Linear Colliders

MelFest 2023

Maximilian Swiatlowski

TRIUMF

ATLAS
EXPERIMENT

Disclaimers

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    - (I know this is a hadron crowd: please no tomatoes!)
    - There are many new ideas out there: check out LCWS2023!

Why a Higgs Factory?

Why a Higgs Factory?

European Strategy

3

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Broad consensus that
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Broad consensus that a Higgs factory should be the next collider

Nathaniel Craig

Seven Questions

Does the Higgs…

✓ …have a size?

✓ …interact with itself?

✓ …mediate a yukawa force?

✓ …connect to the dark sector?

✓ …fulfill the naturalness strategy?

✓ …preserve causality?

✓ …realize electroweak symmetry?

Many fundamental questions we can answer with detailed Higgs studies

Why A Higgs Factory?

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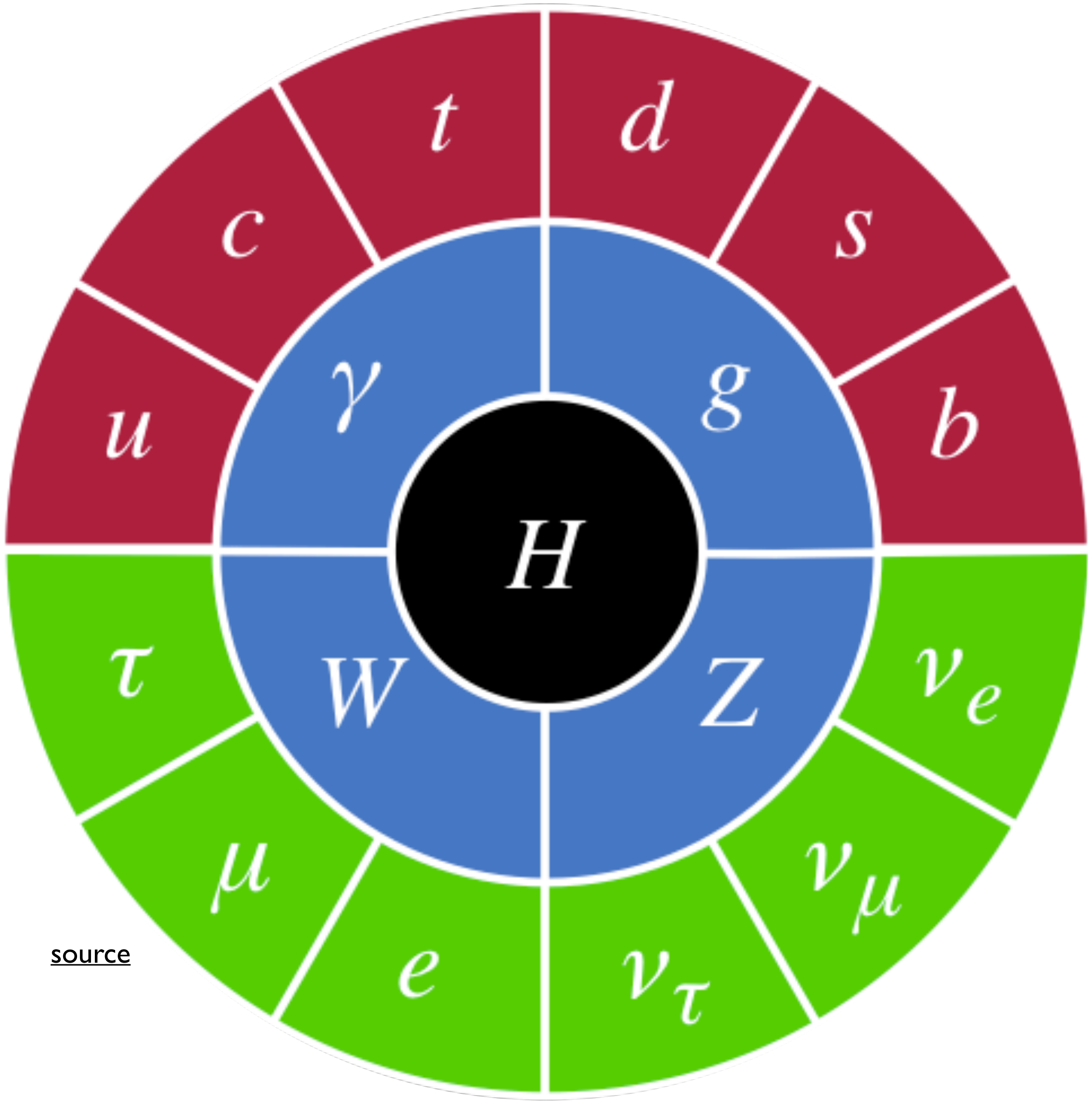

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The Higgs touches everything in the SM:
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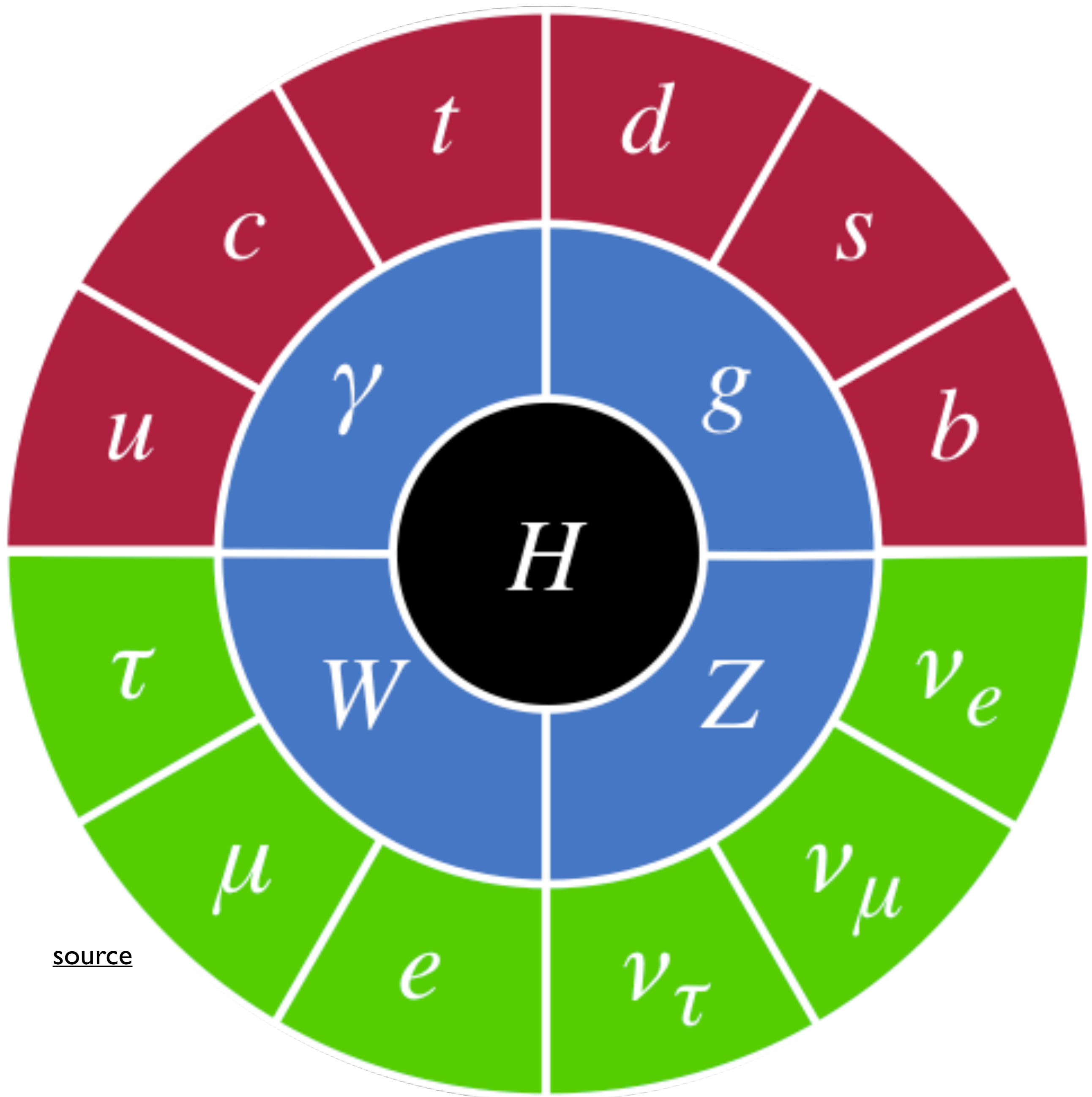
Why A Higgs Factory?



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Snowmass Implementation Task Force

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
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
ReLiC-3	IV					3
MC-3	III					3
LWFA-LC 1-3	IV					4
PWFA-LC 1-3	IV					4
SWFA-LC 1-3	IV					4
MC 10-14	IV					3
LWFA-LC-15	V					4
PWFA-LC-15	V					4
SWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3
Coll.Sea-500	V					4

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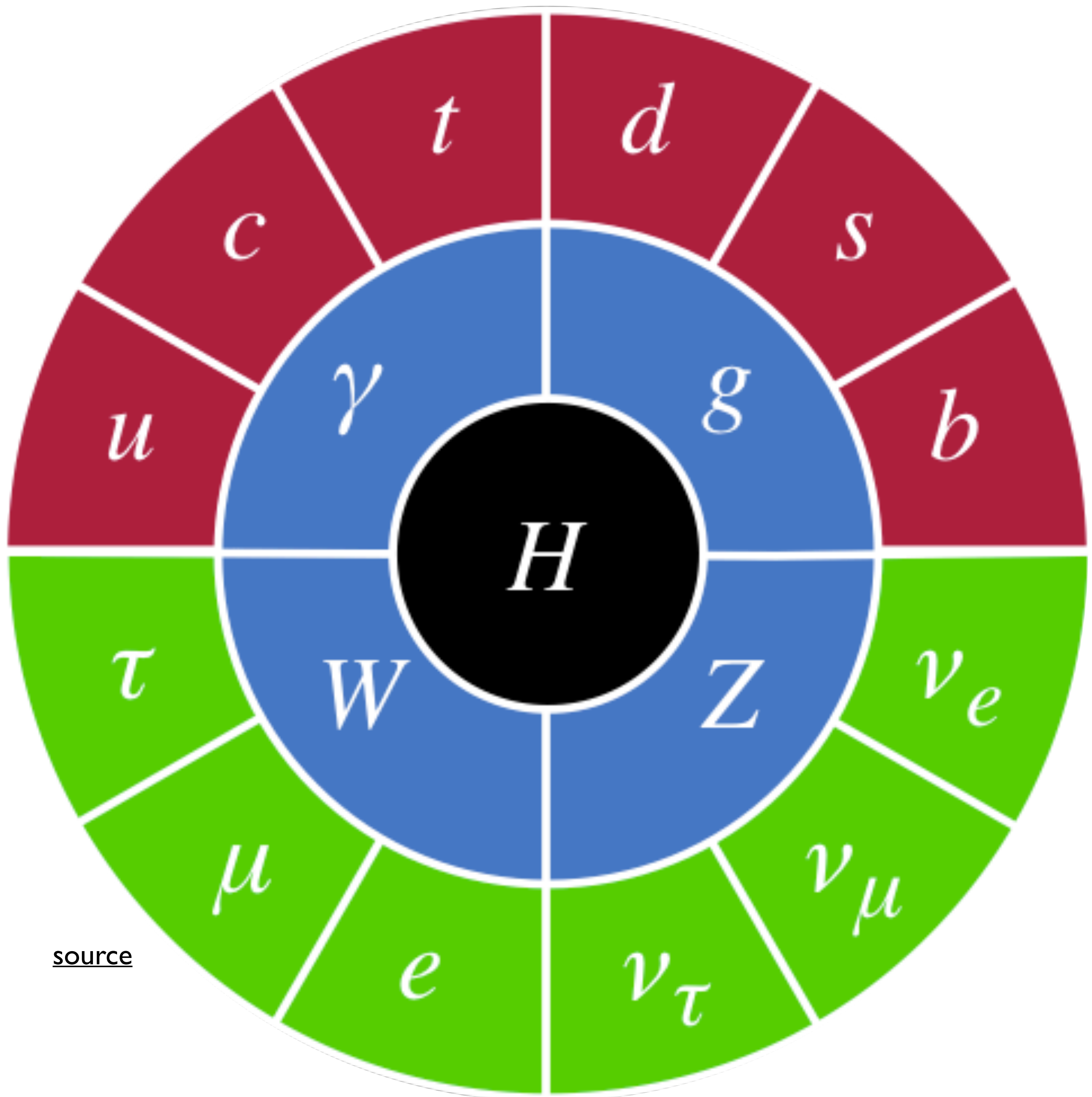
And: **we know how to build Higgs Factories**

Why A Higgs Factory?



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Pros for Linear:

- **No synchrotron radiation**: significantly smaller accelerator
- No trigger needed
- Bunch structure leads to “power pulsing” for detector: no cooling, less material, greater precision
- Energy is upgradeable beyond 380 GeV: can produce Higgs pairs for self-coupling
- Polarized beams can aid physics sensitivity
- Smaller tunnel: less $$$ and less carbon

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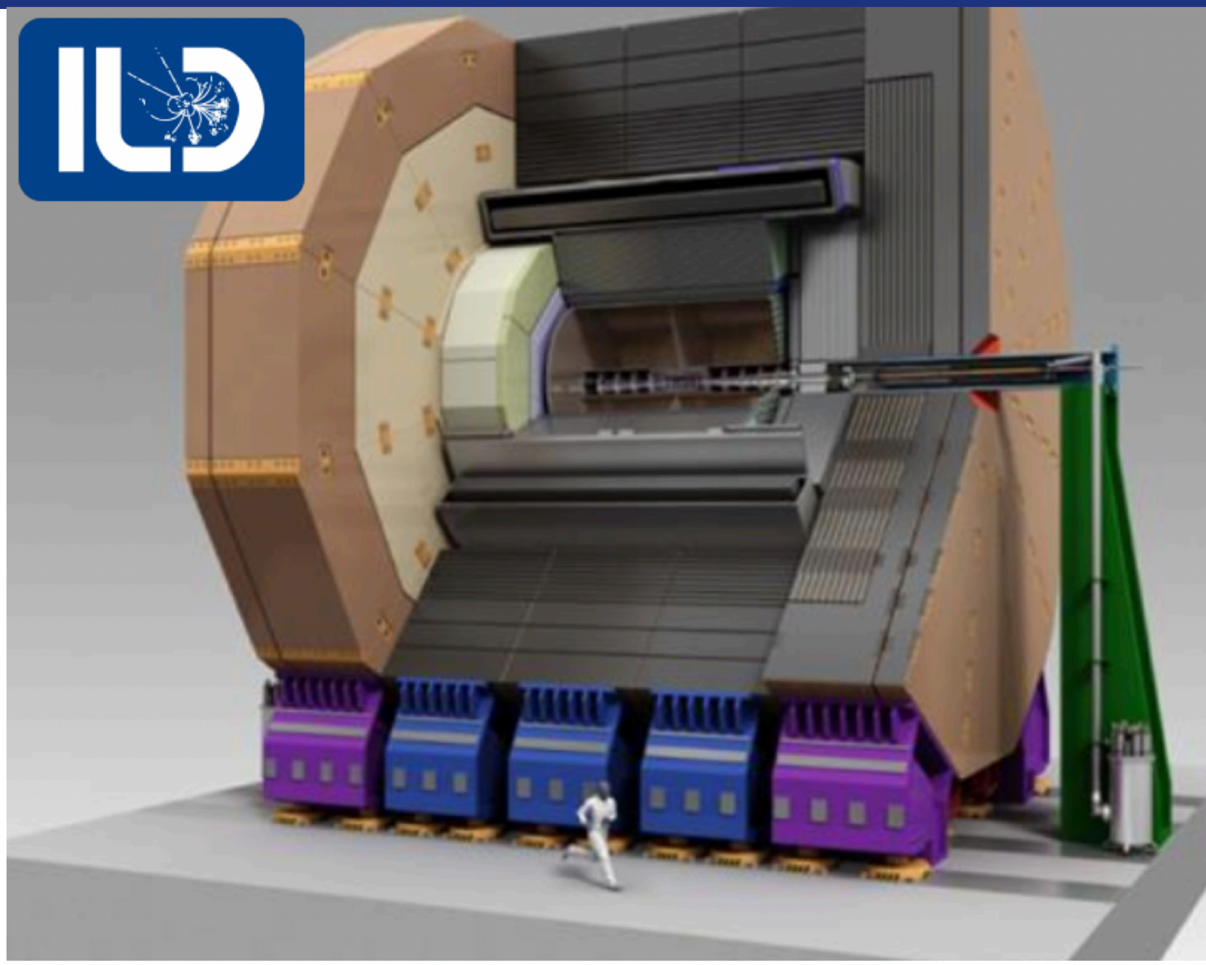
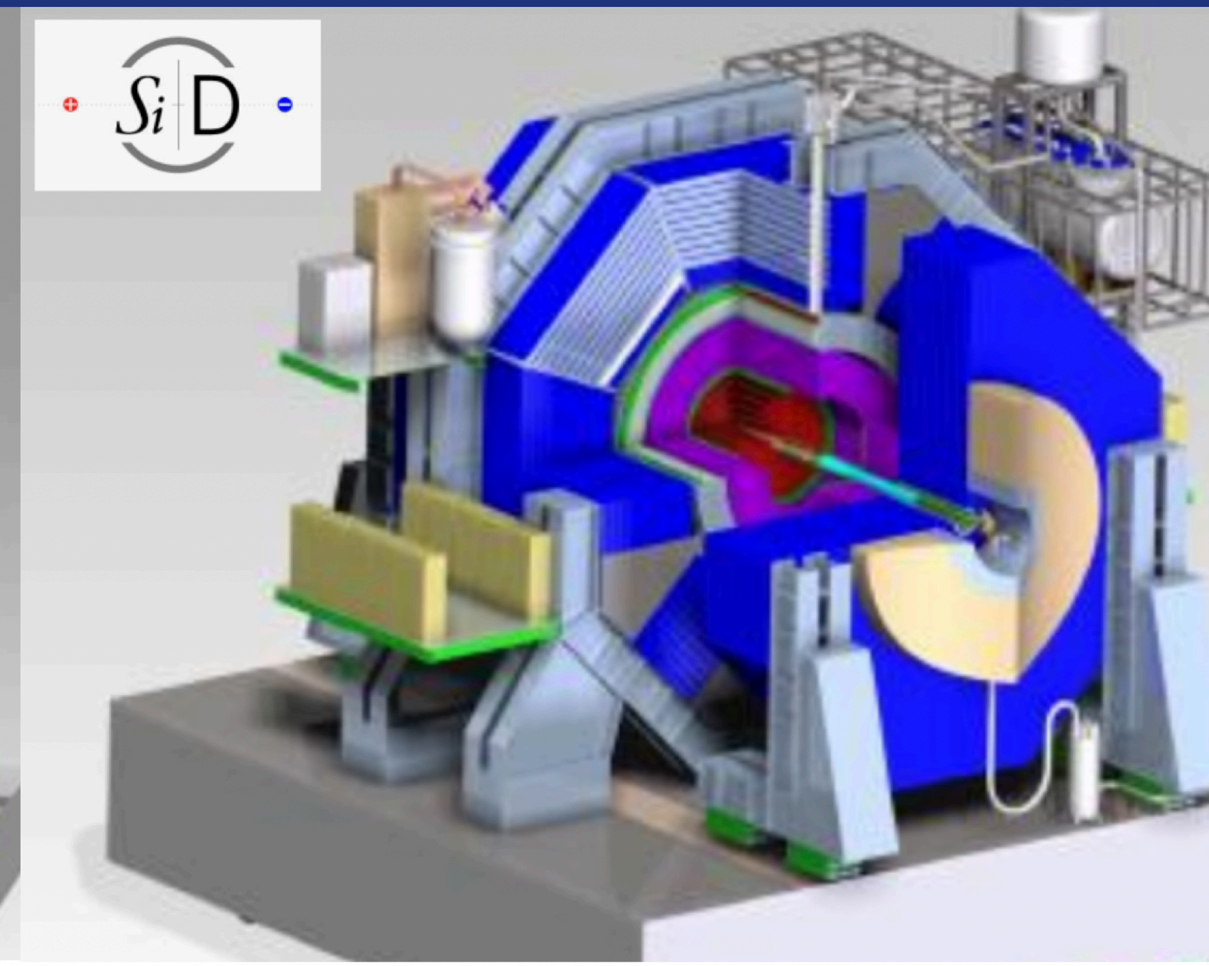
Cons for Linear:

- Low luminosity (and only 1 IP) compared to circular machines
- Less control over beam energy (due to beamstrahlung effects)
- No potential for tunnel re-use for hadrons
- (Potentially) more difficult to tune

Detectors

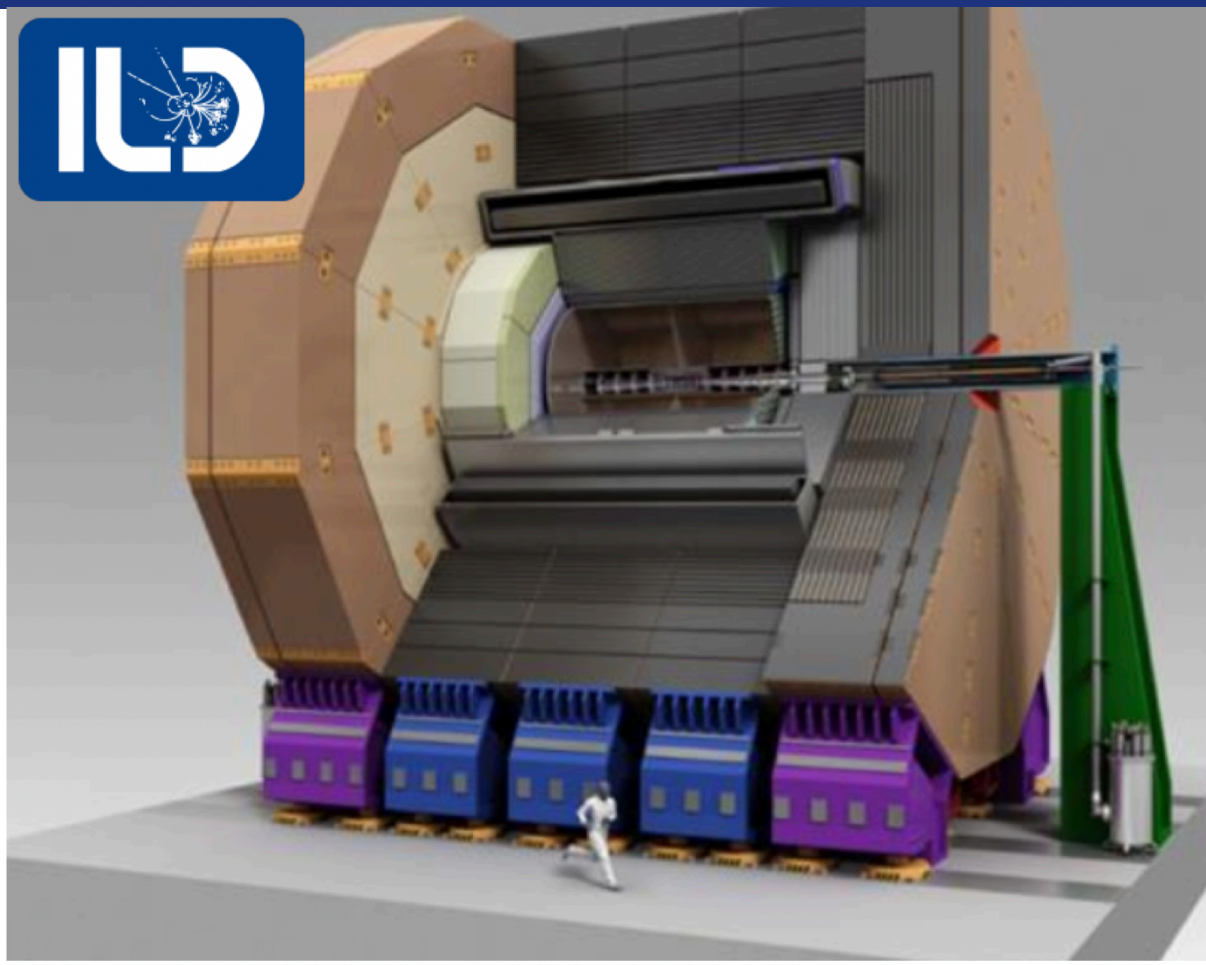
Detectors

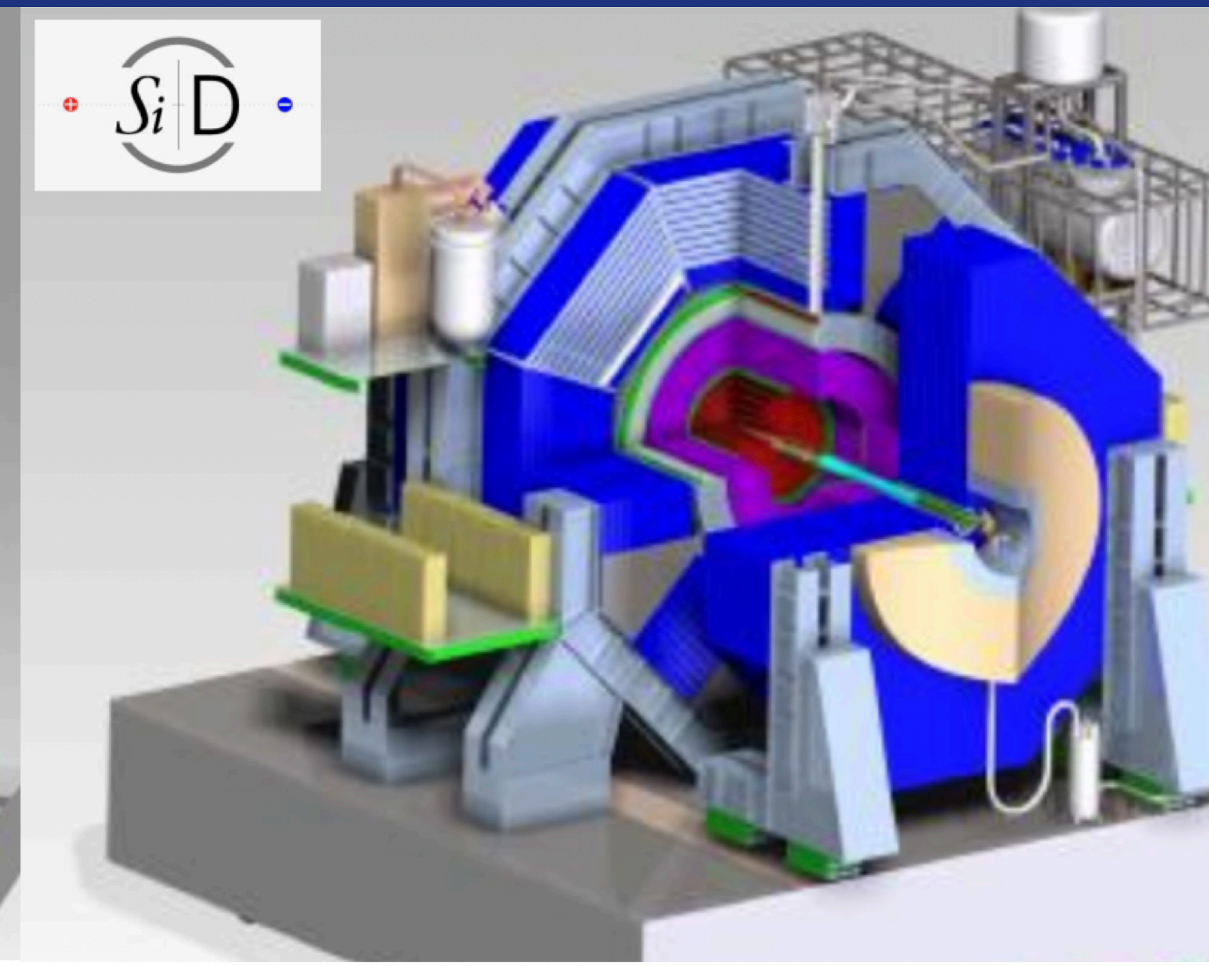




Robust designs for detectors already exist

Detectors





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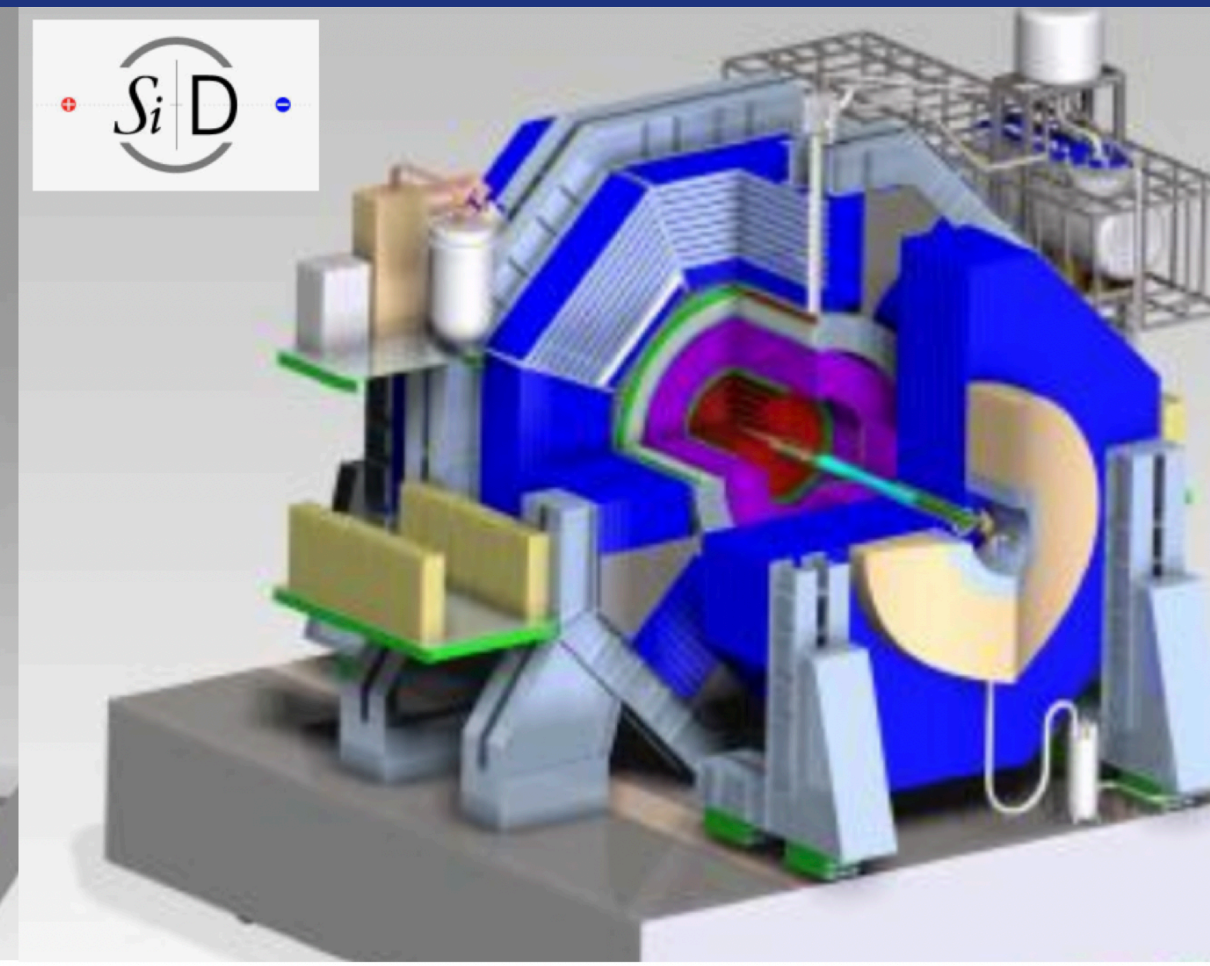

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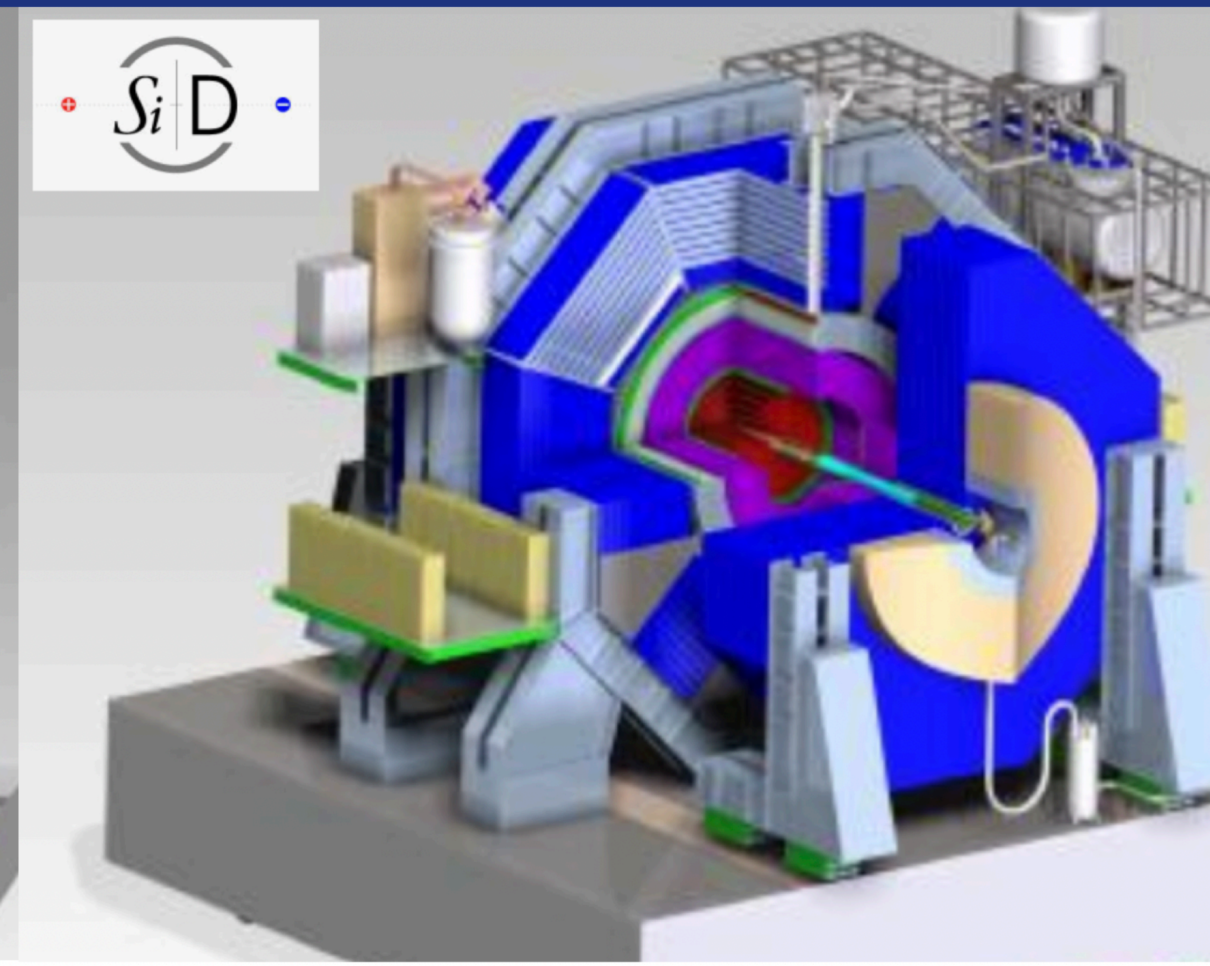

