Next Generation μ-to-e and g-2 at FNAL

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Contents

Proton Accelerators for Science and Innovation Workshop
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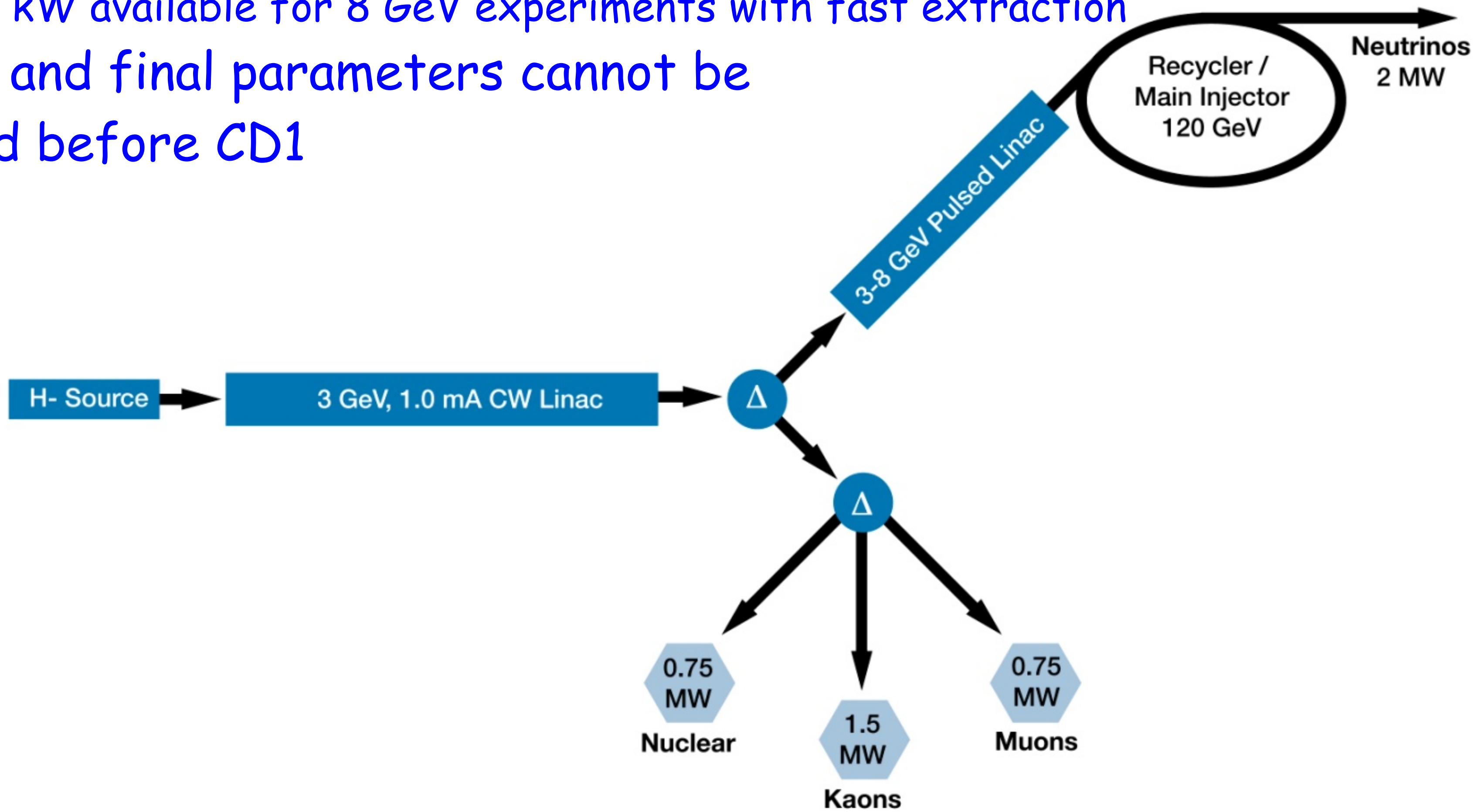
Project X RDR

- Multiple experiments to be carried out simultaneously at 3 GeV
  - RF separation
  - up to ~1 MW per experiment
- ~350 KW delivered to Recycler for fast extraction
  - ~150 kW for 120 GeV 2 MW neutrino program
  - ~200 kW available for 8 GeV experiments with fast extraction
- Staging and final parameters cannot be finalized before CD1

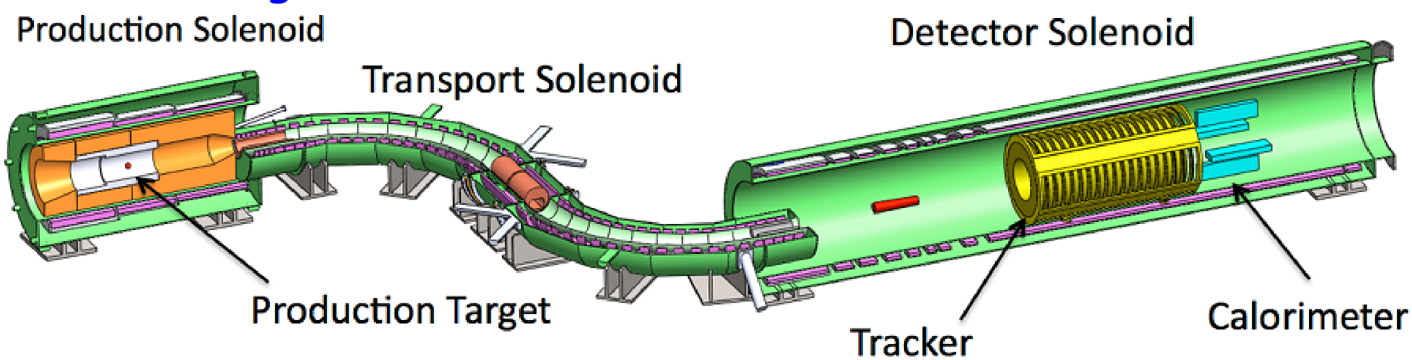


Muon experiments with "continuous" beam

- Beam power up to ~1 MW beam
  - Factor 40-120 larger than the power expected in the μ-to-e
  - Variable time structure of the beam
    - Almost arbitrary within few μs period
- How to use this power?
  - How should the target look like?
- What kind of experiments can be done?
- Which additional possibilities for experiments can the large power result in?
  - Achievable muon flux
  - What else can be done to improve experiments with stopped muons?
    - Can ionization cooling of muons help?

Two Major Types of Muon Sources

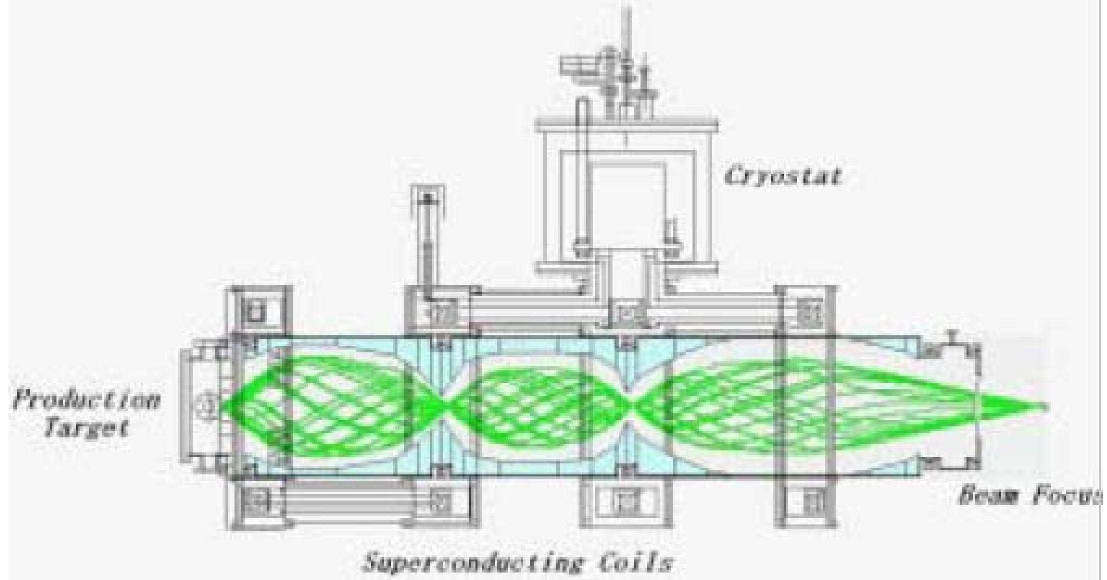
- Solenoid transport based
  - Has large acceptances - both transverse and longitudinal
  - Limited manipulations with beam phase space
  - Expensive
    - Based on large diameter SC solenoids

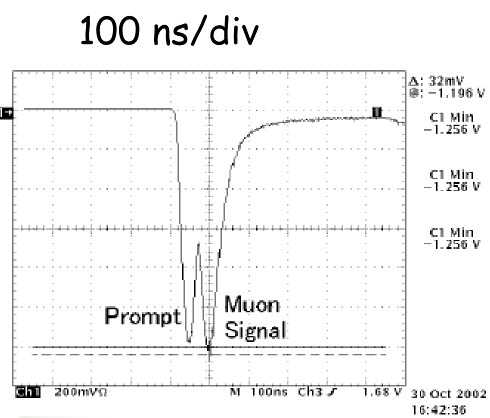


  - Isochronicity can be achieved in limited range of $\Delta p/p$ with helical channel
- General baseline based (large length to achieve good extinction of π^-)
  - Still requires decay solenoid to achieve high muon yield
  - Detector solenoid is required by experiment
  - All types of beam phase space manipulation are possible
    - Isochronous beam transport – short muon pulses
  - Inexpensive – large length results in good pion extinction
    - Based on dipoles with edge focusing (FFAG is a possible choice)
  - Limited phase space reduces the muon flux

Surface Muon Beam

- No decay solenoid
- ~4 orders of magnitude smaller muon yield
  (~$1.6 \cdot 10^{-8}$ /p_GeV for KEK)
- ~30 MeV/c central momentum
- Beam polarization close to 100%





Prompt and muon signal observed at oscilloscope

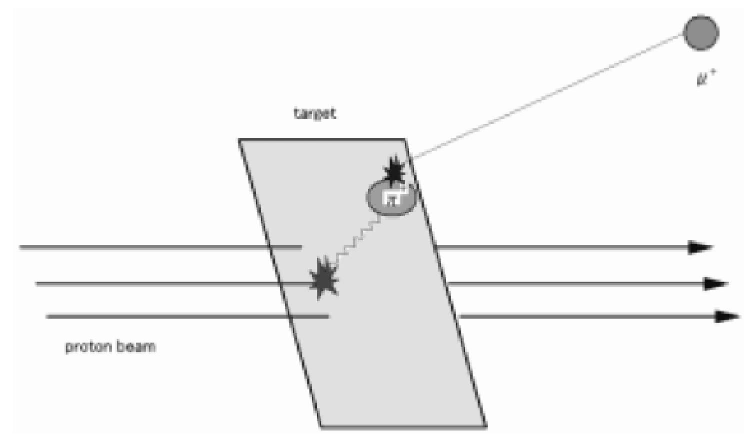
Surface Muon

μ^+ from π^+ decay at the production target.

Low Energy 4MeV (30MeV/c)

100% spin polarization

Suitable for mSR spectroscopy.



