LHC Based Muon-Proton Collider

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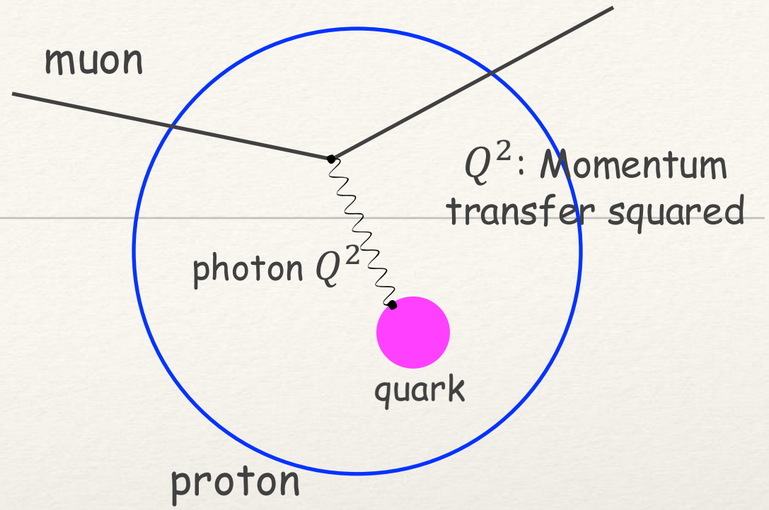
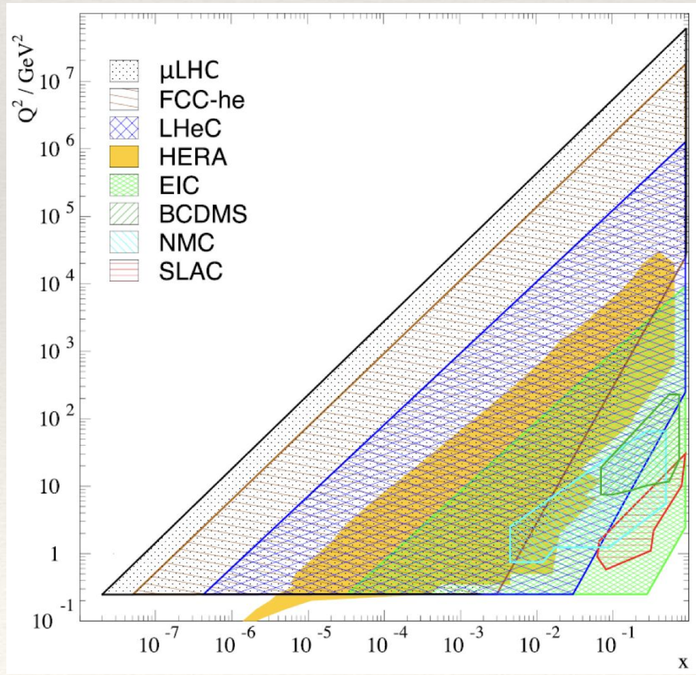
Motivation



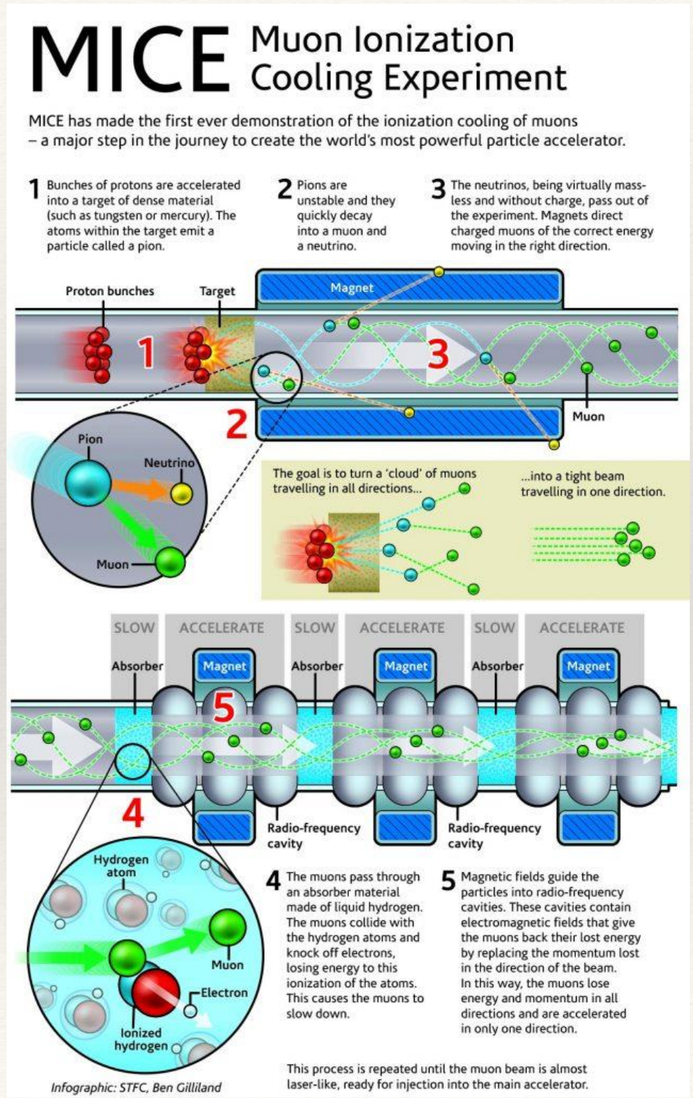
x: fraction of proton's longitudinal momentum carried by the parton

- Combine LHC's 7 TeV proton beam with 1 TeV muon beam will be provide higher center of mass energy (**5.29 TeV**) than electron-proton collider options.
- μLHC will make essential contributions to clarify QCD basics.
- Bridge the gap between hadron and lepton colliders.
- Extend deep-inelastic scattering (DIS) research:
  - Q^2 up to $2.8 \times 10^7 GeV^2$
  - $x \sim 3.6 \times 10^{-7} (Q^2 = 10\ GeV^2)$
  - μLHC pushes the frontier of lepton–hadron scattering, extending the kinematic reach by nearly two orders of magnitude beyond LHeC.
- Test lepton-quark interactions, lepton-flavor universality, BSM scenarios etc.



