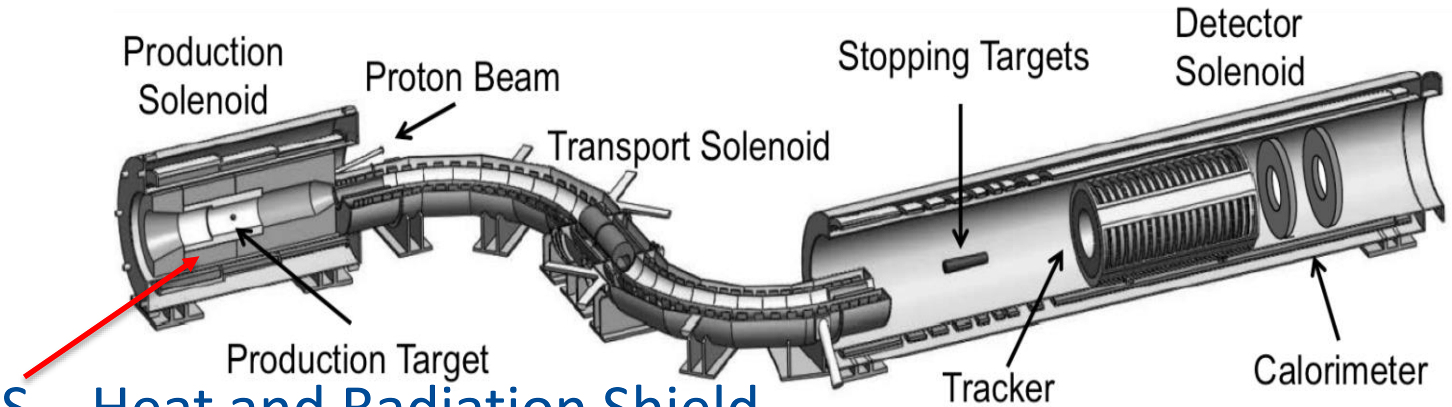

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + (A,Z) \to e^- + (A,Z)\right)}{\Gamma\left(\mu^- + (A,Z) \to \text{capture}\right)}$$

- $R_{\mu e} < 6\times10^{-17}$ (90% CL), factor 10000 improvement over the previous best limit. See arXiv:1501.05241 for Mu2e details, arXiv:1307.1168 for upgrade
- What if no effect is observed ? Upgrade to Mu2e@PIP-II !

# How to upgrade

- An improved proton source will be required for a next generation Mu2e (another factor of ~10 improvement)
- PIP-II (Proton Improvement Plan-II): Mu2e upgrade potential (@800 MeV) > 100 kW (linac), 120 kW (@8 GeV) (Booster), energies within the range were also considered.
- The energy range studied: 0.5 GeV – 8 GeV.
- We need to understand:
  - Expected muon yield and muon stopping rates as a function of proton energy
  - Potential performance constraints as a function of proton beam energy
- The MARS15 code is used because the energy-deposition-related quantities are well modeled. (DPA damage, displacement-per-atom)

