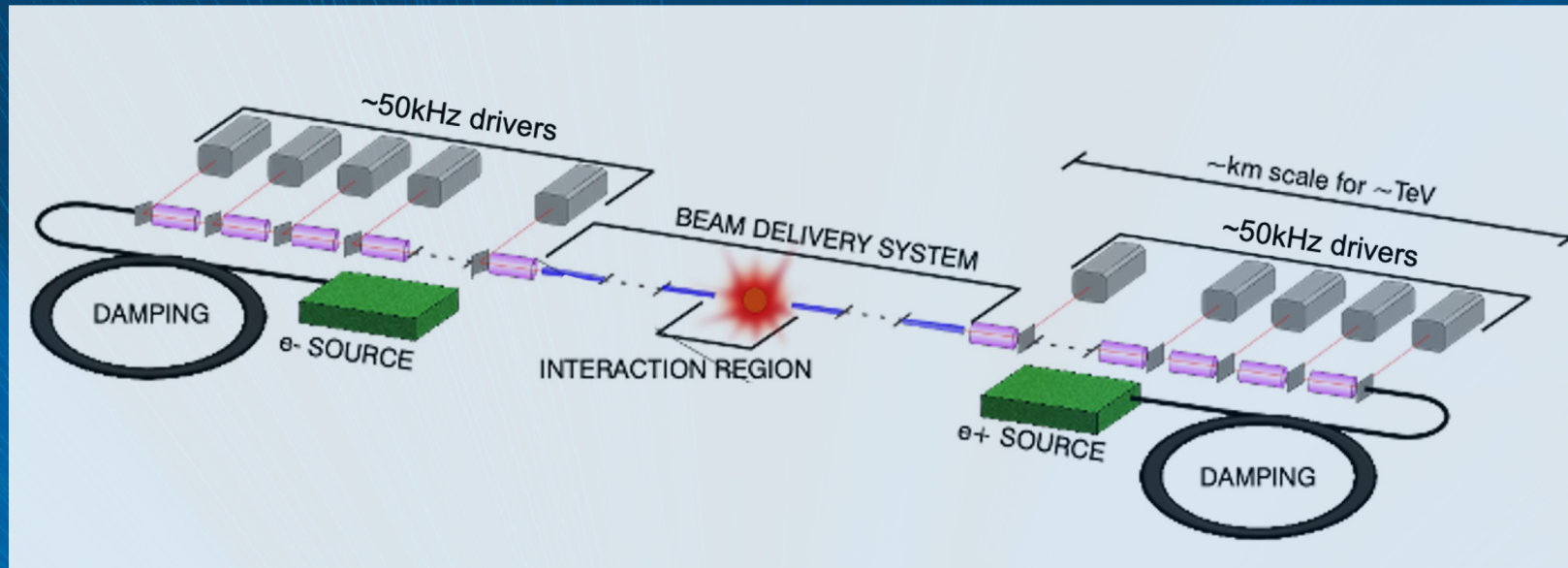


Snowmass, P5, and the 10 TeV Wakefield Design Study



2025

Cameron G.R. Geddes, Director
Accelerator Technology & Applied Physics Division
Lawrence Berkeley National Laboratory

