Imperial College London

THE ROYAL SOCIETY

Muon-to-Electron Conversion Experimental Techniques

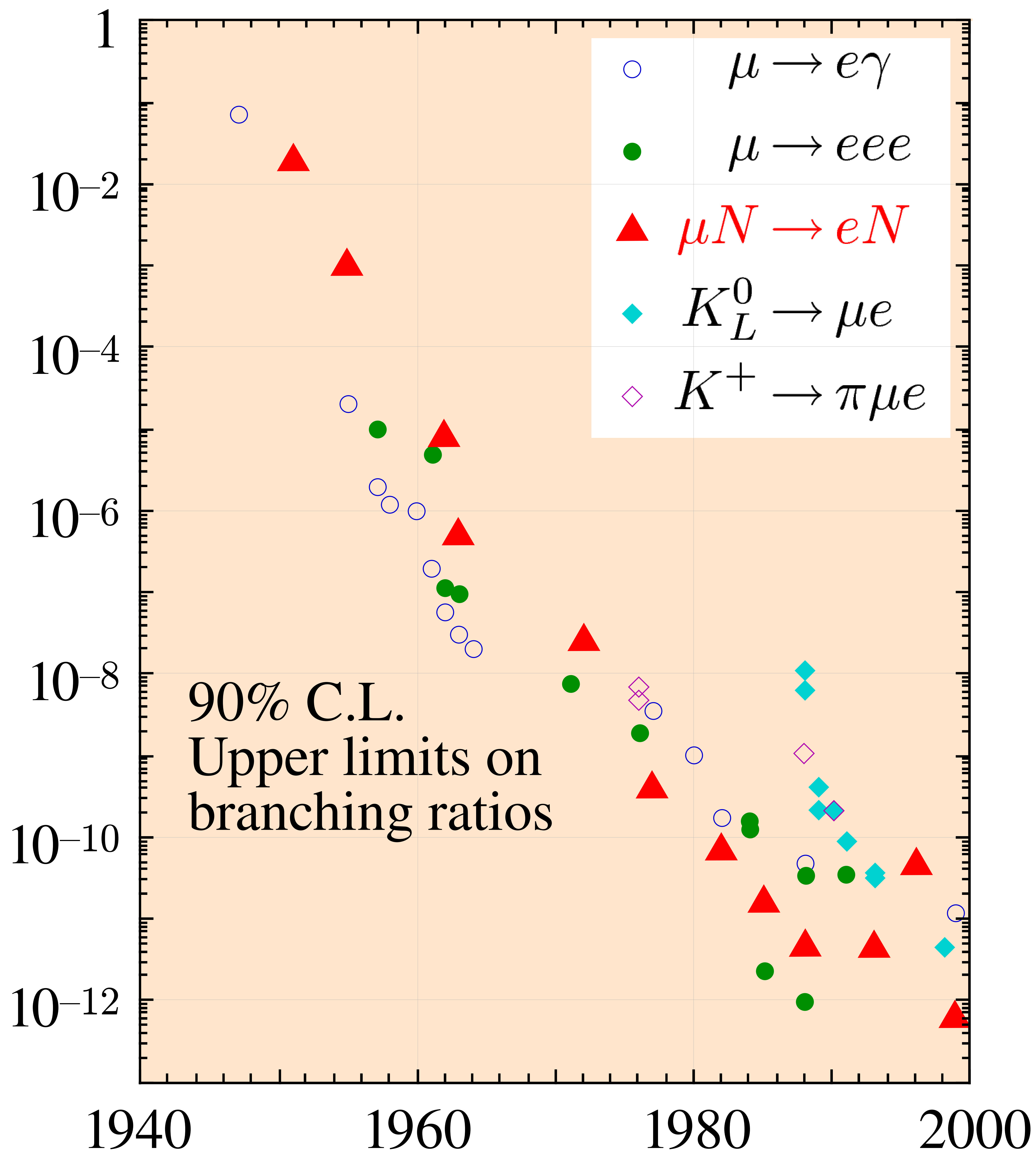
IDS Plenary Meeting in Mumbai
October 2009

Yoshi Uchida

Next Generation Muon-to-Electron Conversion Experiments

- Brief historical background
- The next-generation
  - making the most of modern high-power beams
- COMET and Mu2E
- Signal and Backgrounds
- Technologies

Historical Progress on Charged Lepton Flavour Violation



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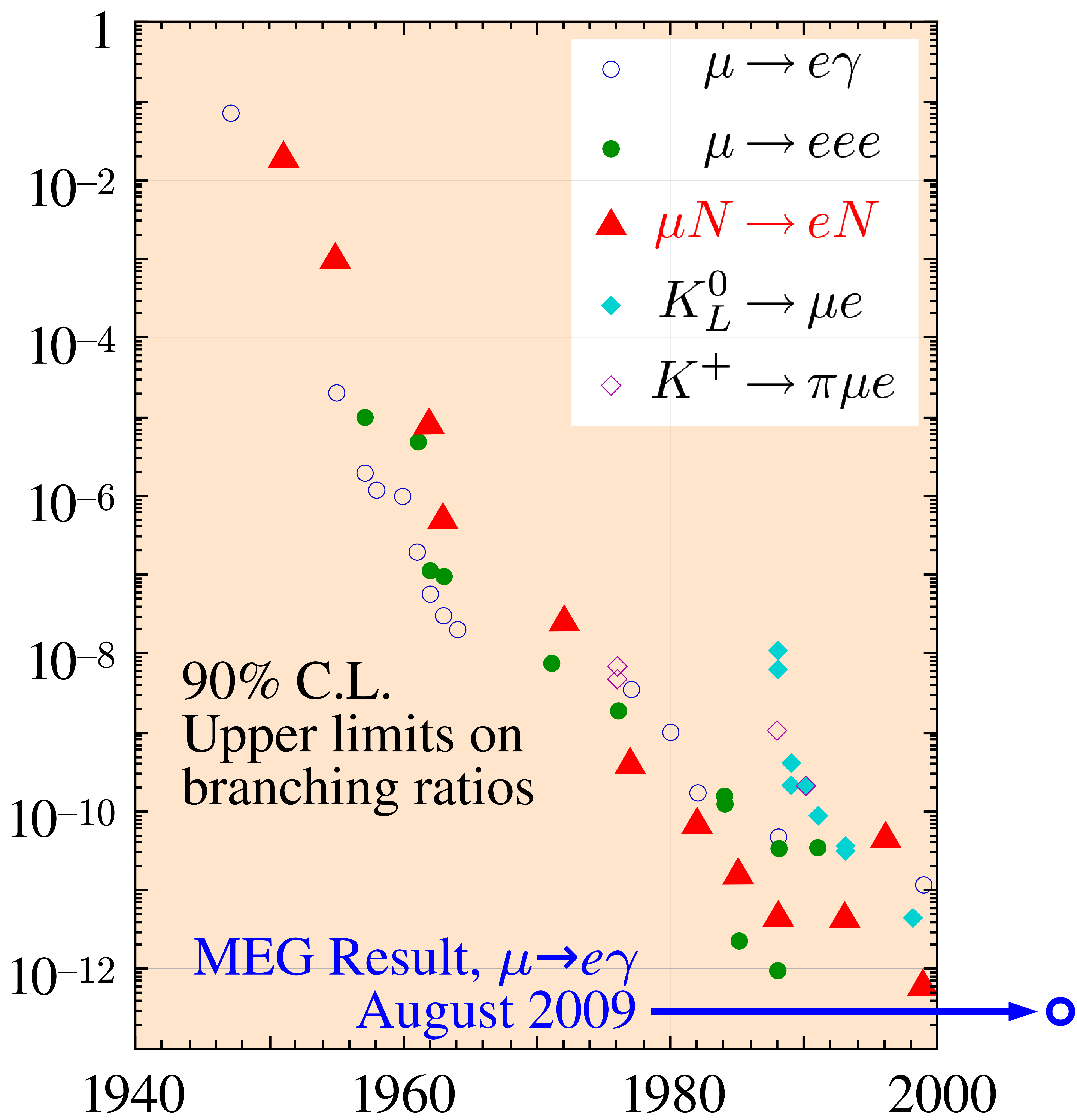

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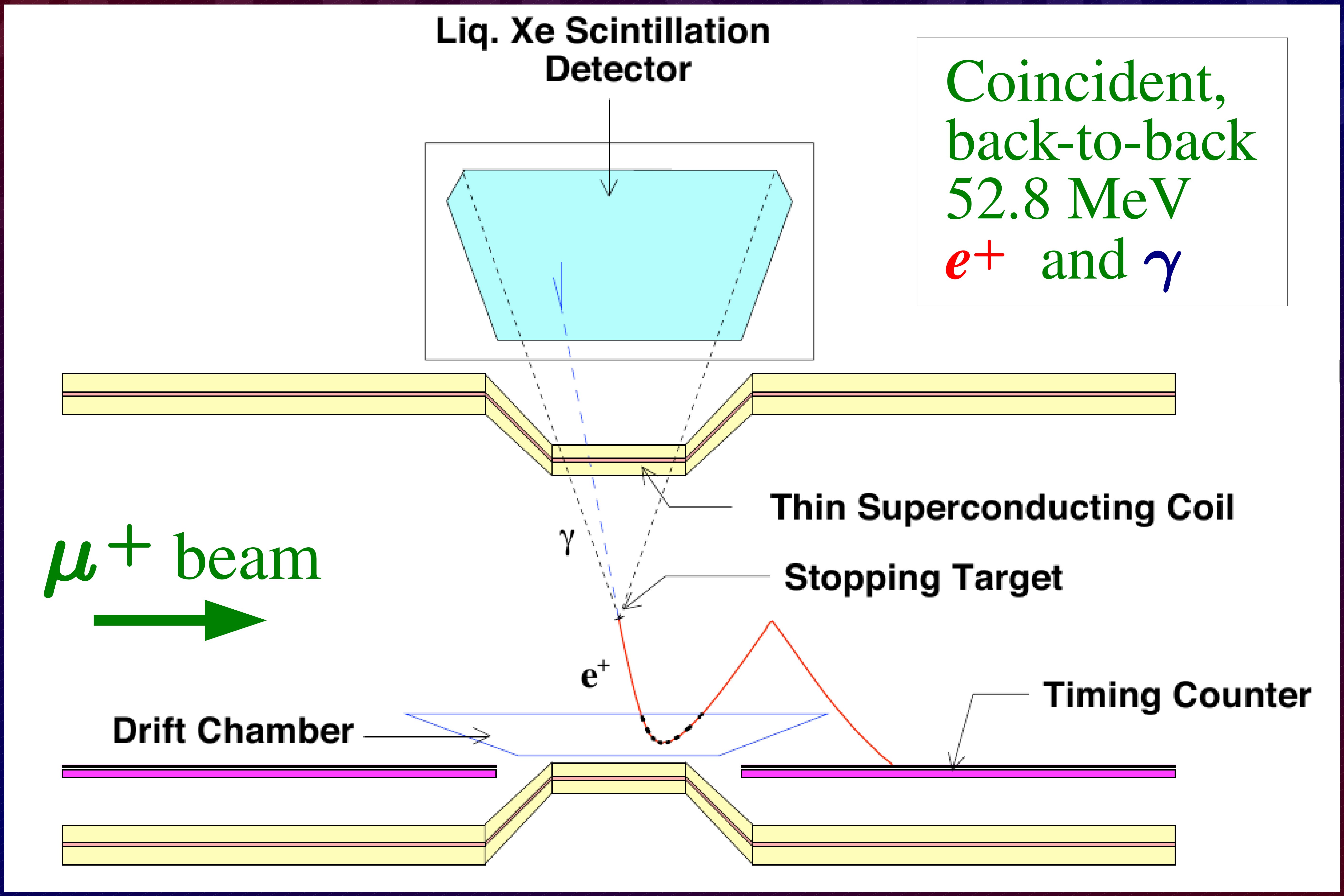
MEG ($\mu \to e\gamma$) at PSI

- Aiming for sensitivity down to branching ratio of 10^{-13}
- First Physics run from September to December 2008



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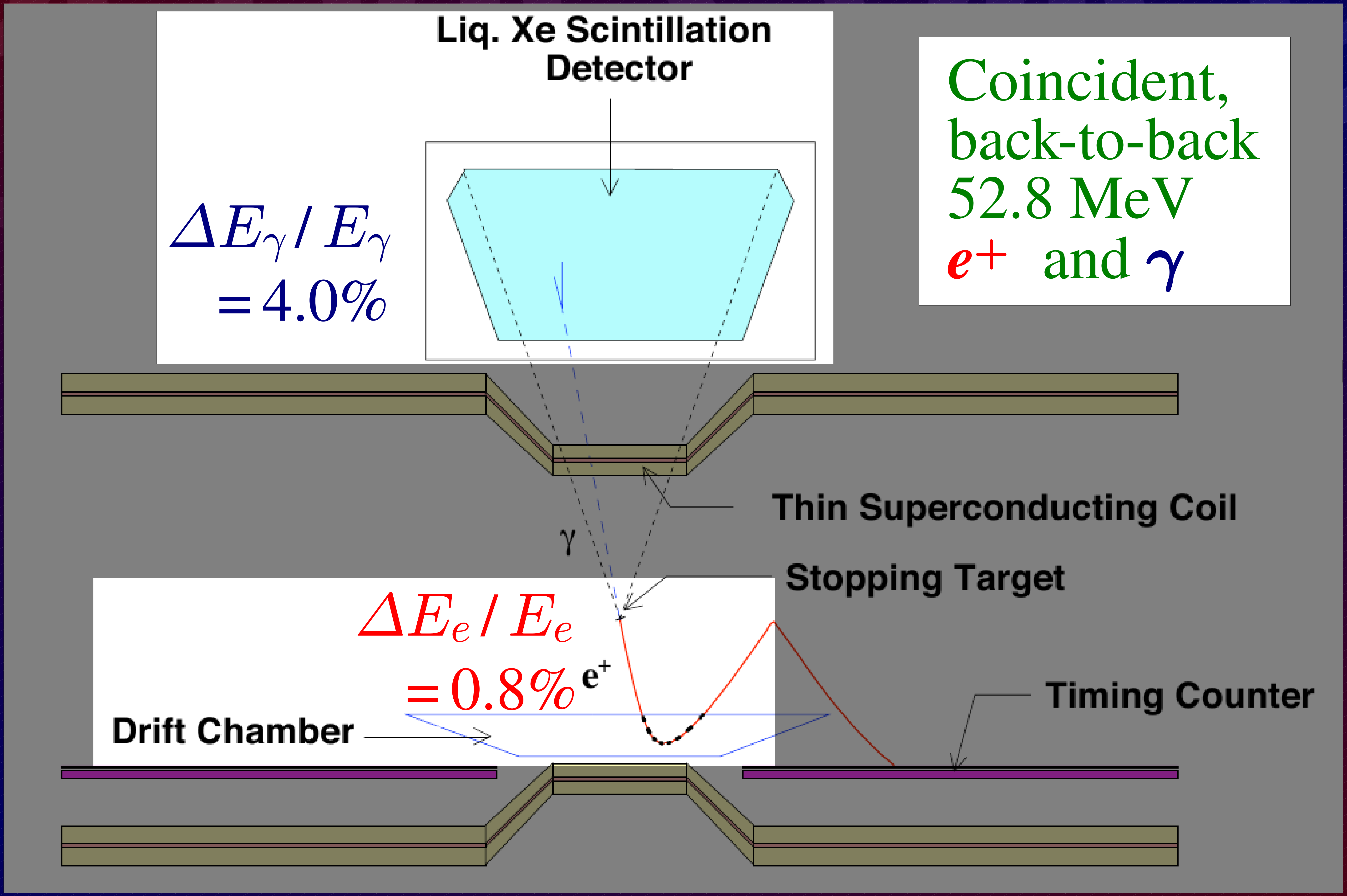

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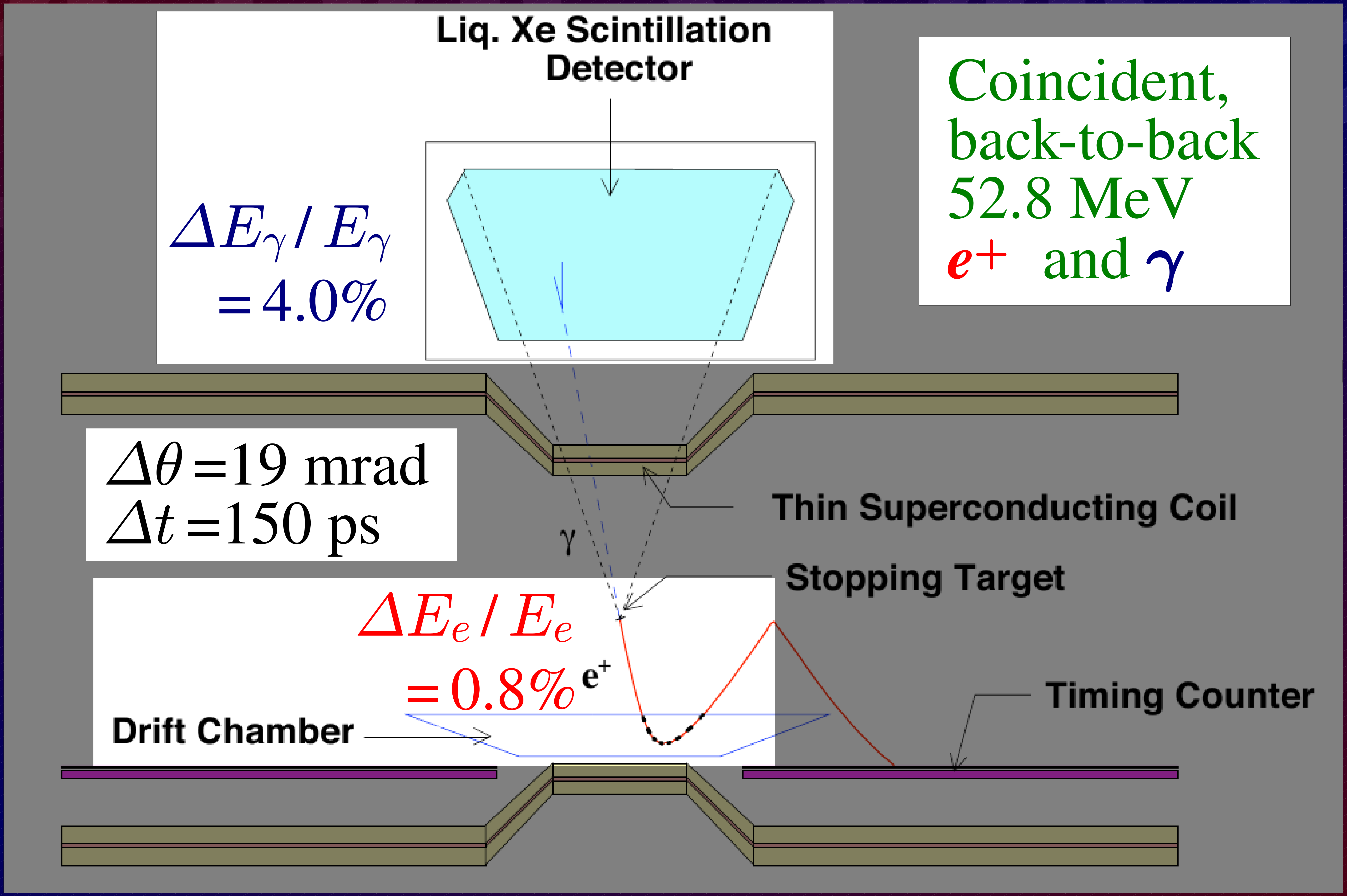

Coincidence requirement makes further improvements in sensitivity with intense beams very difficult

