Imperial College London

THE ROYAL SOCIETY

Intense Muon Technologies for Probing LHC- and GUT-Scale Physics

— COMET/PRISM and other techniques —

Yoshi Uchida

Imperial College London

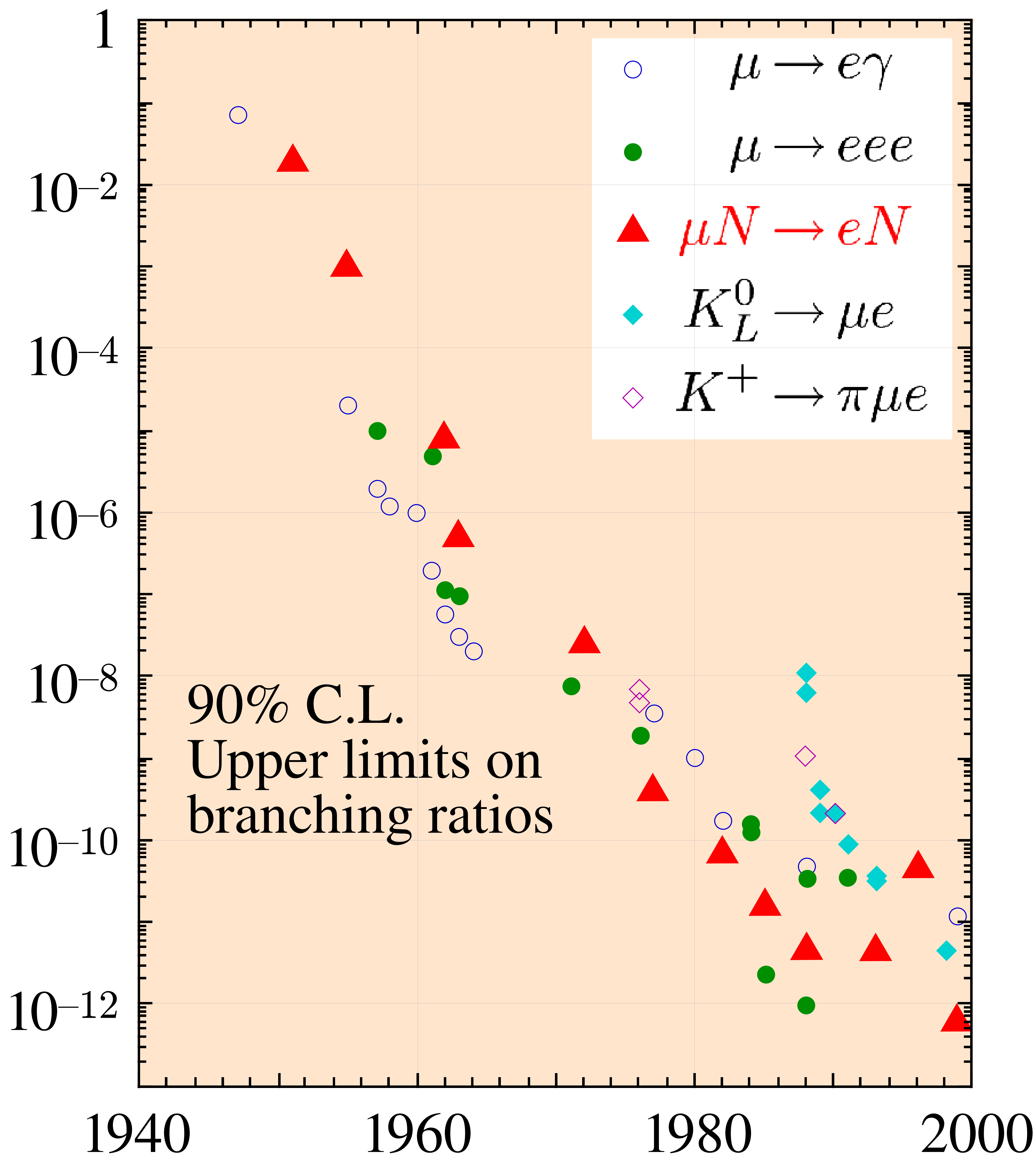
THE ROYAL SOCIETY

Intense Muon Technologies for Probing LHC- and GUT-Scale Physics

Please see other talks at this meeting for physics background and motivation!

Yoshi Uchida

Historical Progress on Charged Lepton Flavour Violation



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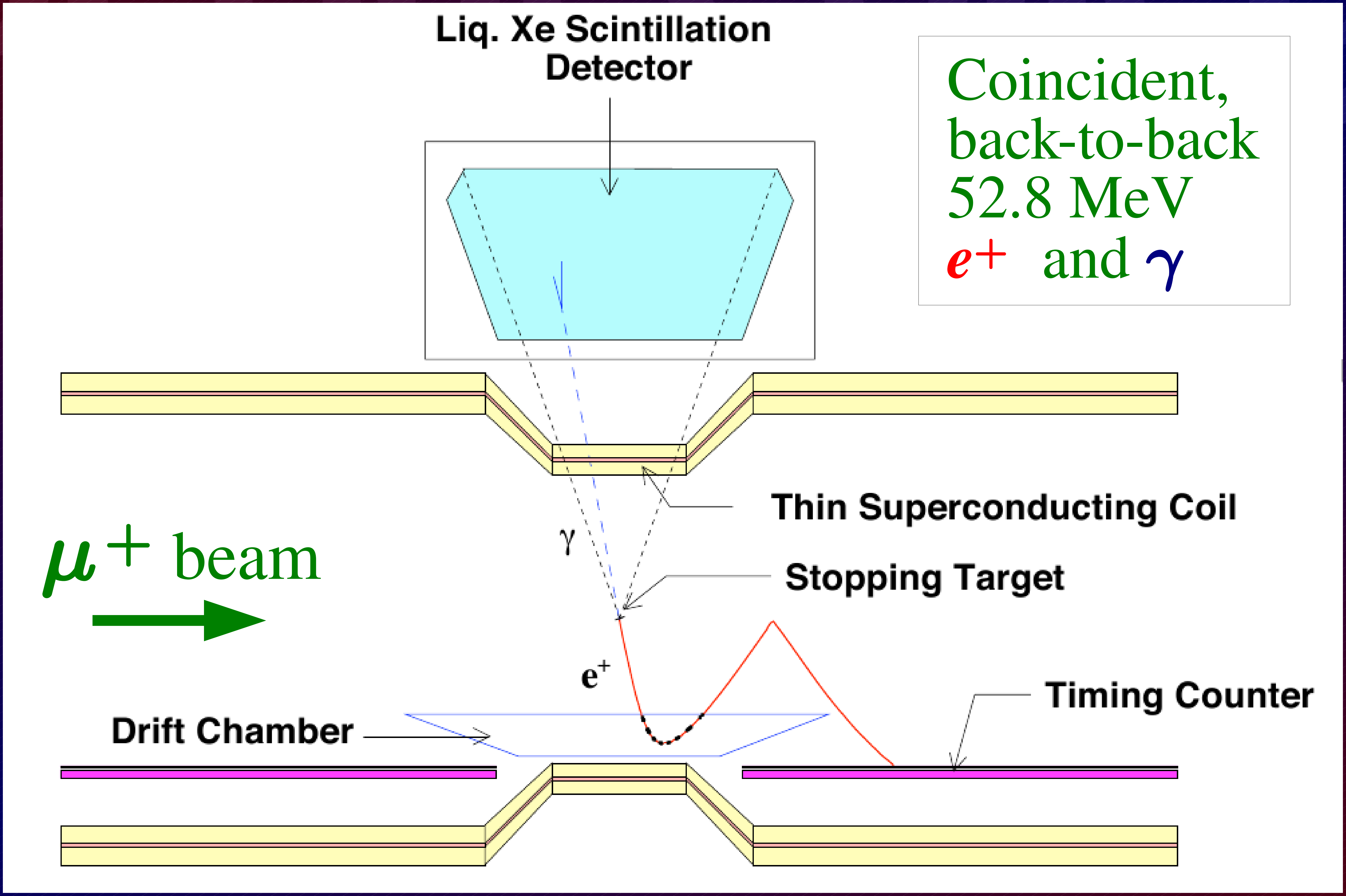
MEG ($\mu \rightarrow e\gamma$) at PSI

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



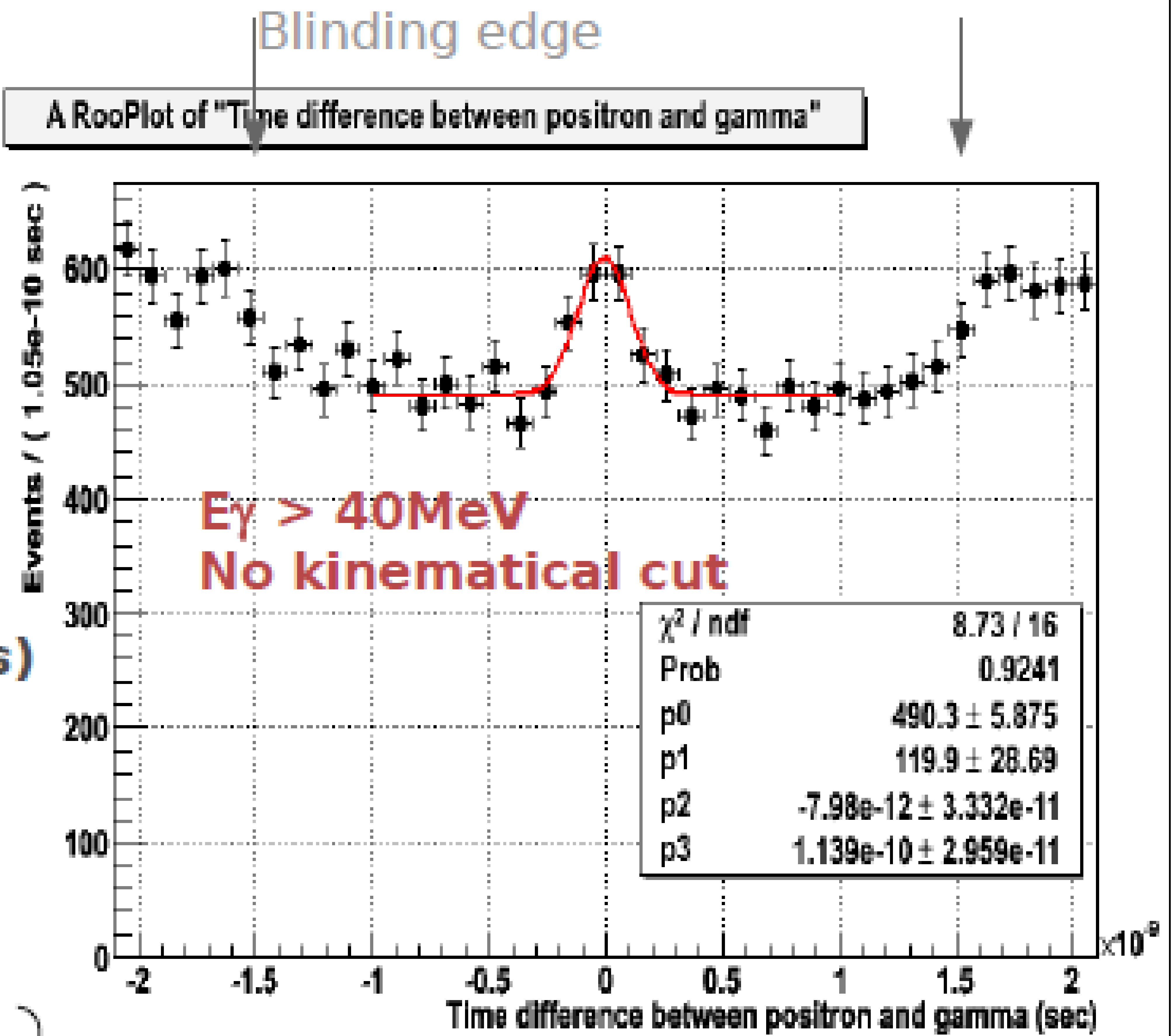
RD Search in MEG Runs

MEG Mu-E-Gamma Collaboration

- We observed RD peak !
  - Even on higher floor of acci.BG
  - Another & powerful time calibration source

- **T0 is well centered**
  - T0 is calibrated using different calibration source
    - Dalitz decay of $\pi 0$
    - Taken in summer $\pi 0$ run
- **Peak width = 114 ± 30 ps (s)**
  - Show the improvement of time resolution as increase of γ energy
  - Close to combined resolution of each detector

$$\left(\begin{array}{c} \text{Xe} \quad \text{TC} \quad \text{Track} \\ 100 \oplus 70 \oplus 50 = 132\text{ps} \end{array} \right)$$



We are really sensitive to the $\mu \rightarrow e\gamma$ signal !

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

- Aiming for sensitivity down to branching ratio of 10^{-13}
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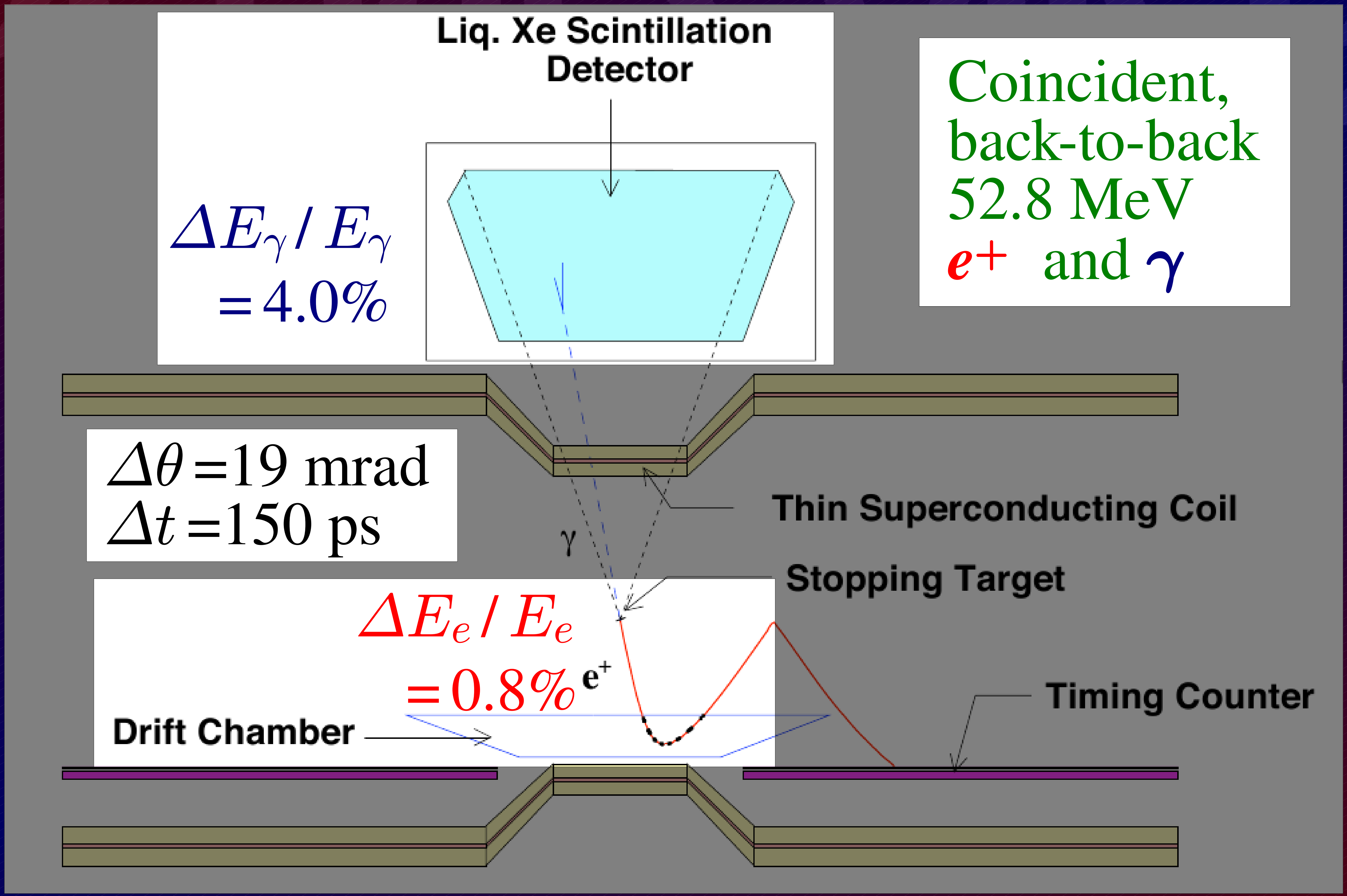


Coincidence requirement makes further improvements in sensitivity with intense beams very difficult

- First results this year
- Running through to 2011 for full sensitivity

Coherent Muon-to-Electron Conversion

- Search for the process

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

muonic atom

$E_e \sim 105\text{MeV}$

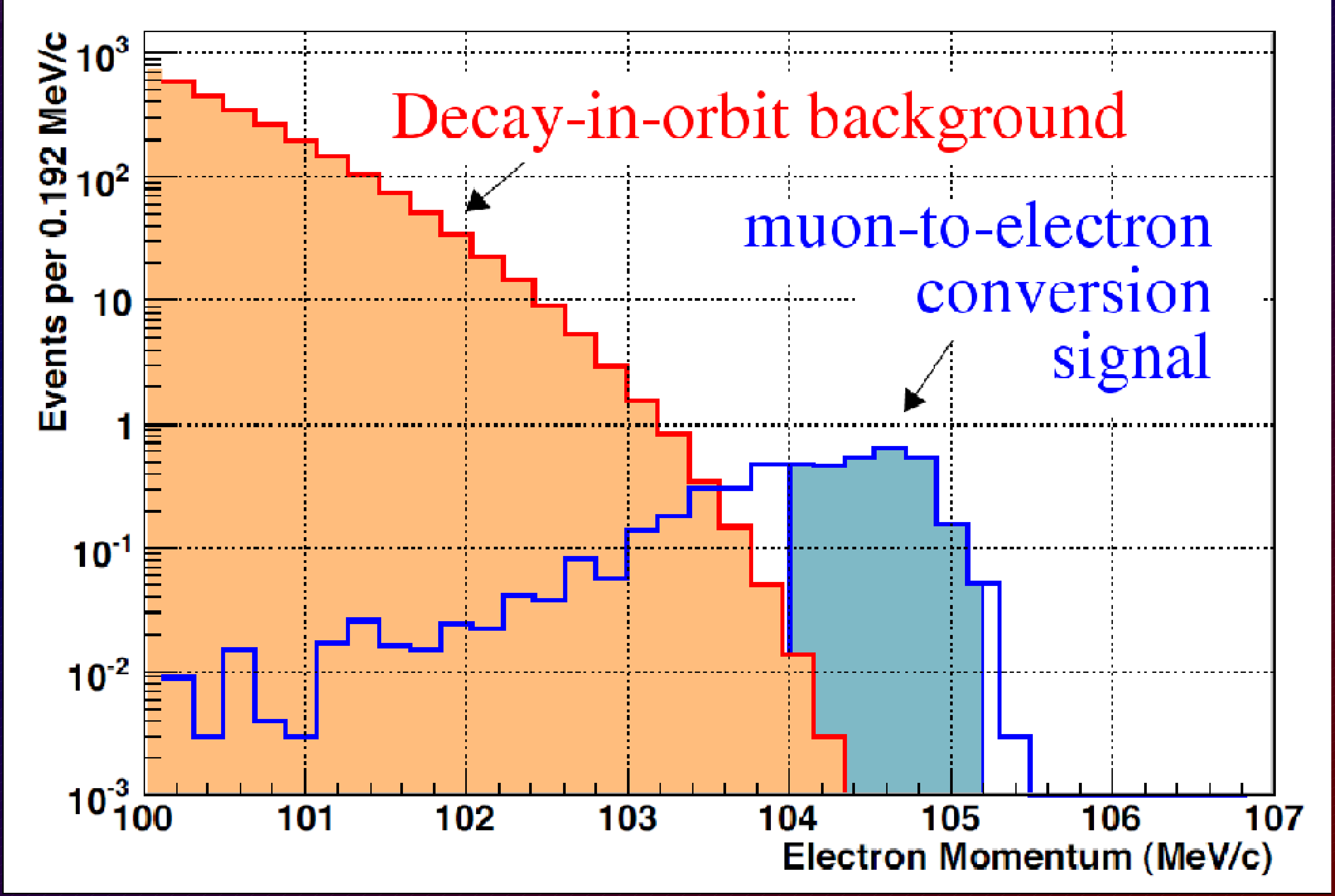
delay since muon stopping $\sim 1\mu s$ (N dependent)

- Entirely non-existent in the Standard Model
- $\sim 10^{-52}$ when extended to include neutrino mass

Searching for Muon-to-Electron Conversion

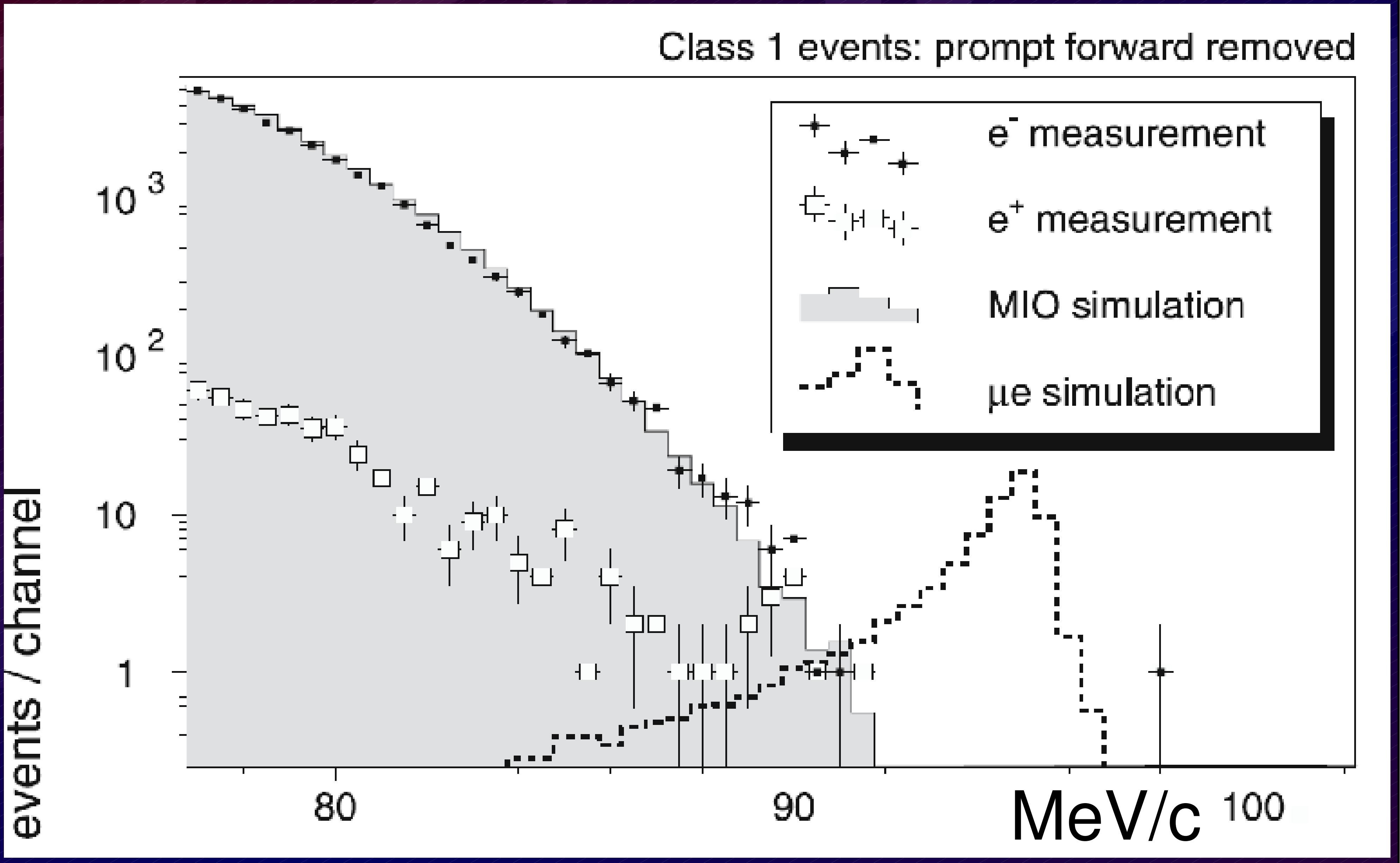
- Produce a burst of muons and stop them on a target
- Muonic atoms form in 1s state — wait several hundred ns
- Observe the emitted electron spectrum over about 100 MeV/c

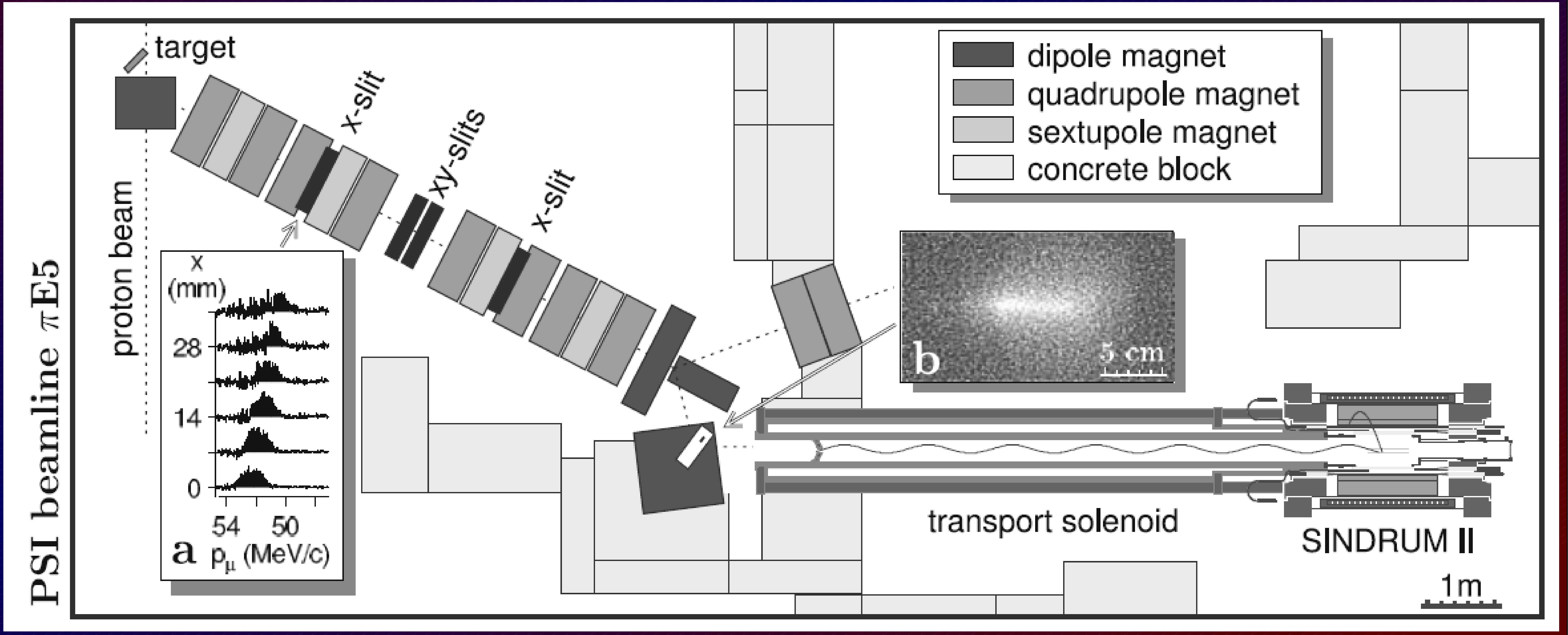
- Minimising and understanding backgrounds, given the extremely high initial particle fluxes, is crucial



