Design Initiative for a 10 TeV pCM Wakefield Collider

A Community-Driven Approach

E. Esarey, C. Geddes, **S. Gessner**, G. Ha,
M. Hogan, C. Jing, X. Lu, R. Margraf-O'Neal,
B. O'Shea, J. Osterhoff, P. Piot, J. Power,
C. Schroeder, J. van Tilborg, J.-L. Vay

SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB
Argonne NATIONAL LABORATORY
Stanford University
U.S. DEPARTMENT OF ENERGY

Introduction

This is a plan for a Design Study of a **10 TeV** parton-center-of-mass (pCM) collider based on **wakefield accelerator (WFA) technology**.

The initiative comes from the 2023 US P5 Report, but it is a **global** undertaking.

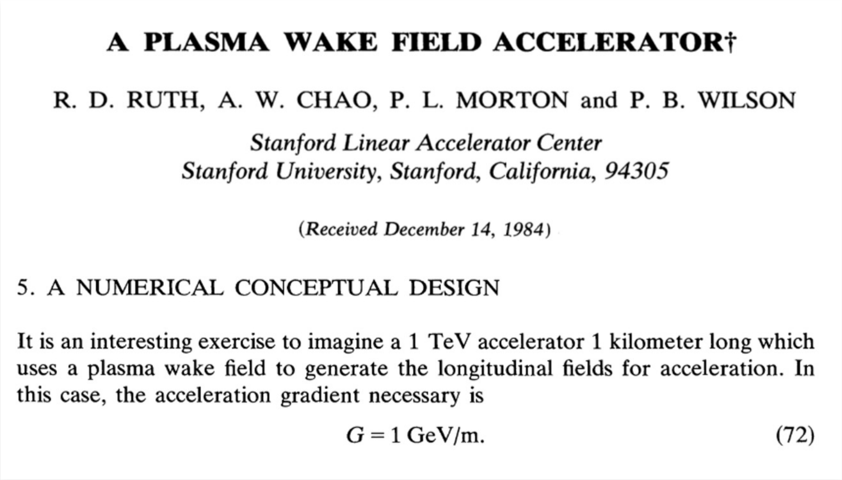
- We will leverage ongoing efforts by ALEGRO and HALHF.

This is an AAC-wide **community** effort:

- The details of this study are under development. You can help to define the study by joining this effort!
- We will solicit your input throughout the workshop, including during a dedicated discussion session Tuesday evening.

Collider considerations have been part of AAC for decades

1984



A PLASMA WAKE FIELD ACCELERATOR†

R. D. RUTH, A. W. CHAO, P. L. MORTON and P. B. WILSON

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

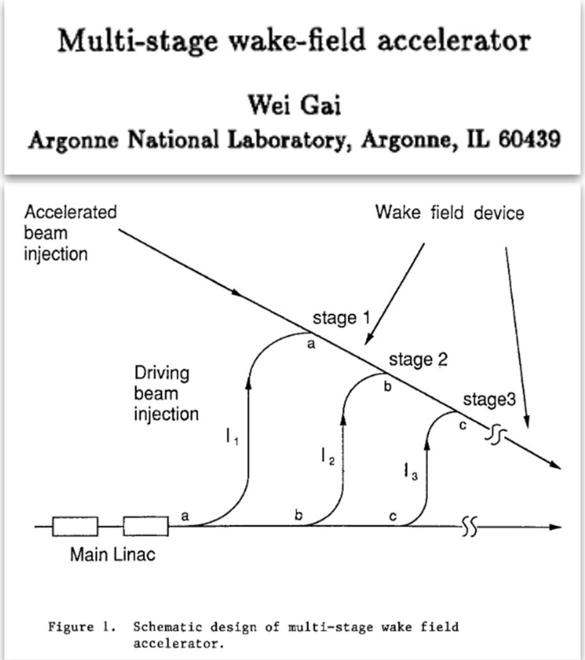
(*Received December 14, 1984*)

5. A NUMERICAL CONCEPTUAL DESIGN

It is an interesting exercise to imagine a 1 TeV accelerator 1 kilometer long which uses a plasma wake field to generate the longitudinal fields for acceleration. In this case, the acceleration gradient necessary is

$$G = 1\ \mathrm{GeV/m}. \qquad (72)$$

1989

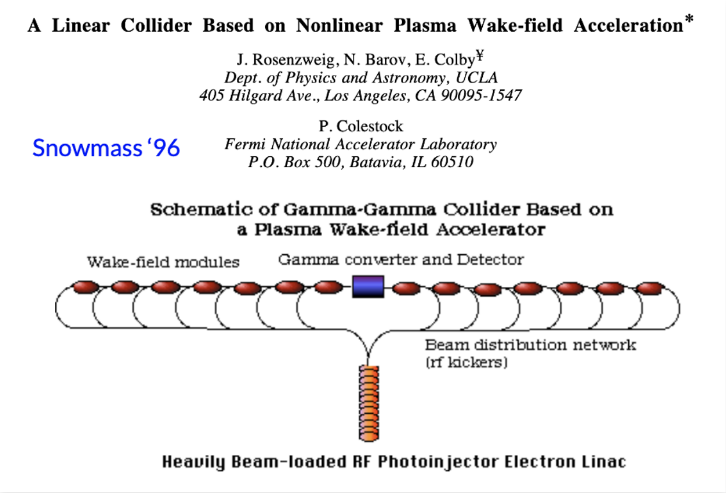


Multi-stage wake-field accelerator

Wei Gai
Argonne National Laboratory, Argonne, IL 60439

Figure 1. Schematic design of multi-stage wake field accelerator.

1996



A Linear Collider Based on Nonlinear Plasma Wake-field Acceleration*

J. Rosenzweig, N. Barov, E. Colby¥
Dept. of Physics and Astronomy, UCLA
405 Hilgard Ave., Los Angeles, CA 90095-1547

P. Colestock
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510

Snowmass '96

Schematic of Gamma-Gamma Collider Based on a Plasma Wake-field Accelerator

1996

Studies of Laser-Driven 5 TeV e^+e^- Colliders in Strong Quantum Beamstrahlung Regime

M. Xie[1], T. Tajima[2], K. Yokoya[3]
and S. Chattopadhyay[1]

[1] *Lawrence Berkeley National Laboratory, USA*
[2] *University of Texas at Austin, USA*
[3] *KEK, Japan*

A History of Design

Beam-Driven Plasma

Rosenzweig, Snowmass 1996

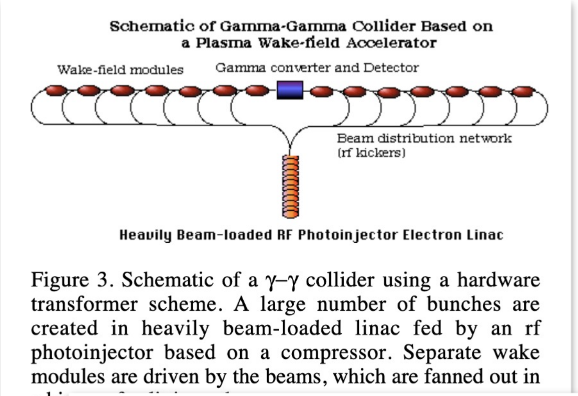
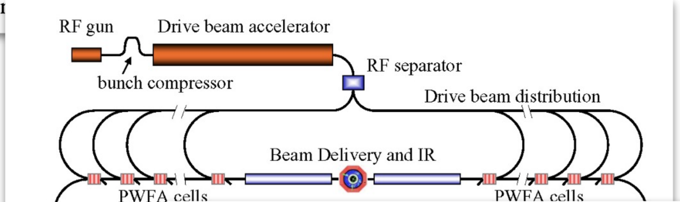


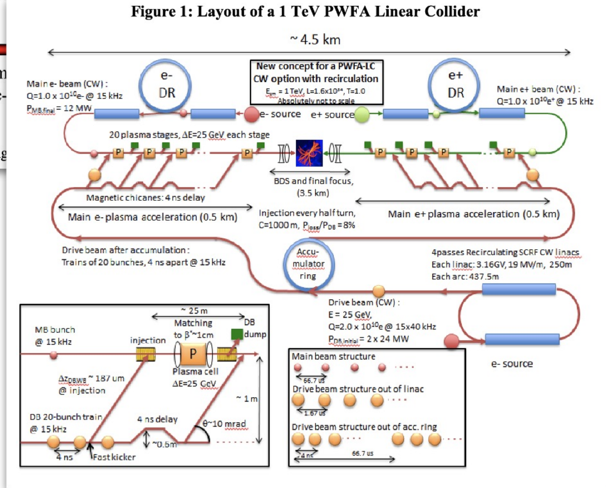
Figure 3. Schematic of a γ–γ collider using a hardware transformer scheme. A large number of bunches are created in heavily beam-loaded linac fed by an rf photoinjector based on a compressor. Separate wake modules are driven by the beams, which are fanned out in a bi

Seryi, PAC09 2009



Adli, Snowmass 2013

Figure 1: Layout of a 1 TeV PWFA Linear Collider



Structure-Based Acceleration

Gai, AAC 1998

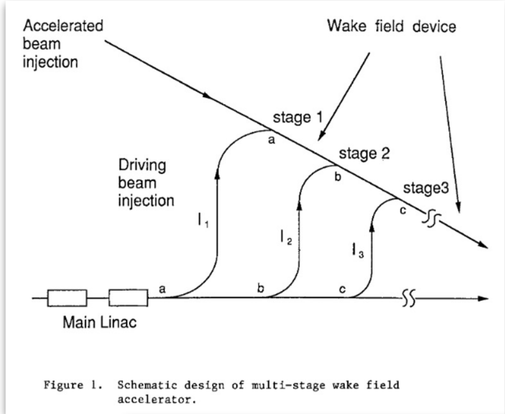
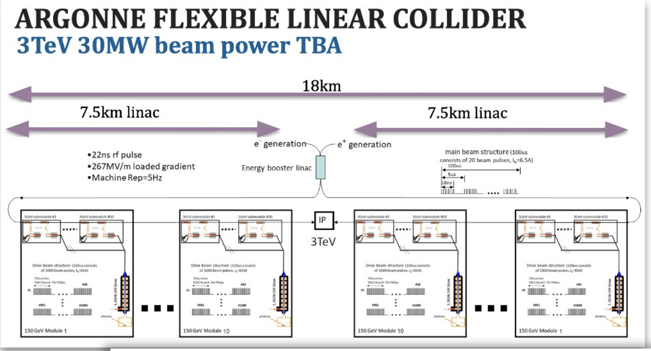


Figure 1. Schematic design of multi-stage wake field accelerator.