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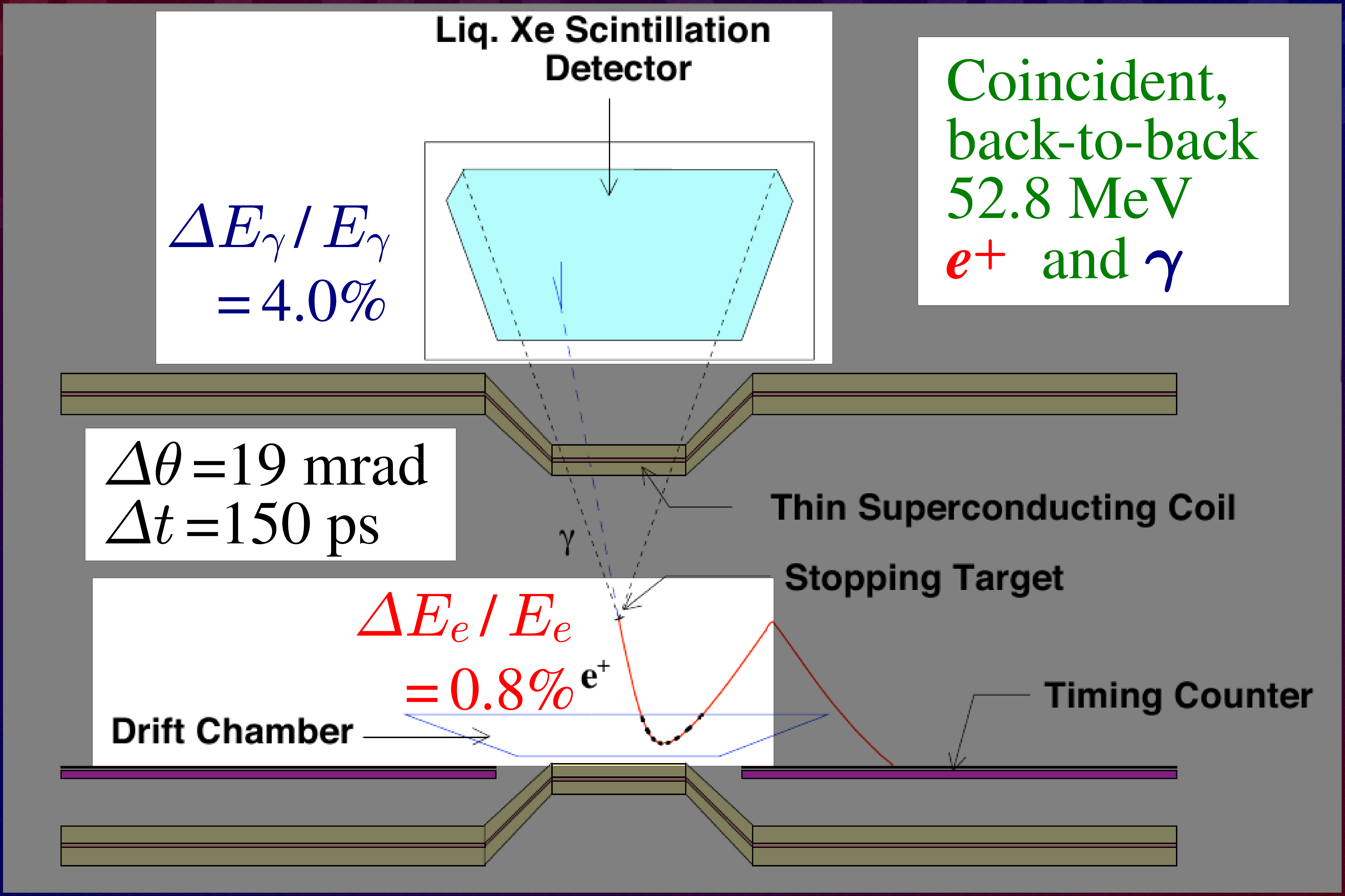


Coincidence requirement makes further improvements in sensitivity with intense beams very difficult

- 3×10^{-13} limit Aug 2009
- Running through to 2011 for full sensitivity

Coherent Muon-to-Electron Conversion

- Search for the process

$$\underbrace{\mu^- + N(A,Z)}_{\text{muonic atom}} \rightarrow e^- + N(A,Z)$$

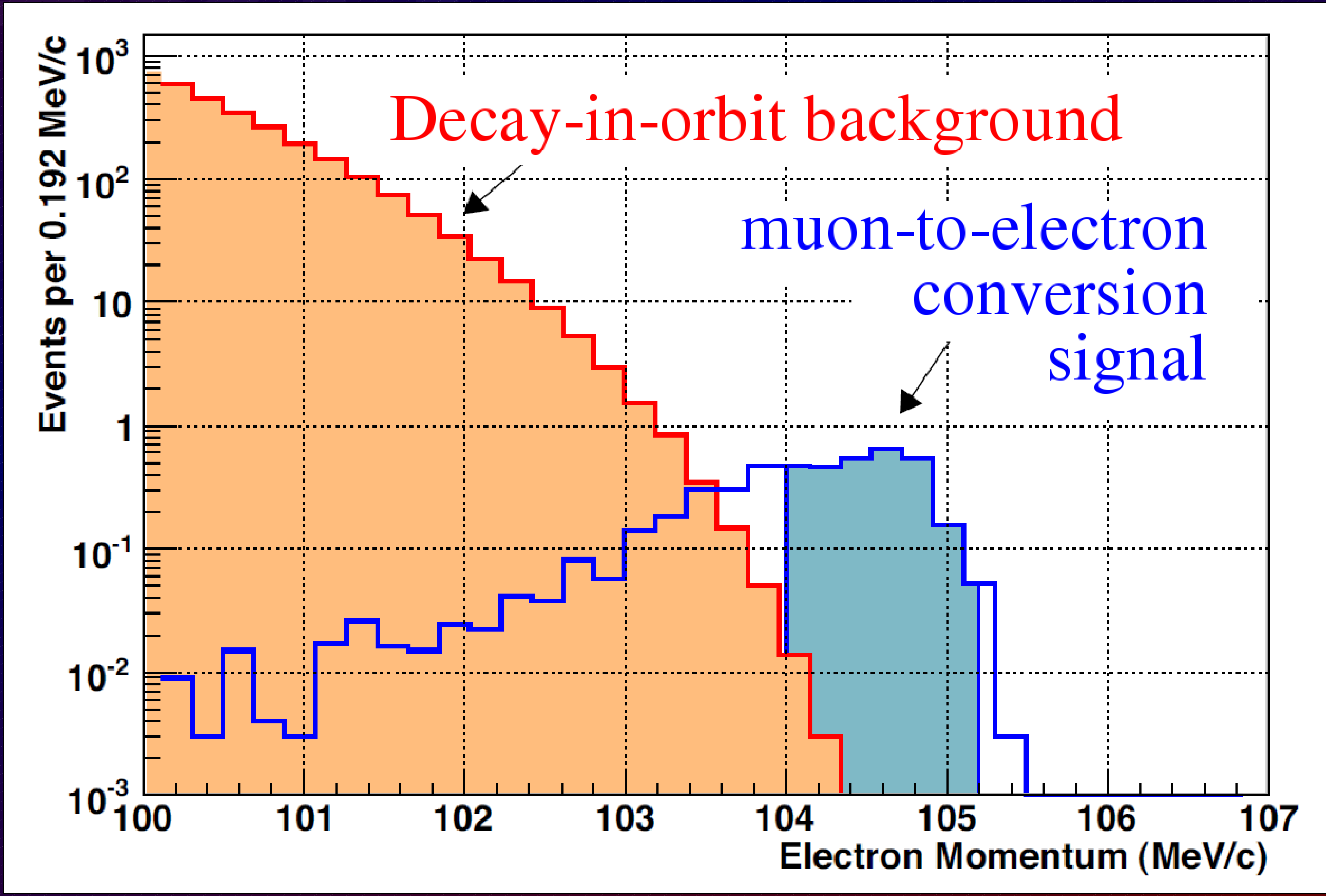
$E_e \sim 105\mathrm{MeV}$

delay since muon stopping $\sim 1\mu s$ (*N* dependent)

- Entirely non-existent in the Standard Model
- $\sim 10^{-52}$ when extended to include neutrino mass
- E_e is muon mass less the atomic binding energy

Searching for Muon-to-Electron Conversion

- Produce muons and stop them on a target
- Muonic atoms form and cascade to 1s state — so wait several hundred ns
- Observe the emitted electron spectrum over about 100 MeV/c



Coherent Muon-to-Electron Conversion

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$$\underbrace{\mu^- + N(A,Z)}_{\text{muonic atom}} \rightarrow e^- + N(A,Z)$$

muonic atom

$E_e \sim 105\text{MeV}$

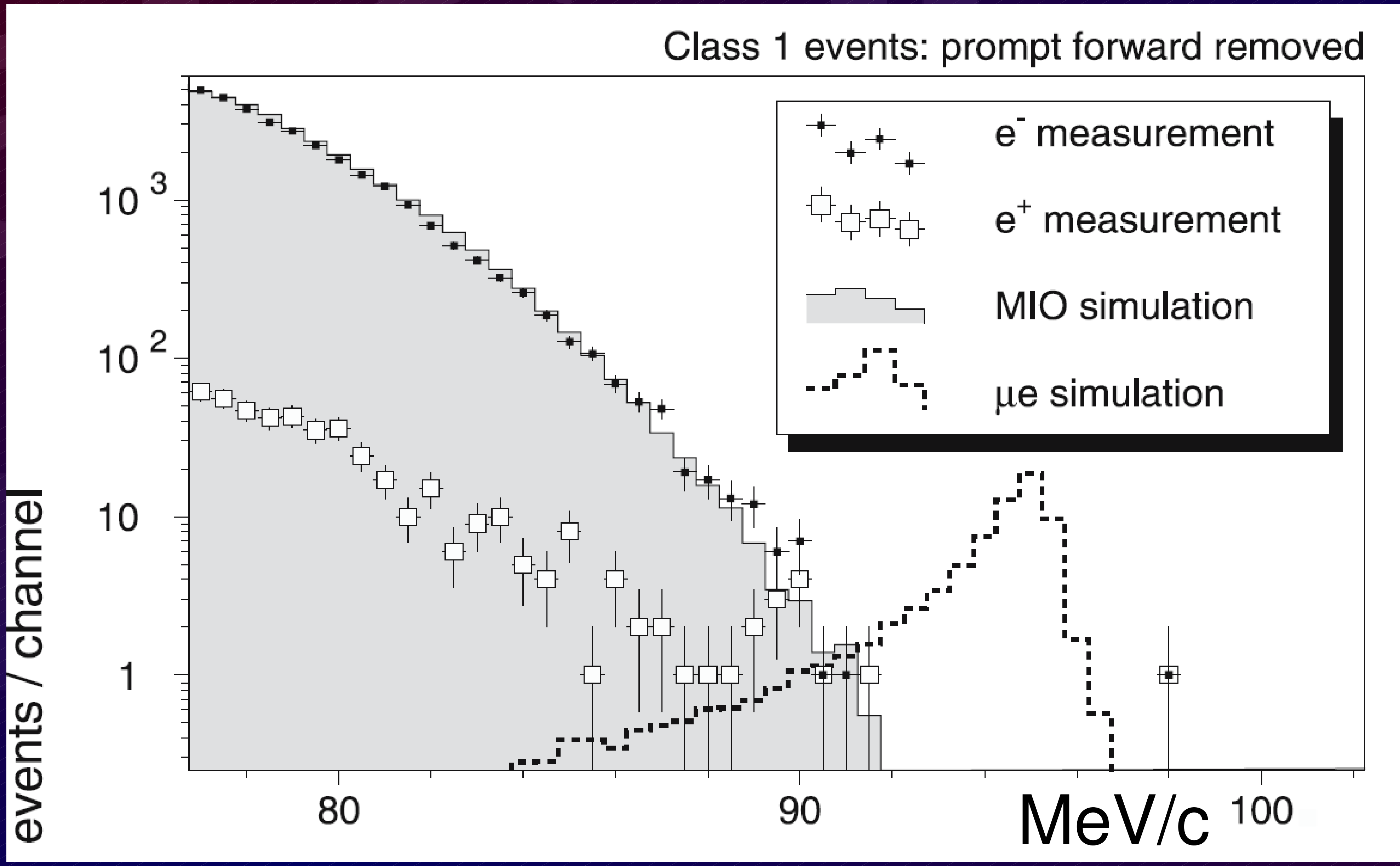
- The present limit is about

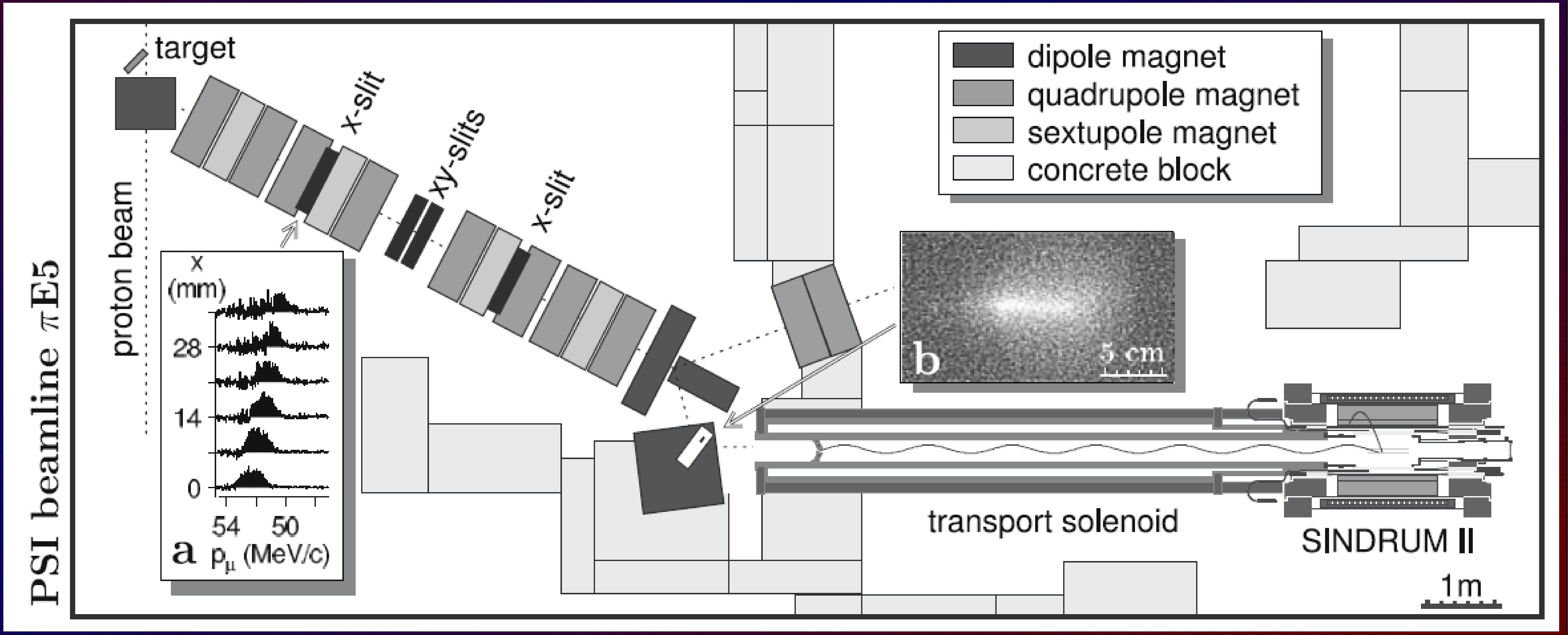
$$< 7 \times 10^{-13}$$

for the branching ratio on Gold (Sindrum II)

SINDRUM II at PSI

- $10^7 - 10^8\ \mu$/sec
- Effectively a “one-by-one” measurement
- Total rate limited by beam veto counter





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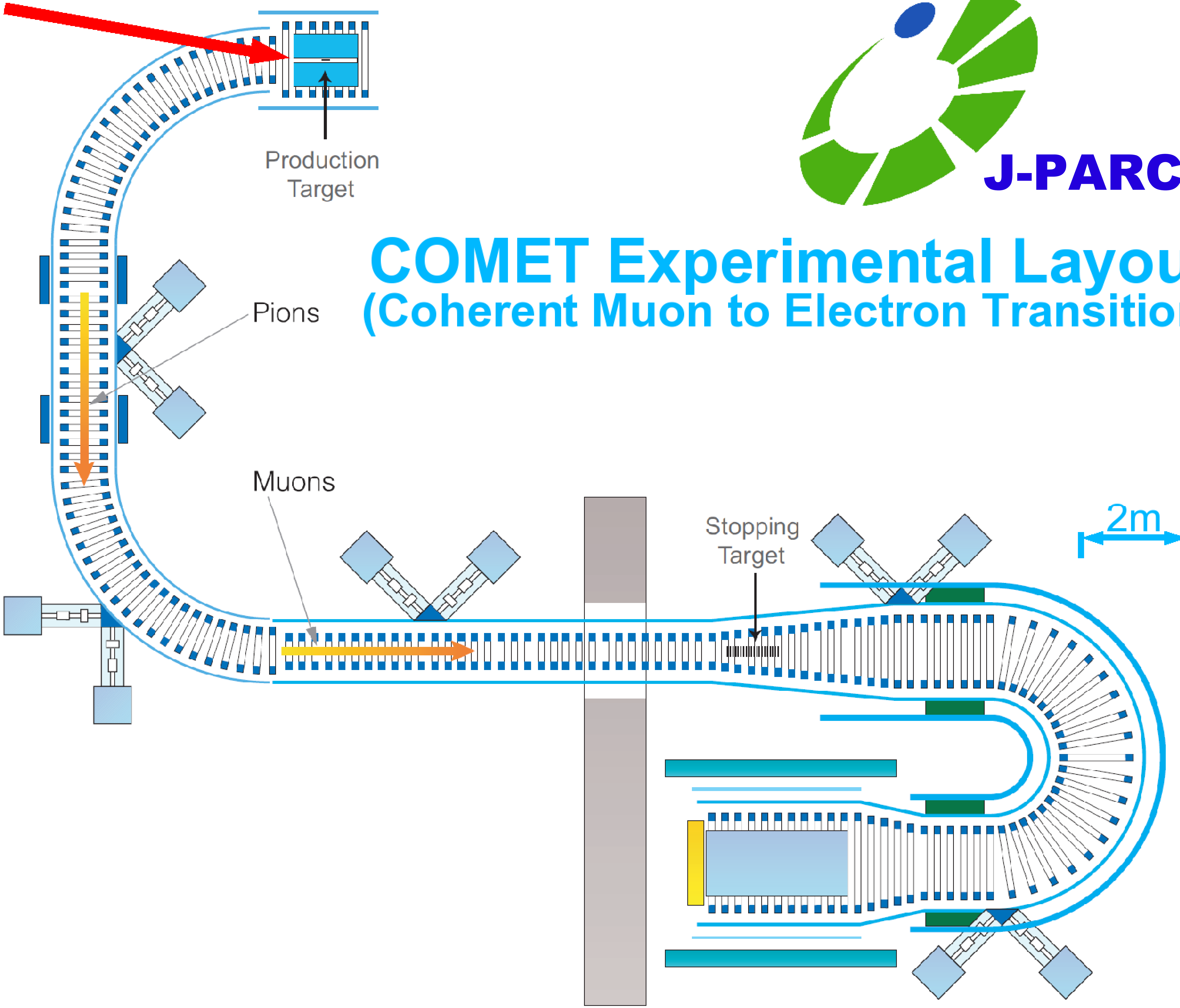
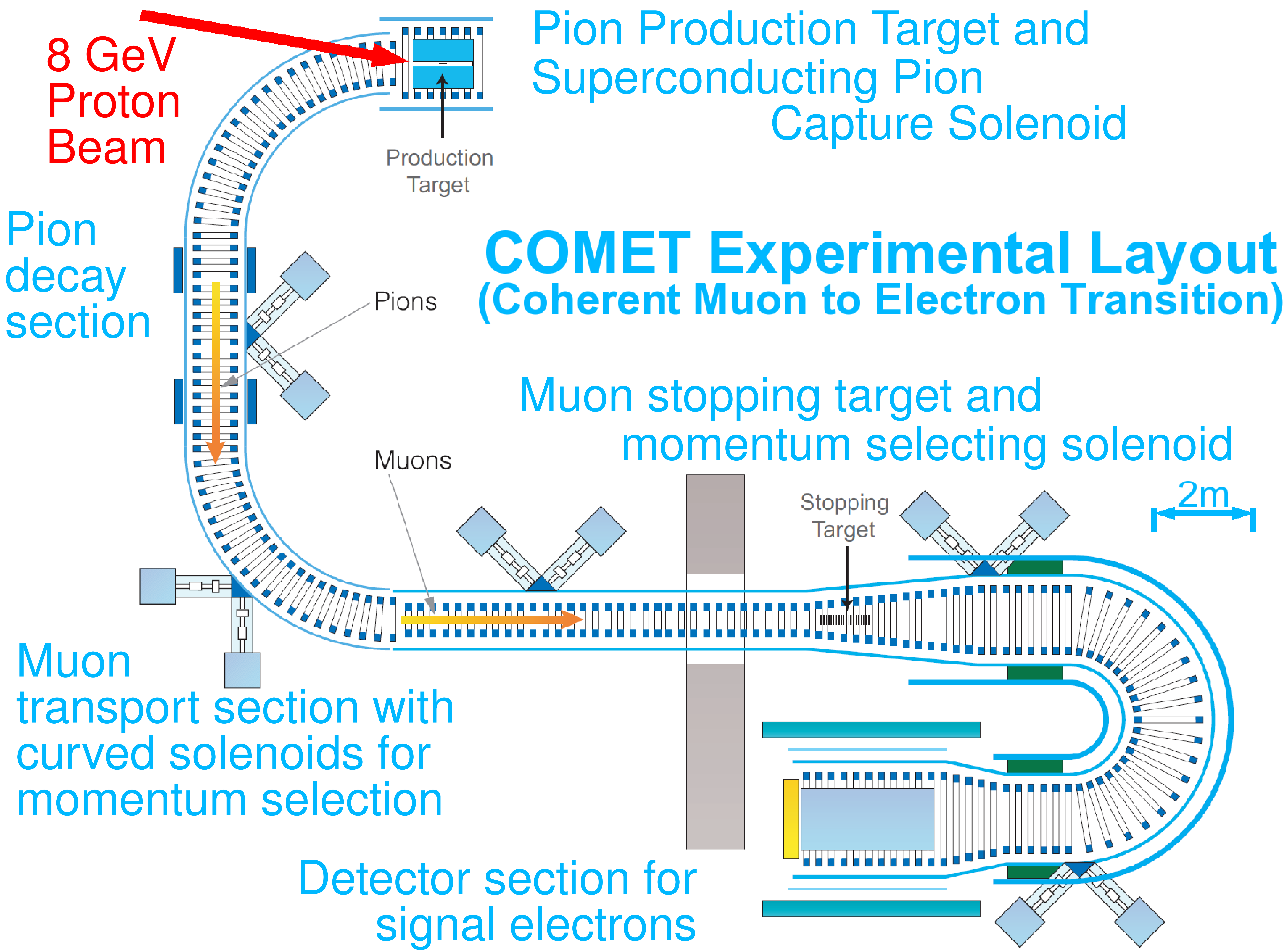
for the branching ratio on Gold (Sindrum II)