Outline

Physics and P5 perspective

10 TeV wakefield path

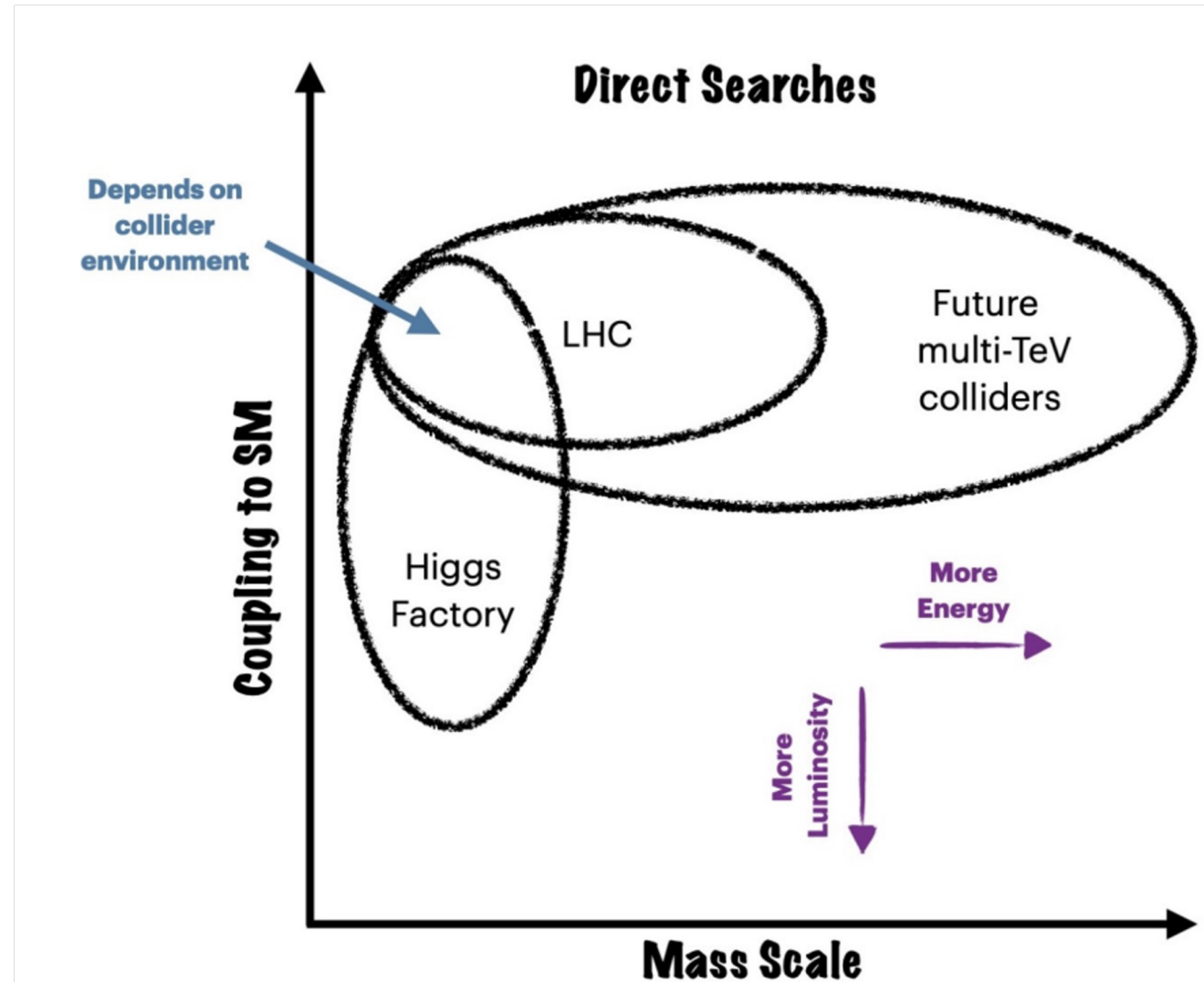
Collider study

Technology development

Future Colliders Will Access the Next Discovery Frontiers

A Higgs Factory electron-positron collider at 90-350+ GeV enables precision Higgs physics

- Precision measurements of Higgs couplings and some production modes
- Improve knowledge of coupling to charm quark, potentially accessing coupling to strange quark
- Order of magnitude improved sensitivity to Higgs invisible decays
- Improved sensitivity to direct searches for feebly coupled light states, such as heavy neutral leptons and axion-like particles
- EW sector consistency checks, testing through quantum loops that relate W & Z bosons, the top quark, and the Higgs, extend the probed energy scale by a factor of 3–10 beyond the HL-LHC

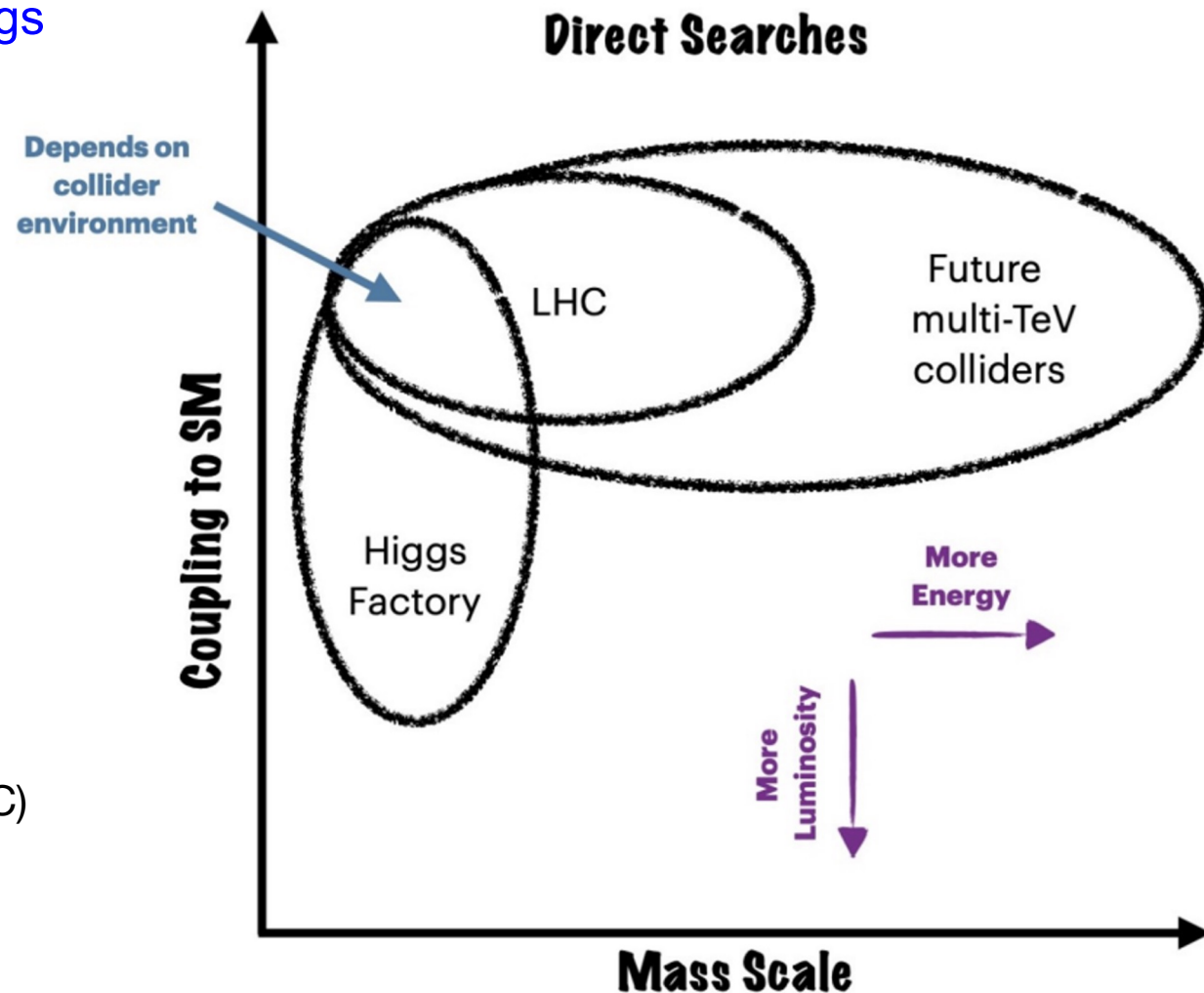


Future Colliders Will Access the Next Discovery Frontiers

A future 10 TeV parton center of mass (pCM) collider combines the ultimate characterization of the Higgs sector and a broad new physics search program

- Higgs self-coupling precision of 5%, (order of magnitude better than HL-LHC)
- Improved precision for Higgs couplings (e.g. top quark-Higgs coupling, muon pairs, $Z\gamma$)
- Direct discovery of particles (potential deviations observed at Higgs factory)
- Sensitivity for new gauge bosons, fermions, other resonances (an order of magnitude higher than at HL-LHC)
- Access to rare decays and new hidden sectors (mass reach to new particles well beyond the HL-LHC)
- Reach the thermal WIMP target for minimal WIMP candidates