Jing, IPAC 2013

ARGONNE FLEXIBLE LINEAR COLLIDER

3TeV 30MW beam power TBA



- 22ns rf pulse
- 267MV/m loaded gradient
- Machine Rep=5Hz

Jing, JINST 2022

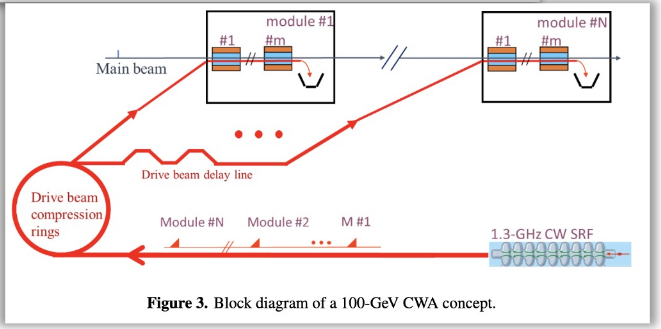
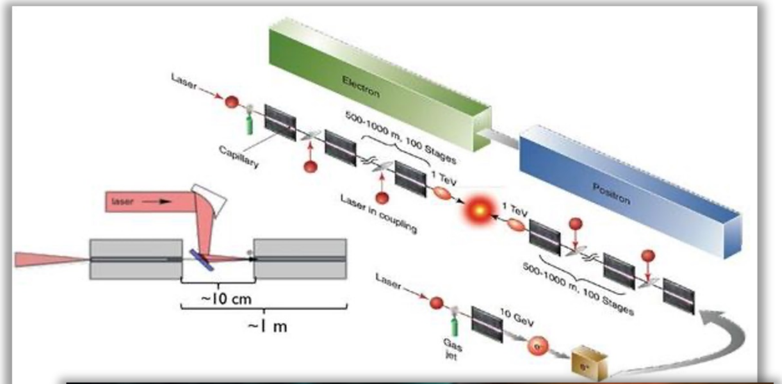


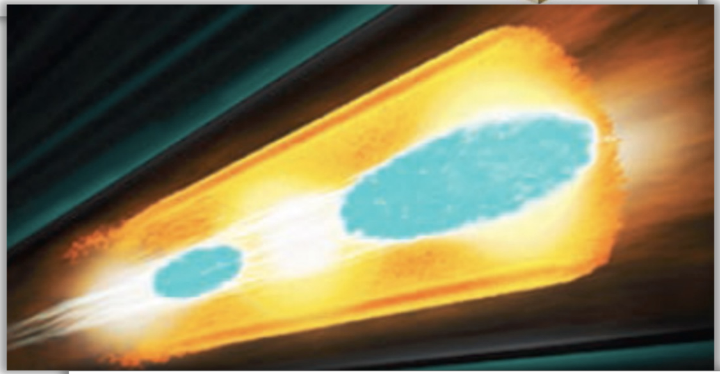
Figure 3. Block diagram of a 100-GeV CWA concept.

Laser-Driven Plasma

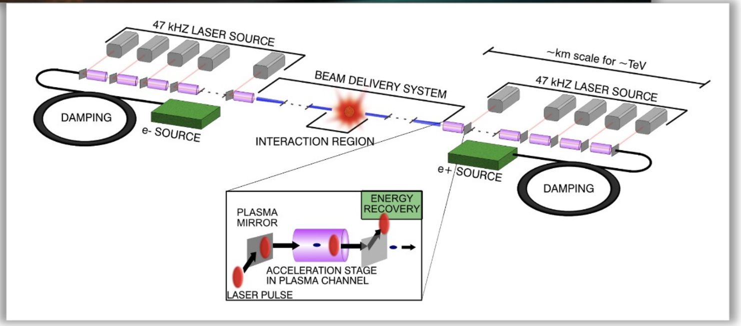
Leamans, Phys. Today 2023



Schroeder, NIM A 2016



Schroeder, JINST 2023



The 2020-2023 Snowmass and P5 Process

2020

2021

2022

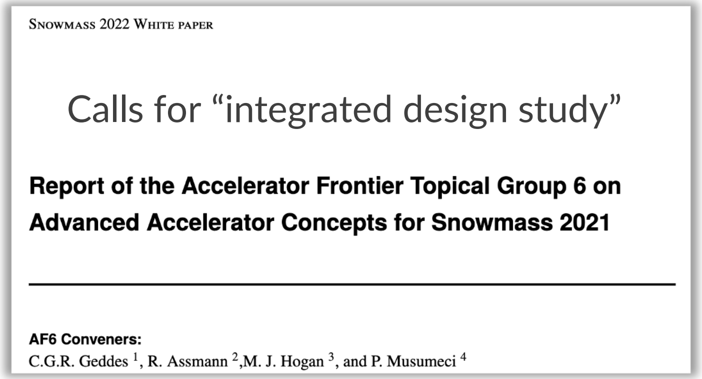
2023

Snowmass 2021

Snowmass Letter of Intent submissions began Spring 2020

Deadline for white papers and Community Summer Study pushed to 2022

Hundreds of physicists gather at the University of Washington for CSS in 2022



Snowmass 2022 White paper

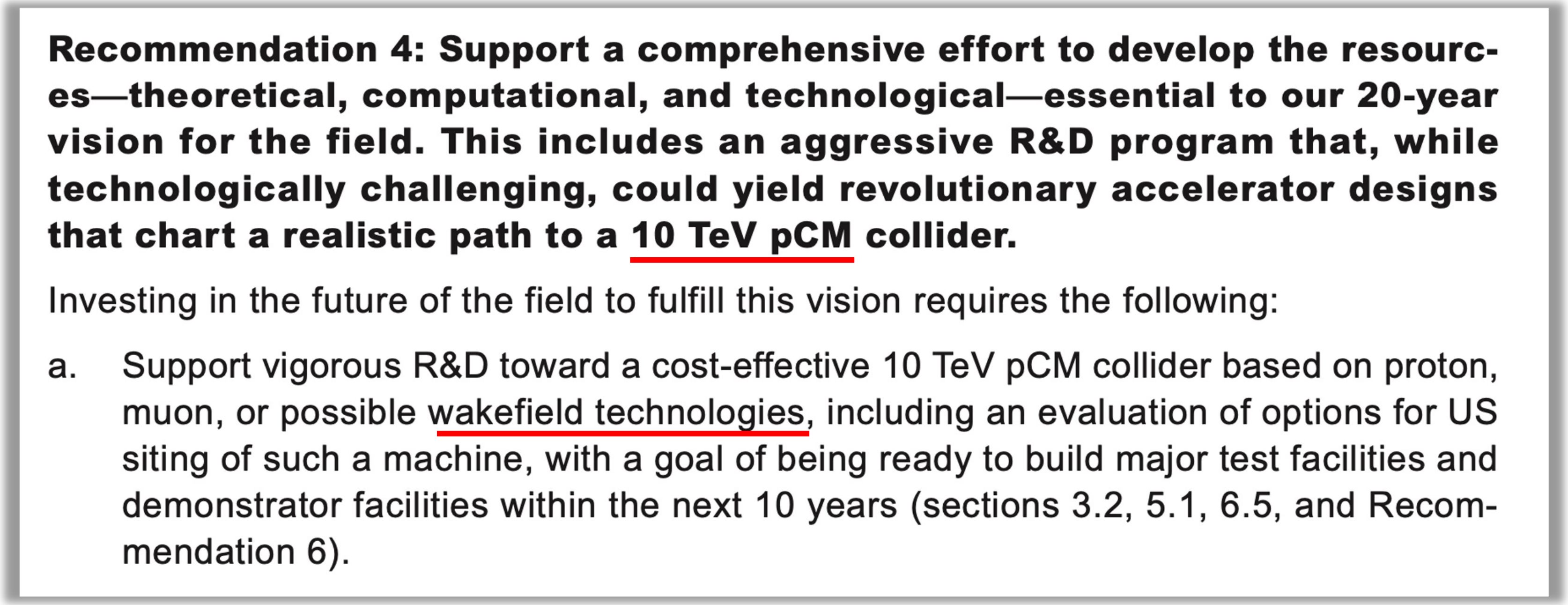
Calls for “integrated design study”

Report of the Accelerator Frontier Topical Group 6 on Advanced Accelerator Concepts for Snowmass 2021

AF6 Conveners:
C.G.R. Geddes [1], R. Assmann [2],M. J. Hogan [3], and P. Musumeci [4]

The P5 panel deliberates throughout 2023 and delivers the report in December

Recommendations from the P5 Process



Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

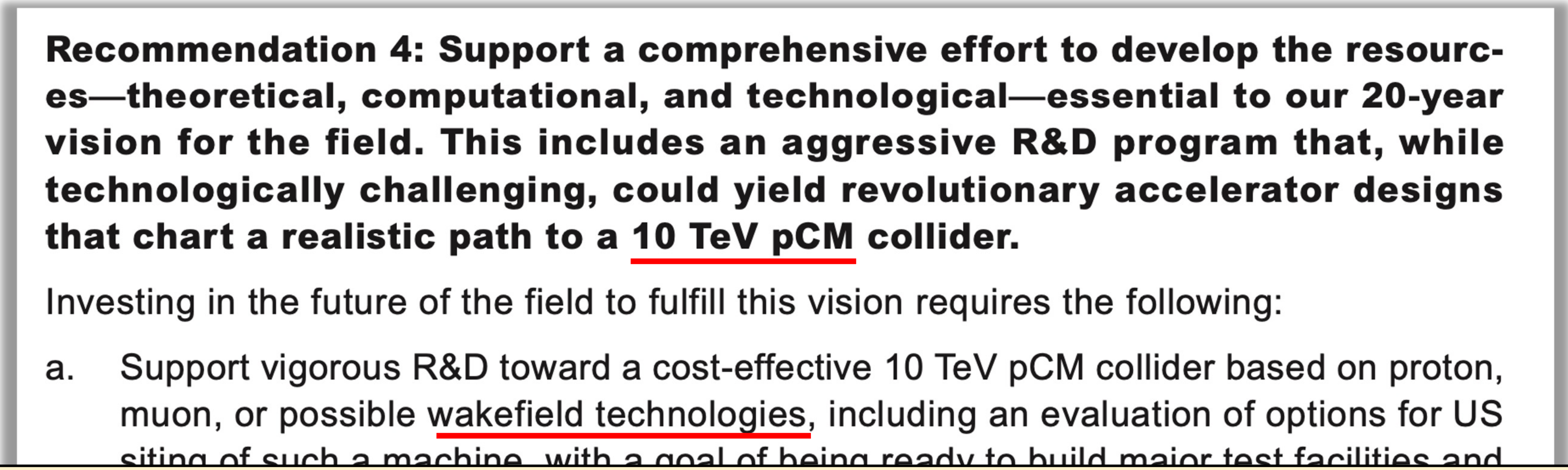
Investing in the future of the field to fulfill this vision requires the following:

a. Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years (sections 3.2, 5.1, 6.5, and Recommendation 6).

