European Strategy
for Particle Physics

PLENARY / Large-scale accelerator projects at CERN

A Linear Collider Vision:
future perspectives with advanced technologies

Jenny List (DESY)
on behalf of the LCVision team

Linear Collider Vision

23-27 JUNE 2025 Lido di Venezia

Outline

of the talk

- Introduction
- Routes to Higher Energy
- Higher Luminosity, Photon Collisions & Beyond
- Conclusions

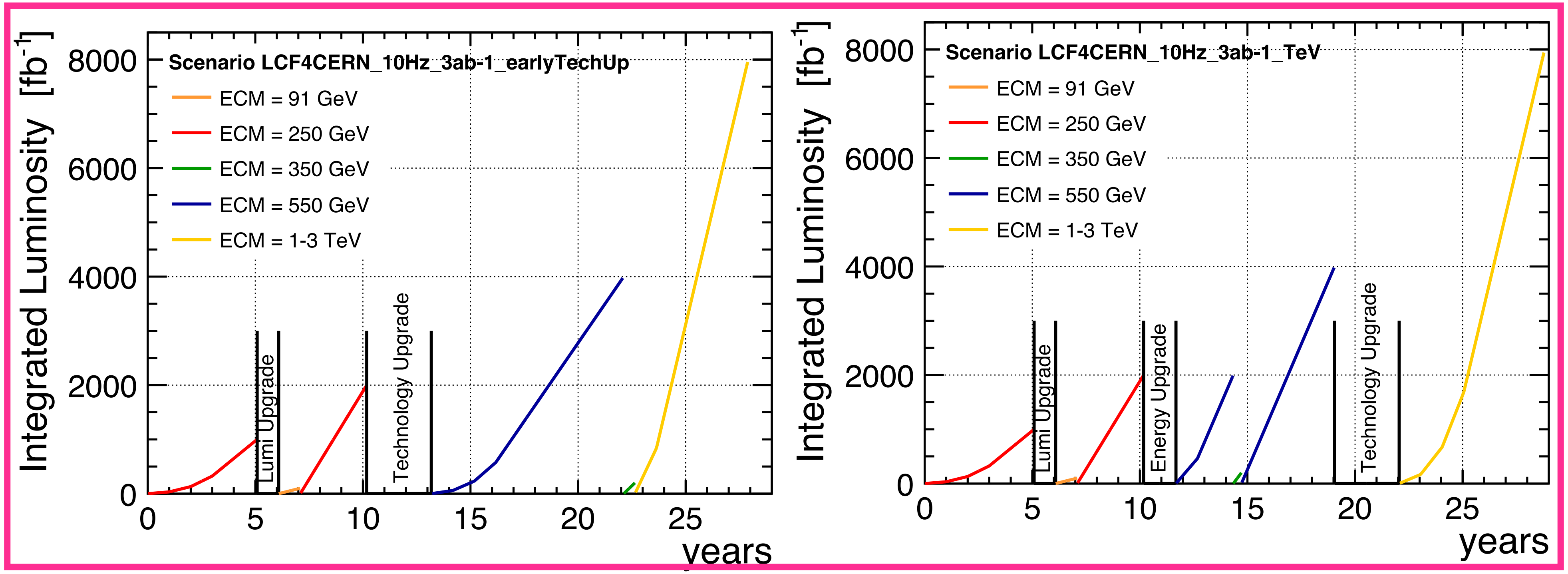
Introduction

What this talk is about

Steinar’s talk showed: **a Linear Collider**

- can be built with today’s technologies
- combines adequate precision with large energy range providing new insights and consistency checks

This talk: what can be done after an initial 10…20 year program by making use of advanced accelerator concepts and technologies?



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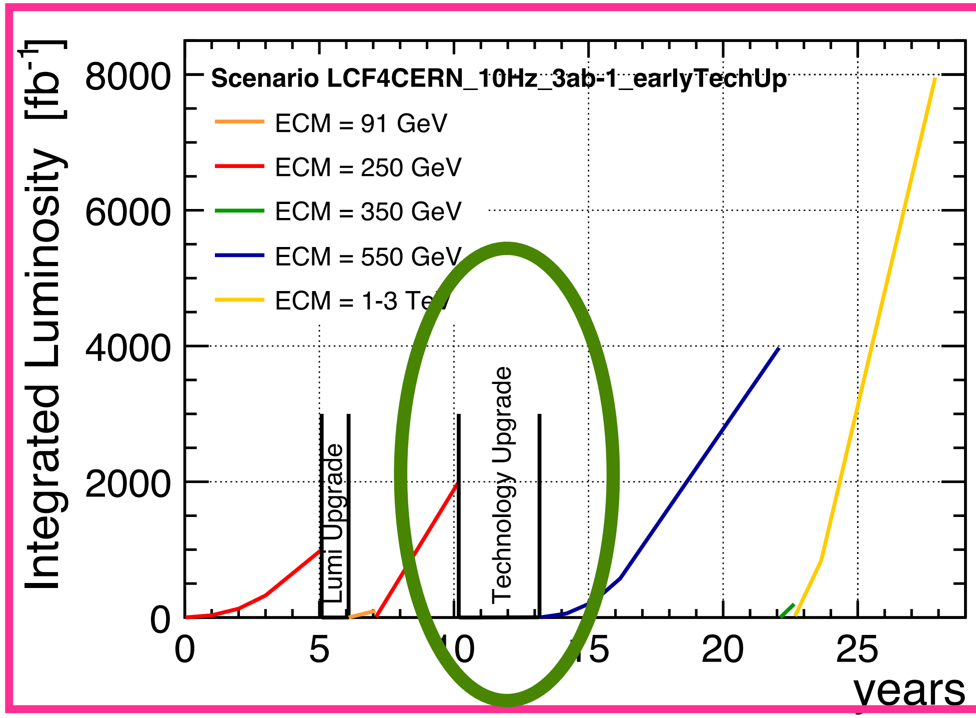

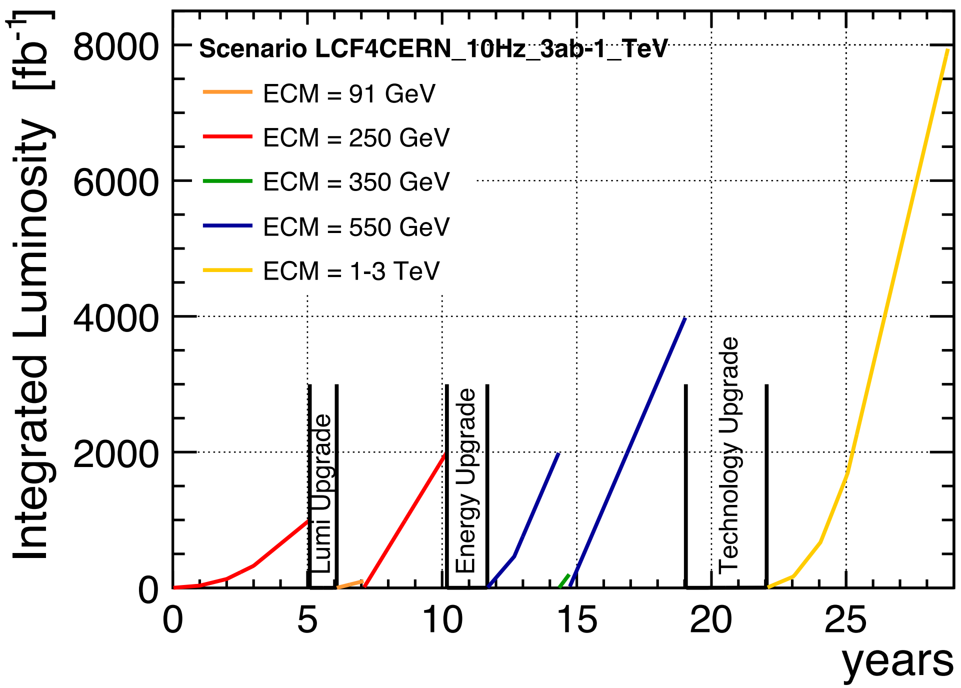

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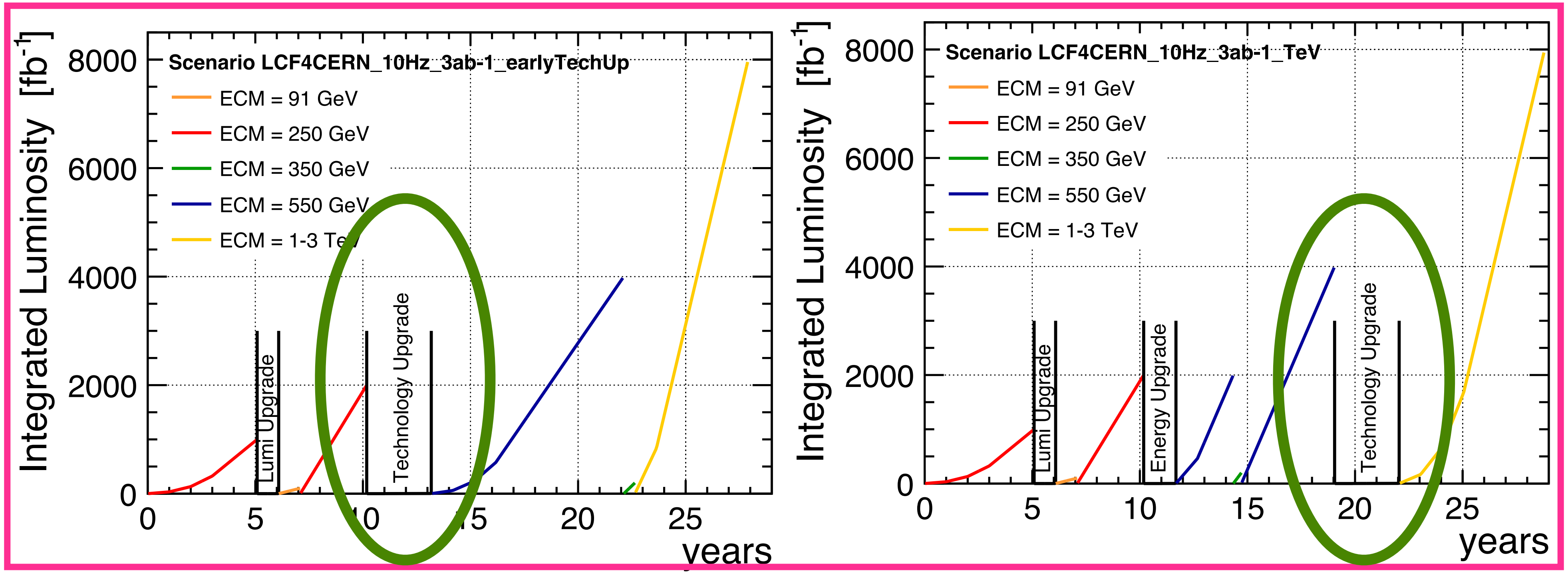

Looking into the crystal ball…

for the future of a Linear Collider Facility

assume we had a 33.5km straight tunnel… (c.f. Steinar's talk)

- …with some initial Linear Collider inside, starting to take data mid 2040ies
- **10…20 years later:**
  2050ies - 2060ies => obviously very conceptual now — lots of opportunies!