With content credit to Tulika Bose
and other P5 colleagues



2023 P5 Supports Strong Accelerator Development

Particle Physics Project Prioritization Panel

- Decadal plan, leveraging Snowmass community input

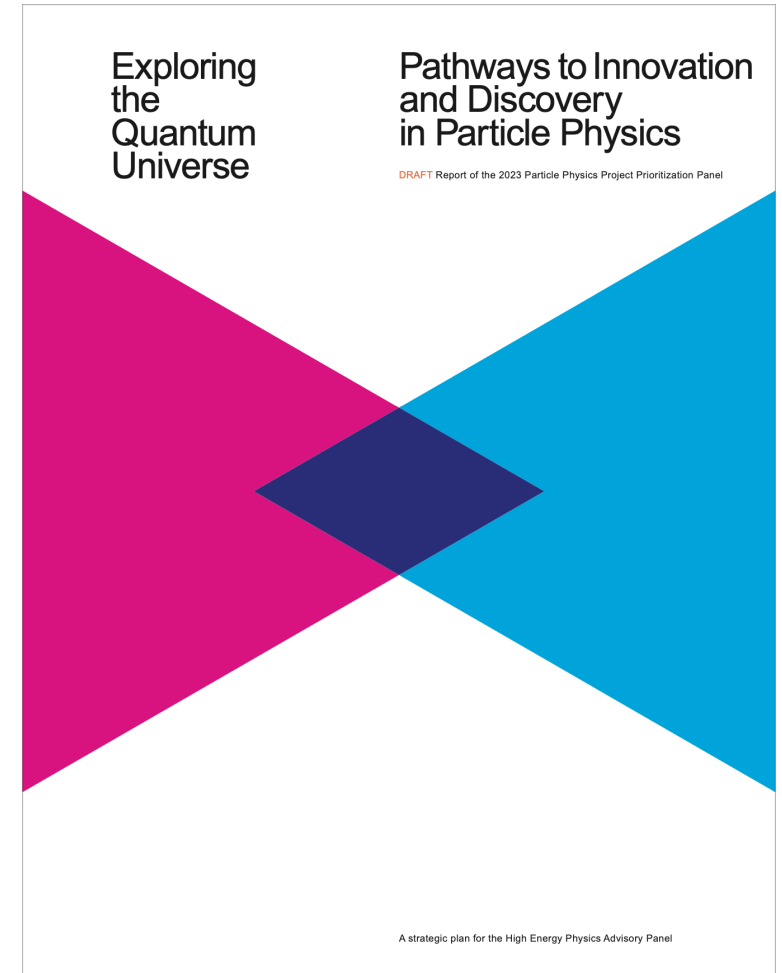
Sequence of next colliders for precision, new physics

- High Luminosity LHC, upgrades in progress
- Higgs factory: off shore, mid-decade start targeted
- Vision for 10 TeV/parton Center of Mass collider

Enabled by strengthened support for development

- General accelerator R&D: long term technologies
 - Timely to Magnet and Exascale projects ending
- Collider R&D: new program for integrated design
- Test facilities: crucial for training, technology
- Reinforcing applications/cross-office: light sources, etc.
- Upgrade FNAL complex, study long term future

Coordinate ALEGRO effort to leverage/reinforce this path



<https://www.usparticlephysics.org/2023-p5-report/>

New Physics Frontiers at 10 TeV parton Center of Mass

Next physics scale anticipated at 10 TeV
electrons or muons, 80-100 TeV for protons

- No technology ready for this challenge
- Beam dynamics at Exascale and precision controls essential to all concepts
- P5: R&D to enable decision in 20 year scale (pg. 44,85)

Proton path could re-use FCCee tunnel

- High field magnets key (also: detector)
- R&D leveraging US Magnet development program

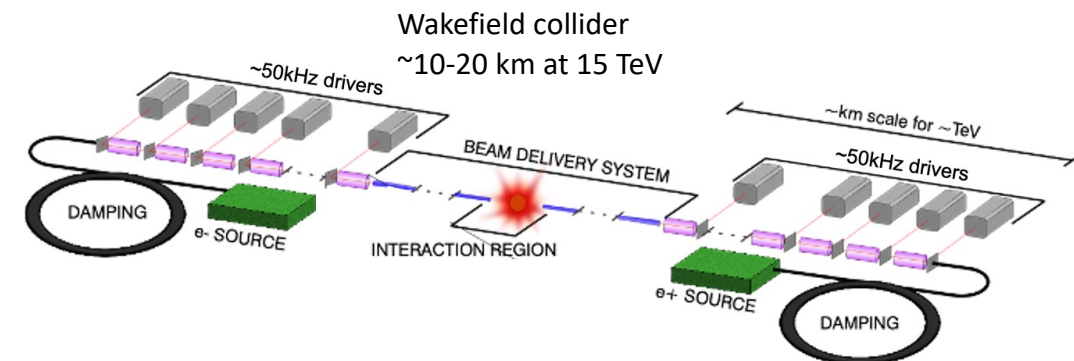
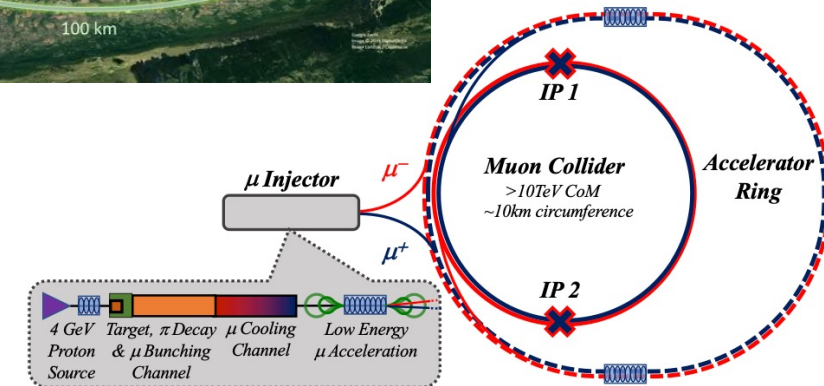
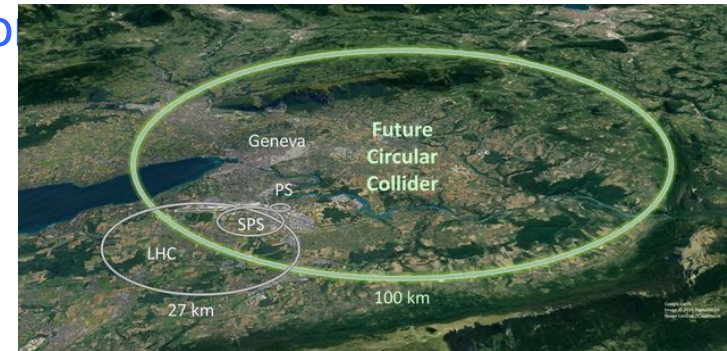
Muon path reinvigorated, potential FNAL leverage

