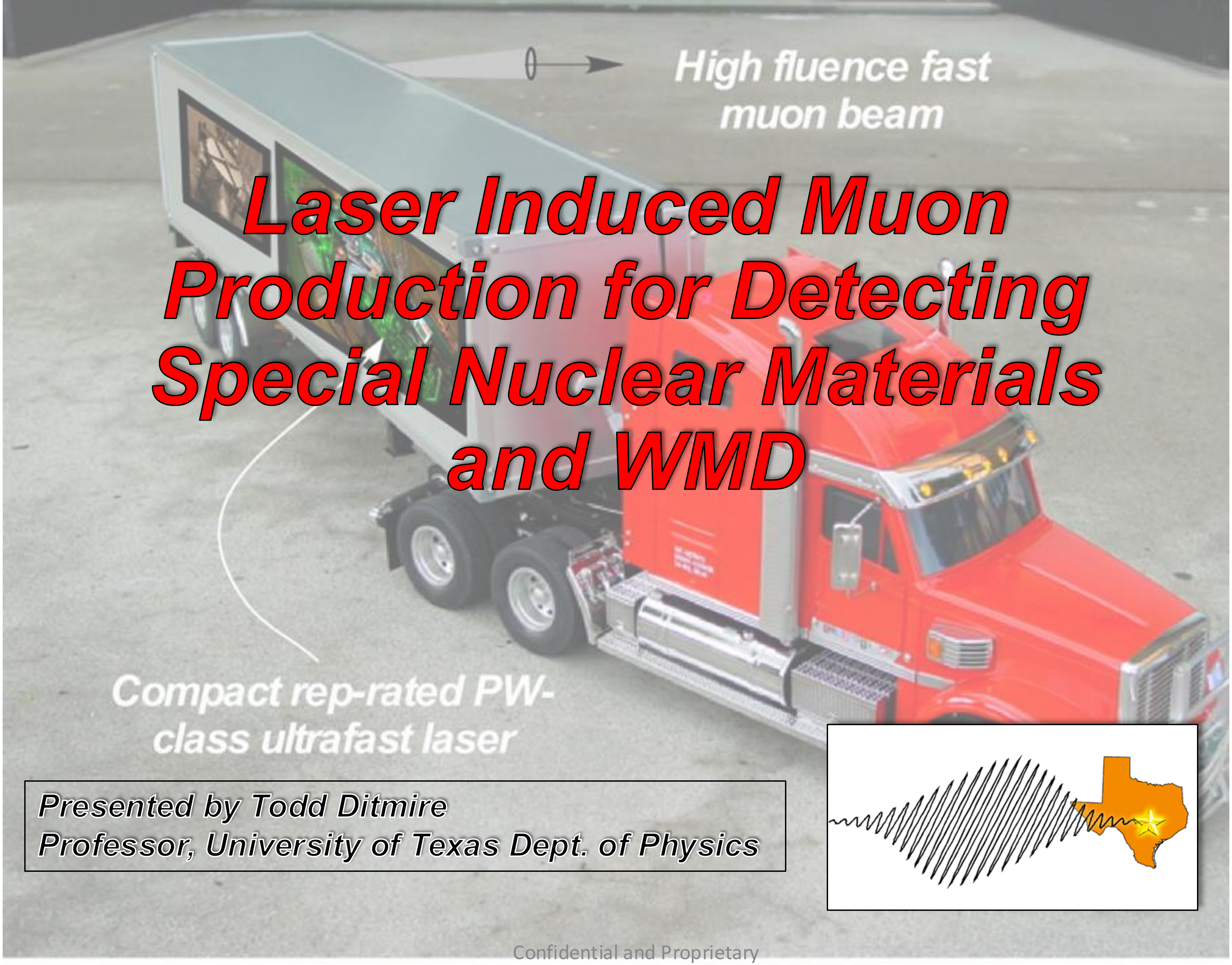
Laser Induced Muon Production for Detecting Special Nuclear Materials and WMD



Presented by Todd Ditmire
Professor, University of Texas Dept. of Physics

Inspecting cargo for special nuclear materials is a large gap in US port security

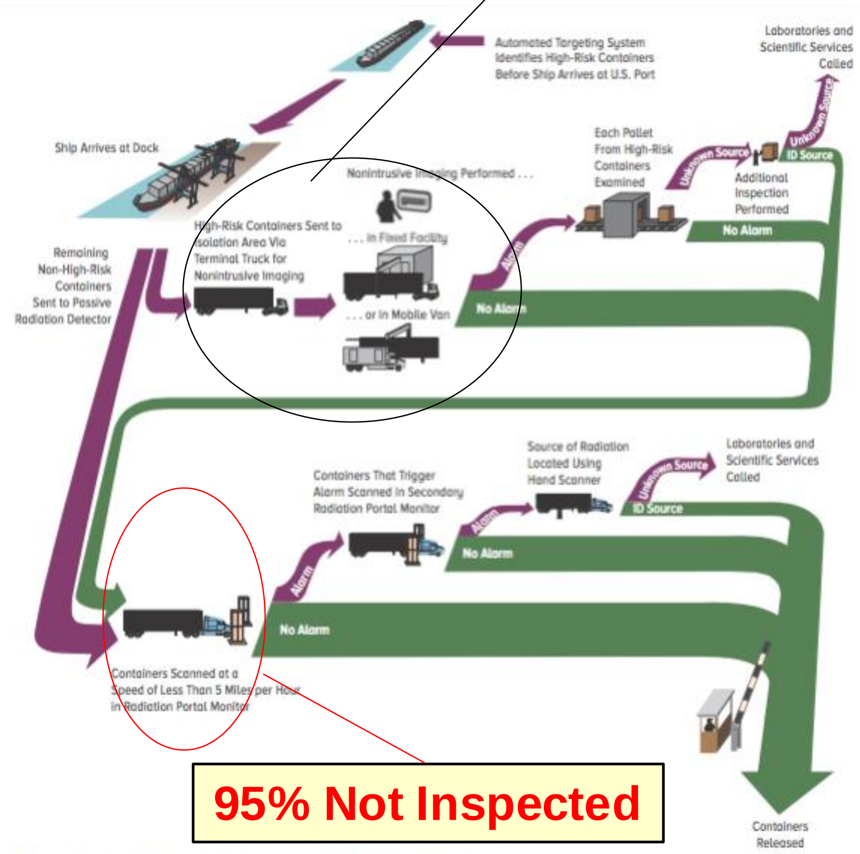
- In 2006, Congress tasked the Department of Homeland Security with 100% cargo inspection
- More than 12 million cargo containers enter US ports every year
- Now, over 15 years later, less than 5% of incoming cargo containers are inspected
- Current inspection techniques use high energy X-rays or Gamma radiation which are dangerous, costly and slow
- ***Producing muons with compact lasers is a disruptive technology that potentially enables rapid and cost effective detection of SNM and WMDs***

Failure to inspect incoming cargo for dangerous nuclear materials remains a significant risk

Current inspection systems use a combination of methods

- **High energy X-rays** are required to penetrate the steel walls of cargo containers
- **Exposure** to these X-rays can be extremely **dangerous** to operators and personnel on site
- Scan **times** can be **long**
- X-rays scan for **density**, but require trained operators to identify the materials they detect
- A 2016 Congressional Budget Office (CBO) study estimated **3 containers per hour** as the CBP's average throughput, with up to 10 per hour possible
- Noninvasive imaging techniques are used on only a **few containers**

5% Inspected



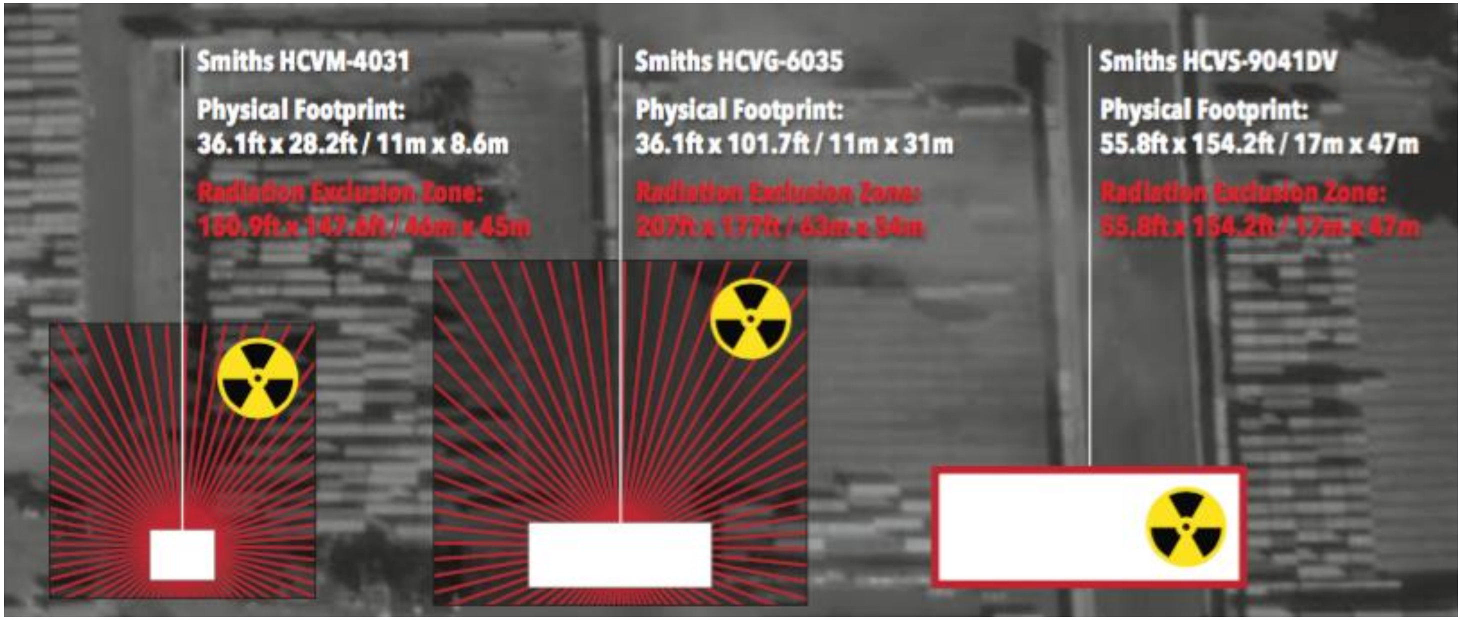
95% Not Inspected

Source: Congressional Budget Office, using information from Customs and Border Protection.

Current detection methods are inadequate for national security

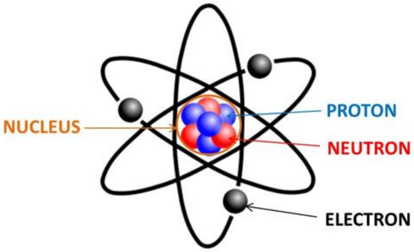
There are limitations to current inspection imaging techniques

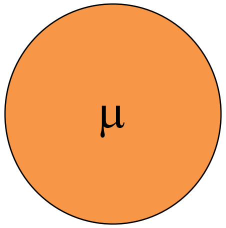
- **Current technology uses X-ray or Gamma beams**
  - Intensities are high. Drivers must exit their vehicles during the scan. There are concerns about long-term exposures. Large radiation exclusion zone.
  - **Scanning is slow –** 3 containers an hour is typical today, 10/hr is high, equipment manufacturers claim it may be possible to get as high as 20/hr (2x CBO estimate)



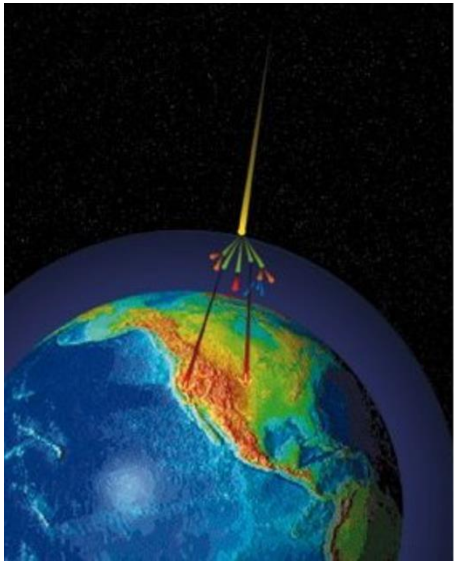
May never be viable because this technique is dangerous and very slow

An alternate form of radiation exists which can be used to interrogate cargo: the muon





<u>Muons are like electrons but with 200 times the mass</u>:
Because muons are much heavier they can traverse much more massive objects than electrons



Muons were discovered in 1936 at Caltech

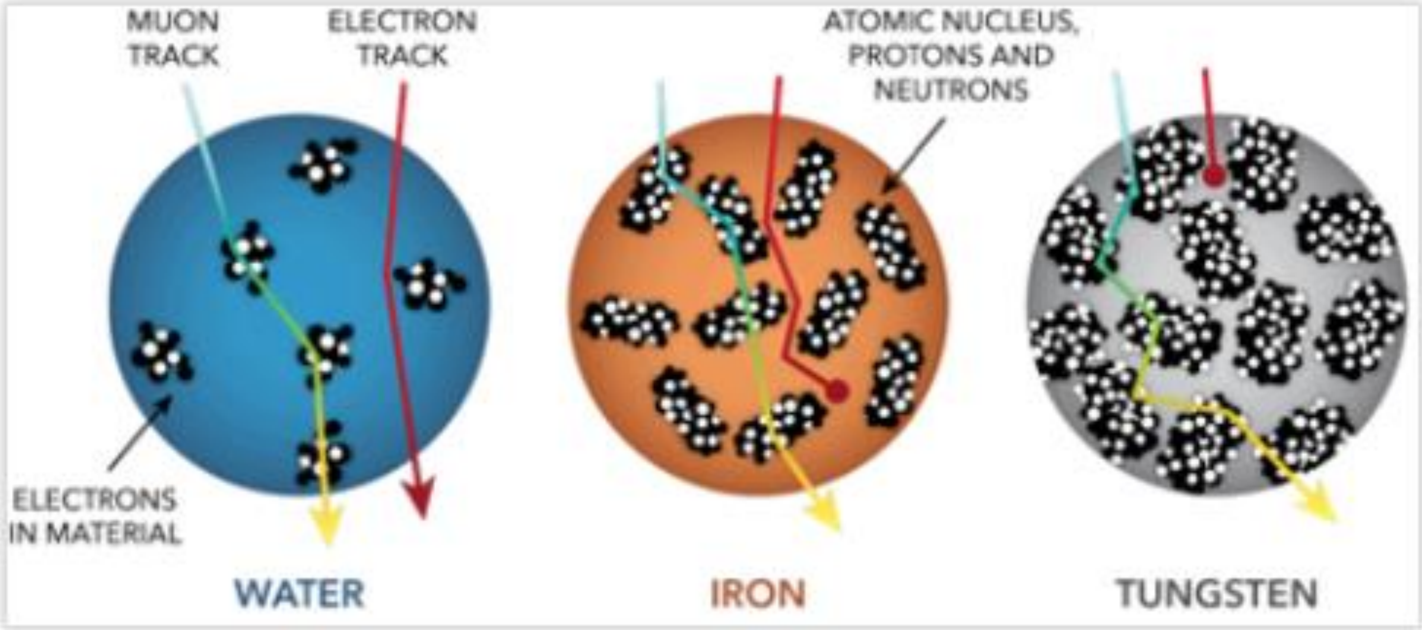
The main natural source of muons is from cosmic rays striking the earth's atmosphere

