Lecture 24

Muon Collider
JAI Student Design Project 2019-2020

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Accelerator Physics Graduate Course
John Adams Institute for Accelerator Science
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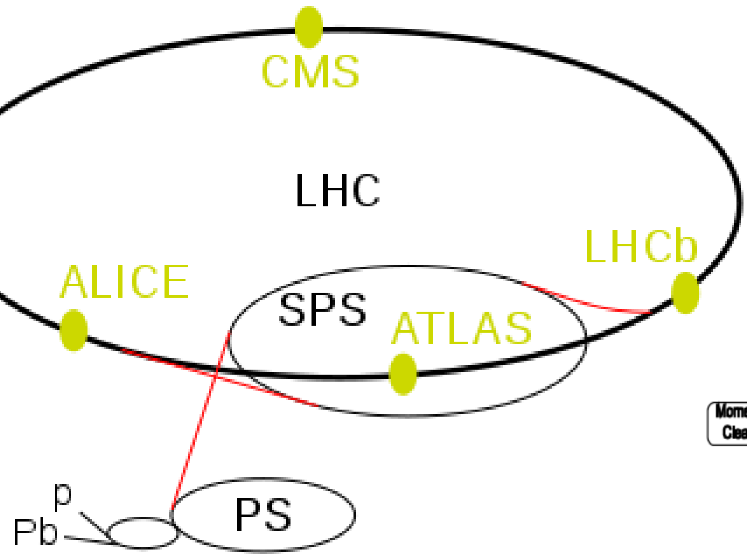
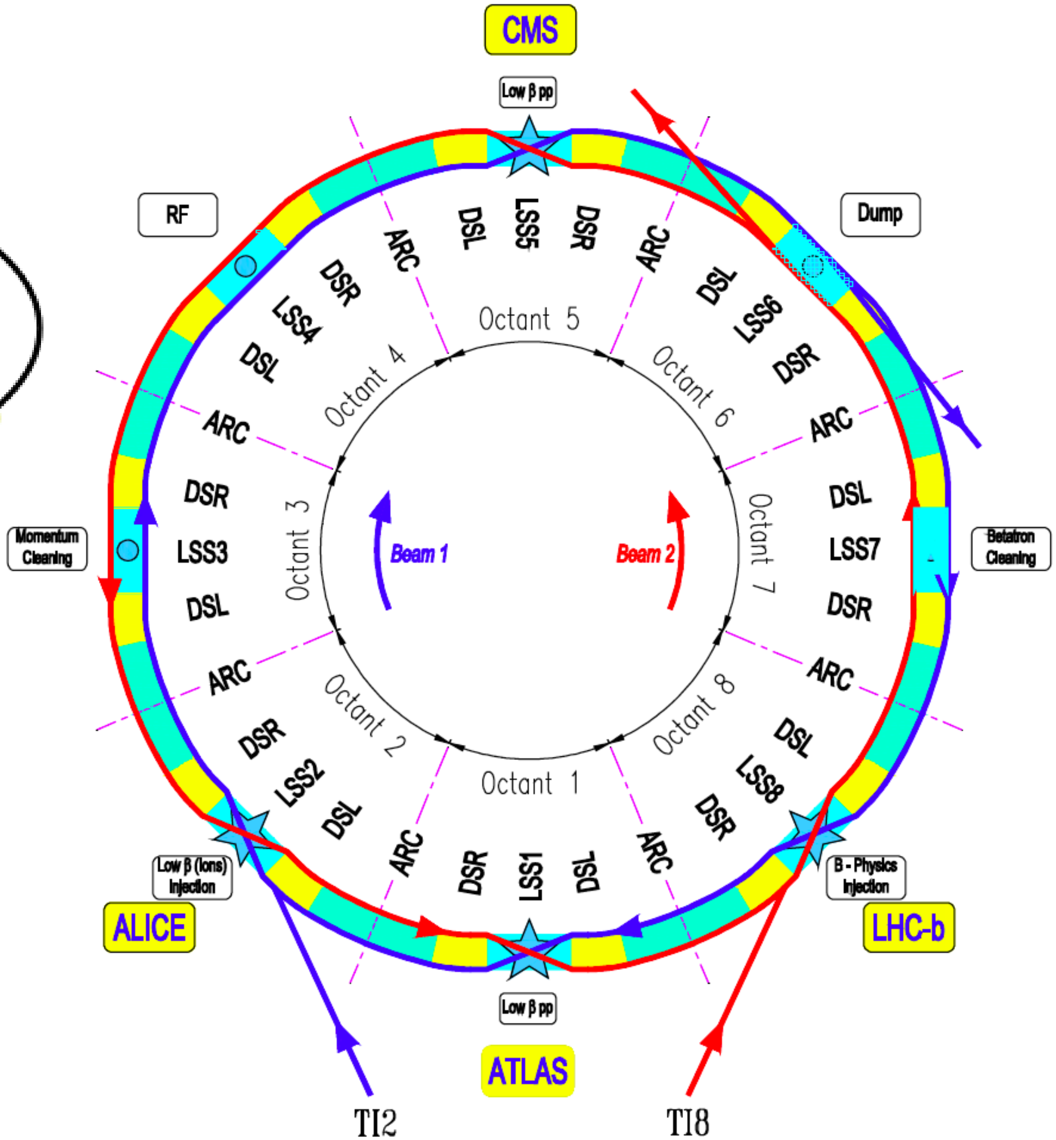
- First – briefly remind about
  - LHC
  - HL-LHC (High Lumi LHC)
- Then
  - FCC (Future Circular Collider)
  - Linear Colliders
- And then
  - Describe Muon Collider
- And after that describe
  - Topics of possible contribution

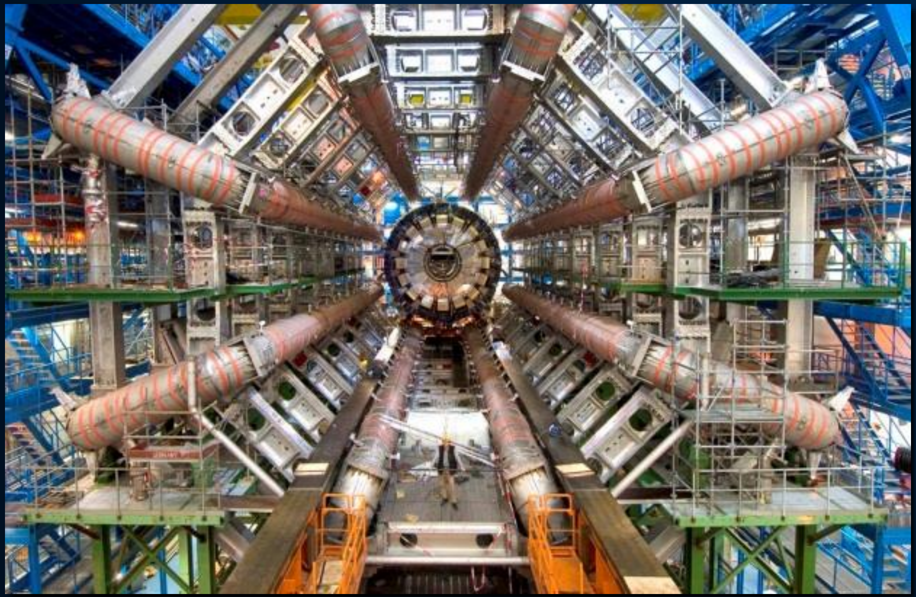
Future Colliders at the High Energy Frontier