High Intensity Surface Muon Beam

Upgrading of primary proton acceralator

KEK:$2.5 \times 10^5 \mu^+$/sec (500MeV, 5μA)

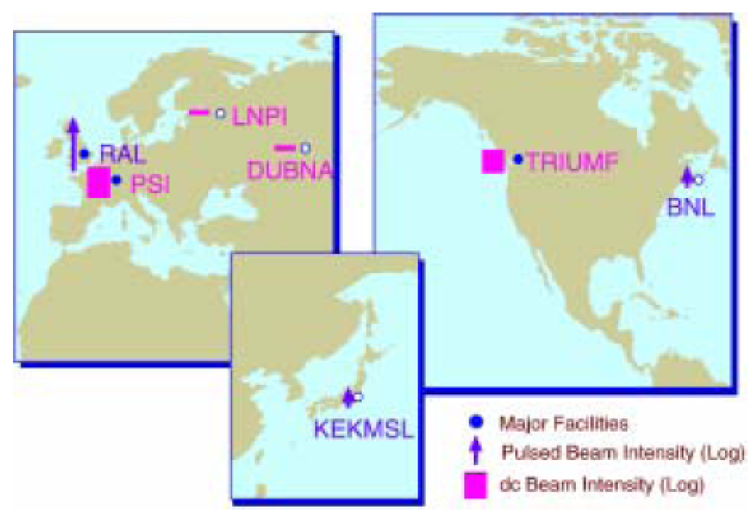
RAL:~$10^6 \mu^+$/sec (800MeV, 200μA)

J-PARC:$3 \times 10^7 \mu^+$/sec (3GeV, 333μA)

Upgrading of acceptance of muon channel

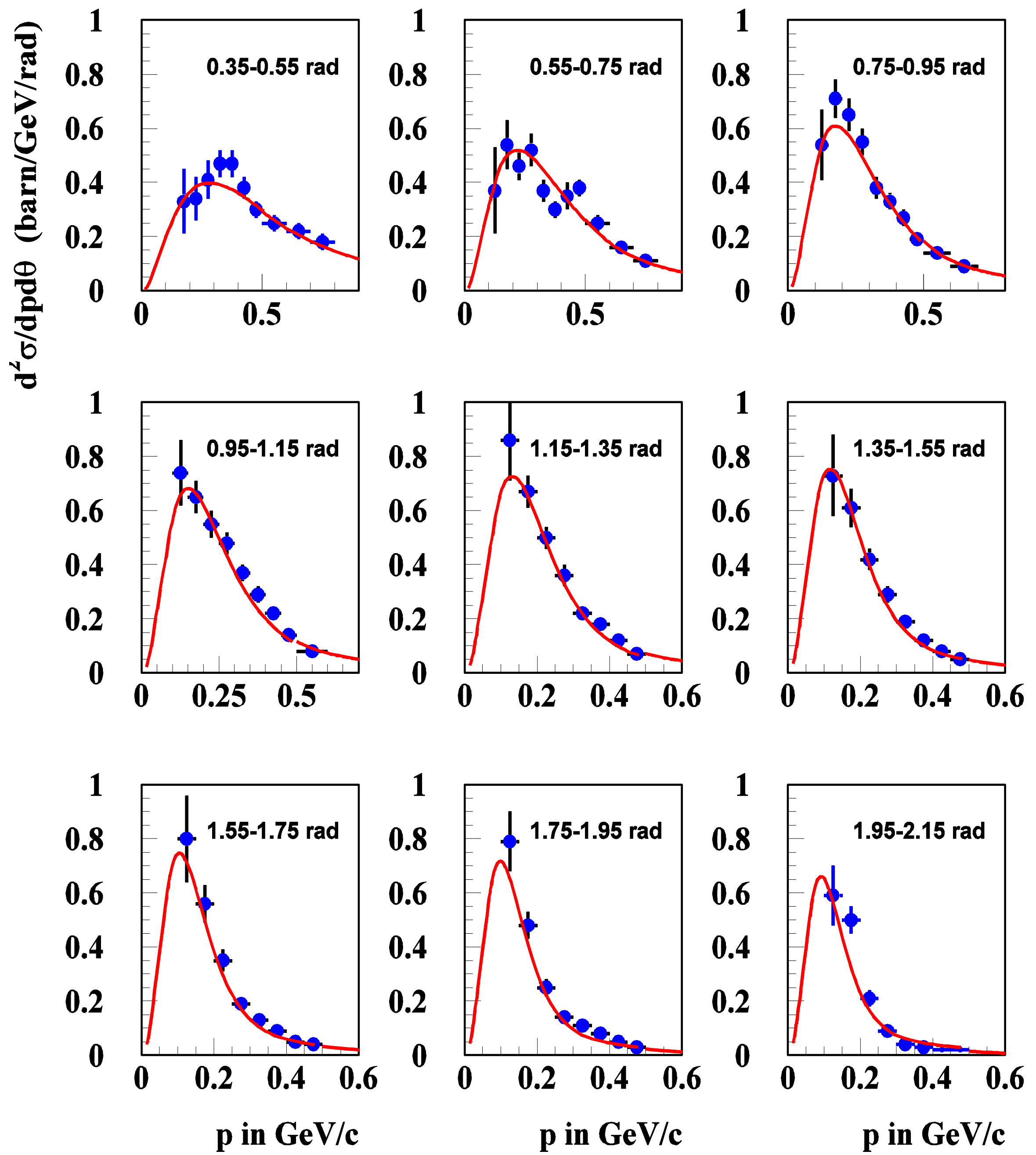
Solid angle acceptance of conventional muon channel ~50msr

Less than 1% of produced surface muon is transported.



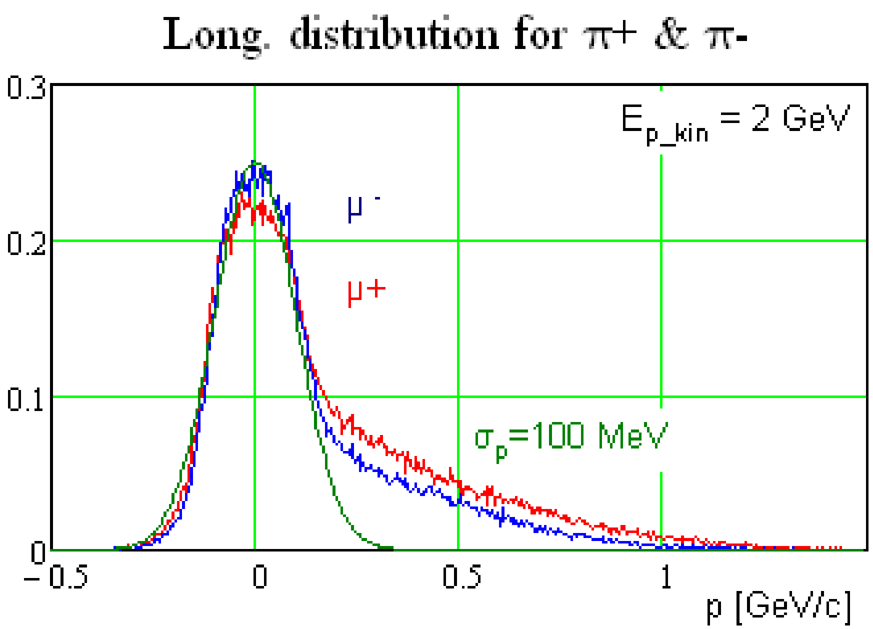
Particle Production Simulations

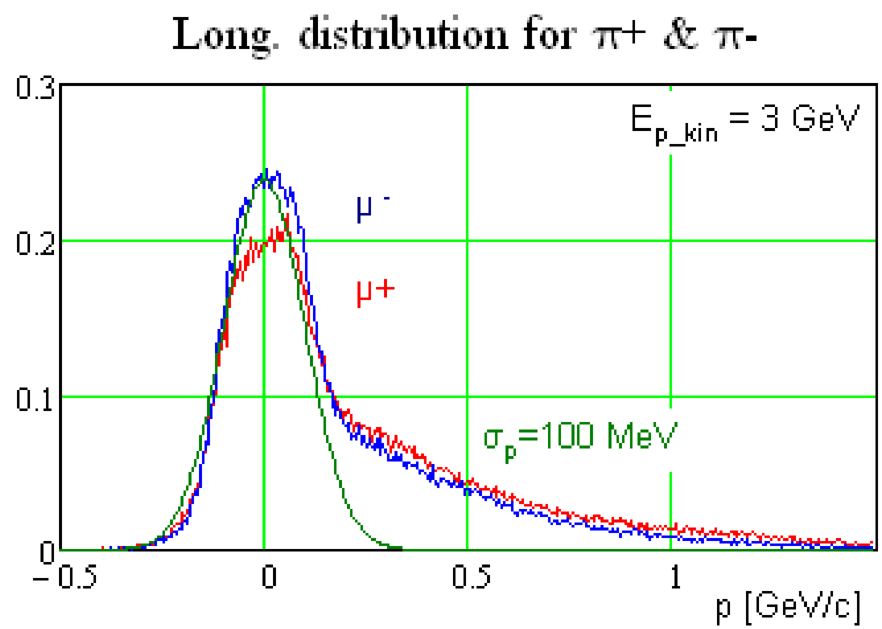
- $p + A \rightarrow \pi + \ldots \rightarrow \mu + \nu + \ldots$
- There are no solid theoretical base for models of multiple particle production in hadron-nucleon interaction.
- There are a lot of experimental data on charged pion production
- MARS particle production model was tuned to recent measurements of HARP collaboration
  - p = 2, 3, 8 GeV/c
- Two HARP groups have published different results based on same measurements
  - Difference for π^- is not significant



π^- production in proton tantalum interaction at 3 GeV/c

Pion Production in a Pencil-like Target





Pion longitudinal distribution function $(df/dp_{||})/E_{p\_kin}$ [c/GeV^2]

Target - nickel cylinder, L=10 cm, r=0.4 cm; no magnetic field

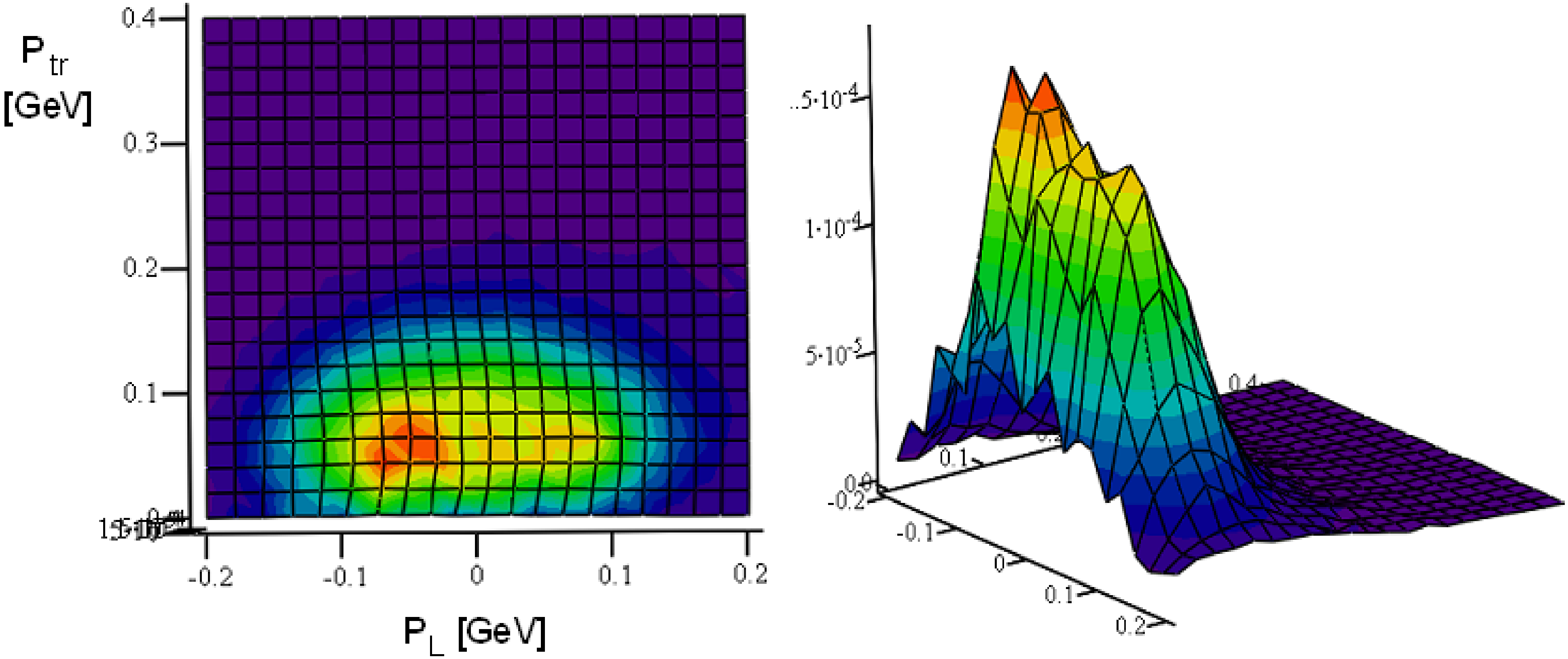
Total production per unit energy of incoming protons

Ekin=2 GeV: forward 5.3% p_GeV^{-1}; backward – 2.9% p_GeV^{-1}

Ekin=3 GeV: forward 6.3% p_GeV^{-1}; backward – 2.8% p_GeV^{-1}

- Longitudinal pion distribution is close to the Gaussian one, $\sigma_p \approx$ 100 MeV/c
- Central part of distribution has weak dependence on the incoming proton energy in the range [2-8] GeV
  - High energy tail grows with proton energy

Pion Production in a Pencil-like Target (continue)



Pion distribution over momentum, d^3N/dp^3 ,

Nickel cylinder, L = 10 cm, r = 0.4 cm; no magnetic field

- Distribution function approaches zero due to particle deceleration at the target surface

Pion Deceleration due to Ionization Loss

For $\gamma\beta \in [0.1,\ 1]$ one can write $\frac{dE}{dx} \approx \frac{1}{\beta^2}\left(\frac{dE}{dx}\right)_0$