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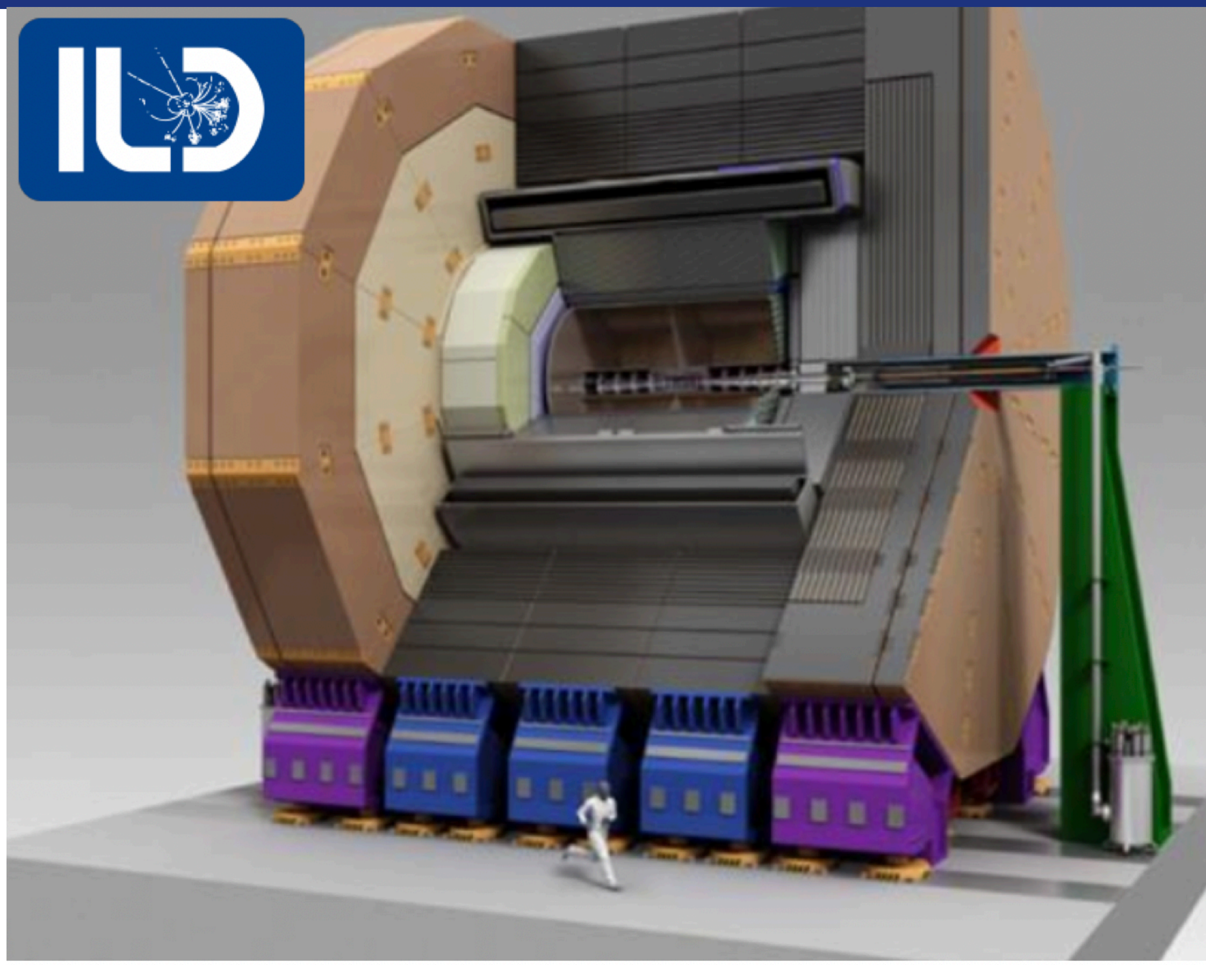

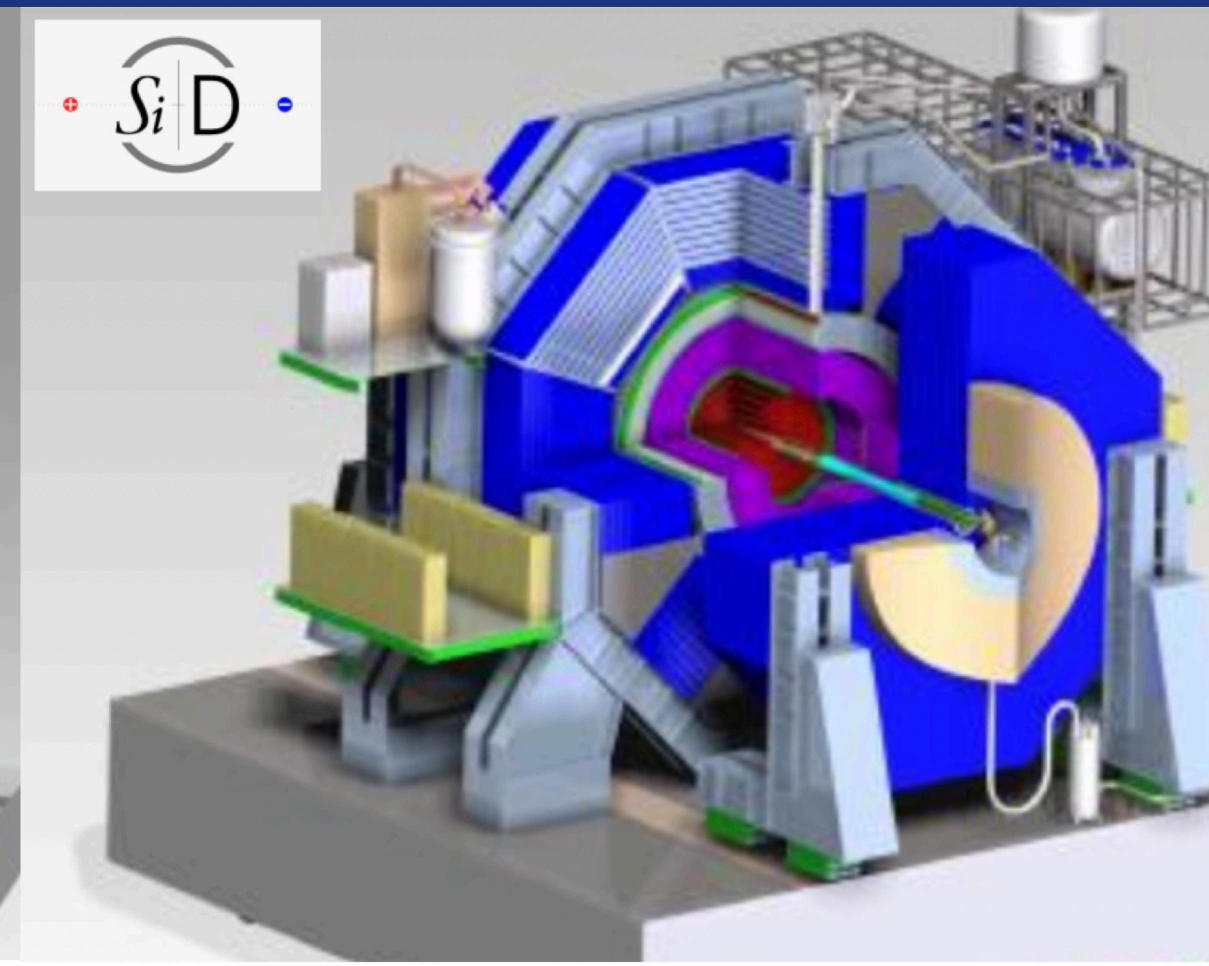

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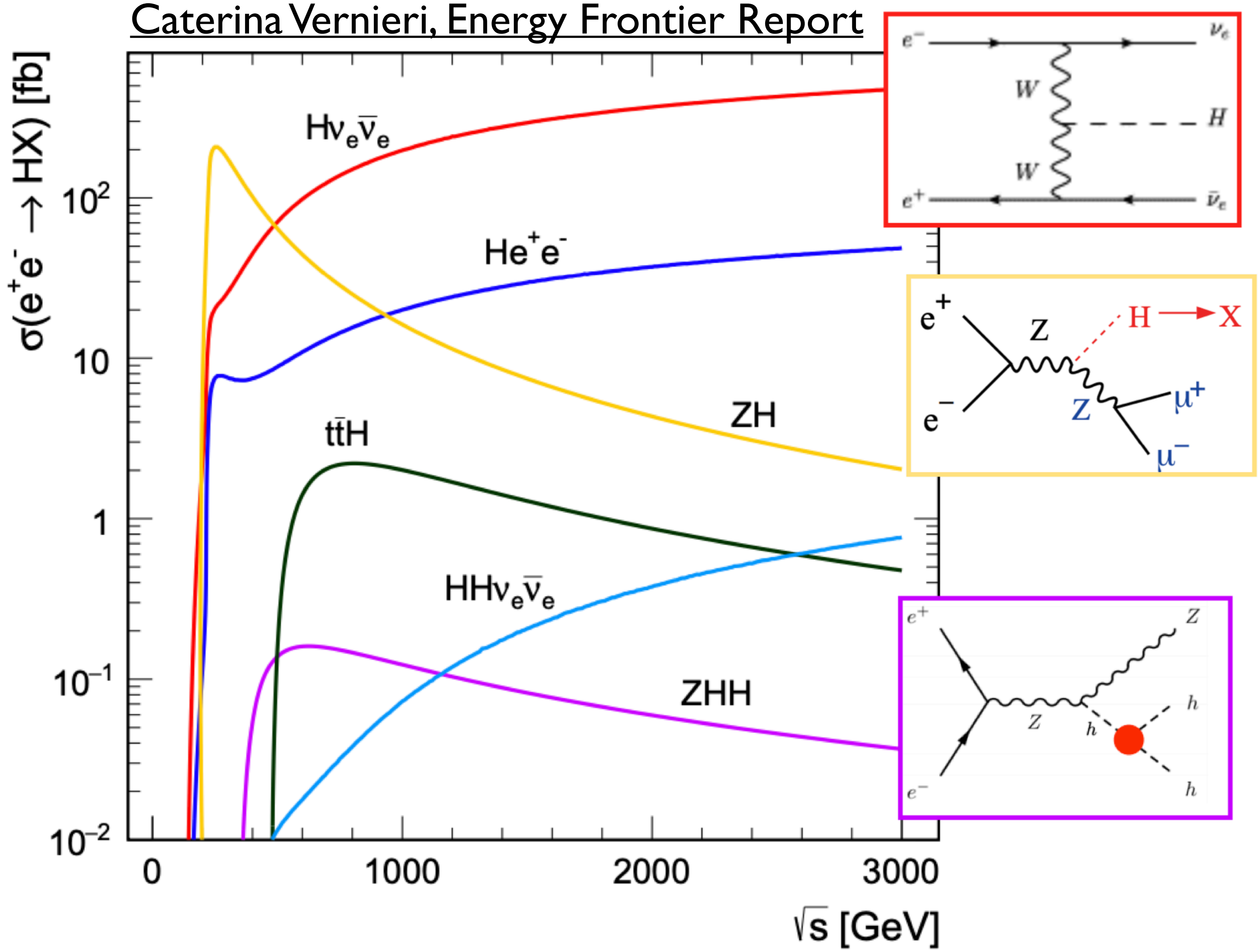
Minimal material, precision-oriented detectors

Producing Higgs

Producing Higgs

[Caterina Vernieri, Energy Frontier Report](#)



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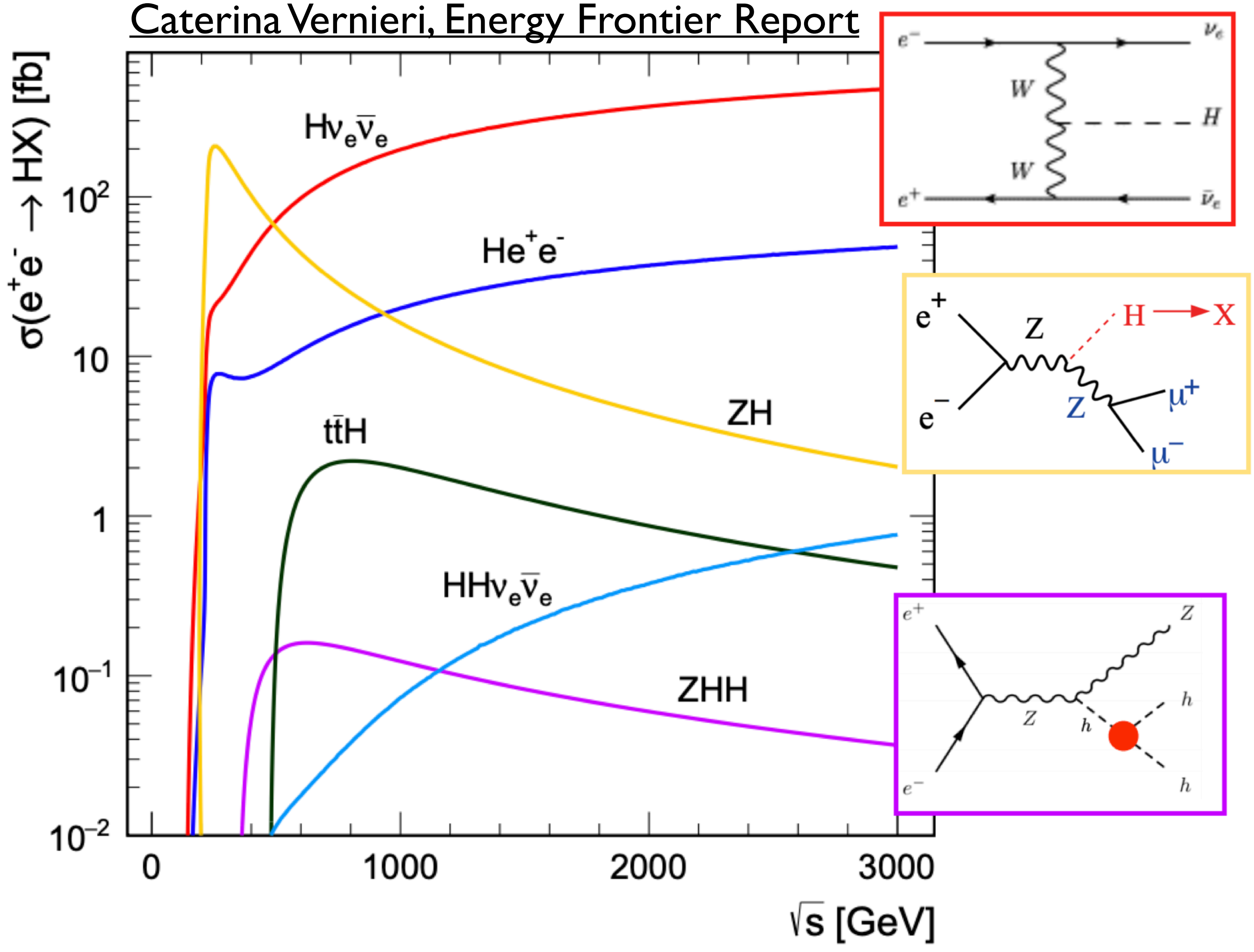

ZH cross-section peaks at 250 GeV: natural first target for Higgs factories

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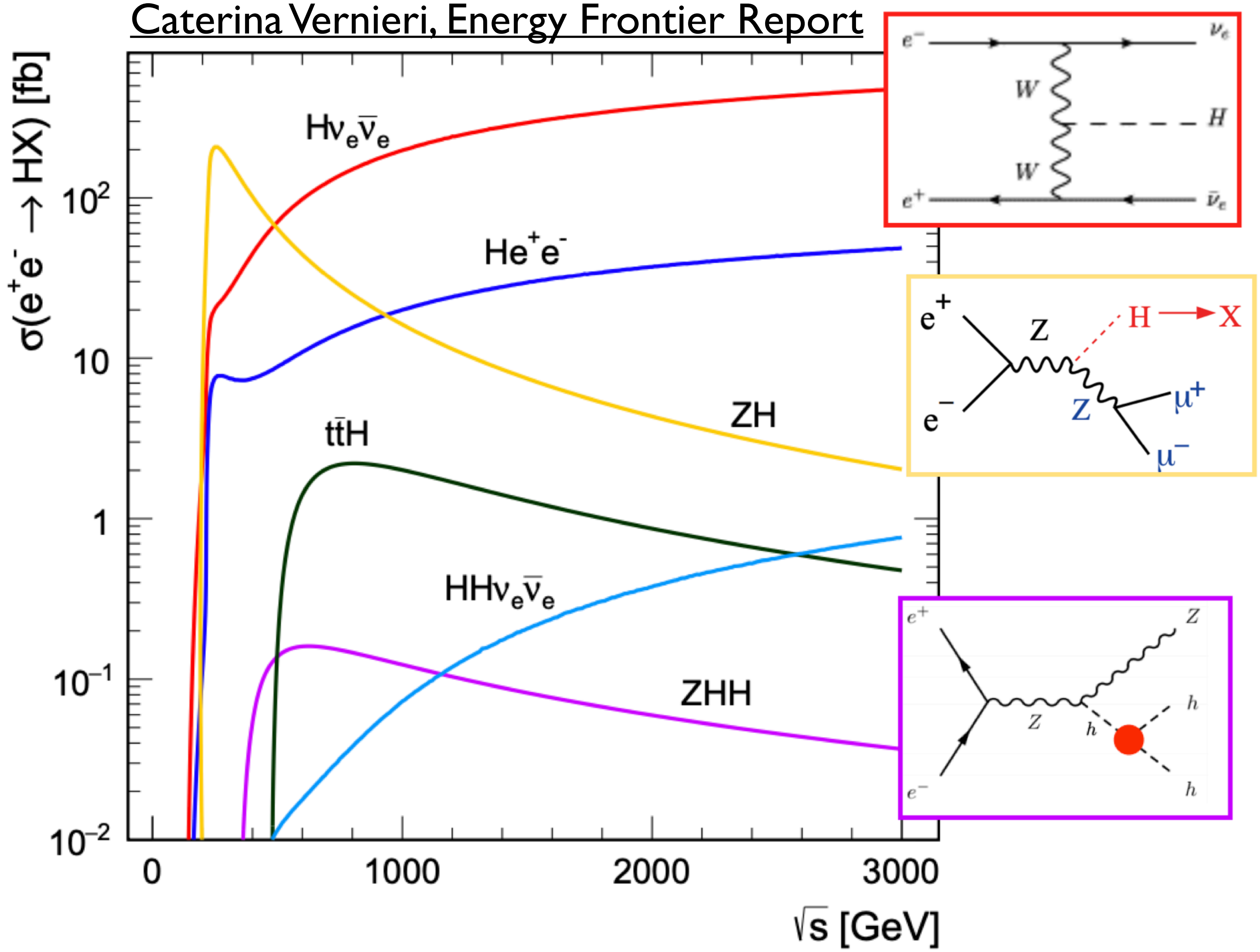

ZH cross-section peaks at 250 GeV: natural first target for Higgs factories

ZHH production peaks at 550 GeV: natural second target for Higgs factories

Higgs Self-Coupling

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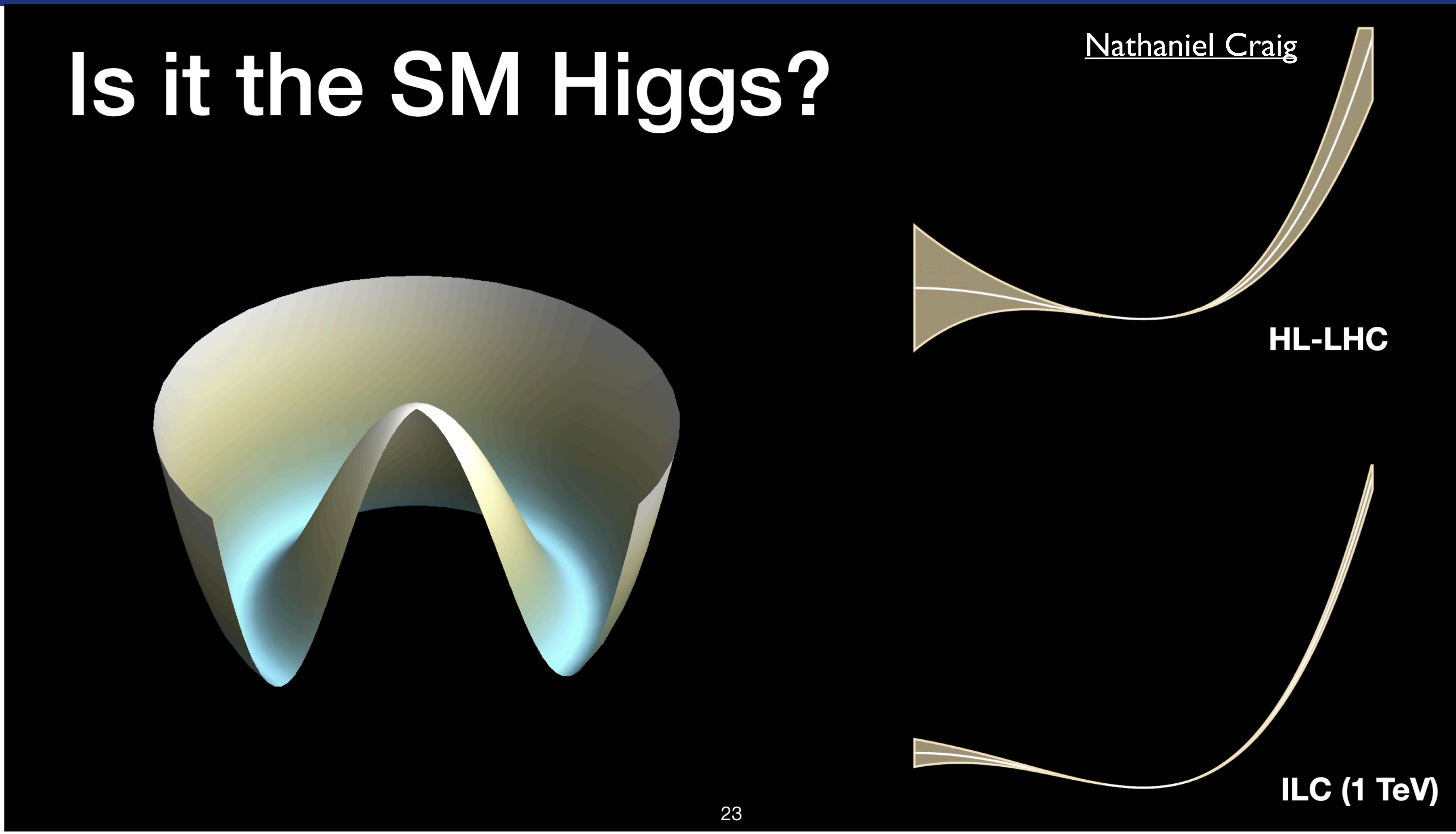

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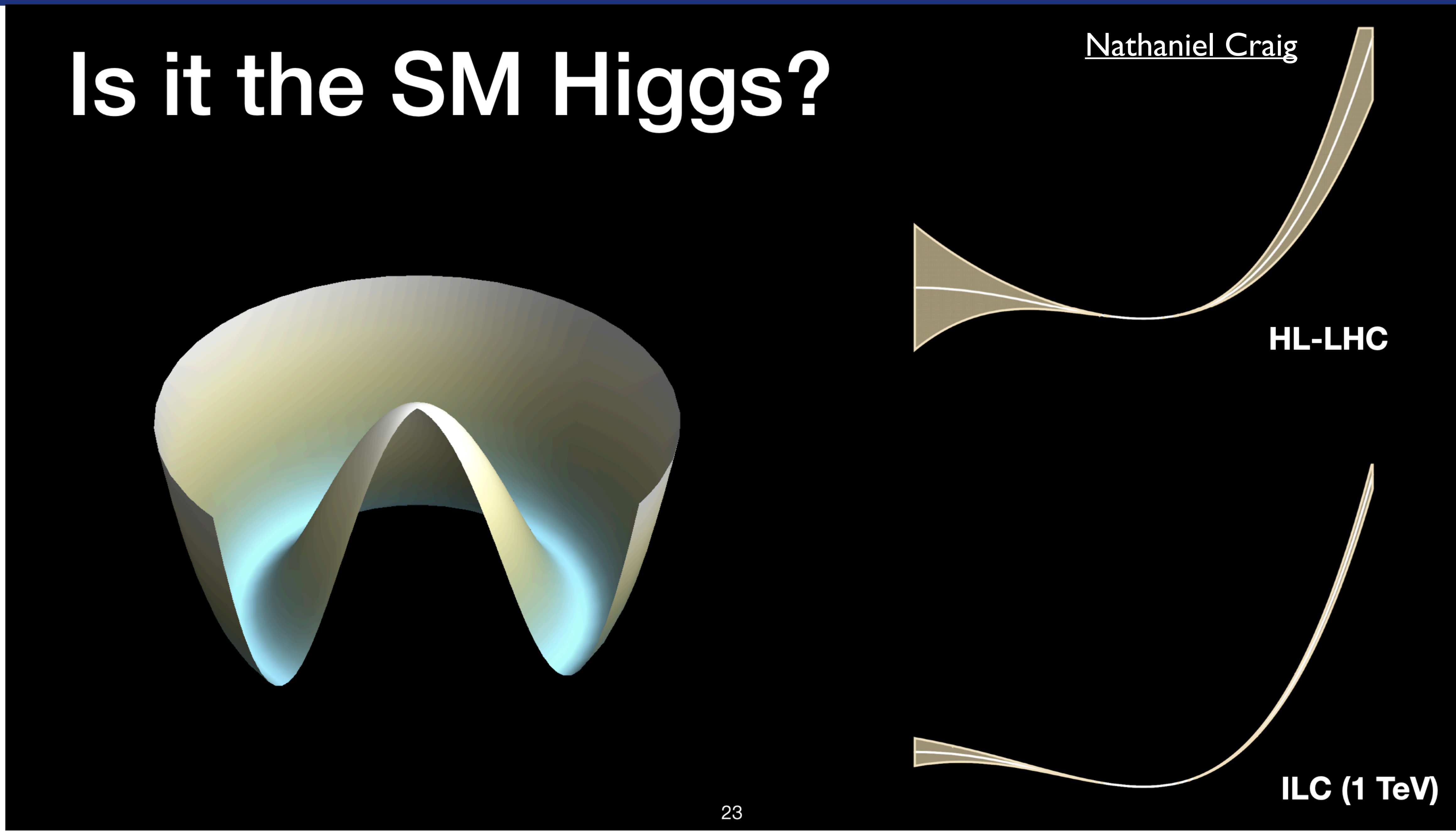

The Higgs potential will remain moderately measured (~50%) at the LHC

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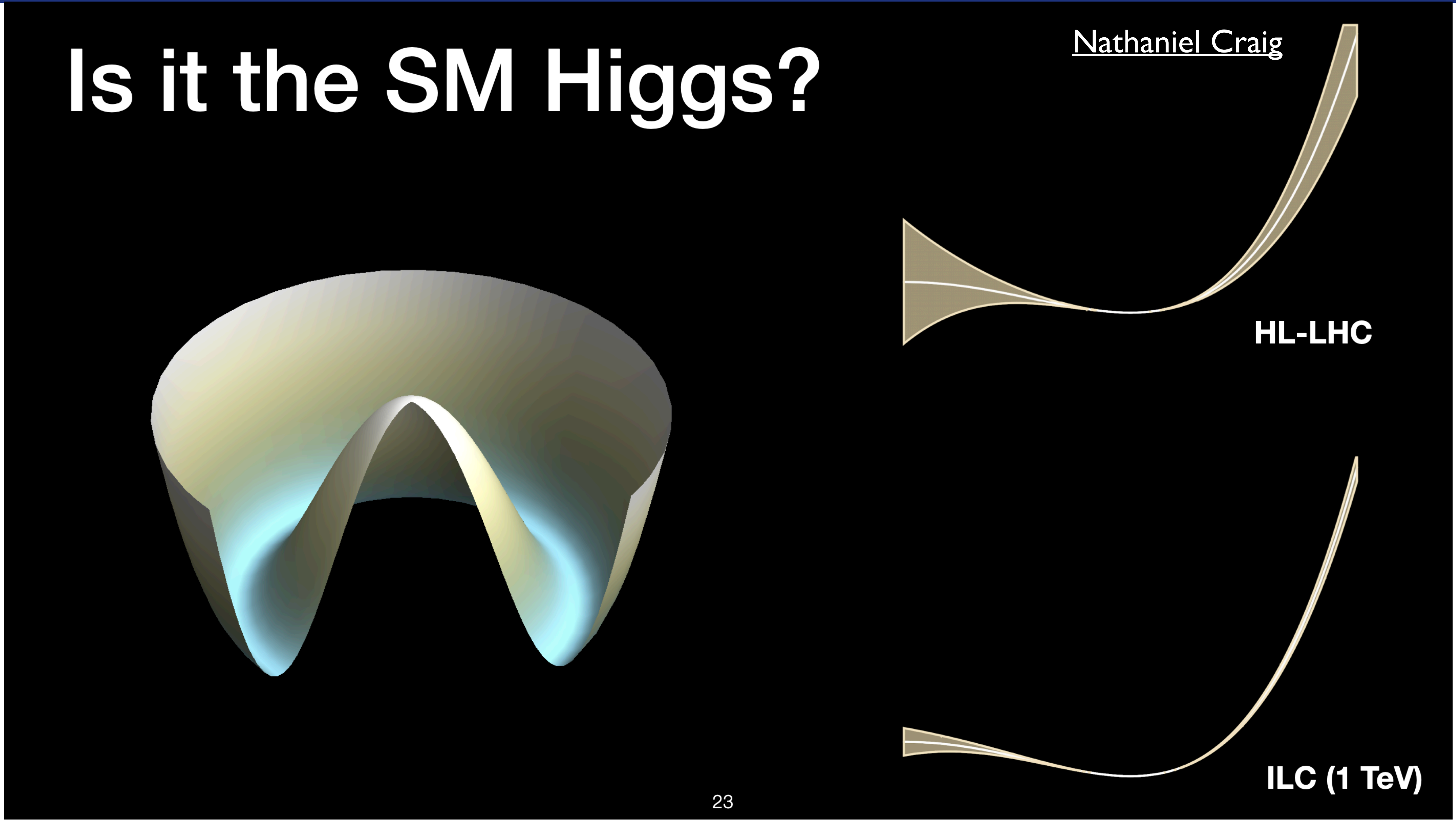

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Linear colliders can provide ~20% (550 GeV) or ~10% (1 TeV) accuracy!

A Word on Costs

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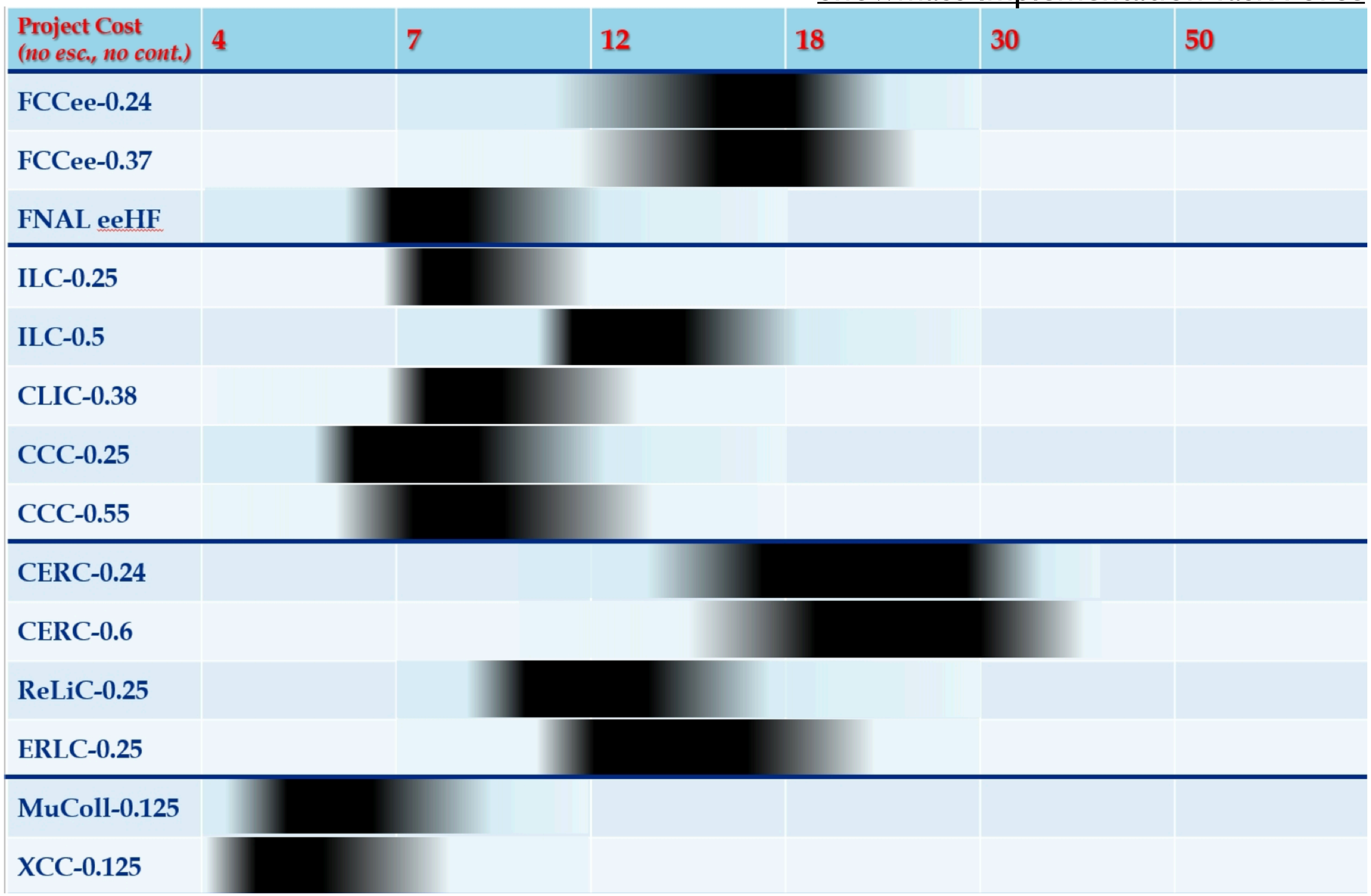
Snowmass Implementation Task Force



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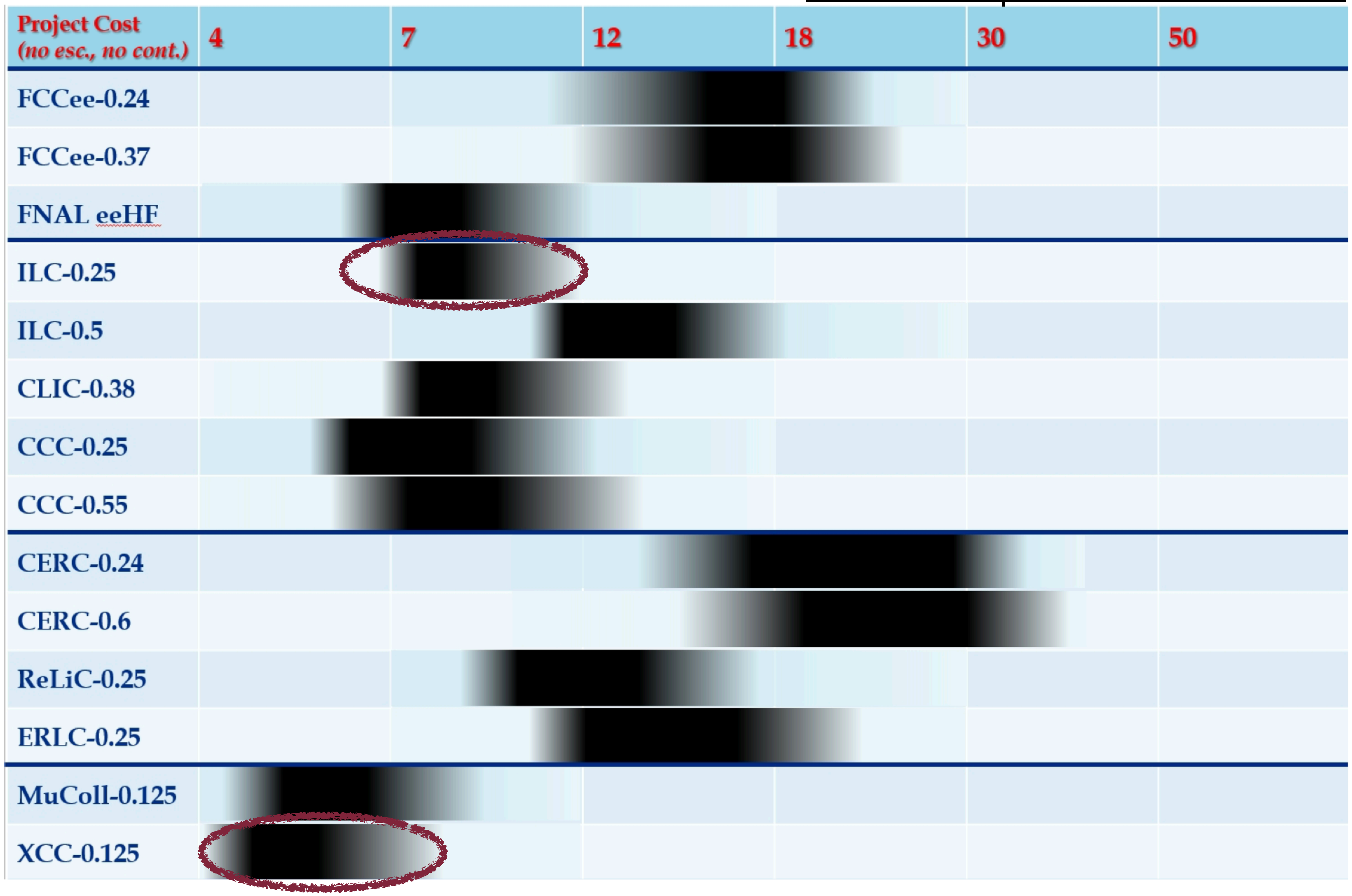

Linear collider options typically <<$$ compared to circular

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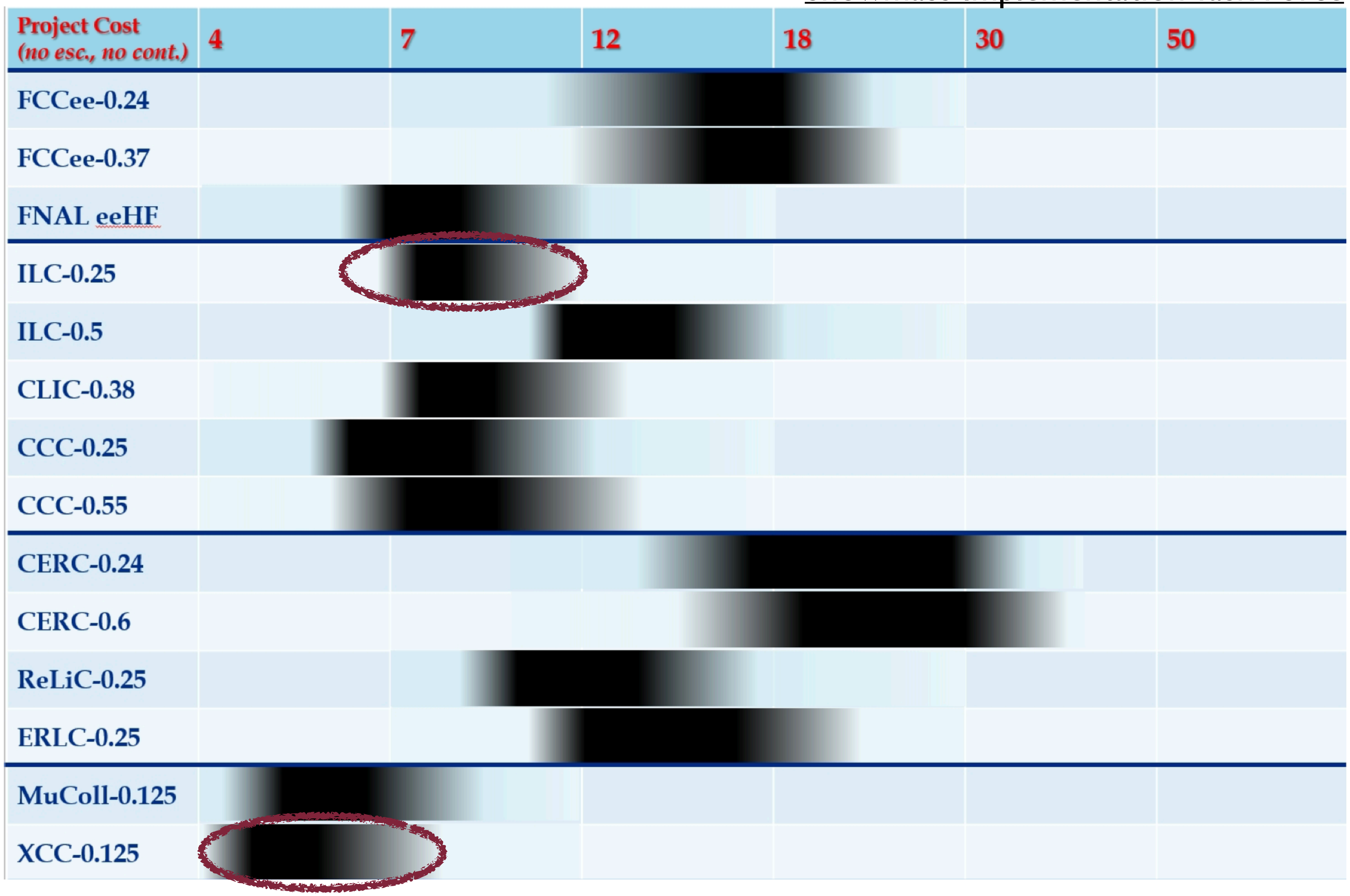

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More on this later!