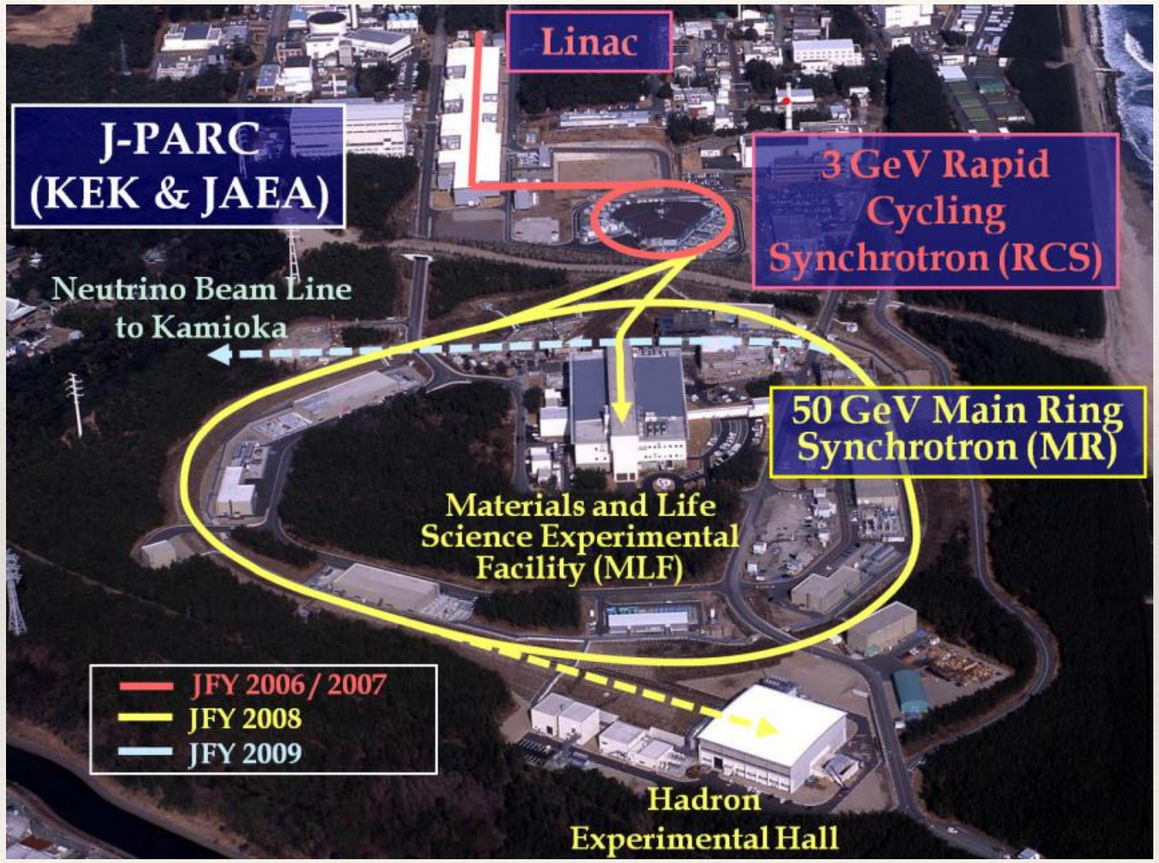
Why Anti-muon ?

- Muons decay rapidly (τ_0 = 2.2 μs) → cooling and acceleration must be completed within milliseconds.
- **Both μ^- and μ^+ beams must be cooled** to achieve the emittance required for high-luminosity **muon colliders**.
- For μ^- **beams**, **ionization cooling** is the only viable method due to their short lifetime (2.2 μs).
- Ionization cooling remains one of the key technological challenges and is expected to reach full demonstration in the **2030s**, following the MICE experiment's initial proof-of-principle.
- For **μ^+ beams**, the cooling problem has been effectively addressed at **J-PARC**, using the **room-temperature muonium** (μ^+e^-) laser-ionization source to produce low-emittance μ⁺ beams.



https://scitechdaily.com/breakthrough-in-muon-ionization-cooling-experiment-building-the-worlds-most-powerful-particle-accelerator/