Large Hadron Collider



27 km circumference,
up to 14 TeV CM,
8.33 T magnets





Large Hadron Collider
LHC

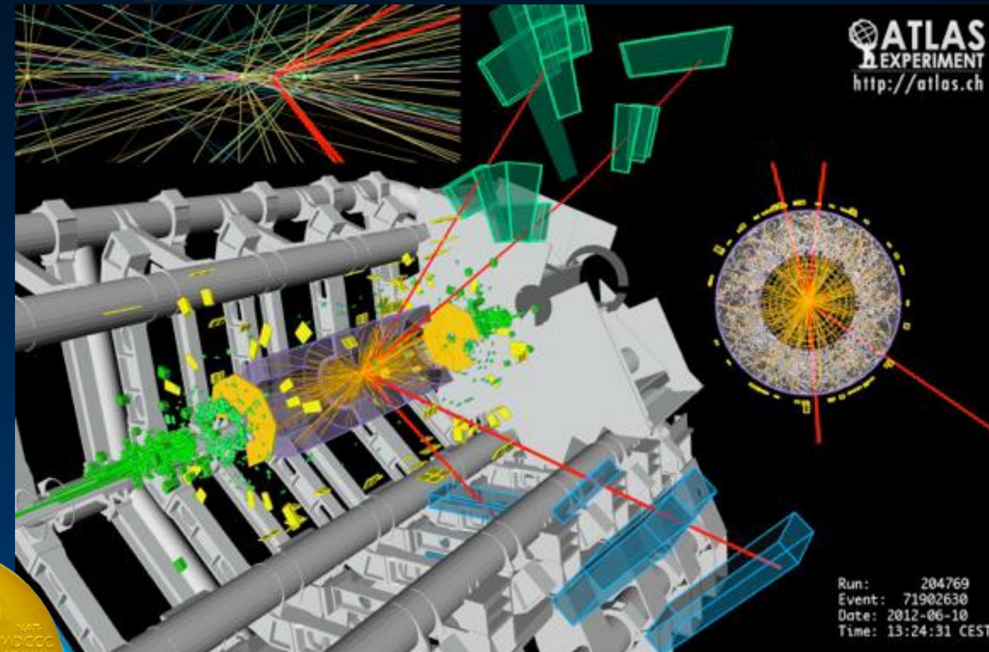
Theory: 1964

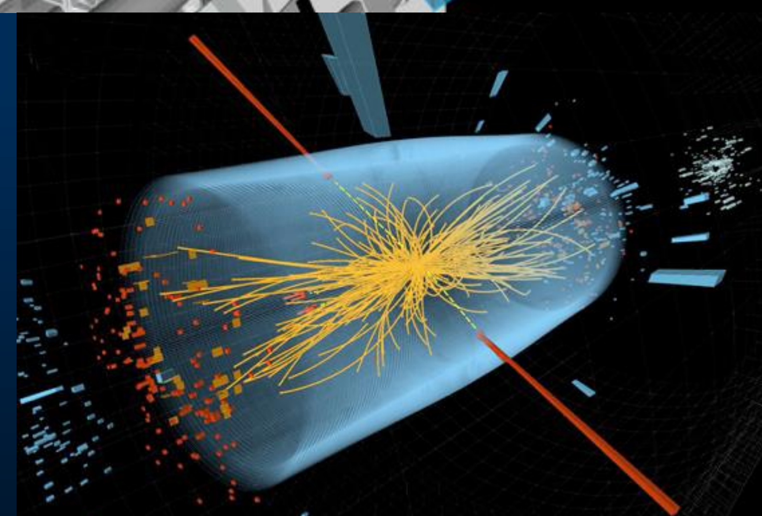
Discovery of Higgs boson

Experimental project: 1984

Construction of collider and detectors: 1998

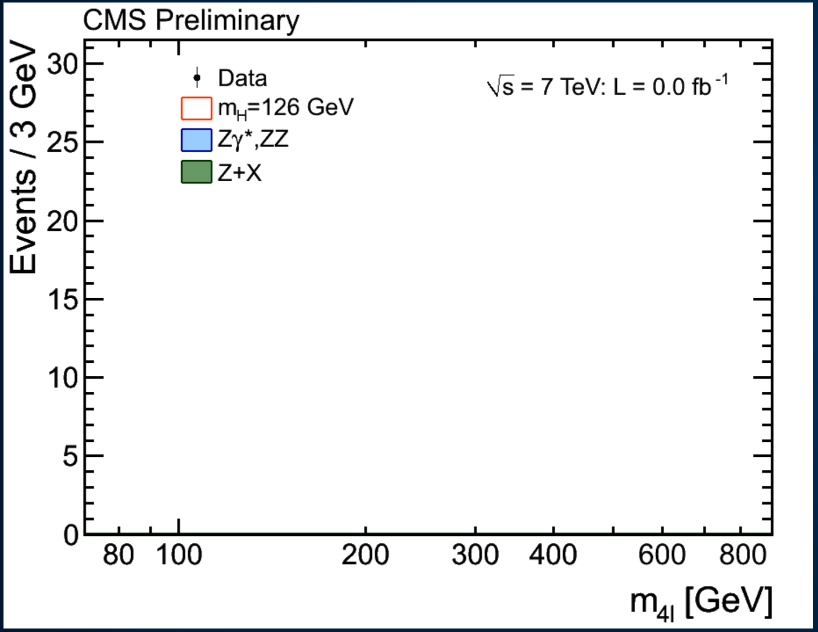
Discovery: 2012

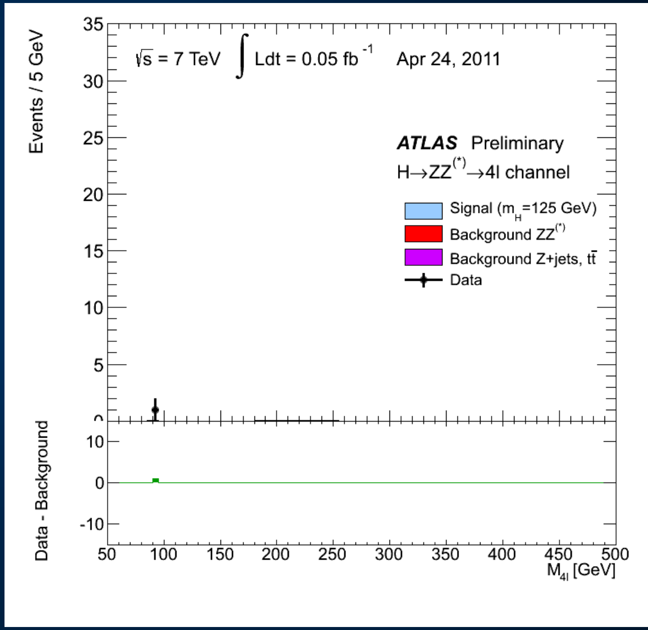




The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

The Discovery of the Higgs Boson





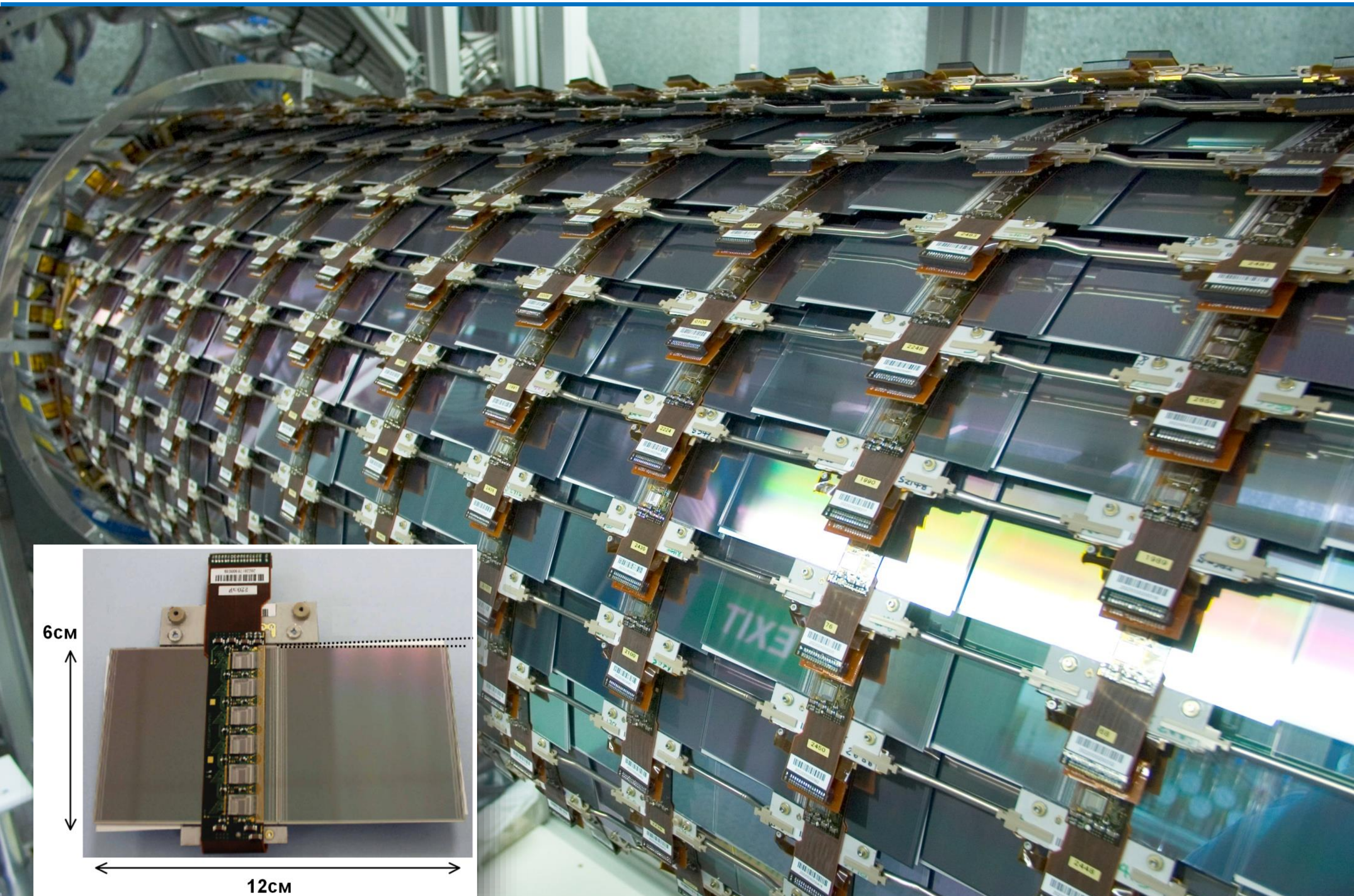
$m_H = 125.8 \pm 0.5 \pm 0.3$ GeV

$m = 0.91^{+0.30}_{-0.24}$

$m_H = 124.3 \pm 0.6 \pm 0.4$ GeV

$m = 1.5 \pm 0.4$ (at 125.5 GeV)

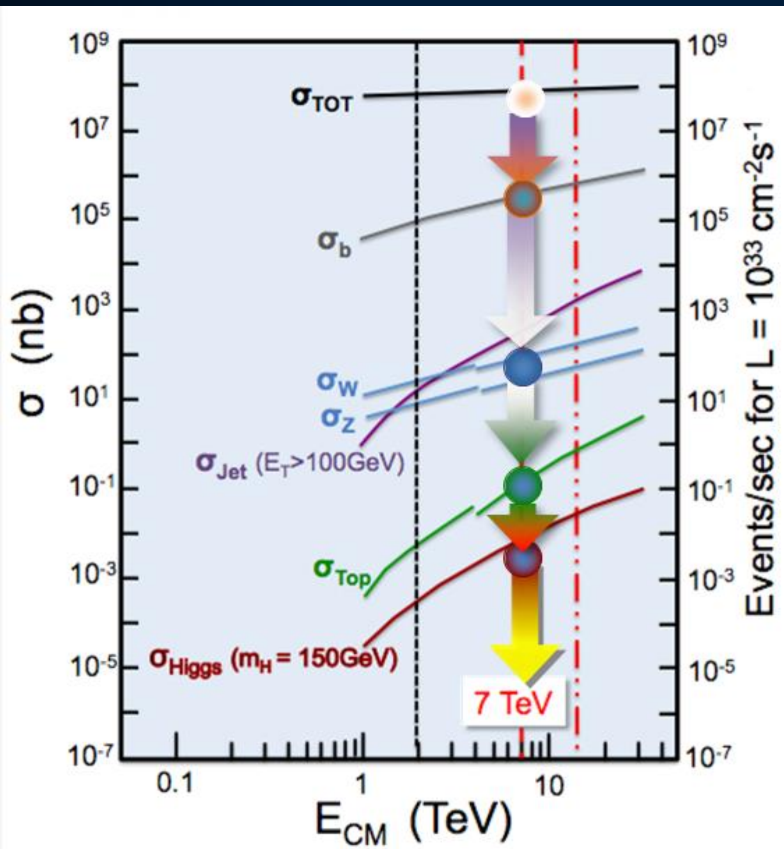
Central Part of ATLAS Silicon Detector Made in Oxford



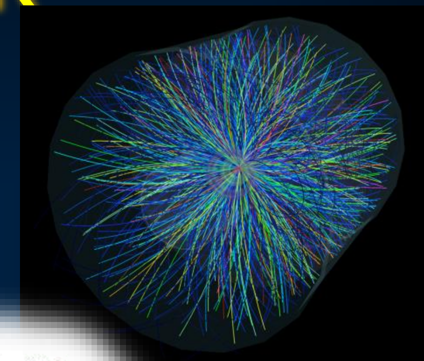
New Physics

Higgs and Standard Model do not explain everything
There must be new physics out there
Supersymmetry – one of possibilities