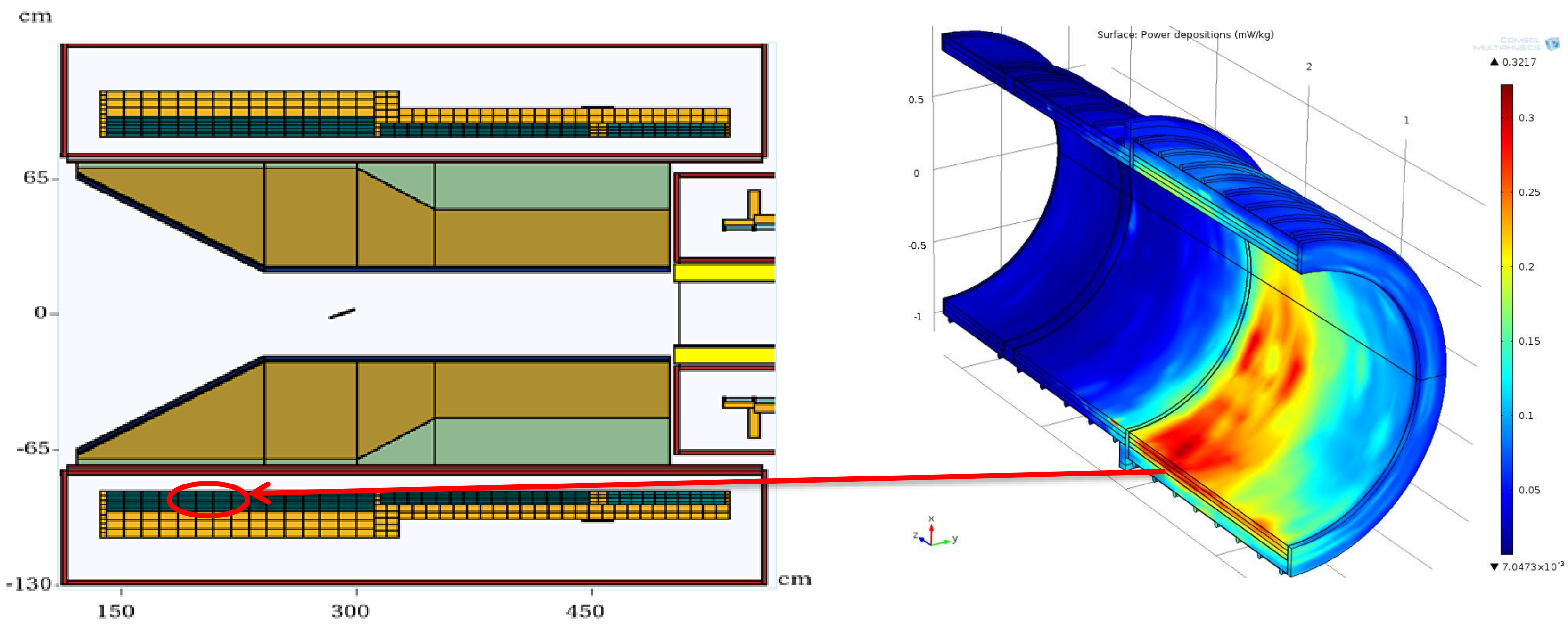
# Baseline Mu2e and MARS15 simulations




HRS – Heat and Radiation Shield

- 8 GeV 8 kW proton beam
- Au target L=16 cm D=0.6 cm (beam σ=0.1 cm)
- Bronze HRS (tungsten HRS considered for upgrade), CDR design is used for the study, (Al stopping target)
- In MARS15 simulations: LAQGSM, thresholds: $1 \times 10^{-12}$ GeV for neutrons, 100 keV for charged hadrons, muons, photons
- DPA and power density vs beam energy,  vs HRS material
- Muon yield/stopping rate vs beam energy
- Figure of merit (stopping rate per  DPA)

# DPA, power density, and other limits




| Quantity | DPA, $10^{-5}$ | Power density, μW/g | Absorbed dose, MGy/yr | Dynamic heat load, W |
|---|---|---|---|---|
| Specs | 4-6 | 30 | 0.35 | 100 |

DPA damage: RRR degrades from ~600 to 100 (warm-up to anneal once a year).