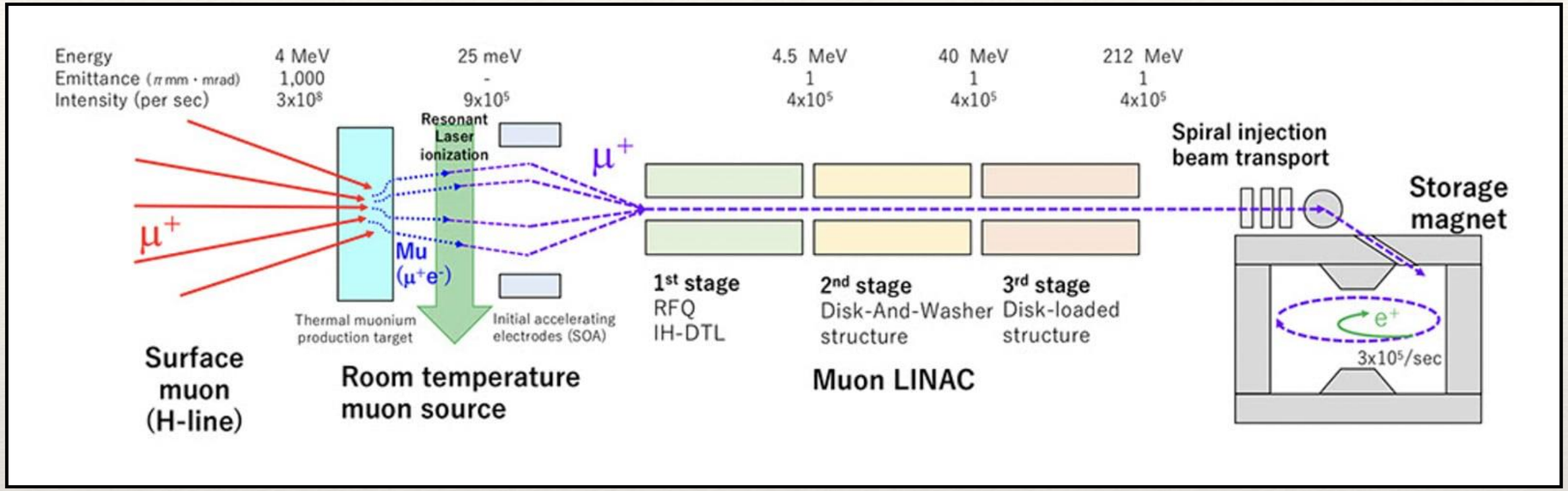
J-PARC MLF



Conceptual layout of the J-PARC muon g-2/EDM experiment, highlighting the ultra-cold muon beamline and storage ring.

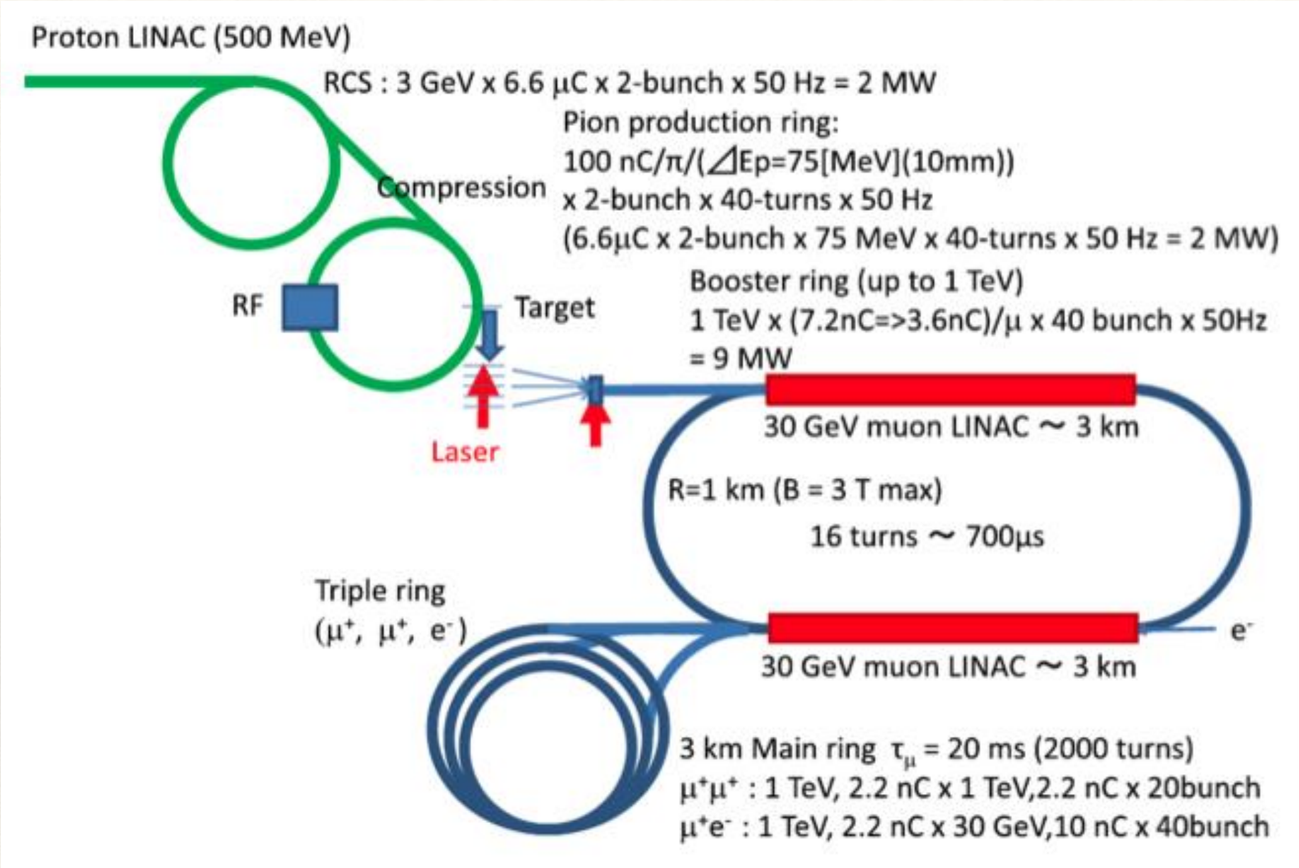
- Negative hydrogen ions (H^-) are accelerated using a 400 MeV linear accelerator.
- These H^- ions are injected into a 3 GeV Rapid Cycling Synchrotron (RCS) via the charge-exchange injection method.
- The RCS produces a 3 GeV, 1 MW proton beam, which is then extracted and directed toward a muon production target.
- The interaction of this high-power proton beam with the target generates secondary pions, which subsequently decay into muons.

