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Muon Colliders – "Light at the End of the Tunnel" for HEP

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"*Muon Collider Explorations*" Meeting

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ABSTRACT

Tighter requirements of new green standards for power consumption, the need to stay within reasonable costs of accelerator facility while aspiring for order of magnitude beyond the LHC center of mass energy in particle collisions call for a drastic paradigm shift from the **"bigger, more powerful and more costly"** tradition of HEP colliders of the past 50 years. I will review comparative advantages and challenges of multi-TeV muon colliders and argue that only since very recently we have proven the machine feasibility and are ready to start working toward complete technical design two decades from now for the concept of muon colliders, which offer unique option to advance the particle physics frontier and open the *Promise land* beyond the Standard Model.

High Energy $\mu+\mu-$ Colliders

Advantages:

- ***μ***’s do not radiate when bent → acceleration in rings →

smaller footprint

low cost

great power efficiency

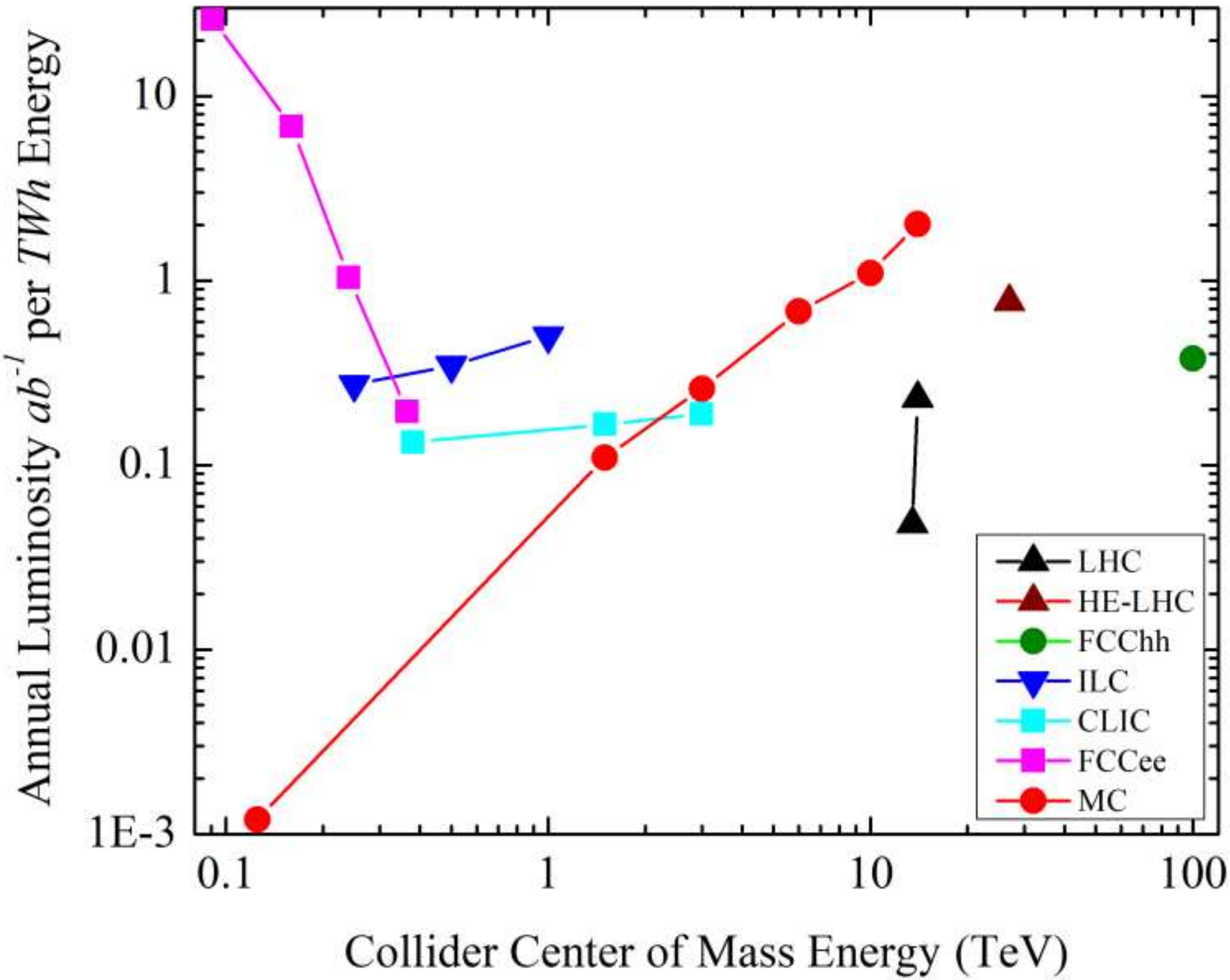
- ~ x7 energy reach vs *pp*

Offer *“moderately conservative - moderately innovative”* path **to cost affordable** energy frontier colliders:

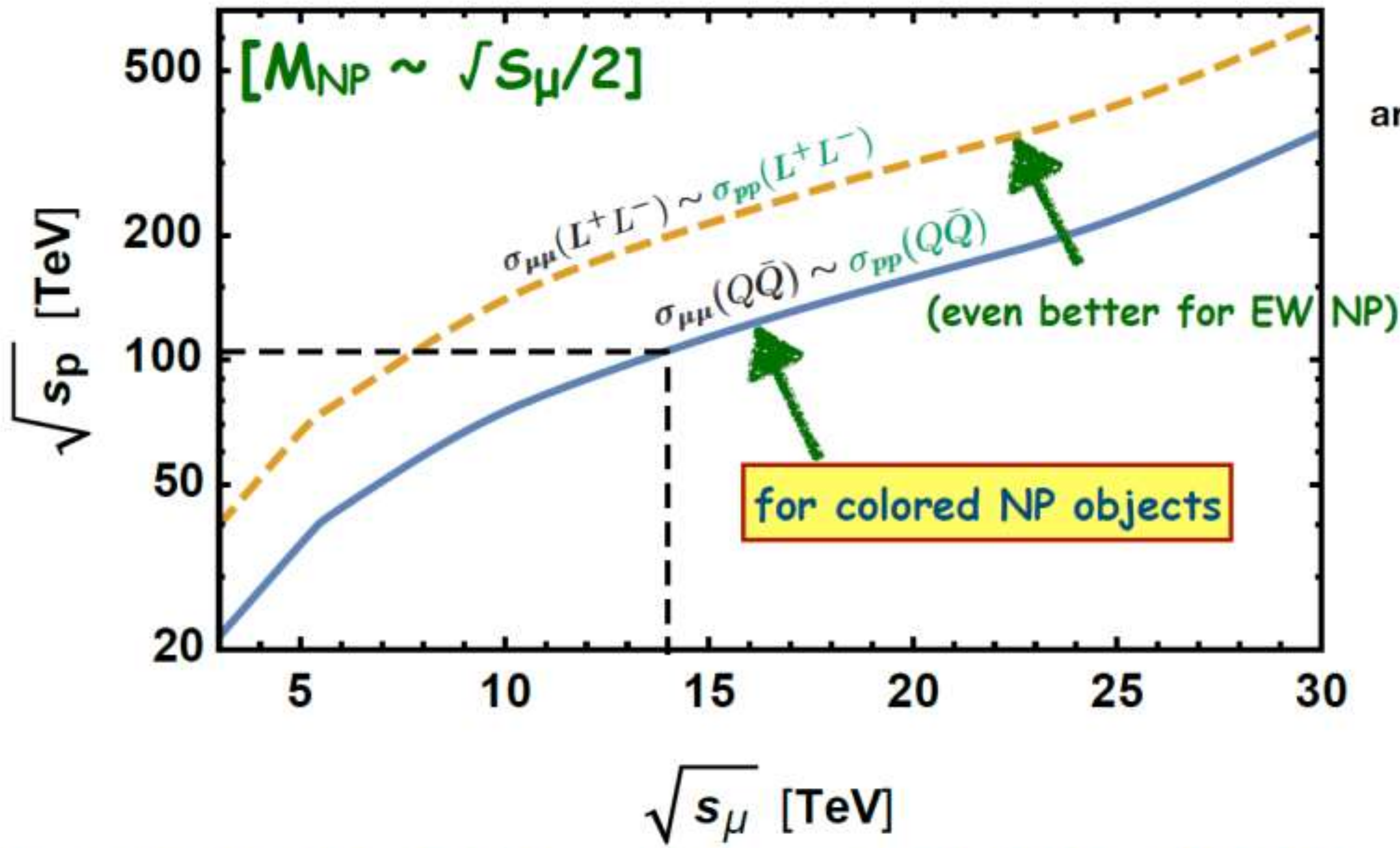
Power efficiency

arXiv:2003.09084

to appear in Nature Physics



"equivalent" reach in pp after rescaling for pdf's



arXiv:1901.06150

- ✱ μμ @ 14 TeV → pp @ 100 $(200)_{EW}$ TeV !
- ✱ μμ @ 30 TeV → pp @ 350 $(600)_{EW}$ TeV !!

yet unexplored pheno !!!