Another Cost: Carbon

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Carbon footprint is an important consideration for our next projects

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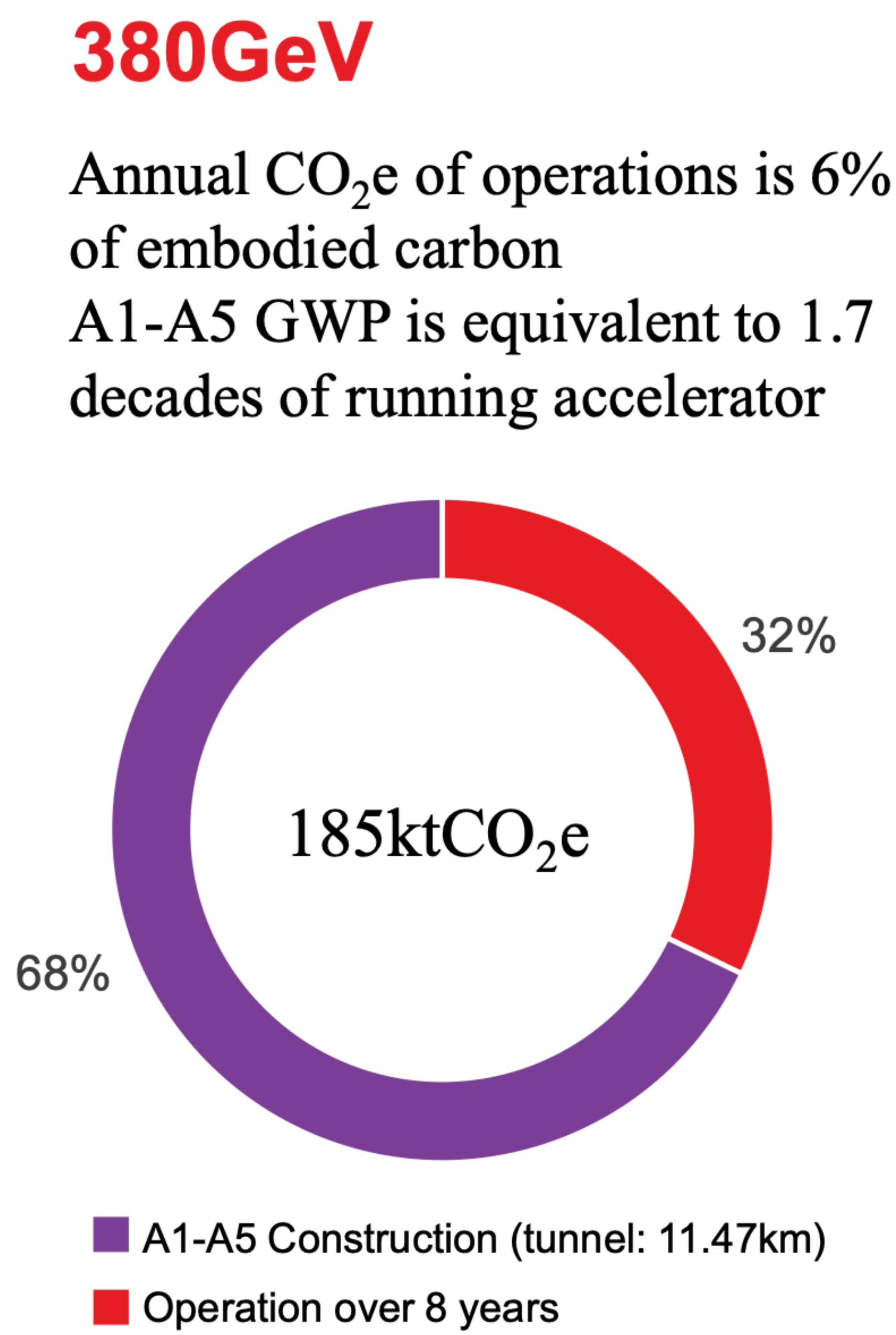
"ktCO_2e per Higgs" is a reasonable metric…

Another Cost: Carbon

Suzanne Evans



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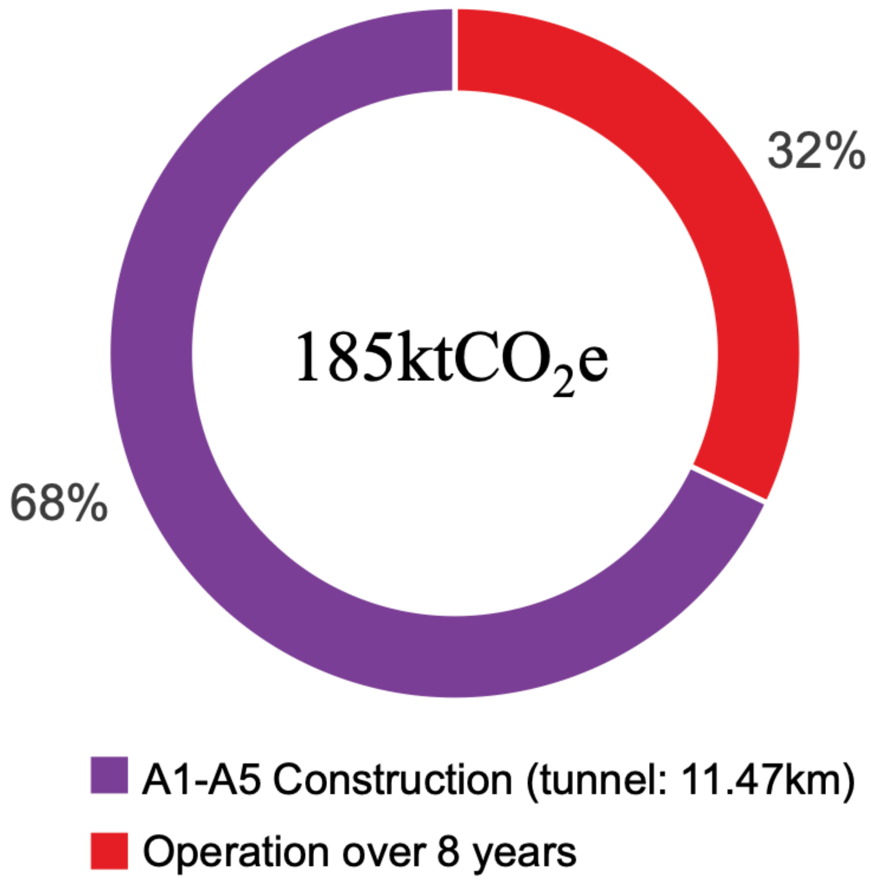
But **construction** carbon can significantly outweigh **operational** carbon

Another Cost: Carbon

Suzanne Evans

380GeV

Annual CO_2e of operations is 6% of embodied carbon
A1-A5 GWP is equivalent to 1.7 decades of running accelerator



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But **construction** carbon can significantly outweigh **operational** carbon

Here see an analysis for 11km CLIC tunnel… 90 km FCC tunnel will be ~9x greater in construction "cost"!

Success at SLC

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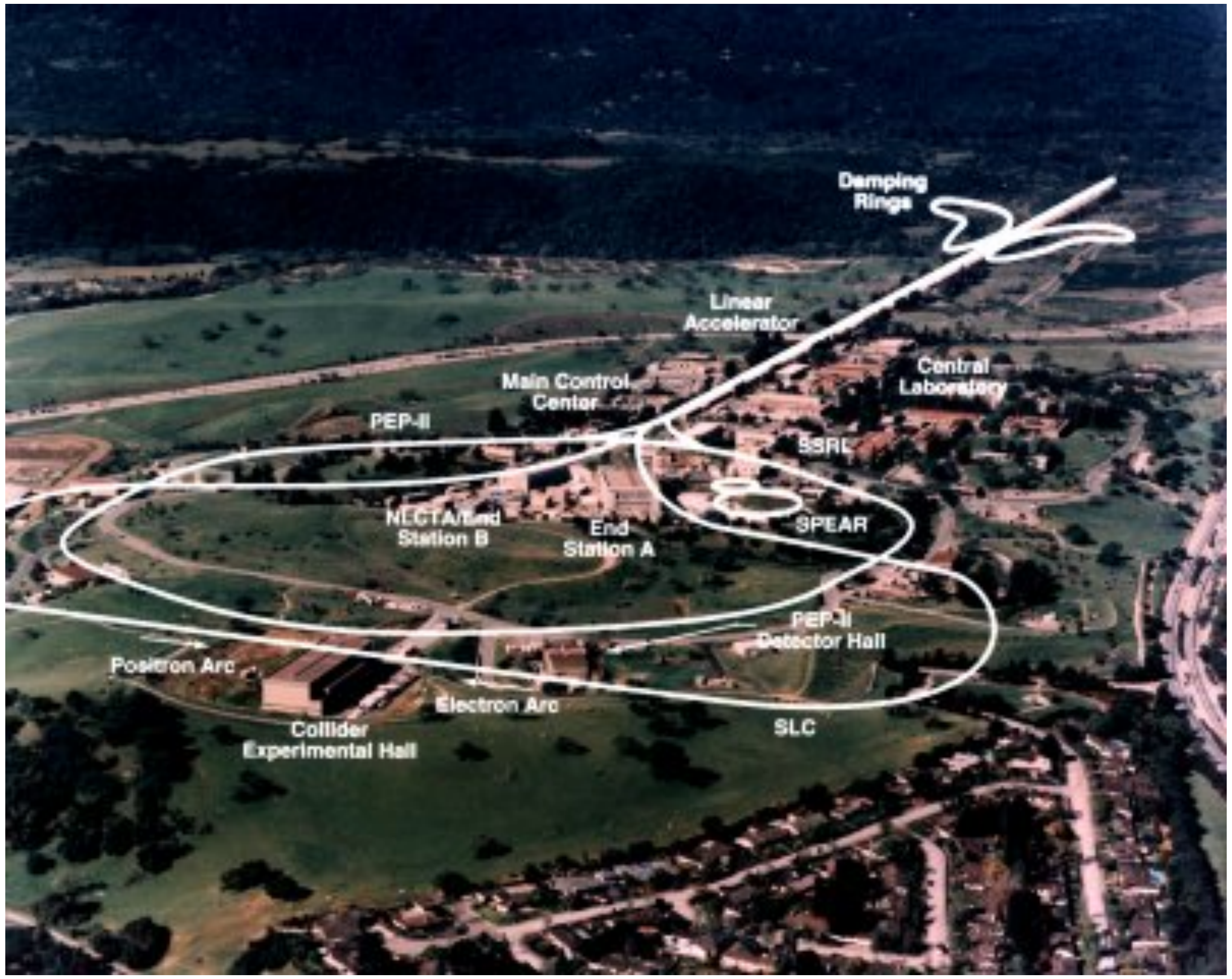
As I am a SLAC alumni, would be remiss for me to not mention the world's first linear collider!

Success at SLC



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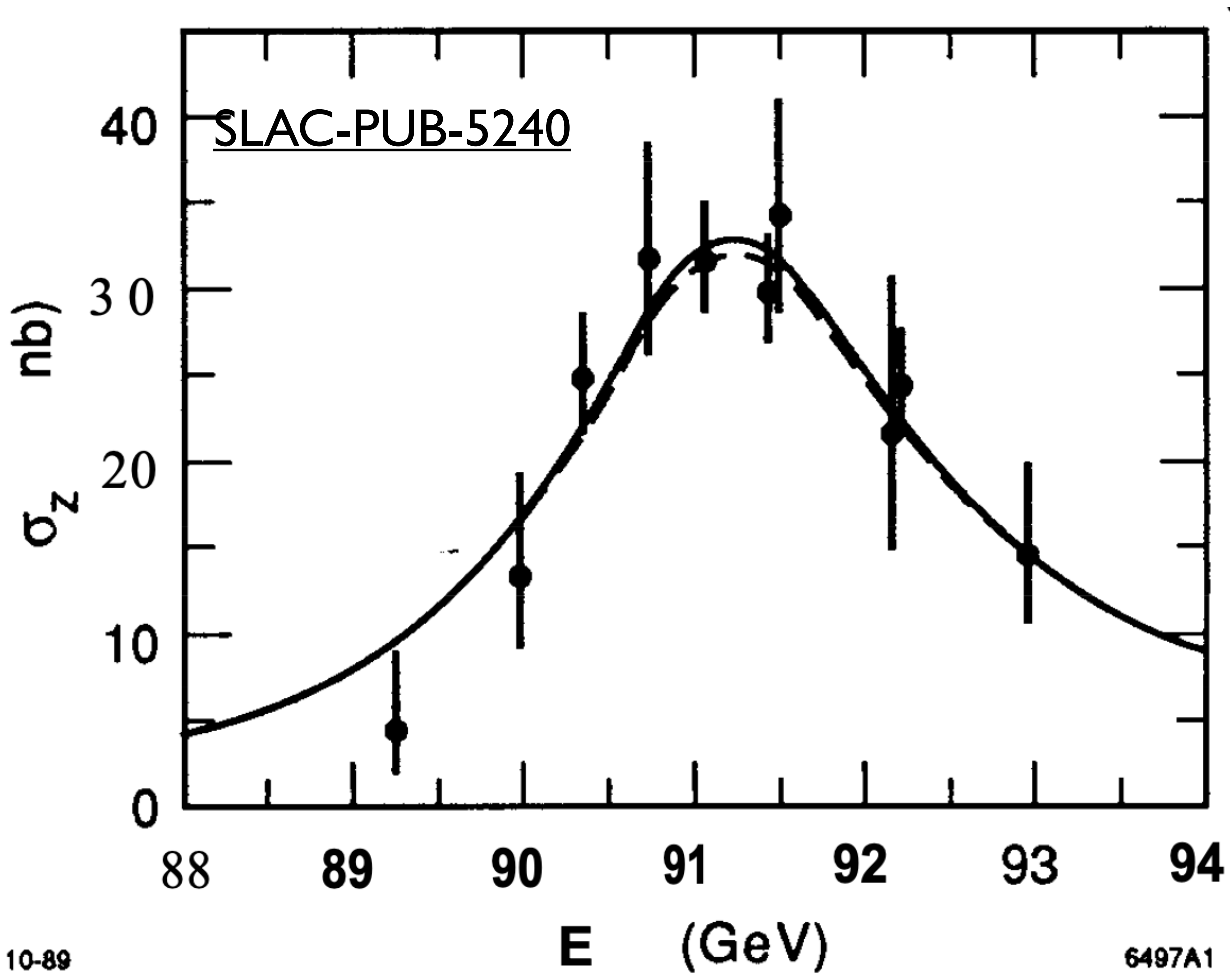

The Main Actors

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The Old Guard

The New Kids

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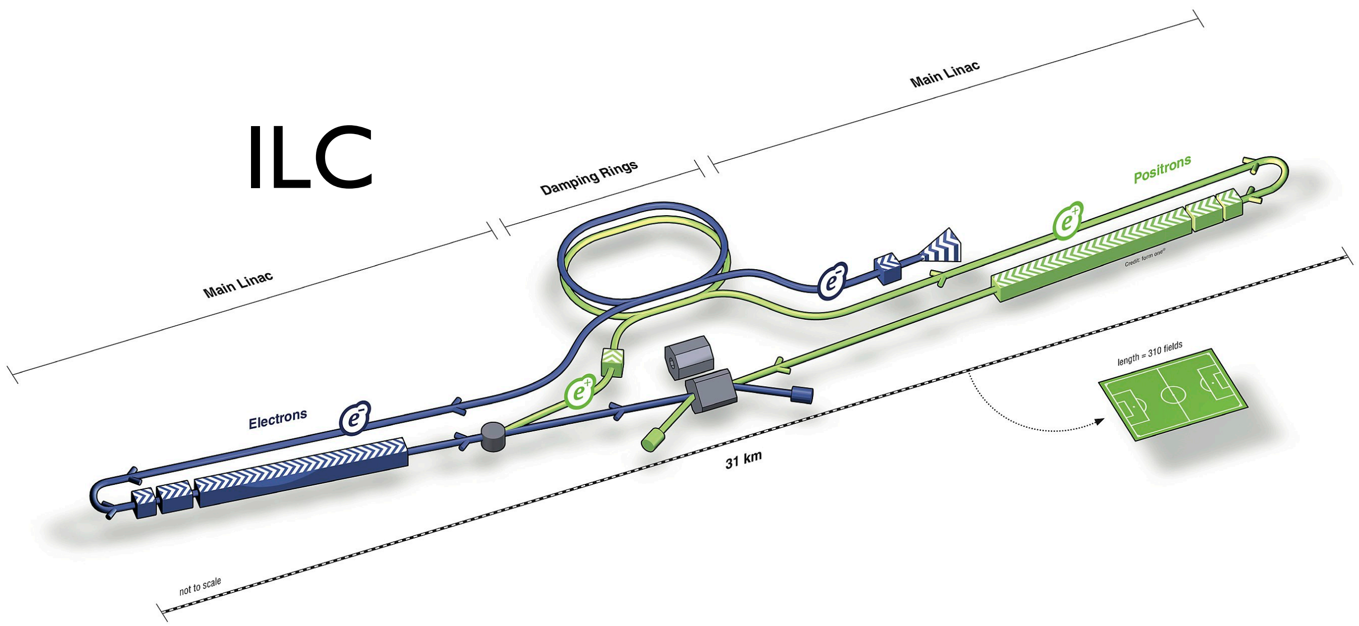
The New Kids

ILC



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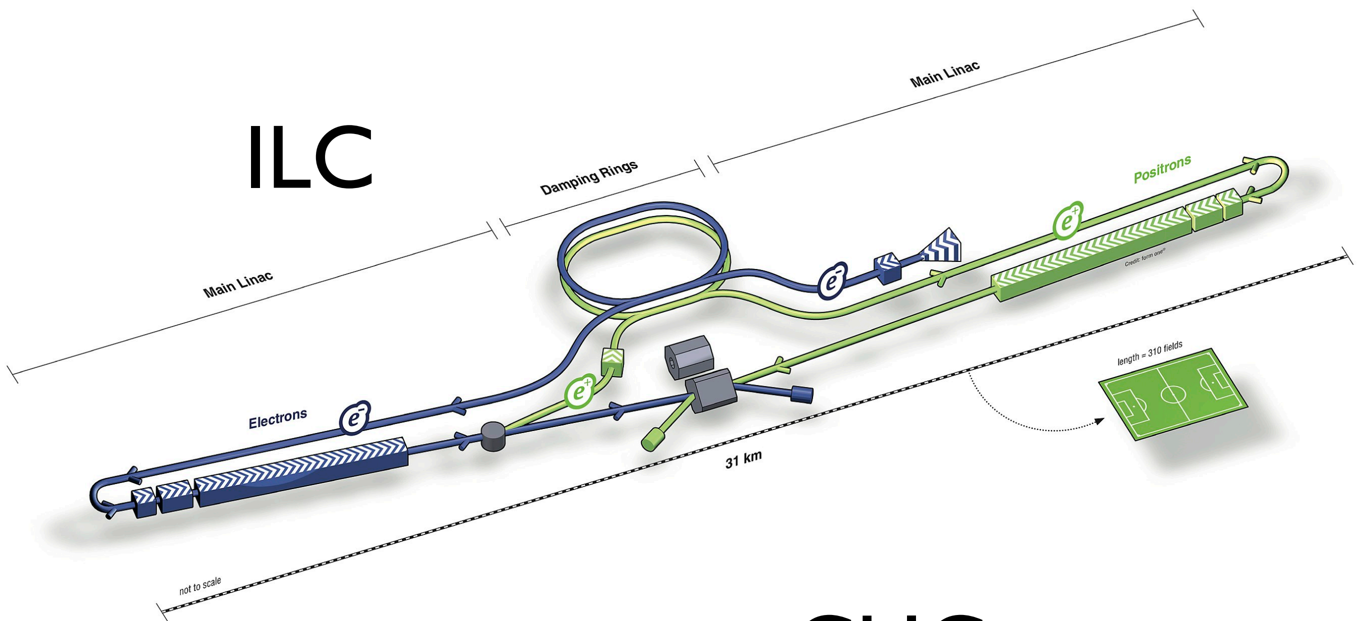
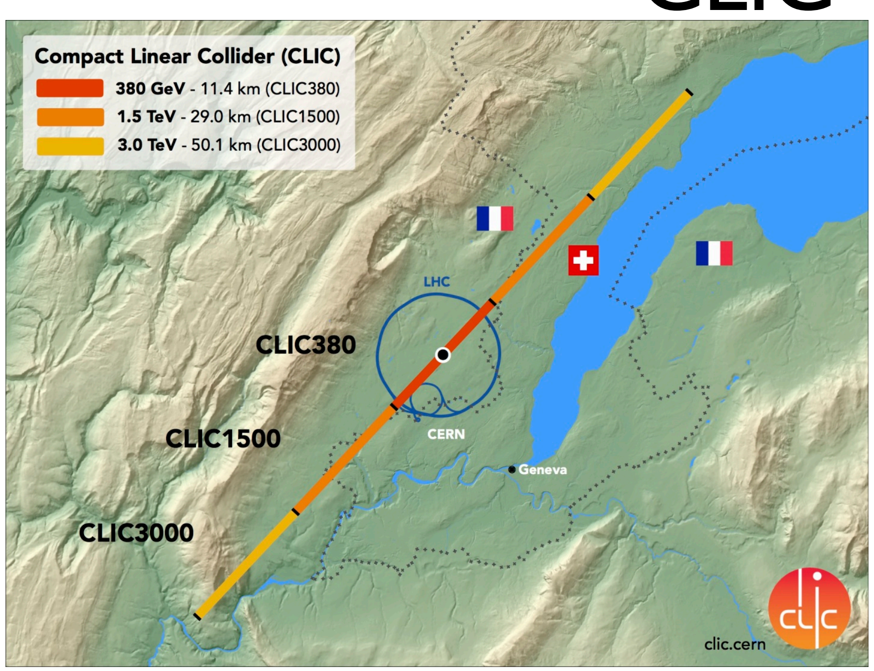


CLIC



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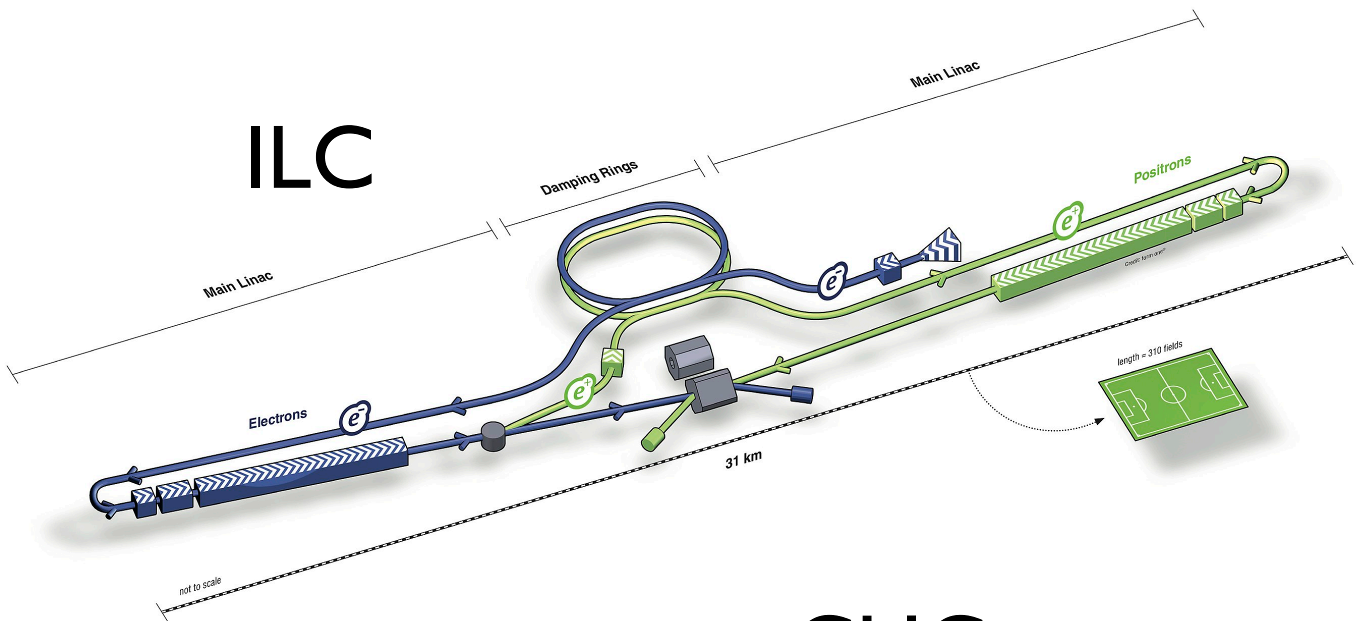

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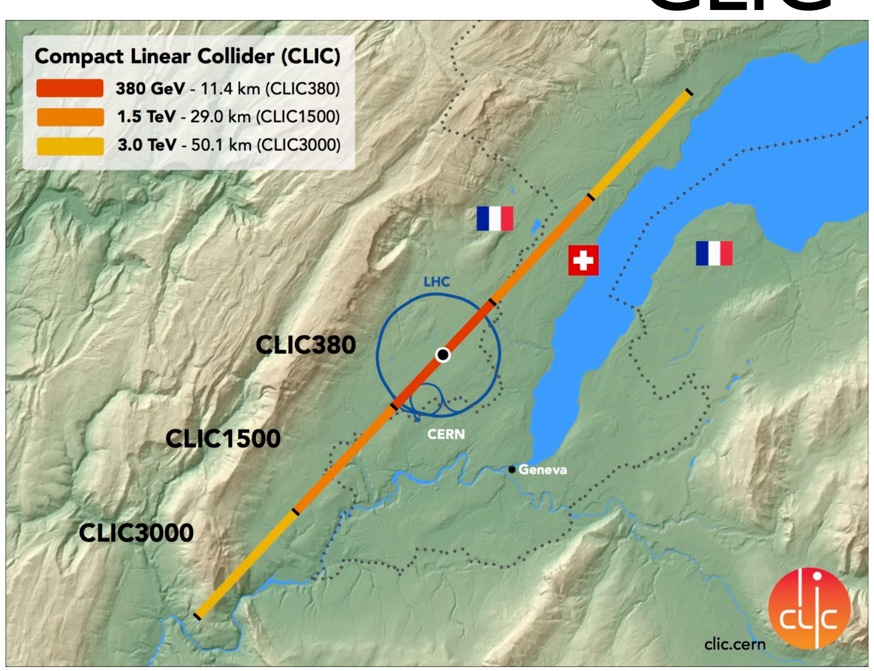

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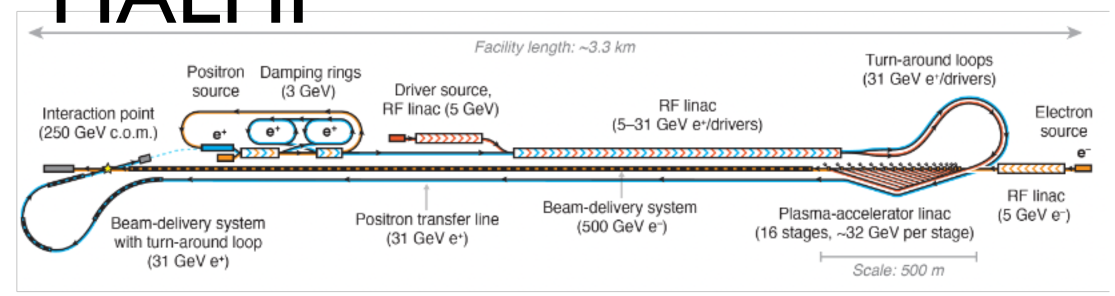
HALHF



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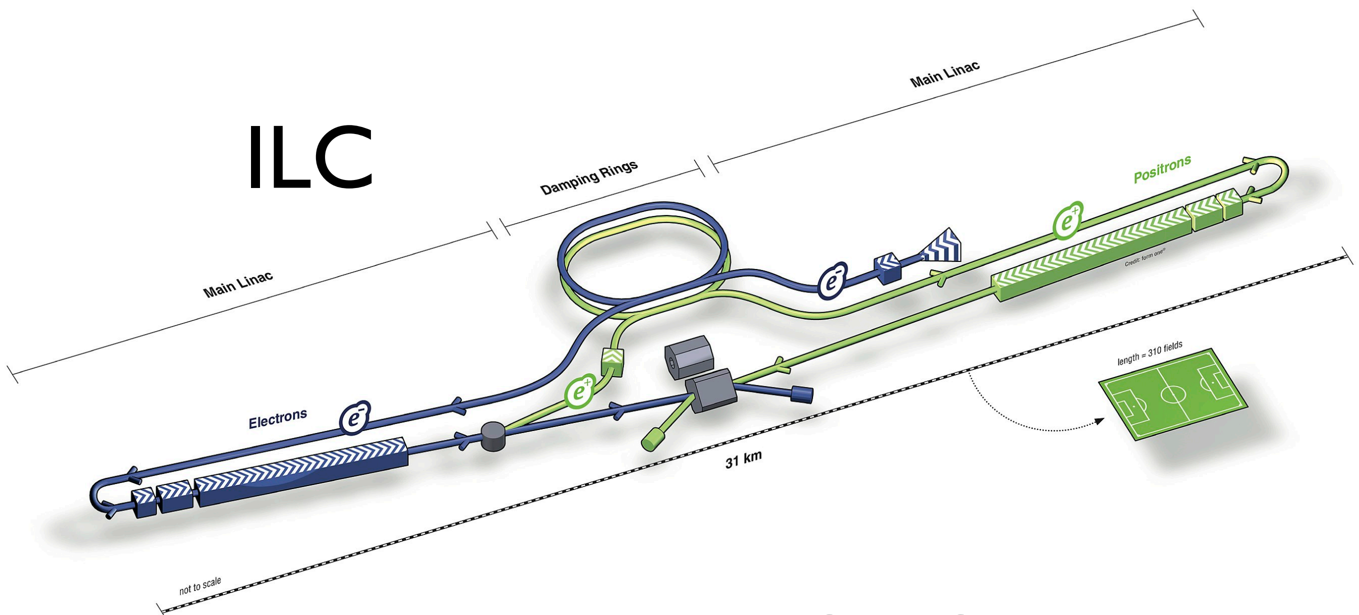

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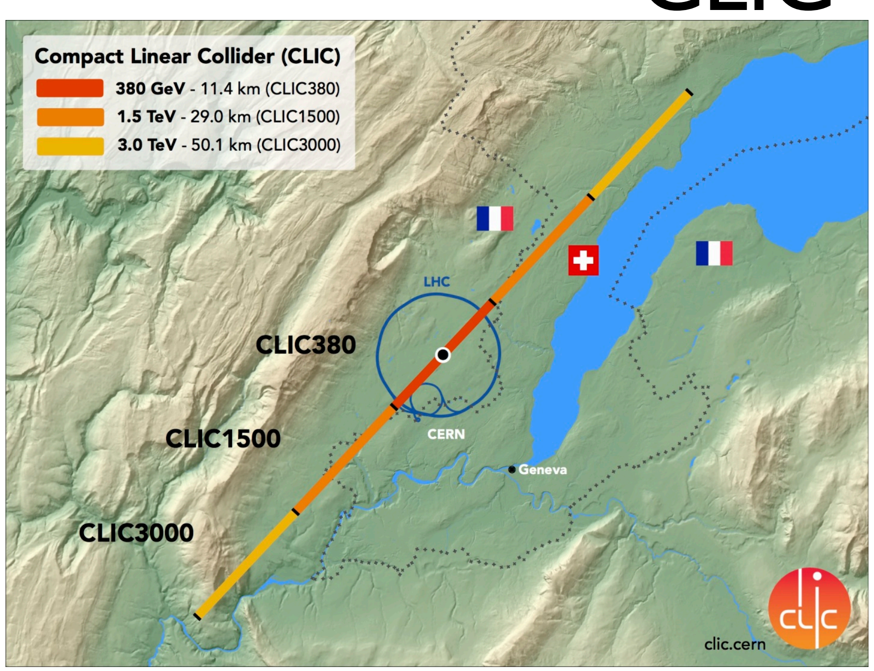

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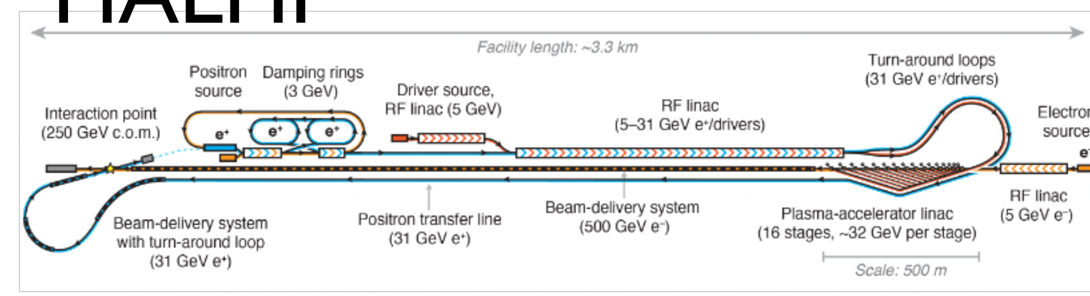