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  - cool copper cavities
  - warm copper cavities
  - wakefield acceleration

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- **go for higher luminosity - ERL:**
  - ReLiC / ERLC
- **go for photon collisions:**
  - with optical lasers or a la XCC
- **beyond-collider opportunities**
  - beam dump / fixed-target / R&D ….

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LCVision reviewed
how these could be embedded as upgrade of initial facility
— obviously each technology could be used for a stand-alone project, too!

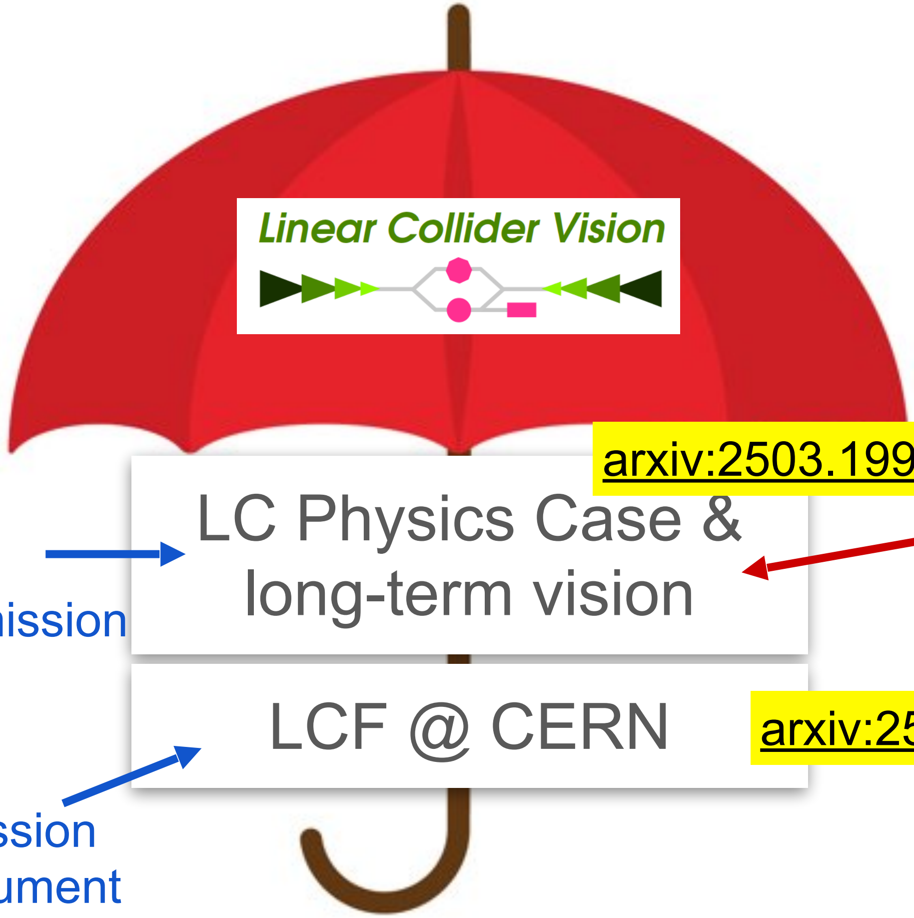
LCVision: a bottom-up community organisation

started at LCWS2024: Linear Colliders in view of the ESPPU

- **all linear colliders share the same scientific goals:**
  - formulate a coherent physics program
  - define energy stages etc science-driven
- **beyond an individual technology:**
  - design a linear collider *facility*
  - infrastructure compatible with various technologies
  - plus beam-dump / fixed-target exp's / R&D facilities
- **study the Higgs in e+e- now - but maintain flexibility for the future:**
  - start now with an *affordable* project
  - maintain scientific diversity
  - strengthen accelerator R&D towards 10 TeV pCM collider
  - **decide on upgrades / new projects based on future developments - or even break-throughs:**
    - **scientifically: a discovery at HL-LHC or elsewhere**
    - **technologically: higher gradients / muon cooling / high-field magnets**

LCVision ESPPU documents

… and relation to other inputs



arxiv paper & ESPPU submission

LC Physics Case & long-term vision

arxiv:2503.19983

LCF @ CERN

arxiv:2503.24049

ESPPU submission & back-up document

Technologies and upgrades

ILC in Japan (IDT)

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C^3

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10 TeV Wakefield

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Beyond Collider

https://cds.cern.ch/record/2927631

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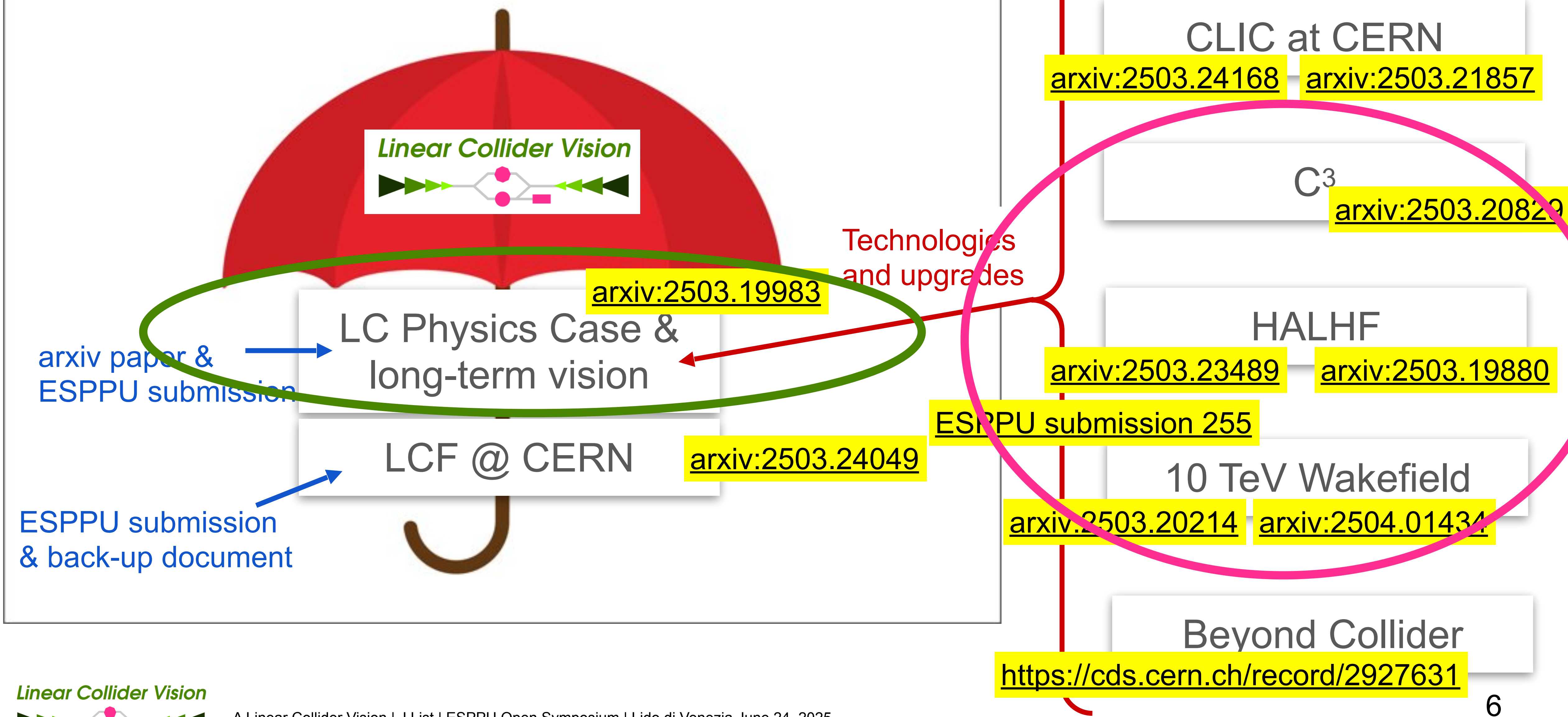
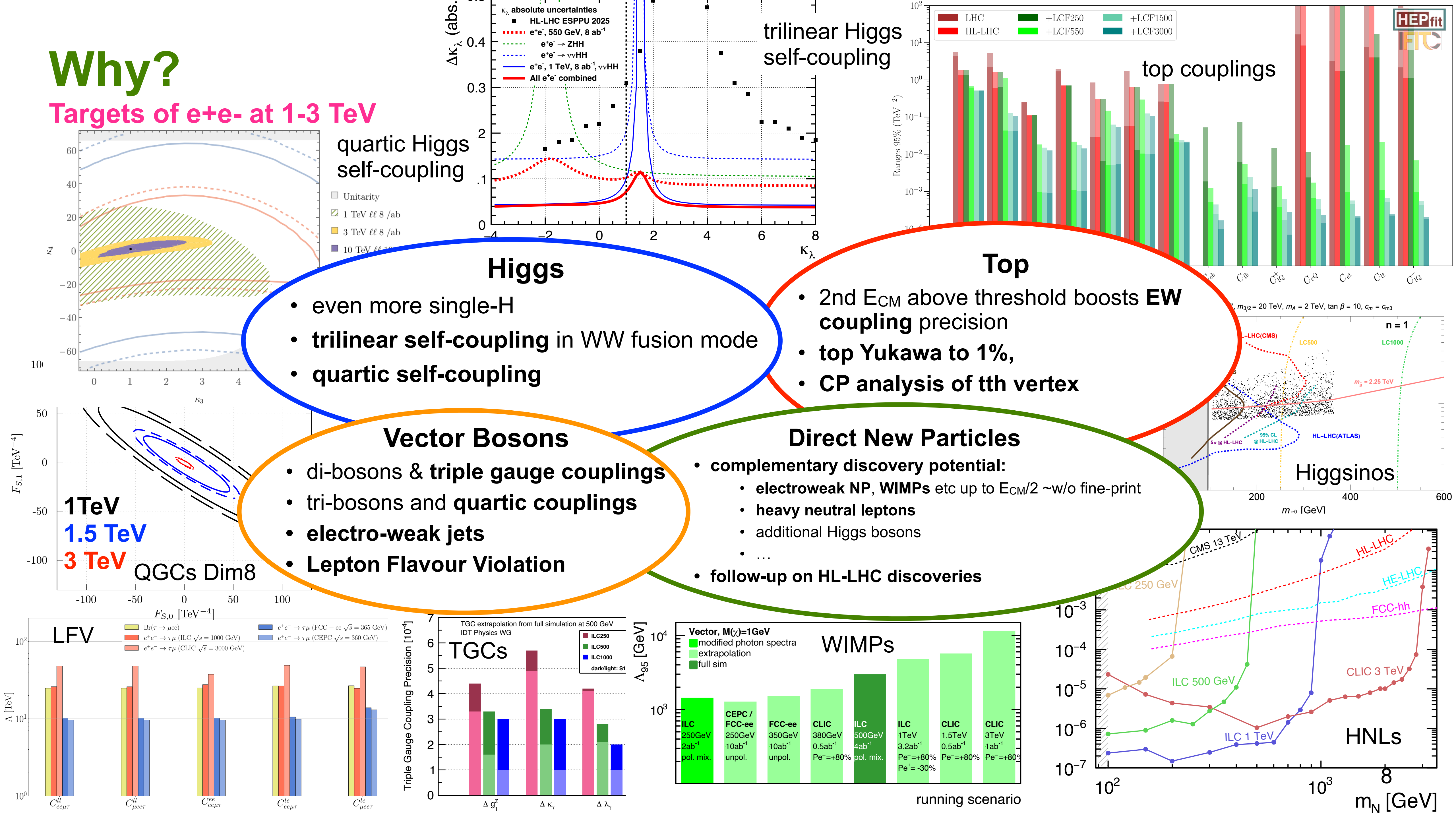