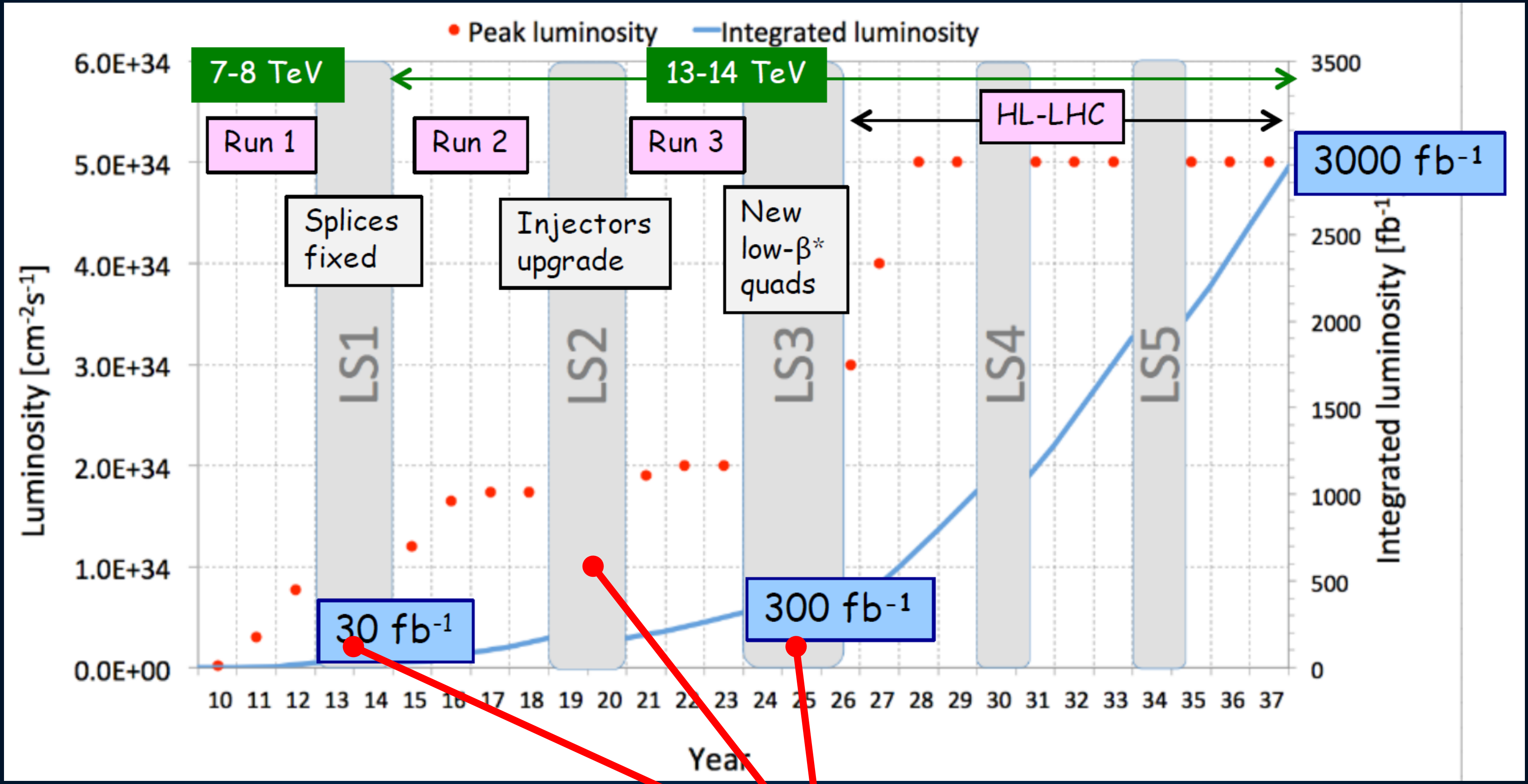
A Needle in a Haystack



10^{10}



LHC – Next steps



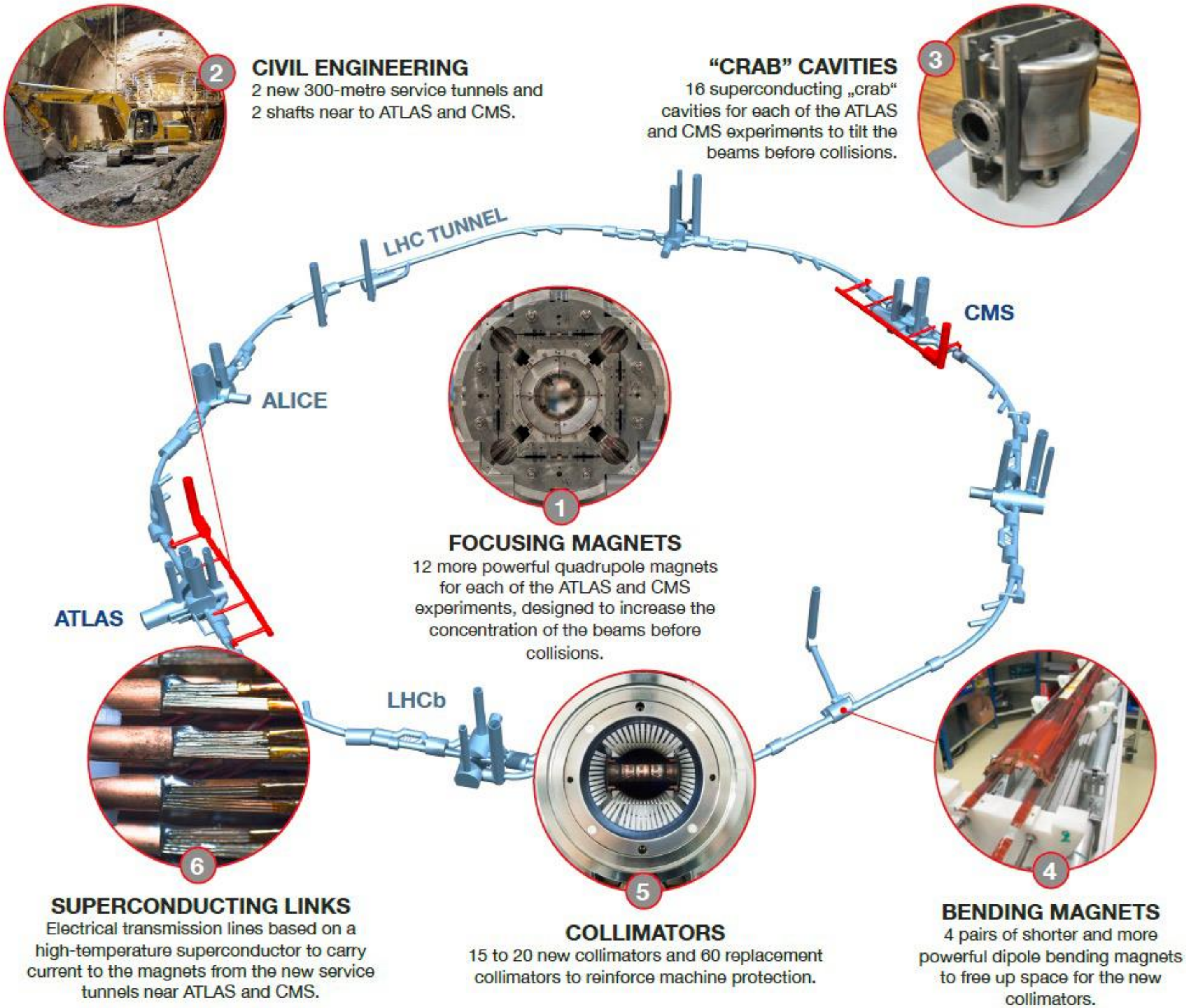
Storing the data

High Luminosity upgrade project

Much more data:

100 times more data in 2037!

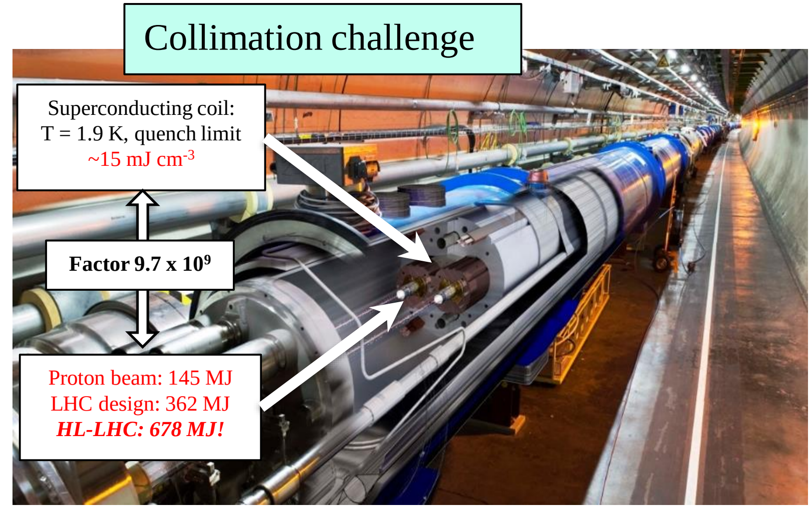
High Luminosity LHC project



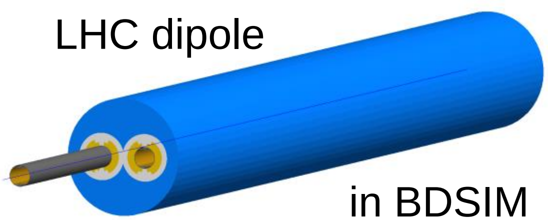
JAI contribution to High Luminosity LHC

Collimation challenge:

- **to efficiently clean the LHC beam, while…**
- **protecting cryogenic magnets from huge stored beam energy (doubles at HL-LHC!)**
- **mitigating beam backgrounds that reach the experiments!**

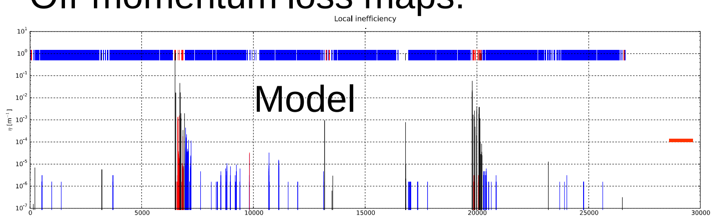


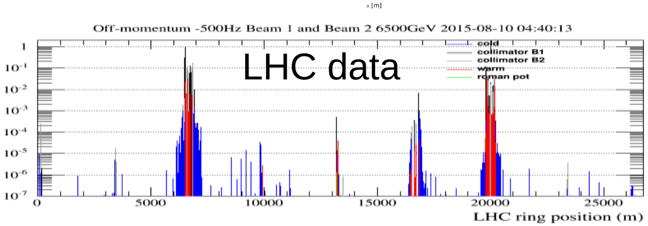
LHC dipole



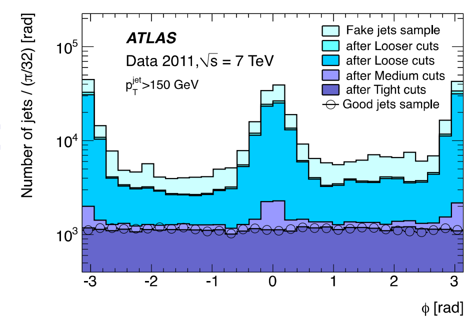
in BDSIM

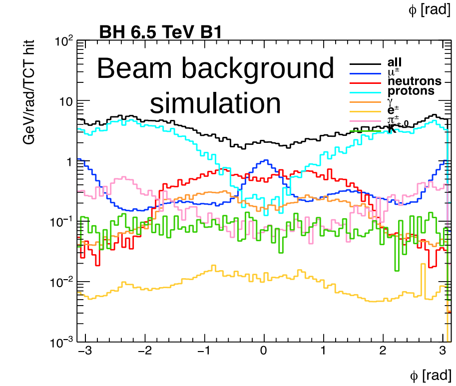
Off-momentum loss maps:





- JAI-RHUL experts already integrated in team at CERN. Main contributions:
  - **Off-momentum loss maps**: new model recently validated with energy deposition measurements at LHC.
  - **Advanced simulations of beam dynamics** to design the new triplet layout for HL-LHC.
  - RHUL-developed tool (BDSIM) to model **LHC beam backgrounds measured at ATLAS**.

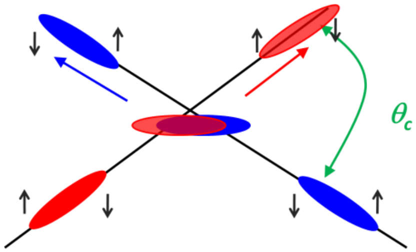


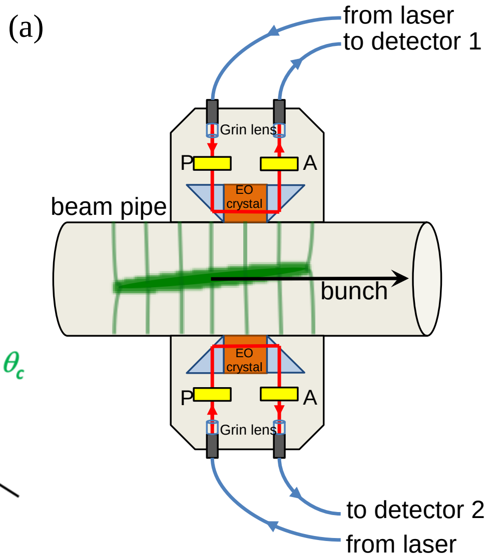


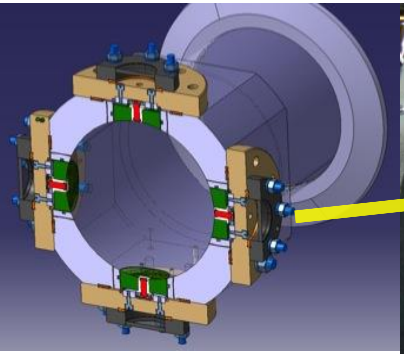
JAI for High Luminosity LHC

Diagnostics: Electro-optic Beam Position Monitors

- **HL-LHC crab cavities require new instrumentation to monitor bunch rotation and optimize performance.**
- **High bandwidth electro-optical pick-ups enable intra-bunch measurements of transverse position.**
- **JAI built prototype installed in 2016 at CERN SPS for proof of principle tests, in collaboration with CERN BI group.**

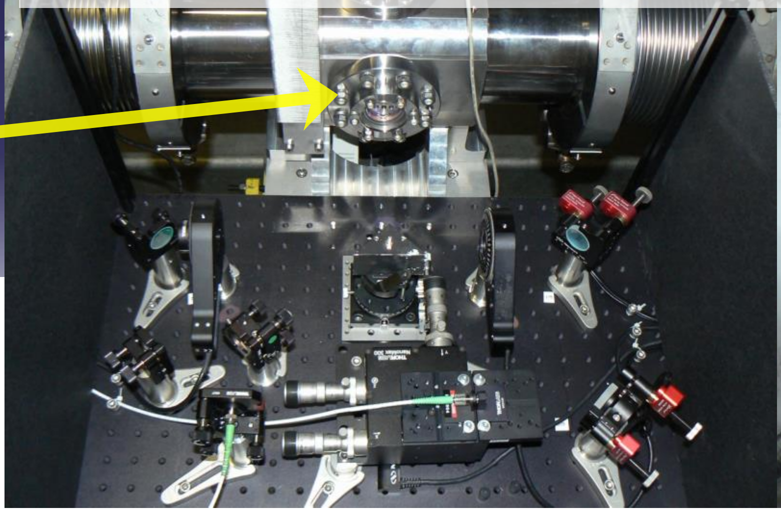


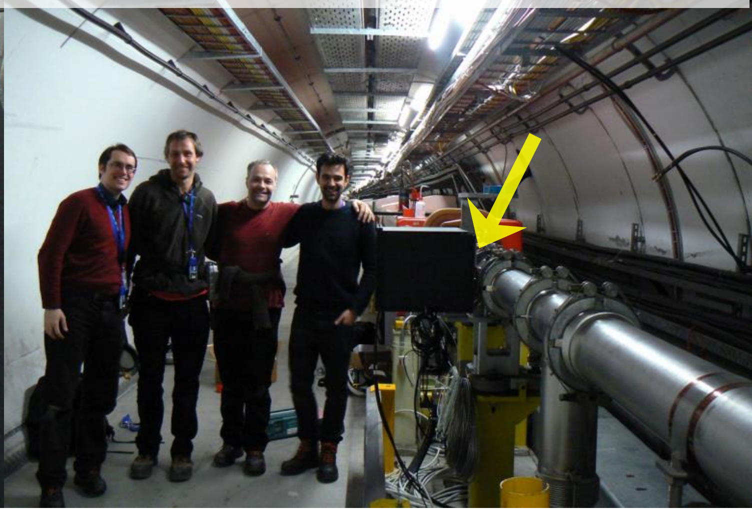




Second prototype planned for LHC, before deployment at HL-LHC

JAI built prototype already installed for tests at CERN SPS

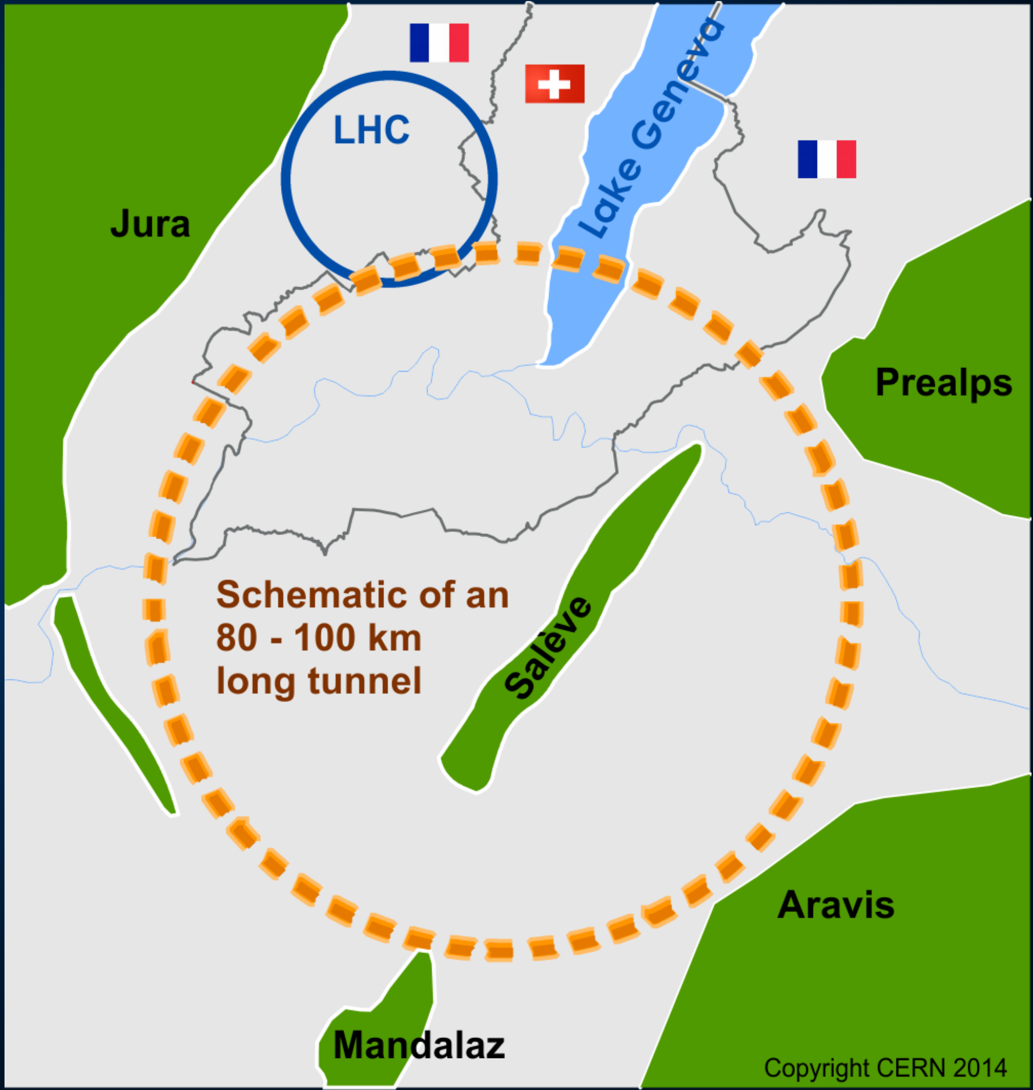




Circular Collider after LHC – FCC (CERN)