One cosmic ray muon passes through an area the size of ones hand roughly every 10 sec

Cosmic ray muons have been used to image the inside of the pyramids

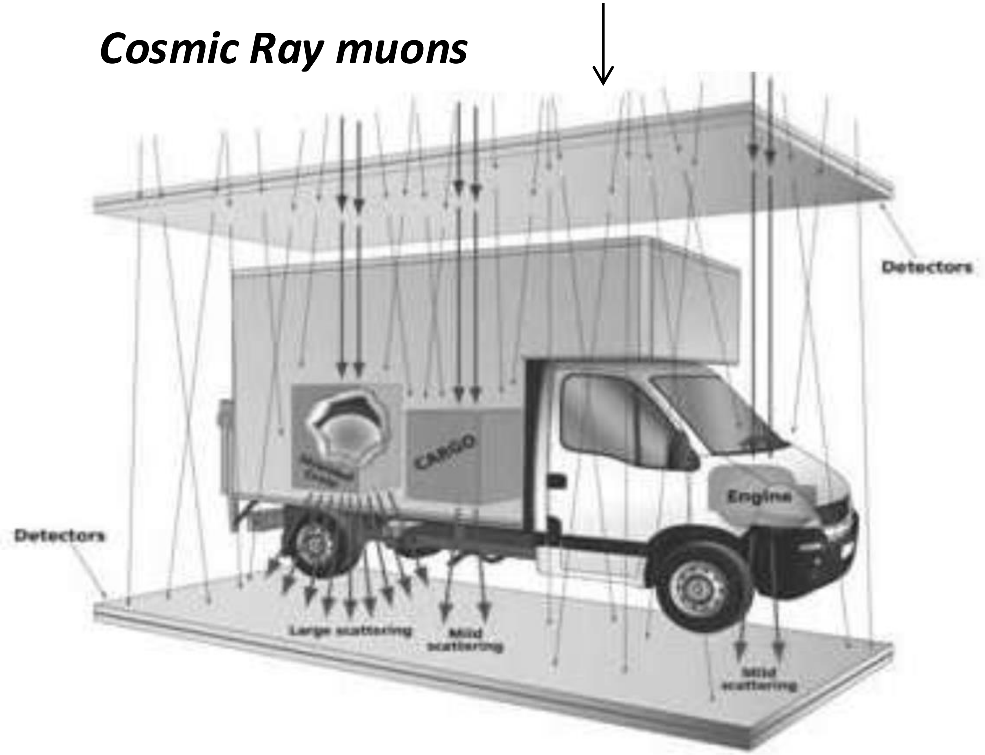
Naturally occurring muons can be used to identify dense substances

- Approximately 10,000 muons reach every square meter of the earth's surface a minute.
- Muons can penetrate tens of meters into rocks and other matter before attenuating as a result of absorption or deflection by other atoms.
- The **density** of the material influences the energy and scatter of the muon, which is a fingerprint for the material under inspection ***Nuclear materials are very dense***



Scan times are limited by availability of naturally occurring muons

The idea of using muons for detecting Special Nuclear Materials is not new



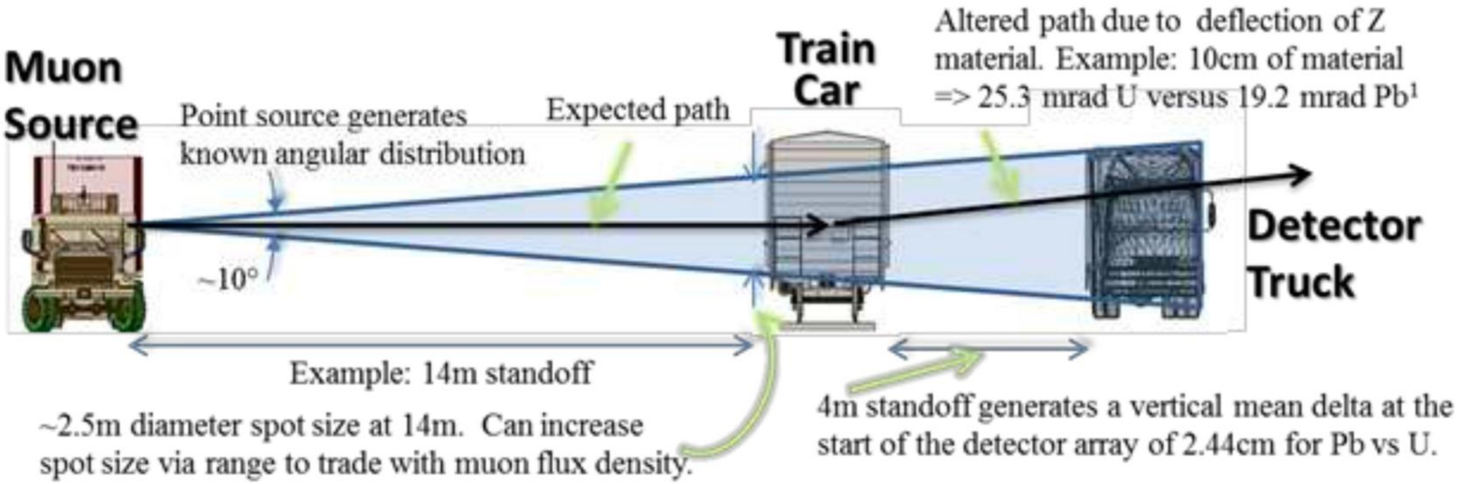
Labs such as Los Alamos have done extensive work examining the possibility of using cosmic ray muons to detect Special Nuclear Materials in cargo

Advantage*: Completely safe to occupants of the cargo laden vehicle or workers*

Disadvantage*: There are so few cosmic ray muons that scanning is very slow*

Consequently this technique has been largely dismissed as a viable method for rapidly scanning incoming cargo

Muons could be a game changing technology if there were a compact active source of muons available



Point source generates known angular distribution

Altered path due to deflection of Z material. Example: 10cm of material => 25.3 mrad U versus 19.2 mrad Pb[1]

Example: 14m standoff

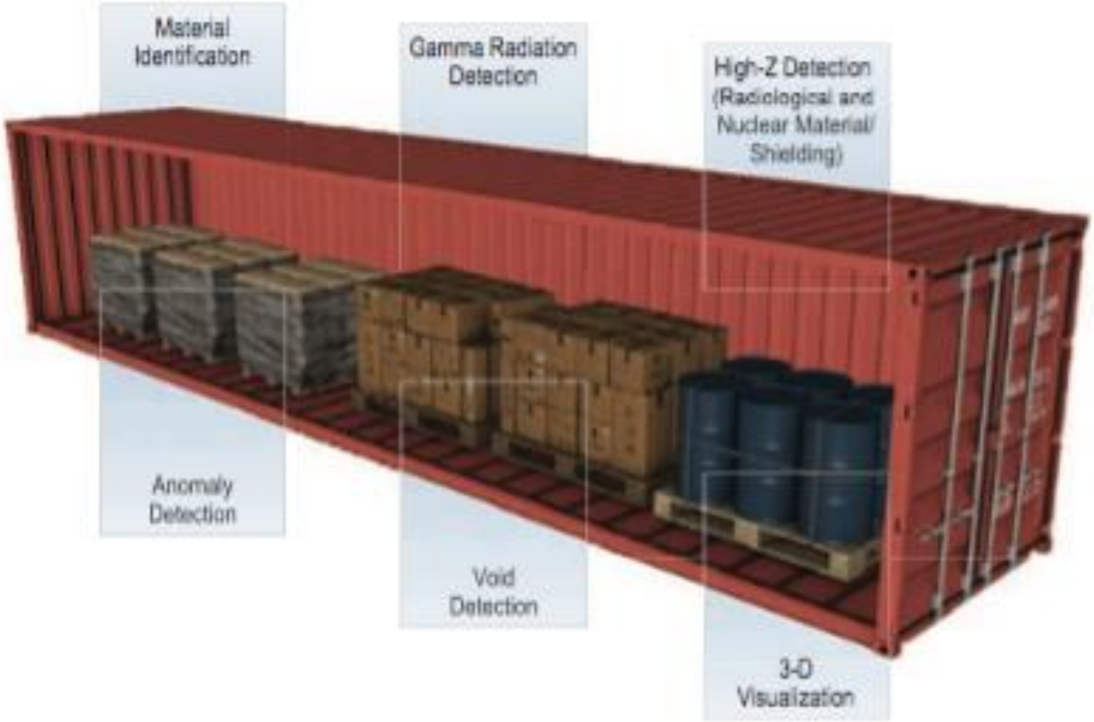
~2.5m diameter spot size at 14m. Can increase spot size via range to trade with muon flux density.

4m standoff generates a vertical mean delta at the start of the detector array of 2.44cm for Pb vs U.

Technology challenge: create a COMPACT muon source that could produce a flux of muons ~10,000 times that of the cosmic ray flux

There are many potential advantages in using a man made source of muons

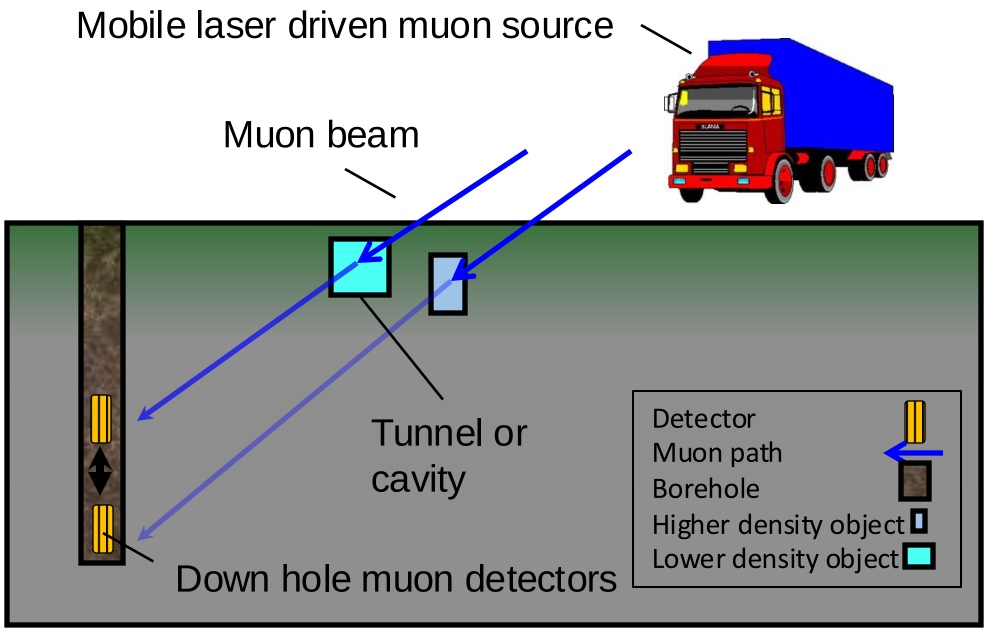
- Muons can be used to detect many different materials
- They are not hazardous to life forms or the environment



- ***<u>However, detection is slow (2-4 min) due to the source of muons</u>***

Muons detect many materials and Failure to inspect incoming cargo has been identified as a significant risk

A laser driven muon source may have other important national security applications



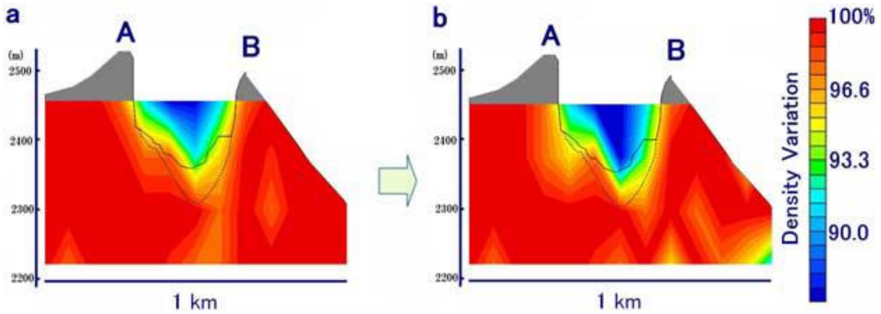
Mobile laser driven muon source

Muon beam

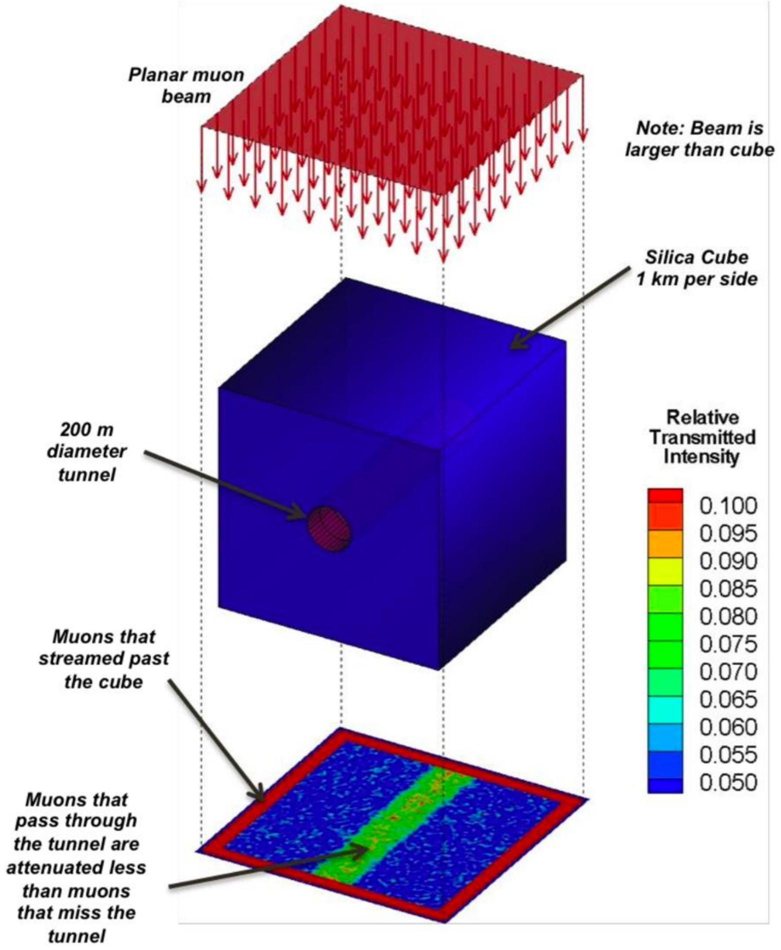
Tunnel or cavity

Down hole muon detectors

Detector	▮
Muon path	←
Borehole	▩
Higher density object	▯
Lower density object	▭



Tanaka, et al., 2009, *Detecting a mass change inside a volcano by cosmic-ray muon radiography (muography): First results from measurements at Asama volcano, Japan*, Geophysical Research Letters, v. 36, L17302.