Power density limit depends on cooling scheme and other assumptions

Dynamic heat load scales with the number of cooling stations



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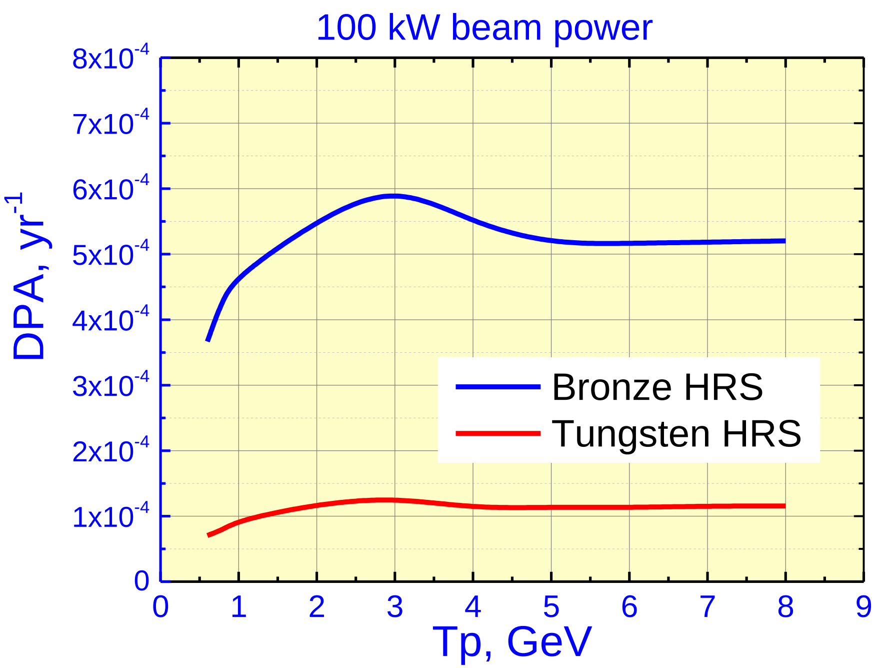
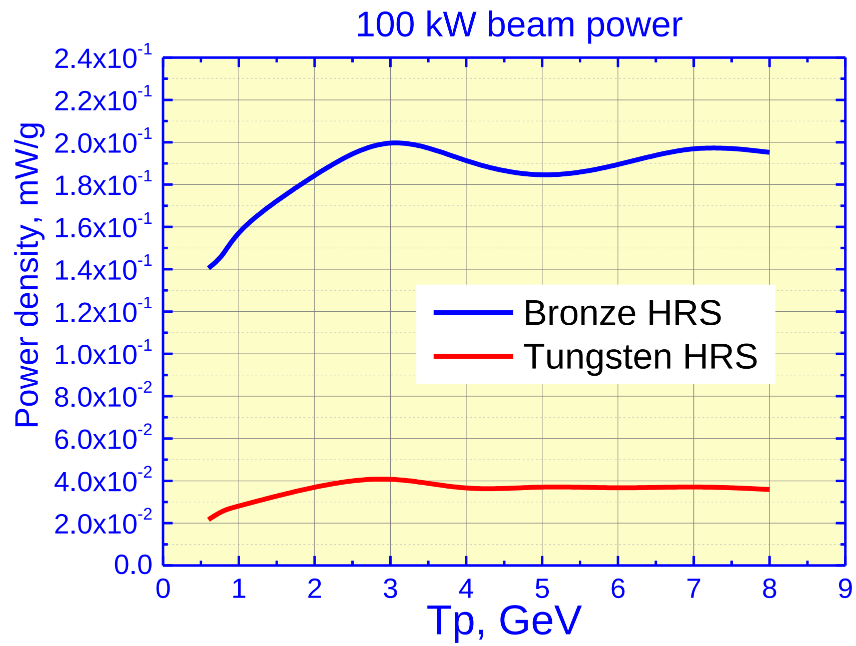
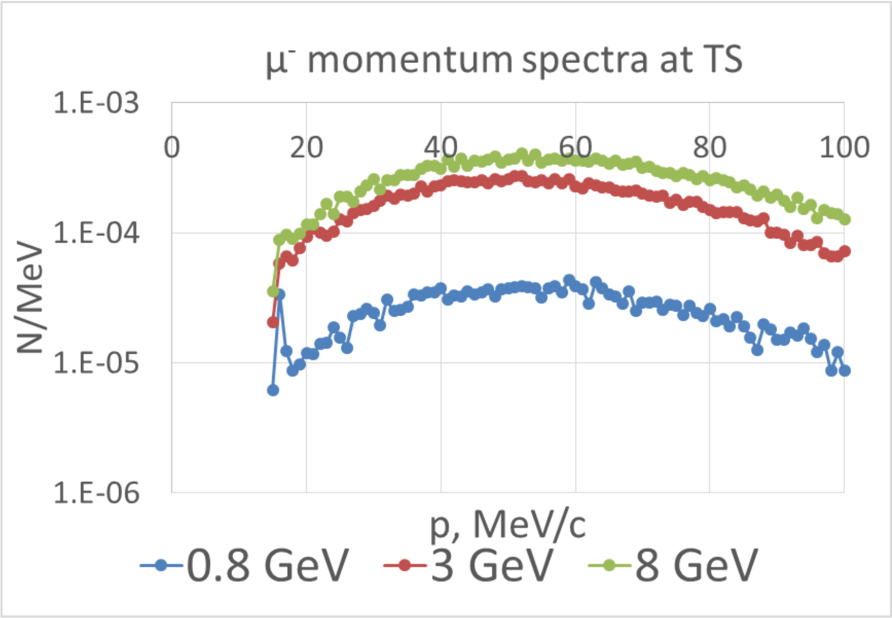
# DPA and power density @ 100 kW