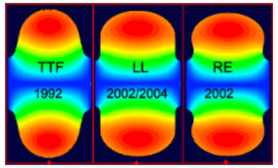
Routes to Higher Energy


Why?
Targets of e+e- at 1-3 TeV
quartic Higgs self-coupling
Unitarity
1 TeV ℓℓ 8 /ab
3 TeV ℓℓ 8 /ab
trilinear Higgs self-coupling
κλ absolute uncertainties
HL-LHC ESPPU 2025
e+e-, 550 GeV, 8 ab-1
e+e- → ZHH
e+e- → ννHH
e+e-, 1 TeV, 8 ab-1, ννHH
All e+e- combined
top couplings
LHC
HL-LHC
+LCF250
+LCF550
+LCF1500
+LCF3000
Higgs
• even more single-H
• trilinear self-coupling in WW fusion mode
• quartic self-coupling
Top
• 2nd ECM above threshold boosts EW coupling precision
• top Yukawa to 1%,
• CP analysis of tth vertex
Vector Bosons
• di-bosons & triple gauge couplings
• tri-bosons and quartic couplings
• electro-weak jets
• Lepton Flavour Violation
Direct New Particles
• complementary discovery potential:
• electroweak NP, WIMPs etc up to ECM/2 ~w/o fine-print
• heavy neutral leptons
• additional Higgs bosons
• …
• follow-up on HL-LHC discoveries
1TeV
1.5 TeV
3 TeV
QGCs Dim8
Higgsinos
LFV
TGCs
TGC extrapolation from full simulation at 500 GeV
IDT Physics WG
ILC250
ILC500
ILC1000
Triple Gauge Coupling Precision
WIMPs
Vector, M(χ)=1GeV
modified photon spectra
extrapolation
full sim
ILC 250GeV 2ab-1 pol. mix.
CEPC / FCC-ee 250GeV 10ab-1 unpol.
FCC-ee 350GeV 10ab-1 unpol.
CLIC 380GeV 0.5ab-1 Pe-=+80%
ILC 500GeV 4ab-1 pol. mix.
ILC 1TeV 3.2ab-1 Pe-=+80% Pe+= -30%
CLIC 1.5TeV 0.5ab-1 Pe-=+80%
CLIC 3TeV 1ab-1 Pe-=+80%
running scenario
CMS 13 TeV
HL-LHC
HE-LHC
FCC-hh
ILC 250 GeV
ILC 500 GeV
ILC 1 TeV
CLIC 3 TeV
HNLs
mN [GeV]
8

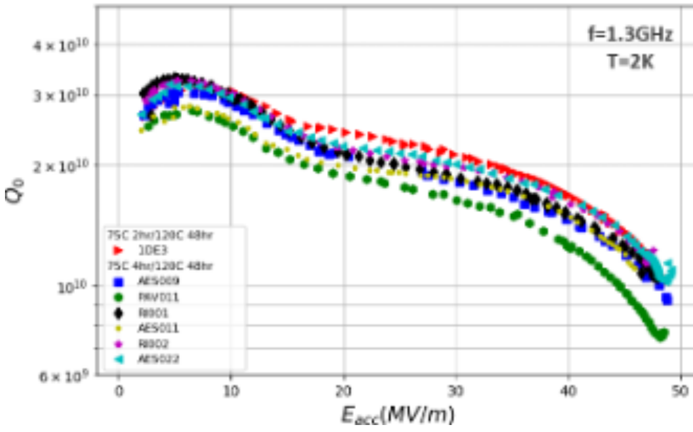
Super-conducting RF Upgrades

Need ~60 MV/m to reach 1 TeV in LCF tunnel

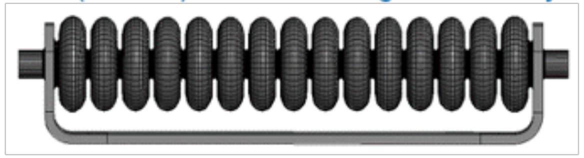
- SCRF is one of the key directions of Accelerator R&D Roadmap
  - significant synergies with ERL needs
  - needs to be accompanied by R&D on high-efficiency klystrons, couplers, He refrigerators, …
  - progress is funding limited
- **5-year horizon:** standing-wave, bulk niobium cavities: **50-60 MV/m**
  - new baking: **2-step (75º/120º) or mid-T followed by low-T**
  - new shapes
- **10-year horizon:** traveling-wave cavities **60-70 MV/m** “HELEN”
  - substantially lower k_M => higher gradients for same magnetic quench limit
  - 2x higher R/Q => lower losses
  - higher stability of field distribution -> longer structures
- **>10-year or break-through:** Nb_3Sn or multilayer cavities **100 MV/m**
  - ~2x higher transition T than Nb: 2K -> 4K
  - ~2x higher DC superheating field than Nb
  - to-date only reached gradients up to 24MV/m with Nb_3Sn

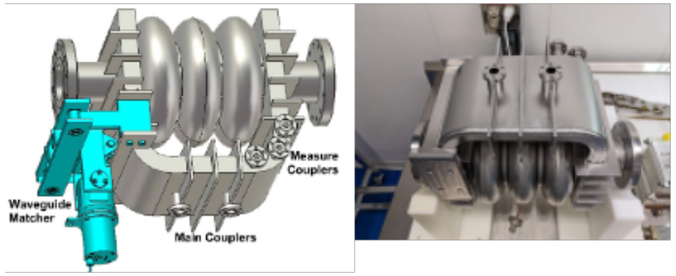


Examples of optimized cavity geometries

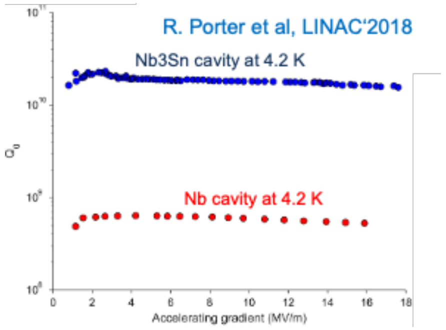



ILC (TESLA) 9-cell standing wave cavity


Traveling wave 15-cell SRF cavity



Proof-of-principle 3-cell cavity



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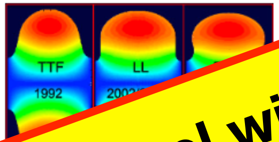
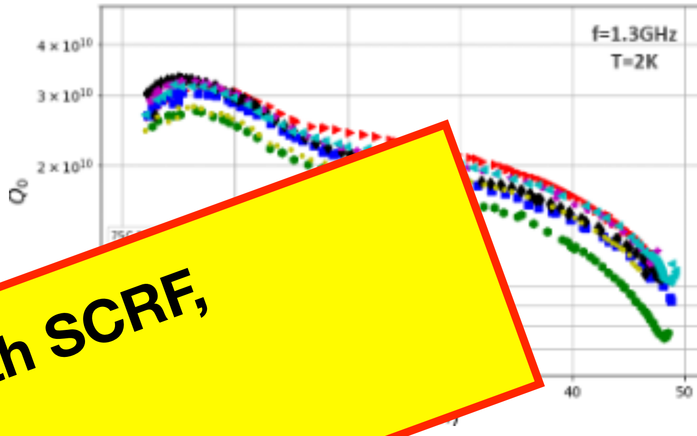
Excellent chances to reach ≥1 TeV in LCF tunnel with SCRF, at reduced power consumption, minimal changes apart from cryomodules





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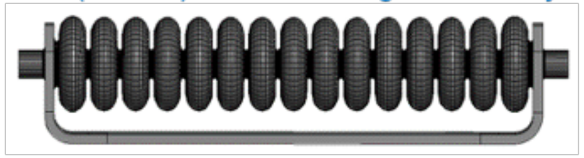

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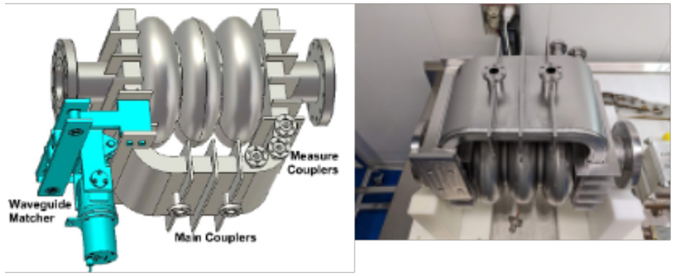

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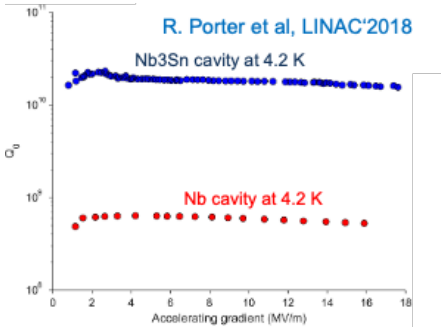
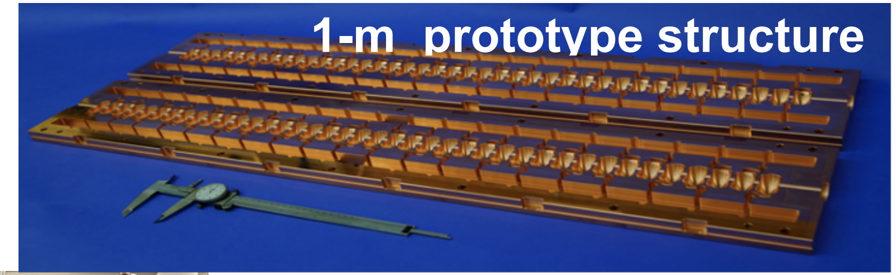
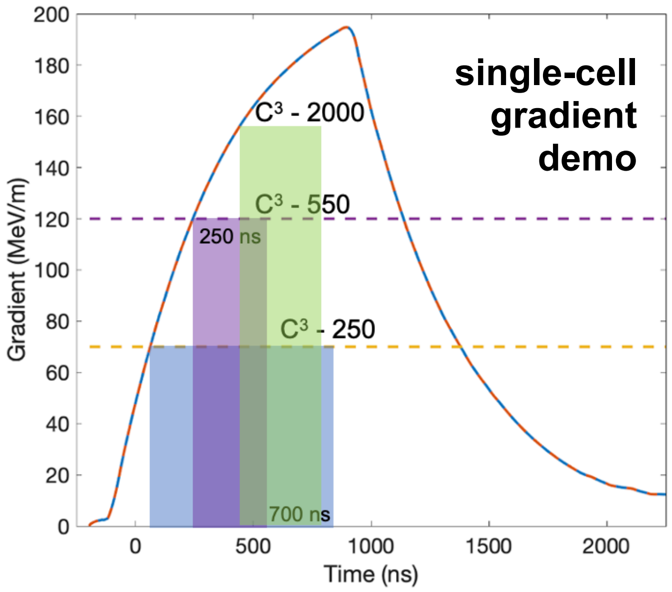