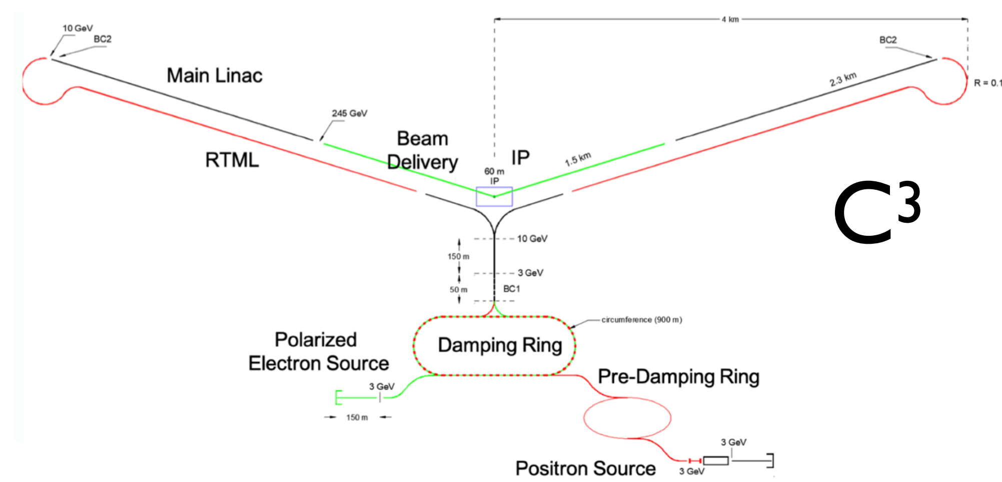

C^3

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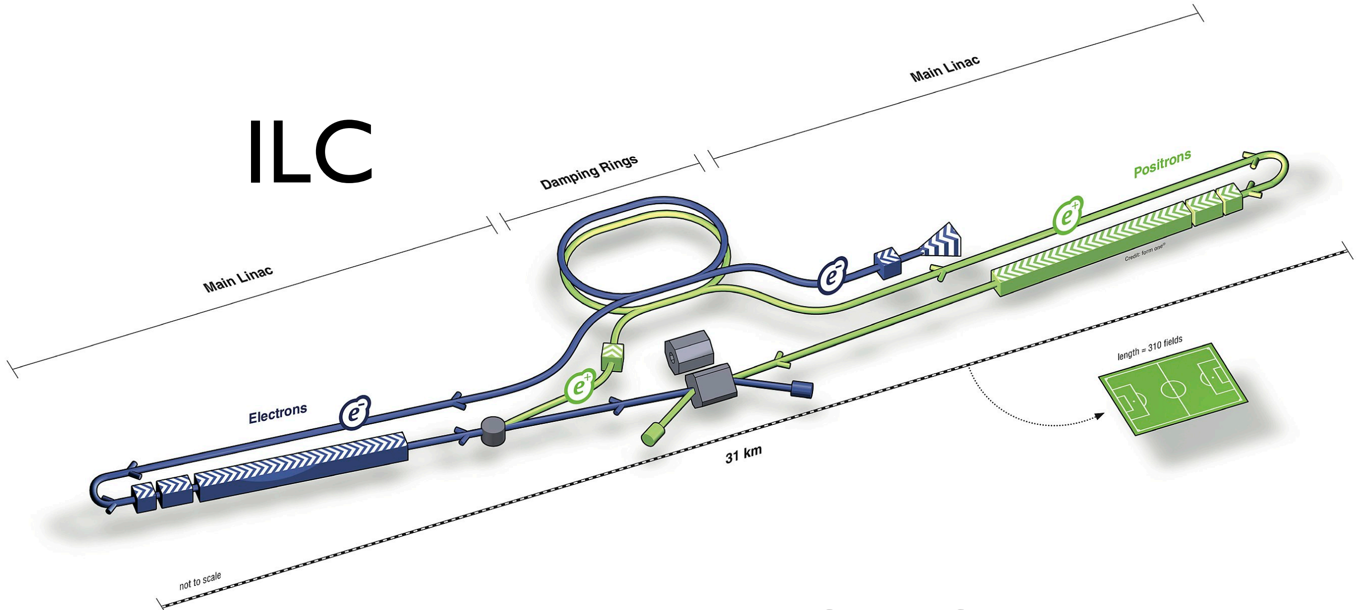

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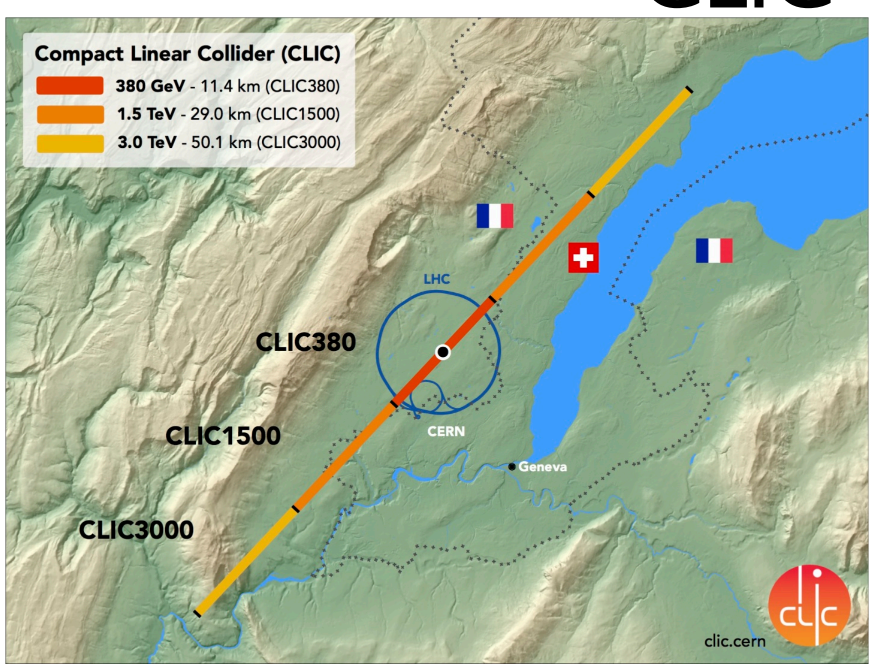

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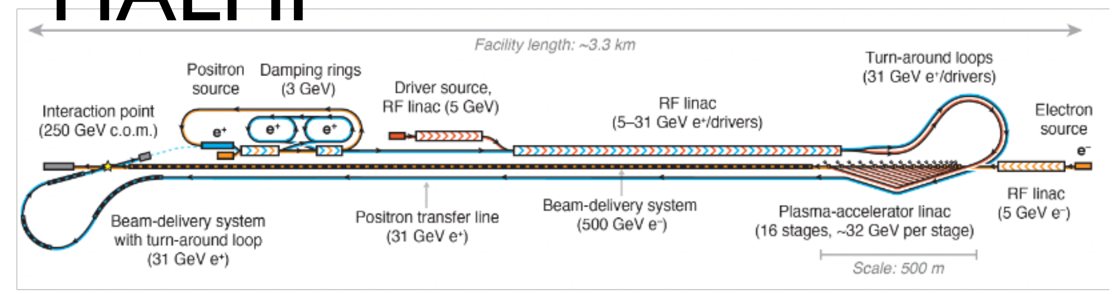
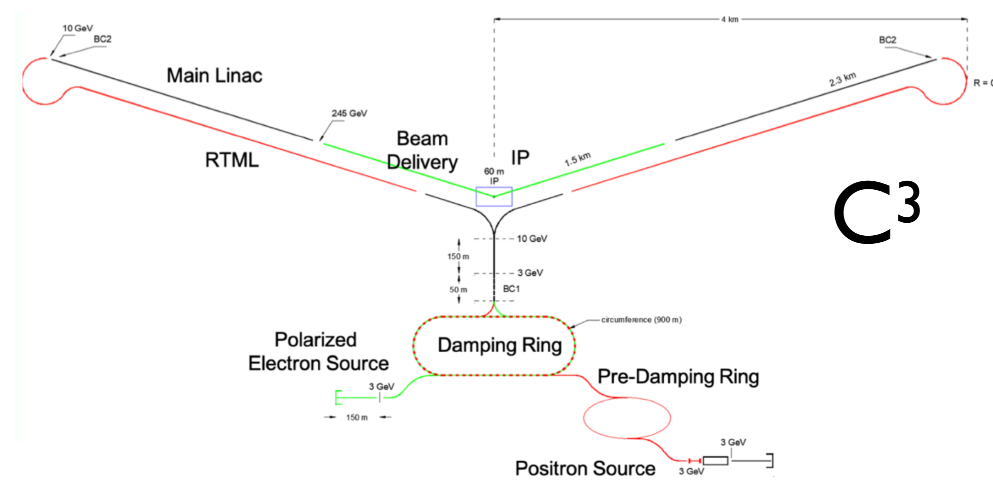
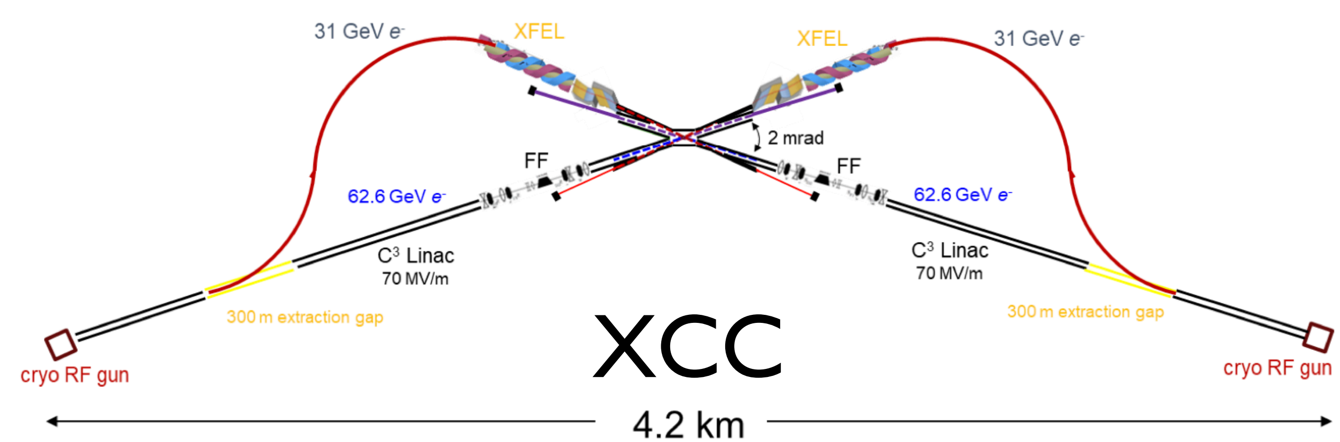


C³



XCC



ILC: Still the Fastest Path

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Collider Name - c.m.e. (TeV)	Subm'd R&D Durat'n to CDR (yrs)	Subm'd Design to TDR Durat'n (yrs)	Subm'd Project Constrn. Time (yrs)	ITF Judgement Duration Preproject R&D to CDR	ITF Judgement Design & Industr'n Duration to TDR	ITF Judgement Project Constrn. Duration post CD4	ITF Judgement Combined "Time to the First Physics"
ILC-0.25	0	4	9	0-2	3-5 yrs	7-10 yrs	$<$ 12 yrs
ILC (6x lumi)	10	5	10	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CLIC-0.38	0	6	6	0-2	3-5 yrs	7-10 yrs	13-18 yrs
FCCee-0.36	0	6	8	0-2	3-5 yrs	7-10 yrs	13-18 yrs
CEPC-0.24	6	6	8	0-2 ?	3-5 yrs	7-10 yrs	13-18 yrs
CCC-0.25	2-3	4-5	6-7	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
FNALee-0.24	tbd	tbd	tbd	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CERC-0.6	3	5	10	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs
HELEN-0.25	tbd	tbd	tbd	5-10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
ReLiC-0.25	3	5	10	5-10 yrs	5-10 yrs	10-15 yrs	$>$ 25 yrs
ERLC-0.25	8	5	10	5-10 yrs	5-10 yrs	10-15 yrs	$>$ 25 yrs
MC-0.125	11	4	tbd	$>$ 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
XCC-0.125	2-3	3-4	3-5	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs
SWLC-0.25	8	5	10	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs

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ILC-0.25	0	4	9	0-2	3-5 yrs	7-10 yrs	$<$ 12 yrs
ILC (6x lumi)	10	5	10	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CLIC-0.38	0	6	6	0-2	3-5 yrs	7-10 yrs	13-18 yrs
FCCee-0.36	0	6	8	0-2	3-5 yrs	7-10 yrs	13-18 yrs
CEPC-0.24	6	6	8	0-2 ?	3-5 yrs	7-10 yrs	13-18 yrs
CCC-0.25	2-3	4-5	6-7	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
FNALee-0.24	tbd	tbd	tbd	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CERC-0.6	3	5	10	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs
HELEN-0.25	tbd	tbd	tbd	5-10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
ReLiC-0.25	3	5	10	5-10 yrs	5-10 yrs	10-15 yrs	$>$ 25 yrs
ERLC-0.25	8	5	10	5-10 yrs	5-10 yrs	10-15 yrs	$>$ 25 yrs
MC-0.125	11	4	tbd	$>$ 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
XCC-0.125	2-3	3-4	3-5	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs
SWLC-0.25	8	5	10	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs

Even after decade(s) of delay, ILC is
still the fastest path to a Higgs factory

ILC: Still the Fastest Path

Snowmass Implementation Task Force

Collider Name - c.m.e. (TeV)	Subm'd R&D Durat'n to CDR (yrs)	Subm'd Design to TDR Durat'n (yrs)	Subm'd Project Constrn. Time (yrs)	ITF Judgement Duration Preproject R&D to CDR	ITF Judgement Design & Industr'n Duration to TDR	ITF Judgement Project Constrn. Duration post CD4	ITF Judgement Combined "Time to the First Physics"
ILC-0.25	0	4	9	0-2	3-5 yrs	7-10 yrs	< 12 yrs
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HELEN-0.25	tbd	tbd	tbd	5-10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
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That story has been told, without apparent success :(

ILC: Still the Fastest Path

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Even after decade(s) of delay, ILC is
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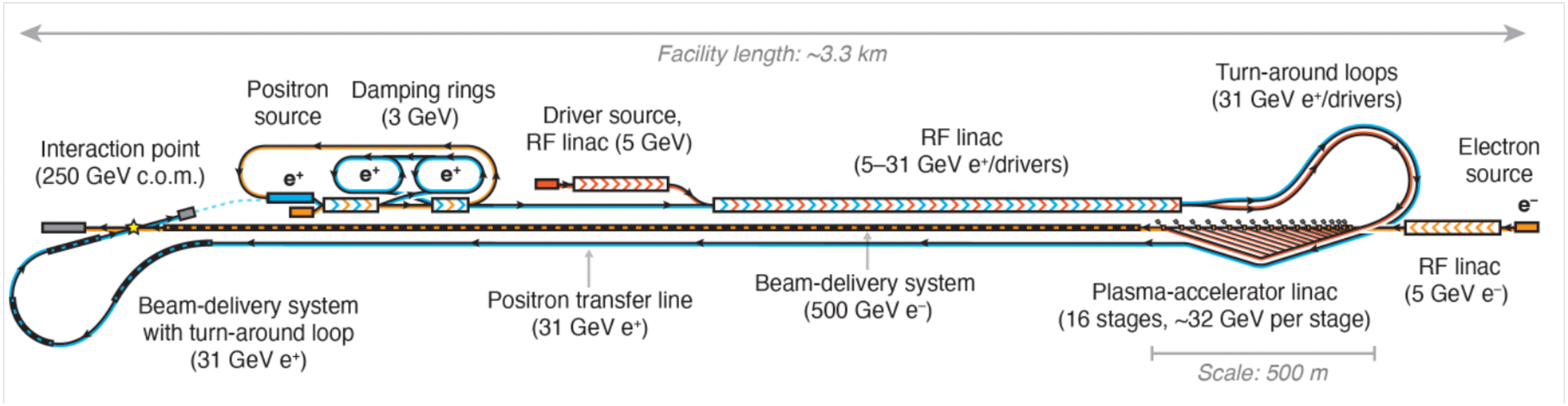
That story has been told, without apparent success :(

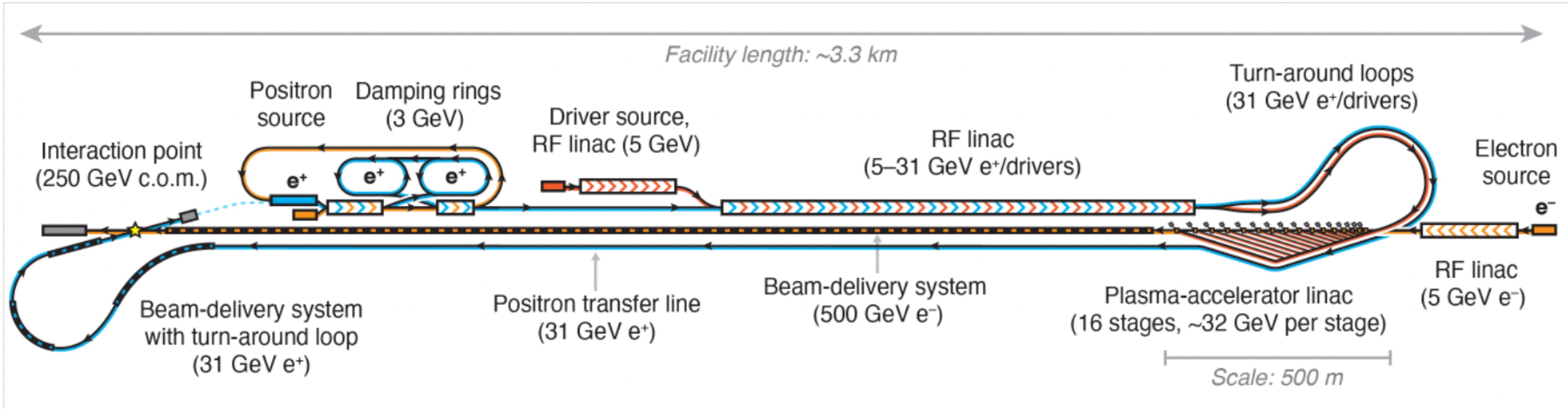
Today, I will focus on the **new kids** instead

HALHF

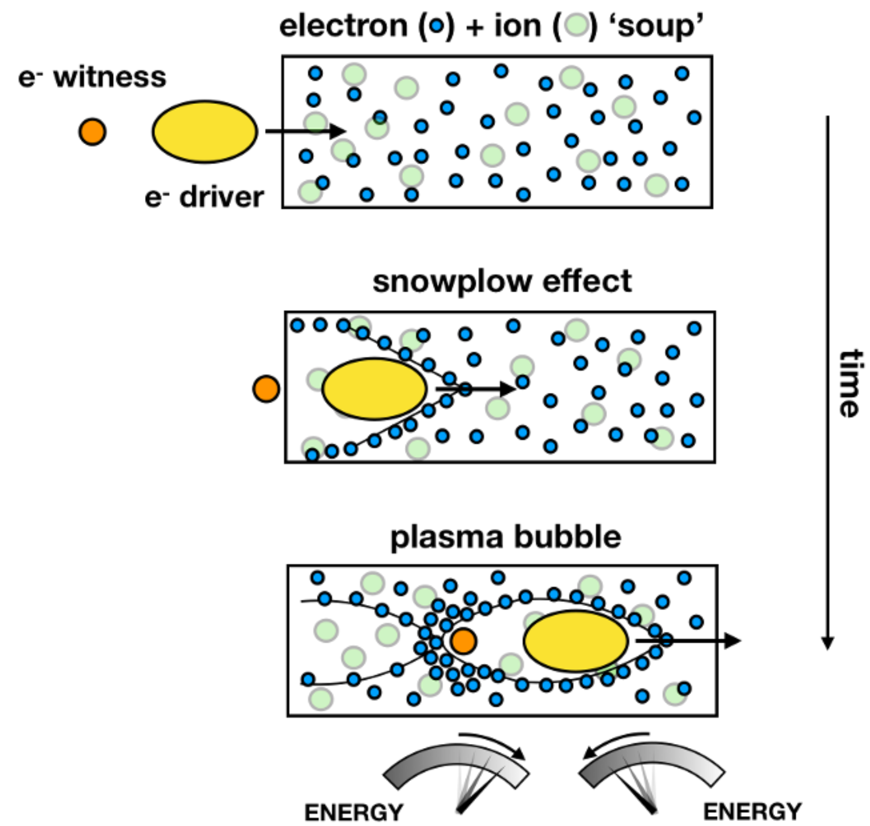
HALF


Facility length: ~3.3 km
Positron source
Damping rings (3 GeV)
Driver source, RF linac (5 GeV)
RF linac (5–31 GeV e+/drivers)
Turn-around loops (31 GeV e+/drivers)
Interaction point (250 GeV c.o.m.)
Electron source
e+
e+
e+
e−
Beam-delivery system with turn-around loop (31 GeV e+)
Positron transfer line (31 GeV e+)
Beam-delivery system (500 GeV e−)
Plasma-accelerator linac (16 stages, ~32 GeV per stage)
RF linac (5 GeV e−)
Scale: 500 m

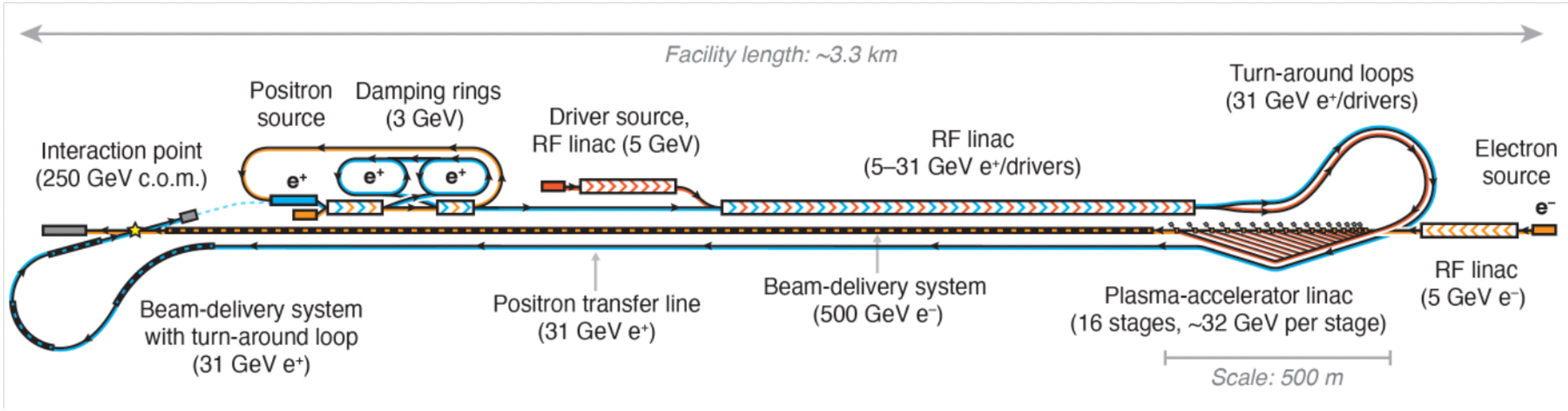
HALF



Plasma wakefield acceleration is extremely promising: > 1 GeV/m gradient seems plausible (FACET experiments)



HALHF



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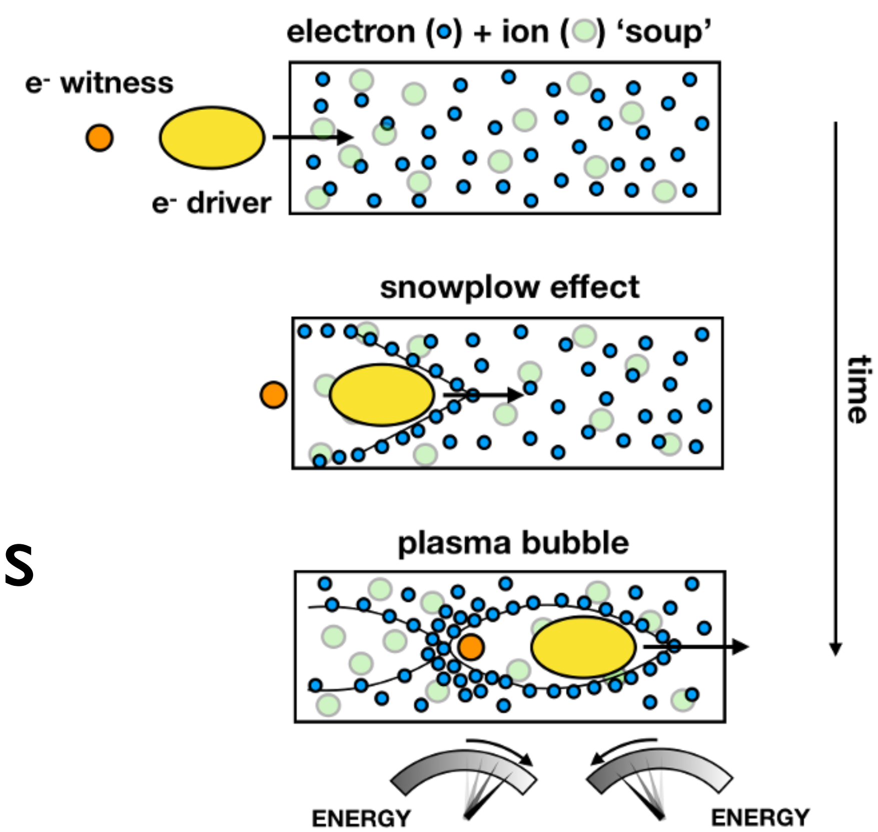
Huge challenge in accelerating positrons



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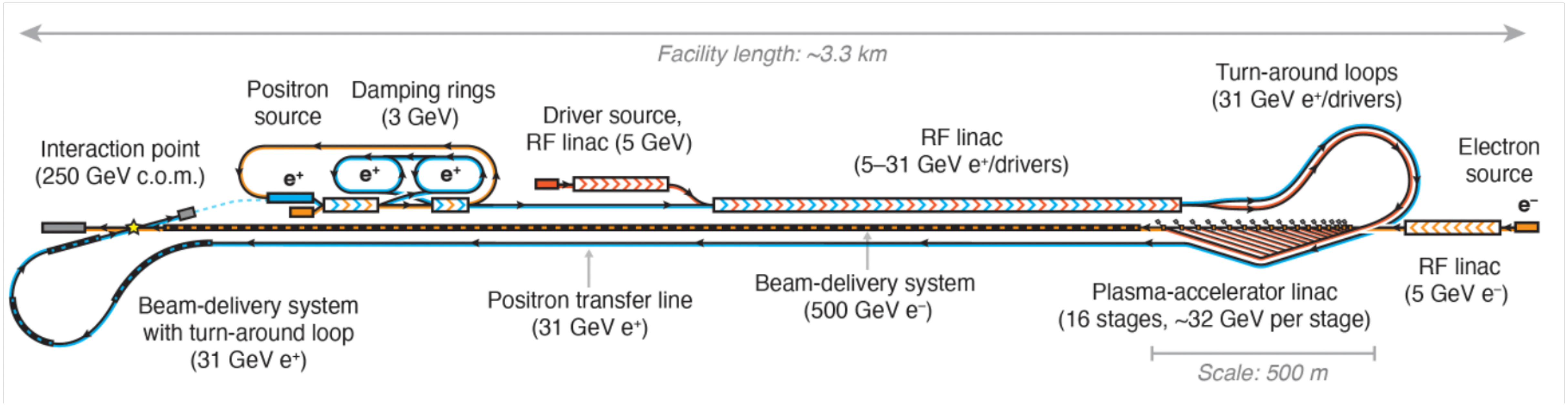

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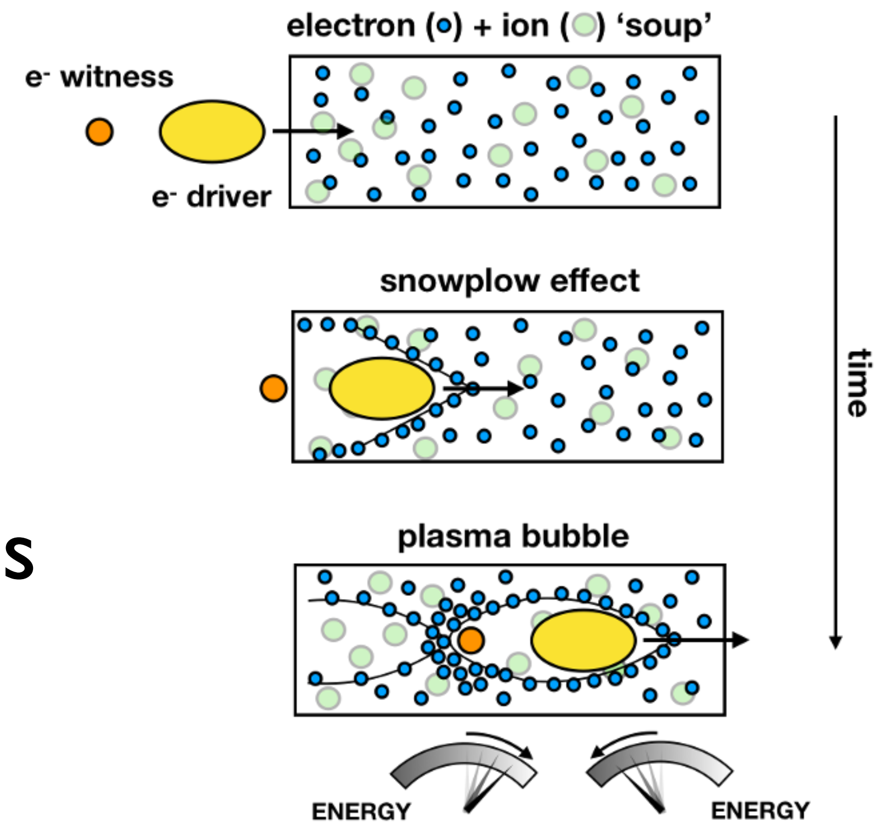
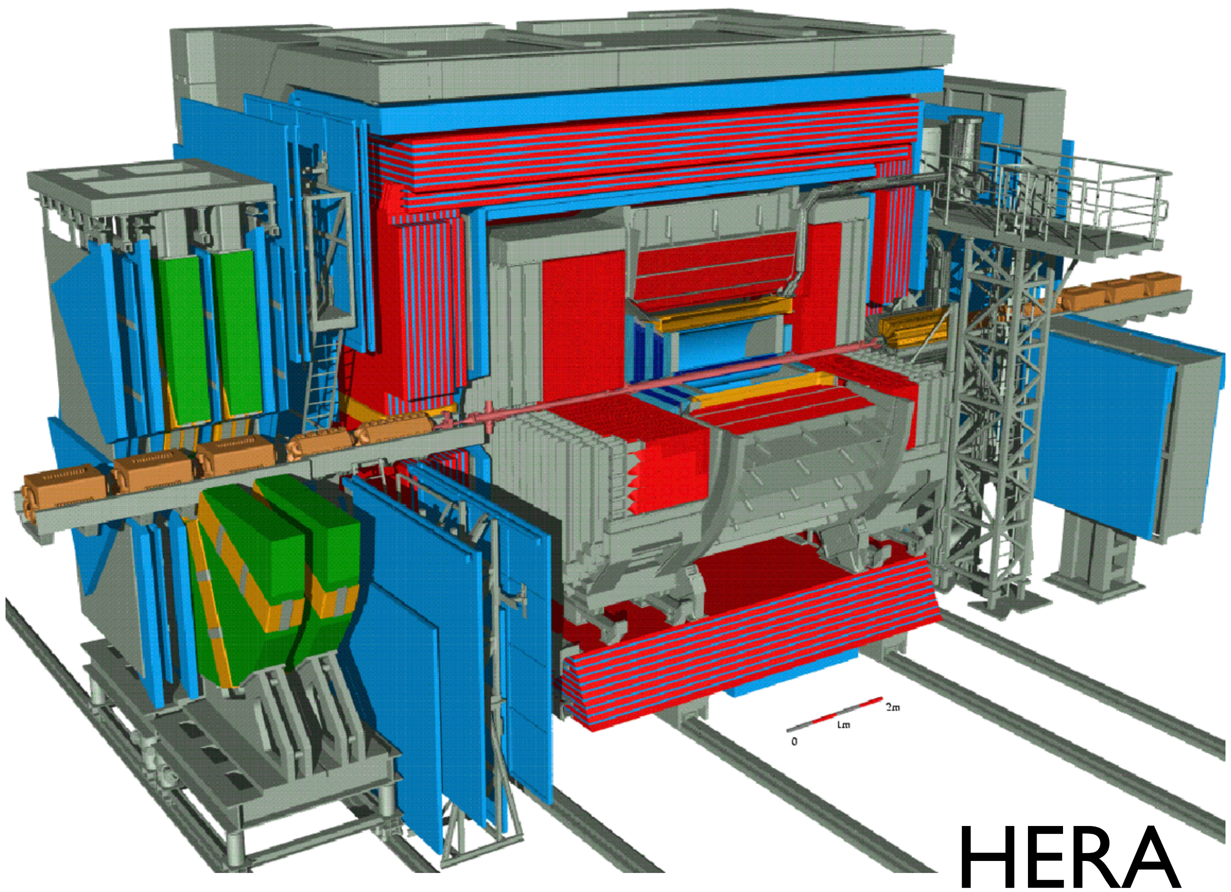


Huge challenge in accelerating positrons

Give up on positrons: collide 500 GeV e^- and 31 GeV e^+

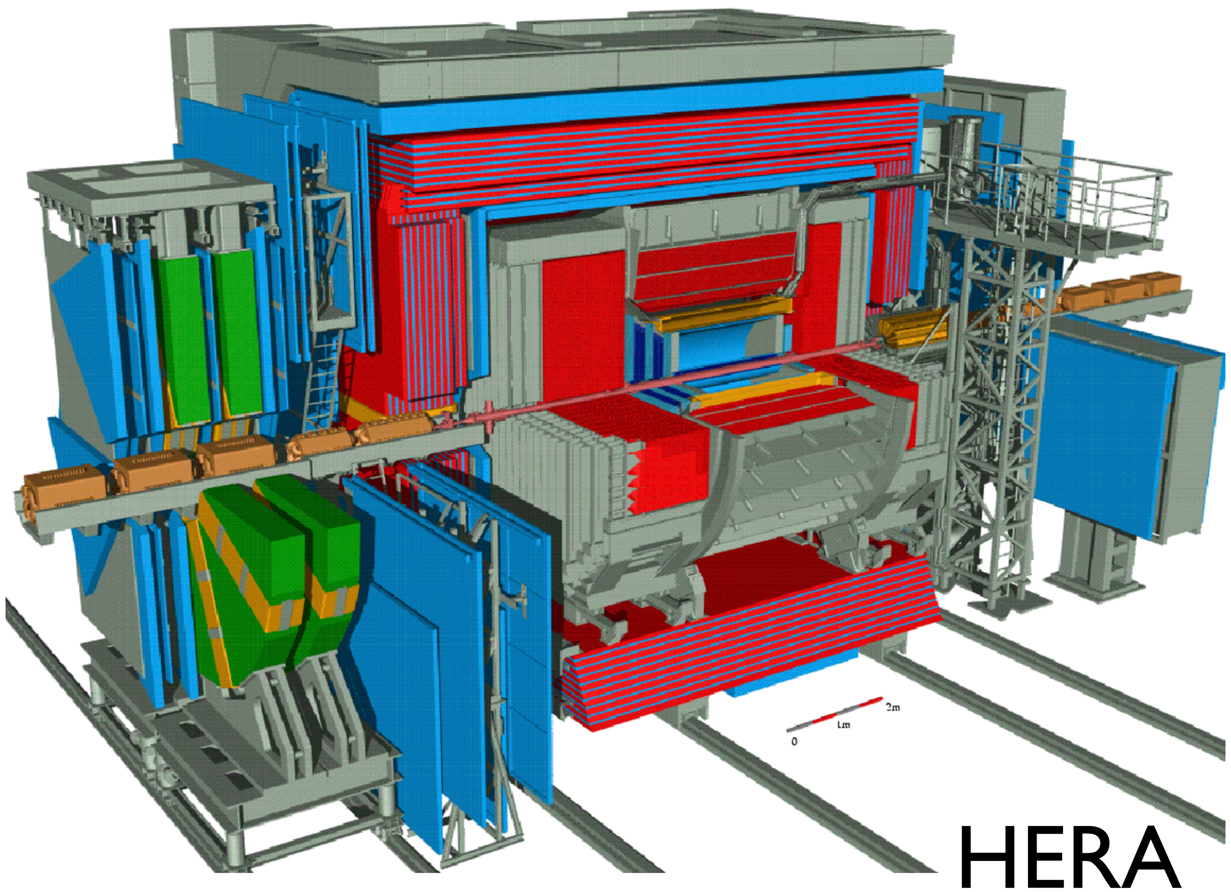
HALHF

HALHF



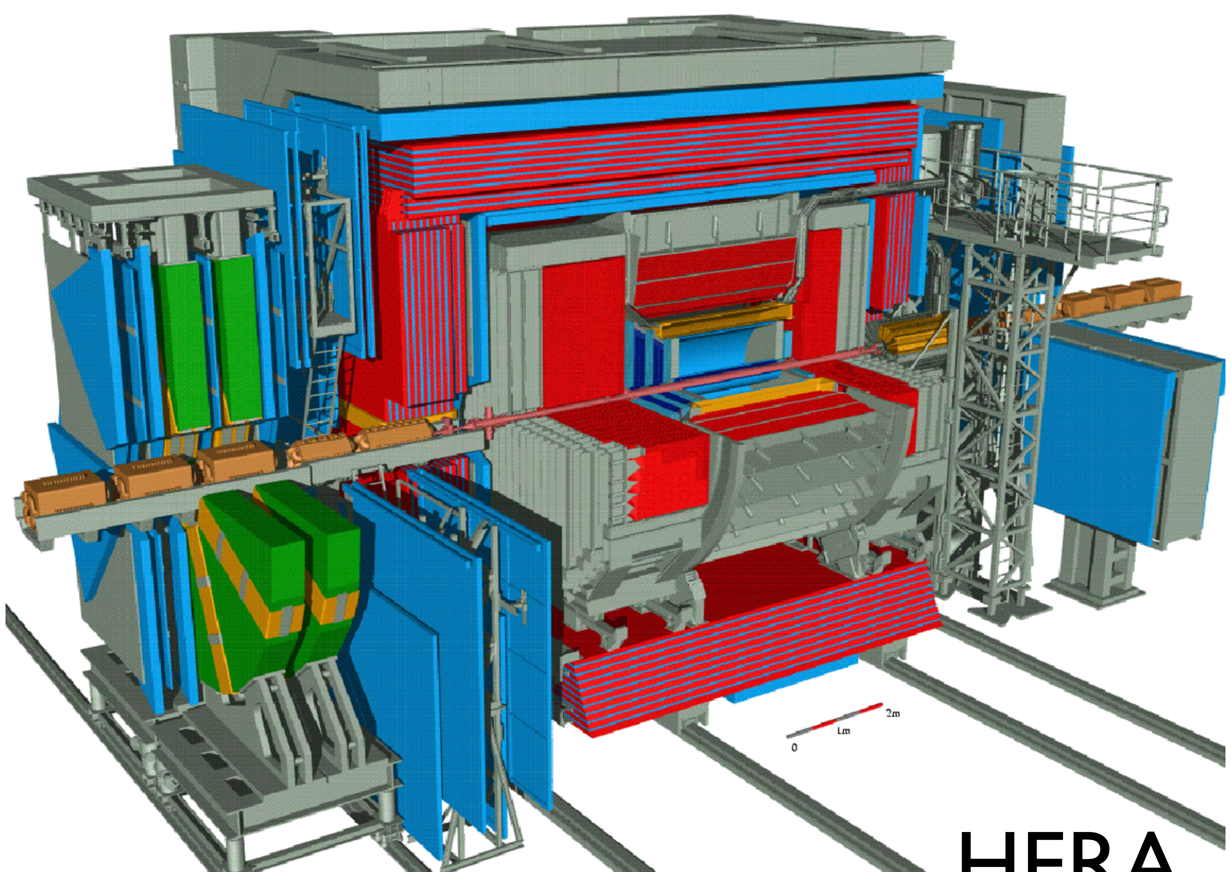
HERA

HALHF



Boost factor of $\gamma = 2.13$:
significantly less than HERA.
Physics shouldn't be a problem!