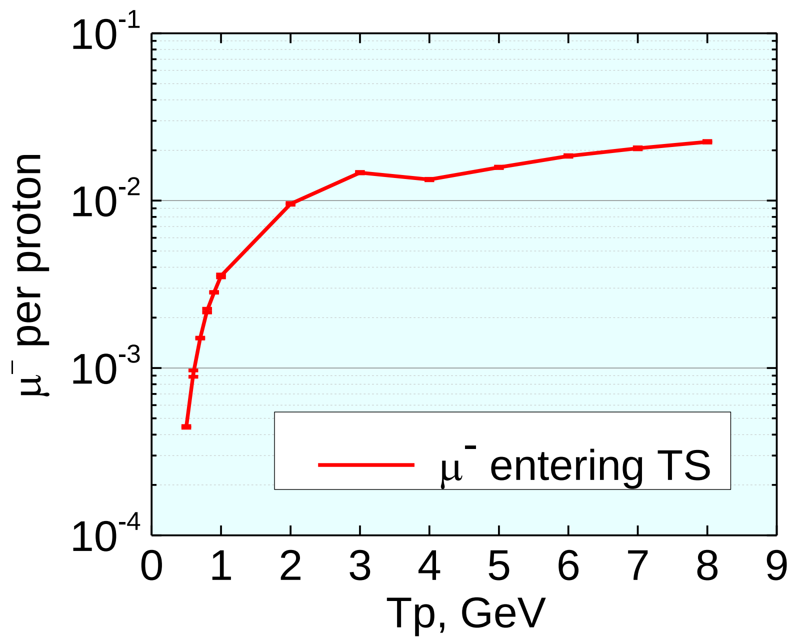



- DPA: Current coil design might tolerate 100 kW at proton energies < 1 GeV (if HRS thickness is increased).
- Power density: current coil design/cooling scheme can tolerate 100 kW at Ep = 0.8 GeV and lower. For higher energies another cooling scheme may be required.
- Above 1 GeV (DPA) or 2 GeV almost flat with energy.