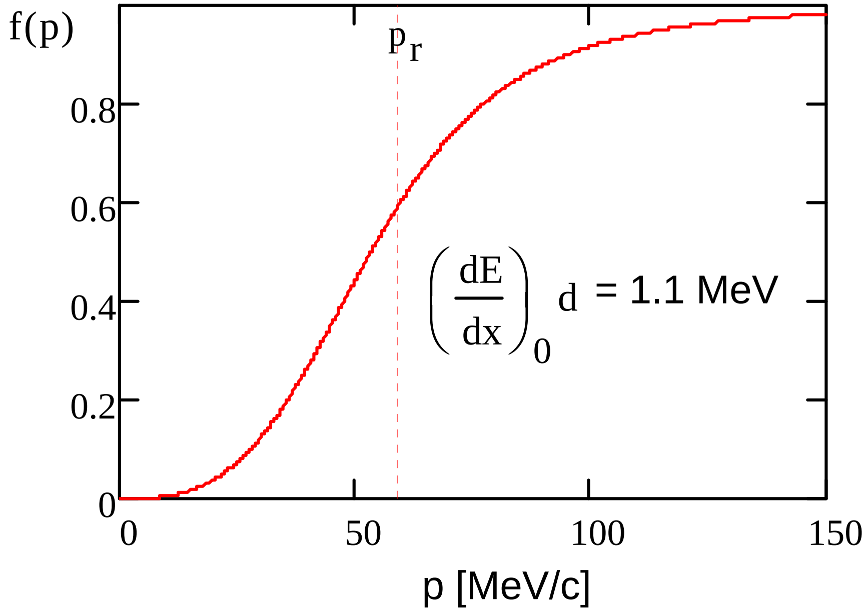
For non-relativistic case $E = m_\pi c^2 \beta^2 / 2$ => $p_{fin}{}^4 \approx p_{in}{}^4 - 4m_\pi{}^3 c^2 \left(\frac{dE}{dx}\right)_0 L$

Distribution function change is: $f(p_{fin}) = \frac{f(p_{in})}{dp_{fin}/dp_{in}}$

Combining one obtains:

$$f'(p_{fin}) \propto p_{fin}{}^3 / \left(p_{fin}{}^4 + p_r{}^4\right)^{3/4}$$

where: $p_r \approx \sqrt[4]{4m_\pi{}^3 c^2 L \left(dE/dx\right)_0 / c}$

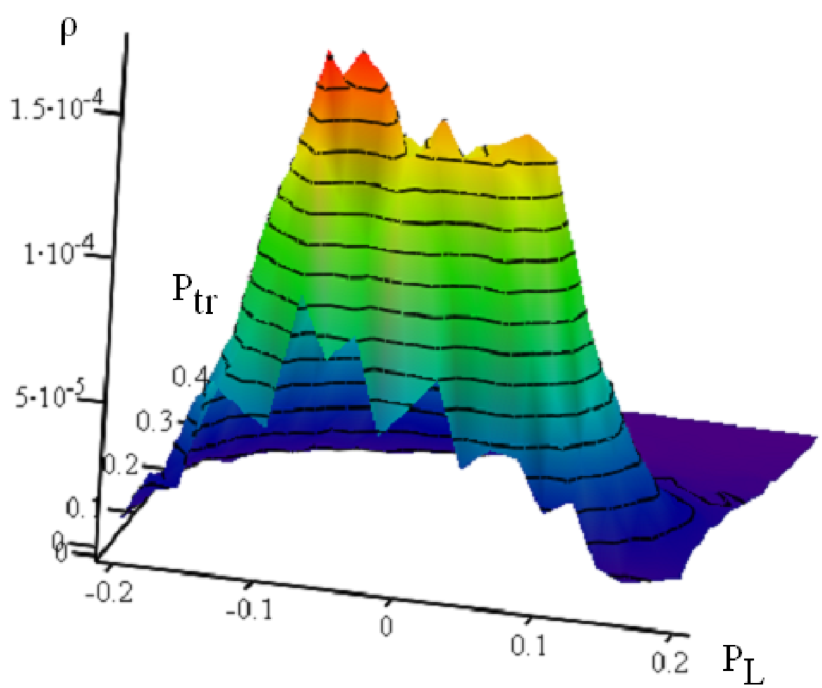


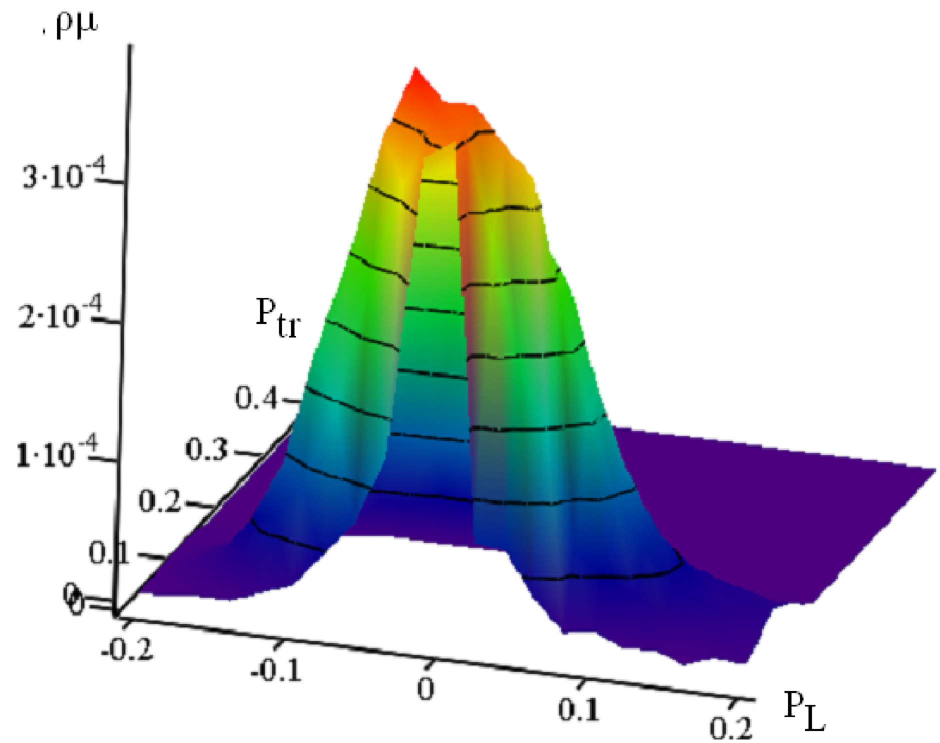
- p_r has comparatively weak dependence on medium properties
  $(dE/dx)_0$ ~1.6 MeV/(g/cm^2)); $p_r \approx 1$ MeV/c for $L \approx 1$ mm
- $m_\pi \approx m_\mu \Rightarrow$ fluxes of pions and surface muons are not significantly different for p ≤ 30 MeV/c !!!

Muon distribution over momentum

- After decay a muon inherits the original pion momentum with Δp correction depending on the angle of outgoing neutrino, Δp_{cm}=29.8 MeV/c
- For most of pions (p > 60 MeV/c) a decay makes a muon with smaller *p*

  ⇒ Momentum spread in μ-beam is smaller than in π-beam





Phase Density and Emittance of Muon Beam

- Pions
  - For short target, $L_{t\arg} < F$, (antiproton source)

    $$\beta^*_{opt} \approx \frac{L_{t\arg}}{6} \quad \Rightarrow \quad \varepsilon \approx \frac{L_{t\arg}}{6}\sigma_\theta^{\ 2}$$

  - For small energy pions this approximation does not work, i.e $L_{t\arg} \geq \beta$
    - In this case
      - $\varepsilon \approx \beta\sigma_\theta^{\ 2}$ where $\beta = \dfrac{2pc}{eB}$
      - and the beam emittance does not depend on the target length

      ⇨ Phase density of pions grows with the magnetic field
- Muons
  - To reduce emittance growth due to pion decays the pions are transported in a solenoidal magnetic field
  - Pions are produced in the solenoid center

    ⇨ they have small angular momentum
  - Pion decays have little effect on the angular momentum and the beam emittance

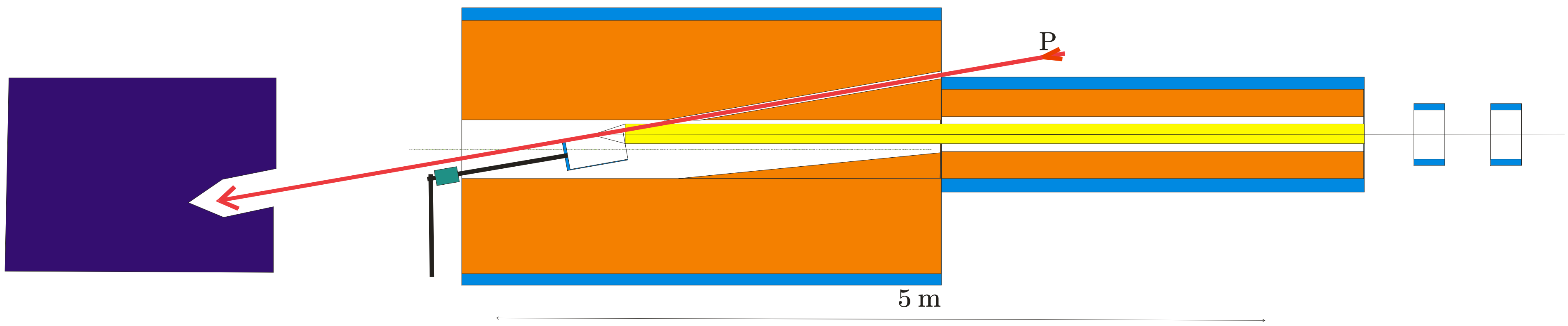
    ⇨ Phase density of the muons is proportional to pion density and, consequently,

    ⇨ the number of muons in a given phase space grows with target magnetic field

    ⇨ and muons do not have x-y correlations after exiting the solenoid

Target and Target Cooling

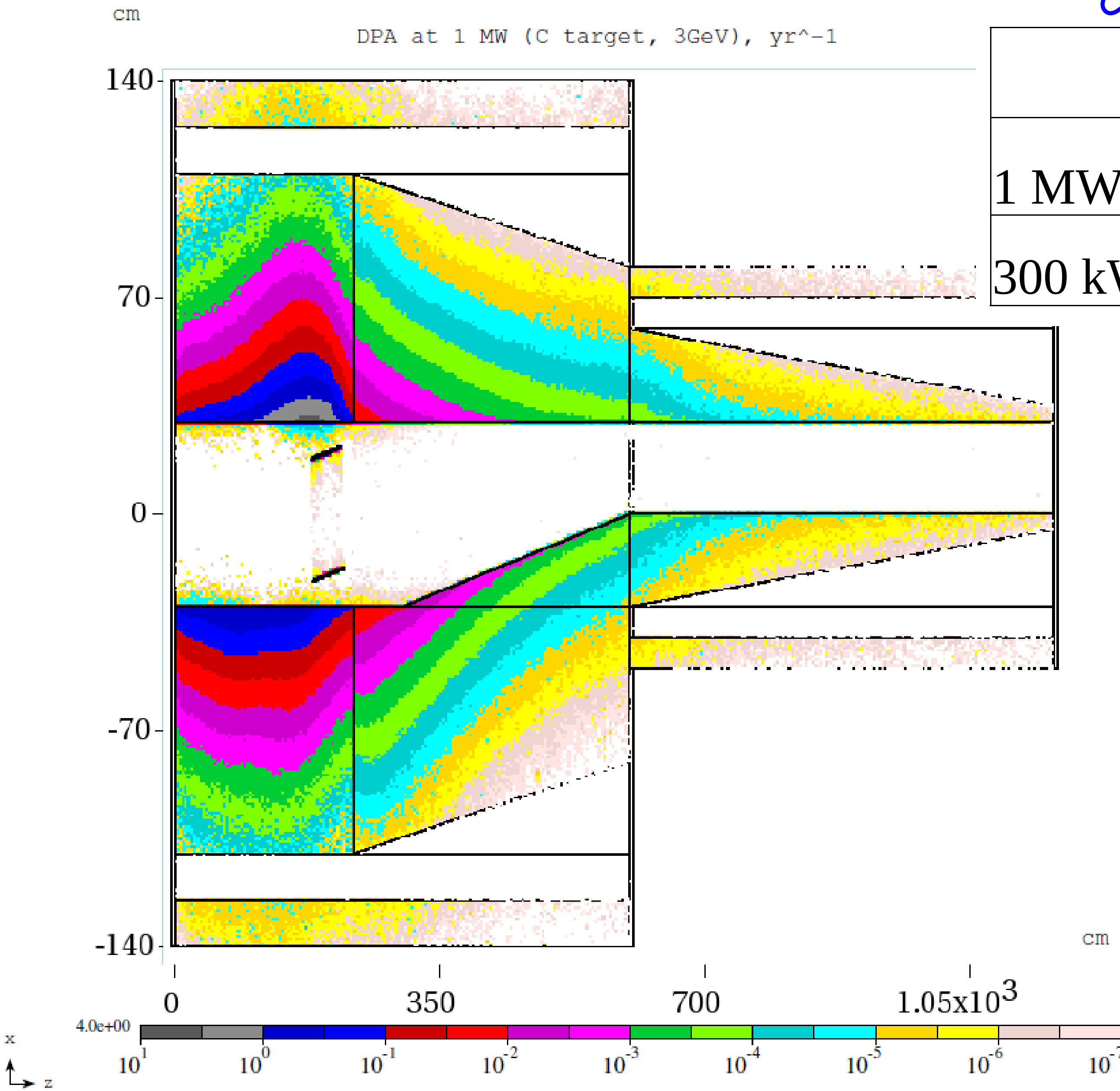
- Optimal target length should be ~1.5 of nuclear interaction length
  - ⇒ i.e.: carbon ~60 cm; tantalum ~15 cm
- The beam leaves ~10% of its energy in the target;
- For 1 MW beam power the power left in the target is ~ 100 kW
- Large beam power prohibits usage of pencil-like target
  - ♦ Heat cannot be removed from pencil target: $dP/dS \geq 2\ kW/cm^2$ for R~0.5cm
  - ♦ Mercury stream is another possibility but it has significant problems with safety. Therefore it was not considered.
- Cylindrical rotating target looks as the most promising choice
  - ♦ Carbon (graphite) and tantalum targets were considered
  - ♦ Tantalum or any other high Z target has a problem with heating