Section 6.4.1 Particle Physics Accelerator Roadmap:

Wakefield concepts for a collider are in the early stage of development. A critical next step is the delivery of an **end-to-end design concept**, including cost scales, with self-consistent parameters throughout. This will provide an important yardstick against which to measure progress along this emerging technology path.

Recommendations from the P5 Process



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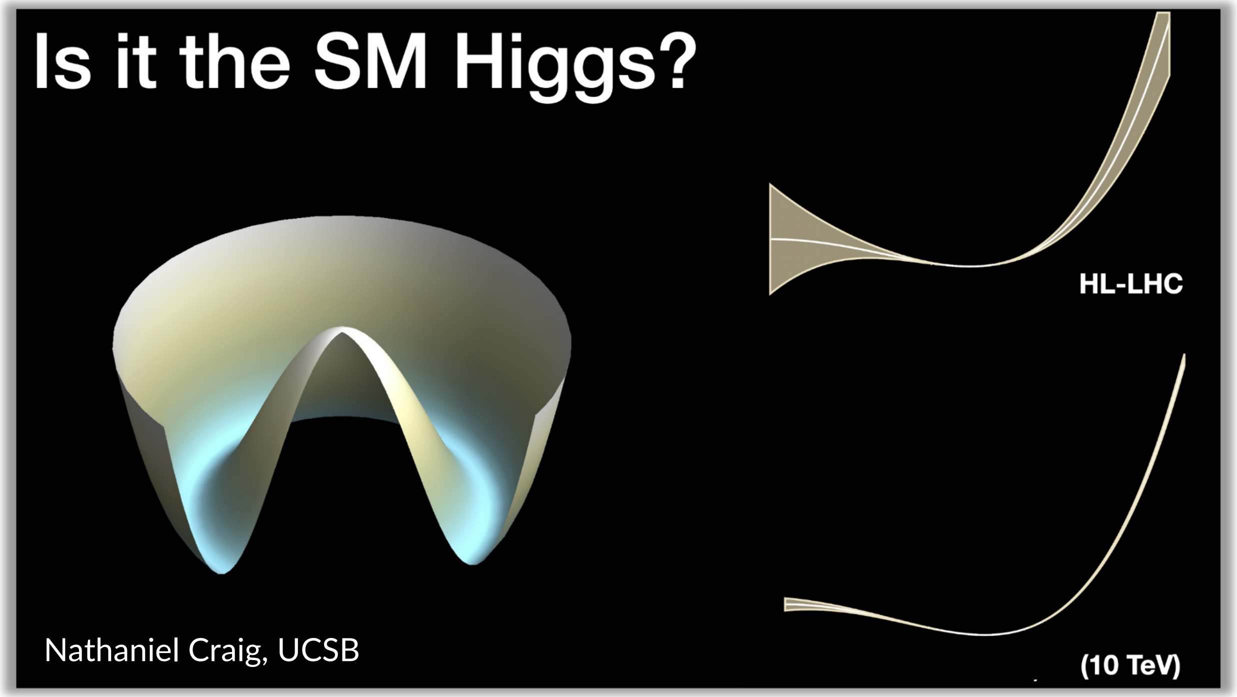
The U.S. AAC community, in partnership with colleagues around the world, will pursue an end-to-end design study for a 10 TeV pCM collider using beam-driven plasma, laser-driven plasma, and structure-based accelerator technology.

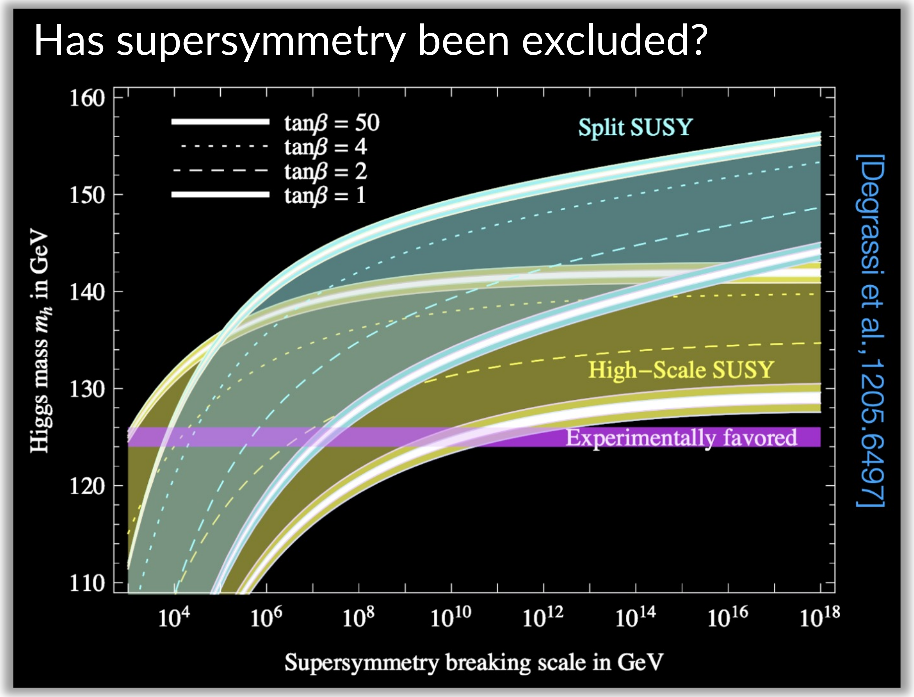
Wakefield concepts for a collider are in the early stage of development. A critical next step is the delivery of an **end-to-end design concept**, including cost scales, with self-consistent parameters throughout. This will provide an important yardstick against which to measure progress along this emerging technology path.

First: Why 10 TeV?



Is it the SM Higgs?

Nathaniel Craig, UCSB



Has supersymmetry been excluded?

[Degrassi et al., 1205.6497]

A 10 TeV pCM collider is a discovery machine that will allow us to explore nature at energy scales far beyond the capabilities of the LHC.

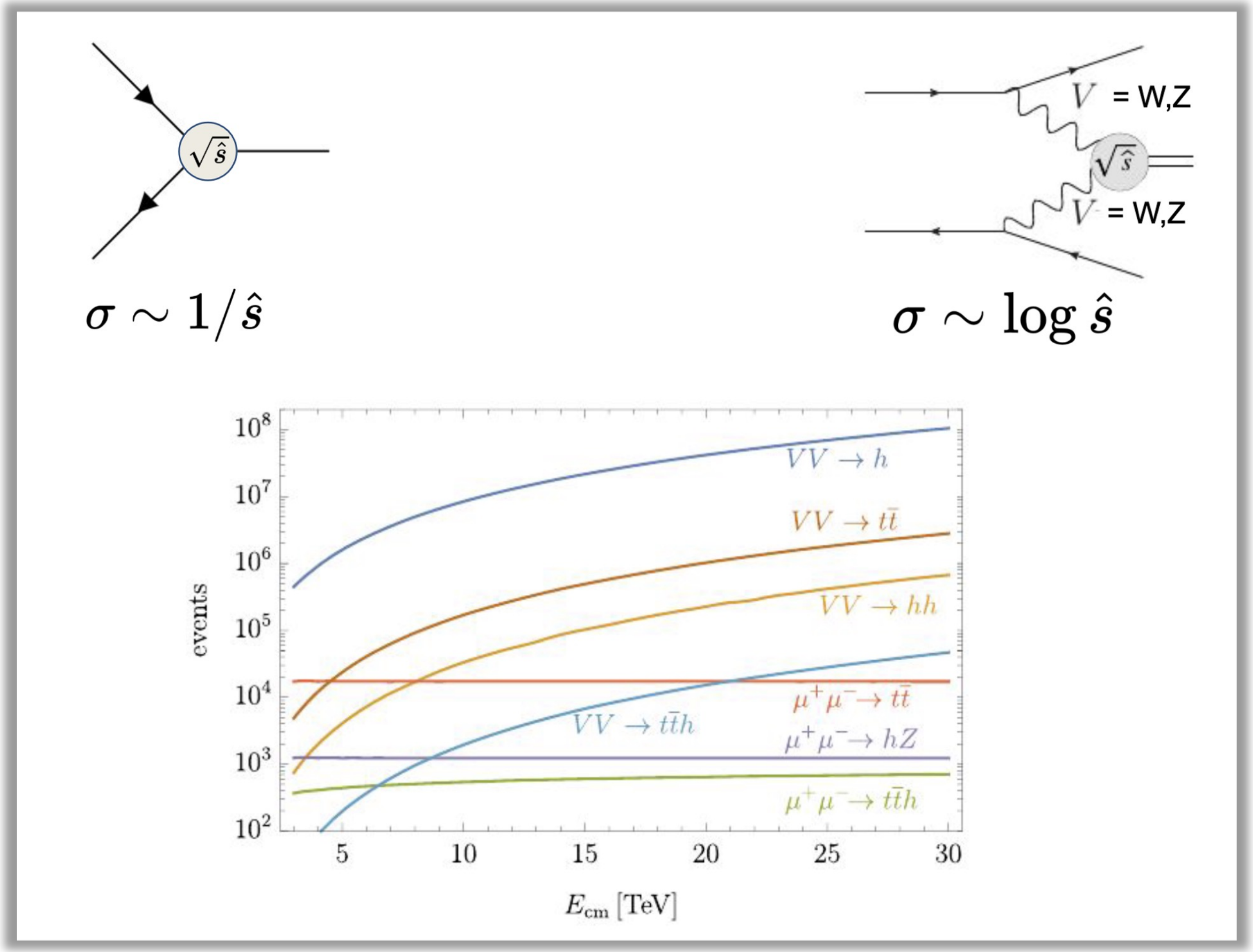
10 TeV: A new paradigm

At 10 TeV, there is a very high cross section for Vector Boson Fusion (VBF).

Most of the luminosity comes from the VBF process, rather than s-channel annihilation traditional associated with electron-positron linear colliders.

VBF provides the largest production channels for high-energy e^+e^-, e^-e^-, $\gamma\gamma$, and $\mu^+\mu^-$ colliders.