- μ2e and **COMET** aim to improve sensitivity by **×10,000**
- (**PRISM** extends this to a factor of **1,000,000**)

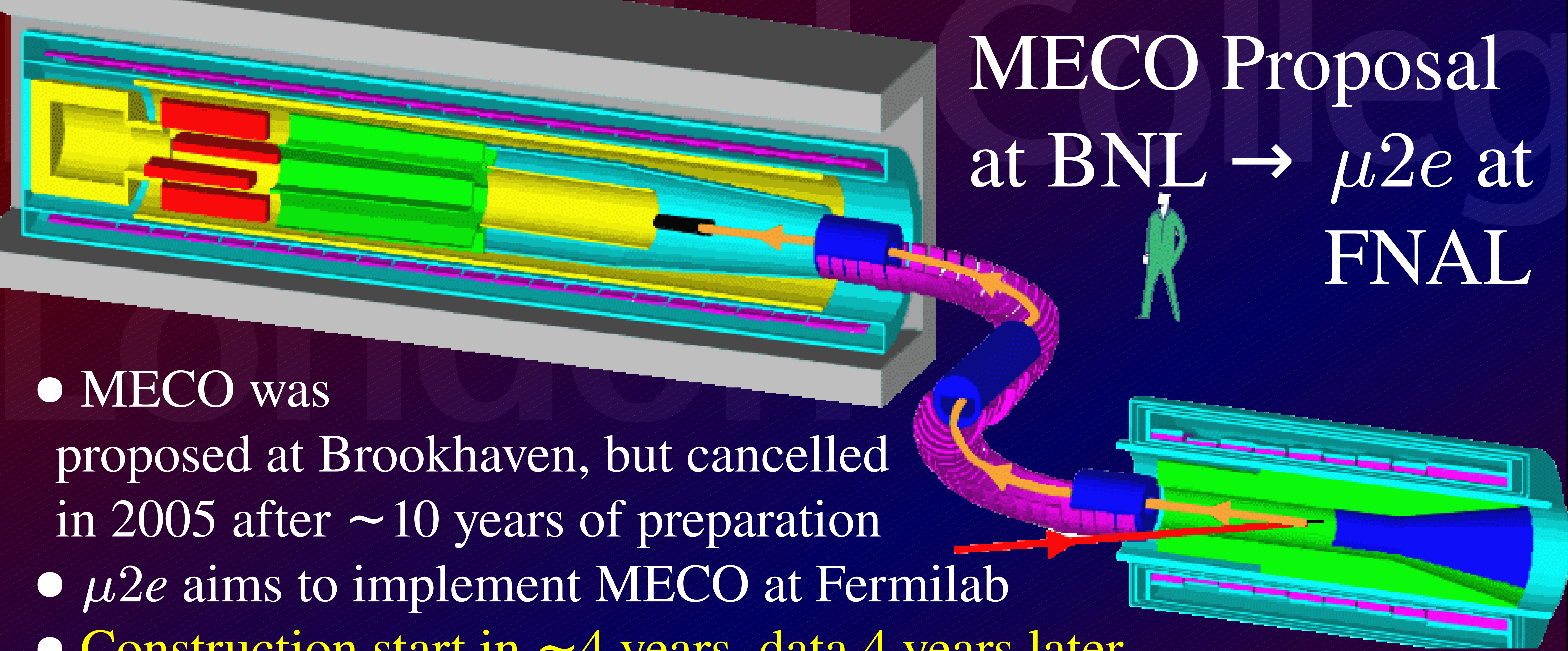
COMET Experimental Layout
(Coherent Muon to Electron Transition)

J-PARC



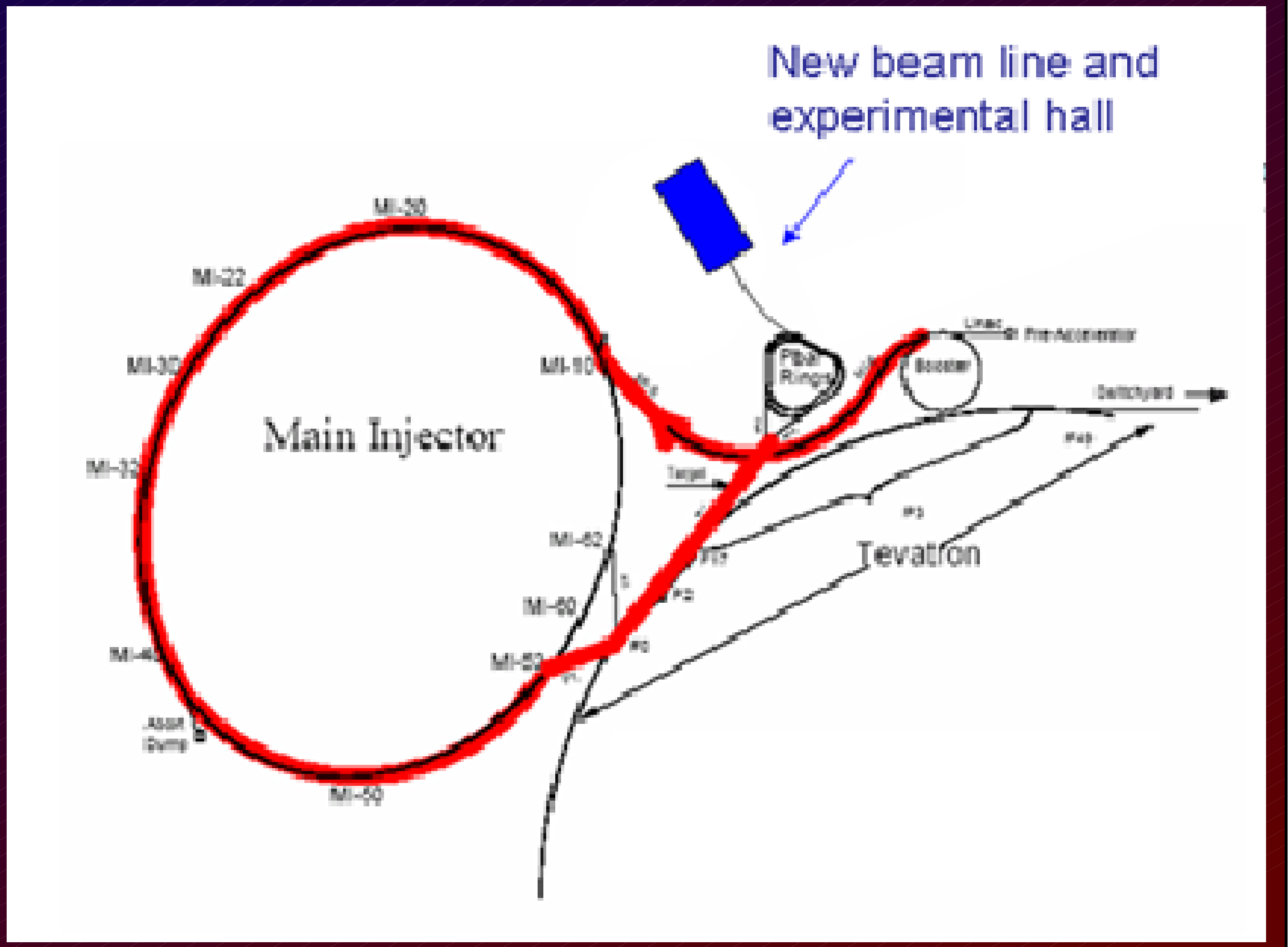


8 GeV Proton Beam
Pion Production Target and Superconducting Pion Capture Solenoid
Production Target
COMET Experimental Layout
(Coherent Muon to Electron Transition)
Pion decay section
Pions
Muon stopping target and momentum selecting solenoid
Muons
Stopping Target
2m
Muon transport section with curved solenoids for momentum selection
Detector section for signal electrons



MECO Proposal at BNL → $\mu 2e$ at FNAL

- MECO was proposed at Brookhaven, but cancelled in 2005 after ∼10 years of preparation
- $\mu 2e$ aims to implement MECO at Fermilab
- Construction start in ∼4 years, data 4 years later
- $\mu 2e$ and COMET* share basic principles, but some significant design differences
  - muon sign/momentum selection through collimation (“S-shaped” solenoid)
  - no sign/momentum selection after stopping target



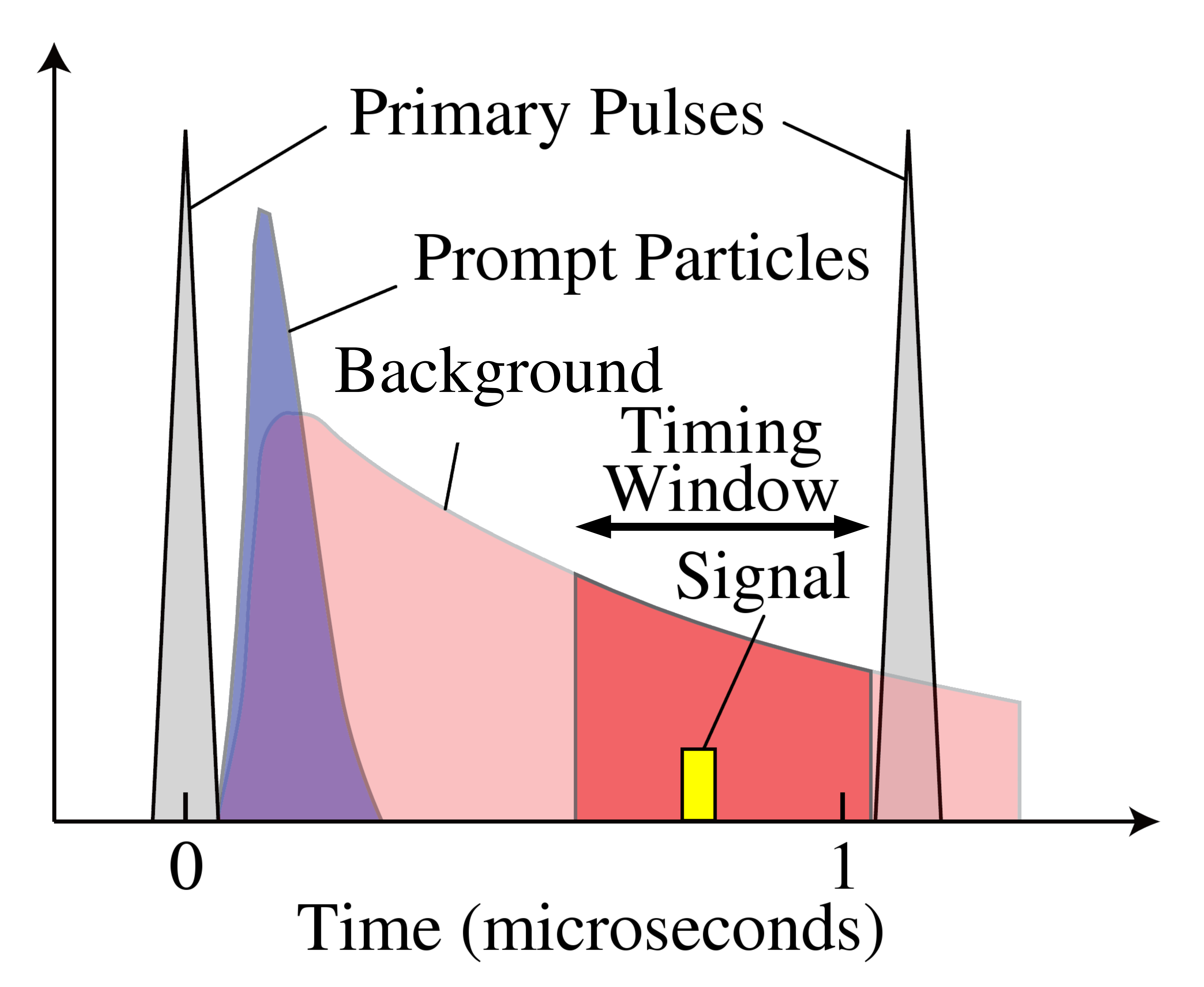
*MOU signed this year

For reasons of specificity, I will follow the COMET CDR for most of the forthcoming slides

Use of a High-Power Primary Beam

- Large backgrounds occur promptly with incoming muons
- Signal events occur with a delay

  ⇒ Pulse primary beam to separate prompt backgrounds from signal
- Characteristic times for capture vary with target
- Use energy and time to separate signal from backgrounds



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Background Event Categories

- Intrinsic physics backgrounds
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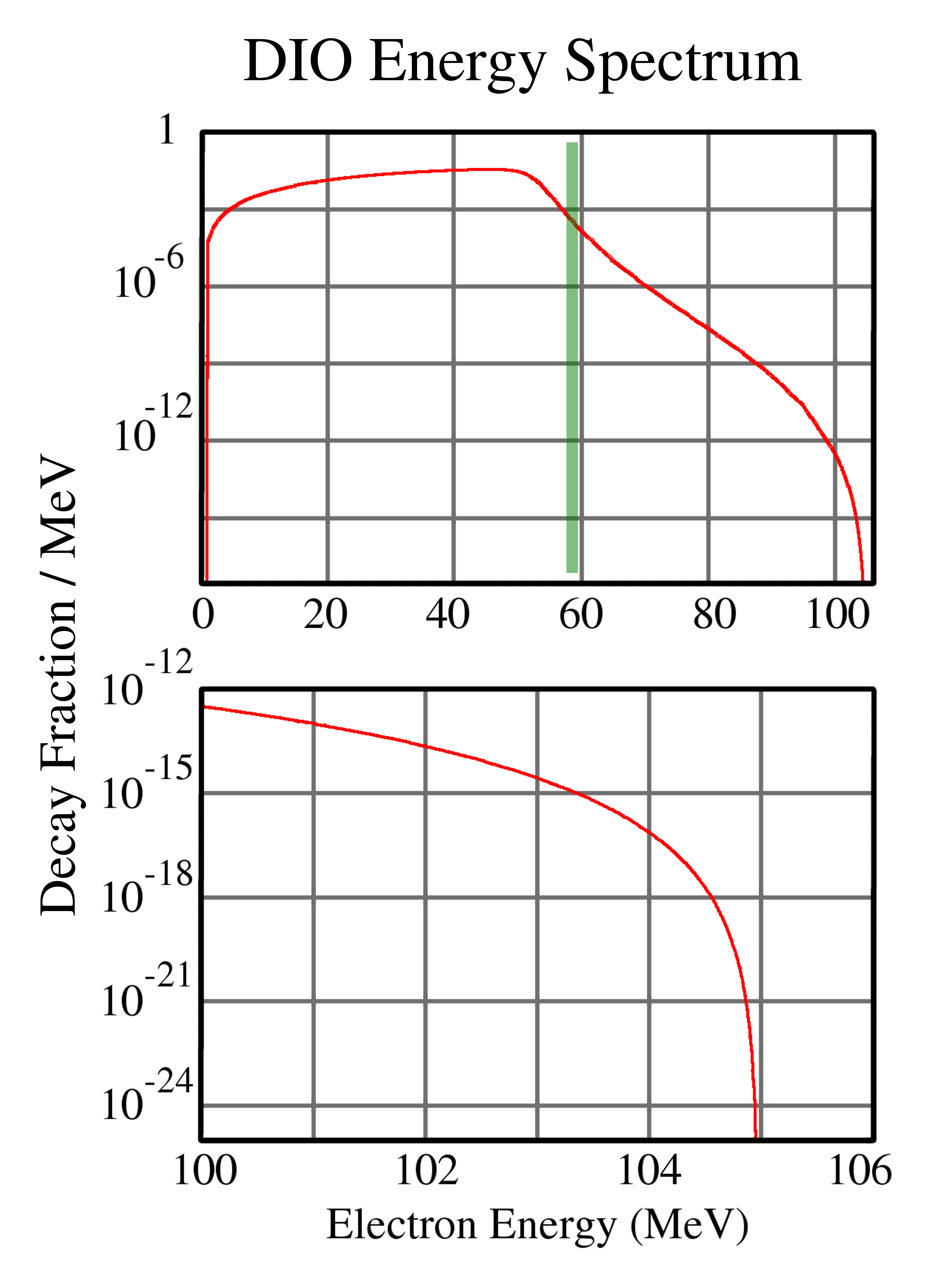
- Beam-related prompt backgrounds
  - due to protons which arrive outside of their beam buckets
- Beam-related delayed backgrounds
  - from on-time protons, but producing delayed events
- Cosmics and other backgrounds

Intrinsic Physics Backgrounds

- Muon Decay in Orbit (DIO)
  - $\mu + N \rightarrow N + \nu_\mu + \overline{\nu}_e + e^-$
  - muon decay kinematics modified by atomic environment
- Radiative Muon Capture
  - $\mu + N \rightarrow N' + \nu_\mu \Rightarrow N' \rightarrow N + \gamma \Rightarrow \gamma \rightarrow e^+ + e^-$
- Muon Capture with Neutron Emission
  - $\mu + N \rightarrow N' + \nu_\mu \Rightarrow N' \rightarrow N + n \Rightarrow$ neutrons produce e^-
- Muon Capture with Charged Particle Emission
  - $\mu + N \rightarrow N' + \nu_\mu \Rightarrow N' \rightarrow N + X \Rightarrow X$ (protons, deuterons, alphas etc) produces e^-

Decay-in-Orbit (DIO) Electrons

- Free muon decay has end-point of 58.3 MeV
- Nuclear recoil modifies the energy spectrum for DIO
- End-point can reach up to μ-e conversion energy
- $\propto\ (E_{\mu\text{-}e} - E)^5$ near end-point
- Crucial to understand spectrum near 105 MeV