Planar muon beam

Note: Beam is larger than cube

Silica Cube 1 km per side

200 m diameter tunnel

Muons that streamed past the cube

Muons that pass through the tunnel are attenuated less than muons that miss the tunnel

A laser-based muon source could be very important

- Treaty verification
- Underground facility detection
- Border and facility security
- Reservoir volume assessment

Tunnels in the News:

Nearly **170 tunnels** have been found nationwide since 1990, most along the Arizona and California border with Mexico. USA today 1/14/2014

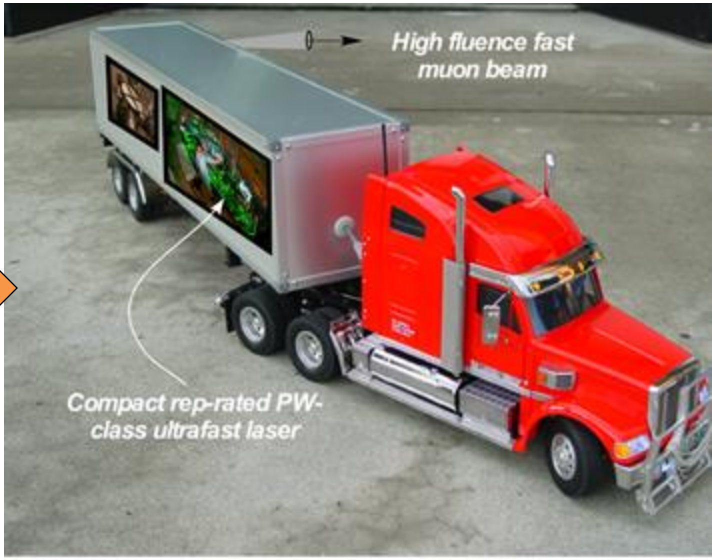
- April 2014 – Two **drug tunnels**, with rail systems, found at U.S.-Mexico border.
- Nov. 2013 – Two “**terror tunnels**” in Gaza expected for kidnapping were destroyed by Israelis killing 4 Palestinian fighters.
- Nov. 2013 – Iranian dissidents claim Iran has built a tunnel complex as a “**nuclear site**”.
- Oct. 2013 – “super tunnel” for drug smuggling between San Diego and Tijuana.
- Aug. 2013 – Raytheon was awarded **$10M** to detect border tunnels in Egypt.

The technology challenge is to shrink and make cost effective standard accelerator production of muons

Because of the large mass of muons, accelerators capable of producing GeV particles are needed to produce muons

Existing facilities are typically large

Proposed technology is compact and mobile



Established accelerator technology for producing muons is very large, costly and NOT mobile, however laser technology offers a path forward

New laser based muon production technology can produce muons at a rate comparable to traditional accelerator based sources

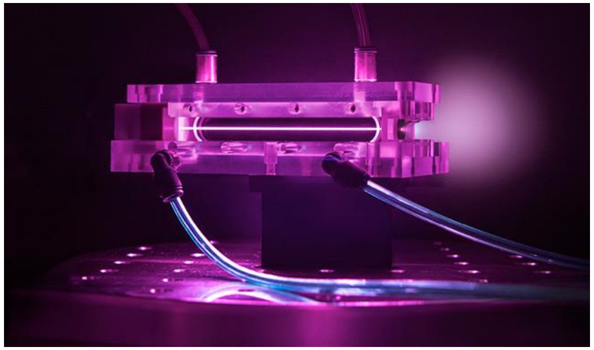
800 MeV Proton Ring accelerator → Gold or Carbon target → Pions produced, decay to Muons → 4×10^5 μ^+ / second
50 Hz

Diode pumped 1 PW laser → Wakefield accelerator → Gold target → Direct Muon pair production → ~10^6 $\mu^{+/-}$ / second
@ 10 Hz

- Both of these method results are based on current technology
- Current Muon detection systems require 6.8×10^5 μ for the largest container and natural background radiation of Muons takes 2 minutes to deliver this dose
- Laser-based muon production using current technology would reduce exposure time to ~2 sec by enhancing the natural background rate.

Over the past 10 years electron acceleration to many GeV with table top lasers has developed

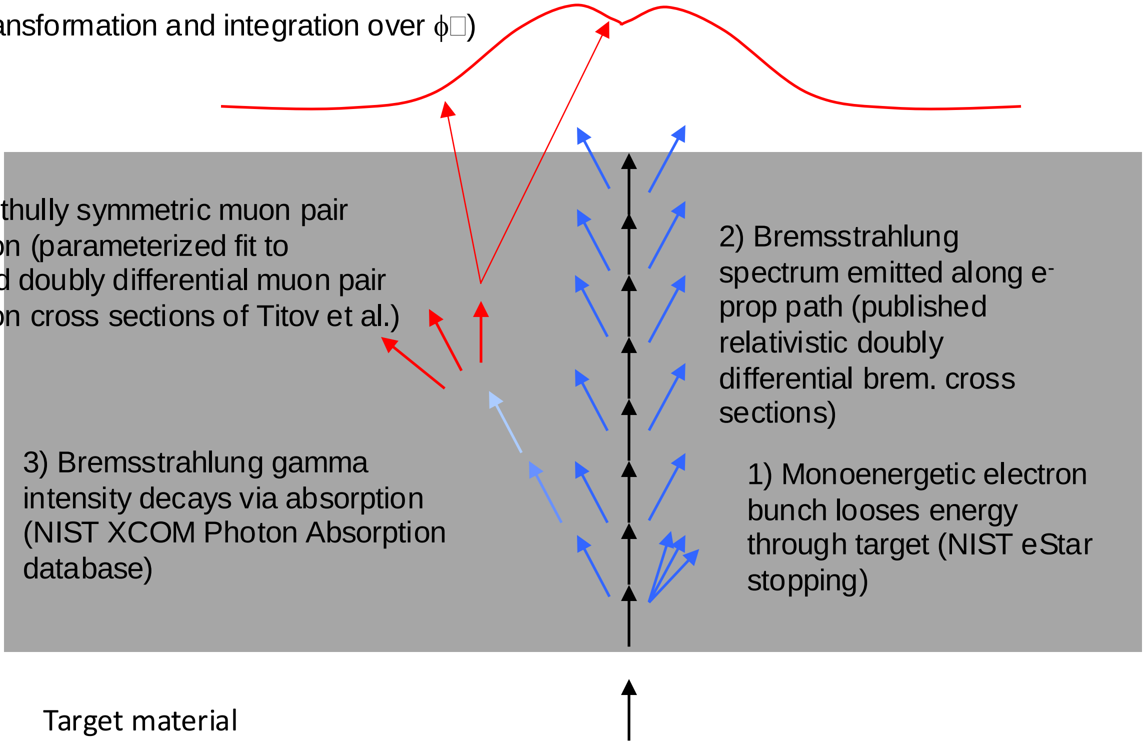
- Laser plasma acceleration shrinks electron accelerators from kilometers to centimeters
- Emerging laser sources can be made compact and efficient
- These laser sources have demonstrated the capability of producing muons in quantities that are orders of magnitude beyond naturally occurring muons



9 cm laser plasma accelerator at LBL

Using laser technology, it is possible to produce man-made muons with a compact, inexpensive mobile machine

Elements of laser muon production



5) Muon distribution in Lab frame
(transformation and integration over ϕ)

4) Azimuthully symmetric muon pair production (parameterized fit to published doubly differential muon pair production cross sections of Titov et al.)

2) Bremsstrahlung spectrum emitted along e^- prop path (published relativistic doubly differential brem. cross sections)

3) Bremsstrahlung gamma intensity decays via absorption (NIST XCOM Photon Absorption database)

1) Monoenergetic electron bunch looses energy through target (NIST eStar stopping)

Target material
(Pb, Au, W)
Thickness = L

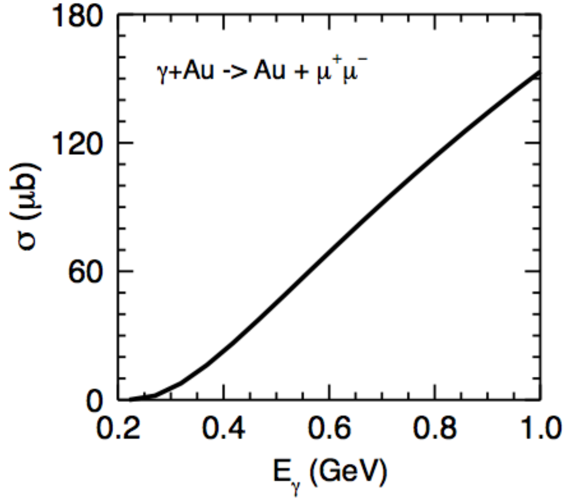
0) Monoenergetic electron bunch enters target

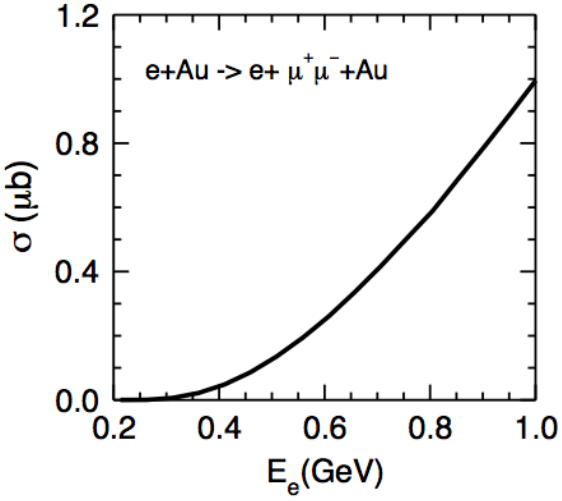
There are two avenues of muon production with a laser driven electron accelerator

$$\gamma + A \rightarrow A + \mu^- + \mu^+$$

$$e + A \rightarrow e' + A + \mu^- + \mu^+$$

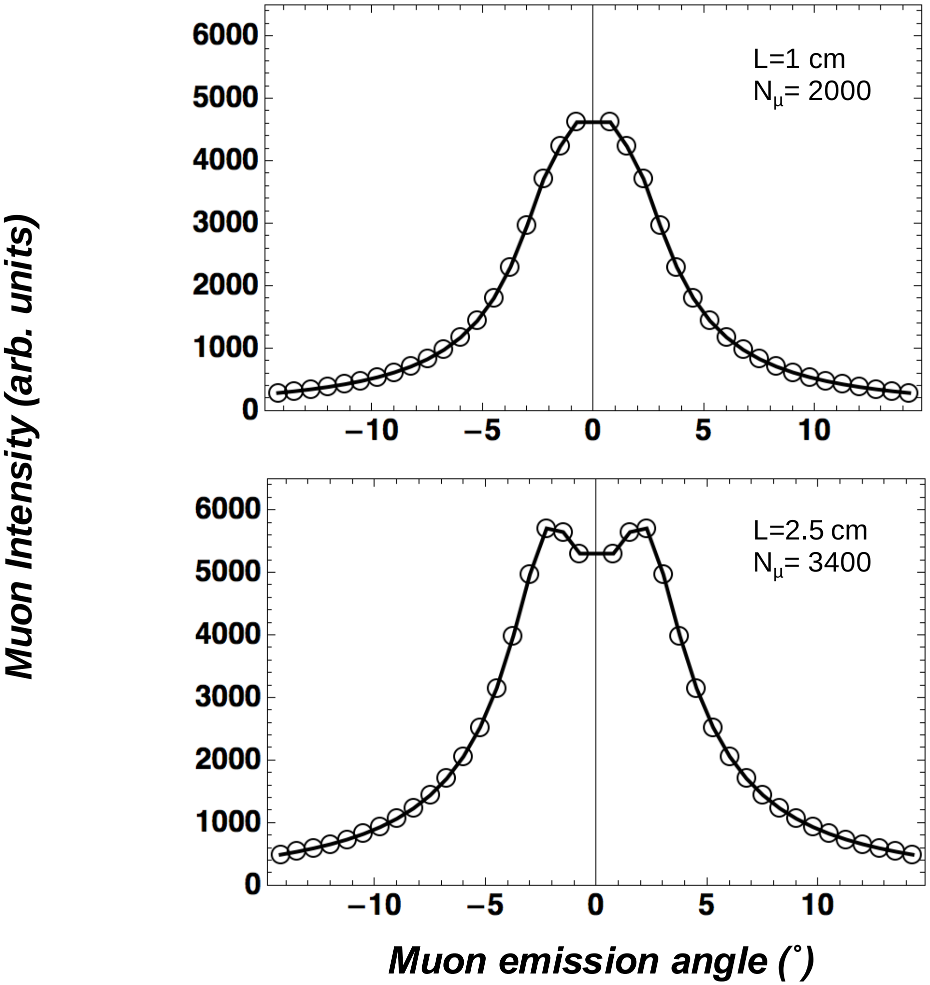
The first process is the analog of the well known Bethe-Heitler process for electron-positron pair production. The second is the analog of the “Trident” process. The total integrated cross sections for these two processes grows quite rapidly for incident electron or photon energies up from negligible values near 100 MeV to significant cross sections around 1 GeV. Figure 17 shows plots of the muon pair production cross sections when the target nucleus is a gold nucleus. These graphs make clear that the photo production pathway has about two orders of magnitude higher cross section than the trident process.



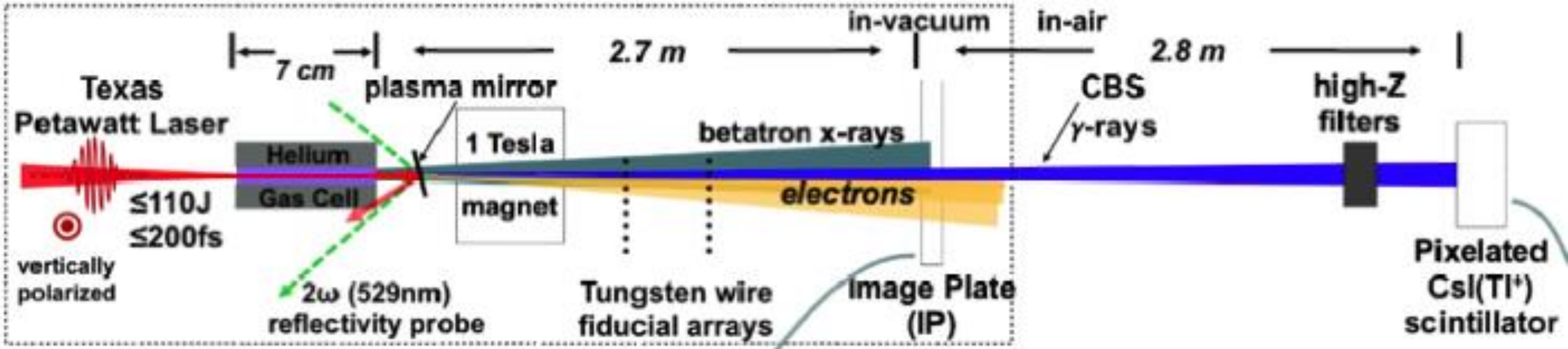


A. I. Titov and H. Takabe in *Laser-Driven Relativistic Plasmas Applied to Science, Industry and Medicine,* AIP (2009), p. 201.