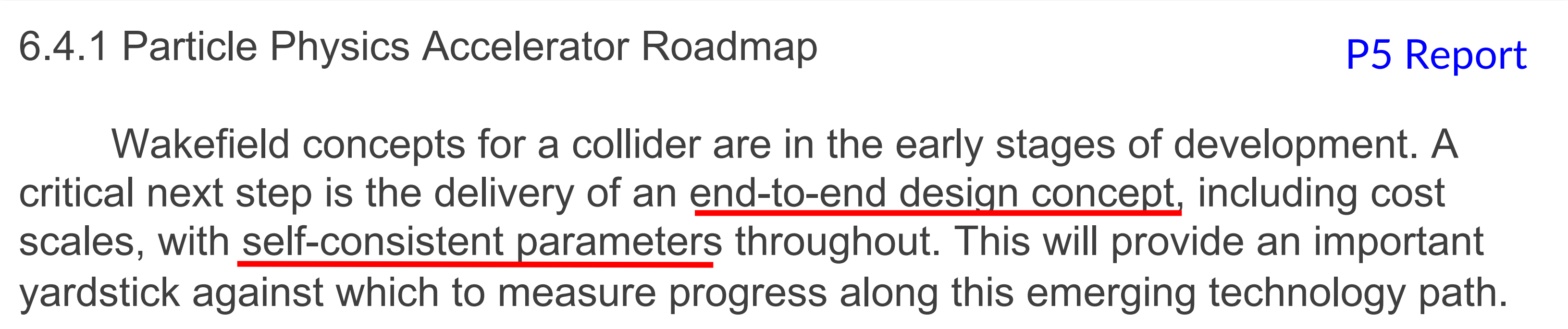
A 10 TeV linear collider does not have to be an electron-positron collider.



Simone Pagan Griso, LBNL and
Muon Collide Forum Report
arXiv:2209.01318

A New Study

A New Study



6.4.1 Particle Physics Accelerator Roadmap

P5 Report

Wakefield concepts for a collider are in the early stages of development. A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout. This will provide an important yardstick against which to measure progress along this emerging technology path.

In responding to the P5 call, we propose a study with the following features:

- Self-consistent beam parameters.
- End-to-end design with reduced models where appropriate.
- Environmental impact considered throughout.
- Close partnership with HEP theorists and experimentalists to define a physics program with commensurate machine and detector parameters.
- Community-driven design process.

The study will yield a unified design concept that points a path forward.

Unified Design Concept

The 10 TeV pCM WFA Design Study is a unified activity with a unified product: *A paper study on the end-to-end design concept of a WFA collider.*

The unified concept is a 10 TeV machine that collides e^+e^-, e^-e^-, or $\gamma\gamma$ at the target luminosity.

- Our methodology is consistent with multiple designs based on different technology options, or a collider that is comprised of multiple accelerator technologies!
- We assume that parts of the machine will be based on traditional technologies.

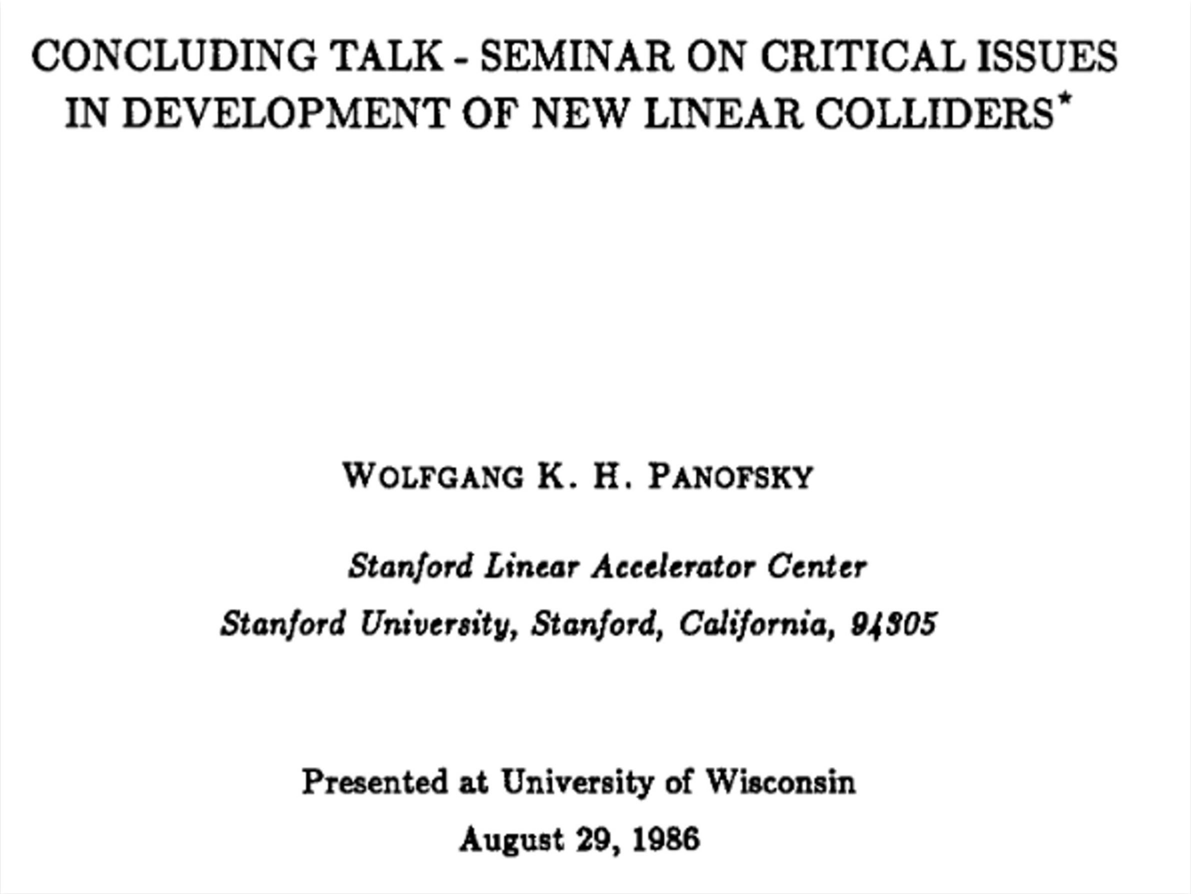
Multiple paths are a strength (reflects the current approach towards colliders of HEP as a whole) and it acknowledges our humility.

- We do not yet know which accelerator technologies are the most feasible.

We will use community-defined metrics and self-consistency to adopt the most appropriate parameters for the machine.

What goes into collider design?

