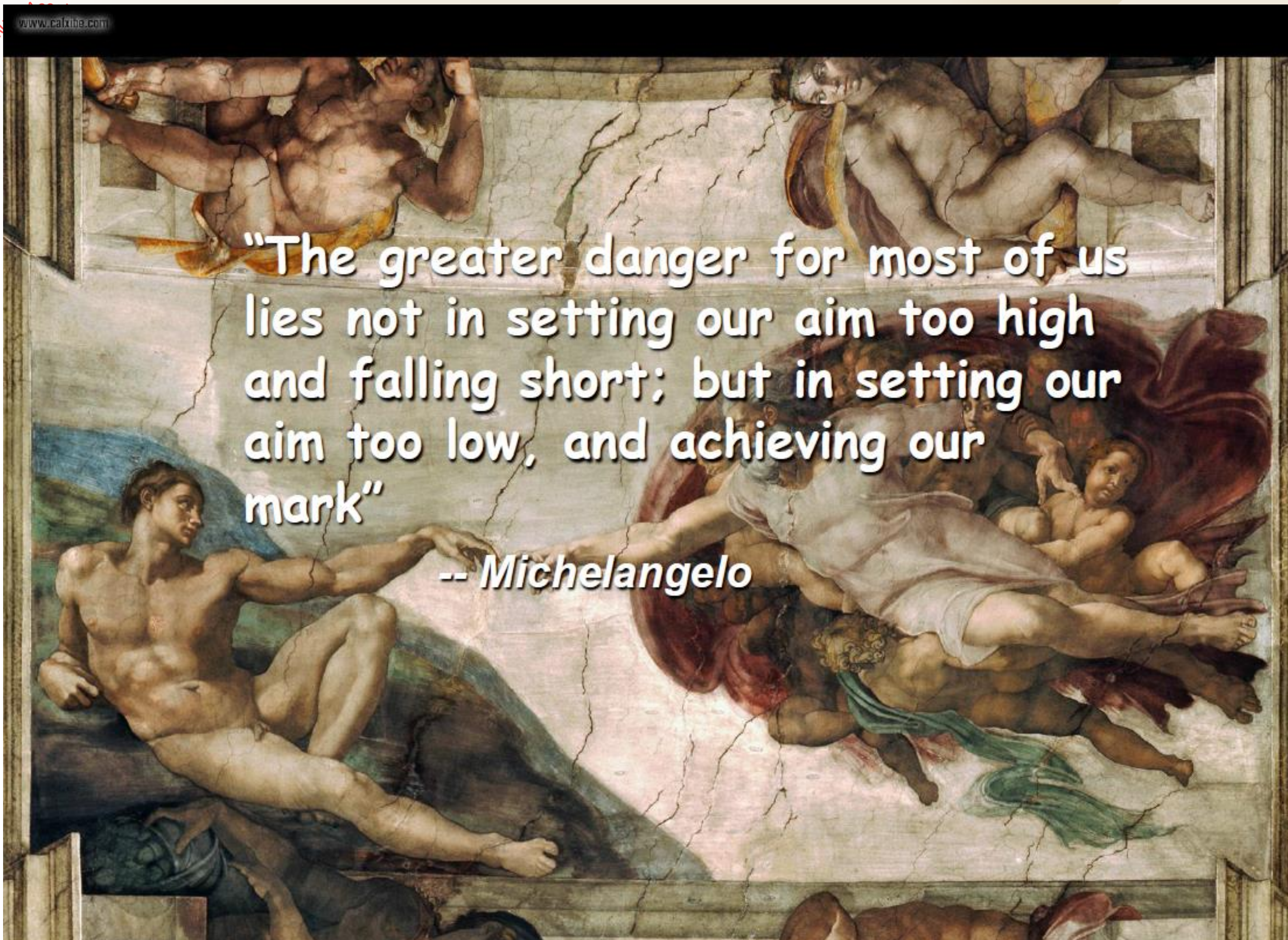
A Staged Muon Accelerator Facility for future Neutrino and Collider Physics in the multi-TeV energy range

J.P. Delahaye / CERN

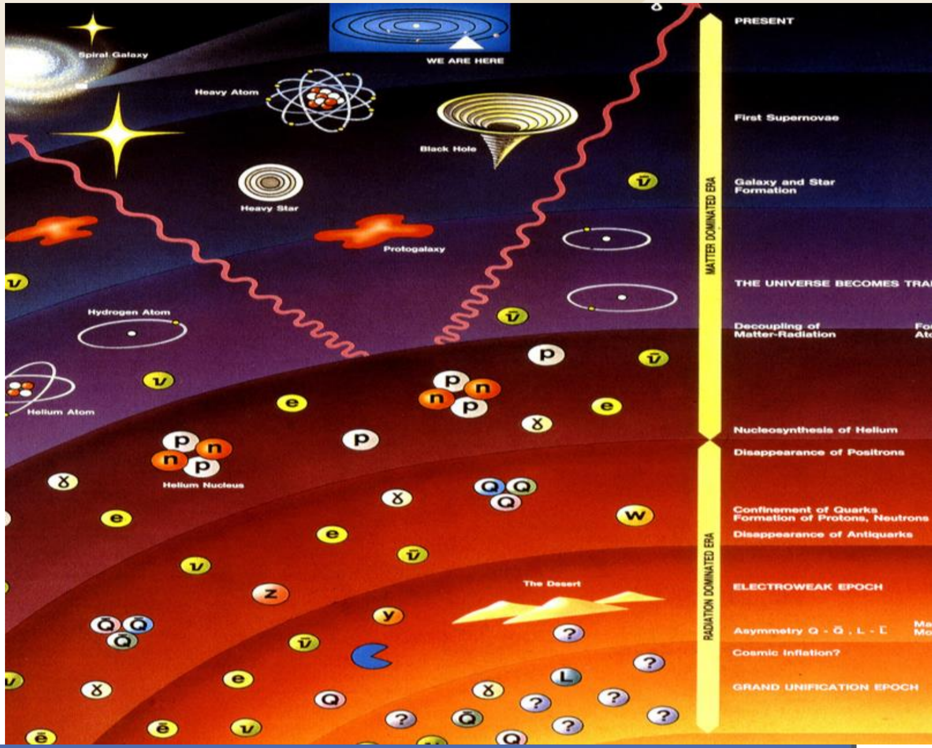

www.calxibe.com
"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark"
-- Michelangelo

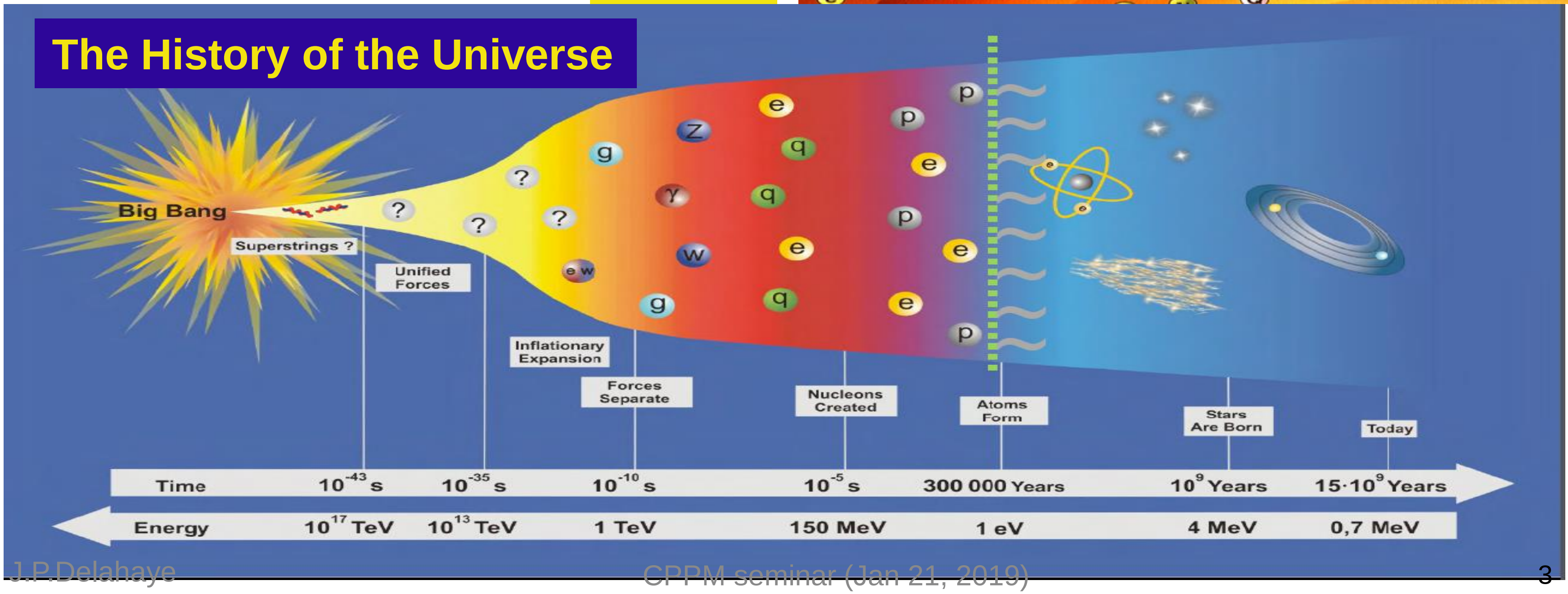
Particle Physics

Particle physics studies the fundamental nature of energy, matter, space, and time, and applies that knowledge to understand the birth, evolution and fate of the universe

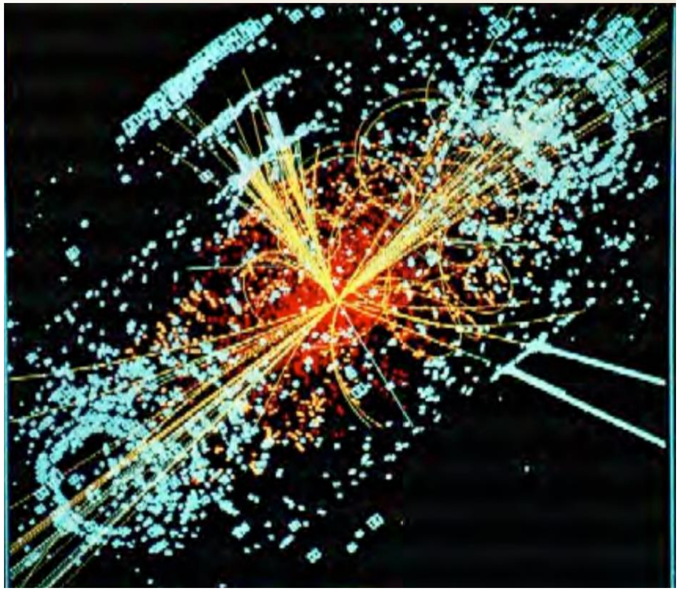
Time

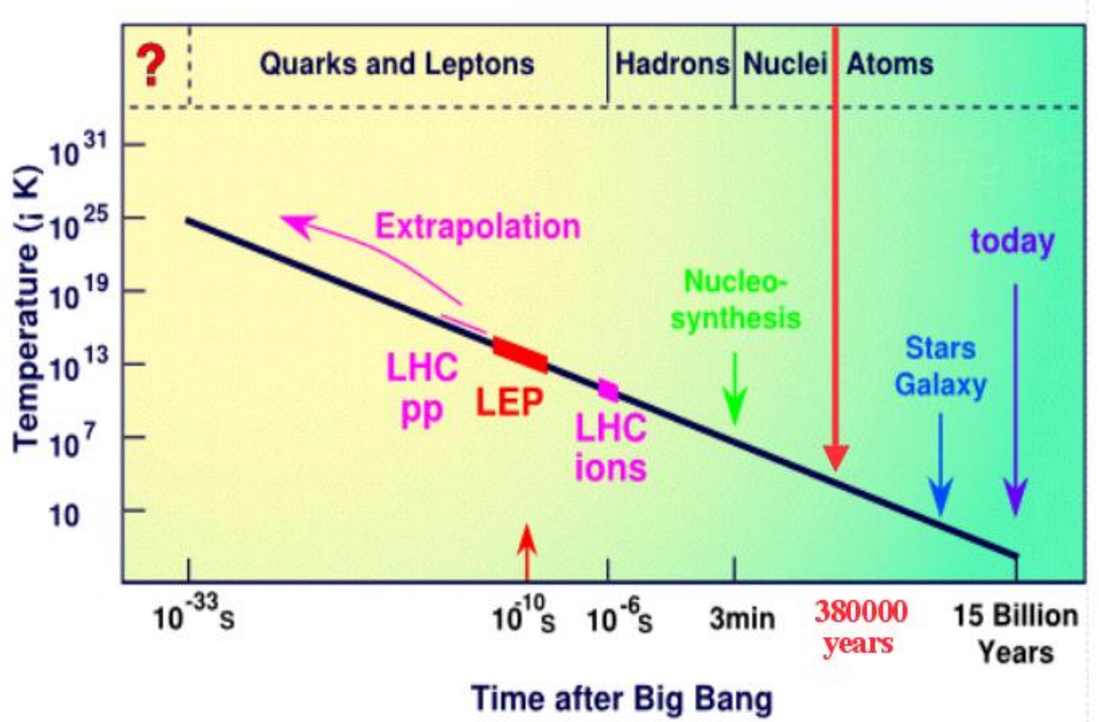
BIG BANG



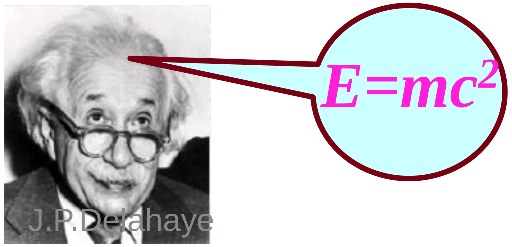


Particle Accelerators recreating conditions at the early stages of the universe



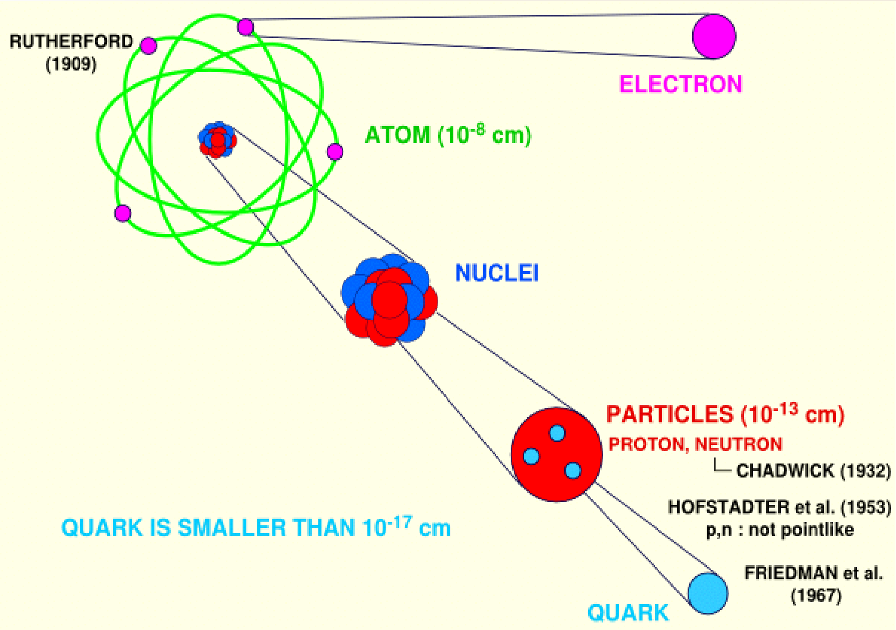


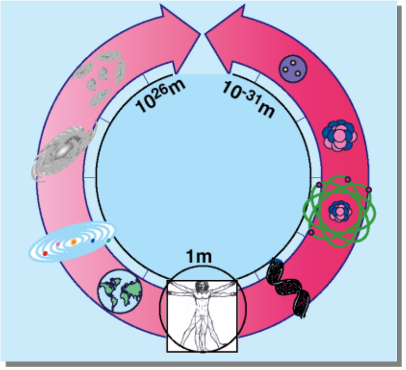
Collisions in Particle Accelerators with energy density comparable to early Universe and generating particles:



- Present exploration from 10^{-15} s after Big Bang
- Performing the archeology of particles from this early date to today
- Observing the rules governing their evolution
- More powerful collisions required to simulate conditions closer to Big Bang

Accelerators acting as "super-microscpe" at the dimensions of sub-particles

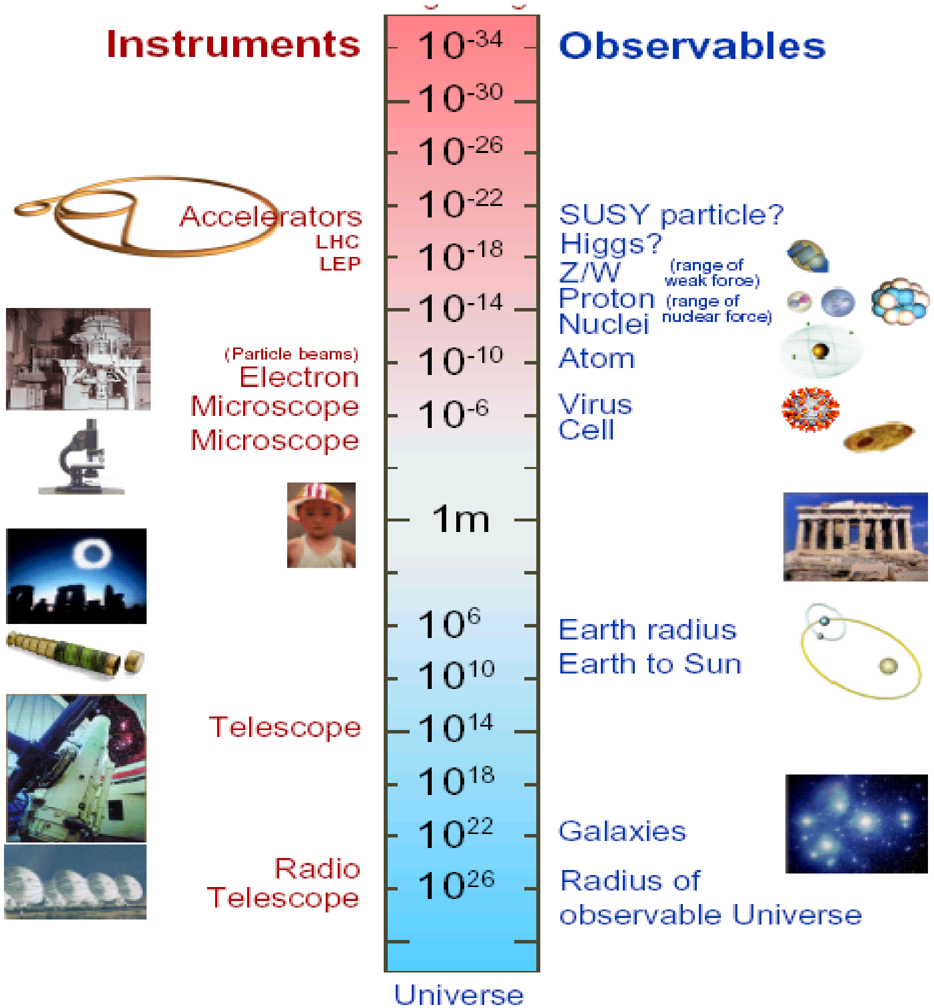




Complementarity between experiments:

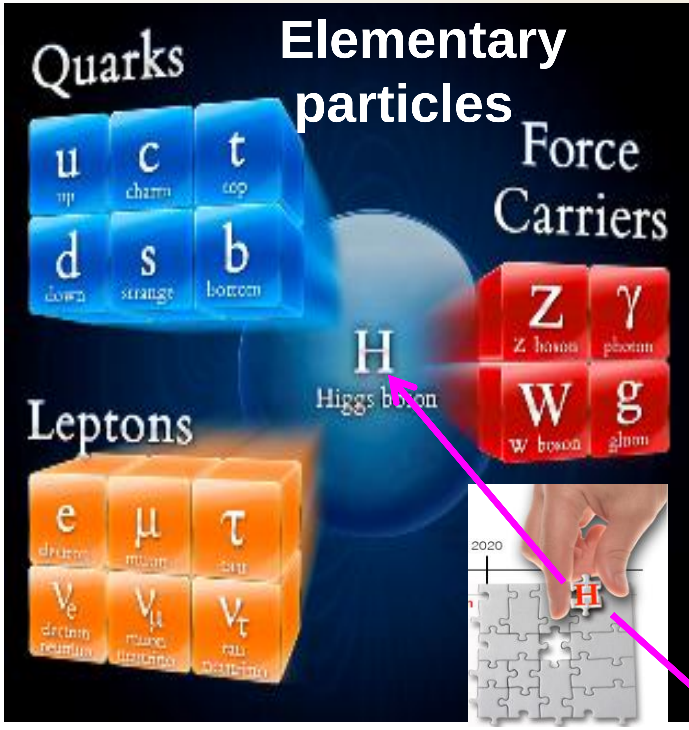
- **infinity small scale (particle physics)**
- **infinity large scale (cosmology)**

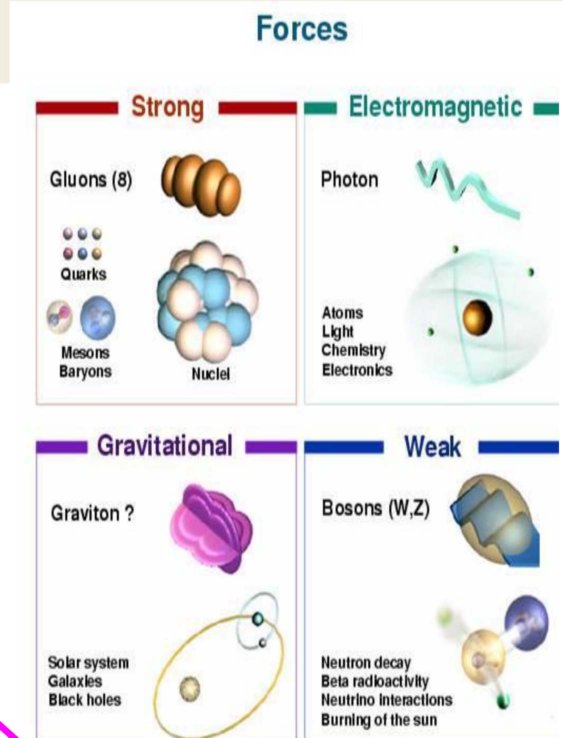
de Broglie: $\lambda \sim 1/E$

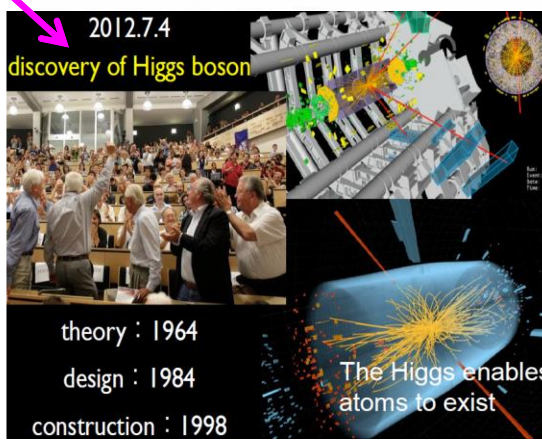


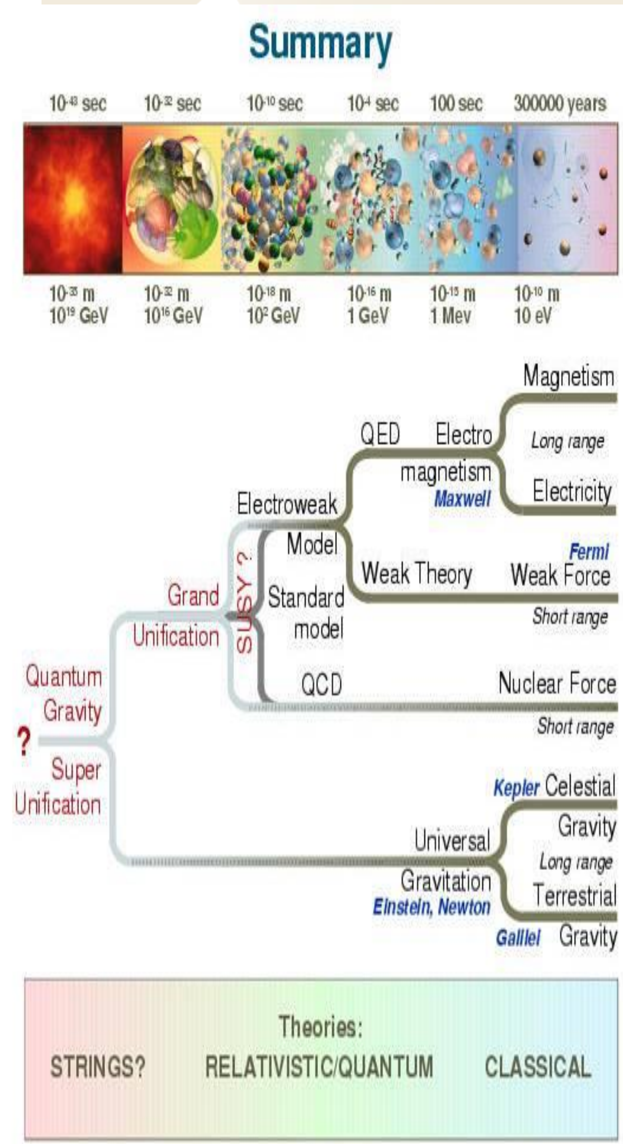
Higher resolution requires even more powerful accelerators

A powerful & successful "standard model"









Model consistent with up to now observations and with extremely high precision

Strong predictive power:

Higgs boson interaction by which fundamental particles get mass

Many questions still to be answered

There are many mysteries of the Universe: our big questions

...a partial list

Neutrino Mass / Theory of Flavor
Higgs Boson Naturalness
Dark E

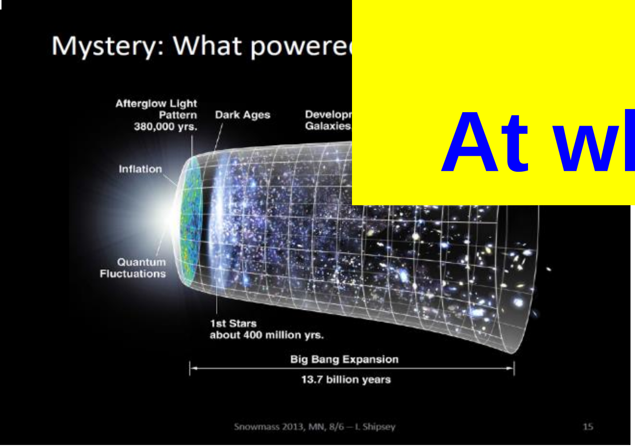
The Standard Model has 61 elementary particles.[15]

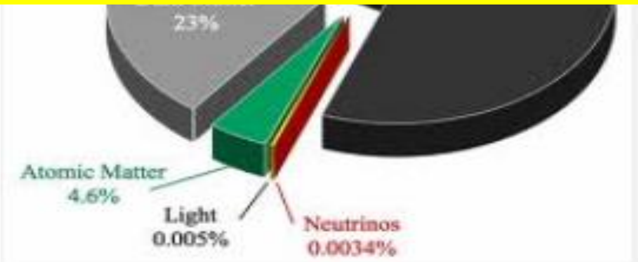
Elementary Particles

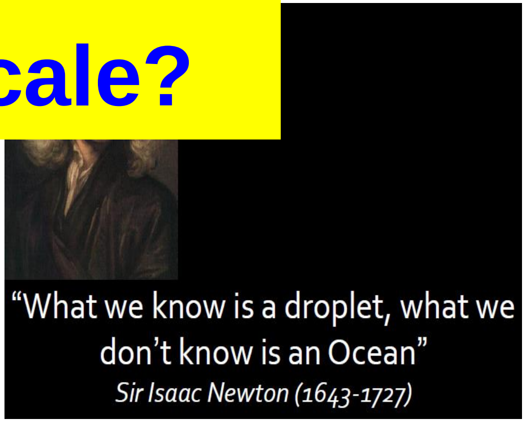
Why so many types of elementary particles?