- Emphasis due to changed energy scale, leverage
- R&D needs on targets, cooling, SRF, design

Wakefield path could re-use LC tunnel; potential lower cost

- Strong progress: high gradient, quality, collider concepts
- R&D needs on collider design, staging, drivers...

fo



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Wakefield Colliders Towards 10 TeV pCM

Electrons/positrons as compared to protons, muons

- Similar physics to muons, 10 TeV = 10 TeV pCM
- Strong synchrotron radiation – linear collider at high E
- High gradient important to size, power a challenge

Wakefield accelerators: potential for 10 TeV e^+e^- , $\gamma\gamma$...

- 10 GeV/m – smaller footprint & carbon load
- Bright beam generation – reduce/improve cooling
- Strong focusing, short beams – improve lumi/power

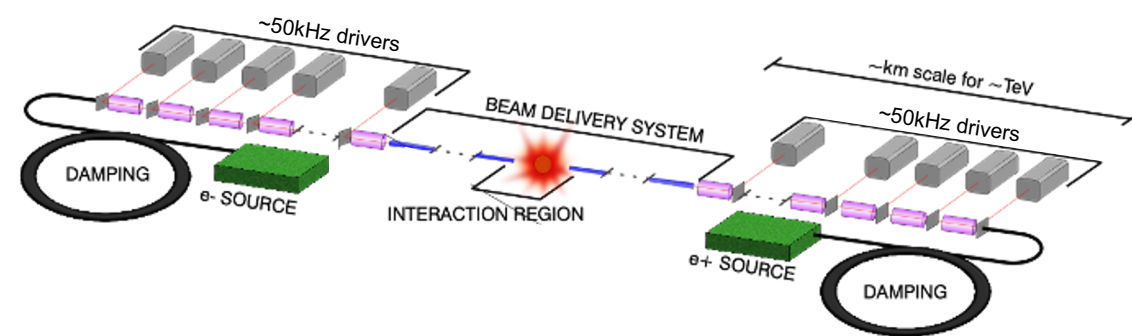
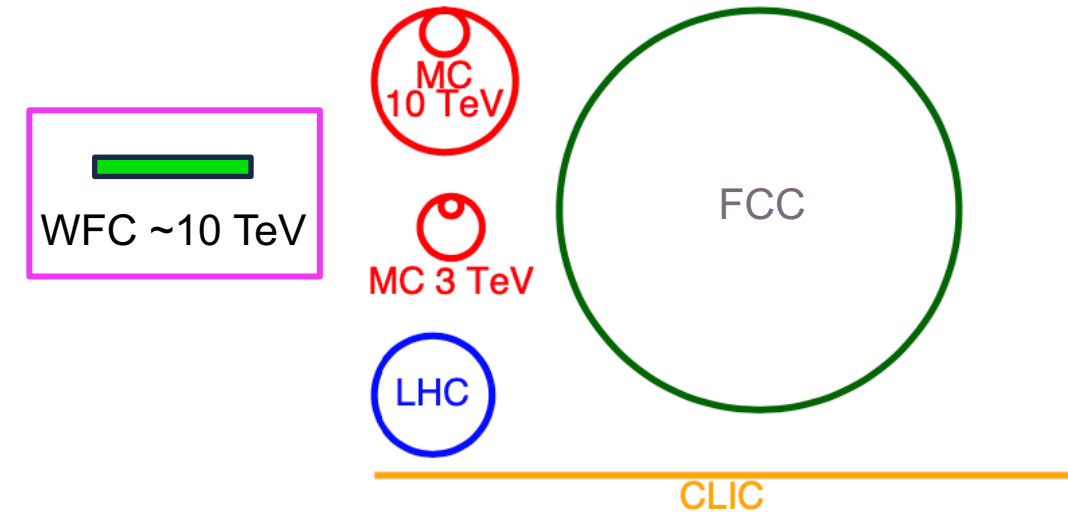
Potential to combine small footprint, high efficiency

- Luminosity $\sim 50 \text{ E}34$ at 15 TeV
- Est. power $\sim 450\text{-}1000 \text{ MW}$
- Potential for FNAL site, ILC reuse

Note: different
E, L than MC
example

e^+/e^- are light – interaction point physics important

- New regime of beam-beam interaction, tight alignment
- Drive for understanding of luminosity, detector needs



Wakefield Collider Accelerators

High brightness beams

- Generated $0.1 \mu\text{m}$ norm. emittance, $\leq 1\% \Delta E/E$
- Path to 10 nm and $\ll 1\%$: precision injection control

High gradient established: 8 GeV in 20 cm

- Separately: extraction of 40% of wake energy, short length
- Individual beam properties/shots approaching some needs
- Opens potential for energy recovery to extend Lumi/Power

