Muon Collider: Challenges and Benefits

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Collaboration

MuCol

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With thanks to the Muon Accelerator Programme and International Muon Collider Collaboration

UK RI

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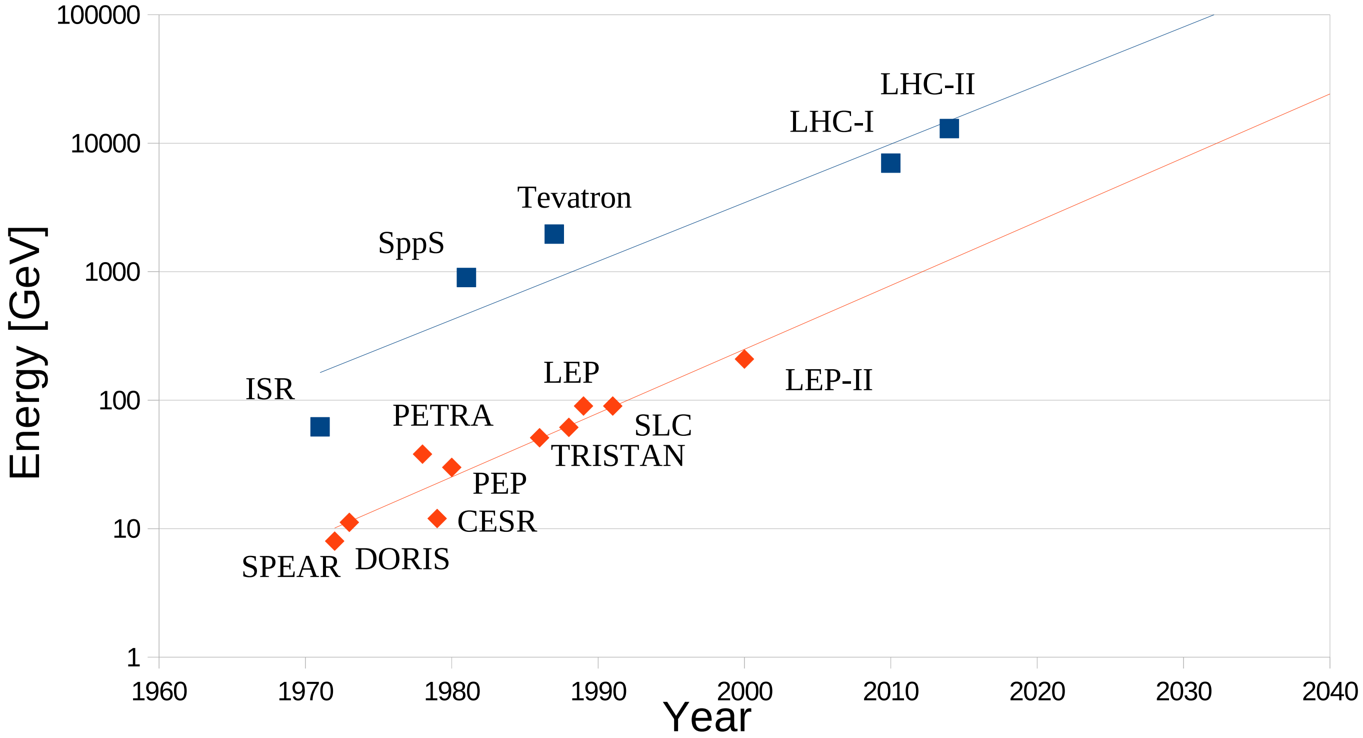
Decision Point

- HL LHC upgrade to LHC complex under construction
  - Order of magnitude improvement in luminosity
  - First data 2029
- Strong future hides a growing challenge
  - No clear winner for next generation in energy reach
  - Options look costly, in money and electricity consumption
- Lead time is 25 years for next collider – must start now

Back to the Future…



- Effort to explore phenomena at higher and higher energies
- Corresponds to smaller scales
- Higher energy → bigger, more expensive, more power hungry
- How to move forward?

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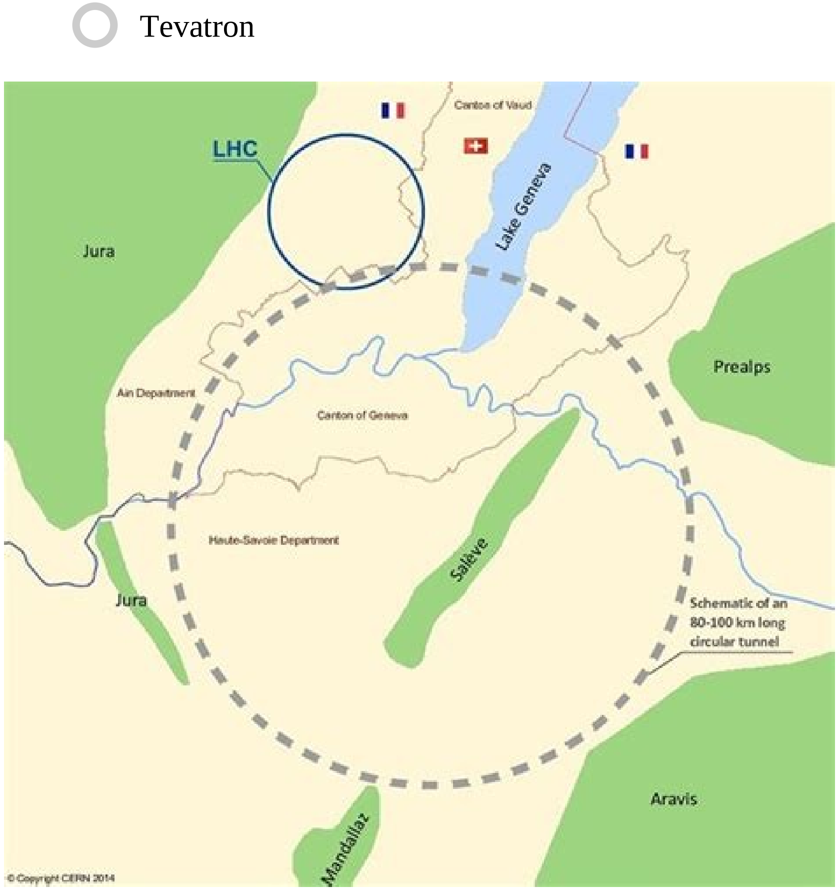
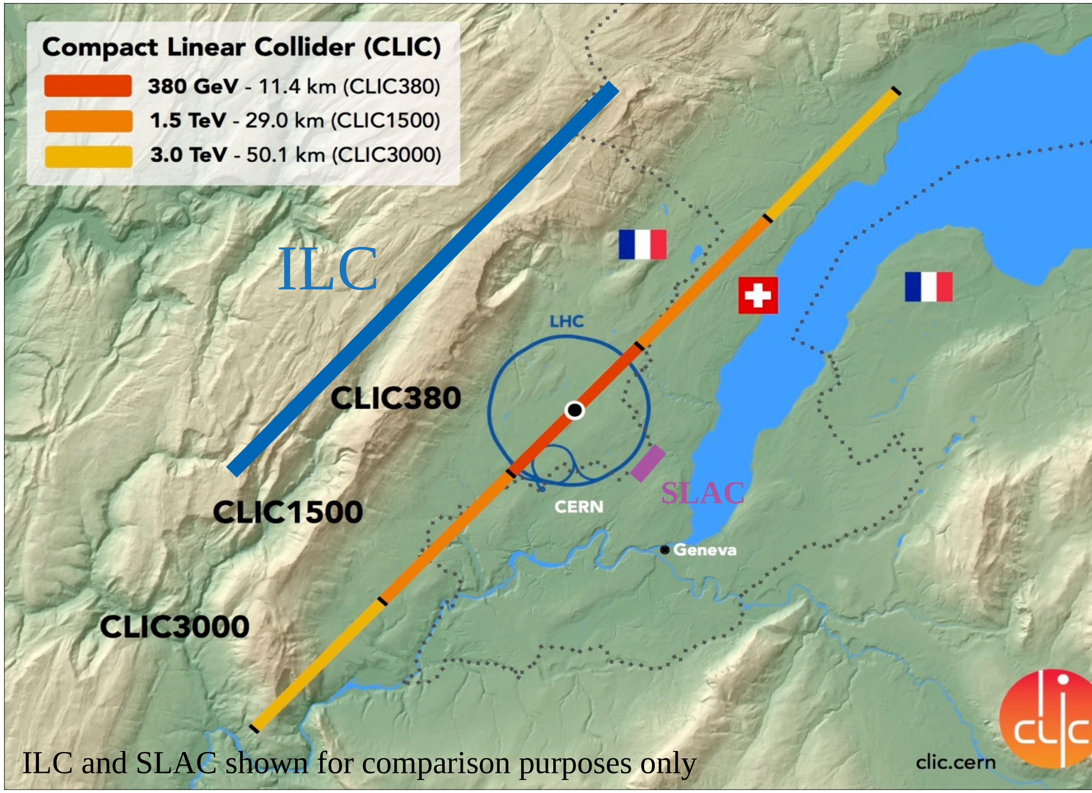
E.g. circular colliders

- Tevatron
  - 1.96 TeV proton - antiproton
  - 6.2 km circumference
- LEP/LHC
  - 14 TeV proton proton (LHC)
  - 209 GeV e^+e^- (LEP)
  - 27 km circumference
- FCC & CepC (proposed)
  - 90 – 350 GeV e^+e^-
  - 100 TeV proton-proton
  - 90-100 km circumference



E.g. linear colliders

- SLAC (California)
  - 3 km length
  - 90 GeV e^+e^-
- ILC (proposed)
  - 31 km
  - 500 GeV e^+e^-
- CLIC (proposed)
  - 380 GeV e^+e^-
  - 11 km
  - Upgradeable to 3 TeV



ILC and SLAC shown for comparison purposes only

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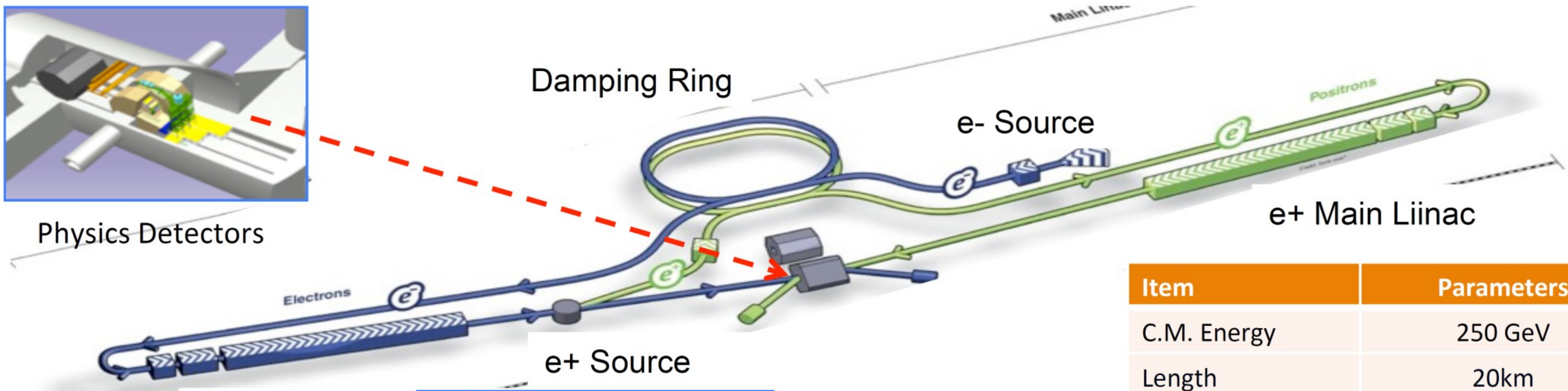
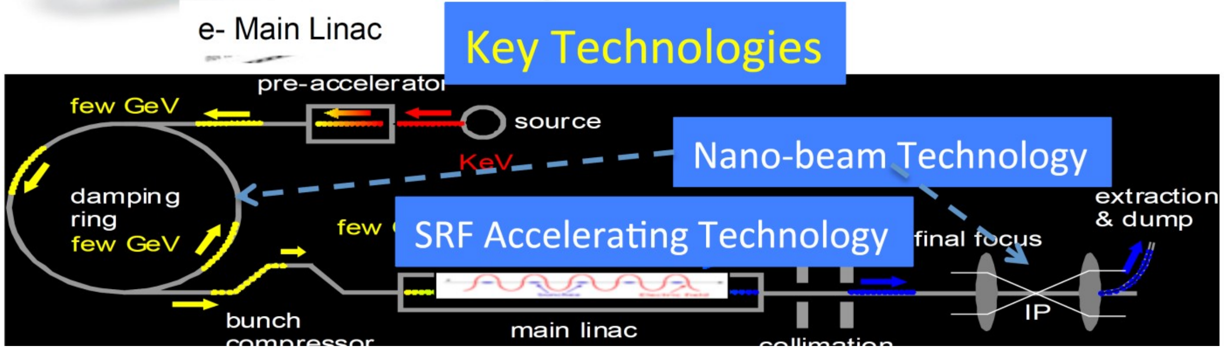
Electron-positron colliders