Target cooling

- Rotating cylinder is cooled by the black body radiation
  - PSI uses a rotating graphite target at 1 MW beam power
  - Tantalum, R=10 cm, d=0.5 cm, L=15 cm, 400 rev/min
    - T ≈ 3000 K (melting T = 3270 K), ΔT ≈ 50 C
  - Graphite (C), R=10 cm, d=0.5 cm, L=40 cm, 60 rev/min
    - T ≈ 1800 K (melting T = 3270 K), ΔT ≈ 50 C
  - For graphite temperature looks OK but we still have to address
    - ⇒ Bearing lifetime under radiation (rotation)
- Relative to the pulsed beam the CW beam drastically reduces stress in target

Effects of radiation



Shielding estimate

C[t] / W[t] /Rmax [cm]

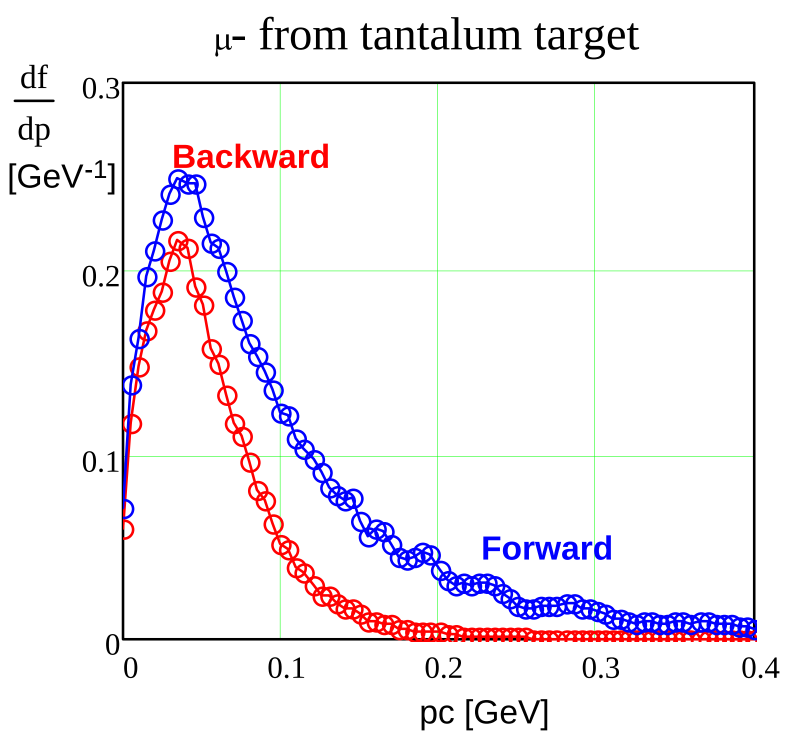
	C target	Ta target
1 MW	140/80 (110)	180/100 (125)
300 kW	100/55 (95)	110/65 (100)

This preliminary absorber design satisfies typical requirements for SC coils

- peak DPA 10^{-5} year^{-1})
- power density (3 μW/g)
- absorbed dose 60 kGy/yr
- Dynamic heat load is 10 W

- Transition from 25 kW of μ-to-e to 1 MW increases the shield radius from ~80 cm 110 cm => B = 5 T → 3 T for the same stored energy

Muon Yield from Cylindrical Target



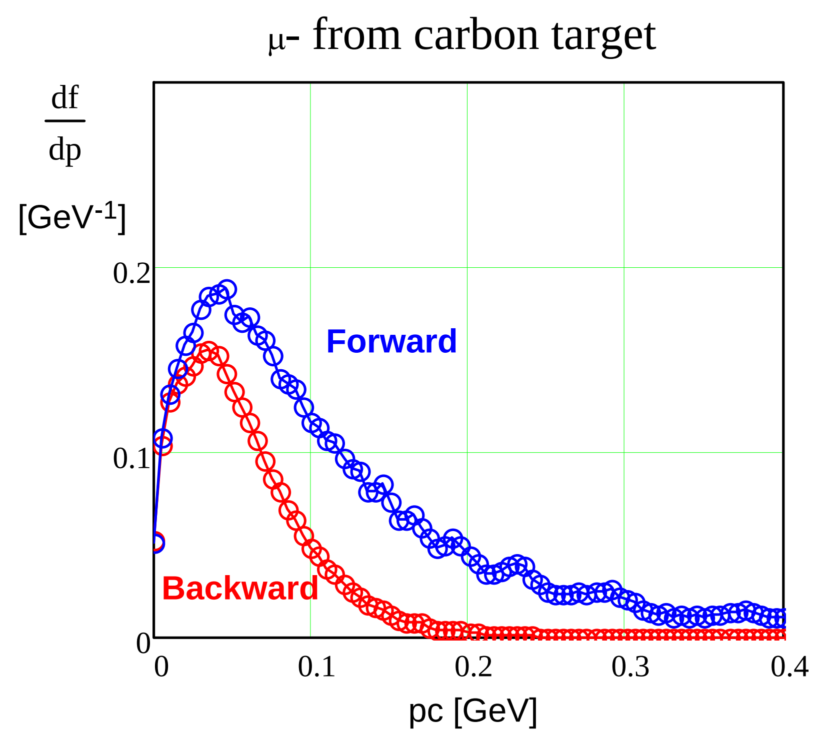
Tantalum hollow cylinder

R_{out}=20 cm, ΔR=5 mm, L=16 cm, θ=300 mrad

Total muon yield at ±10 m

Forward – 1.4% per proton GeV

Backward – 0.73% per proton GeV



Carbon hollow cylinder

R_{out}=20 cm, ΔR=5 mm, L=40 cm, θ=200 mrad

Total muon yield at ±10 m

Forward – 1.3% per proton GeV

Backward – 0.59% per proton GeV

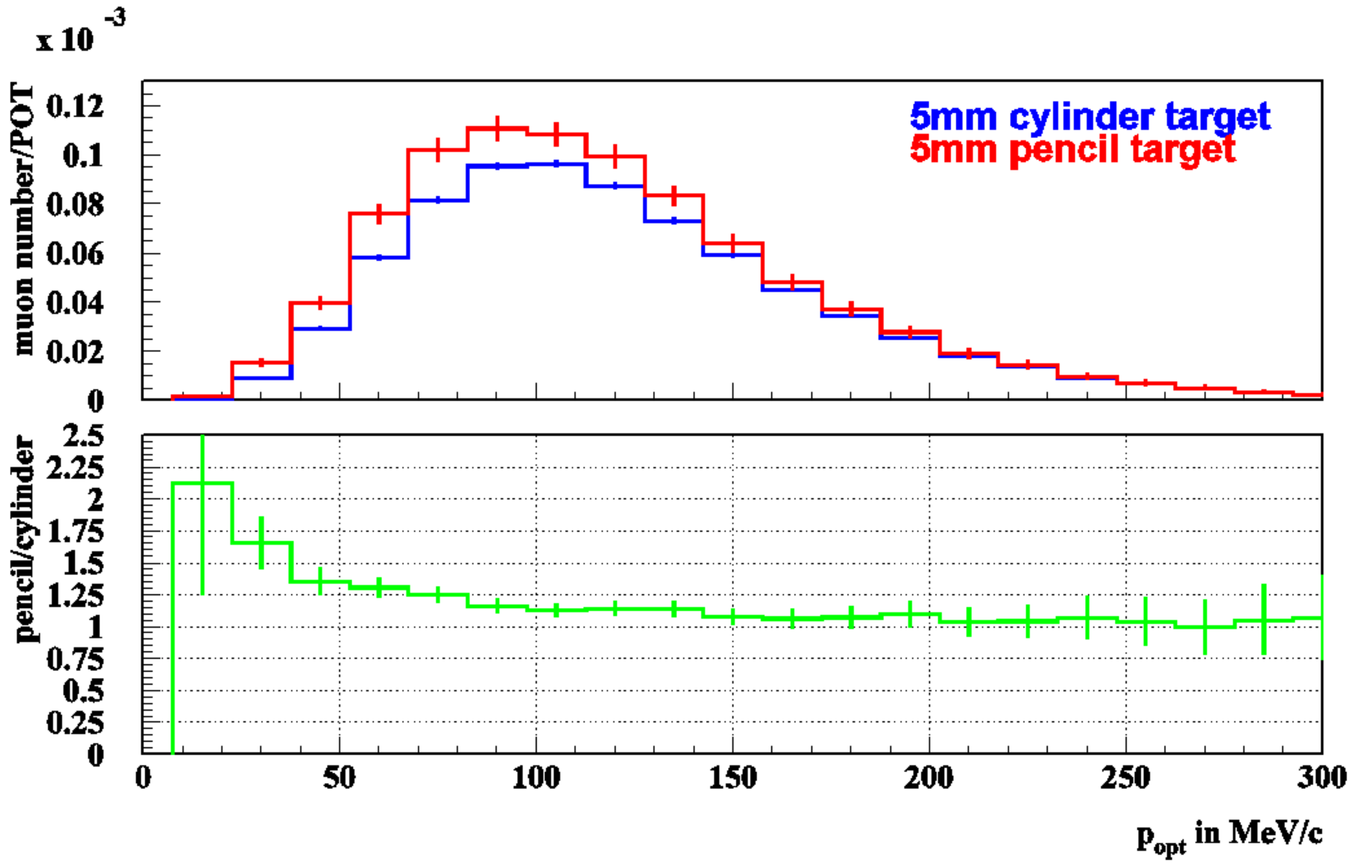
Yield per 1 GeV of proton energy: pc=3 GeV/ (E_{kin}=2.2 GeV),

$\sigma_x = \sigma_y$ = 1 mm – parallel beam, proton multiple scattering unaccounted

- Small difference between forward and backward muons for Pc<50 MeV
- For pc<120 MeV a weak dependence on E_{kin_prot} for $E_{kin\_prot} \in [2, 8]$ GeV/c

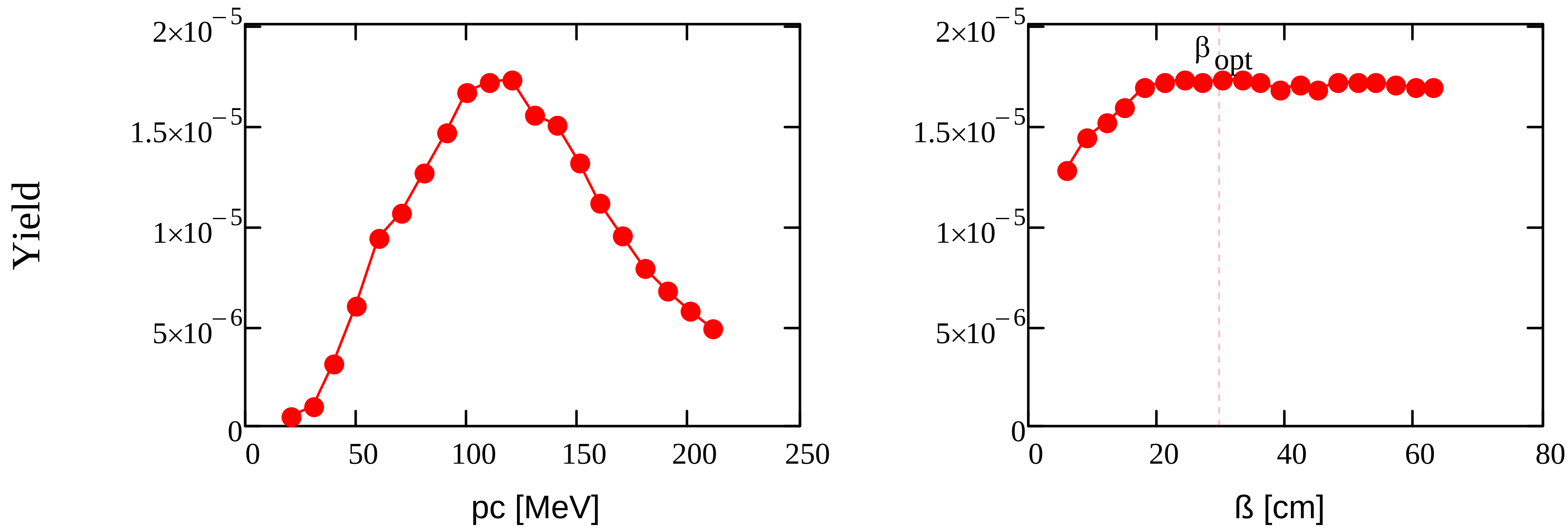
Muon Yield from Cylindrical Target (continue)