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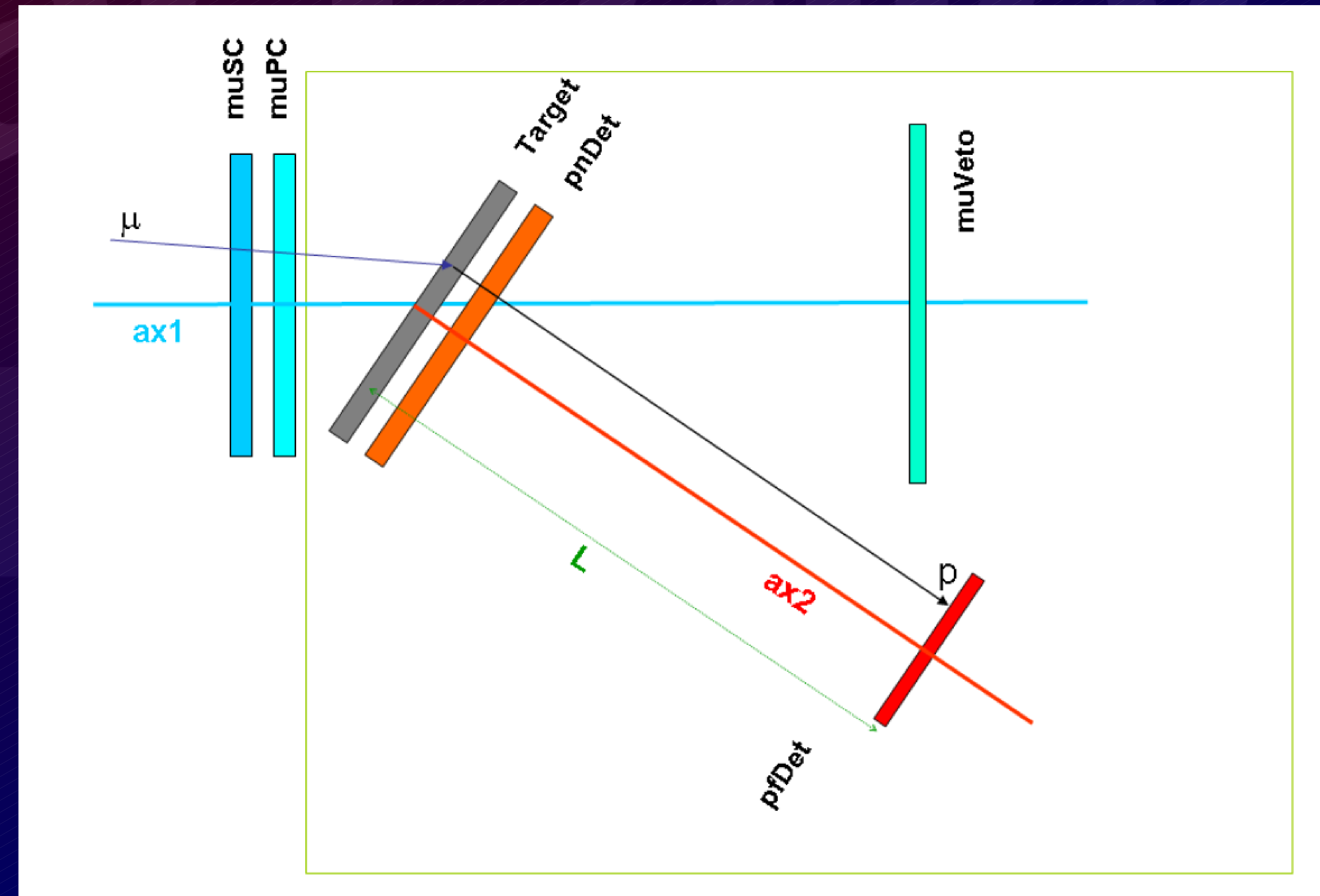
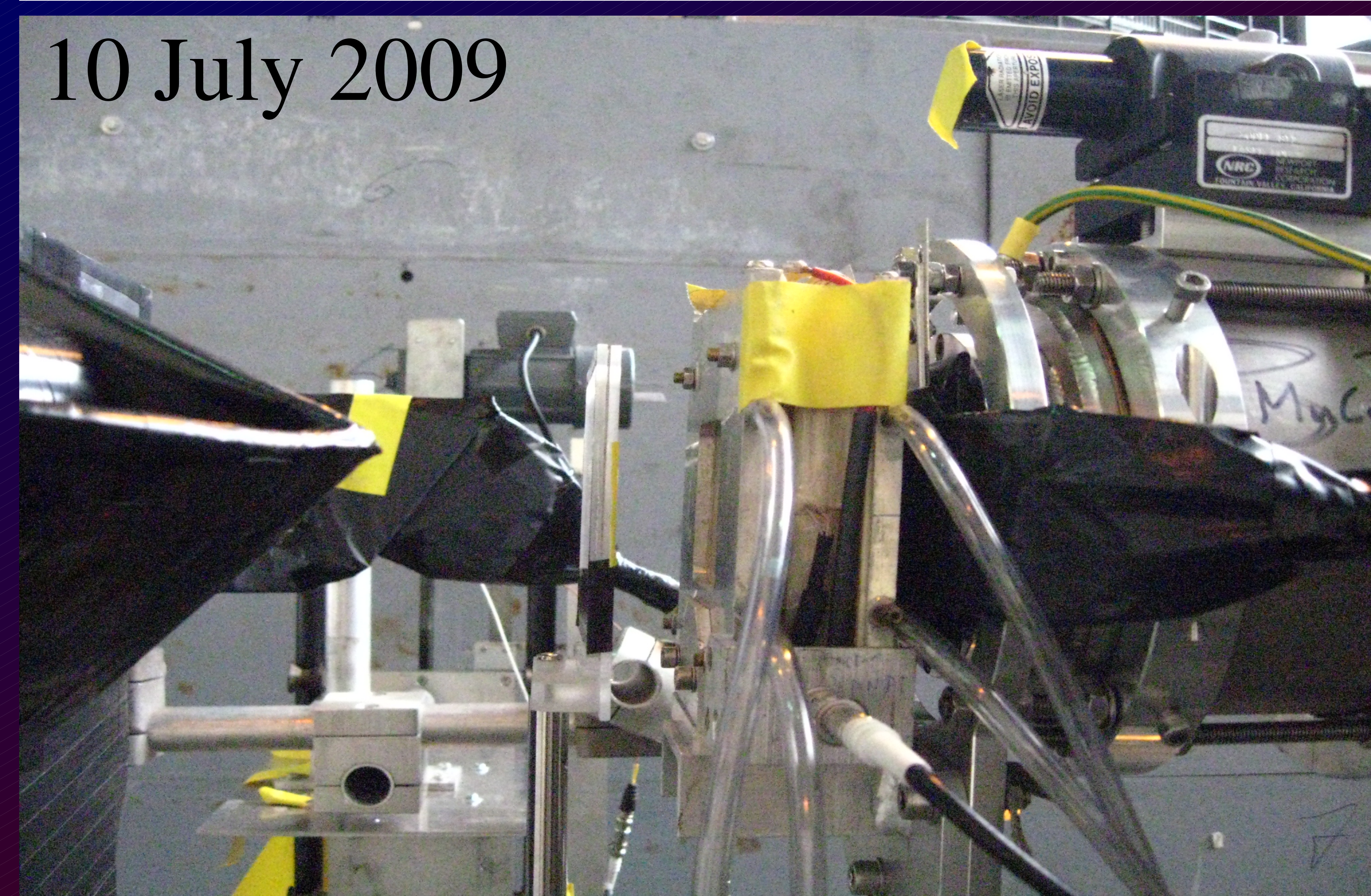
Background Production Studies at PSI

- Measurement programme at PSI πE3 muon beam, led by $\mu 2e$ group
- To directly observe charged particle emissions from stopping target materials
- First runs conducted this past summer, with some COMET student participation
- Initial focus mainly protons





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- Cosmics and other backgrounds

Prompt Backgrounds

- Radiative pion capture
  - $\pi^- + N \rightarrow \gamma + N' + \ldots \Rightarrow \gamma \rightarrow e^+ + e^-$
- Beam electrons
  - e^- scattering off a muon stopping target
- Muon decay in flight
  - μ decays in flight producing e^-
- Pion decay in flight
  - π^- decays in flight producing e^-
- Neutron induced backgrounds
  - neutrons hit material producing e^-

Beam Extinction

- Very high beam extinction performance necessary between proton pulses
- 10^{-9} extinction needed
- Methods undergoing R&D
- Internal extinction
  - remove off-pulse protons during circulation
- External extinction
  - AC dipole on proton beamline to experiment
  - joint Mu2E / COMET R&D

Beam Monitor for Beam Extinction Tests and Measurements at J-PARC

(Preliminary measurement of 4×10^{-5}
⇒ 10^{-9} goal achievable with internal and external extinction)

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Beam-Related Delayed Backgrounds

- Antiproton interactions
  - interactions of $\bar{p}$, which travel slowly, producing e^-
- Radiative capture of pions
  - very large number of pions produced – some may result in late radiative captures

Beamline design critical ⇒ see Ajit Kurup's talk

Background Event Categories

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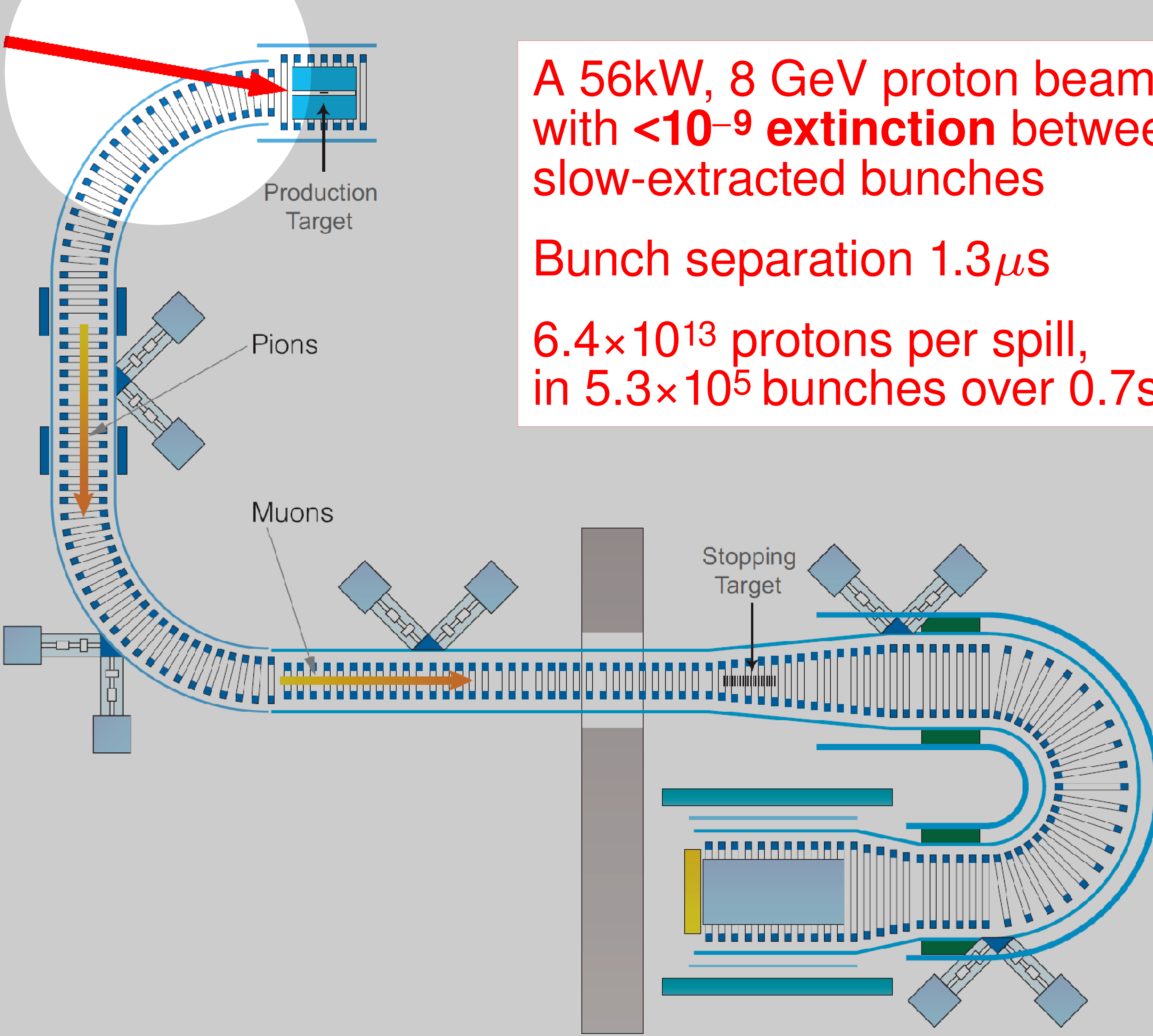
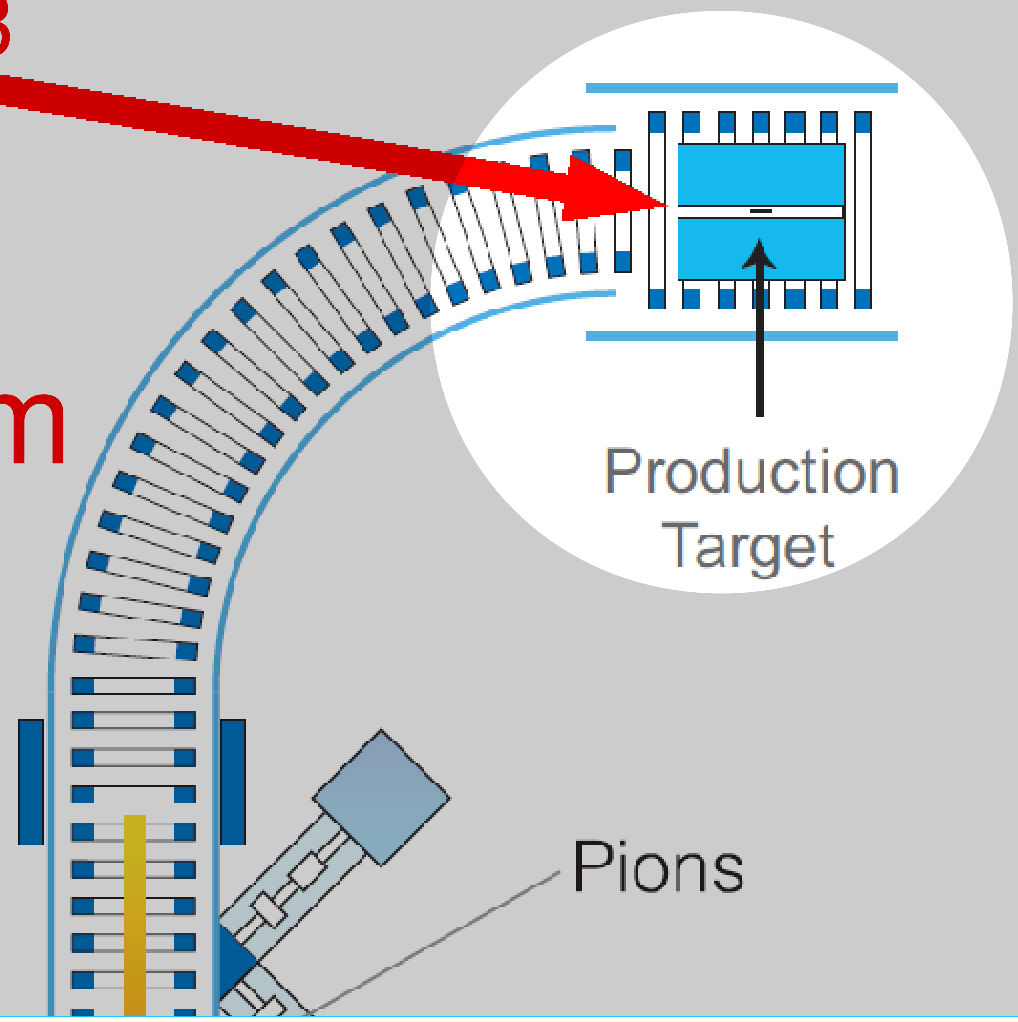
A 56kW, 8 GeV proton beam with **<10^{-9} extinction** between slow-extracted bunches

Bunch separation 1.3μs

6.4×10^{13} protons per spill, in 5.3×10^{5} bunches over 0.7s

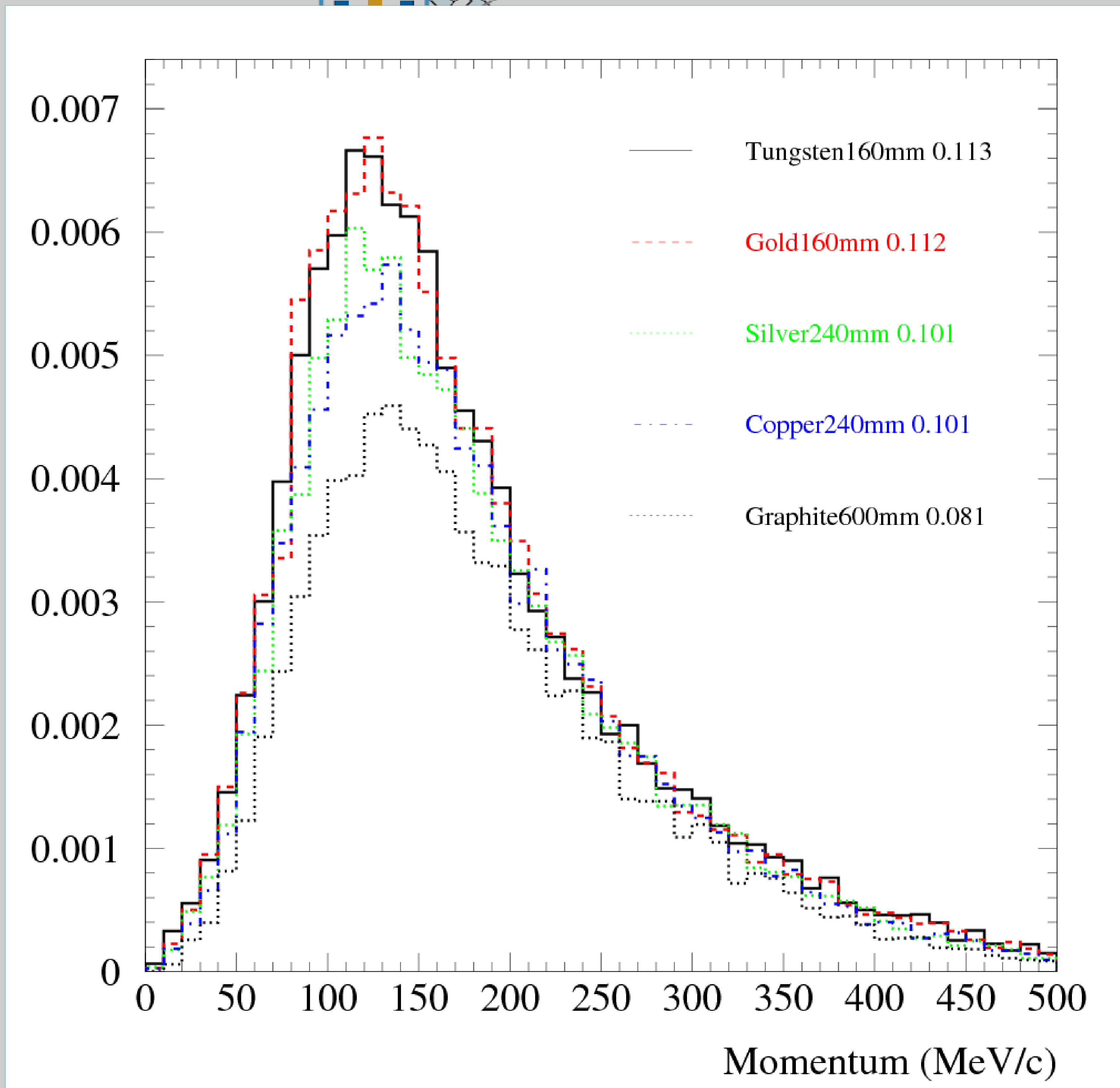


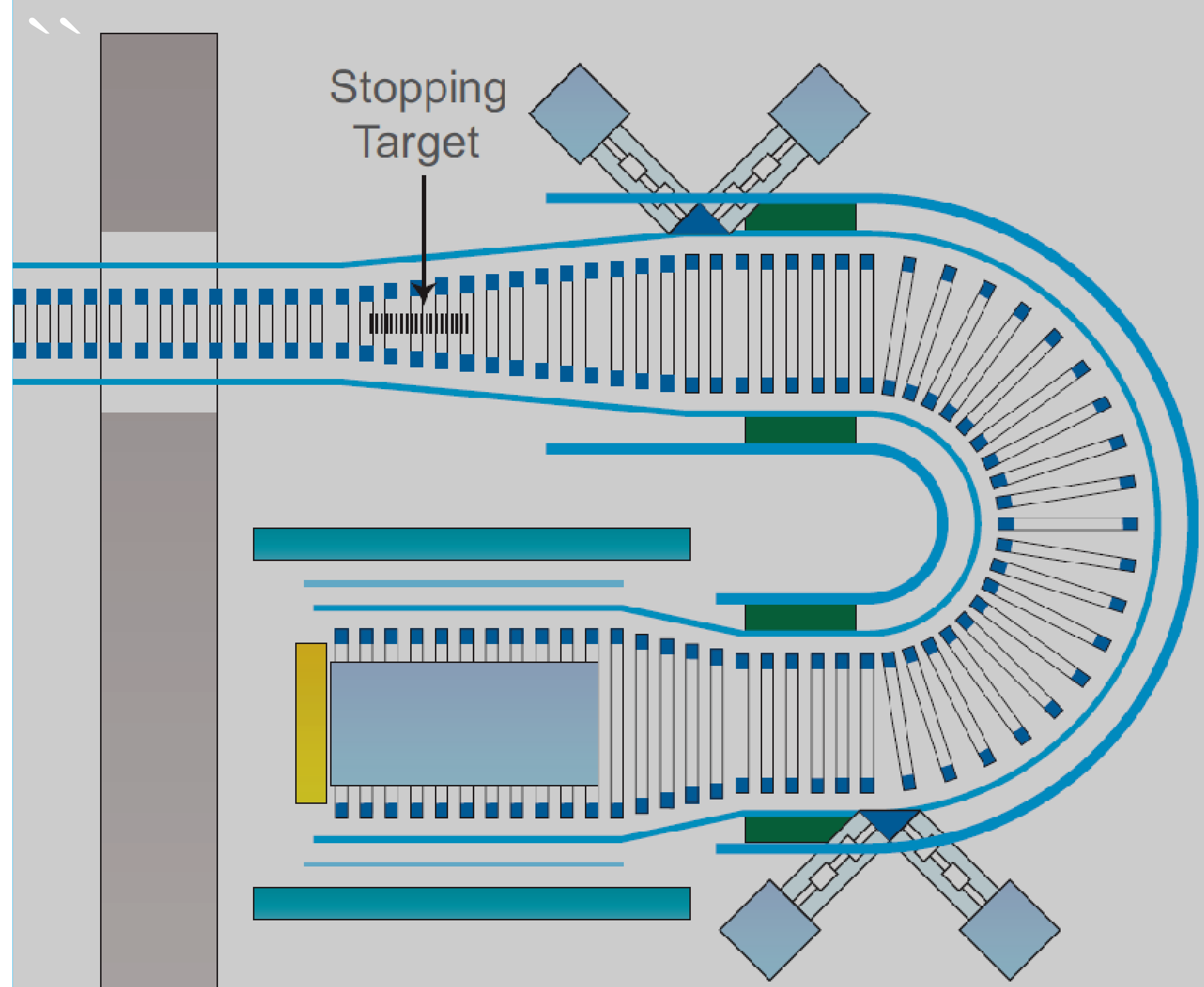
6.4×10^{13} 8 GeV protons per beam spill