New Physics Beyond Standard Model (BSM) mandatory

Which Physics?
At which energy and scale?

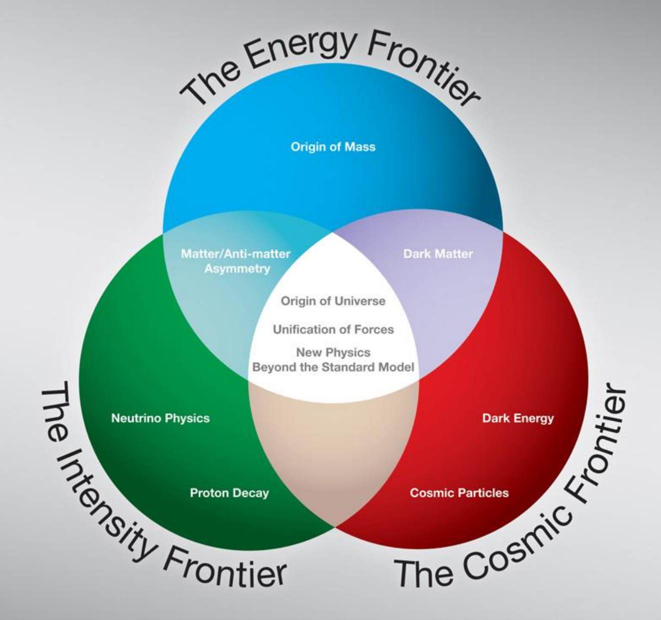




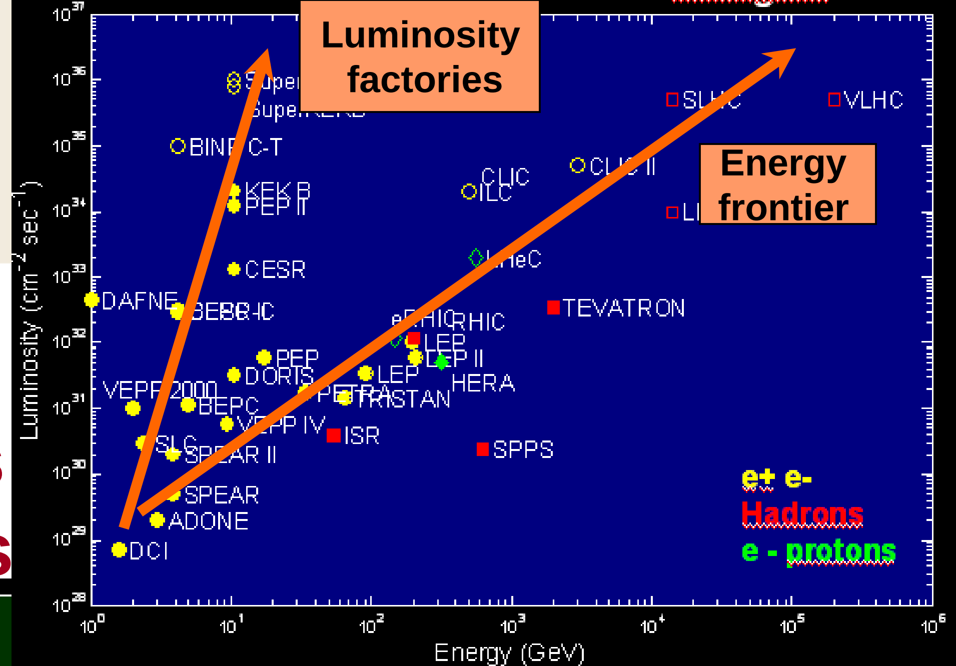


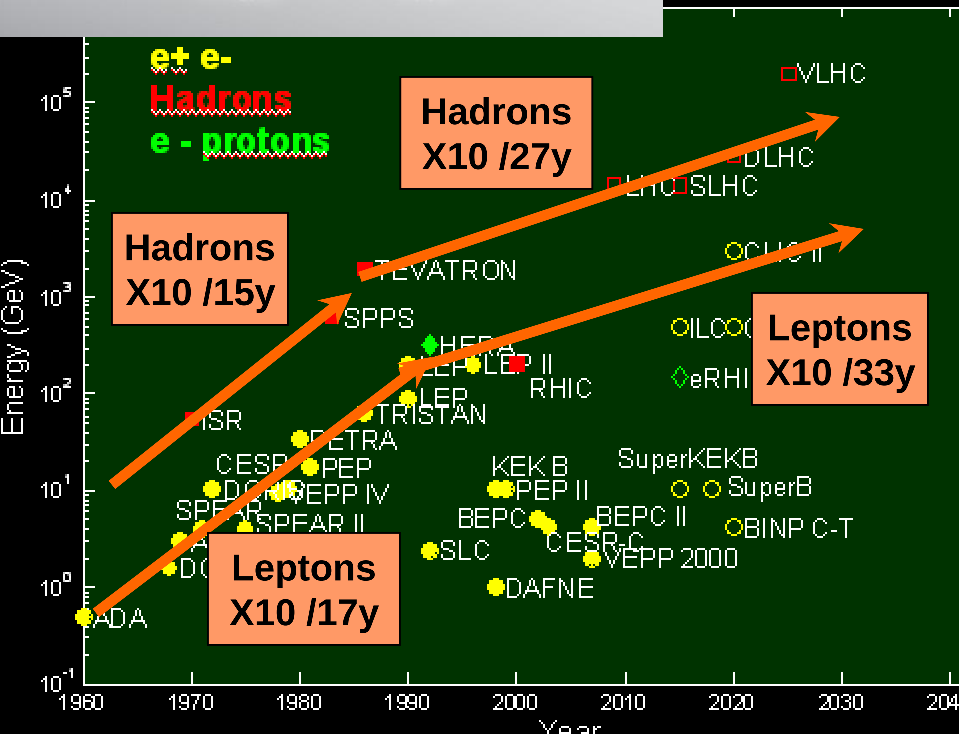
Why universe made of matter ? What happened to antimatter?

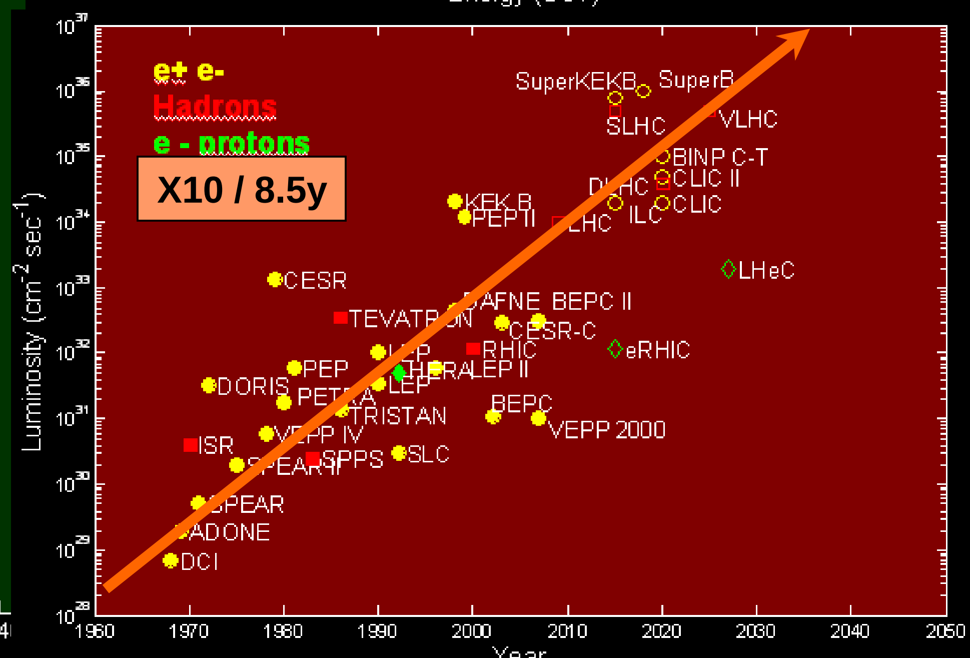
What about dark energy & dark matter = 96% universe?



Trends of High Energy Physics facilities







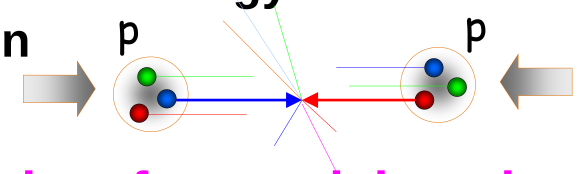
Towards Energy frontier

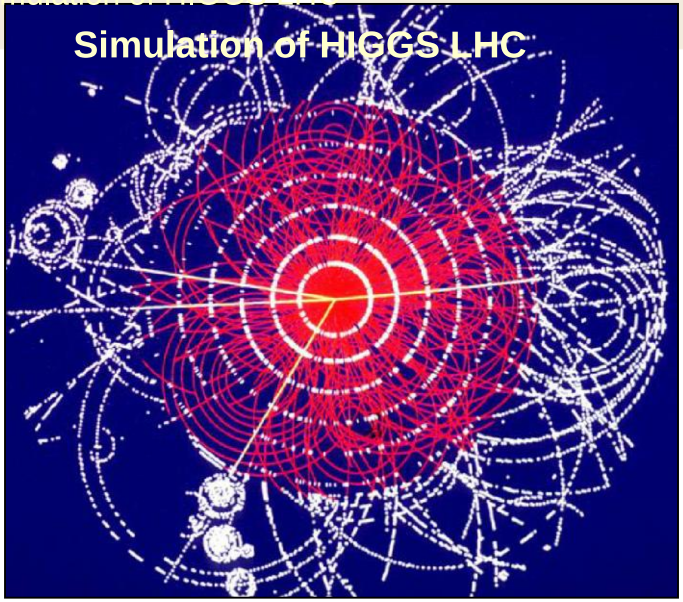
Towards Luminosity frontier

Hadron & Lepton Colliders complementary for High Energy Physics

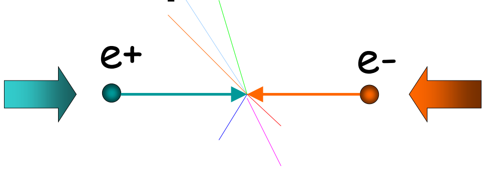
- **Hadron colliders as discovery facilities**

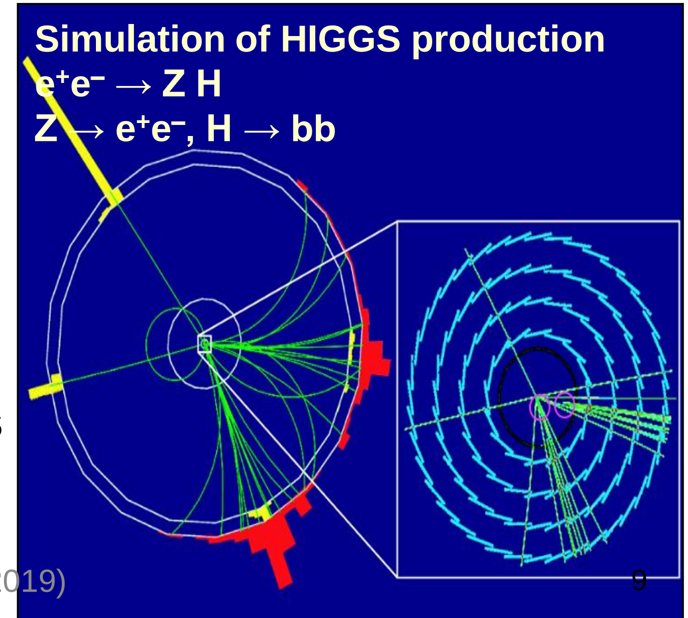
  at the energy frontier
  - huge QCD background
  - not all nucleon energy available in collision





- **Lepton colliders for precision physics**
  - well defined initial energy for reaction
  - Colliding "point" like particles

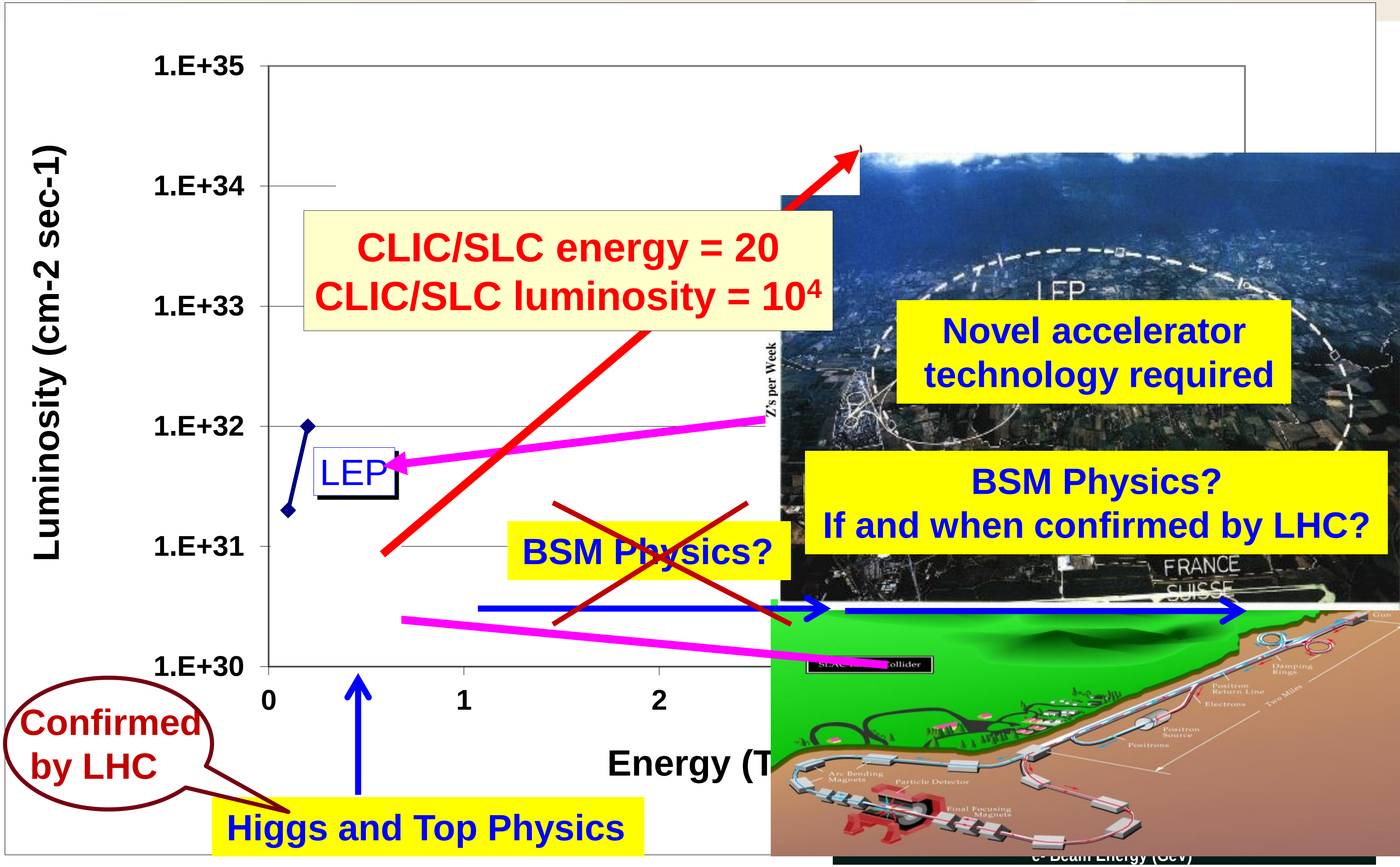




- **Consensus for Lepton Collider as next facility @ High Energy Frontier after LHC**
  - energy determined by LHC discoveries
  - Study in detail the properties of new physics identified by LHC (when and if confirmed?):

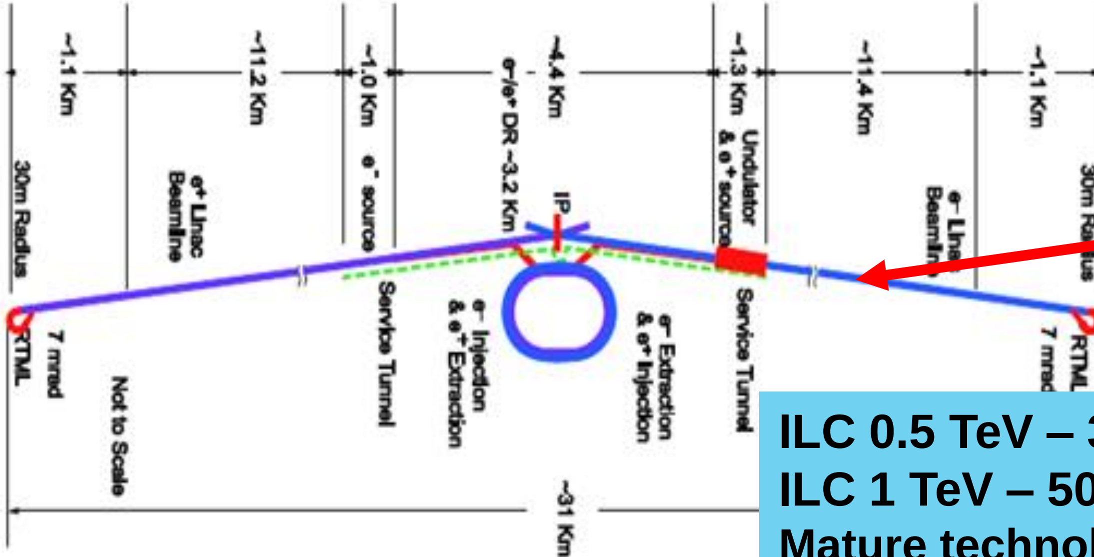
    presently HIGGS, possibly BSM in the future

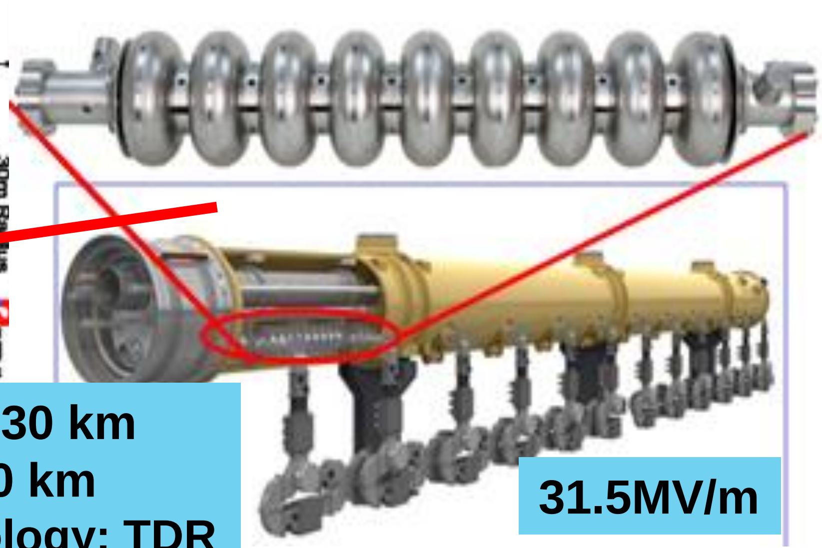
Lepton Colliders at the Energy Frontier



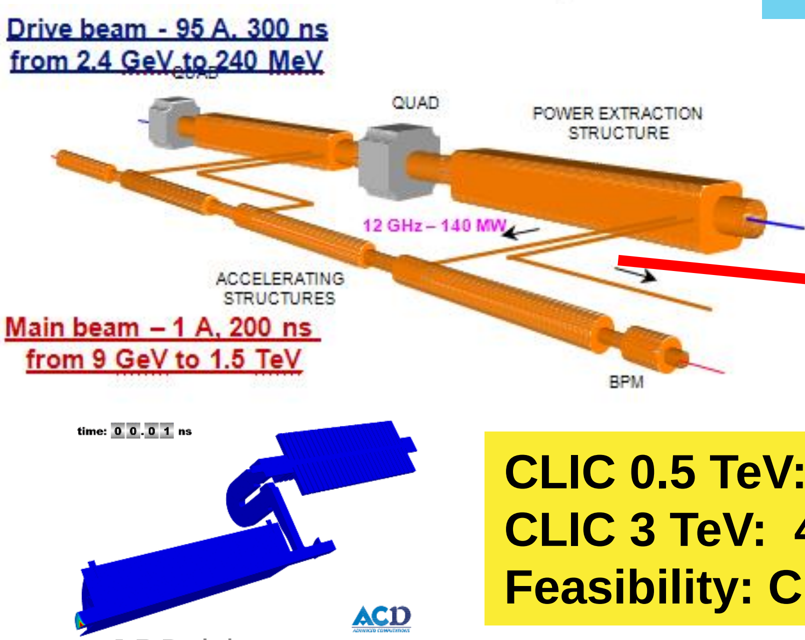
Linear Collider layouts

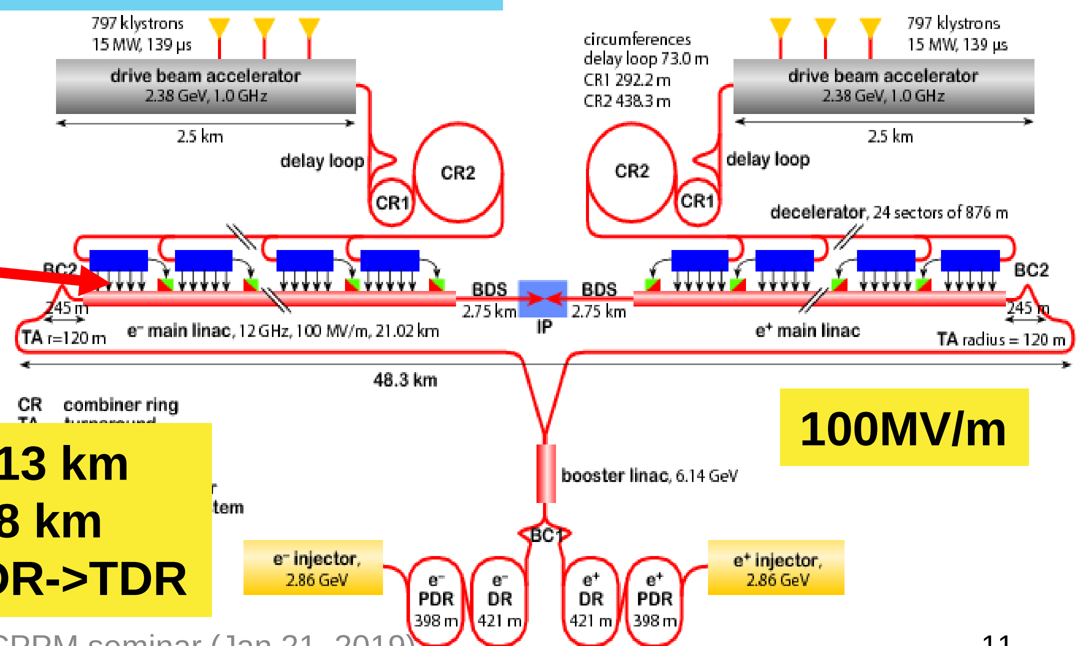
http://www.linearcollider.org/cms   http://clic-study.web.cern.ch/CLIC-Study/