- For pc < 120 MeV the carbon target has smaller yield but
  - Less problems with cooling due to larger length
  - It also makes less neutrons
- Compared to a pencil like target a hollow cylinder target has smaller muon yield
  - But it allows one to use much larger beam power
- Beam damp inside solenoid would be a formidable problem therefore below we assume:
  - Backward muons
  - Carbon target



Muon Yield into a Beamline with Finite Acceptance

- In some applications beam transport in a beam line can be desirable
- It allows
  - Isochronous transport preventing bunch lengthening
  - but it significantly reduces the acceptance and momentum spread
- Below we assume that the beam line limits maximum acceptance and momentum spread to $\varepsilon \approx$ 0.3-3 cm, $\Delta p/p \approx \pm 0.15$
  - Beam line can be matched to decay solenoid to maximize the capture $\Rightarrow \beta_{opt}$

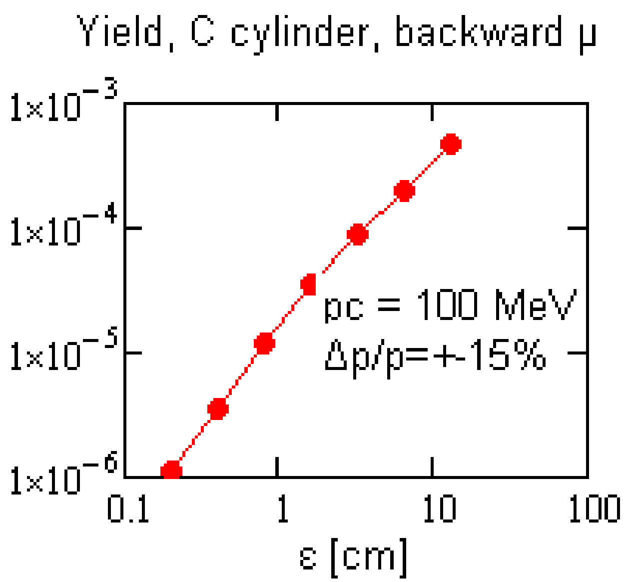


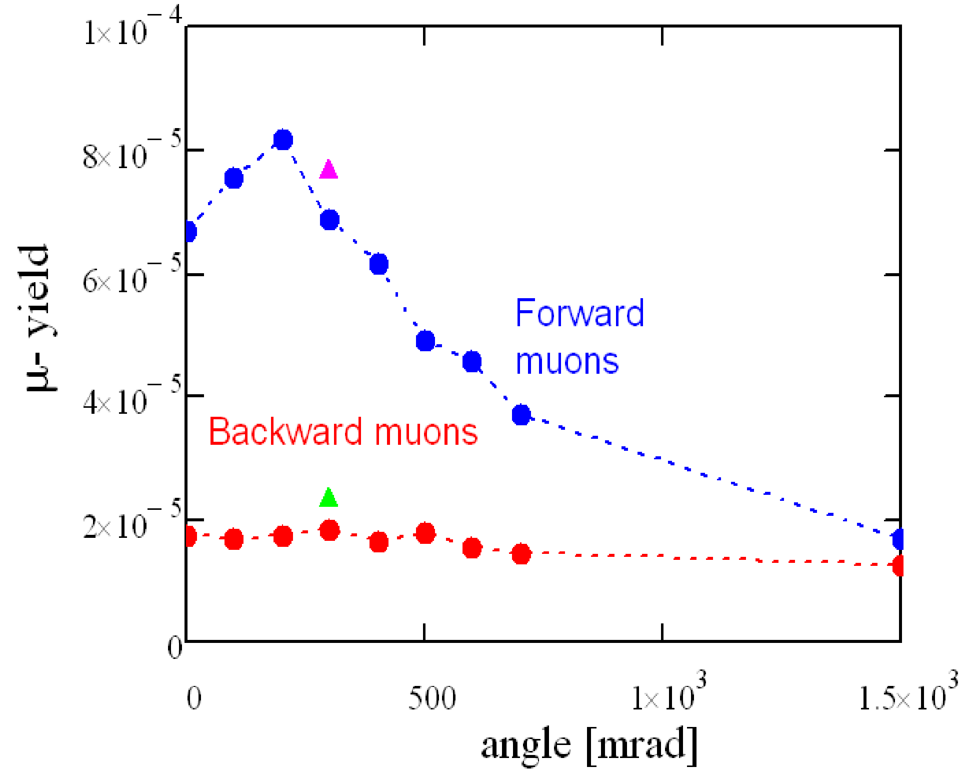
Graphite cylind. target, backward muons, p_{prot}=2 GeV/c, $\varepsilon_x=\varepsilon_y$=1 cm, $\Delta p/p=\pm0.15$, θ=200 mrad, B=2.5T

- For small emittance the dependence of muon yield on the β–function is weak
- Strong suppression of small energy muons (pc<50 MeV) by deceleration in medium

Muon Yield into a Beamline with Finite Acceptance (continue)

- Absence of x-y correlations after beam exit from magnetic field requires axial symmetric exit from solenoid $\Rightarrow$ i.e. the beam center has to coincide with solenoid axis
- Yield is proportional to B_{target}
  - 2.5 T $\rightarrow$5 T would double the yield
- Yield is $\propto \Delta p/p$ (for $\Delta p/p \ll 1$)
- Yield is $\propto \varepsilon^{1.5}$



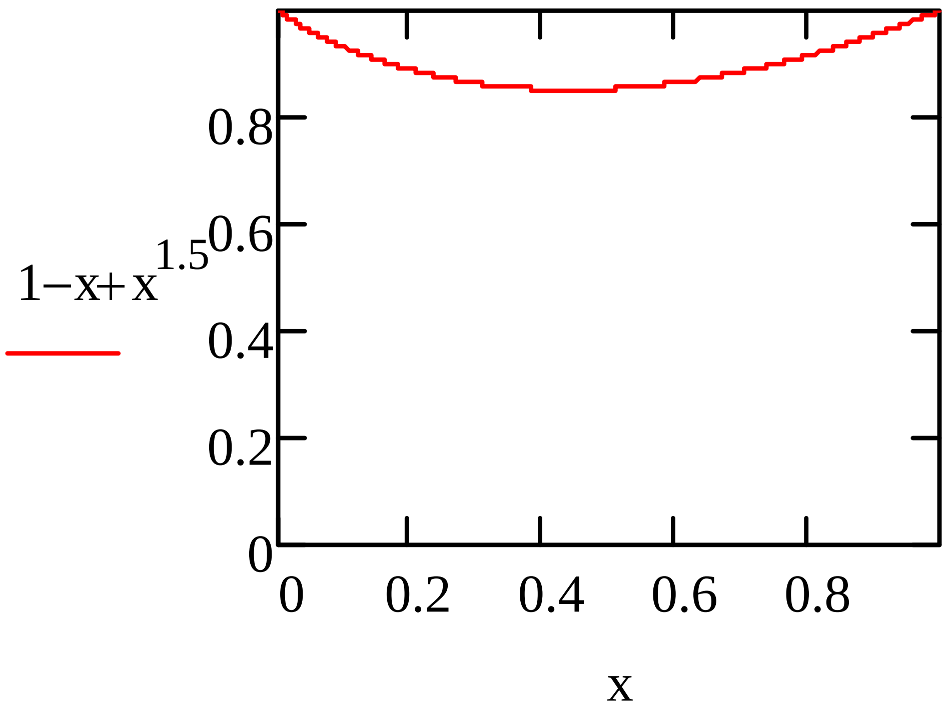


Dependence of muon yield on the target angle relative to magnetic field for carbon target into the following phase space: $\varepsilon_x=\varepsilon_y=1$ cm, $\Delta p/p=\pm15\%$, p_{prot} = 3 GeV/c, (E_{kin}=2.21 GeV)
Optimal momenta are: 100 MeV/c for backward and 200 MeV/c for forward muons
Triangles show results for tantalum target

- Capturing the beam in a beam line reduces the muon flux by about 20 - 50 times

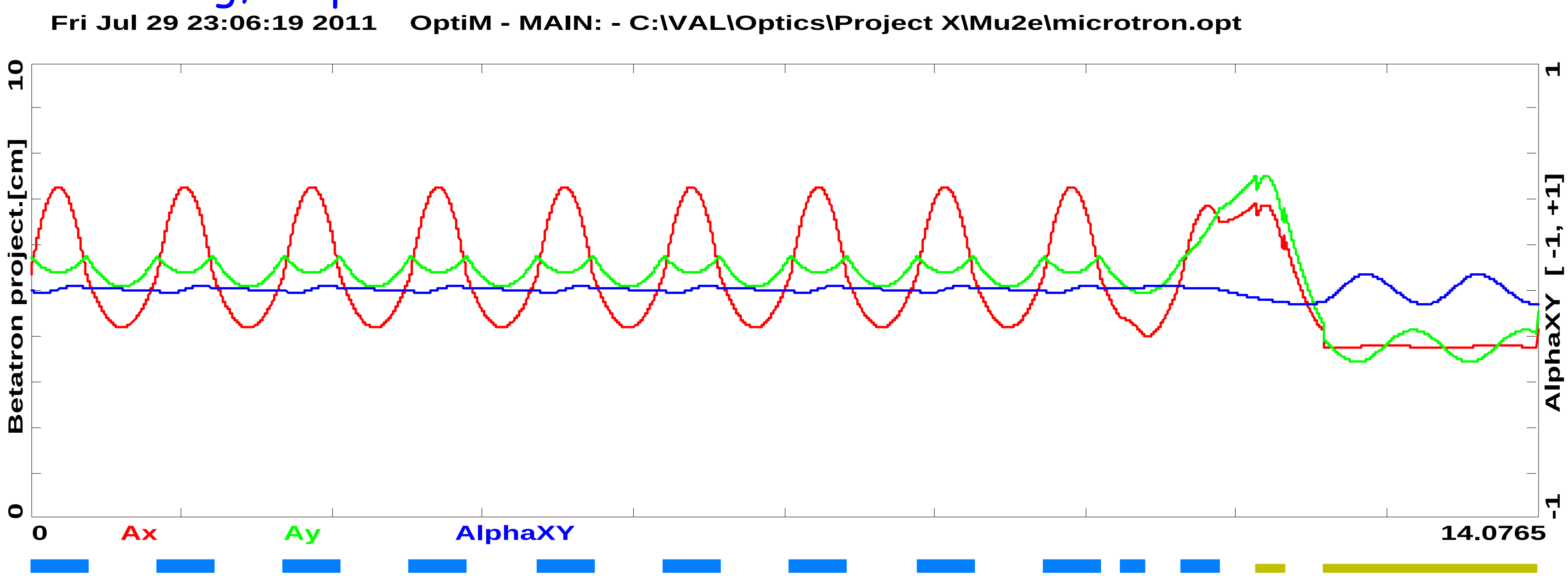
Multiple scattering of protons in the target

- Multiple scattering limits the thickness of cylindrical target to a few millimeters
- Optimal target thickness is weakly affected by its material
  - Heavy target has larger scattering but is shorter
    - It has approximately the same overall effect on the beam envelope growth due to multiple scattering
- Small proton beam emittance in Project X allows some reduction of multiple scattering effects
  - the beam is focused to the small spot at the target end



Beam transport in Helical Transport Line

- If isochronicity of beam transport is required then the beam transport in a "standard" line is the only choice
- The line may consist of downward spiral
  - It is matched to the production and detector solenoids with two dipoles and one or two solenoids at each end
- Toy example
  - One revolution includes 4 dipole magnets: B=5 kG (Pc=50 MeV), L=52.3 cm, R=33.3 cm, gap 13 cm, good field region width: ±15 cm
  - The line acceptance 0.41 cm; Momentum spread ±0.15, it descends with angle of 2.591 deg, step of the helix is 23.973 cm



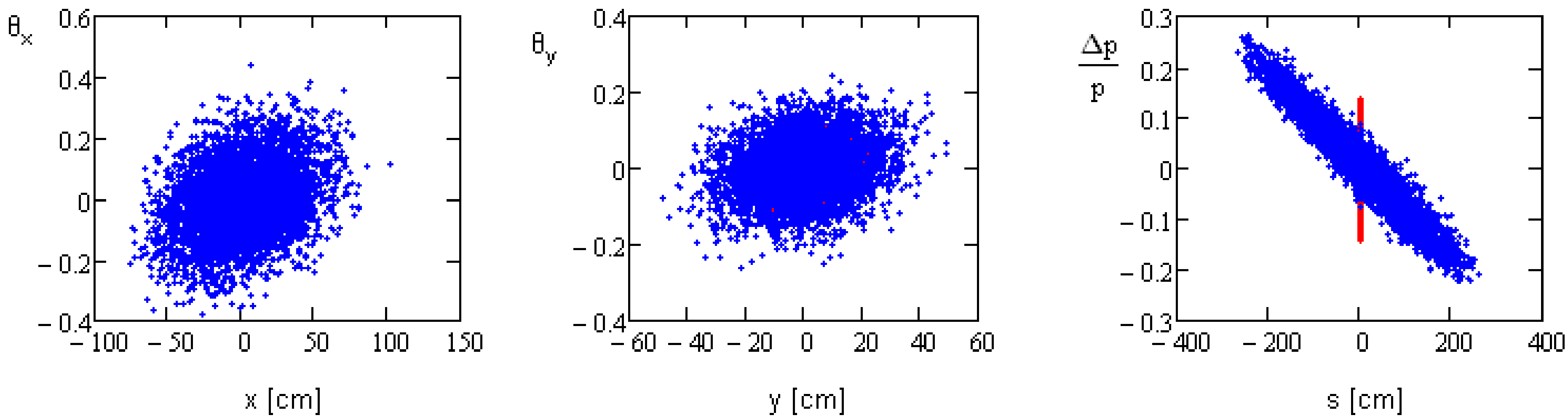
Betatron beam envelopes for helix and match to the detector solenoid. Acceptance 0.41 cm