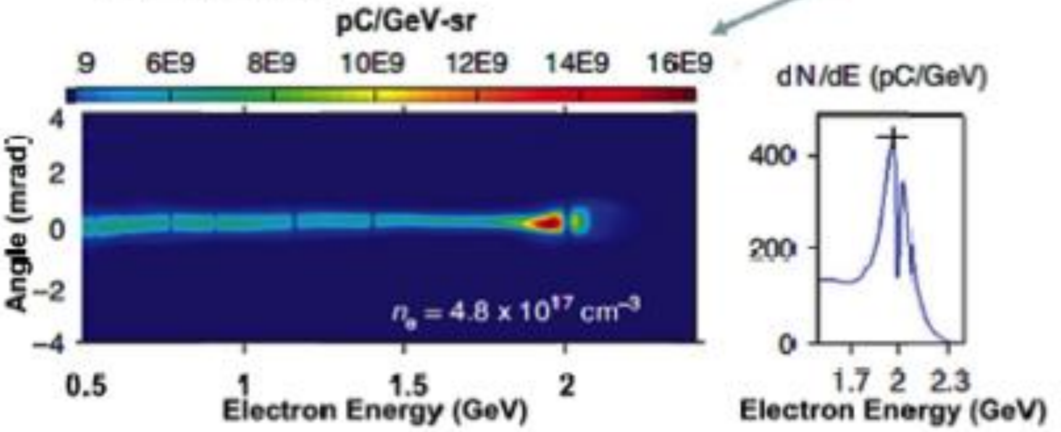
Numerical simualtions predict 3400 muons from 1 inch thick Pb target with 100 pC of 2 GeV electrons

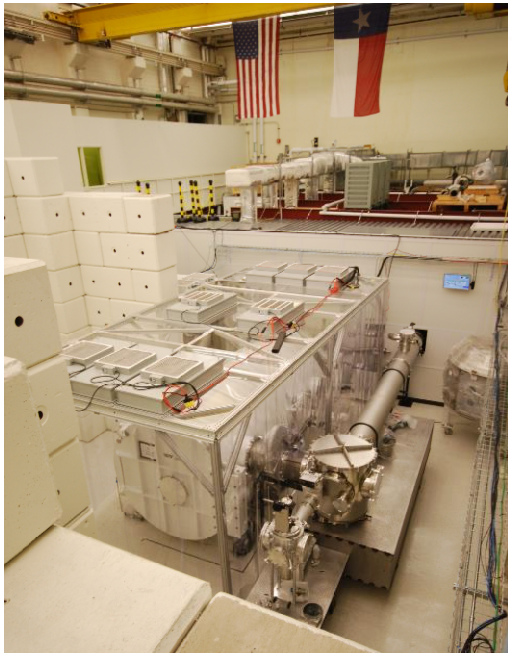


At the University of Texas Prof. Mike Downer has developed Petawatt laser driven acceleration to >10 GeV



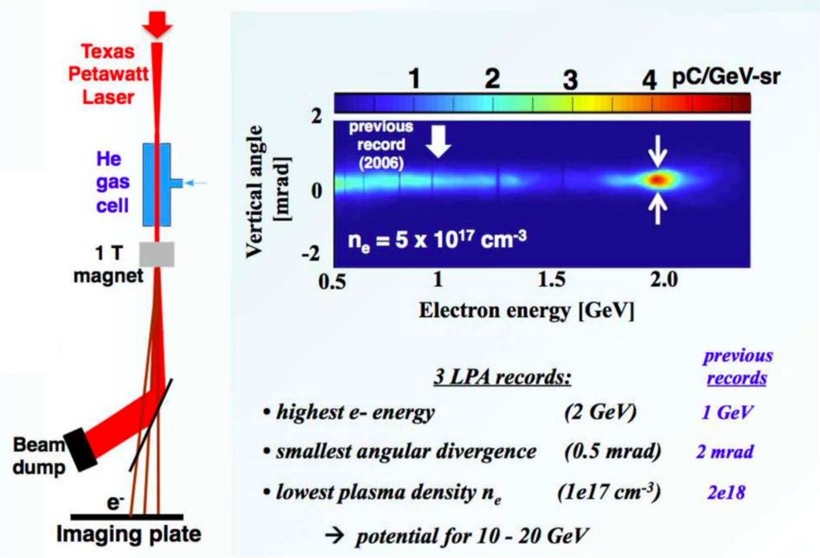
e⁻ acceleration up to 2 GeV, <0.25 mrad





We have core technology that could make laser-based muon production a reality

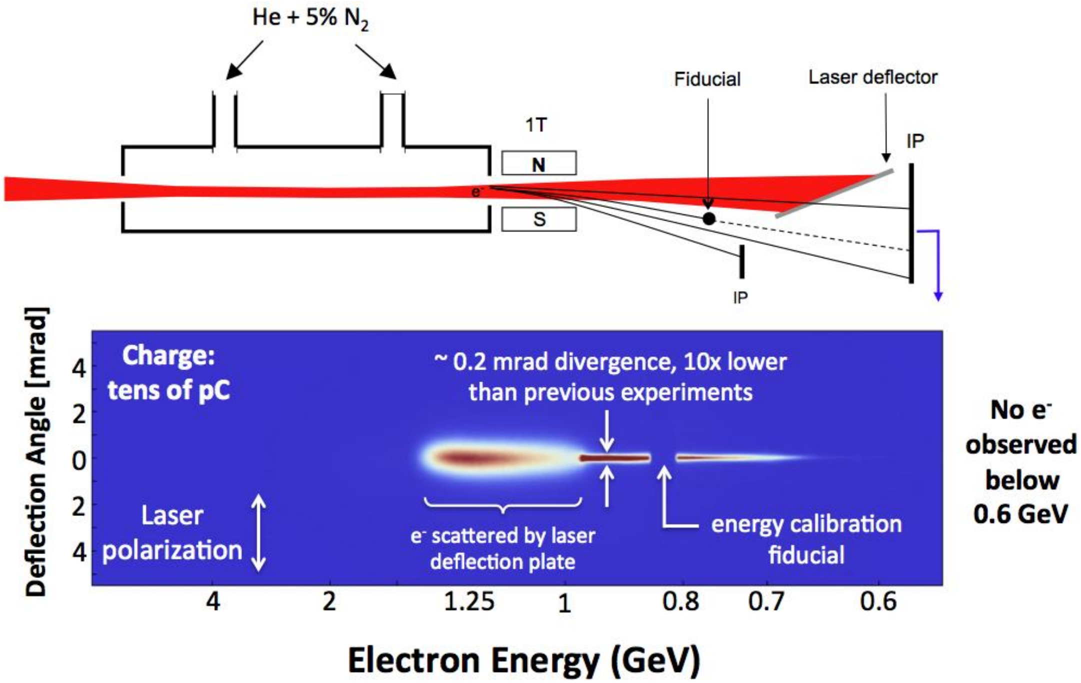
- We have extensive experience with ultra-intense laser sources that would produce the necessary photon intensities
- Muon generation with protons has been done using synchrotron facilities.
- We have experience with Wakefield accelerators to generate the electron beams
- We have experience generating particle beams with targets
- Muons generated by a laser system could be made portable
- We have technology to improve laser repetition rates to make detection almost instantaneous



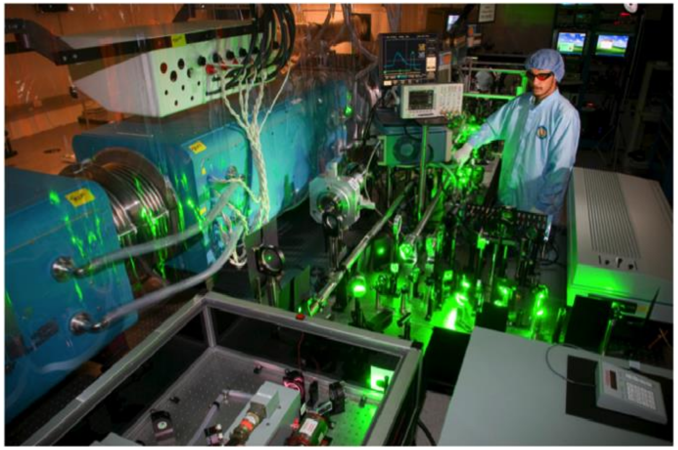
3 LPA records:		*previous records*
• *highest e- energy*	*(2 GeV)*	*1 GeV*
• *smallest angular divergence*	*(0.5 mrad)*	*2 mrad*
• *lowest plasma density n_e*	*(1e17 cm^{-3})*	*2e18*

→ *potential for 10 - 20 GeV*

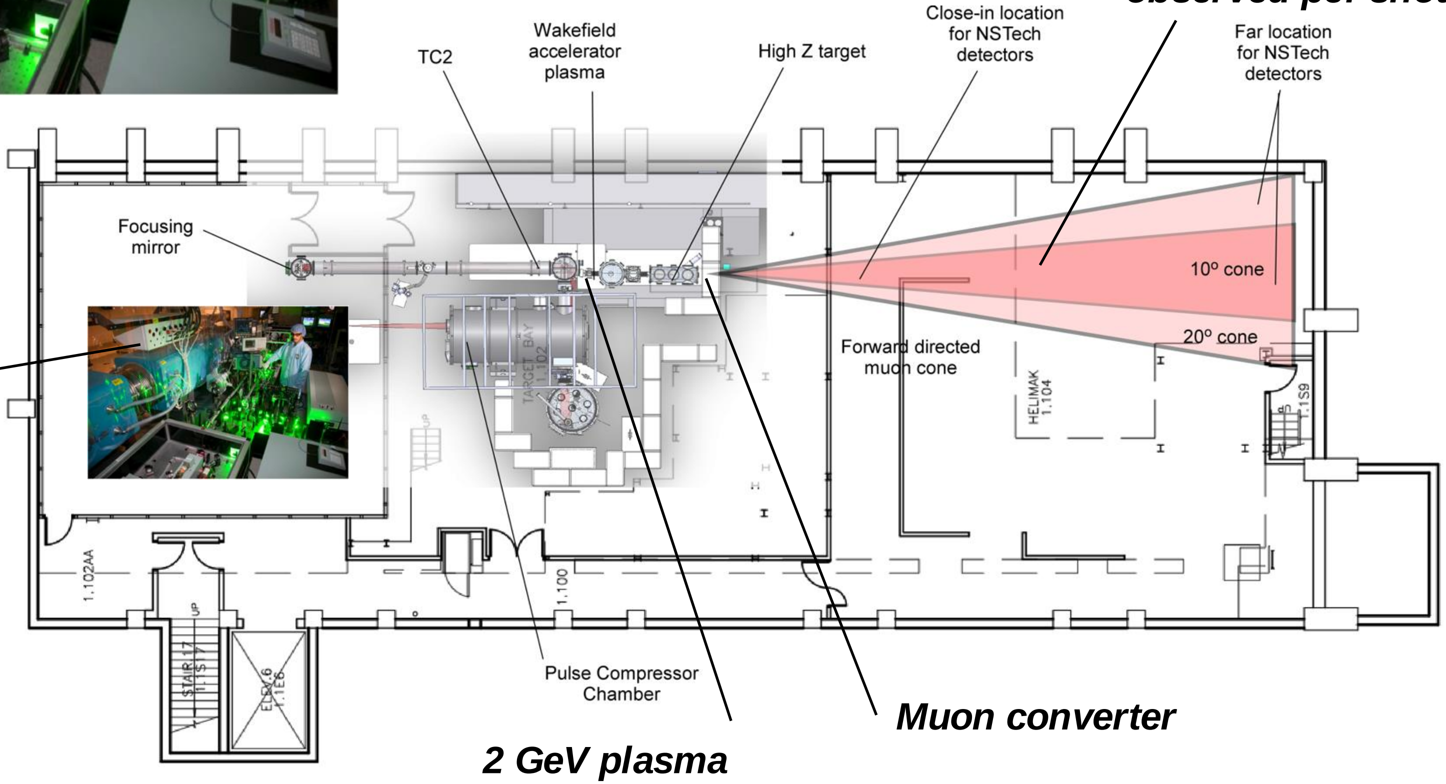
Example e- acceleration result on the Texas Petawatt



We have demonstrated the physics behind laser driven muon production



This laser uses old style amplifiers which can only shoot once every 30 min



~10,000 muons observed per shot

Texas Petawatt Laser

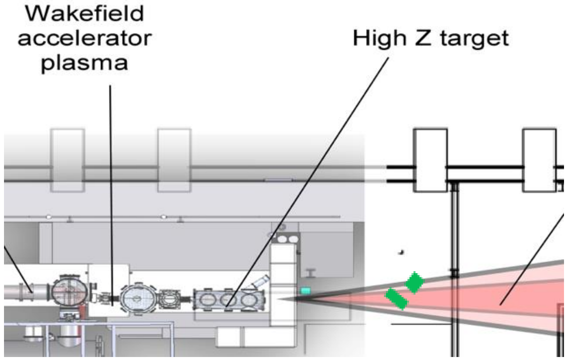
Muon converter

2 GeV plasma accelerator

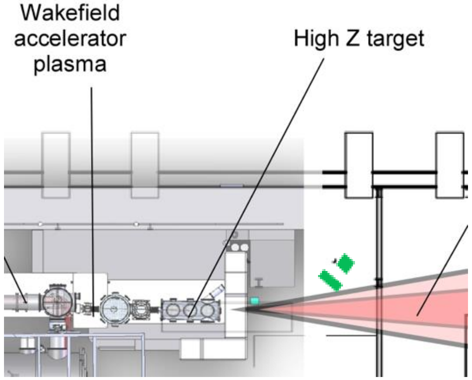
Beam profile was observed via angle scan with imaged scintillator

- Evaluating angular dependence in muon beam is a major experimental goal
- Muon tracker frequently swamped and thus is not suitable for angle scan
- Camera imaged scintillator screen used instead
- Beam evaluated at 0, 13, and 24 degrees
- Due to experimental necessities, shielding conditions varied across angle scan
- Enough overlap to be comparable