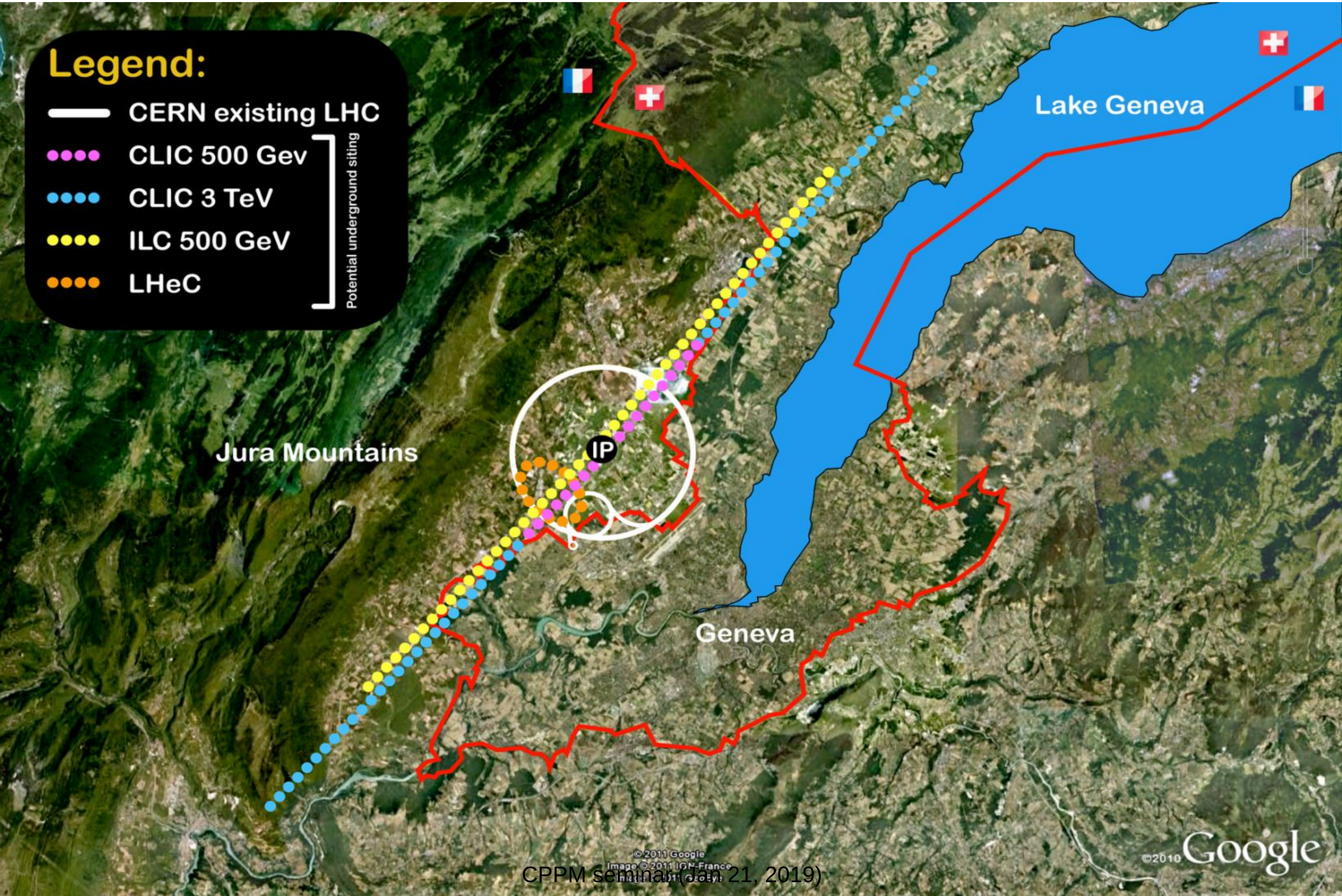
ILC 0.5 TeV – 30 km
ILC 1 TeV – 50 km
Mature technology: TDR



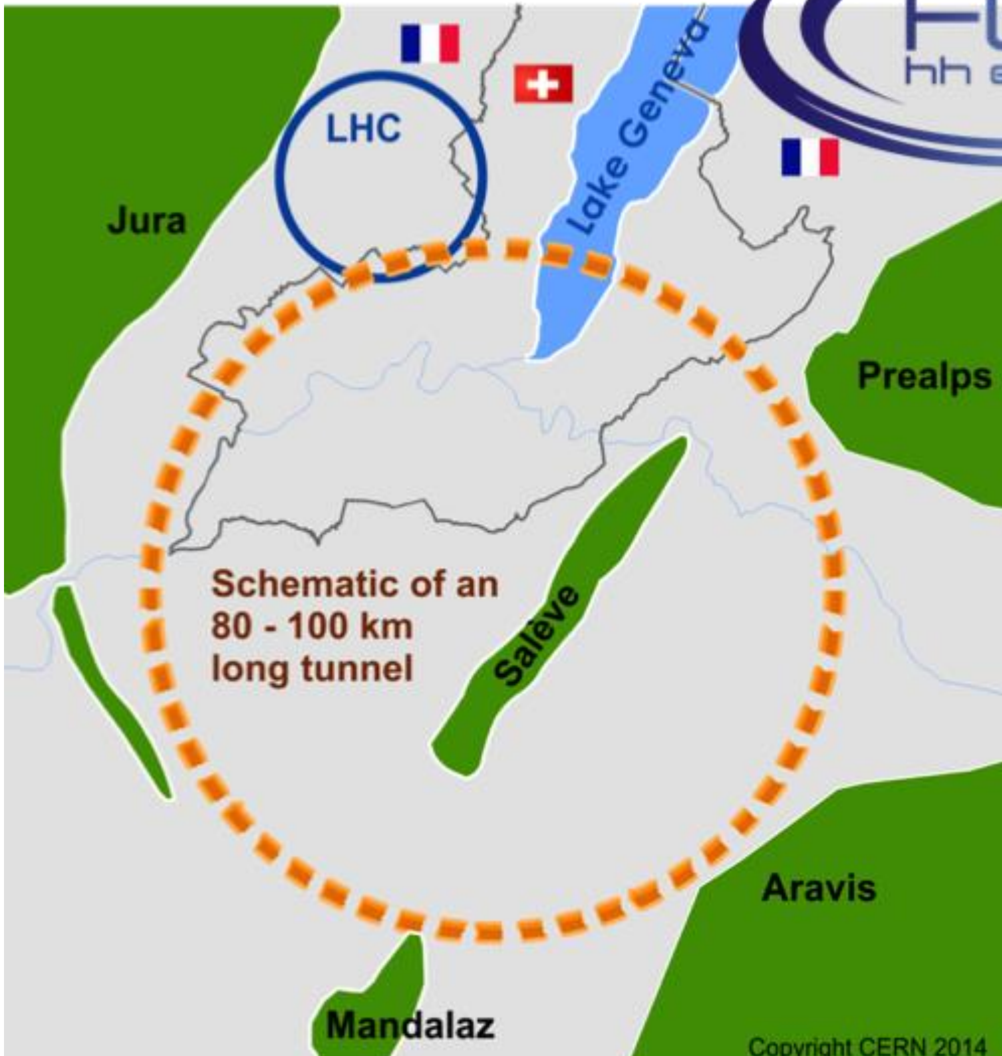


CLIC 0.5 TeV: 13 km
CLIC 3 TeV: 48 km
Feasibility: CDR->TDR

ILC and CLIC layouts in CERN area



Future Circular Collider (FCC) study
100TeV Hadron Collider in new 100km tunnel



	Z	Z	W	H	tt
Circumference [km]	100				
Bending radius [km]	11				
Beam energy [GeV]	45.6		80	120	175
Beam current [mA]	1450		152	30	6.6
Bunches / beam	30180	91500	5260	780	81
Bunch spacing [ns]	7.5	2.5	50	400	4000
Bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7
Horizontal emittance ε [nm] Vertical emittance ε [pm]	0.2 1	0.09 1	0.26 1	0.61 1.2	1.3 2.5
Momentum comp. [10^{-5}]	0.7	0.7	0.7	0.7	0.7
Betatron function at IP - Horizontal β* [m] - Vertical β* [mm]	 0.5 1	 1 2	 1 2	 1 2	 1 2
Horizontal beam size at IP σ* [μm] Vertical beam size at IP σ* [nm]	10 32	9.5 45	16 45	25 49	36 70
Crossing angle at IP [mrad]	30				
Energy spread [%] - Synchrotron radiation - Total (including BS)	 0.04 0.22	 0.04 0.09	 0.07 0.10	 0.10 0.12	 0.14 0.17
Bunch length [mm] - Synchrotron radiation - Total	 1.2 6.7	 1.6 3.8	 2.0 3.1	 2.0 2.4	 2.1 2.5
Energy loss / turn [GeV]	0.03		0.33	1.67	7.55
SR power / beam [MW]	50				
Total RF voltage [GV]	0.4	0.2	0.8	3	10
RF frequency [MHz]	400				
Longitudinal damping time [turns]	1320		243	72	23
Energy acceptance RF [%]	7.2	4.7	5.5	7.0	6.7
Synchrotron tune Q_s	0.036	0.025	0.037	0.056	0.075
Polarization time τ_p [min]	11200		672	89	13
Interaction region length L_i [mm]	0.66	0.62	1.02	1.35	1.74
Hourglass factor H (L_i)	0.92	0.98	0.95	0.92	0.88
Luminosity/IP for 2IPs [10^{34} $cm^{-2}s^{-1}$]	207	90	19.1	5.1	1.3
Beam-beam parameter - Horizontal - Vertical	 0.025 0.16	 0.05 0.13	 0.07 0.16	 0.08 0.14	 0.08 0.12
Luminosity lifetime [min]	94	185	90	67	57
Beamstrahlung critical	No/Yes	No	No	No	Yes

First phase: e^+/e^- collider with colliding beam energy of up to 350 GeV

Novel technologies for high gradient acceleration

- High gradient acceleration requires high peak power and structures that can sustain high fields
  - Beams and lasers can be generated with high peak power
  - Dielectrics and plasmas can withstand high fields

- Many paths towards high gradient acceleration
  - RF source driven metallic structures
  - Beam-driven metallic structures

  ~100 MV/m

  - Laser-driven dielectric structures
  - Beam-driven dielectric structures

  ~1 GV/m

  - Laser-driven plasmas
  - Beam-driven plasmas

  ~10 GV/m

Courtesy
Tor Raubenheimer

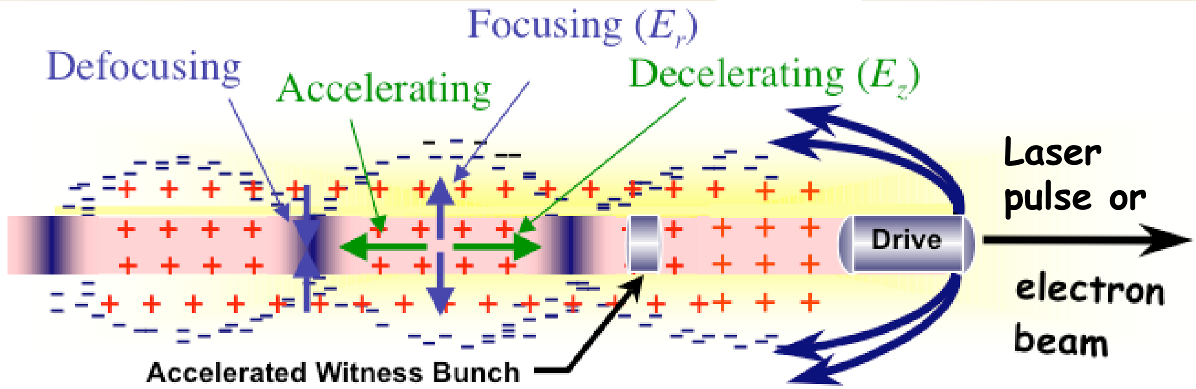
New Acceleration Techniques
Page 10

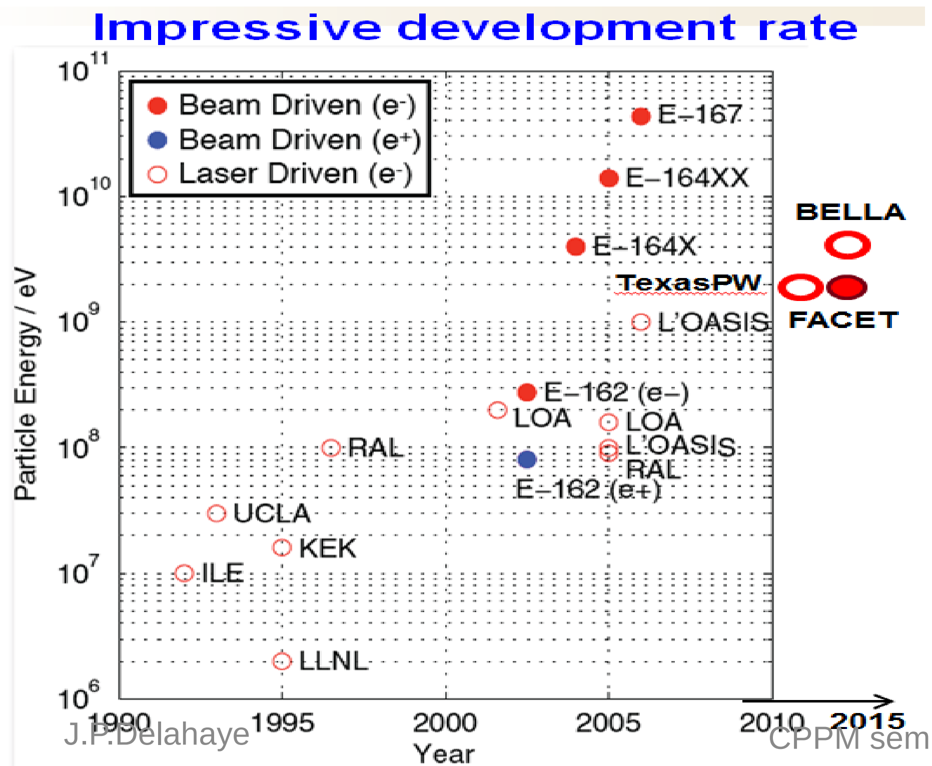
SLAC NATIONAL ACCELERATOR LABORATORY

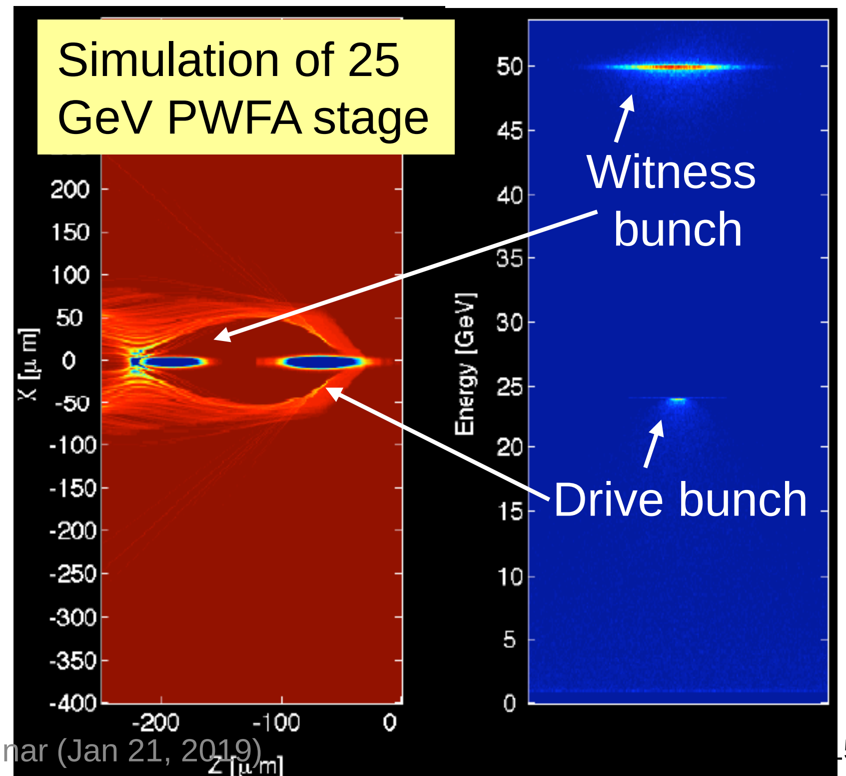
Plasma Acceleration (Beam-driven or Laser-driven)

50 GV/m demonstrated

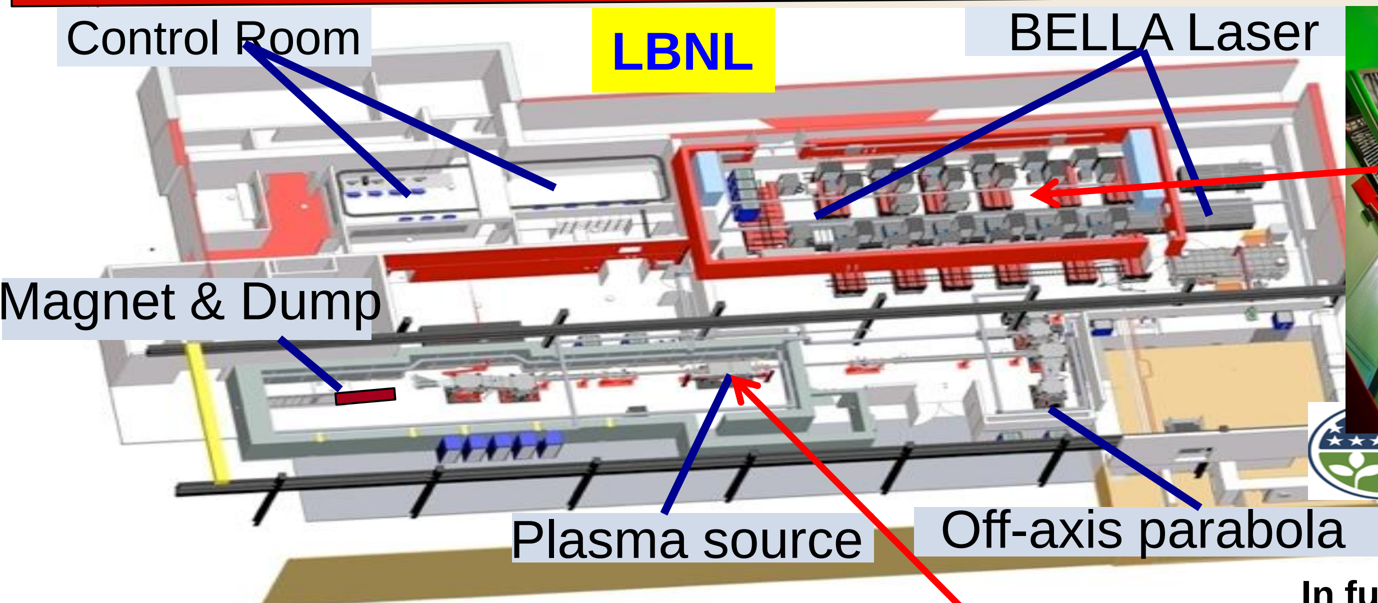
Potential use for linear colliders and radiation sources







A state-of-the-art PW-laser for laser plasma accelerator science in BELLA /LBNL – demonstrator for 10 GeV module



~$30 M investment: 2009-2012

Primary goal

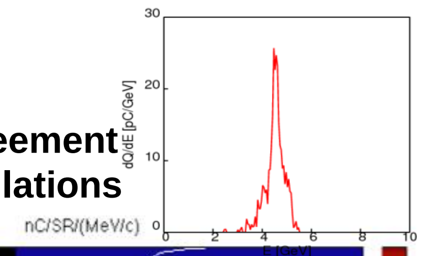
- **Demonstrate high quality electron beams at 10 GeV**
- **Staging of two LPA modules at 1GeV level**

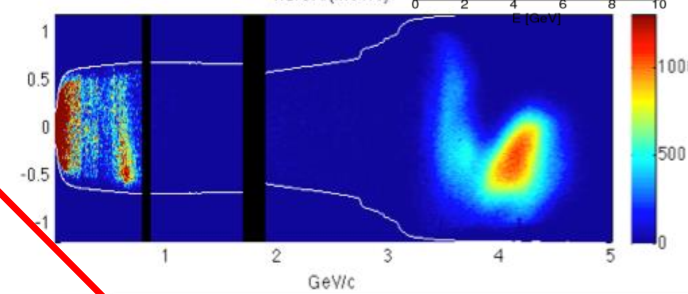
Achieved with BELLA laser limited to 0.39TW:

- **4.3 GeV acceleration in 9cm plasma channel**
- **50 GV/m accelerating field**
- **1.5% FWHM momentum spread**

Next experiments aim at 10 GeV with full laser energy

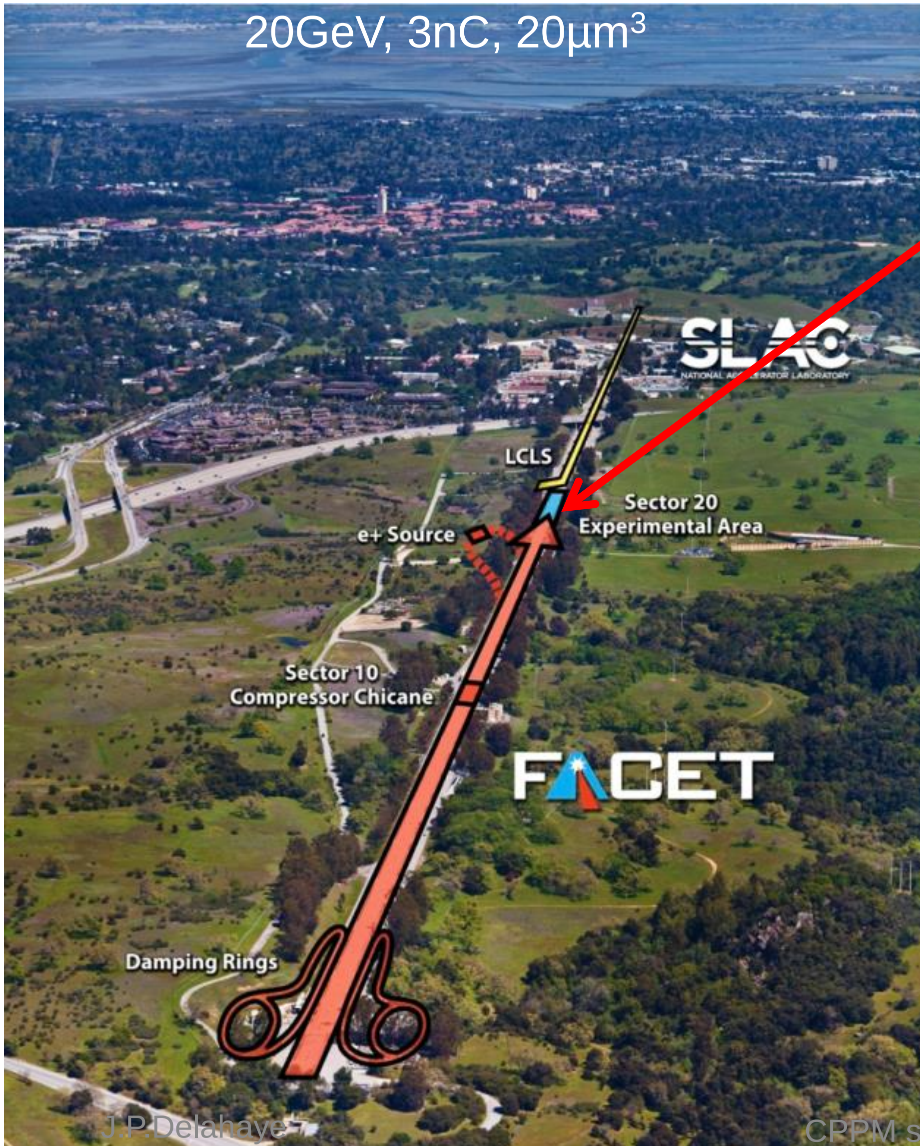
In full agreement with simulations

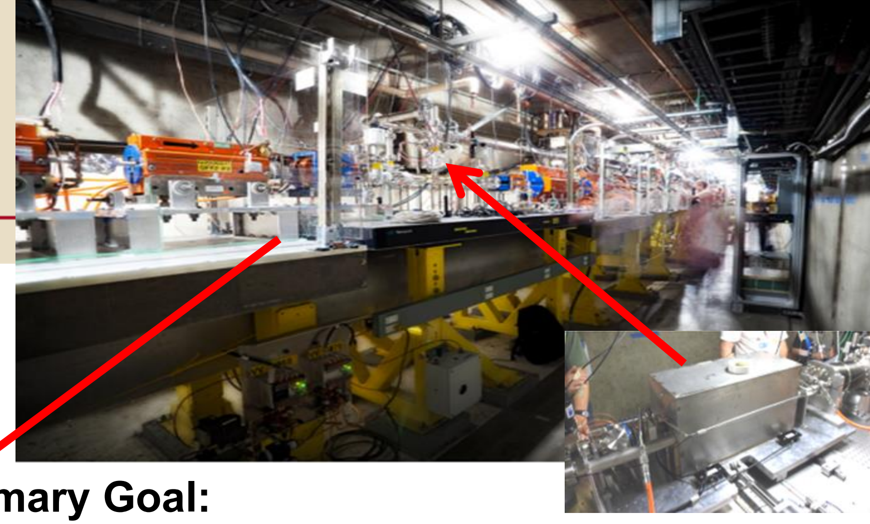




9 cm long capillary discharge

PWFA development & test @ FACET /SLAC

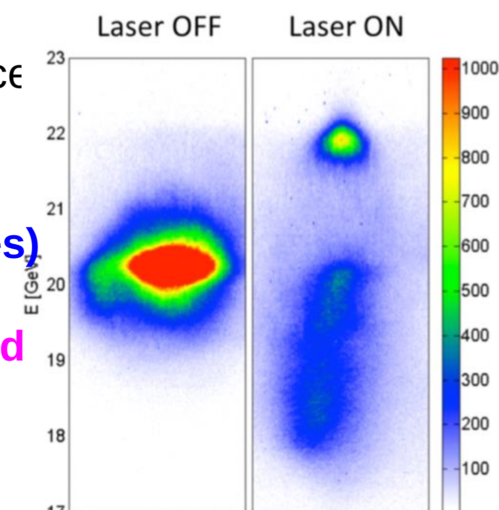




Primary Goal:

Demonstrate a single-stage high-energy plasma accelerator for electrons.