μ^+ production at J-PARC MLF



- Surface muons (μ^+) with about 4 MeV energy and relatively high emittance are first produced at the H-line target station.
- These μ^+ particles stop in a thermal muonium production target, forming muonium atoms (μ^+e^-) at room temperature.
- Using resonant laser ionization, the muonium atoms are re-ionized, producing low-emittance μ^+ beams (around 25 meV energy).
- The μ^+ beams are then accelerated in a three-stage muon LINAC: 1st stage: RFQ + IH-DTL → 4.5 MeV 2nd stage: Disk-and-Washer structure → 40 MeV 3rd stage: Disk-loaded structure → 212 MeV
- (Finally, the accelerated μ^+ beam is transported via spiral injection into a storage magnet, where it circulates at a rate of about 3×10^5 μ^+ per second.)

μTRISTAN

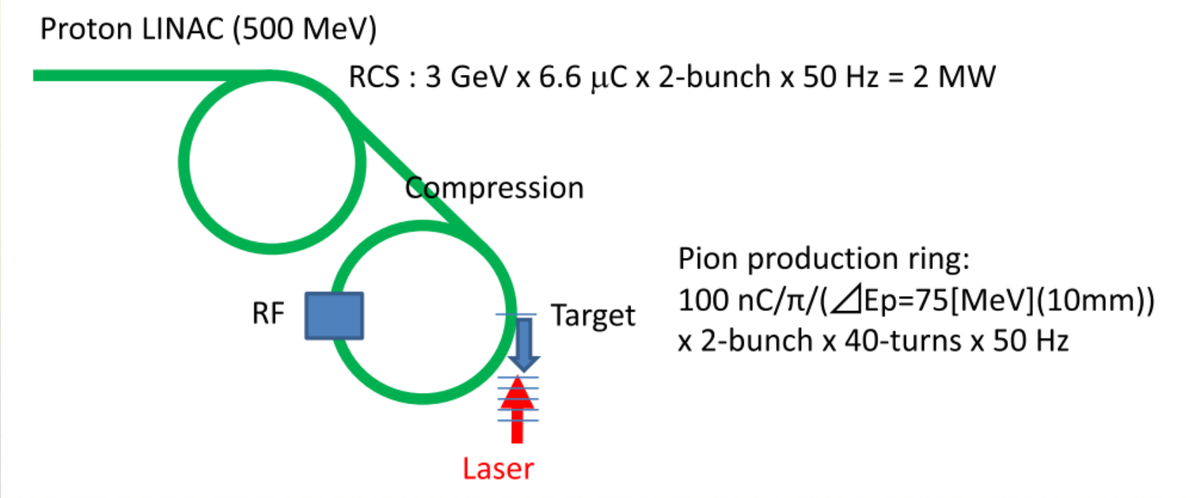


- The **proton linac (500 MeV)** and **rapid-cycling synchrotron (RCS, 3 GeV, 2 MW)** serve as the primary drivers for pion production.
- Pions generated at the target decay into **muons (μ^+)**, which are then captured and cooled.
- A **resonant laser system** assists in muonium (μ^+e^-) ionization and selective μ^+ production.
- Two **30 GeV muon linacs (~3 km)** accelerates μ^+ beam.
- **The booster ring** increases the beam energy up to **1 TeV**, with 40 bunches (1.7×10^{10} muons/bunch) at 50 Hz repetition rate.

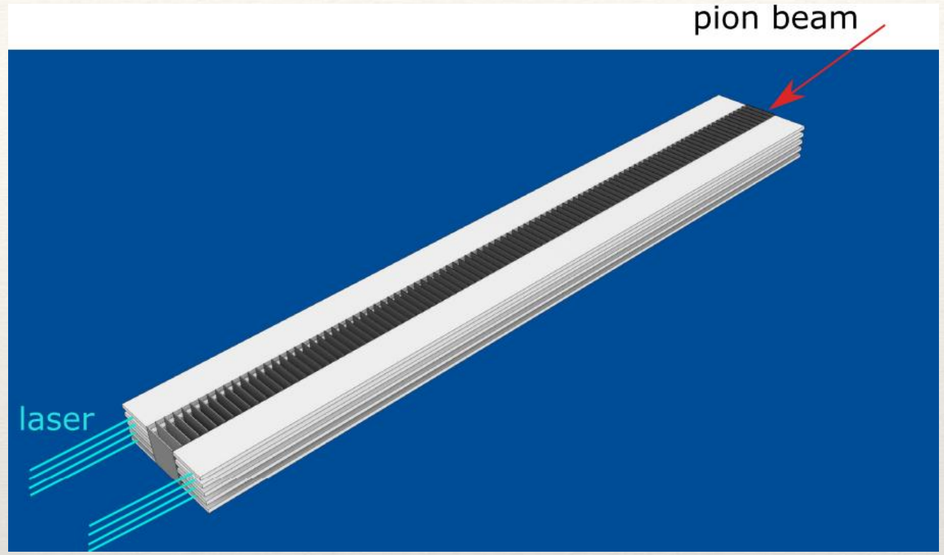
- The **main triple ring** (radius ≈ 3 km) accommodates **μ^+, μ^+, and e^- beams** for various collider configurations.
- The muon beam lifetime in the main ring corresponds to **$\tau \approx 20$ ms (~2000 turns)**, allowing multiple collision cycles before decay.