# Mu- spectra and yields at TS

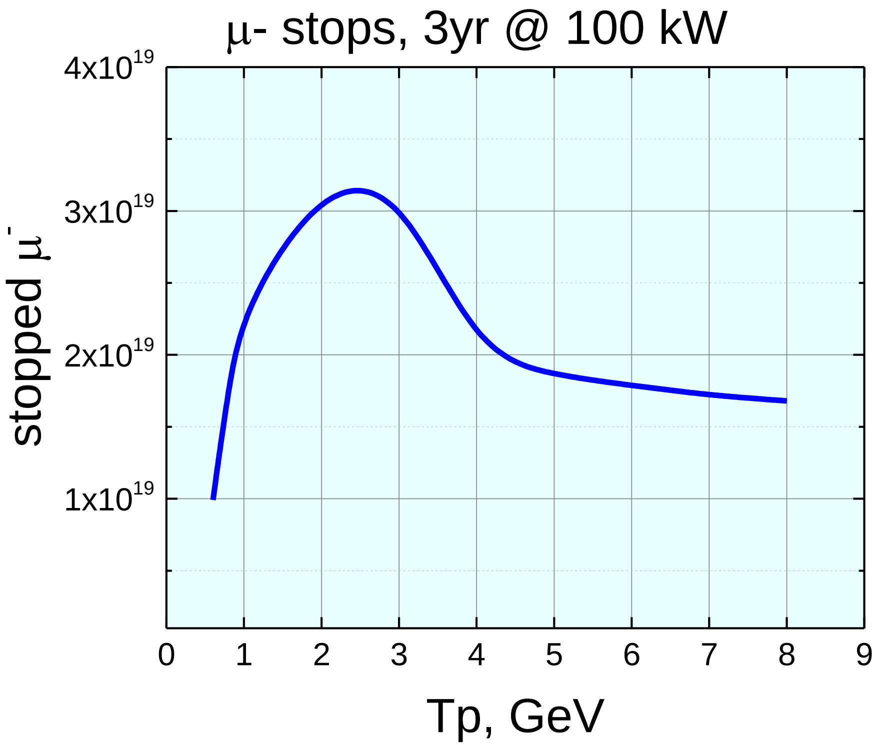


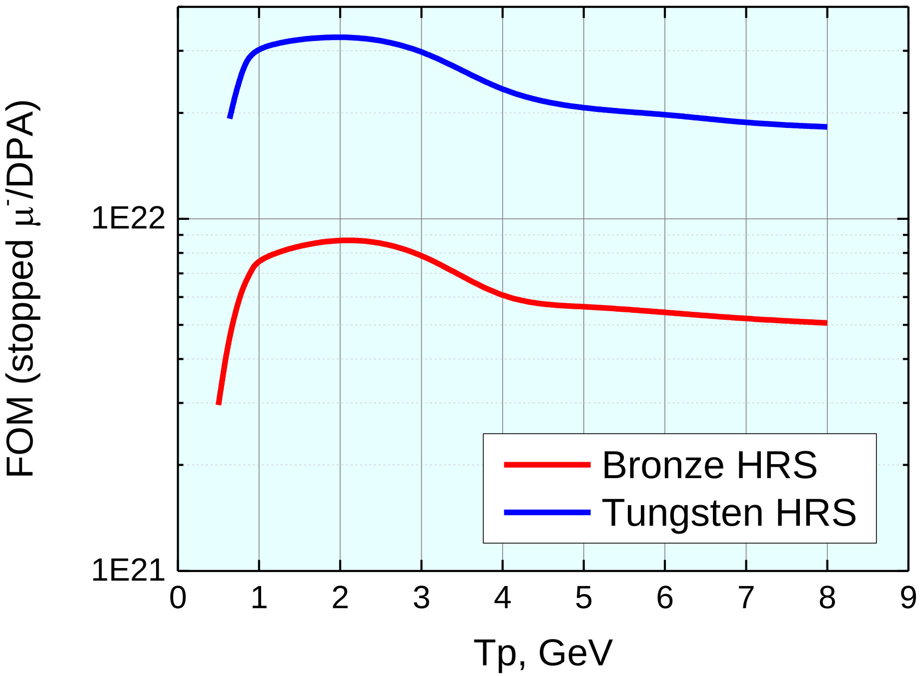




Muon yields at 0.8 GeV are ~ a factor 10 lower than at > 3 GeV

Steepest rise in $\mu^-$ yields is between 0.5 and 2 GeV.

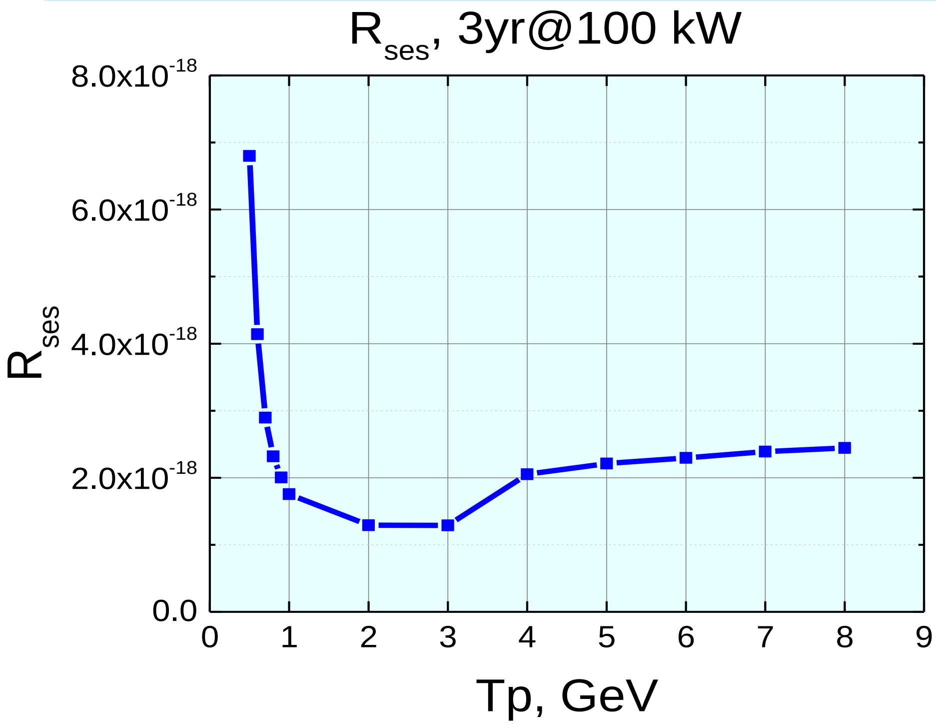
# Mu- stopping rates and Figure of Merit