Beam transport limitations

- To achieve the yield of $\sim 10^{-4}$ we need to have a line with acceptance of ~3 cm (backward muons from carbon target)
  - Similarity of optics yields: $\varepsilon \propto a \propto \beta_{x,y} \propto R_o$
  - Isochronicity requires soft focusing, $Q_x \sim 1$
  - Magnetic fields are reduced with increase of R_o making magnet price affordable
  - Total length and number of turns is determined by required pion extinction (~70 m for 50 MeV/c and extinction of 10^{-14})

Possibilities with Deceleration and Degrading

- Deceleration in electro-magnetic structure results in the adiabatic antidumping, with consequential 6D emittance growth $\propto p^{-3}$, i.e. 8 times for every factor of 2 in momentum
- Deceleration in the material looks much better at large p ($p \geq m_\mu$) but behaves the same way ($\propto p^{-3}$) for non-relativistic particles
  - ♦ even worse than it if multiple scattering is important (large $\beta_{x,y}$ at absorber)
  - ♦ Redistribution of damping decrements in realistic simulation partially helps but does not address the problem



$g_L \equiv 1$

$\kappa_{scat} \equiv 1$

$\mu_x \equiv 2\cdot\pi\cdot 0.25$

$\mu_y \equiv 2\cdot\pi\cdot 0.25$

$D \equiv 150$ cm

$\varepsilon_x \equiv 3$ cm

$\beta_x \equiv 200$ cm

$\beta_y \equiv 200$ cm

$D_p \equiv 0.0$

$\varepsilon_y \equiv 3$ cm

$\alpha_x \equiv -0.3$

$\alpha_y \equiv -0.2$

$M_{56} \equiv 0$

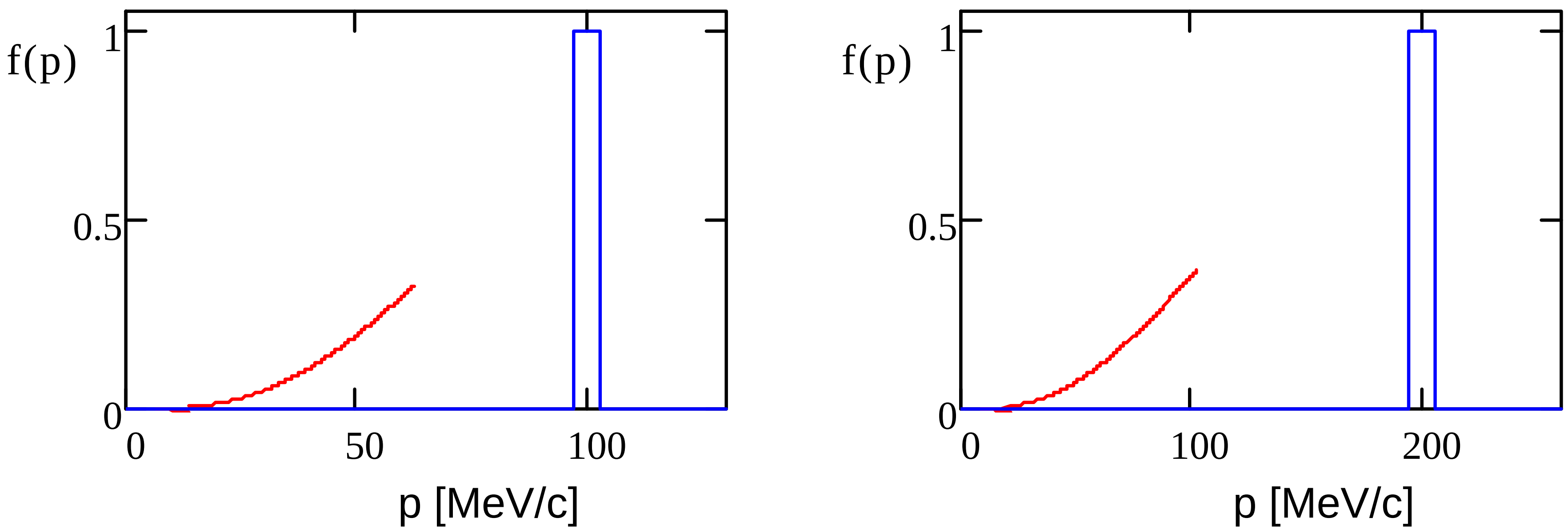
$\sigma_p \equiv 0.15$

$\kappa_{eff} = 0.281$

$\frac{\varepsilon x_{fin}}{\varepsilon x_{in}} = 6.89$ $\frac{\varepsilon y_{fin}}{\varepsilon y_{in}} = 2.54$ $\frac{\sigma p_{fin}}{\sigma p_{in}} = 1.758$

Deceleration (Degrading) after Ionization Cooling

- Ionization cooling looks rather hypothetical possibility because:
  - In difference to the muon collider the CW operation is required
    - It makes the cooling much more difficult and presently hardly feasible
  - Cost prohibitive
- Even if the cooling problem is solved at pc = 100 - 200 MeV the deceleration to low energy is quite ineffective



Degrading of the rectangular distribution with ±3% momentum spread

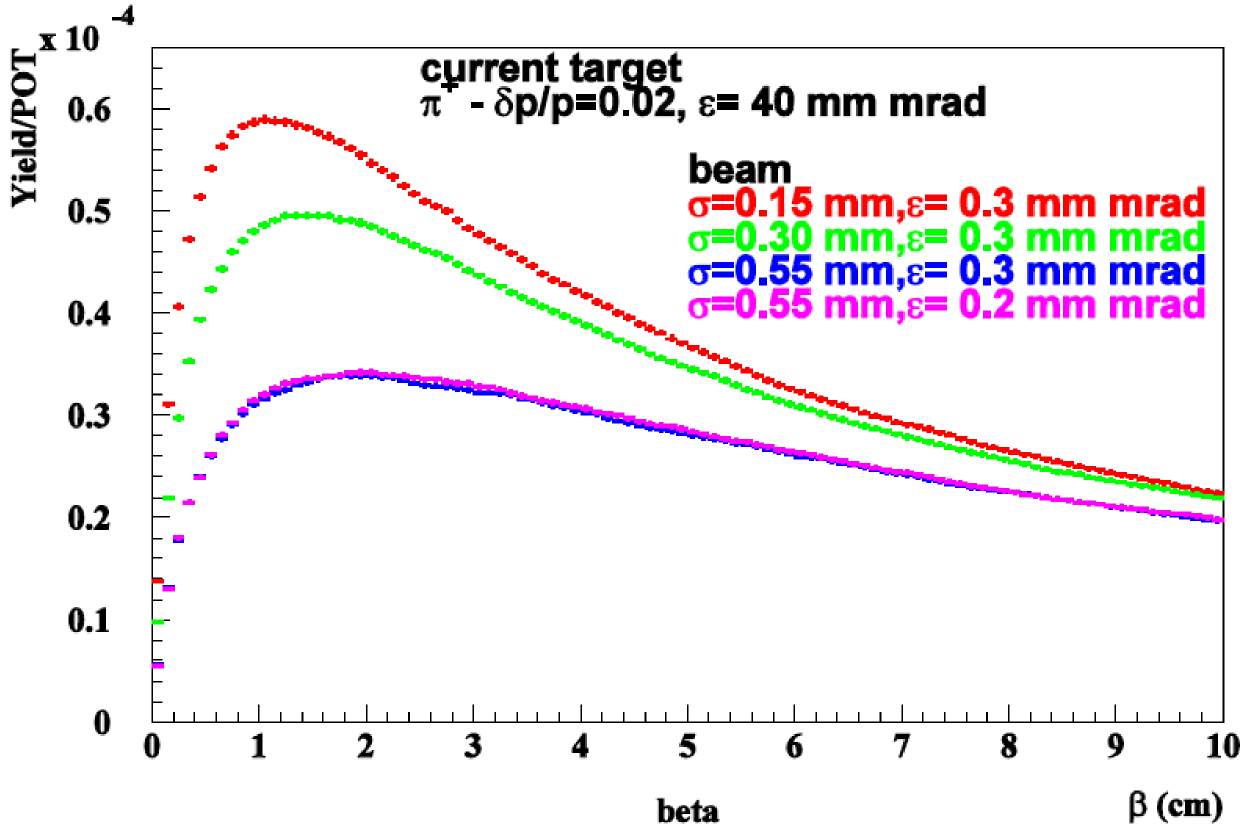
- The ionization cooling graded with energy looks even more exotic

g-2 present and future

Muon yield for g-2 (present)

- Tight beam focusing on target (σ~150 μm, β*~7 cm)
- Small beta-function on the target for outgoing pions β* = 2 - 2.5 cm
  - Lithium lens operating at ~15 Hz

Dependence of pion yield on beta function for current pbar target (Δp/p=0.02)



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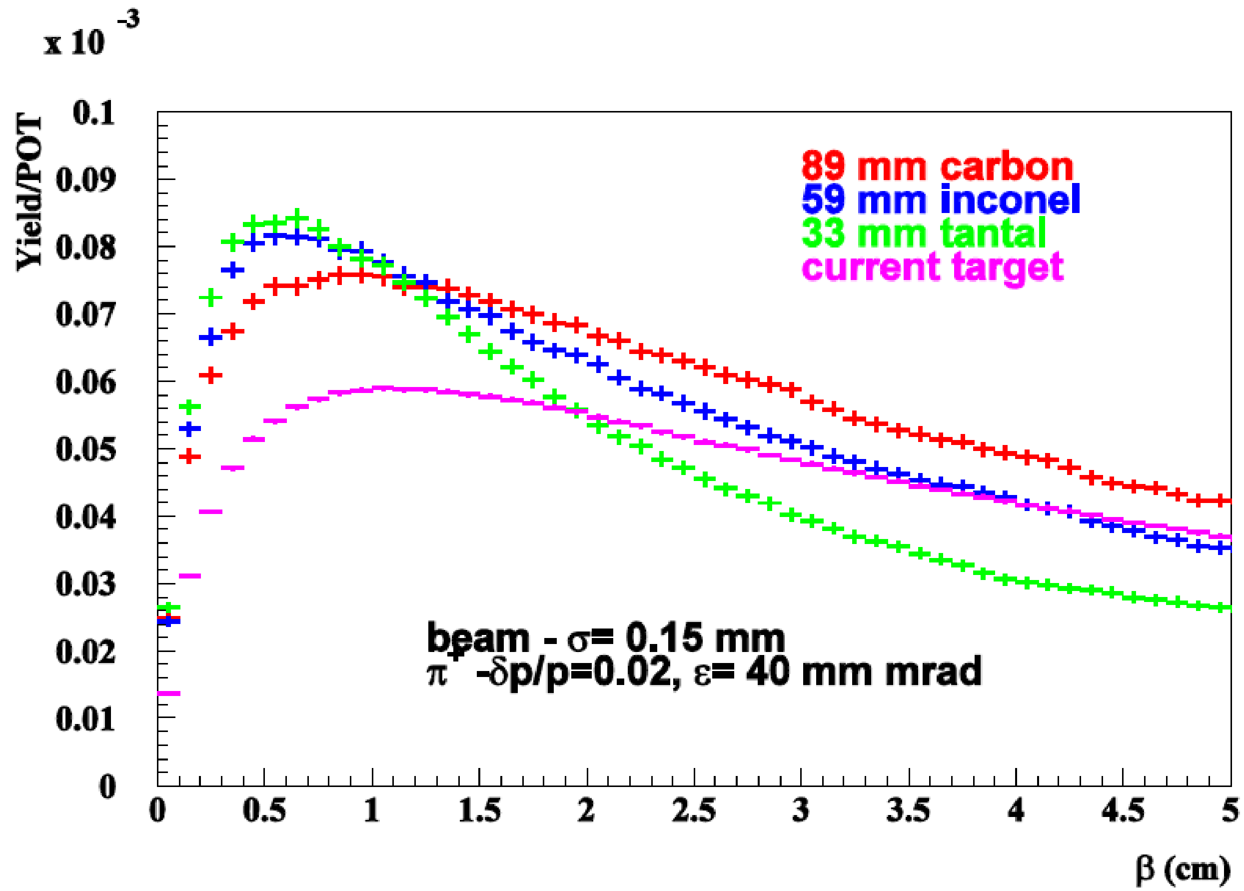
- Weak dependence of pion yield on target material
  - Inconel (present pbar target) looks as a good choice
- Using thin disc target yields ~30% improvement relative to the presently used "solid piece" target (Be spacers between disks)

Dependence of pion yield on beta function for different material ($\Delta p/p=0.02$).