Cost

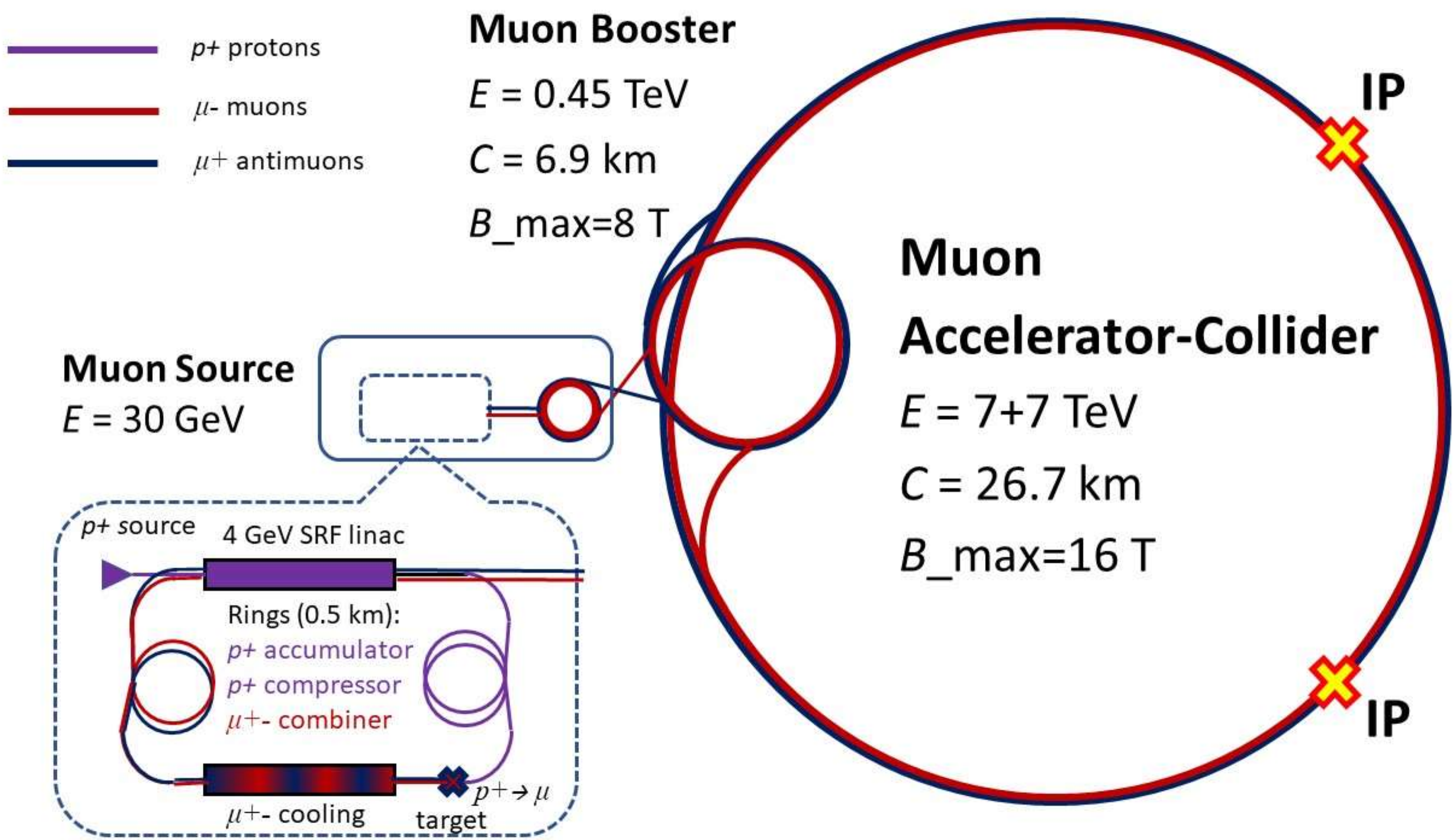
arXiv:2003.09084

to appear in ***Reviews of Modern Physics (Mar'2021)***

Project	Type	Energy (TeV, c.m.e.)	$N_{\rm det}$	$\mathcal{L}_{\rm int}$ ($\rm ab^{-1}$)	Time (years)	Power (MW)	Cost
ILC	e^+e^-	0.25	1	2	11	129	4.8-5.3BILCU
		0.5	1	4	10	163(204)	8.0 BILCU
		1	1			300	+(n/a)
CLIC	e^+e^-	0.38	1	1	8	168	5.9 BCHF
		1.5	1	2.5	7	370	+ 5.1 BCHF
		3	1	5	8	590	+7.3 BCHF
CEPC	e^+e^-	0.091&0.16	2	16+2.6	2+1	149	5 B USD
		0.24	2	5.6	7	266	+(n/a)
FCC-ee	e^+e^-	0.091&0.16	2	150+10	4+1	259	10.5 BCHF
		0.24	2	5	3	282	
		0.365 & 0.35	2	1.5+0.2	4+1	340	+1.1 BCHF
LHeC	ep	1.3	1	1	12	(+100)	1.75* BCHF
HE-LHC	pp	27	2	20	20	220	7.2 BCHF
FCC-hh	pp	100	2	30	25	580	17(+7) BCHF
FCC-eh	ep	3.5	1	2	25	(+100)	1.75 BCHF
Muon Collider	$\mu\mu$	14	2	50	15	290	10.7* BCHF

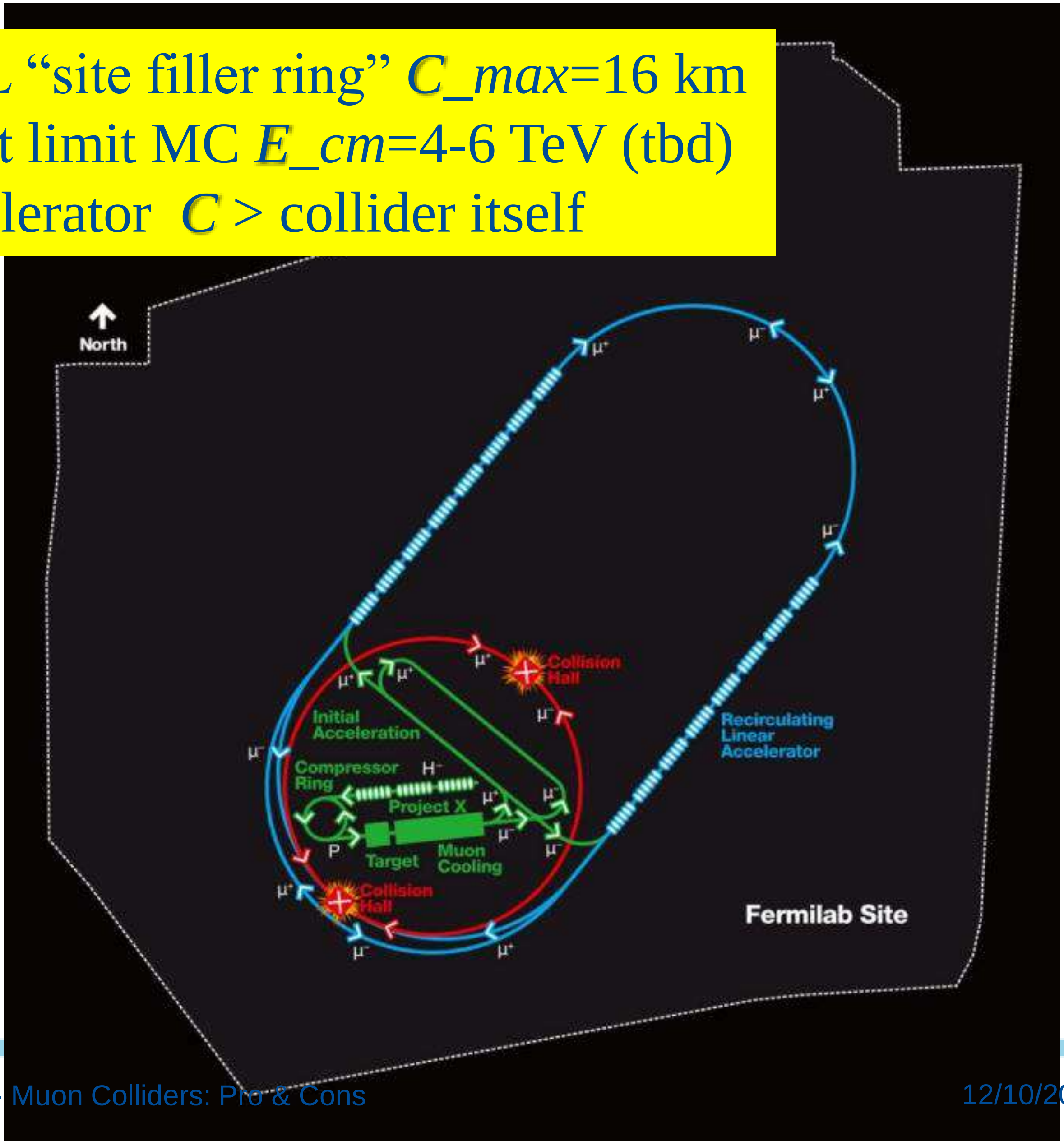
* the estimates are taken from the EPPSU'2019 presentations, by proponents, none has been critically reviewed (except ILC – though not by the US methodology); there is an Implementation Task Force (ITF) created in the Snowmass'21 Accelerator Frontier to develop metrics for comparable evaluation

Muon Collider (2020) : Sub-Systems (approx. to scale)