HALHF



HERA

Subsystem	Original cost (MILCU)	Comment	Scaling factor	HALHF cost (MILCU)	Fraction
Particle sources, damping rings	430	CLIC cost [69], halved for e^+ damping rings only[a]	0.5	215	14%
RF linac with klystrons	548	CLIC cost, as RF power is similar	1	548	35%
PWFA linac	477	ILC cost [47], scaled by length and multiplied by 6[b]	0.1	48	3%
Transfer lines	477	ILC cost, scaled to the ∼4.6 km required[c]	0.15	72	5%
Electron BDS	91	ILC cost, also at 500 GeV	1	91	6%
Positron BDS	91	ILC cost, scaled by length[d]	0.25	23	1%
Beam dumps	67	ILC cost (similar beam power) + drive-beam dumps[e]	1	80	5%
Civil engineering	2,055	ILC cost, scaled to the ∼10 km of tunnel required	0.21	476	31%
			Total	1,553	100%

[a] Swiss deflator from 2018 → 2012 is approximately 1. Conversion uses Jan 1st 2012 CHF to $ exchange rate of 0.978.
[b] Cost of PWFA linac similar to ILC standard instrumented beam lines plus short plasma cells & gas systems [illegible]/chicanes. The factor 6 is a rough estimate of extra complexity involved.
[c] The positron transfer line, which is the full length of the electron BDS, dominates; this plus two turn-arounds, the electron transport to the positron source plus small additional beam lines are costed.
[d] The HALHF length is scaled by $\sqrt{E}$ and the cost assumed to scale with this length.
[e] Length of excavation and beam line taken from European XFEL dump.

Extremely optimistic cost (driven by huge civil cost savings: only a 3.3 km tunnel!)

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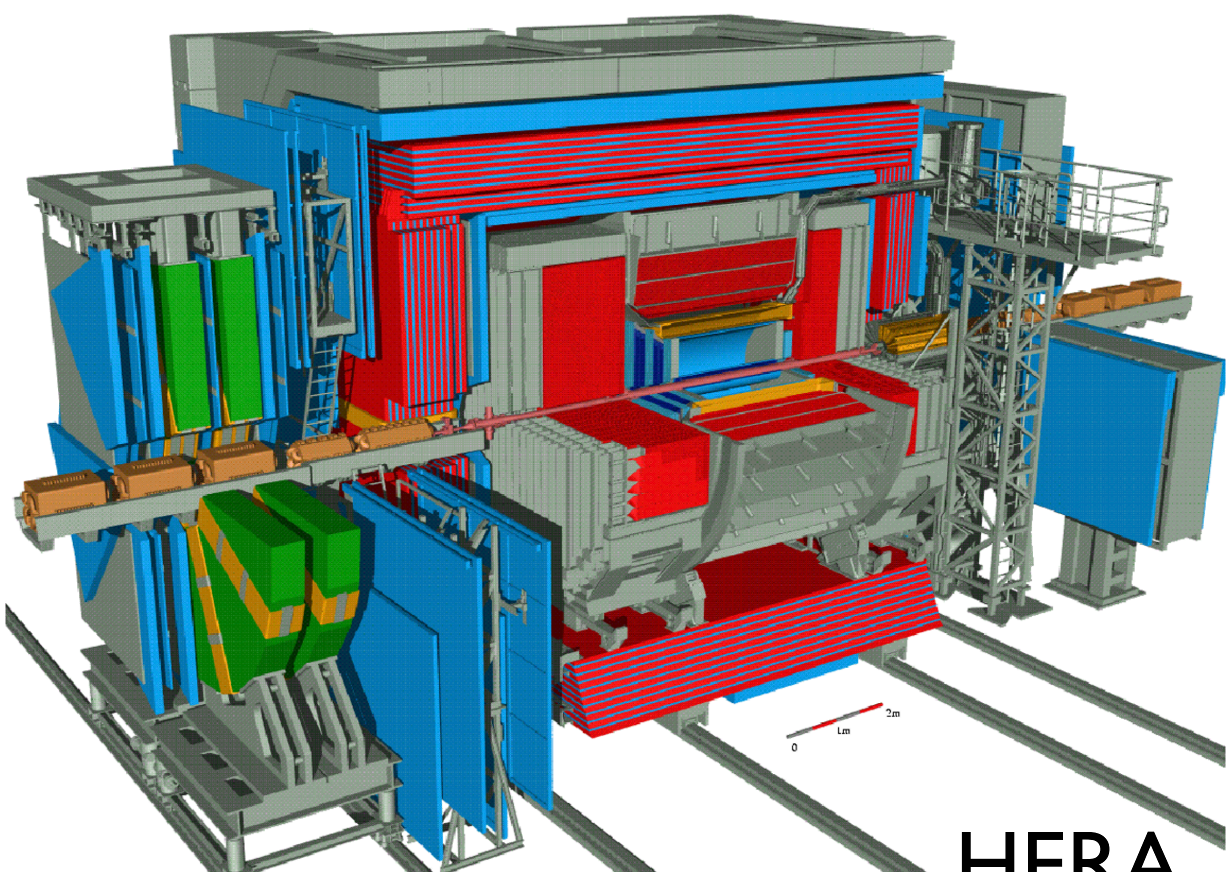

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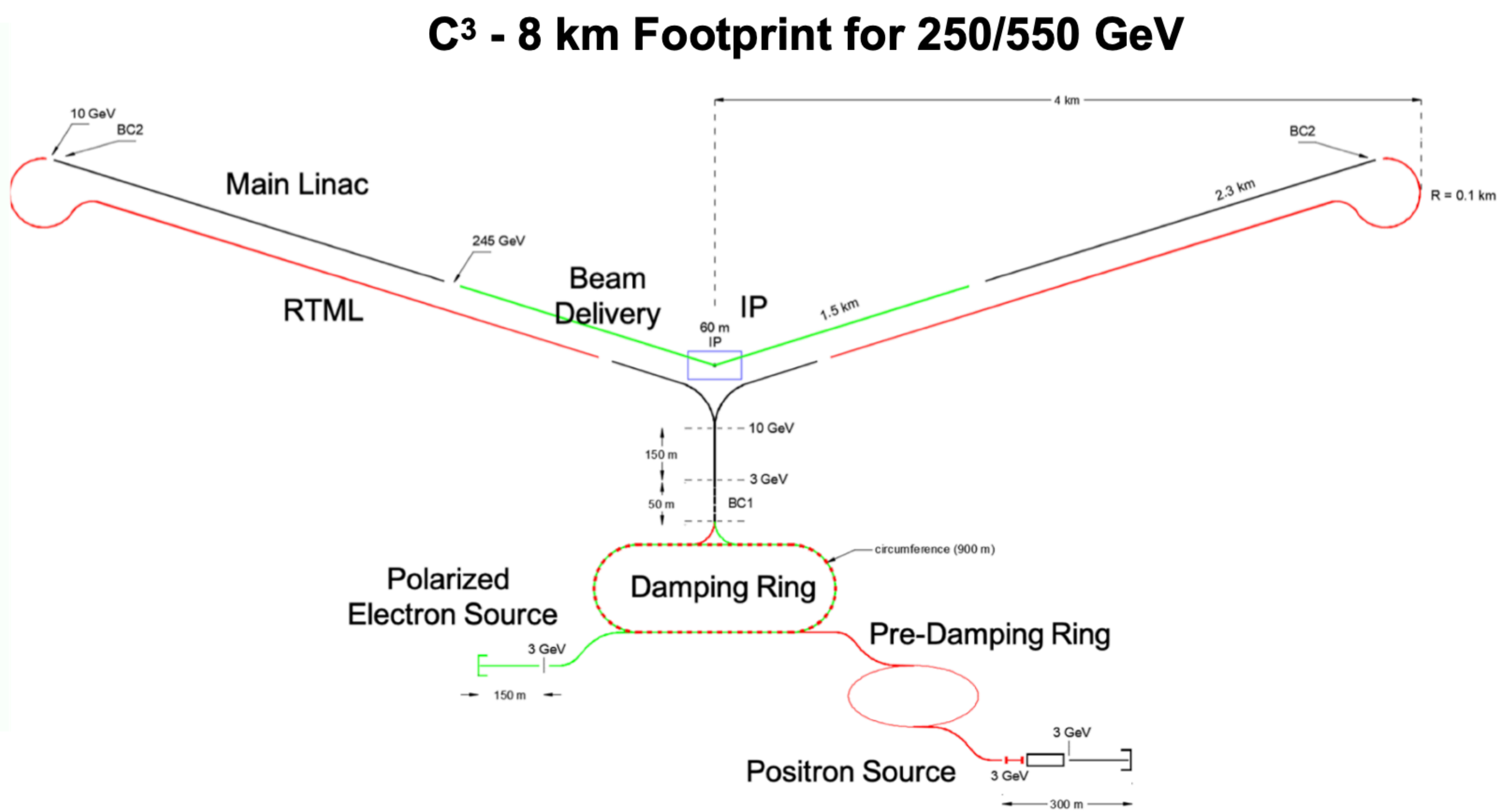
HOWEVER: requires >decade of R&D on PWFA (but this also benefits other accelerator users, who have more $$)

C^3: Cool Copper Collider

C³: Cool Copper Collider



A serious proposal for a 8 km 550 GeV collider (starting at 250 GeV)

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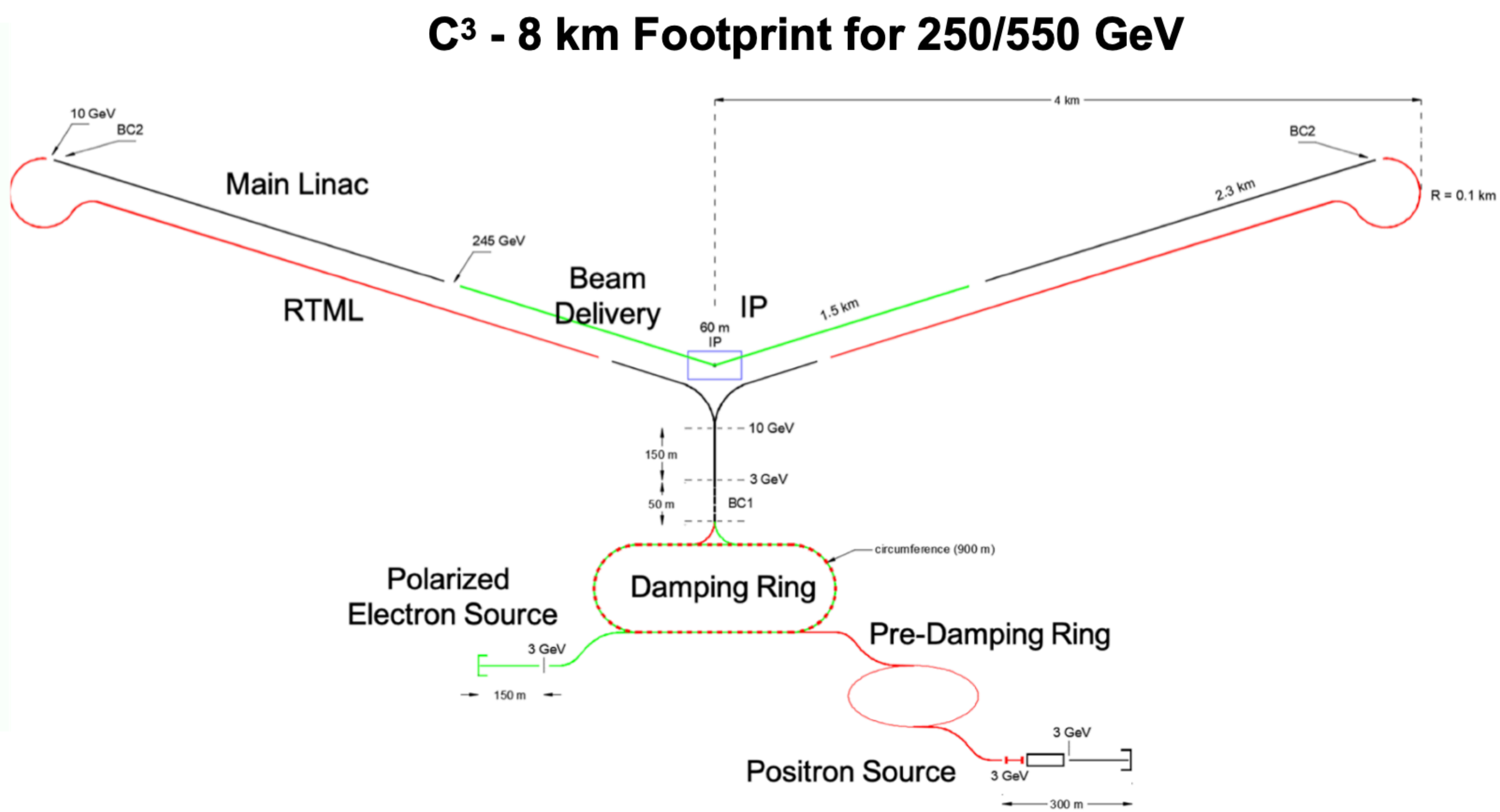

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250 GeV could even start at just 3.7 km long

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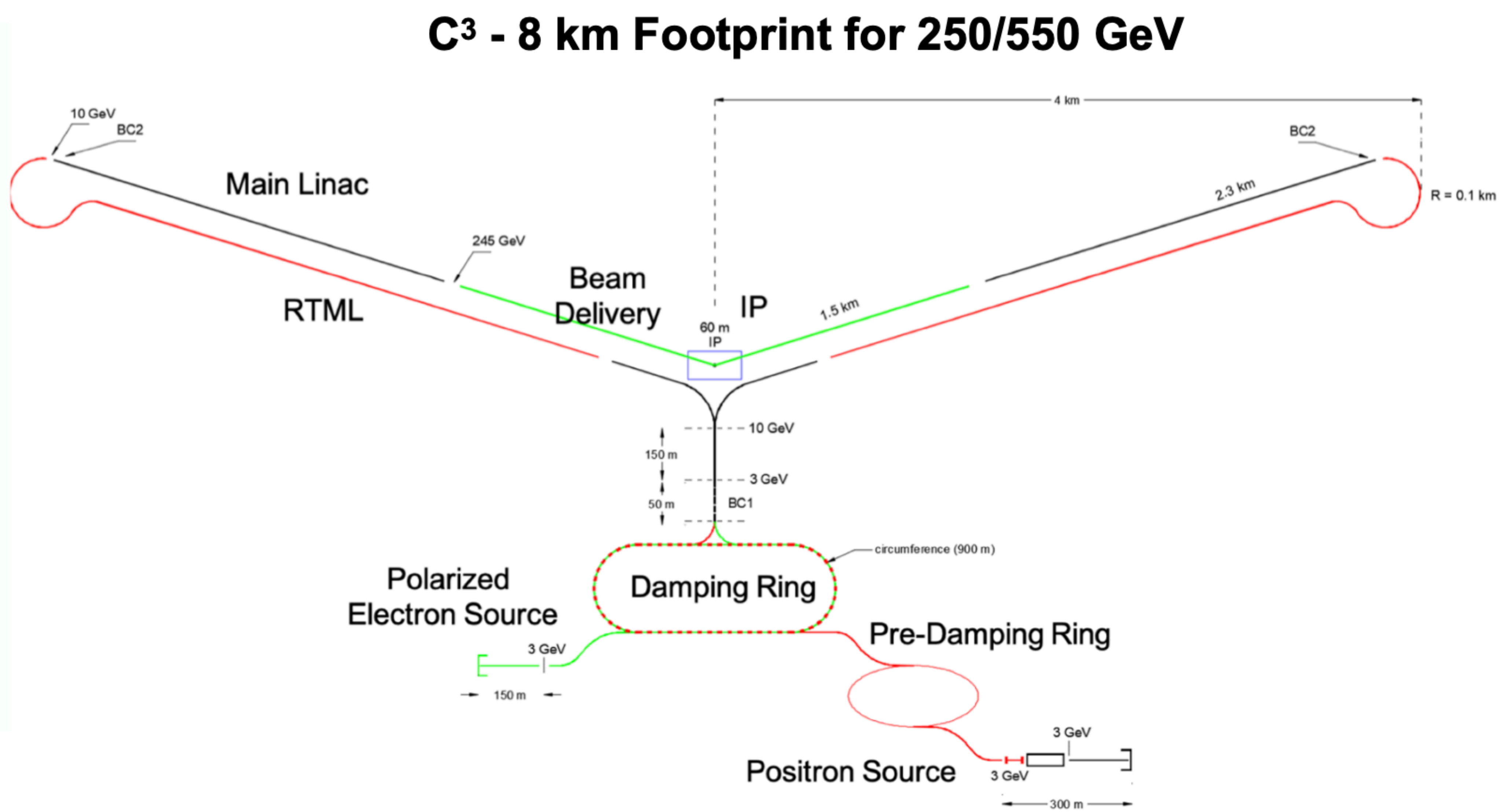

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Huge cost savings from reduced tunnelling

C^3: New Tricks

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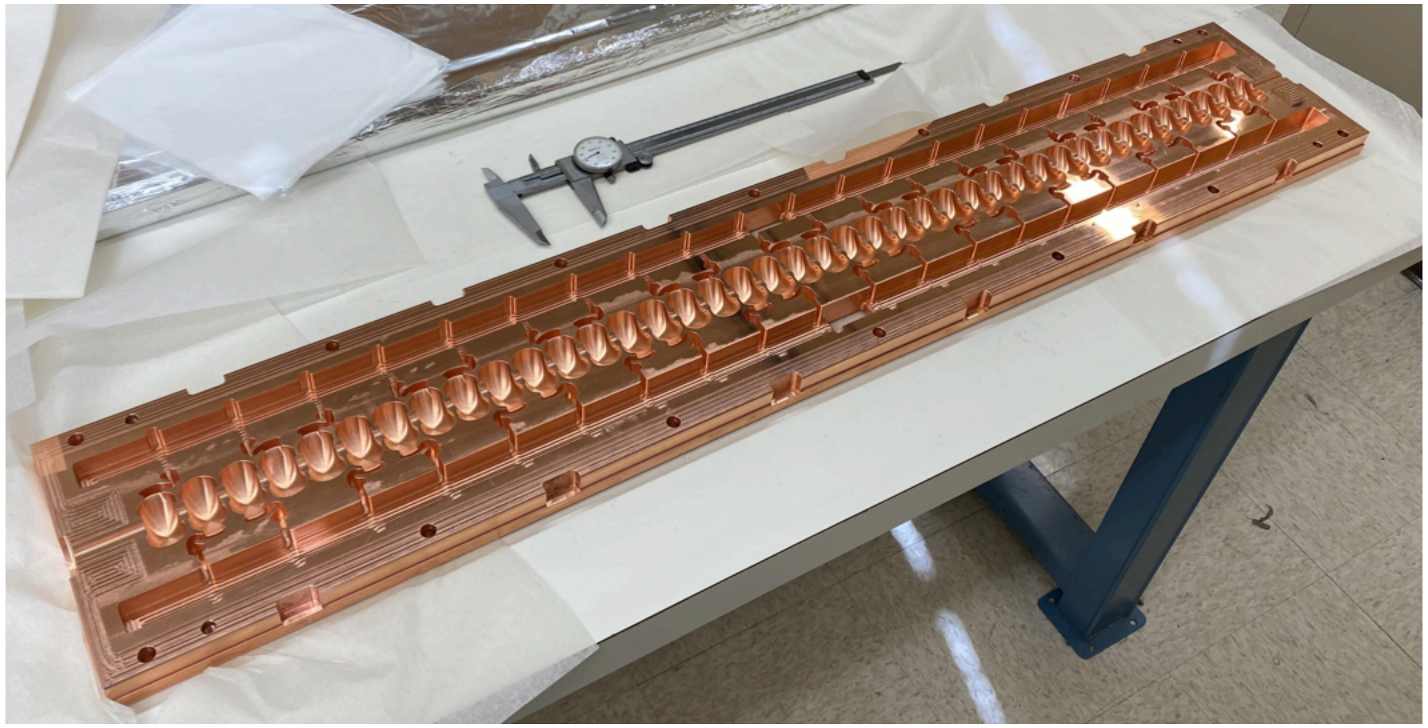
arXiv:2110.15800



1. Supercomputer optimized cavities, improved copper machining

C^3: New Tricks

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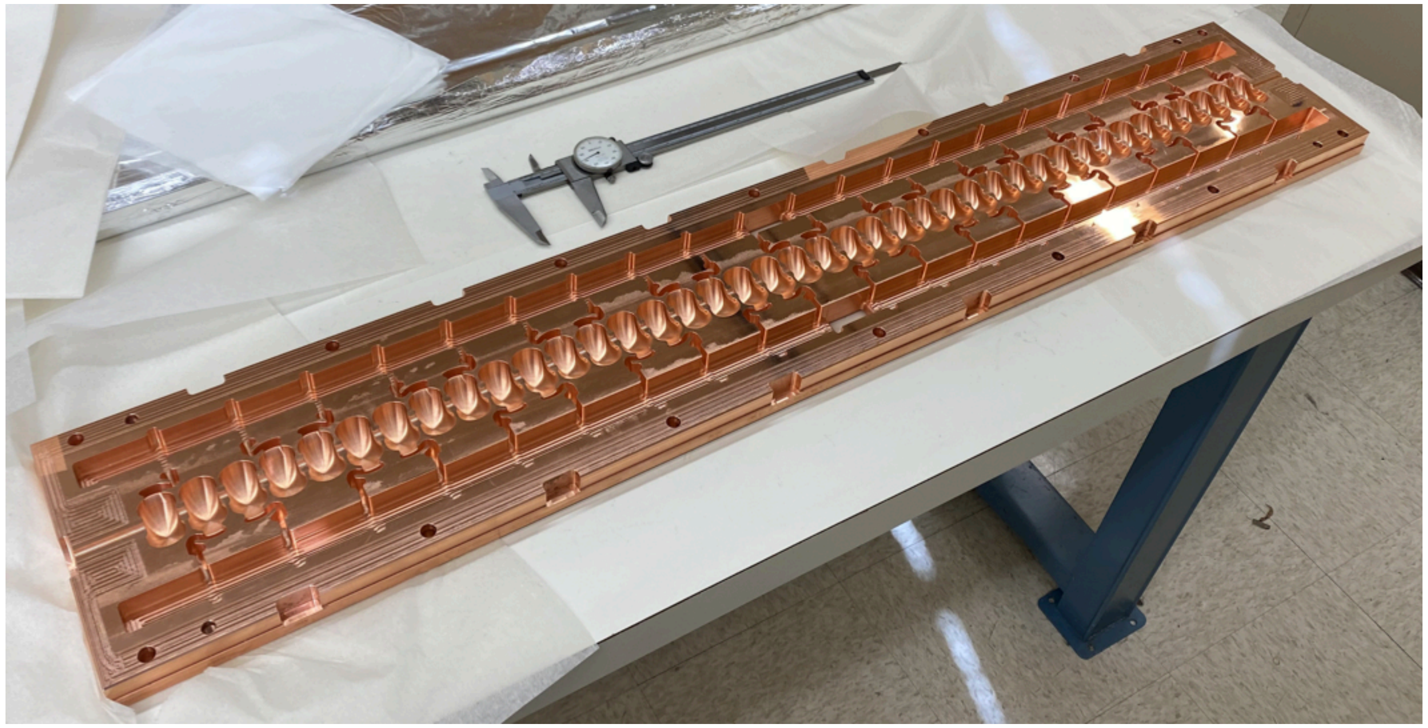

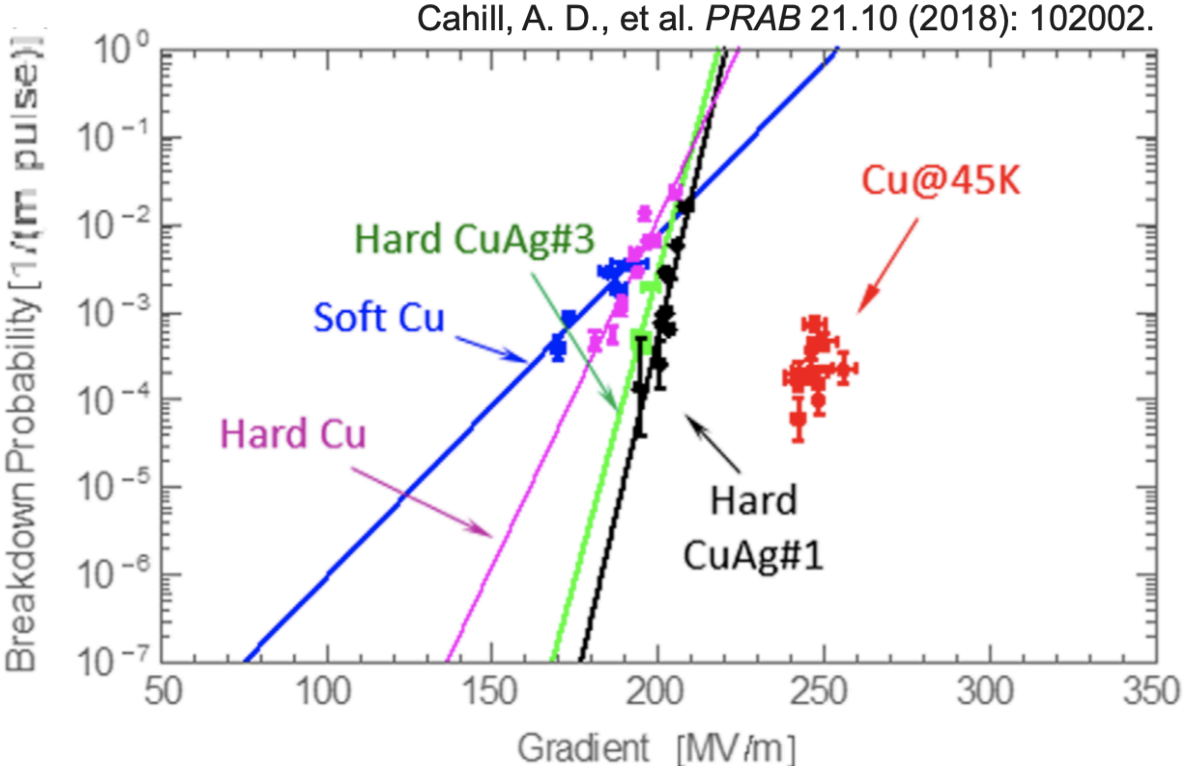

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2. Cryogenic temperatures lower resistance: higher performance

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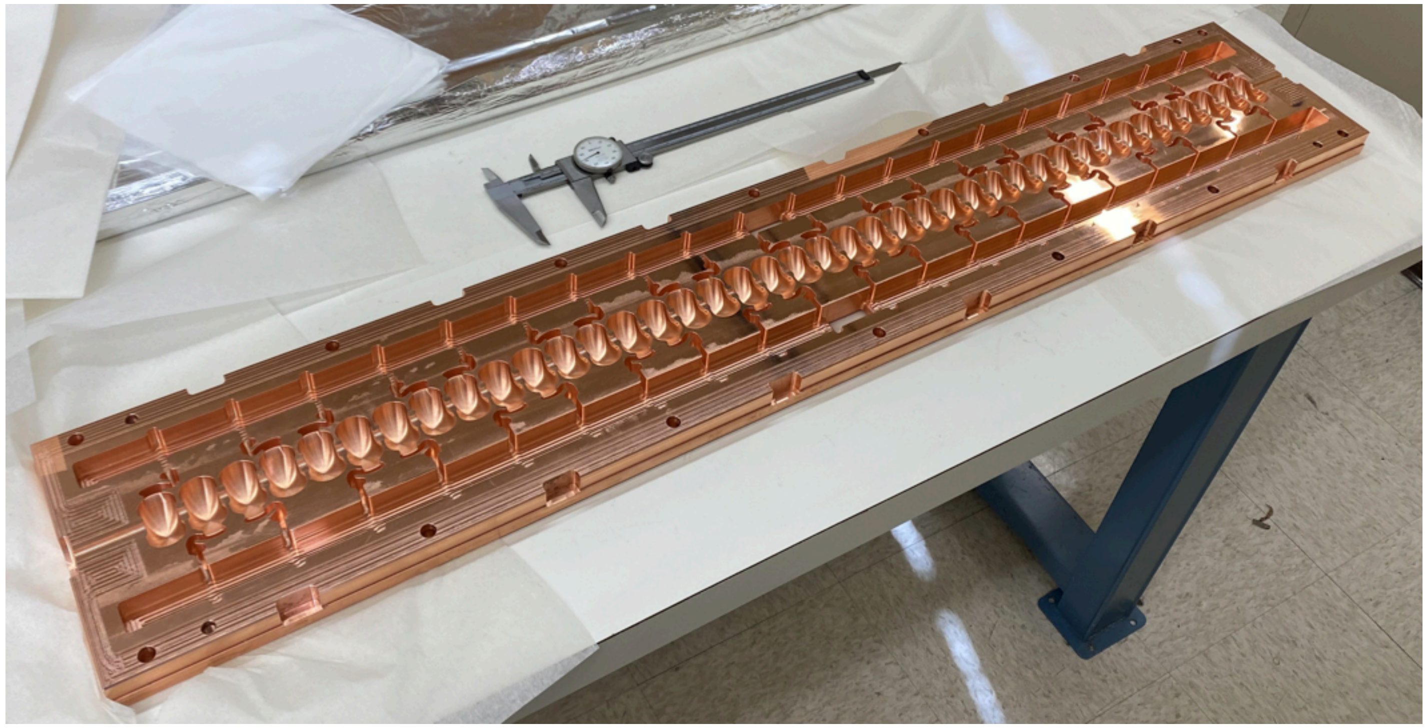
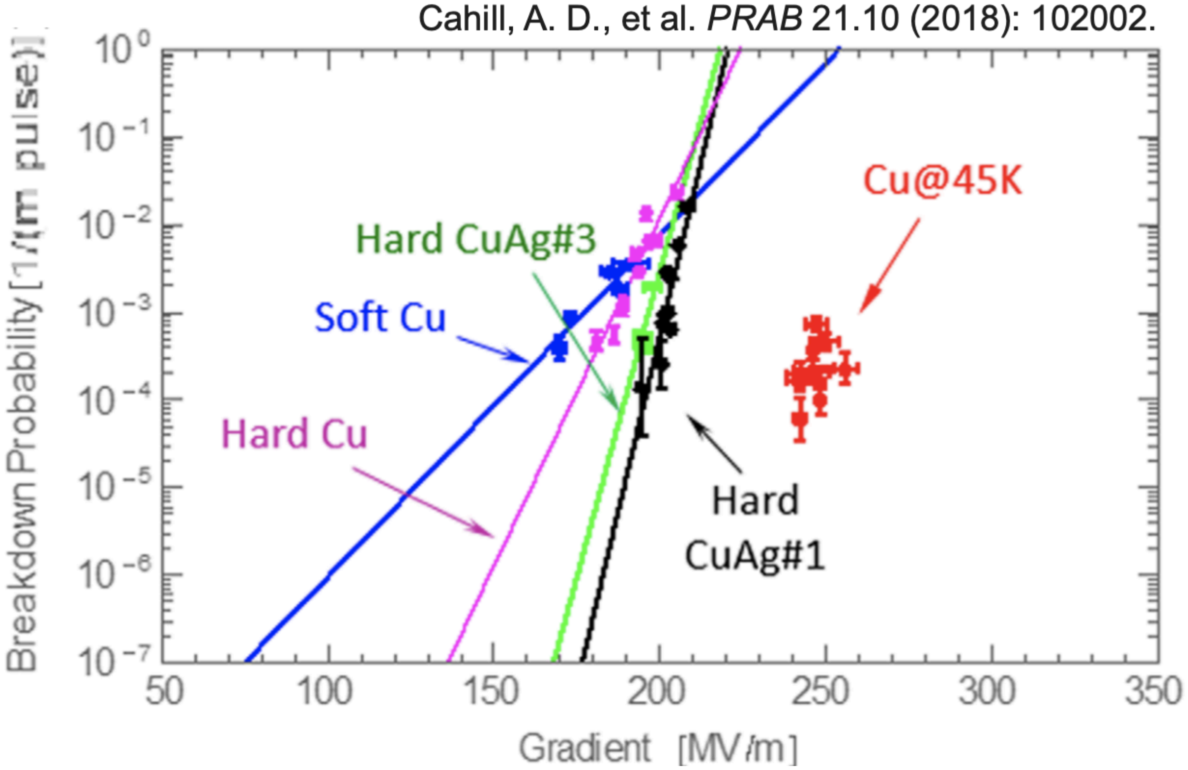
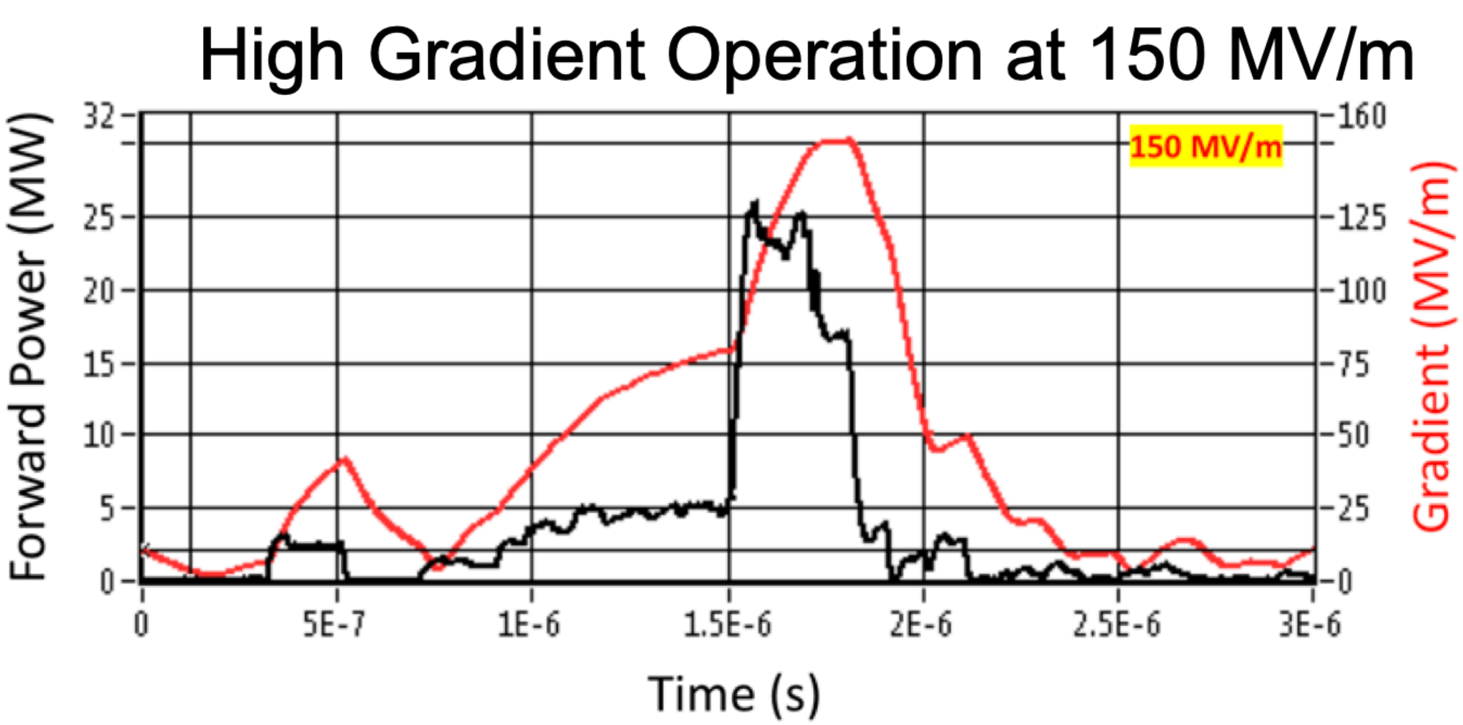


Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.

