Muon Collider

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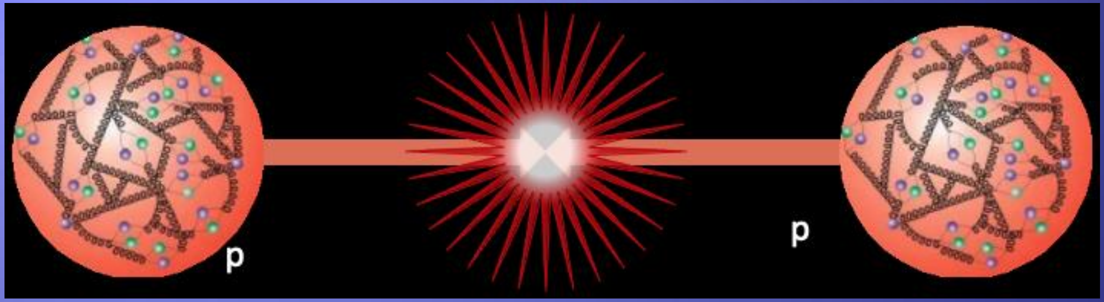
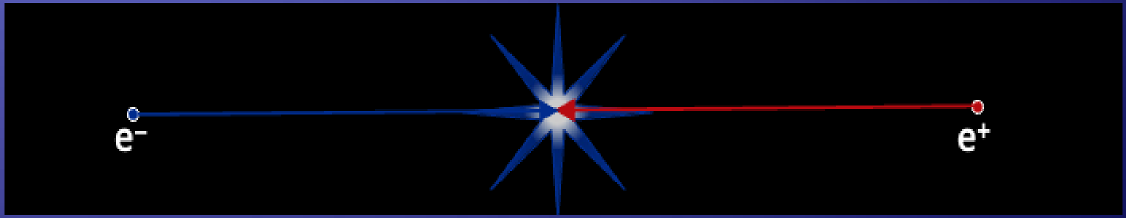
HEP Particle Colliders

- Proton-proton Collider:
  - Offer highest center-of-mass collision energies
  - Collisions of composite particles
  - Discovery potential via Electroweak and Strong Interactions



- Electron-positron Collider:
  - Collision of point-like fermions with well-defined initial state
  - Precision measurements via Electroweak Interactions
  - At multi-TeV energies – electroweak boson colliders



Higher Energy Collider

- How far can go to higher energy collider?

$$B \approx 3\left(\frac{E}{1\ \mathrm{TeV}}\right)\left(\frac{1\ \mathrm{km}}{R}\right)\ \mathrm{T}$$

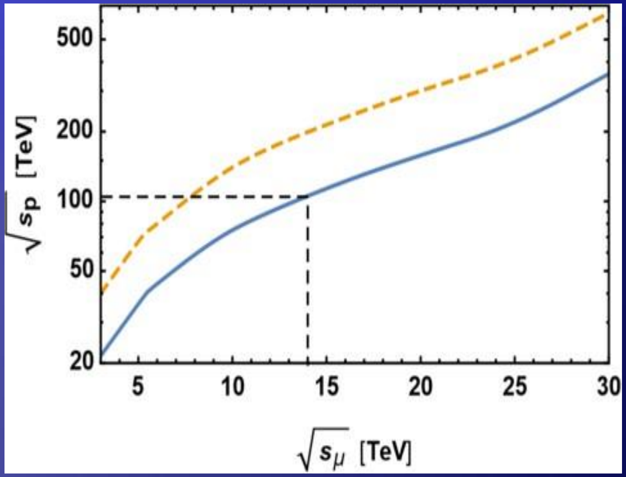
- From 14 TeV to 100 TeV
  - LHC: 27 km size with 8 T magnet
  - FCC-hh:~90 km size with ~16 T magnet

LHC (CERN)
13.6 TeV

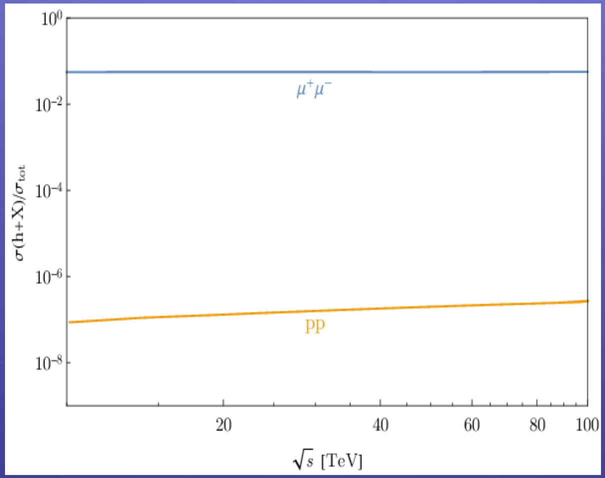
Why muon collider?

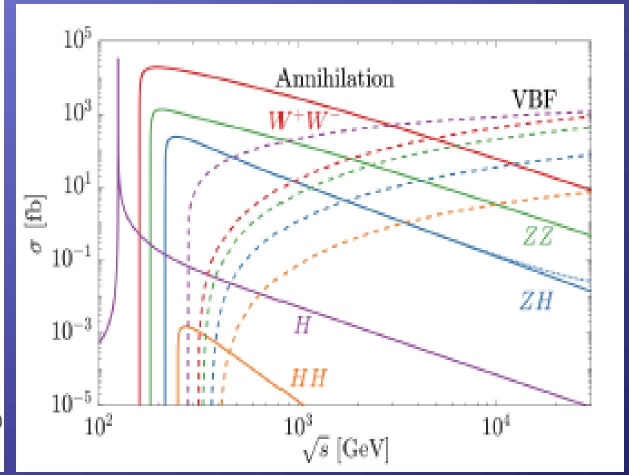
- Higher mass: avoids synchrotron radiation

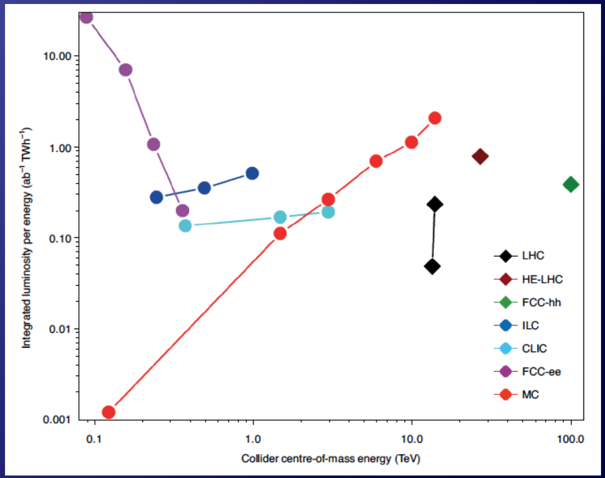
$$P \approx 3 \times 10^{-7} \left(\frac{1\ \text{km}}{R} \right)^2 \left(\frac{E}{m} \right)^4 \text{eV/s}$$



- Point-like particle: can get higher energy reach with lower energy beam compared to protons
- Cleaner to access a EWK machine
- Bonus: luminosity increases linearly with energy for fixed power







Muon Collider

- **Why Muon Collider?**
  - A unique, compact, high-energy (10 TeV scale) electroweak collider
  - A paradigm-shifting collider: combine the high-energy frontier of pp collider and the high precision of e^-e^+ collider
  - Natural next step after HL-LHC and a complement to a future low-energy Higgs factory
  - Can be realized within one generation (not two!)