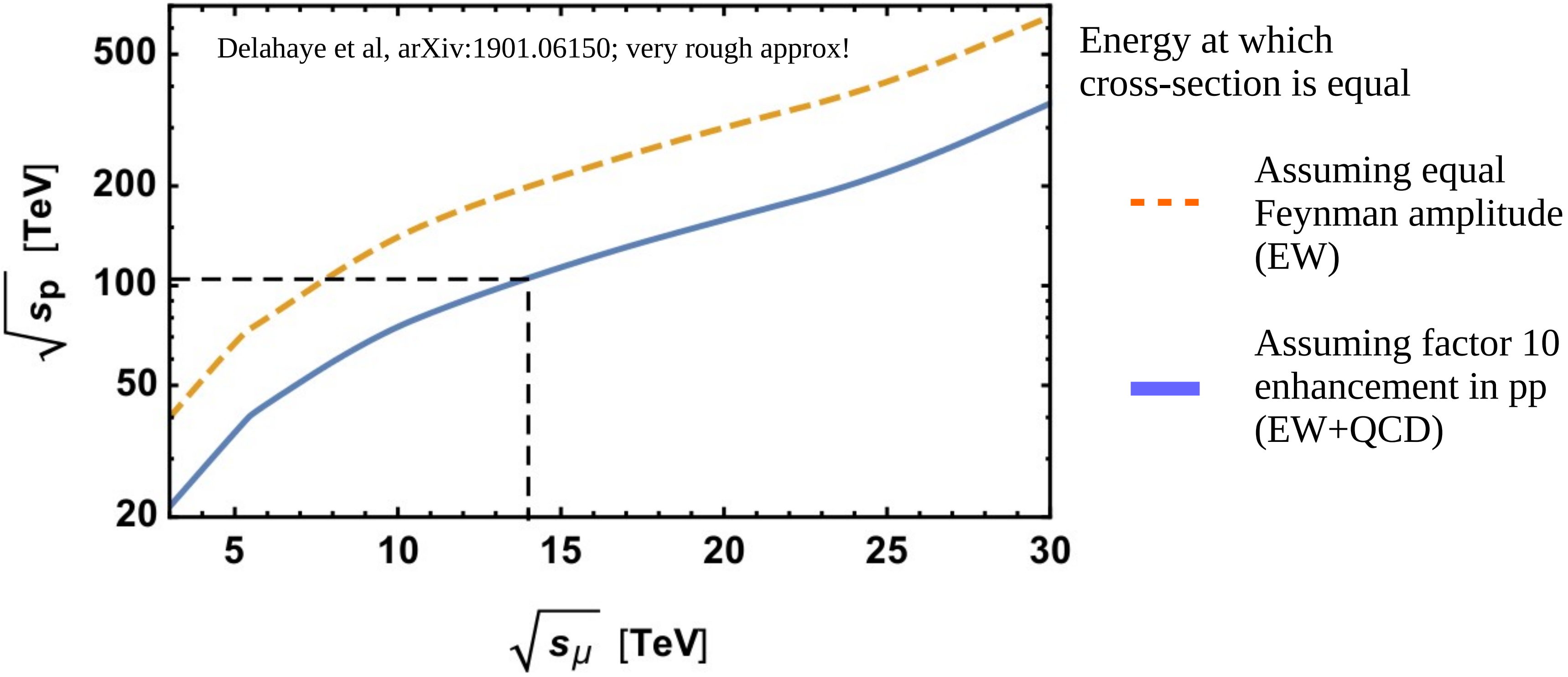
- Circular e^+e^- machines limited by synchrotron radiation
  - Power emitted ~ E^4/m^4
  - Practically limits centre-of-mass energy to ~ 100s GeV
- Linear e^+e^- machines limited by available RF acceleration
  - Practically limits centre-of-mass energy to ~ 100s GeV





Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G.	31.5 MV/m

What about protons?


Delahaye et al, arXiv:1901.06150; very rough approx!

Energy at which cross-section is equal

- Proton collision energy is shared between quarks
  - Effective energy significantly reduced
- Seek a particle which
  - Is not so low mass as an electron
  - Is a fundamental particle
- **Muons!**

Muons

- Muon
  - Half-life 2.2 µs
  - Mass 105.658 MeV/c
  - 207 times electron mass
- What would a muon collider look like?

The Muon Collider

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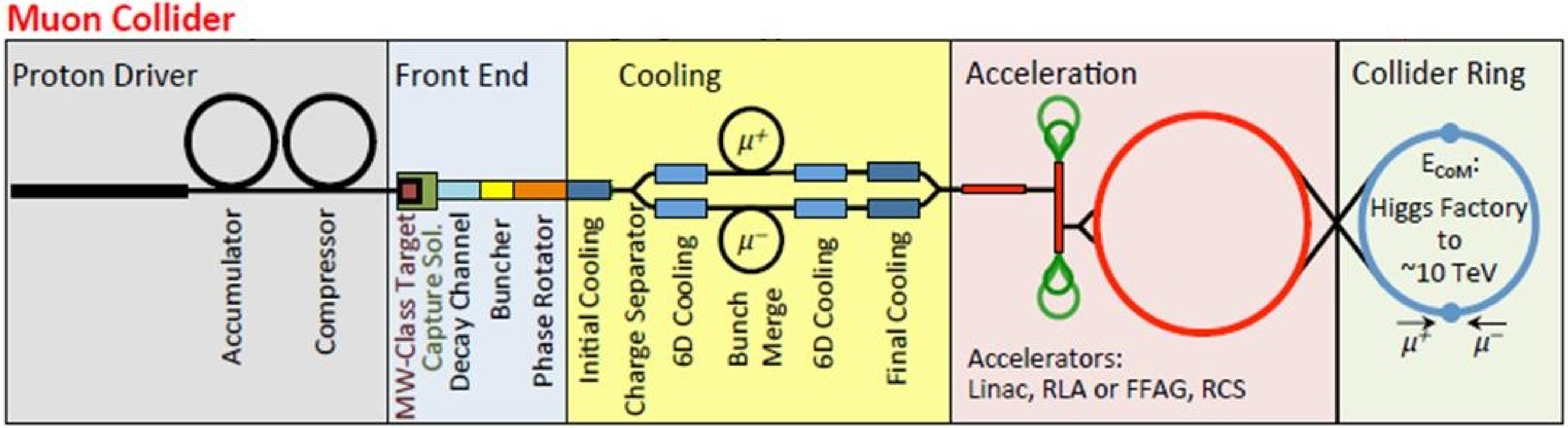
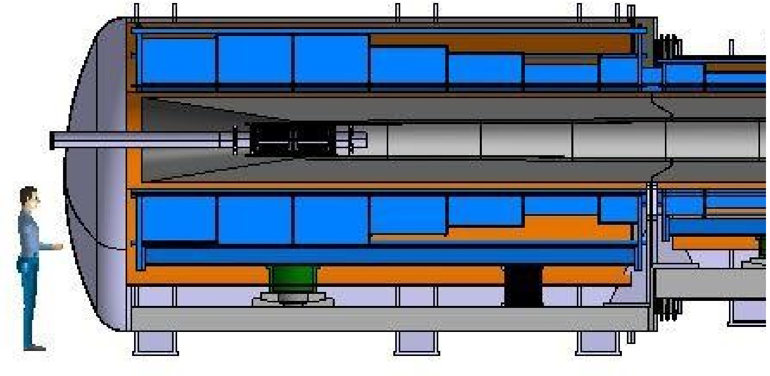
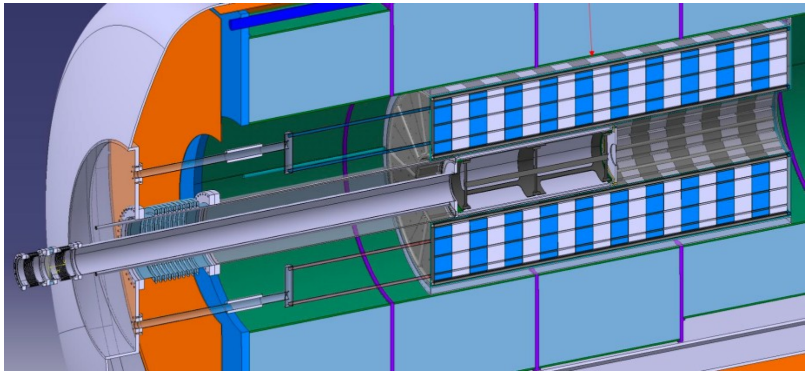
Muon Collider



- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV & Collisions
- Critical Issues:
  - Short muon lifetime & decay
  - Large initial muon beam emittance

MuC Target

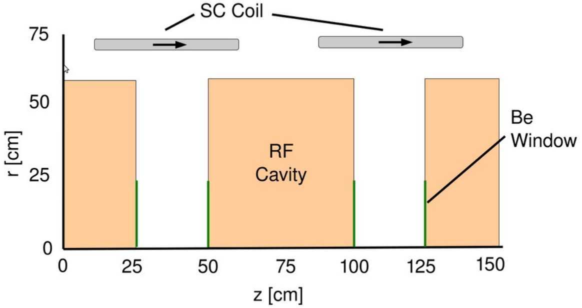


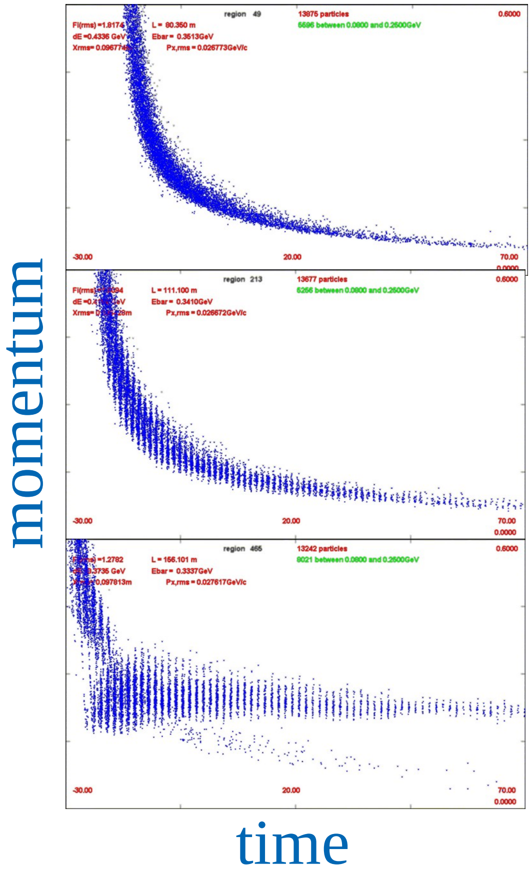


- Protons on target → pions → muons
  - Graphite target takes proton beam to produce pions
    - Back up options under investigation
  - Heavily shielded, very high field solenoid captures π^+ and π^-
- Challenge: Solid target and windows lifetime
- Challenge: Energy deposition and shielding of solenoid

Buncher/Phase Rotator

- Drift to develop energy-time relation
- Buncher adiabatically ramp RF voltages
- Phase rotator misphase RF
  - High energy bunches decelerated
  - Low energy bunches accelerated