(See Appendix-2 by Dilara Aktürk in Saleh's presentation for complementary information.)

Enhanced μ^+ production



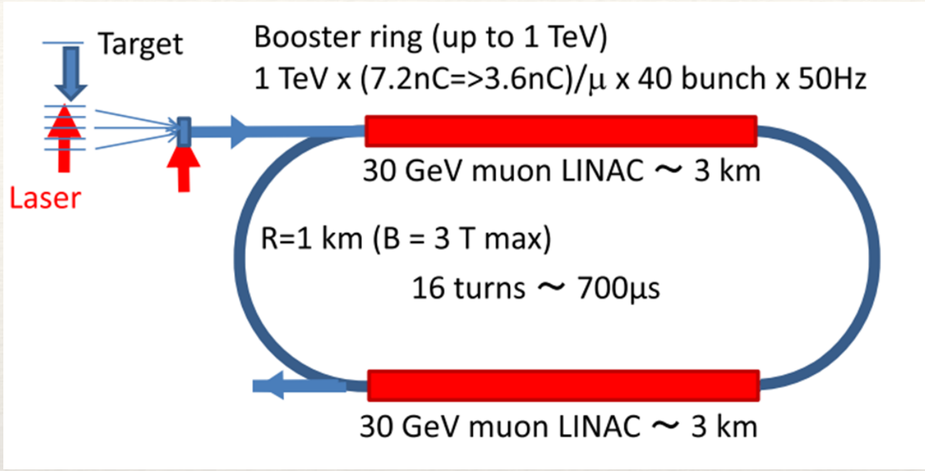
- In contrast to the **MLF configuration**, where only pions stopping within a thin graphite region contributed to muon production, the **μTRISTAN design** introduces a **recirculating proton beam** for pion generation.
- Each proton bunch is **recirculated 40 times** over a **10 mm graphite target**, resulting in an **enhanced pion yield**.

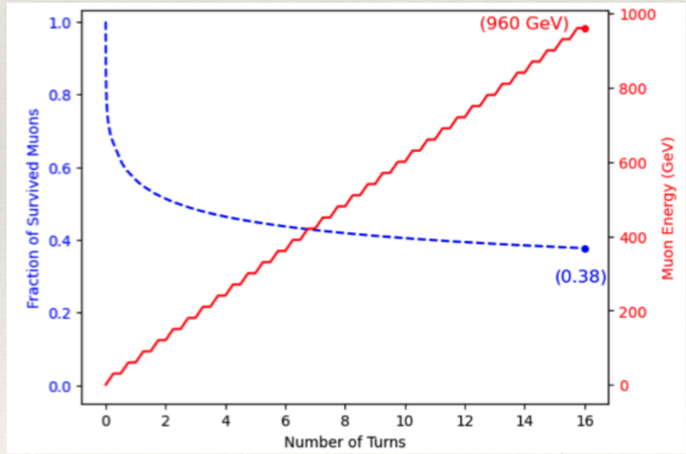


- According to the **μTRISTAN project**, the ultra-cold muon production is 9×10^{13}/s.
- This improvement mainly stems from the **efficient utilization of forward-going pions**, which are now **transported to a large, multi-layered stopping target** instead of being lost after initial production.