- **Growing International Interest:**
  - Most of R&D has been done by Muon Accelerator Program in US
  - Now International Muon Collider Collab. (IMC) hosted by CERN + FNAL start to work for muon colliders (3 TeV, 10 TeV)
  - Strong community enthusiasm: Aim High and "Shoot for the muon!"
  - Innovative technologies (accelerator, detector, magnets) attracting early-career researchers

Physics Case

- **Precision Standard Model (SM) Measurements:**
  - Probe the high-energy regime of "unbroken" electroweak symmetry
  - High-precision studies of Vector Boson Scattering (VBS) at the TeV scale: “first tests of electroweak symmetry breaking "unitarization"
- **Exploring Beyond the Standard Model (BSM) Physics:**
  - **Higgs Boson:** Precision study of properties & potential (next-gen Higgs factory)
  - Electroweak phase transition, baryogenesis, vacuum stability, Higgs portal
  - **Dark Matter (DM):** Unmatched probes of new Electroweak (EW) particles
  - **Others:** New gauge forces, fermion interactions, neutrino masses (Heavy Neutral Leptons) up to O(100) TeV scales
- **Unique High-Energy Neutrino Program:** Complements existing neutrino experiments

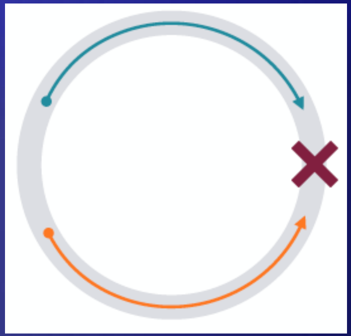
Challenges with Muon

- Short Lifetime: 2.2 μs
- Avg. decay time in lab

$$\tau'_\mu = 21\ \text{ms} \times \left(\frac{E}{1\ \text{TeV}}\right)$$

- Time between collisions

$$t = 33\ \mu s \times \left(\frac{L}{10\ \text{km}}\right)$$



- Avg. beam crossing for each inject muons: Lum. is proportional to E

$$\langle n_{\text{crossings}} \rangle = 620 \times \left(\frac{E}{1\ \text{TeV}}\right) \times \left(\frac{10\ \text{km}}{L}\right)$$

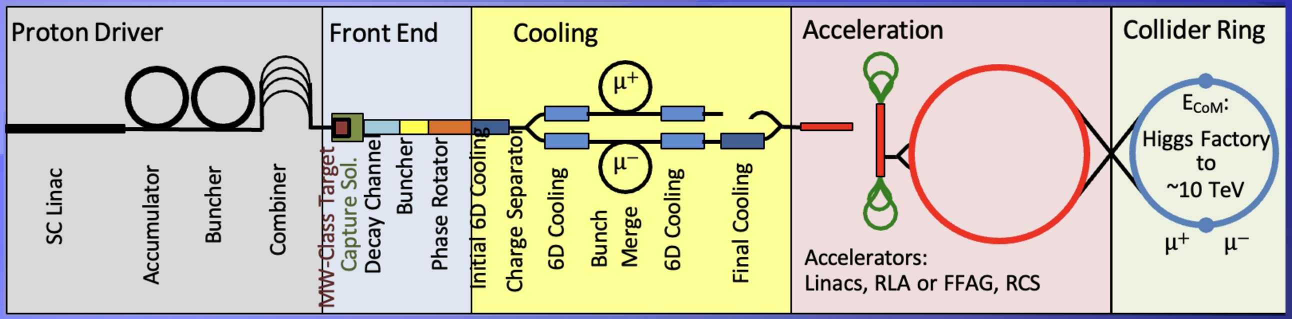
- Fraction of muons decaying within 20m of the interact

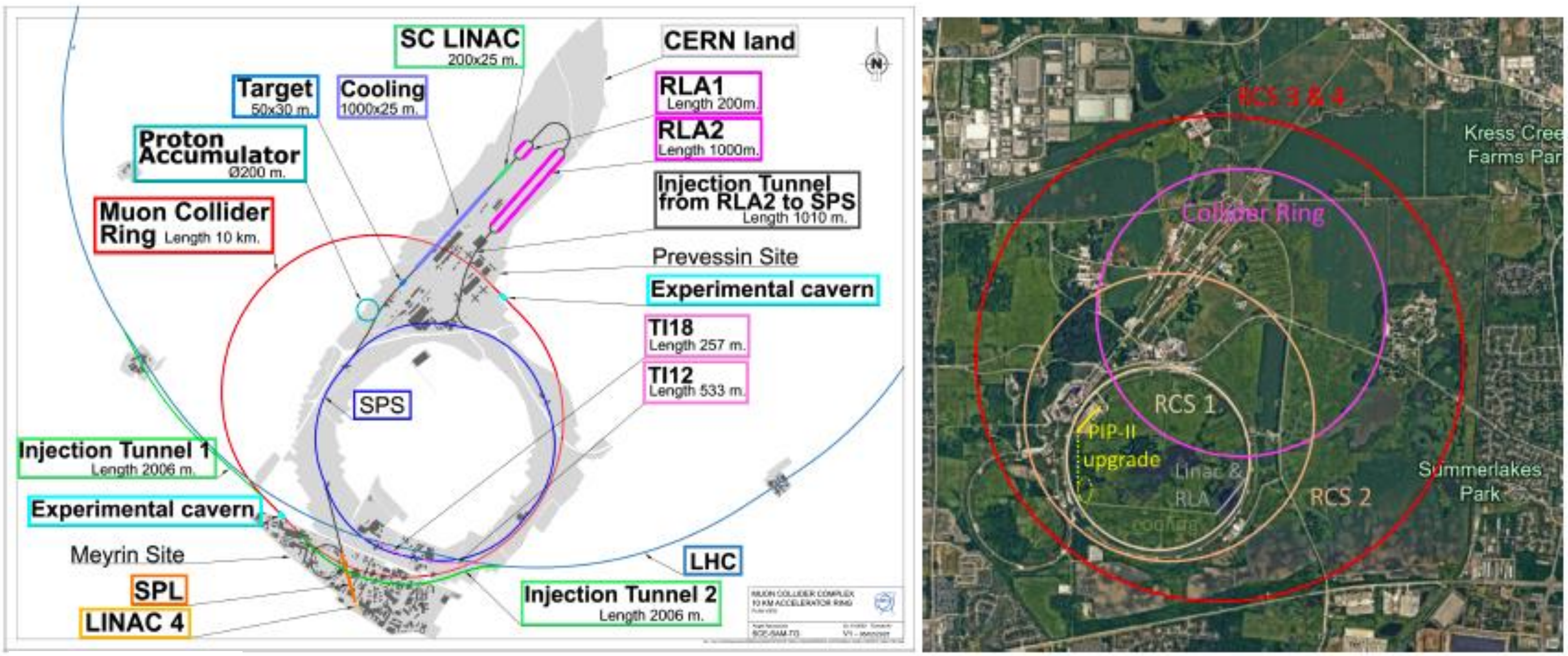
$$f \approx 6.4 \times 10^{-6} \times \left(\frac{1\ \text{TeV}}{E}\right)$$

- Total energy of decay products within 20m

$$E_{\text{decay}} = 13\ \text{EeV} \times \left(\frac{n_\mu/\text{bunch}}{2 \times 10^{12}}\right)$$