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Muon Cooling

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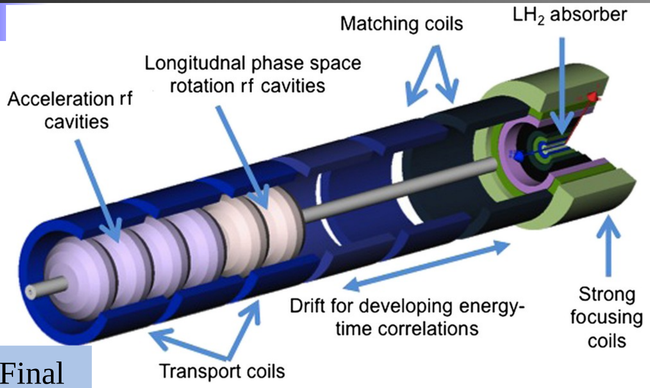
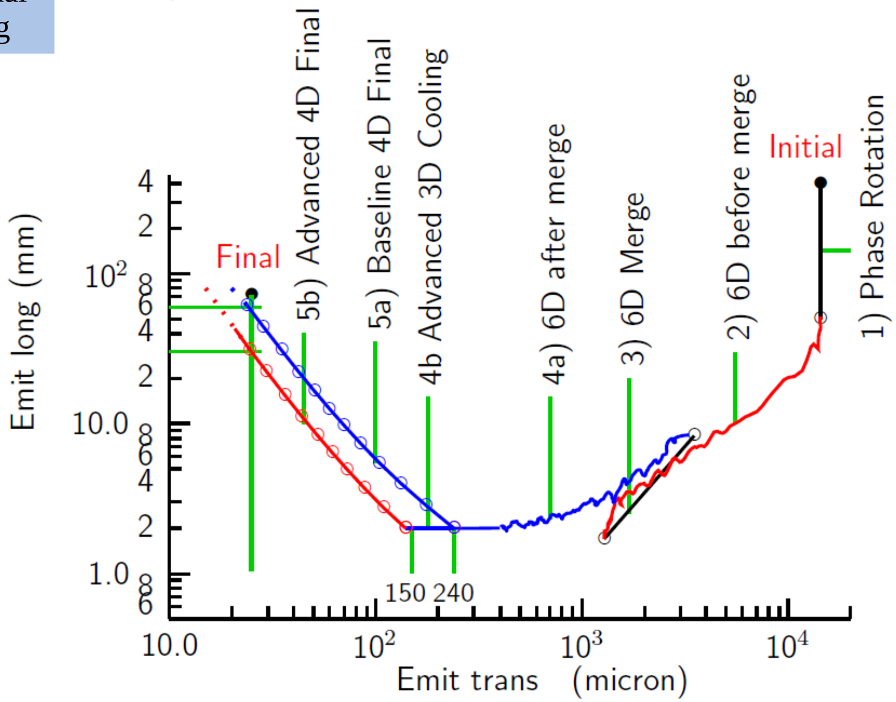
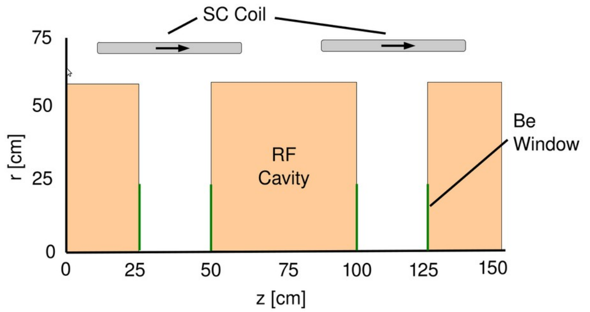


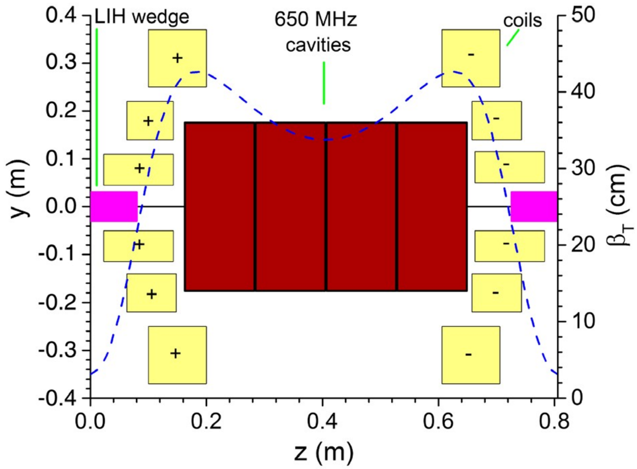
4D Final cooling



Phase rotation



6D cooling



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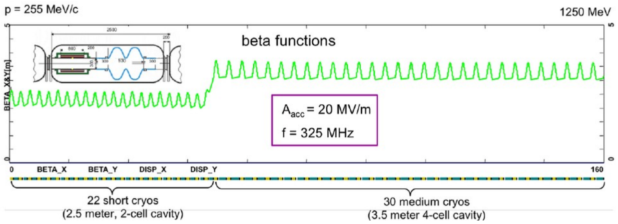
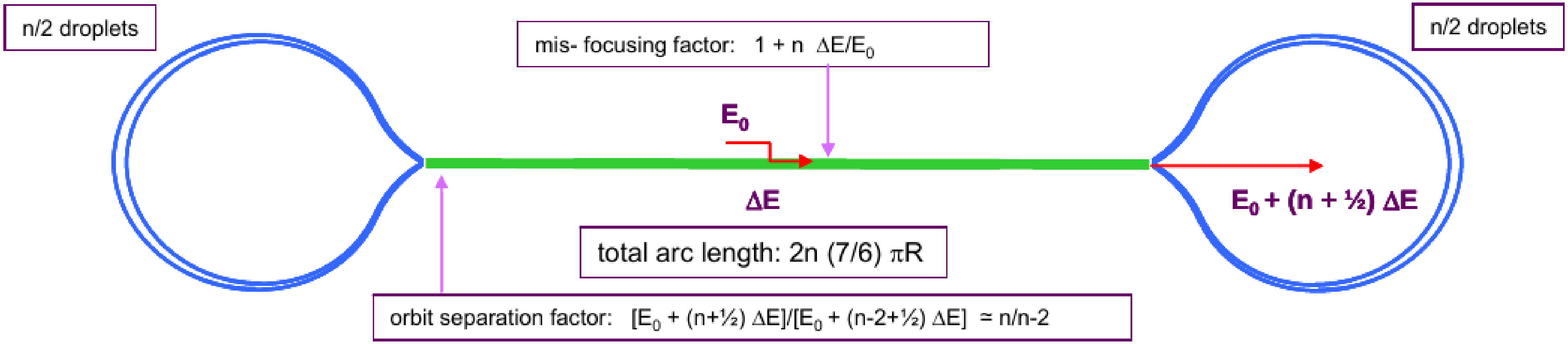
Acceleration – Linac and RLA





n/2 droplets

mis- focusing factor: 1 + n $\Delta E/E_0$

n/2 droplets

E_0

ΔE

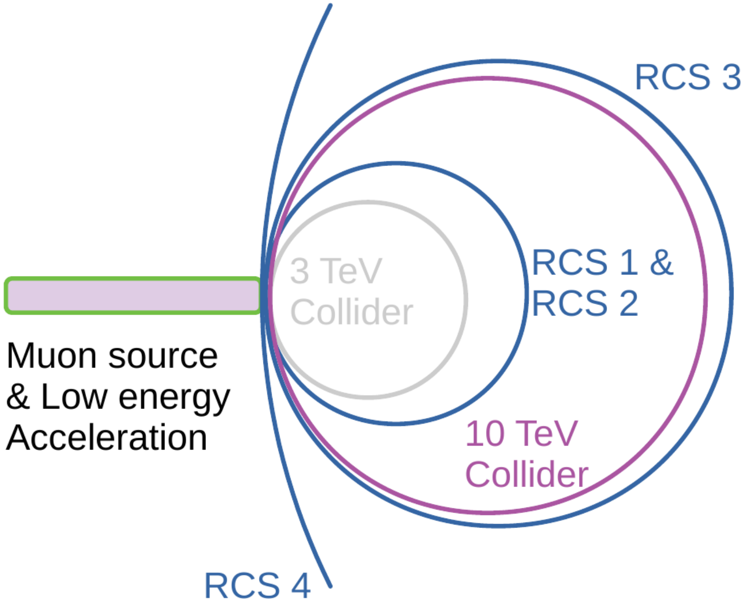
$E_0 + (n + ½)\ \Delta E$

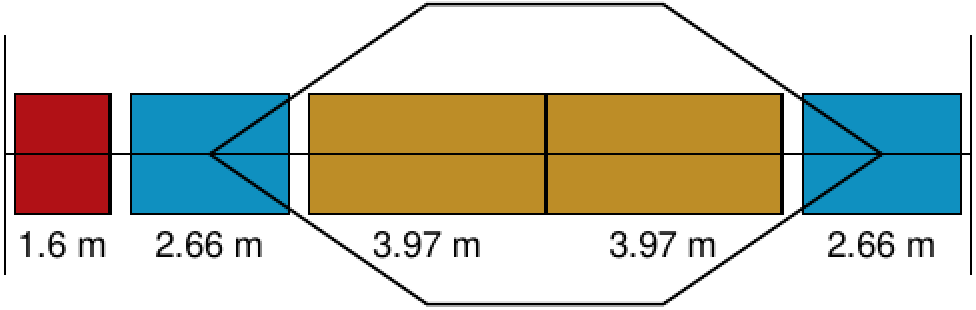
total arc length: 2n (7/6) πR

orbit separation factor: $[E_0 + (n+½)\ \Delta E]/[E_0 + (n-2+½)\ \Delta E] \approx n/n-2$

- First acceleration – use linac
  - Get highest real-estate gradient
- At higher energies – recirculate through the linac
  - More efficient use of equipment
  - Need to pay attention to (mis)focusing effects and timing with RF