SINDRUM II at PSI

- 10^7 – 10^8 μ/sec
- Total rate limited by beam veto counter





Coherent Muon-to-Electron Conversion

- Search for the process

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

muonic atom

$E_e \sim 105\mathrm{MeV}$

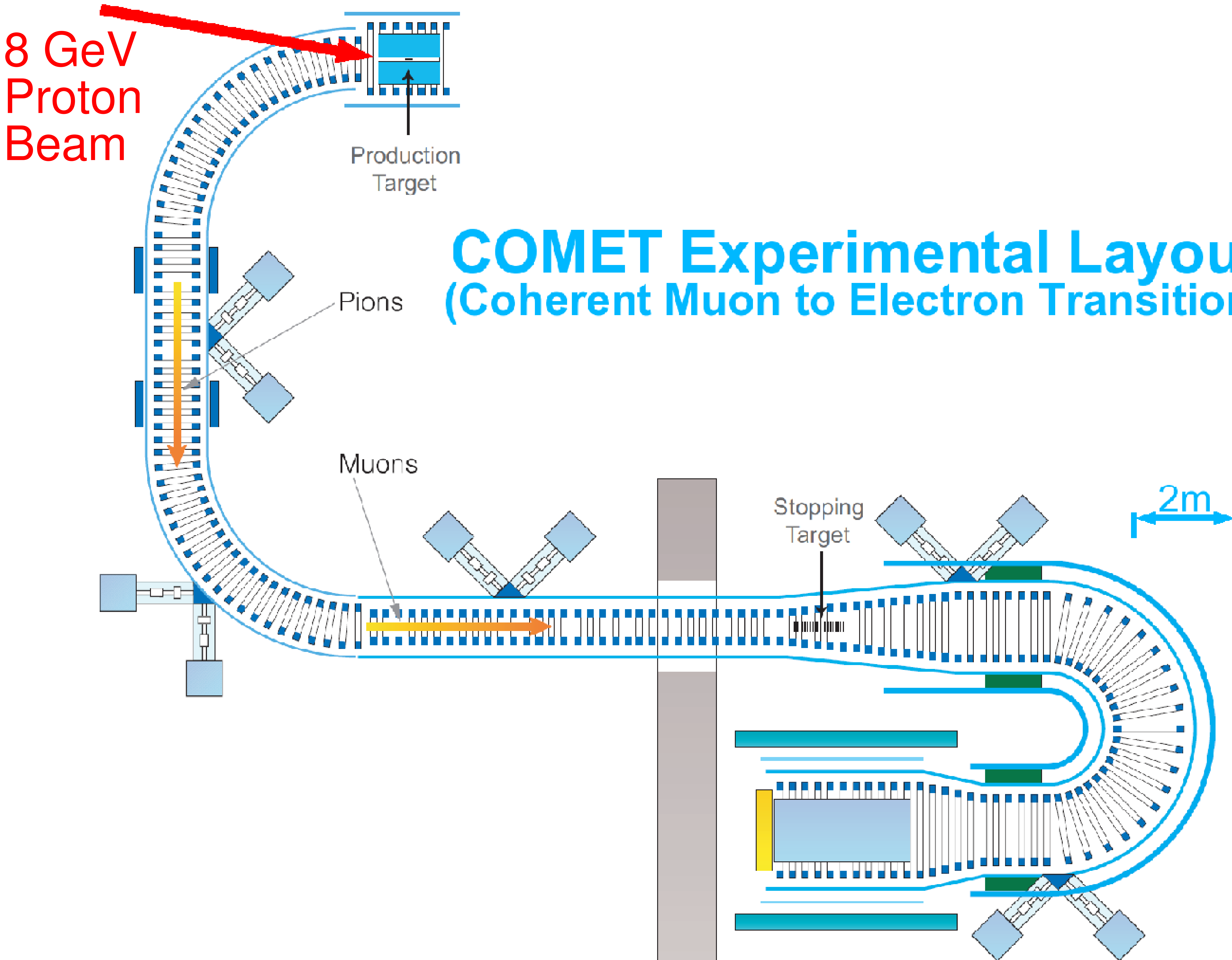
- The present limit is about

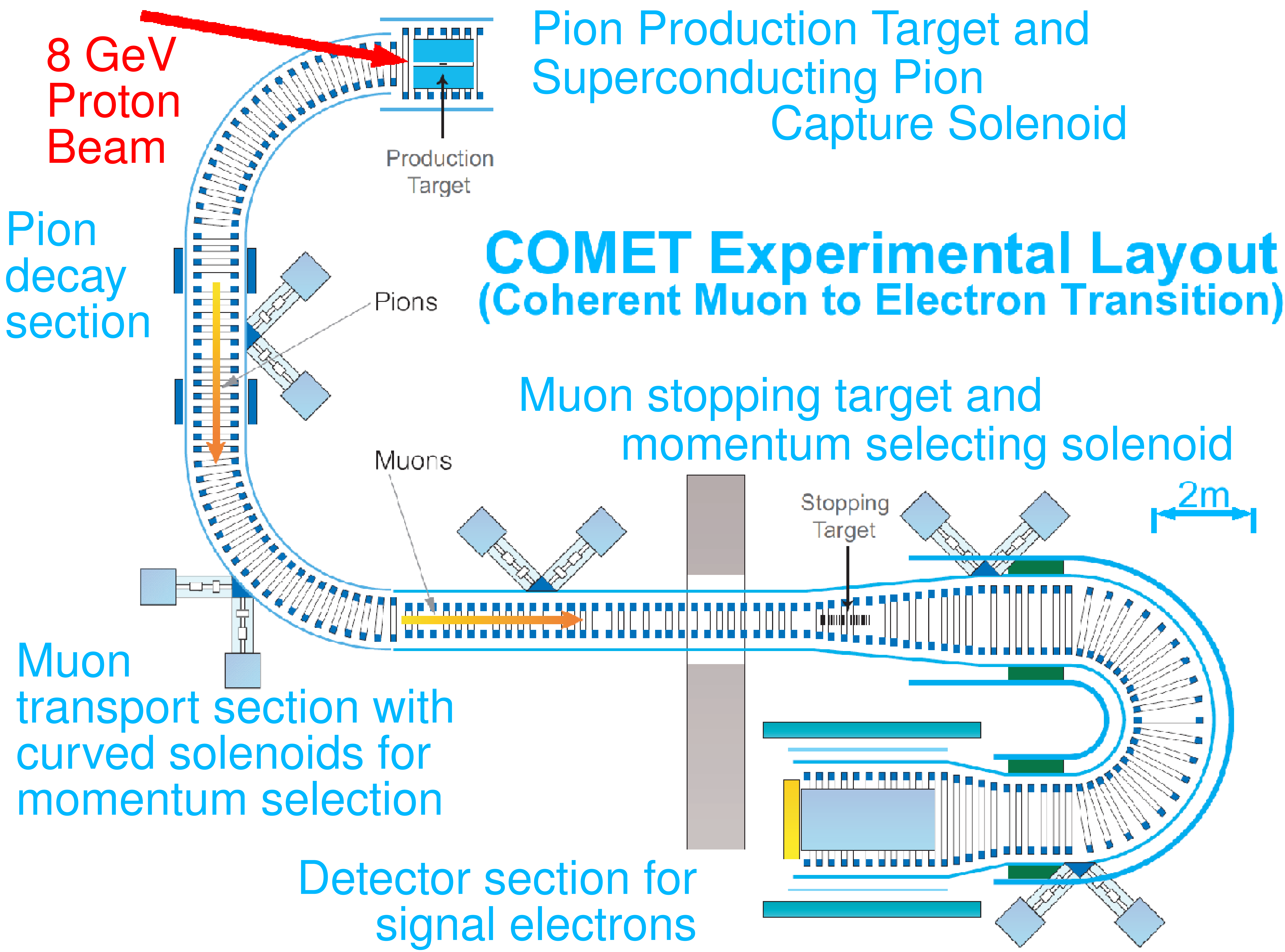
$$< 7 \times 10^{-13}$$

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**

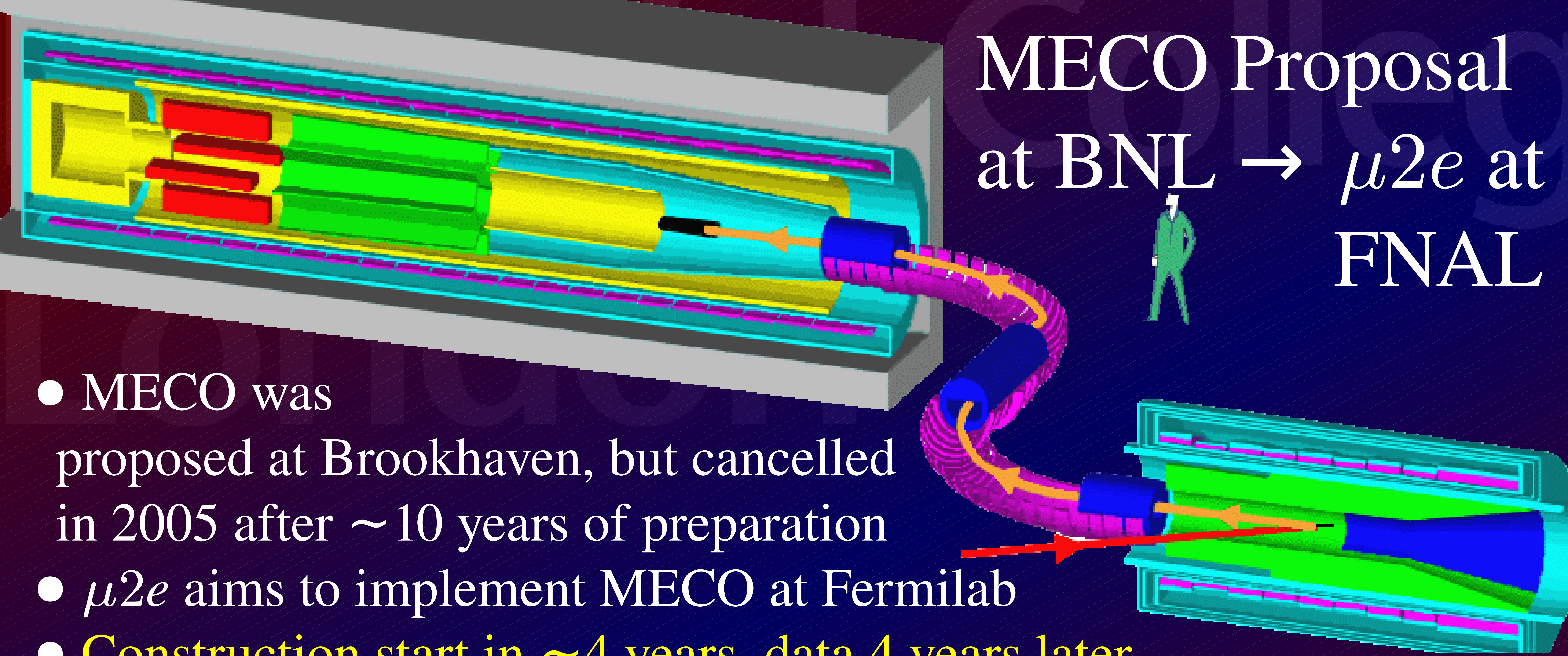
COMET Experimental Layout
(Coherent Muon to Electron Transition)



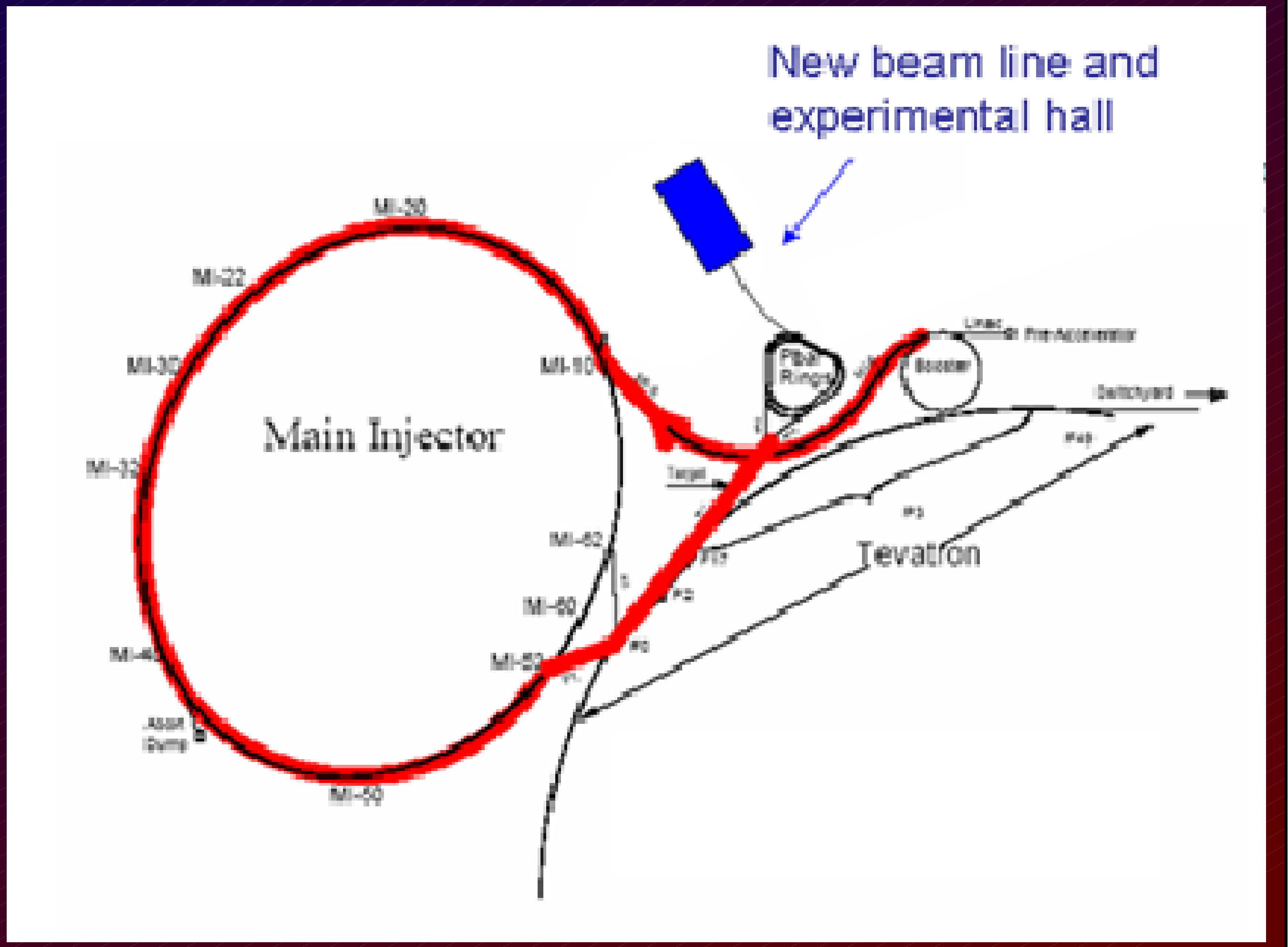


8 GeV Proton Beam
Pion Production Target and Superconducting Pion Capture Solenoid
Production Target
COMET Experimental Layout
(Coherent Muon to Electron Transition)
Pion decay section
Pions
Muons
Muon stopping target and momentum selecting solenoid
Stopping Target
2m
Muon transport section with curved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

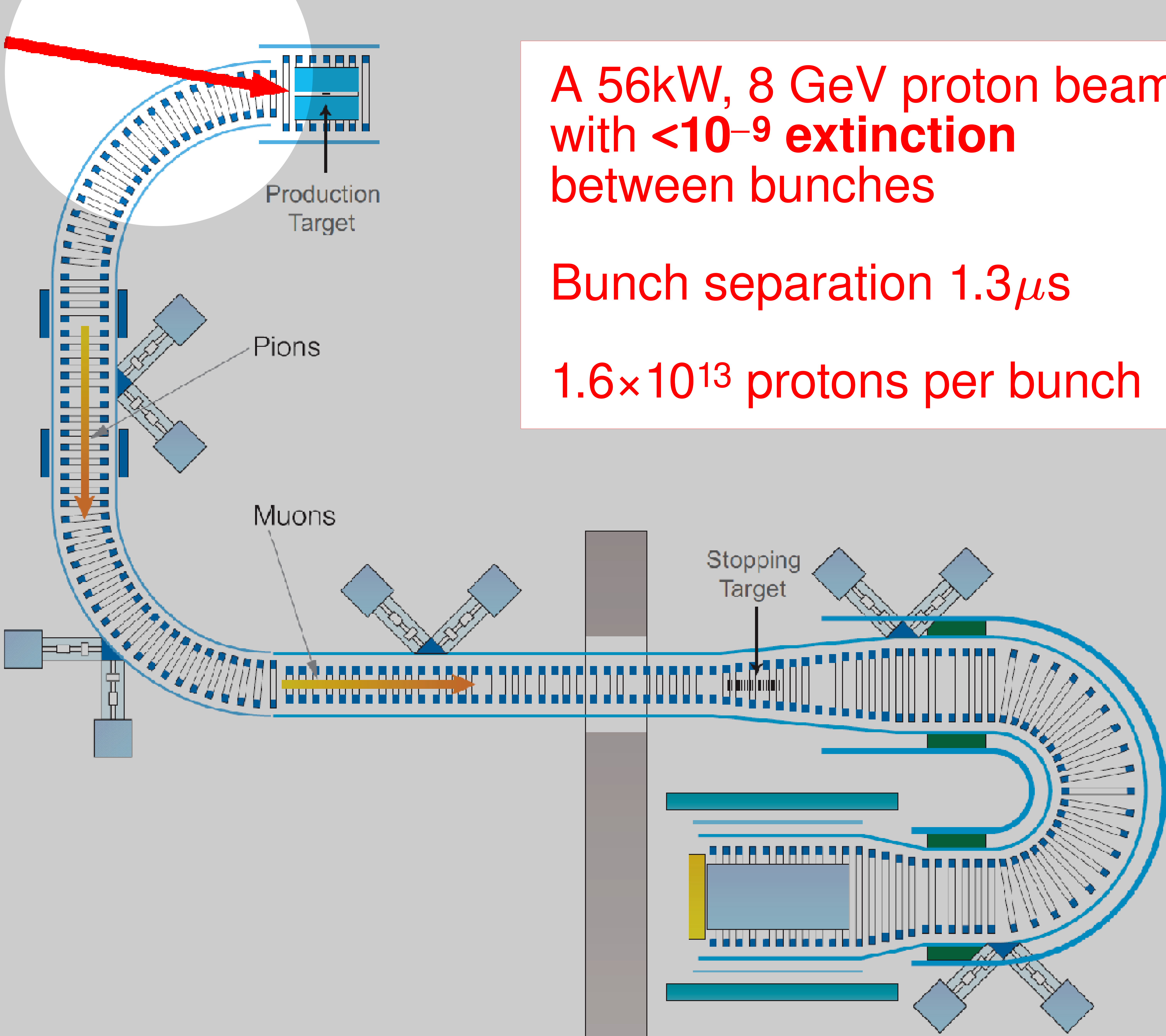
MECO Proposal at BNL → $\mu 2e$ at FNAL



- 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

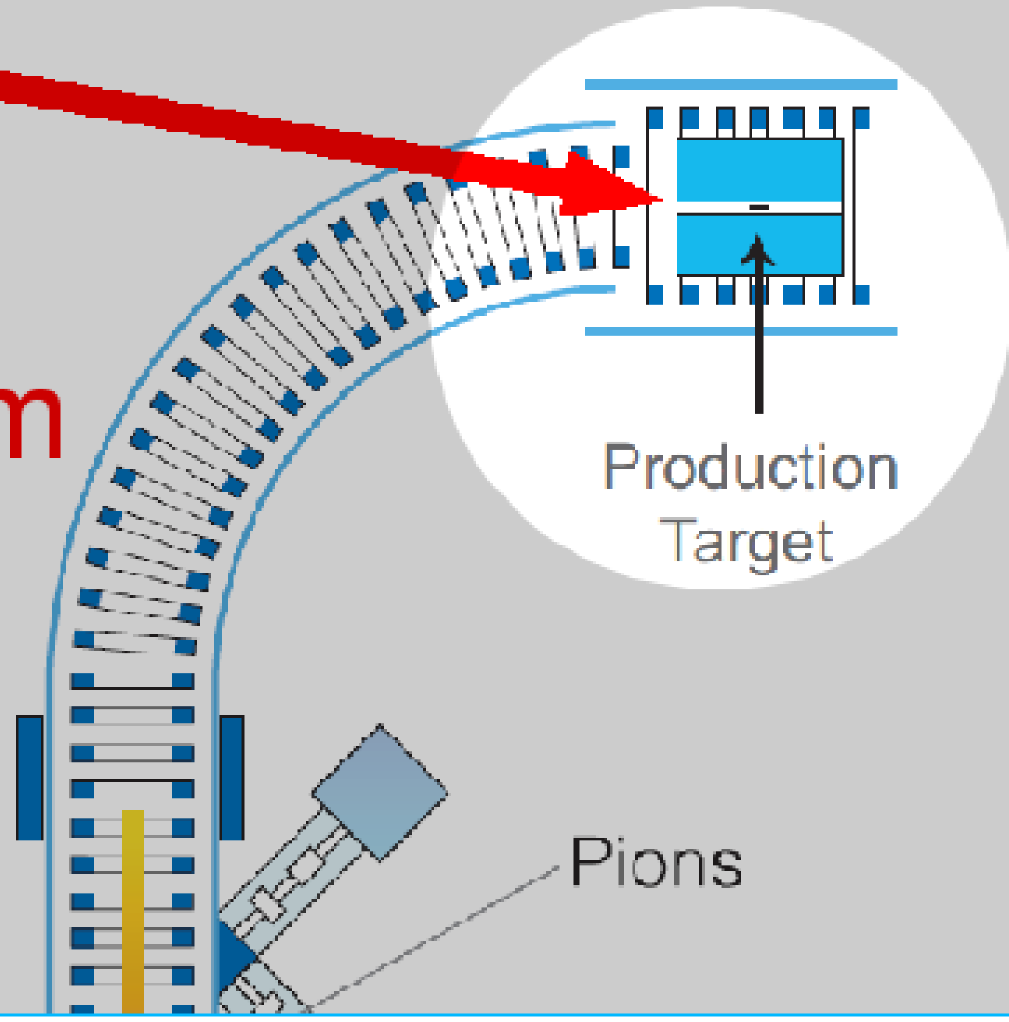


A 56kW, 8 GeV proton beam with **<10^{-9} extinction** between bunches

Bunch separation 1.3μs

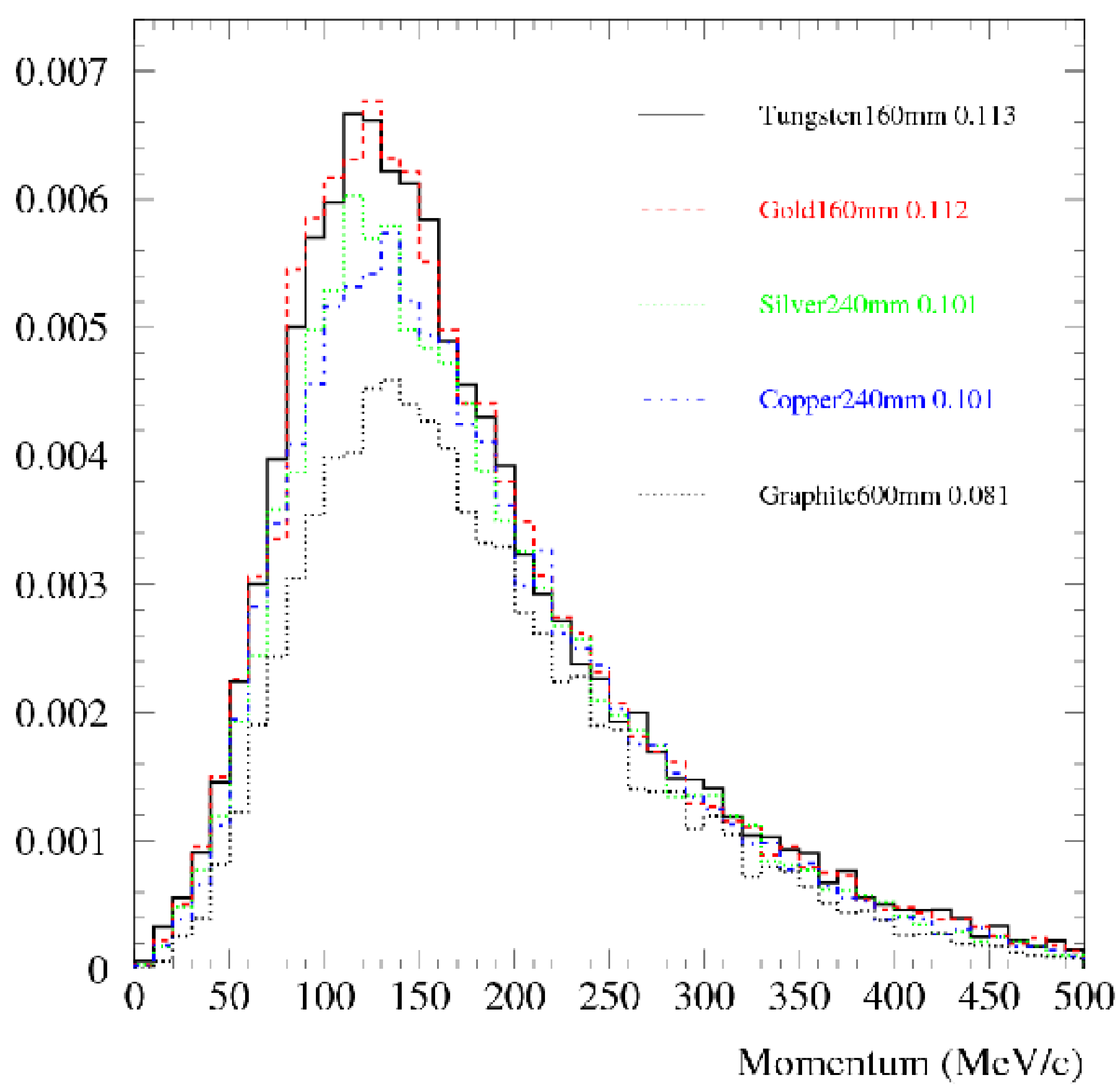
1.6×10^{13} protons per bunch

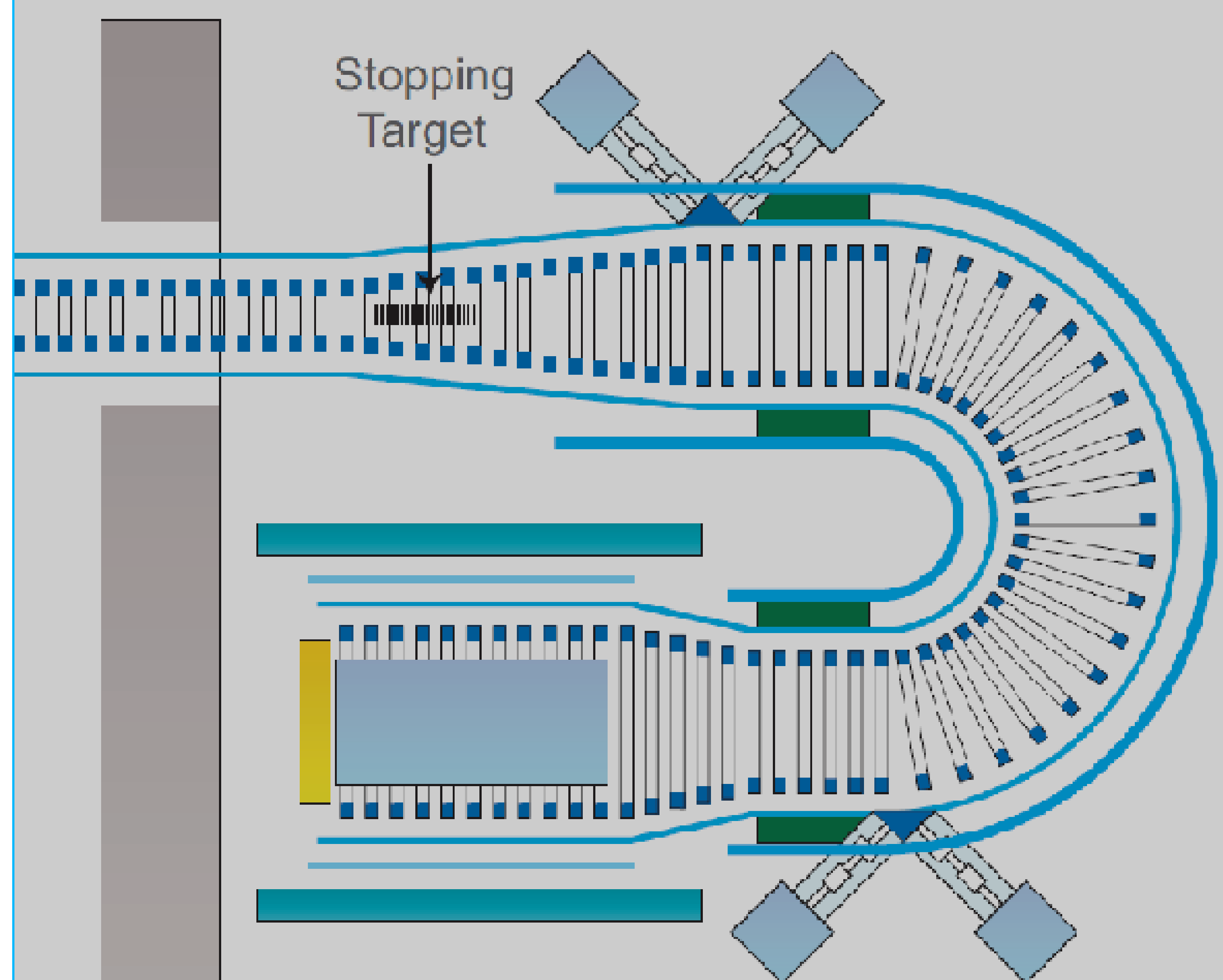
1.6×10^{13} 8 GeV protons per beam bunch