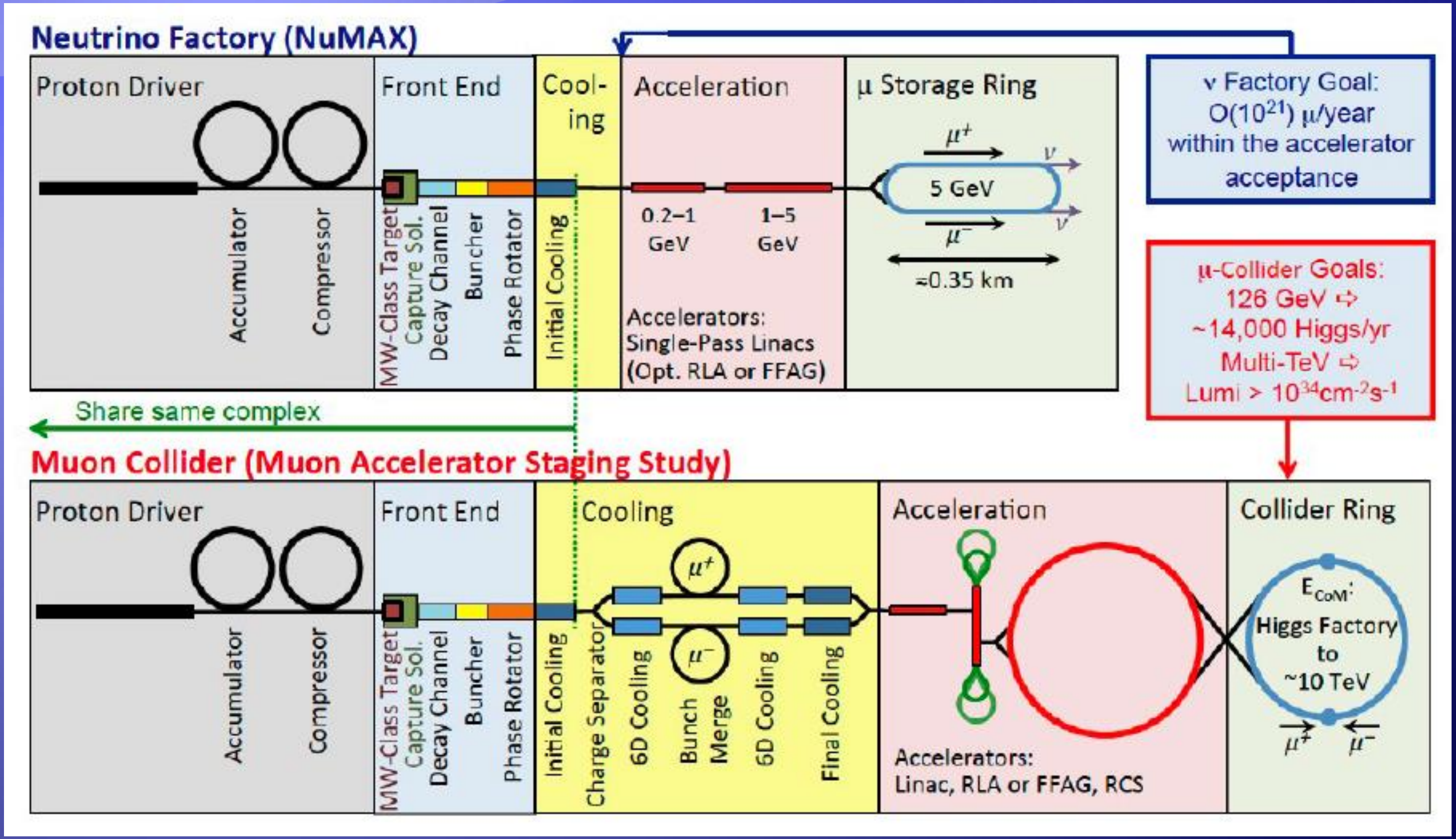
Muon Collider Concept



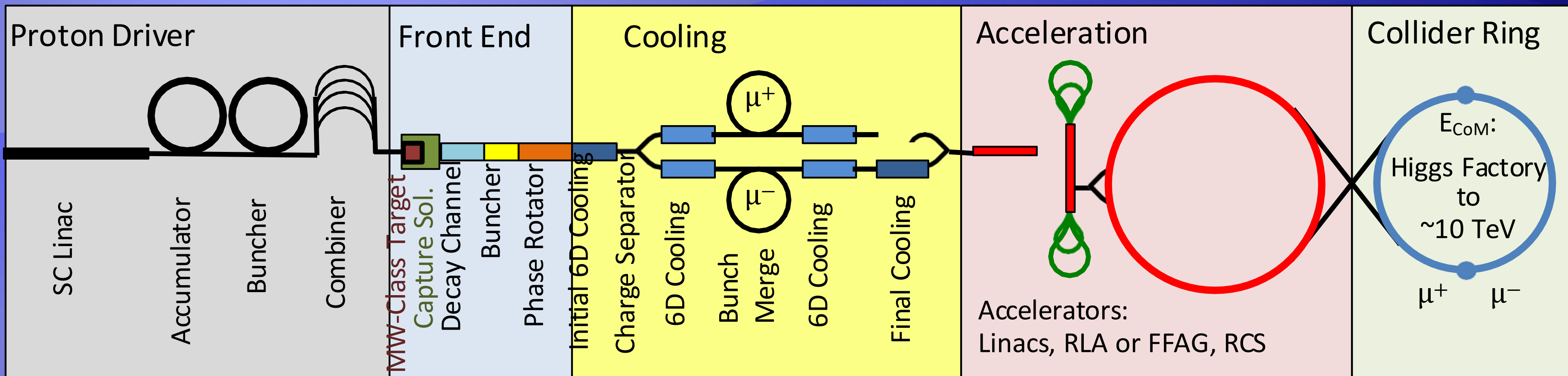


Conceptual layout of the muon collider at CERN (left) and Fermilab (right).

Synergy with neutrino factory



Muon Collider Concept



- Accelerator design is driven by the short muon lifetime
- Key Components
  - Proton Driver: produce short, high-intensity proton pulses
  - Target & Front End: Protons hit a target, producing pions, decaying into muons
  - Cooling Stages: Reduce beam emittance (a core technology!) using absorbers and RF cavities in high magnetic fields.
  - Acceleration System: LINAC, Recirculating Linear Accelerators (RLAs), and high-energy accelerator rings (to 1.5 TeV or 5 TeV).
  - Collider Ring: Muon beams collide at full energy.

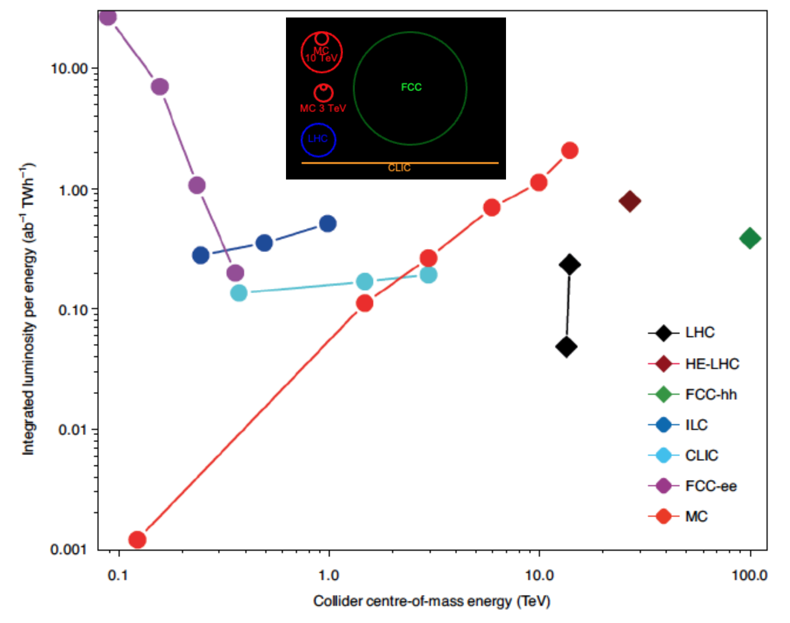
Muon Collider Parameters

- For a 10 TeV muon collider
  - N = 2×10^{12} particles/bunch
  - $\sigma_{x,y}$ ~ 1 µm, β^* = 1.5 mm, $\varepsilon_{x,y}(norm)$ = 25 µm-rad
  - n_{turns}~10^3
  - f_{bunch}=5 Hz

  (injection rate of bunches)

$$L = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y} = \frac{\langle N^2 \rangle_{n_{turns}} n_{turns} f_{bunch}}{4\pi\sigma_\perp^2}$$