A few $\times10^{12}$ pions produced per spill (some physics uncertainty)

lower-energy, backward pions captured and sent to transfer solenoid

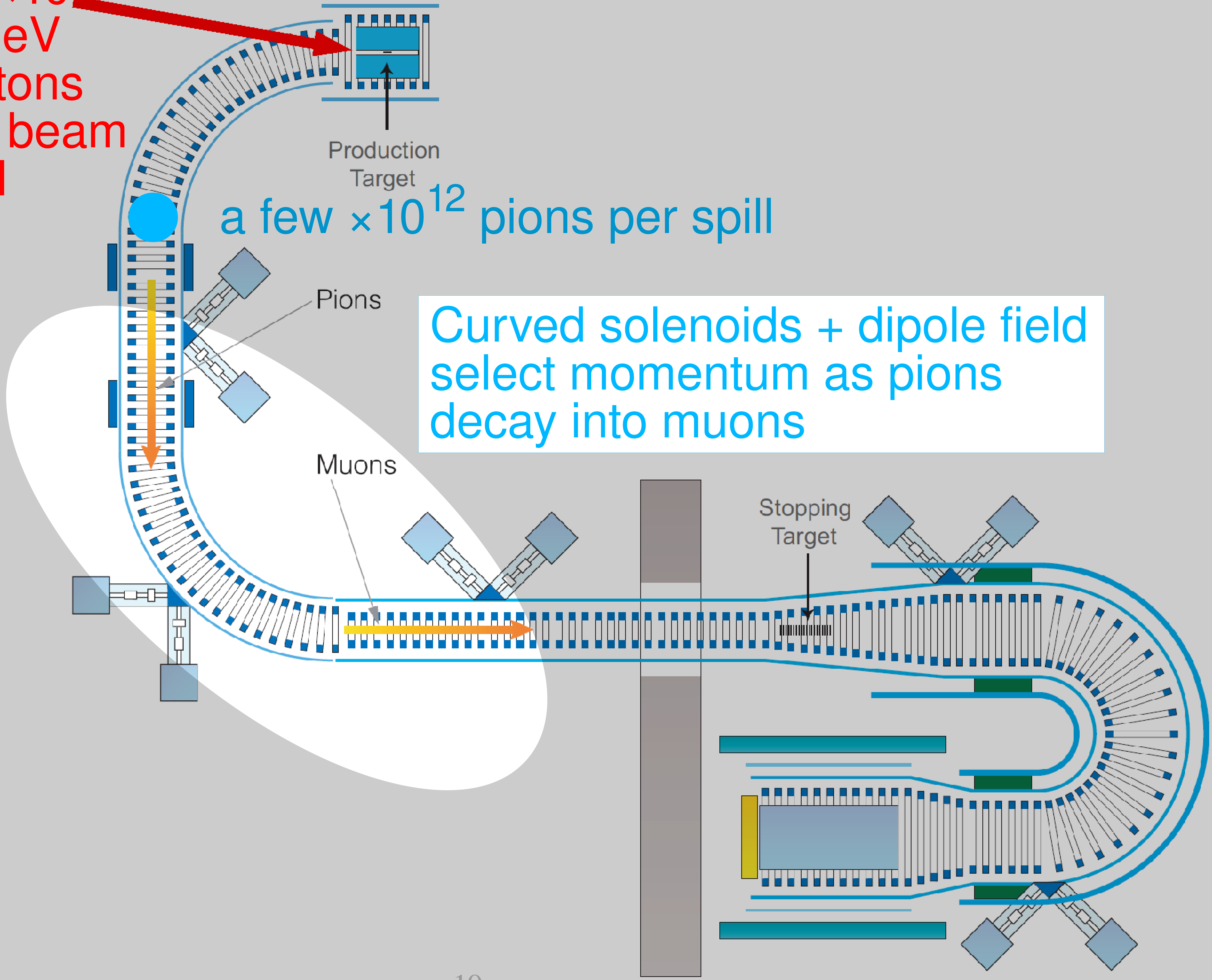


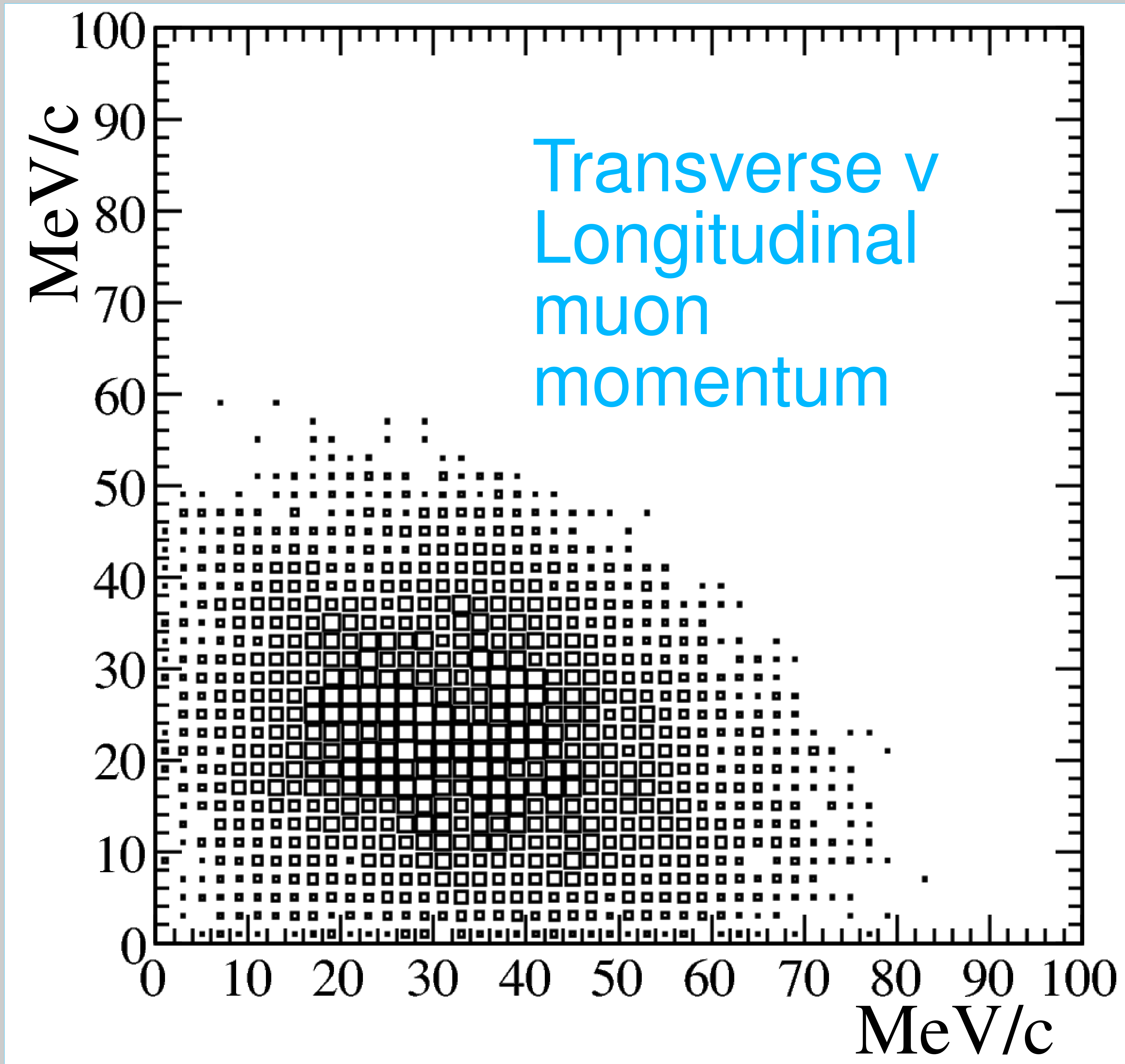


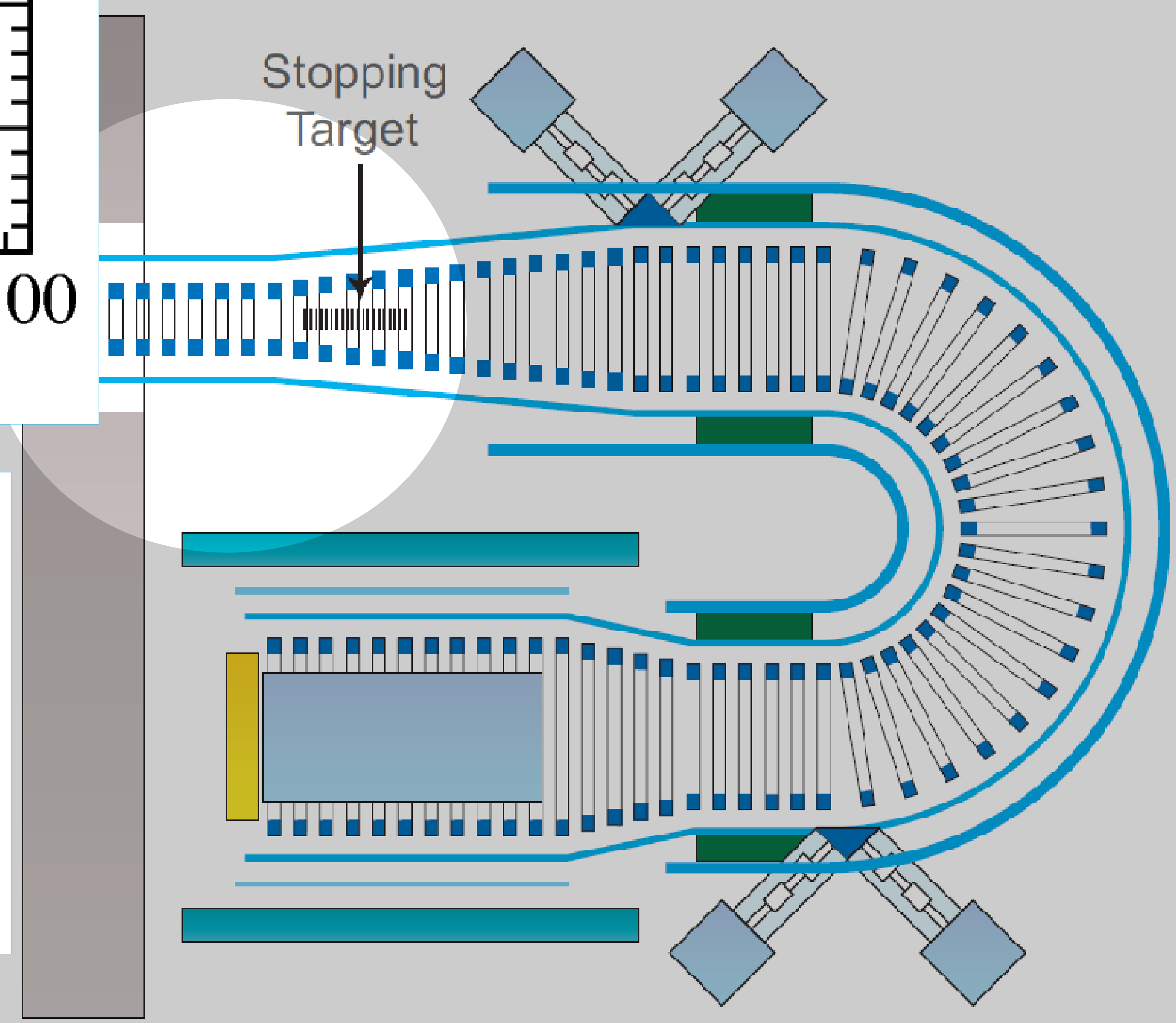
6.4×10^13
8 GeV
protons
per beam
spill

a few ×10^12 pions per spill

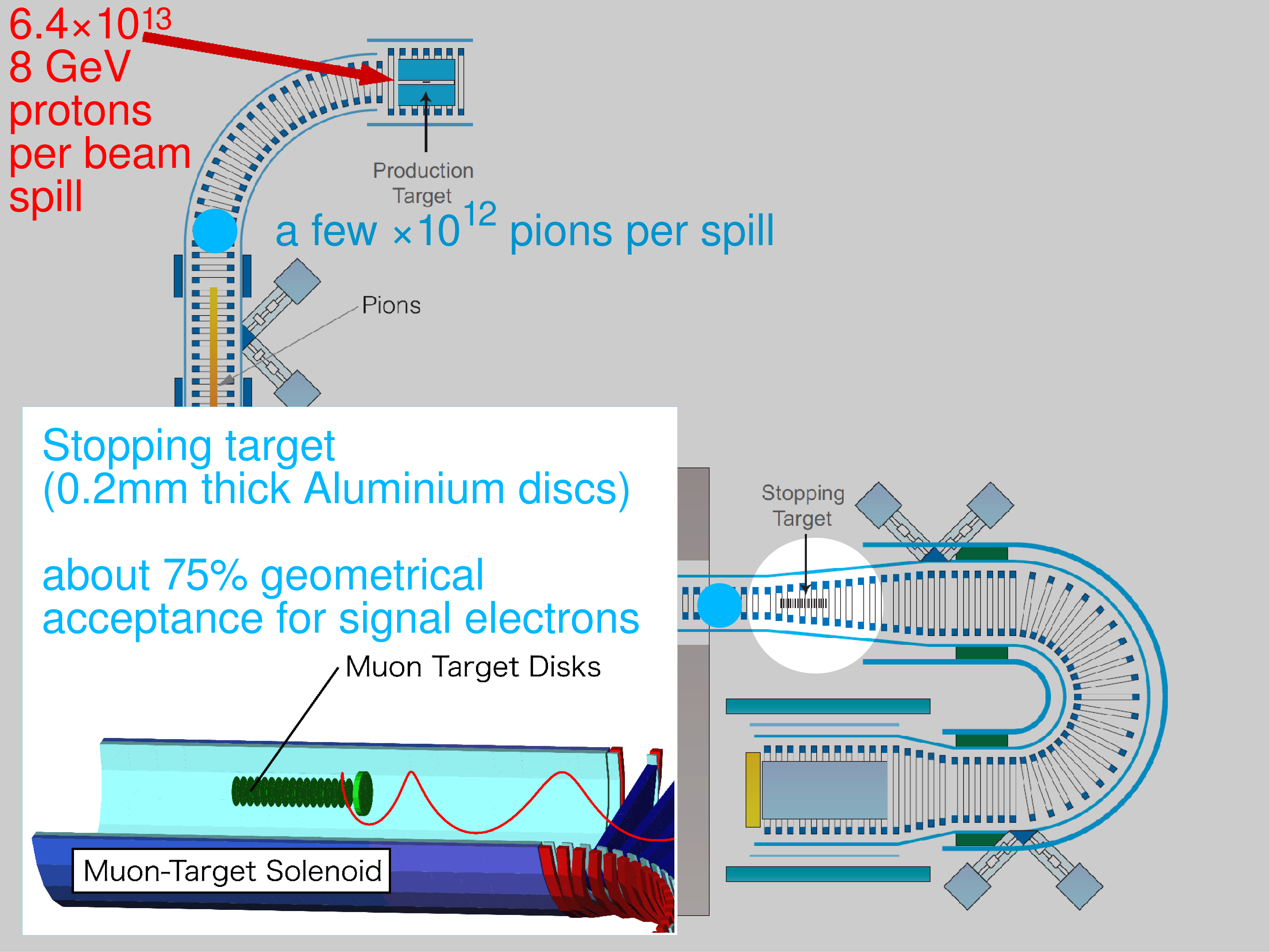
Curved solenoids + dipole field select momentum as pions decay into muons







10^{10} to 10^{11} muons
below 85 MeV/c arrive at
stopping target per spill
(current best is 10^8/sec at PSI)