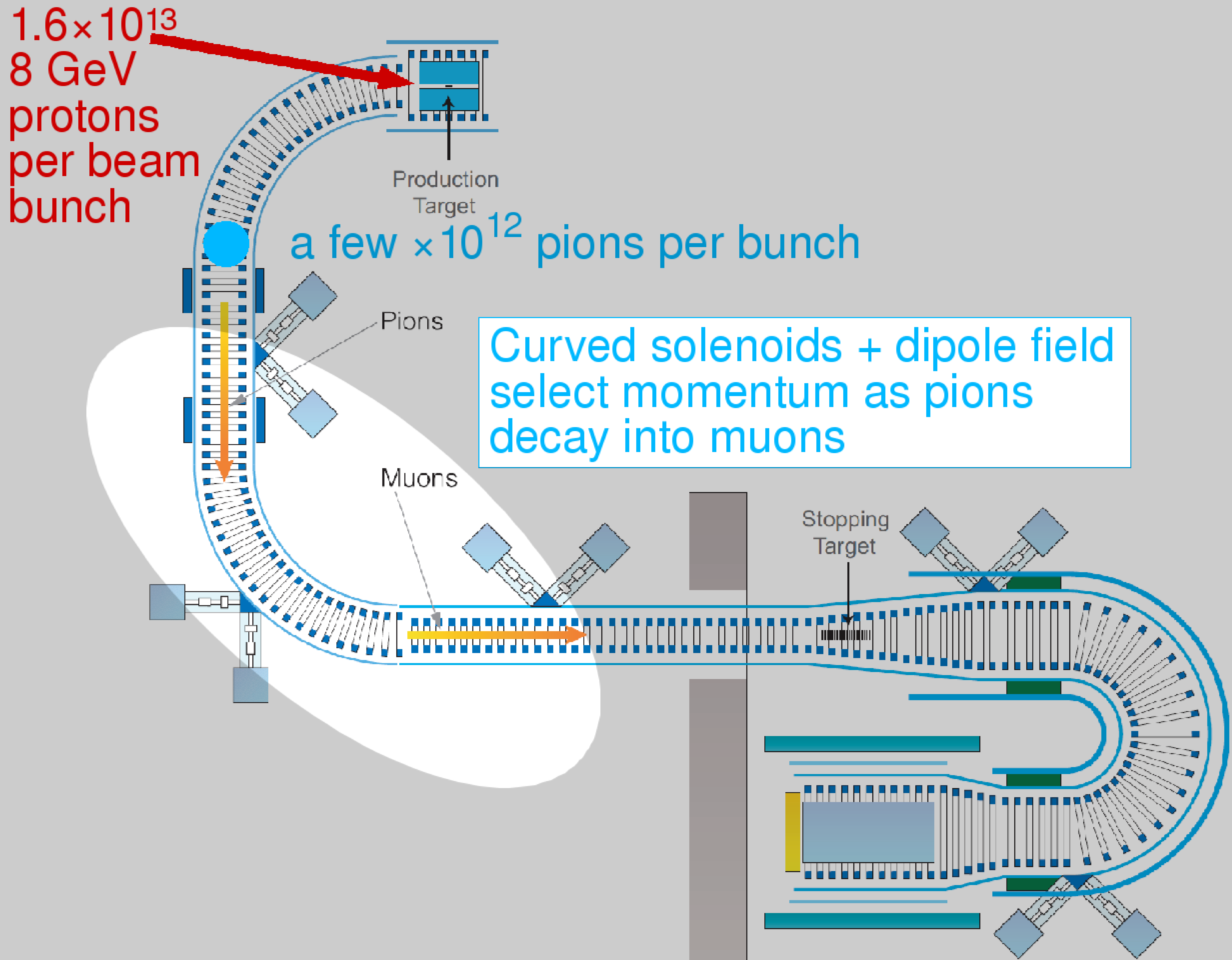


A few $\times 10^{12}$ pions produced per bunch (some physics uncertainty)

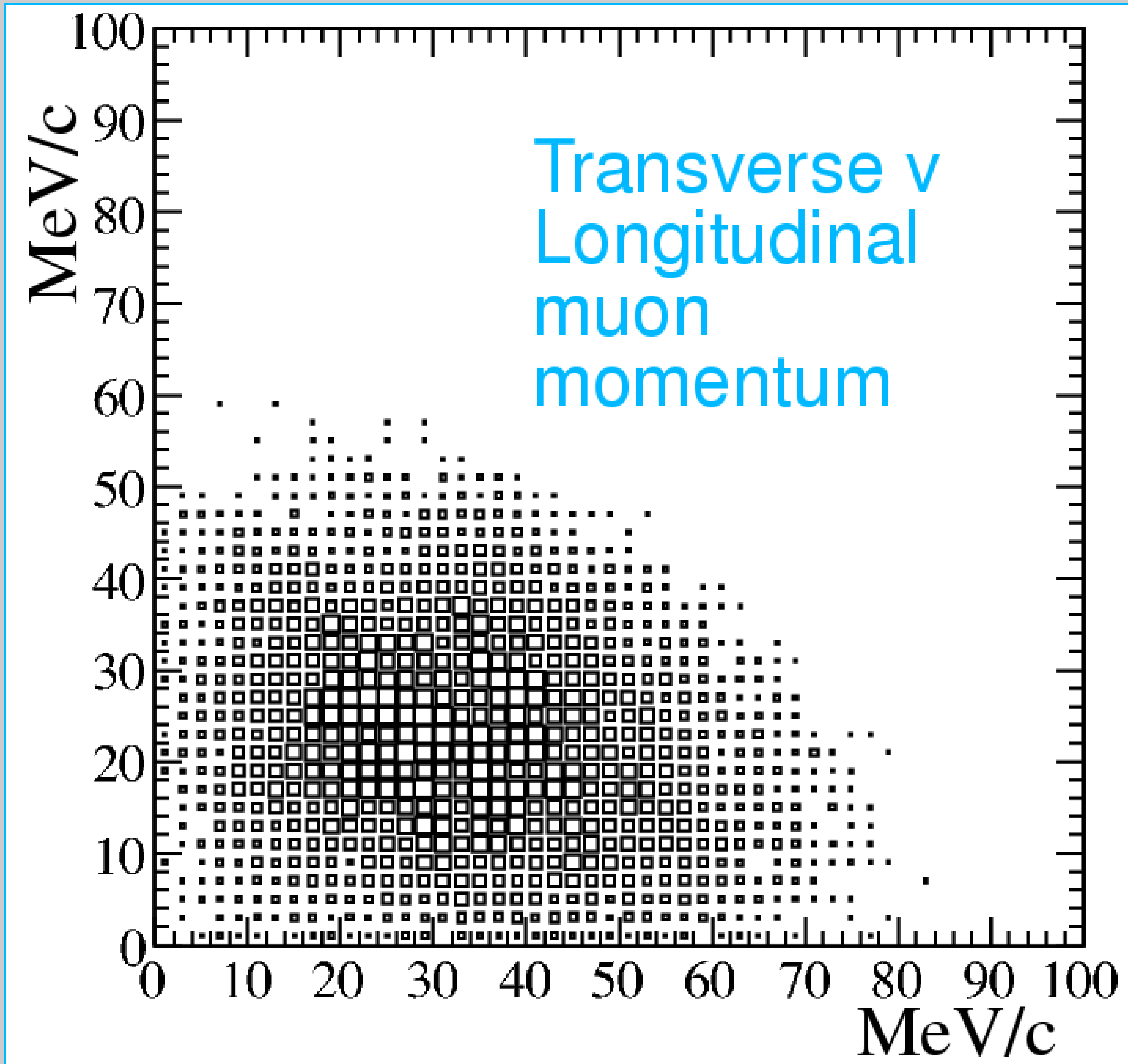
lower energy, backward pions captured and sent to transfer solenoid



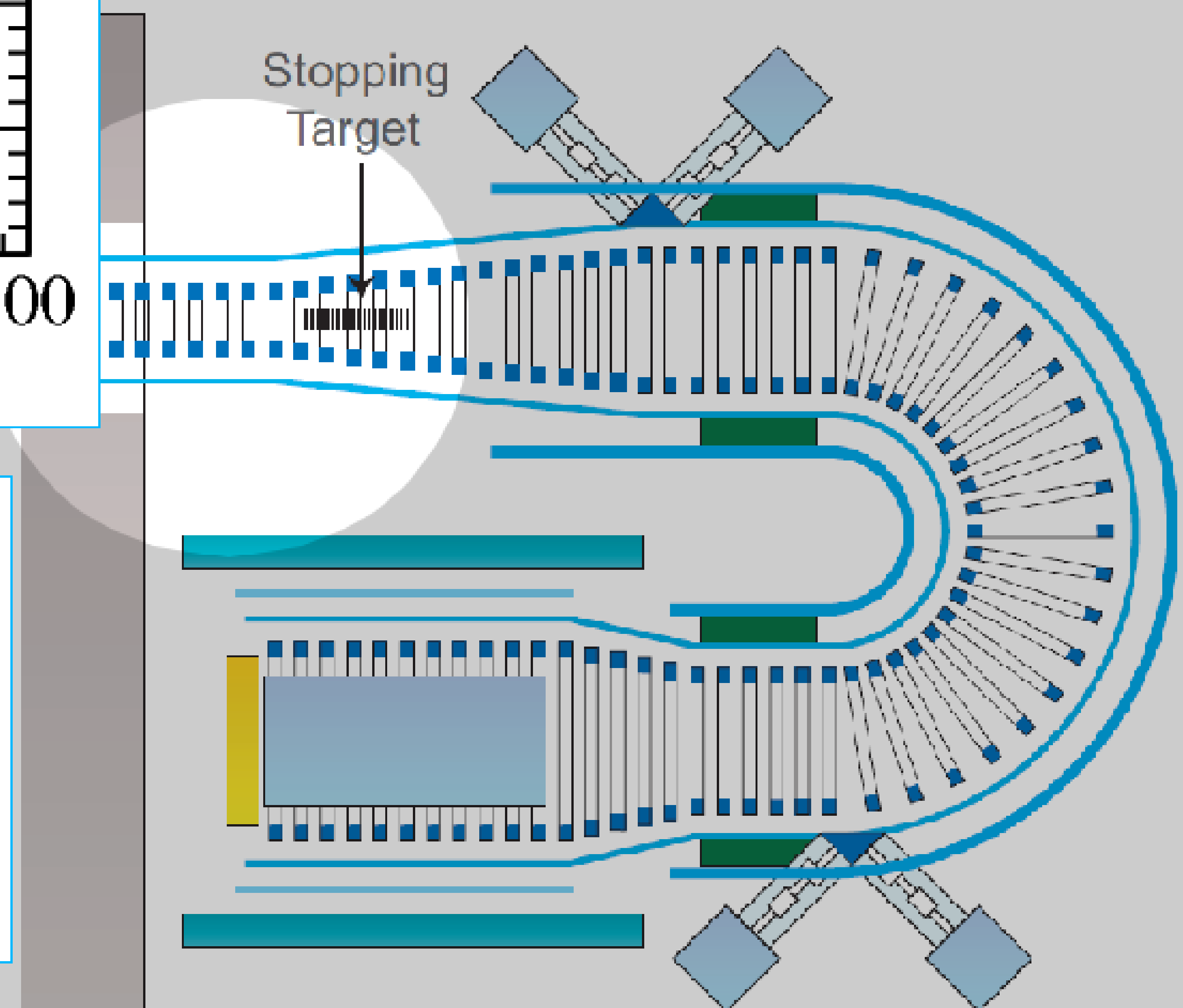




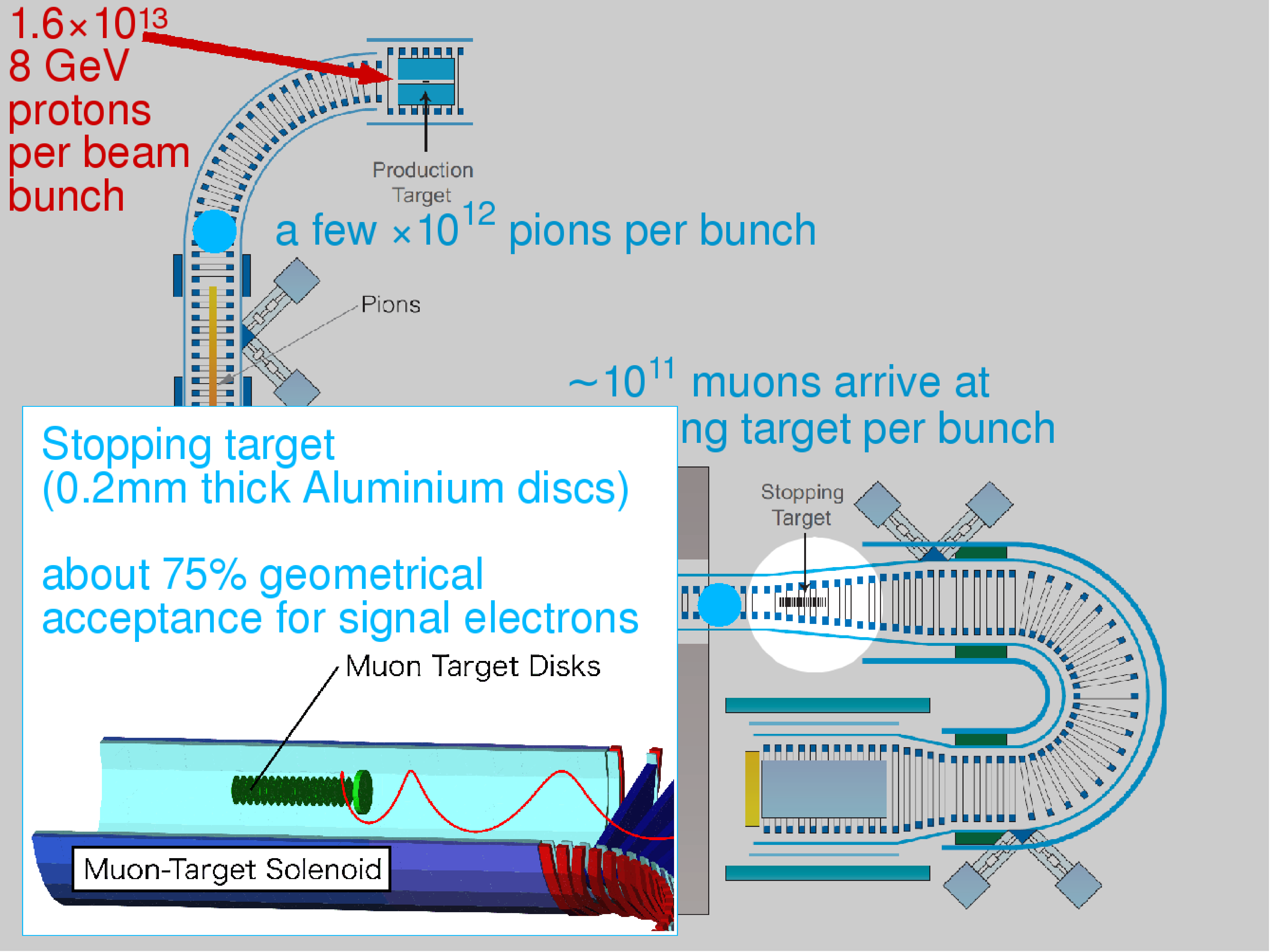
Curved solenoids + dipole field select momentum as pions decay into muons



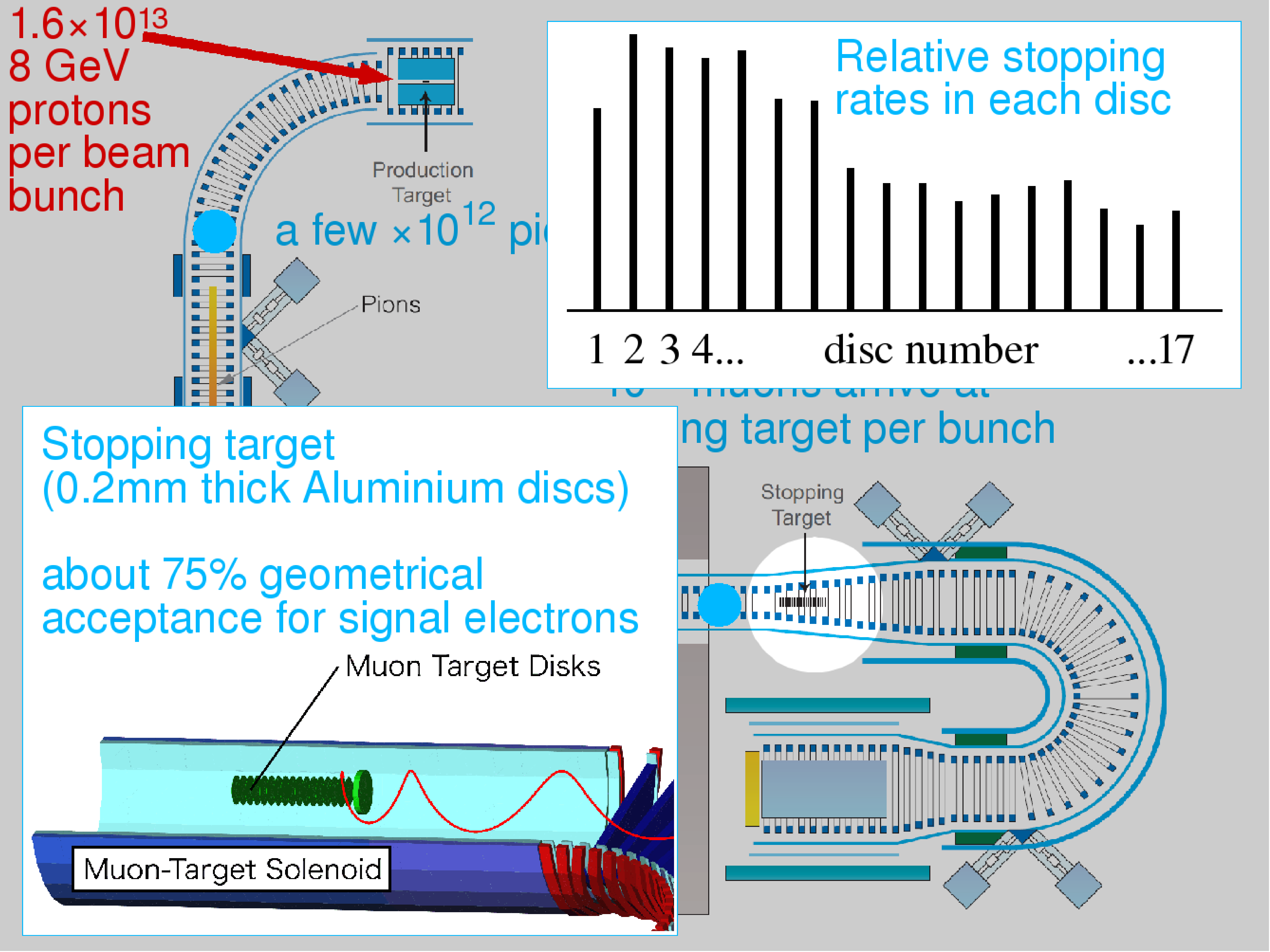
bunch



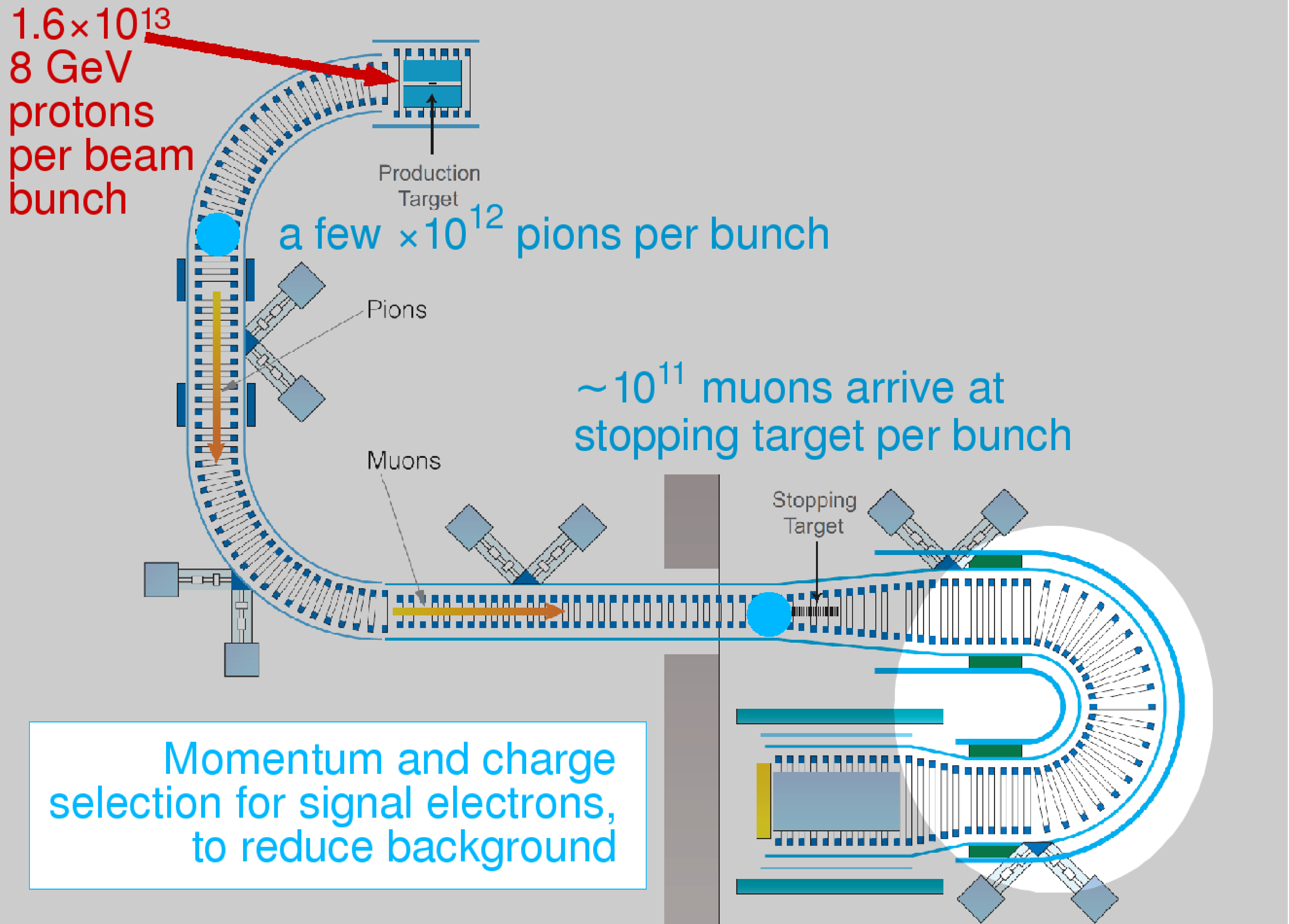
10^{10} to 10^{11} muons below 85 MeV/c arrive at stopping target per bunch (current best is 10^{8}/sec at PSI)



1.6×10^{13}
8 GeV protons per beam bunch
Production Target
a few ×10^{12} pions per bunch
Pions
~10^{11} muons arrive at
ng target per bunch
Stopping target
(0.2mm thick Aluminium discs)
about 75% geometrical acceptance for signal electrons
Muon Target Disks
Muon-Target Solenoid
Stopping Target



1.6×10^13
8 GeV
protons
per beam
bunch
Production
Target
a few ×10^12 pi
Pions
Relative stopping
rates in each disc
1 2 3 4...
disc number
...17
ng target per bunch
Stopping target
(0.2mm thick Aluminium discs)
about 75% geometrical
acceptance for signal electrons
Muon Target Disks
Muon-Target Solenoid
Stopping
Target

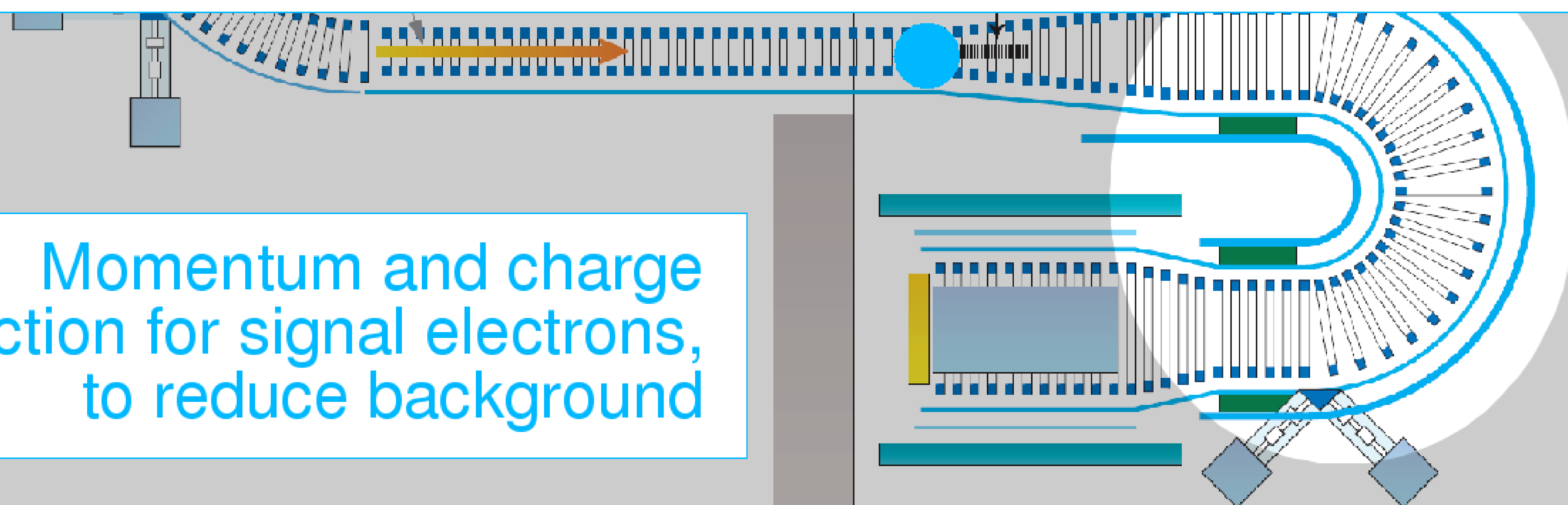


1.6×10^{13} 8 GeV protons per beam bunch
Production Target
a few $\times10^{12}$ pions per bunch
Pions
$\sim10^{11}$ muons arrive at stopping target per bunch
Muons
Stopping Target
Momentum and charge selection for signal electrons, to reduce background

1.6×10^{13}
8 GeV
pro
per
bur

Backgrounds after the curved solenoid

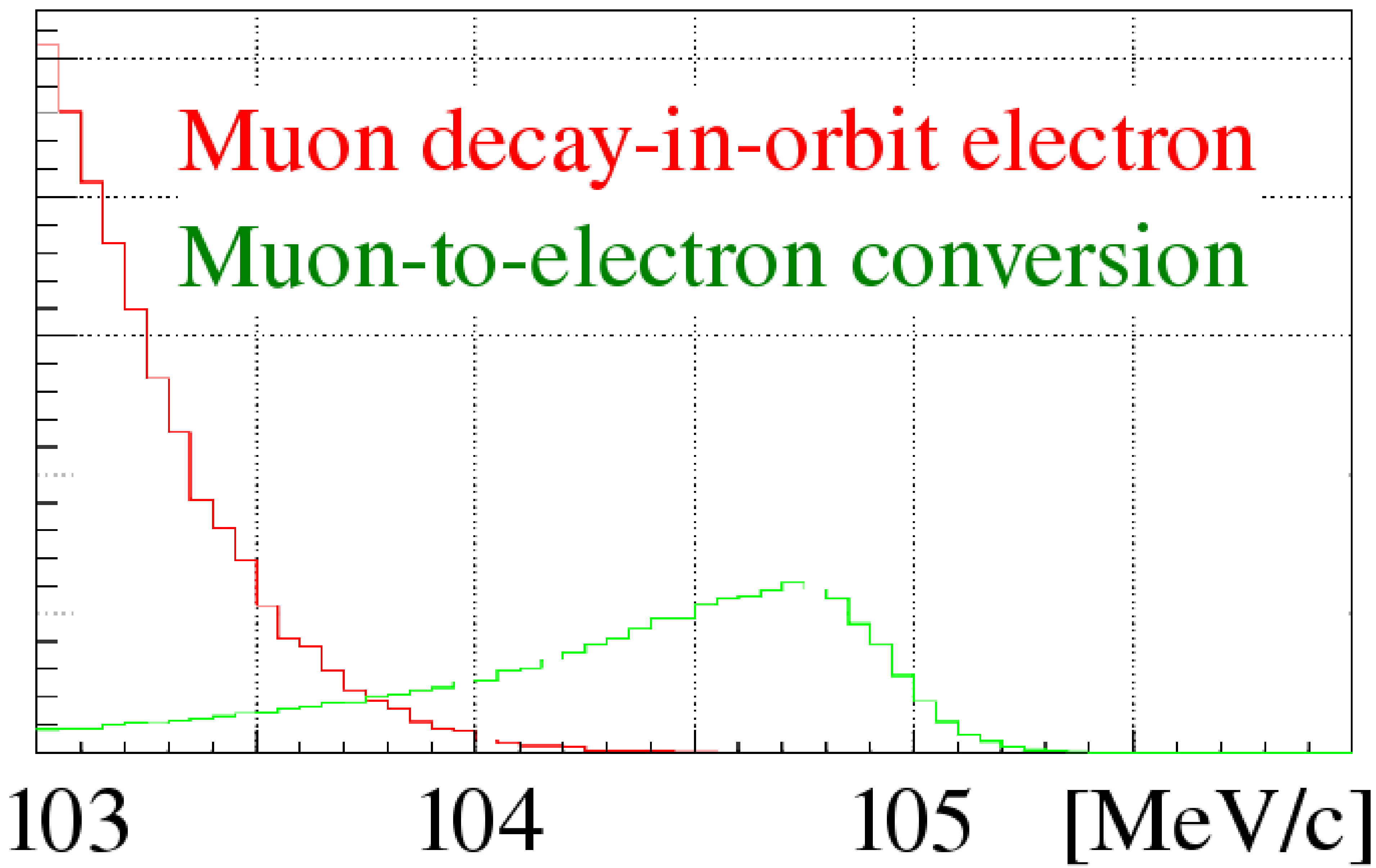
	Timing	Tracker (kHz)	Calorimeter (kHz)	Energy (MeV)
DIO electrons	Delayed	10	10	50 60
Back-scattering electrons	Delayed	15	200	< 40
Beam flash muons	Prompt	$< 150^{\ddagger}$	$< 150^{\ddagger}$	15 35
Muon decay in calorimeter	Delayed	—	$< 150^{\ddagger}$	< 55
DIO from outside of target	Delayed	< 300	< 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