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

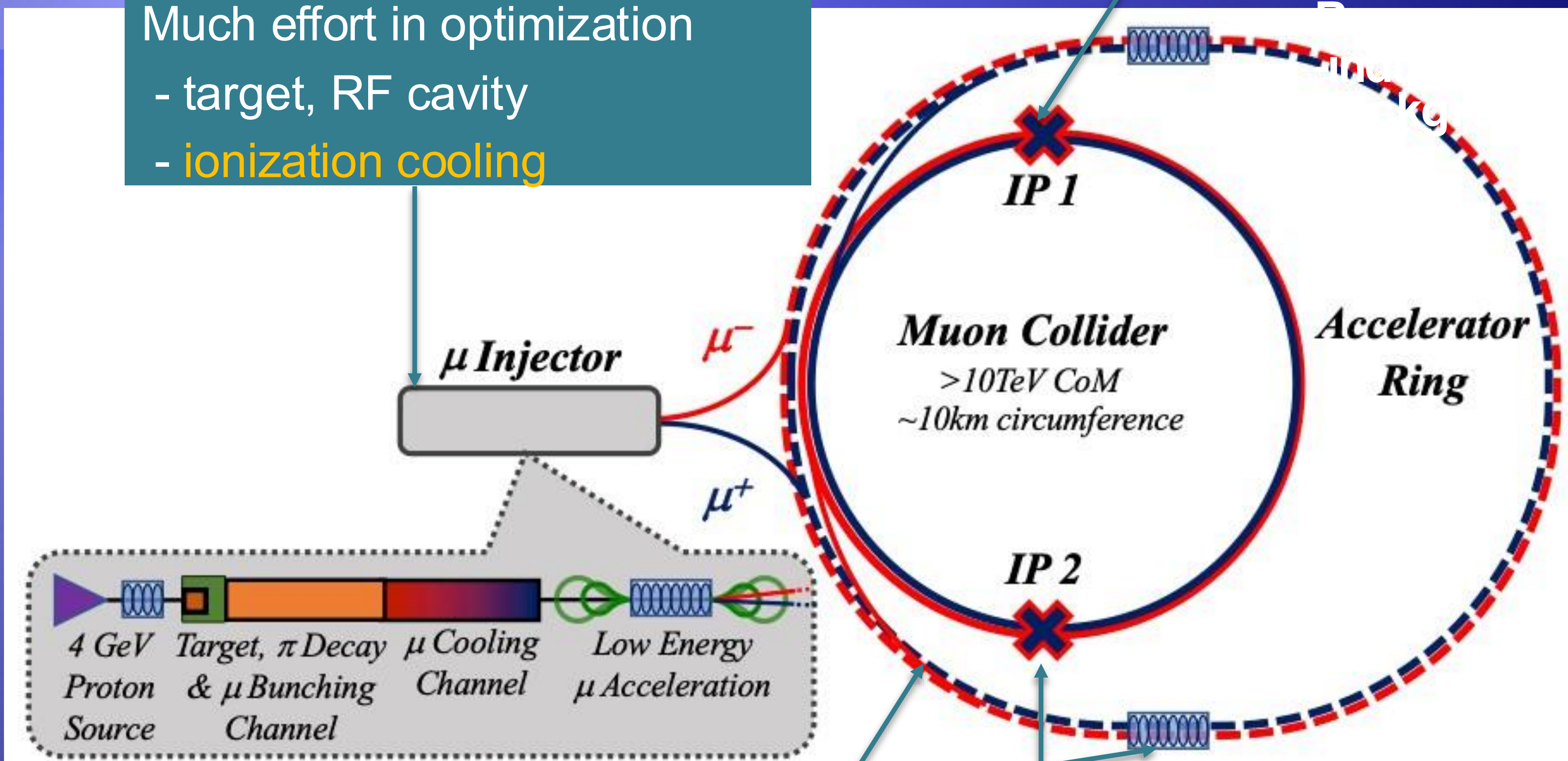


Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Key Challenges

Drives beam quality:
Much effort in optimization
- target, RF cavity
- ionization cooling

Beam-Induced bkgd

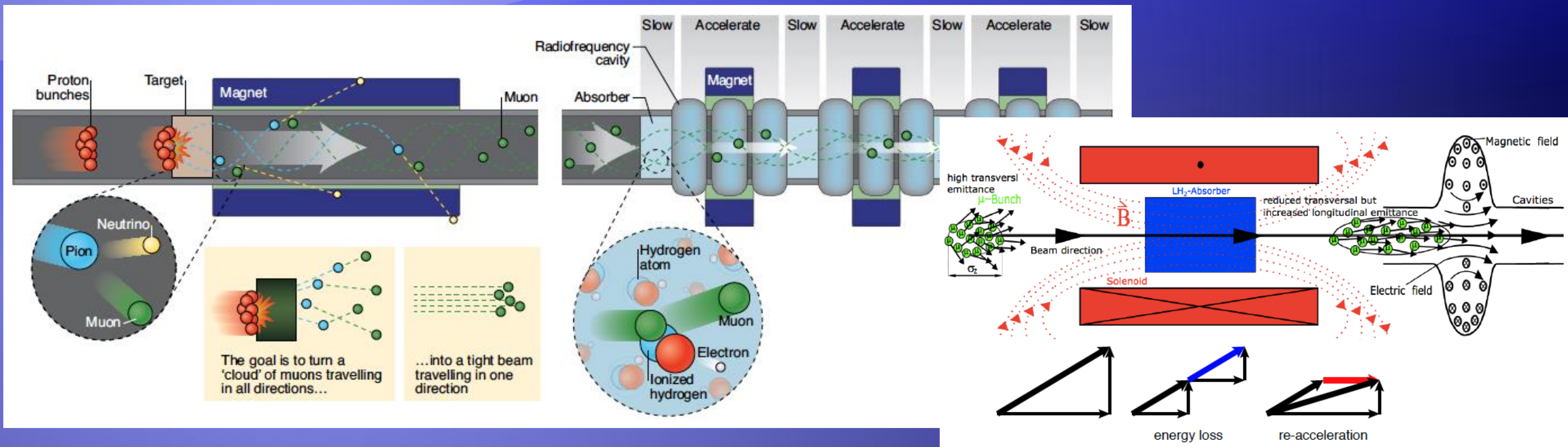


Dense neutrino flux

Cost and power consumption limit energy reach, 10 km collider ring

Muon Ionization Colling

- Ionization Cooling: a fast, unique technique proposed for muons

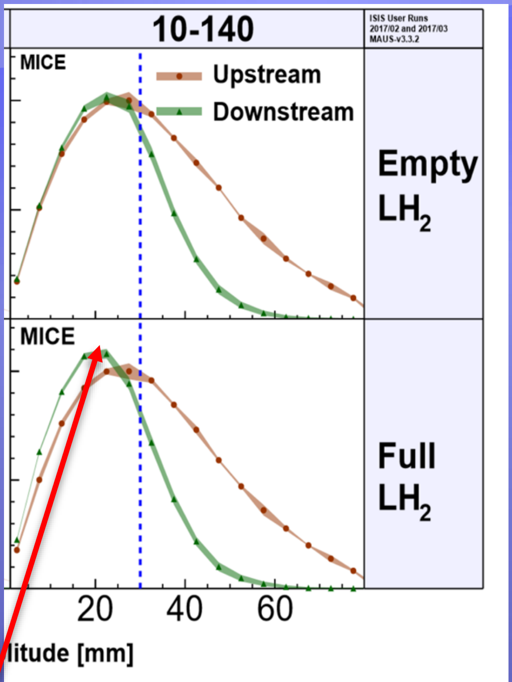


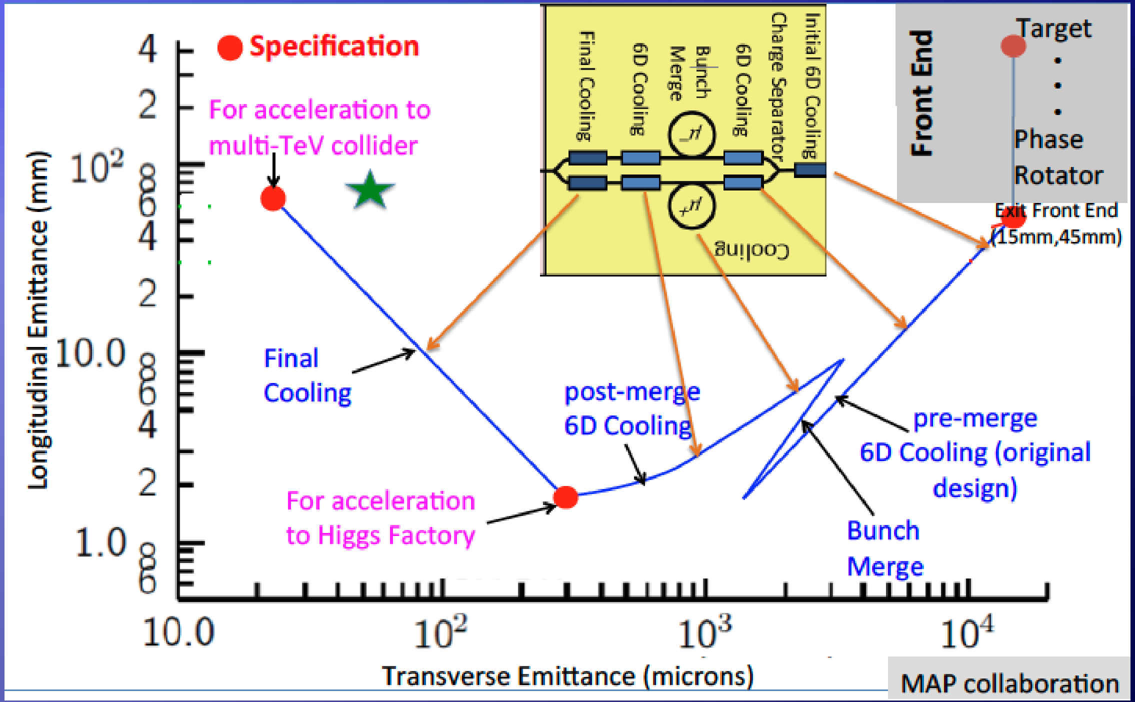
1. Muons pass through a low-Z material (e.g., liquid hydrogen)
   - Causes energy loss via ionization in all directions (transverse + longitudinal)
2. Then, muons are reaccelerated using RF cavities
   - Only the longitudinal momentum is restored
3. Net reduction in transverse momentum ⇒ reduced transverse emittance

- MICE demonstrated (10%) reduction of the transverse emittance of 140 MeV/c muons passing a cell

Emittance Development

Nature volume 578, 53–59 (2020)