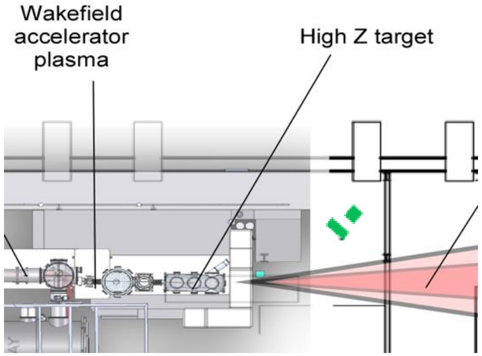
0 Degree



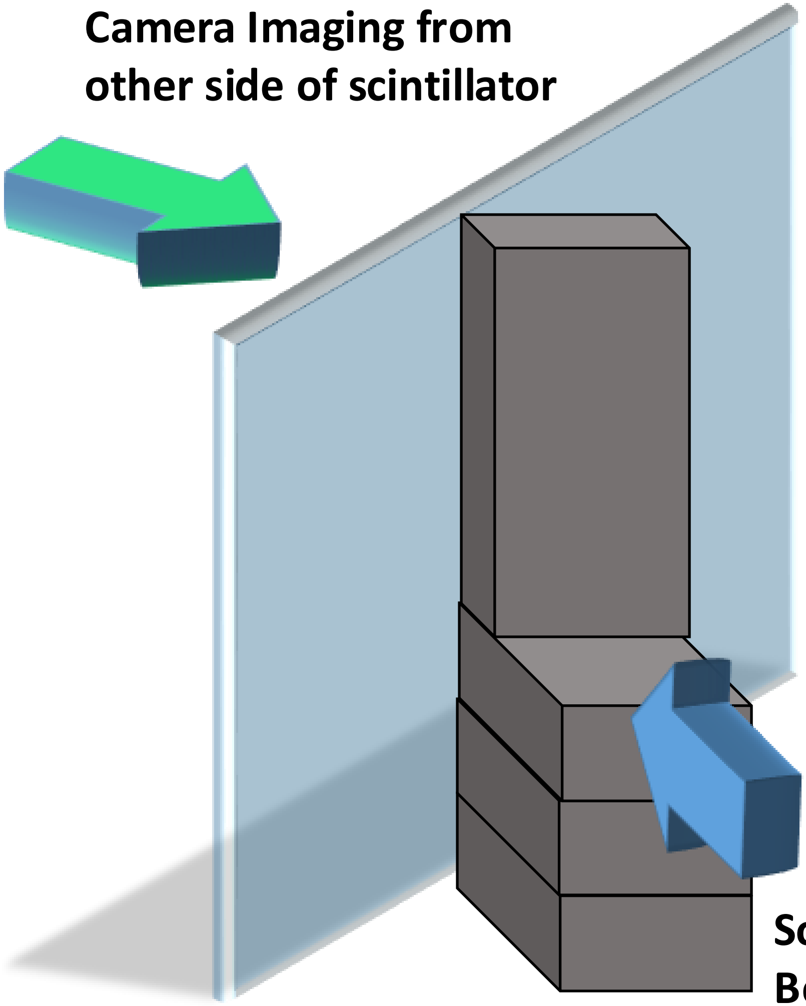
13 Degrees



24 Degrees



A scintillation screen was used to detect charged particles in a forward cone



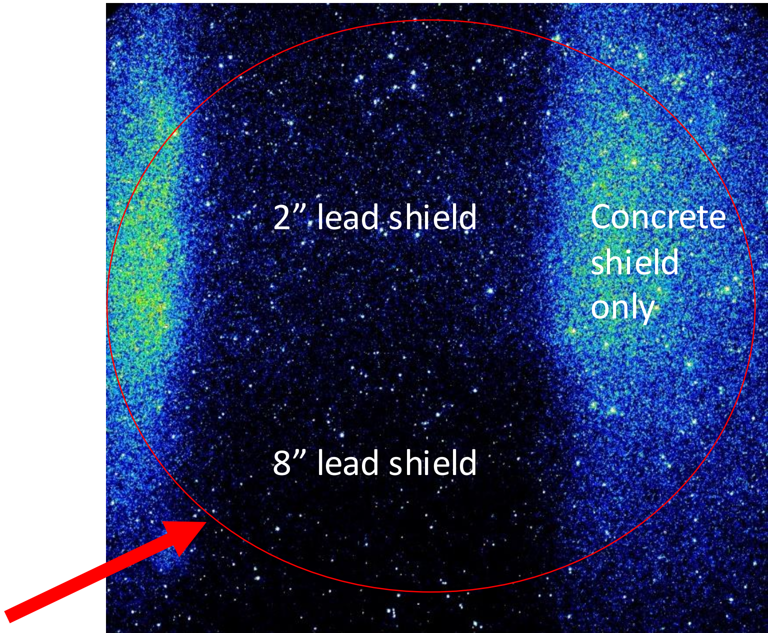
Camera Imaging from other side of scintillator

Source Beamline

When placing shielding directly in front of the scintillator we used a "step wedge" configuration

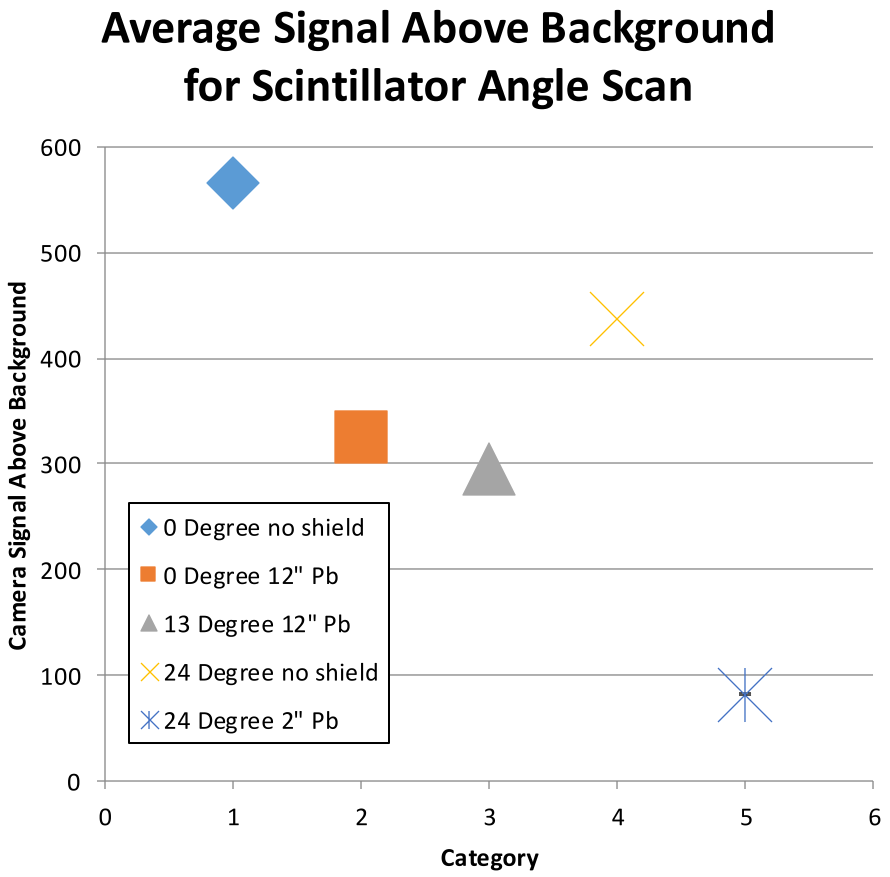
- By stacking lead bricks in different orientations we were able to create areas of the scintillator shadows by different thicknesses of shielding
- We can use a single shot's worth of data for a full differential attenuation analysis
- Comparison between the shadowed section of the image and the unshielded part also allows us to more visualize the portion of the scintillation signal which is not due to high energy photons.

Scinitillator image



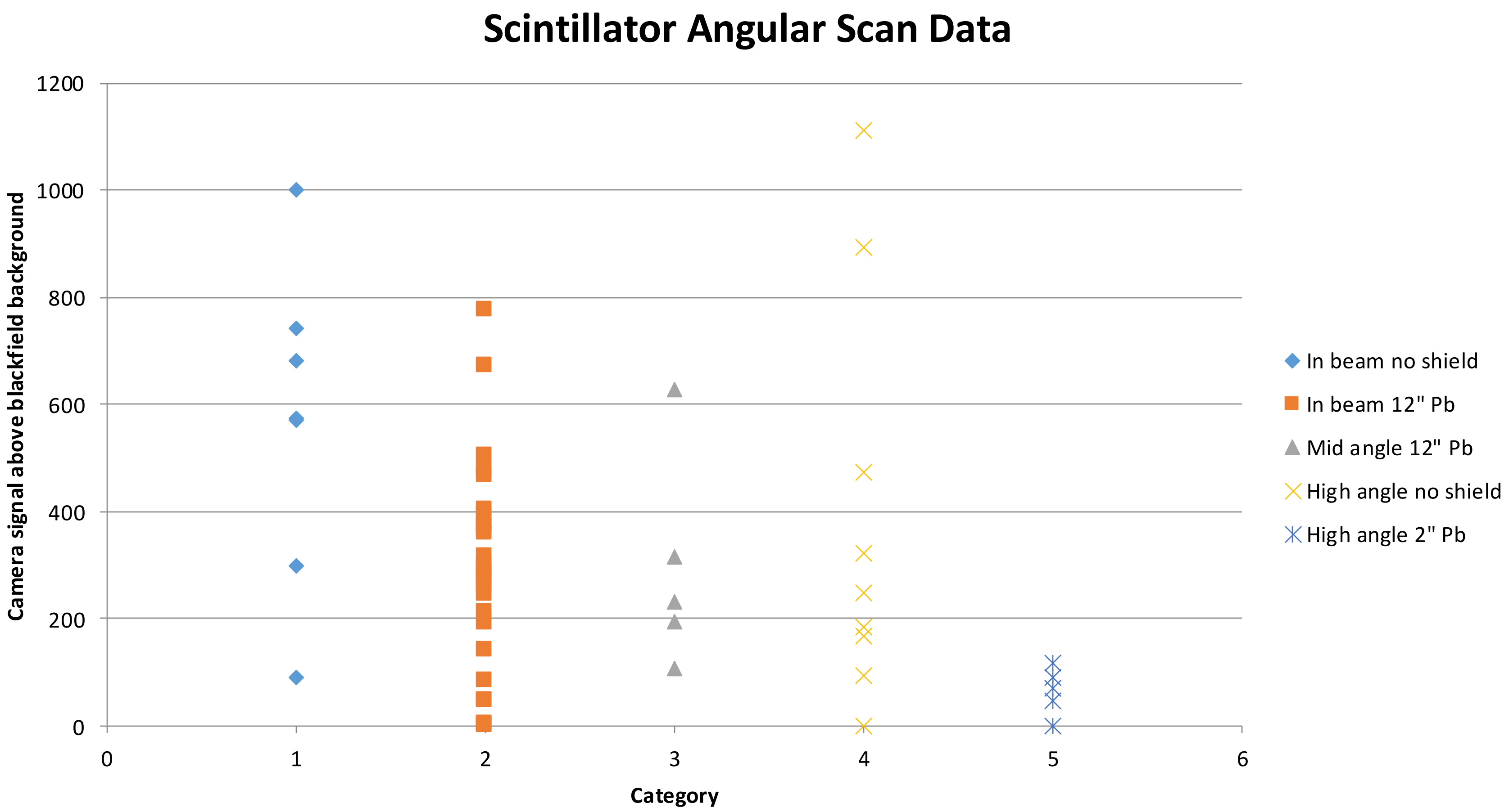
Forward directed beam of gammas and muons

Beam profile was observed via angle scan with imaged scintillator



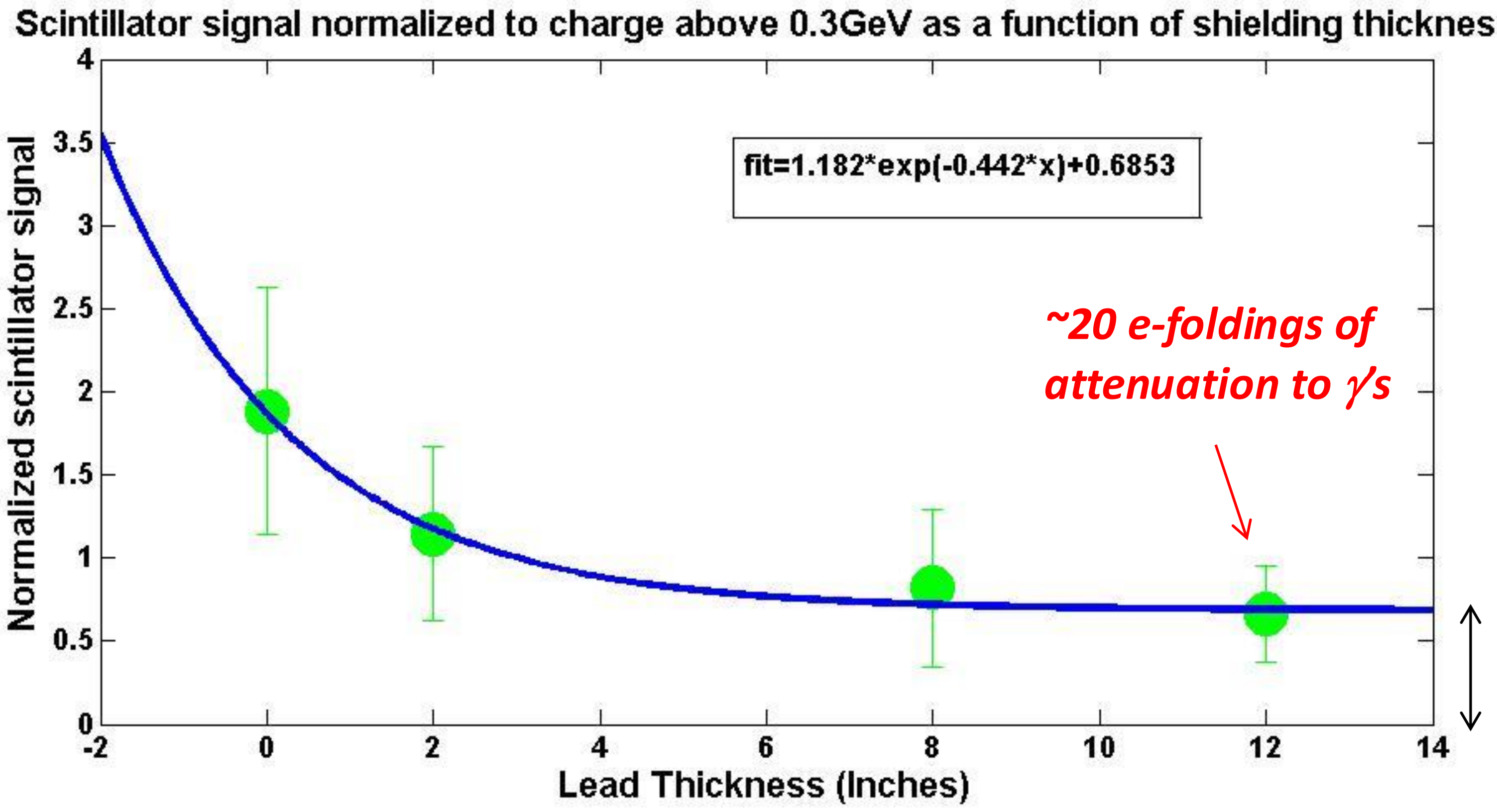
- Strong signal above background behind 12 inches of lead at both 0 and 13 degrees
- Unshielded signal drops slightly from 0 to 24 degrees
- Shielded signal drops significantly at 24 degrees despite being behind only 2 inches of lead