Pulsed Synchrotrons

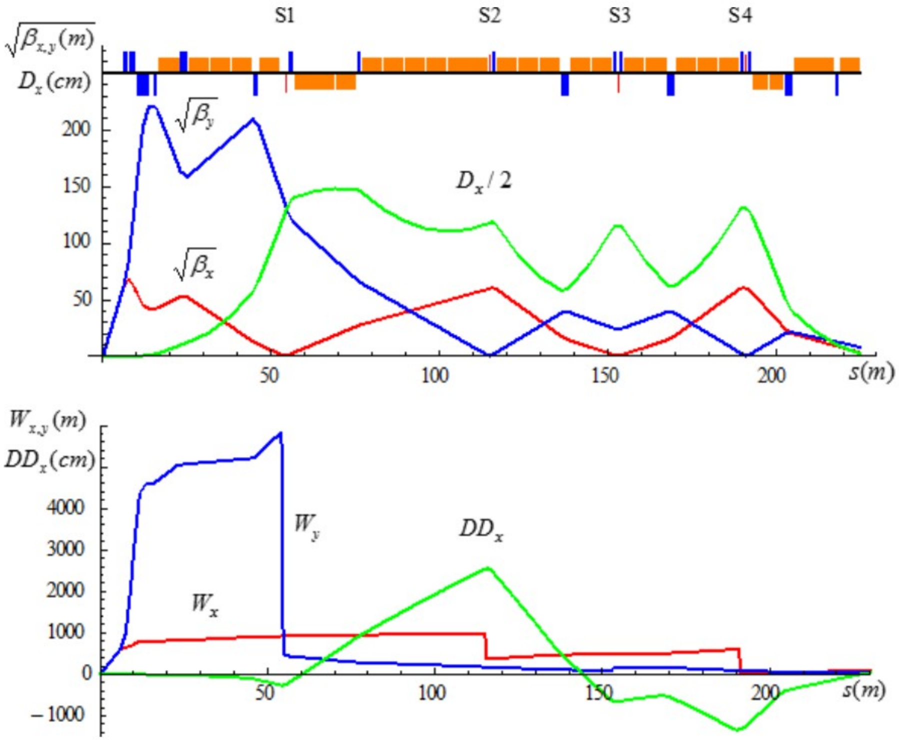




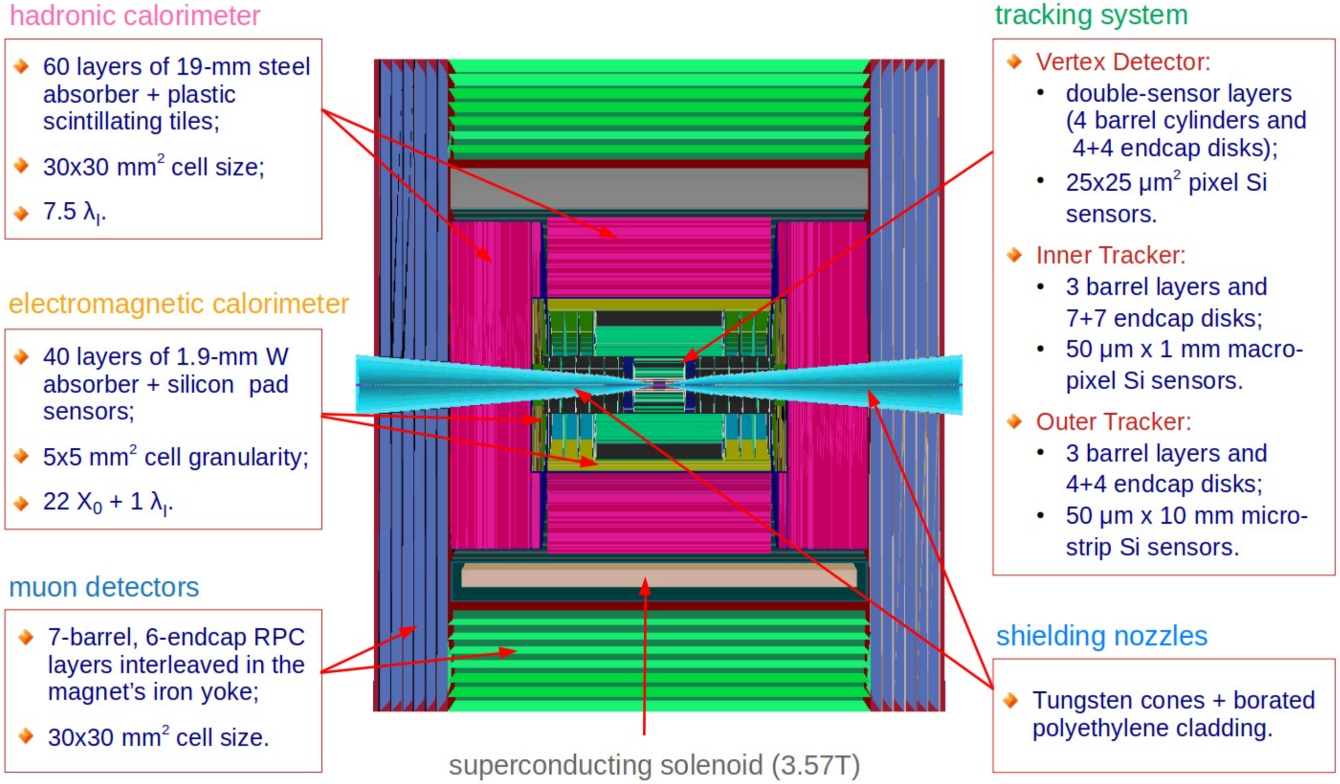
- At higher energy, can use synchrotrons
  - Ramp magnets in synchronisation with increasing beam energy
  - Need extremely fast ramp < few ms
  - To keep ring compact, use combination of
    - Fixed superconducting and
    - Pulsed normal conducting magnets
  - Shielding components from decay losses

Collider ring

- Luminosity increases for shorter collider ring
  - Seek to achieve highest possible mean dipole field
  - Low radius, many bunch crossings before decay
- Luminosity increases for tight final focusing
  - Correction for chromatic aberrations → focusing strength vs energy
  - Require very short bunches → whole bunch at the focus at same time



Muon Collider Detector



hadronic calorimeter

- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.

superconducting solenoid (3.57T)

tracking system

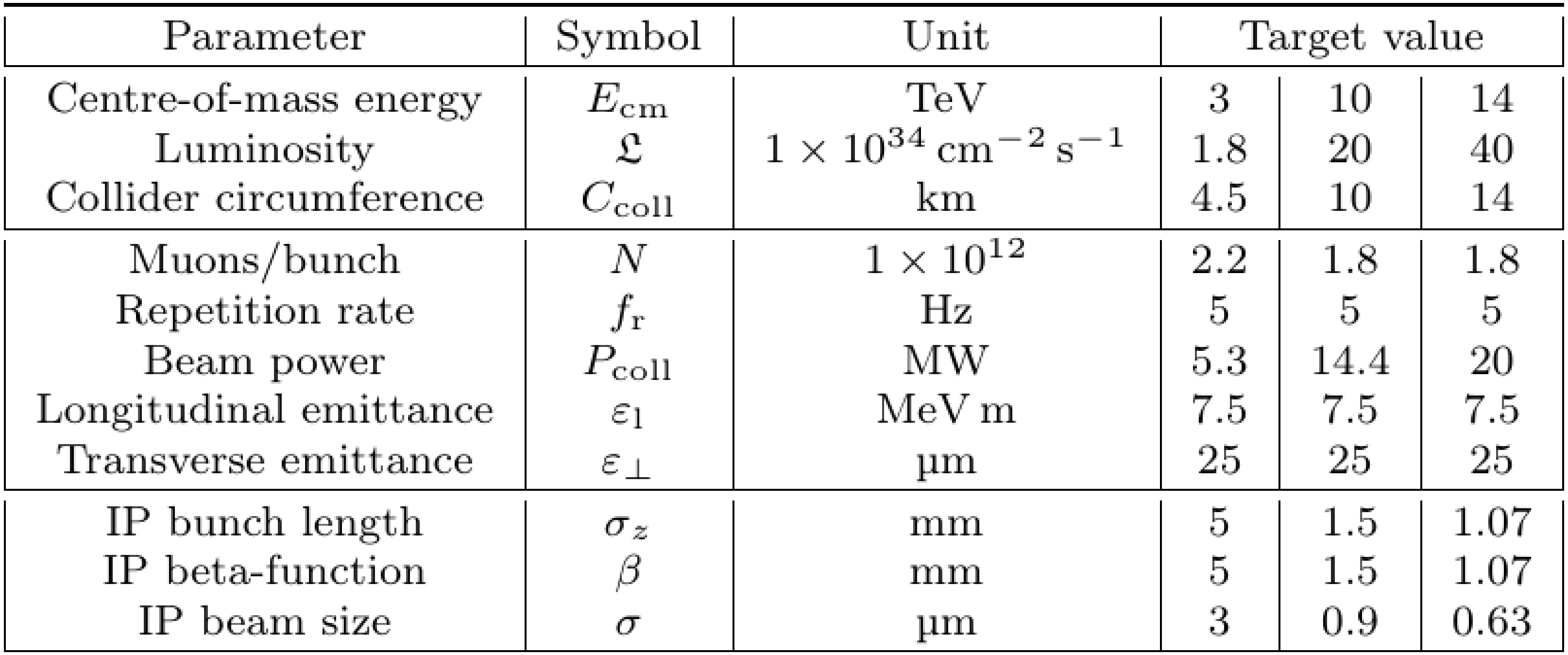
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

- Muon collider
  - Rather standard detector arrangement
  - Based on e^+e^- detector

Parameters



Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ε_{l}	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	µm	3	0.9	0.63

Challenges

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Challenges

- What are the challenges?
  - Neutrino beams
  - Rapid acceleration
  - Interaction region and beam induced background
  - Muon production
  - Time scale
- As we will see – all of these challenges can be met with current or next-generation equipment
  - But putting this together is entirely novel

Neutrino beams

- Muon decay
  - $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- Neutrinos are highly penetrating
- Neutrino beam opening angle $\approx 1/\gamma$
  - Width [m] = 0.1 Baseline length [km]/Muon Energy [TeV]
- Multi-TeV ν make a weak neutron shower
  - The ν beam must be spread out so that the shower is comparable with existing particle accelerators
    - ALARA: "As Low As Reasonably Achievable"
    - Far below any legal limit
  - Absolutely highest priority of IMCC

Acceleration efficiency

- During acceleration, muon lifetime is constantly increasing due to Lorentz time dilation.
- Starting from time dilated radioactive decay:

$$\frac{dN}{dt} = -\frac{1}{\gamma\tau_\mu}N = -\frac{m_\mu c^2}{E\tau_\mu}N$$

Change in number of muons with time

Time dilated muon lifetime with time

Use

$$\gamma = \frac{E}{m_\mu c^2}$$

Acceleration efficiency

$$\frac{dN}{dt} = -\frac{1}{\gamma\tau_\mu}N = -\frac{m_\mu c^2}{E\tau_\mu}N$$

- We want acceleration efficiency with energy

$$\frac{dN}{dE} = \frac{dN}{dt}\frac{dt}{dE}$$

$$\frac{dE}{dt} = \bar{V}c$$

$$\frac{dN}{dE} = -\frac{N}{\delta_\tau E}$$

Change in γ in muon lifetime:

$$\delta_\tau = q\bar{V}\tau_\mu/mc$$

- Integrate

$$N_\pm = N_{0\pm}\left(\frac{E}{E_0}\right)^{-1/\delta_\tau}$$

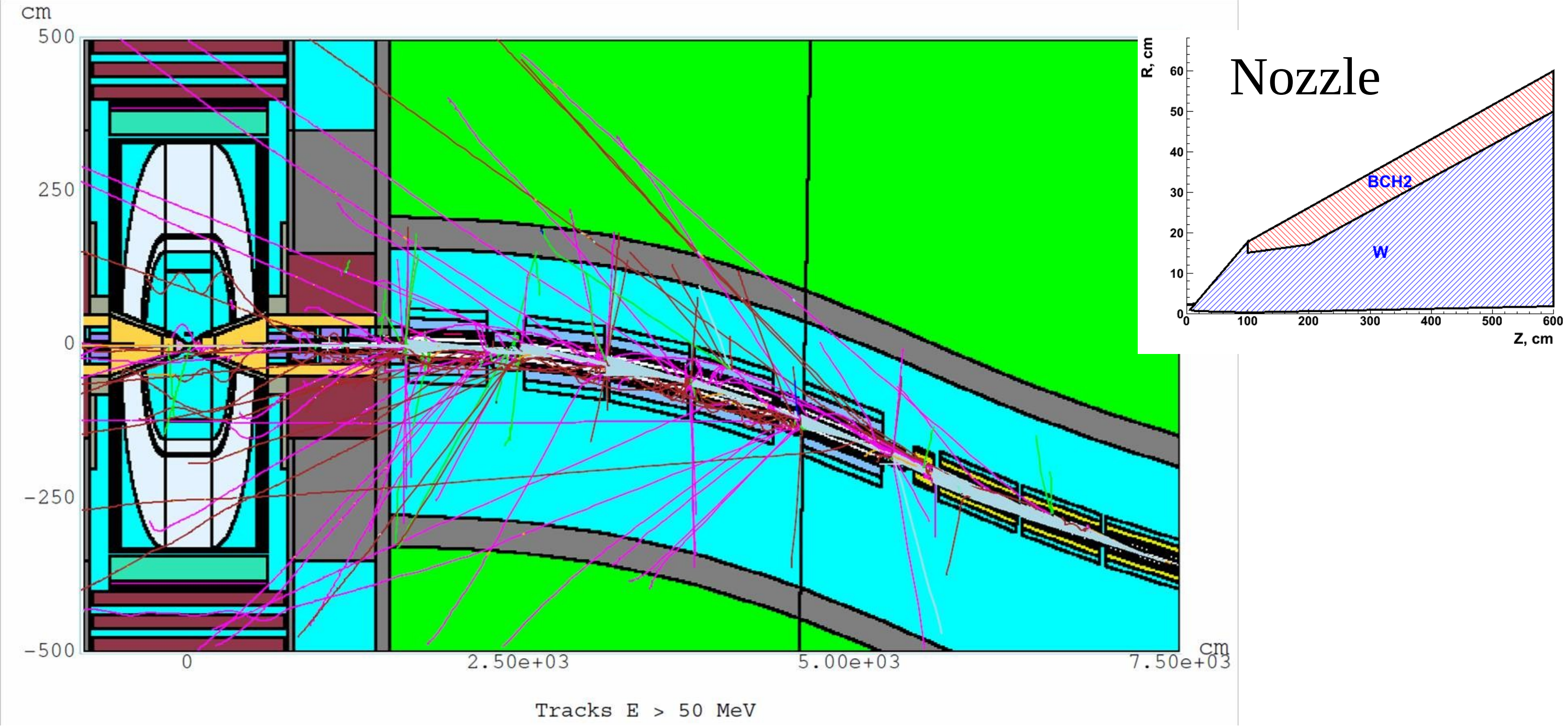
Acceleration efficiency

- Chaining multiple acceleration stages

$$\eta_\tau = \frac{N_\pm}{N_{0\pm}} = \prod_i \left(\frac{E_{i+1}}{E_i}\right)^{-1/\delta_{\tau,i}}$$