First Option: μTRISTAN tangential to LHC

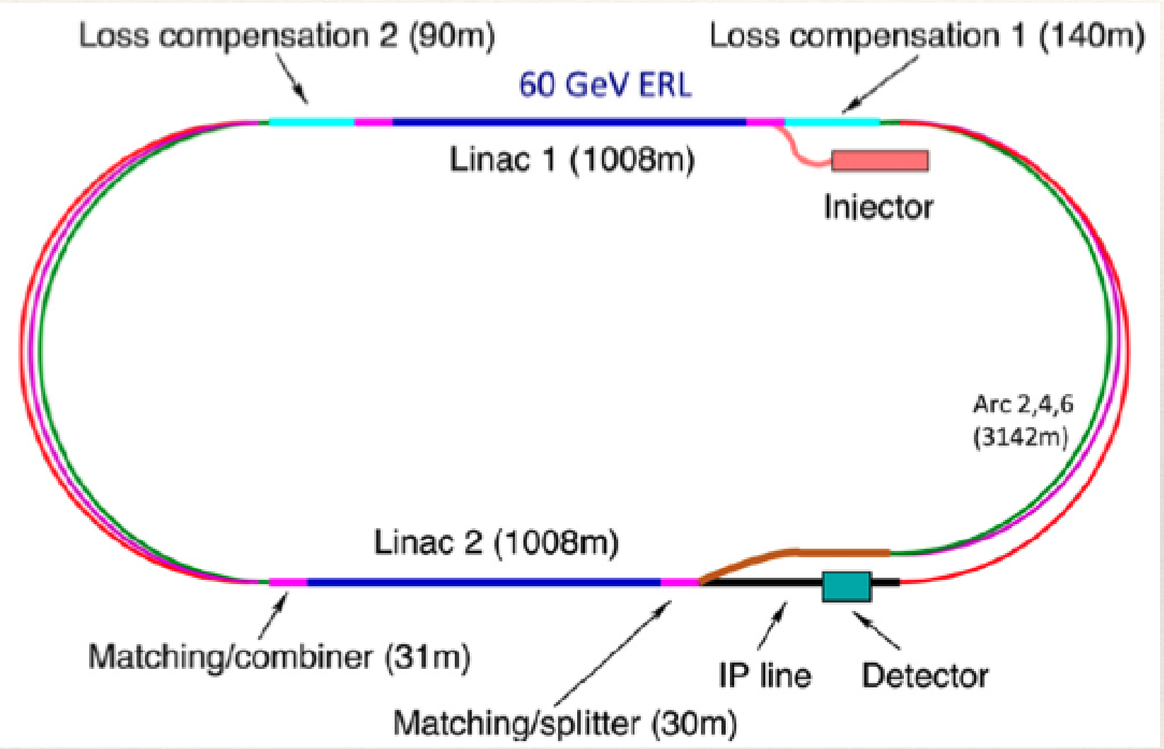
- μTRISTAN tangential to LHC



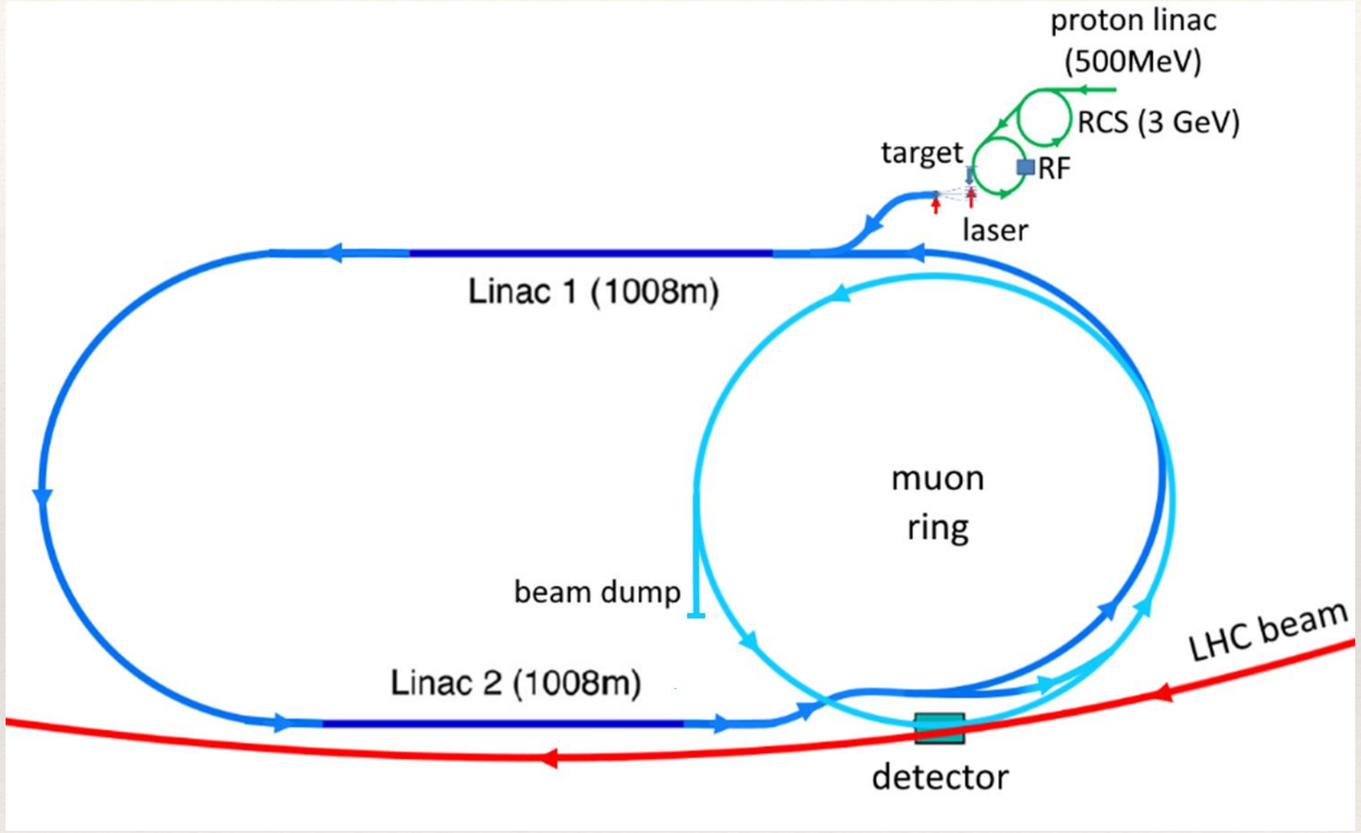


μTRISTAN study: about **50% of muons** survive. (7.2 nC → 3.6 nC)
In this option muon (212 MeV → 960 GeV) **survival rate is 38%**
4.5×10^{10} → 1.7×10^{10}