Angular scan data



We have good evidence for muon production on the TPW experiment

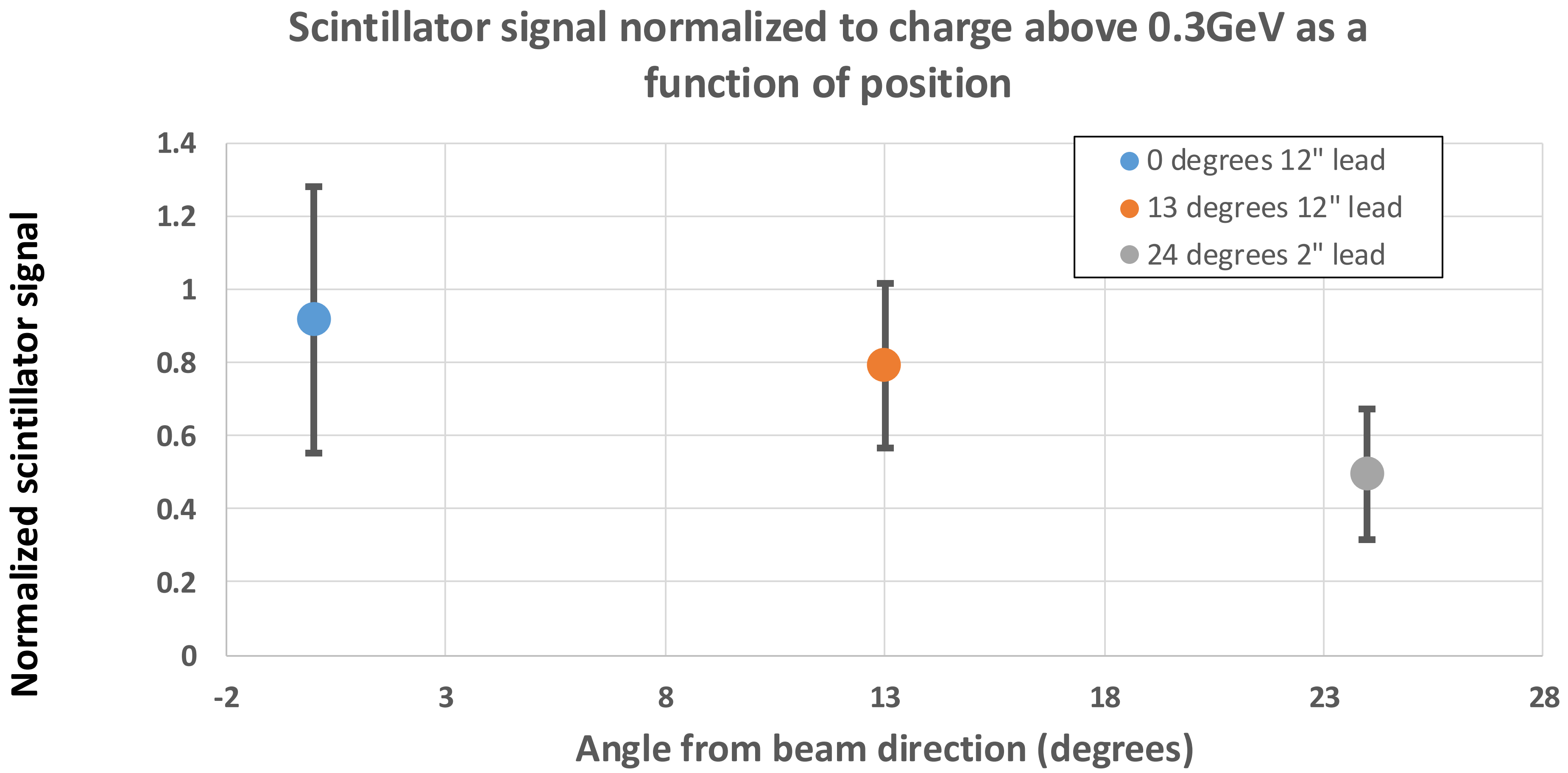
We carefully measured scintillator signal as a funciton of lead shield thickness



~20 e-foldings of attenuation to γs

Believed muon signal

Angular distribution of muons

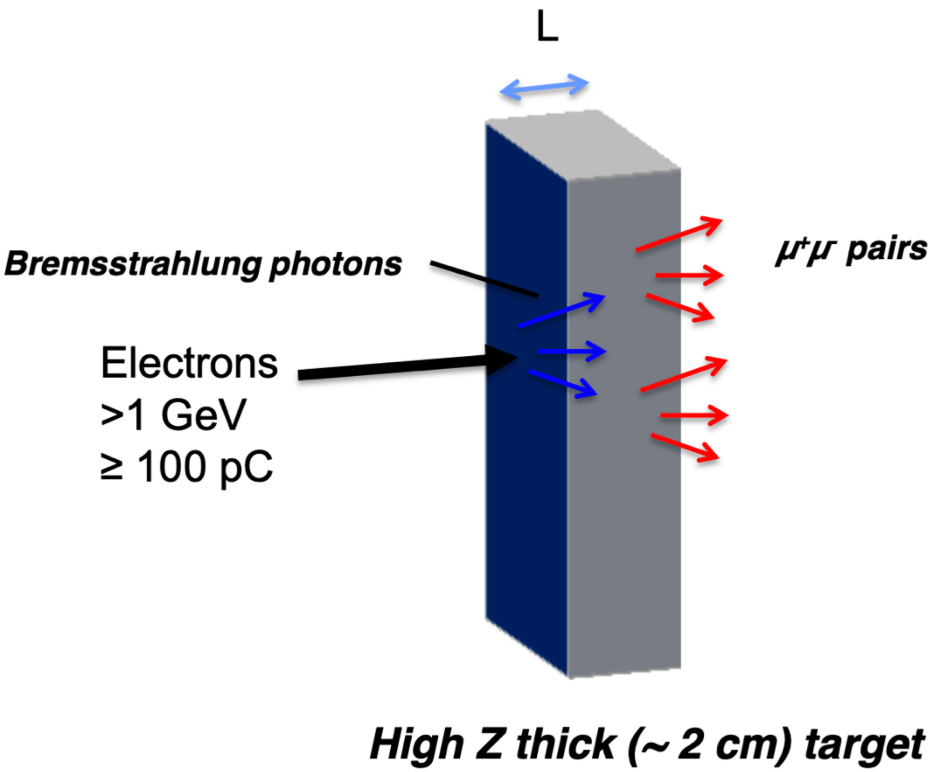


These data imply a muon beam with roughly 40˚ angular width

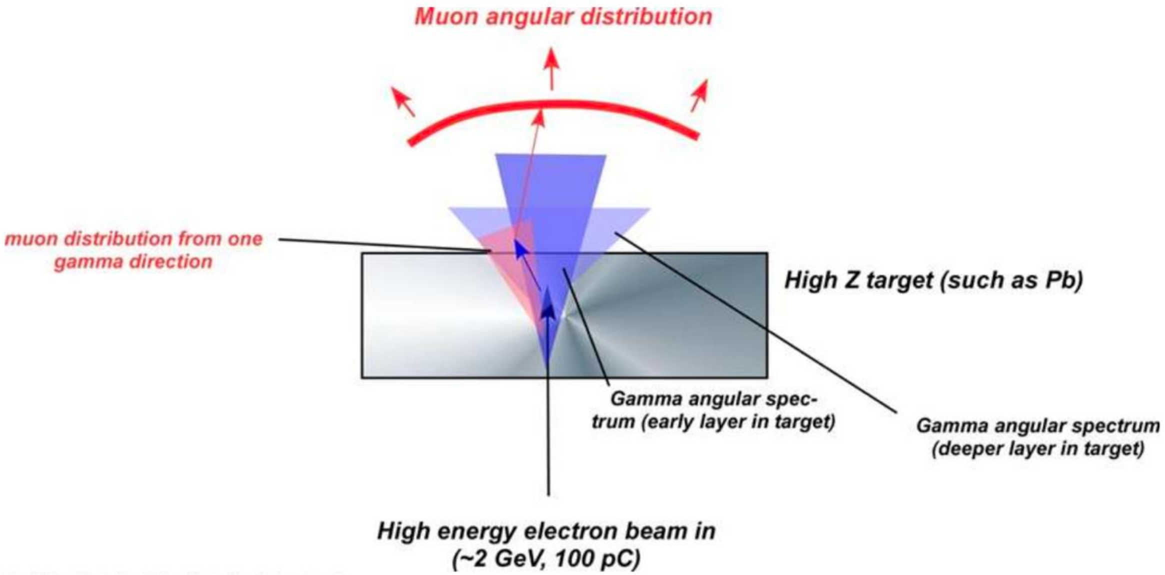
I have constructed a rudimentary model for the muon production

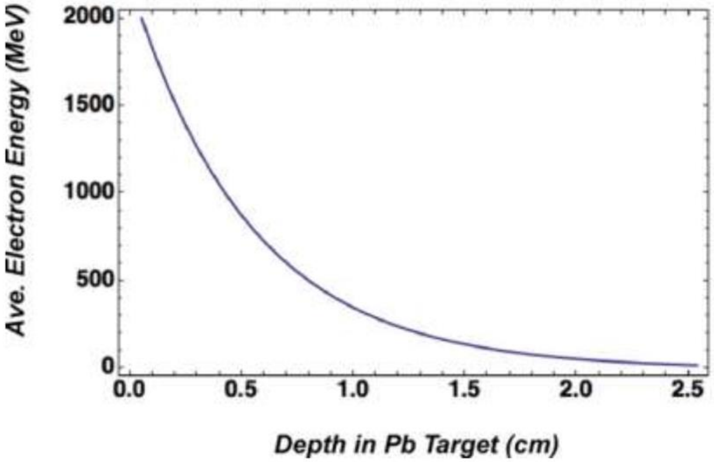
1) Bremsstrahlung conversion: $e + A \rightarrow e' + A + \gamma$

2) Photo-muon pair production: $\gamma + A \rightarrow A + \mu^- + \mu^+$



First one needs to estimate gamma propogation

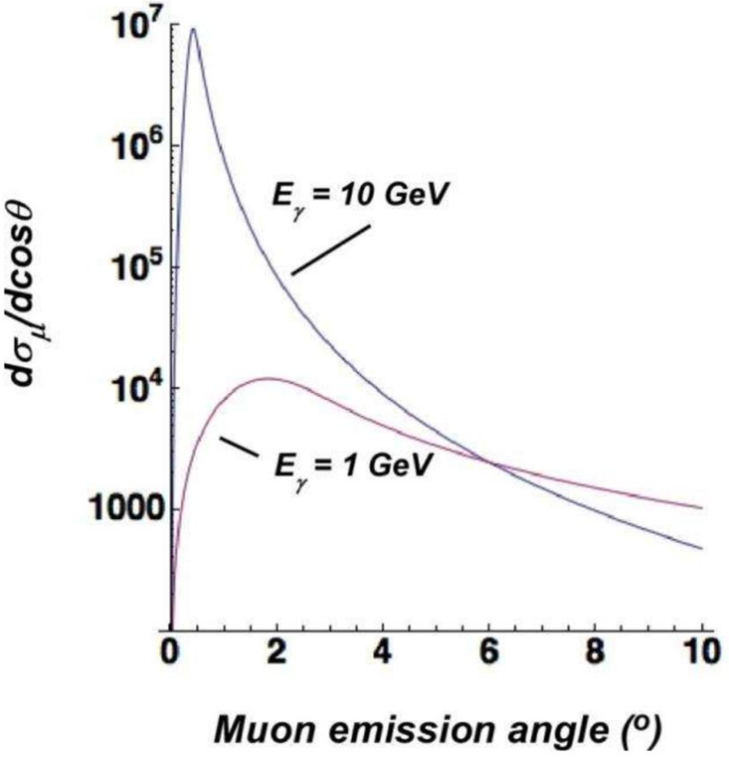




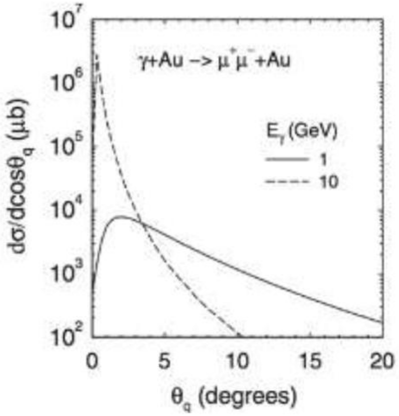
Example energy drop as 2 GeV electrons propagate through 1 inch of solid Lead.

I used standard published differential muon production cross sections

Muon pair production cross sections when the target nucleus is a gold nucleus. Because photo production of muons has about a 10^2 higher cross section than direct electron production, the mechanism we propose here uses laser accelerated electrons in a two-step process.



Differential muon cross section vs Angle



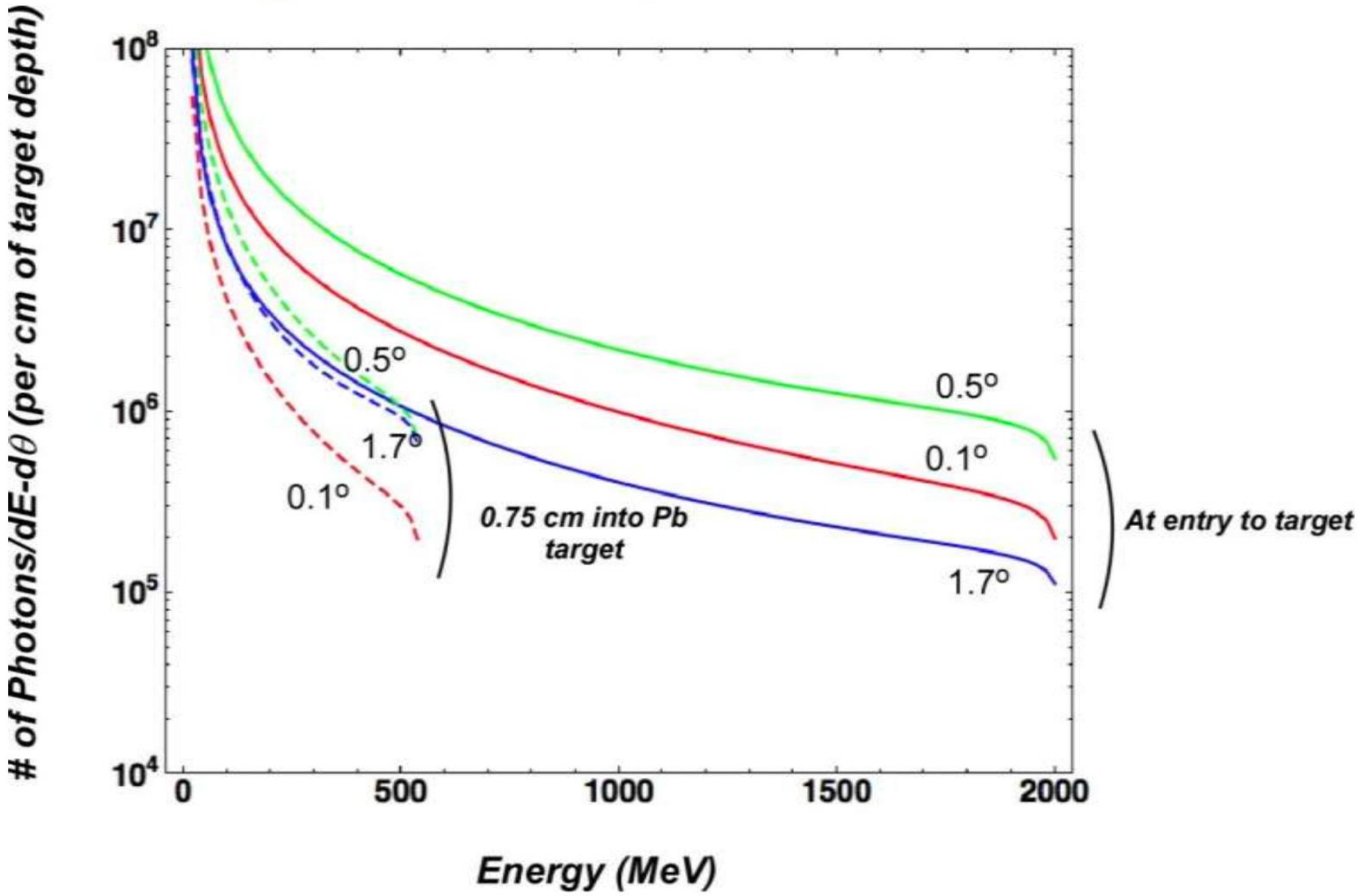
Step 1) Bremsstrahlung conversion: $e + A \rightarrow e' + A + \gamma$