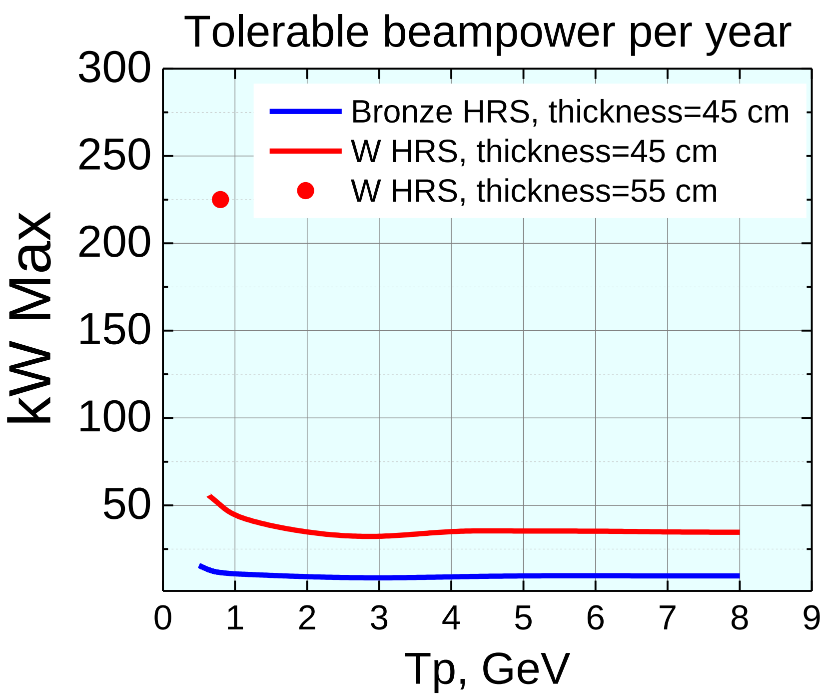



- 3 years@100 kW = 4.5E21 protons on target @ 8 GeV
- If only stopped muons are considered: 2-3 GeV is optimal
- If DPA is also considered: 1-3 GeV is optimal
- The FOM for 0.8 GeV is higher than for 8 GeV (25% for bronze and 50% for tungsten HRS)

# Single-event sensitivity and limiting beam power




- Rses – single event sensitivity, 100 kW of beam power is assumed,
- Rses is taken for 3 yr running at different POT
- beam power = 100 kW, i.e. 4.5E21 POT at 8 GeV, or 3.6E22 POT at 1 GeV etc.
- No. of stopped $\mu^-$ is based on POT and $\mu^-$ yield.