Symposium on Advanced Accelerator Concepts, Madison, WI, 1986

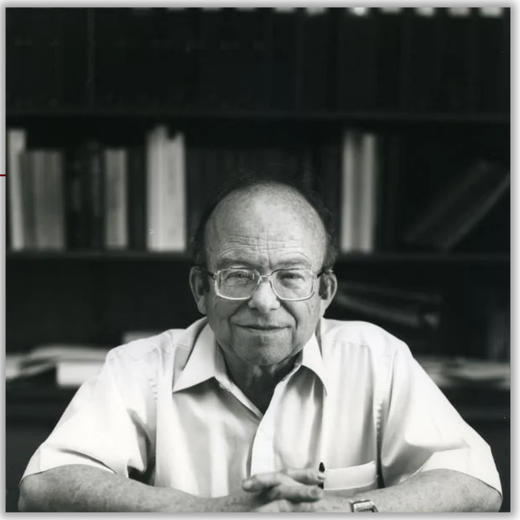


CONCLUDING TALK - SEMINAR ON CRITICAL ISSUES
IN DEVELOPMENT OF NEW LINEAR COLLIDERS*

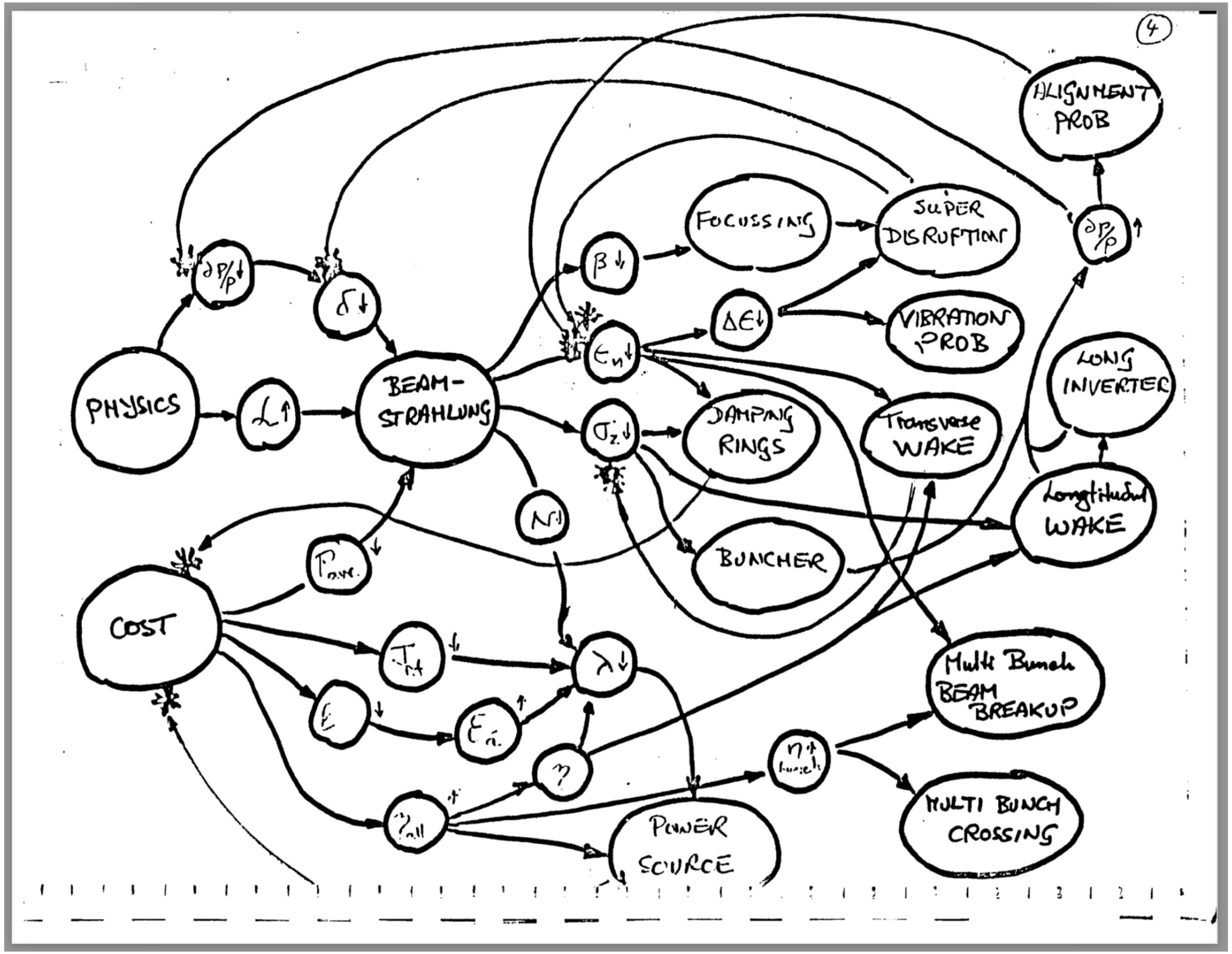
WOLFGANG K. H. PANOFSKY

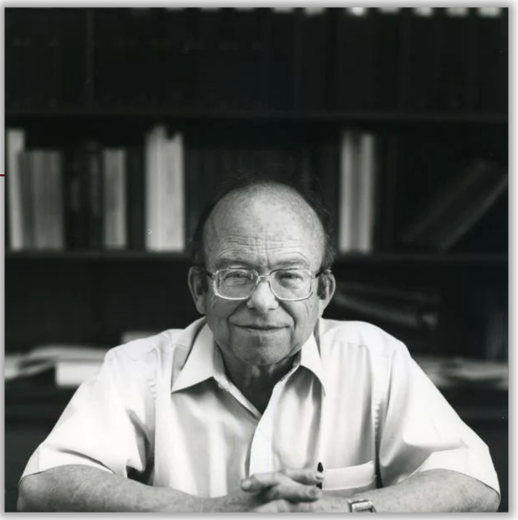
Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

Presented at University of Wisconsin
August 29, 1986

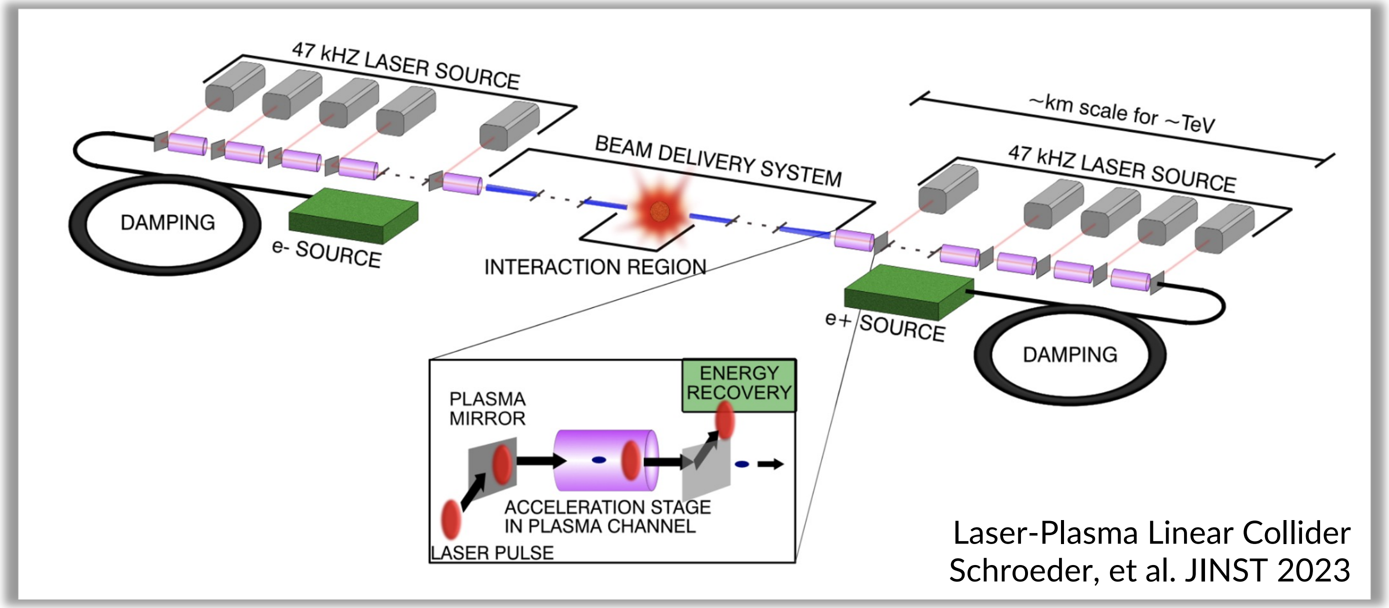


What goes into collider design?





What is an End-to-End Design Study?



Laser-Plasma Linear Collider
Schroeder, et al. JINST 2023

Challenges

Stability

Energy Recovery

Repetition Rate

Efficiency

Geometric gradient

Positron Acceleration

Staging

Beam Delivery Systems

Jitter budget

How do these components fit together?

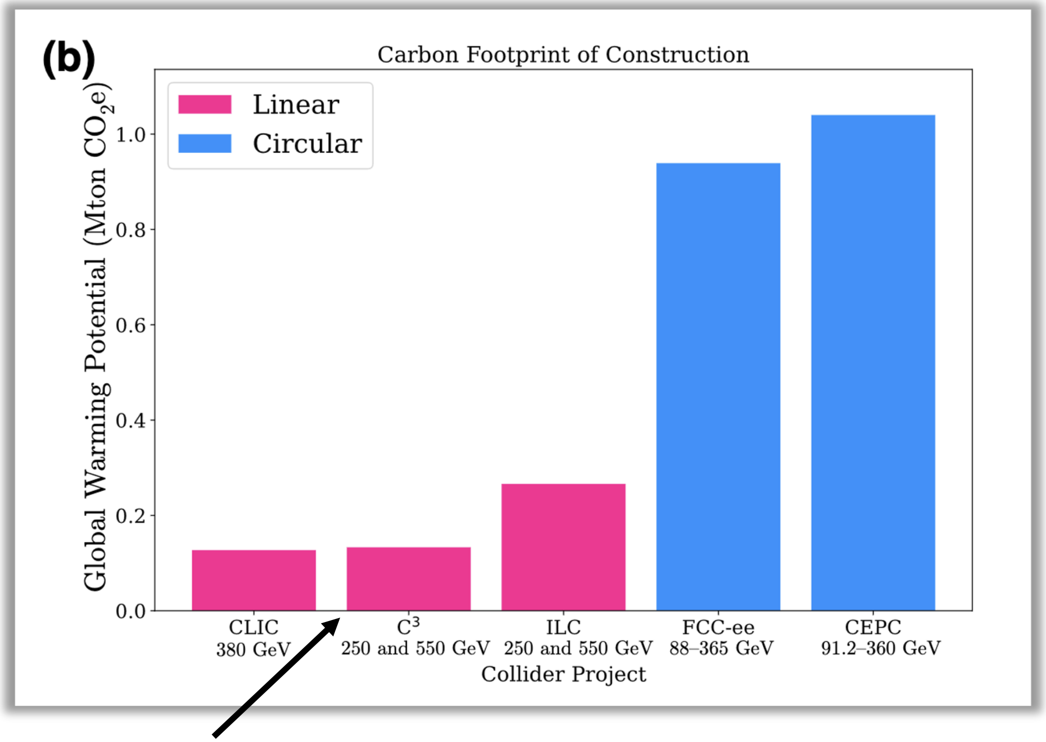
Environmental Impact: A “new” constraint

Environmental considerations are an explicit constraint on future colliders designs.

In Europe, the war in Ukraine has brought energy consumption considerations to the foreground of the upcoming European Strategy for Particle Physics (ESPP).

The carbon impact of colliders comes from:
- Construction
- Operation

PRX ENERGY 2, 047001 (2023)



Compact colliders use less concrete!

Environmental Impact: A “new” constraint

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The carbon impact of colliders comes from:

- Construction
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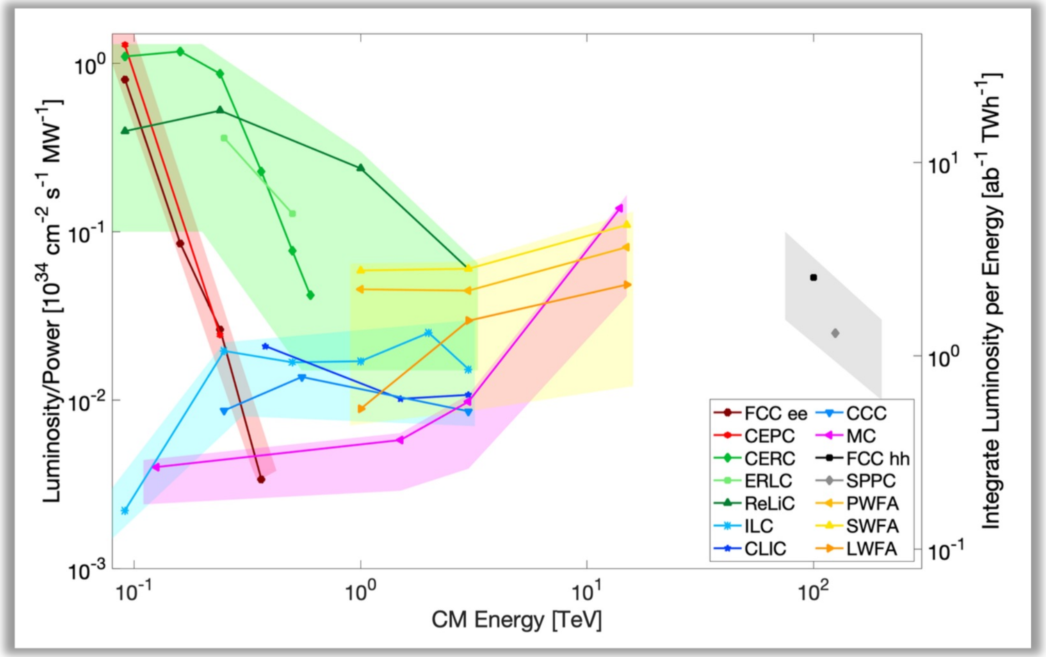
ITF Report, JINST (2023)



The key metric is “luminosity-per-beam-power”.

Environmental Impact: A “new” constraint

For a given luminosity and energy target, we can place strong constraints on collider designs.