- Meter scale
- High gradient
- Preserved emittance
- Low energy spread
- High efficiency



Achieved (two bunches)

- **2 GeV Acceleration**
- **6 GV/m acceler. field**
- **2% mom. spread**

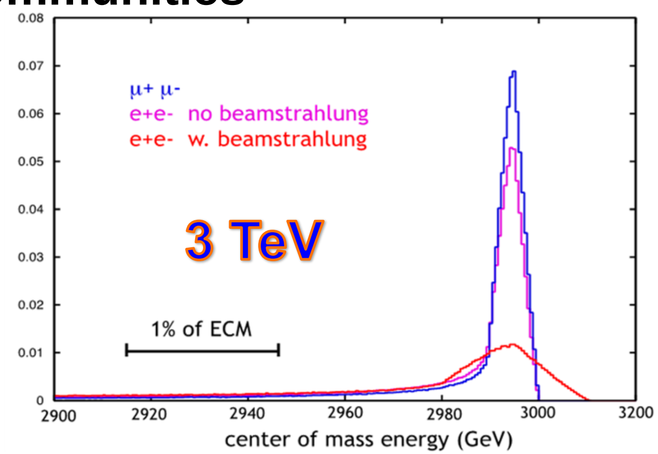
Timeline:

- Commissioning (2012)
- Drive & witness e^- bunch (2012-2013)
- Optimization of e^- acceleration (2013-2015)
- First high-gradient e^+ PWFA (2014-2016)

Muons, an attractive alternative with high potential and critical challenges

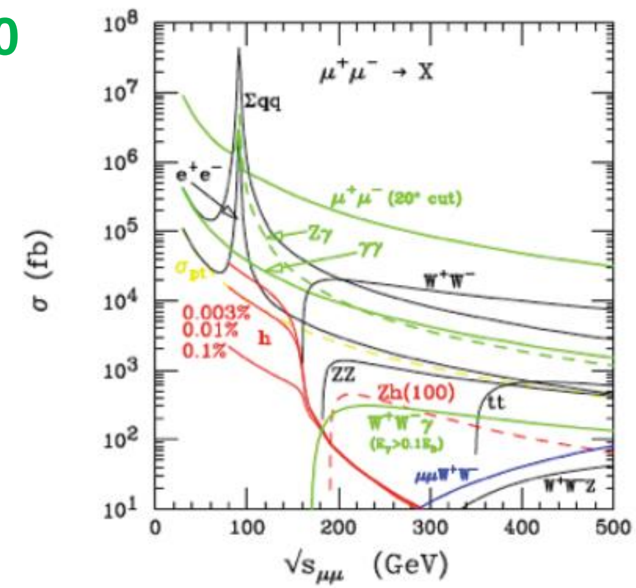
Muons are leptons like electrons & positrons but with a mass 207 times larger

- Negligible synchrotron radiation emission (α m^{-2})
  - Multi-pass collisions (1000 turns) in ring
    - High luminosity with reasonable beam power and power consumption
      - relaxed beam emittances & sizes, alignment & stability
    - Multi-detectors supporting broad physics communities
    - Large time (15 μs) between bunch crossings
  - No beam-strahlung at collision:
    - narrow luminosity spectrum
  - Multi-pass acceleration:
    - Cost effective construction & operation
    - Compact acceleration system and collider
  - No cooling by synchrotron Radiation in standard Damping rings
    - Requires development of novel cooling method



The beauty of Muons

- **Strong coupling to Higgs mechanism by s channel**
  - **Cross section enhanced by $(m_\mu/m_e)^2$ =40000 with sharp peak at 126GeV resonance**



☺
- **Higgs factory allowing energy scan with high energy resolution for direct mass and width measurements at half colliding beam energy and 10^3 less luminosity than with e+/e-**

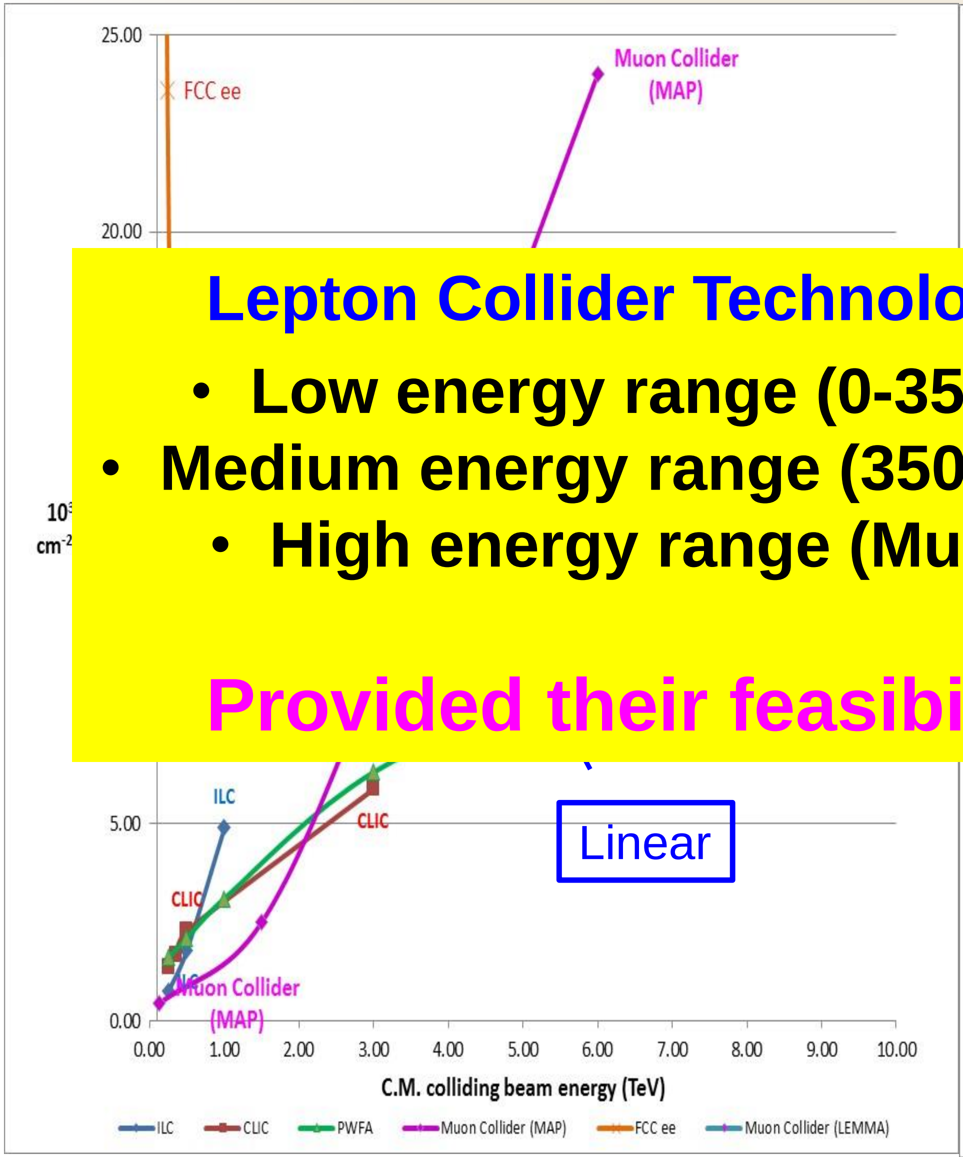
☹
- **Requires colliding beam with extremely small momentum spread ($4\ 10^{-5}$) and high stability**

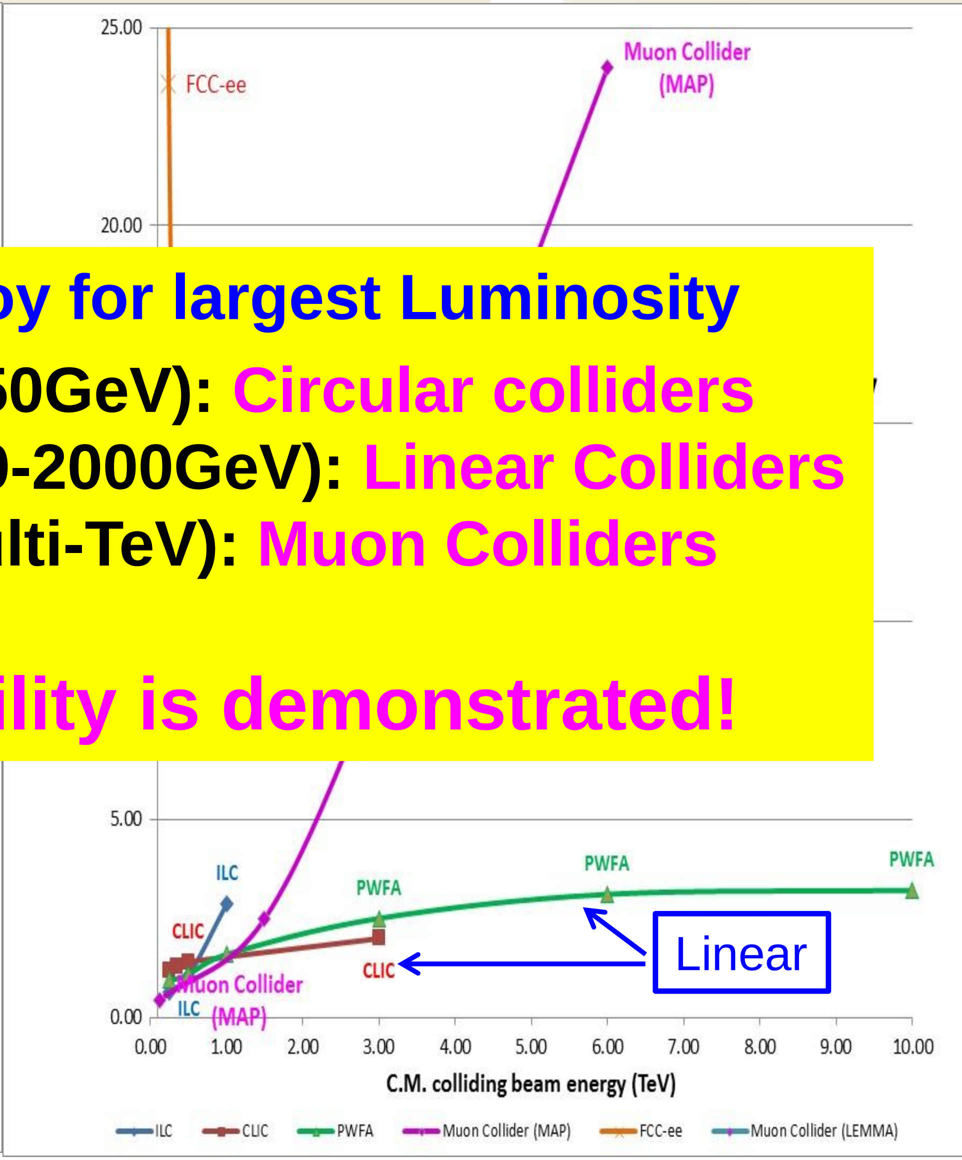
As with an e^+e^- collider, a $\mu^+\mu^-$ collider offers a precision probe of fundamental interactions

without limitations in energy:

- **By synchrotron radiation as in circular colliders**
- **By beamstrahlung as in linear colliders**

Muon Colliders extending high energy frontier with excellent performance in the Multi-TeV range





Lepton Collider Technoloy for largest Luminosity

- **Low energy range (0-350GeV): Circular colliders**
- **Medium energy range (350-2000GeV): Linear Colliders**
- **High energy range (Multi-TeV): Muon Colliders**

Provided their feasibility is demonstrated!

Muons: Issues & Challenges

- **Limited lifetime: 2.2 μs at rest**

☹
  - **Race against death: fast generation, acceleration & collision before decay**
  - **Muons decay in accelerator and detector**
    - **Physics feasibility with large background?**
    - **Shielding of detector and facility irradiation**
  - **Decays in neutrinos:**
    - **Ideal source of well defined electron and muons neutrinos in equal quantities :**

☺

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

The neutrino factory concept

- **Generated as tertiary particles in large emittances**

☹
  - **powerful MW(s) driver**
  - **novel cooling method (6D 10^6 emittance reduction)**

Development of novel technologies

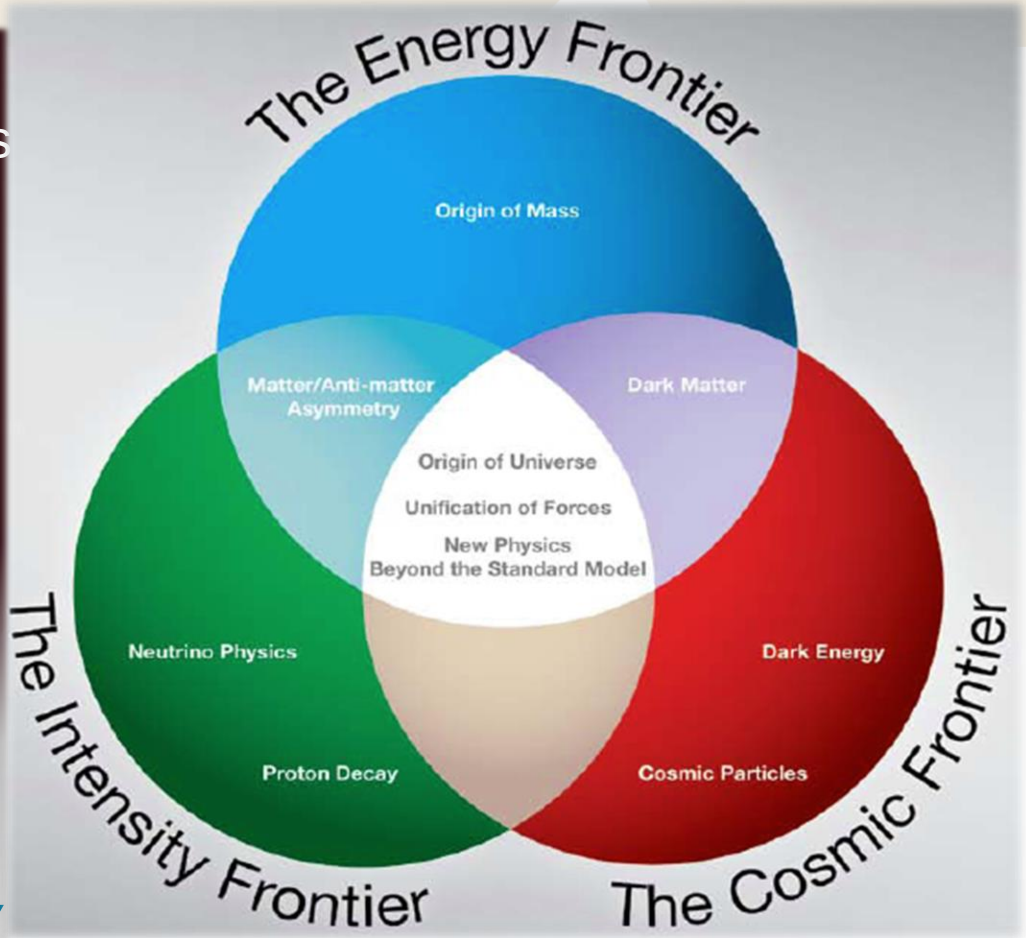
with key accelerator and detector challenges

Muon Accelerator Program (MAP @ FNAL/USA) addressing feasibility of muon based accelerators

focused on developing a facility that can address critical questions spanning two frontiers…

The Intensity Frontier:
with a ***Neutrino Factory*** producing well-characterized ν beams for precise, high sensitivity studies

The Energy Frontier:
with a ***Muon Collider*** capable of reaching multi-TeV CoM energies
and a
Higgs Factory *with unique property*

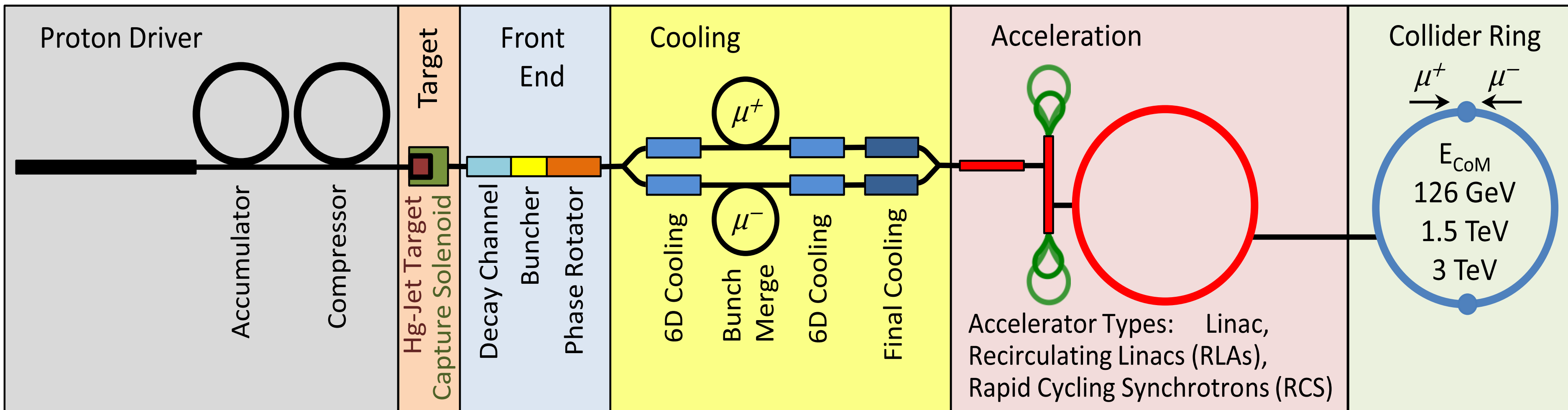


The unique potential of a facility based on muon accelerators is physics reach that SPANS 2 FRONTIERS

Muon Accelerator Concept
Muon production from Proton driven Pions decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Key issues and R&D to address feasibility



Key Challenges

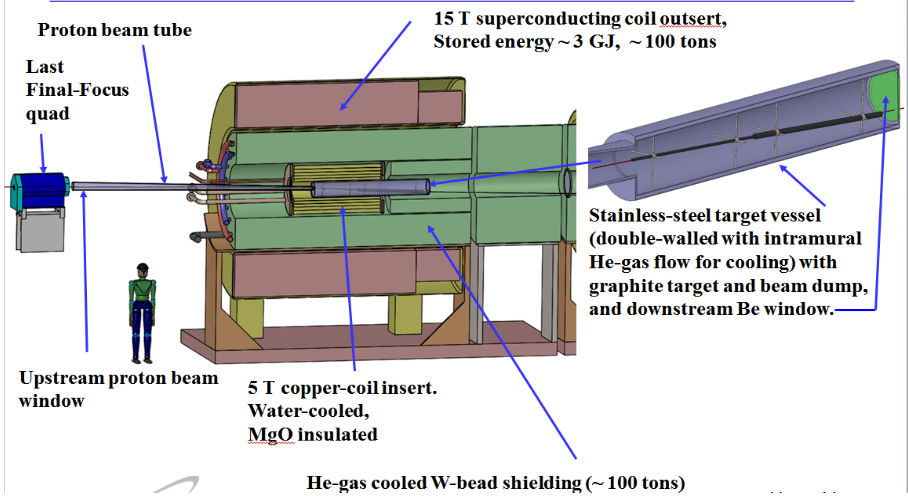
- ~10^{13}-10^{14} μ / sec
  Tertiary particle
  $p \rightarrow \pi \rightarrow \mu$:
- Fast cooling (τ=2μs) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

Key R&D

- MW proton driver
  MW class target
  NCRF in magnetic field
- Ionization cooling
  High field solenoids (30T)
  High Temp Superconductor
- Cost eff. low RF SC
  Fast pulsed magnet (1kHz)
- Detector/ machine interface

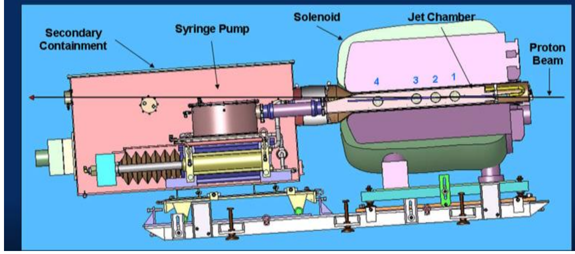
Technical challenges
Muon production as tertiary particle

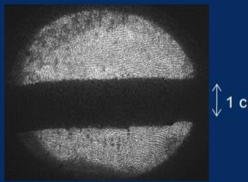
A MW class Target with Graphite Core



Multi-MW class liquid HG target

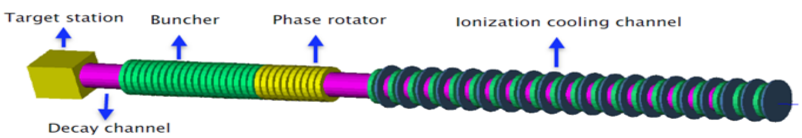
- The MERIT Experiment at the CERN PS
  - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
  - ⇨ Jets could operate with beam powers up to **8 MW** with a repetition rate of 70 Hz
- MAP staging aimed at initial 1 MW target

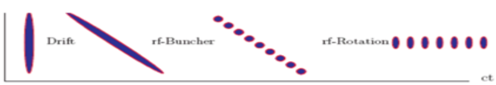


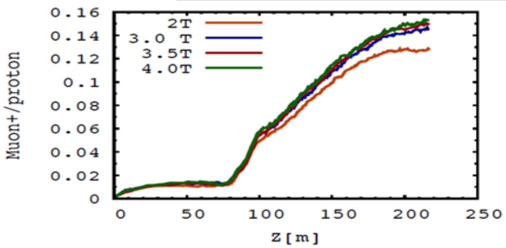


Hg jet in a 15 T solenoid with measured disruption length ~ 28 cm

An Efficient Front End for Tertiary Particle Production







A MW class proton source enables muons from pions decay to be produced, captured and bunched in a front end with an overall efficiency of 0.15 muon / proton before being cooled to fit within the acceptances of an accelerator

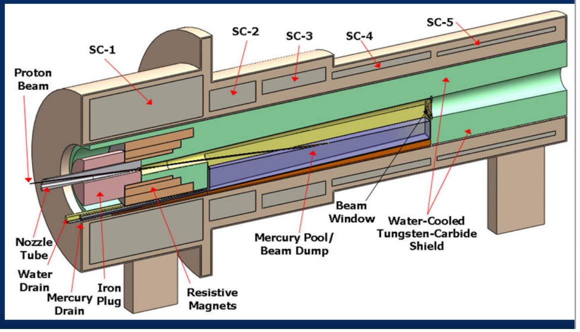
Technology Challenges – Capture Solenoid

- A Neutrino Factory and/or Muon Collider Facility requires challenging magnet design in several areas:
  - Target Capture Solenoid (15-20T with large aperture)

E_{stored} ~ 3 GJ

O(10MW) resistive coil in high radiation environment

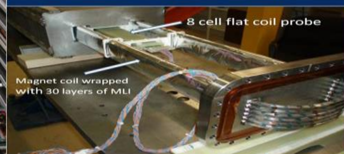
Possible application for High Temperature Superconducting magnet technology



Technical challenges
Fast and cost efficient acceleration

Technology Challenges - Acceleration

- Muons require an ultrafast accelerator chain
  ⇨ *Beyond the capability of most machines*
- Solutions include:
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient (FFAG) Machines
  - Rapid Cycling Synchrotrons (RCS)



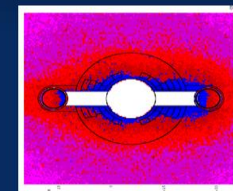
RCS requires 2 T p-p magnets at f = 400 Hz (U Miss & FNAL)

JEMMRLA Proposal: JLAB Electron Model of Muon RLA with Multi-pass Arcs

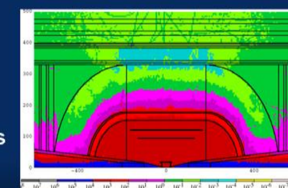
Fermilab

Technology & Design Challenges Ring, Magnets, Detector

- Emittances are relatively large, but muons circulate for ~1000 turns before decaying
  - Lattice studies for 126 GeV, 1.5 & 3 TeV CoM
- High field dipoles and quadrupoles must operate in high-rate muon decay backgrounds
  - Magnet designs under study
- Detector shielding & performance
  - Initial studies for 126 GeV, 1.5 TeV, and 3 TeV using MARS background simulations
  - Major focus on optimizing shielding configuration



MARS energy deposition map for 1.5 TeV collider dipole



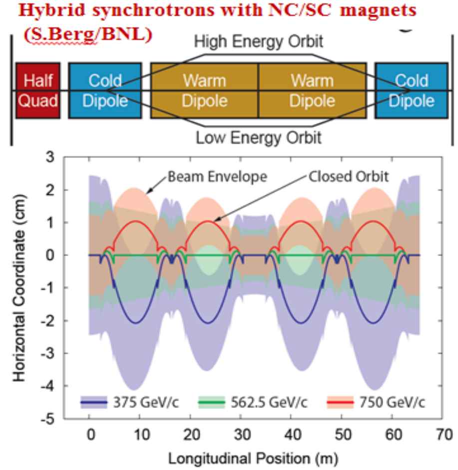
Cost efficient low frequency Super-Conducting RF Cavities

Nb coated Cu cavities (D.Hartill / Cornell)

- Two 500 MHz cavities spun from explosion bonded Nb-Cu sheets
- Research partnership with Epner Technologies to study Cu on Nb electroforming

Fast Pulsed Normal Conducting Dipole for hybrid (NC/MC magnets) Rapid Cycling Synchrotrons (RCS)

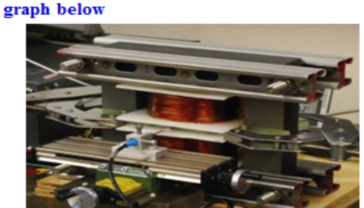
Hybrid synchrotrons with NC/SC magnets (S.Berg/BNL)



1.8 T, 400Hz Dipole – D. Summers, U Miss.

A 1.8 T dipole magnet using thin grain oriented silicon steel laminations has been constructed as a prototype for a muon synchrotron ramping at 400Hz

The dipole has run at 1.8 Tesla both at both 425 Hz and 1410 Hz as well as DC as shown in the graph below