Next: stable, efficient, high brightness stage

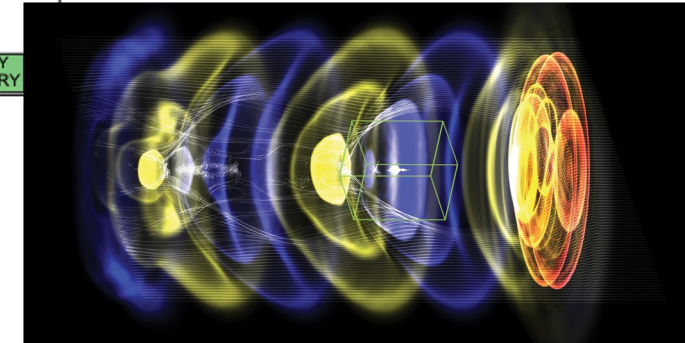
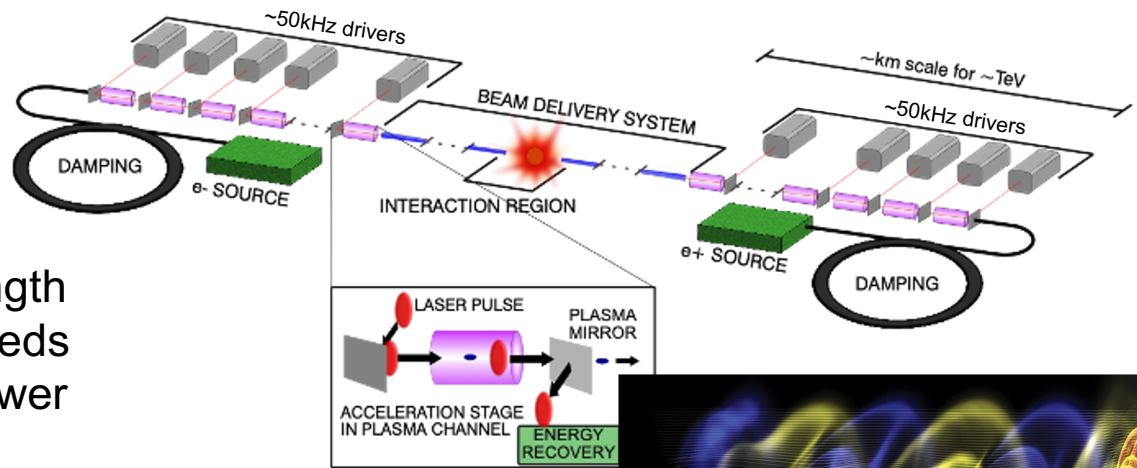
- Controlled particle injection, beam loading
- Precise guiding, shaping of driver in plasma

Staging of 100's of stages at $> 99\%$ coupling

- Two stages combined to date at low energy/efficiency
- Multi-GeV, efficient coupling in progress
- High gradient plasma lenses, optics for close coupling

Broad applications reinforce collider development

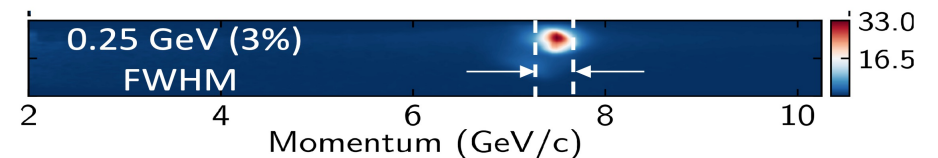
- Demonstration of FEL lasing, inter-agency applications
- Strong potential for cost reduction (new technology)



H₂ over 30 cm, 1% N₂ over 12 cm



H₂ over 30 cm, 5% N₂ over 12 cm



Picksley, et al. Phys. Rev. Lett. 133, 255001 & U.Md Colab.

Towards a Wakefield Collider

Beam dynamics studies indicate 10+ TeV potential

- Shaped bunches, ion motion control growth in ΔE , emit.
- Wall plug power limit: comparable L/P potential to others

Positron acceleration asymmetric

- First acceleration (SLAC): develop precision structure
- Source, cooling at $\sim 10\times$ ILC rate, 10's kHz

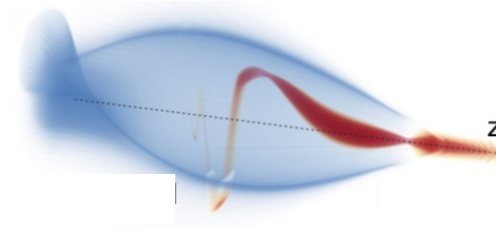
From 1 Hz to 10's of kHz enabling active feedback

- Stage control to reach performance potential
- New laser tech, or SRF, offers efficient $\geq$ kHz driver

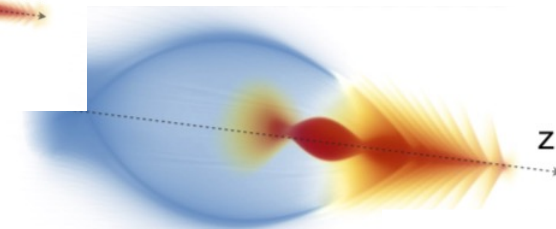
Multi-TeV beam delivery, Beamstrahlung & detectors

- Develop new tools and model interaction region
- Assess detector and physics drivers
- $\gamma\gamma$ or ee collider easiest – explore physics potential