Step 2) Photo-muon pair production: $\gamma + A \rightarrow A + \mu^- + \mu^+$

$$\sigma_\mu \cong \frac{28}{9} Z^2 \alpha r_{\mu 0}^2 \left(\ln\left[\frac{2E_\gamma}{m_\mu c^2}\right] - \frac{109}{42} \right)$$

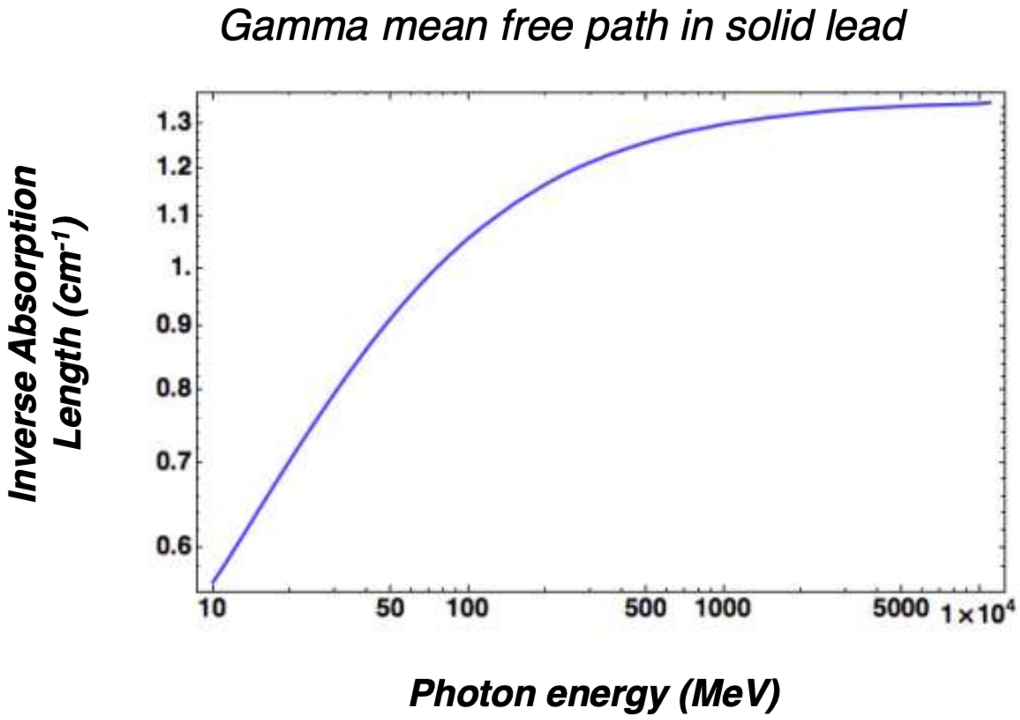
A. I. Akhiezer and V. B. Berestetsky *Quantum Electrodynamics* (Interscience, New York, 1965).

I estimated the bremsstrahlung specta from a typical TPW electrons bunch of 100 pC at 2 GeV



Calculated gamma spectra at three different angles in a Pb target from a 100 pC bunch of 2 GeV electrons. Curves are shown for spectra emitted at the entrance of the lead target and 0.75 cm into the lead target, where the electron energy has dropped to nearly 500 MeV from radiative losses.

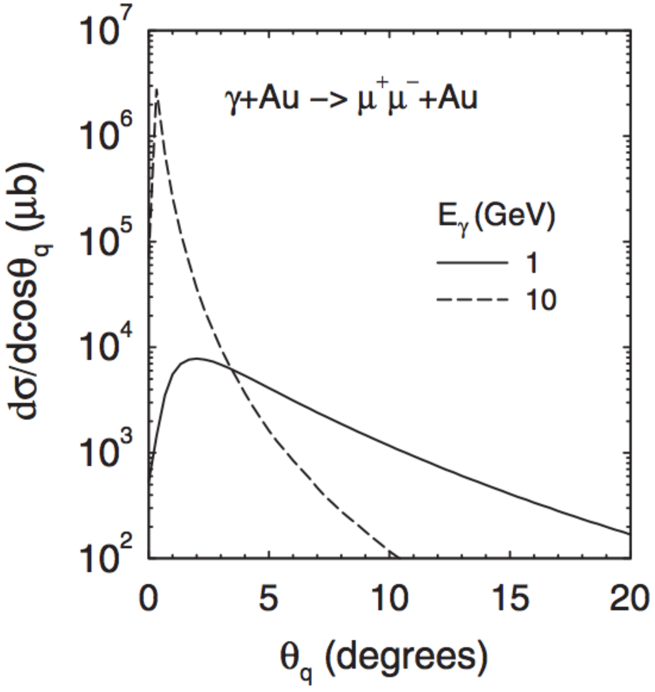
I then used NIST data base photon mean free path

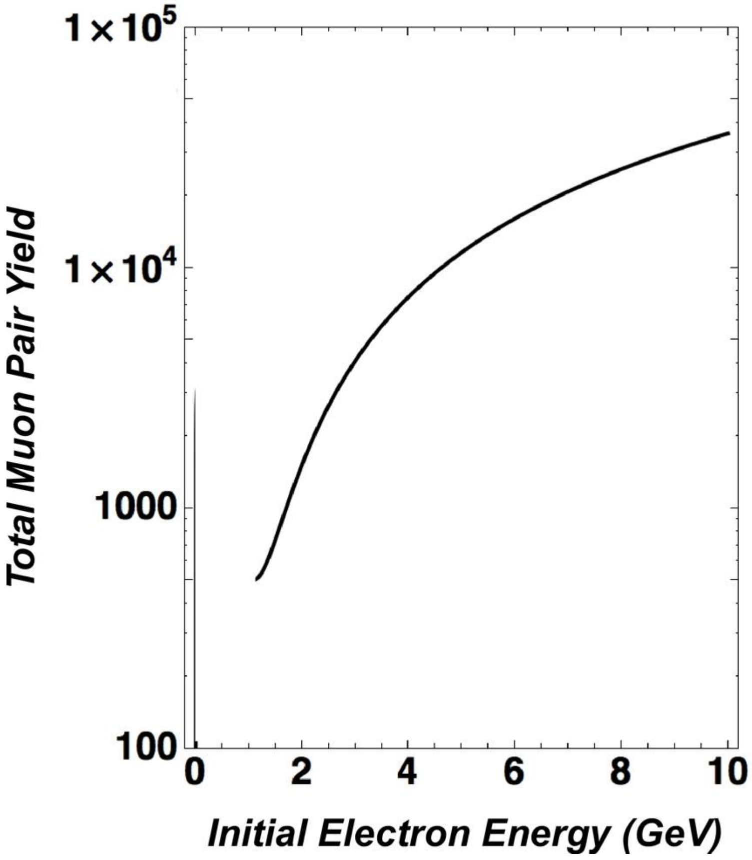


Using paramertized cross sections to generate to generate a formula to estimate muon yield from a 100 pC electron bunch

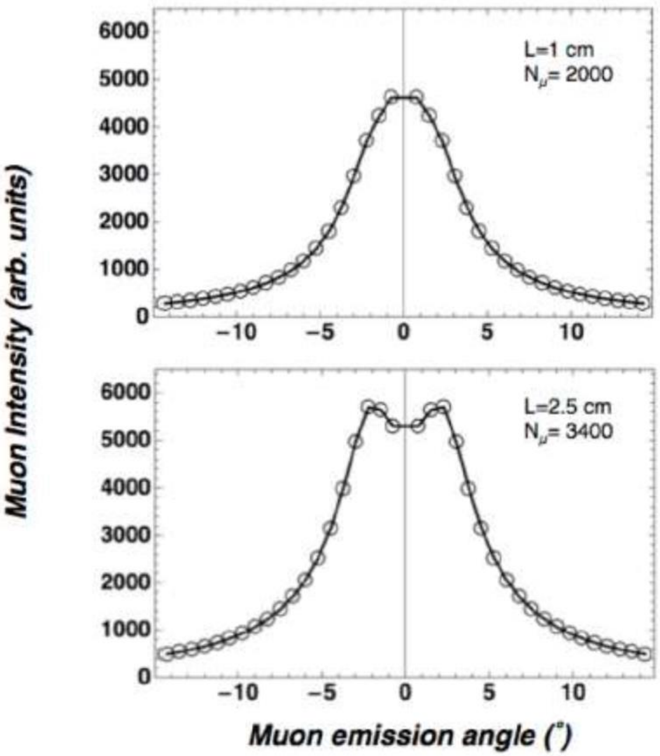
$$L_{stop} \approx 1.8\, E_e^{0.3}\ [cm]$$

$$N_\mu \cong 89\left(E_e^{(0)}\right)^{0.6}\left\{65 - 109\ln\left[\frac{E_e^{(0)}}{0.71}\right] - 21\left(\ln\left[\frac{E_e^{(0)}}{.053}\right] - \ln\left[\frac{E_e^{(0)}}{.11}\right]\ln\left[\frac{E_e^{(0)}}{0.026}\right] + \ln\left[\frac{E_t}{.11}\right]\ln\left[\frac{E_t}{.026}\right]\right)\right\}$$

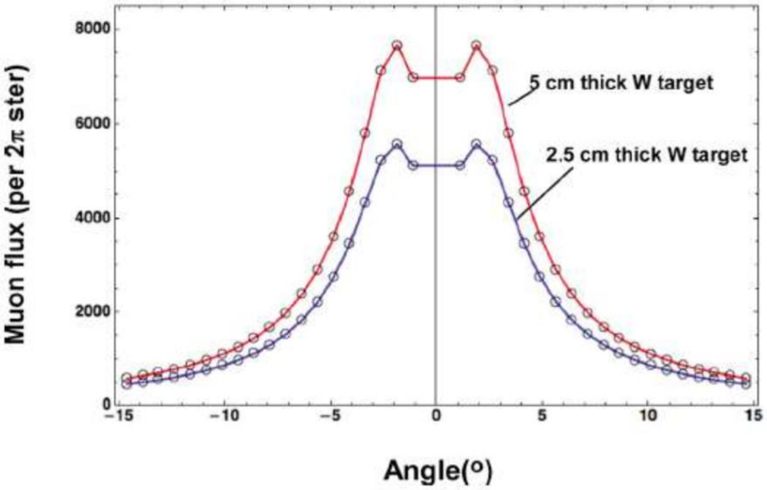




I calculated muon emission angles

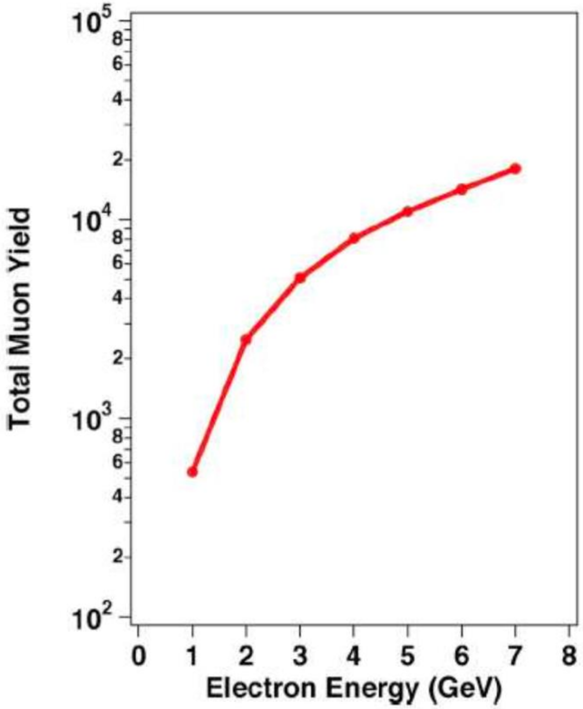


Angular distribution of muons predicted from 1.0 cm (top) and 2.5 cm (bottom) thickness Pb targets with 2 GeV incident electrons

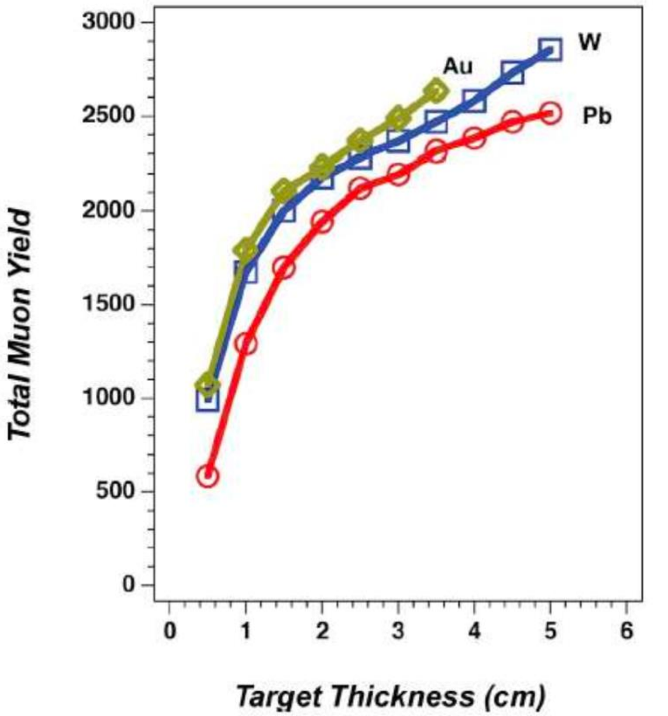


Angular distribution of muons predicted from 2.5 cm (blue curve) and 5.0 cm (red curve) thickness W targets with 2 GeV incident electrons

I examined different generation materials



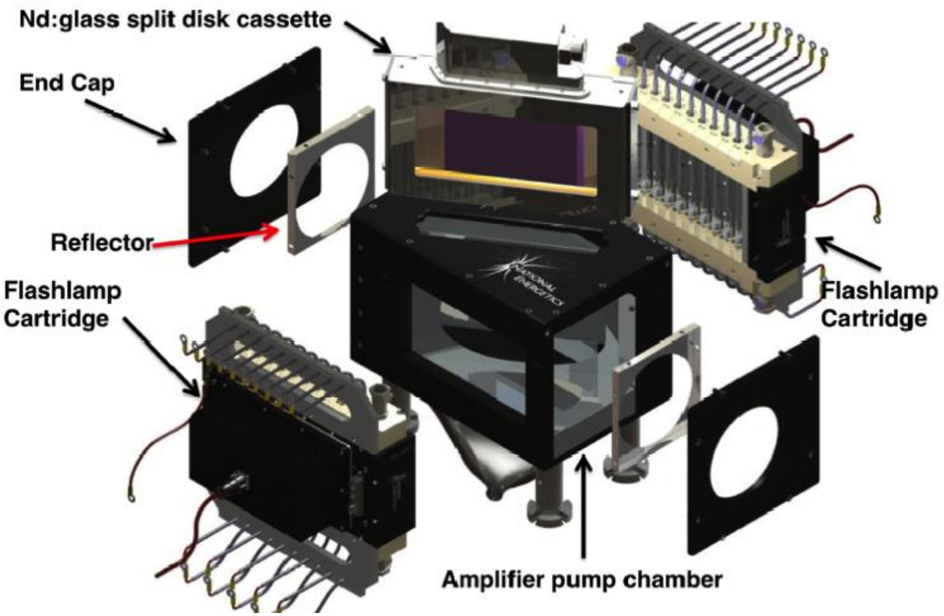
Total muon yield as a function of incident electron energy for a 65 pC bunch incident on a 2.5 cm thick W target