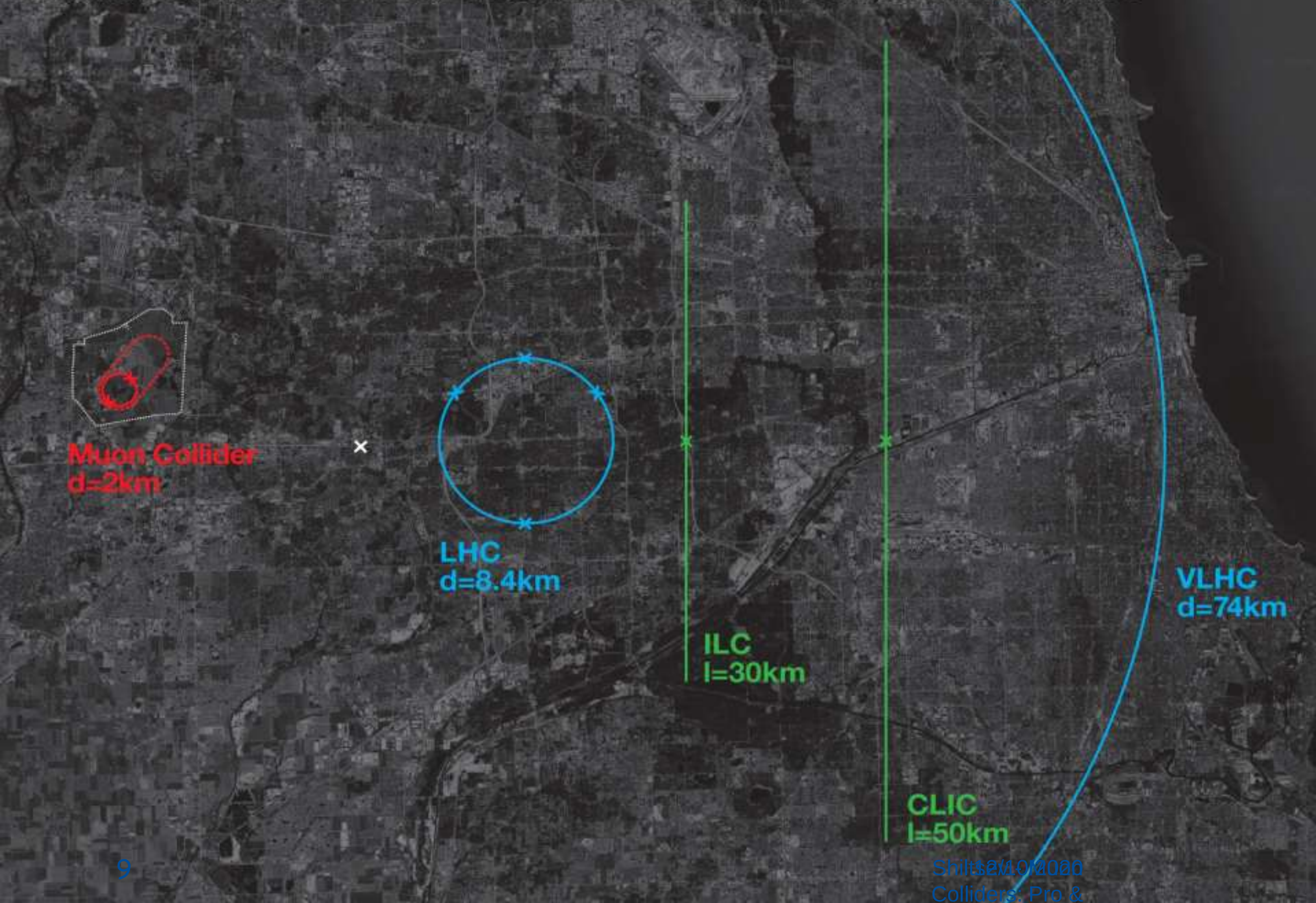
1.5-4 TeV Muon Collider (ca.2007)

Note: FNAL “site filler ring” *C_max*=16 km
…that might limit MC *E_cm*=4-6 TeV (tbd)
…final accelerator *C* > collider itself



Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.



Why the cost is so low ?

A. (Most important) much less RF

B. (Smaller) size matters

C. (Lower) Power consumption

! WARNING !

$\alpha\beta\gamma$ - Cost Estimate Model:

$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

a) **±33% estimate, for a "green field" accelerators**

b) **"US-Accounting" = TPC !** (~ 2-2.5 × *European Accounting*)

c) **Coefficients** (units: 10 km for *L*, 1 TeV for *E*, 100 MW for *P*)

- **α≈ 2B$/sqrt(*L*/10 km)**
- **β≈ 10B$/sqrt(*E*/TeV)** for SC/NC RF **!!!**
- **β≈ 2B$ /sqrt(*E*/TeV)** for SC magnets **!!**
- **β≈ 1B$ /sqrt(*E*/TeV)** for NC magnets **!**
- **γ≈ 2B$/sqrt(*P*/100 MW)**

USE AT YOUR OWN RISK!

* Subject of the AF Implementation Task Force review

Luminosity goal

arXiv:1901.06150

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$$

Collecting 100 events might be sufficient to discover new particles with easily identifiable decay products, such as Stops and Top Partners related with Naturalness. An instantaneous luminosity of $2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$, at 10 TeV, would be sufficient to probe these particles up to the collider reach. Ten thousands events would instead be needed to aim at percent-level measurements of electroweak SM processes at high invariant mass, allowing to probe hundreds of TeV New Physics scales indirectly as previously mentioned. In this case the luminosity requirement becomes:

b

Parameter table

(* indicates collider rings which fit the LHC tunnel)

Center of mass energy $\sqrt{s}$ (TeV)	.126	3	14
Circumference (km)	.3	4.5 (26.7*)	14 (26.7*)
Interaction regions	1	2	2
Peak luminosity (10^{34} cm^{-2} s^{-1})	0.008	4.4	40
Int. lum. per exp. (ab^{-1}/year)	0.001	0.5	3
Time between coll. (μs)	1	0.025	90
Cycle rep. rate (Hz)	1	6(35*)	4(7*)
Energy spread (rms, %)	0.004	0.1	0.1
Bunch length (rms, mm)	63	5	1
IP beam size (μm)	75	3.0	0.6
β^*, amplitude function at IP (mm)	17	5	1
Avg. magnetic field (T)	10(?)	8(5.5*)	10.5(5.5*)
Max. magnetic field (T)	10(?)	12	16
Proton driver beam power (MW)	4	4	1
Total facility AC power (MW)	200	230	290

Another Parameter table

(* as developed by the US MAP)

RAST, Vol 10, No. 01, pp. 189-214 (2019)

Table 3. Main parameters of the various phases of an MC as developed by the MAP effort.

Parameter	Units	Higgs	Top-high resolution	Top-high luminosity	Multi-TeV		
CoM energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. luminosity	10^{34} cm^{-2}s^{-1}	0.008	0.07	0.6	1.25	4.4	12
Beam energy spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs production/10^7 sec		13,500	7000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5–2)	0.5 (0.3–3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. trans. emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. long. emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton driver power	MW	4	4	4	4	4	1.6
Wall plug power	MW	200	203	203	216	230	270

*Accounts for off-site neutrino radiation

Yet Another Parameter table

(* under consideration by the CERN-led *Muon Collider Collaboration* - 2020)

Target integrated luminosities

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

Reasonably conservative

- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Tentative target parameters, scaled from MAP parameters