FCC = Future Circular Collider

100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements *with possibility of e+-e- and p-e*



Preliminary parameters (FCC-hh):

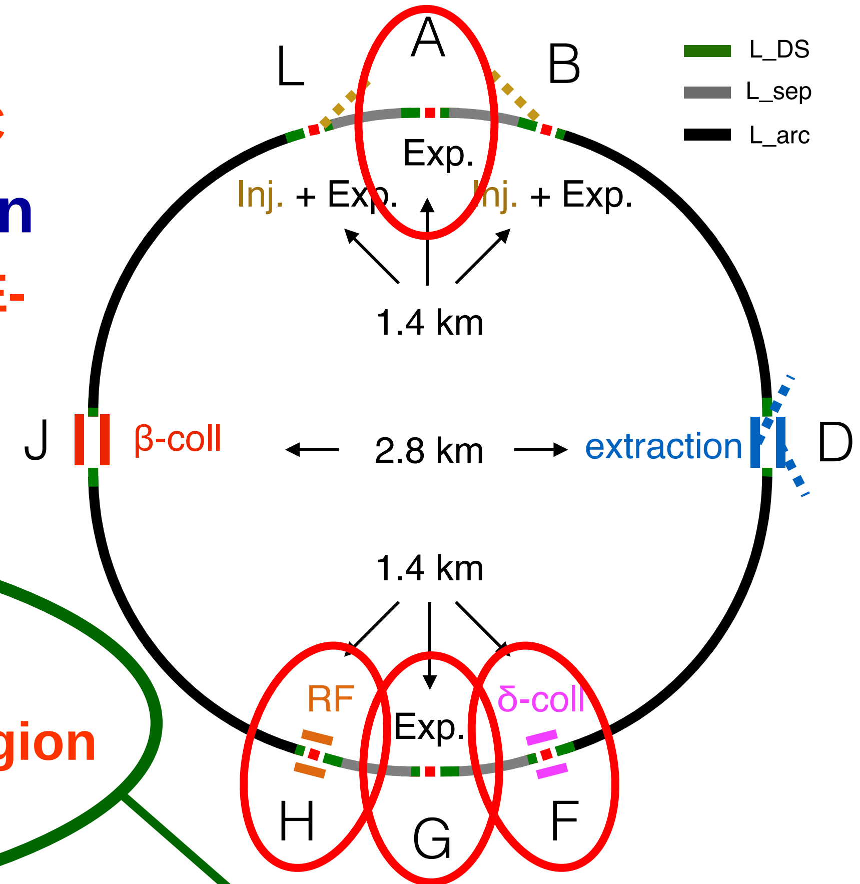
CM energy	**100 TeV**
Circumference	**100 km**
Dipole field	**16 Tesla**
Peak Lumi	**5E34 $cm^{-2}s^{-1}$**

Hadron Collider Parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		**27**	14
dipole field [T]	16		**16**	8.3
circumference [km]	100		**27**	27
beam current [A]	0.5		**1.12**	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		**2.2**	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		**25 (12.5)**	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (2.2)		**2.5 (1.25)**	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	**0.25**	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	**25**	(5) 1
peak #events / bunch Xing	170	1000 (500)	**800** (400)	(135) 27
stored energy / beam [GJ]	8.4		**1.4**	(0.7) 0.36
SR power / beam [kW]	2400		**100**	(7.3) 3.6
transv. emit. damping time [h]	1.1		**3.6**	25.8
initial proton burn off time [h]	17.0	3.4	**3.0**	(15) 40

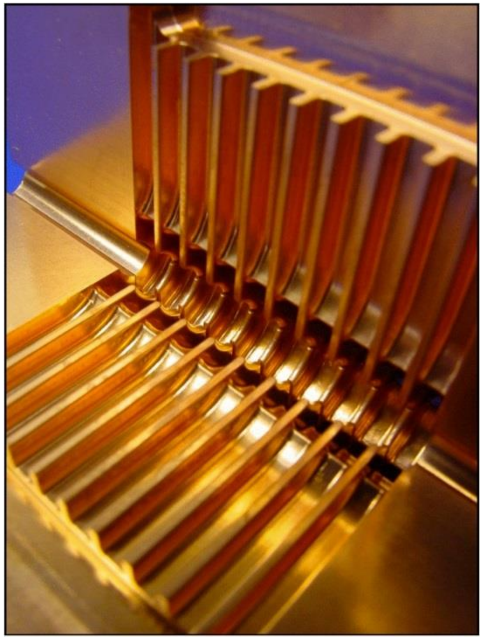
WP4.3: FCC-hh and MDI

- **Future Circular Collider**
  - **Possible 100km successor of HLC**
- **Experimental Interaction Region**
  - **Critical areas defining FCC-hh (HE-LHC) performance**
- **Design tasks of EuroCirCol IR Work Package**
  - **Coordination**
    - **JAI/Oxford (lead), CERN, task 3.1**
  - **Development of the interaction region lattice**
    - **JAI/Oxford (lead), CERN, task 3.2**
  - **Design of machine detector interface**
    - **CI/Manchester (lead), INFN, CERN, task 3.3**
  - **Study of beam-beam interaction**
    - **EPFL (lead), CERN, task 3.4**

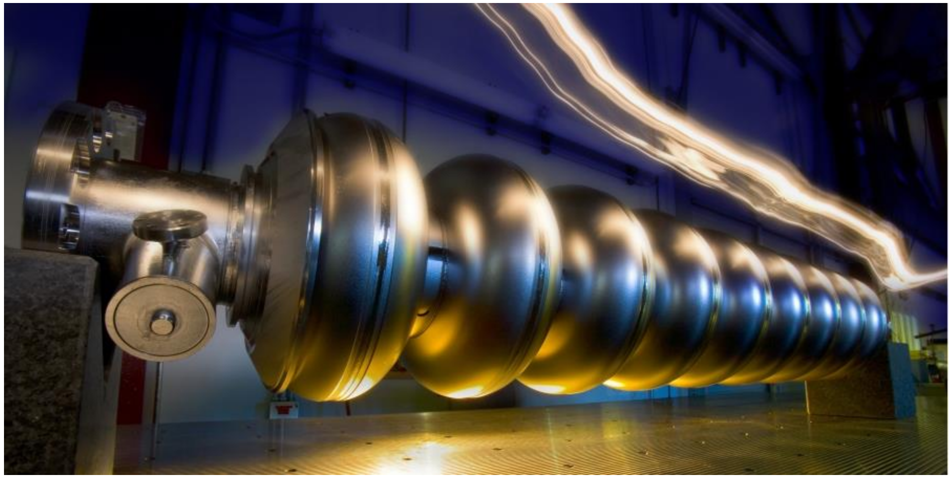


Responsibility of JAI

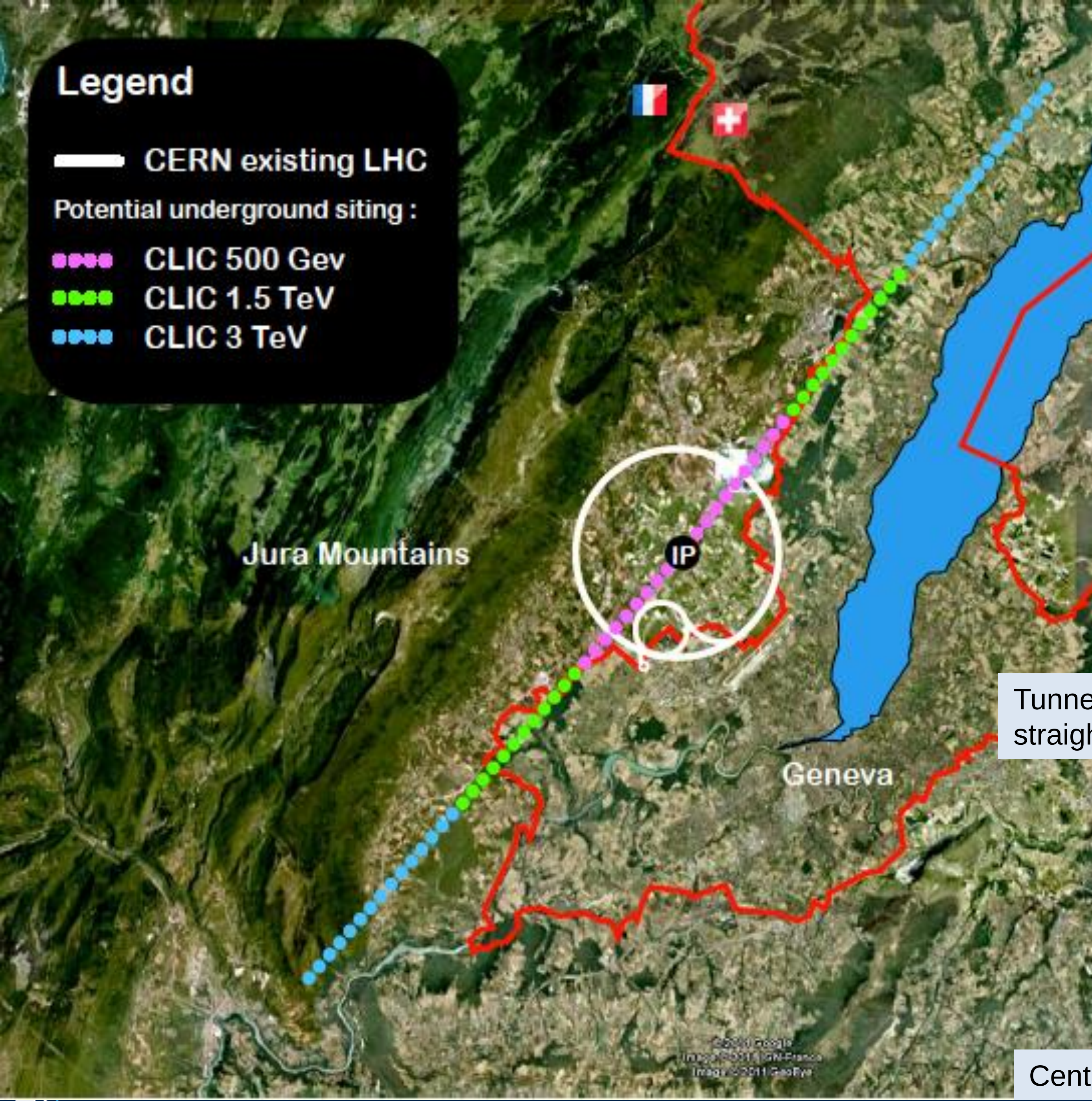
ILC and CLIC

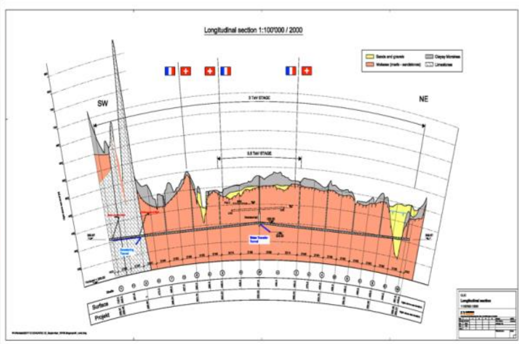


2-beam acceleration scheme at room temperature.
Gradient 100 MV/m.
$\sqrt{s}$ up to 3 TeV.
Physics + Detector studies for 350 GeV - 3 TeV.