Acknowledge challenges, as for all 10 TeV approaches

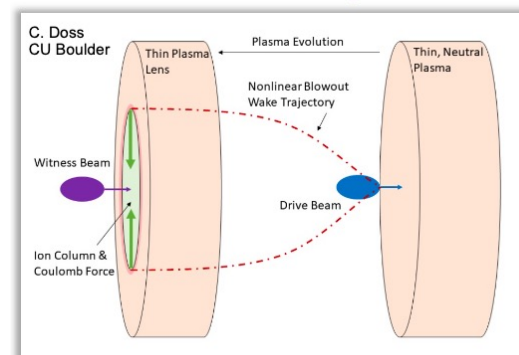


Preservation of
Beam quality

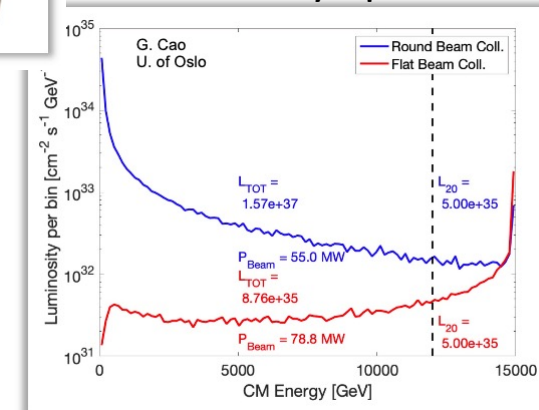


A. Martinez de la Ossa et al. PRL 121, 064803 (2018)

Strong focusing
Plasma lens



Large γ
Luminosity Spectrum



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Wakefield Collider Path

Concepts up to 15 TeV colliders, ~10 TeV on FNAL site

- Potential to re-use facilities of near-term Higgs LC
- Collider concepts set ranges for stage energy, size, repetition rate; motivates next steps and test facilities
- Significant projects in Europe, Asia: AWAKE at CERN, EuPRAXIA user facility, ELI. HALHF Higgs concept...
- US contributions & engagement important to path

2030 goals

R&D: retire technical risk

- Use current facilities to demonstrate multi-GeV staging, and high quality stages, continuing strong R&D
- Start new test facilities to demonstrate e⁺ (FACET-II), high quality & efficiency (kBELLA), structures (AWA)

Design: Self consistency, detailing future demonstrator, integrated with detector, collider, physics communities

TABLE I. LPA stage laser and plasma parameters

Laser pulse energy	6.5 J
Laser (FWHM) pulse duration	130 fs
Laser pulse peak power	50 TW
Laser wavelength	1 μm
Plasma density	10^{17} cm^{-3}
Plasma channel length	1.7 m
Plasma channel radius	22 μm
Peak accelerating field	6 GV/m
Beam peak current	3 kA
RMS beam length	8.5 μm
Loaded accelerating gradient	3 GV/m
Particle energy gain per stage	5 GeV

Schroeder *et al.*, “Linear colliders based on laser-plasma accelerators” in Snowmass Proc., JINST 18 T06001 (2023)

Area Notes - Wakefields

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 with this emerging technology path.**

Use of the existing test facilities should be maximized. [...] Key acceleration and beam requirements of a stage for a future collider based on wakefield technology, including energy gain with high brightness beams at high efficiency, can be developed using FACET-II at SLAC, BELLA at LBNL, AWA at ANL, ATF at BNL, ZEUS at University of Michigan (NSF), and other facilities. In addition to demonstrating a single self-contained stage, some of these facilities, particularly BELLA and potentially ZEUS, can demonstrate the next step toward a plasma wakefield collider, operation with two linked stages.

- Viewed as longer term than other options, less engagement in Snowmass
- Emphasize on designs with self-consistent parameter sets, identified technology gaps to guide & assess
- Engage of broad accelerator/particle physics communities: advance design & collider assessment

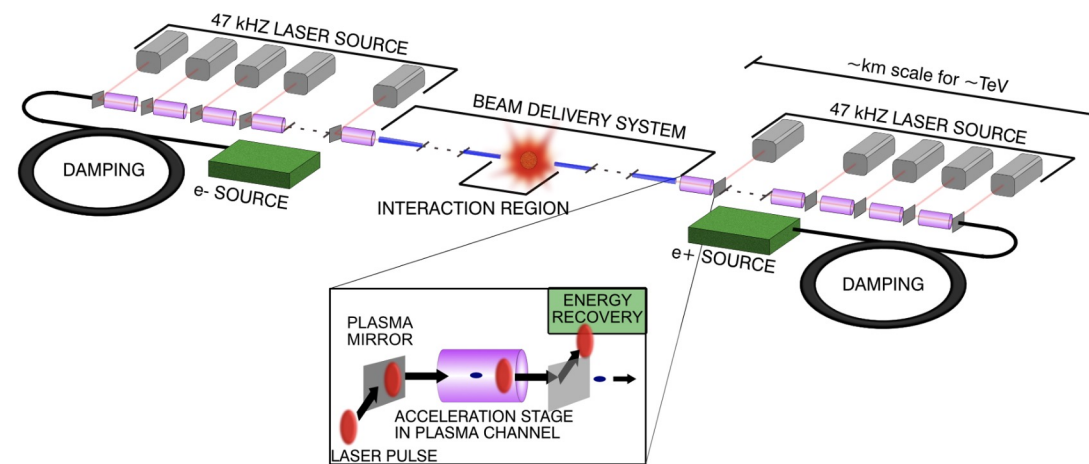
Wakefield Collider Design Study Formed

Working Groups:

- System integration and optimization
- Beam sources (incl. damping rings)
- Drivers
 - Laser
 - Beams - SWFA
 - Beams - PWFA
- Linacs
 - LWFA
 - SWFA
 - PWFA
- Beam delivery system
- Beam-beam interactions
- Beam diagnostics
- Machine-detector interface
- HEP detector
- HEP physics case
- Environmental impact
- Simulations/computing/AI

Green = Broader accelerator community
Orange/blue/purple = AAC specific
Red = HEP and broader community

Goal: end-to-end design
with self-consistent parameters.



