Snowmass 2021

Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Muon Colliders: Fighting the Perception, R&D Needs

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MC Physics and Detector Workshop

Fermilab, Dec 15, 2022

“…Muon Collider is not feasible”

Respected Scientist A

“..It requires 11 (or 5 or 7) miracles to have a MC”

Experts B, C and D

“…We heard enough promises on MC…

…it’s not real”

“A Big Conference” hallways

Equally "strong" and "puzzling" might be some public statements of the Muon Collider proponents

"Muons are particles of the future!"... etc

Most of us (as "competent outsiders") try find out *"What is the evidence?"* and/or *"What are the arguments?"*

*That's a **wrong** approach!*

According to *SCIENCE* – correct is the

Three Filters Approach

1. Is the source credible?

2. Does the source have expertise?

3. Is there a consensus among the relevant experts?


INSIGHTS

POLICY FORUM

EDUCATION

Science, misinformation, and the role of education

"Competent outsiders" must be able to evaluate the credibility of science-based arguments

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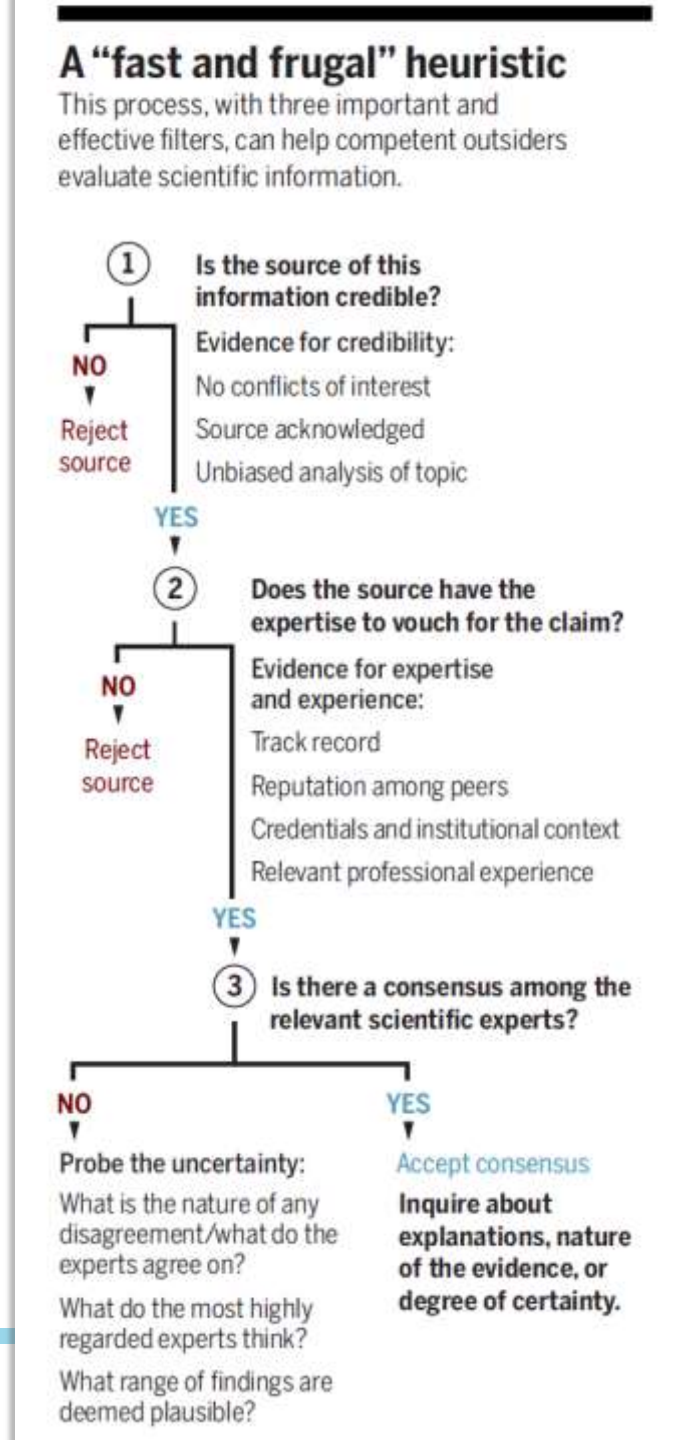

We are lucky! **– the Snowmass'21 allowed to come to a consensus on feasibility and R&D required for many (all) future colliders under consideration now, all thanks to the:**

Implementation Task Force

Implementation Task Force

https://arxiv.org/abs/2208.06030

- The Accelerator Frontier **Implementation Task Force (ITF)** is charged with developing metrics and processes to facilitate a comparison between collider projects:
  - Higgs/EW factories (12 options)
  - Lepton colliders with 3 TeV cme (8
  - Lepton and hh colliders 10
  - eh colliders (3 opti
- ITF addres):
  - Phys arameters
  - Size, c environment
  - Technic adiness, and R&D required
  - Cost and schedule