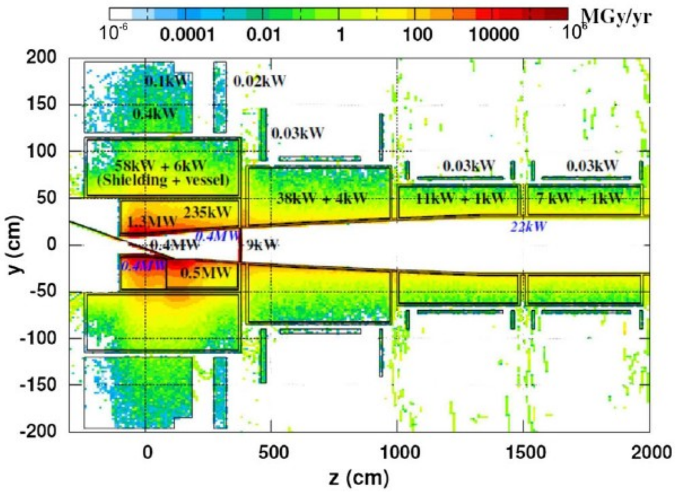
- Seek to accelerate from 0.2 GeV to 5 TeV
- E_f/E_i=2.5e4
- Average gradient ~ 10 MV/m → 84 % survival rate
- Average gradient ~ 1 MV/m → 19 % survival rate
- Compare with ILC → 23 MV/m
  - But we don’t want to use a linac all the way to 10 TeV!
- Compare with Fermilab booster → 10^{-3} MV/m
  - But this is designed to work with (stable) protons
- Can we design an accelerator that can give sufficient gradient?

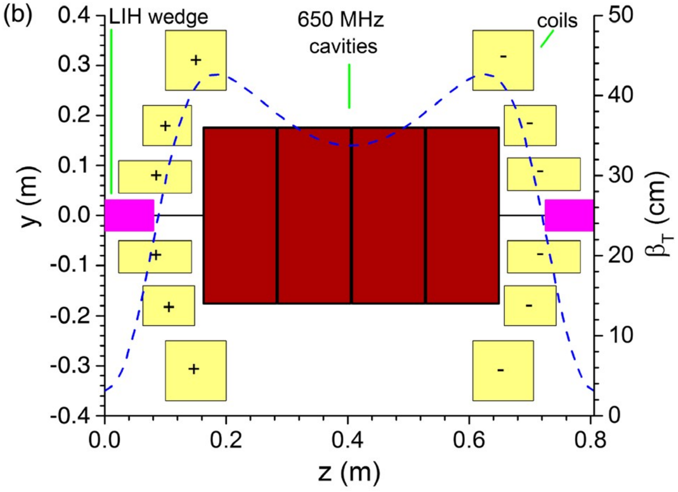
Muon Collider - BIB



- Beam induced background (BIB) arising due to muon decays
- Shield detector from direct radiation
- Timing cut to remove background
- Background comparable to High Luminosity LHC

Muon Production





- To produce muons with high beam brightness
- Muon target must be immersed in strong magnet field
  - Superconducting magnets do not like radiation!
- Muon beam must be cooled by many orders of magnitude
  - Ionisation cooling technology has barely been demonstrated
  - Very strong solenoids are required
  - RF cavities don’t like magnetic fields
- This all looks very hard
  - Lots of work to demonstrate the technologies

Muon Collider - Timeline

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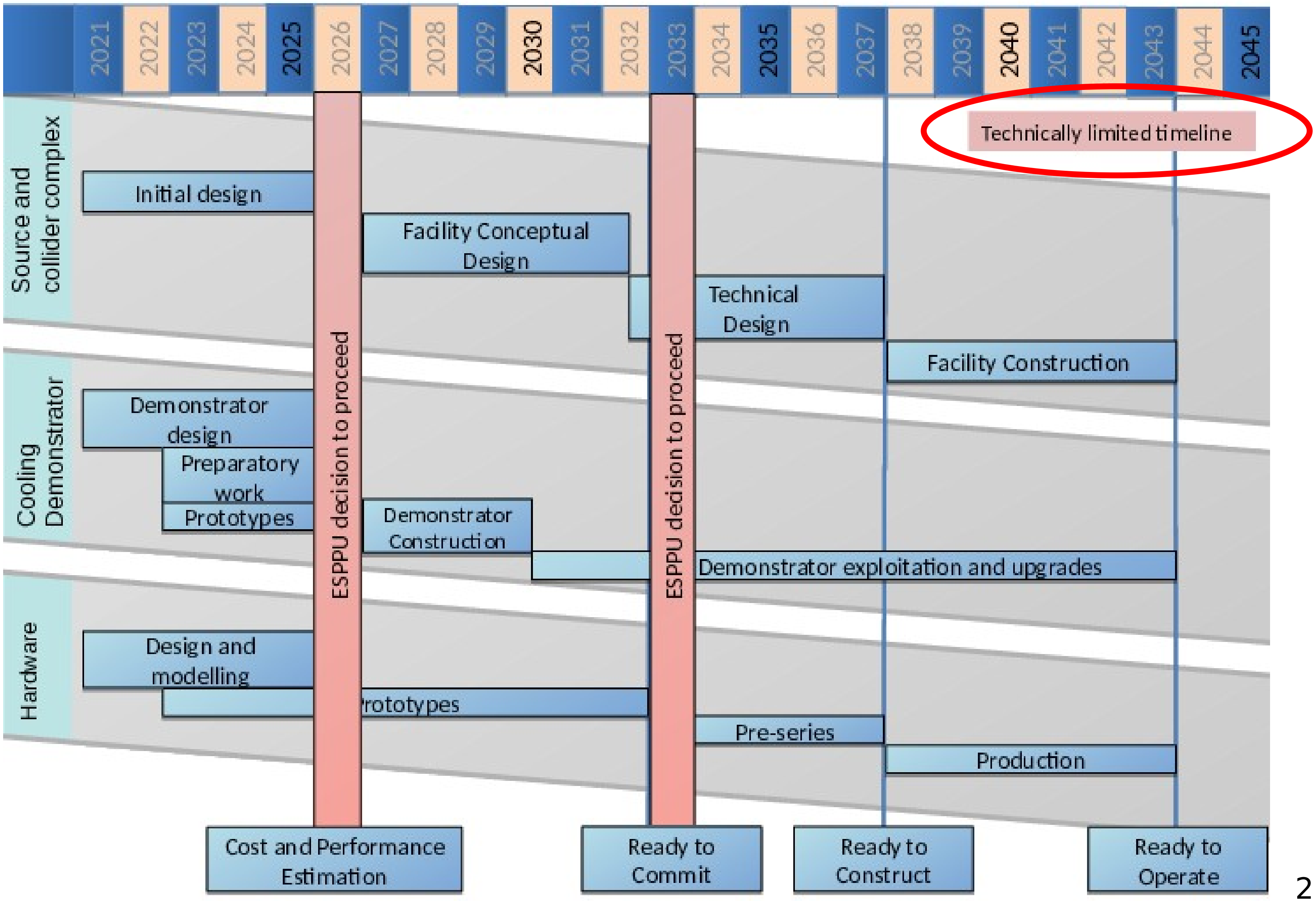

2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Source and collider complex
- Initial design
- Facility Conceptual Design
- Technical Design
- Facility Construction

Cooling Demonstrator
- Demonstrator design
- Preparatory work
- Prototypes
- Demonstrator Construction
- Demonstrator exploitation and upgrades

Hardware
- Design and modelling
- Prototypes
- Pre-series
- Production

ESPPU decision to proceed

ESPPU decision to proceed

Cost and Performance Estimation

Ready to Commit

Ready to Construct

Ready to Operate

Benefits - It’s All About Luminosity

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Luminosity

- **Luminosity** is key challenge
  - Number of events per cross-section per time
  - Diffuse beam → low chance of particles colliding → low luminosity
- Change in integrated luminosity per beam jth crossing

$$\Delta\mathfrak{L} = \frac{N_{+,j}N_{-,j}}{4\pi\sigma_\perp^2}$$

$N_{+/-}$ = Number of
μ^+ or μ^- on jth crossing

$\sigma_\perp$ = size of the beam in x/y
… assume cylindrical symmetry

- What drives luminosity? Can we relate luminosity to
  - Repetition rate of accelerator
  - Efficiency of muon creation
  - Proton beam parameters
  - Etc

Luminosity – stored muons (1)

$$\Delta\mathfrak{L} = \frac{N_{+,j}N_{-,j}}{4\pi\sigma_\perp^2}$$

- The number of particles is always falling due to muon decay

Number of particles entering collider

Distance between collisions i.e. collider circumference

$$N_{\pm,j} = N_\pm \exp\left(\frac{-2\pi Rj}{c\gamma\tau_\mu}\right)$$

Muon speed

Muon lifetime in the lab

Luminosity – stored muons (2)

- Luminosity (change in integrated luminosity per time)

$$\mathfrak{L} = f_r n_b \sum_{j=0}^{\infty} \Delta\mathfrak{L}$$

Number of bunches per acceleration cycle

Repetition rate (number of acceleration cycles per second)

$$\Delta\mathfrak{L} = \frac{N_{+,j} N_{-,j}}{4\pi\sigma_\perp^2}$$

$$N_{\pm,j} = N_\pm \exp\left(\frac{-2\pi R j}{c\gamma\tau_\mu}\right)$$

$$\mathfrak{L} = f_r n_b \frac{N_+ N_-}{4\pi\sigma_\perp^2} \sum_{j=0}^{\infty} \exp\left(-\frac{4\pi R}{\gamma c\tau_\mu} j\right)$$

Luminosity – stored muons (3)

$$\mathfrak{L} = f_r n_b \frac{N_+ N_-}{4\pi\sigma_\perp^2} \sum_{j=0}^{\infty} \exp\left(-\frac{4\pi R}{\gamma c \tau_\mu} j\right)$$

- Assuming muon lifetime is long compared to ring time-of-flight

$$\boxed{R = p/(e\bar{B}) \approx \gamma m_\mu c/(e\bar{B})}$$

$$\mathfrak{L} \approx f_r n_b \frac{N_+ N_-}{(4\pi)^2 \sigma_\perp^2} \frac{\gamma c \tau_\mu}{R}$$

- So

$$\mathfrak{L} \approx f_r n_b \frac{N_+ N_-}{(4\pi)^2 \sigma_\perp^2} \frac{\tau_\mu e\bar{B}}{m_\mu}.$$

Luminosity – Facility efficiency

$$N_\pm = \frac{\eta_\tau \eta_\pm P_p}{n_b f_r}$$

Efficiency of muon acceleration

Number of muons per proton beam power

$$\mathfrak{L} = f_r n_b \sum_{j=0}^{\infty} \Delta\mathfrak{L}$$

Number of bunches per acceleration cycle

Repetition rate (number of acceleration cycles per second)

Luminosity – $\sigma_\perp$ (1)

$$\mathfrak{L} \approx f_r n_b \frac{N_+ N_-}{(4\pi)^2 \sigma_\perp^2} \frac{\tau_\mu e \bar{B}}{m_\mu}.$$