6.4×10^13
8 GeV
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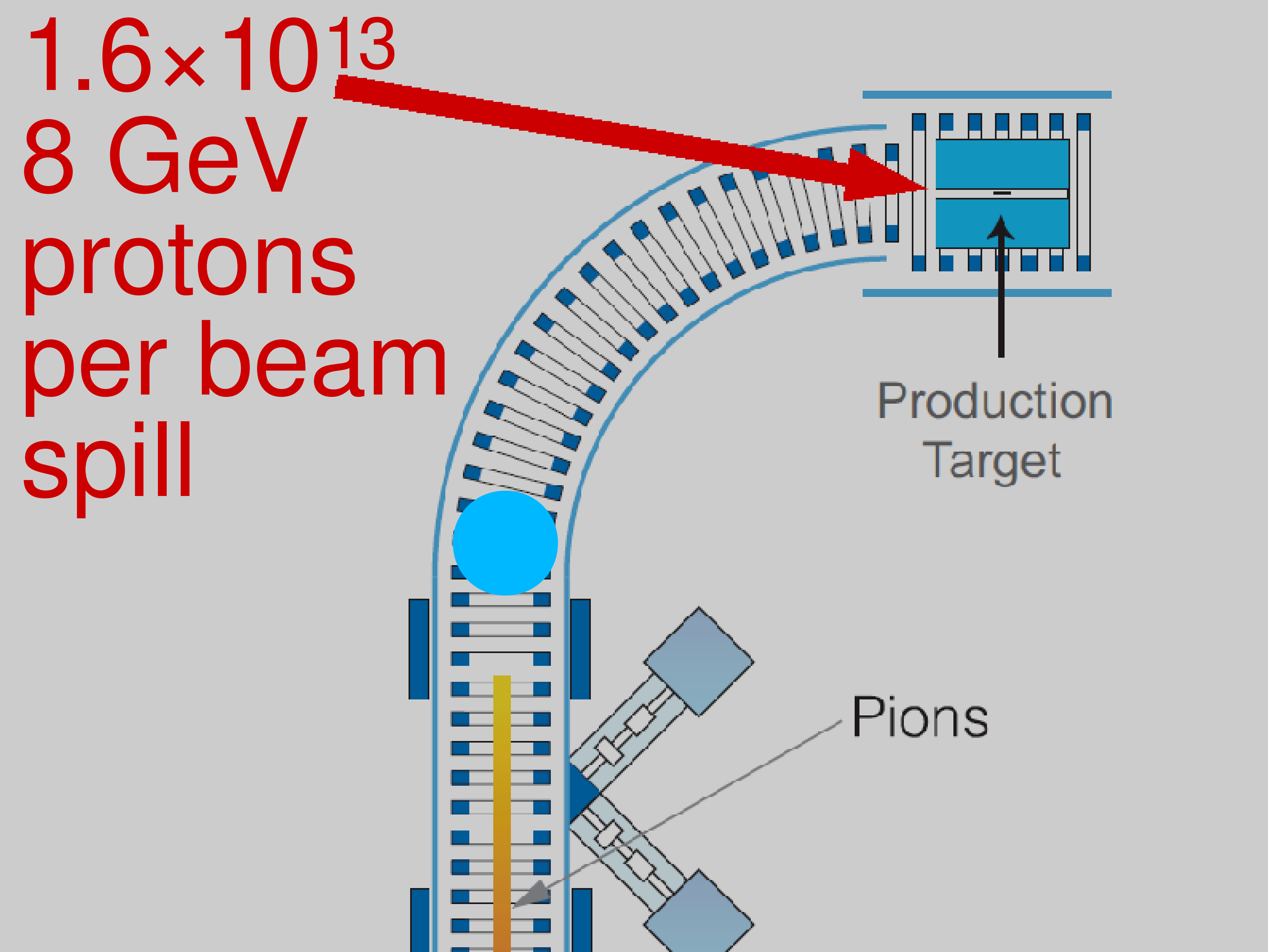
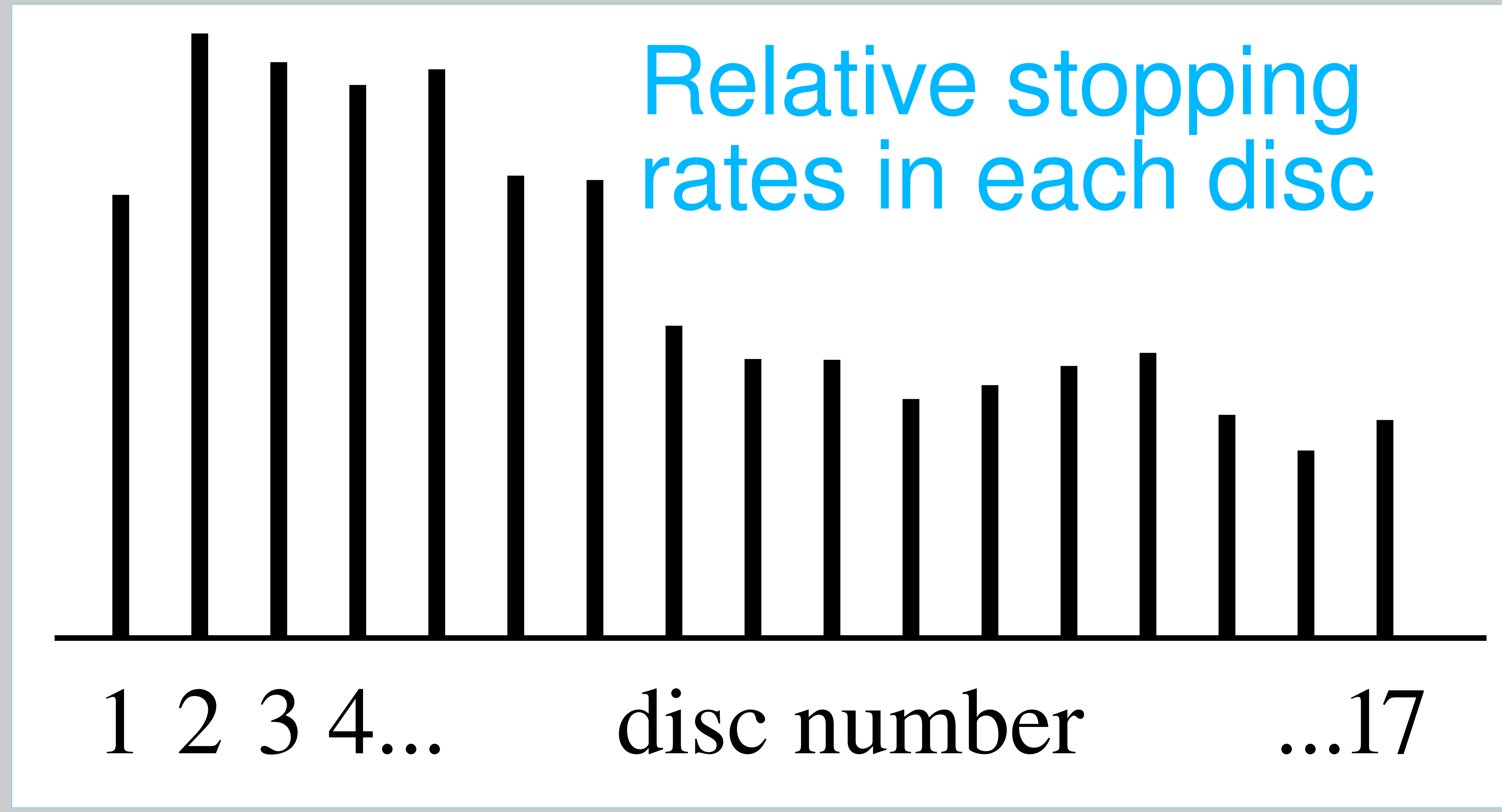
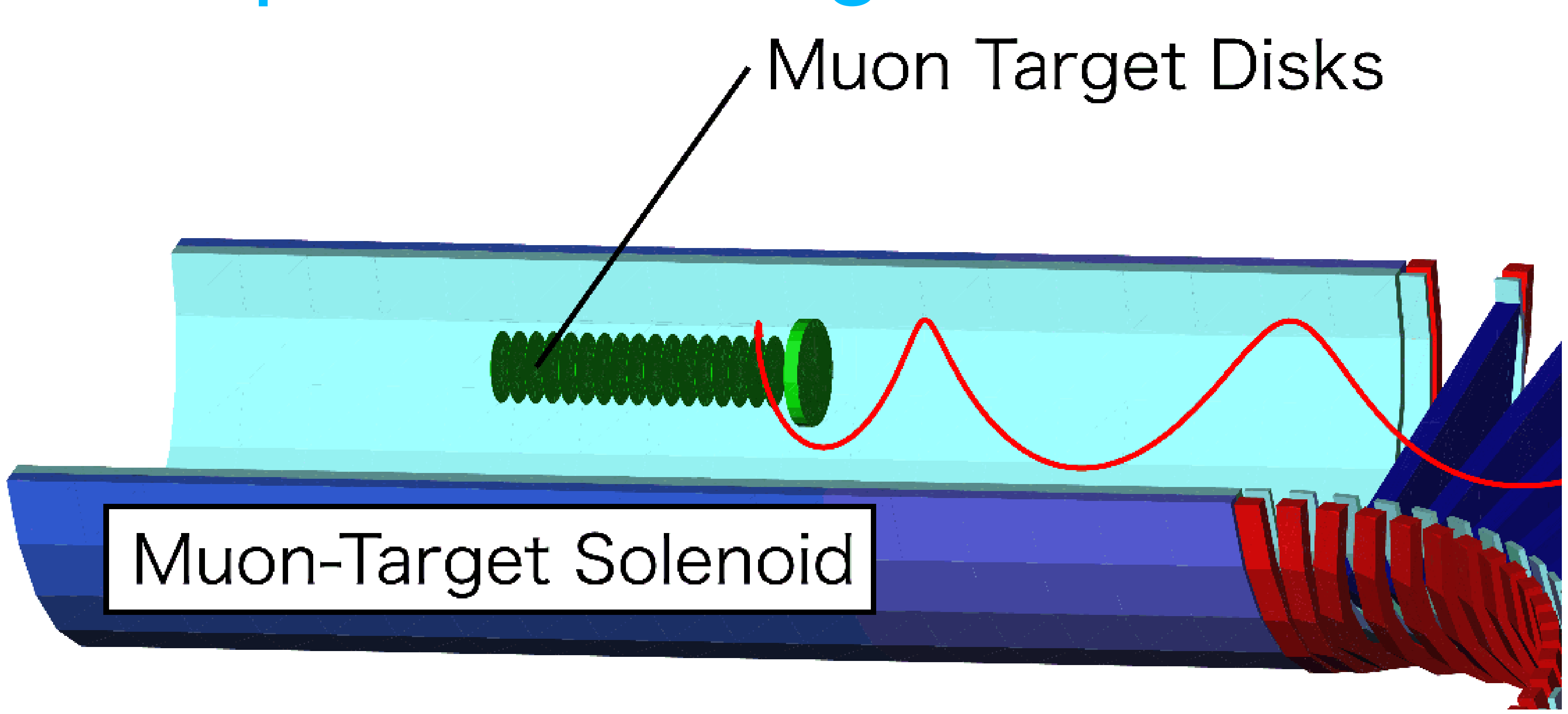
Production
Target
a few ×10^12 pions per spill
Pions
Stopping target
(0.2mm thick Aluminium discs)
about 75% geometrical
acceptance for signal electrons
Muon Target Disks
Muon-Target Solenoid
Stopping
Target

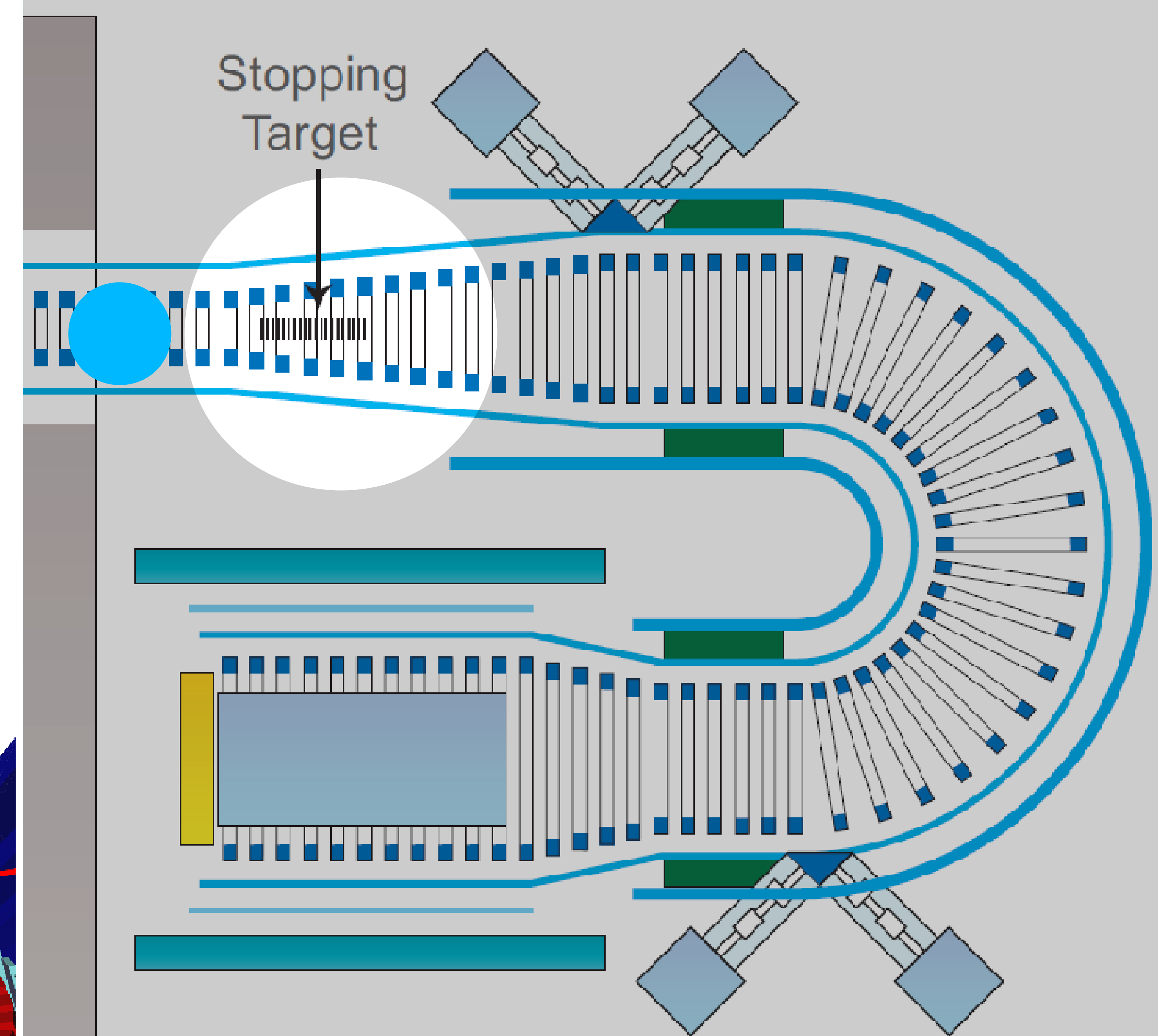


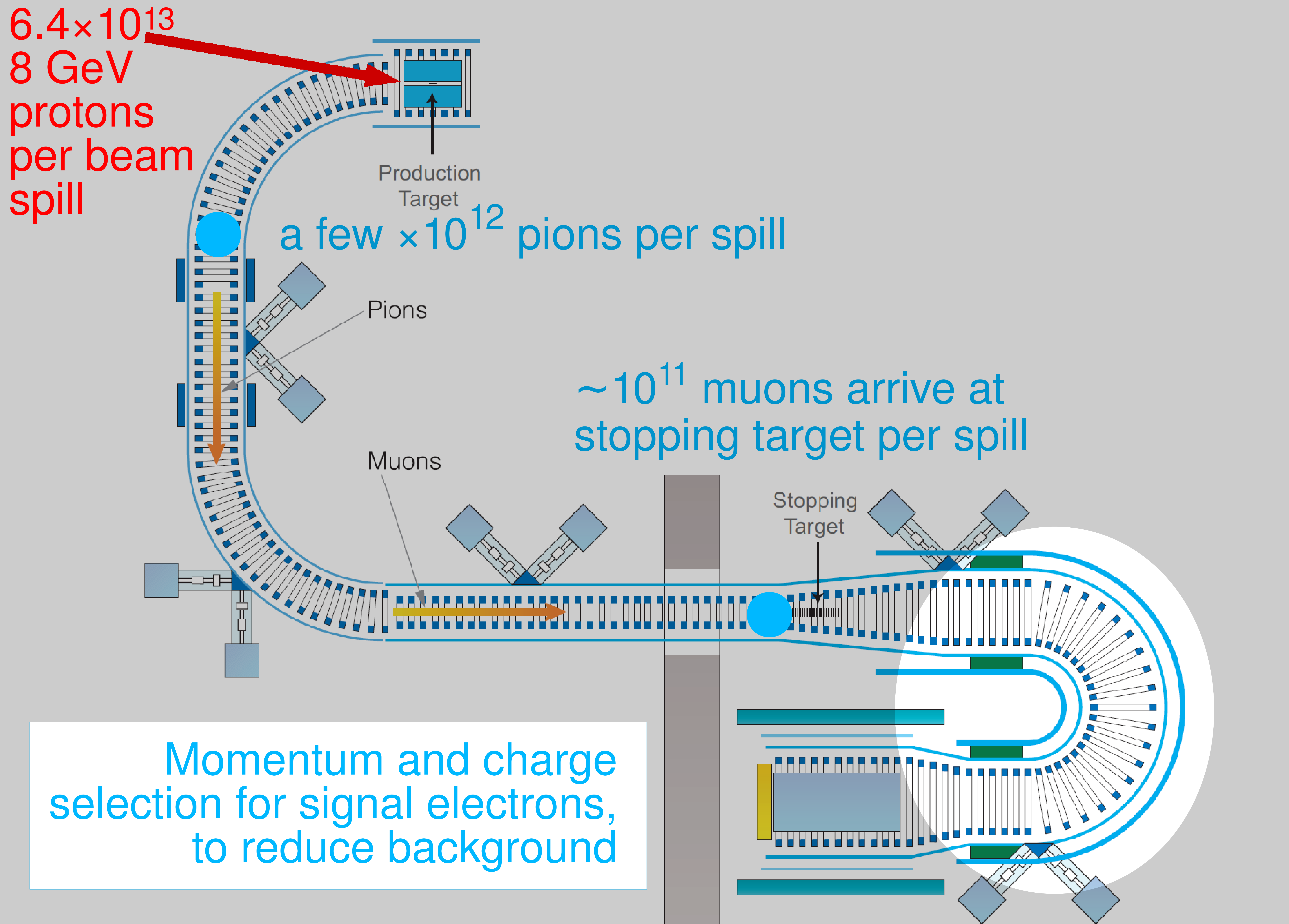


Stopping target
(0.2mm thick Aluminium discs)

about 75% geometrical
acceptance for signal electrons



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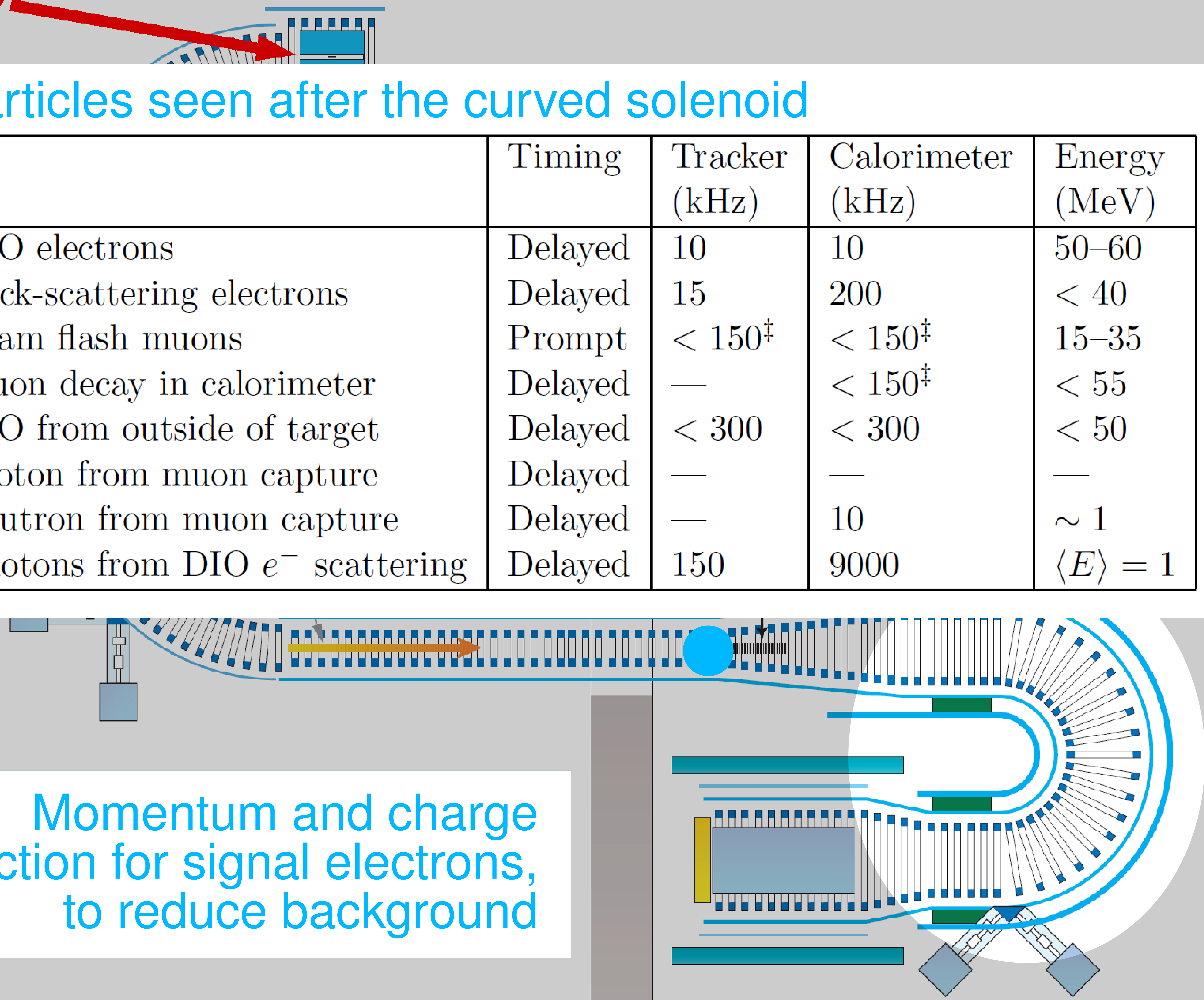
Muons
Stopping
Target
Momentum and charge
selection for signal electrons,
to reduce background

6.4×10^{13}
8 GeV
pro
per
spi

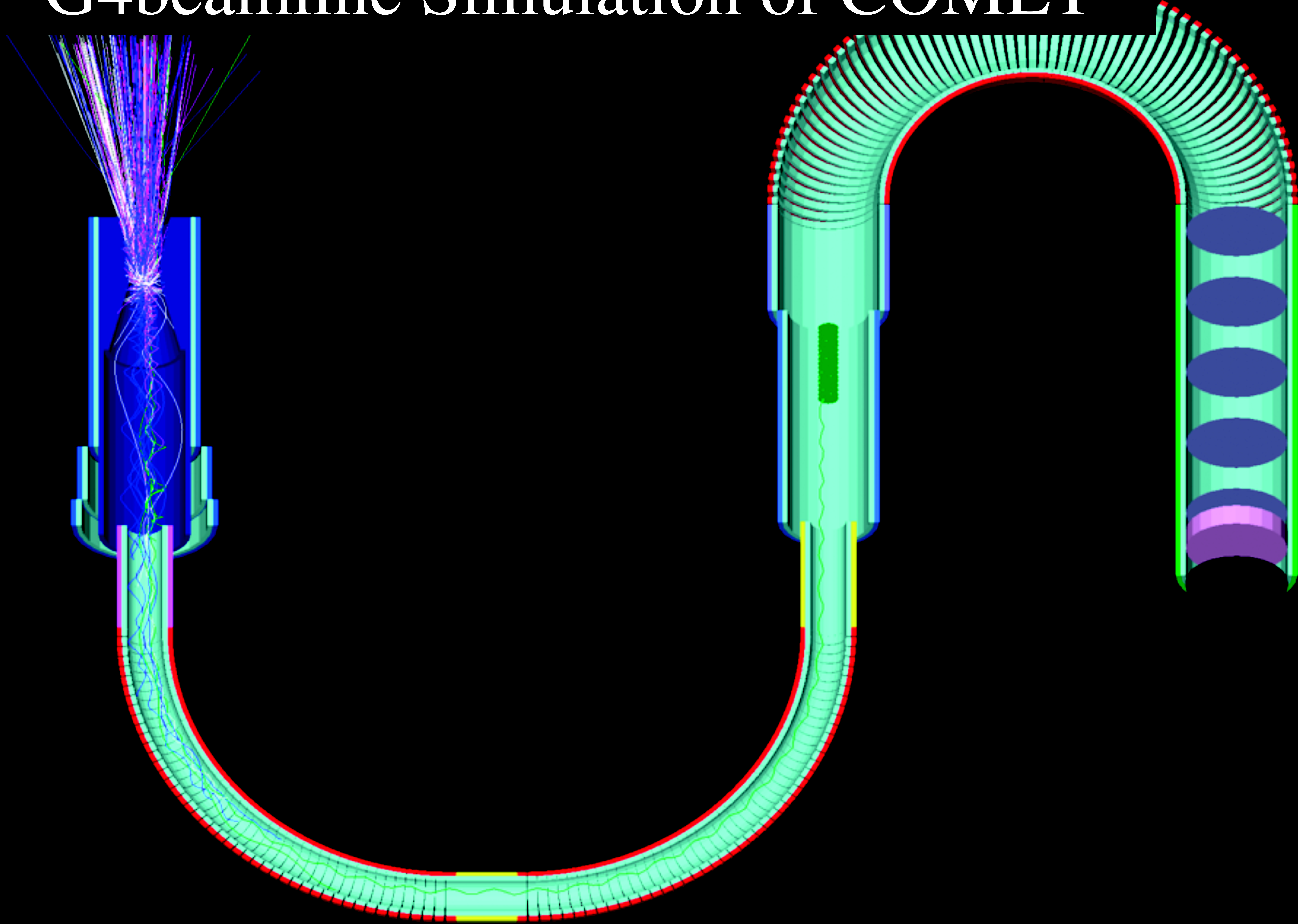
Particles seen after the curved solenoid