Participation welcome, contact:
Co-organizers [S. Gessner](#), SLAC
and [J. Osterhoff](#), LBNL

ANL
Arizona State U
BNL
Euclid Tech Labs
LBNL
LLNL
JLAB
Northern Illinois U
SLAC
U Michigan

CERN
CLF, UK
DESY, Germany
INFN Frascati, Italy
IST, Portugal
TRIUMF, Canada
U Oslo, Norway
U Oxford, UK
U Paris-Saclay, France

Wakefield Collider Physics Studies Needed

Vector boson fusion: large cross section for electroweak and Higgs at 10 TeV

More signal than s-channel often associated with electron-positron colliders

Similar for muons, e+e-; detectors differ

Analysis of new particle production starting: e+e-, ee, and $\gamma\gamma$ cases

Some e+e- studies similar to muon collider

Broader luminosity spectrum

New ee, and $\gamma\gamma$ studies underway (no s-channel)

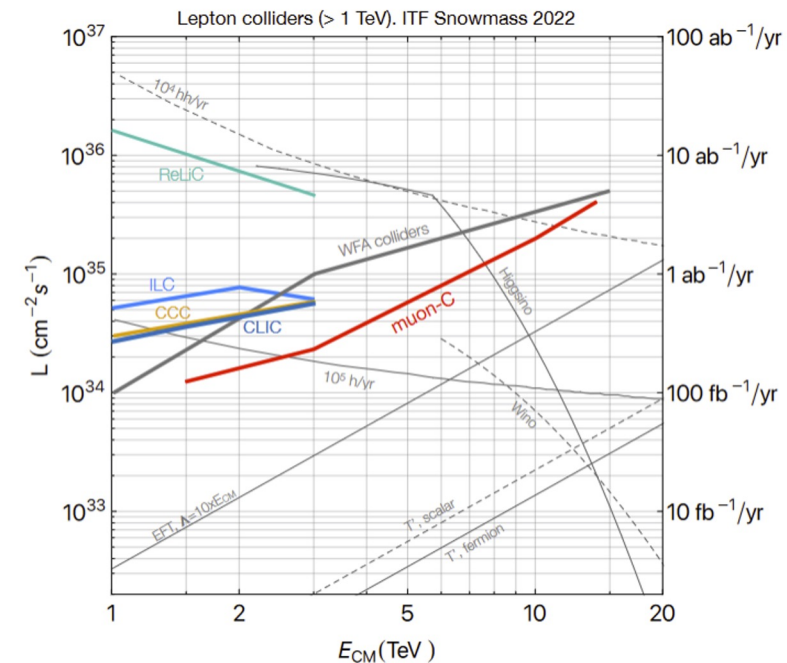
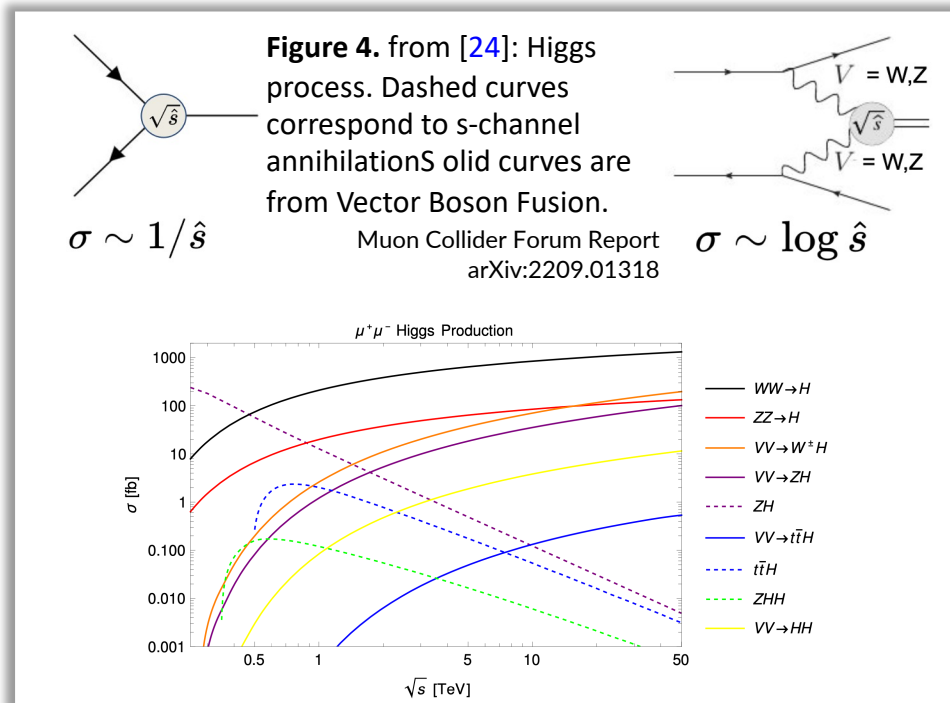


Fig2. Snowmass Implementation Task Force Report ArXiv 2208.06030

Wakefield: e+e-

Thin lines:
SM processes,
BSM models

Note: differences
due to collider
example chosen
not capability

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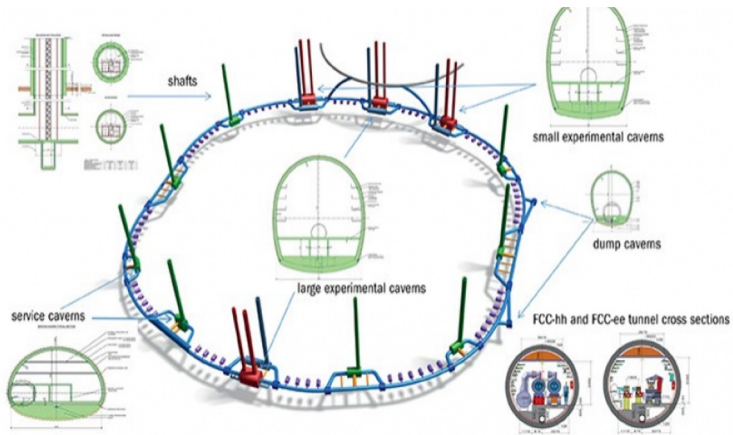
Collider study