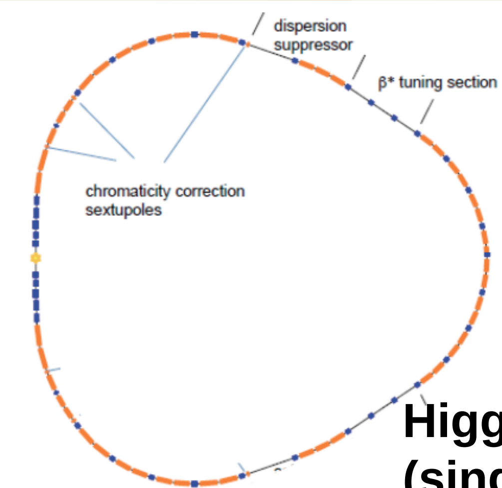


Reached 1.8T - further design & prototype work in progress

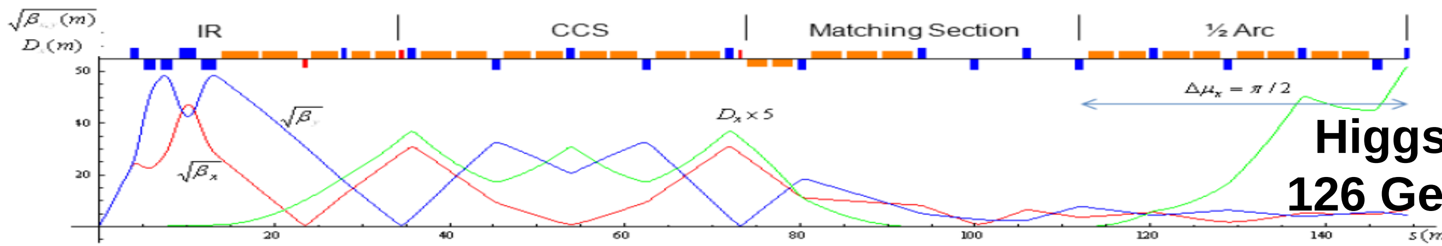
Technical challenges Collider Rings

Detailed optics studies for Higgs, 1.5 TeV, 3 TeV and now 6 TeV CoM

- **With supporting magnet designs and background studies**

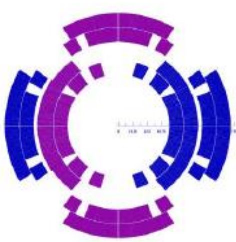


Higgs Ring (single IR)

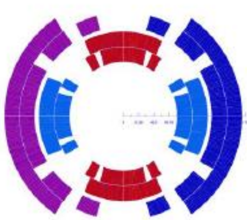


Higgs 126 GeV

Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP

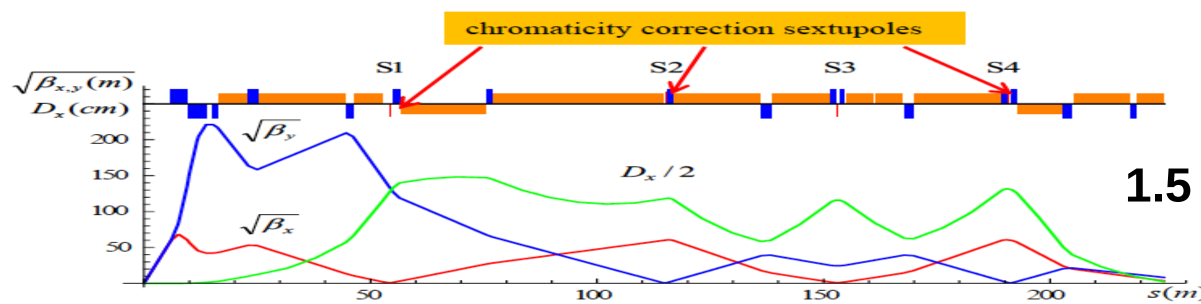


Dipole/Quad

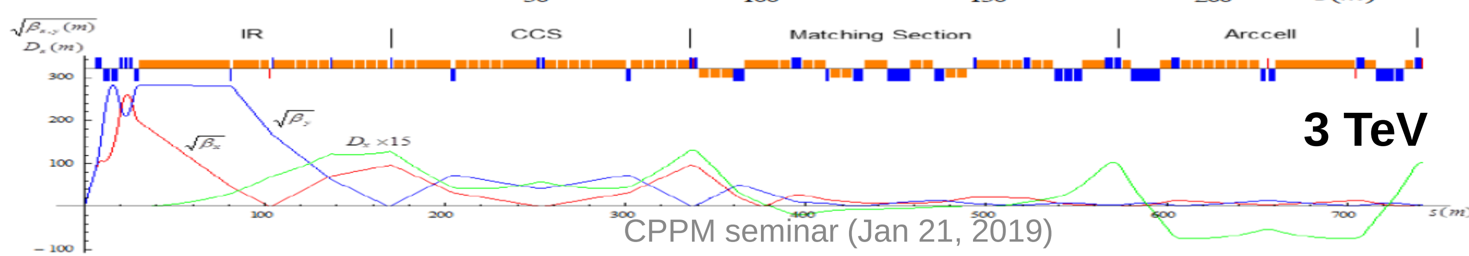


Quad/Dipole

β*=1cm



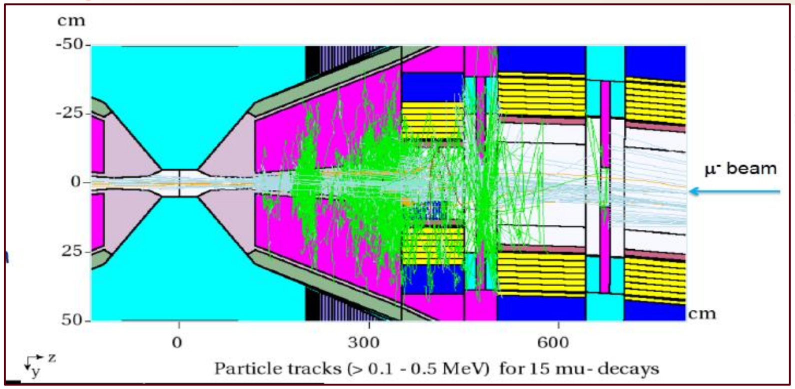
1.5 TeV

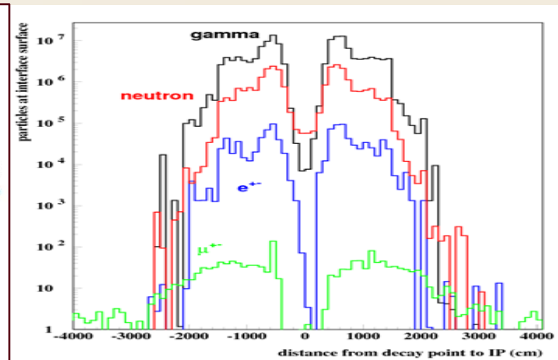


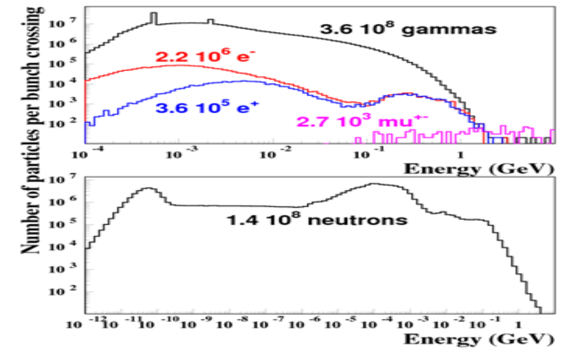
3 TeV

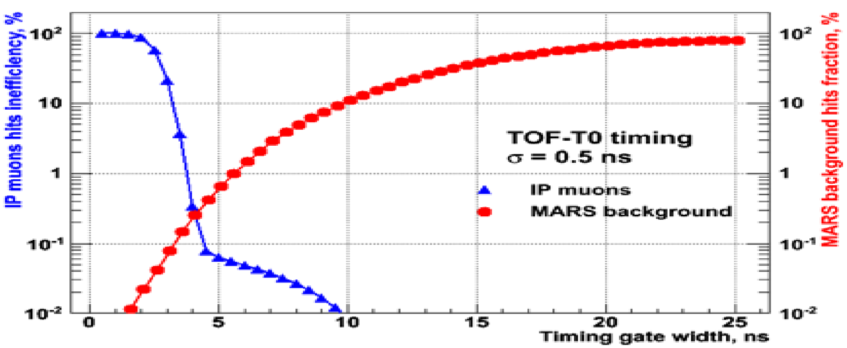
Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm

Machine Detector Interface
Background mitigation

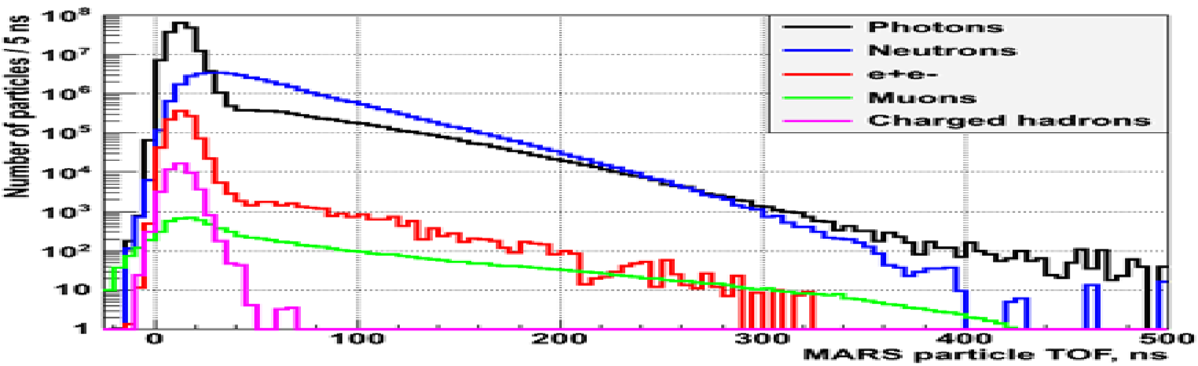








	Cut	Rejection
Tracker hits	1 ns, dedx	9×10^{-4}
Calorimeter neutrons	2 ns	2.4×10^{-3}
Calorimeter photons	2 ns	2.2×10^{-3}



Much of background soft and out of time

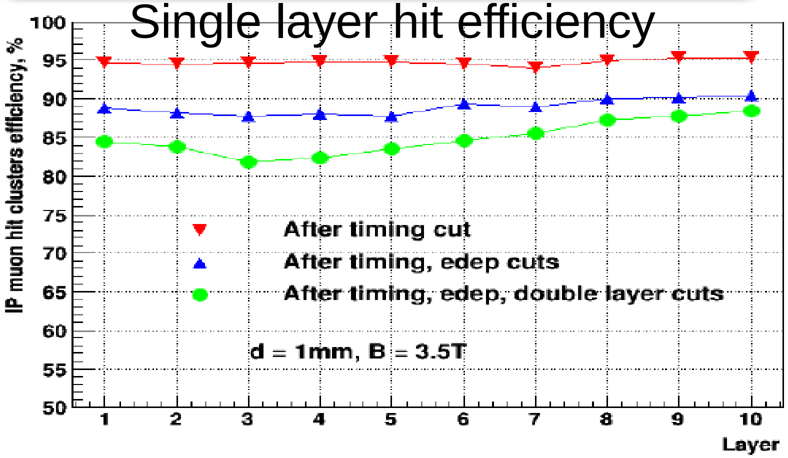
Timing window with ns resolution is key to reduce background by three orders of magnitude

Requires a detector with fast, pixelated tracker and calorimeter

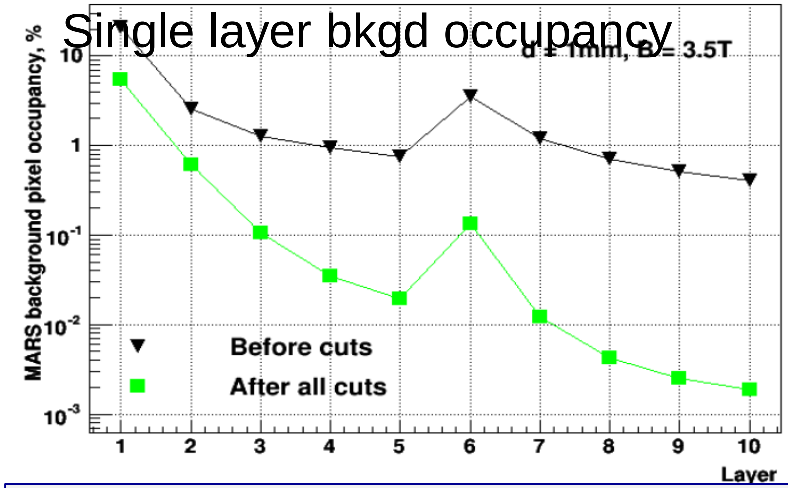
Technical Challenge
Detector with Background Mitigation

Trackers: Employ double-layer structure with 1mm separation for neutral background suppression

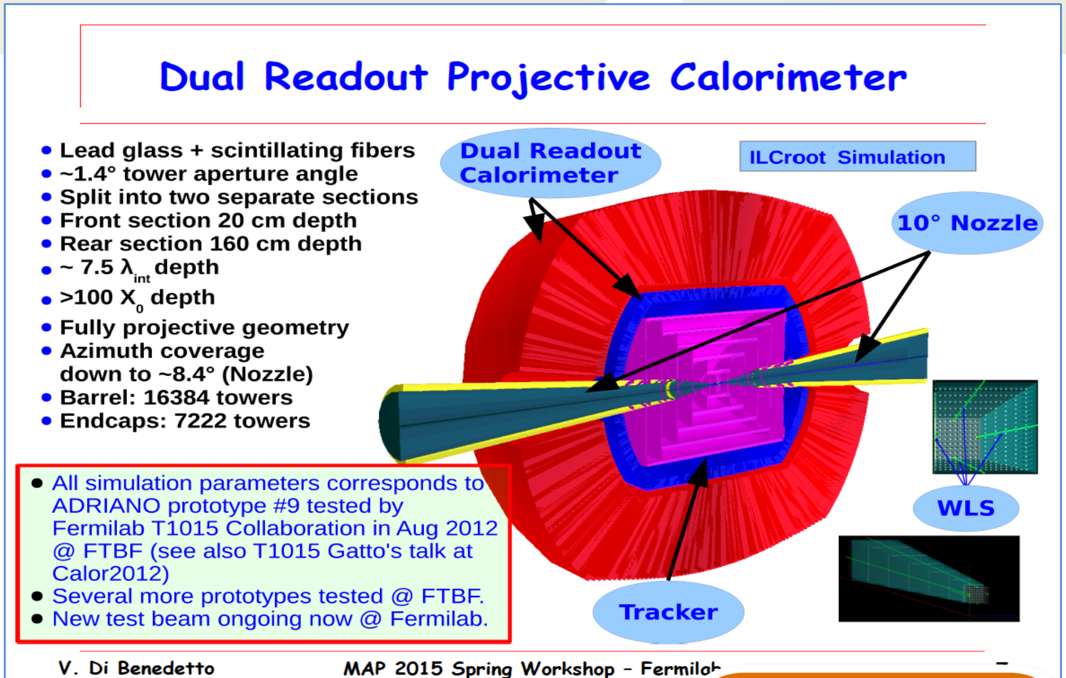
Single layer hit efficiency



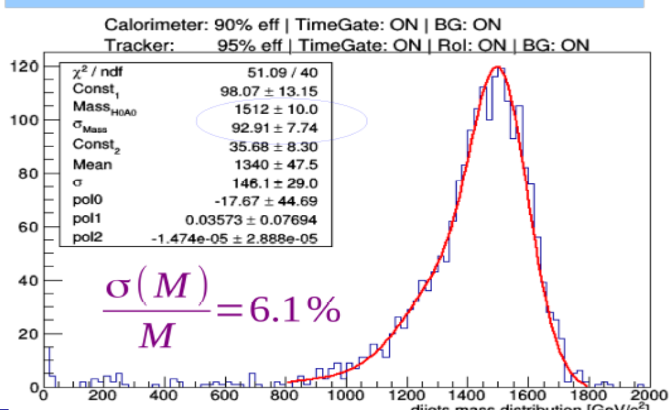
Single layer bkgd occupancy



MARS Bkgds ⇨ ILCRoot Det Model



Time gate & RoI ON – BG ON



Preliminary detector study promising
- 1st pass setup: Further improvements anticipated

Cooling Methods

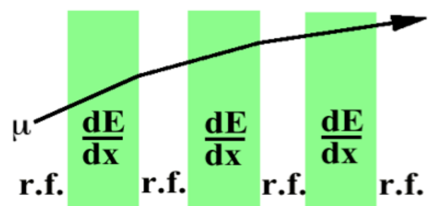
The challenge of muon cooling is due to the short muon lifetime (2 μs at rest)

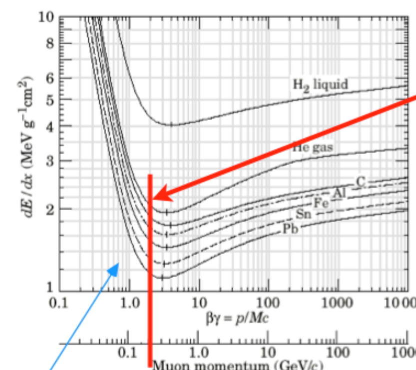
- Cooling must take place very quickly
- More quickly than any of the cooling methods presently in use

⇨ Utilize energy loss in materials with RF re-acceleration

- Muons cool via dE/dx in low-Z medium

Ionization Cooling





- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower *p*
  - straggling & expense of reacceleration at higher *p*

– Absorbers:

$$\begin{cases} E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta_{space}^{rms} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

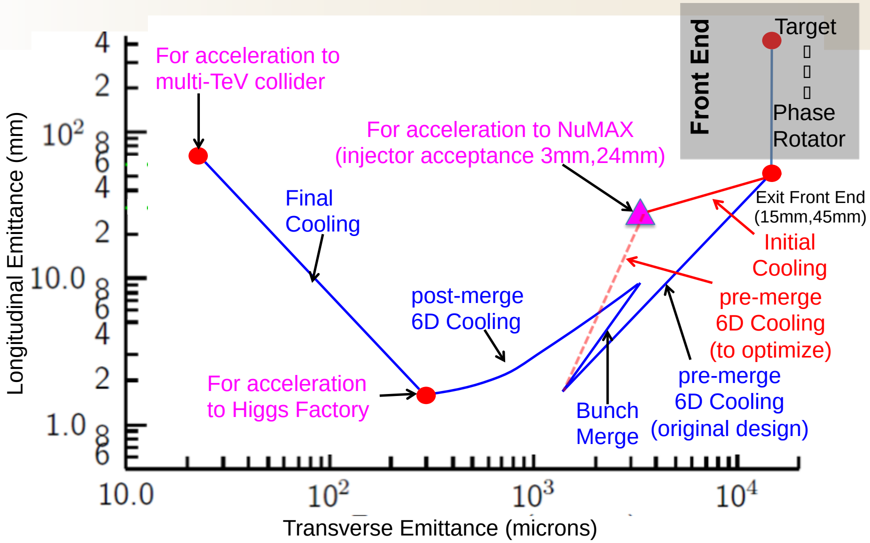
- 2 competing effects ⇒ ∃ equilibrium emittance

– RF cavities between absorbers replace ΔE

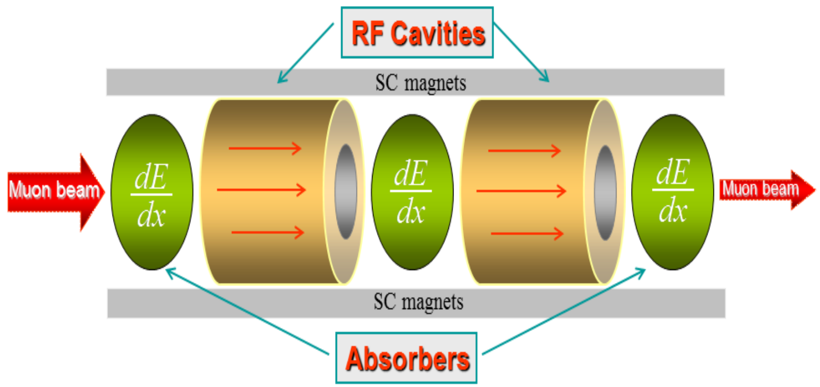
– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$ (emittance change per unit length)

Novel Muon Ionization Cooling



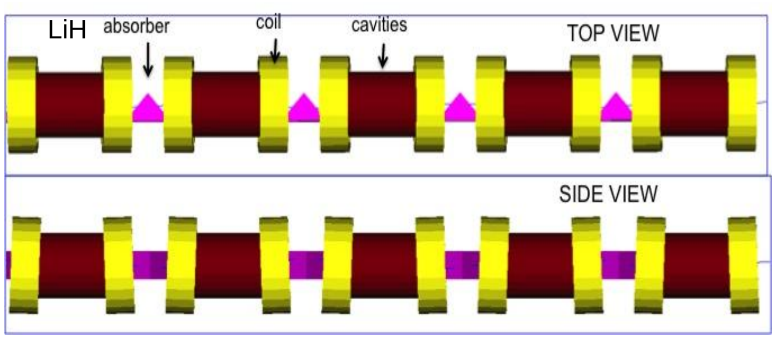
Ionization cooling

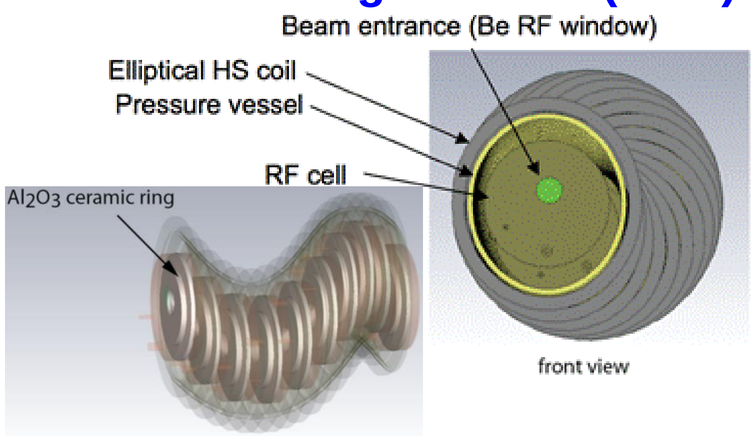


Vacuum Cooling Channel (VCC)

Helical Cooling Channel (HCC)

Two methods



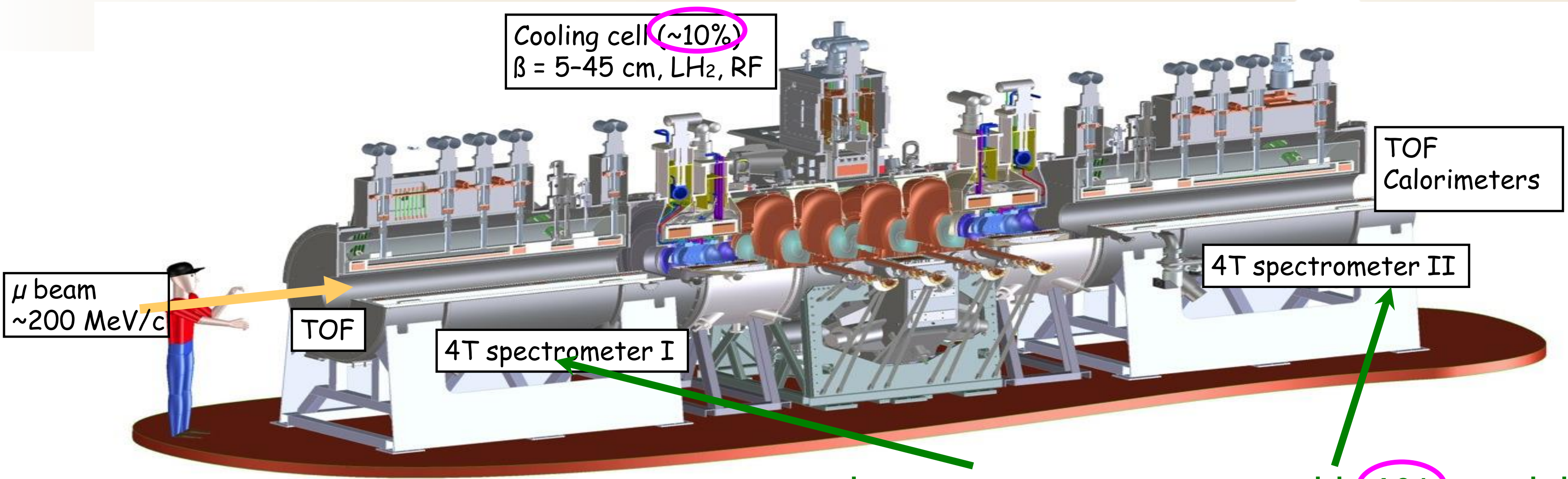


Major challenges

Accelerating field limitation by magnetic field (10 T)

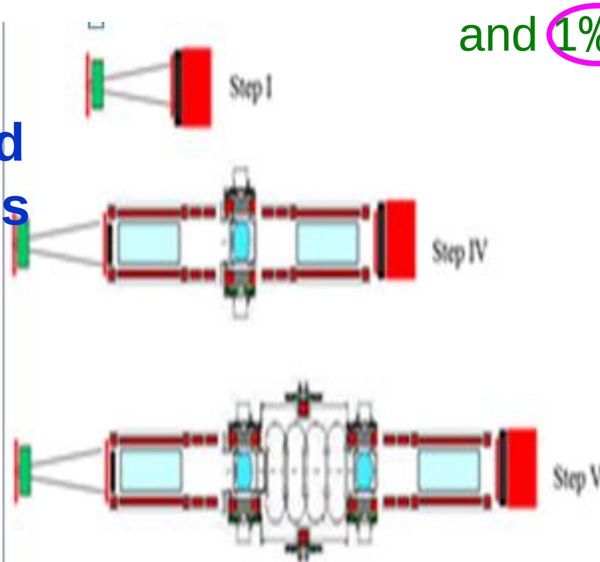
High pressure (160atm) Gas (GH_2) filled RF cavities