1.6×10¹³

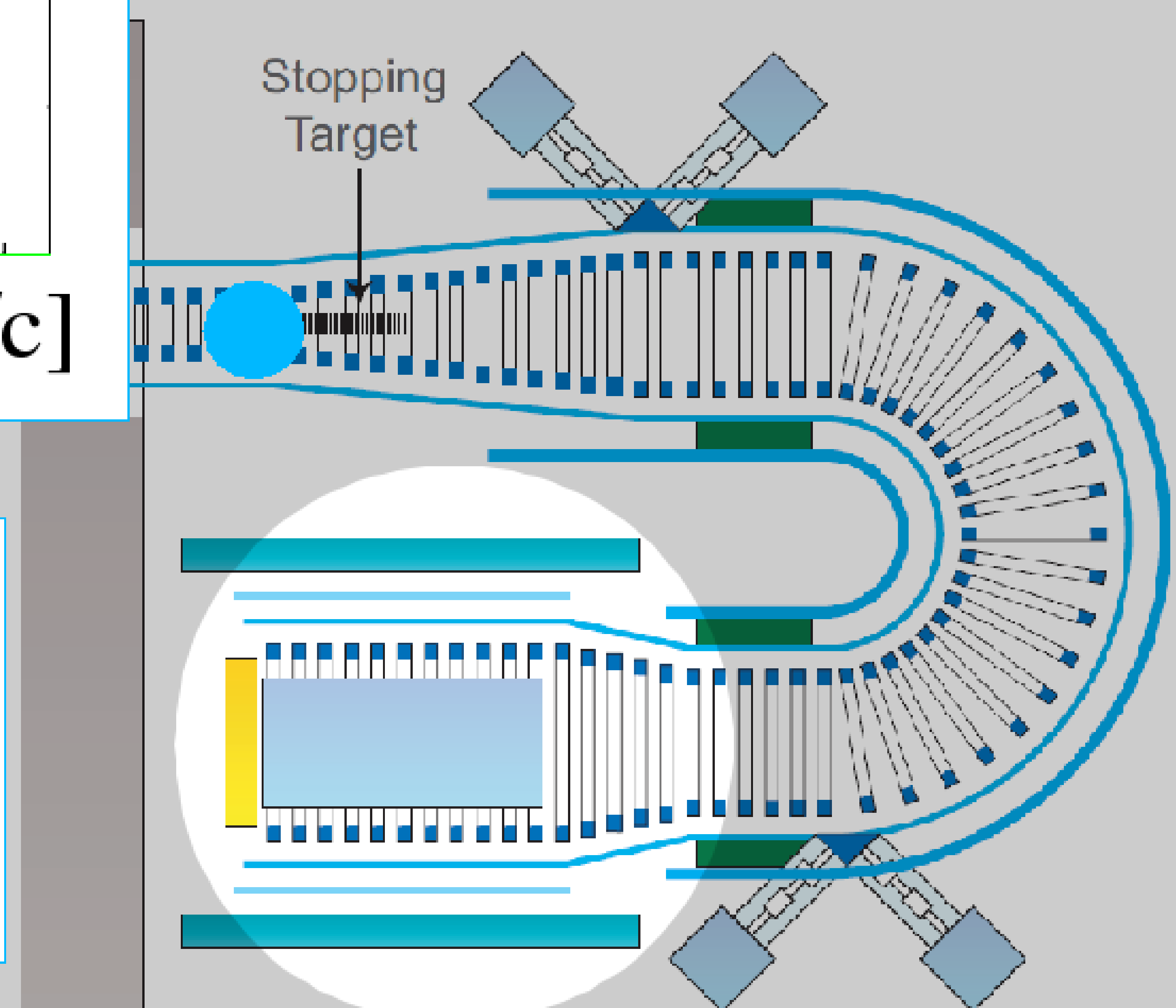
Relative signal and background spectra for branching ratio of 10^{-16} statistics ×100 (including energy loss and tracker resolution)



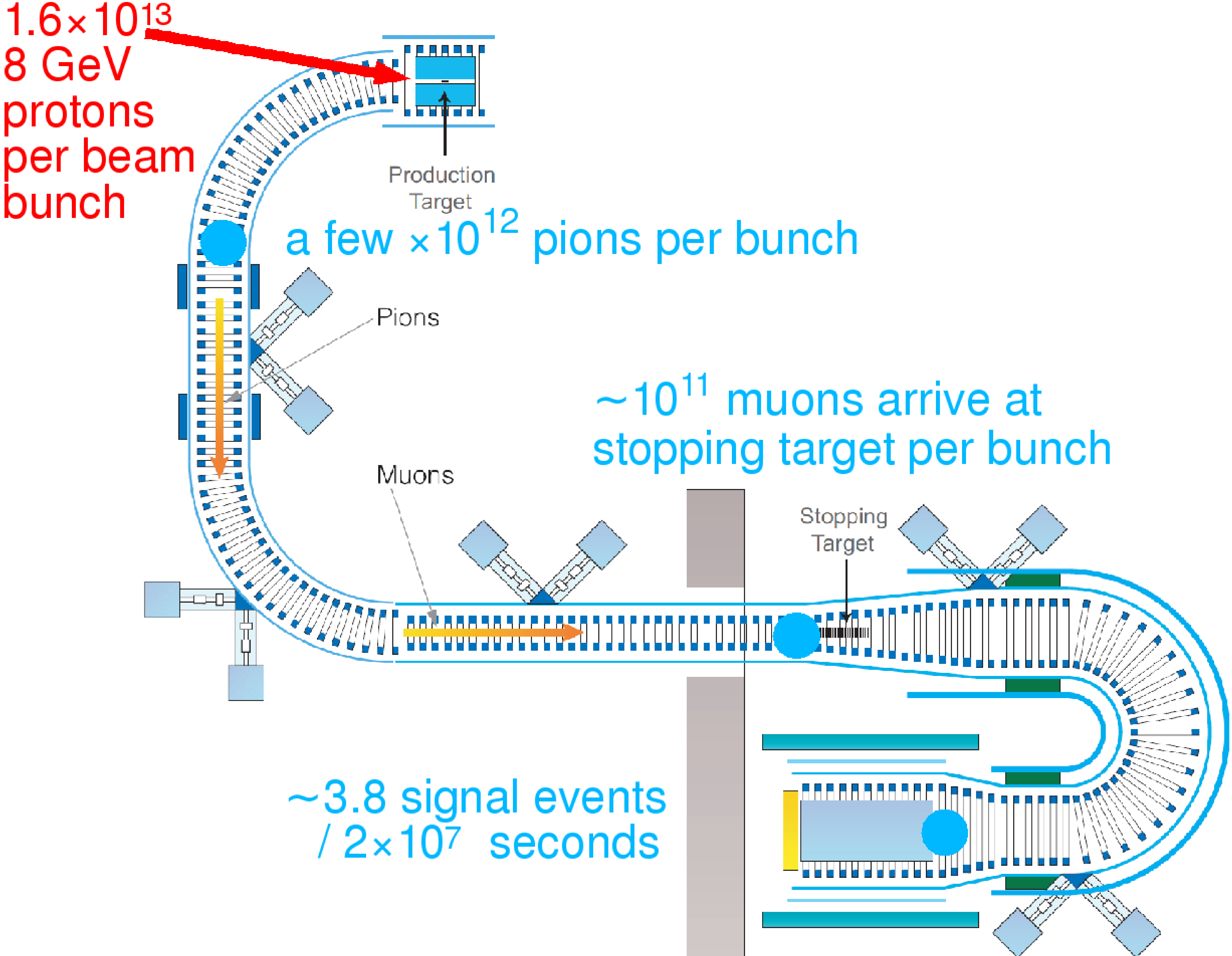
bunch

muons arrive at

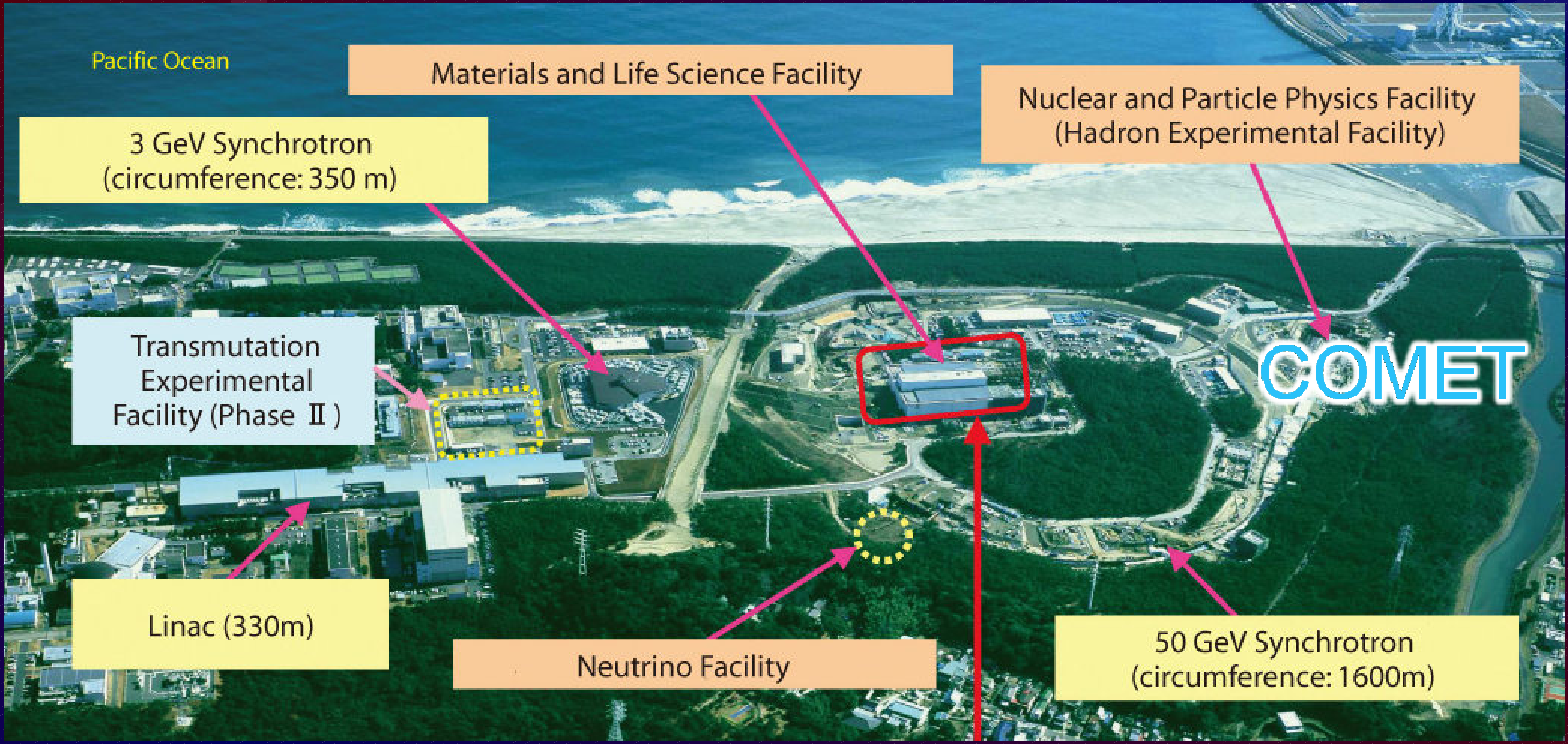
g target per bunch



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


1.6×10^13
8 GeV
protons
per beam
bunch
Production
Target
a few ×10^12 pions per bunch
Pions
~10^11 muons arrive at
stopping target per bunch
Muons
Stopping
Target
~3.8 signal events
/ 2×10^7 seconds

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)

The COMET Collaboration (March 2009)

JINR, Dubna, Russia
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E. Hungerford

Los Alamos National Laboratory, USA
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THE ROYAL SOCIETY
CELEBRATING 350 YEARS

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

Extended presentation requested by PAC for mid-July

Collaboration in process of growing

The COMET Collaboration

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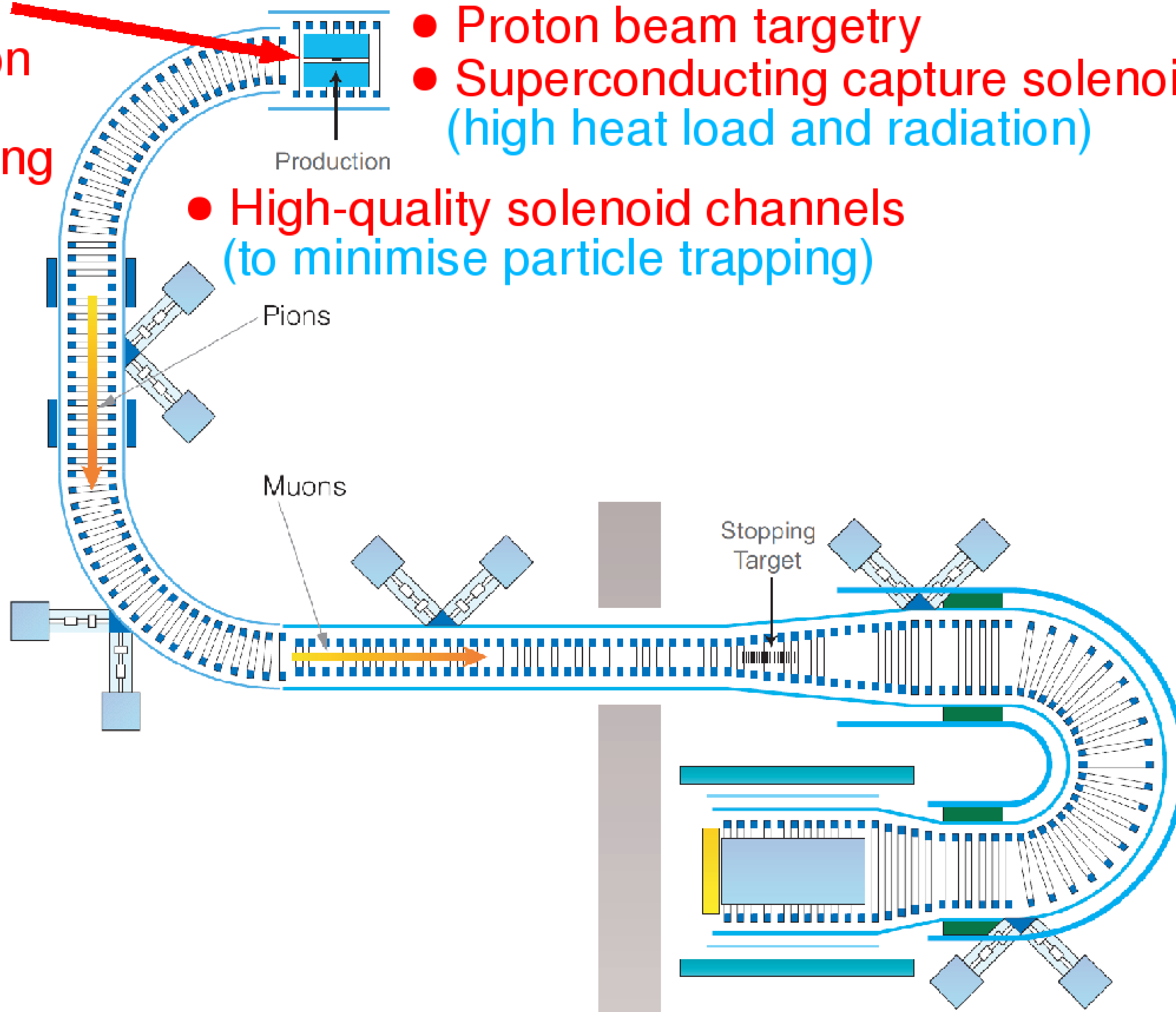
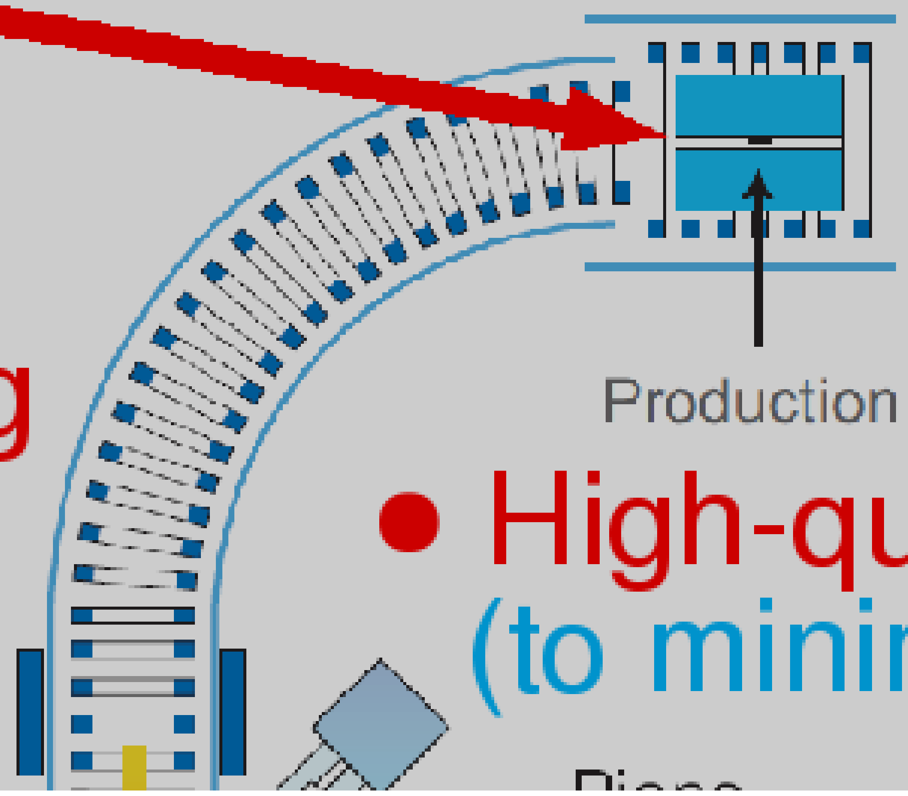
Available at http://www.hep.ph.ic.ac.uk/muec

- Beam extinction and monitoring
- Proton beam targetry
- Superconducting capture solenoid (high heat load and radiation)
- High-quality solenoid channels (to minimise particle trapping)



- Beam extinction and monitoring



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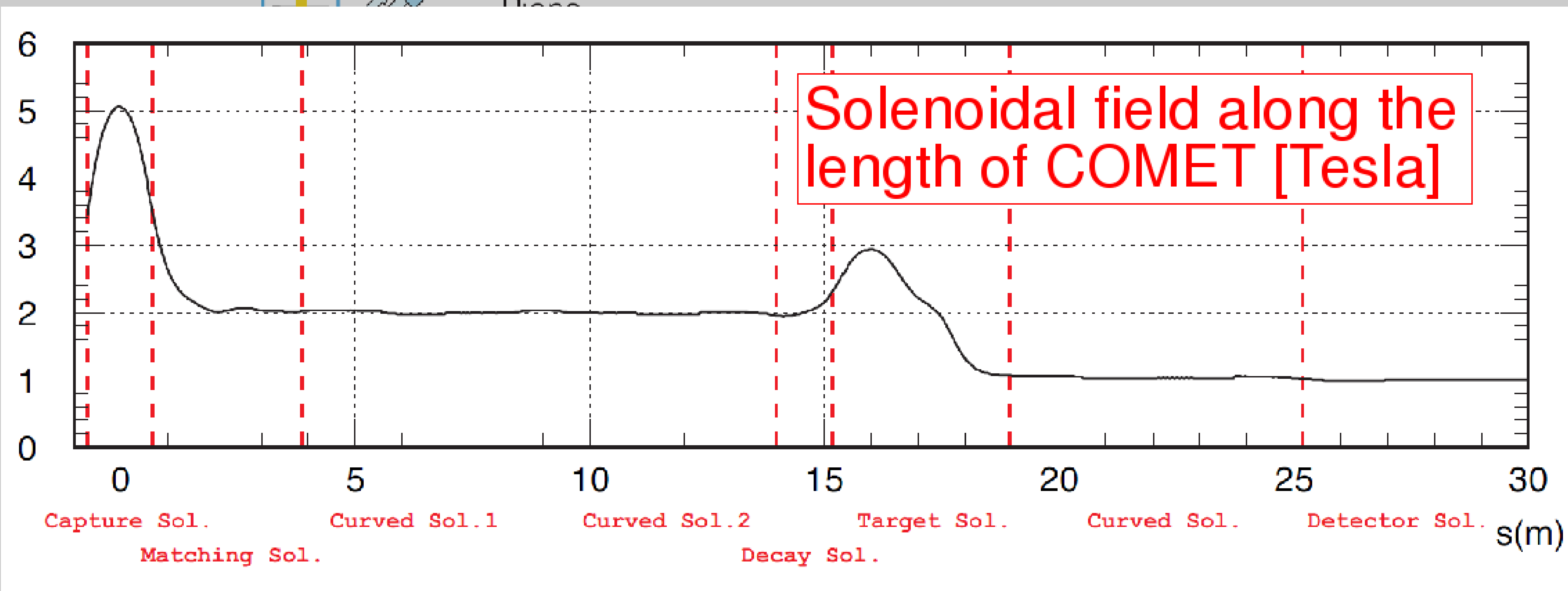
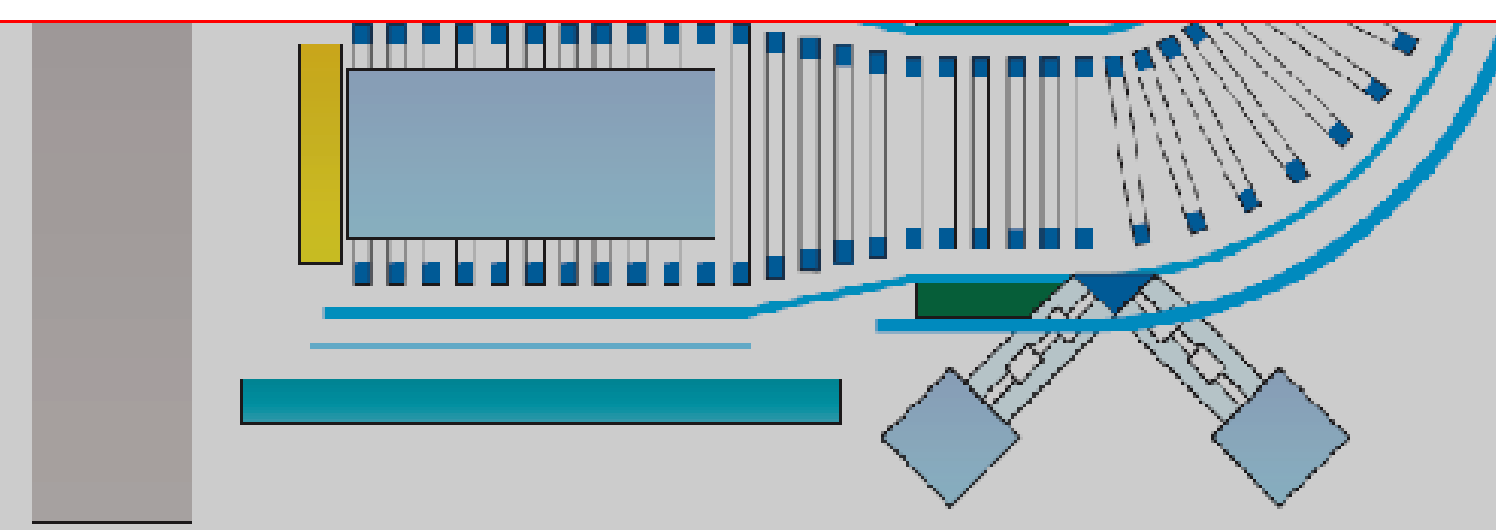
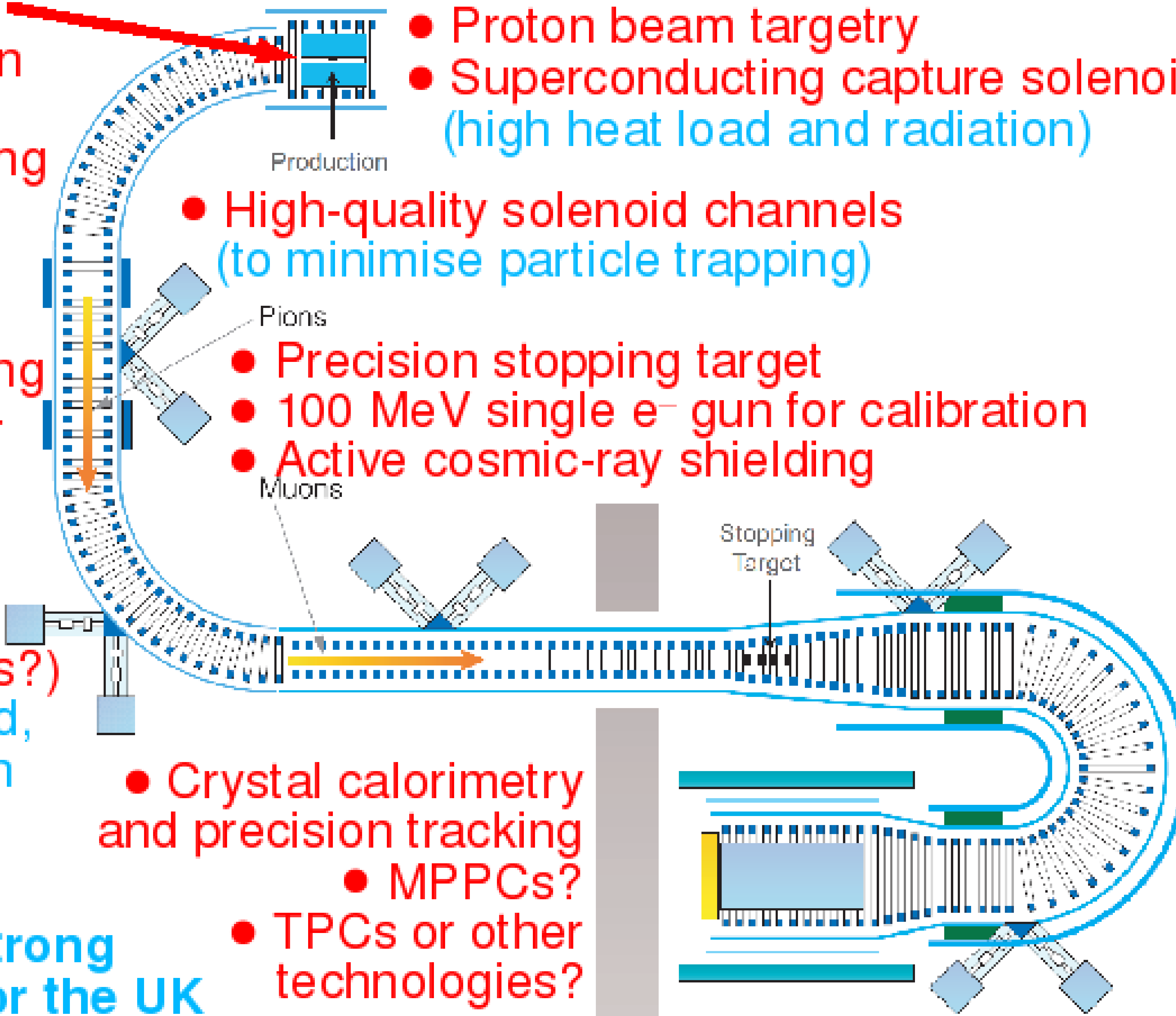




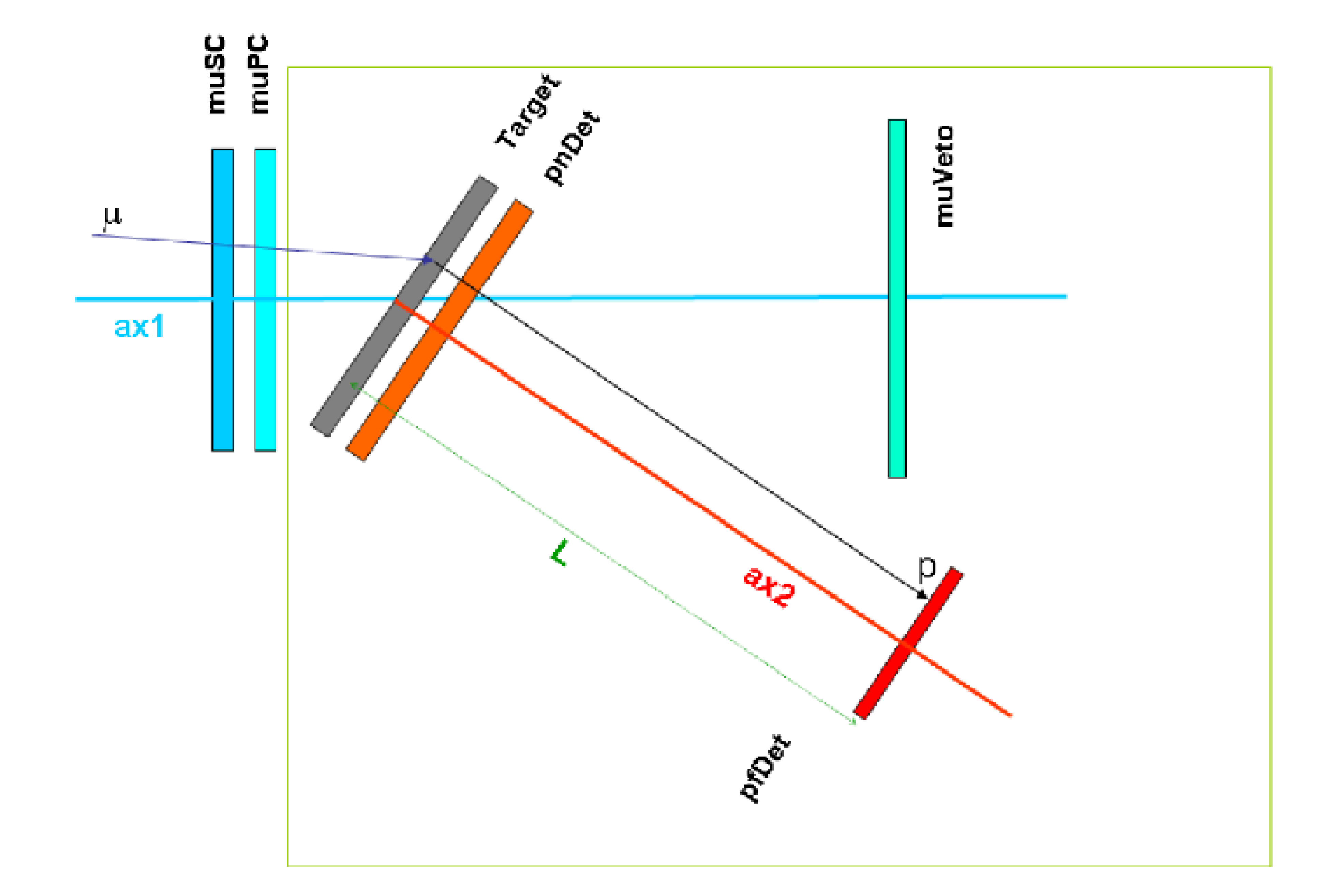
- Beam extinction and monitoring
- Proton beam targetry
- Superconducting capture solenoid (high heat load and radiation)
- High-quality solenoid channels (to minimise particle trapping)
- Muon beam monitoring and late-arriving particle tagging (silicon detectors?) Rad-hard, very high dynamic ranges
- Precision stopping target
- 100 MeV single e⁻ gun for calibration
- Active cosmic-ray shielding
- Crystal calorimetry and precision tracking
- MPPCs?
- TPCs or other technologies?