Transverse beam size

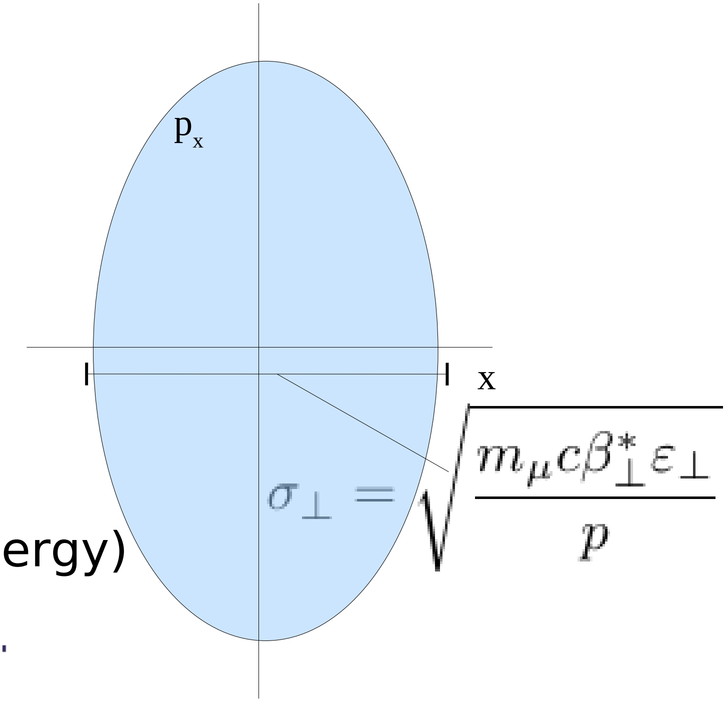
- Definition of emittance

$$\sigma_\perp = \sqrt{\frac{m_\mu c \beta_\perp^* \varepsilon_\perp}{p}}$$

Twiss function

Emittance

- Need very tight focusing!
- Limits:
    - Focusing strength of magnets
    - Chromaticity (focusing depends on energy)
    - Hour glass effect (next slide)



$$\sigma_\perp = \sqrt{\frac{m_\mu c \beta_\perp^* \varepsilon_\perp}{p}}$$

Luminosity – $\sigma_\perp$ (2)

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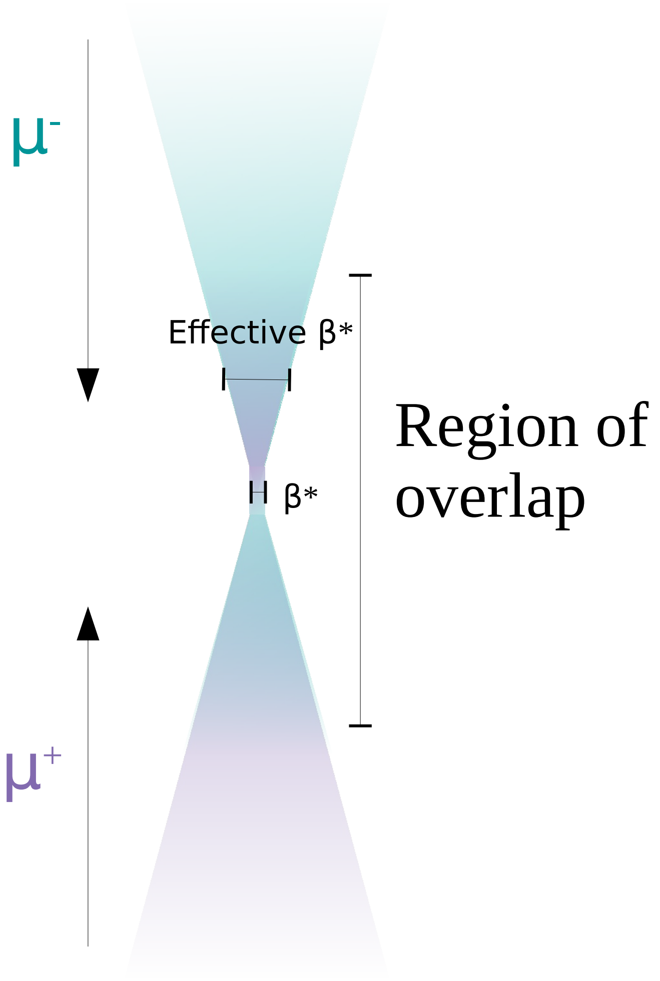
- Hour glass effect
  - Even for collider ring with super small β*
  - Small β* means short focal length
  - Region of overlap is very short
  - Bunch needs to be short as well!
- Introduce hour-glass factor f_{hg}
  - Relates the effective to lattice β^*

$$\beta^*_{eff} = \frac{\beta^*}{f_{hg}}$$

- If $\sigma_z = \beta^*$
  - Hour-glass factor is 0.76

$$\sigma_\perp = \sqrt{\frac{m_\mu c \sigma_z \varepsilon_\perp}{p f_{hg}}}$$



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Luminosity – $\sigma_\perp$ (3)

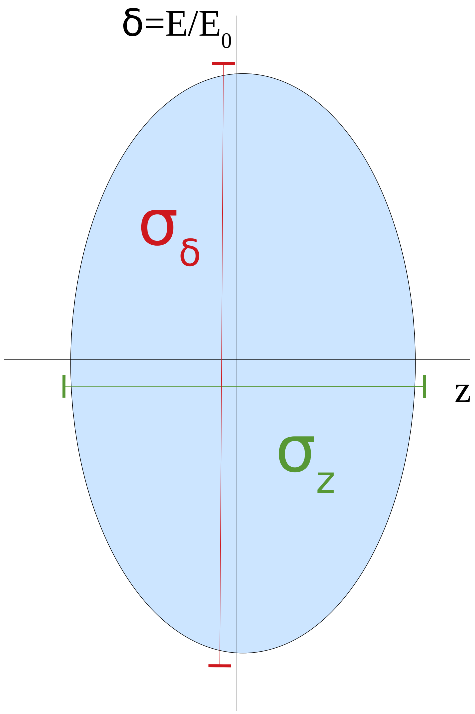
- Definition of longitudinal emittance

$$\varepsilon_l = \gamma m_\mu c^2 \sigma_\delta \sigma_z$$

- So

$$\sigma_\perp = \sqrt{\frac{m_\mu c \sigma_z \varepsilon_\perp}{p f_{hg}}}$$

$$\sigma_\perp^2 = \frac{\varepsilon_l \varepsilon_\perp}{p f_{hg} \gamma c \sigma_\delta}$$



- Recalling the expression for luminosity and N

$$\boxed{\mathfrak{L} \approx f_r n_b \frac{N_+ N_-}{(4\pi)^2 \sigma_\perp^2} \frac{\tau_\mu e \bar{B}}{m_\mu}.} \qquad \boxed{N_\pm = \frac{\eta_\tau \eta_\pm P_p}{n_b f_r}}$$

- Bringing everything together

$$\mathfrak{L} \approx \underbrace{\frac{e\tau_\mu}{(4\pi m_\mu c)^2}}_{K_L} \frac{f_{hg} \sigma_\delta \bar{B}}{\varepsilon_\perp \varepsilon_L n_b f_r} \underbrace{\eta_+ \eta_- (\eta_\tau P_p \gamma m_\mu c^2)^2}_{P_+ P_-}$$

Luminosity

$$\mathfrak{L} \approx \underbrace{\frac{e\tau_\mu}{(4\pi m_\mu c)^2}}_{K_L} \frac{f_{hg}\sigma_\delta \overset{\boxed{2}}{\bar{B}}}{\underset{\boxed{4}}{\varepsilon_\perp \varepsilon_L} \underset{\boxed{3}}{n_b f_r}} \underbrace{\overset{\boxed{4}}{\eta_+\eta_-}(\overset{\boxed{5}}{\eta_\tau} P_p \overset{\boxed{1}}{\gamma m_\mu} c^2)^2}_{P_+P_-}$$

1) Luminosity increases with the square of muon energy/power
   - Number of collisions per bunch increases as muon lifetime increases
   - Beam size decreases as energy increases (geometric emittance)
2) High field, low circumference collider ring → more luminosity
   - Shorter path length, more collisions before muon decay
3) Low repetition rate, few bunches is best
   - Assume that the bottleneck is in the number of protons
   - Fewer collisions, but each collision is more intense
4) High quality muon source is essential
   - Low emittance, good capture efficiency
5) Good efficiency acceleration is essential
   - High voltage systems

- The whole muon collider is designed to maximise luminosity!

ITF Report

Report of the Snowmass'21 Collider Implementation Task Force

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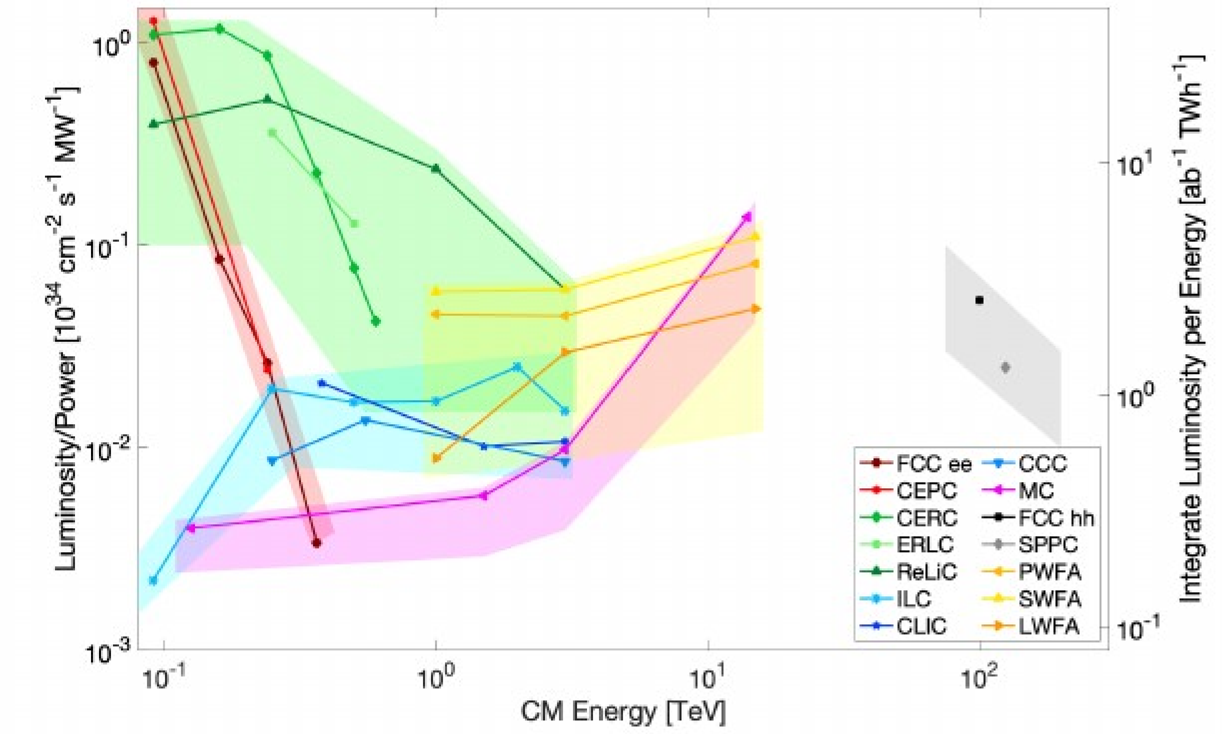
Abstract

The Snowmass'21 Implementation Task Force has been established to evaluate the proposed future accelerator projects for performance, technology readiness, schedule, cost, and environmental impact. Corresponding metrics has been developed for uniform comparison of the proposals ranging from Higgs/EW factories to multi-TeV lepton, hadron and *ep* collider facilities, based on traditional and advanced acceleration technologies. This report documents the metrics and processes, and presents evaluations of future colliders performed by Implementation Task Force.