Geometric Luminosity

$$\mathcal{L} = \frac{f N^2}{4\pi\sigma_x\sigma_y}$$

Figure of Merit:
Luminosity per beam power

$$\frac{\mathcal{L}}{P_{tot}} = \frac{\eta N}{4\pi\sigma_x\sigma_y E_b}$$

10 TeV collider: E_b = 5 TeV and $\mathcal{L}$ = 10^{35} cm^{-2} s^{-1}

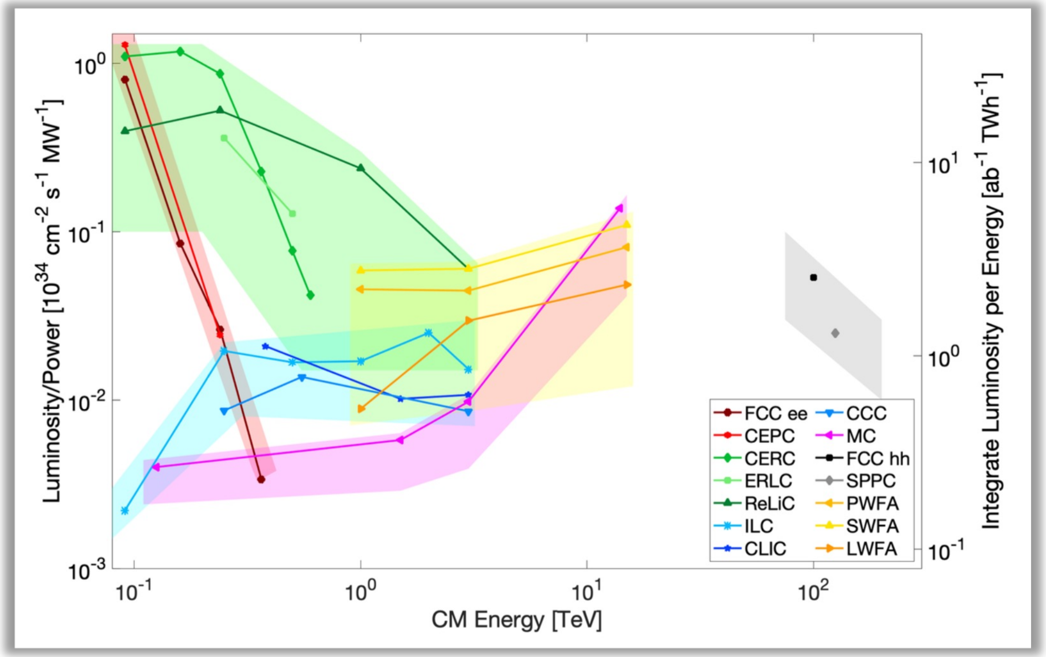
$$P_{tot} = \underbrace{\mathcal{L}E_b}_{\text{Fixed}} \frac{4\pi\sqrt{\beta_x\varepsilon_x}\sqrt{\beta_y\varepsilon_y}}{\eta N}$$

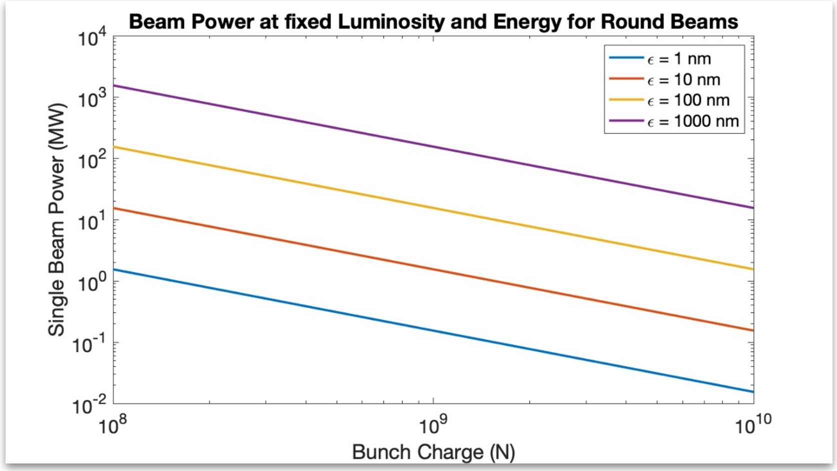
Minimize

Maximize

For a fixed luminosity and collision energy, higher bunch charges are favored.

ITF Report, JINST (2023)





But wait! Beamstrahlung . . .

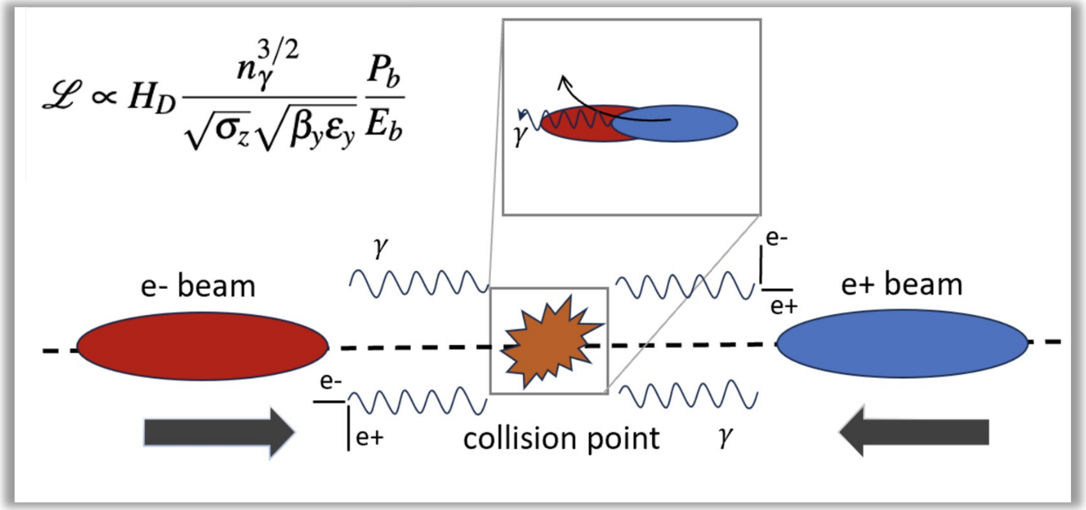
Beamstrahlung (radiation during collisions) reduces the energy of the colliding particles. This is a significant effect at 10 TeV.

Traditional linear colliders desire low beamstrahlung:

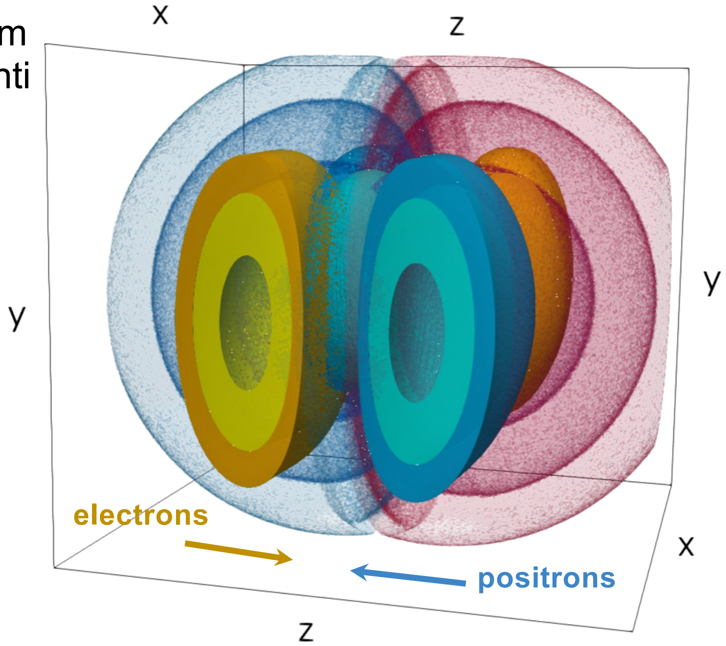
- High-charge bunches not necessarily favored.
- Flat beams are favored.

At 10 TeV, large beamstrahlung may be inevitable. We will consider:

- e^+e^-, e^-e^-, $\gamma\gamma$ collisions
- Round beam collisions in addition to flat beam collisions.



WarpX Sim
A. Formenti
LBNL



Collider designs examine tradeoffs at every stage.

Study Details

The following slides provide an outline of the design process.

All details are tentative!

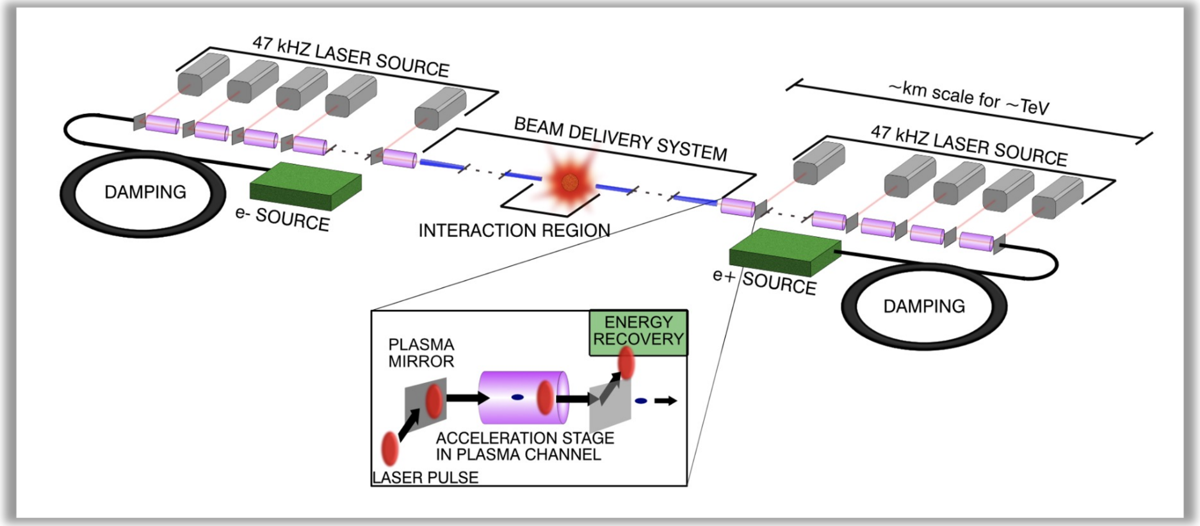
It is up to the community to define the study.

Working Groups

Working groups are connected to collider components:

- Sources (incl. damping rings)
  Drivers
  - Laser
  - Beams - SWFA
  - Beams - PWFA

  Linacs (including staging)
  - LWFA
  - SWFA
  - PWFA
- Beam delivery system
- Beam-beam interactions
- Beam diagnostics
- Machine-detector interface
- HEP detector
- HEP physics case
- Environmental impact



Green = Advanced acc. technology independent

Orange/blue/purple = technology specific

Red = HEP and broader community

The community will decide if this is the appropriate set of working groups.