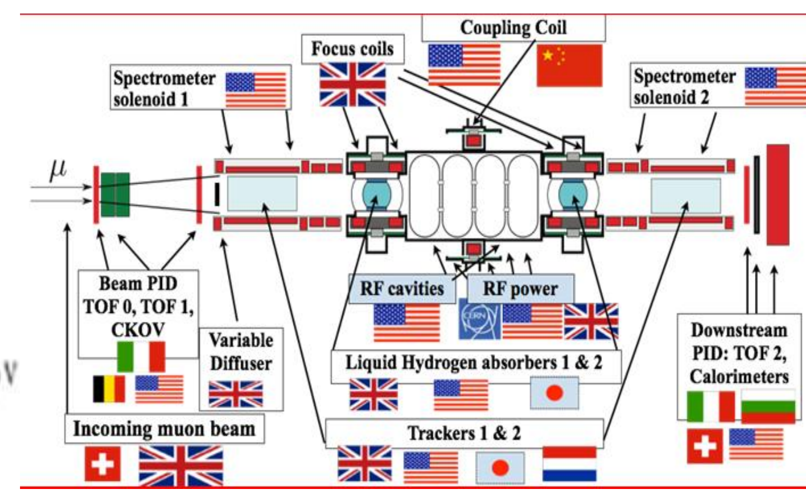
Muon Ionization Cooling Experiment MICE @ RAL (International Collaboration)



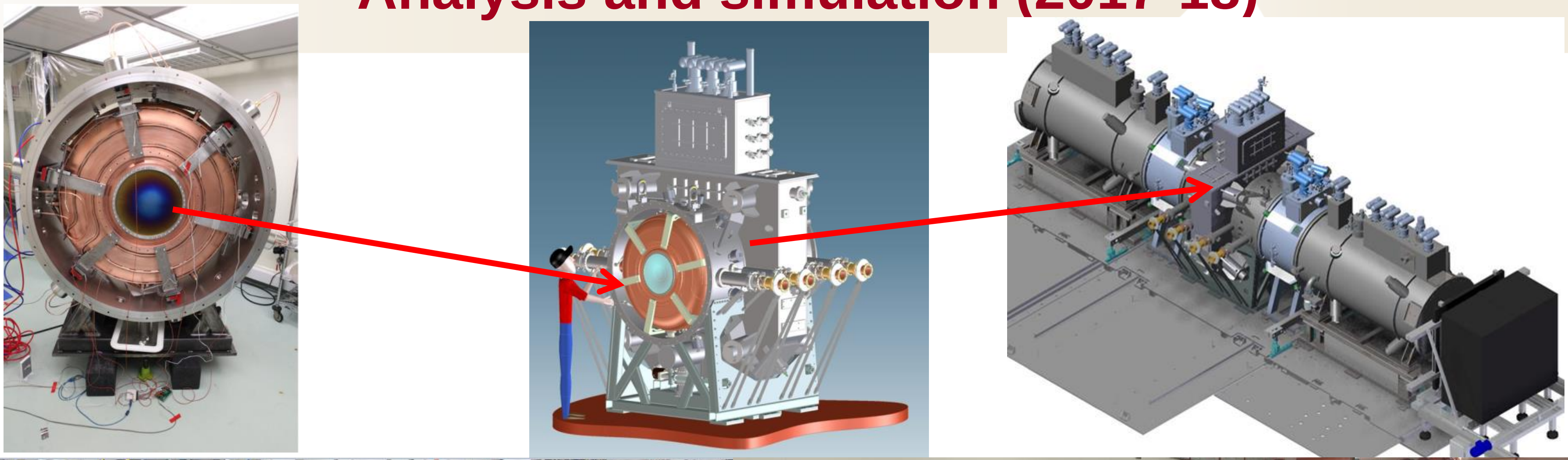
emittance measurements with 1% precision and 1‰ resolution (muon by muon)

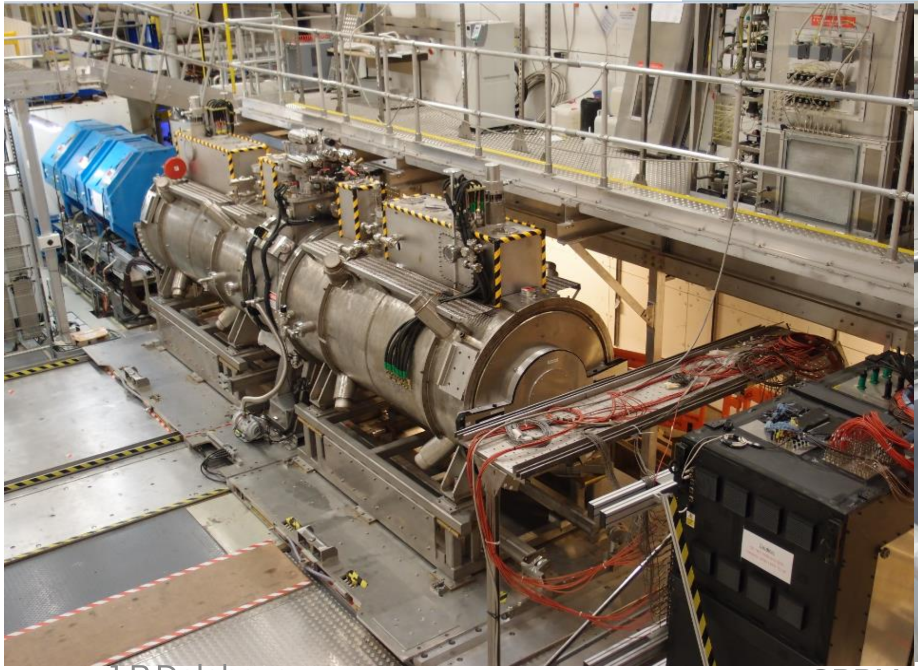
Goals:
- **Demonstrate in steps the method with beam and its feasibility**
- **Validate cooling simulation tools**
- **System integration**

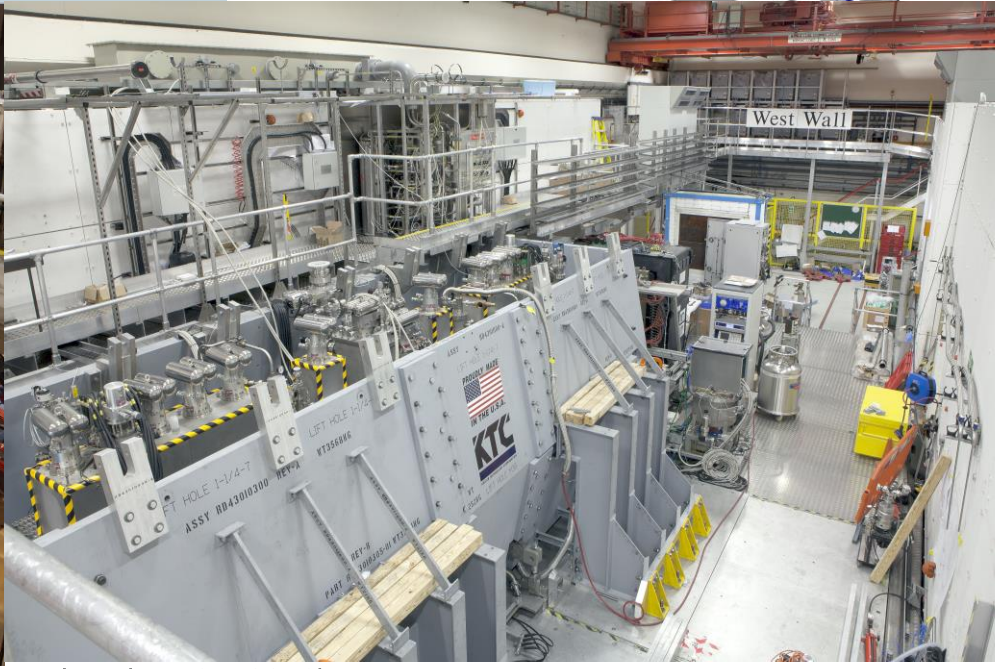




MICE completed (2015)
Data taking with beam (2016-17)
Analysis and simulation (2017-18)







MICE experimental results
First ionization cooling demonstation
Validation of beam dynamics & simulation tools

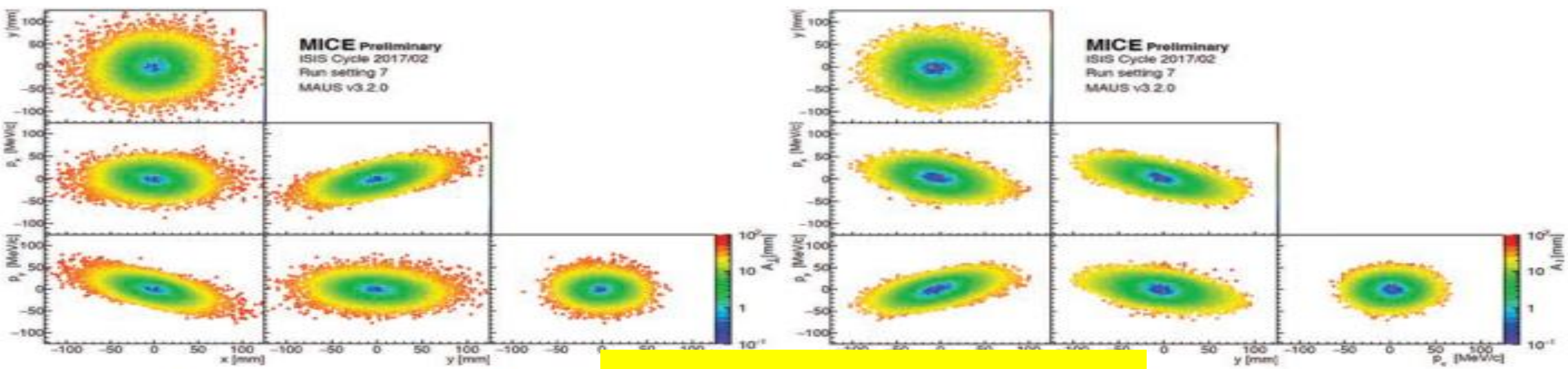


FIGURE 9. Beam amplitude for 140 MeV/c bea … se-space components (a) upstream and (b) …

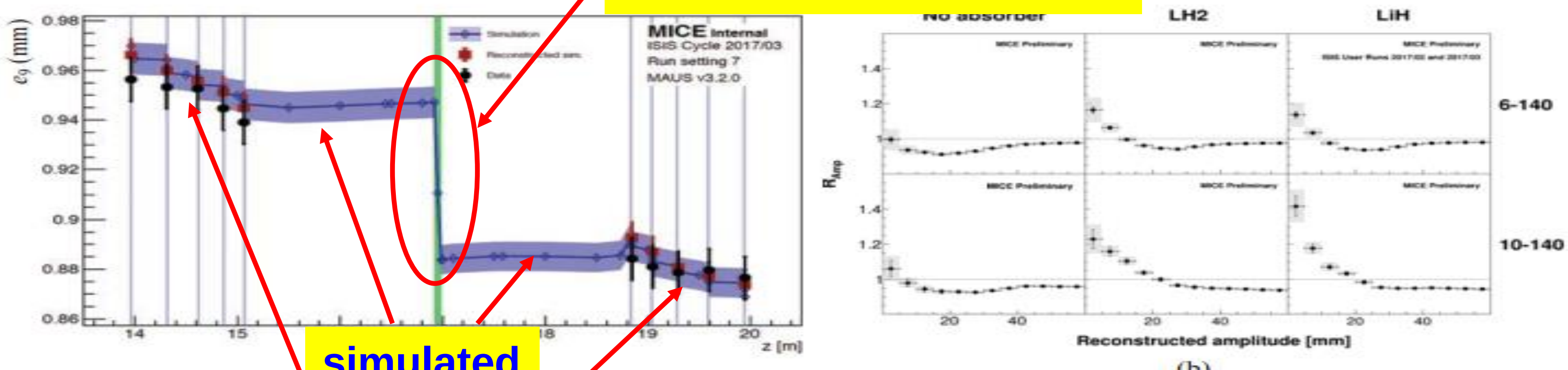
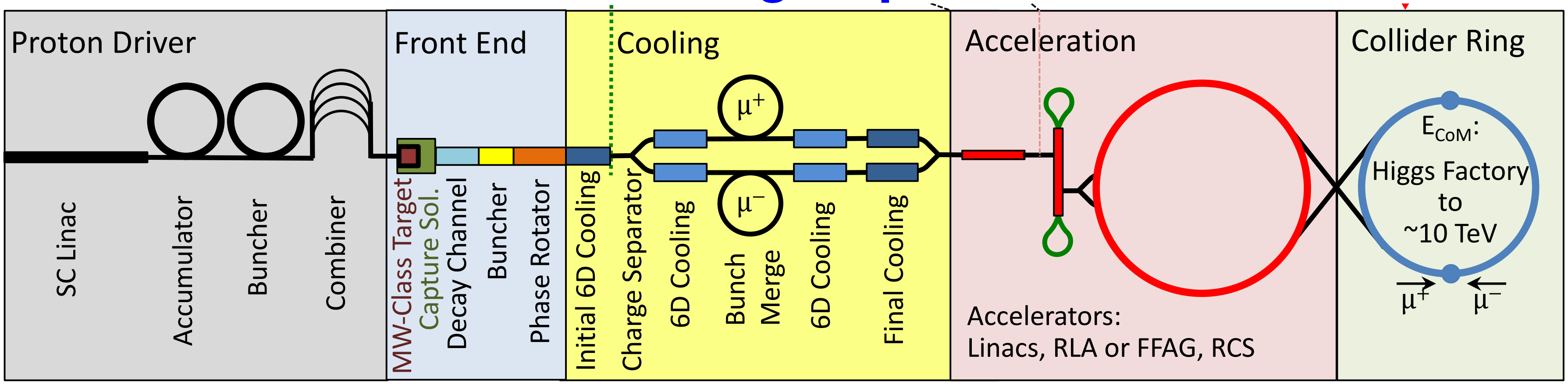


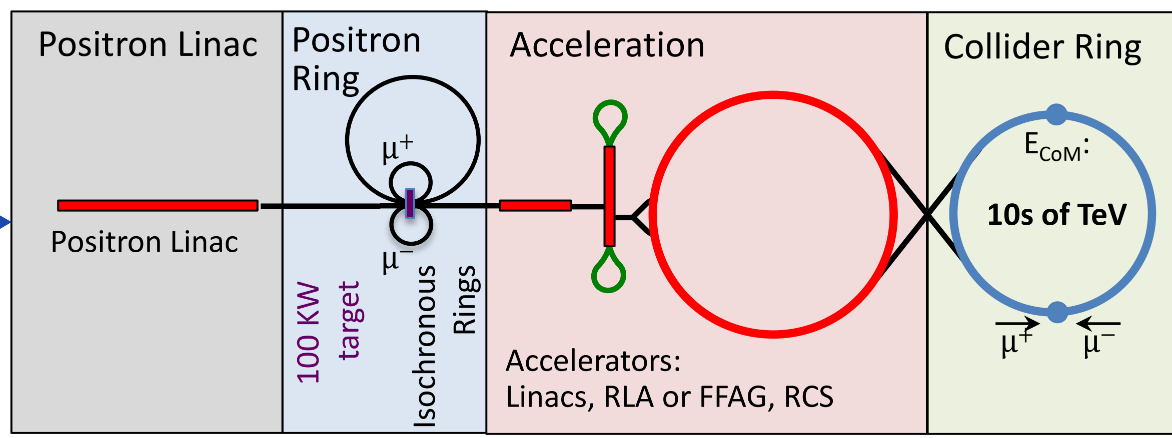
FIGURE 10. (a) Behavior of e_9 subemittance (emittance of central 9% of beam) in MICE, compared to simulation, for nominal 6 mm input emittance … sorber: shaded band shows systematic uncertainty; (b) cumulative amplitude ratios measured in MICE f … t beam emittance and three absorber configurations: solid error bars are statistical … ertainties, gray-shaded bands are systematics.

An attractive novel alternative Low Emittance Muon Accelerator (LEMMA)

Muon production by e+/e- annihilation at 45 GeV threshold no cooling required



Low EMmittance Muon Accelerator (LEMMA):
10^{11} ∝ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

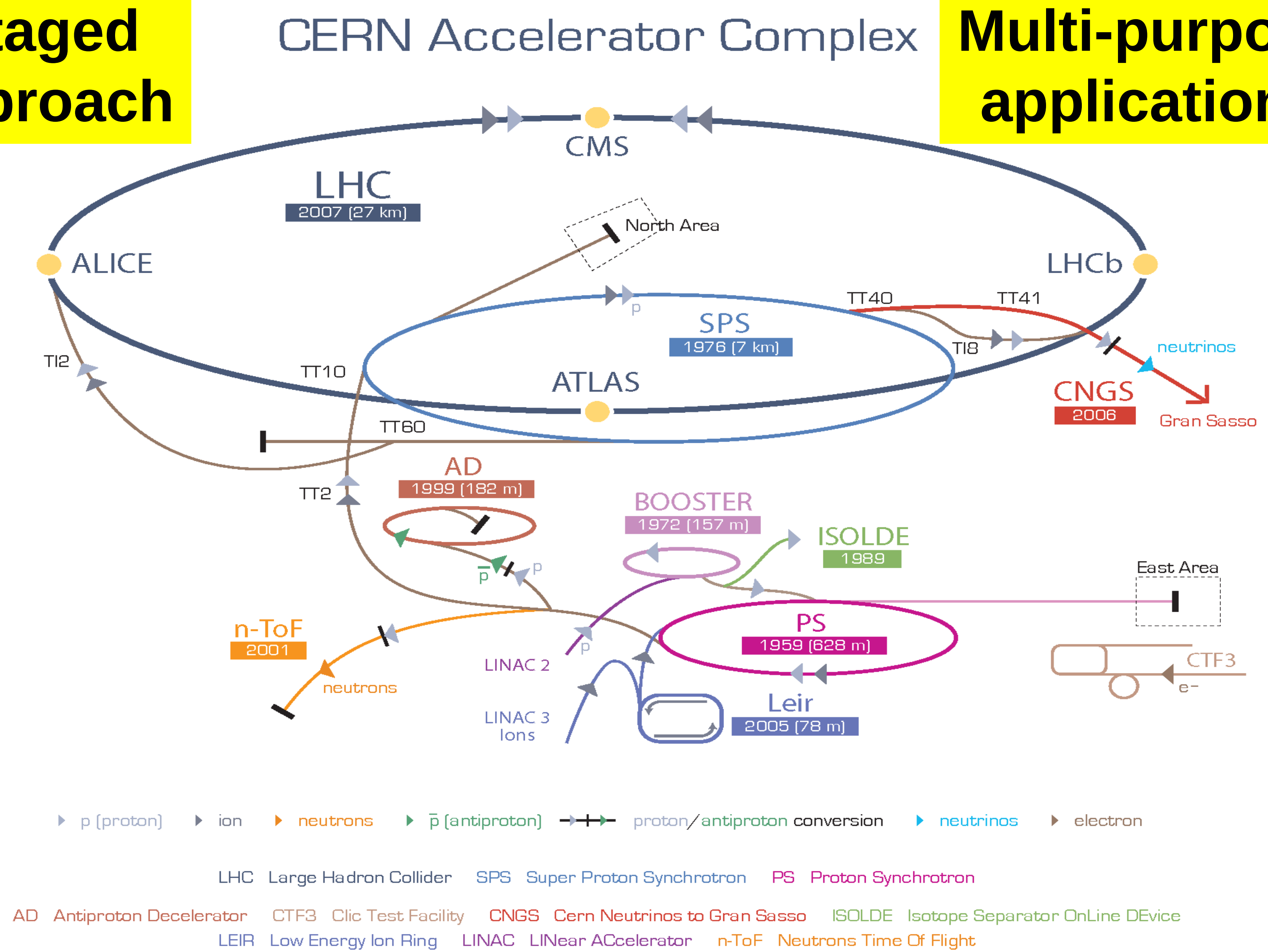


Major challenge: Large positron flux (10^{18} e^+/s) required

CERN, a success story

Staged approach

Multi-purpose applications



Principles of an ideal project scenario

Series of STAGED facilities

- **physics interest at each stage**
- **Technology with increasing complexity progressively developed and validated**

Possibly MULTIPURPOSE

- **maximizing supported physics community and funding!**

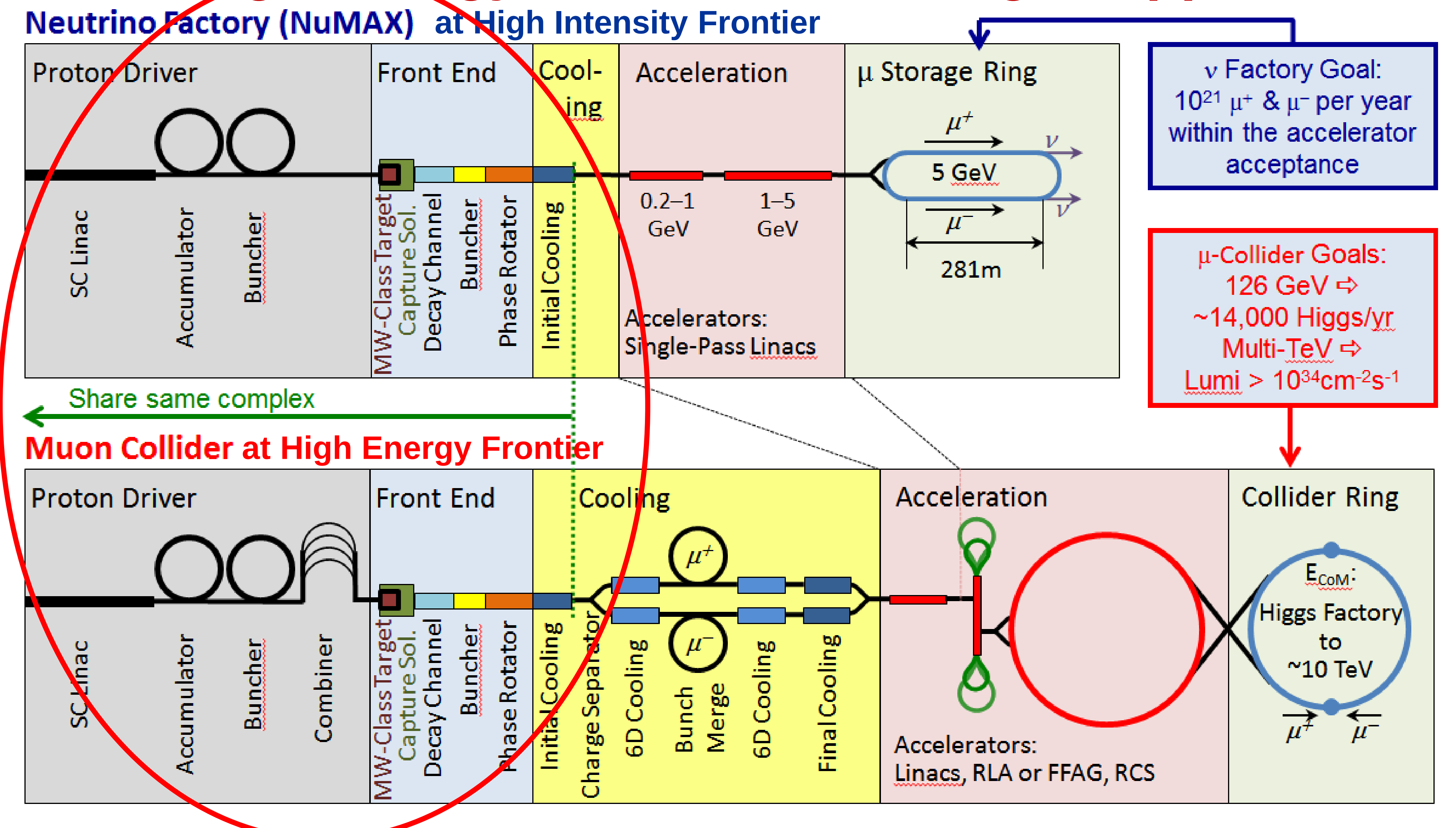
Affordable steps (<1 G$) from one facility to next

- **Stage built-on previous stage with additional facilities**

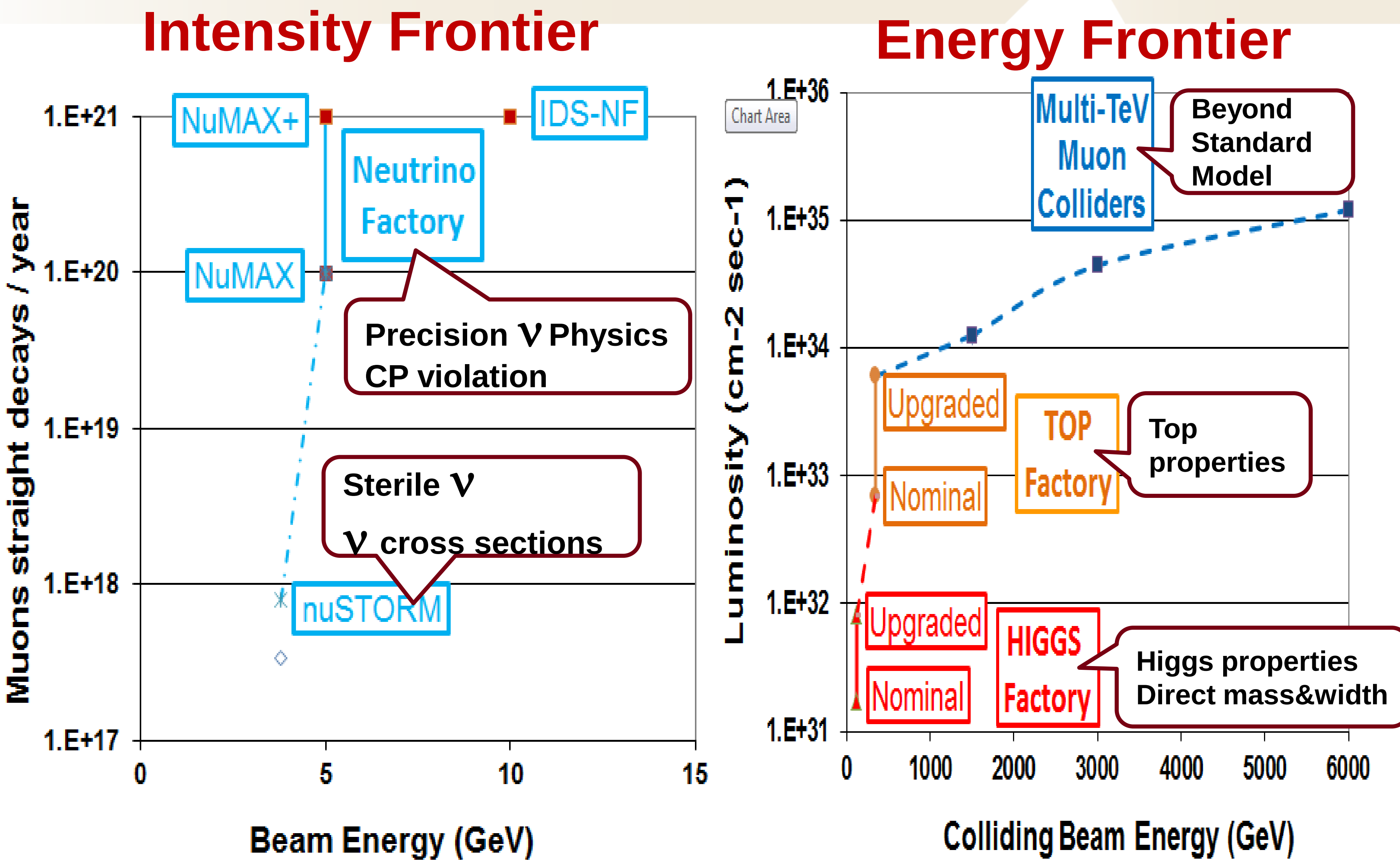
Taking advantage of existing facilities

- **synergy between present and future program**

Unique opportunity of Muon based accelerators to enable facilities at both High Intensity and High Energy Frontiers in a staged approach