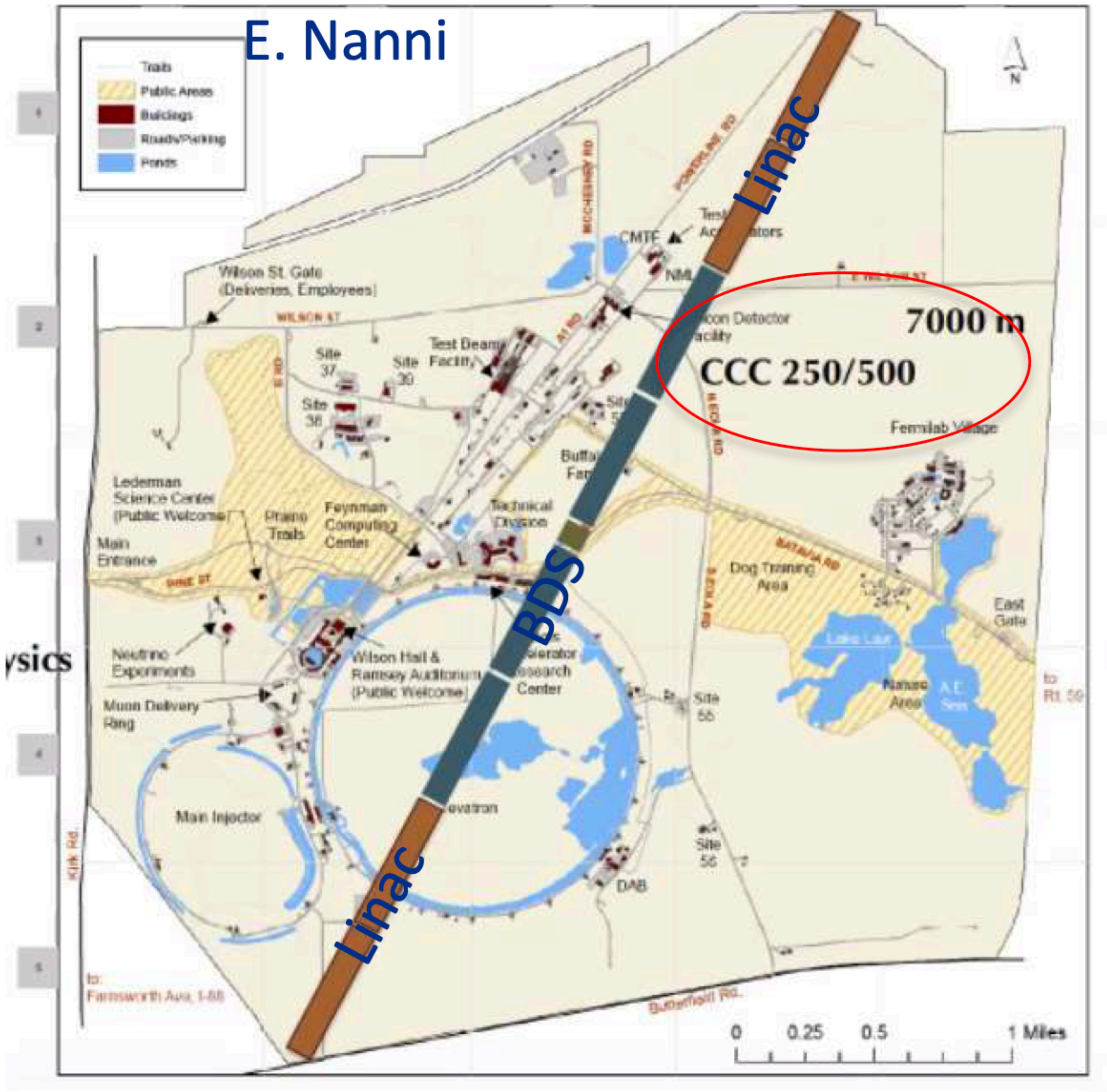




1. Supercomputer optimized cavities, improved copper machining
2. Cryogenic temperatures lower resistance: higher performance
3. 70-120 MV/m (or beyond?) is now possible!

C^3: Locations

C³: Locations



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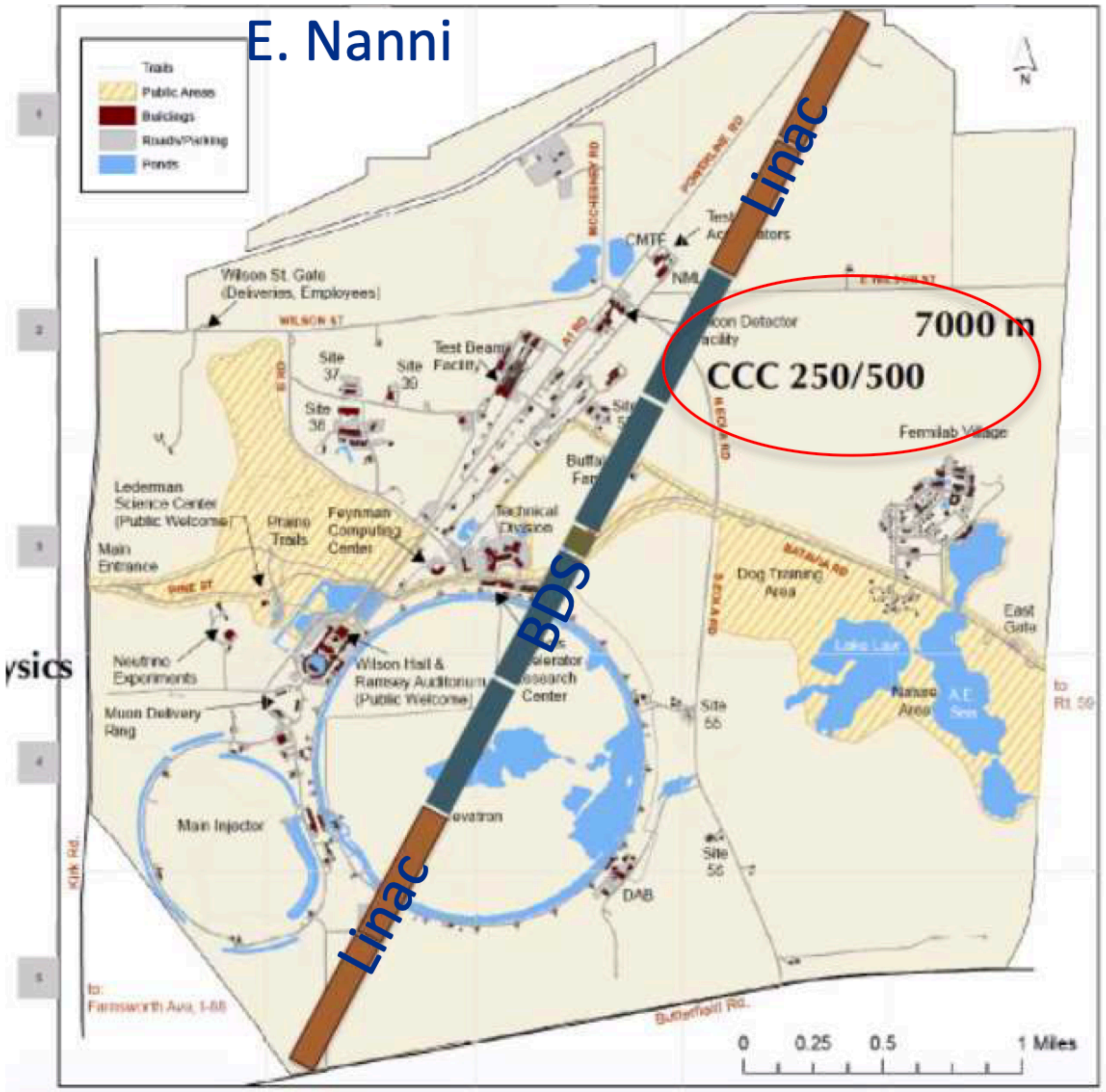

Electrons at FNAL?
Heresy?

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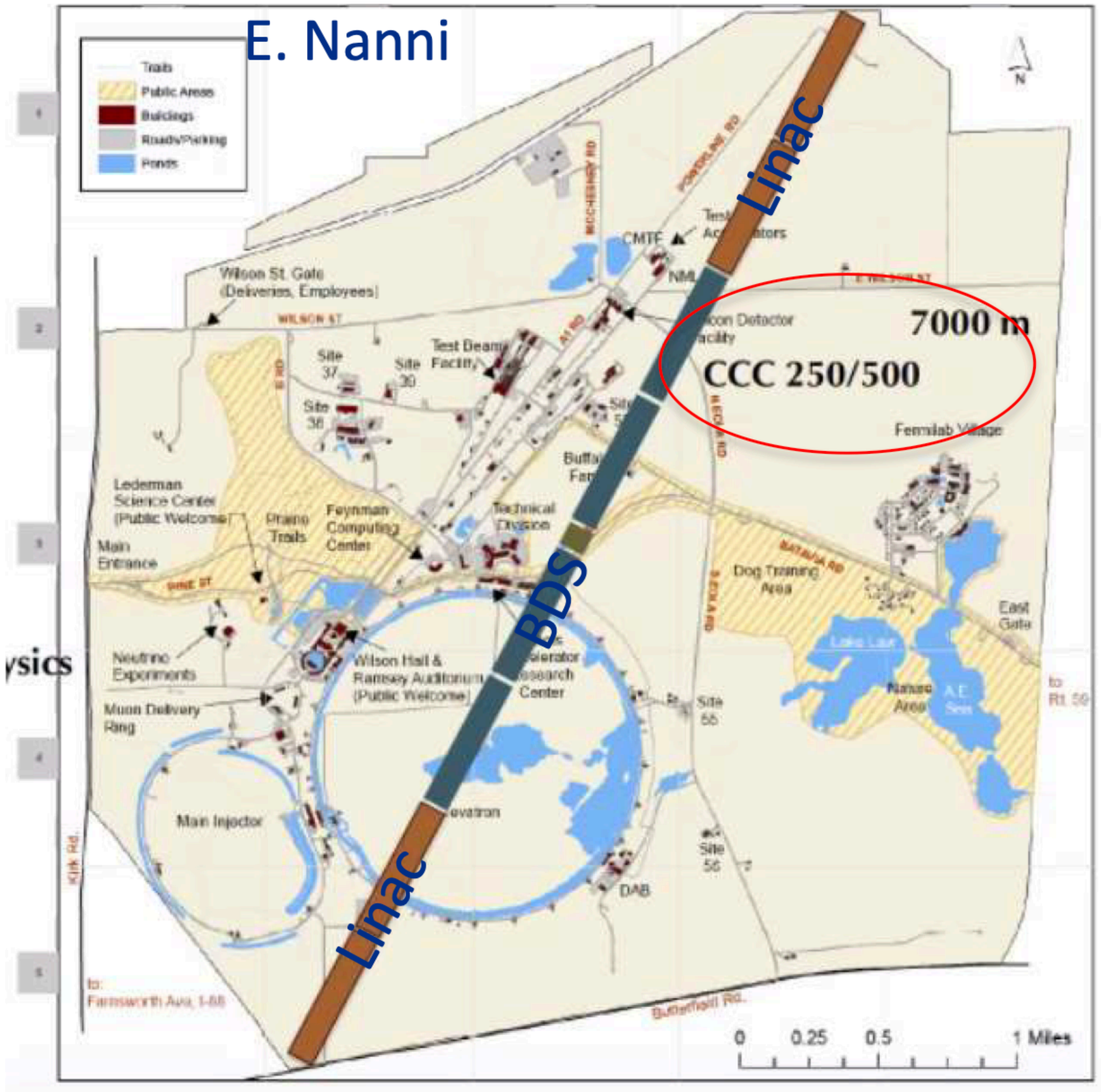

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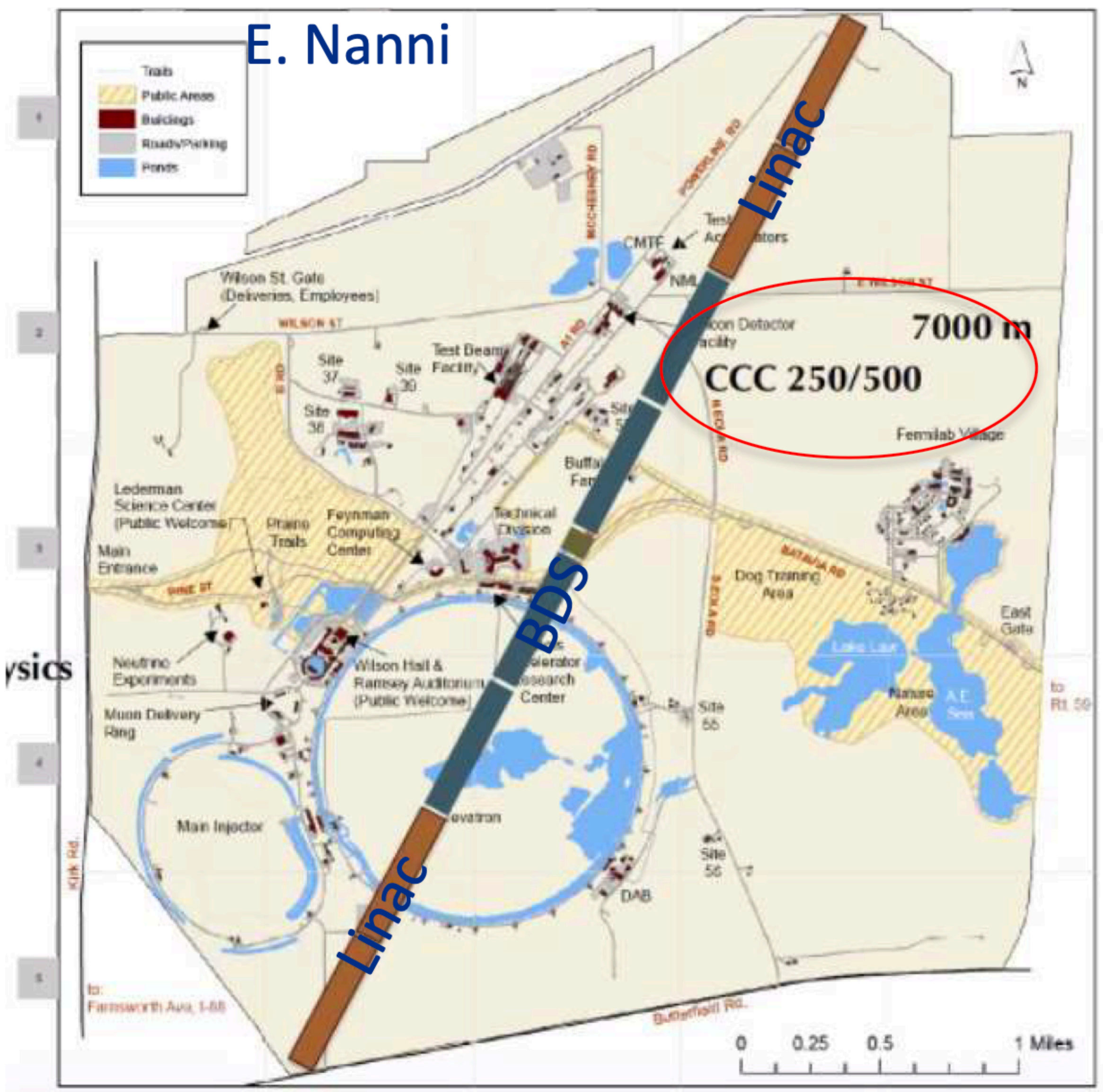

Electrons at FNAL?
Heresy?

Lots of space at Hanford:
room for TeV and beyond?

C^3: Locations

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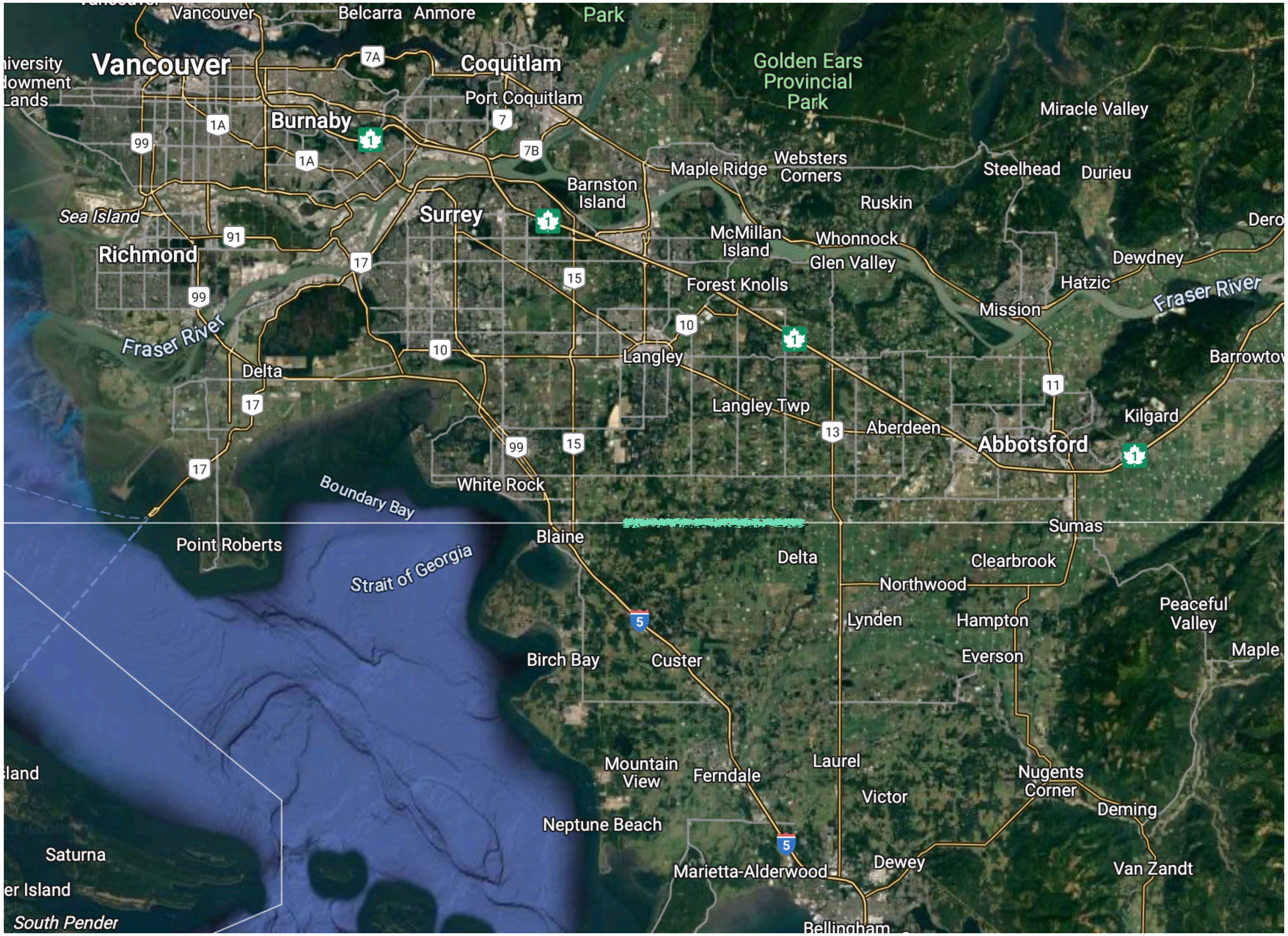
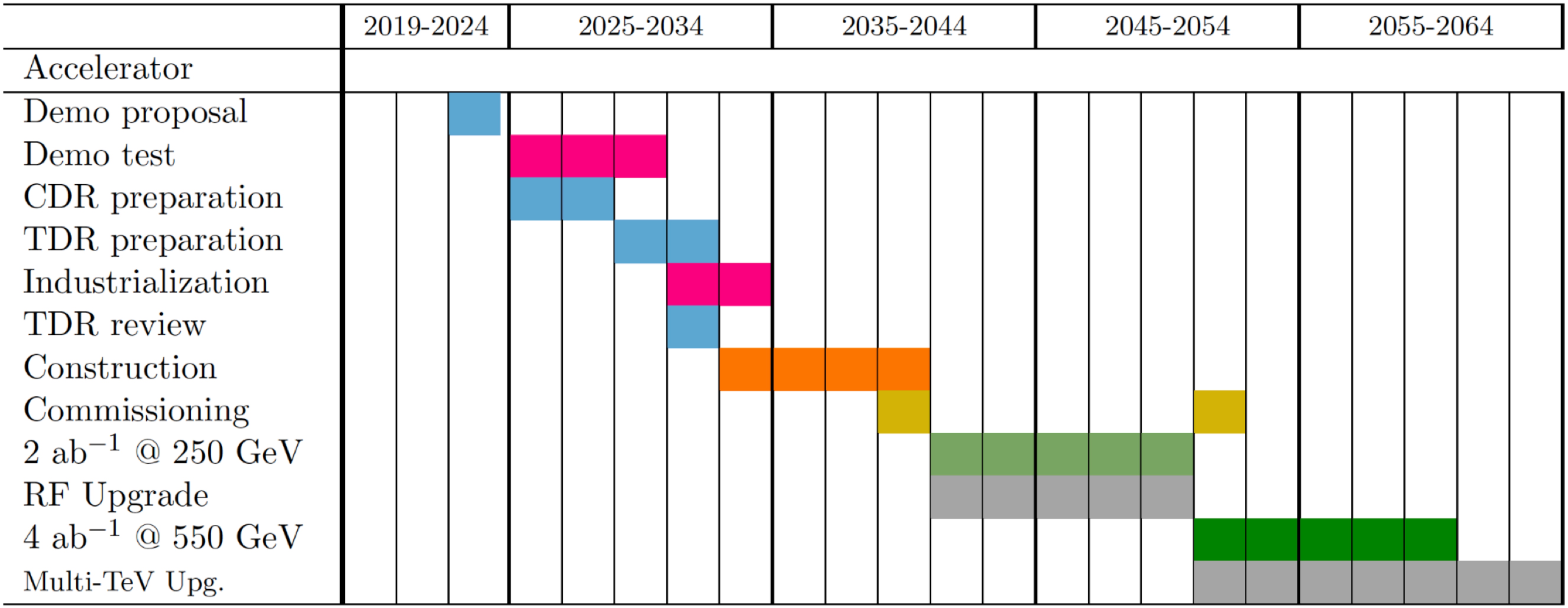


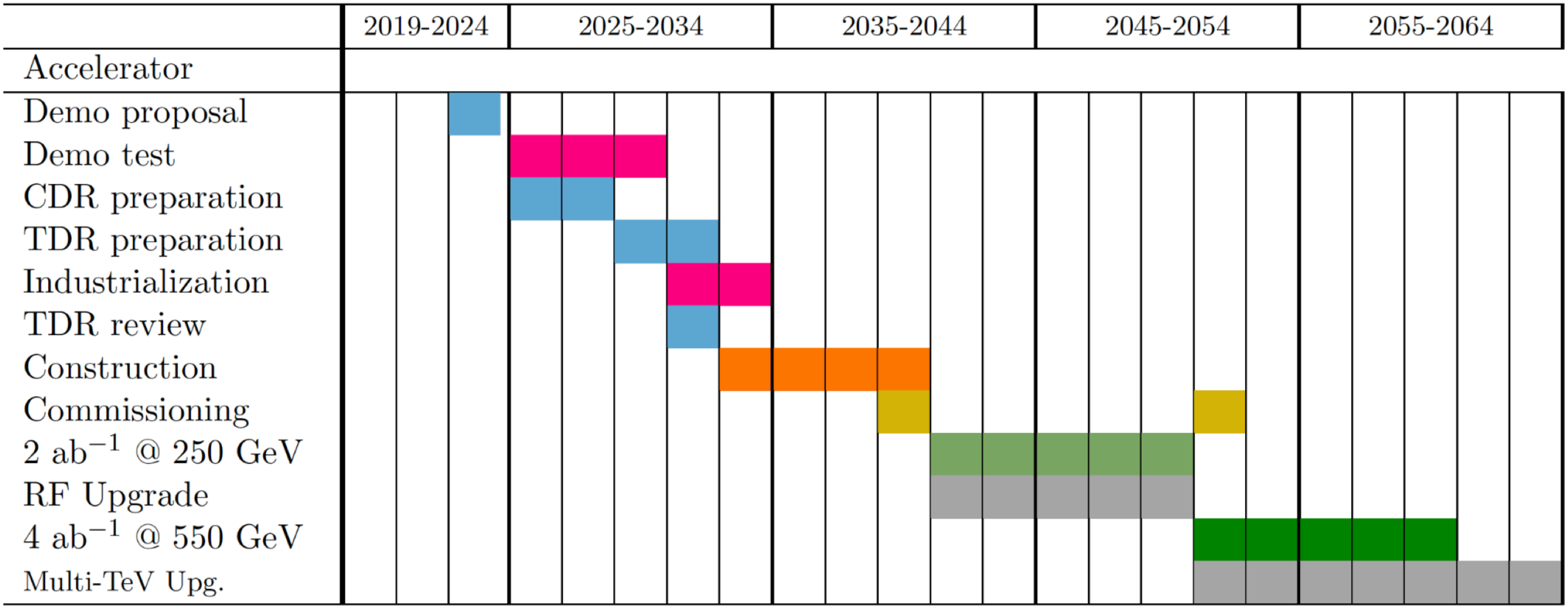
A truly international project?

C^3 Timeline

C^3 Timeline

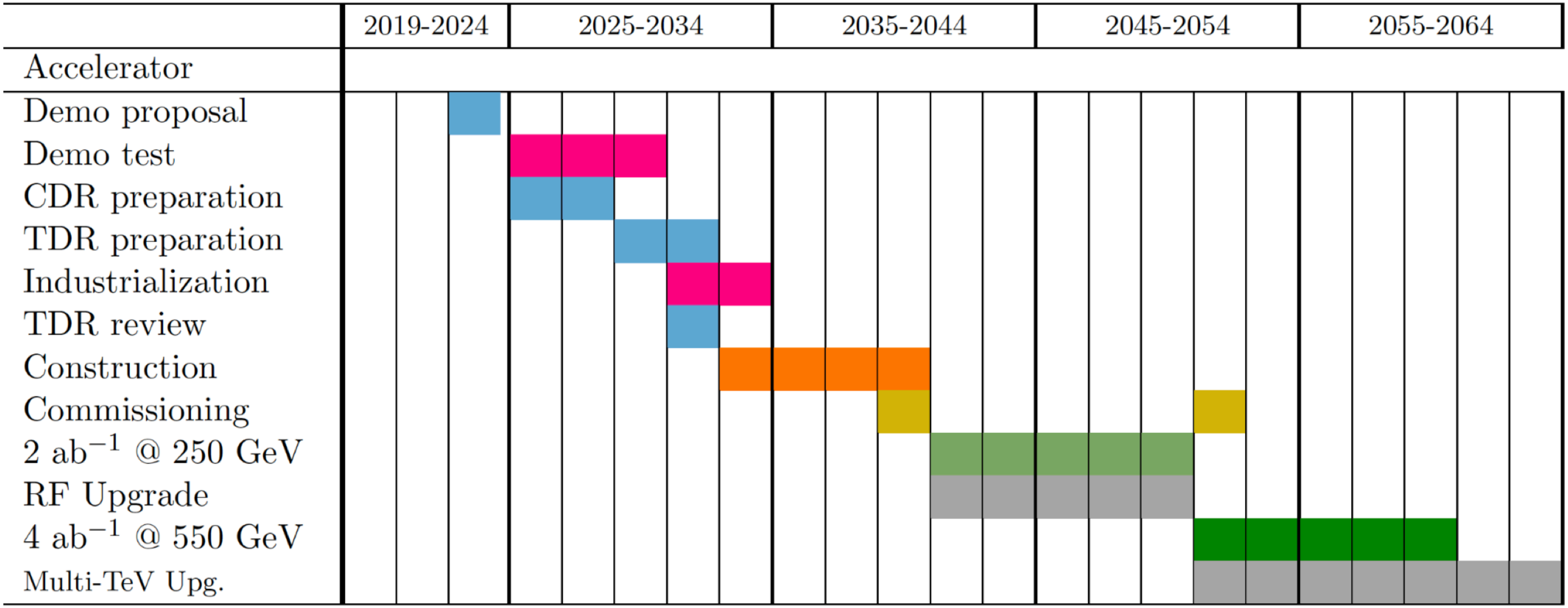

2019-2024
2025-2034
2035-2044
2045-2054
2055-2064
Accelerator
Demo proposal
Demo test
CDR preparation
TDR preparation
Industrialization
TDR review
Construction
Commissioning
2 ab^{-1} @ 250 GeV
RF Upgrade
4 ab^{-1} @ 550 GeV
Multi-TeV Upg.

C^3 Timeline



Demonstration facility is the next step: one "cryomodule" unit

C³ Timeline



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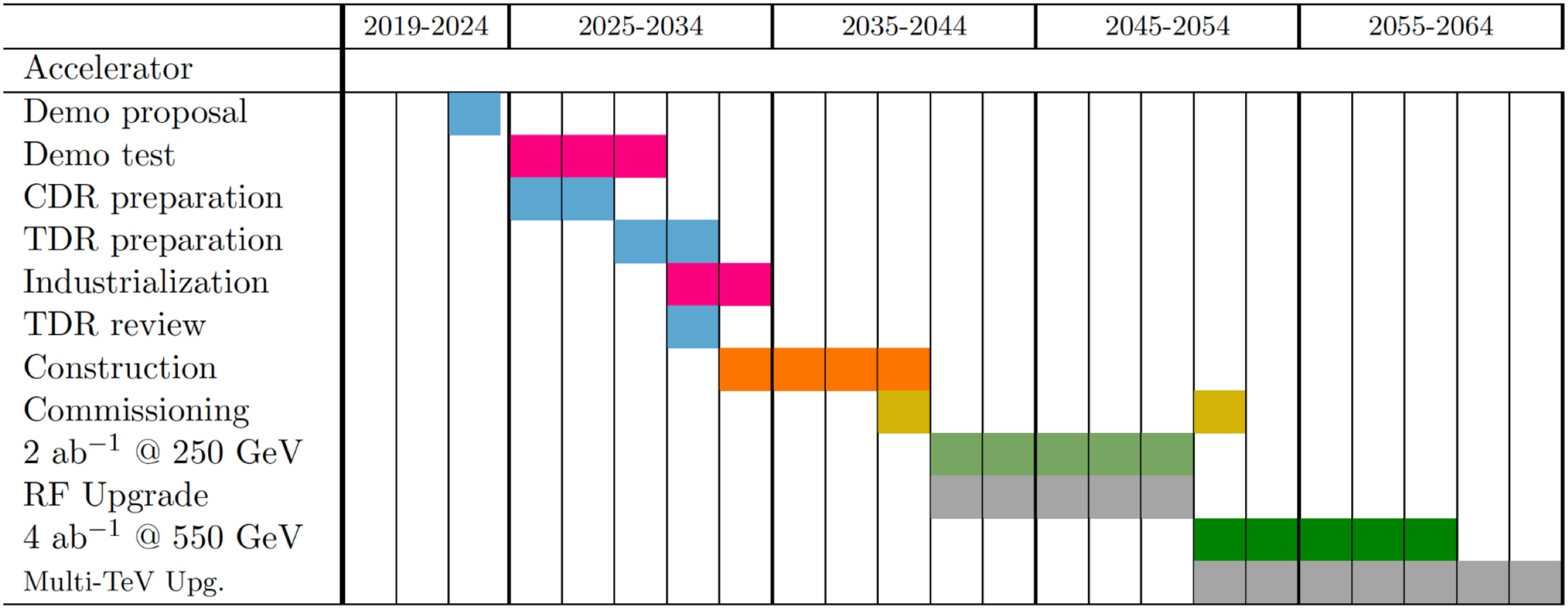

Demonstration facility is the next step: one "cryomodule" unit

R&D needed, but feasibility will be clear from demo

Potentially ~$1b in cost savings, with "moderate" risk!

XCC: $\gamma\gamma$ Collisions

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How to save even more $$$? Go below 250 GeV!