Technology development

Accelerator technology must reach technical maturity for 10 TeV pCM

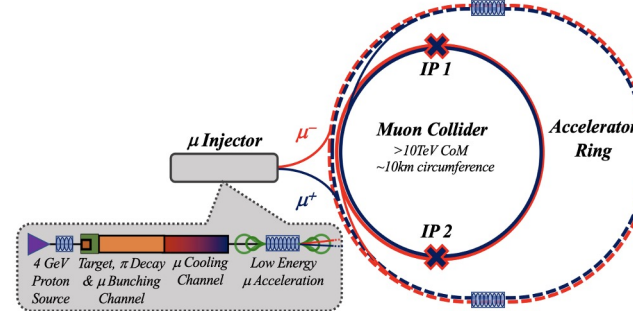
Proton collider

Key need: high field magnets



Muon collider

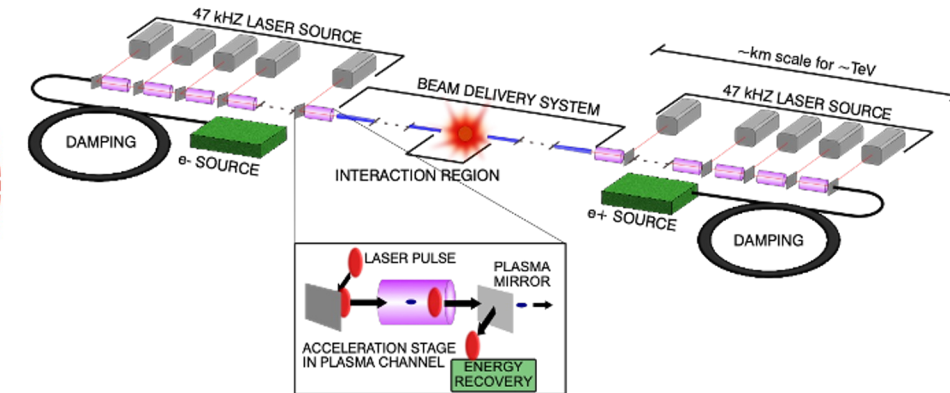
Needs: targets, cooling...



Linear wakefield lepton collider

Test facility needs:

cool copper
kBELLA (avg. power, efficiency, precision)
FACET-II (positrons), AWA (transformer ratio)



“All options for a 10 TeV pCM collider are new technologies under development and R&D is required before we can embark on building a new collider”

P5 (2023), p. 17

Challenges for all concepts: size, luminosity, power, detector

- Ambition to decide in ~20 years requires intensive R&D

e+e- collisions offer similar physics to muons

- Potential advantage: relatively clean detector environment

New Test Facilities are Essential to Develop Technology

Test facilities are ever more important to develop the advanced technology for future machines [P5, pg 87], supporting Recommendations 4a, 4c

Current facilities, and new:

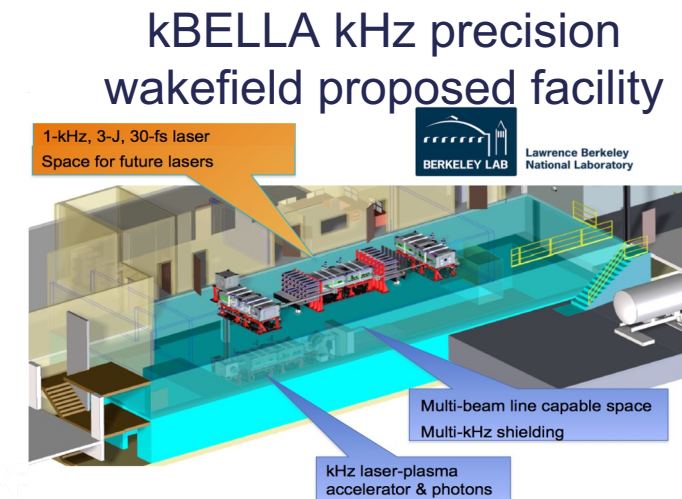
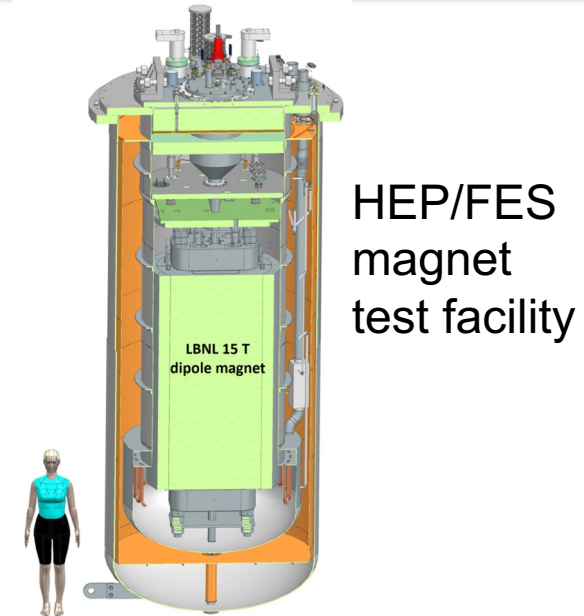
- High field magnets including in-progress cable test facility
- Cool copper tests: high gradient normal conducting RF

Wakefields:

- FACET-II e+ to enable study positron acceleration
- AWA upgrade to support GeV advanced structures
- New kW-class efficient lasers, and use of their kilo-hertz repetition rate for active feedback at kBELLA, will advance stage performance.. beam tests

These, together with muon collider development, will advance the technology and feed into a future demonstrator facility to make possible a 10 TeV pCM collider (see Sec. 6.5). [P5, pg 87]

Construct small facilities, and prepare technical/scientific plans at mid & large scale for review, informed by collider R&D [Rec 6 & Area Rec.]



Looking Forward

- Wakefield Collider Design Study central: with self consistent parameter sets, cost ranges (muon collider success in the last decade)
 - Integrating: injection, staging, efficiency, cooling alignment and jitter effects and tolerances, matching/coupling between many stages, BDS and Final focus
 - Engaging: the detector, high energy physics and conventional collider communities, & internationally
 - Framing a common wakefield collider concept with techniques offering technical risk mitigation
 - Integrating accelerator, particle and detector physicists
- Develop a staged collider approach, in coordination with nearer term LCs and applications
 - Engage with ILC, CLIC, C3, muon and other collider communities; facility upgrades, injectors...
 - Identify R&D topics for the Wakefield Collider Design Study and to benefit near-term Higgs Factories
 - Leverage near term applications to advance collider path and reduce cost and risk; cross agency
 - Engage strongly in non-AAC meetings and workshops: IPAC, LCWS, IMCC, C3, APS April
- Synchronize R&D across institutions, identify challenges and continue strong R&D progress