https://arxiv.org/abs/2208.06030

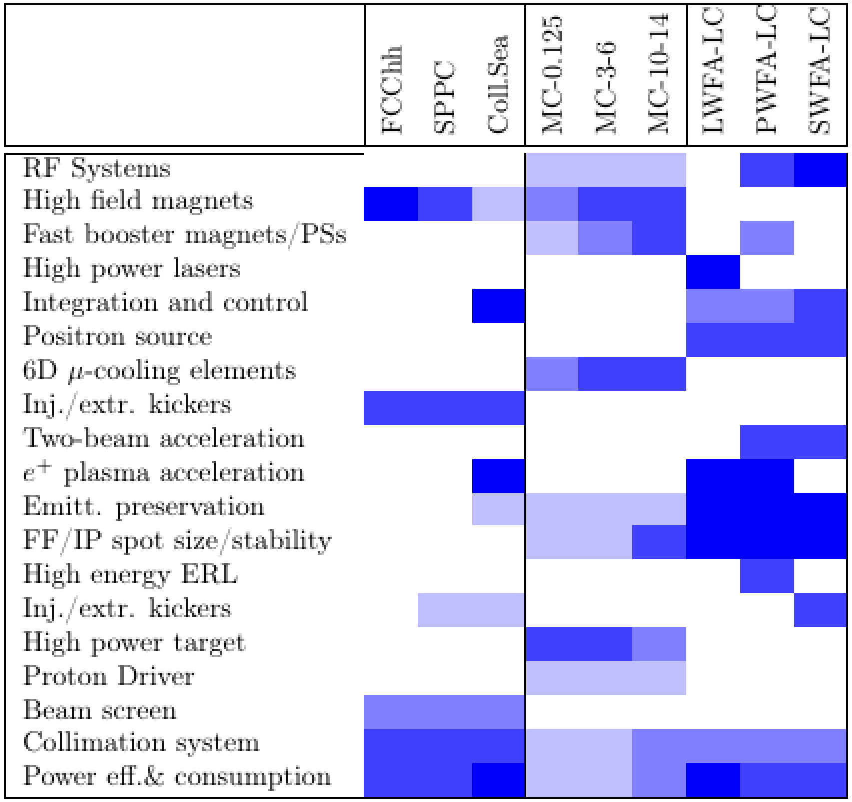
- All numbers have large error bars
    - A lot of work needed to reduce the errors

Luminosity vs beam power



- Muon collider offers high luminosity for beam power
  - Crossing point with e^+e^- at ~ TeV

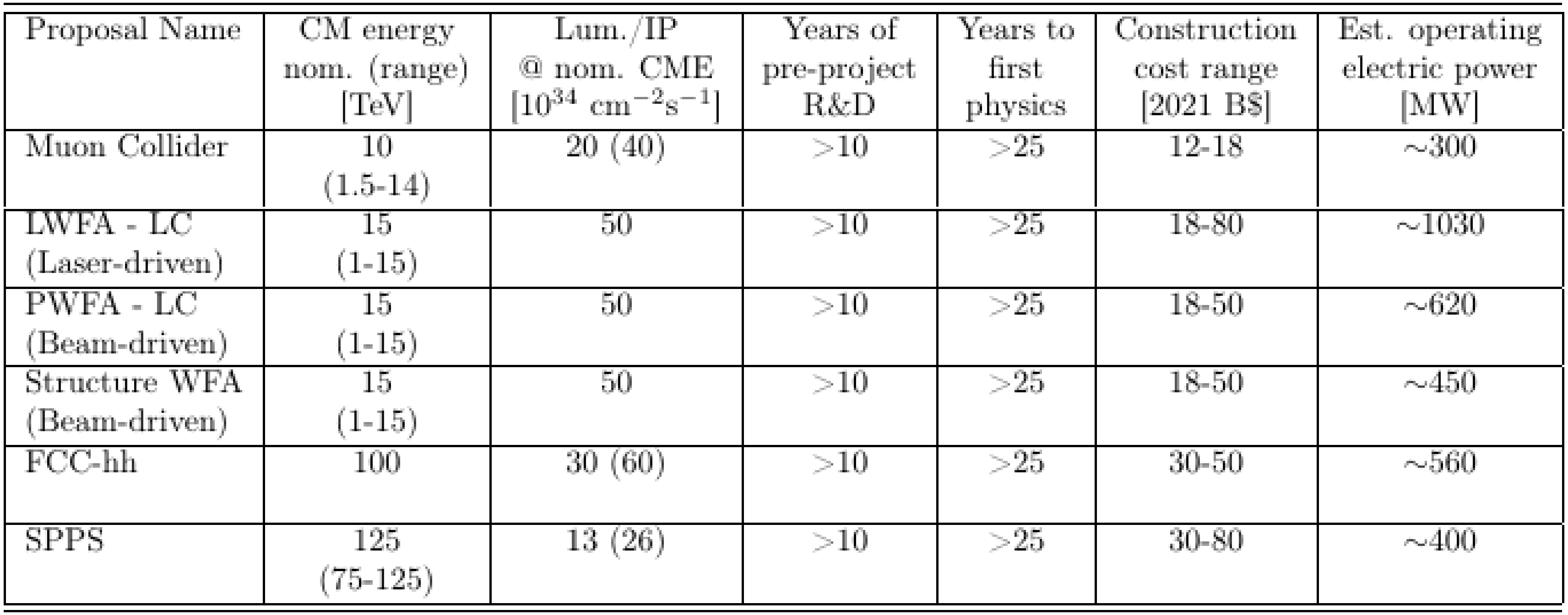
Technical risk



	FCChh	SPPC	Coll.Sea	MC-0.125	MC-3-6	MC-10-14	LWFA-LC	PWFA-LC	SWFA-LC
RF Systems				░	░	░		▓	█
High field magnets	█	▓	░	▒	▓	▓			
Fast booster magnets/PSs				░	▒	▓		▒	
High power lasers							█		
Integration and control			█				▒	▒	▓
Positron source							▓	▓	▓
6D μ-cooling elements				▒	▓	▓			
Inj./extr. kickers	▓	▓	▓						
Two-beam acceleration								▓	▓
e^+ plasma acceleration			█				█	█	
Emitt. preservation			░	░	░	░	█	█	█
FF/IP spot size/stability				░	░	▓	█	█	█
High energy ERL								▓	
Inj./extr. kickers		░	░						▓
High power target				▓	▓	▒			
Proton Driver				░	░	░			
Beam screen	▒	▒	▒						
Collimation system	▓	▓	▓	░	░	▒	▒	▒	▒
Power eff.& consumption	▓	▓	█	░	░	▒	█	▓	▓

- Muon collider offers high luminosity for beam power
  - Crossing point with e^+e^- at ~ TeV

Cost & power



Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	$\sim$300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	$\sim$1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	$\sim$620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	$\sim$450
FCC-hh	100	30 (60)	>10	>25	30-50	$\sim$560
SPPS	125 (75-125)	13 (26)	>10	>25	30-80	$\sim$400

- Muon collider offers high luminosity for beam power
  - Crossing point with e^+e^- at ~ TeV

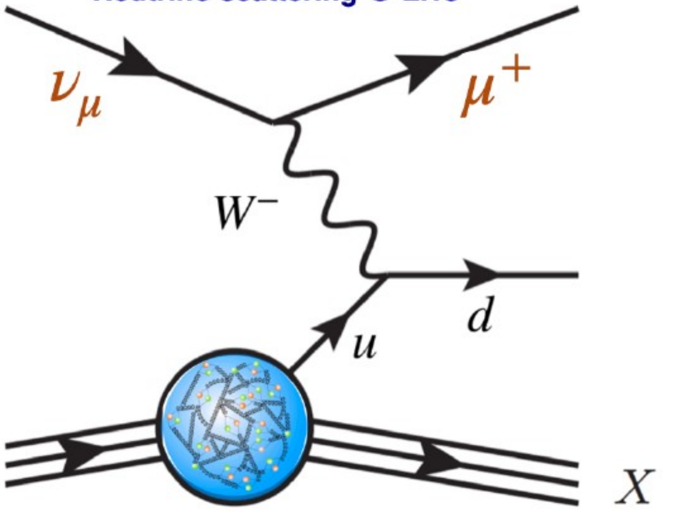
Non-Collider Physics

- Low energy muon beams are in high demand
  - Fundamental science → messengers from high energy
  - Production of precision neutrino beams
  - Muons for material sciences
- To date applications are limited by the available beams
  - More in the next lecture
- The muon collider can support a programme of non-collider high energy physics
  - It is vital to support a large part of the fundamental physics community at a future collider

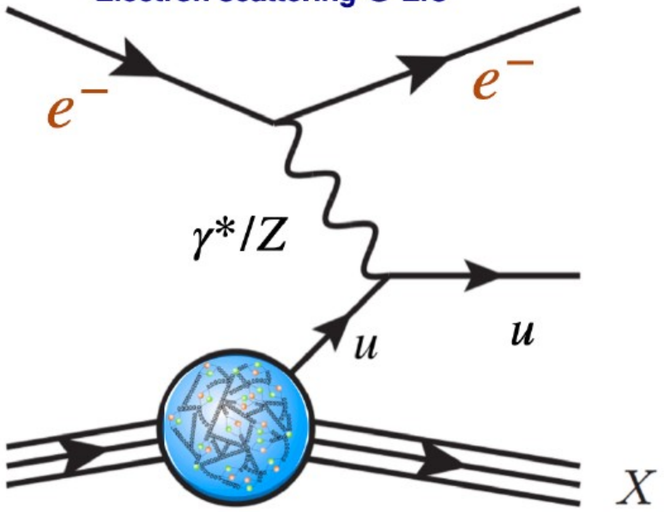
Nuclear Physics

- LHC is a neutrino source
  - Charged current analogue of EIC
  - Faser2 experiment
- Muon collider neutrino beams
  - Much higher intensity
  - Much better characterised
  - Expect better resolutions
    - TBC

Neutrino scattering @ LHC



Electron scattering @ EIC



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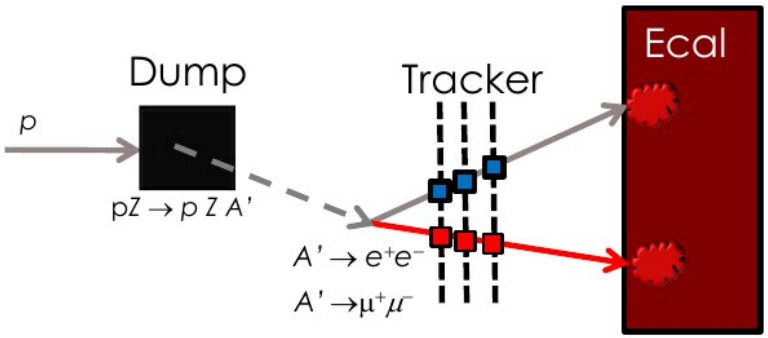
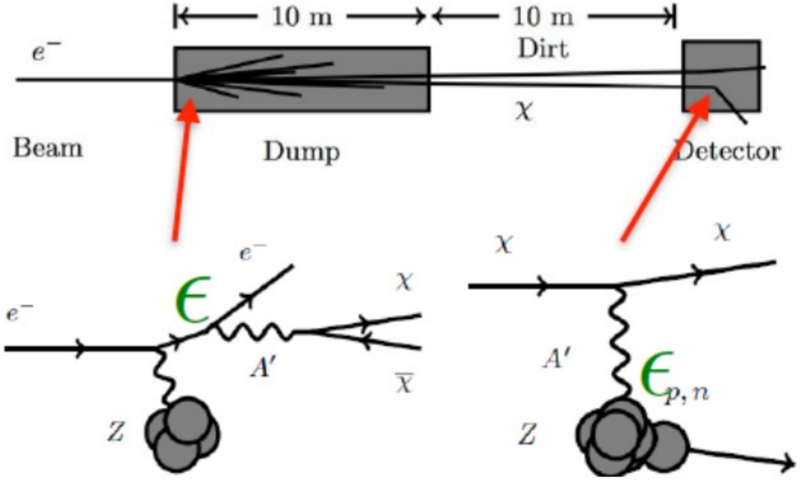
Proton dump experiments

p dump experiment visible



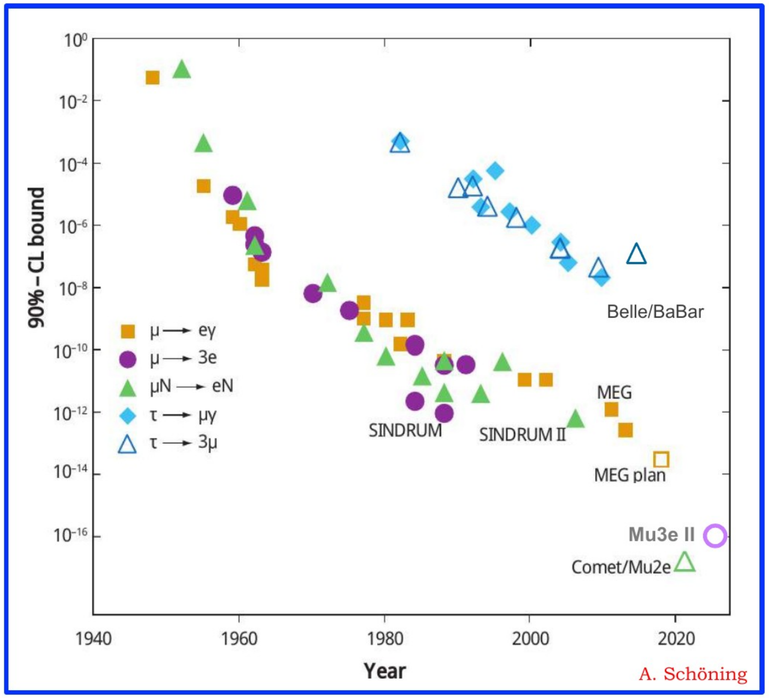
(charm, NA62, U70)