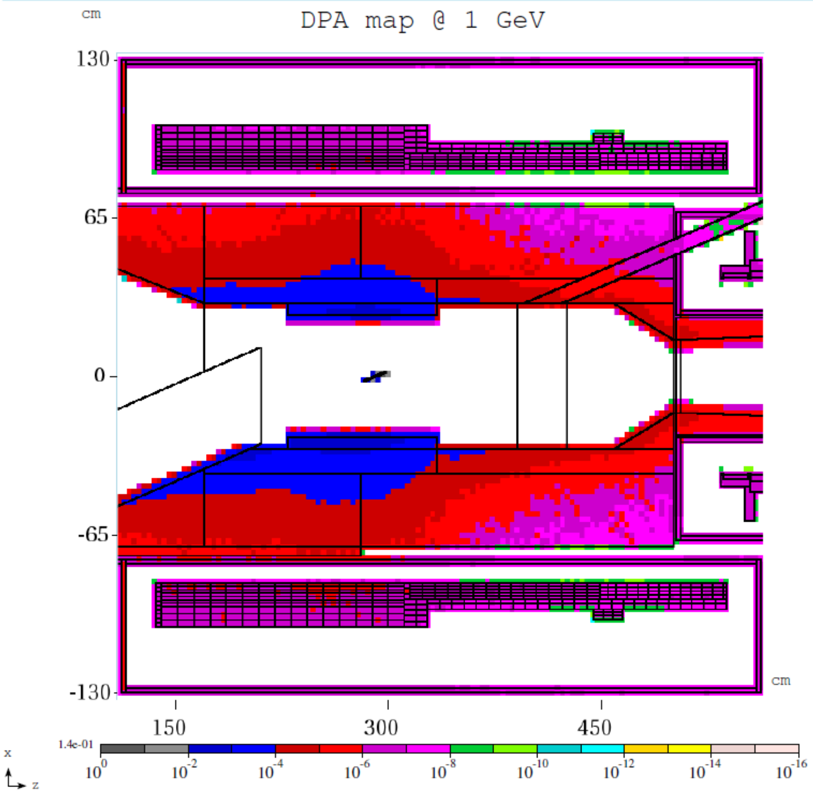
# Conclusions

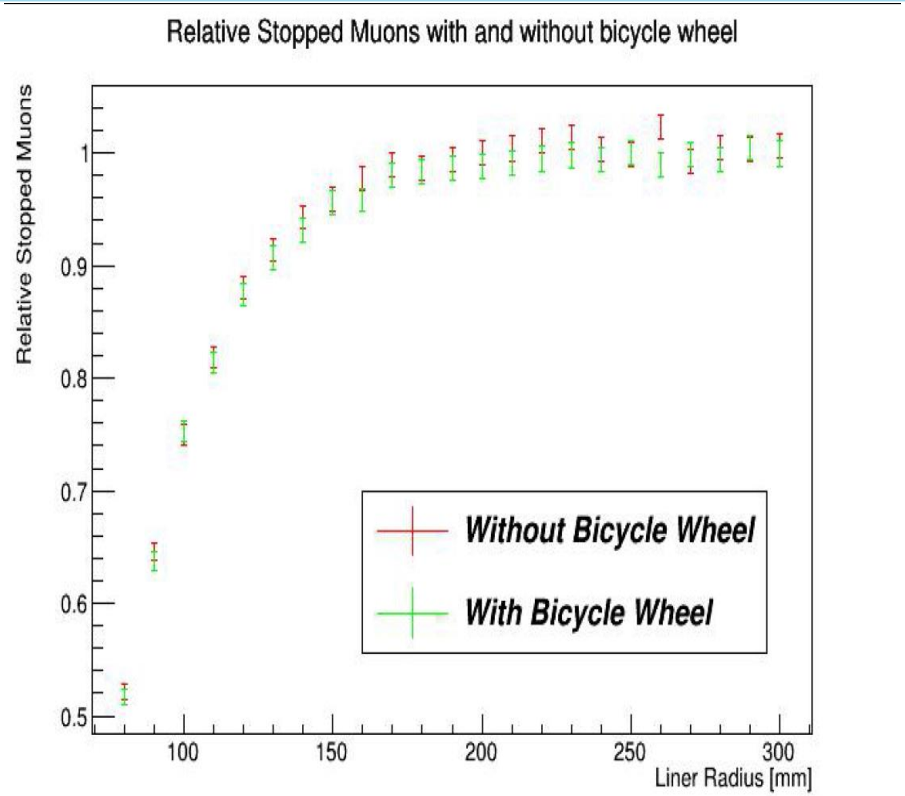
- Energy dependence of DPA damage, power density, muon yield and muon stopping rate is studied.
- Figure of Merit (stopped muon to DPA ratio) is proposed and analyzed.
- Current coil/ tungsten HRS design can likely tolerate 100 kW @ energies < 1 GeV (HRS inner bore optimization is required).
- FOM for 0.8 GeV is 50% (for tungsten) better than that at 8 GeV.
- Single-event sensitivity at 0.8 GeV is comparable to that at 8 GeV.
- 0.8 GeV proton beam @ 100 kW can be considered for Mu2e@PIP-II

Thank you!