Combined experience in construction and commissioning of >20 accelerator projects


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REPORT


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Below I mostly follow T.Roser presentation in Seattle

The ITF Report on MuCollider (1)

1. (Snowmass Energy Frontier) HEP aspires 10+ TeV cme/parton
2. Muon Collider is a viable option for the HEP future:
   - Combines discovery reach and precision physics
   - x7 energy reach vs *pp* – eg 14 TeV *μμ* = 100 TeV pp
   - *μ*'s do not radiate when bent → acceleration in rings:
     - *Smaller(est) footprint* – 10-15 km vs 50-100 km
     - *(Best) power efficiency* – *Lumi/Power* grows with energy
     - *Low(est) cost* – due to compactness and power efficiency
3. 3-10 TeV Muon Collider can be designed in ~10-15 yrs, built in 20-25 yrs from T_0, cost range 12-18 2021B$ (7-12B$ for 3TeV)
   – *Past studies in the US and UK (+now in CERN) – big advance*
   – *No insurmountable obstacles identified*
   – *But challenging technologies and design require R&D*

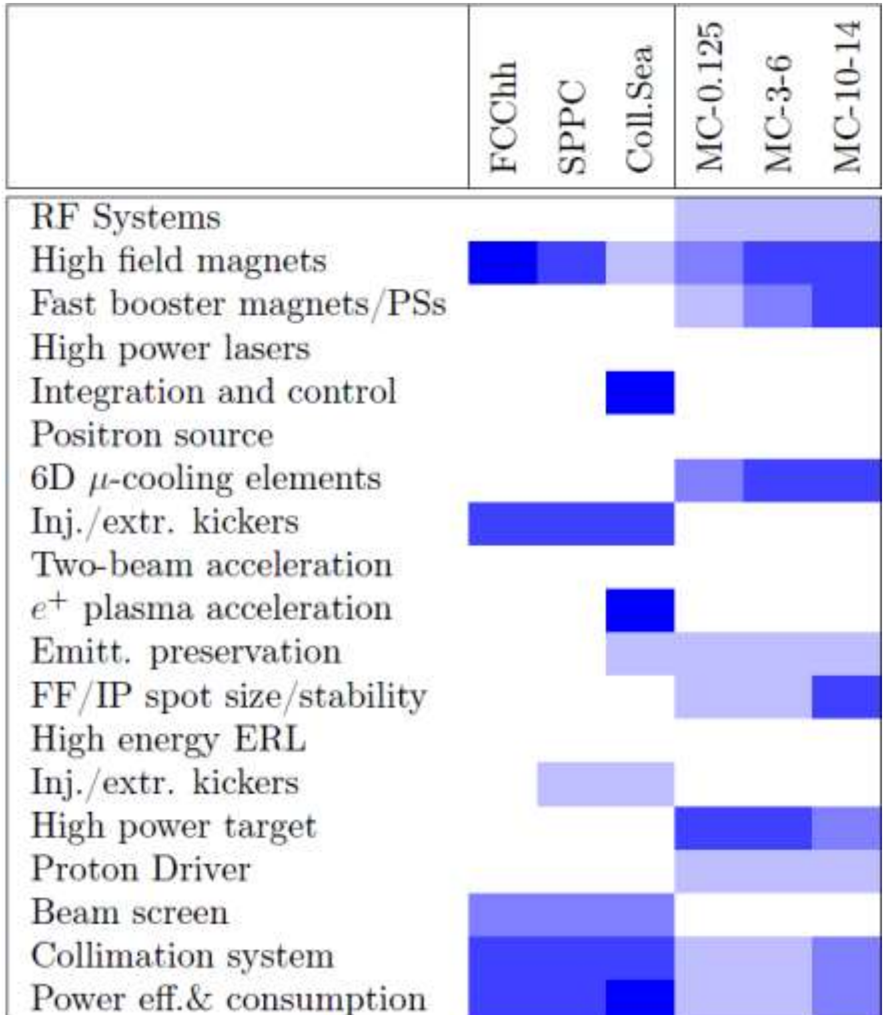
ITF's Look Beyond Higgs Factories

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

ITF Report – T.Roser, et al, arXiv:2208.06030

The ITF Report on MuCollider (2):

4. Technical Risk Registry of Accelerator Systems/Components



Total for muon colliders:
11 lines
total “Weight” = 5 ¼

For FCC hh/CEPC:
6 lines , W=3 ¾

For CLIC-3 TeV:
7 lines, W = 3 ¾

Plasma WFA:
11 lines , W = 9 ¼

Table 8: Lighter colors indicate progressively higher TRLs (less risk), white is for either not significant or not applicable.