Charge to the Working Groups

1. Maintain a bi-weekly cadence of meetings.

2. Perform a review of technology options, including “traditional” accelerator technologies.

3. Develop metrics – how well does a given technology perform?
    - Gradient
    - Stability
    - Efficiency
    - Experimental demonstrations

Example: Particle Sources Working group

Technology metrics:

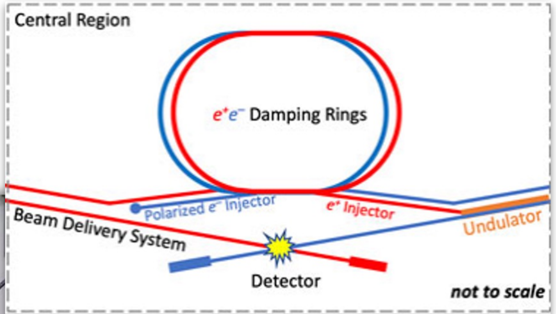
- Bunch charge
- Emittance
- Brightness
- Stability
- Experimental demonstrations

The development of metrics by each working group will inform the global design metrics for the colliders.

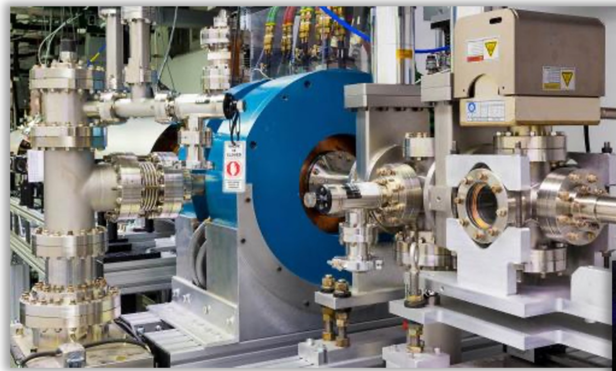
Working groups will then reconsider their technologies based on global metrics.

Possible Technologies:

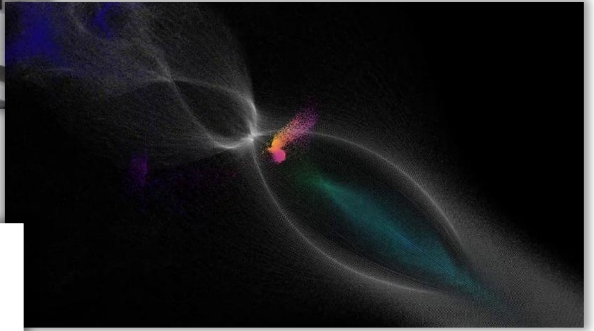
Damping rings



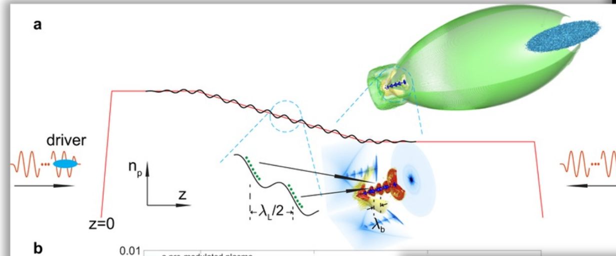
RF Photocathode



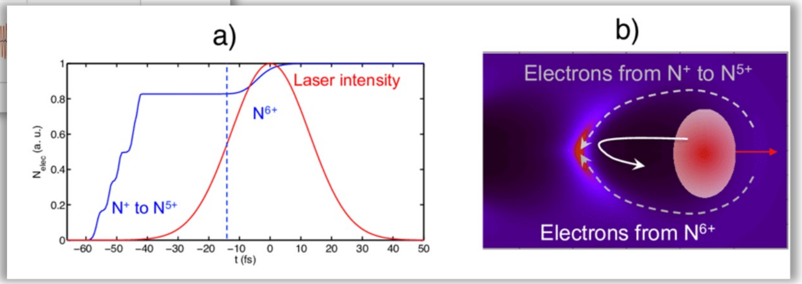
Trojan Horse



Downramp Injection



Ionization Injection



Tentative Study Timeline

Ongoing	1 year	2 year	3 year	4 year
Study organization.	Unified study of SWFA/PWFA/LWFA for electron arm of linac	Review tech options and converge on accelerator concepts.	Collaboration on designs and self-consistent parameters.	End-to-end design study report due sometime in 2028.
Solicit input from HEP physicists on e^+e^-, e^-e^-, $\gamma\gamma$ collisions.	Intensify engagement on “traditional systems” and begin work on BDS, sources, etc	Review options and converge on HEP collider type (e^+e^-, e^-e^-, $\gamma\gamma$)	Identification of required R&D and demo facilities	
	Provide community input for the next ESPP, March 2025	Intensify engagement with HEP on detectors		

Engagement beyond AAC

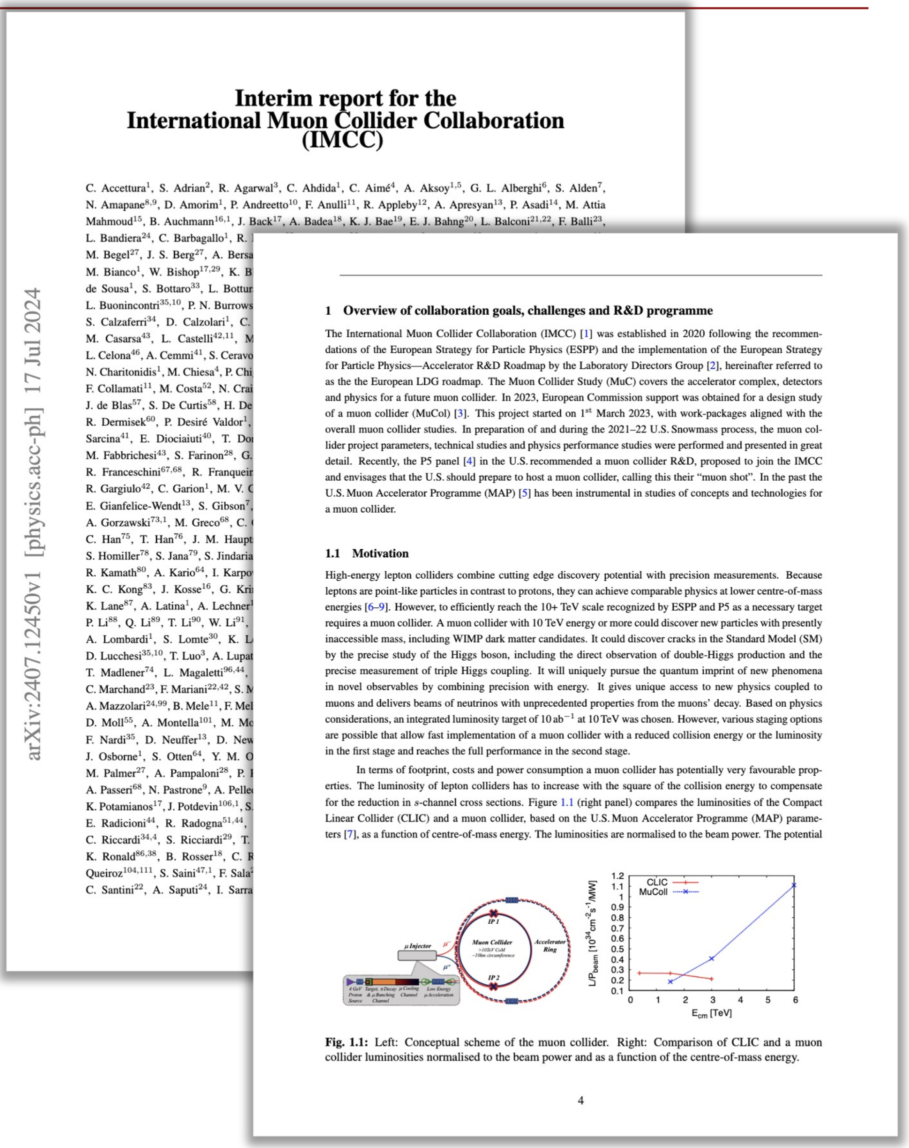
Tentative Deliverables

Year 1:
- WG metrics and technology options.
- Global metrics determined by community.
- Input to ESPP.

Year 2:
- Interim “metric-aware” design report.

Year 3:
- R&D and facilities roadmap.
- Design report updates.

Year 4:
- End-to-end design study on 10 TeV collider.



arXiv:2407.12450v1 [physics.acc-ph] 17 Jul 2024

Interim report for the International Muon Collider Collaboration (IMCC)

C. Accettura[1], S. Adrian[2], R. Agarwal[3], C. Ahdida[1], C. Aimé[4], A. Aksoy[1,5], G. L. Alberghi[6], S. Alden[7],
N. Amapane[8,9], D. Amorim[1], P. Andreetto[10], F. Anulli[11], R. Appleby[12], A. Apresyan[13], P. Asadi[14], M. Attia
Mahmoud[15], B. Auchmann[16,1], J. Back[17], A. Badea[18], K. J. Bae[19], E. J. Bahng[20], L. Balconi[21,22], F. Balli[23],
L. Bandiera[24], C. Barbagallo[1], R.
M. Begel[27], J. S. Berg[27], A.
M. Bianco[1], W. Bishop[17,29], K.
de Sousa[1], S. Bottaro[33], L.
L. Buonincontri[35,10], P. N. Burrows
S. Calzaferri[34], D. Calzolari[1], C.
M. Casarsa[43], L. Castelli[42,11],
L. Celona[46], A. Cemmi[41], S.
N. Charitonidis[1], M. Chiesa[4], P.
F. Collamati[11], M. Costa[52], N.
J. de Blas[57], S. De Curtis[58], H.
R. Dermisek[60], P. Desiré Valdor[1],
Sarcina[41], E. Diociaiuti[40], T.
M. Fabbrichesi[43], S. Farinon[28], G.
R. Franceschini[67,68], R.
R. Gargiulo[42], C. Garion[1], M. V.
E. Gianfelice-Wendt[13], S. Gibson[7],
A. Gorzawski[73,1], M. Greco[68], C.
C. Han[75], T. Han[76], J. M.
S. Homiller[78], S. Jana[79], S.
R. Kamath[80], A. Kario[64], I.
K. C. Kong[83], J. Kosse[16], G.
K. Lane[87], A. Latina[1], A.
P. Li[88], Q. Li[89], T. Li[90], W. Li[91],
A. Lombardi[1], S. Lomte[30], K.
D. Lucchesi[35,10], T. Luo[3], A.
T. Madlener[74], L. Magaletti[96,44],
C. Marchand[23], F. Mariani[22,42], S.
A. Mazzolari[24,99], B. Mele[11], F.
D. Moll[55], A. Montella[101], M.
F. Nardi[35], D. Neuffer[13], D.
J. Osborne[1], S. Otten[64], Y. M.
M. Palmer[27], A. Pampaloni[28], P.
A. Passeri[68], N. Pastrone[9], A.
K. Potamianos[17], J. Potdevin[106,1], S.
E. Radicioni[44], R. Radogna[51,44],
C. Riccardi[34,4], S. Ricciardi[29], T.
K. Ronald[86,38], B. Rosser[18], C.
Queiroz[104,111], S. Saini[47,1], F.
C. Santini[22], A. Saputi[24], I.