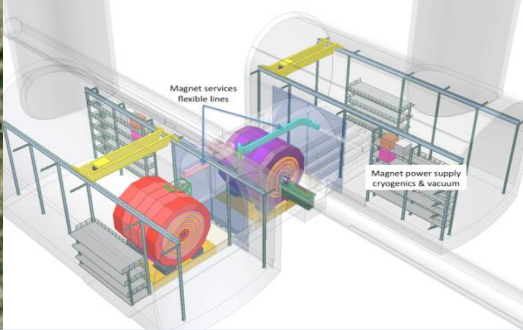


- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV





Tunnel implementations (laser straight)



Central MDI & Interaction Region

Muon Collider

Physics with Muon Beams

– **Muon Beams and the Neutrino Sector**

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\% \bar{\nu}_e + 50\% \nu_\mu$$

Produces high energy neutrinos

- **Decay kinematics well known**
- **$\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable wrong-sign μ**

– **Muon Beams and the Energy Frontier**

- **Point particle makes full beam energy available for particle production.**
  - **Couples strongly to Higgs sector**
- **Muon Collider has almost no synchrotron radiation**
  - **Narrow energy spread**
  - **Fits on existing laboratory sites**

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\, MeV/c^2$$
$$\tau_\mu = 2.2\,\mu s$$

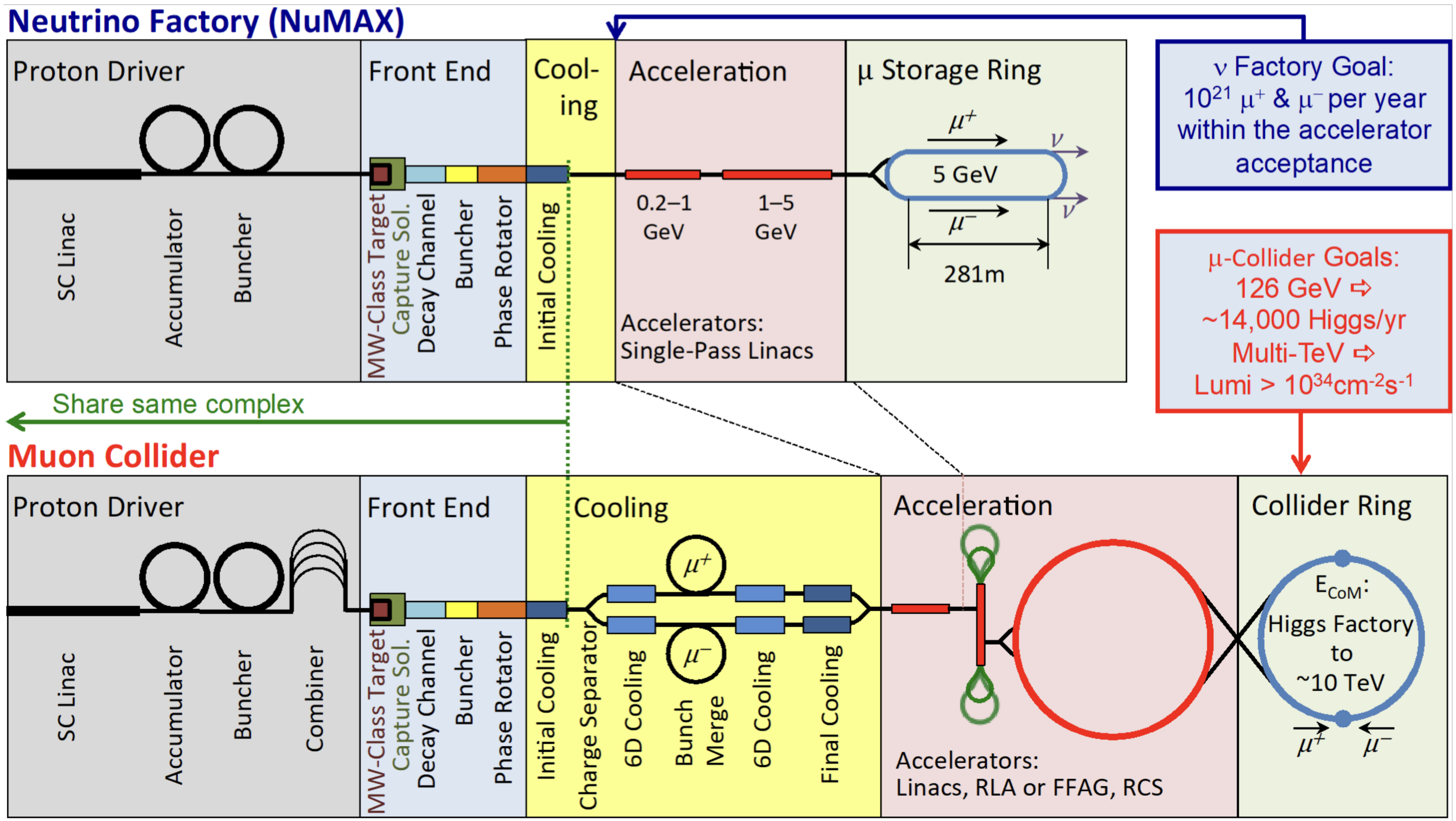
- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs
  - Reduced synchrotron radiation ⇨ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT*** **accelerator complex/detector must be able to handle the impacts of ∝ decay**

$$\square \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4 \times 10^4$$

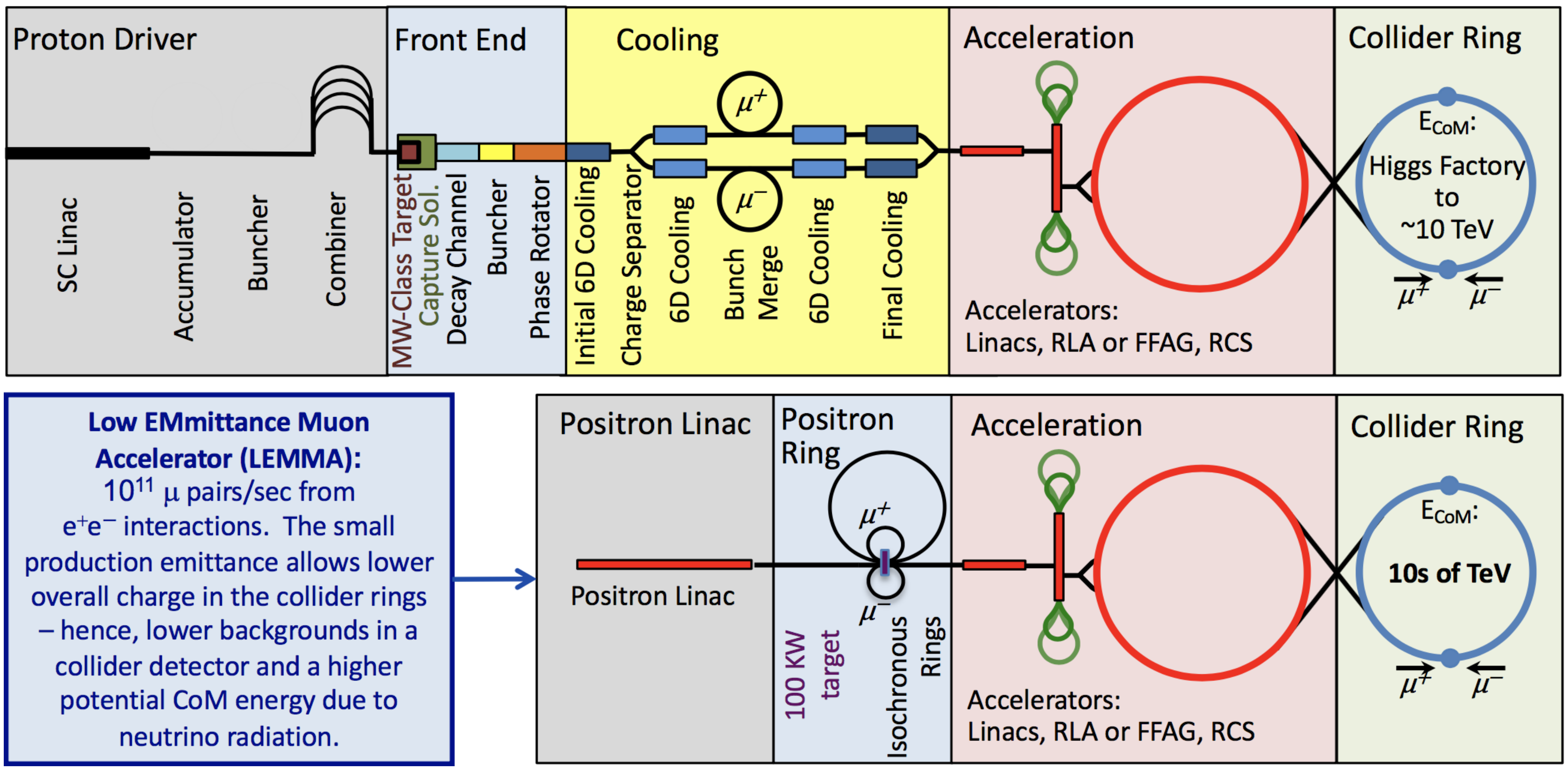
- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

Muon Accelerator Synergies



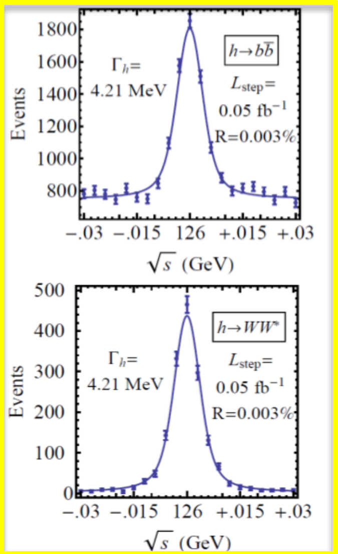
Low Emittance Positron Driver (LEMMA)



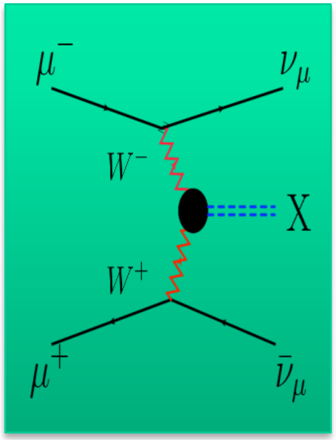
Muon Collider complexes based on the proton driver scheme (top) and on the low emittance positron driver scheme (bottom).

Features of the Muon Collider

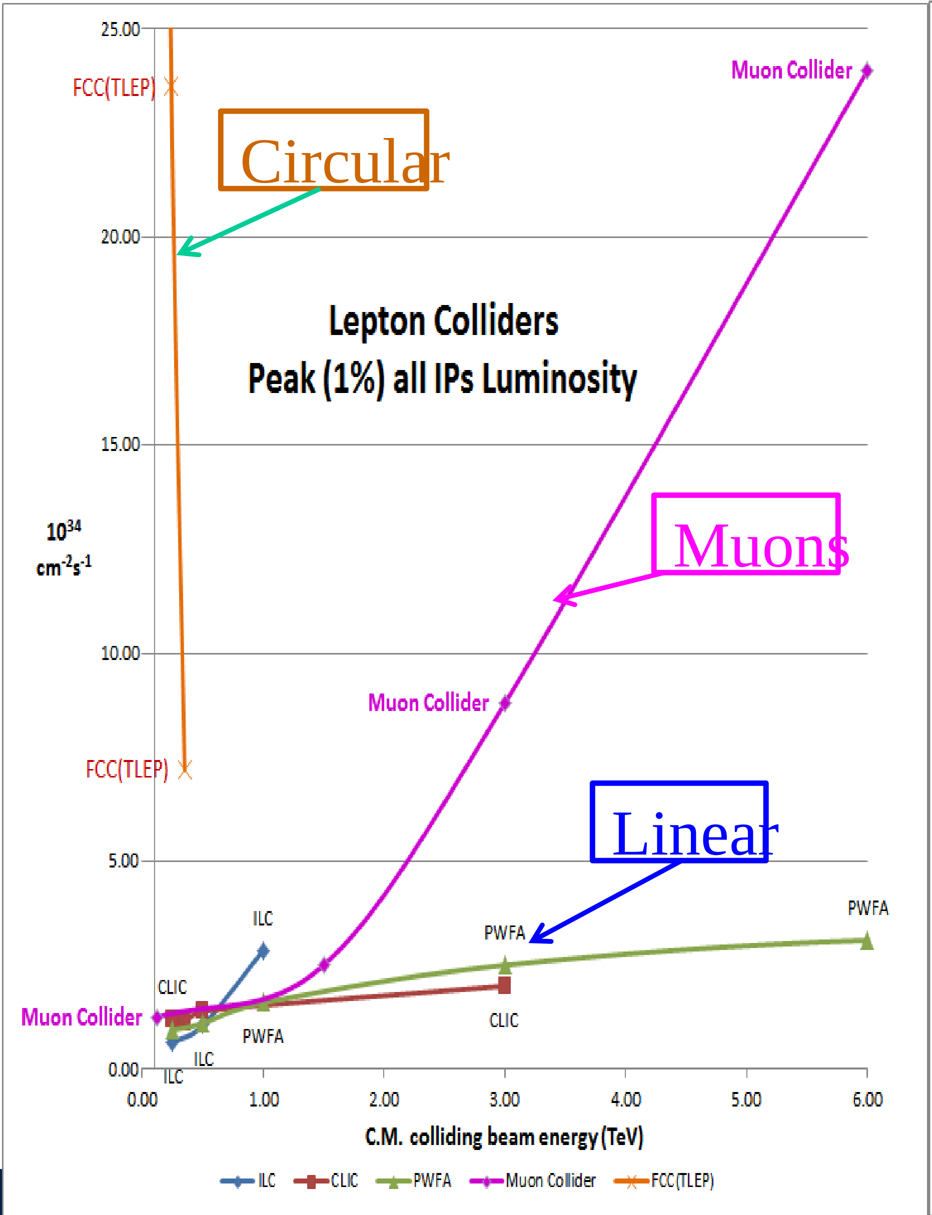
- Superb energy resolution
  - SM thresholds and s-channel Higgs Factory operation
- Multi-TeV Capability (≤ 10TeV)
  - Compact & energy efficient machine
  - Luminosity > 10^{34} cm^{-2} s^{-1}
  - Option for two detectors in the ring