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

Snowmass process to give feedback on this

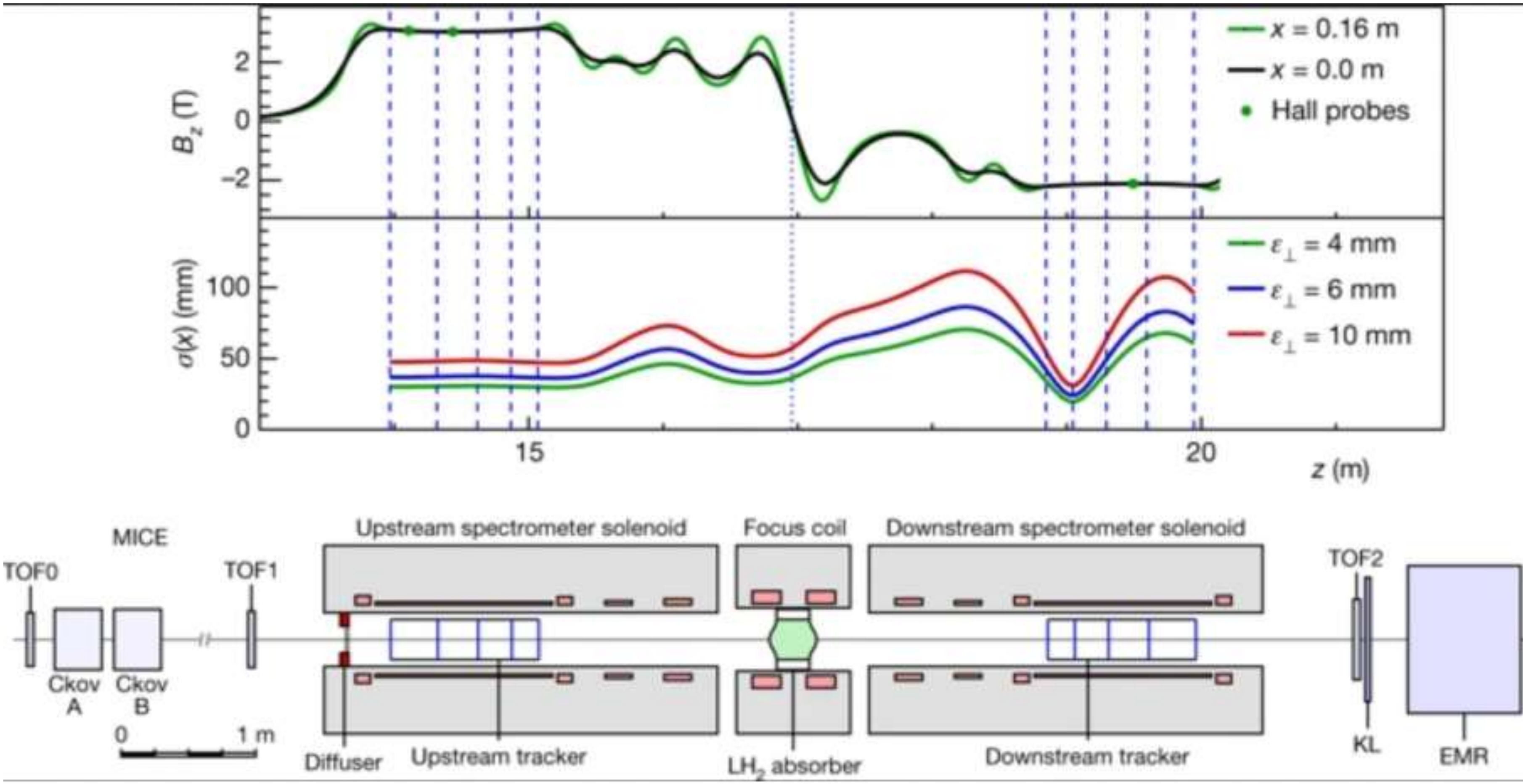
Subsystems

- (i) a high power proton driver (SRF 4 GeV 2-4 MW H- linac);
- (ii) pre-target accumulation and compressor rings, in which high-intensity 1-3 ns long proton bunches are formed;
- (iii) a liquid mercury target for converting the proton beam into a tertiary muon beam with energy of about 200 MeV;
- (iv) a multi-stage ionization cooling section that reduces the transverse and longitudinal emittances and, thereby, creates a low emittance beam;
- (v) a multistage acceleration (initial and main) system --- the latter employing a series recirculating rapid cycling synchrotrons (RCS) to accelerate muons in a modest number of turns up to 3-7 TeV using high gradient superconducting RF cavities;
- (vi) about 8.5 km diameter collider ring located some 100 m underground, where counter-propagating muon beams are stored and collide over the roughly 1000--2000 turns corresponding to the muon lifetime.

** From the point of beam physics, complexity of a Muon Collider is closer to that of the Tevatron (higher) than to that of the LHC (lower)*

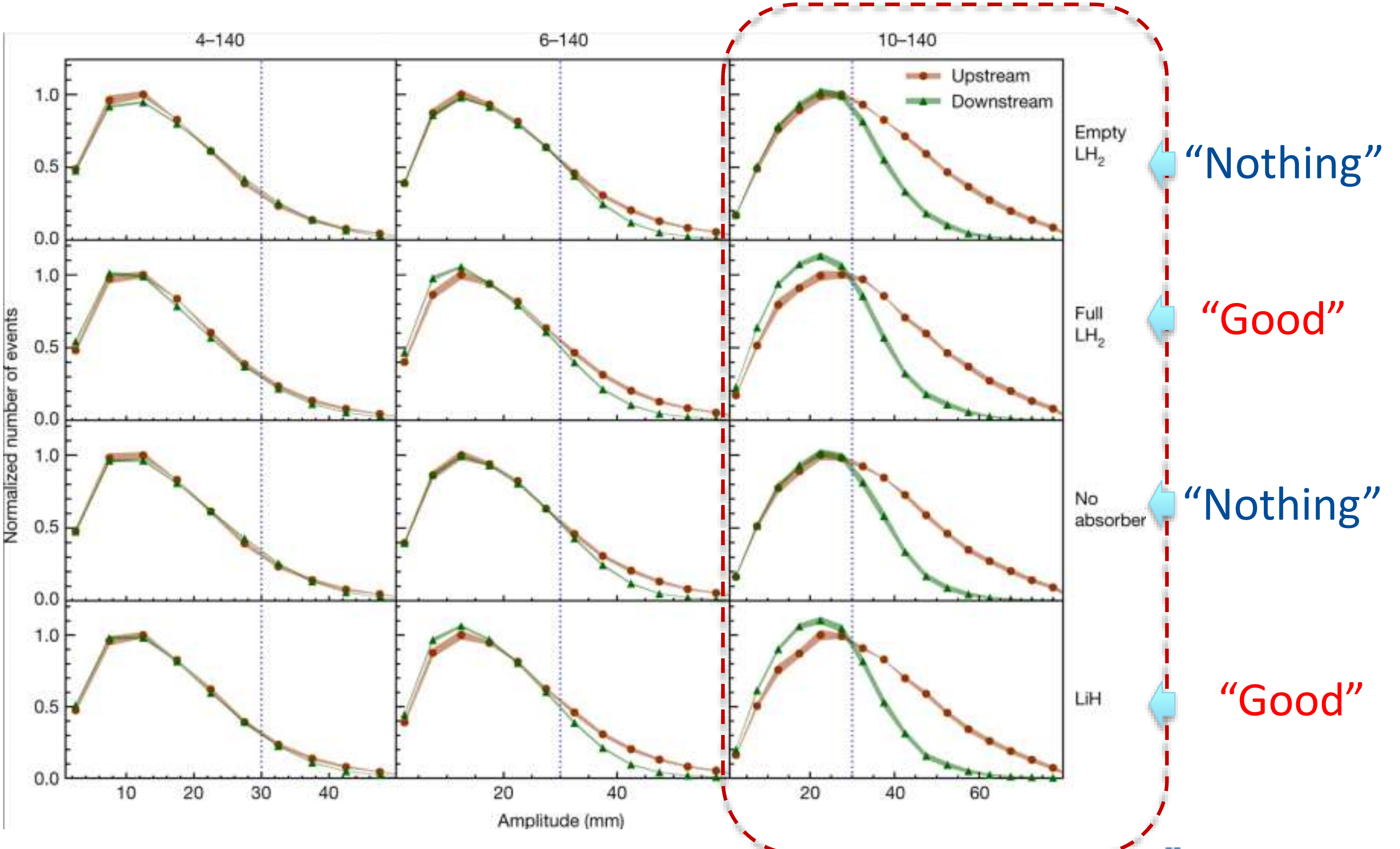
MICE(1)