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1 Overview of collaboration goals, challenges and R&D programme

The International Muon Collider Collaboration (IMCC) [1] was established in 2020 following the recommendations of the European Strategy for Particle Physics (ESPP) and the implementation of the European Strategy for Particle Physics—Accelerator R&D Roadmap by the Laboratory Directors Group [2], hereinafter referred to as the the European LDG roadmap. The Muon Collider Study (MuC) covers the accelerator complex, detectors and physics for a future muon collider. In 2023, European Commission support was obtained for a design study of a muon collider (MuCol) [3]. This project started on 1st March 2023, with work-packages aligned with the overall muon collider studies. In preparation of and during the 2021–22 U.S. Snowmass process, the muon collider project parameters, technical studies and physics performance studies were performed and presented in great detail. Recently, the P5 panel [4] in the U.S. recommended a muon collider R&D, proposed to join the IMCC and envisages that the U.S. should prepare to host a muon collider, calling this their “muon shot”. In the past the U.S. Muon Accelerator Programme (MAP) [5] has been instrumental in studies of concepts and technologies for a muon collider.

1.1 Motivation

High-energy lepton colliders combine cutting edge discovery potential with precision measurements. Because leptons are point-like particles in contrast to protons, they can achieve comparable physics at lower centre-of-mass energies [6–9]. However, to efficiently reach the 10+ TeV scale recognized by ESPP and P5 as a necessary target requires a muon collider. A muon collider with 10 TeV energy or more could discover new particles with presently inaccessible mass, including WIMP dark matter candidates. It could discover cracks in the Standard Model (SM) by the precise study of the Higgs boson, including the direct observation of double-Higgs production and the precise measurement of triple Higgs coupling. It will uniquely pursue the quantum imprint of new phenomena in novel observables by combining precision with energy. It gives unique access to new physics coupled to muons and delivers beams of neutrinos with unprecedented properties from the muons’ decay. Based on physics considerations, an integrated luminosity target of $10\,\mathrm{ab}^{-1}$ at 10 TeV was chosen. However, various staging options are possible that allow fast implementation of a muon collider with a reduced collision energy or the luminosity in the first stage and reaches the full performance in the second stage.

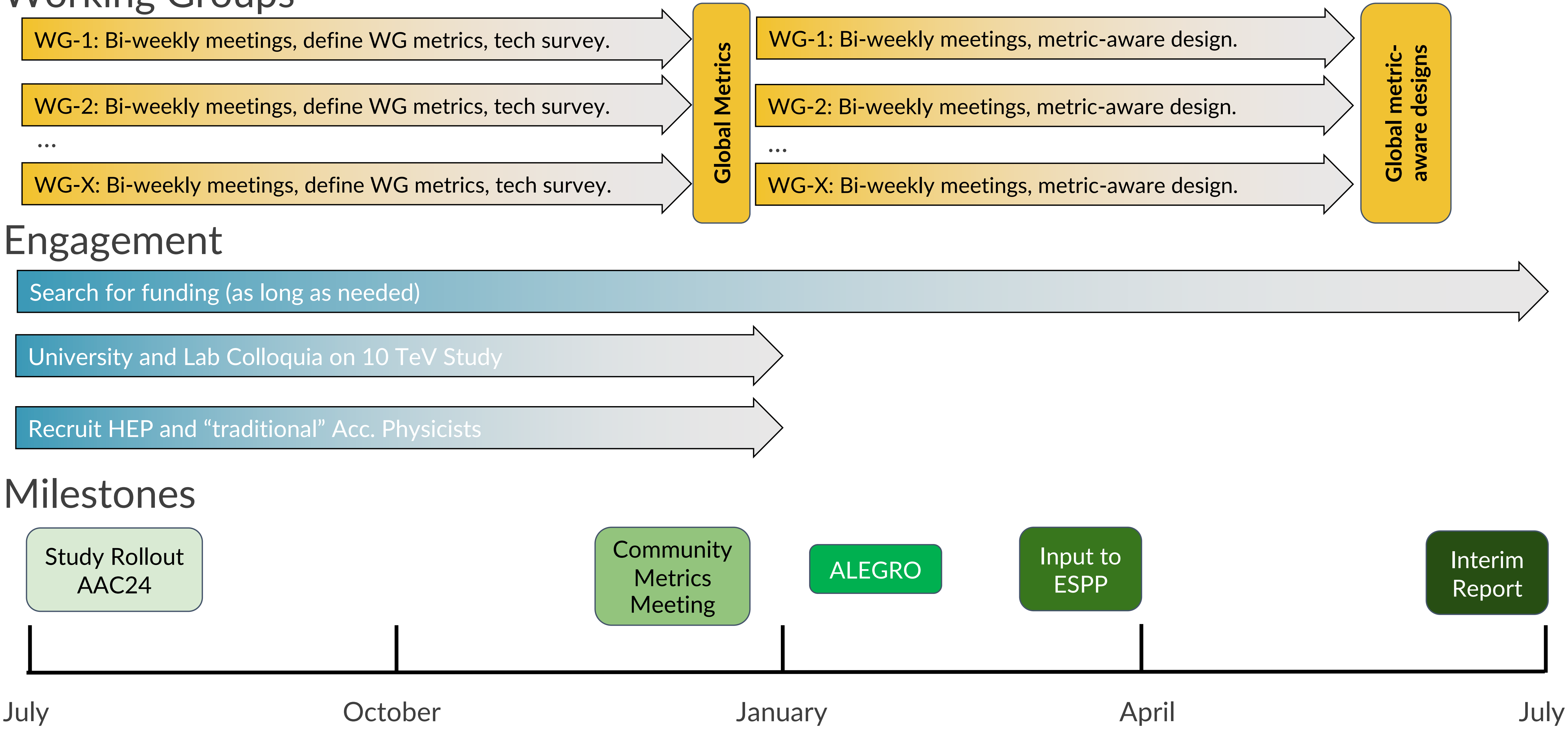
In terms of footprint, costs and power consumption a muon collider has potentially very favourable properties. The luminosity of lepton colliders has to increase with the square of the collision energy to compensate for the reduction in s-channel cross sections. Figure 1.1 (right panel) compares the luminosities of the Compact Linear Collider (CLIC) and a muon collider, based on the U.S. Muon Accelerator Programme (MAP) parameters [7], as a function of centre-of-mass energy. The luminosities are normalised to the beam power. The potential

Fig. 1.1: Left: Conceptual scheme of the muon collider. Right: Comparison of CLIC and a muon collider luminosities normalised to the beam power and as a function of the centre-of-mass energy.

4

https://arxiv.org/pdf/2407.12450

Tentative Year 1 Timeline



Working Groups

WG-1: Bi-weekly meetings, define WG metrics, tech survey.

WG-2: Bi-weekly meetings, define WG metrics, tech survey.

…

WG-X: Bi-weekly meetings, define WG metrics, tech survey.

Global Metrics

WG-1: Bi-weekly meetings, metric-aware design.

WG-2: Bi-weekly meetings, metric-aware design.

…

WG-X: Bi-weekly meetings, metric-aware design.

Global metric-aware designs

Engagement

Search for funding (as long as needed)

University and Lab Colloquia on 10 TeV Study

Recruit HEP and “traditional” Acc. Physicists

Milestones

Study Rollout AAC24

Community Metrics Meeting

ALEGRO

Input to ESPP

Interim Report

Funding a 10 TeV Design Study

The 10 TeV pCM WFA Design Study is not a “side hustle”. It requires dedicated effort in the form of FTEs.

The P5 panel envisioned a test facilities review panel in late this decade. The 10 TeV design document is critical for that review.

- We need to start now!
- We hope that individuals will incorporate this effort into their existing programs.

No funding for the study from DOE or NSF is available in FY25. Nobody knows what will happen in FY26! We need to explore:

- Lab LDRDs
- Private foundation funding (Moore and Templeton Foundations contacted).

We estimate 10 FTEs or FTE-equivalents per year for 4 years for the end-to-end design concept.

- Approximately $6M over 4 year.

Action Items During AAC24

1. Discussions on technologies and concepts for a 10 TeV collider in newly-formed WG7.

2. Community discussion on design study scheduled for Tuesday evening led by J. Osterhoff.

3. Start forming working groups and preliminary nominations for WG conveners.

We hope that you will join us!

WG7 Session Tuesday afternoon.

16:00

Adiabatic plasma lens designs for the final focus of TeV electrons — *Qianqian Su* — 16:00 - 16:15

Application of laser-plasma accelerators to future linear colliders — *Carl Schroeder* — 16:15 - 16:30

Beam Delivery and MDI design considerations for advanced colliders — *Andrei Seryi* — 16:30 - 16:45

Energy Upgrades of a linear Higgs factory — *Emilio Nanni* — 16:45 - 17:00

17:00

Interactions of Lasers and Electron Beams for Collider-Directed R&D at FACET-II — *Alexander Knetsch* — 17:00 - 17:15

Overview of PWFA Collider Proposals — *Brendan O'Shea* — 17:15 - 17:30

Overview of SWFA for TeV collider — *Chunguang Jing* — 17:30 - 17:45

18:00

Poser [Atrium]: Poster Session 2

NIU Naperville Conference Center — 18:00 - 19:30

19:00

WG7: Community inputs on Wakefield collider design study — 19:30 - 20:30

20:00

Conclusion

The P5 Report and the broader HEP community call on us to deliver an End-to-End Design Study of 10 TeV pCM collider based on WFA technology.

AAC will meet this challenge as a community!

What is needed for the study to be successful?

- Community buy-in at the start of the study.
- Community engagement throughout the process
- Community endorsement of the final product.

What does our final product look like?

- A self-consistent, unified concept that specifies the flavor of particle collisions (e^+e^-, e^-e^-, $\gamma\gamma$) that satisfy the energy and luminosity requirements.
- One or more accelerator designs that provide the necessary beam parameters.

Please join us for a discussion at the 7:30 PM session on Tuesday.