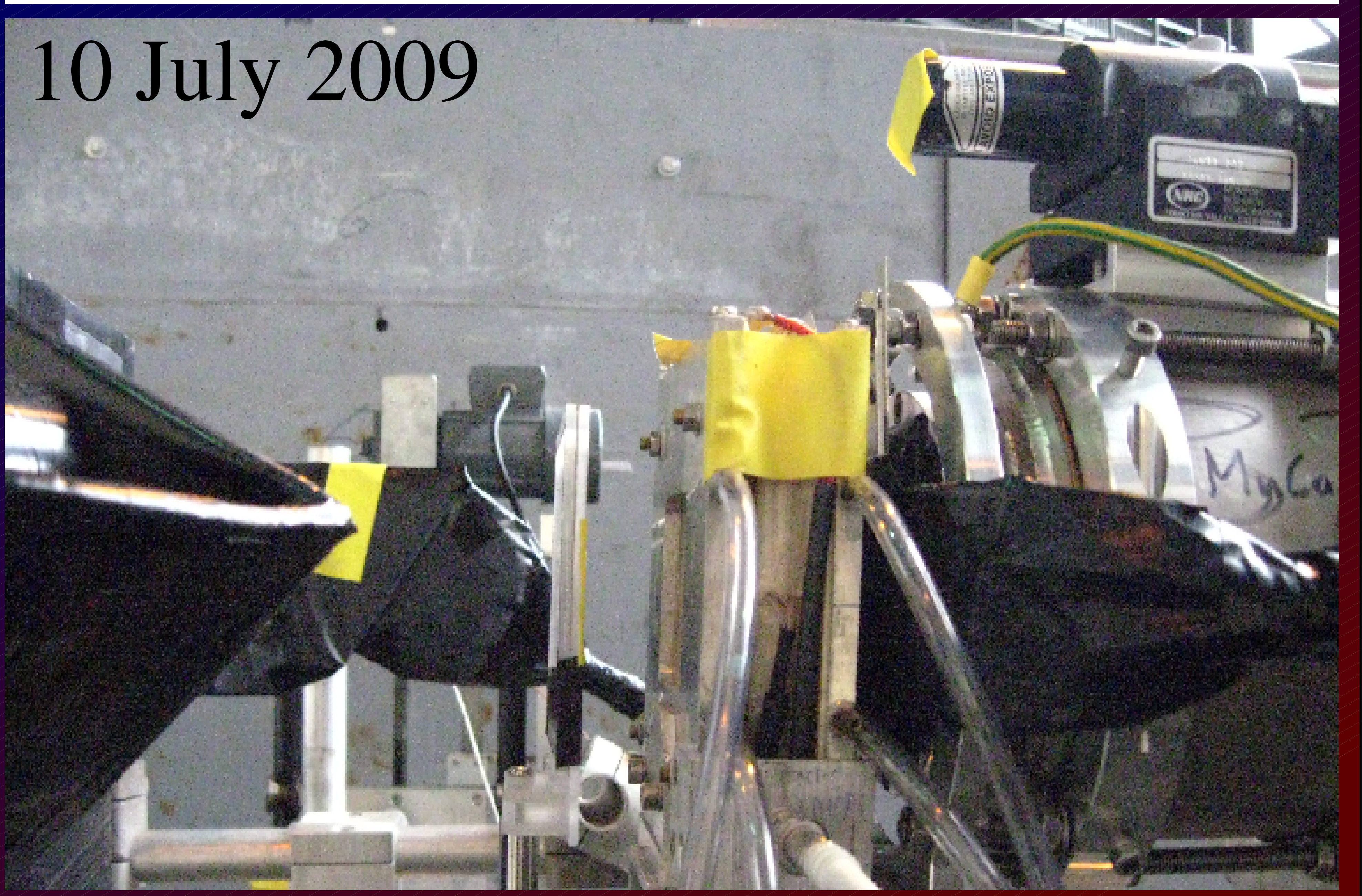


Many strong areas for the UK

Background Production Studies at PSI

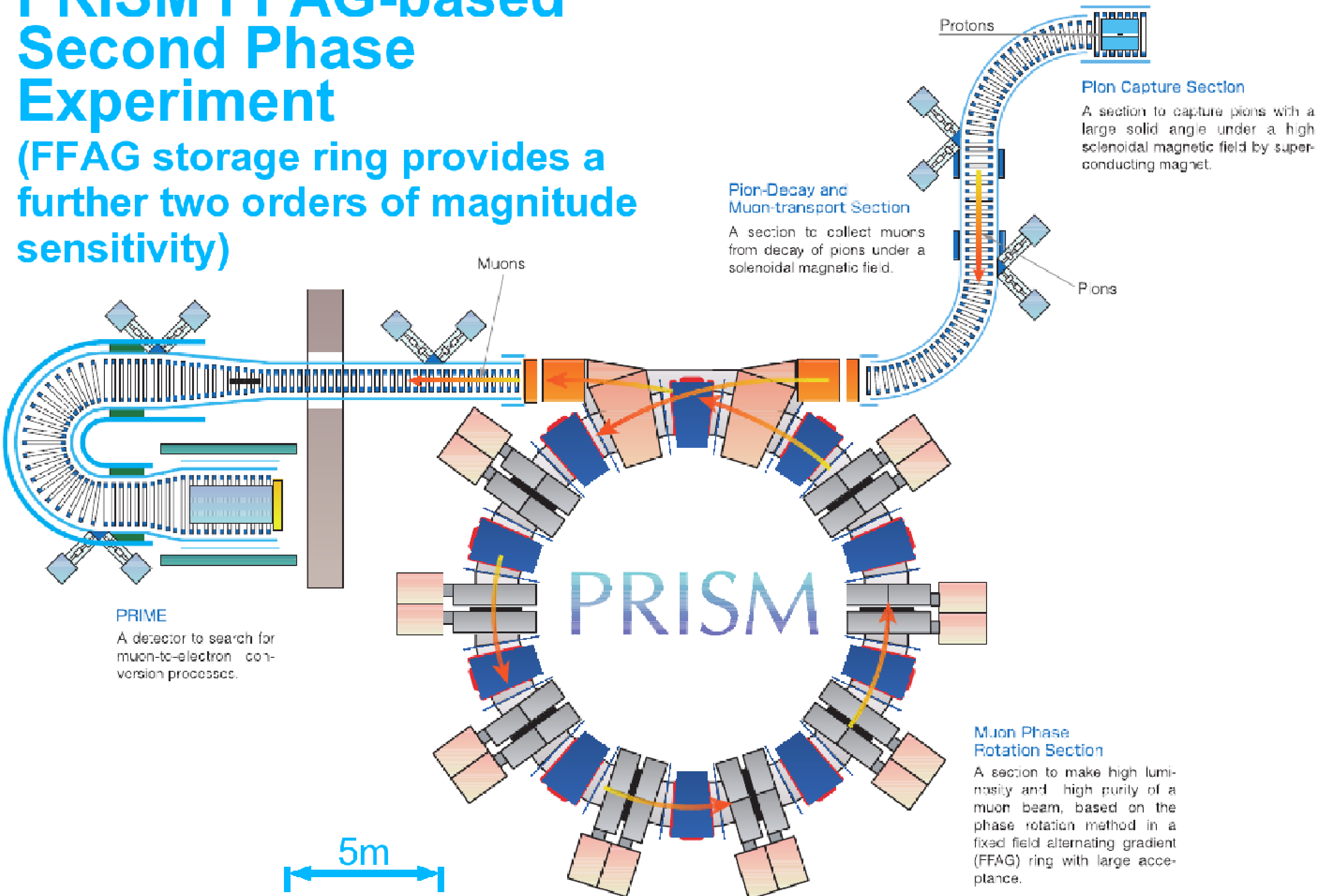
- Measurement programme just starting at PSI πE3 muon beam, led by $\mu 2e$ group
- To directly observe charged particle emissions from stopping target materials
- Initially protons, which COMET should be less sensitive to
- Many other R&D studies possible
- UK students participating





PRISM FFAG-based Second Phase Experiment

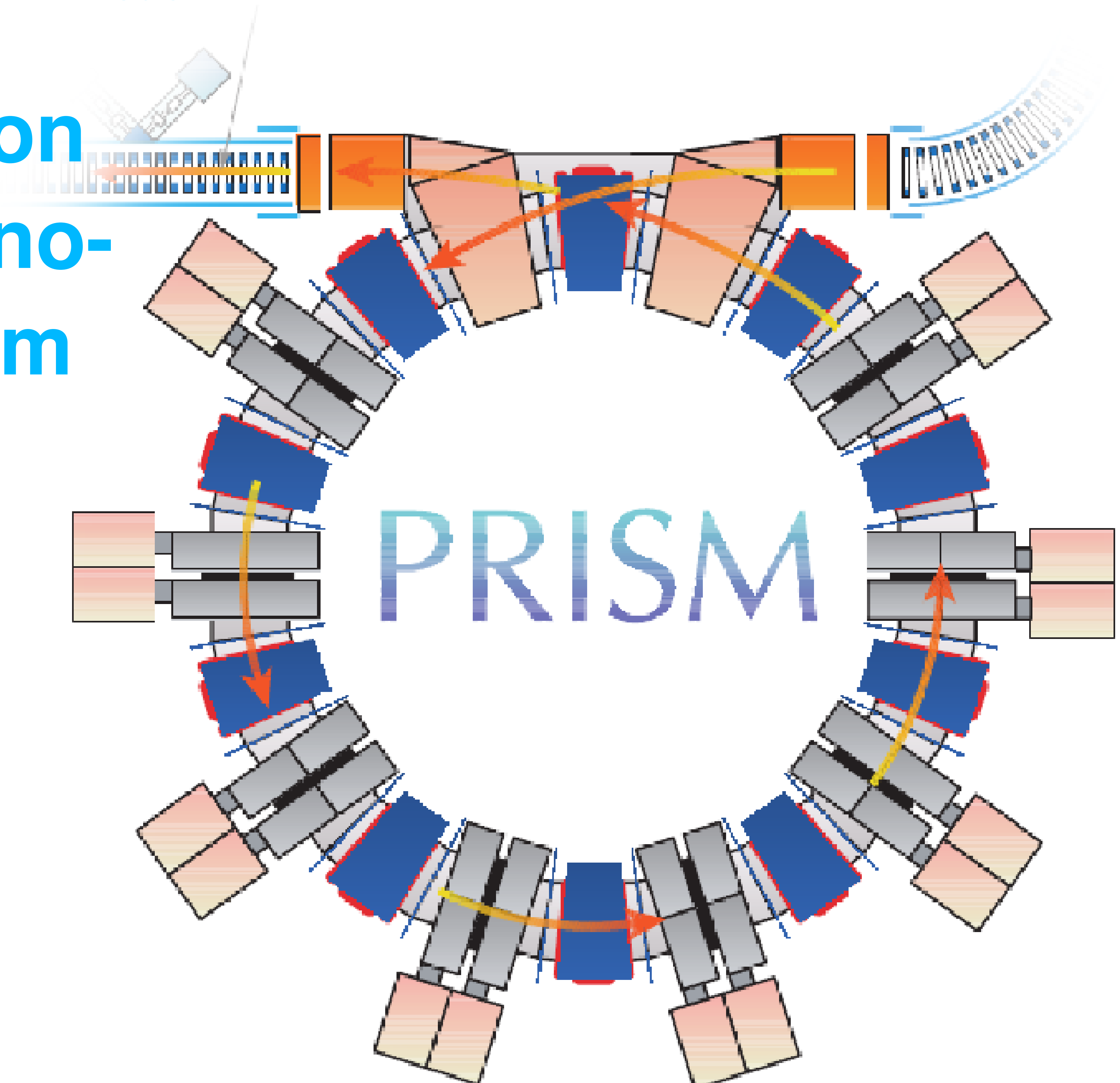
(FFAG storage ring provides a further two orders of magnitude sensitivity)



PRISM/FFAG

Muon Storage Ring

- **high acceptance**
  H: 40000 π mm mrad
  V: 6500 π mm mrad
- **phase-rotation produces mono-energetic beam**
- **8 turns gives a 150m path length**



PRISM/FFAG

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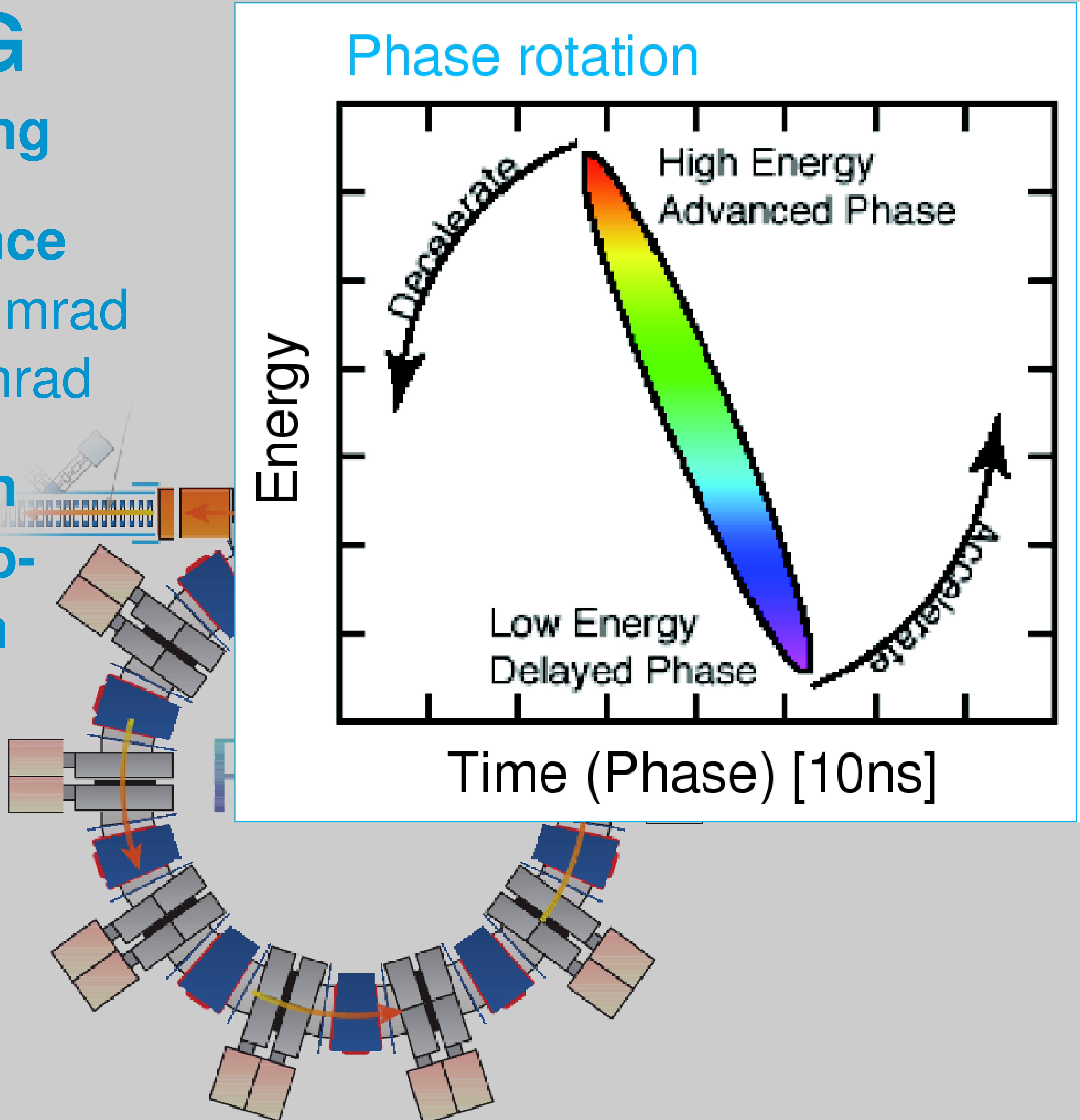


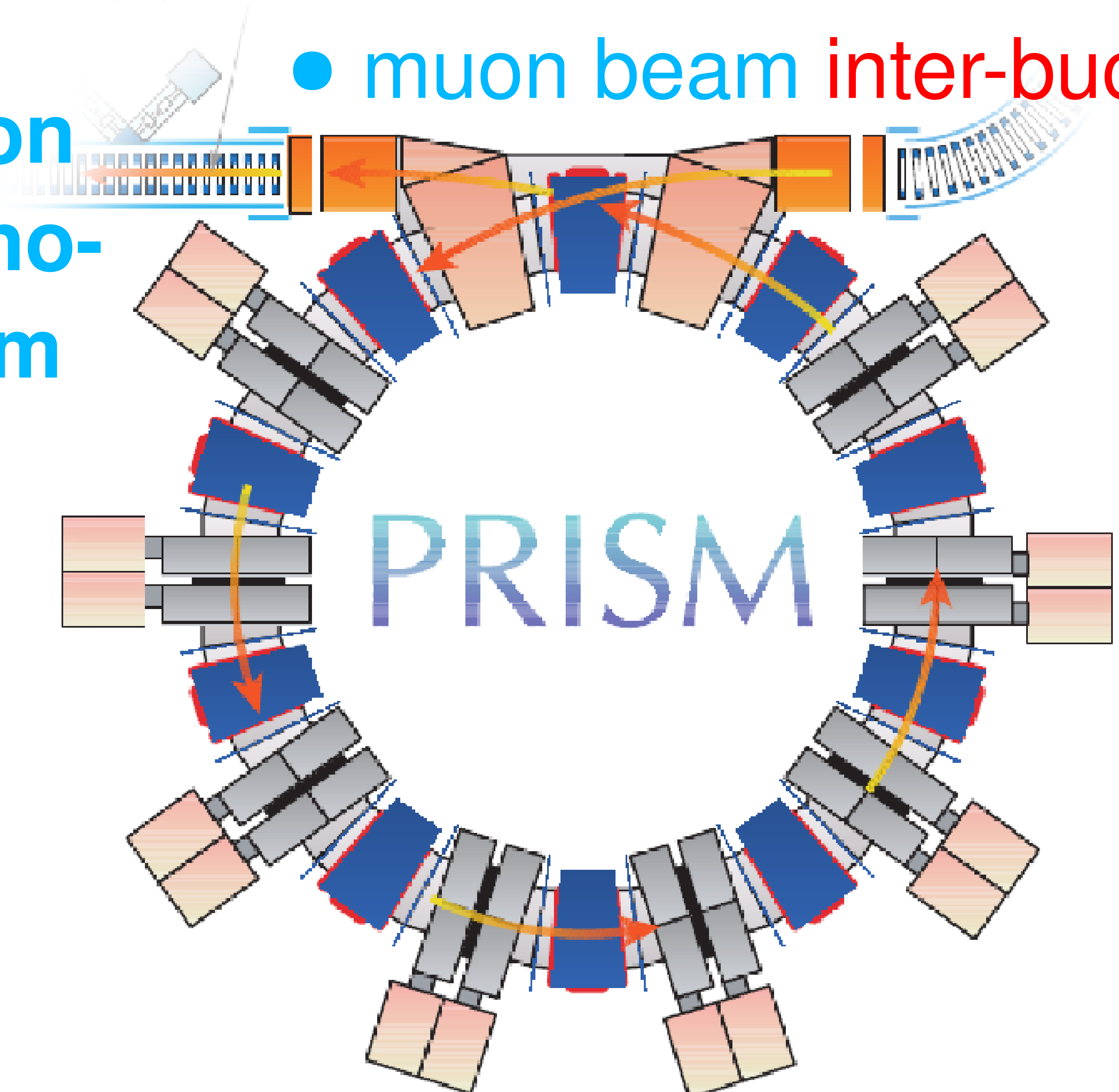
PRISM/FFAG

Muon Storage Ring

- **high acceptance**
  H: 40000 π mm mrad
  V: 6500 π mm mrad
- **phase-rotation produces mono-energetic beam**
- **8 turns gives a 150m path length**

Benefits:

- narrow momentum spread allows for thinner, better-optimised stopping target
- long path length makes residual pions negligible ($<10^{-20}$)
- muon beam inter-bucket extinction

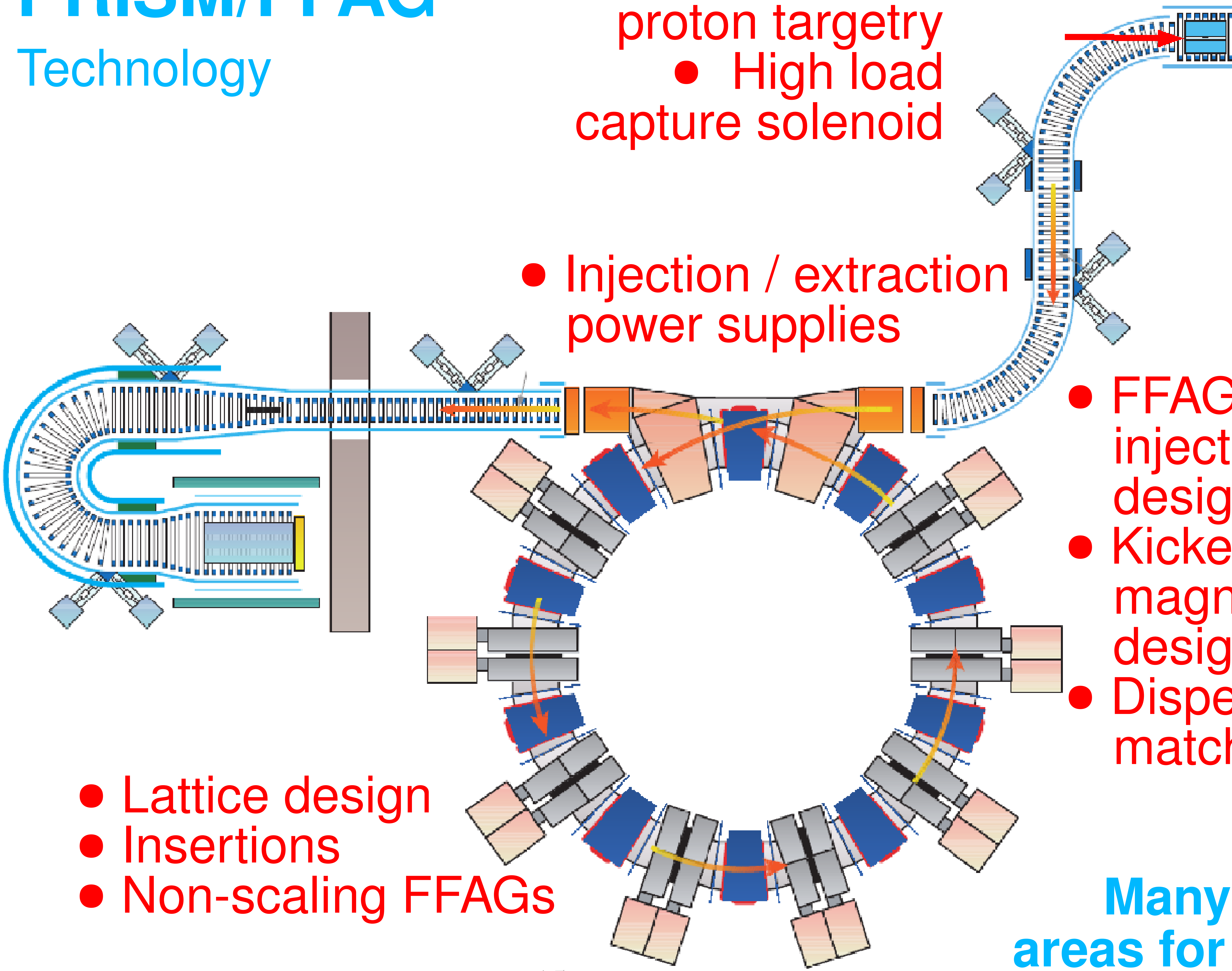


- allows higher intensity running
- lower duty cycle to reduce cosmic backgrounds

PRISM/FFAG

Technology

- 2MW-range proton targetry
- High load capture solenoid
- Injection / extraction power supplies
- FFAG beam injection design
- Kicker magnet design
- Dispersion matching

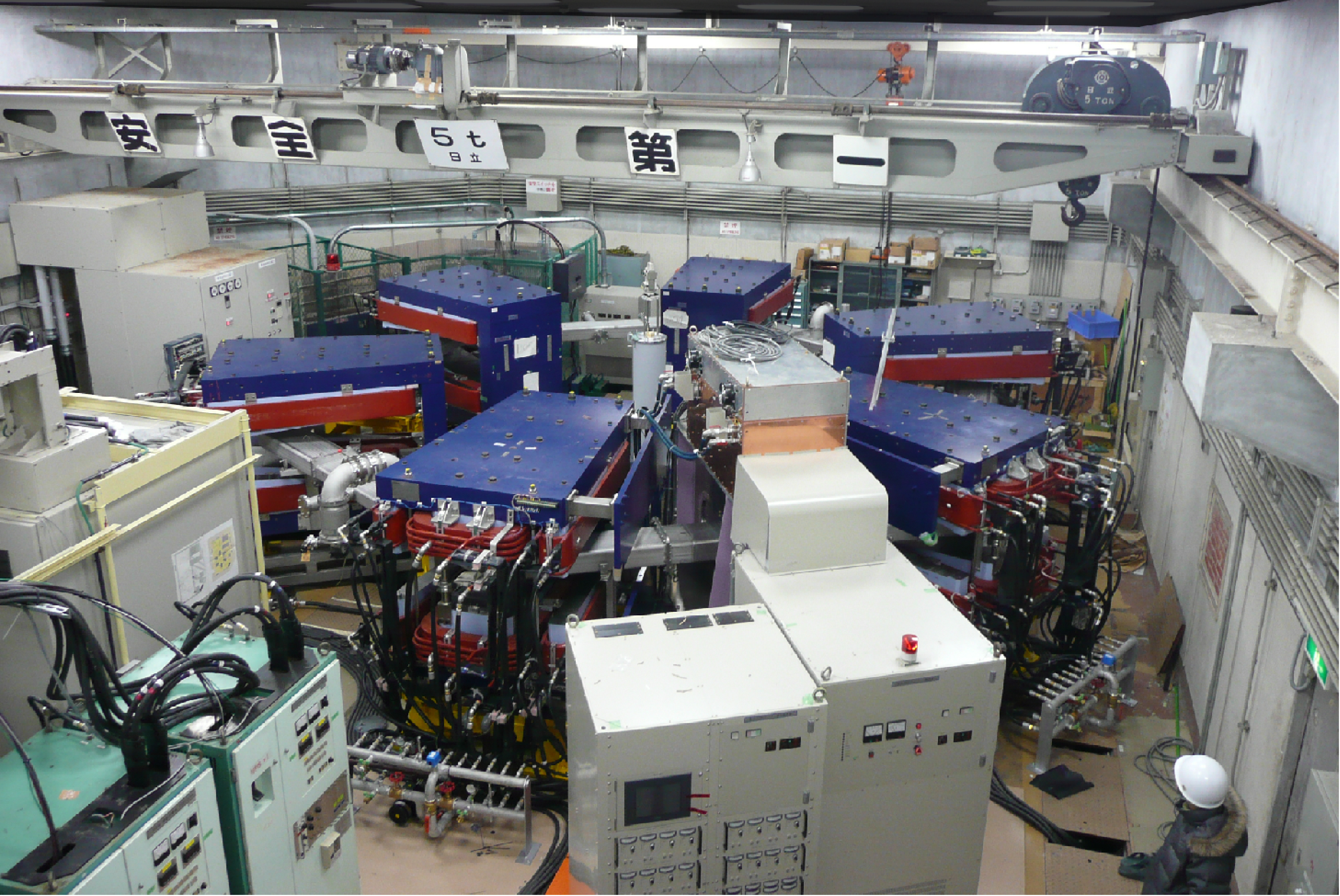


- Lattice design
- Insertions
- Non-scaling FFAGs

Many strong areas for the UK

The PRISM FFAG Ring for Muon-to-Electron Conversion

Prototype ring at Osaka University



PRISM Task Force

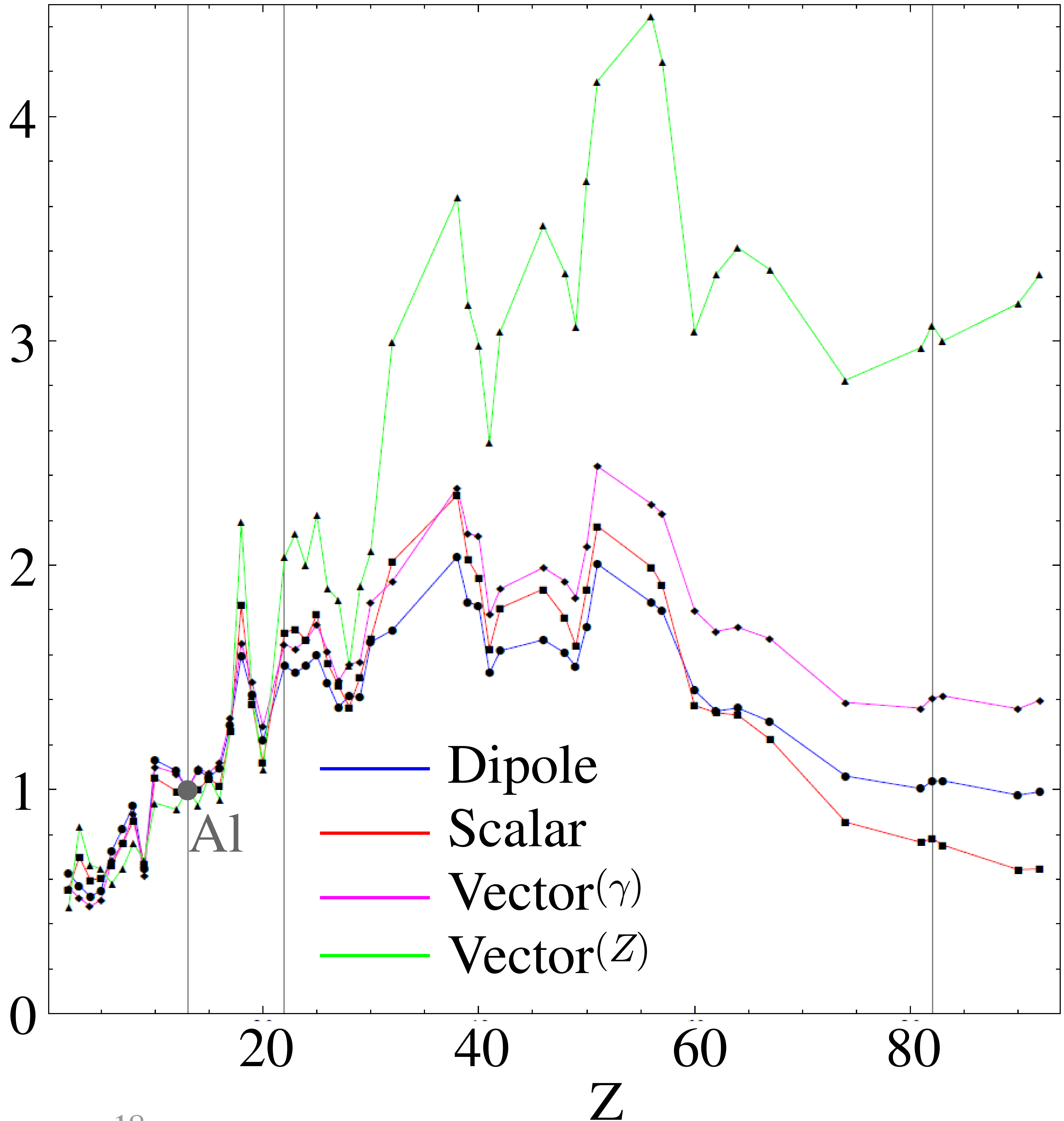
Recent PRISM/FFAG Workshop

- Recently formed to tackle outstanding issues
  - Targetry, pion capture, superconducting solenoids
  - FFAG ring design, injection and kicker design
  - Potential for non-scaling FFAG use etc
- To produce a Conceptual Design Report in about a year
- International membership with participants from
  - UK: Currently RAL and Daresbury labs, ASTeC, Cockcroft Institute, the John Adams Institute, Imperial and UCL
  - Osaka, Kyoto, KEK & possibly the US, France etc
- Report from Task Force could bring forward plans for PRISM