# Spare slides

# Future plans




Inner bore radius=20 cm

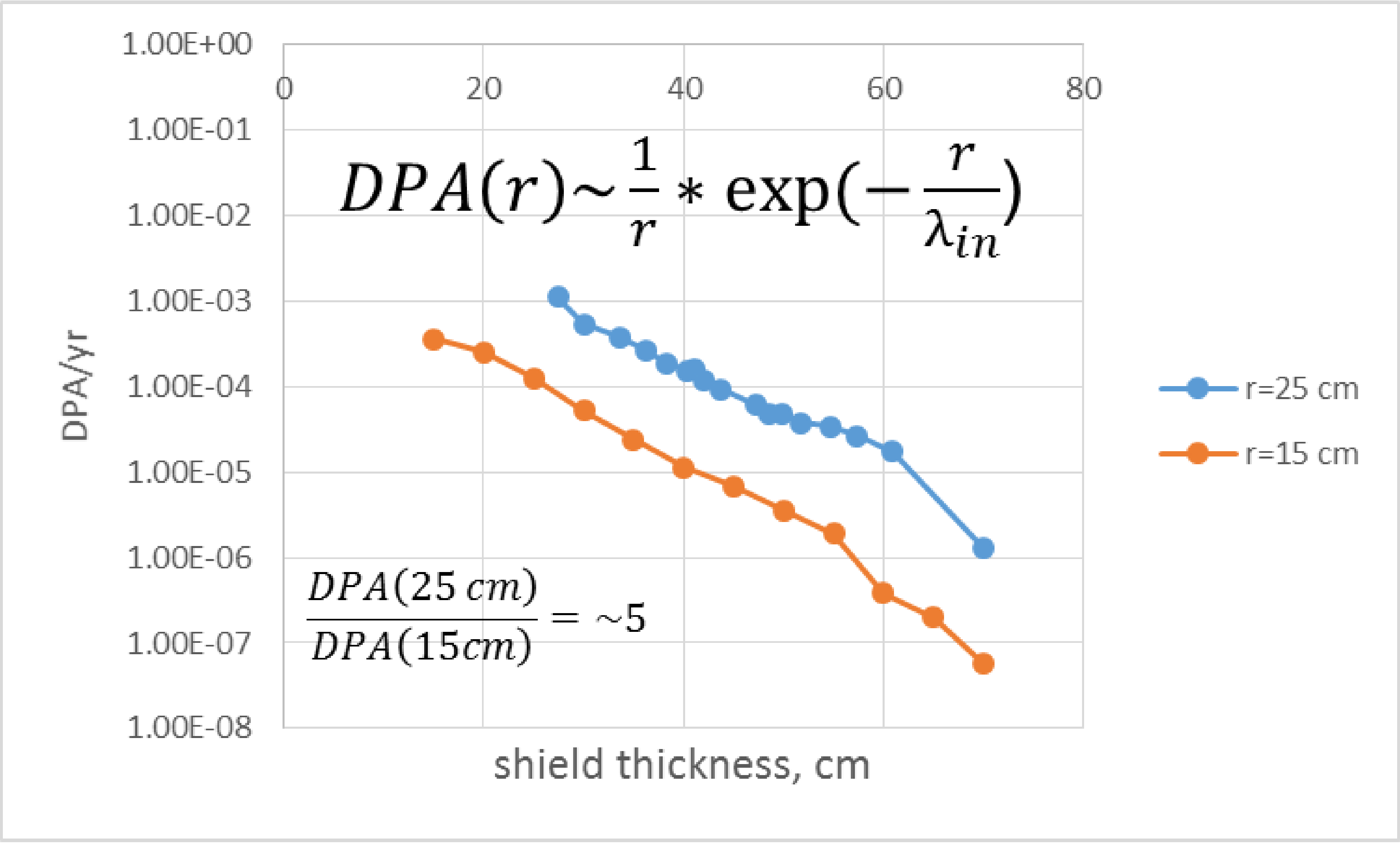
No yield drop for R>17 cm

K.Lynch and J.Popp

Muon yield change with liner radius

Investigate the DPA and Power density deposition for a tungsten HRS with a reduced inner bore

# DPA as a function of shield thickness



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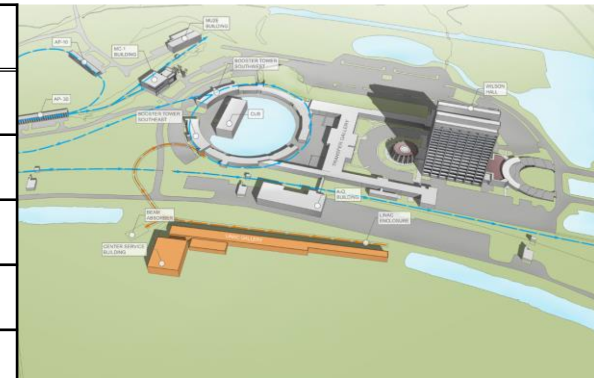
# Mu- entering TS

| Ep, GeV | Mu-/proton | Stat. uncertainty | Stat. uncertainty, % |
|---|---|---|---|
| 0.5 | 4.45E-04 | 5.17E-06 | 1.2 |
| 0.6 | 9.26E-04 | 3.96E-05 | 4.3 |
| 0.7 | 1.51E-03 | 9.53E-06 | 0.6 |
| 0.8 | 2.20E-03 | 5.51E-05 | 2.5 |
| 0.9 | 2.83E-03 | 1.31E-05 | 0.5 |
| 1 | 3.55E-03 | 7.06E-05 | 2.0 |
| 2 | 9.57E-03 | 1.16E-04 | 1.2 |
| 3 | 1.47E-02 | 1.44E-04 | 1.0 |
| 4 | 1.34E-02 | 1.38E-04 | 1.0 |
| 5 | 1.58E-02 | 1.50E-04 | 0.9 |
| 6 | 1.85E-02 | 1.93E-04 | 1.0 |
| 7 | 2.06E-02 | 2.83E-04 | 1.4 |
| 8 | 2.25E-02 | 2.51E-04 | 1.1 |

# Mu2e@PIP-II upgrade plans

| Performance Parameter | PIP | PIP-II | |
|---|---|---|---|
| Linac Beam Energy | 400 | 800 | MeV |
| Linac Beam Current | 25 | 2 | mA |
| Linac Beam Pulse Length | 0.03 | 0.5 | msec |
| Linac Pulse Repetition Rate | 15 | 15 | Hz |
| Linac Beam Power to Booster | 4 | 13 | kW |
| Linac Beam Power Capability (@>10% Duty Factor) | 4 | ~200 | kW |
| Mu2e Upgrade Potential (800 MeV) | NA | >100 | kW |
| Booster Protons per Pulse | $4.2\times10^{12}$ | $6.4\times10^{12}$ | |
| Booster Pulse Repetition Rate | 15 | 15 | Hz |
| Booster Beam Power @ 8 GeV | 80 | 120 | kW |
| Beam Power to 8 GeV Program (max) | 32 | 40 | kW |
| Main Injector Cycle Time @ 120 GeV | 1.33 | 1.2 | sec |
| LBNF Beam Power @ 120 GeV* | 0.7 | 1.2 | MW |
| LBNF Upgrade Potential @ 60-120 GeV | NA | >2 | MW |

Table from S.Holmes, Neutrino Summit, 2014



- Early next decade
- 250 meter linac (20 Hz)?
- 800 MeV proton beam (2 mA)
- -> Booster -> 8 GeV (120 kW)
- -> Main Injector/Recycler
- ->120 GeV (1.2 MW)