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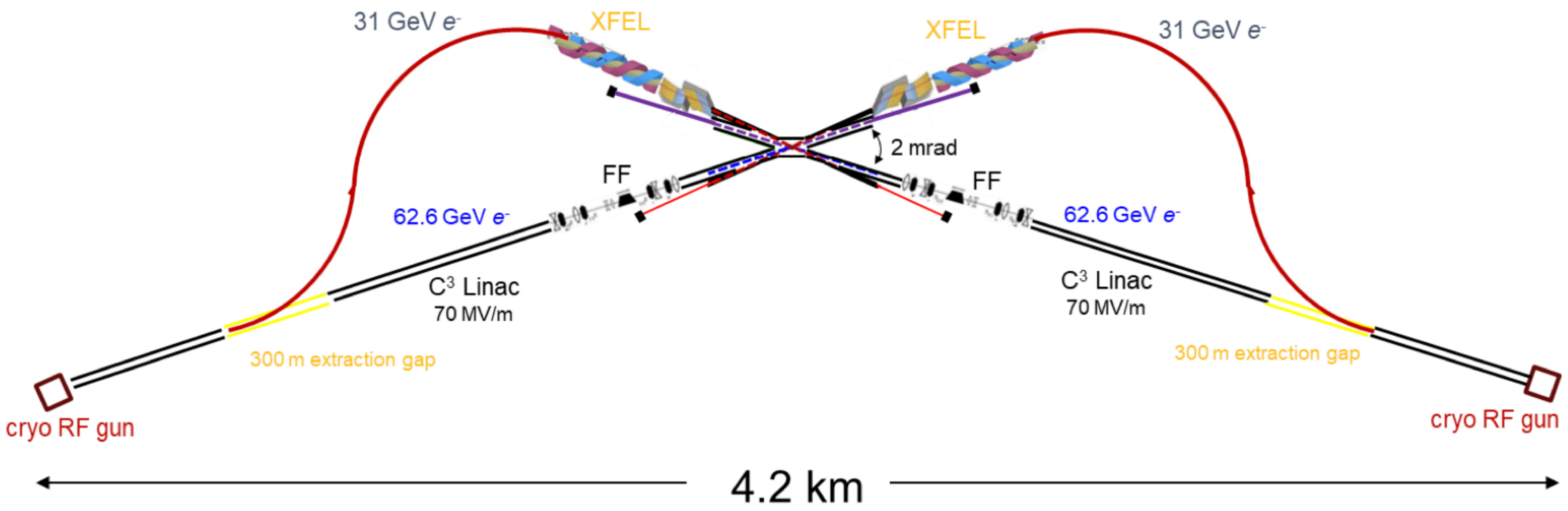

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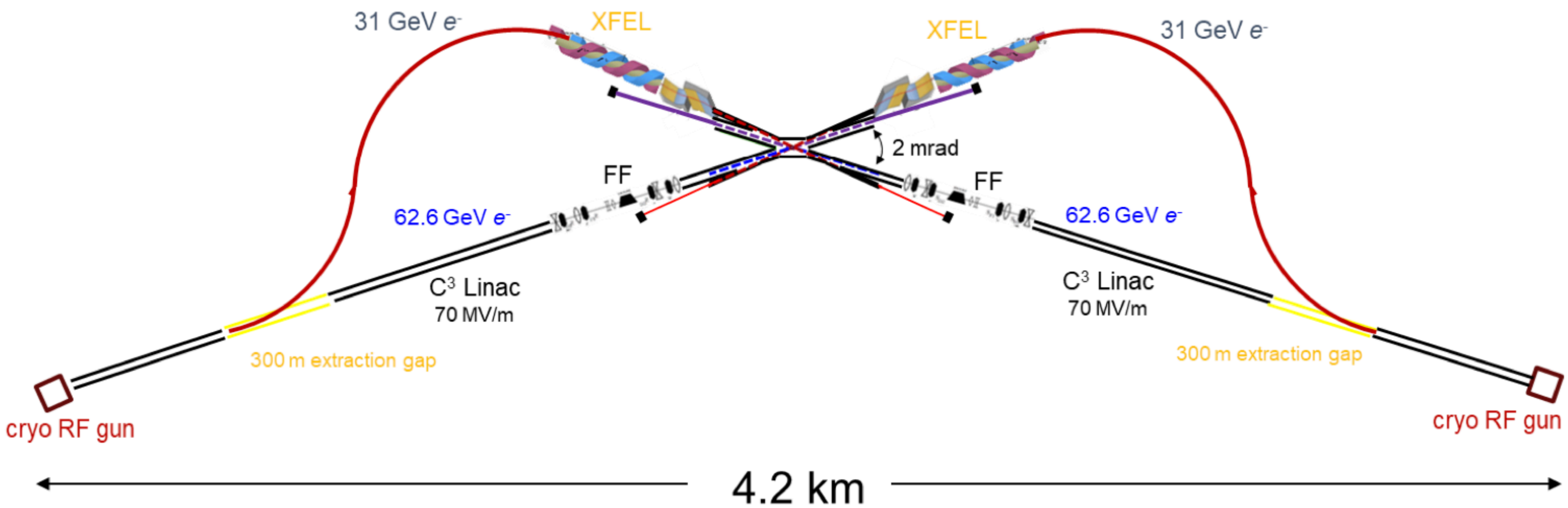

Accelerate electrons to 31 GeV, spin off half to a X-FEL, accelerate the rest to 62.6 GeV

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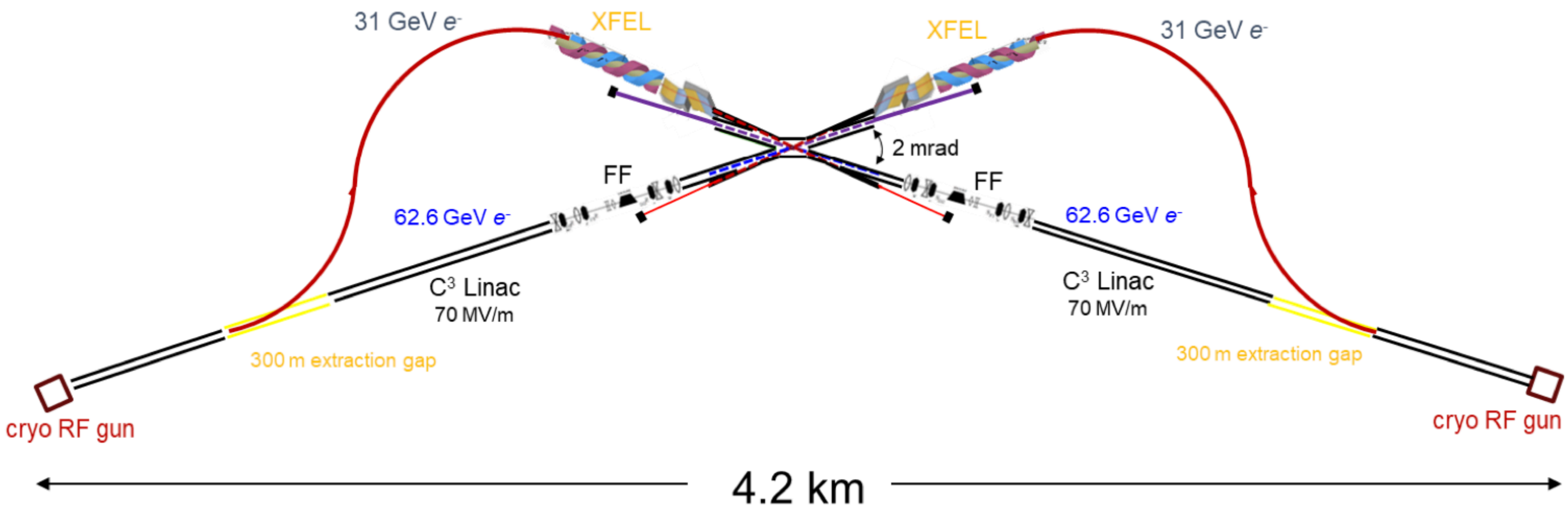

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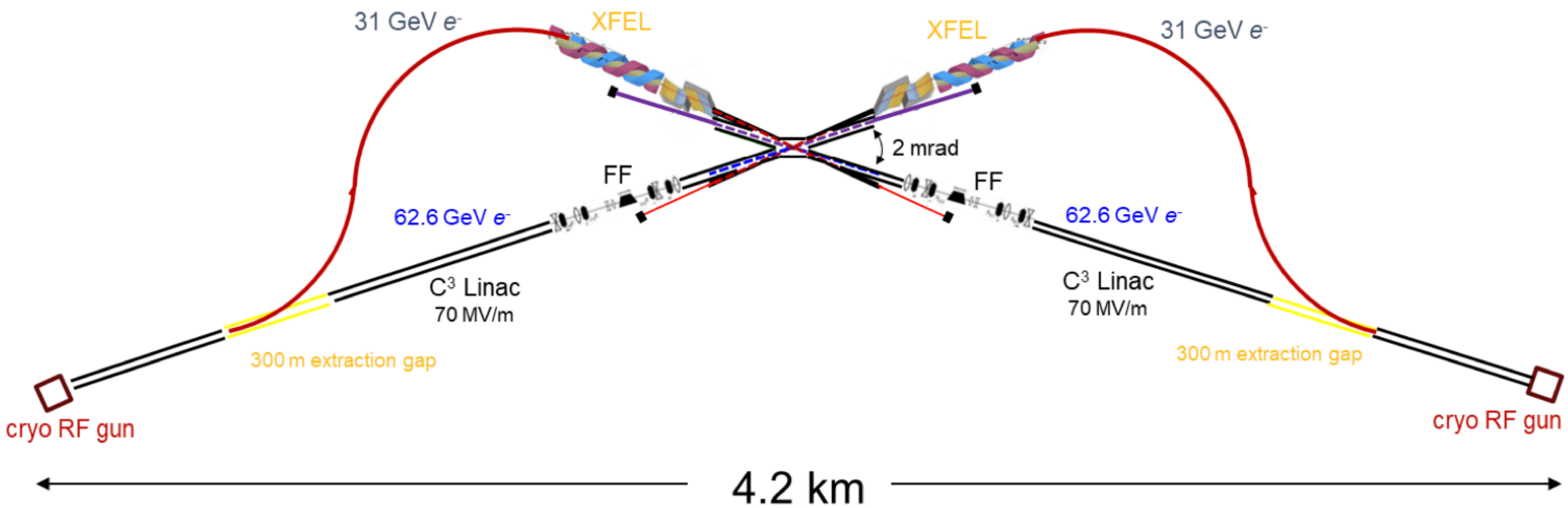

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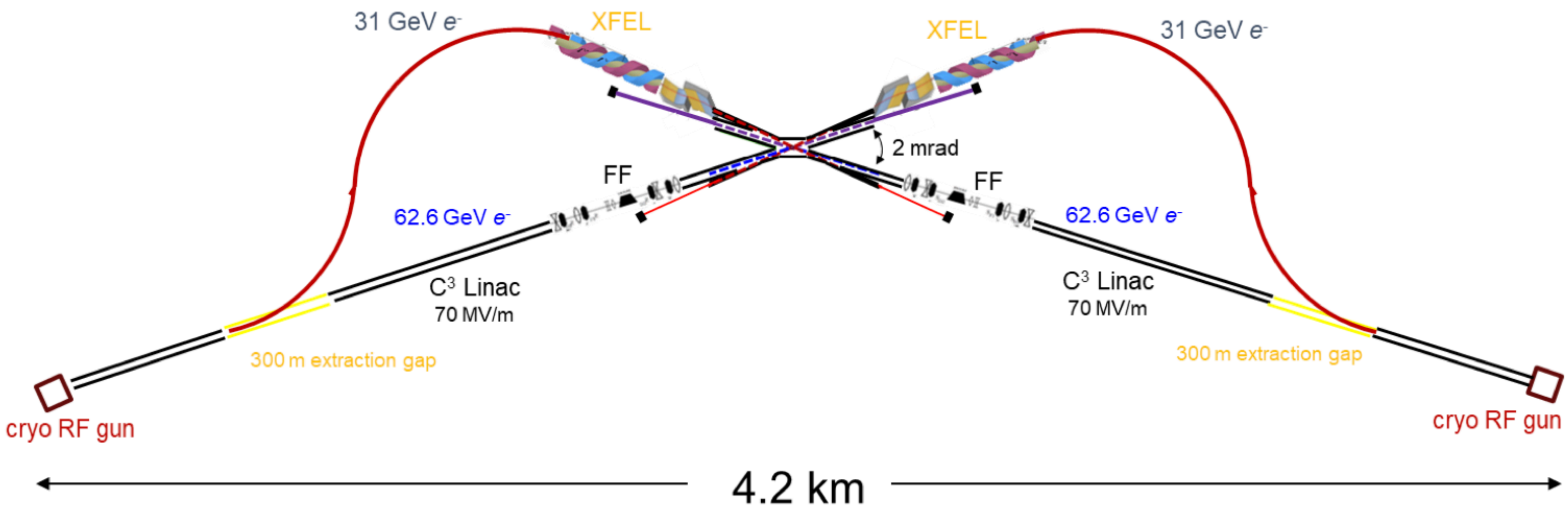

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Huge cost savings from tunnelling and no positrons

Physics at XCC

Physics at XCC

ILC/C^3 vs. XCC Physics Comparison

Tim Barklow

Stage I & II Parameters

Colliding Particles	ILC/C^3 e^+e^-	XCC $\gamma\gamma$
Stage I:		
$\sqrt{s}$ (GeV)	250	125
Luminosity (fb^{-1})	2000	460
Beam Power (MW)	5.3 / 4.0	4.0
Run Time (yr)	10	10
# Single Higgs	0.5×10^6	1.3×10^6
Stage II:		
$\sqrt{s}$ (GeV)	550	380
Luminosity (fb^{-1})	4000	4900
Beam Power (MW)	11 / 4.9	4.9
Run Time (yr)	10	10
# Single Higgs (I+II)	1.5×10^6	1.3×10^6
# Double Higgs	840	1800
# $t\bar{t}$	2.0×10^6	2.9×10^6

Stage I, 10 years

κ framework $\text{BR}_{\text{BSM}} = 0$

coupling a	HL-LHC† Δa (%)	ILC/C^3 Δa (%)	XCC Δa (%)
HZZ	2.4	0.46	0.83
HWW	2.6	0.44	0.84
Hbb	6.0	0.83	0.85
$H\tau\tau$	2.8	0.98	0.89
Hgg	4.0	1.6	1.1
Hcc	-	1.8	1.2
$H\gamma\gamma$	2.9	1.1	0.10
$H\gamma Z$	-	-	1.5
$H\mu\mu$	6.7	4.0	3.5
Γ_{tot}	5	1.6	1.7

† S1 from Table 36 in arXiv:1902.00134 [hep-ph]

Stage I+II, 20 years

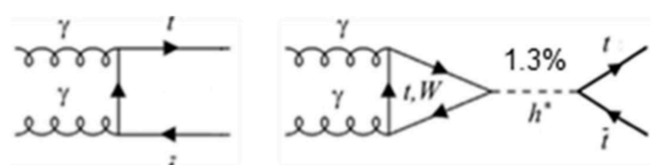
Model Independent EFT

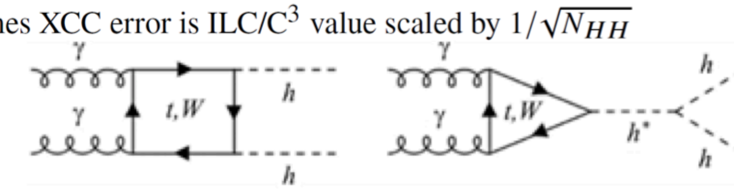
coupling a	ILC/C^3 Δa (%)	XCC # Δa (%)
HZZ	0.38	0.94
HWW	0.37	0.94
Hbb	0.60	0.95
$H\tau\tau$	0.77	0.99
Hgg	0.96	1.2
Hcc	1.2	1.2
$H\gamma\gamma$	1.0	0.44
$H\gamma Z$	4.0	1.5
$H\mu\mu$	3.8	3.5
Htt	2.8	4.6
HHH	20	14*
Γ_{tot}	1.6	2.4
Γ_{inv}†	0.32	–
Γ_{other}†	1.3	1.5

† 95% C.L. limit

*assumes XCC error is ILC/C^3 value scaled by $1/\sqrt{N_{HH}}$

XCC achieves model independence through measurement of $\Gamma_{\gamma\gamma}$ using monochomatic electron in $e^-\gamma \to e^- H$ during $\sqrt{s} = 380$ GeV $\gamma\gamma$ run.





Physics at XCC compatible with ILC: even better for self-coupling!

XCC Costs and Timelines

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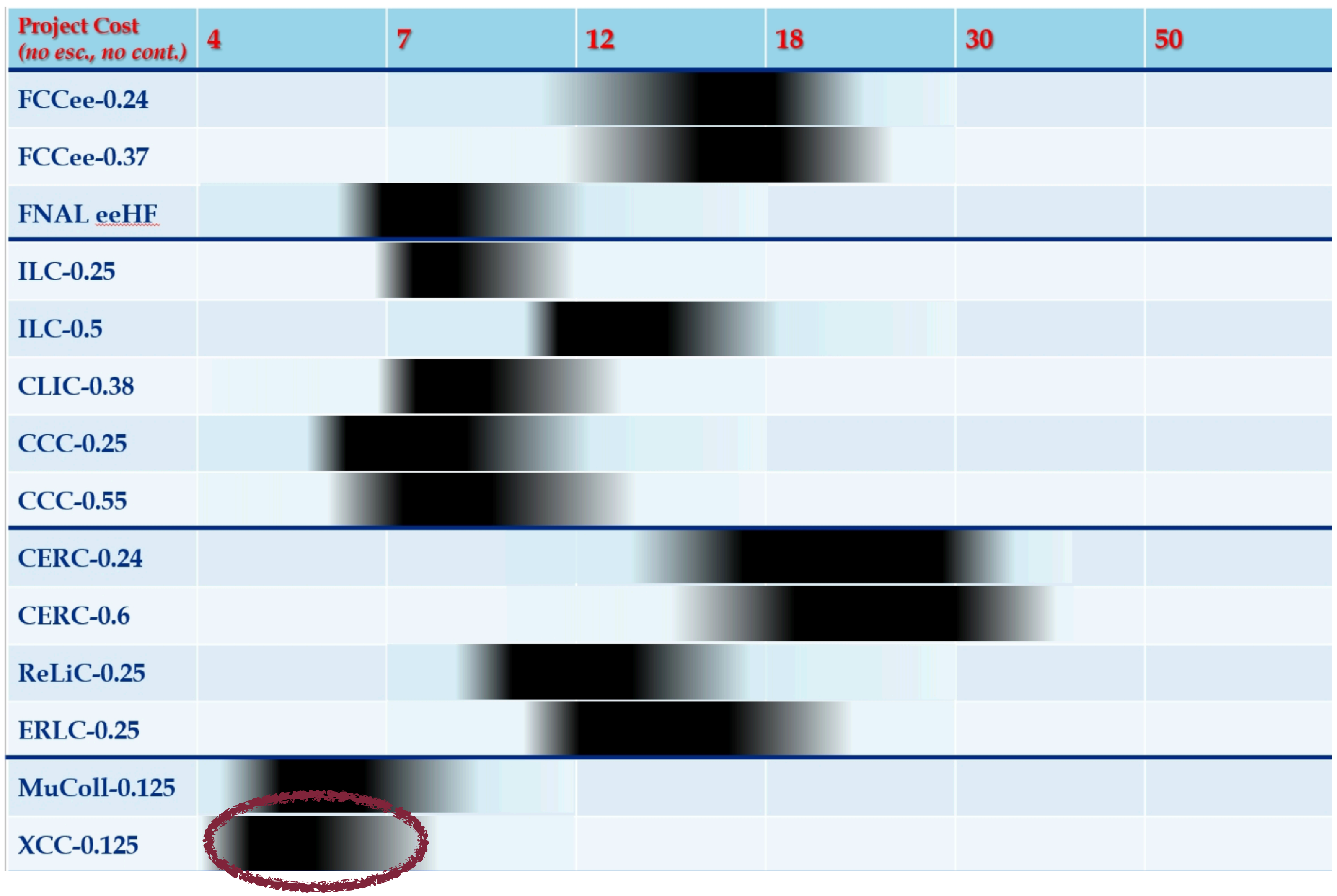

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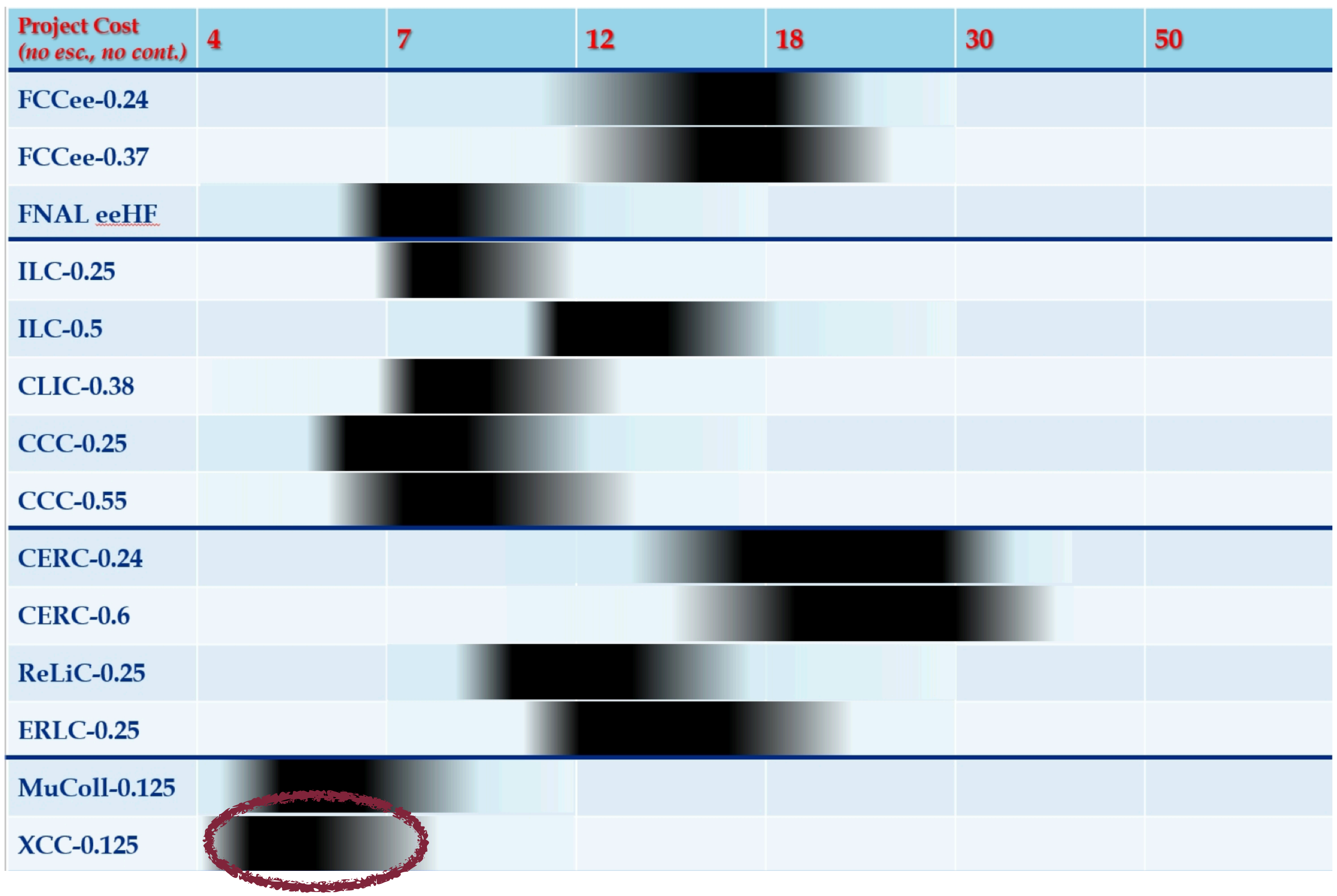

Costs of this device are potentially substantially lower than every other Higgs factory: ~$5B

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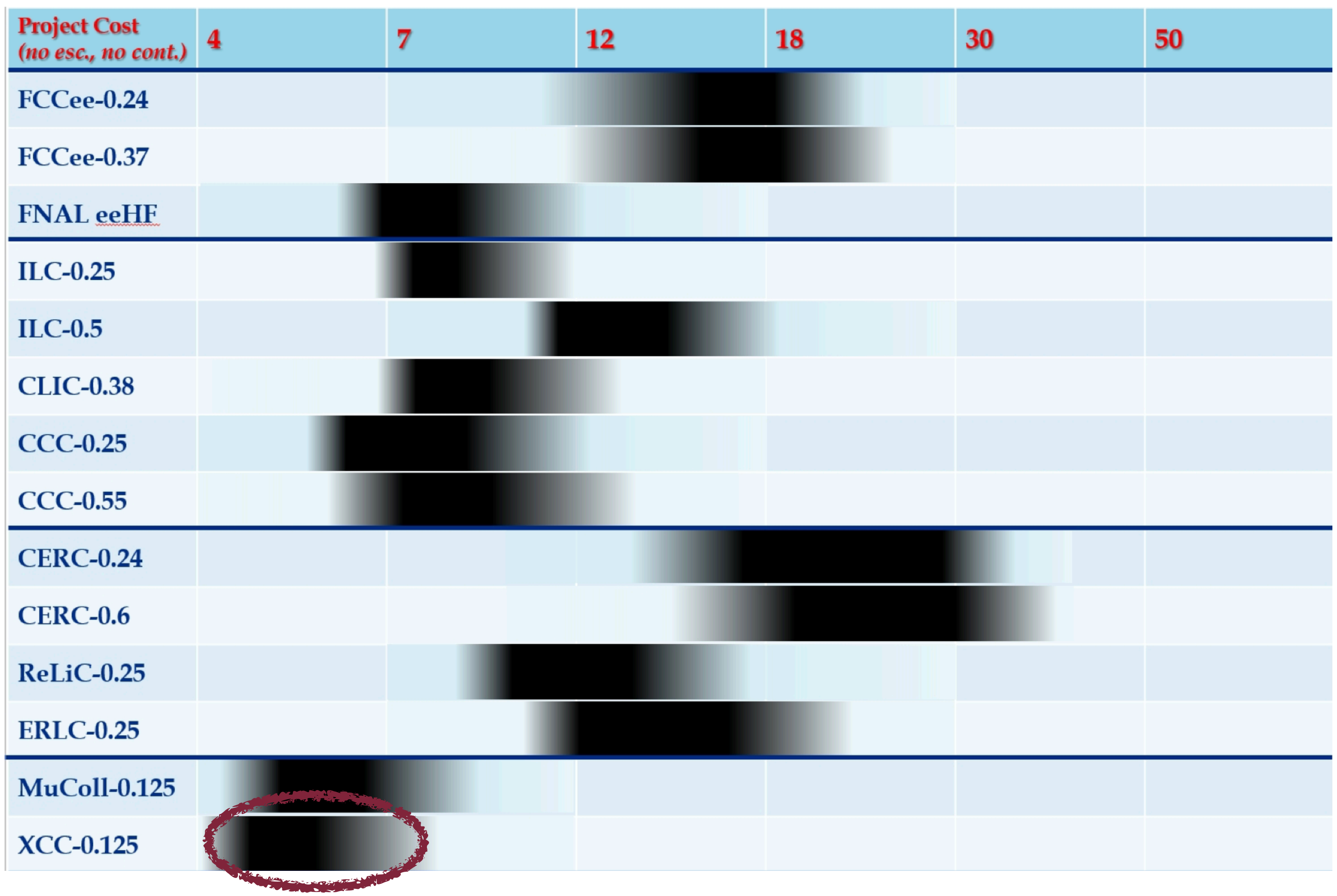

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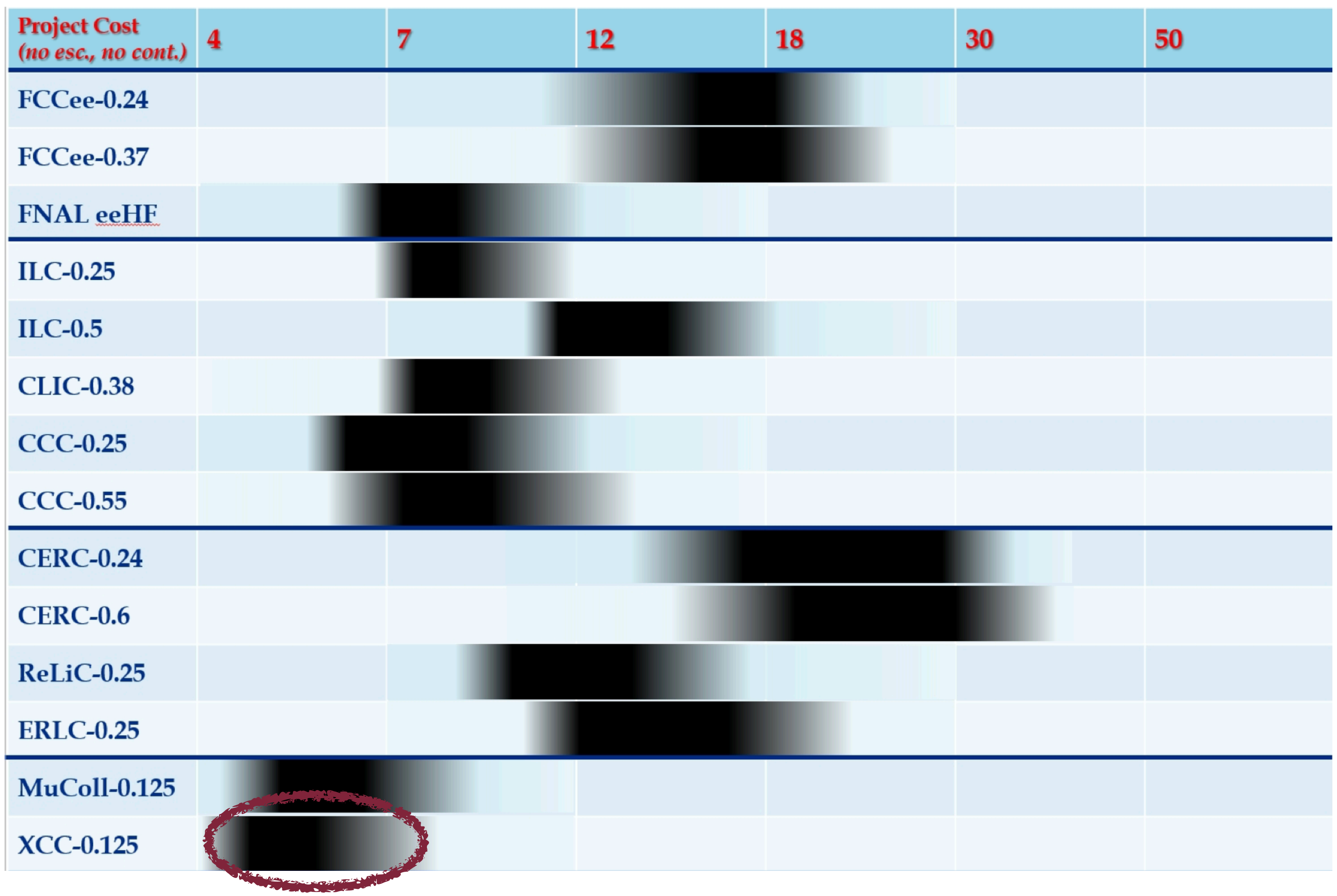

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>15 year outlook

A Radical (?) Vision

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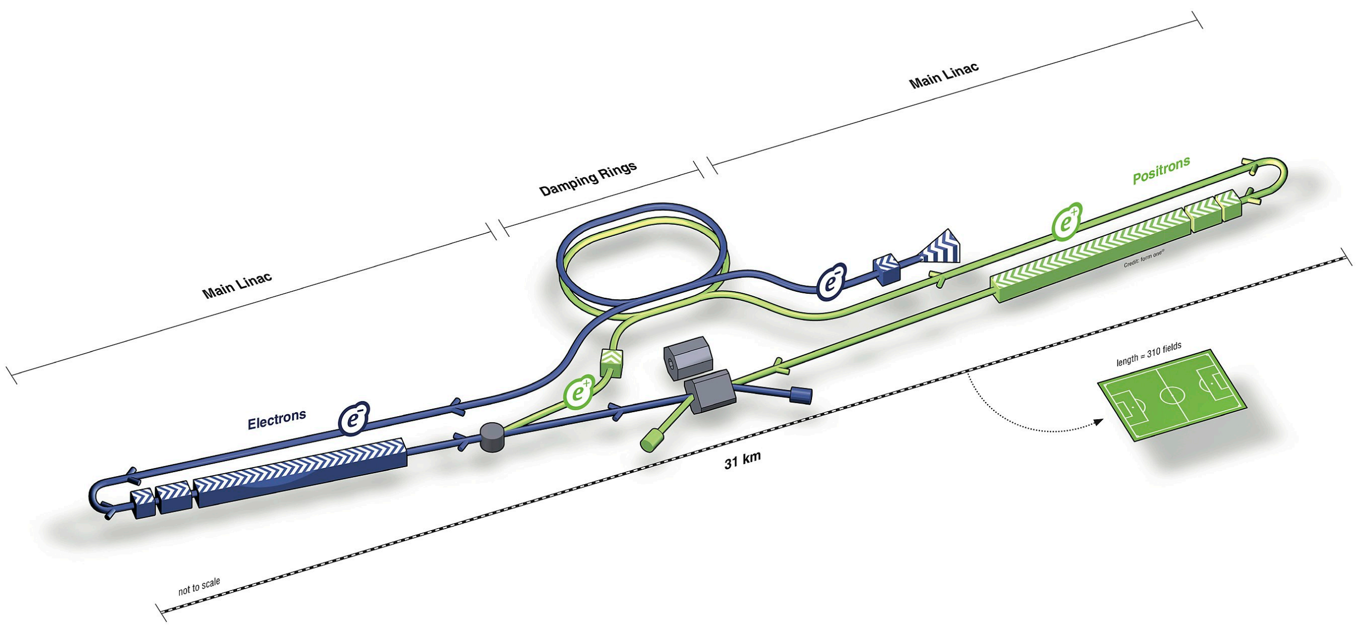

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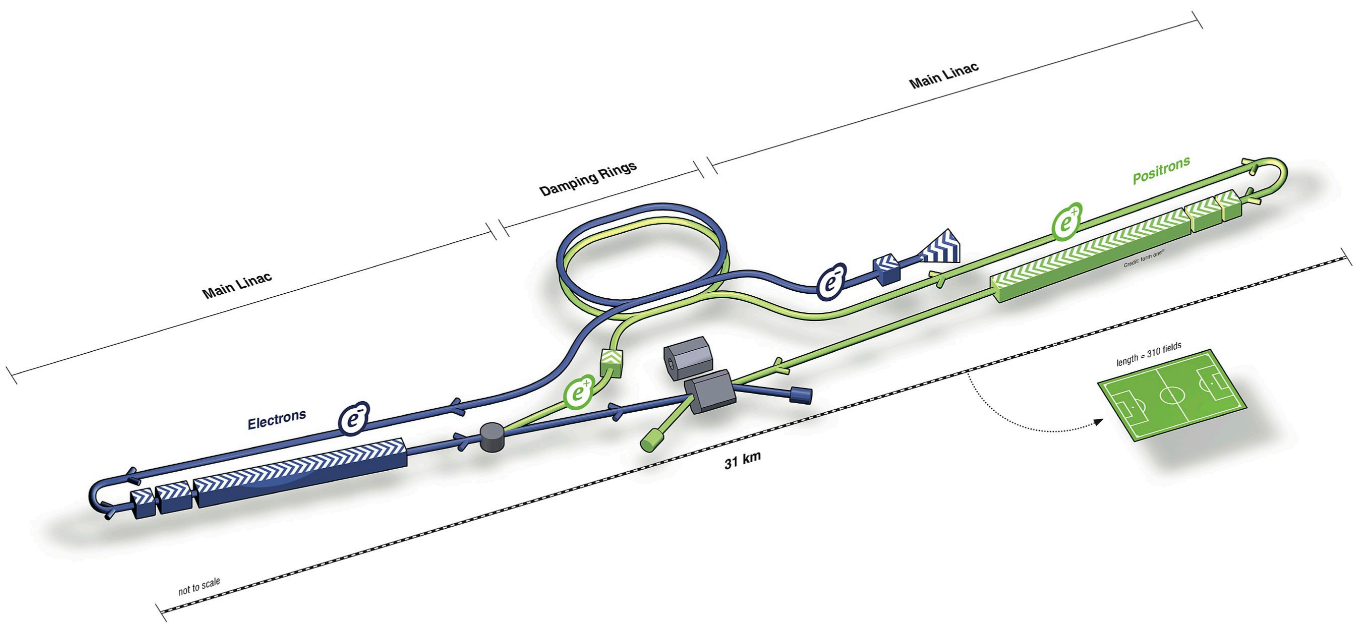
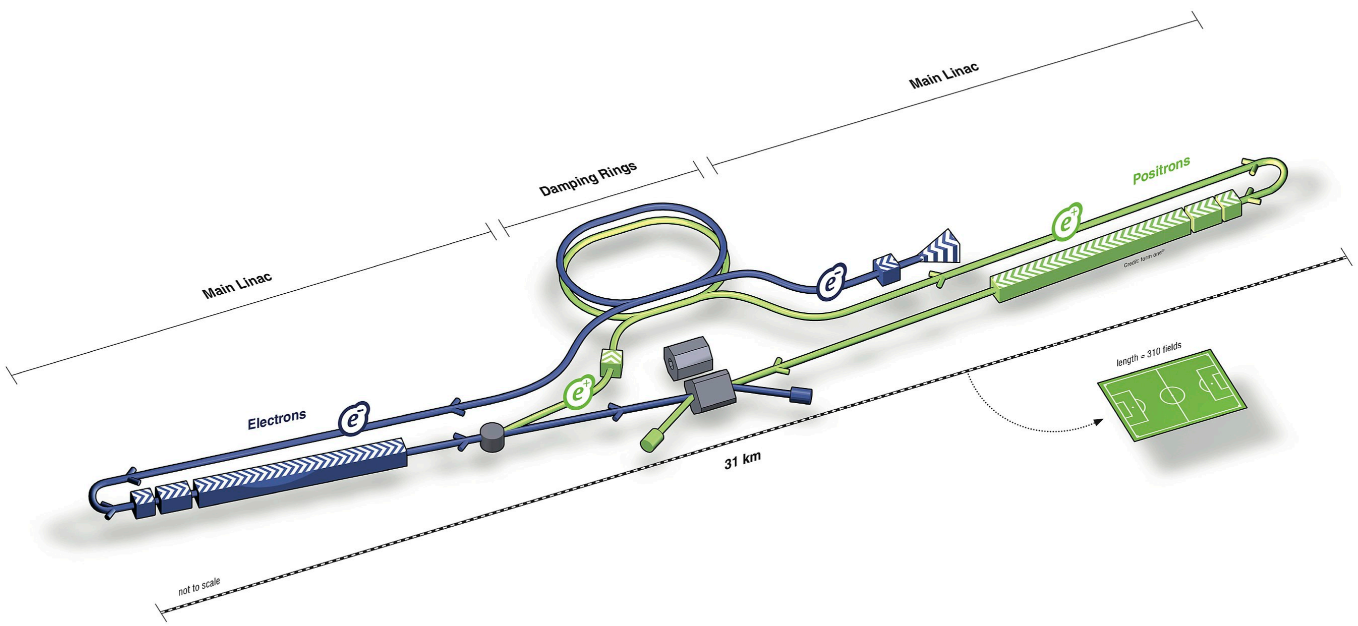


Why haven't we built the ILC?

A Radical (?) Vision



Why haven't we built the ILC?

Is it cost?

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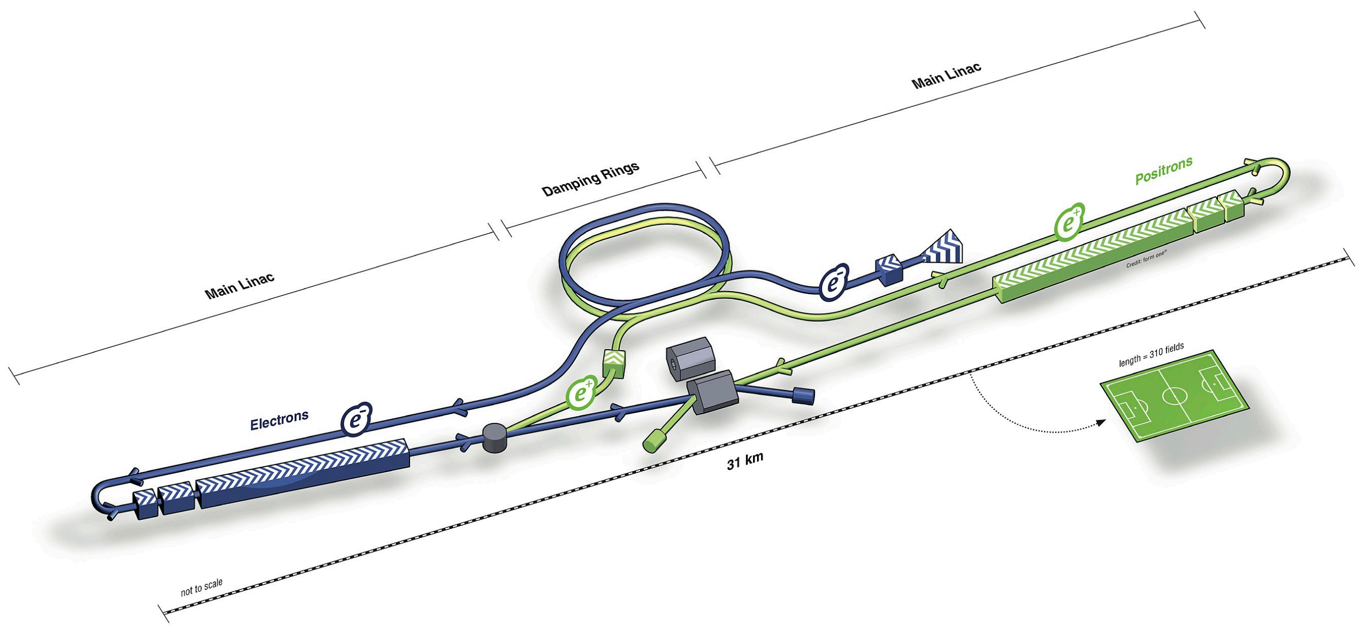

Why haven't we built the ILC?