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Experiments with fast extracted beam at Project-X era (first glance on g-2, no real work done)

- Available power up to 200 kW
- Beam in Recycler can be pre-bunched to g-2 structure (~50 ns)
  - ~100 kW at @ ~ 200 - 500 Hz (kicker?)
- Using antiproton source rings is required to get power above ~100 kW
- Pion yield reduction with repetition rate increase (> 15 Hz)
  - Loss of lithium lens gradient
  - Using normal quads does do the same strong focusing
- Extra beam power should help but its optimal use need to be found!!!

Conclusions

- 1 MW target in a few Tesla solenoidal field is feasible
  - Graphite rotating cylinder cooled by the black-body radiation
  - Radiation shielding: R ≈ 80 cm (for μ-to-e) → R ≈ 110 cm
    - ⇒ Smaller B if the same energy is stored in the field;
      - Magnetic field change: $B \propto R^{-3/2} \approx (80/110)^{3/2} \approx 0.6$
      - overall loss of muon yield is smaller than factor of 2
      - ~ 20 times more muons than present Mu2e (1 MW, 2 - 3 GeV)
- Muon yield per unit power weakly depends on proton energy[2-8 GeV]
  - for 1 GeV beam
    - ~15% reduction if the energy is reduced from 2.2 to 1 GeV for Ta target
    - ~2.5 times reduction for graphite target!!!
- Beam line option
  - Creates wide possibilities for the phase space manipulations
    - Isochronicity of beam transport
  - Muon flux reduction by more than an order of magnitude
  - Decelerating or degrading of muons does not look promising
  - Ionization cooling of muon is presently hardly feasible
  - Requirement to have only low energy muons for stopping in a thin target (pc<<100 MeV) results in drastic reduction of muon flux

Backup Slides

Muon Physics

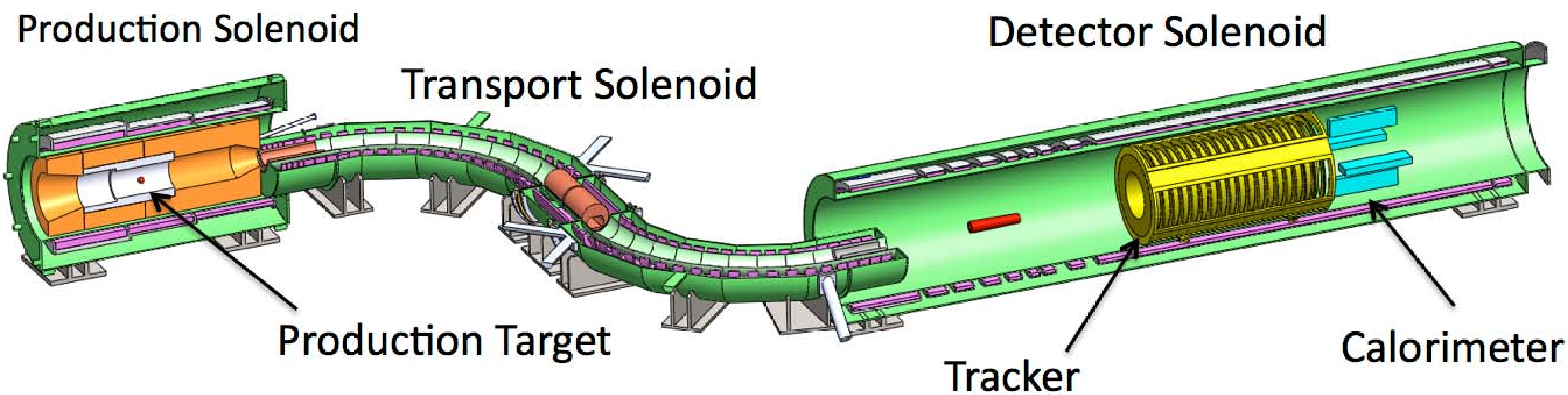
- Possible experiments
  - Next generation $(g-2)_\mu$ if motivated by next round (theory, LHC)
  - Next generation μ-to-e
    - new techniques for higher sensitivity and/or other nuclei.
  - μ edm
  - $\mu \to 3e$
  - $\mu^+ e^- \to \mu^- e^+$
  - $\mu^- A \to \mu^+ A'$; $m^- A \to e^+ A'$; $m^- e^-(A) \to e^- e^-(A)$
  - Systematic study of radiative muon capture on nuclei.

Major types of experiments

- High energy, small repetition rate (~10-100 Hz, fast extraction from ring)
  - $(g-2)_\mu$
- Small energy, high repetition rate (~1-10 MHz)
  - decays on a fly
  - Stopped muons: μ-to-e,
    - Ultimate requirements to a muon source:
      - Small energy, pc < 10-20 MeV (E_{kin} < 0.5 – 4 MeV) is desirable
      - Large flux ~10^{13} s^{-1}

Present μ-to-e

- Conversion – 2.1·10^{-3} ($dN_p/dt=2.4\cdot10^{13}\ s^{-1}$, P=25 kW, $dN_\mu/dt=5\cdot10^{10}\ s^{-1}$)
- Extinction <10^{-10} (sensitivity 6·10^{-17}(90% C.L.))
- Target (gold, L~16 cm, r=0.5 cm, water cooled)
  - Total power - 25 kW
  - Power left in the target – 2 kW
- Secondary target
  - 17 Al discs, 0.2 mm thick, 5 cm apart, tapered radii – r_d = 8.3 → 6.53 cm
- Magnetic fields
  - Production solenoid: 5T -> 2.5 T, internal radius 0.75 m (reflection of muons)
  - Transport solenoid – 2 T
  - Detector solenoid : 2T -> 1T (reflection of electrons with negative $p_{||}$)



Major Requirements to a New Generation μ-to-e Experiment†

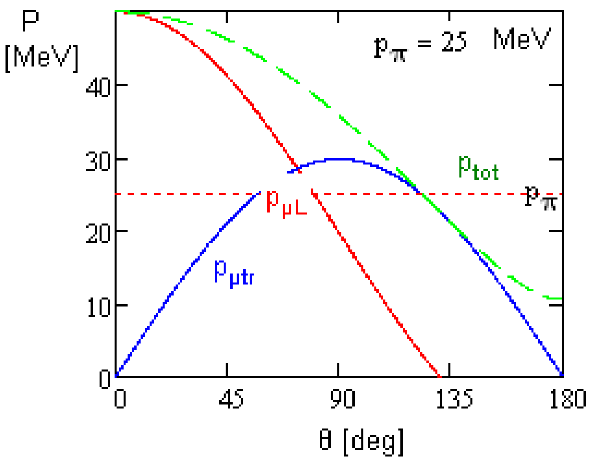
- ~100 times better than μ-to-e
  - single event sensitivity $2\cdot10^{-19}$ (or $6\cdot10^{-19}$ at 90% CL)
    - ⇒ $5\cdot10^{18}$ muons: 2 years of $2\cdot10^{7}$ s each
    - ⇒ $5\cdot10^{12}$ muons/s
  - Pc < 20 MeV i.e. E_{kin}<1.9 MeV (stopped in 0.4 mm Al foil)
  - Extinction $<10^{-14}$ for pions; no antiprotons
  - Short pulse: t < 10 ns
  - Detector is located underground (≥12 m)
- Short pulse and very good extinction imply that the beam transport has to be in an isochronous beam line
  - Drastic reduction of transverse and longitudinal acceptances
    - ⇒ 1 MW Project X power should be helpful
- Limitation of maximum energy to <1 MeV points out to the muon deceleration as a possible choice

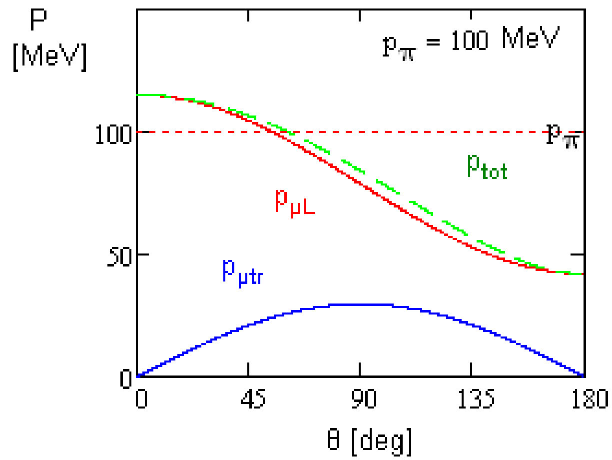
† Bernstein & Prebys, July 26, 2011

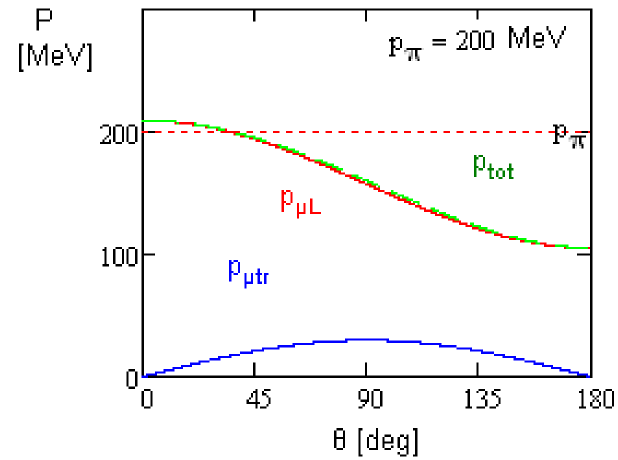
Muon distribution over momentum

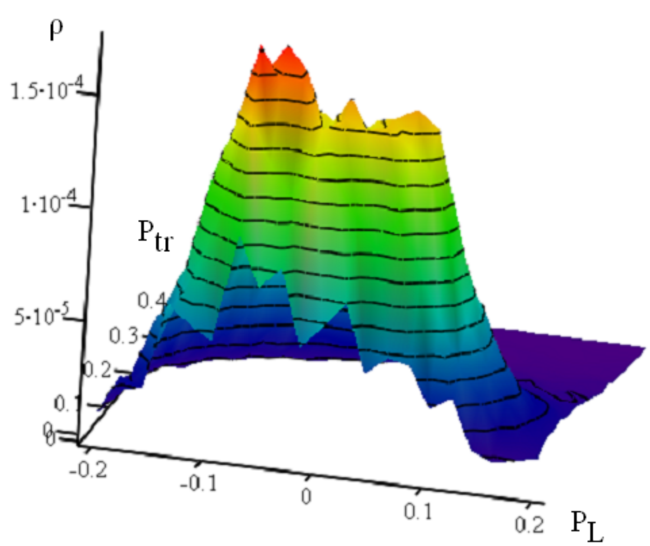
- After decay a muon inherits the original pion momentum with Δp correction depending on the angle of outgoing neutrino, Δp_{cm}=29.8 MeV/c
- For most of pions (p > 60 MeV/c) a decay makes a muon with smaller *p*

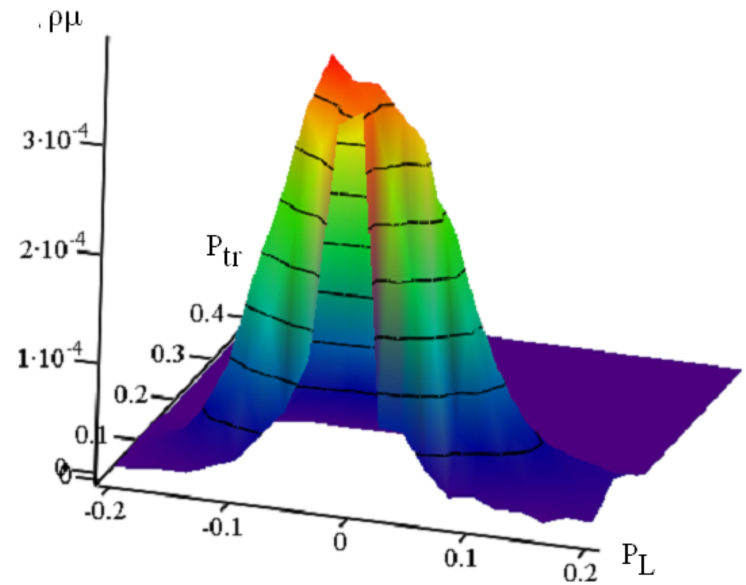
  ⇒ Momentum spread in μ-beam is smaller than in π-beam