Second Option: Boosting μ^+ at ERL's tunnel

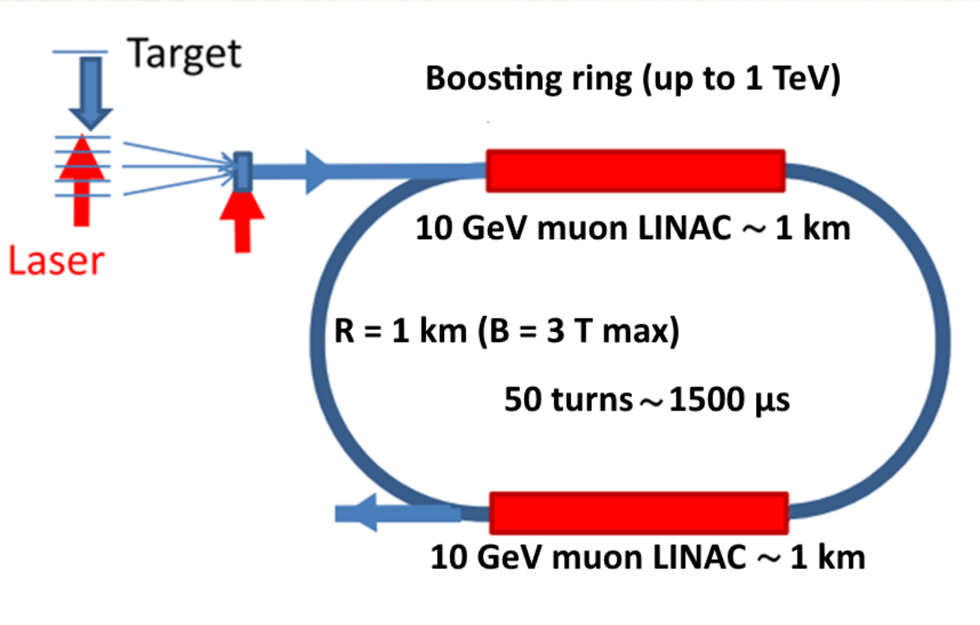


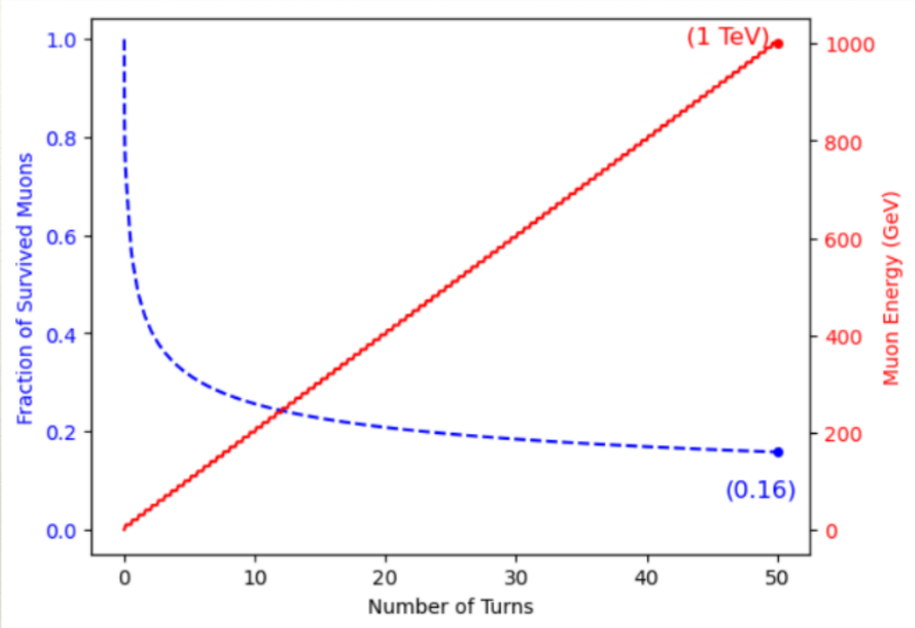
Schematic view of the three-turn LHeC configuration at 60 GeV (50 GeV) final energy scale with two oppositely positioned electron linacs and three arcs housed in the same tunnel.



Schematic view of the μLHC which uses single-pass ERL as a booster ring integrated with a main ring in a manner similar to that proposed for μTRISTAN.

Boosting μ^+ at ERL's tunnel





In this option muon **survival rate is 16%** (compare with 38% for μTRISTAN based option)

$4.5 \times 10^{10} \rightarrow 7.2 \times 10^{9}$

μLHC Luminosity Calculation

Parameter	μTRISTAN-based	ERL-based
Number of muons per bunch [10^9]	17	7.2
Beam energy [GeV]	1000	
β_x @ IP [cm]	3	
β_y @ IP [cm]	0.7	
Bunch length [mm]	2	
Norm. horizontal emittance [μm]	4	
Norm. vertical emittance [μm]	4	
Number of bunches per ring	40	
Collision frequency [MHz]	4	
Circumference [km]	3	

Parameter	μTRISTAN-based		ERL-based	
$\sqrt{s}$ [TeV]	5.29		5.29	
L [10^{33} $cm^{-2}s^{-1}$]	4.1		1.7	
Parameter	μ^+	p	μ^+	p
$\sigma_{x,y}$ [μm]	4.3	4.3	4.3	4.3
$\xi_{x,y}$ [10^{-4}]	600	10	600	4.4

- The HL-LHC parameters have been tuned to match the requirements of the LHeC configuration.

Parameter	p
Number of Particle per Bunch [10^{10}]	22
Beam Energy [TeV]	7
β function @ IP [cm]	7
Norm. Emittance [μm]	2
Number of Bunches per Ring	2760
Rev. frequency [Hz]	11245
Circumference [km]	26.7

(See Appendix-1 by Burak Dağlı in Saleh's presentation for complementary information.)