The ITF Report on MuCollider (3):

5. TRL category , design status and risk

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
MC-3	III					3
MC 10-14	IV					3
LWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3

Table 14: The first column "Design Status" indicates current status of the design concepts: I - TDR complete, II - CDR complete, III - substantial documentation; IV - limited documentation and parameter table; V - parameter table. Middle columns – TRLs, etc. The last column is for overall risk tier category: Tier 1 (lower overall technical risk) to Tier 4 (multiple technologies that require further R&D).... **MC is in the pack with FCChh/SPPC/CCC-3TeV**

The ITF Report on MuCollider (4):

6. Complexity

Complexity is about

Dissimilarity

magnets, RF, plasma, cooling, drivers, FF, etc

and Scale

# of elements in each category (log)

Affects:

Construction complexity

Commissioning time

Operational reliability

Proposal Name	Complexity
ILC (3 TeV)	II
CLIC (3 TeV)	III
CCC (3 TeV)	II
ReLiC (3 TeV)	III
MC (3 TeV)	II
LWFA (3 TeV)	II
PWFA (3 TeV)	II
SWFA (3 TeV)	II
MC (14 TeV)	III
LWFA (15 TeV)	III
PWFA (15 TeV)	III
SWFA (15 TeV)	III
FCC-hh (100 TeV)	II
SPPC (125 TeV)	II

Table 16: Complexity of colliders: Category I (FCCee, ILC) to III.

MC-3 is similar to CLIC-0.38 (Cat. II)

MC-14 is less complex than CLIC-3 (Cat. III)

The ITF Report on R&D (5):

7. Cost of R&D – Table 15 – eg CLIC 500M$ over ~25 years

CLIC key R&D items	***Muon Collider key R&D items***
>100 MV/m RF structures	6D muon cooling
PETS (ON/OFF power extr.)	Fast accel. options (RCS, RLA)
Drive beam accelerator	Proton driver accelerator
Combiner ring/delay loops	Targetry and collection solenoids
Damping rings	Combining bunches
Polarized e-	RF μ acceleration and sources
Linac stabilization/jitter control	High field collider magnets
Final focus system	Final focus system/MC optics
Spent beam system	Neutrino flux dilution
Design incl MDI	Design incl MDI
CTF/CTF-2/CTF-3 facilities	**MC cooling/accel demo facility**

https://cds.cern.ch/record/932030/files/ab-2006-012.pdf

Muon Collider Forum Report https://arxiv.org/abs/2209.01318

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Are those “miracles”?! Not denying technical risks – it’s more like a “laundry list“!

Near-Term Priorities (now – 2030)

1. Get P5 approval of the National Integrated Future Collider R&D Program (assuming MC is part of the NIFC-RDP)
2. Join IMCC:
   - Our priority is pre-CDR design of the 6-10 TeV FNAL site MC by 2030
   - Contribute to the CERN demo facility design/construction (by'2030) /ops
3. (Assuming MC is part of the NIFC-RDP) the MC R&D in the US in this decade (2023-2030) can concentrate on:
   - *Feasibility study and pre-CDR of 6-10 TeV MC @ FNAL*
   - *MDI and detector work, develop plan for CDR/TDR phase in 30's*
   - *Technical elements:*
     - *12-16 T large aperture dipole and its tilting support (design/prototype)*
     - *1-3 kT/s HTS fast ramping magnets (design, prototype, tests)*
     - *4 MW proton targets (design/prototype)*
     - *30-40 T HTS target solenoid solutions*
     - *Develop elements (tbd) for CERN cooling demo facility*

Specific Qs (Sergo J, et al)

1. what could be done in an R&D phase that would be convincing essentially? and how much would it cost compared to the final facility?
2. what are the most urgent accelerator R&D areas
3. what is a reasonable funding for R&D program in the next 5 years (can use IMCC estimates)
4. what R&D is needed for 10 TeV that is not needed for ~3 TeV

What could be done in an R&D phase that would be convincing essentially? and how much would it cost compared to the final facility?

i. All key technical elements prototyped and tested, all key technologies (like cooling, neutrino mitigation and fast acceleration) demonstrated, and self-consistent design report compiled.

ii. Altogether (for the next ~15 years, from all collaborators) about **400-600M$** (incl. ~1500 FTE-yrs and demo facilities), that is about **5%** of the total MC facility cost

What are the most urgent accelerator R&D areas

i) design work; ii) 6D and final cooling; iii) fast acceleration systems; iv) SC dipoles; v) muon production

What is a reasonable funding for R&D program in the next 5 years (can use IMCC estimates)

i. In the US: ~40-50M$ (US accounting, incl. ~50-100 FTE-yrs)

ii. Assuming ~70MEur at CERN/Europe: some 200-450 FTE-yrs + 10-20 MCHF of M&S (before/not incl. facility construction)

What R&D is needed for 10 TeV that is not needed for ~3 TeV

Seemingly, just one - the 3 TeV final focus parameters are within the existing Nb3Sn technology, while the 10+ TeV collider might need HTS magnets (= needs R&D).

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Thanks for your attention!

Questions?