Staged pathway of a series of facilities with physics interest at each stage



Staged Neutrino Factory and Muon Colliders
Increasing complexity and challenges
main parameters

Neutrino Factory at intensity frontier

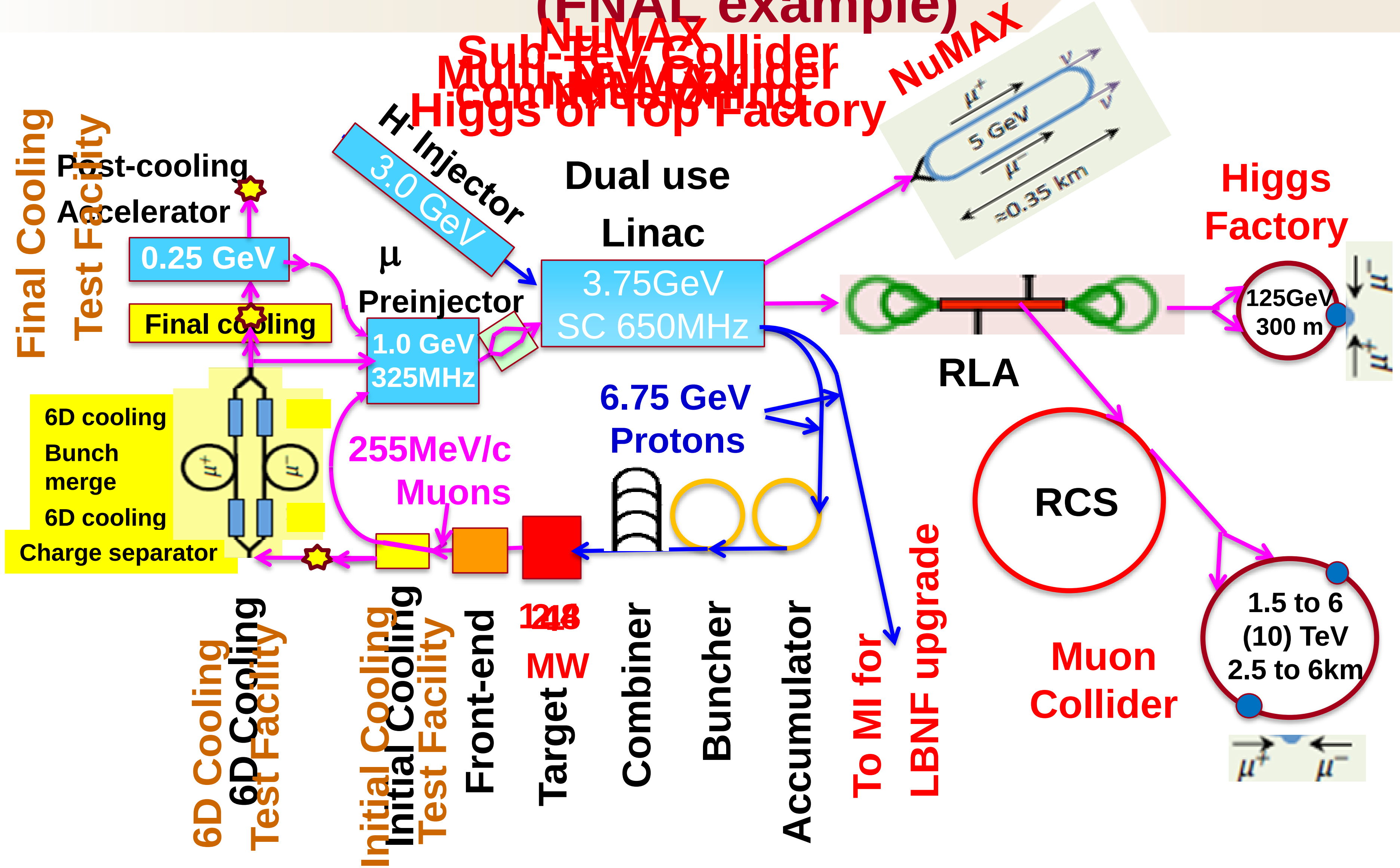
System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Detector	*Far Detector:*	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
	Distance from Ring	km	1.9	1300	1300	1300
	Mass	kT	1.3	100 / 30	100 / 30	100 / 30
	Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	1	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum	GeV/c	3.8	5	5	5
	Circumference (C)	m	480	737	737	737
	Straight section	m	184	281	281	281
	Number of bunches	-		60	60	60
	Charge per bunch	1×10^{9}		6.9	26	35
Acceleration	Initial Momentum	GeV/c	-	0.25	0.25	0.25
	Single-pass Linacs	GeV/c	-	1.0, 3.75	1.0, 3.75	1.0, 3.75
		MHz	-	325, 650	325, 650	325, 650
	Repetition	Hz	-	30	30	60
Cooling			No	No	Initial	Initial
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam	GeV	120	6.75	6.75	6.75
	Protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition	Hz	0.75	15	15	15

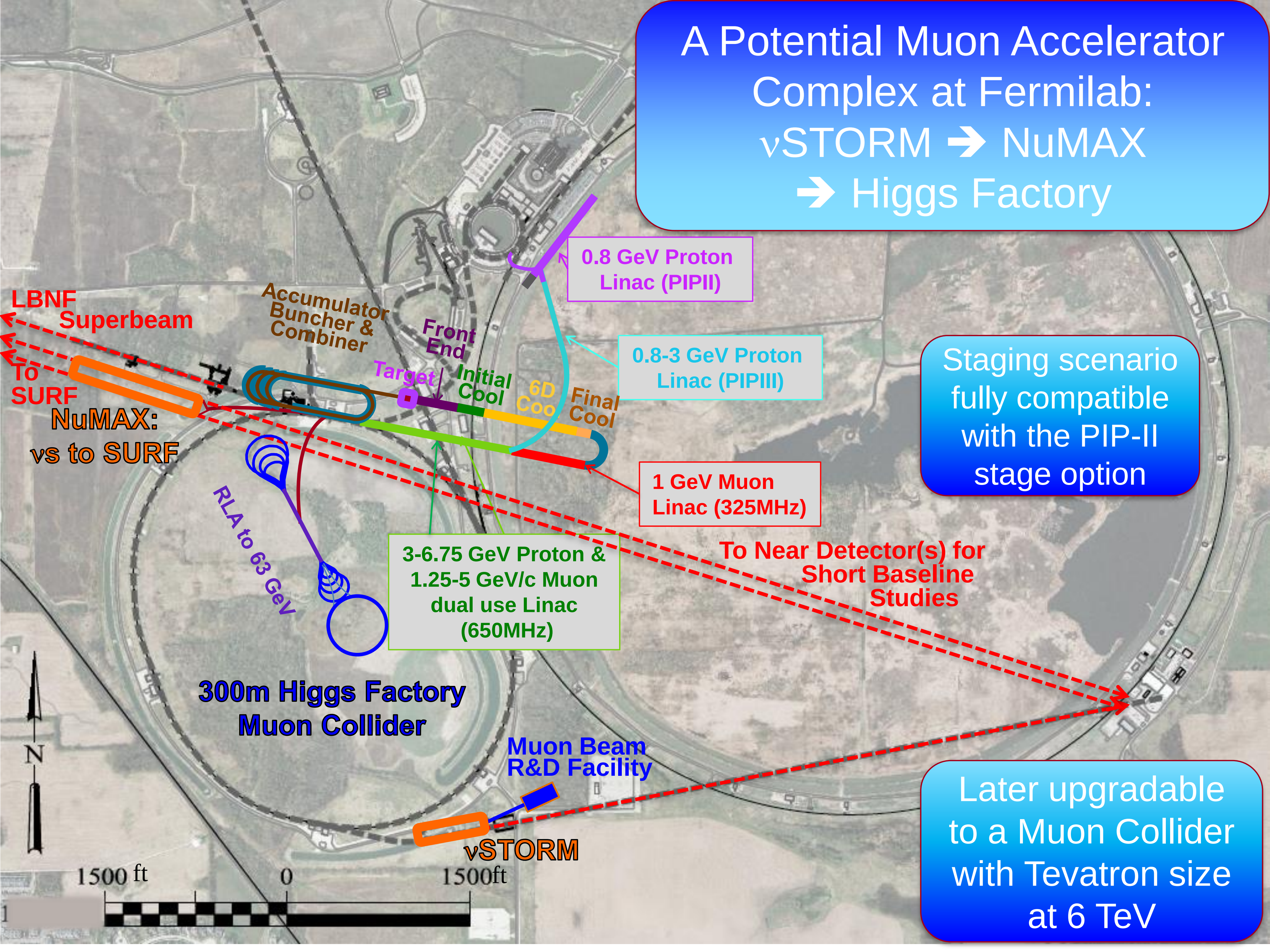
Muon Collider at the energy frontier

		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	*Units*	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top† Production/10^7sec		3,500*	13,500*	7,000†	60,000†	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	$4^{\sharp}$	4	4	4	4	4	1.6

Cooling — 6D no final — Full 6D

Progressive installation in stages with technology validation at each stage (FNAL example)





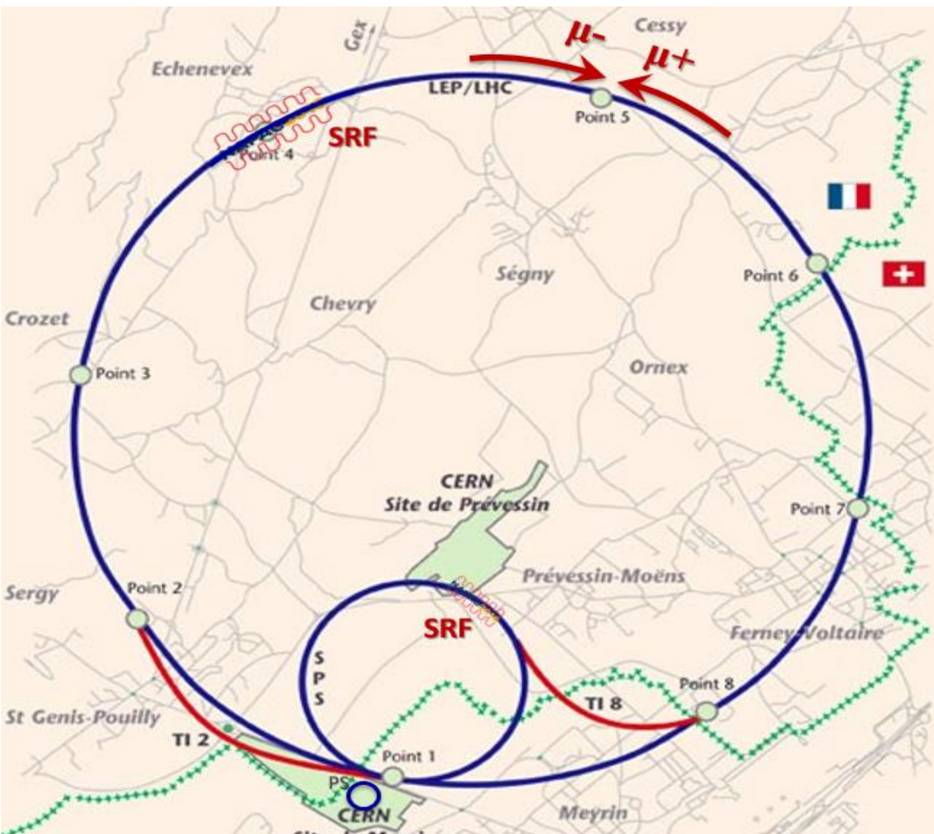
A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory
0.8 GeV Proton Linac (PIPII)
0.8-3 GeV Proton Linac (PIPIII)
Staging scenario fully compatible with the PIP-II stage option
LBNF Superbeam
To SURF
Accumulator Buncher & Combiner
Front End
Target
Initial Cool
6D Cool
Final Cool
NuMAX: νs to SURF
1 GeV Muon Linac (325MHz)
RLA to 63 GeV
3-6.75 GeV Proton & 1.25-5 GeV/c Muon dual use Linac (650MHz)
To Near Detector(s) for Short Baseline Studies
300m Higgs Factory Muon Collider
Muon Beam R&D Facility
νSTORM
Later upgradable to a Muon Collider with Tevatron size at 6 TeV
N
1500 ft
0
1500ft

D.Neuffer
V.Shiltsev

A Muon Collider in the CERN LHC tunnel Unique and attractive opportunity in Europe for a realistic precision & exploratory facility

Taking advantage of CERN LHC tunnel and injectors infrastructure for substantial cost savings

14 TeV muon collider in the (existing) 27kms LHC tunnel

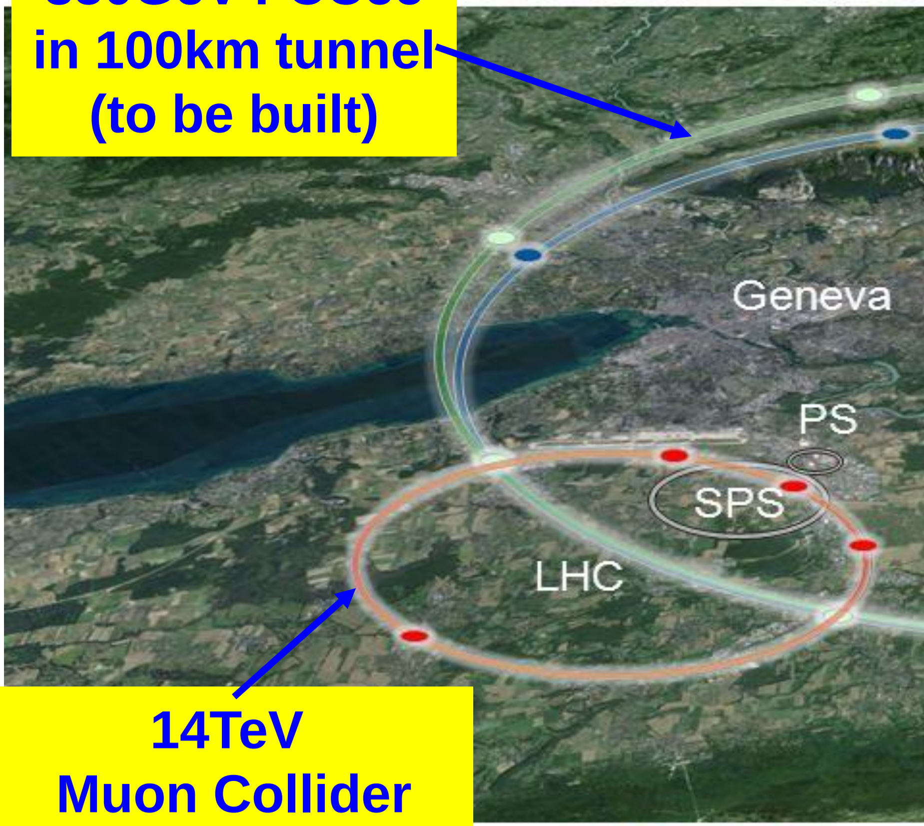


Parameter	"PS"	"MAP"	"LEMC"
Luminosity $cm^{-2}s^{-1}$	$1.2\cdot10^{33}$	$3.5\cdot10^{35}$	$2.4\cdot10^{32}$
Beam δE/E	0.1%	0.1%	0.2%
Rep rate, Hz	5	5	2200
N_μ/bunch	$1.2\cdot10^{11}$	$2\cdot10^{12}$	4.5×10^{7}
n_b	1	1	1*
$\varepsilon_{t,N}$ mm-mrad	25	25	0.04
β^*, mm	1	1	0.2
σ^*(IR), μm	0.6	0.6	0.011
Bunch length, m	0.001	0.001	0.0002
μ production source	24 GeV p	8 GeV p	45 GeV e^+
p or e/pulse	$8\cdot10^{12}$	$2\cdot10^{14}$	$3\cdot10^{13}$
Driver beam power	0.15MW	1.3MW	40 MW
Acceleration,	1-3.5, 3.5-7 RCS	1-3.5, 3.5-7 RCS	75 GV, RLA 100 turn
ν rad. (unmitigated)	0.02	0.30	0.003 mSv/yr

14 TeV c.m. at constituants level equivalent energy reach

100 TeV FCChh
350GeV FCCee
in 100km tunnel
(to be built)

FCC-hh : 100 TeV pp collider



14TeV
Muon Collider
27km LHC tunnel
(existing)

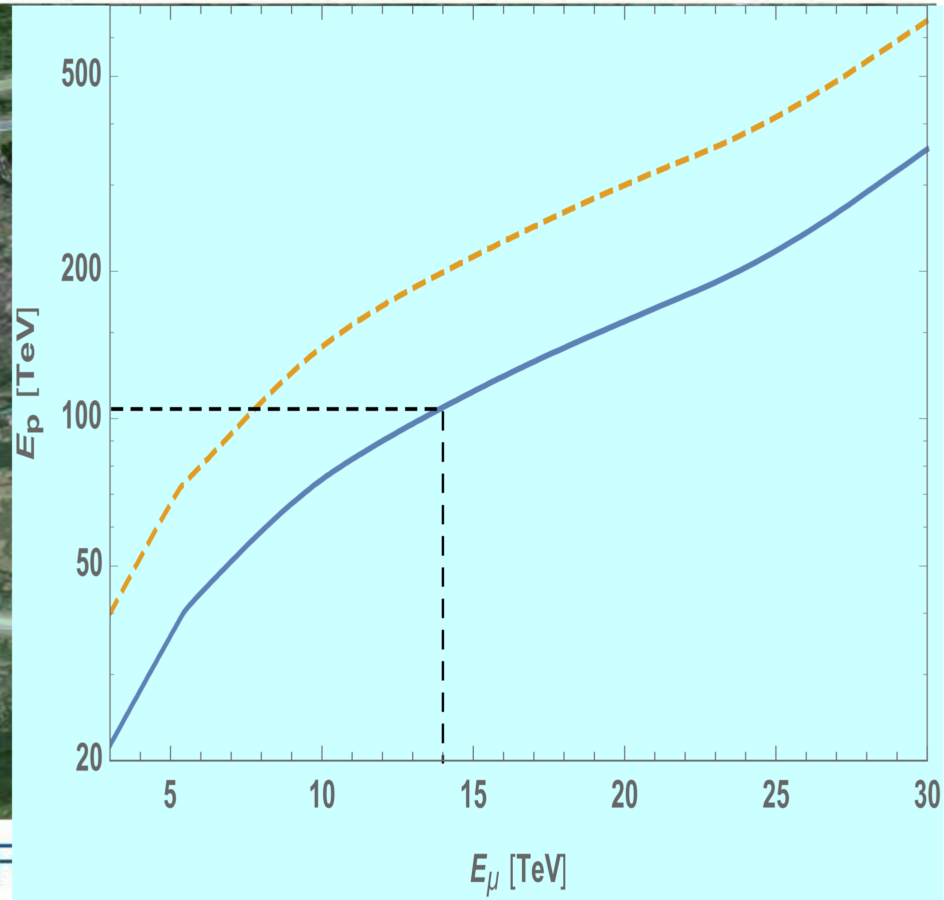


Figure 1: The energy at which the proton collider cross-section equals that of a muon collider. The dashed line assumes comparable Feynman amplitudes for the muon and the proton production processes. A factor of ten enhancement of the proton production amplitude squared, possibly due to QCD production, is considered in the continuous line.

14 TeV (c.m.)

“HE-LHC”
27 km, **20 T**
33 TeV (c.m.)

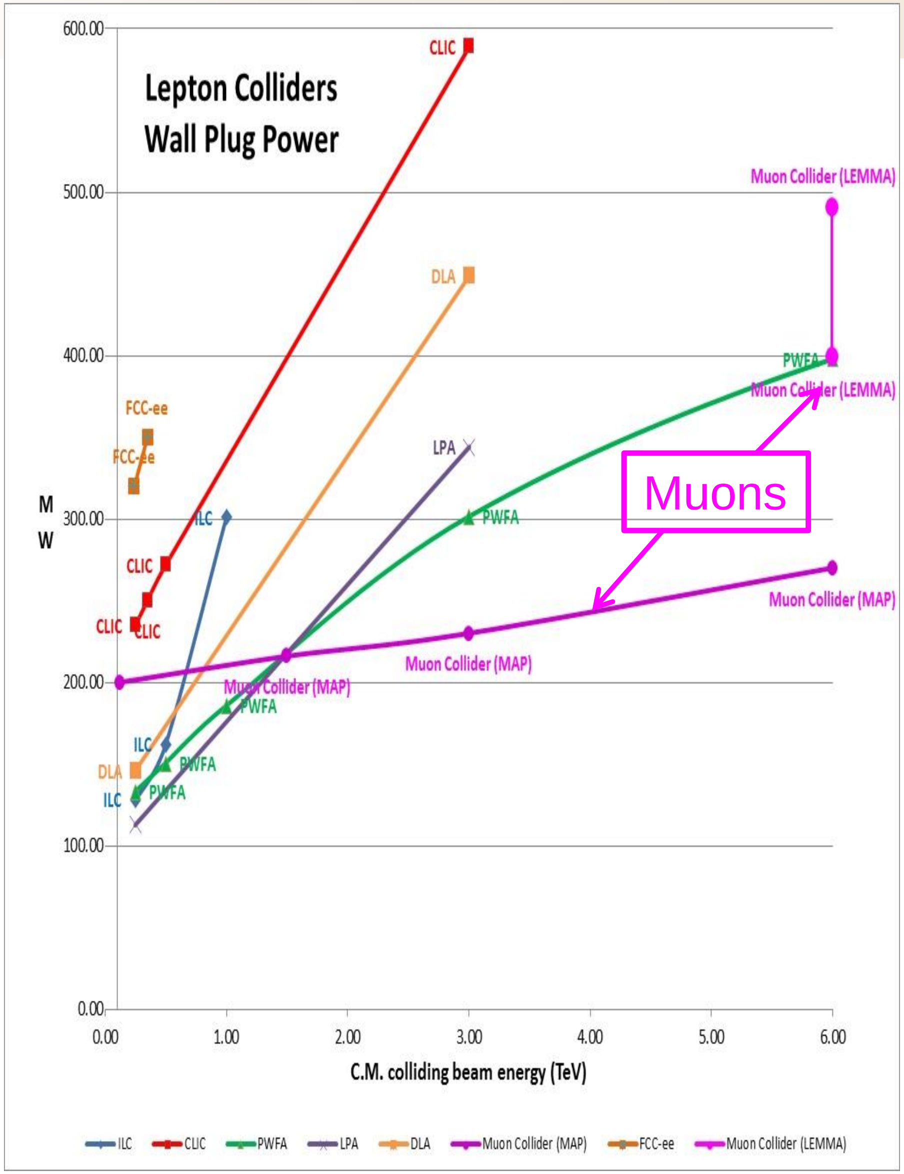
F

PPAP communit

Courtesy V. Shiltsev,

July 2014

Limitation of HEP facilities by practicalities Wall-plug power consumption



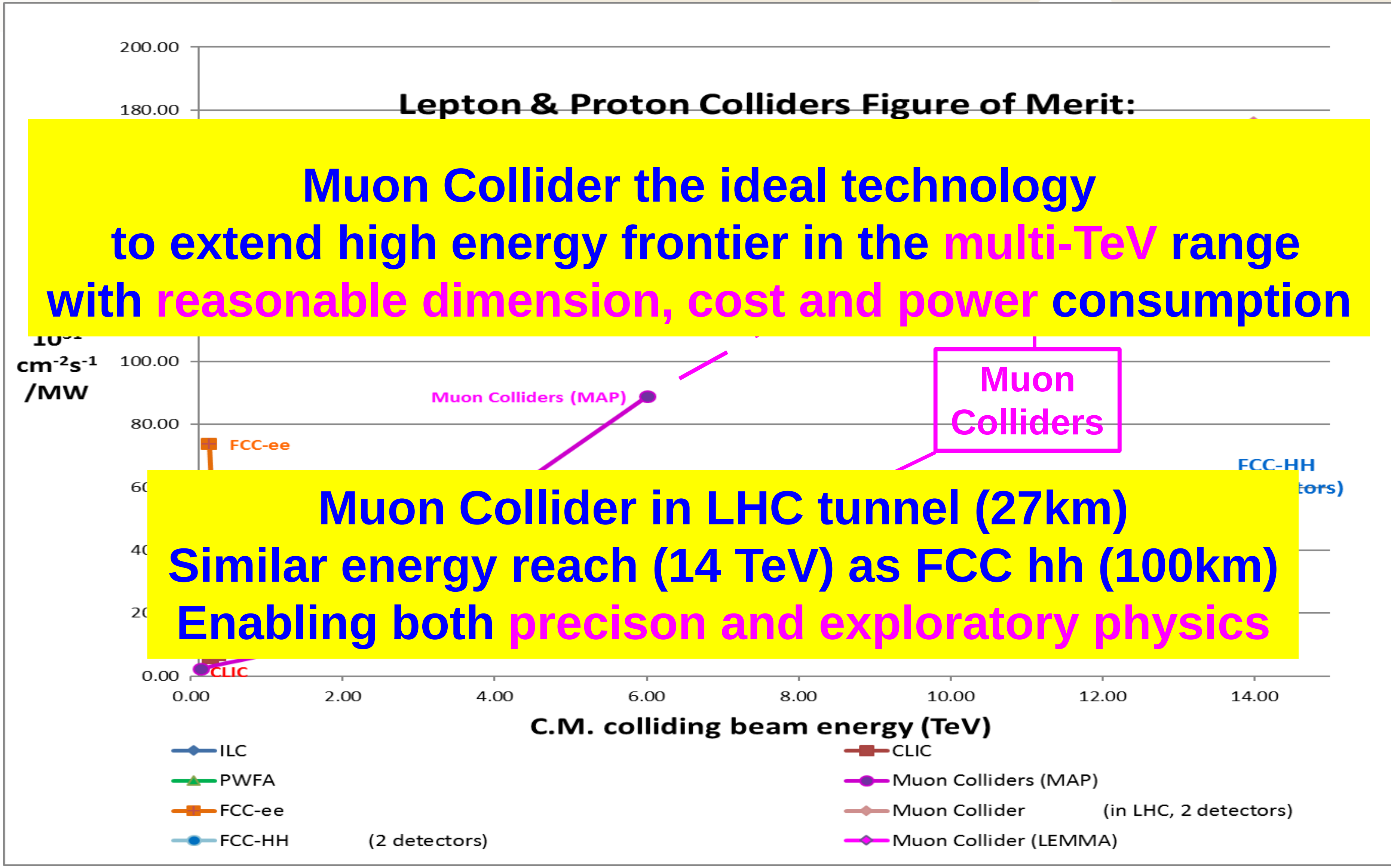
Wall-plug power consumption function of energy and luminosity