The relative dependences of the muon-to-electron conversion branching ratio on the target nucleus, for different models of New Physics interactions

Cirigliano, Kitano, Okada, and Tuzon, arXiv:0904.0957

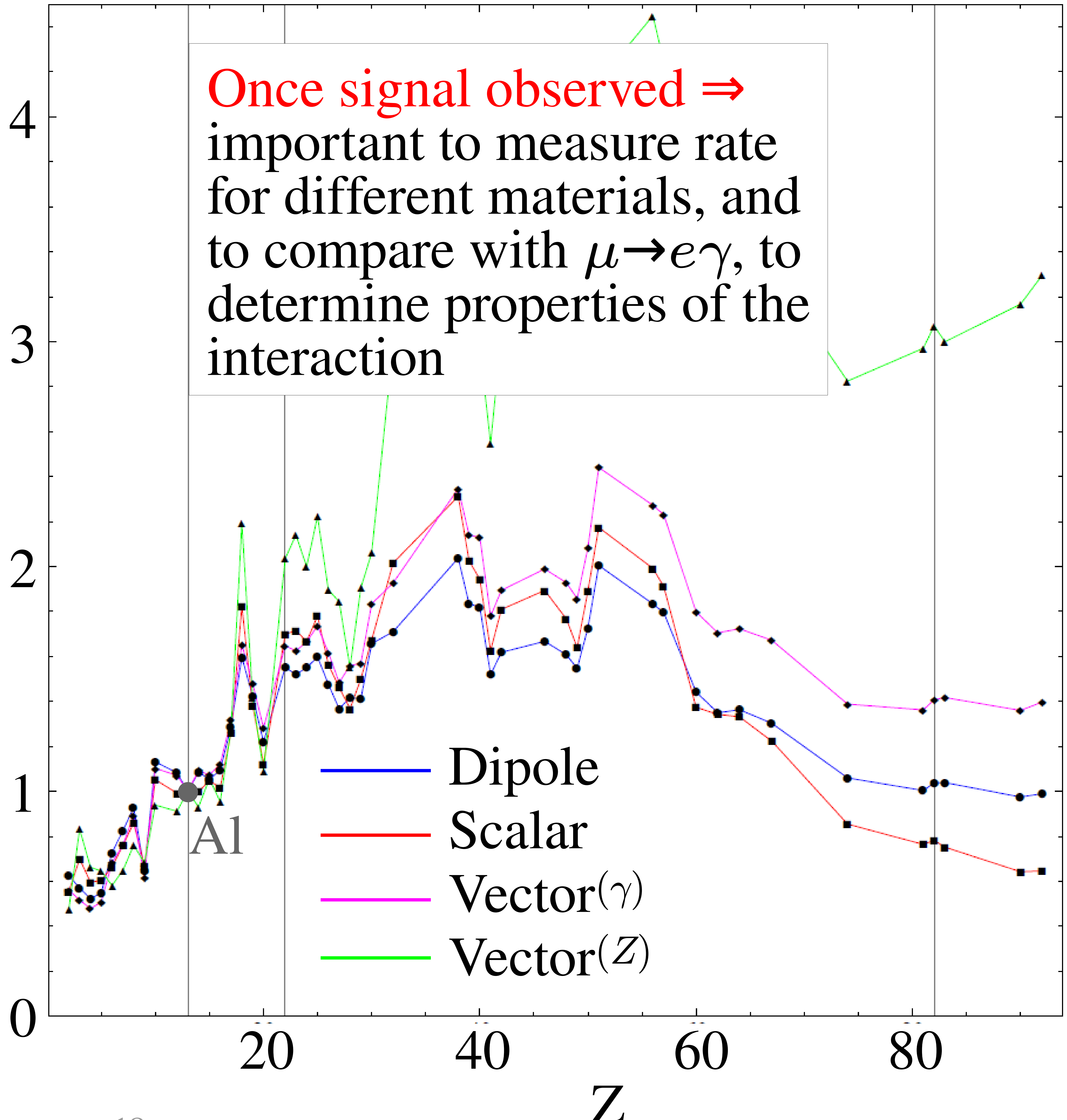
(Predictions for $\mu \to e\gamma$ also given)



The relative dependences of the muon-to-electron conversion branching ratio on the target nucleus, for different models of New Physics interactions

Cirigliano, Kitano, Okada, and Tuzon, arXiv:0904.0957

(Predictions for $\mu \to e\gamma$ also given)



Once signal observed ⇒ important to measure rate for different materials, and to compare with $\mu \to e\gamma$, to determine properties of the interaction

The COMET/PRISM Programme

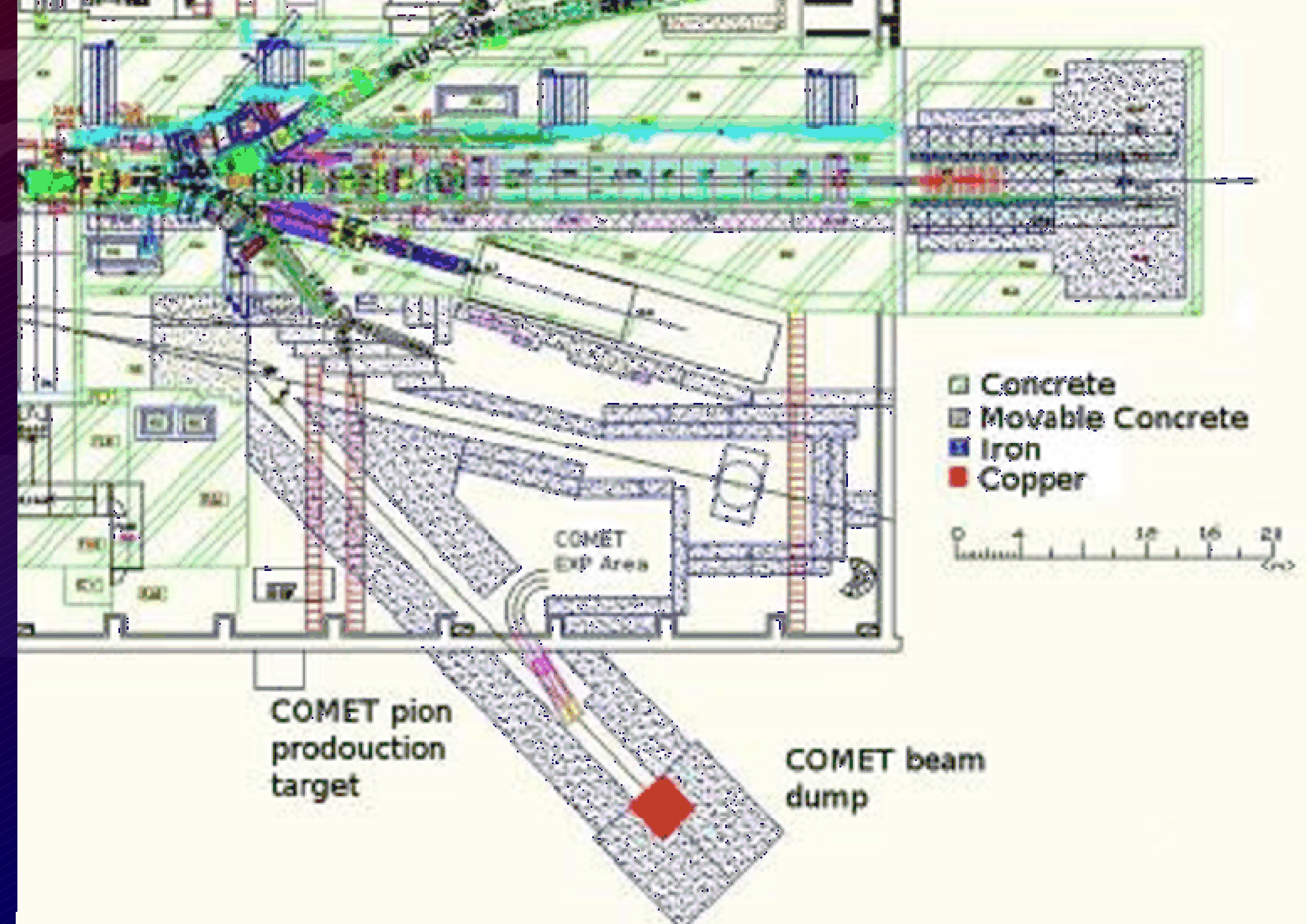
COMET: construction start in 3, 4 years, data 4 years later

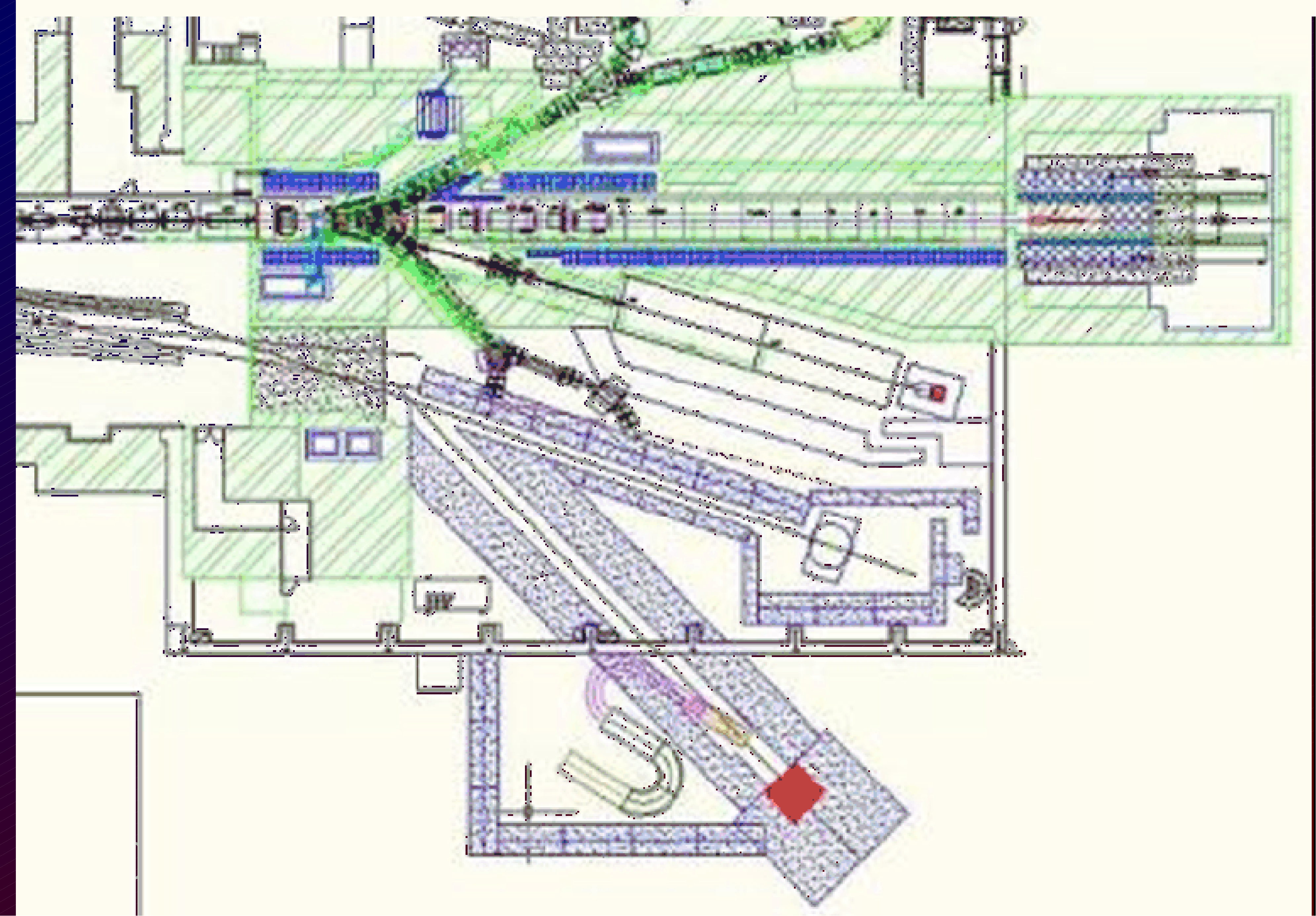
Roughly £50M for hardware ($\sim$50% SC solenoids)

PRISM: to follow COMET

Still much freedom in the implementation choices

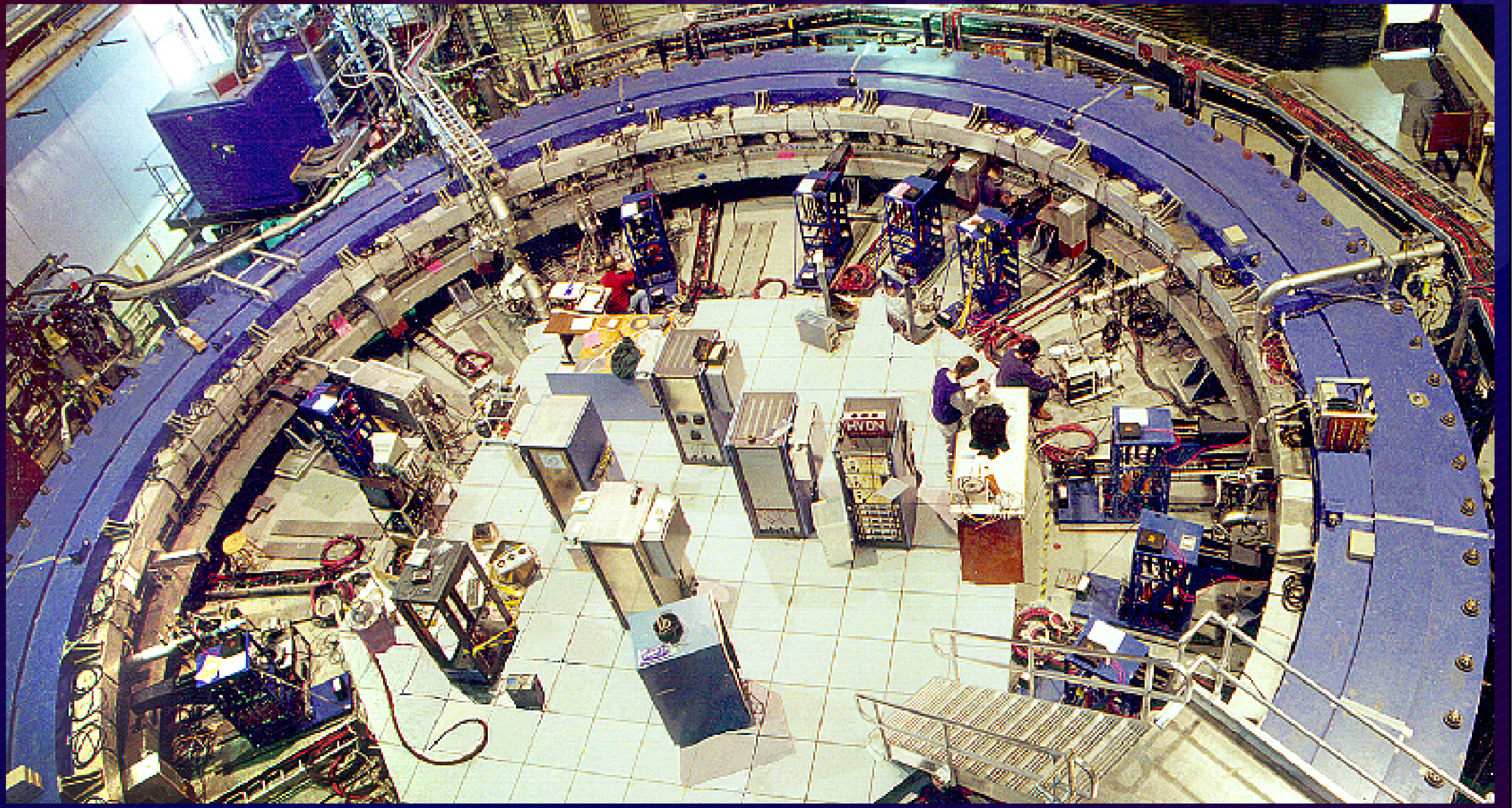
- layout
- technologies
  - Beam monitors, Electron detector, TPCs etc, Calibration
- PRISM location and R&D programme

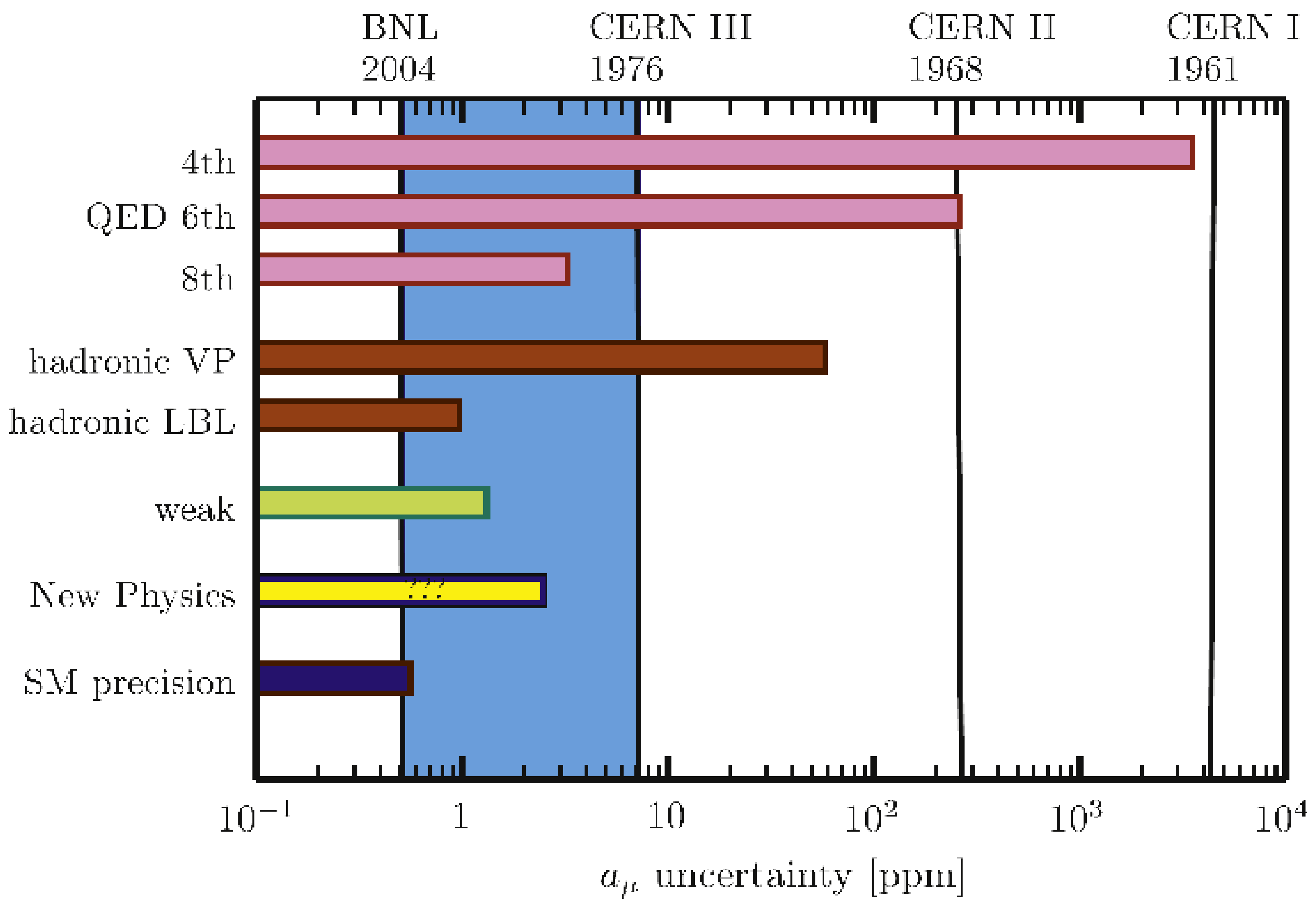




Muon $g-2$

- Beautiful experiment at Brookhaven (0.54ppm result, a factor 14 improvement), final result statistics dominated
- About 3.2σ (2.5ppm) discrepancy with SM theory (low-E hadronic uncertainties)
- Proposal to move experiment to Fermilab, set up with $\mu 2e$ (< $20M additional cost)
  - beamline and detector upgrades for improved statistics and contamination
- Separate proposal at J-PARC





Conclusions

- Muons highly promising for huge leap in new physics sensitivity
  - directly related to UK interest in neutrinos oscillations etc
- μ-e conversion particularly suited to very high muon intensities
- Potential for major discovery then precision measurements
- World-class muon-to-electron conversion technology development is already being pursued in the UK (silicon detectors, calorimetry, MPPCs, Neutrino Factory, FFAGs, MICE, ISIS upgrades etc)
- Current UK expertise ready for COMET, a next-generation experiment
  - gain experience in building and using novel, tailor-made muon beamlines and performing challenging signal searches
- PRISM offers factor 1,000,000 sensitivity improvement, where UK technological contributions will be critical
- UK community already involved in both COMET and PRISM


Comet
California
CPFC

Current Experimental Limits on Lepton Flavour Violation

- 90% C.L. upper limits on the branching ratio

Reaction	Present limit
$\mu^+ \to e^+\gamma$	$< 1.2 \times 10^{-11}$
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$
$\mu^- Ti \to e^- Ti$	$< 6.1 \times 10^{-13}$
$\mu^- Au \to e^- Au$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$
$\tau \to e\gamma$	$< 3.9 \times 10^{-7}$
$\tau \to \mu\gamma$	$< 3.1 \times 10^{-7}$
$\tau \to \mu\mu\mu$	$< 1.9 \times 10^{-7}$
$\tau \to eee$	$< 2.0 \times 10^{-7}$
$\pi^0 \to \mu e$	$< 8.6 \times 10^{-9}$
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+\mu^+e^-$	$< 2.1 \times 10^{-10}$
$K_L^0 \to \pi^0\mu^+e^-$	$< 3.1 \times 10^{-9}$
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau\mu$	$< 1.2 \times 10^{-5}$