	Timing	Tracker (kHz)	Calorimeter (kHz)	Energy (MeV)
DIO electrons	Delayed	10	10	50–60
Back-scattering electrons	Delayed	15	200	< 40
Beam flash muons	Prompt	$< 150^{\ddagger}$	$< 150^{\ddagger}$	15–35
Muon decay in calorimeter	Delayed	—	$< 150^{\ddagger}$	< 55
DIO from outside of target	Delayed	< 300	< 300	< 50
Proton from muon capture	Delayed	—	—	—
Neutron from muon capture	Delayed	—	10	~ 1
Photons from DIO e^{-} scattering	Delayed	150	9000	$\langle E \rangle = 1$

Momentum and charge selection for signal electrons, to reduce background

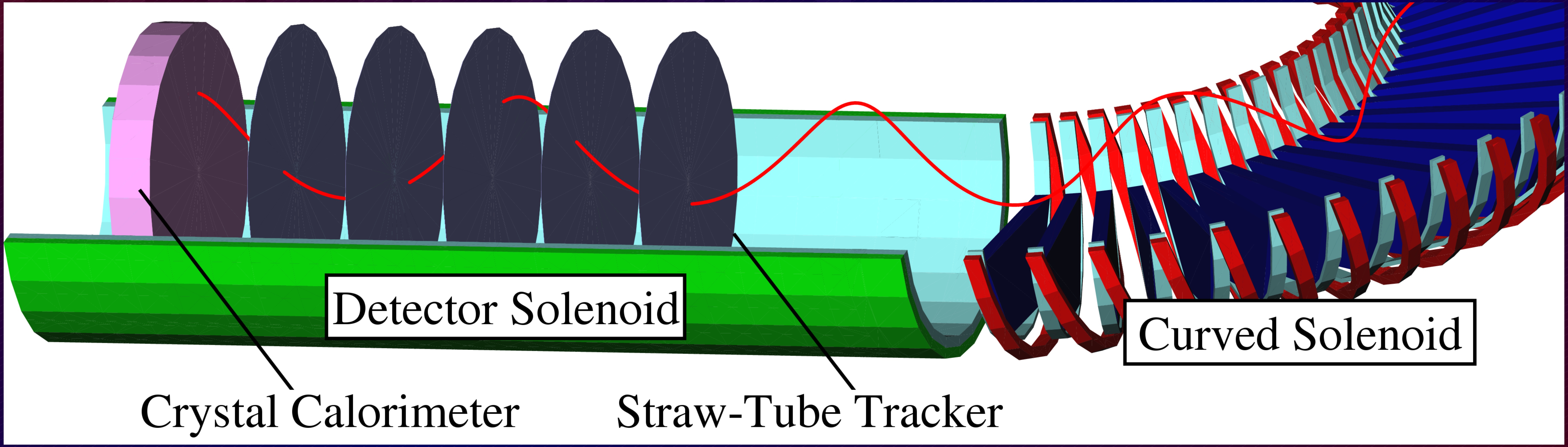


G4beamline Simulation of COMET



COMET Detector Section

- Straw-tube electron tracker in 1 Tesla field
  - 800 kHz charged particle and 8 MHz gamma rates
  - 0.4% momentum and 700 micron spatial resolution required

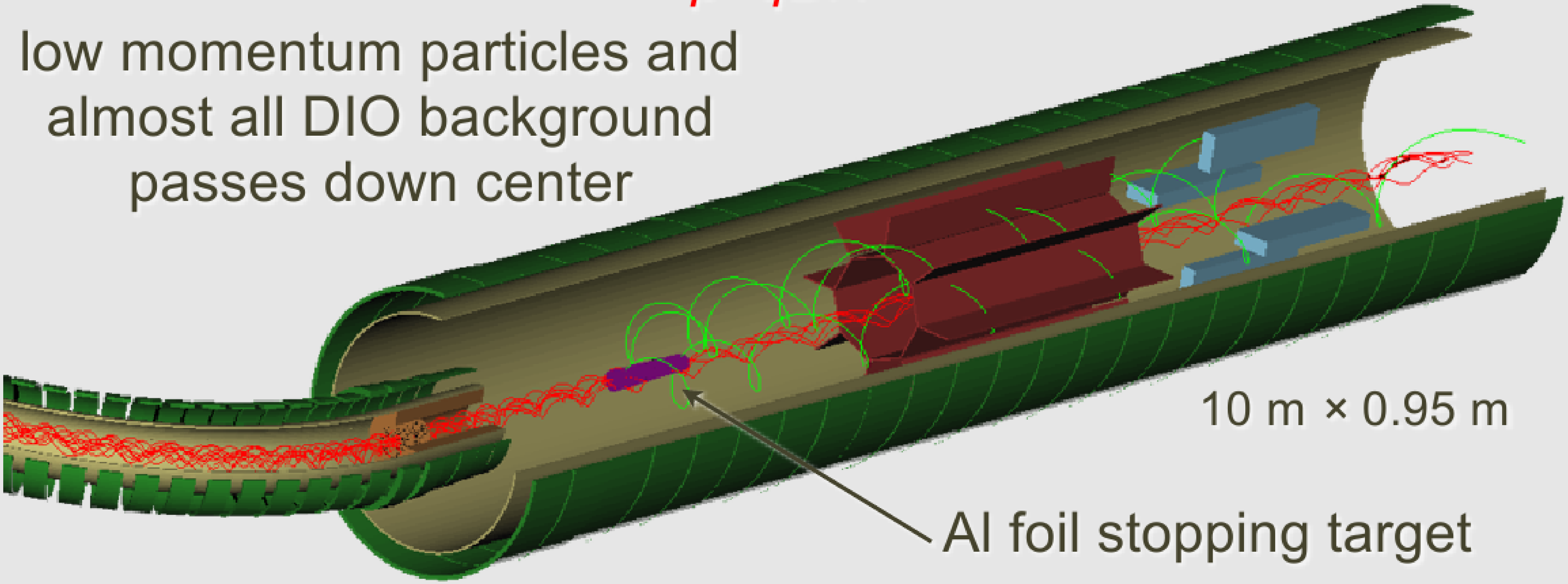


- Crystal calorimeter
  - for energy and position measurement, PID, trigger signal
  - 5% energy and 1cm spatial resolution at 100 MeV
  - eg. 1cm square GSO crystals with MPPC readout

Detector Solenoid

octagonal tracker surrounding central region: radius of helix proportional to momentum, p=qBR

low momentum particles and almost all DIO background passes down center



10 m × 0.95 m

Al foil stopping target

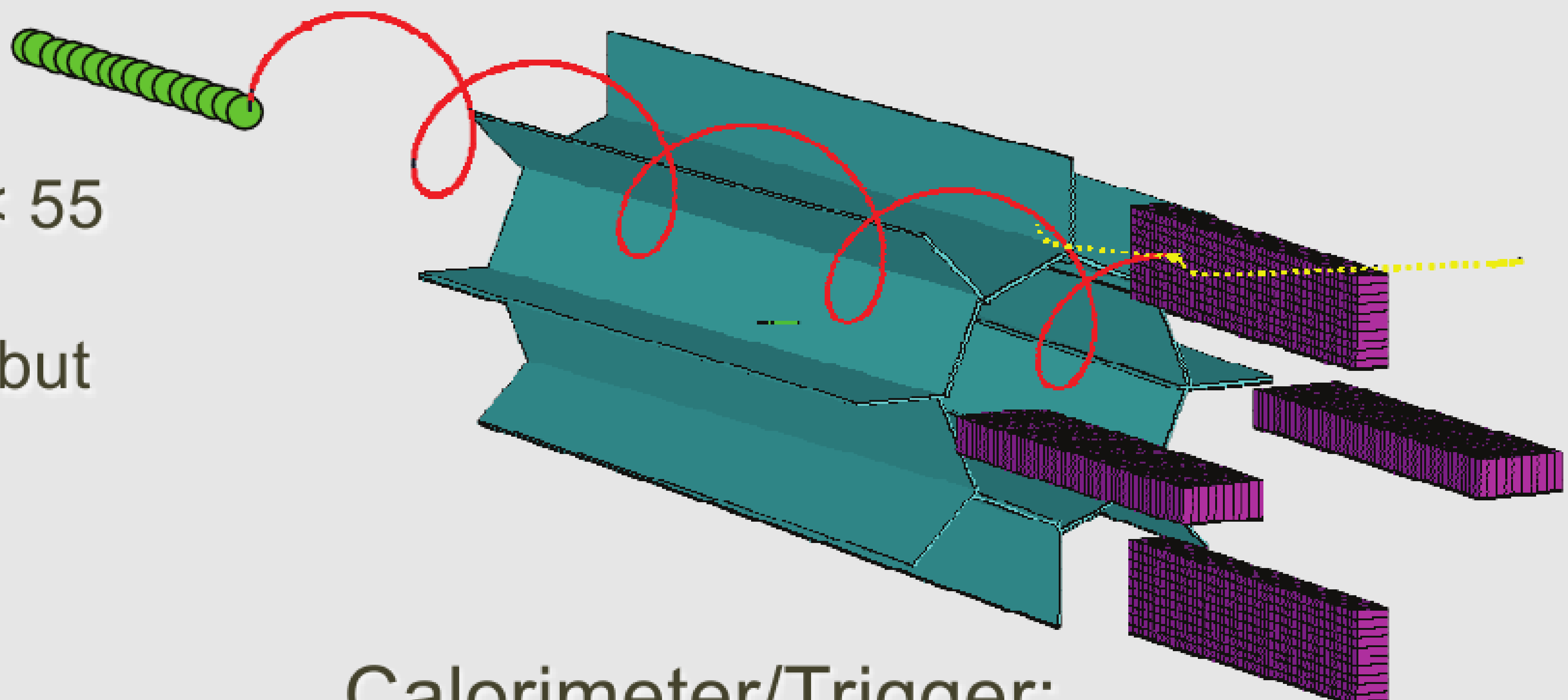
signal events pass *through* octagon of tracker and produce hits

Detector

- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field, so particle follows near-helical path
- Particles with $p_T < 55$ MeV do not pass through detector, but down the center
- Followed by Calorimeter

$\sigma = 200\ \mu$ transverse, 1.5 mm axially

2800 axial straw tubes, 2.6 m by 5 mm, 25μ thick

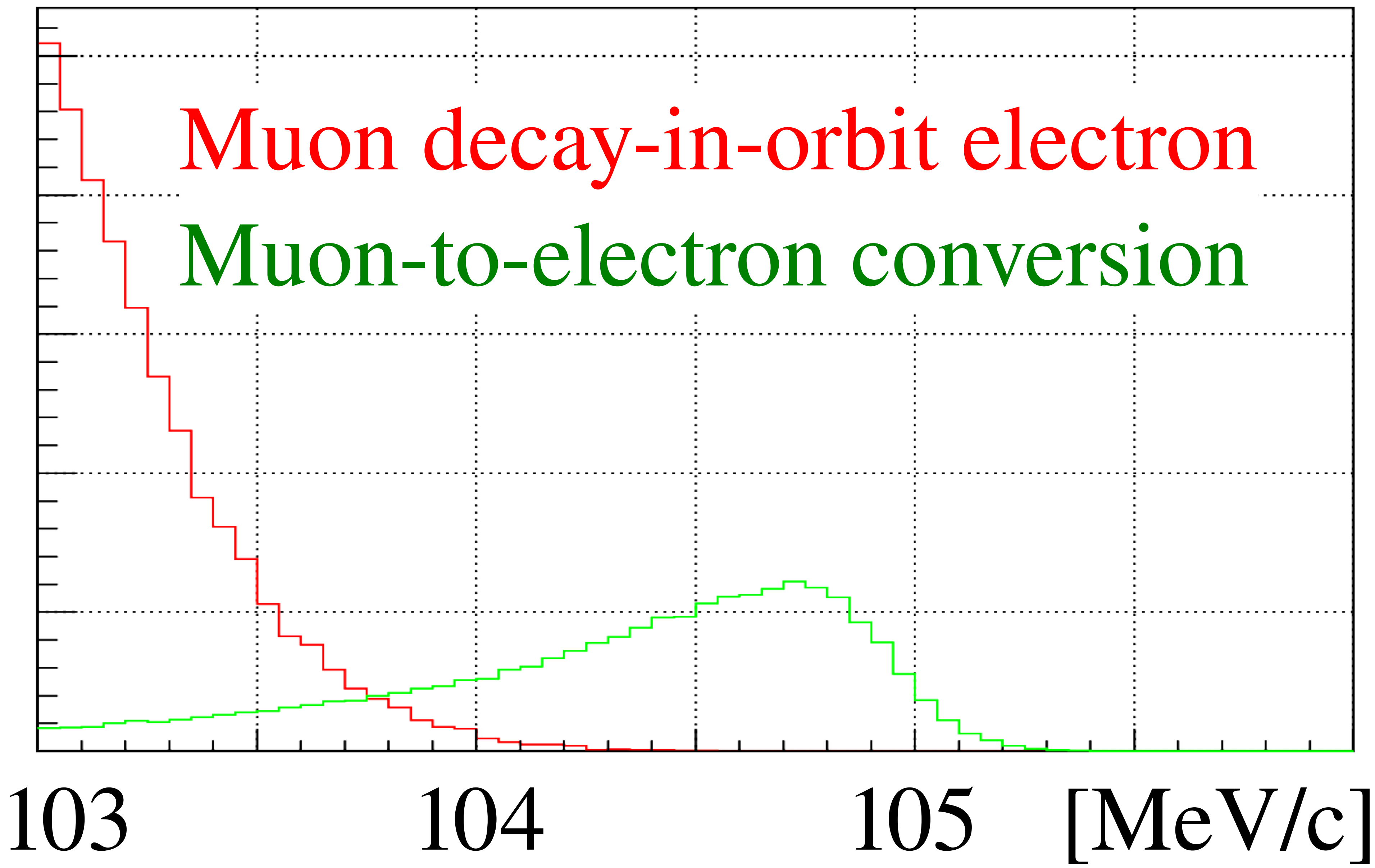


Calorimeter/Trigger:

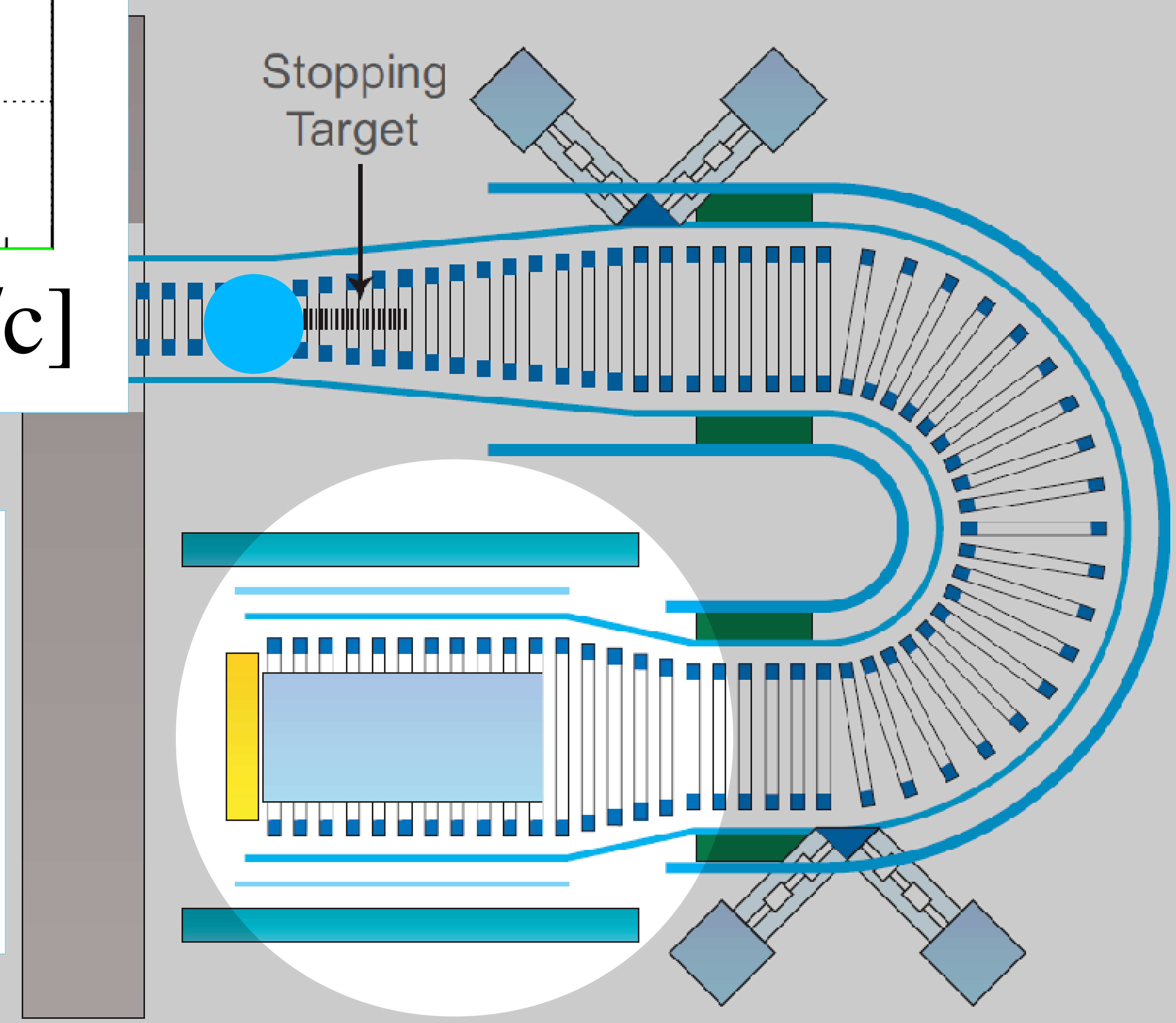
$\sigma / E = 5\%$, 1024 $3.5 \times 3.5 \times 12$ cm $PbWO_4$