- **In linear collider:**
- **P ∝ L*E + offset (Injectors+ conventional facilities)**

Fair comparison through a Figure of merit (FoM):

FoM = Luminosity / Wall Plug consumption (L per MW)

Figure of merit of future candidates of Proton & Lepton colliders



Muon Collider the ideal technology to extend high energy frontier in the multi-TeV range with reasonable dimension, cost and power consumption

Muon Collider in LHC tunnel (27km)
Similar energy reach (14 TeV) as FCC hh (100km)
Enabling both precison and exploratory physics

Conclusion (1)

Most appropriate Lepton Collider Technoloy depends on Colliding Energy

- Low energy range (0-350GeV): Circular Colliders
- Medium energy range (350-2000GeV): Linear Colliders
- High energy range (Multi-TeV): Muon Colliders

Muon based technology provides unique opportunity to enable facilities at both the high intensity and the high energy frontiers

- High precision neutrino physics and lepton colliders in multi-TeV range
- Great progress of R&D addressing key issues & feasibility of novel, challenging tech.
- Mature proton driven MAP & novel positron driven LEMMA scenarios

Muon colliders greatest potential to extend energy frontier in the multi-TeV colliding beam energy range

- High energy for exploratory physics & High luminosity for precision physics
- Ideal tool for physics beyond standard model
- With reasonable dimensions, cost & power consumption

Conclusion (2)

A multi-TeV Muon Collider especially attractive in the existing CERN/LHC tunnel

- Taking advantage of available infrastructures & injectors for substantial cost savings
- Potential of equivalent energy reach as a FCCpp in a (to be built) 100km tunnel
- Building-up on impressive R&D and progress during last 30 years
- Exploratory study to be confirmed by feasibility study

Proposal to European Particle Physics Strategy Upgrade by dedicated Muon Collider Working Group

- Set-up International Collaboration to promote Muon Colliders
- Define road map for a CDR by next European Strategy Upgrade (5 years)
- Develop Muon Collider concepts based on proton driven and positron driven scenarios
- Carry-out R&D towards Muon Collider (Accelerator & Detector)

All welcome to join & participate

Documentation

Muon Collider Working Group web site (under construction)

https://muoncollider.web.cern.ch/

Proposal of Muon Collider study to European Particle Physics Strategy Upgrade, http://arxiv.org/abs/1901.06150

Recent RAST review about the various muon based scenarios

M. Boscolo, J. P. Delahaye and M. Palmer, “The future prospects of muon colliders and neutrino factories,”

Rev. of Acc. Sci. and Tech. vol 9 (2018) 1-25.

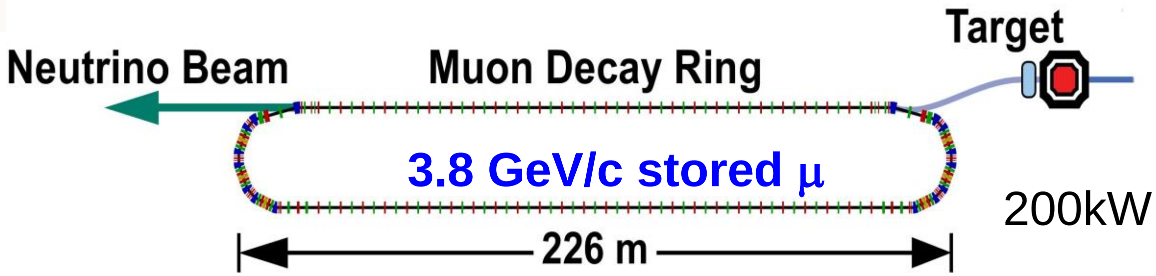
or arXiv:1808.01858

Supporting slides

nuSTORM

neutrinos from STOred Muons

A.Bross



An entry-level NF?

DOES NOT
Require Development of ANY New Technology

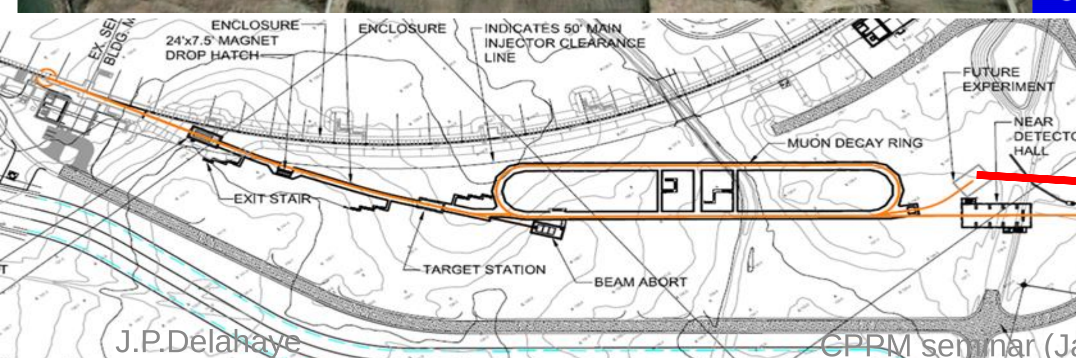
νSTORM

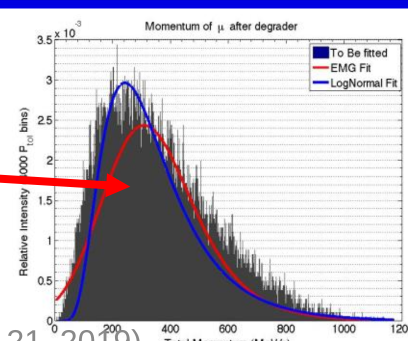
Low energy, low luminosity muon storage ring. Provides with 1.7×10^{18} μ^+ stored, the following oscillated event numbers

$\nu_e \to \nu_\mu$ CC	330
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47000
$\nu_e \to \nu_e$ NC	74000
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122000
$\nu_e \to \nu_e$ CC	217000

and each of these channels has a more than 10 σ difference from no oscillations

With more than 200 000 ν_e CC events a %-level ν_e cross section measurement should be possible





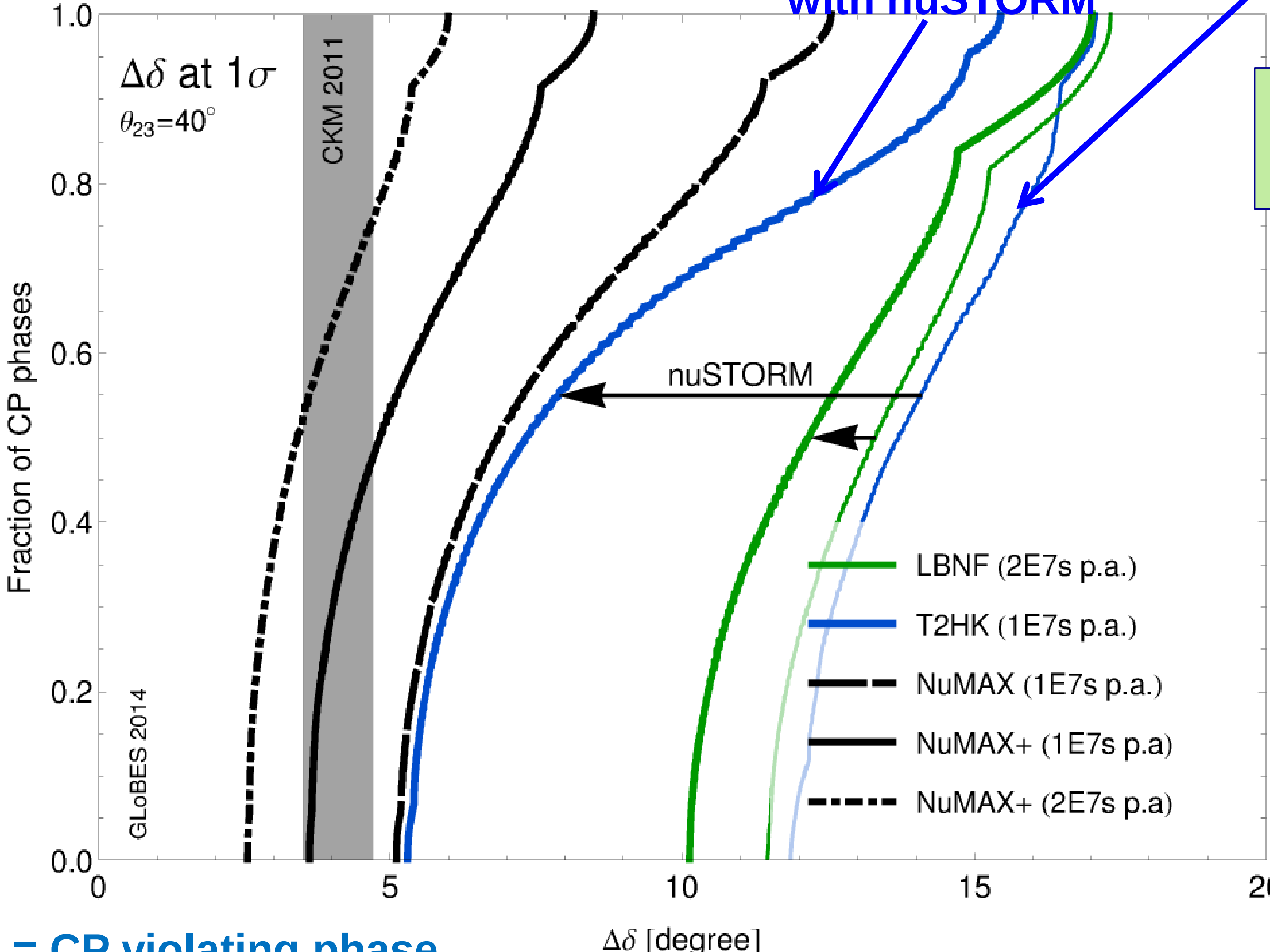
10^{10} μ / 1μs pulse
Ideal R&D platform to get experience, test & validate muon technology

Example of leverage potential by νSTORM for Long Baseline Experiments

P. Coloma
P.Huber

Super-Beams with nuSTORM

Super-Beams alone

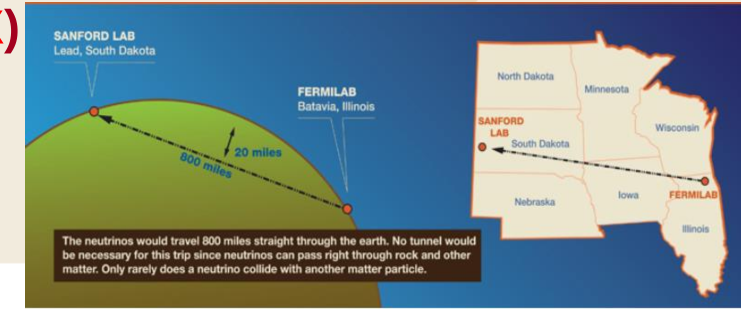


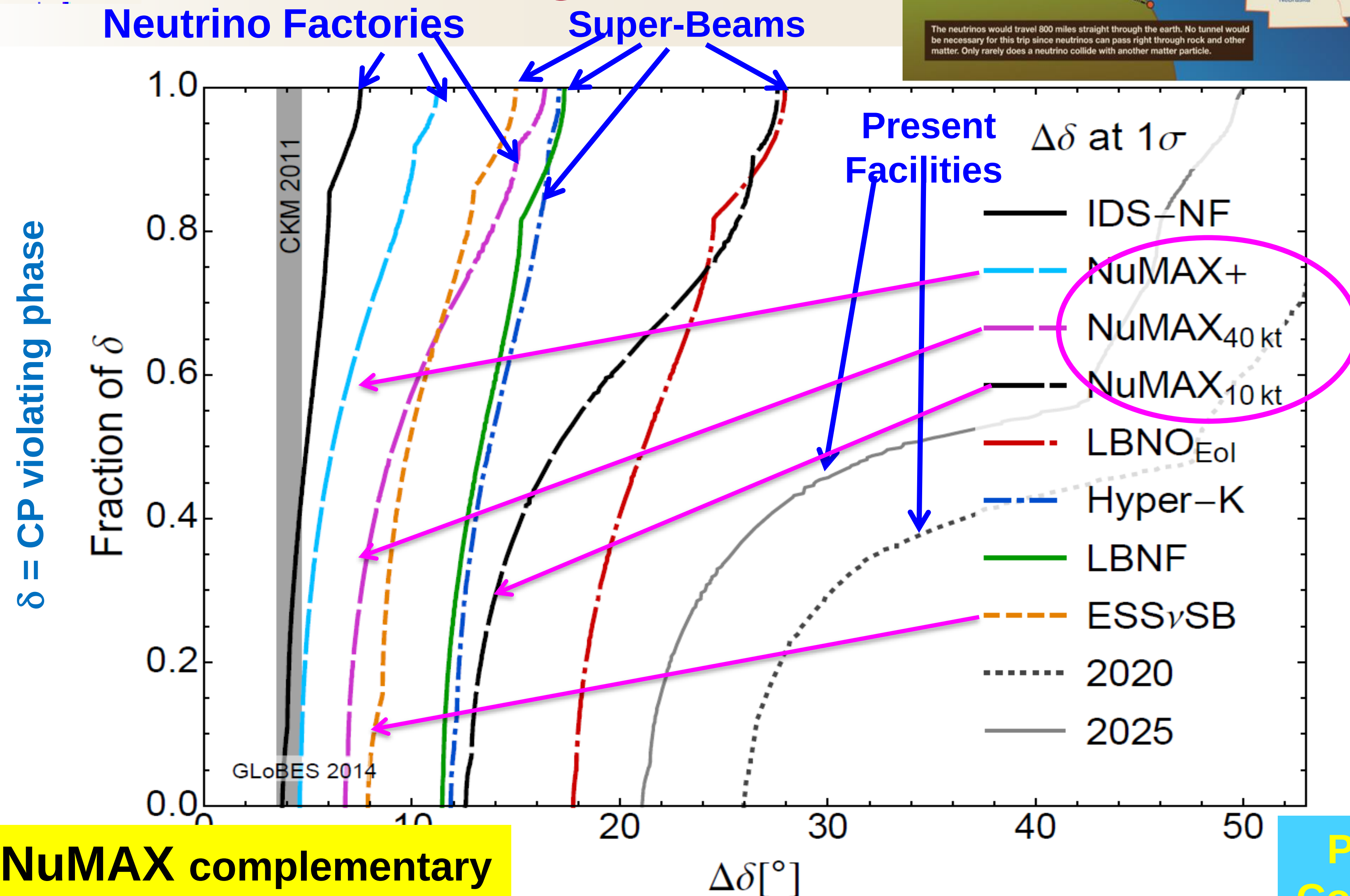
nuSTORM + T2HK offers significantly improved sensitivity vs T2HK alone

GLoBES comparison of potential performance of the various Advanced Concepts

δ = CP violating phase

NuMAX (Neutrinos from Muon Accelerator CompleX)
A 5GeV staged Neutrino Factory with far detector @ SURF





NuMAX complementary to ESSnuSB

Pilar Coloma

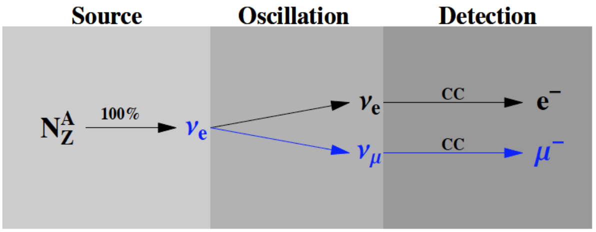
Accelerator based neutrino production methods

(Euronu comparison as a service to the community: http://euronu.org)

- **Unstable Ions Beta decay:**

$$^{6}He \rightarrow {}^{6}Li + e^{-} + \bar{\nu}_e$$

$$^{18}Ne \rightarrow {}^{18}F + e^{+} + \nu_e$$

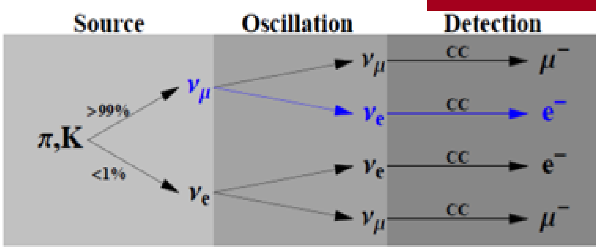


Only: ν_e or $\bar{\nu}_e$

- **Pions decay:**

$$\pi^{+} \rightarrow \mu^{+} + \nu_\mu$$

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_\mu$$



Neutrinos as secondary particles

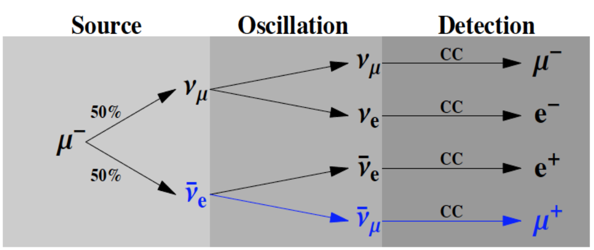
Mainly: ν_μ and $\bar{\nu}_\mu$

The only method in existing accelerator based facilities

- **Muons decay**

$$\mu^{+} \rightarrow e^{+} + \bar{\nu}_\mu + \nu_e$$

$$\mu^{-} \rightarrow e^{-} + \nu_\mu + \bar{\nu}_e$$



Neutrinos as tertiary particles

Equal quantities of:

ν_μ, ν_e, $\bar{\nu}_\mu$ and $\bar{\nu}_e$

Multitude channels available

Neutrino beam known to% level

Clean muon detection but imp.

detector with magnetic field

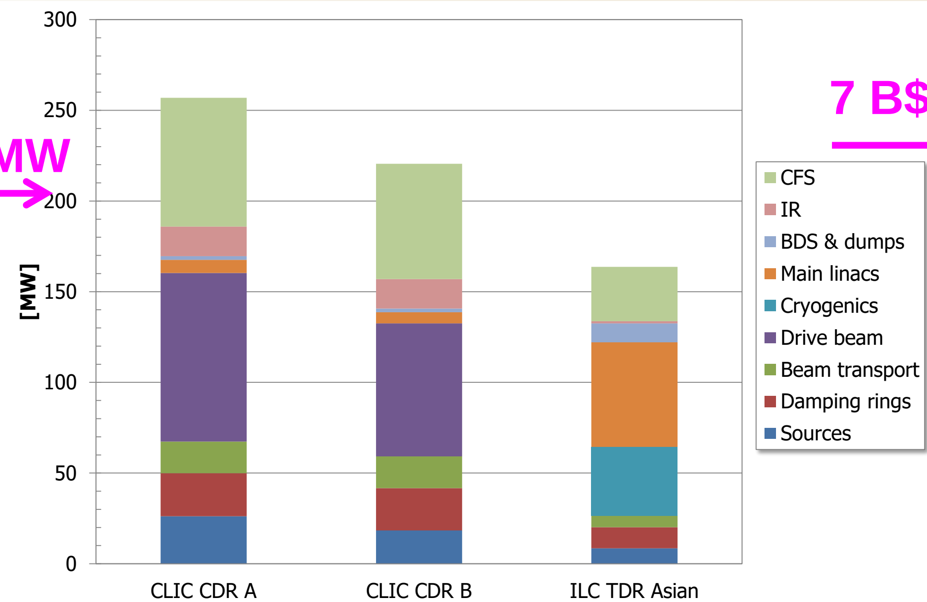
to distinguish μ^+ from μ^-

More challenging (expensive)

Linear Colliders (CLIC and ILC) at 500 GeVc.m.

Power | Cost

200MW



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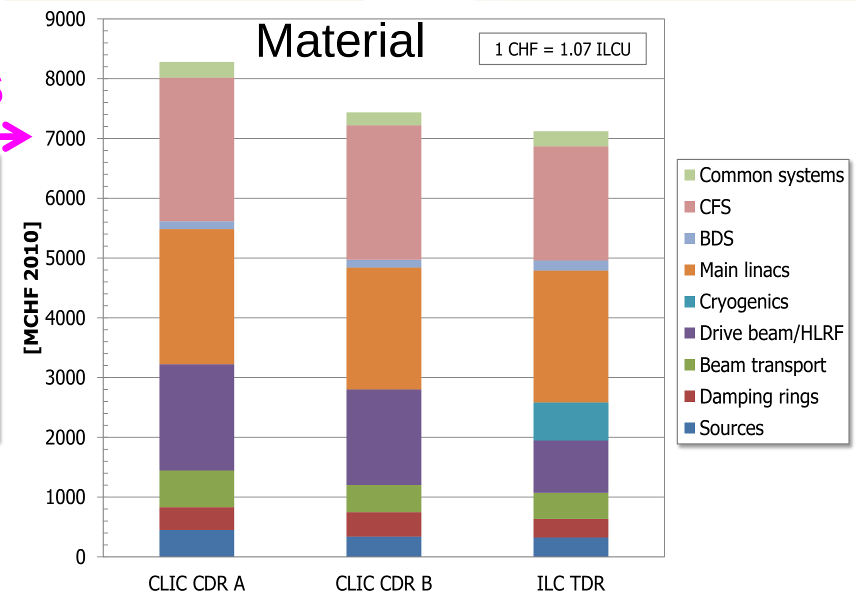

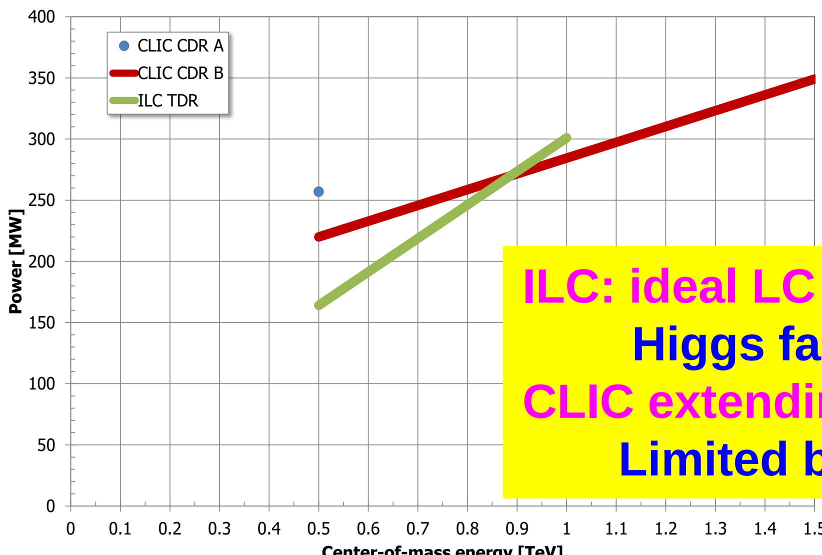

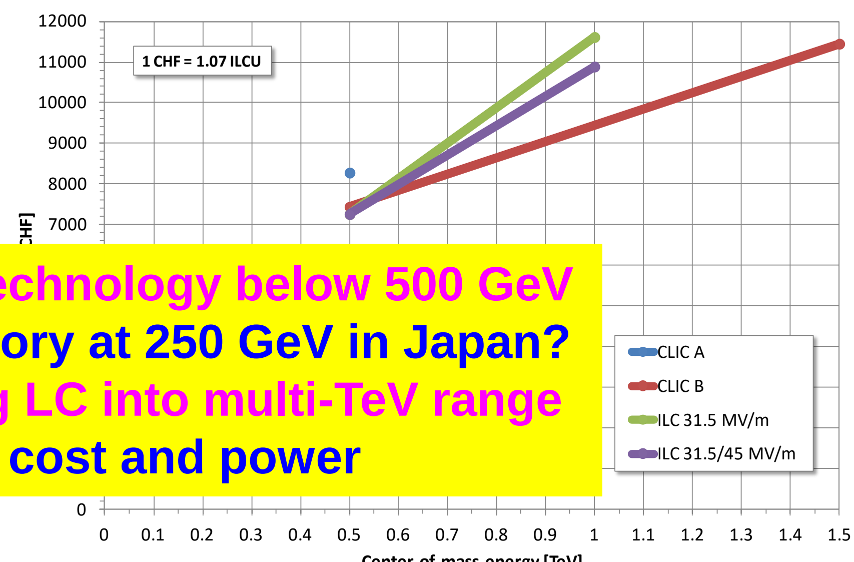

ILC: ideal LC technology below 500 GeV
Higgs factory at 250 GeV in Japan?
CLIC extending LC into multi-TeV range
Limited by cost and power