Cool Copper Technology

Idea and R&D

- **C3 technology:**
  - normal-conducting C-band copper cavities
  - operated at cryogenic temperatures (LN_2 ~80K)
  - gradients demonstrated up to 155 MV/m
- R&D:
  - plan towards demonstrator established during Snowmass
  - since then significant progress on system design, accelerator structure design, high gradient testing, vibration measurements, damping materials, alignment system, low-level rf & klystrons, … and **cryo-module design**
- **stand-alone facility 8km**: 250 /550 GeV (70 /120 MV/m)





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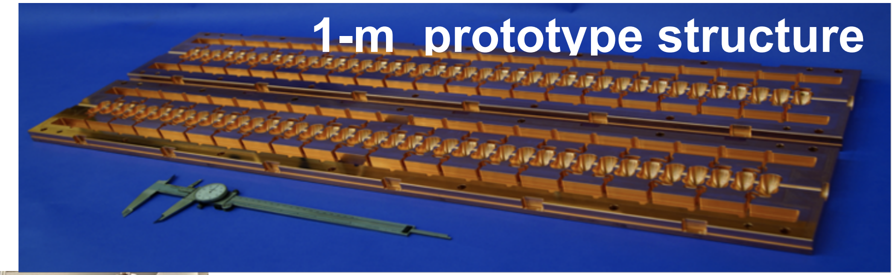

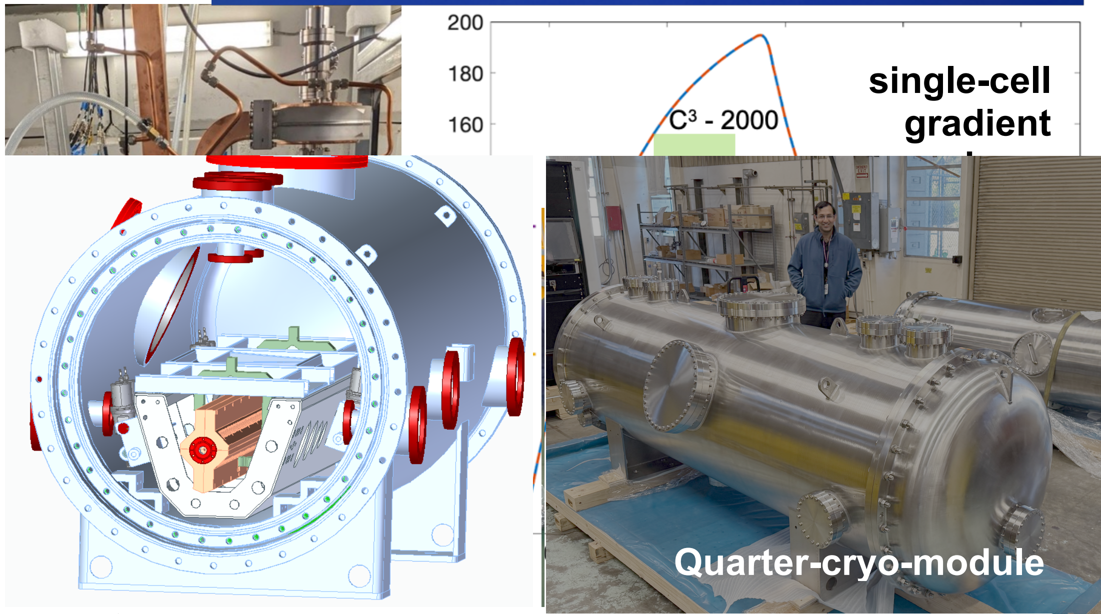

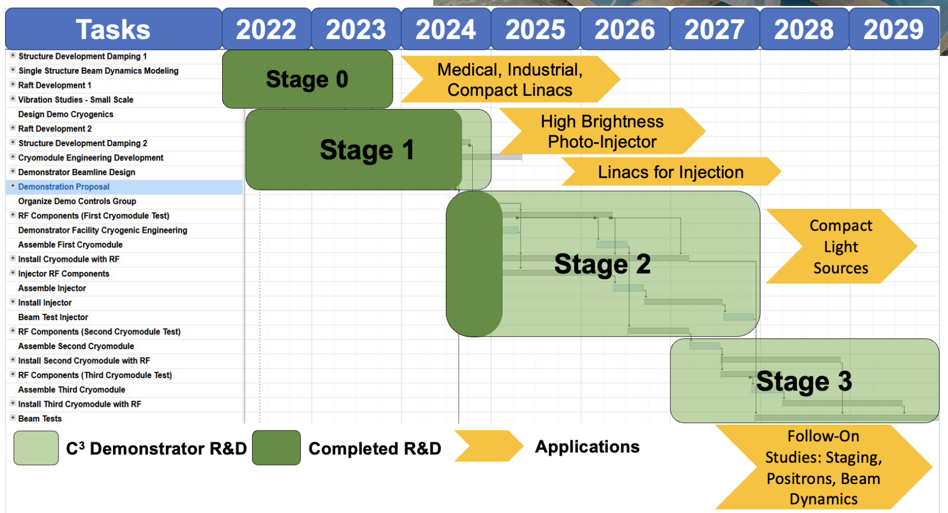

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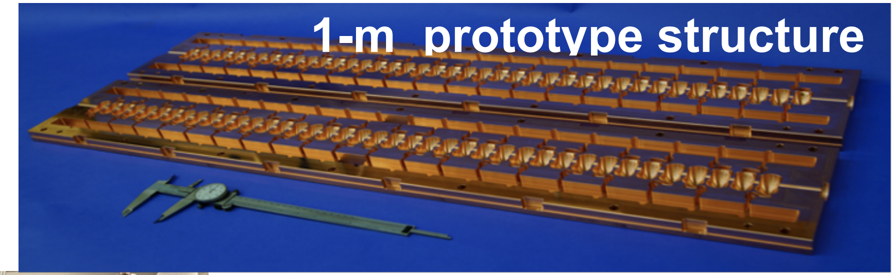

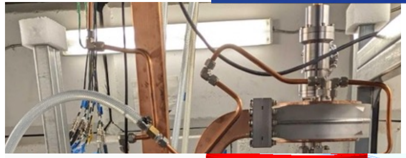

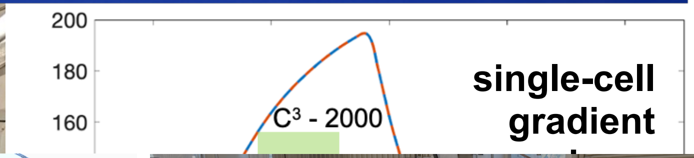

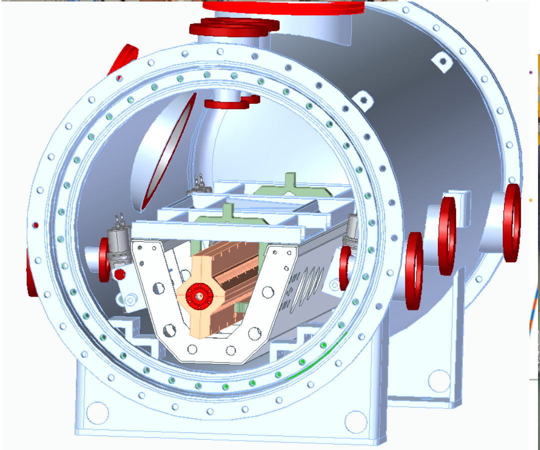

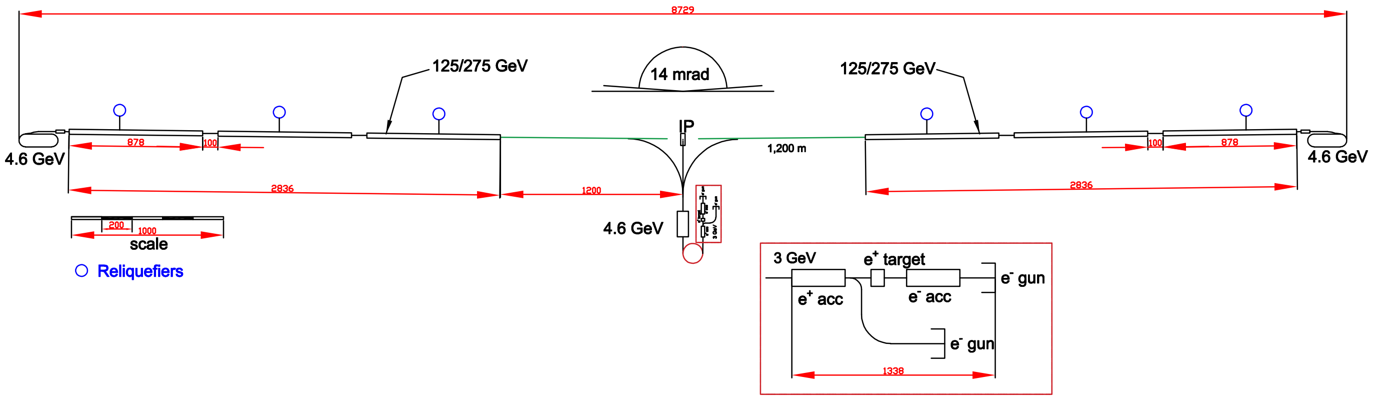

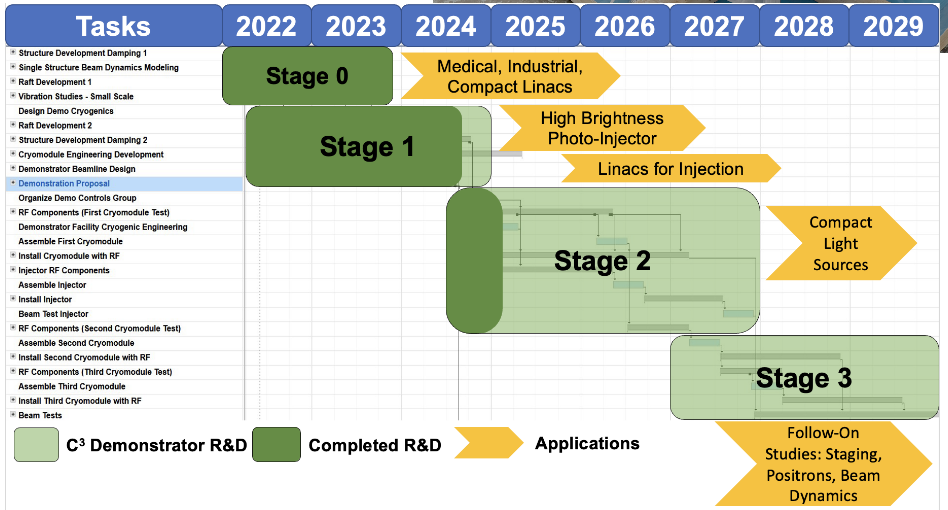

C3 as upgrade for LCF

the route to 3 TeV

- studied in context of LCVision
- **LCF injector complex and damping rings compatible with C3:**
  - larger LCF DRs = lower risk
  - replace fast->slow kickers (kick whole trains)
  - bunch compressor length / emittance sufficient

  => substantial part of infrastructure could be reused
- cryo-plants need modification
- SRF cryomodules could be sold / donated for XFELs / medical linacs /.. round the world
- to be considered in design of beam delivery systems and dumps