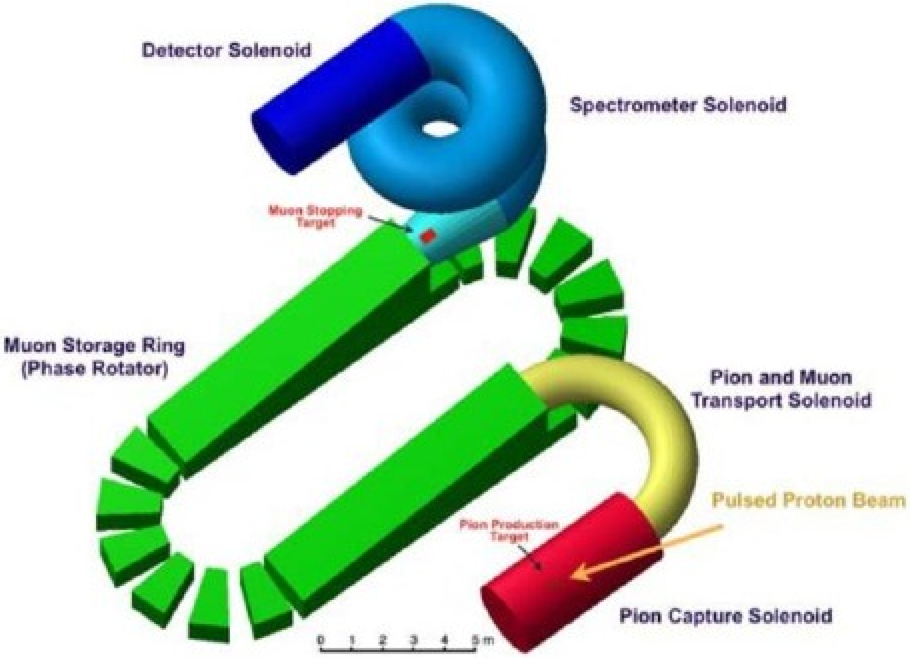
p dump experiment invisible



- Proton beam dump supports search for
  - Vector state mixing to photon
  - Scalar state mixing to higgs boson
  - Heavy neutral leptons
  - Axion-like particles

Charged Lepton Flavour Violation





- Charged lepton flavour violation → messenger of BSM at higher energies
    - Large and pure flux of muons required

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Final Thoughts

International
MUON Collider
Collaboration

Final Word

- The muon collider
  - Higher **energy** and **luminosity** reach than e^+e^- colliders
  - **Smaller footprint** than equivalent proton colliders
- Many technical challenges
  - It’s a hard machine to build
  - All are manageable with current or near-to-current technologies
  - Must demonstrate practical solutions
- Broad “beyond collider” physics programme
  - More to come in the next lecture
- Muon collider can advance particle physics by decades
  - It is now for us to deliver it

Backup

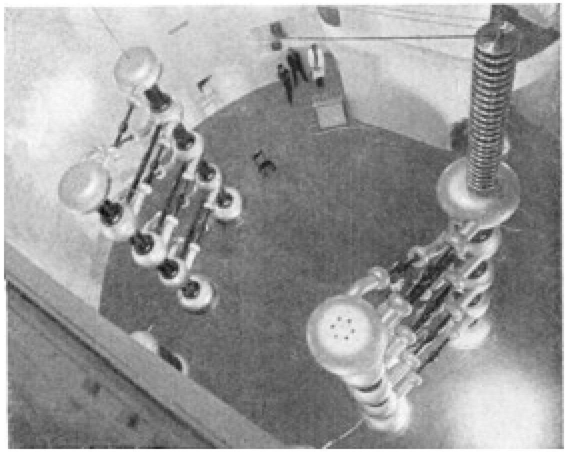
International
MUON Collider
Collaboration

C. T. Rogers
Rutherford Appleton Laboratory

Accelerators in Physics

International
UON Collider
Collaboration

- First accelerators built in 1920s/30s
  - Accelerating protons, ions and electrons
- Antiproton acceleration in 1980s
  - Made possible by stochastic cooling
- Accelerators were originally a tool for fundamental physics
  - Now many uses
- Hadron colliders
  - E.g. LHC
  - “Discovery machines”
- Lepton colliders
  - E.g. Large Electron Positron Collider (LEP)
  - “Precision machines”
- Secondary+ particle production
  - Muons, pions, kaons, neutrinos …



UK RI Science and Technology Facilities Council

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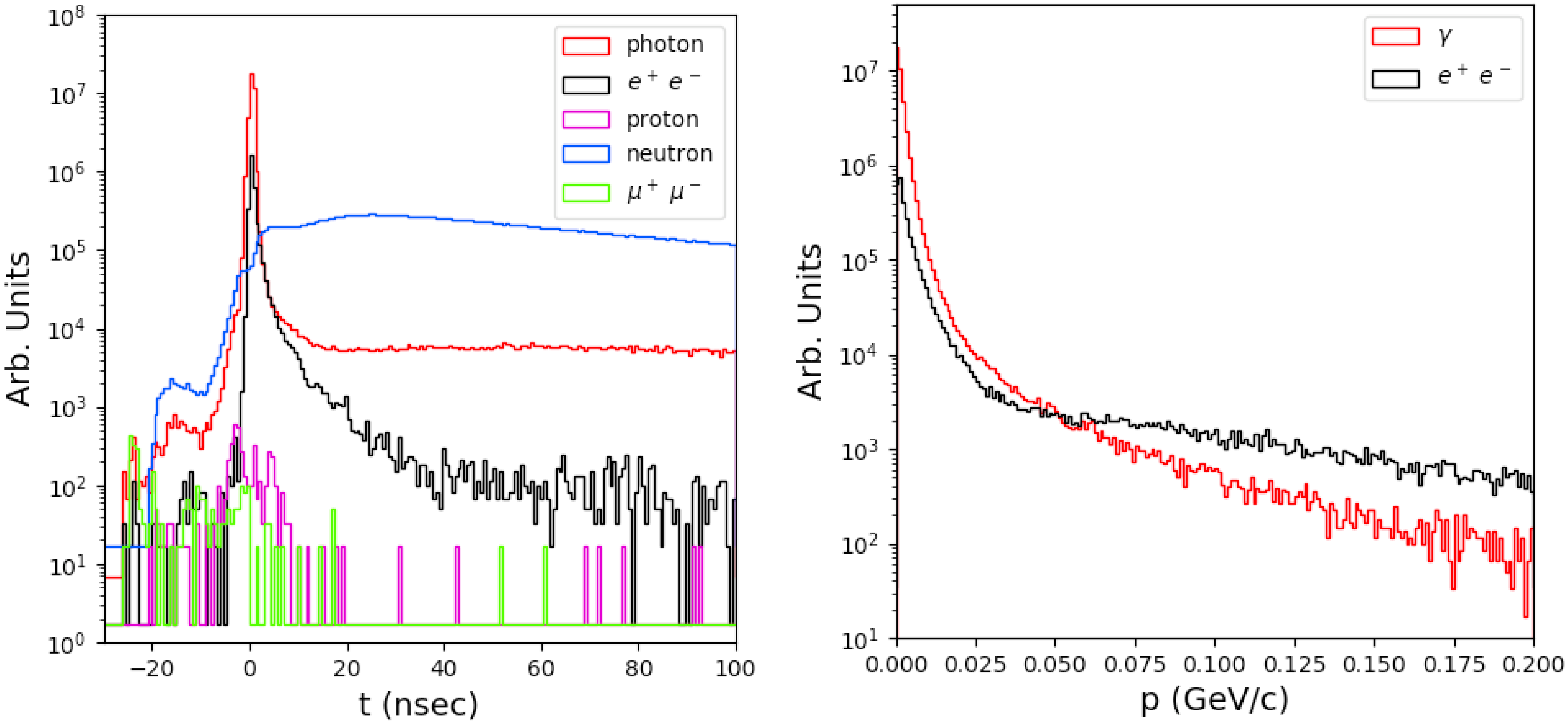
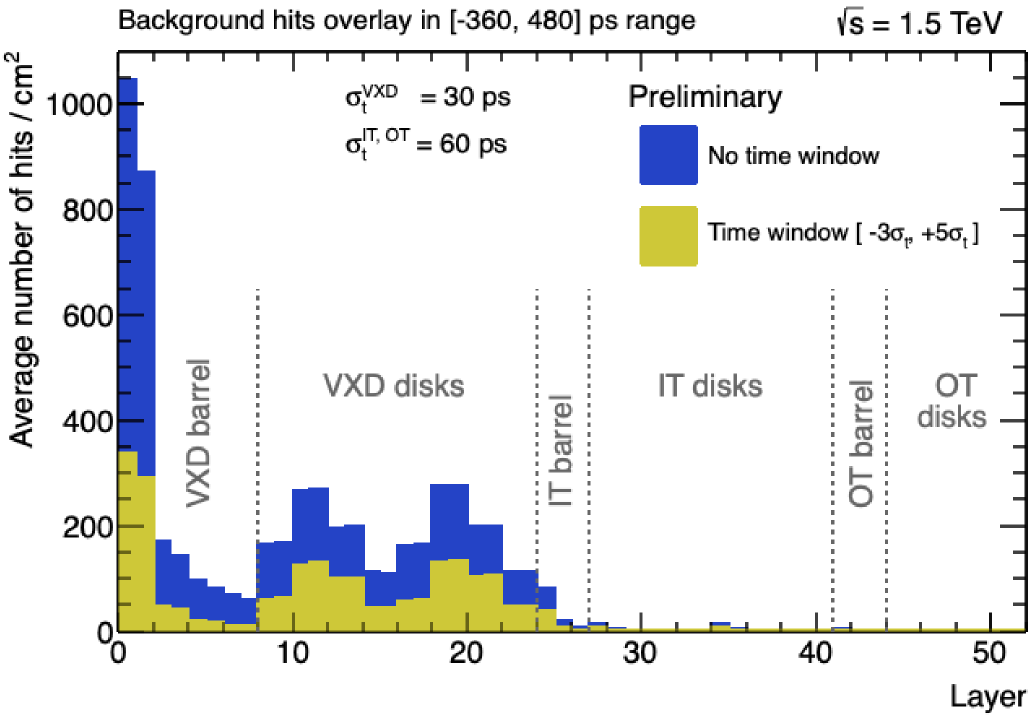
BIB Characteristics



- Beam induced background (BIB) arising due to muon decays

BIB Rejection



- Beam induced background (BIB) arising due to muon decays

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