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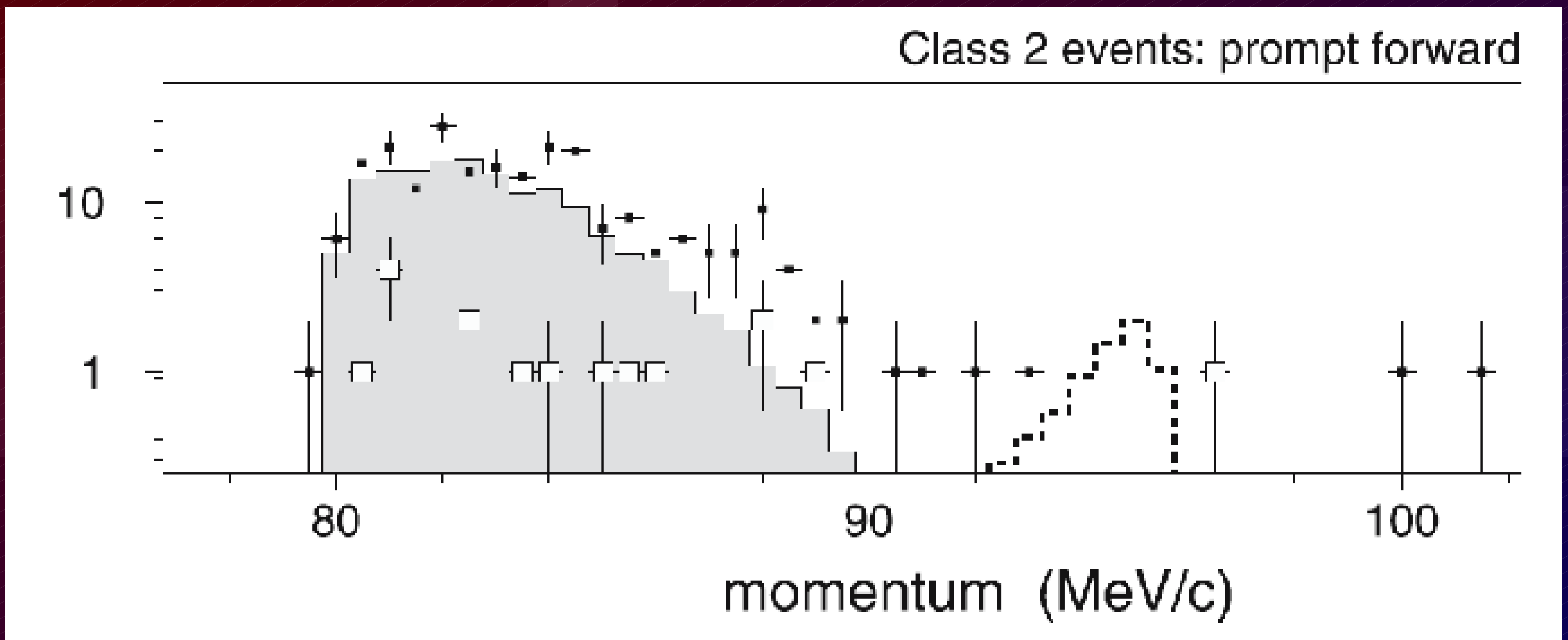
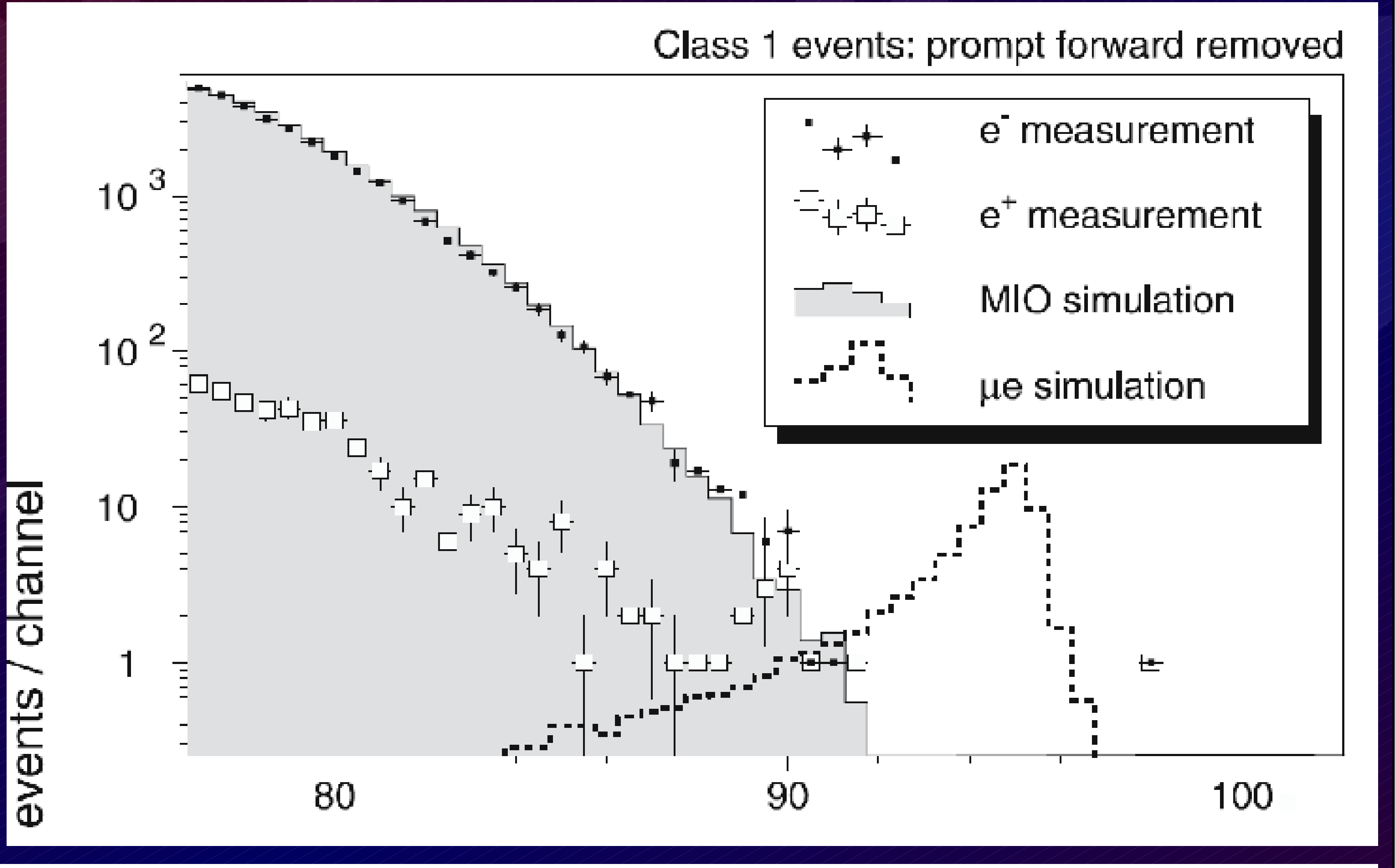
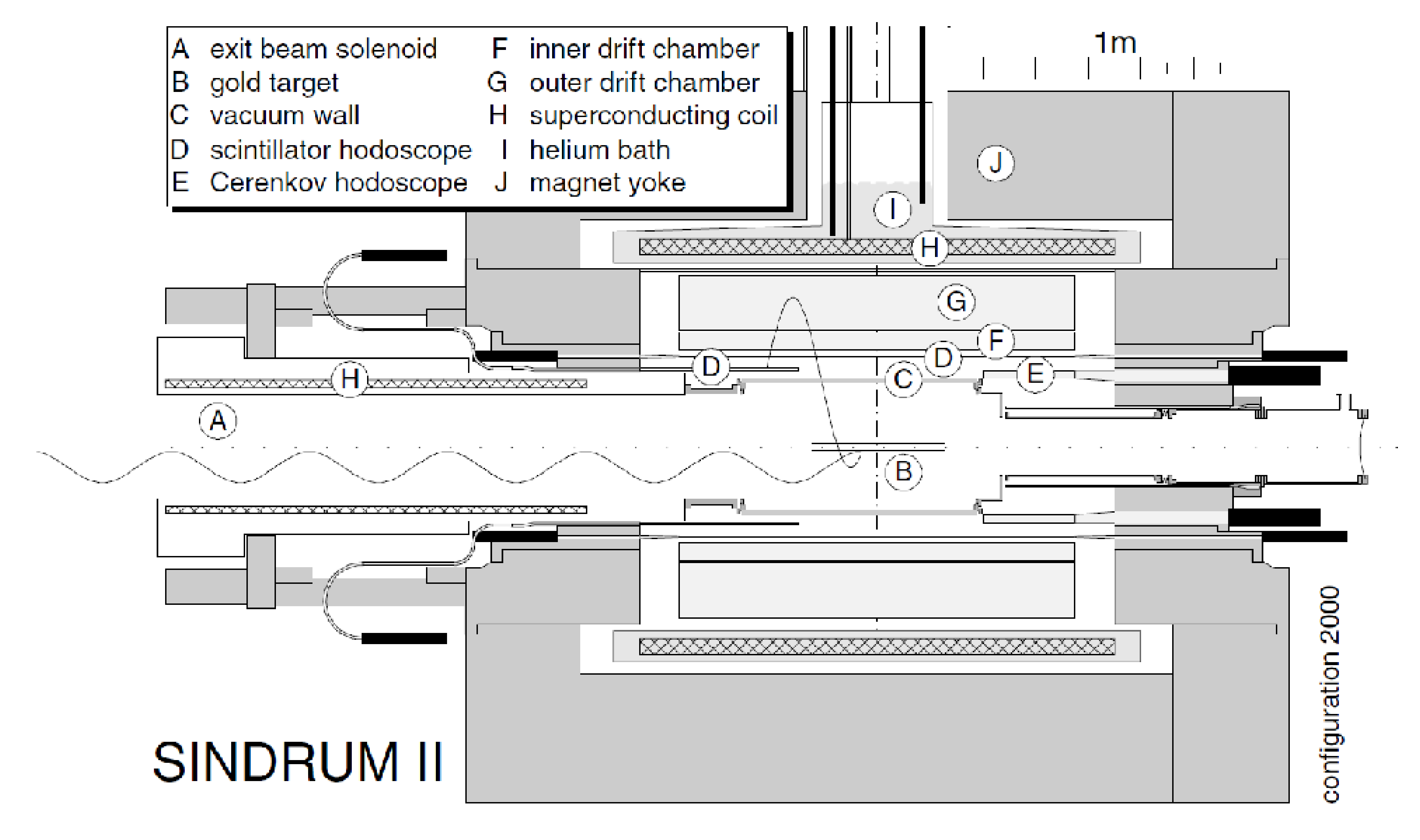
SINDRUM II at PSI







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Pion Capture Solenoid Design

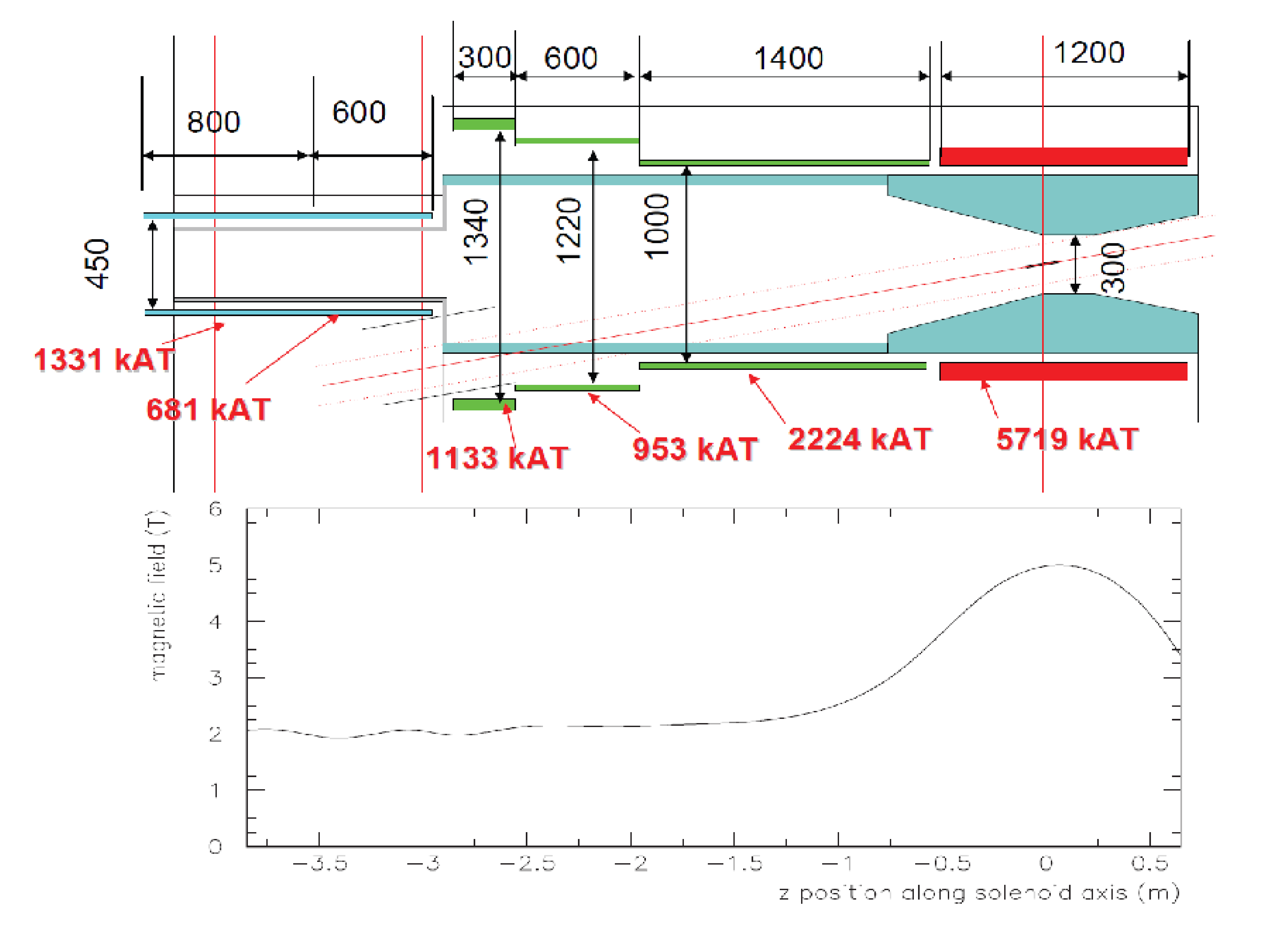

Figure 12.1: A layout of the pion capture solenoid system.

- 30 W heatload
- About 6.6×10^{21} neutrons/m^2

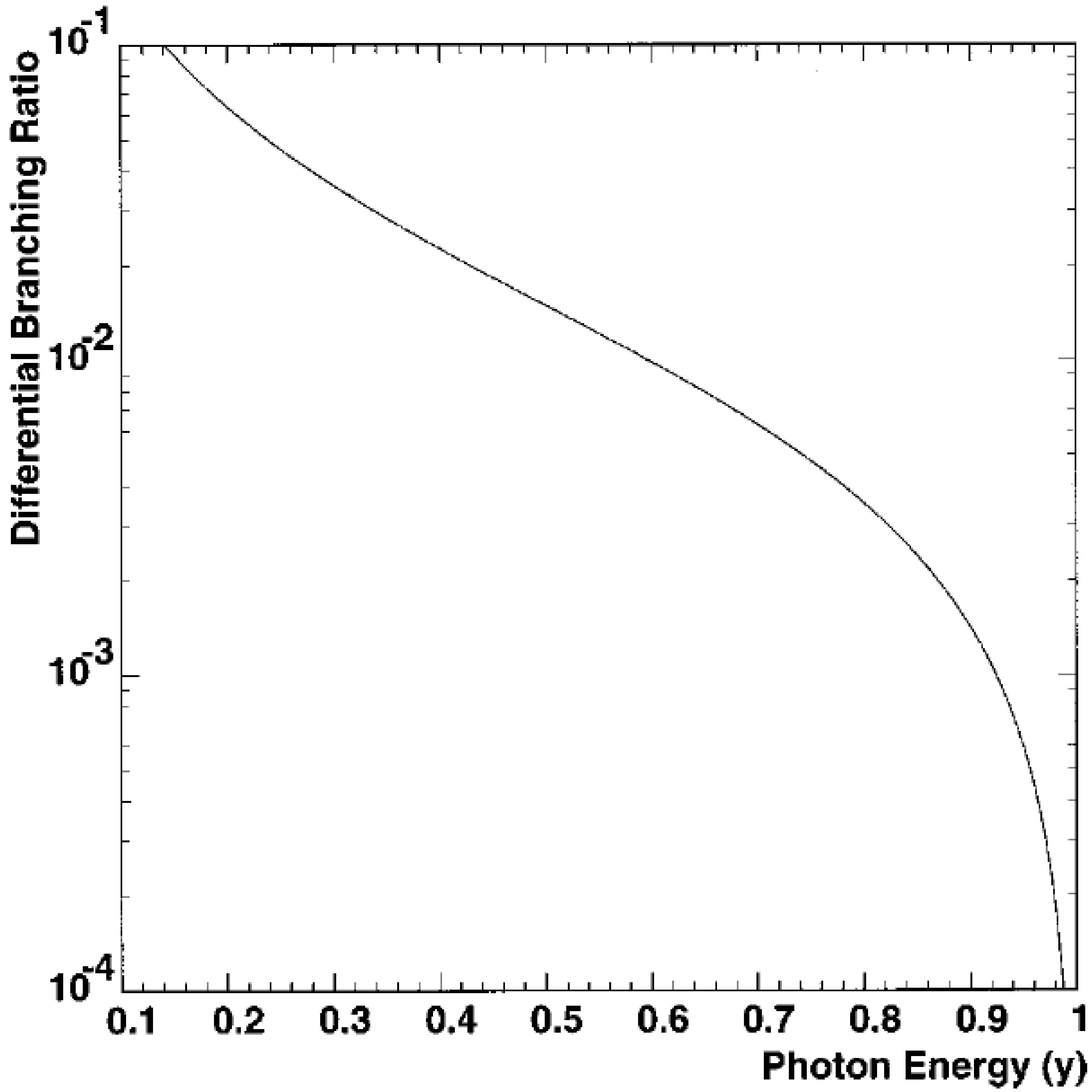

FIG. 3. Differential branching ratio of the $\mu^{\pm} \to e^{\pm} \nu \overline{\nu} \gamma$ decay as a function of the photon energy ($y \equiv 2E_{\gamma}/m_{\mu}$). This branching ratio is obtained by integrating over the e^{+} energy and the angle between an e^{+} and a photon.

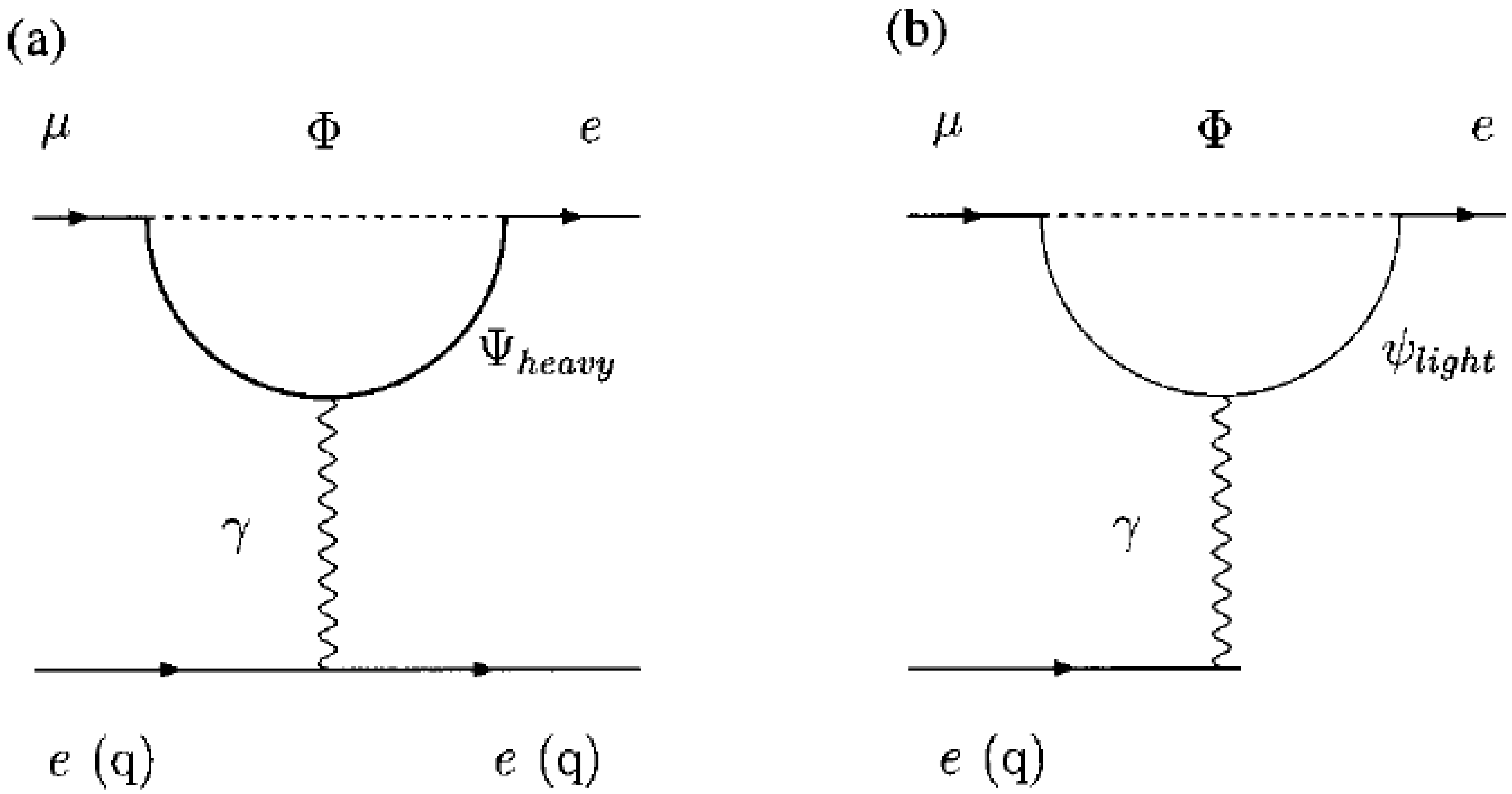

FIG. 4. Photonic penguin diagrams for $\mu - e$ trans
as $\mu^+ \rightarrow e^+ e^+ e^-$ or $\mu^- - e^-$ conversion: (a) the cas
particle (Ψ_{heavy}) in the loop; (b) the case of a li
(ψ_{light}) in the loop. Φ is a scalar field.

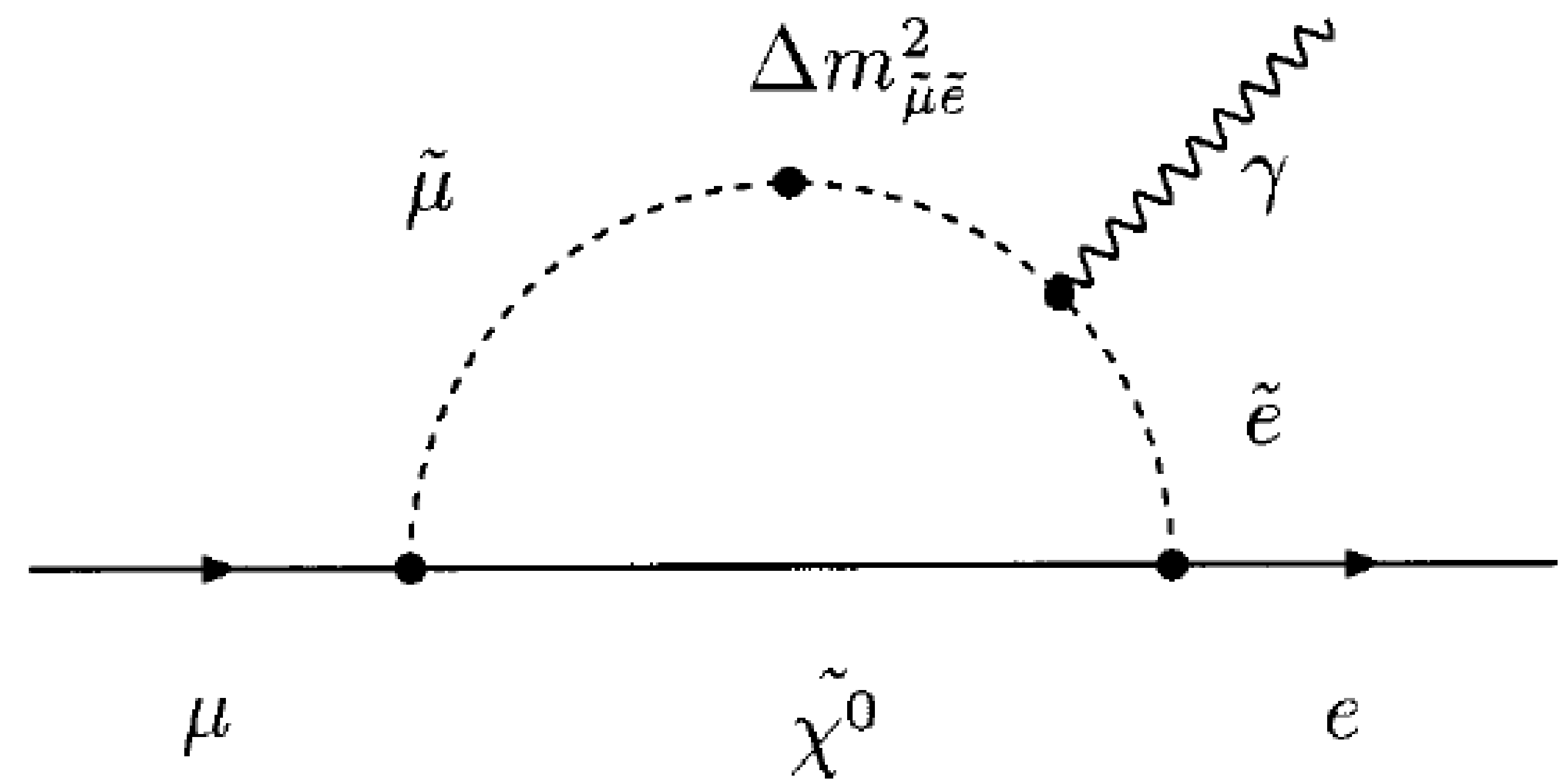

FIG. 5. Feynman diagram for $\mu^+ \rightarrow e^+ \gamma$ decay induced by slepton flavor mixing ($\Delta m^2_{\tilde{\mu}\tilde{e}}$).

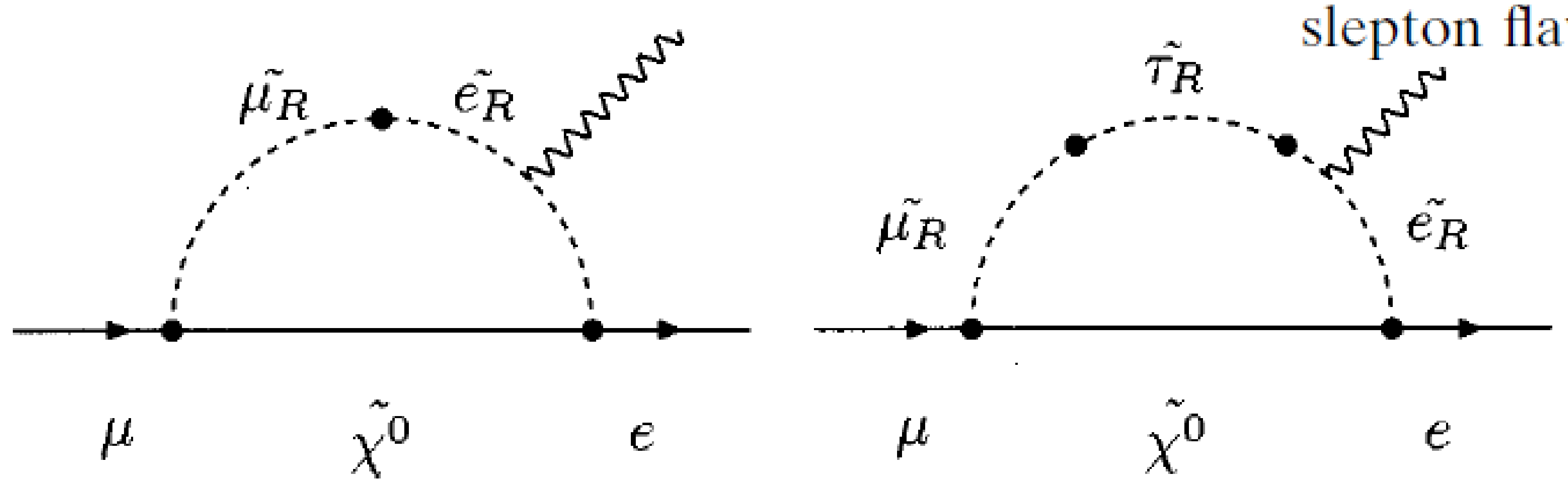

FIG. 7. Feynman diagrams for the $\mu^+ \rightarrow e^+ \gamma$ decay in $SU(5)$ SUSY GUT. The closed blobs represent the flavor transitions due to the off-diagonal terms of the slepton mass matrices.

Table 11.9: Summary of Estimated Backgrounds.

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

‡ Monte Carlo statistics limited.

Muon yield breakdown for COMET (from the CDR)

Total number of protons: N_p	8.5×10^{20}	
Proton kinetic energy	8	[GeV]
Harmonics of MR	8	
Bunch time spacing	657	[nsec]
Number of RF bunches filled with protons per spill	4	
Time between adjacent filled bunches	1314	[nsec]
Number of protons in each RF bunch	1.6×10^{13}	
Cycle time of MR (=spill period)	1.47	[sec]
Flat top for the slow extraction	0.7	[sec]
Number slow-extracted pulse in a spill	5.3×10^{5}	[pulses/spill]
Number of Protons in each slow-extracted pulse	1.2×10^{8}	
Average beam current	7.0	[μA]
Average beam power	56	[kW]
Average proton intensity	4.4×10^{13}	[protons/sec]
Total running time	2.0×10^{7}	[sec]
Running time per year	1.0×10^{7}	[sec/year]
Number of stopped muons per proton: $N_{\mu/p}^{stop}$	0.0023	[muons/proton]
Rate of muons per proton transported to the target	0.0035	[muons/proton]
Muon stopped acceptance	0.66	
Number of stopped muons: $N_{\mu/year}^{stop}$	1.0×10^{18}	[muons/year]
Total number of stopped muons: N_{μ}^{stop}	2.0×10^{18}	

Summary of the expected sensitivity for 2.0×10^7 sec running (I)

Total number of protons: N_p	$\mathbf{8.5 \times 10^{20}}$	
Proton kinetic energy	8	[GeV]
Harmonics of MR	8	
Bunch time spacing	657	[nsec]
Number of RF bunches filled with protons per spill	4	
Time between adjacent filled bunches	1314	[nsec]
Number of protons in each RF bunch	1.6×10^{13}	
Cycle time of MR (=spill period)	1.47	[sec]
Flat top for the slow extraction	0.7	[sec]
Number slow-extracted pulse in a spill	5.3×10^5	[pulses/spill]
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Average beam power	56	[kW]
Average proton intensity	4.4×10^{13}	[protons/sec]
Total running time	2.0×10^7	[sec]
Running time per year	1.0×10^7	[sec/year]

Number of stopped muons per proton: $N_{\mu/p}^{stop}$	**0.0023**	[muons/proton]
Rate of muons per proton transported to the target	0.0035	[muons/proton]
Muon stopped acceptance	0.66	
Number of stopped muons: $N_{\mu/year}^{stop}$	1.0×10^{18}	[muons/year]
Total number of stopped muons: N_{μ}^{stop}	2.0×10^{18}	

Summary of the expected sensitivity for 2.0×10^7 sec running (II)

Fraction of captured muon: f_{cap}	**0.61**

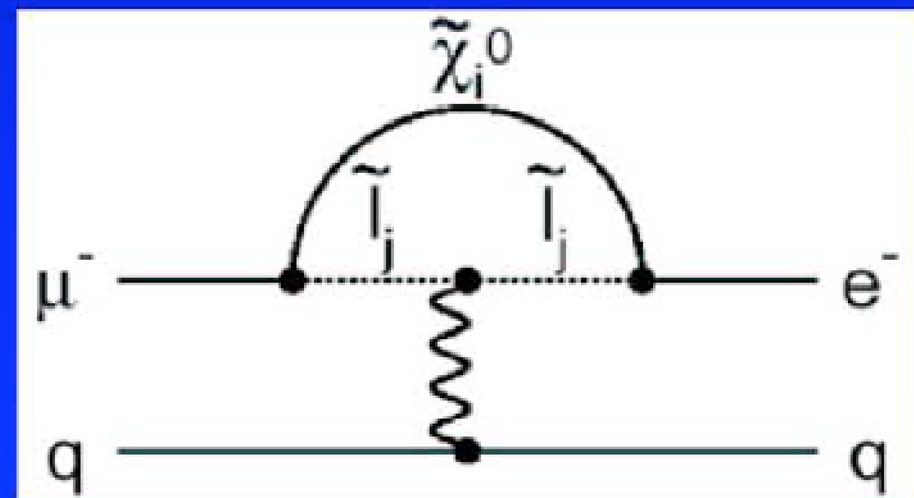
Net acceptance: $A_{\mu\text{-}e}$	**0.031**
Geometrical acceptance, fitting and selection criteria	0.09
Solid angle with mirroring acceptance	*(0.73)*
Muon beam stop acceptance	*(0.57)*
Curved solenoid acceptance	*(0.47)*
Track reconstruction efficiency	*(0.88)*
Track quality cut efficiency	*(0.89)*
Transverse momentum cut efficiency	*(0.83)*
E/p cut efficiency	*(0.99)*
Helix pitch cut efficiency	*(0.99)*
Momentum selection efficiency	*(0.72)*
Timing window selection efficiency	0.39
Trigger acceptance and DAQ live efficiency	0.90