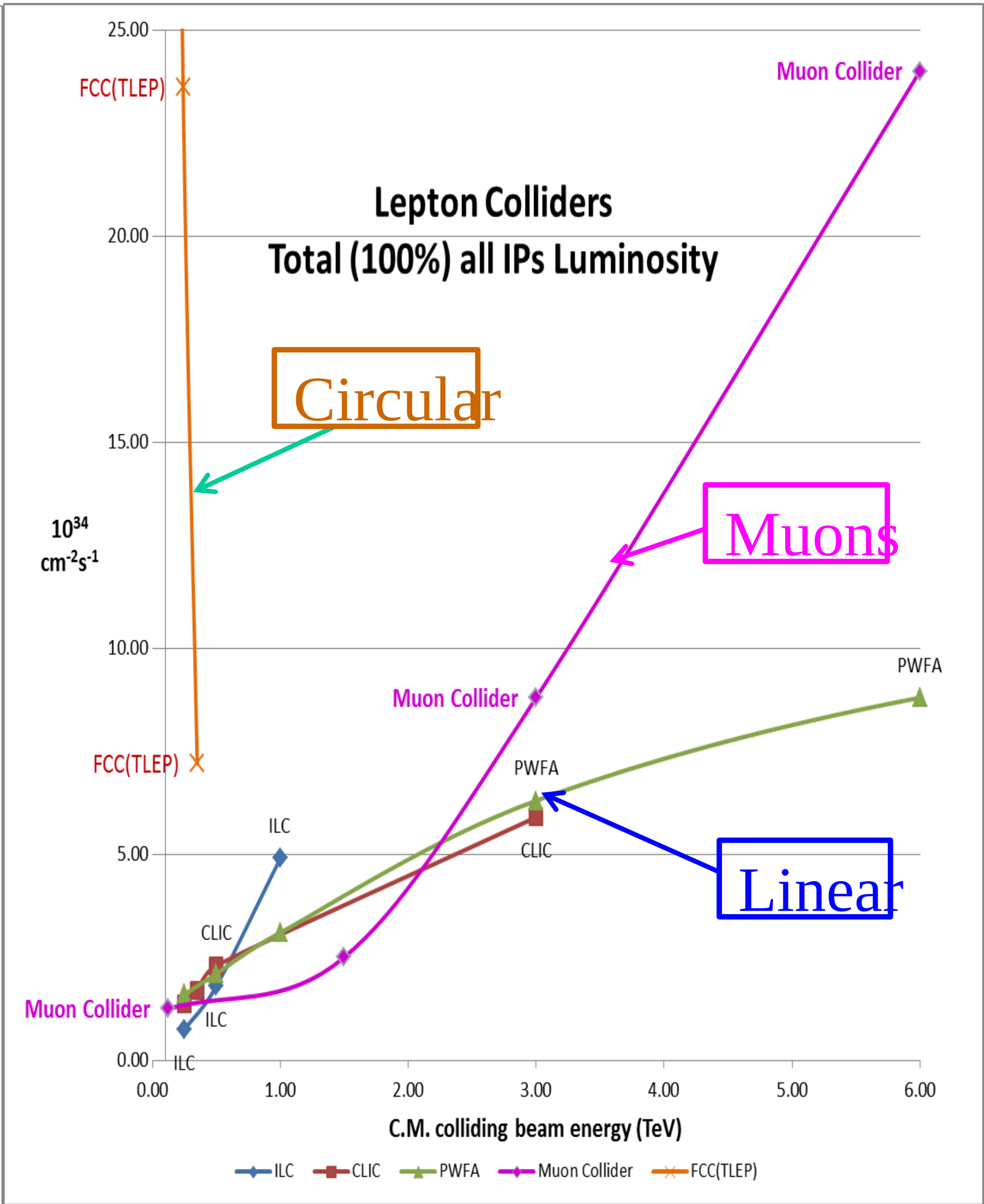


- For √s > 1 TeV: Fusion processes dominate
  - ❑ An Electroweak Boson Collider
  - ❑ Discovery machine complementary to very HE pp collider
- For √s > 5 TeV: Higgs self-coupling resolutions of <10%

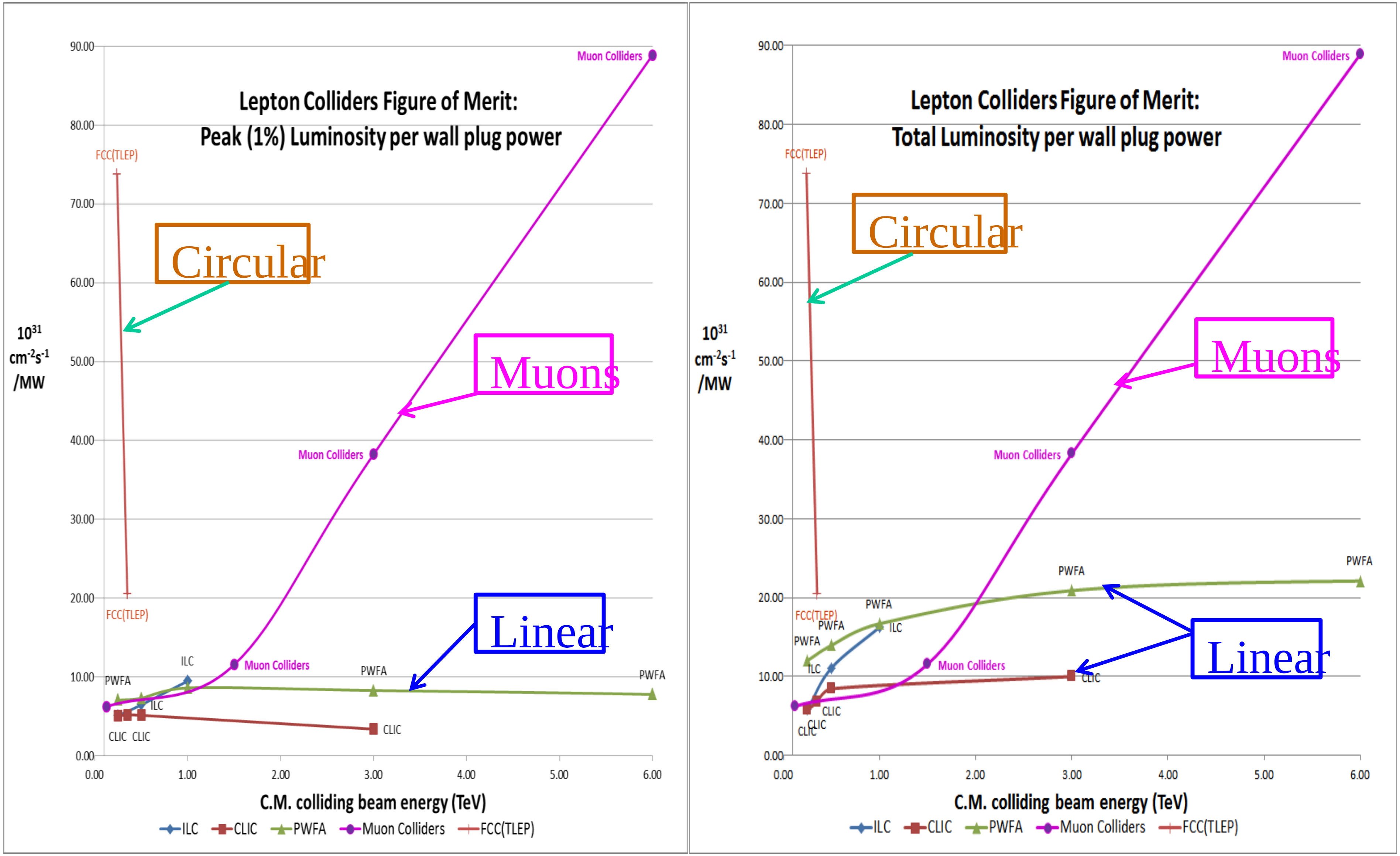


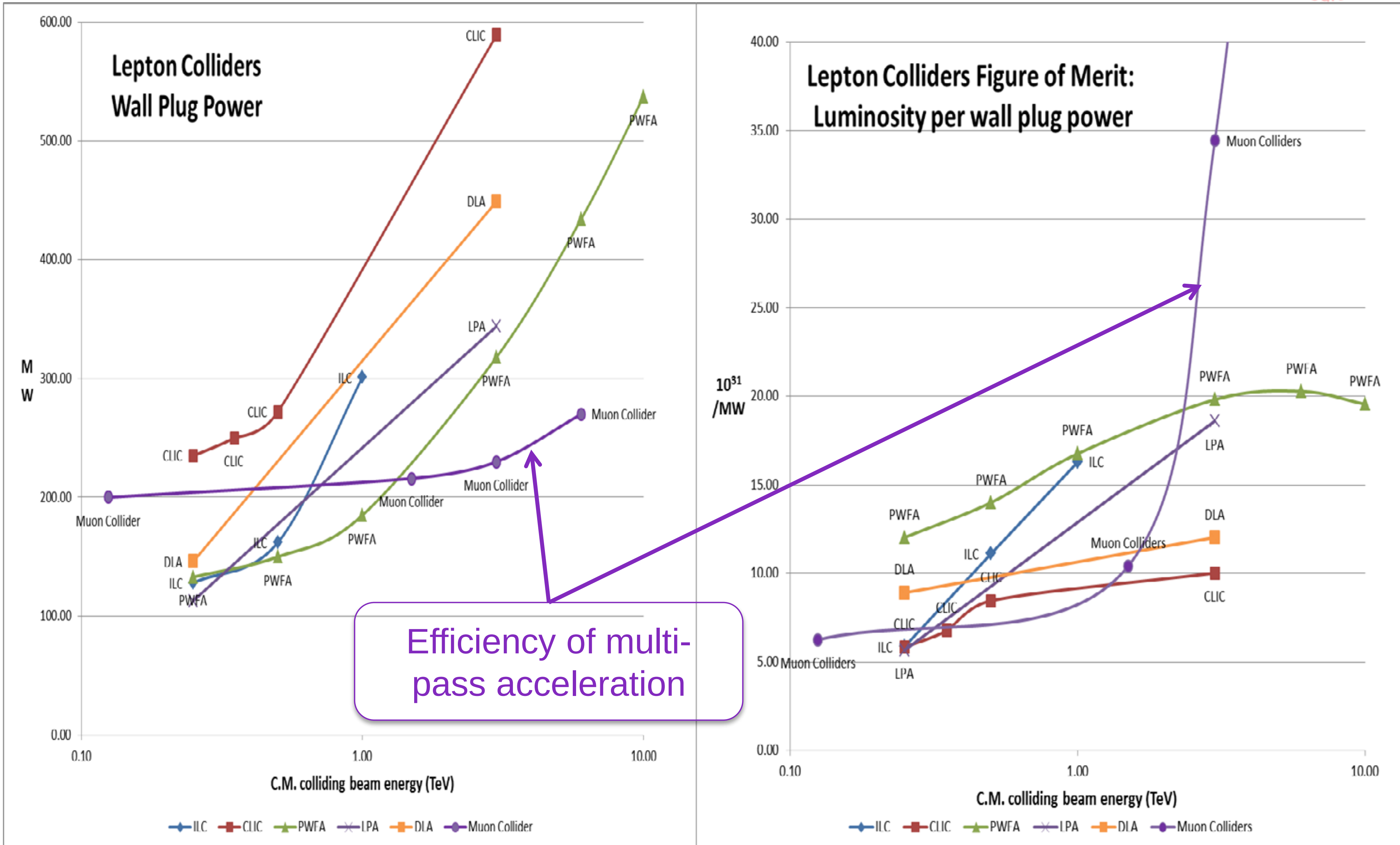
Muon Colliders Extending High Energy Frontier with Improved Performances





Muon Colliders Extending High Energy Frontier with Improved Performances





Lepton Colliders
Wall Plug Power
MW
C.M. colliding beam energy (TeV)
ILC
CLIC
PWFA
LPA
DLA
Muon Collider
Lepton Colliders Figure of Merit:
Luminosity per wall plug power
10^{31} /MW
Muon Colliders
Efficiency of multi-pass acceleration

The Staging Study (MASS)