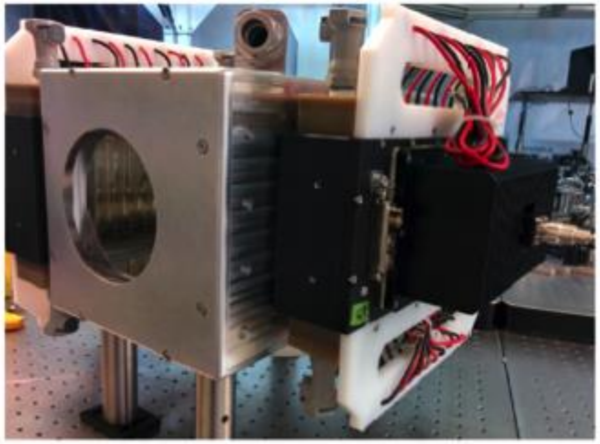


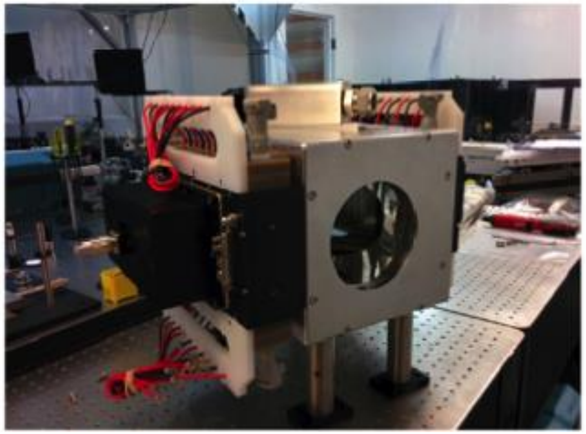
: Calculated total muon yield as a function of target thickness with 65 pC of 2 GeV electrons for three different target materials

Initial estimates for muon pairs using a 2 GeV electron bunch of 65 pC charge. These pairs would be emitted in a ~10˚ cone

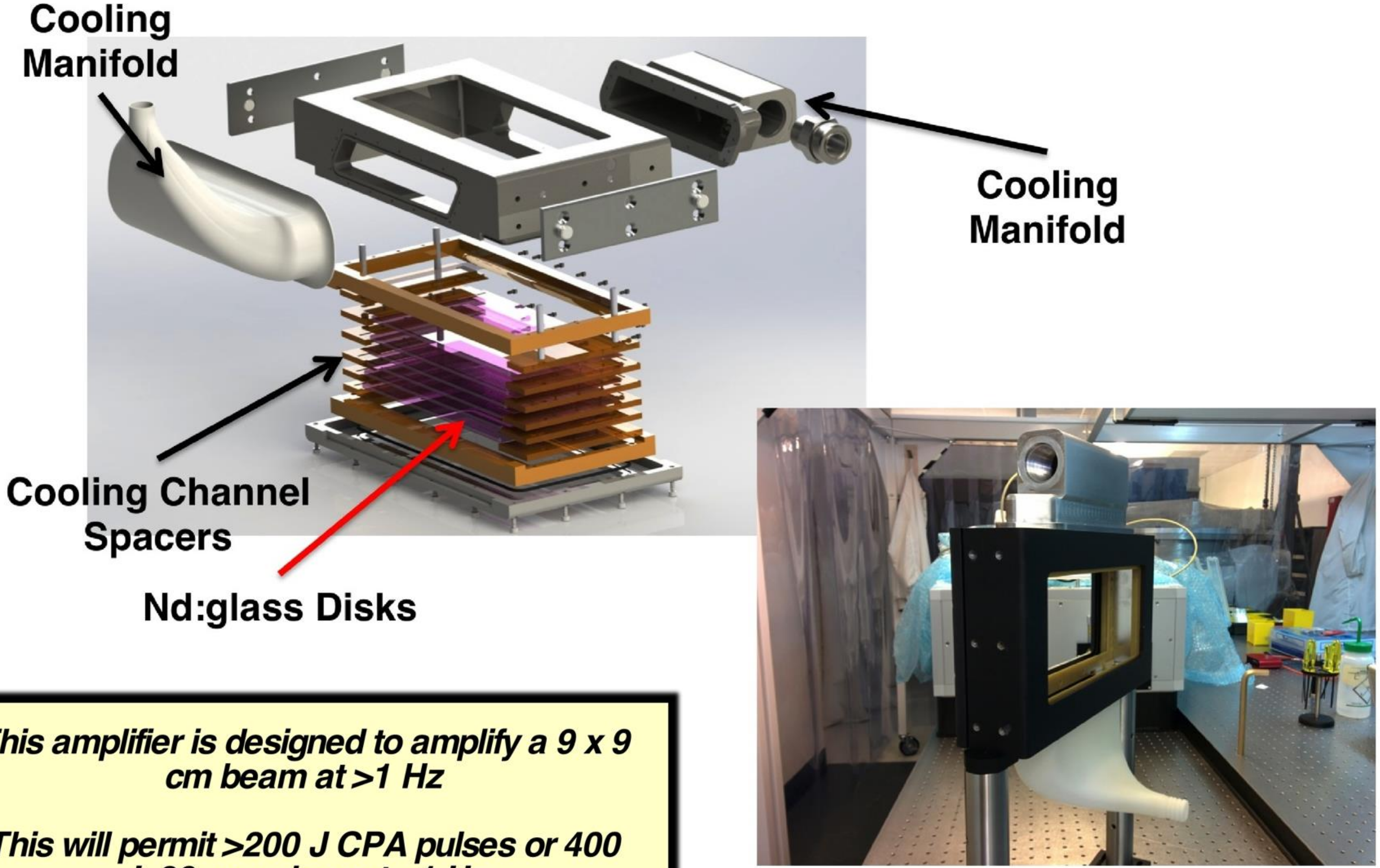
This compact liquid cooled amp technology can be used to build a multi-Hz muon production laser







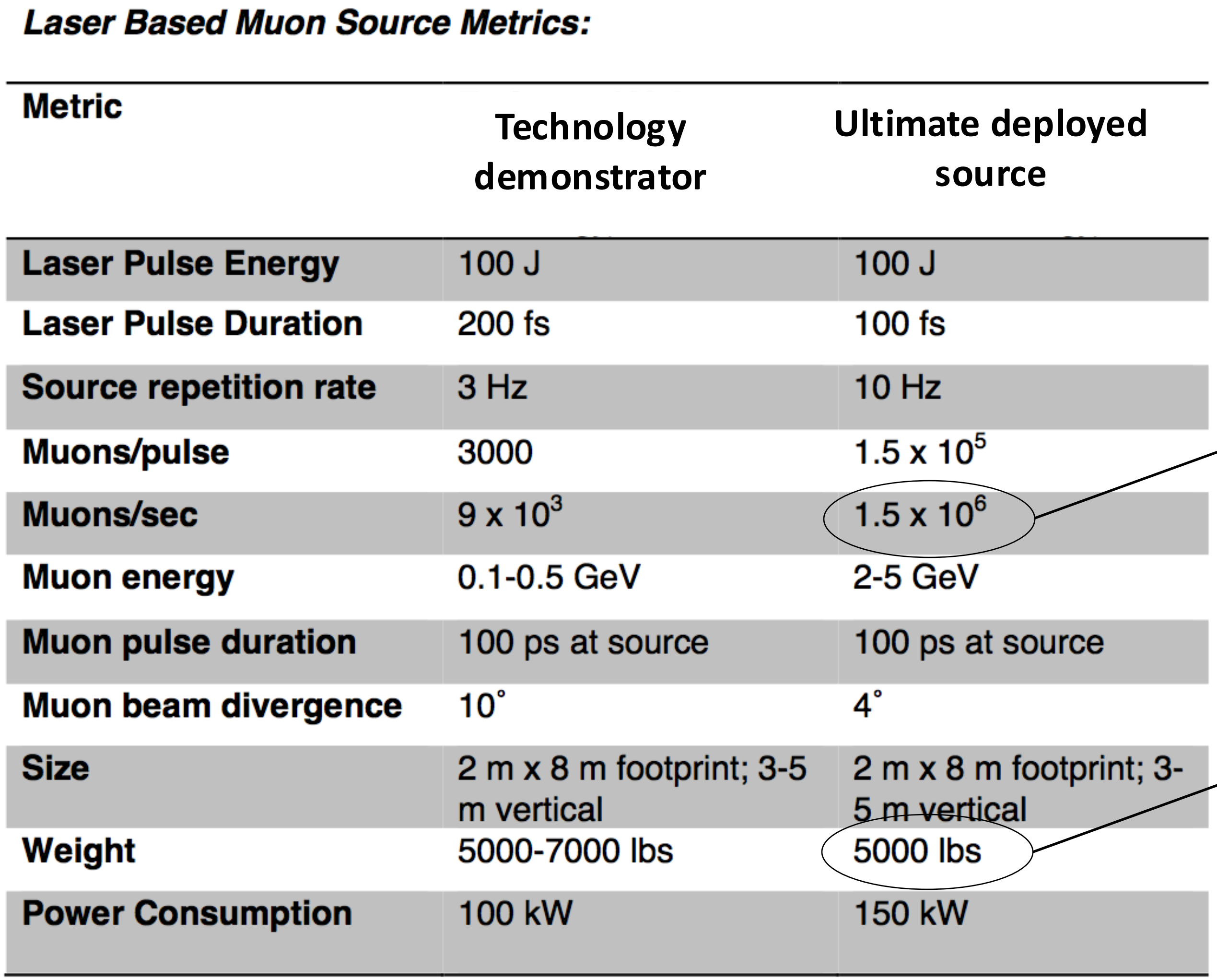
Under previous DARPA funding NE has developed technology to amplify Petawatt pulses at > 1 Hz



This amplifier is designed to amplify a 9 x 9 cm beam at >1 Hz

This will permit >200 J CPA pulses or 400 J, 30 ns pulses at >1 Hz

A compact laser based muon source could be built on a short time scale



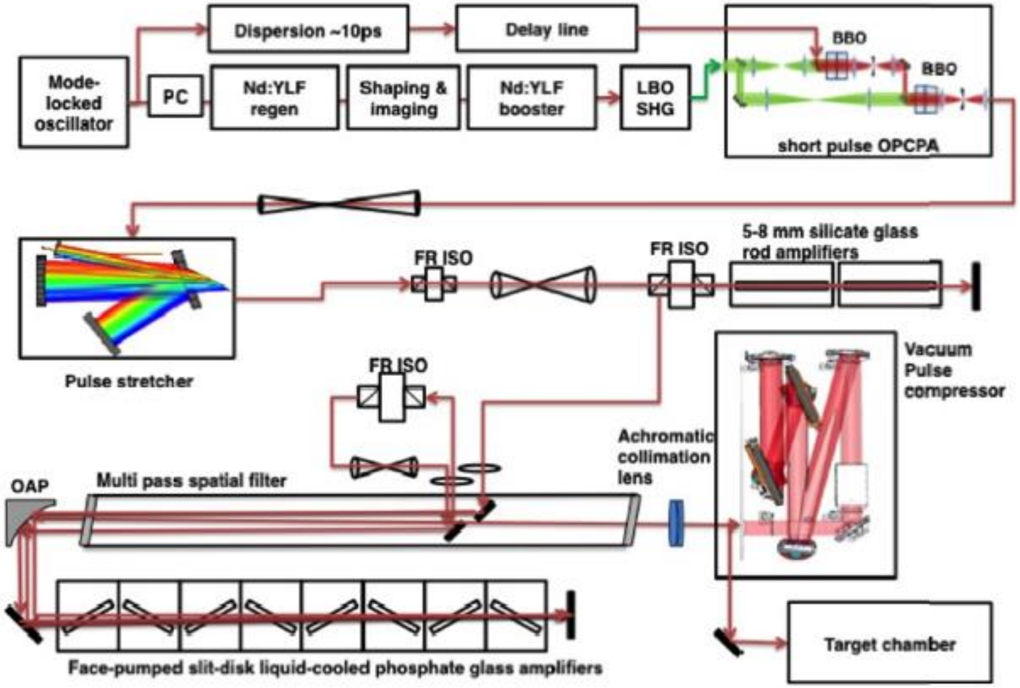
Laser Based Muon Source Metrics:

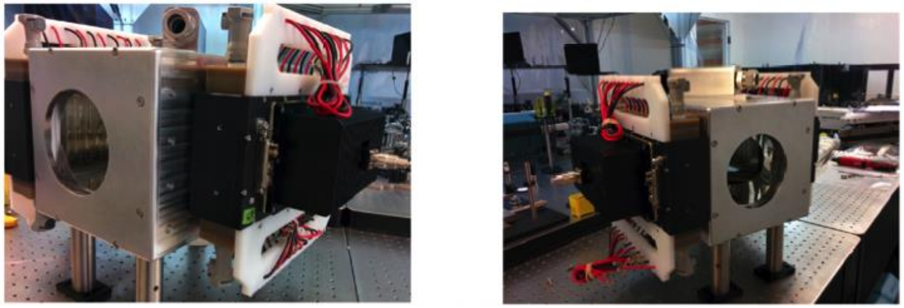
Metric	Technology demonstrator	Ultimate deployed source
Laser Pulse Energy	100 J	100 J
Laser Pulse Duration	200 fs	100 fs
Source repetition rate	3 Hz	10 Hz
Muons/pulse	3000	1.5 x 10^5
Muons/sec	9 x 10^3	1.5 x 10^6
Muon energy	0.1-0.5 GeV	2-5 GeV
Muon pulse duration	100 ps at source	100 ps at source
Muon beam divergence	10°	4°
Size	2 m x 8 m footprint; 3-5 m vertical	2 m x 8 m footprint; 3-5 m vertical
Weight	5000-7000 lbs	5000 lbs
Power Consumption	100 kW	150 kW

Flux over 10 m^2 cargo target roughly 10,000x that of cosmic ray flux

Small enough to be placed in a tractor trailer

The next step is to construct a technology demonstrator laser with muon converter





Technology demonstrator would include:

100 J, 100 fs laser firing at 3 Hz

Wakefield accelerator module producing 1 nC, 1 GeV electron pulses

Muon convertor to produce ~10^5 muons per second

Conclusion

- Congress tasked the Department of Homeland Security with 100% cargo container inspection
- More than 15 years later, less than 5% of incoming cargo containers are inspected
- Emerging technology using muons shows promise for inspection of containers for special nuclear materials and WMD
- Laser produced muons can dramatically enhance scanning speed
- Muon scanning offers the possibility of inspecting cargo for additional threats and contraband in our ports, airports, rail lines and border crossings

Laser induced muon production will enhance cargo container inspections and meet Department of Homeland Security directives