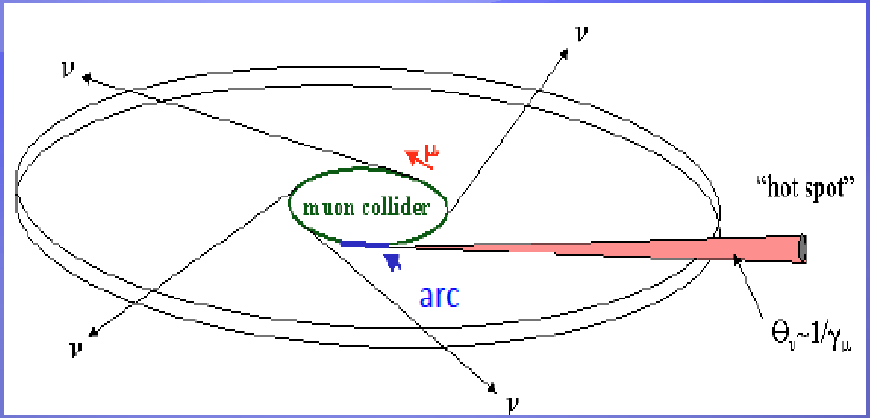


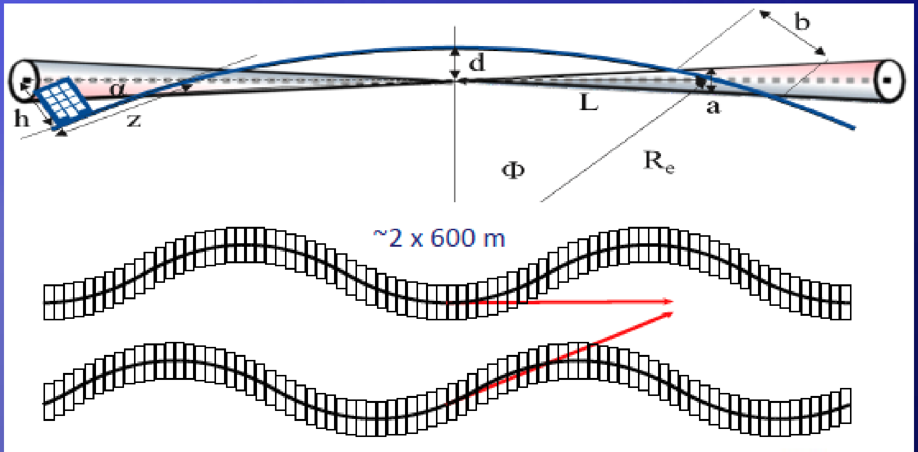


Cooling is demonstrated by MICE; more particle at small amplitude

- Cavities with very high accelerating gradient in strong magnetic field
- Very strong solenoids (> 30 T) for the final cooling:
  - Luminosity is proportional to the field

Neutrino Flux Issue

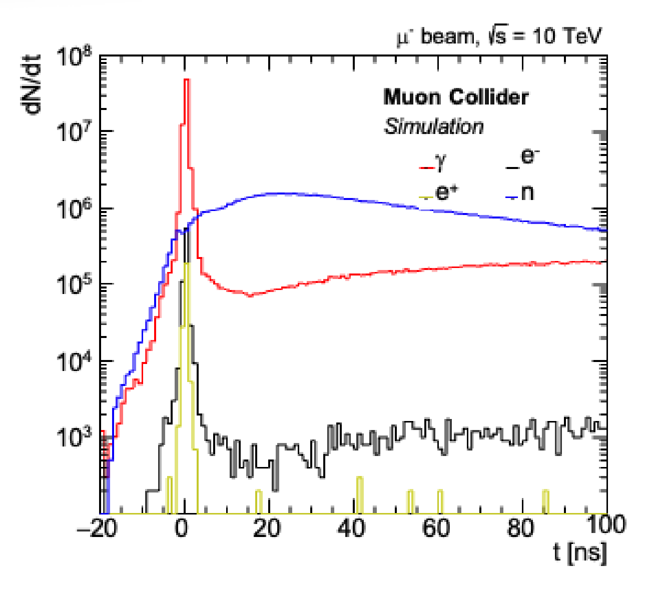


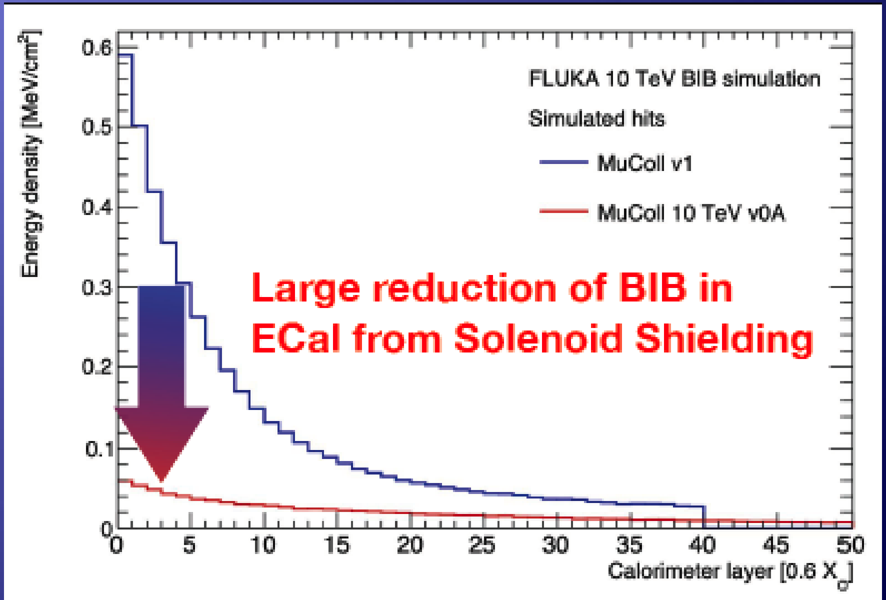


- Particularly high in direction of the straights (interaction region)
  - Typical legal limit 1 mSv/year
  - MAP goal < 0.1 mSv/year
  - LHC achieved < 5 μSv/year
- Move collider ring components, e.g. vertical bending with 1% of main field at the 200m deep tunnel

Detector

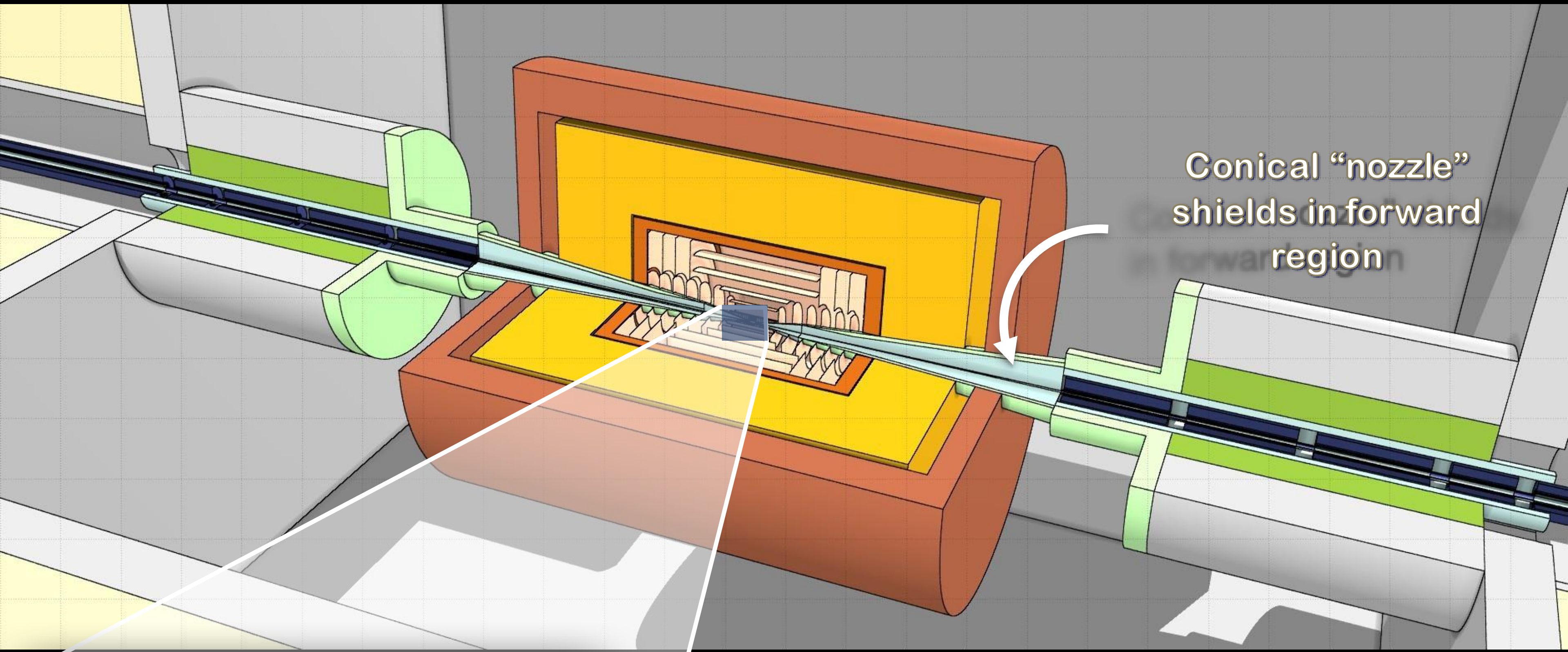
- Build a detector robust against beam induced backgrounds (BIB)
  - In detector region, dominated by MeV-scale neutrals
  - Not particularly in time, and not projective from collision point
  - High precision timing measurements O(10-100) ps
  - Good shielding at interaction points as well as detectors