Possible Challenges

Neutrino induced radiation

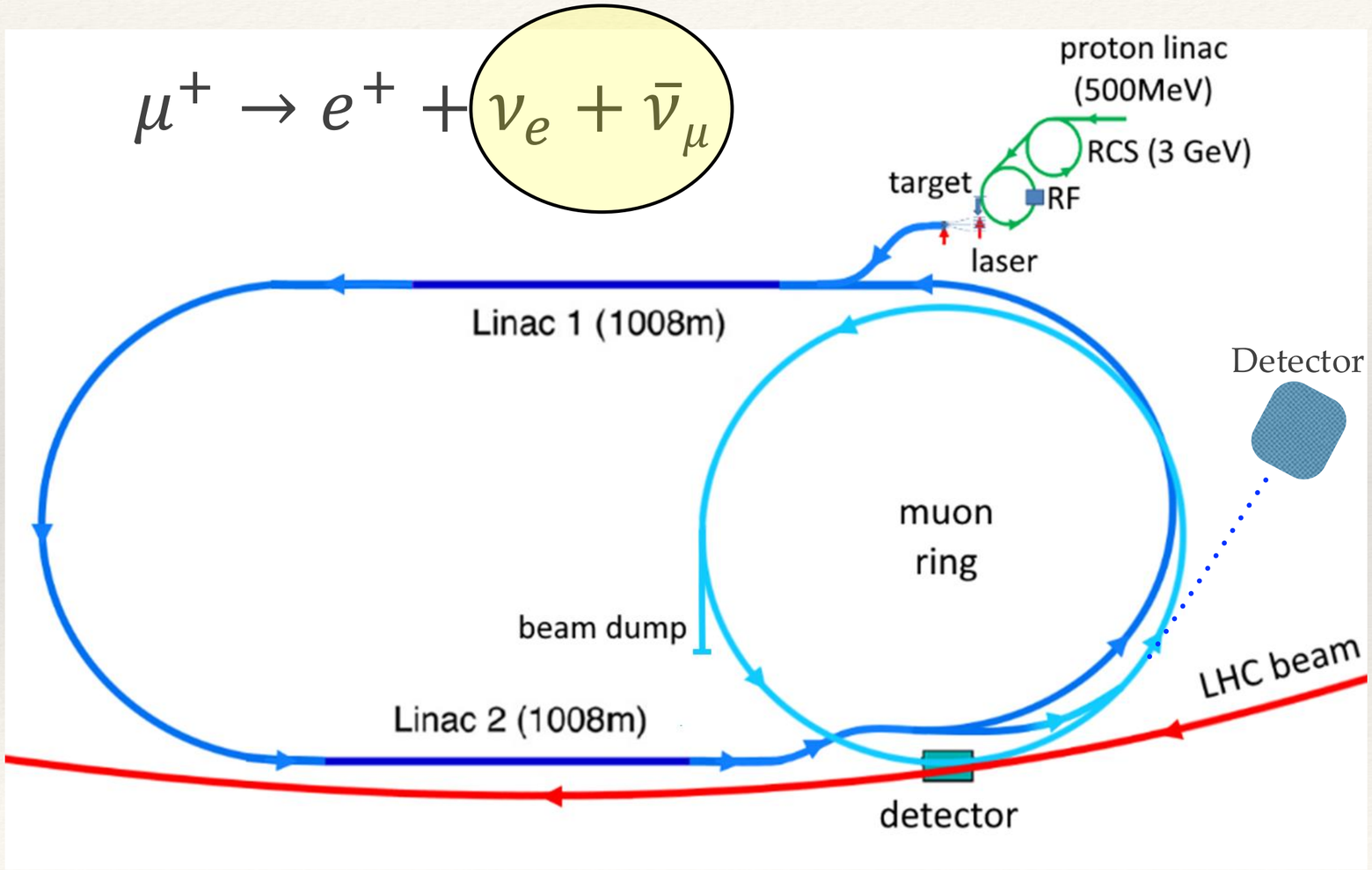
Enviromental neutrino radiation hazard

- At multi-TeV muon energies, these neutrino beams may lead to measurable radiation doses at the surface, depending on ring depth and shielding.
- Deep underground placement of the muon ring significantly reduces neutrino flux reaching the surface.
- Optimized ring orientation and tilt angle are chosen to direct the neutrino emission away from populated or sensitive areas, minimizing surface radiation exposure.

Detector radiation hardness

- High-energy neutrinos emerging from the interaction region can irradiate sensitive detector materials over long periods.
- Cumulative displacement damage in silicon sensors and photodetectors
- Material activation and electronic degradation
- Background noise in precision forward detectors

Possible Neutrino Experiment



- In addition to muon-proton collisions, the proposed facility naturally produces intense neutrino fluxes from muon decays in the storage ring.
- The neutrino detector is placed tangentially to the muon ring, along the direction of neutrinos emitted from muon decays. So, we can investigate:

  Neutrino cross sections at multi-GeV energies

  Neutrino-nucleus interactions

Conclusion

- The μp collider can make essential contributions to the understanding of QCD fundamentals.
- The use of positive muons (μ^+) is technically advantageous and TeV-scale μ^+ beams are expected to become achievable significantly earlier than μ^- beams.
- **Two main design options are under consideration:**

  μTRISTAN based μLHC collider, tangential configuration, providing a luminosity $\sim 4.1 \times 10^{33}\ cm^{-2}s^{-1}$.

  ERL-based μLHC collider, an energy recovery linac used to boost μ^+ beams, offering $\sim 1.7 \times 10^{33}\ cm^{-2}s^{-1}$ with reduced infrastructure requirements.
- To achieve higher muon beam energies, <u>further studies are required on superconducting magnet systems capable of faster ramp-up rates and higher magnetic fields</u>, given the very short lifetime of muon beam.
- Neutrino radiation must be carefully addressed.
- A complementary neutrino detector could turn this challenge into an opportunity.

Backup

μTRISTAN muon production calculation

- In RCS p/bunch is 6.6 μC → 4.1x10^{13} per bunch
- pions/proton = 0.016, pion stopping eff=50%, second muon target eff= 50%, production eff of ultra cold muon= 14%
- 0.016 x 0.5 x 0.5 x 0.14 = 5.5x10^{-4} (ultra cold muon/proton)
- 4.1x10^{13} x 2 proton bunches x 5.5x10^{-4} = 4.5 x 10^{10} (ultra cold muon/bunch) → 7.2 nC
- Hits per proton bunch (in pion production ring) = 40, rep rate = 50 Hz
- 4.5 x 10^{10} x 40 x 50 = 9 x 10^{13} ultra cold muon/s