Nature **578**, 53–59(2020)

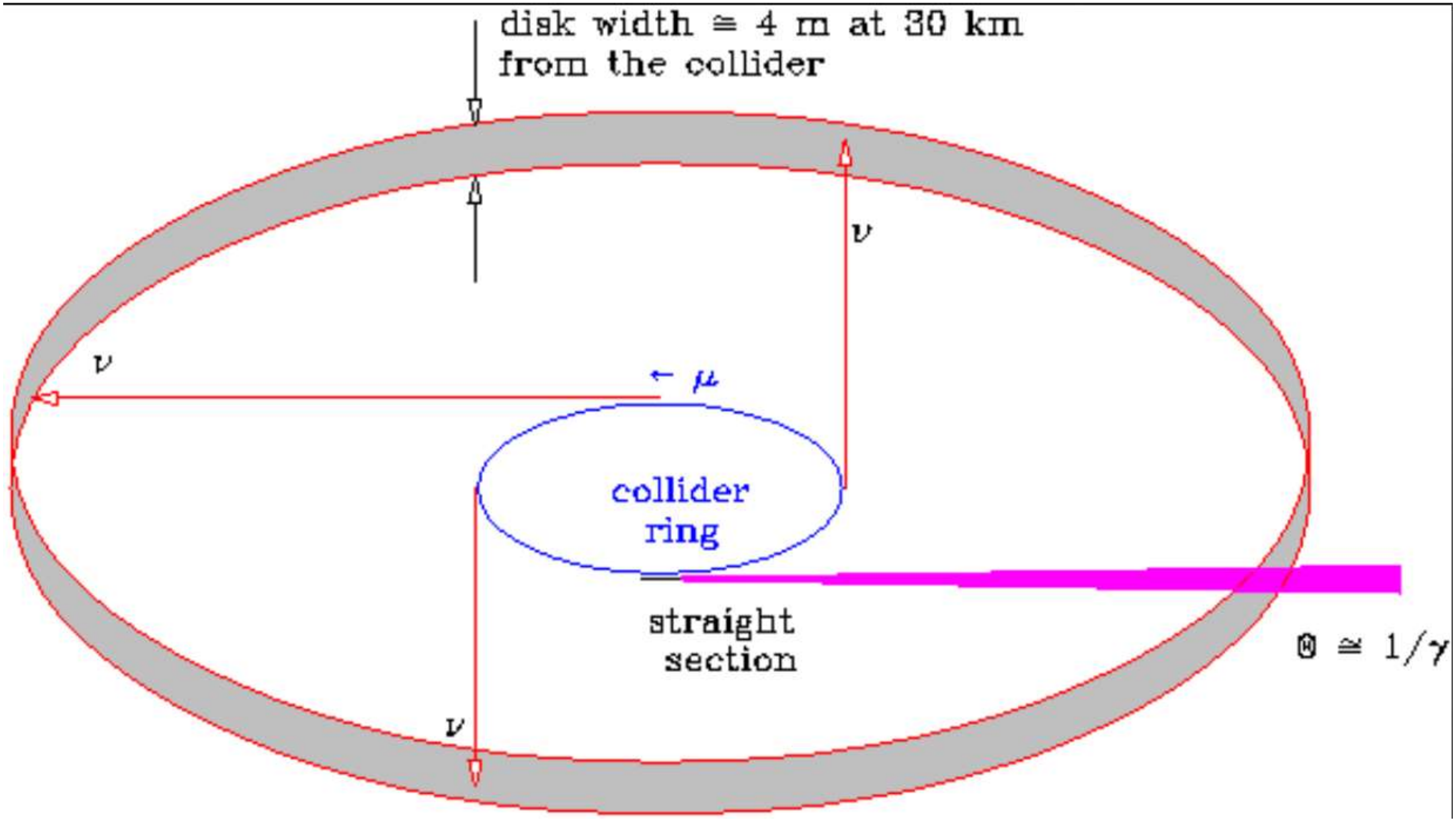


MICE(2)

Nature **578**, 53–59(2020)