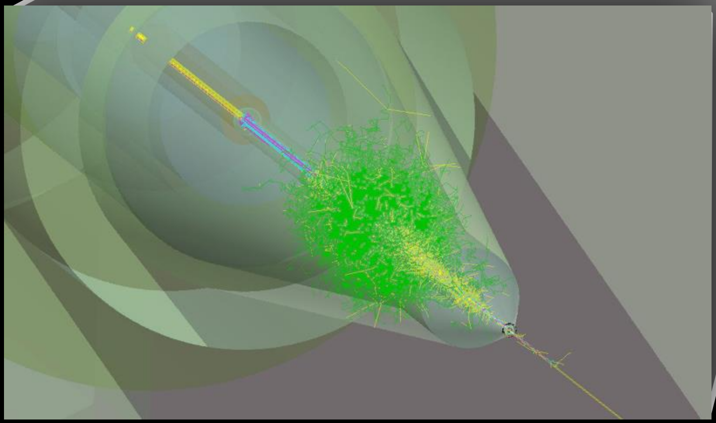




Detector Challenges

- **Major Challenge:** High levels of Beam-Induced Background (BIB)
  - Unprecedented radiation environment due to muon decays
- **Requirements:**
  - Excellent position & timing resolution (e.g., tracker ~10-30 ps, calorimeters ~10 ps aspirational)
  - High radiation hardness
  - Efficient data transmission & on-detector background rejection
  - Low mass, low power consumption
- **Detector Concepts (for 10 TeV):**
  - **MAIA** (Muon Accelerator Instrumented Apparatus)
  - **MUSIC** (MUon System for Interesting Collisions)
  - Common Structure: All-silicon tracker, electromagnetic/hadron calorimeters, muon sub-detector, superconducting solenoid
- **R&D Focus:** Simulation & performance optimization, new technologies (ASICs, magnets), BIB mitigation strategies.





Particle production from single muon decay 25m away
Nicely absorbed by nozzle

Now imagine ~<u>10M</u> of these decays…

$$\boxed{E_{\text{decay}} = 13\ \text{EeV} \times \left(\frac{n_\mu/\text{bunch}}{2\times 10^{12}}\right)}$$

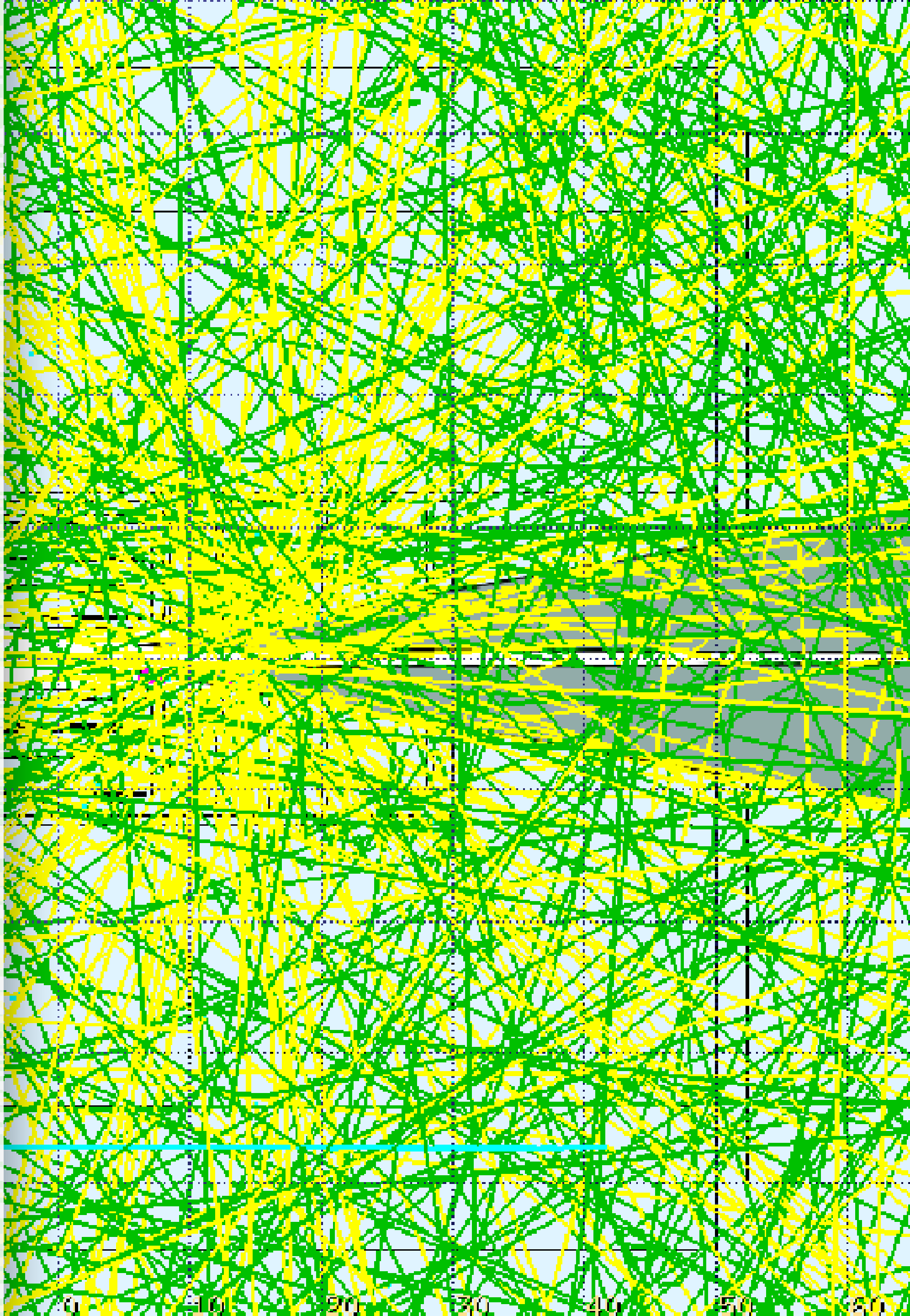
Images from Slides by <u>D. Calzolari</u>

0.0003% of BIB shown

Enormous contribution **into detector region** from glowing nozzles

Neutrons
Photons
Electrons
Positrons

Luckily total ionizing dose/year is **comparable** to **HL-LHC**
And **orders of magnitude less** than **FCC-hh**