Is it cost?

We have cheaper alternatives, but they all trade $$ for time

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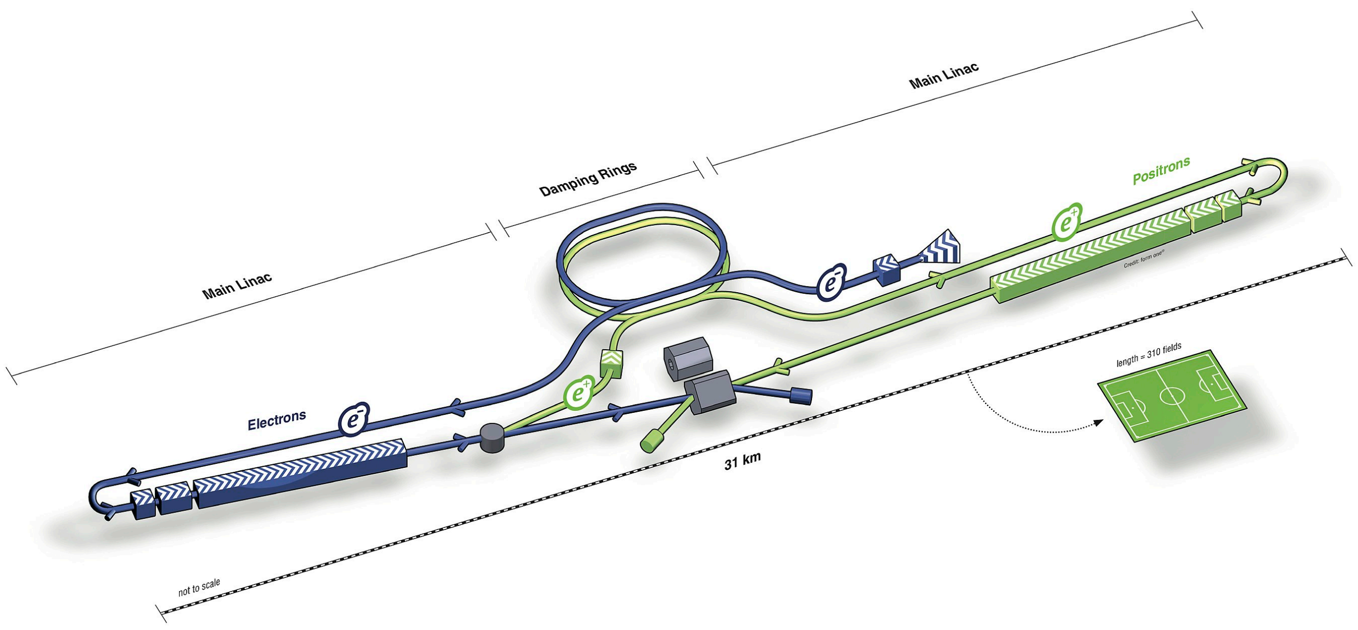

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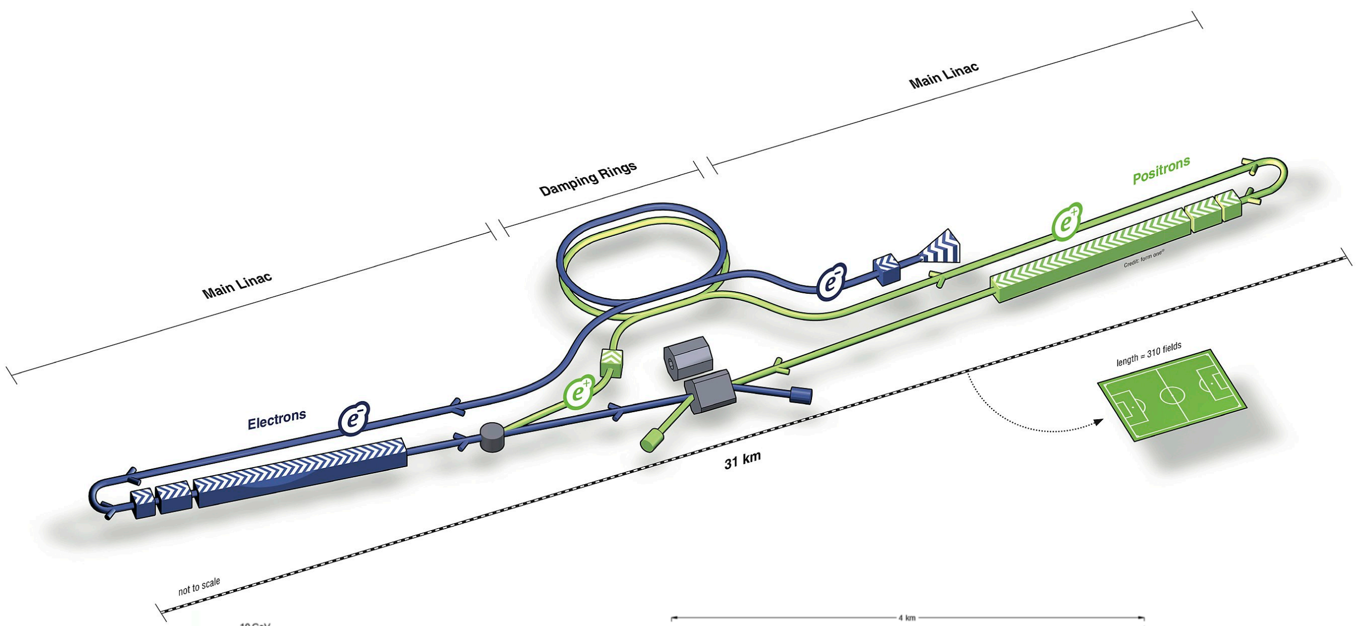

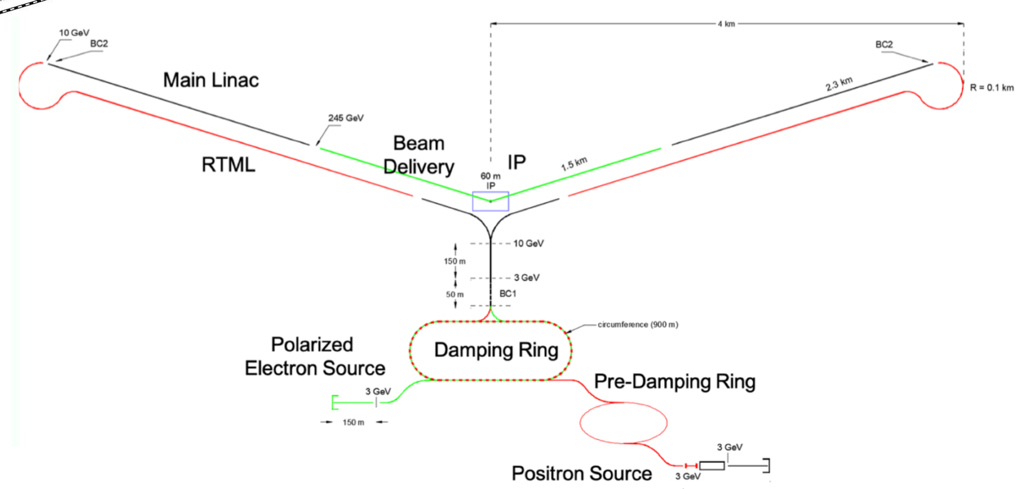

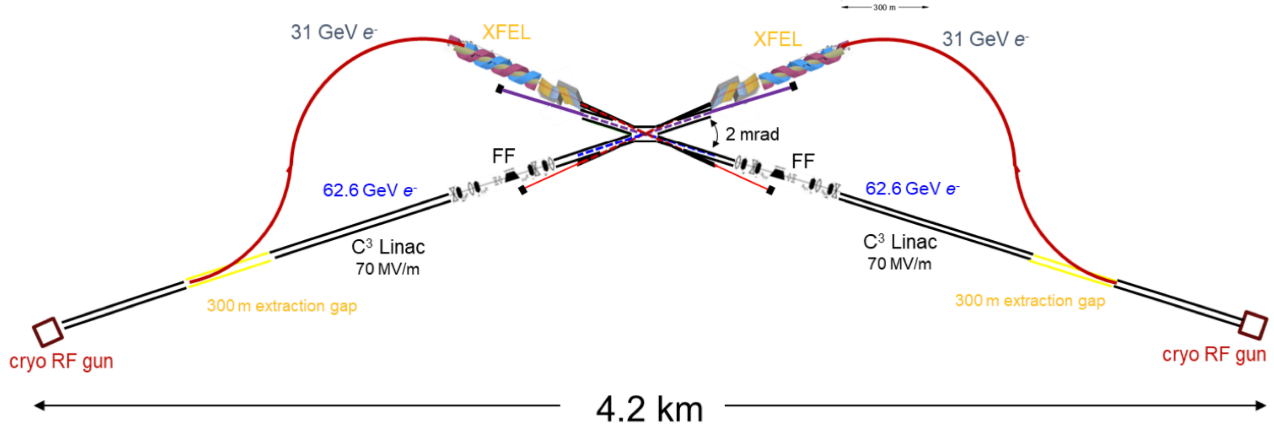

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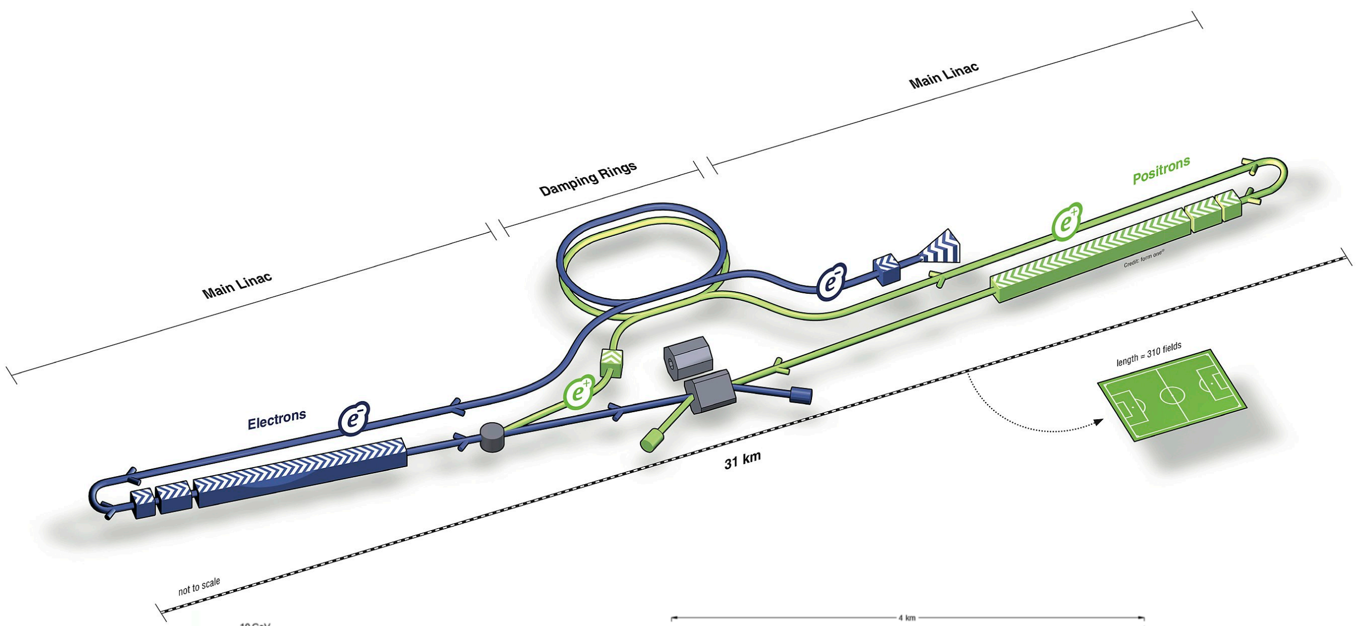

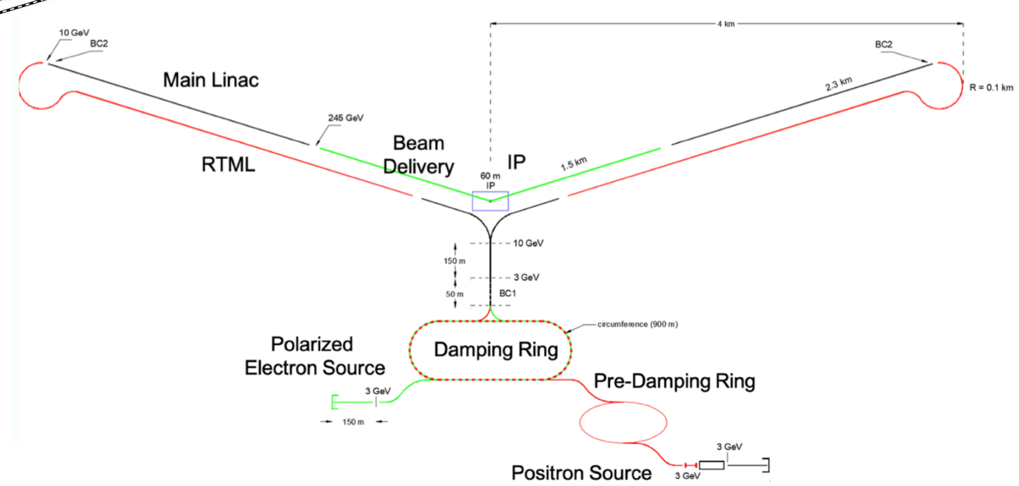

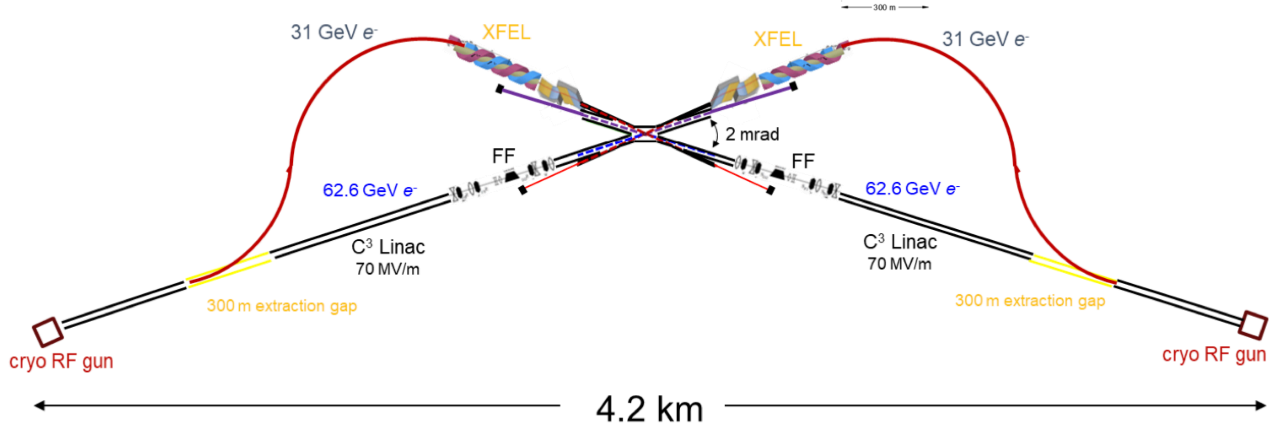

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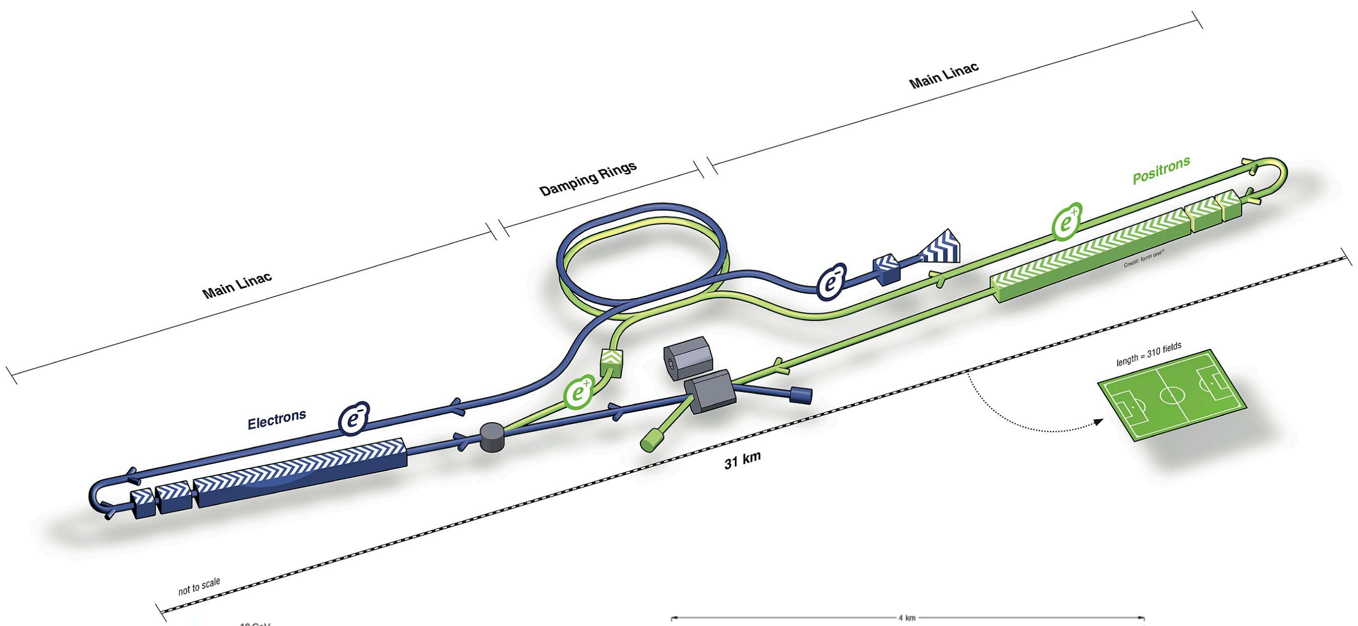

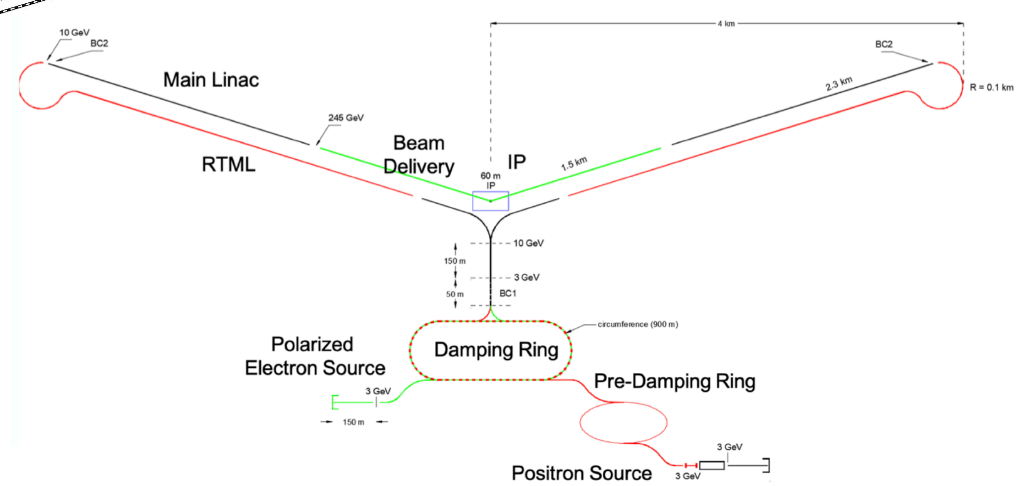

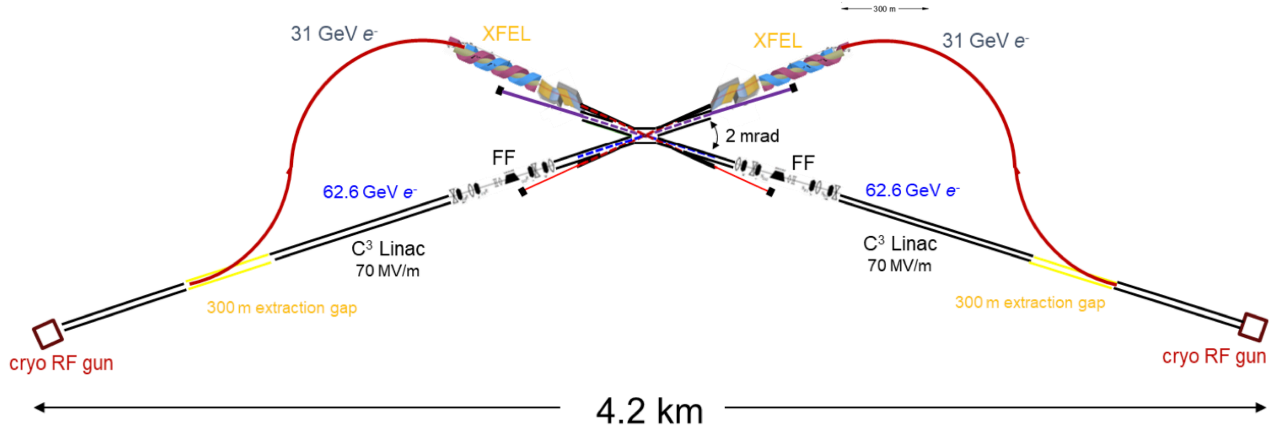

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C^3 and XCC provide affordable, staged paths to Higgs precision

Is it physics?

If the community doesn't want Higgs precision, skip to μC or FCC-hh right away?

My Personal Dream

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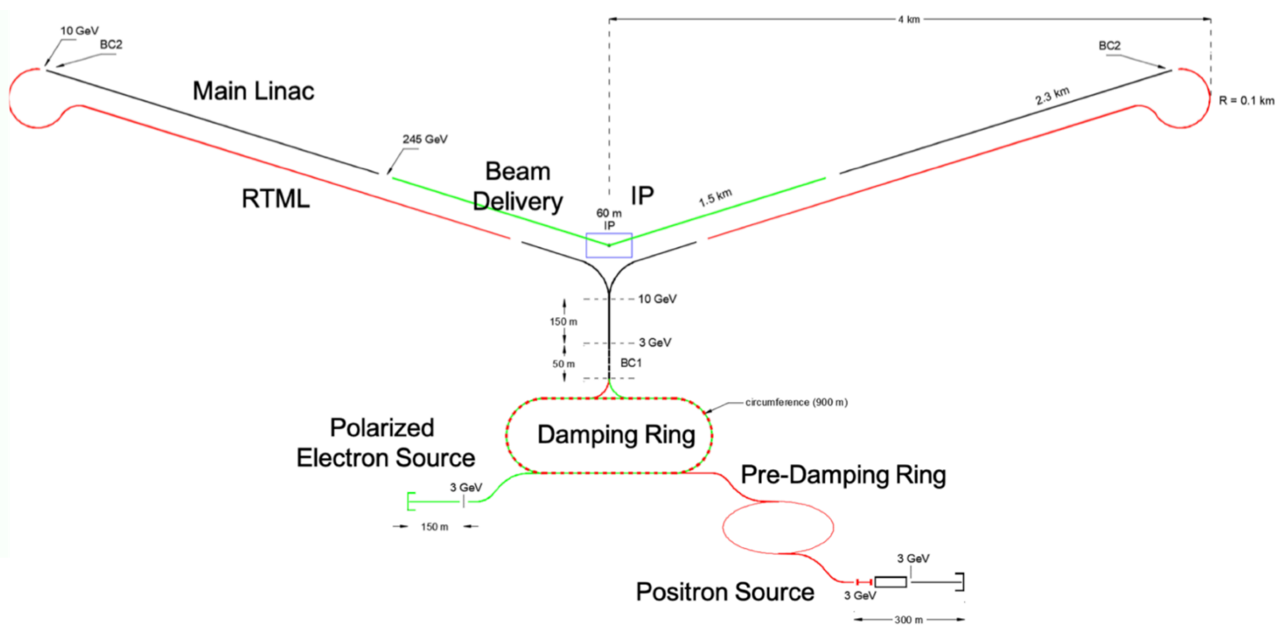

Make a linear collider for
a Higgs factory ***now***

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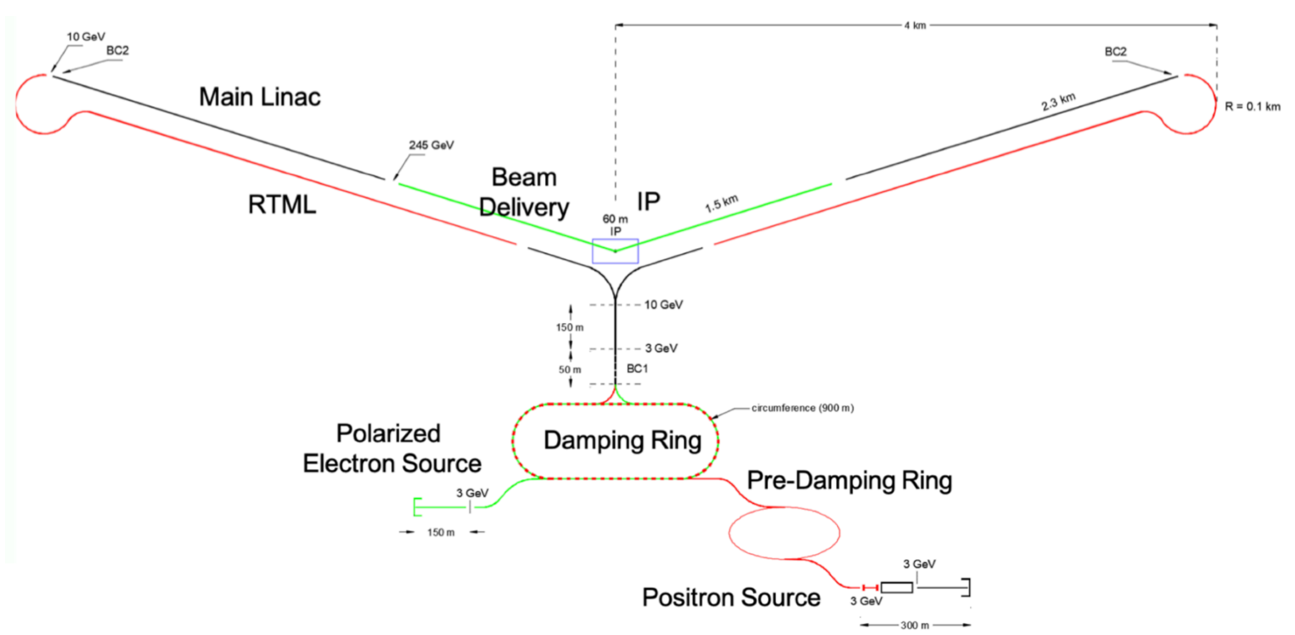

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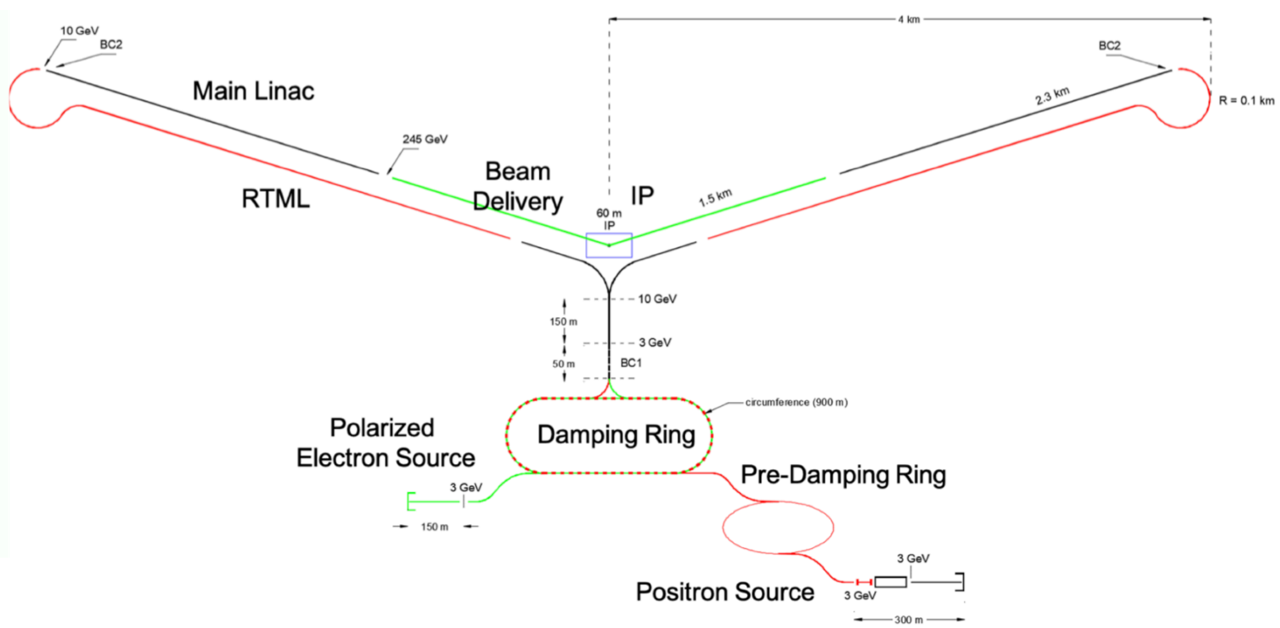

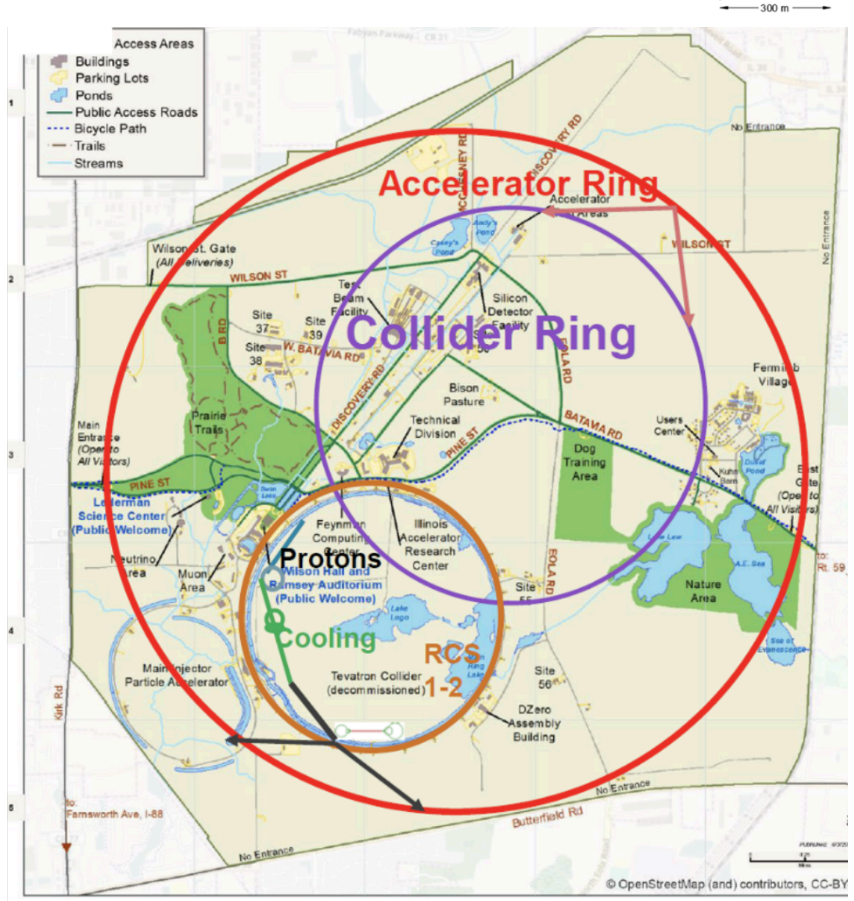

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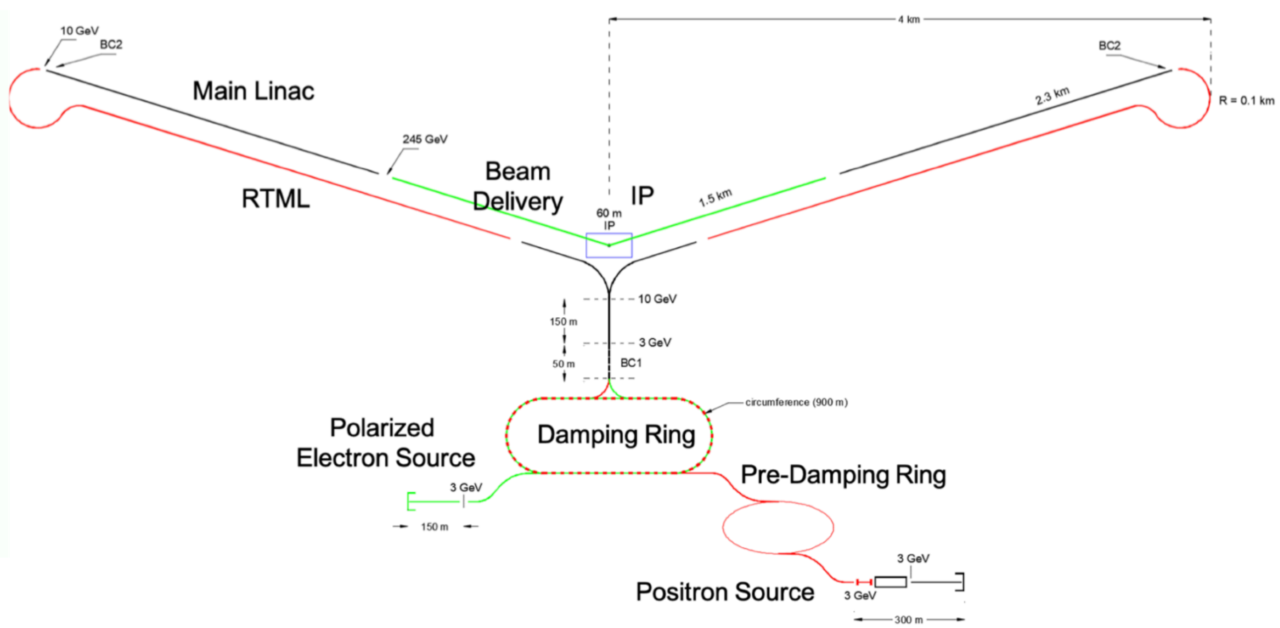

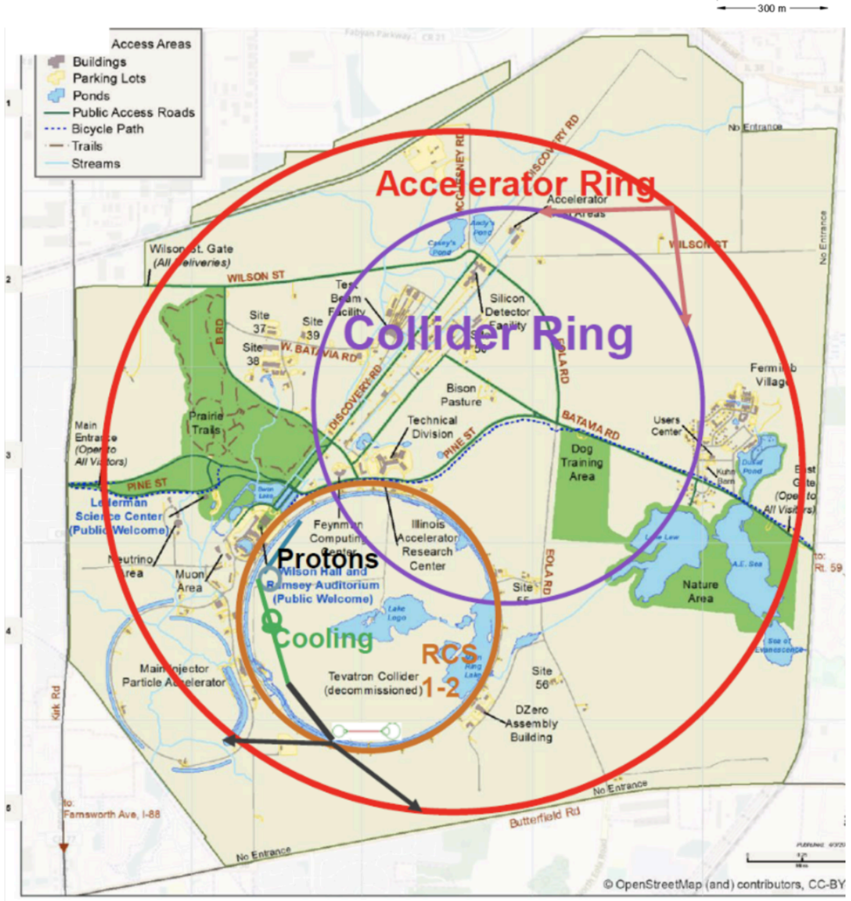

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Remember the costs: ~$30b for FCC-hh, ~$15b for a μC?

Backup

Physics at LC vs CC

arXiv:1801.02840

arXiv:1708.08912

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

Linear and circular have fairly similar reach