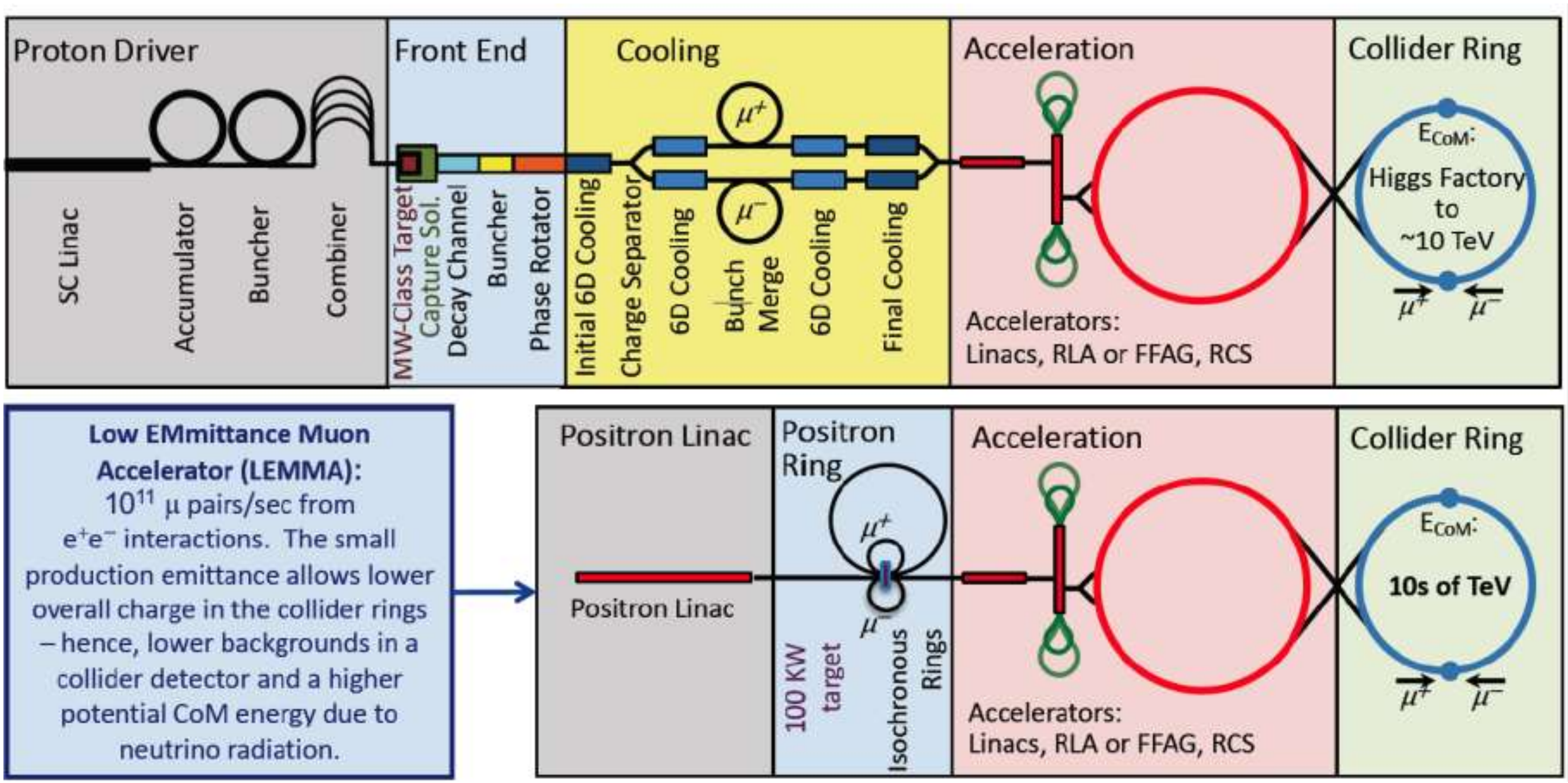


Neutrino Radiation



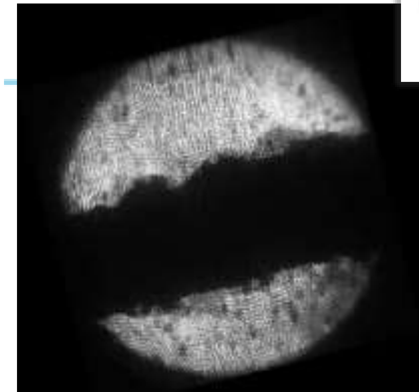
1 mSv/yr mitigation ideas: a) depth; b) few mm vertical collider orbit variation; c) ~cm magnet positions float; e) less muons, eg via positrons

Alternative Concepts: μ's from protons vs μ's from e+

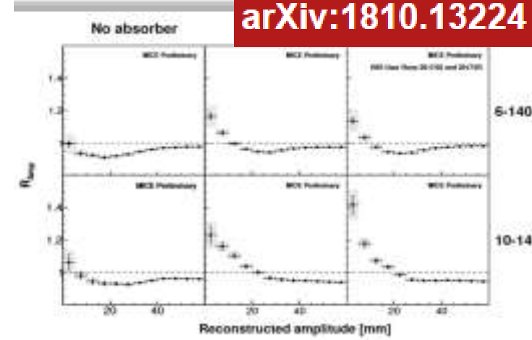


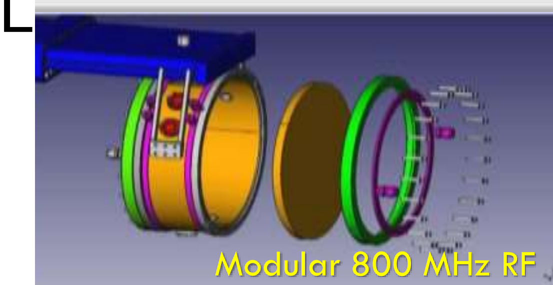
Other notable progress

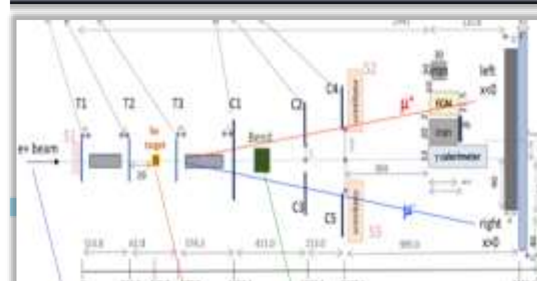
- Liquid mercury targets:
  - MERIT beam test @ CERN
  - Equivalent to ~ 8 MW avg beam power
- NC RF 50 MV/m in 3 T field
  - Developed and tested at Fermilab
- Rapid cycling HTS magnets
  - Record 12 T/s – built and tested at FNAL
- First RF acceleration of muons
  - J-PARC MUSE RFQ 90 KeV
- US MAP Collaboration → Int'l
- Low emittance (no cool) concept
  - 45 GeV $e^+ + e^- \rightarrow \mu^+ \mu^-$: CERN fixed target



arXiv:1810.13224







Path forward

- Become *post-LHC* (TDR by 2040) = CERN Test Facility by 2025
- Key R&D to secure low cost and power and high Lumi:
    1. high field, robust and cost-effective 12-16 T superconducting magnets for the muon production, cooling, acceleration and collision, with power- efficient cryogenics subsystems;
    2. high-gradient and robust normal-conducting RF to minimize muon losses during cooling and power-efficient superconducting RF for fast muon acceleration;
    3. fast ramping normal-conducting, superferric or superconducting magnets that can be used in a RCS to accelerate the muons;
    4. advanced detector concepts and technologies to deal with the background induced by the muon beams, as well as fast, robust, high-resolution beam diagnostics instrumentation.
- **Develop STRONG physics case and detector concepts !!!**