Images from Slides by D. Calzolari

MAIA Detector Concept

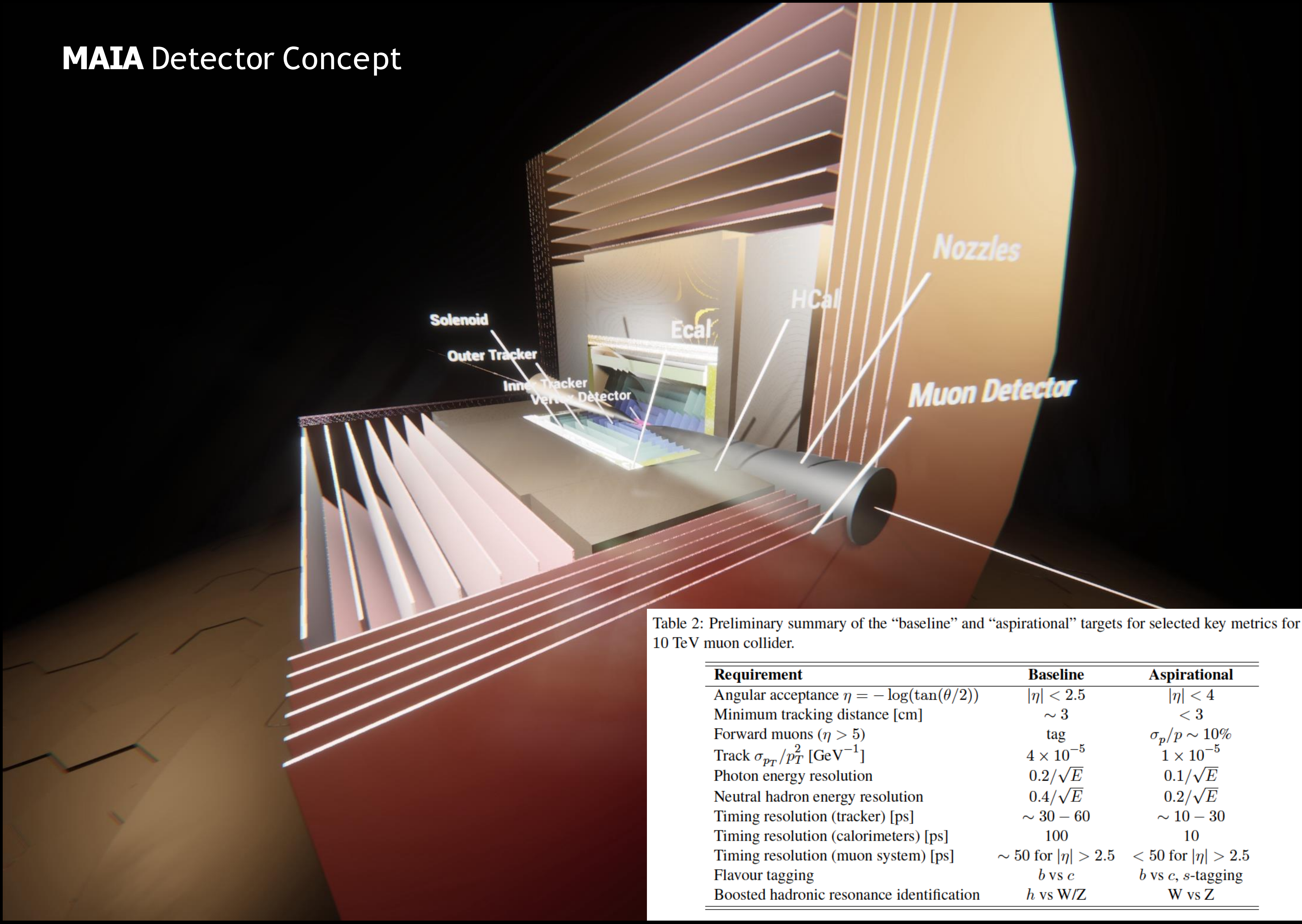


Table 2: Preliminary summary of the “baseline” and “aspirational” targets for selected key metrics for 10 TeV muon collider.

Requirement	**Baseline**	**Aspirational**
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c, s-tagging
Boosted hadronic resonance identification	h vs W/Z	W vs Z

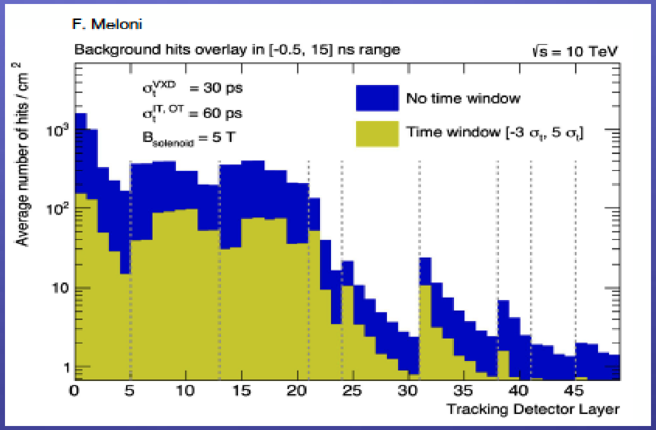
Images from C Bell, LL

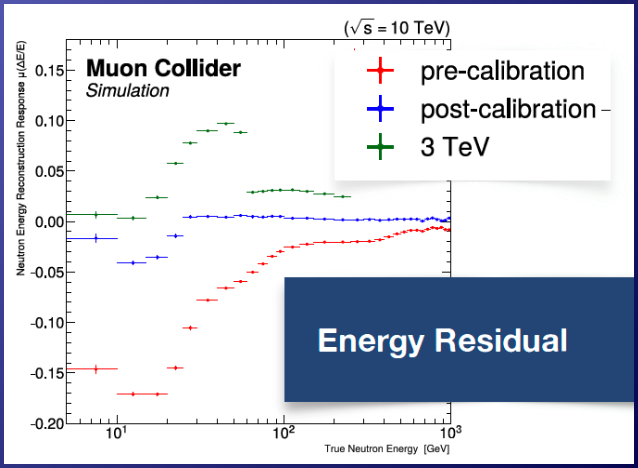
MAIA Detector

- Key feature of MAIA: Solenoid before calorimeters
  - 1.7m radius; 5T, 1T return
  - Allows for bigger calorimeters and high field
  - Before ECal: Reduces e/ɣ precision
  - And shields the calos from BIB!

- Tracker
  - 10 measurements in barrel
  - 30~60ps timing resolution

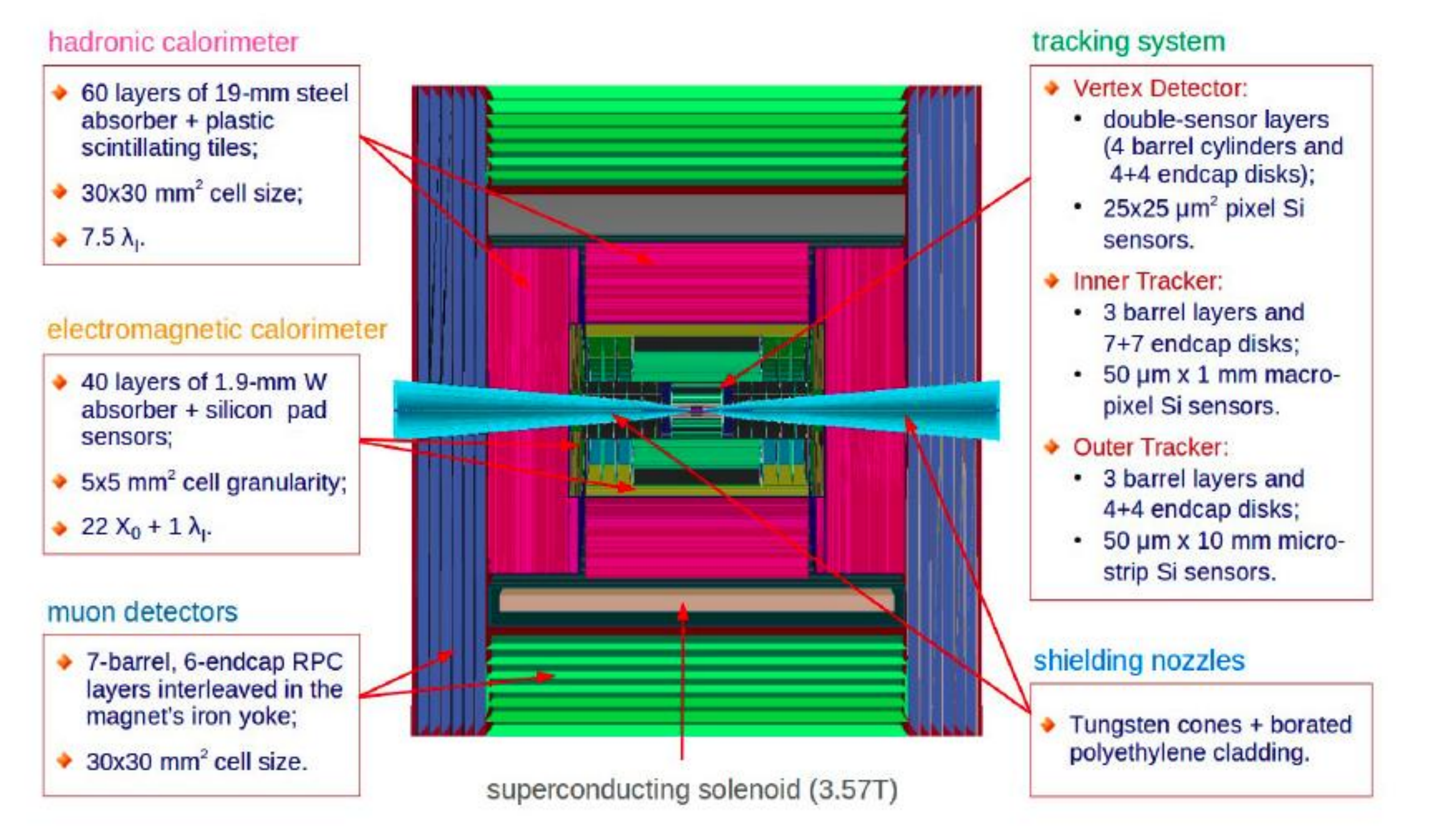
- Calorimeter: W+Si design
  - Sensitive to photon BIB in first few layers
  - Longitudinal segmentation is key to rejecting BIB





MUSIC Detector

- Designed for 3 TeV collider



Time R&D Plan

- **Target Timeline :** First stage operational around 2050 (technically feasible).
  - Potential to be Europe's next flagship project if no Higgs factory realized at CERN.
- **Proposed R&D Program (approx. 10 years):**
  - Budget: Accelerator ~300 MCHF (materials) + ~1800 FTEy (personnel); Detectors ~20 MCHF + ~900 FTEy.