Parameter	Unit	Value	Value	Value
Centre-of-Mass Energy	GeV	1000	2000	3000
Site Length	km	20	20	33
Main Linac Length (per side)	km	7.5	7	10.5
Accel. Grad.	MeV/m	75	155	155
Flat-Top Pulse Length	ns	500	195	195
Cryogenic Load at 77 K	MW	14	20	30
Est. AC Power for RF Sources	MW	68	65	100
Est. Electrical Power for Cryogenic Cooling	MW	81	116	175
Est. Site Power	MW	200	230	320
RF Pulse Compression		N/A	3X	3X
RF Source efficiency (AC line to linac)	%	50	80	80
Luminosity	$\times 10^{34}$ cm^{-2}s^{-1}	$\sim$4.5	$\sim$9	$\sim$14
Single Beam Power	MW	5	9	14
Injection Energy Main Linac	GeV	10	10	10
Train Rep. Rate	Hz	60	60	60
Bunch Charge	nC	1	1	1
Bunch Spacing	ns	3	1.2	1.2

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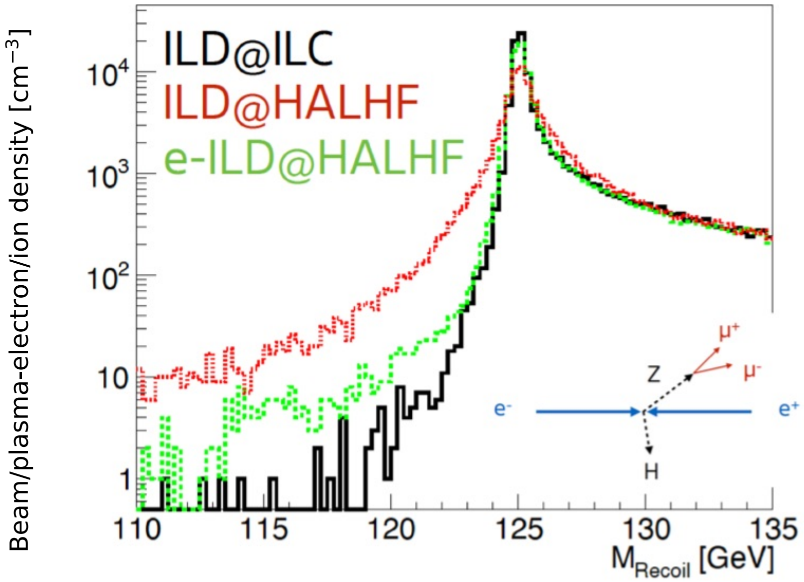
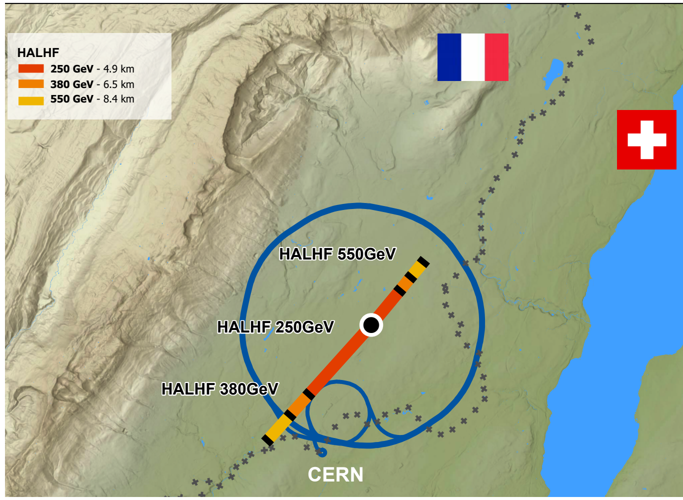
Sustainability: C3 can be 2-4x more power efficient in TeV regime than CLIC / ILC
Very exciting R&D target for the next decade!

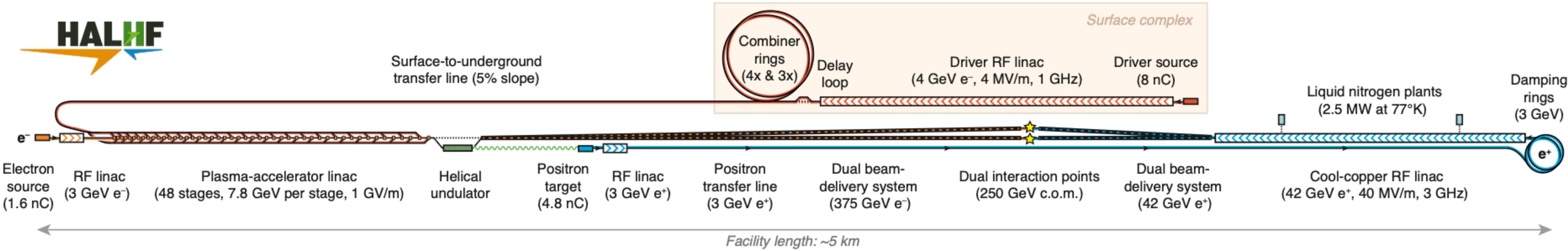
HALHF

Hybrid-Asymmetric Linear Higgs Factory

- e+e- LC using e-beam-driven plasma wakefield acceleration for the e- beam…
- …and RF cavities for the e+ beam
- => asymmetric collisions with γ=1.67 (HERA: γ=3), luminosity ~ILC baseline
- site-length and cost - **small & cheap:**
  - 250 GeV: 4.9 km, 3.8 BCHF
  - 550 GeV: 8.4 km, 6.3 BCHF
- if **R&D** successful - estimated **need**: **213 MCHF & 341 FTEyrs over ~15 years**





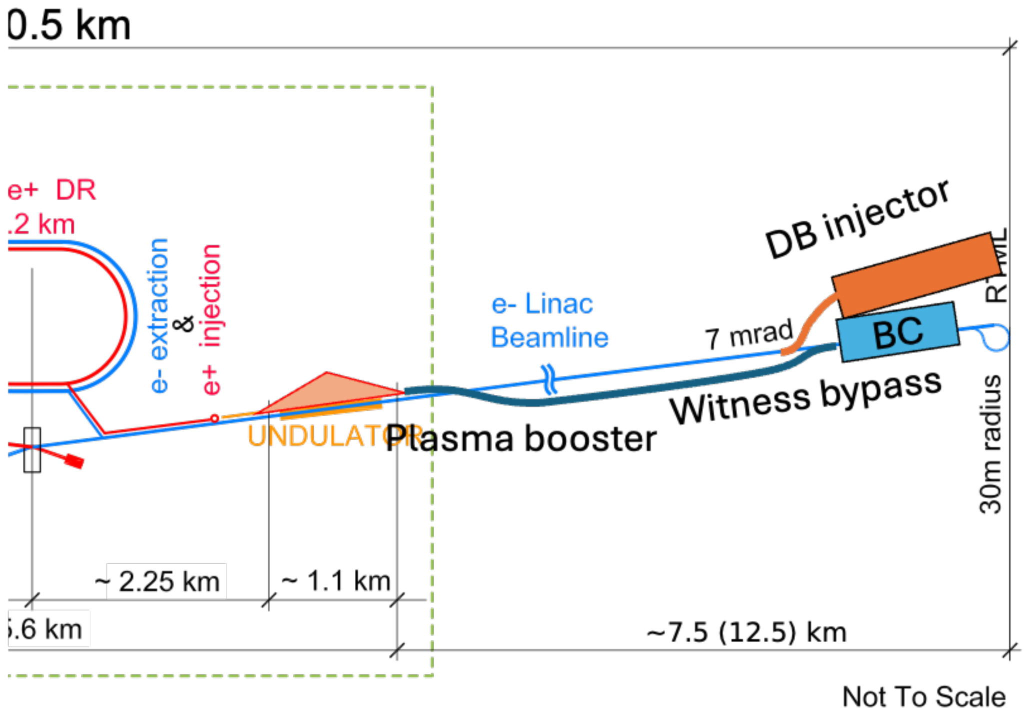


PWA Booster à la HALHF

as upgrade to LCF

- **can one apply the HALHF-scheme to (asymmetrically) double the E_{CM} of a symmetric e+e- LC?**
- **example: 250 GeV (125 GeV on 125 GeV) -> 550 GeV (550 GeV on 137.5 GeV, γ=1.2)**
  - e+ : only small increase in E(e+) needed - either operate at 35 MV/m or add few cryomodules
  - e-: re-purpose main linac to produce drive-beams for plasma stages
    => low gradient - high current operation
  - plasma stages would sit next to undulator source
    => need to foresee lateral space from beginning
  - PWA needs ~10x shorter bunches than LCF standard
    => the HALHF concept assumes that suitable sources will be available - same assumption here
- **conclusion:**
  - conceptually possible
  - in detail many open questions

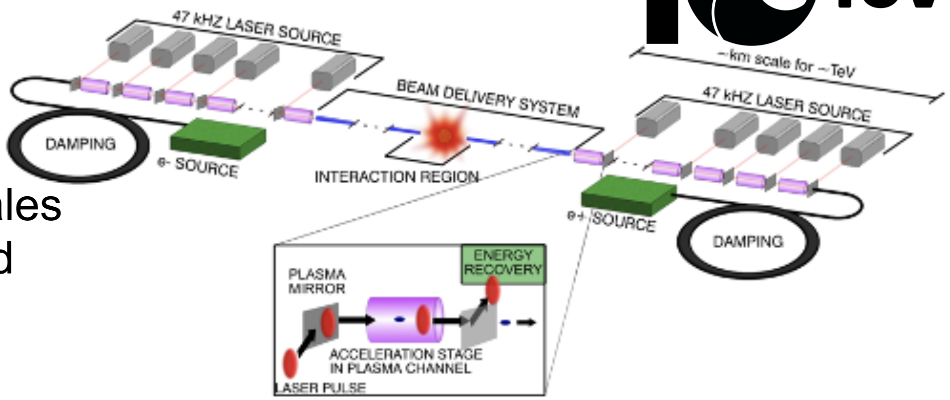
=> room for exciting R&D and creative system design!