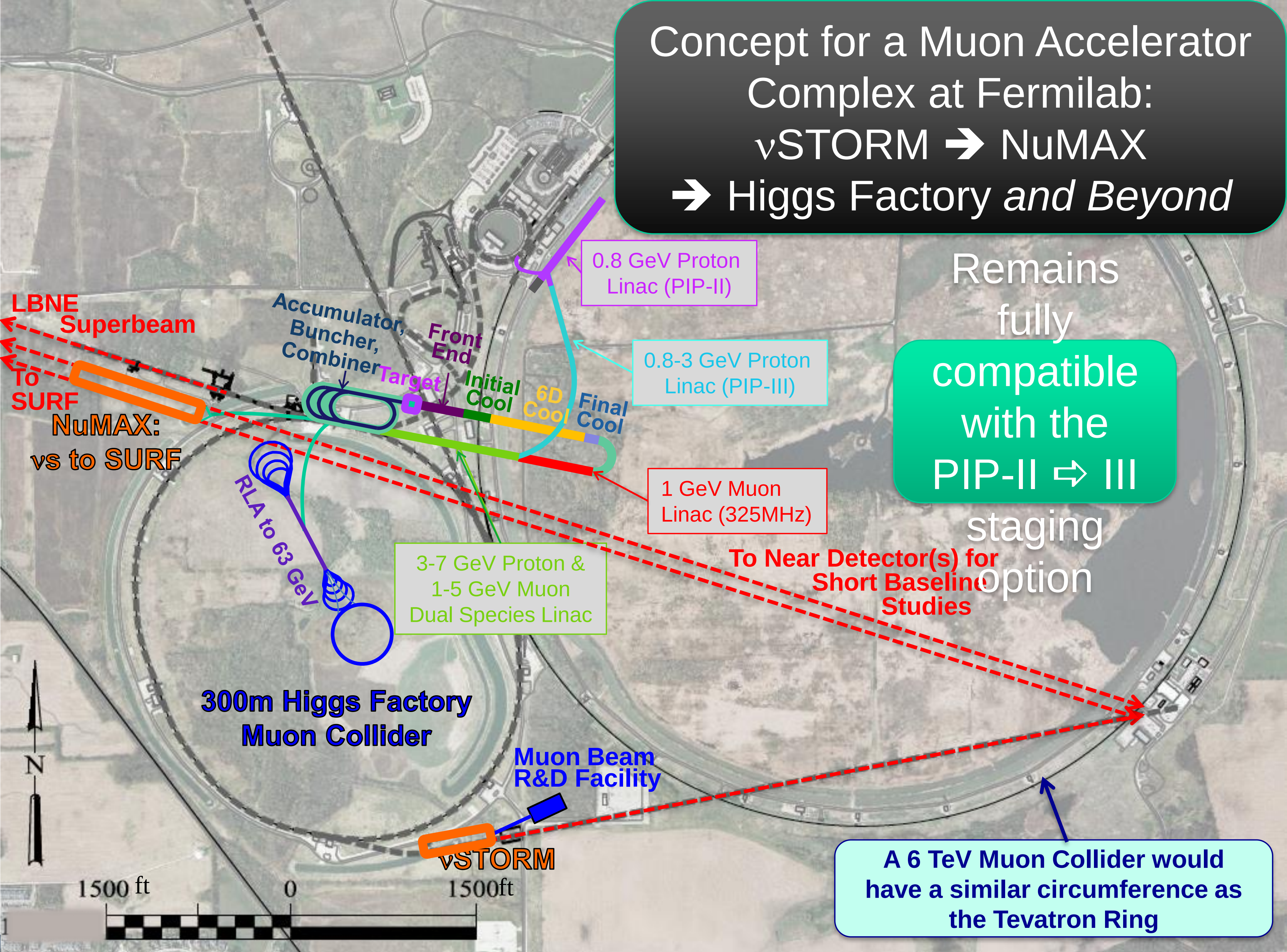
Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the US - http://arxiv.org/pdf/1308.0494

The plan consists of a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

- **nuSTORM:** a short-baseline Neutrino Factory-like ring enabling a defin[illegible]e search for sterile neutrinos, as well as neutrino cross-section measurements th[illegible]imately be required for precision measurements at any long-baseline expe[illegible]
- **NuMAX:** an initial long-baseline Neutrino Factory, o[illegible] SURF, affording a precise and well-characterized neutrin[illegible]lities of conventional superbeam technology.
- **NuMAX+:** a full-intensity Neutrino Fact[illegible]AX, as the ultimate source to enable precision CP-violation mea[illegible]utrino sector.
- **Higgs Factory:** a collider whose baseline [illegible]ions are capable of providing between 3500 (during startup operations) and 1[illegible]0 Higgs events per year (10^7 sec) with exquisite energy resolution.
- **Multi-TeV Collider:** if warranted by LHC results, a multi-TeV Muon Collider likely offers the best performance and least cost for any lepton collider operating in the multi-TeV regime.

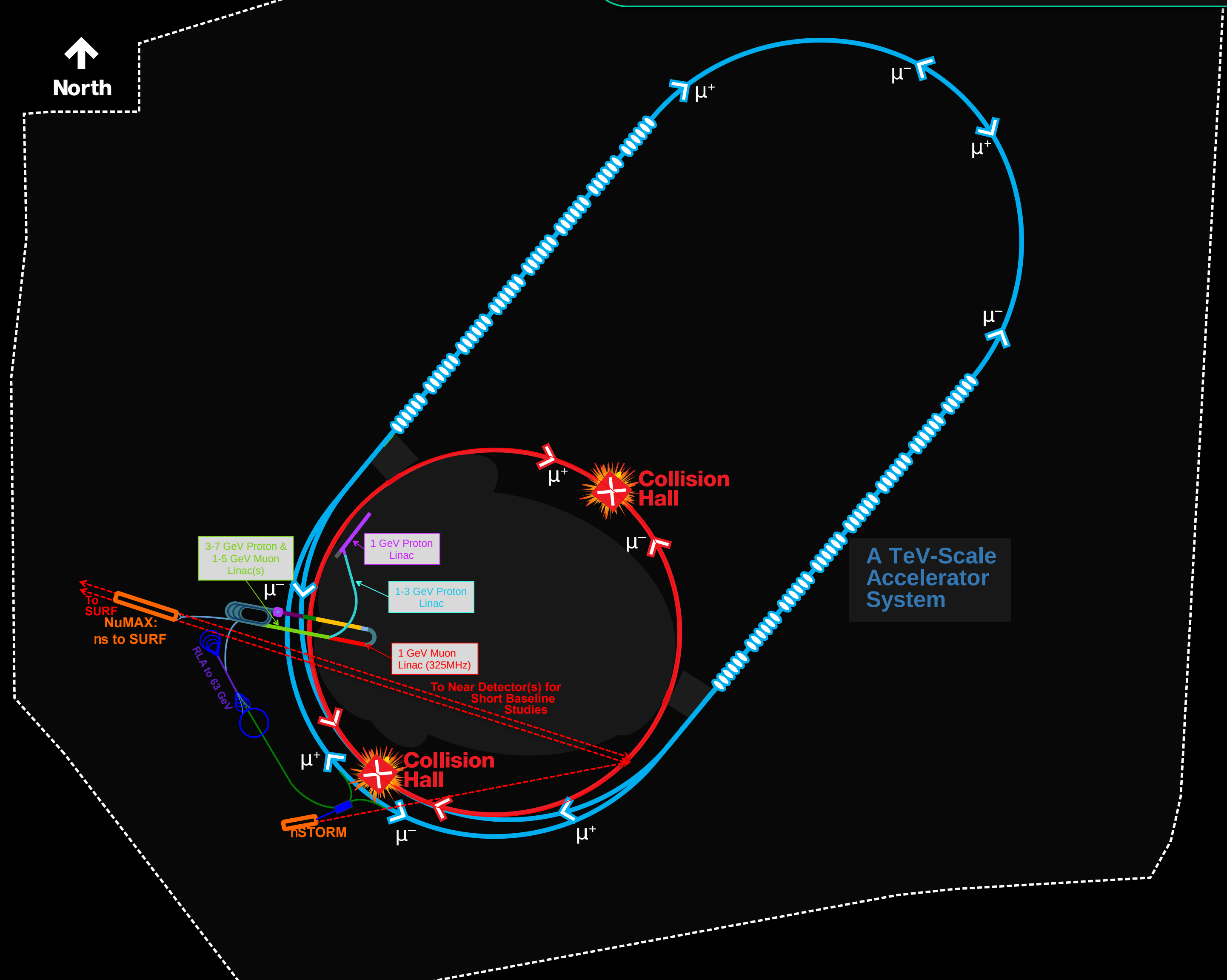
Ability to utilize some or all stages

Concept for a Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory *and Beyond*



Concept for a Muon Accelerator Complex at Fermilab:

➔ Multi-TeV Lepton Collider



Muon Collider Parameters

Muon Collider Parameters								
		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
b*	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, e_{TN}	p mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, s_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	4$^\#$	4	4	4	4	4	1.6

$^\#$ Could begin operation with Project X Stage II beam

Exquisite energy resolution allows direct measurement of Higgs width

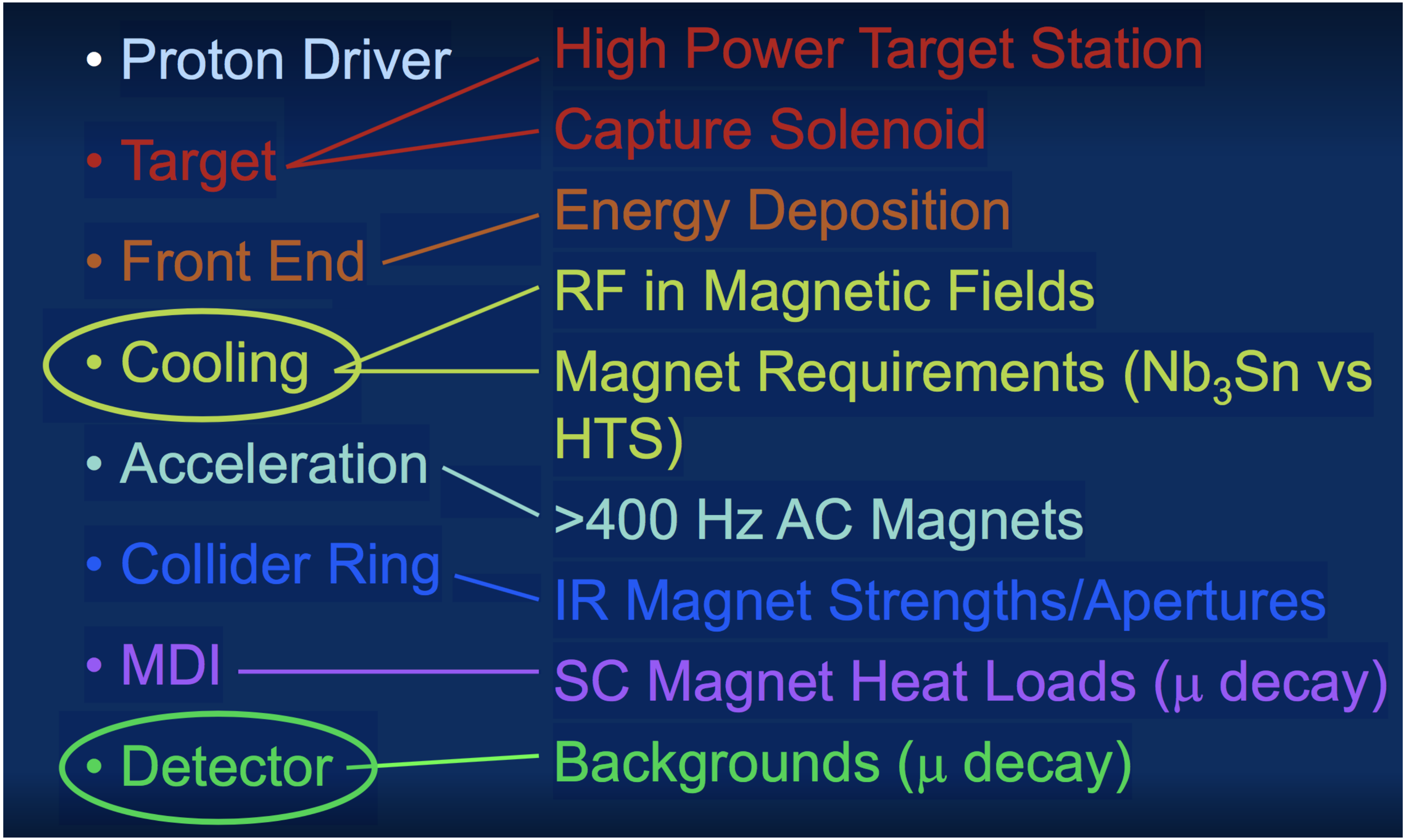
Success of advanced cooling concepts ⇨ several × 10^{32}

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

Muon Beam Challenges

- Muons created as tertiary beam (p → π → μ)
  - Low production rate
    - Need target that can tolerate multi-MW beam
  - Large energy spread and transverse phase space
    - Need solenoidal focusing for the low-energy portions of the facility
      - Solenoids focus in both planes simultaneously,
    - Need acceptance cooling.
    - High-acceptance acceleration system and decay ring.
- Muons have short lifetime (2.2 μs at rest)
  - Puts premium on rapid beam manipulations
    - Presently untested ionization cooling technique
      - High-gradient RF cavities (in magnetic field)
  - Fast acceleration system
- Decay electrons give backgrounds in Collider detectors and instrumentation & heat load to magnets