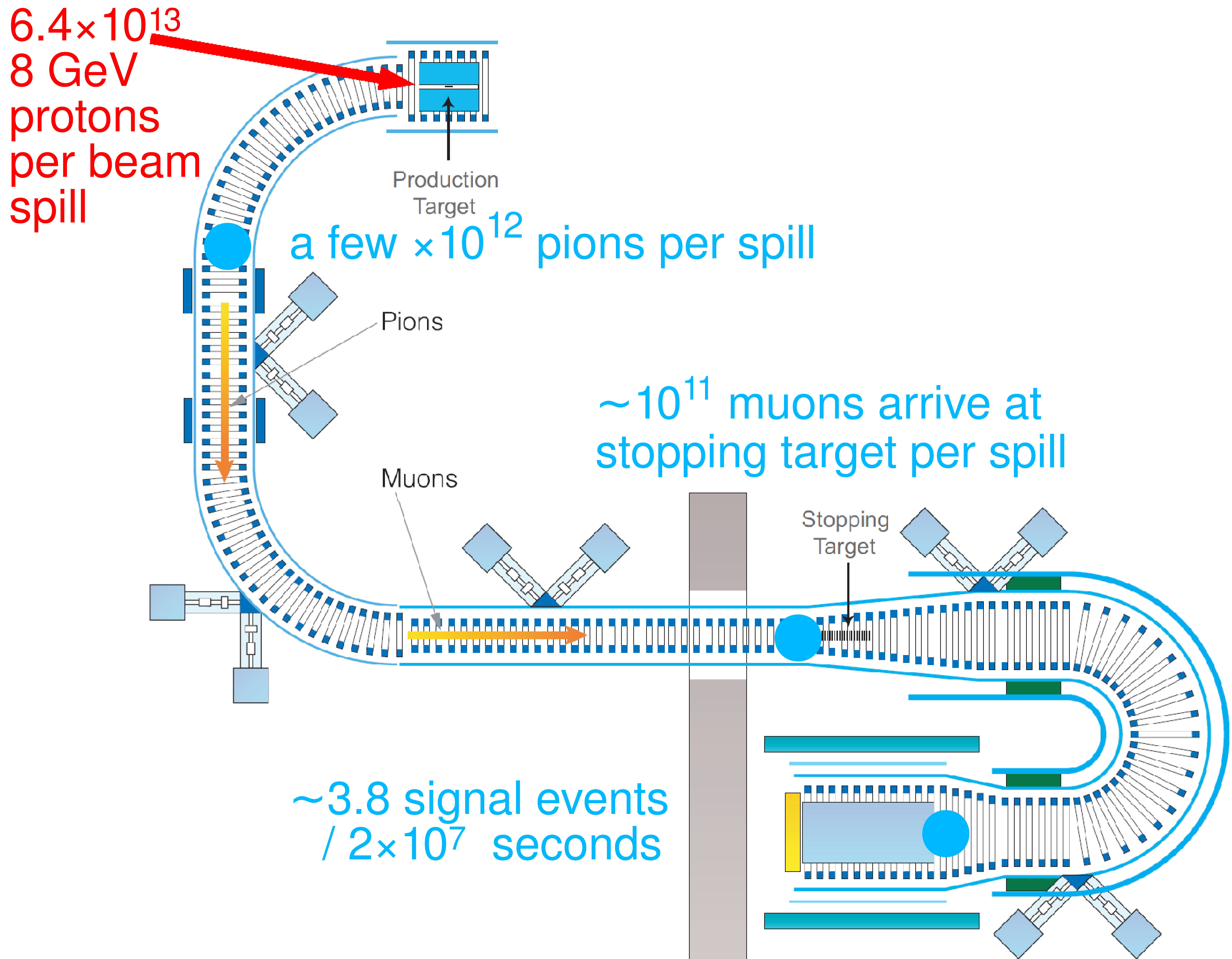
6.4×10^13

Relative signal and background spectra for branching ratio of 10^{-16} statistics ×100 (including energy loss and tracker resolution)



Tracking detector for momentum measurement, calorimeter for energy and triggering redundancy



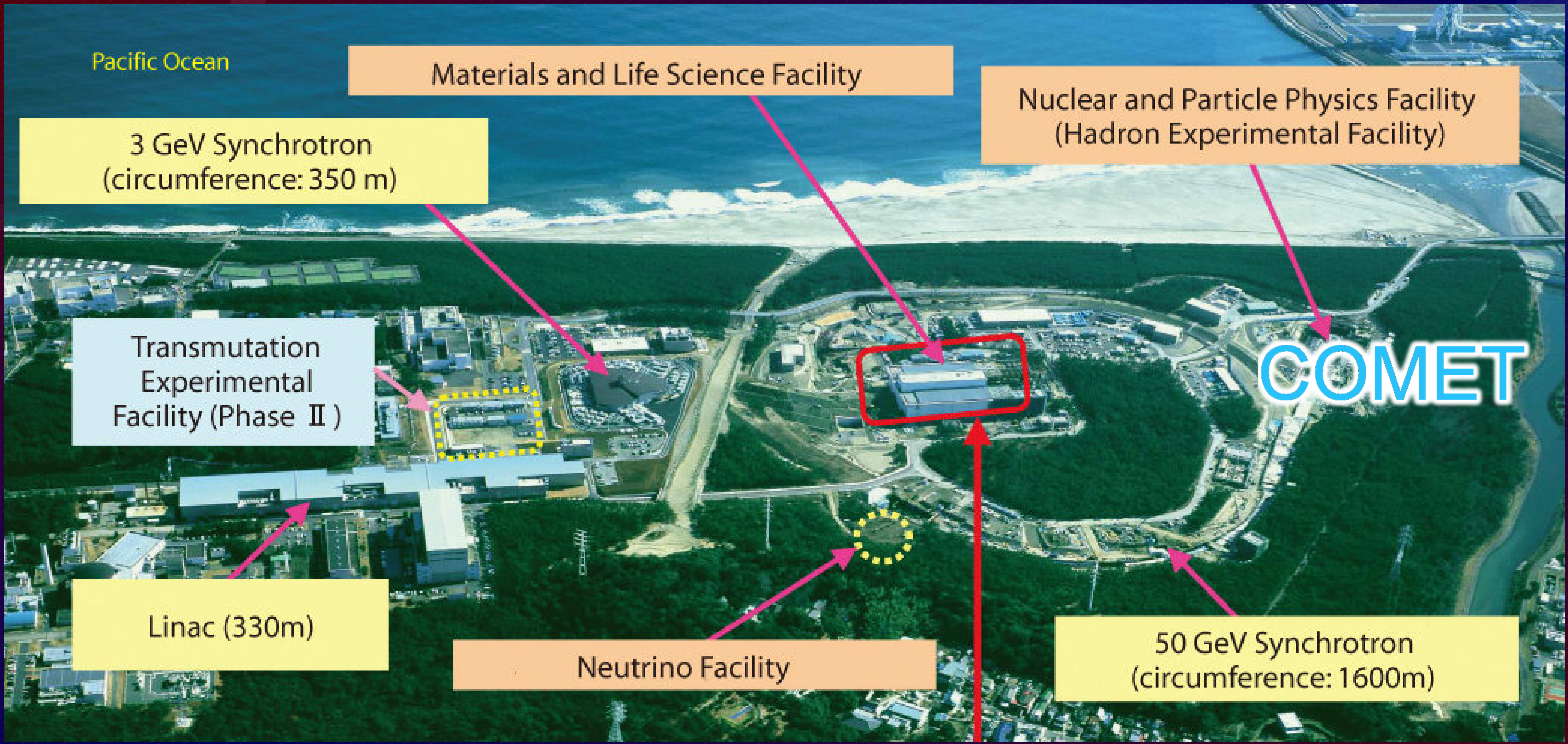


6.4×10^13
8 GeV
protons
per beam
spill
Production
Target
a few ×10^12 pions per spill
Pions
~10^11 muons arrive at
stopping target per spill
Muons
Stopping
Target
~3.8 signal events
/ 2×10^7 seconds

Background Breakdown from COMET CDR (July 2009)

Radiative Pion Capture	0.05
Beam Electrons	$< 0.1^{\ddagger}$
Muon Decay in Flight	< 0.0002
Pion Decay in Flight	< 0.0001
Neutron Induced	0.024
Delayed-Pion Radiative Capture	0.002
Anti-proton Induced	0.007
Muon Decay in Orbit	0.15
Radiative Muon Capture	< 0.001
μ^- Capt. w/ n Emission	< 0.001
μ^- Capt. w/ Charged Part. Emission	< 0.001
Cosmic Ray Muons	0.002
Electrons from Cosmic Ray Muons	0.002
Total	0.34

J-PARC



Pacific Ocean
Materials and Life Science Facility
Nuclear and Particle Physics Facility
(Hadron Experimental Facility)
3 GeV Synchrotron
(circumference: 350 m)
Transmutation
Experimental
Facility (Phase Ⅱ)
COMET
Linac (330m)
Neutrino Facility
50 GeV Synchrotron
(circumference: 1600m)

Conceptual Design Report
for
Experimental Search for Lepton Flavor Violating $\mu^- - e^-$
Conversion at Sensitivity of 10^{-16}
with a Slow-Extracted Bunched Proton Beam
(COMET)

J-PARC P21

CDR submitted to
J-PARC PAC in June 2009

Stage-1 Approval (of two stages) granted July 2009
as a potential flagship experiment at J-PARC

Collaboration in process of growing

First data in 2016?

The COMET Collaboration

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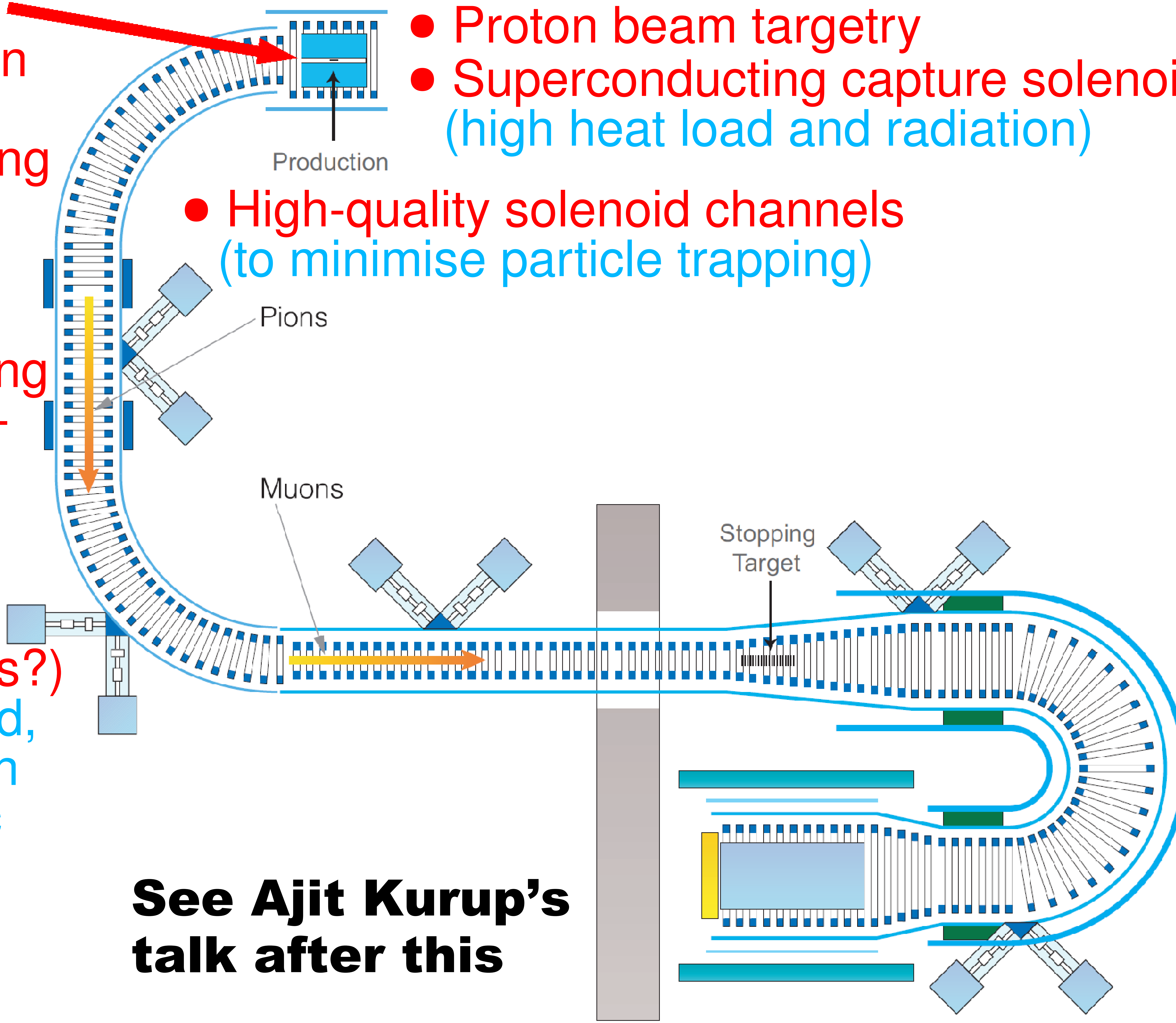
Available at http://www.hep.ph.ic.ac.uk/muec

- Beam extinction and monitoring

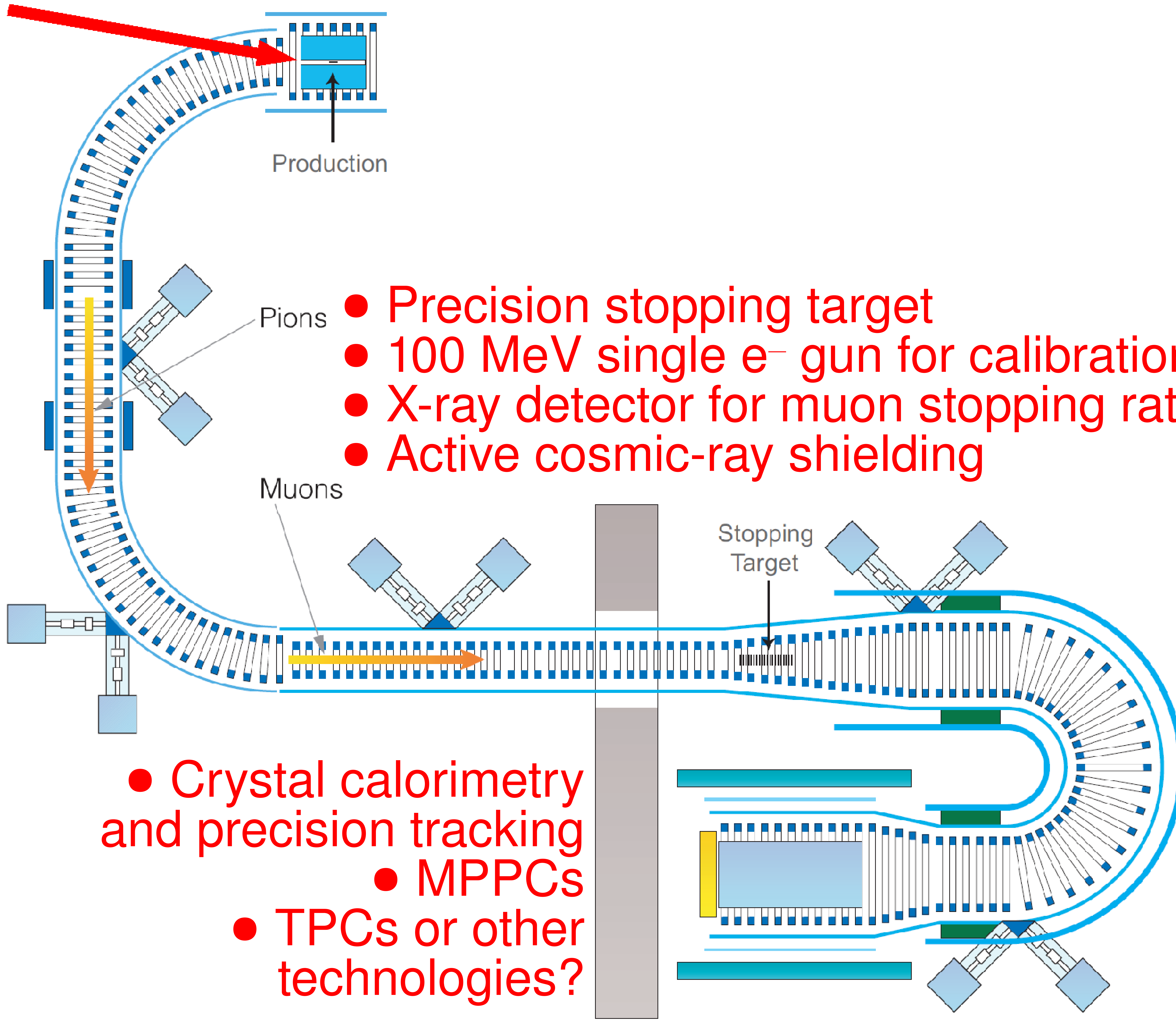
- Proton beam targetry
- Superconducting capture solenoid (high heat load and radiation)

- High-quality solenoid channels (to minimise particle trapping)

- Muon beam monitoring and late-arriving particle tagging (silicon detectors?) Rad-hard, very high dynamic ranges



See Ajit Kurup's talk after this

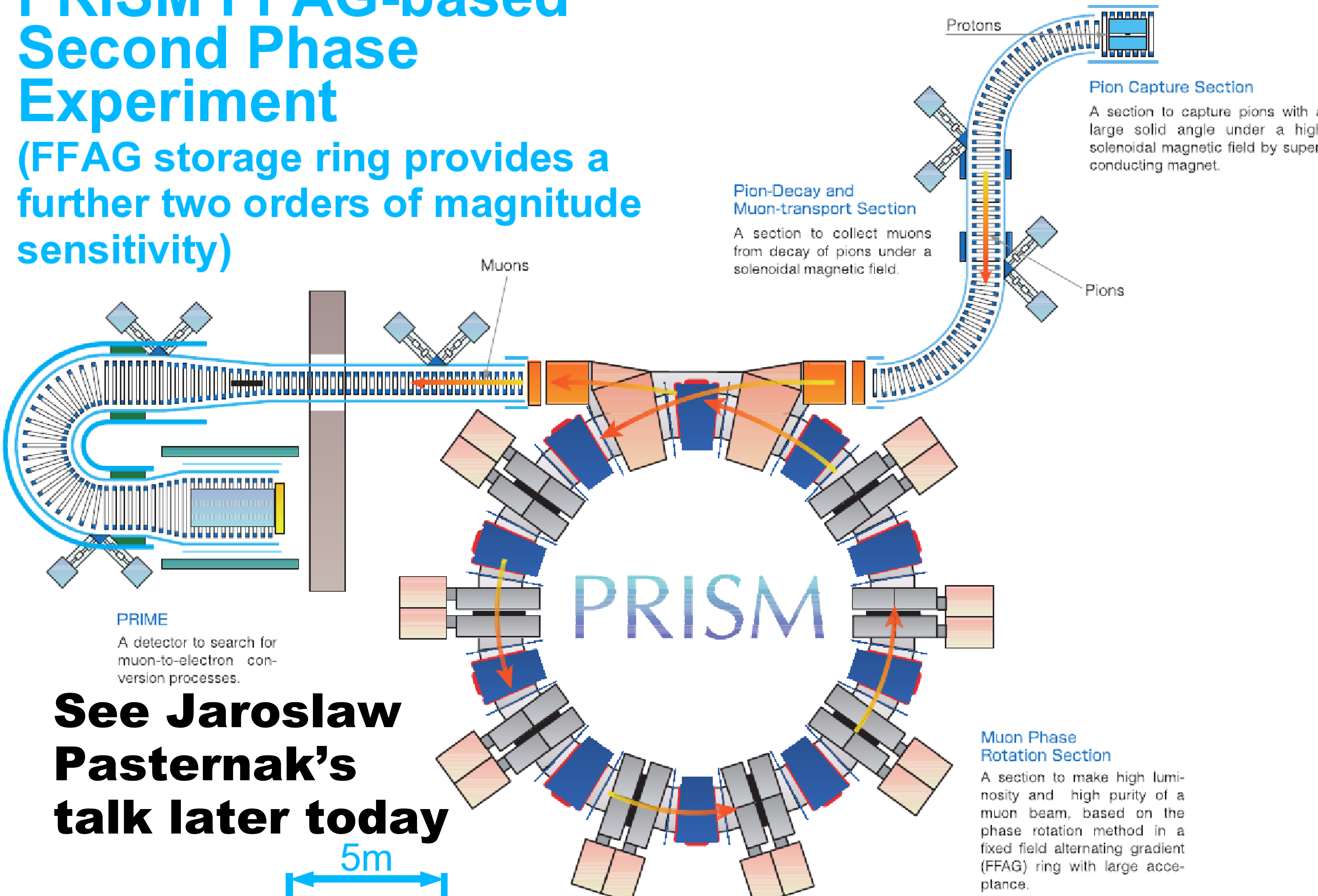


- Precision stopping target
- 100 MeV single e^- gun for calibration
- X-ray detector for muon stopping rate
- Active cosmic-ray shielding

- Crystal calorimetry and precision tracking
- MPPCs
- TPCs or other technologies?

PRISM FFAG-based Second Phase Experiment

(FFAG storage ring provides a further two orders of magnitude sensitivity)



See Jaroslaw Pasternak's talk later today

Conclusions

- Muon-to-Electron Conversion is a highly compelling physics process for Beyond-the-SM-&-Massive-Neutrinos physics
  - See Andre de Gouvea's theory talk
- Muon-to-Electron Conversion is also perfect as the next experimental step in Charged Lepton Flavour Violation Studies
- COMET and Mu2E are both feasible experiments that can push the sensitivity by 4 orders of magnitude (Stage-1 and CD-0 Approved)
- Neutrino Factory technologies and R&D allow this to be the case
  - See talks by Ajit Kurup (pion production and beamline), Jaroslaw Pasternak (PRISM FFAG) and Yoshi Kuno (NF synergies)
- Working hard now towards first data in 2015 / 2016....


Comet
California
CPFC