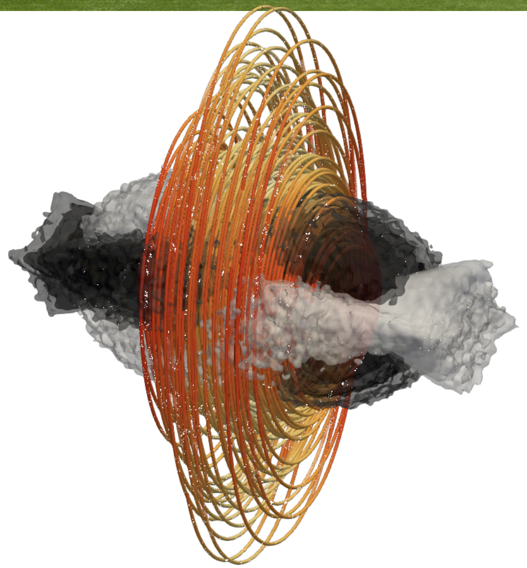


10 TeV pCM wakefield collider

R&D and LCF pave the way

- 10 TeV Wakefield Collider Study
  - by 2028 produce a unified, self-consistent concept, including cost scales for a 10-TeV parton-center-of-mass (pCM) collider based on wakefield accelerator (WFA) technology
  - HEP-wide community effort, involving theorists, experimentalists and Linear Collider experts (~100 participants at last collaboration meeting)
  - investigates the Physics case for 10 TeV pCM e+e-, e-e-, and $\gamma\gamma$ collisions
  - identifies R&D at **current** and proposes the required **new** R&D test facilities
  - would greatly benefit from R&D enabled by LCF
- R&D challenges
  - optimization of power efficiency
  - demonstration of collider plasma modules with 10 GeV energy gain, > 100 pC of charge and normalized emittance < 100 nm
  - staging of collider modules
  - positron acceleration in plasma (not a problem in wake-driven structures or for $\gamma\gamma$)
  - BDS and beam-beam effects at 10 TeV pCM





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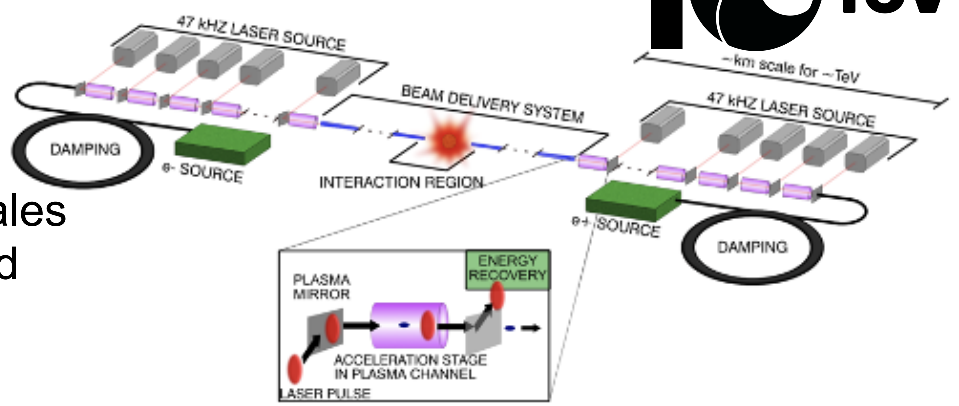
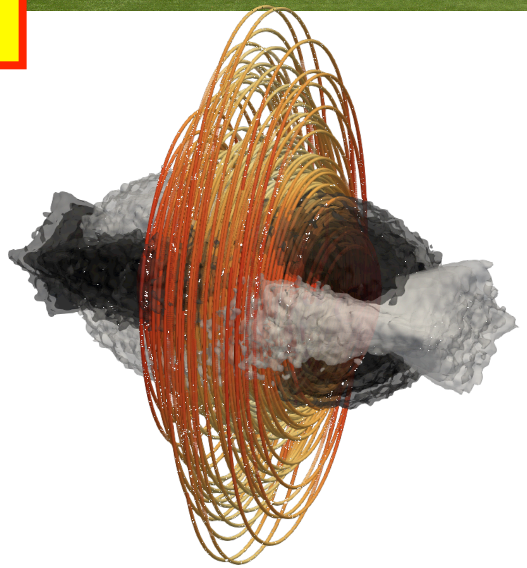


vibrant R&D program at many facilities:
AWAKE (CERN), FACET II (SLAC), FLASH-Forward (DESY), AWA (ANL), BELLA (LBNL), SPARC-LAB (INFN), many high-intensity laser facilities…



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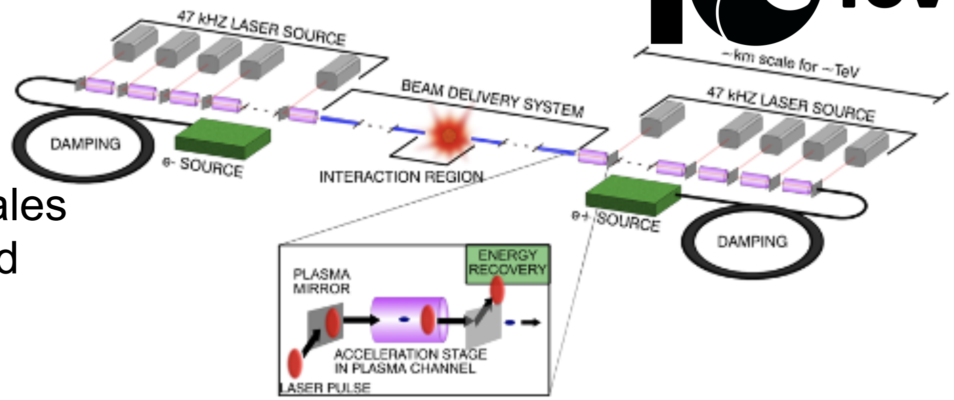

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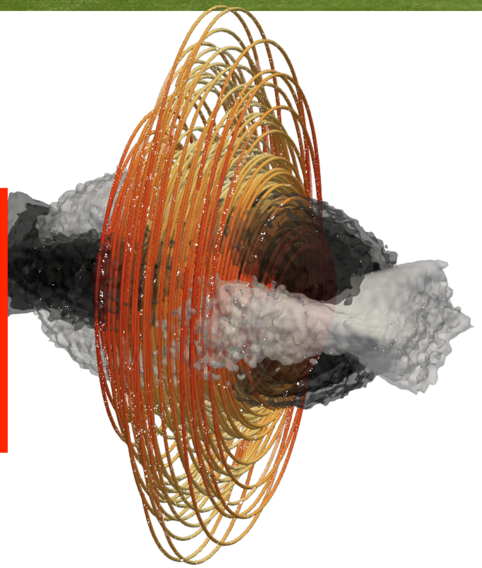
LCVision encourages this R&D as one of the long-term options for a Linear Collider Facility



Higher Luminosity, Photon Collisions & Beyond

Energy- & Particle Recovery as path to High Luminosities

higher luminosity

- Energy and particle recovery:
  - boost luminosity up to 10^{36} / cm^2 / s and high e+ polarisation
  - by re-using particles and energy
    => requires to limit beam-strahlung, far from disruption limit
  - several concepts - e.g. ReLiC, ERLC
- physics motivations for high luminosity in e+e- LC:
  - most measurements statistics limited => gain everywhere
  - e.g. few 0.1% on trilinear, few 10% quartic self-coupling…
  - also: electron Yukawa - effective absence of beam-strahlung allows mono-chromatisation

	LCF	ReLiC[1]	ReLiC[2]	ReLiC[3]	ReLiC[3]
Centre-of-mass energy [GeV]	250	250	250	250	550
Accel. Grad. [MeV/m]	31.5	12.55	12.55	12.55	27.6
Cavity Q_0 [10^{10}]	2	4	4	4	4
Liquid He temperature [K]	2	2	2	4.5	4.5
Bunch population [10^{10}]	2	2.5	2.5	2.5	2.5
Collision frequency [MHz]	2.62	1.5	1.5	1.5	1.5
Duty cycle	0.0012	cw	cw	cw	cw
Beam current, all beams [mA]	0.042	12	12	12	12
Normalised emittance hor.[μm] / vert.[nm]	5/25	4/1	4/1	4/1	4/1
β_x / β_y [m] / [mm]	0.013/0.41	2.2/0.19	2.2/0.19	2.2/0.19	4/0.36
σ_x / σ_y at IP [μm] / [nm]	0.52/7.7	6/0.9	6/0.9	6/0.9	6/0.9
D_x / D_y	0.5/34.5	0.01/87	0.01/87	0.01/87	0.01/88
Υ_{max}	0.068	0.0028	0.0028	0.0028	0.0031
Luminosity [10^{34} cm^{-2}s^{-1}]	2.7	140	140	140	153
AC Site Power [MW]	111	~135	~105	~95	~ 250

[1] ReLiC based on current "conventional" Nb SW SCRF technology [512]. Cryogenics system: 80 MW, damping rings: 70 MW + others

[2] ReLiC based on Nb SW SCRF technology, but COP of 2 K LiHe refrigerators improved 2-fold. Cryogenics system: 45 MW, damping rings: 70 MW + others

[3] ReLiC based on futuristic SCRF technology for Nb3Sn SW cavity with $Q_0 = 4E10$.
250GeV: Cryogenics system: 35 MW, damping rings: 70 MW;
500GeV: Cryogenics system: 95 MW, damping rings: 140 MW

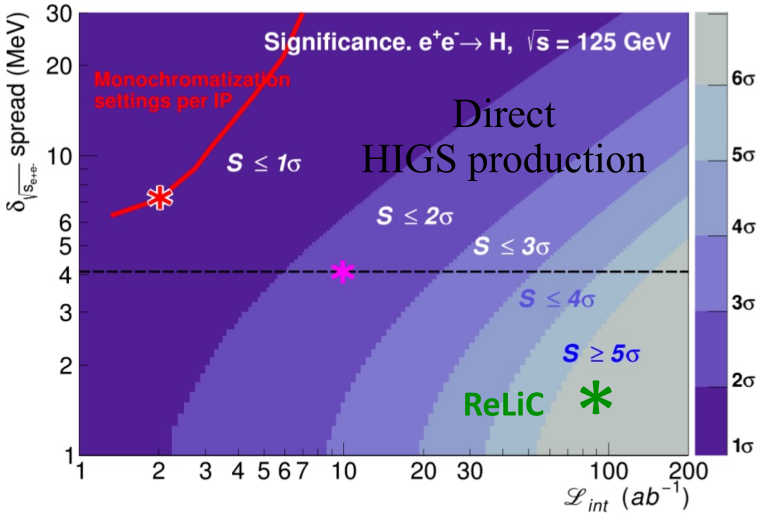
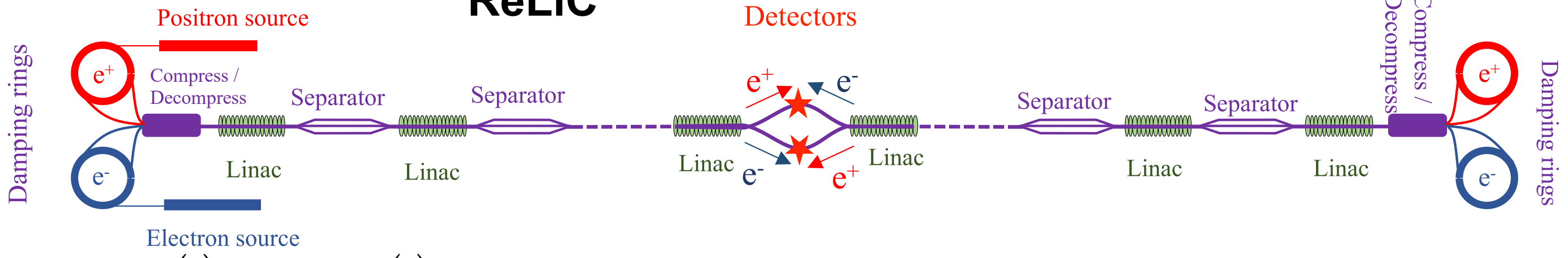
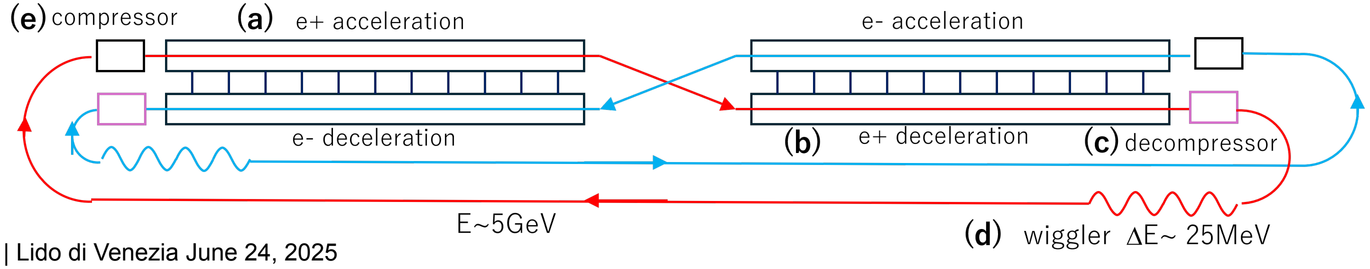