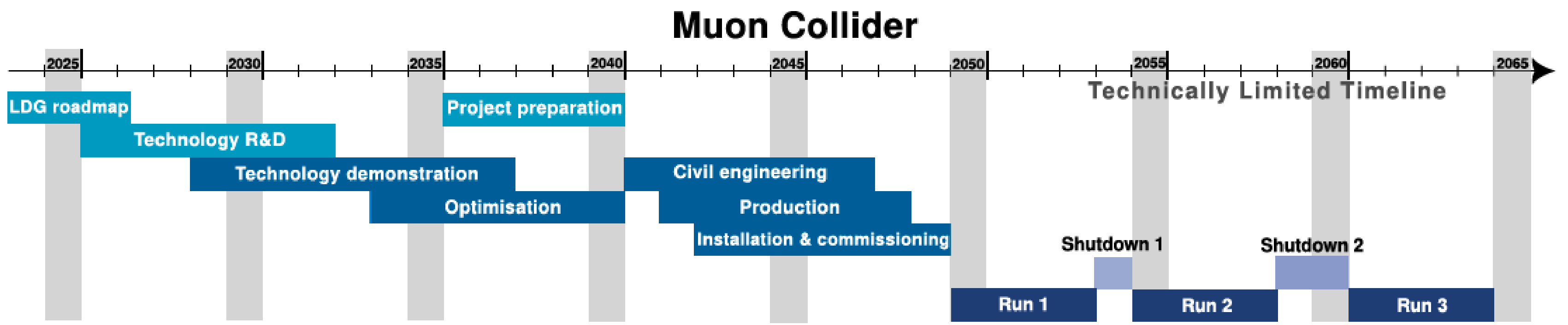
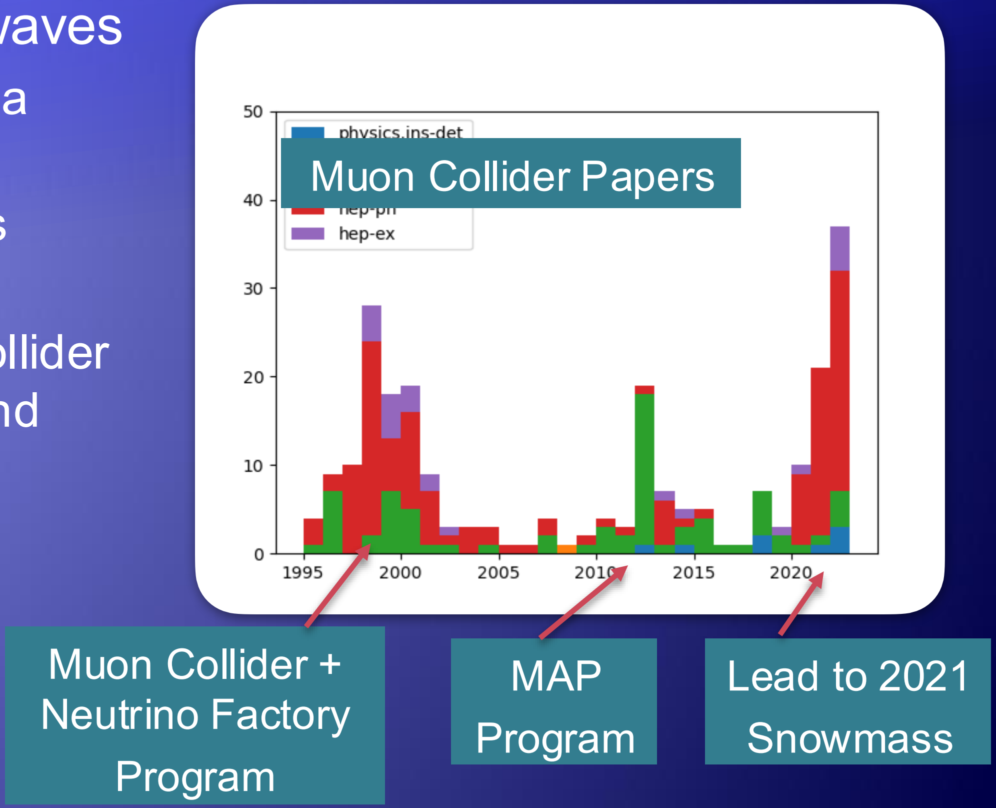


Fig. 5: Technically limited muon collider timeline.

A real muon collider

- Muon collider interest comes in waves
  - First proposed in connection with a neutrino factory at BNL or FNAL
  - MAP program focused on a Higgs factory
  - Now, shifted focus to multi-TeV collider with connections back to Higgs and neutrinos



One Muon Collider for two colliders

- **Muon collider is a unique opportunity for a high energy lepton collider for multi-TeV scale new physics and precision measurements**

- **10 TeV muon collider is achievable**
- Be **smart, open-minded, and take advantage of new opportunities** to achieve physics goals
- **Realize seemingly impossible physics with technology, engineering, ingenuity**

Backup Slides

Accelerator Challenges 1

- Proton Driver:
  - Designs based on existing facilities (5-10 GeV)
  - Challenge: Heat/radiation load (2MW beam) on target
- Muon Cooling System:
  - Optimized design reduces 6D emittance (longitudinal emittance ~3x better than the target parameter, transmission 20% lower)
  - Challenges: Beam loading, heat load on hydrogen absorbers; integration & matching
- Acceleration System (Low & High Energy):
  - Solutions found for LINAC & 2nd RLA. High-energy acceleration simulations (wakefields, counter-rotating beams) show lattice exceeds transmission targets
  - Challenge: Emittance control with lattice errors
- Collider Ring (10 TeV, β=1.5mm):*
  - Requires short bunch, large energy spread
  - Challenges: Chromatic aberration control (0.1% RMS momentum spread); energy acceptance (current lattice below target); magnet misalignments & neutrino flux dilution.

Accelerator Challenges 2

- Magnet Systems:
  - Conceptual designs for critical magnets: 20 T target solenoid, 40 T cooling solenoids, ±1.8T fast-pulsed accelerator magnets, high-field collider dipoles/quads (shielding).
  - Challenge: Resource-loaded hardware development program (critical path).
- RF Systems:
  - 352/704 MHz normal conducting RF for cooling; 1.3 GHz for high-energy acceleration.
  - Challenges: Tight integration with solenoids (cooling RF), up to 32 MV/m field; power coupler interference.
- Muon Cooling Demonstration Program:
  - Integrated engineering design developed (based on typical cooling section).
  - Candidate sites identified (CERN, Fermilab).
  - Challenge: Resource-loaded timeline; on facility critical path.
- Site & Neutrino Considerations (CERN/Fermilab):
  - CERN: Reuse SPS/LHC tunnels possible, surface installations on CERN land.
  - Fermilab: Study underway for infrastructure reuse within site boundaries.
  - Challenge: Neutrino radiation management (dilution, surface detectors for FASERν-like program), environmental impact.

Accelerator Challenges & Key R&D

- **Overcoming Technical Hurdles (No showstoppers identified):**
  - **Proton Driver:** High-intensity, short-pulse beam.
  - **Target System:** 2 MW beam power, managing heat & radiation (graphite target)
  - **Muon Cooling System (Crucial!):** Significant 6D emittance reduction; RF cavities in high magnetic fields; hydrogen absorbers
  - **Acceleration System:** High-efficiency, high-gradient acceleration; beam stability
  - **Collider Ring:** Short bunches, large energy spread control; magnet alignment; neutrino radiation management
  - **Magnet Technology:** High-field solenoids (HTS, ~40T), fast-ramping magnets, high-field dipoles (Nb_3Sn, HTS)
  - **RF System:** High-gradient RF cavities (e.g., 32 MV/m), power couplers

- **Muon Cooling Demonstration Program Proposed:** Integrated validation of key technologies (sites like CERN, Fermilab considered)
- **Site Studies:** CERN (reusing SPS/LHC tunnels), Fermilab.
- **Power Consumption:** ~188 MW for 10 TeV site , ~172 MW for CERN 7.6 TeV