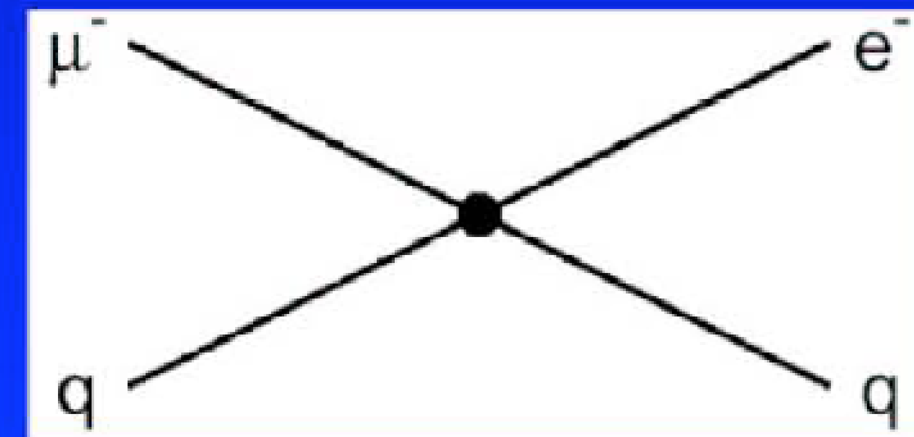
Single event sensitivity = $(N_p \cdot N_{\mu/p}^{stop} \cdot f_{cap} \cdot A_{\mu\text{-}e})^{-1}$	**2.6×10^{-17}**
90% confidence level upper limit	**6.0×10^{-17}**
Events per 1×10^{-16} BR	**3.8**

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}





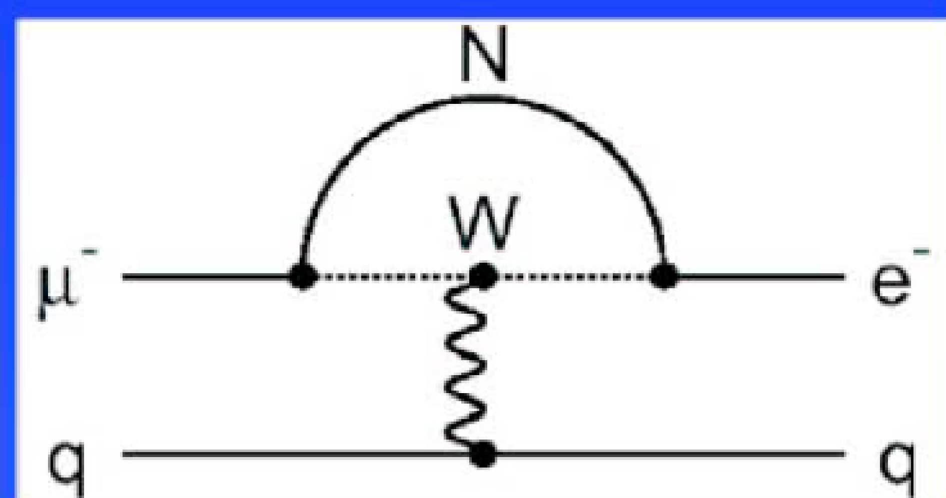
Compositeness

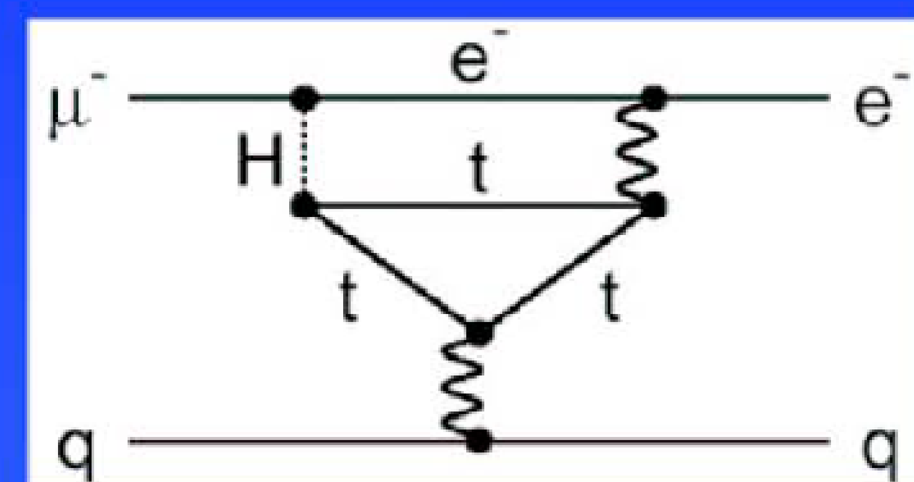
$\Lambda_c = 3000$ TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2 =$

8×10^{-13}





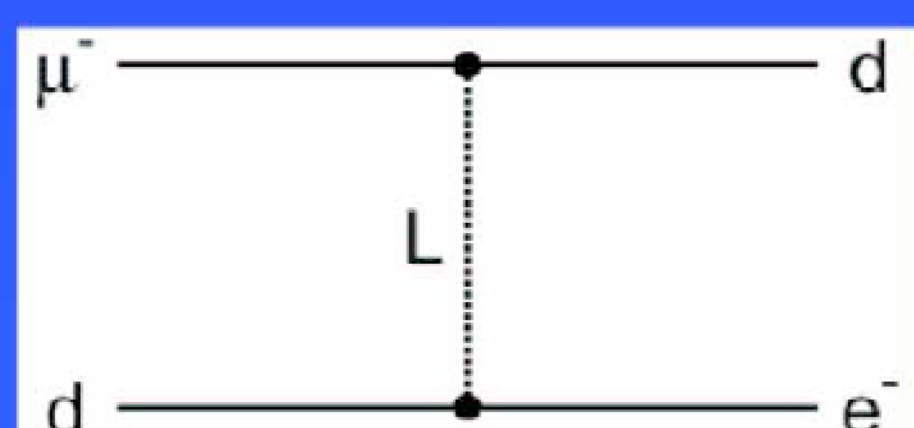
Second Higgs doublet

$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$

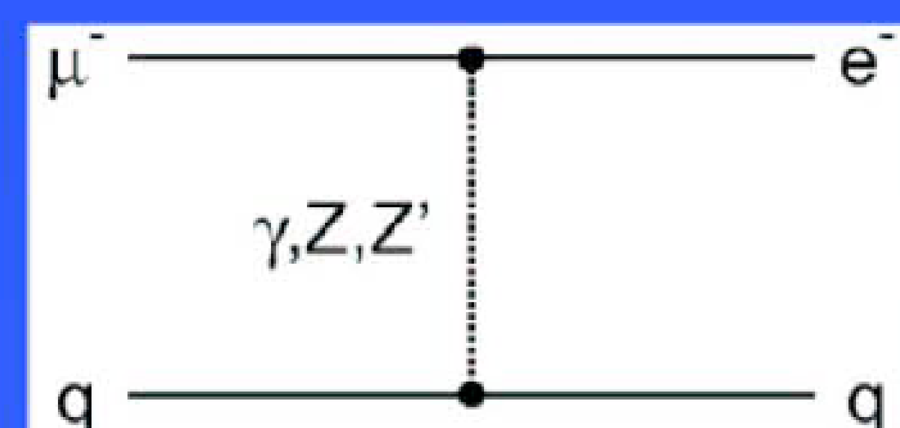
Leptoquarks

$M_L =$

$3000 \, (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



After W. Marciano

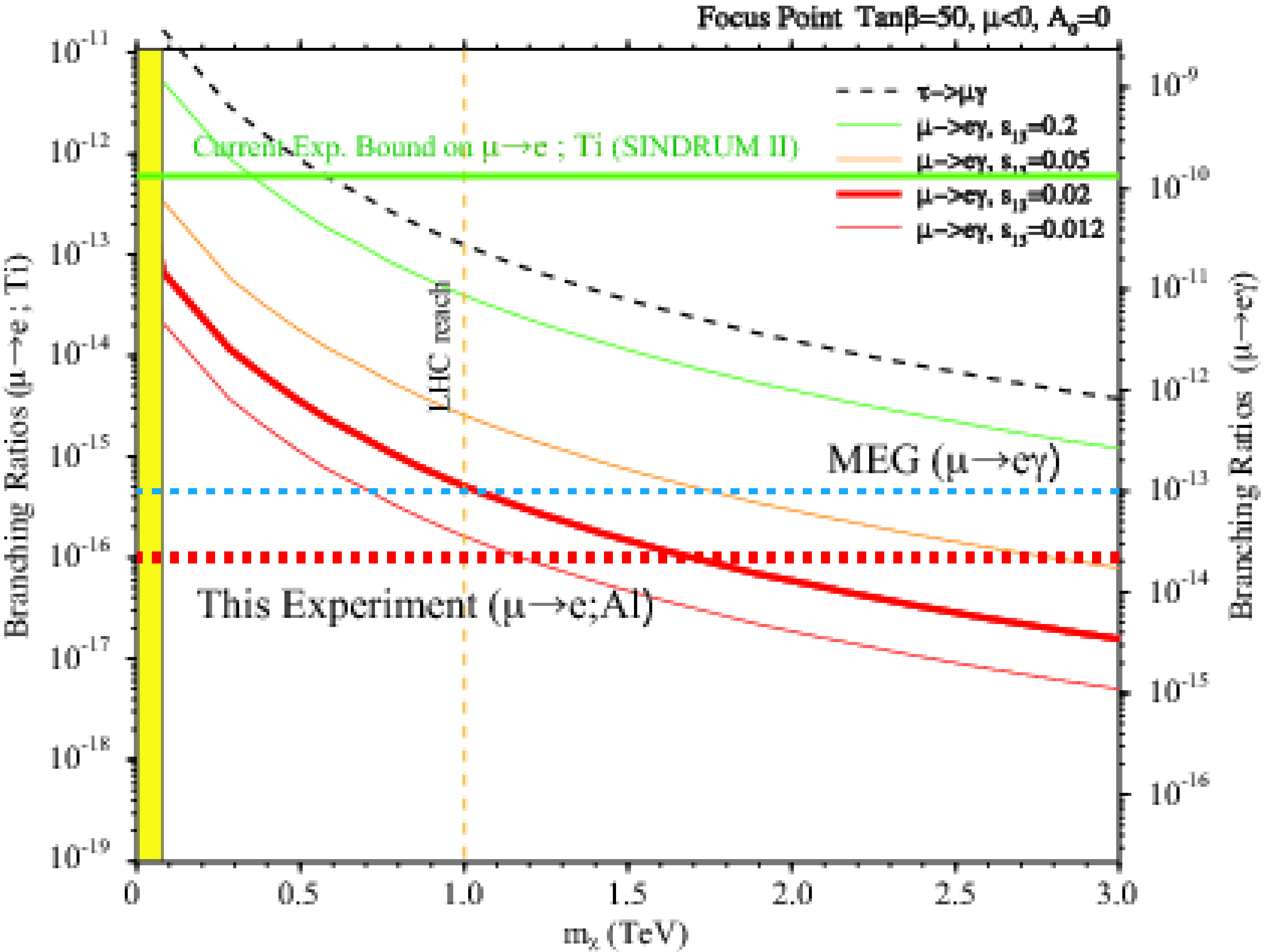


Heavy Z', Anomalous Z coupling

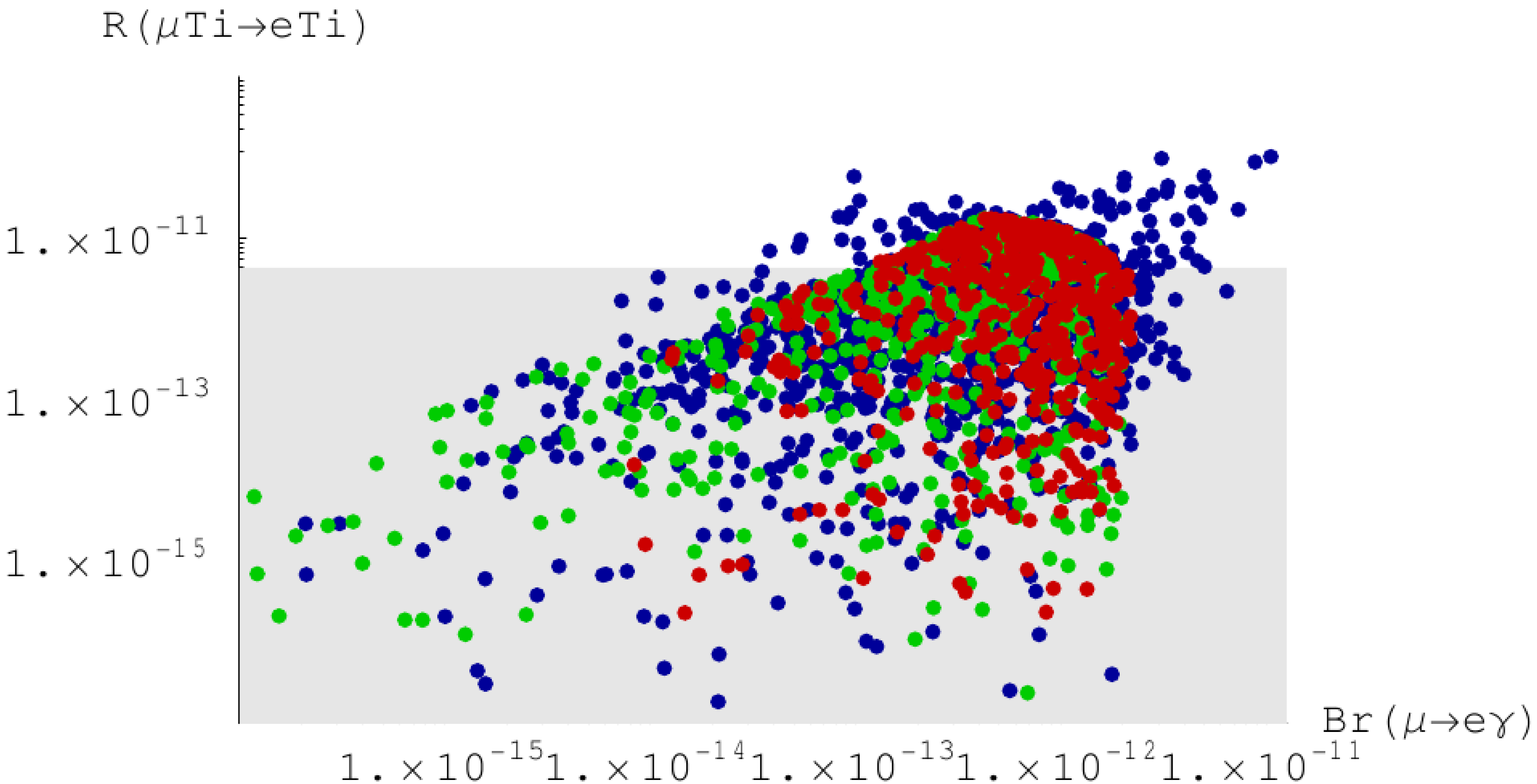
$M_{Z'} = 3000$ TeV/c^2

$B(Z \to \mu e) < 10^{-17}$

Prediction of the muon-to-electron conversion branching ratio in the SUSY-seesaw models as a function of SUSY neutralino mass scale (Masiero, Profumo, Vempoti, and Yaguna JHEP 0403:046)



Muon-to-electron conversion rate as a function of Br(μ → eγ), for littlest Higgs models.
Blanke, Buras, Duling, Poschenrieder, Tarantino JHEP **0705** 013



J-PARC PAC Report March 2008

The PAC is impressed with the physics capabilities of the proposed COMET experiment and believes that this experiment could become one of the flagship experiments in the J-PARC program. On the other hand, this is a very difficult experiment and will demand large resources from the collaboration and the laboratory. A detailed assessment by the PAC and Laboratory of the feasibility for making such a precise measurement will need a more detailed design and simulation of the experiment. For these reasons, the PAC asks for more information to be provided over the next several meetings on the design, capability, and schedule for the experiment.

J-PARC PAC Report March 2009

COMET:

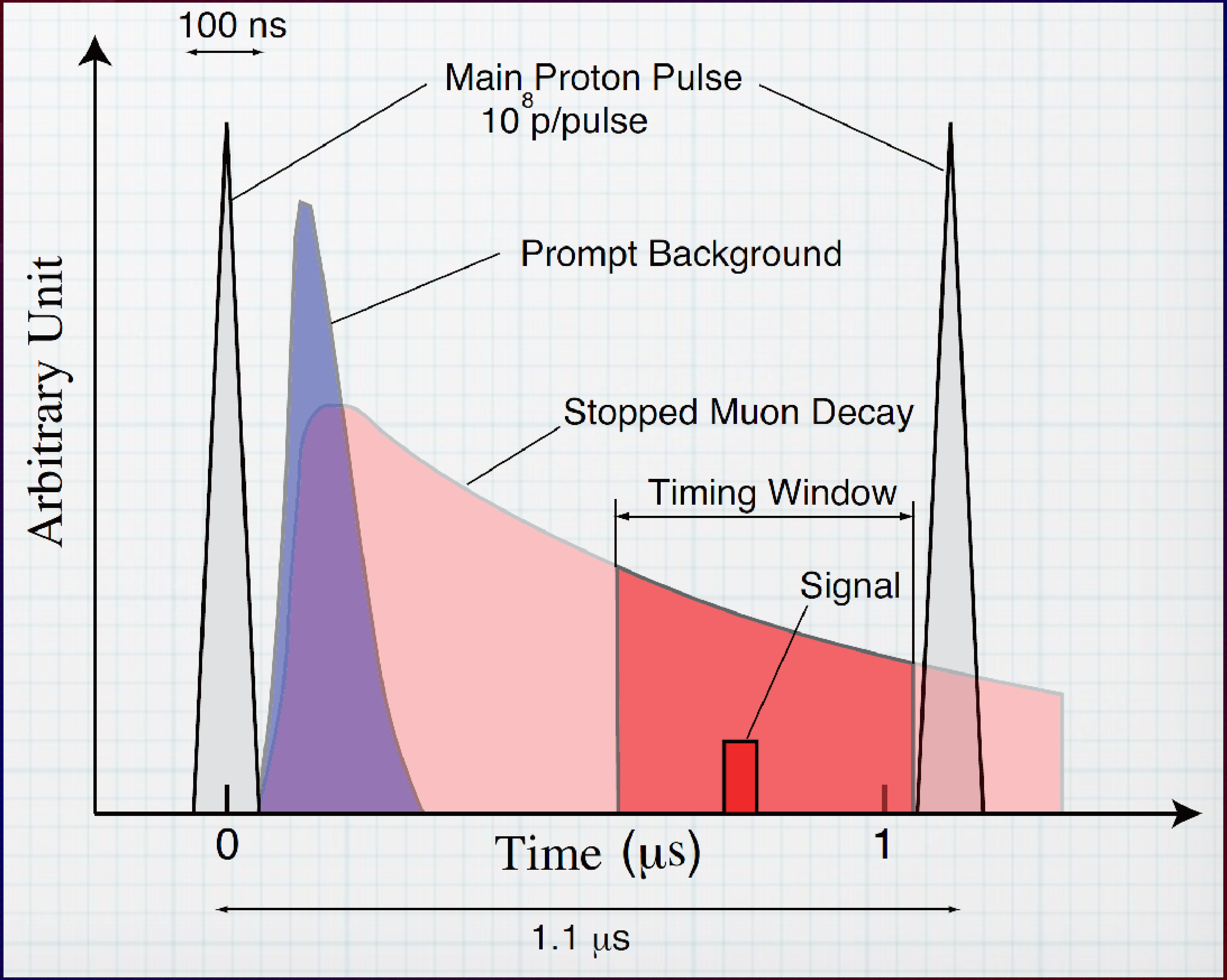
The PAC is pleased with the R&D progress on solenoids, extinction dipole R&D, calorimeter R&D, and growth in the collaboration.

The PAC supports the collaboration's plan to complete the CDR prior to the next PAC meeting in July so that consideration for Stage-1 scientific approval can begin at the July meeting. Stage-1 approval validates that a compelling physics case exists, and that construction and successful execution of the proposed experiment are plausible with reasonably projected resources at J-PARC.

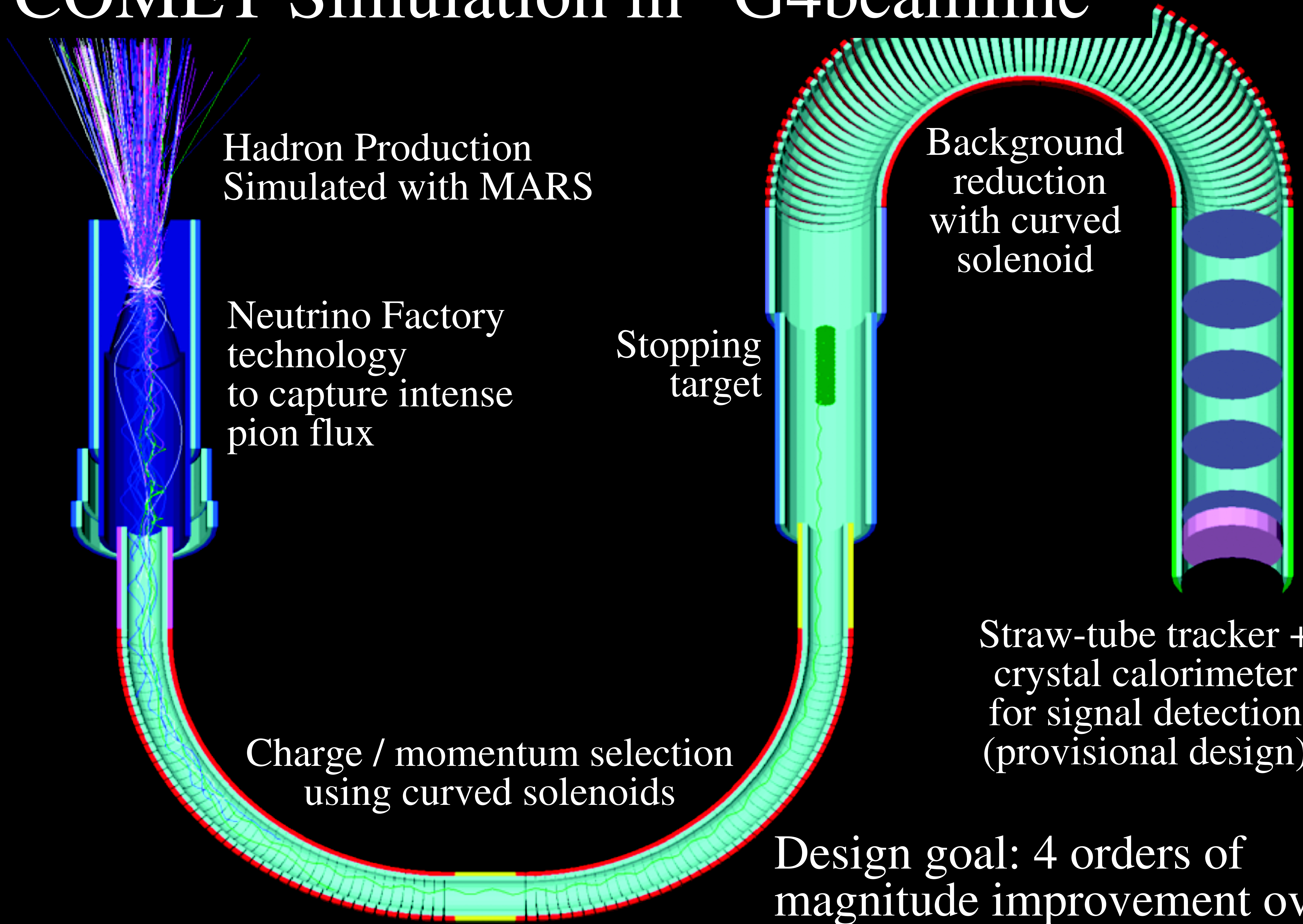
Table 14.4: Cost estimate of the COMET experiment (2009).

Item	Cost (Oku JPY)
Proton beam line	
Proton beam line magnets	17
Proton beam dump	2
Radiation shielding for a proton beam line	3
Superconducting Solenoid	35.7
Detector	
Electron tracker	2.1
Electron calorimeter	2.3
Cosmic ray shield	3
DAQ system	0.5
Infrastructure	
Refrigeration	4.7
Pion production system and tungsten shielding	2.3
Civil construction	
Extension of the NP experimental hall	3
Total	75
Total (with 20% contingency)	90

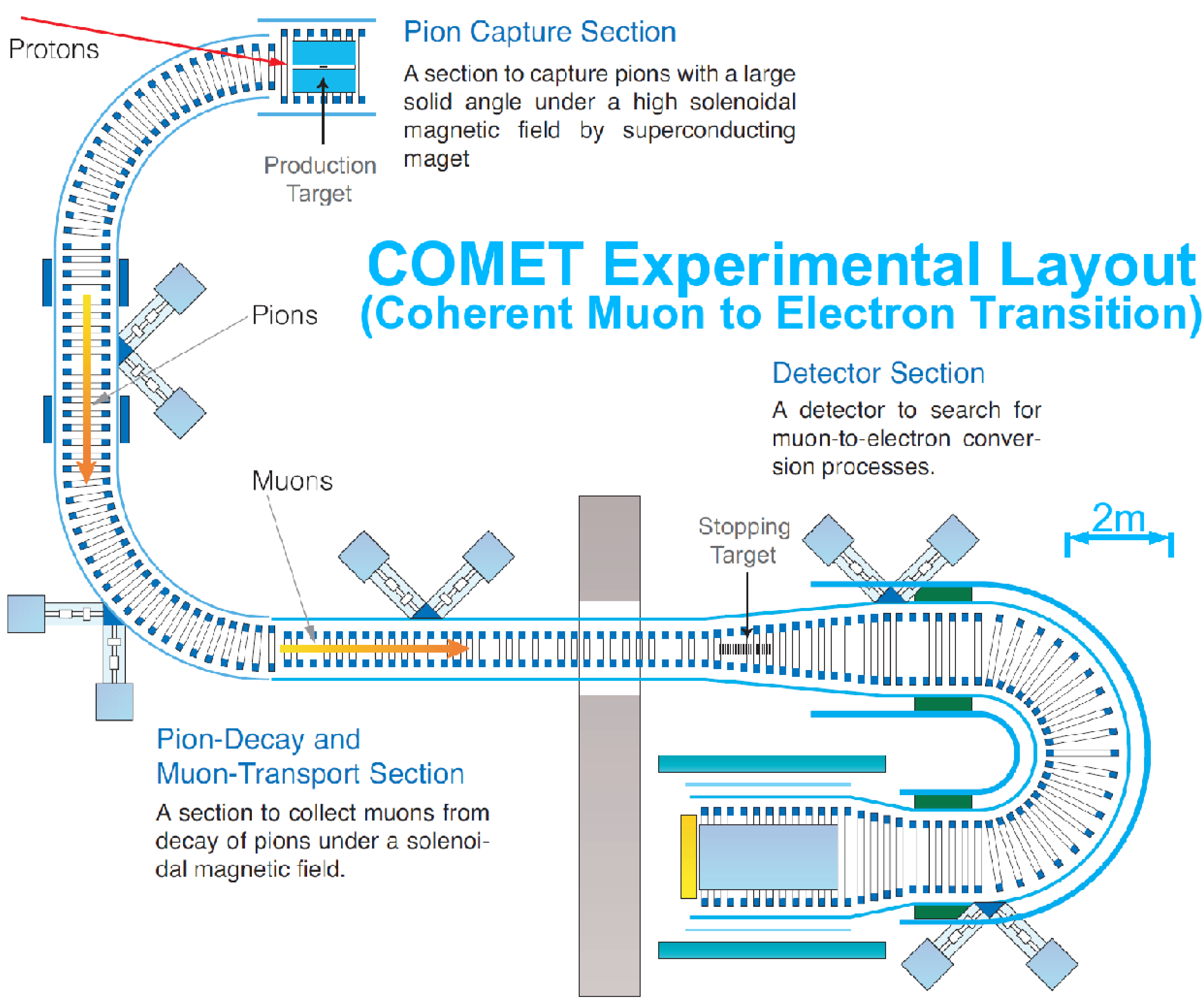
Timing Profile



COMET Simulation in "G4beamline"



Design goal: 4 orders of magnitude improvement over the current limit


COMET Experimental Layout
(Coherent Muon to Electron Transition)
Protons
Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget
Production Target
Pions
Muons
Detector Section
A detector to search for muon-to-electron conversion processes.
Stopping Target
2m
Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoidal magnetic field.

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

Place	Year	$\Delta E_e / E_e$	$\Delta E_\gamma / E_\gamma$	$\Delta t_{e\gamma}$	$\Delta \theta_{e\gamma}$	Upper limit
SIN	1977	8.7 %	9.3 %	1.4 ns	–	$< 1.0 \times 10^{-9}$
TRIUMF	1977	10 %	8.7 %	6.7 ns	–	$< 3.6 \times 10^{-9}$
LANL	1979	8.8 %	8 %	1.9 ns	37 mrad	$< 1.7 \times 10^{-10}$
LANL	1986	8 %	8 %	1.8 ns	87 mrad	$< 4.9 \times 10^{-11}$
LANL	1999	1.2 %*	4.5 %*	1.6 ns	17 mrad	$< 1.2 \times 10^{-11}$
PSI	≈ 2007	0.8 %	4.0 %	0.15 ns	19 mrad	$< 1 \times 10^{-13}$

Muon *g*–2

Standard model theory and experiment comparison [units of 10^{-11}]

Contribution	Value	Error
QED incl. 4-loops + LO 5-loops	116 584 718.1	0.2
Leading hadronic vacuum polarization	6 903.0	52.6
Subleading hadronic vacuum polarization	−100.3	1.1
Hadronic light-by-light	116.0	39.0
Weak incl. 2-loops	153.2	1.8
Theory	116 591 790.0	64.6
Experiment	116 592 080.0	63.0
Exp. - The. 3.2 standard deviations	290.0	90.3