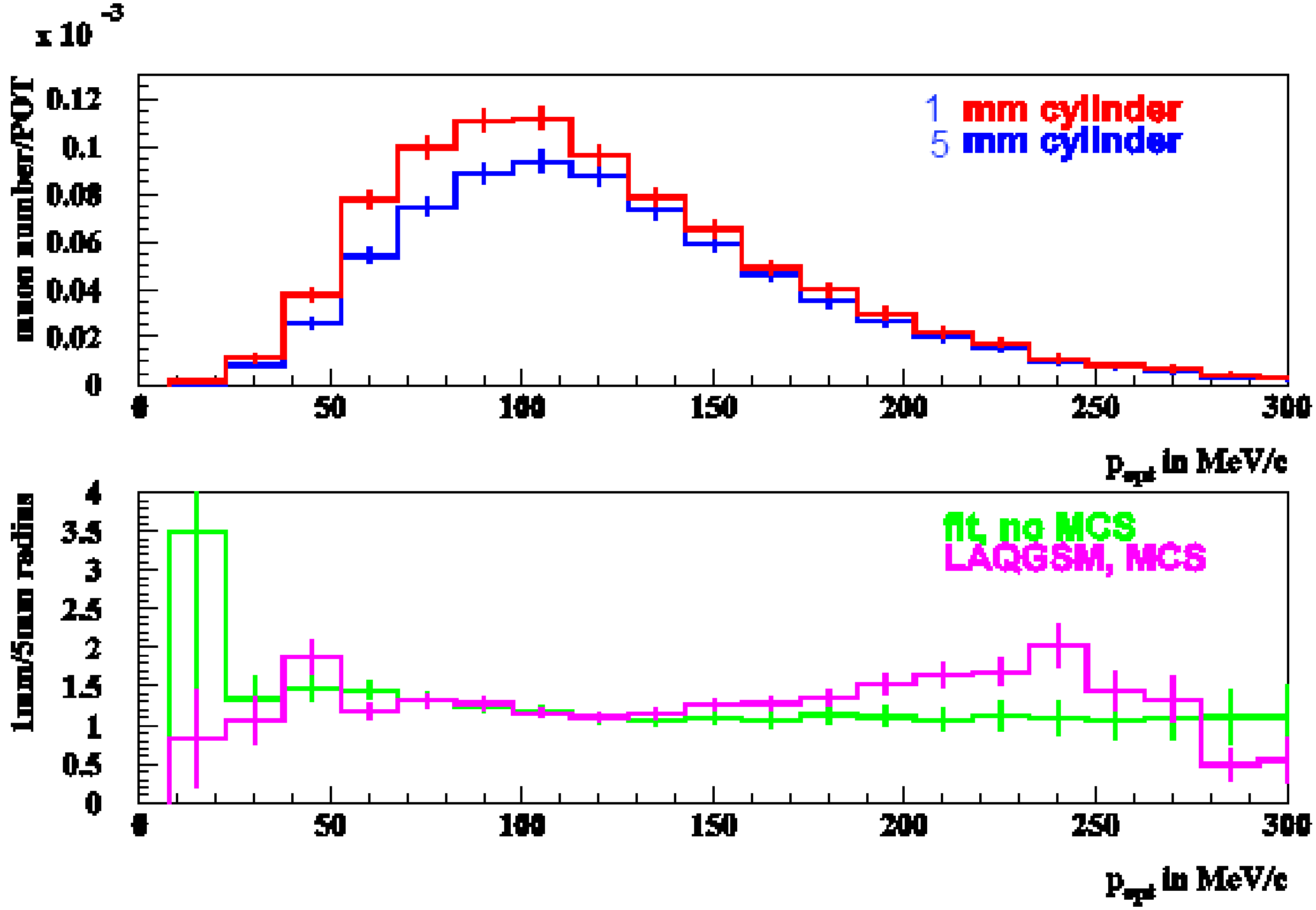








Making slow muons



Dependence on target thickness;
10 m decay channel, 2.5 Tesla, ε=3 cm, 300 mrad angle, backward direction.

- Current model does not take into account scattering of primary proton beam in target.
  - It will reduce dependence on the target radius

Muon Yield into limited acceptance and momentum spread

backward muons, B=2.5 T, p_{opt} = 100 – 120 MeV/c

ε = 3 mm mrad, $\Delta p/p$ = ±15%,

	Graphite		Tantalum	
E_{proton_kin} [GeV]	Total yield	Yield per GeV of E_{kin_proton}	Total yield	Yield per GeV of E_{kin_proton}
1	$1.8\cdot10^{-5}$	$1.8\cdot10^{-5}$	$4.4\cdot10^{-5}$	$4.4\cdot10^{-5}$
pc=2	?	?	?	?
2.205	$9.5\cdot10^{-5}$	$4.3\cdot10^{-5}$	$11.7\cdot10^{-5}$	$5.3\cdot10^{-5}$
pc=7	?	?	?	?

- Large yield reduction for carbon target at 1 GeV

Muon Yield into the μ-to-e solenoidal transport

- μ-to-e acceptance simulation

- Acceptance is defined to be the number of negative muons, as a fraction of the number of negative pions produced in the target, that reach the end of transport solenoid channel

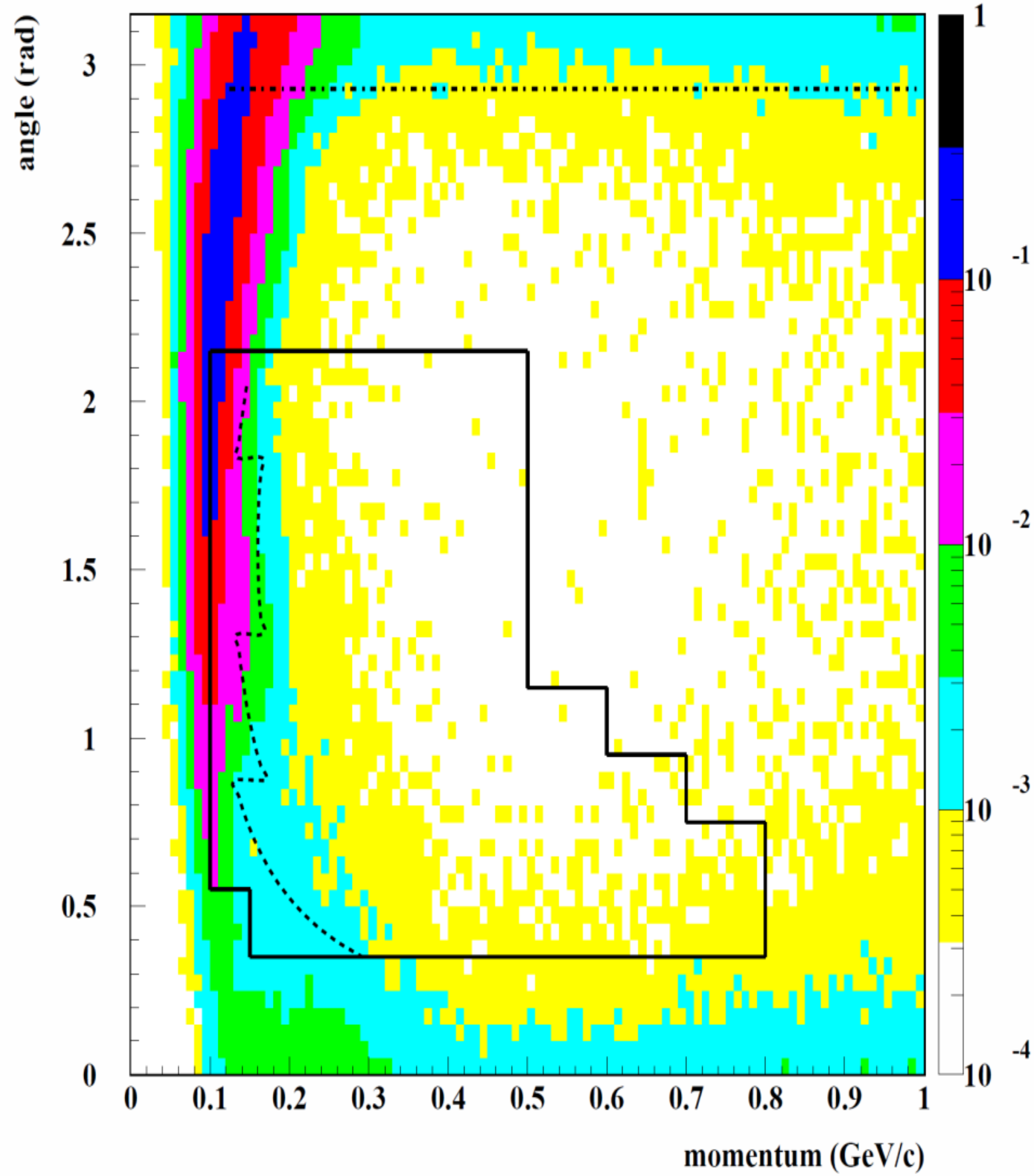
Convolution of acceptance with muon production yields

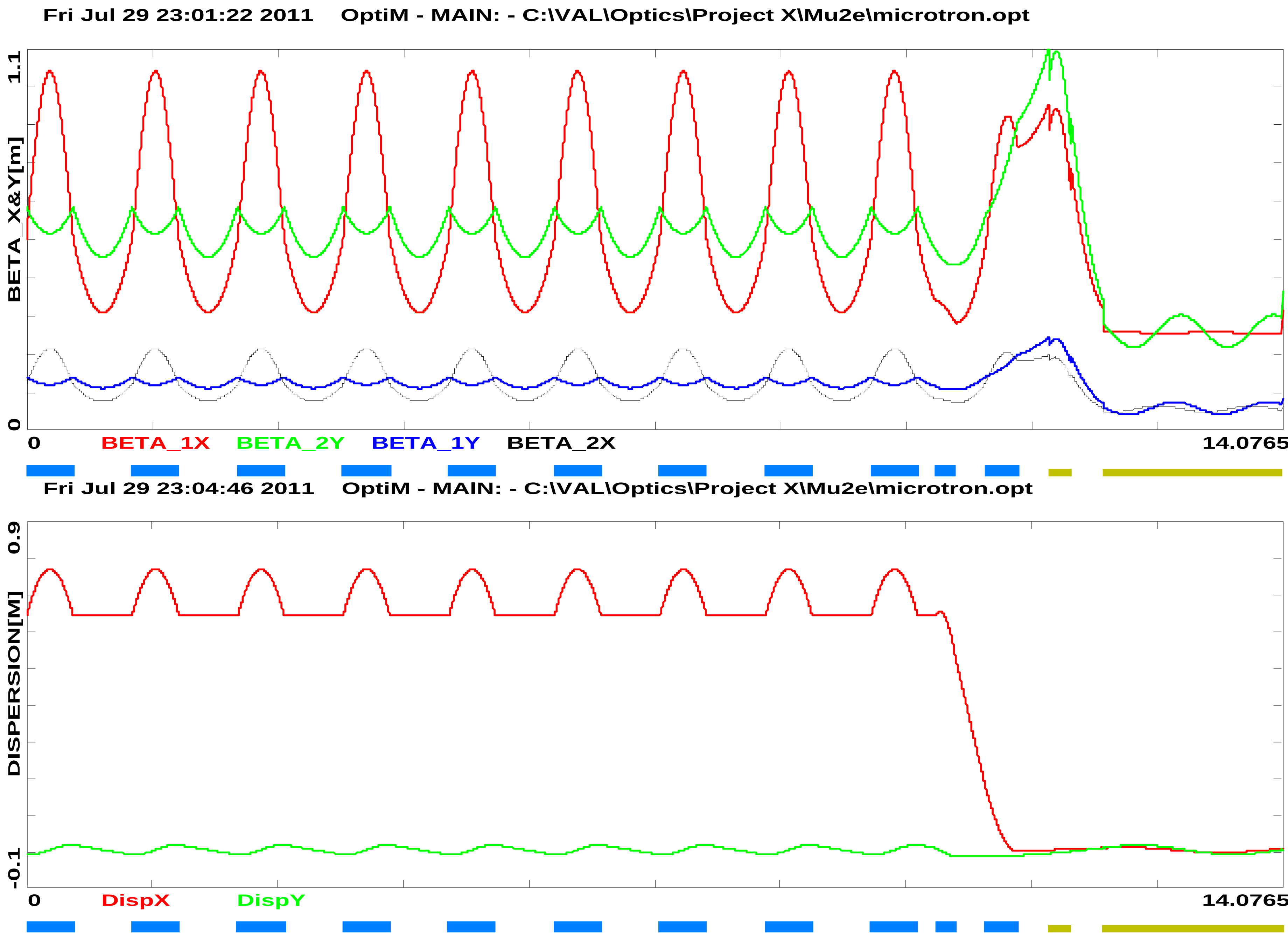
Graphite

E_{proton_kin} [GeV]	Total yield	Yield per GeV of E_{kin_proton}
1	?	?
pc=2	?	?
2.205	$2.73 \cdot 10^{-3}$	$1.24 \cdot 10^{-3}$
7.117	$7.93 \cdot 10^{-3}$	$1.11 \cdot 10^{-3}$

Tantalum

E_{proton_kin} [GeV]	Total yield	Yield per GeV of E_{kin_proton}
1	?	?
pc=2	?	?
2.205	?	?
7.117	?	?





4D beta-functions (top) and dispersions (bottom) for helix and match to the detector solenoid

Dependence of pion yield on beta function for different target length (Δp/p=0.02).