First Steps Toward MC: Europe (1)

EU Strategy → International Design Study

European Strategy Update – June 19, 2020:

3 High-priority future initiatives

High-priority future initiatives [..]In addition to the high field magnets the **accelerator R&D roadmap** could contain:
[..] an **international design study** for a **muon collider**, as it represents a unique opportunity to achieve a *multi-TeV energy domain beyond the reach of e^+e^- colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but *novel ideas are being explored*;

European Large National Laboratories Directors Group (LDG) – July 2

LDG chaired by Lenny Rivkin

Agree to start building the collaboration for international muon collider design study

Accept the proposal of organisation

Accept the goals for the first phase

Daniel Schulte ad interim project leader

Strengthening cooperation and ensuring effective use complementary capabilities

Core team: N. Pastrone, L. Rivkin, D.Schulte

International Muon Collider Collaboration kick-off virtual meeting - July 3

(>250 participants) https://indico.cern.ch/event/930508/

First Steps Toward MC: Europe (2)

Started to address the R&D on muon collider as requested by European Strategy

Formal collaboration at any moment

Actual work started with meetings on design

- Accelerator design (-> daniel.schulte@cern.ch)
- Physics and detectors (-> nadia.pastrone@cern.ch)
- Physics potential (-> andrea.wulzer@cern.ch),
- Detector simulations (-> donatella.lucchesi@pd.infn.it),
- Muon cooling (-> chris.rogers@stfc.ac.uk, klaus.hanke@cern.ch)

Many thanks to all
MAP collaboration, M. Palmer
MICE collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
…

Will have project meeting with accelerator and physics

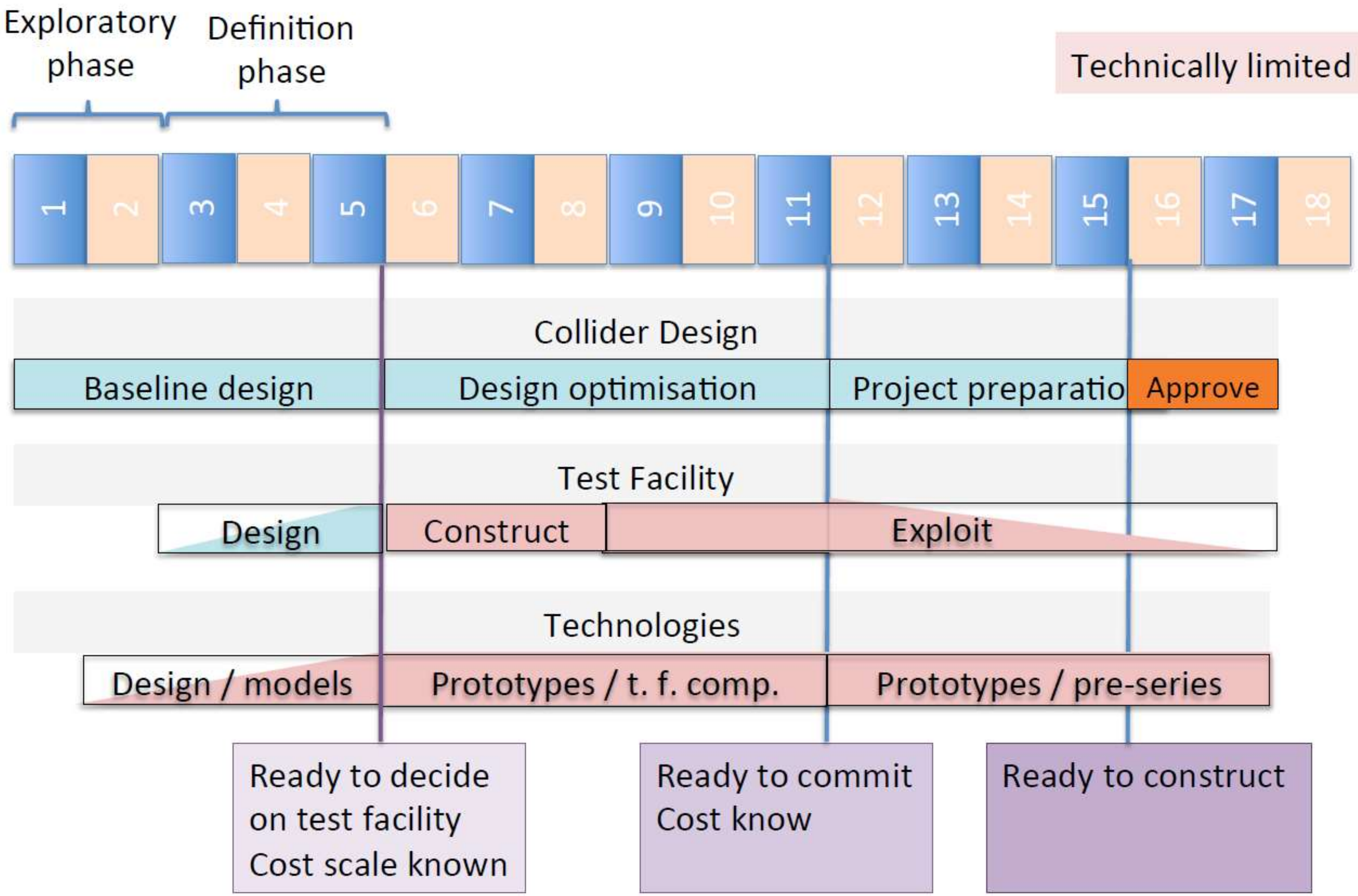
- Every few months, half day long

Web page: http://muoncollider.web.cern.ch

- Find link to meetings in menu "Organisation"

Mailing lists: MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch, MUONCOLLIDER_FACILITY@cern.ch

Proposed *MCC* Timeline



Steps Toward MC: US

- US MAP ended up in 2016… many publications, no CDR…
- Snowmass'21 reflects enormous interest in energy frontier , post-LHC muon colliders:
  1. In EF(energy frontier), AF (accelerator frontier) and IF (instrumentation frontier) communities:
     1. Series of meetings and Workshops: U.Chicago, Fermilab, U.Pitt, joint with Europeans, this one, more to come…
  2. European bold moves (EPPSU → CERN 2M$/yr initial), MCC
  3. Even greater enthusiasm for MC in the US, eg ~6 TeV at FNAL
- We should not repeat past mistakes and make *"physics first"* (develop STRONG physics case and detector concepts) and augment it with accelerator effort
- We should strive for the Snowmass'21 outcome –

Muon Collider Physics R&D and Design work

should become part of the P5 plan

Thank you for your attention!

Back up slides