Critical Feasibility Issues

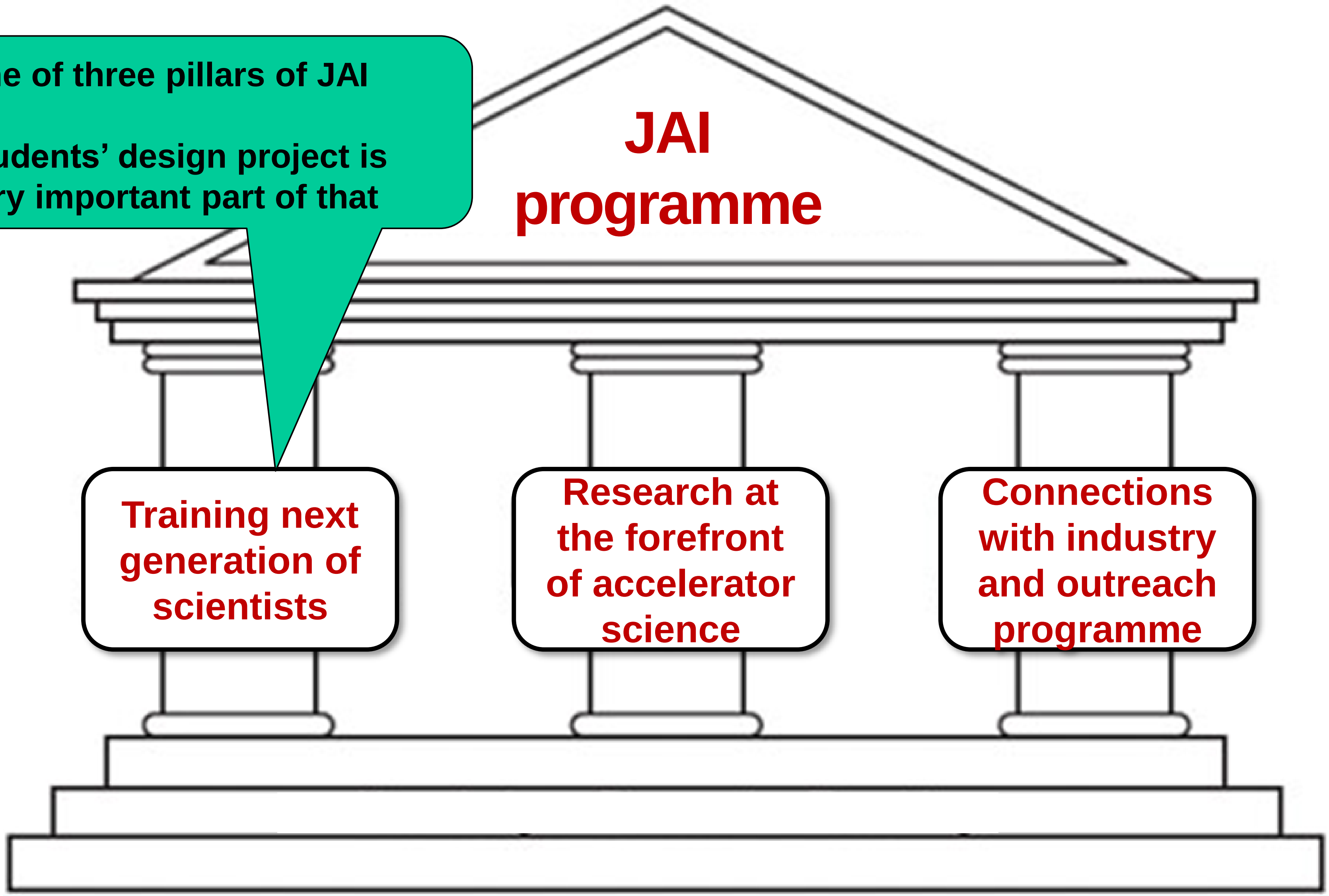


JAI Training

Foundation of JAI programme

One of three pillars of JAI

Students' design project is very important part of that



Research Directions

We have different topics for design projects every year. e.g., last year worked on the Superconducting SPS and before then High Energy LHC, compact ring laser-plasma light source and on FCC e+e-…

2017 -2021

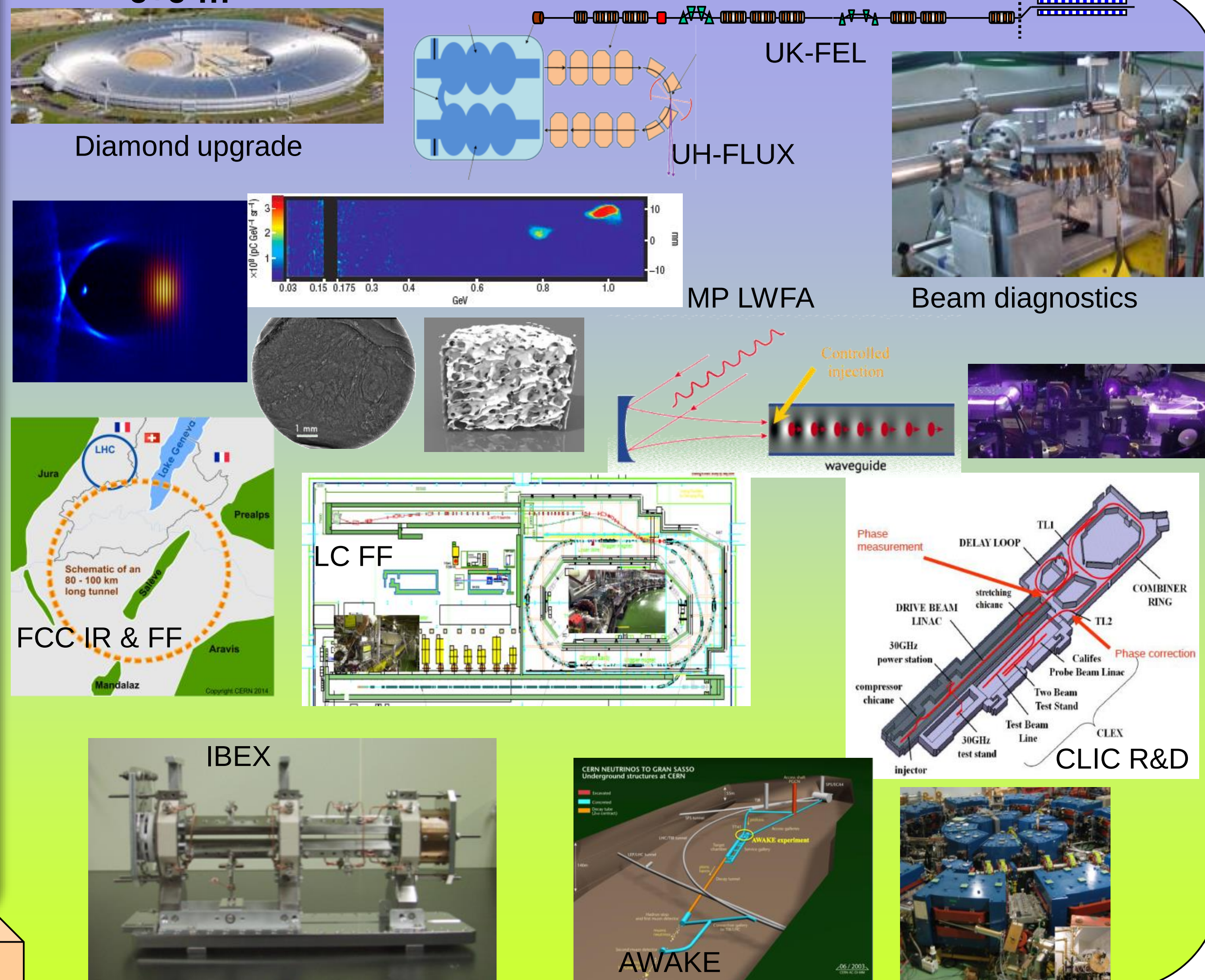
FEL and novel light sources

Plasma acceleration

Future colliders and particle physics facilities

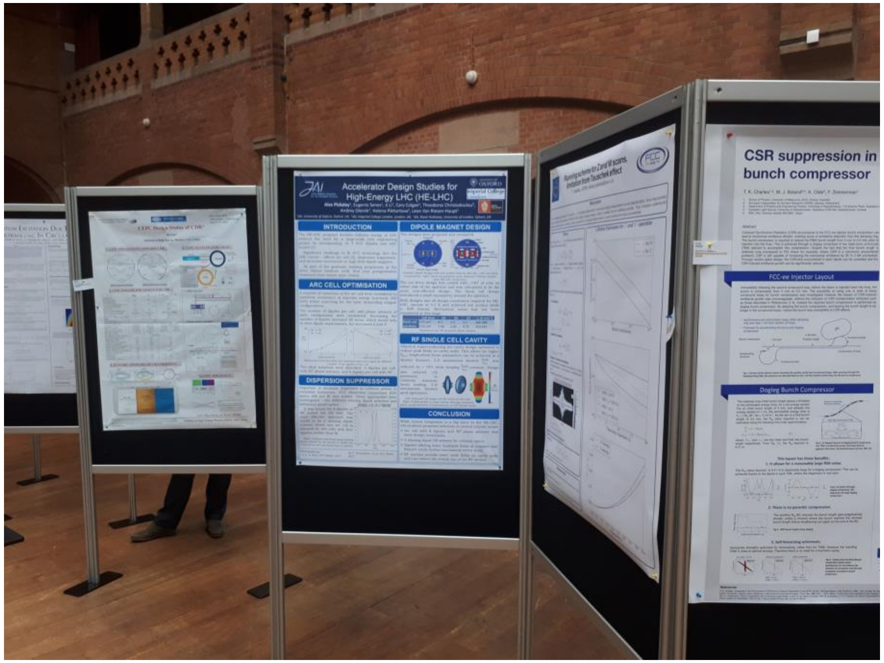
Intense hadron beams

Training



Accelerator Design Project 2017-2018

- **Accelerator Design Studies for the High-Energy LHC (HE-LHC) for 2017-2018**
  - **The aim of this year's JAI student project work was to prepare a design for the HE-LHC.**
  - **Design work consisted of study of the lattice, magnet systems and RF cavities.**
  - **Student presentations made at CERN in June (together with visits to accelerator facilities).**



HE-LHC Student Poster at FCC Week Amsterdam, April 2018

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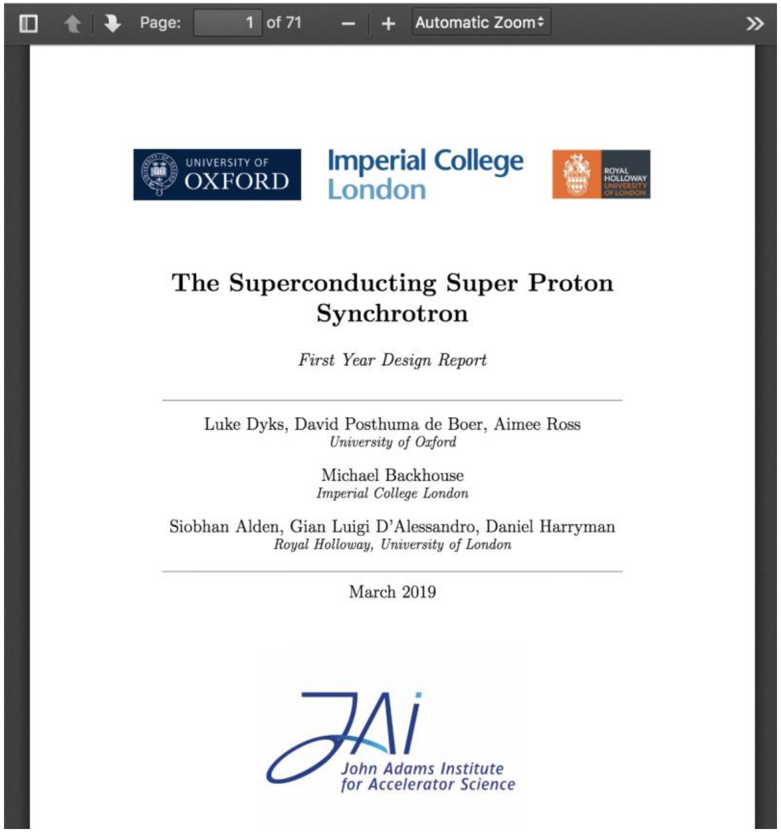
Accelerator Design Project 2018-2019

- **Accelerator Design Studies for the Superconducting SPS (scSPS) for 2018-2019**
  - **The aim of last year's JAI student project work was to prepare a design for the scSPS.**
  - **Design work consisted of study of the lattice, magnet systems and RF cavities.**
  - **Student presentations made at JAI Advisory Board in April and at CERN in June (together with visits to accelerator facilities).**



The Superconducting Super Proton Synchrotron

First Year Design Report

Luke Dyks, David Posthuma de Boer, Aimee Ross
University of Oxford

Michael Backhouse
Imperial College London

Siobhan Alden, Gian Luigi D'Alessandro, Daniel Harryman
Royal Holloway, University of London

March 2019

scSPS Student Publication

cds.cern.ch

Muon Collider Student Design Project Plan

- **Optics Studies**
  - **Study various arc options and optimise cell length.**
  - **Choice of integer tune / working point.**
  - **Injection and extraction energy.**
- **Magnet Design**
  - **Optimise (fast-ramping) dipole and quadrupole magnets.**
  - **Magnet energy storage.**
- **RF System**
  - **Design RF system.**
- **Overall parameter tables and sub-system inventory**