Figure is courtesy of David d'Enterria

ReLiC



ERLC



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Υ_{max}	0.068	0.0028	0.0028	0.0028	0.0031
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	111	∼135	∼105	∼95	∼ 250

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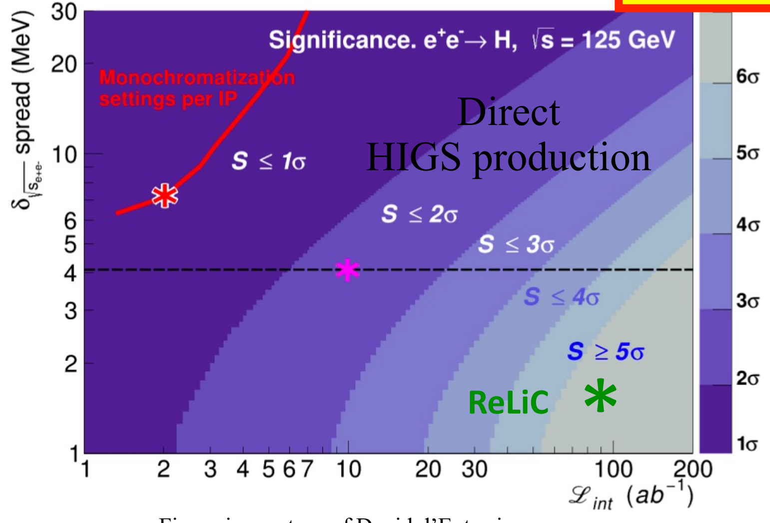
250GeV: Cryogenics system: 35 MW, damping rings: 70 MW;
500GeV: Cryogenics system: 95 MW, damping rings: 140 MW

Key R&D challenges: efficient LHe refrigerators, (Nb3Sn) cavities operating at 4K



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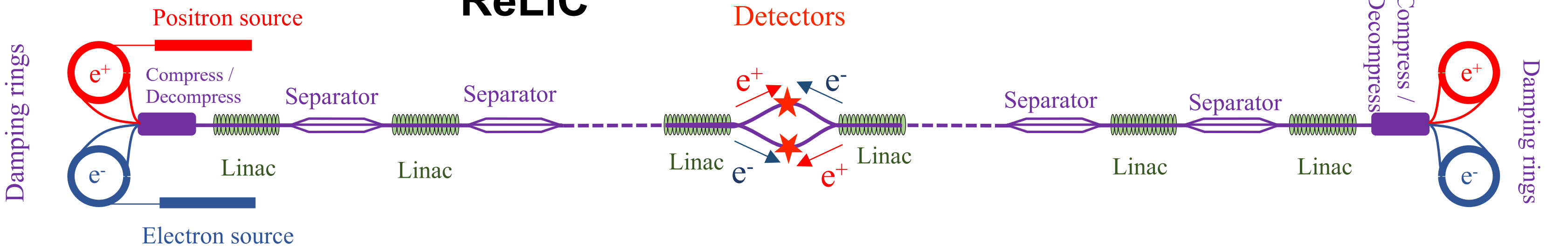

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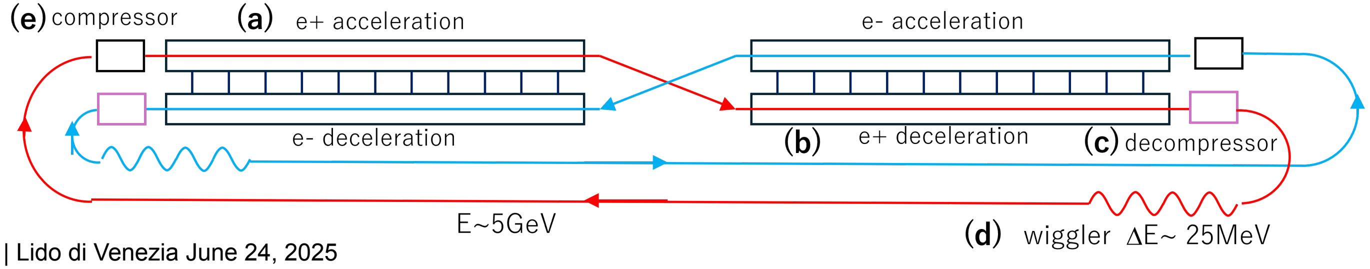


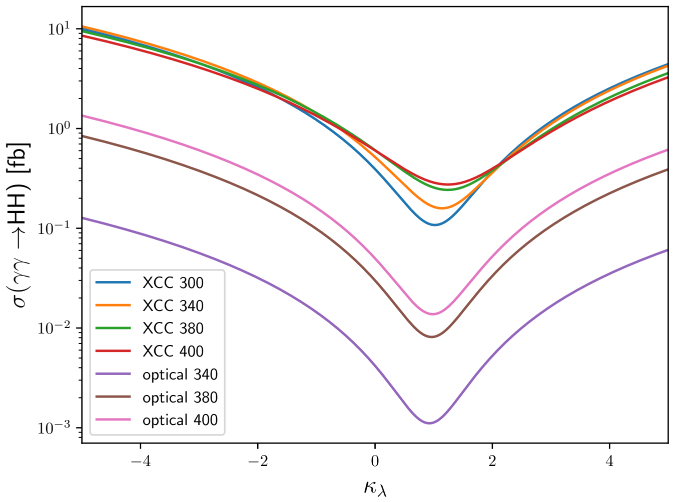
Photon-Photon / e-photon collisions

Photon Collider

- **γγ / eγ offers unique complementary physics opportunities**

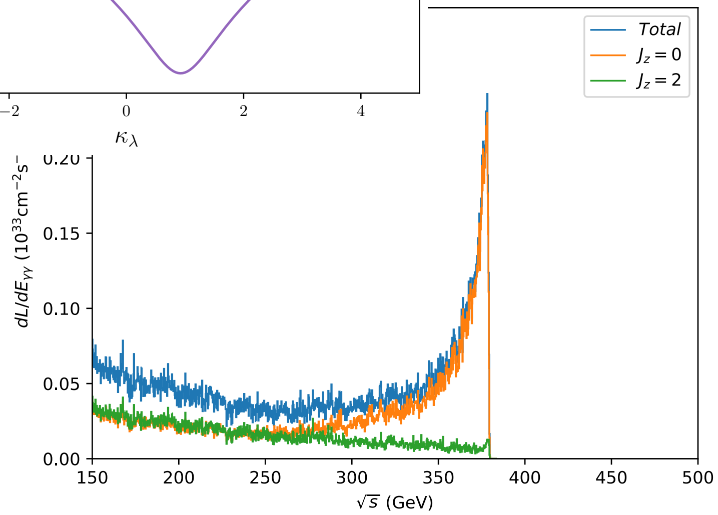
  e.g. self-coupling in **γγ➔HH** with different BSM behaviour than e+e- / pp

- high-intensity lasers convert e beam(s) into γ beam(s) directly at the IP
  => spin-0 luminosity spectrum sharply peaked
- two methods:
  - optical lasers "classic" scheme
  - **recent: X-ray lasers from X-FELs integrated into the facility (XCC)**

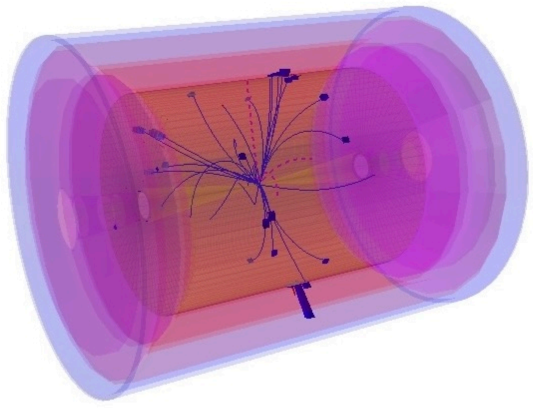


energy-dependent minimum in HH cross section

sharp spin-0 lumi peak

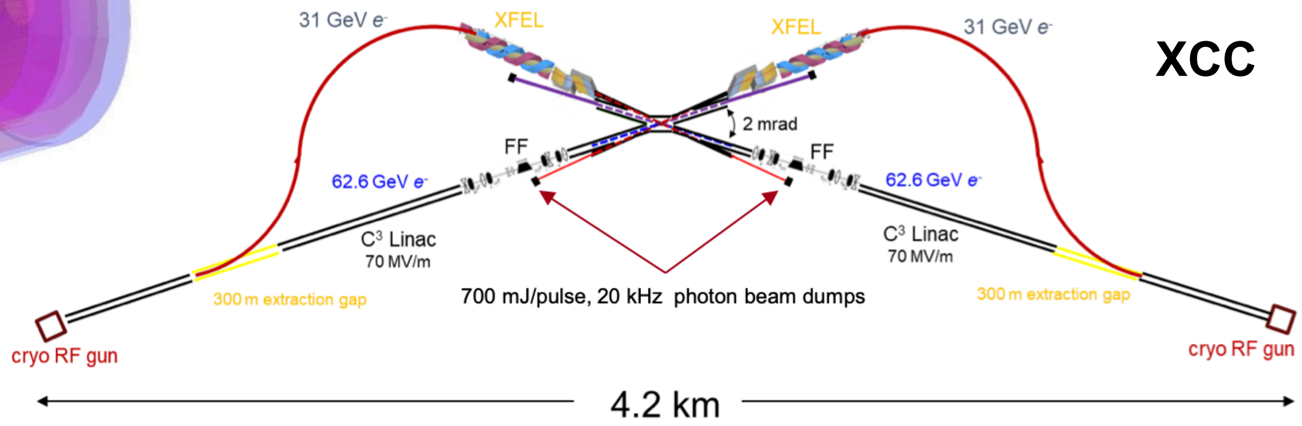


Final Focus parameters	SCRF + Optical Laser	C3 + XFEL
Electron energy [GeV]	250	190
Electron beam power [MW]	10.5	2.1
β_x/β_y [mm]	1.5/0.3	0.01/0.01
$\gamma\epsilon_x/\gamma\epsilon_y$ [nm]	2500/30	60/60
σ_x/σ_y at e^-e^- IP [nm]	88/4.3	1.3/1.3
σ_z [μm]	300	10
Bunch charge [$10^{10}e^-$]	2	0.62
Bunches/train at IP	2625	93
Train Rep. Rate at IP [Hz]	5	120
Bunch spacing at IP [ns]	366	5.2
σ_x/σ_y at IPC [nm]	176/37.5	5,2/5.2
$\mathcal{L}_{\text{geometric}}$ [10^{34}cm^2 s^{-1}]	12	180
δ_E/E [%]		0.1
L^* (QD0 exit to e^-e^- IP) [m]	3.8	1.5 or 3.0
d_{cp} (IPC to IP) [μm]	2600	40
crossing angle [mrad]	20	2 or 20



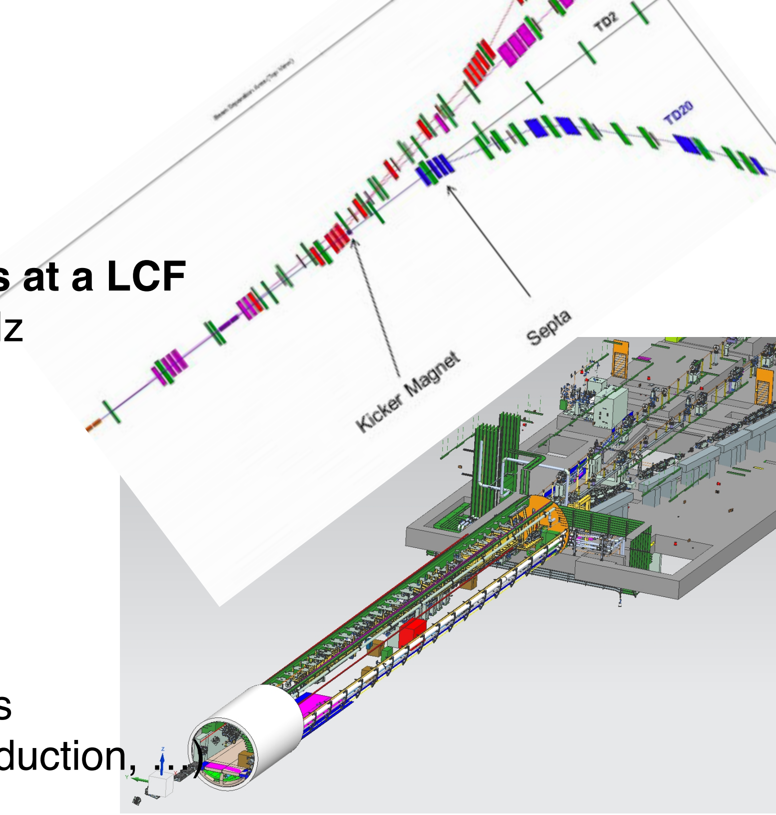
$\gamma\gamma \to$ **HH** $\to$ **4b**

XCC

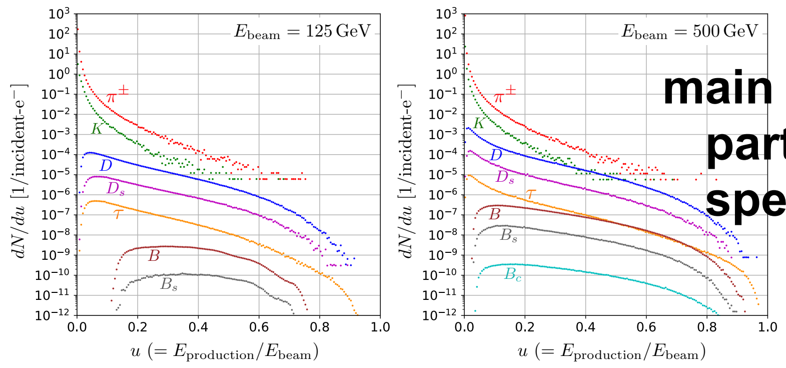


Beyond a collider

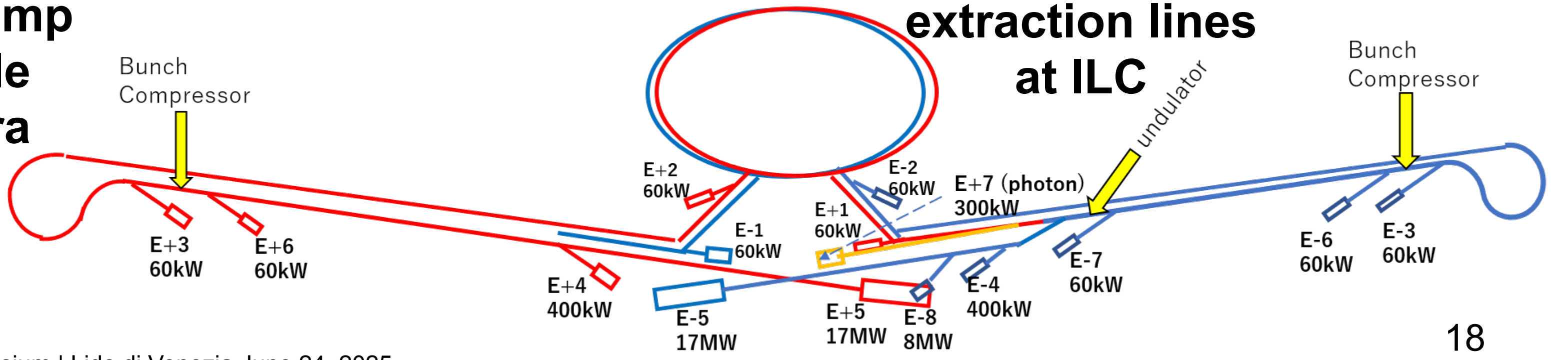
Beam-dump / fixed-target / R&D / irradiation



- **Ample opportunities to foresee beam extraction / dump instrumentation / far detectors at a LCF**
  - extraction of bunches before IP -> mono-energetic, extremely stable, few 10^{10} @ 1-10 Hz
    => super-LUXE (SF-QED χ = O(few hundred) & BSM search), super-LDMX, …
  - disrupted beam after IP -> broad energy and highly divergent, but up to 10^{15} eot / s
    super-SHIP, generic dark photon and ALP searches
    => together with e+e- cover all Dark Sector portals
- **Low-emittance, mono-energetic beams ideal for**
  - high-rate detector and beam instrumentation tests
  - creating **low-emittance beams of photons / muons / neutrons** for various applications (hadron spectroscopy, material science, irradiation, tomography, radioactive isotope production, …)
  - **accelerator development:**
    - high-gradient accelerating structures, new final focus schemes, deceleration (for ERLs), beam and laser driven plasma, …
    - from extracted beam to test small setups - **to large-scale demonstrators for upgrades of the main facility**



main dump particle spectra



dumps / extraction lines at ILC

Conclusions & Invitation

General Considerations

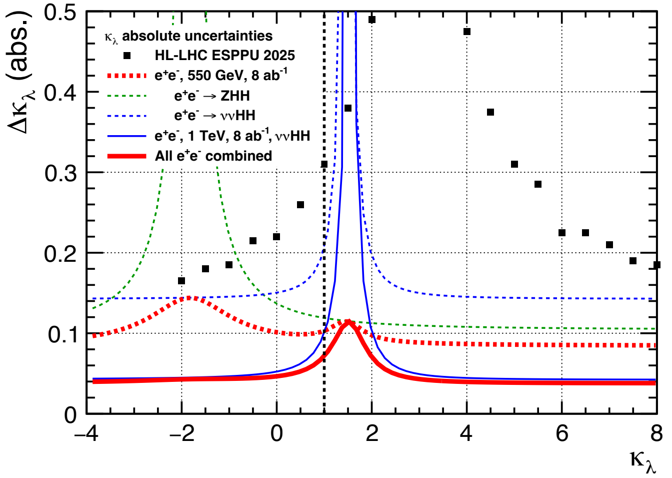
at the heart of LCVision

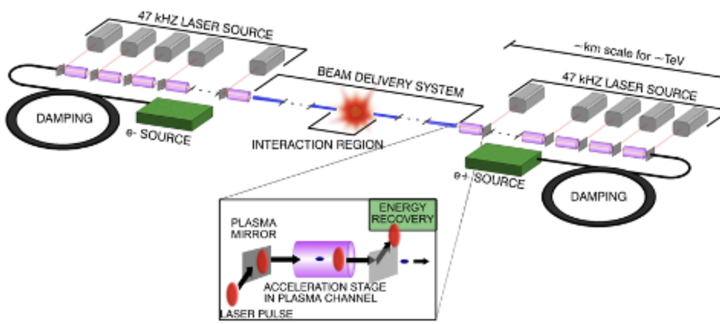
- **Timing is important - need a timely e+e- Higgs factory based on technology in-hand:**
  - current young researchers are key to both the HL-LHC program and the future Higgs factory
  - prolonged uncertainly or delays in decision making discourage ECRs => loss of talent
  - clear and timely transition from HL-LHC to next collider will provide long-term research opportunities
- **Flexibility is important too - keep driving (and profit from) advanced accelerator technologies:**
  - stageable and upgradable approach
  - can decide to switch / upgrade technology at any stage
  - based on **scientific and technological developments** — or even break-throughs
- **Need for intensified accelerator R&D:**
  - goal for the next-to-next generation facility must be a 10-TeV pCM collider
  - there is no affordable technology today
  - all routes (pp <=>HFM; $\mu\mu$ <=> cooling; ee/$\gamma\gamma$ <=> PWFA) need expensive R&D and demonstrators
  - a staged and flexible Higgs factory aligns best with this ambitious R&D program

Conclusions

LCVision for the ESPPU

- **we need a new e+e- collider to study the Higgs - now**
- **a Linear Collider has decisive advantages:**
  - **particle physics:** polarisation & high-energy reach
    => Higgs pair production in two complementary production modes
  - **strategically:**
    - well-understood technology and staged approach allow fast start
    - flexible and responsive to future physics developments
  - **technologically:**
    - flexible upgrades with advanced accelerator technologies
  - **for the next-to-next step:** support R&D towards 10-TeV pCM scale
- **the LCVision team contributed to the ESPPU:**
  - **the physics and technology case for Linear Colliders in general**
  - **and proposed a Linear Collider Facility @ CERN as the next flagship project, in the spirit of the Linear Collider Vision**





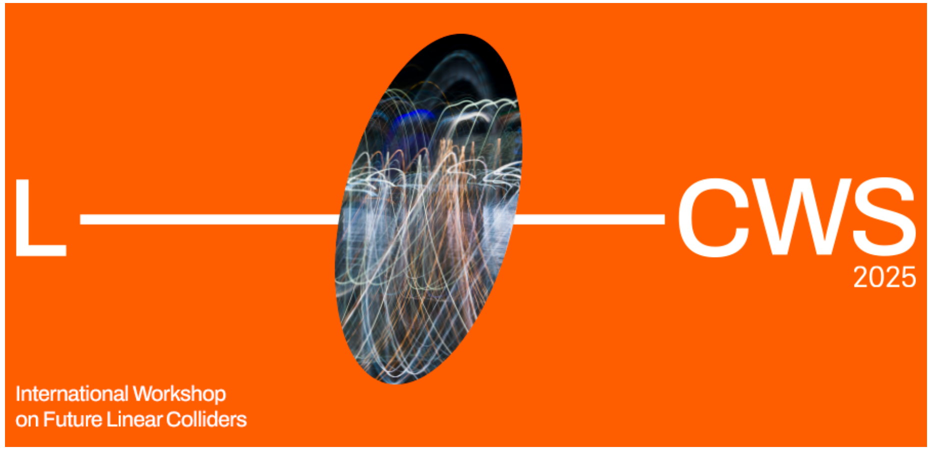
Invitation to participate in LCVision

What you can do

- sign-up for LCVision mailing list (CERN e-group):
  http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=LCVision-General

- **sign up on supporter list for the LCVision documents:**
  - either following link on https://agenda.linearcollider.org/event/10624/program
  - or directly on https://www.ppe.gla.ac.uk/LC/LCVision/index.php?show=instadmin&skey=etUI1visTy25

- **join us at LCWS2025: October 20-24 in Valencia, Spain**



Any Questions?