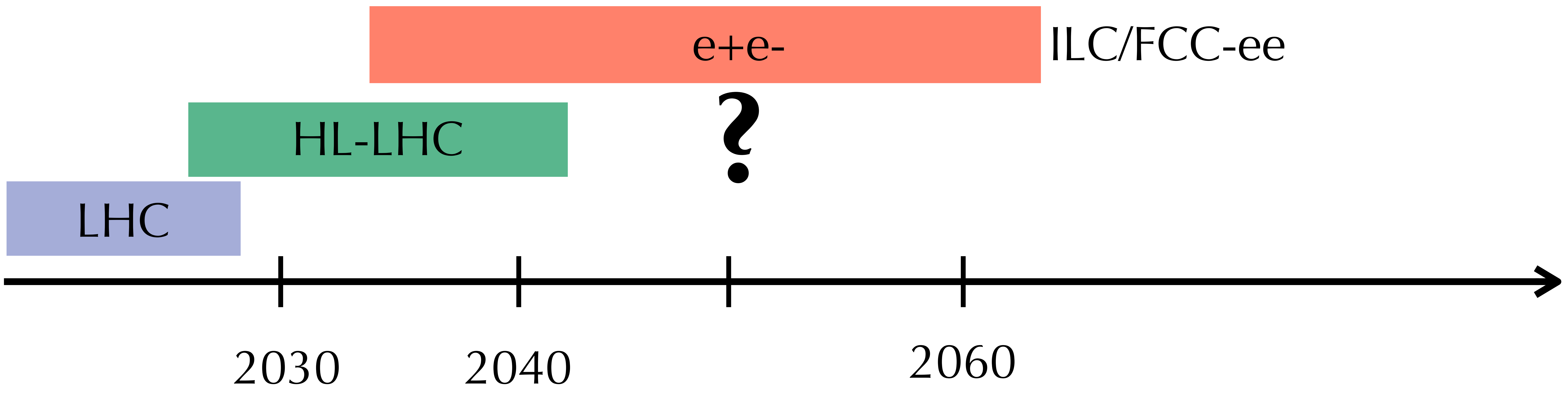
C^3 : Higgs by 2050

Emilio Nanni, Caterina Vernieri

July 15, 2021

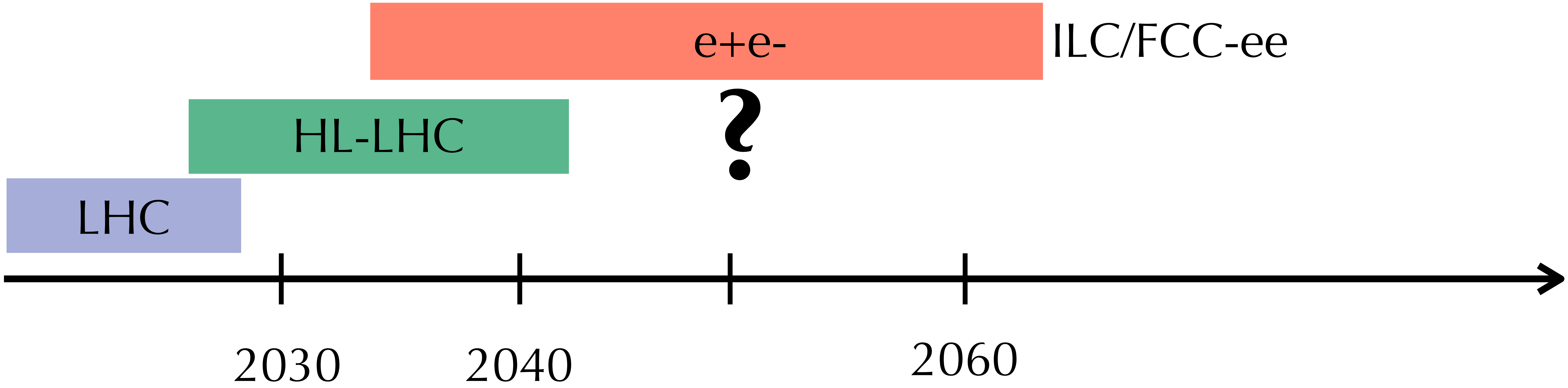
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY



In the study of the Higgs boson properties and in the quest of new physics signs there is a complementarity between hadronic/leptonic colliders (depending on the centre-of-mass of energy) to exploit

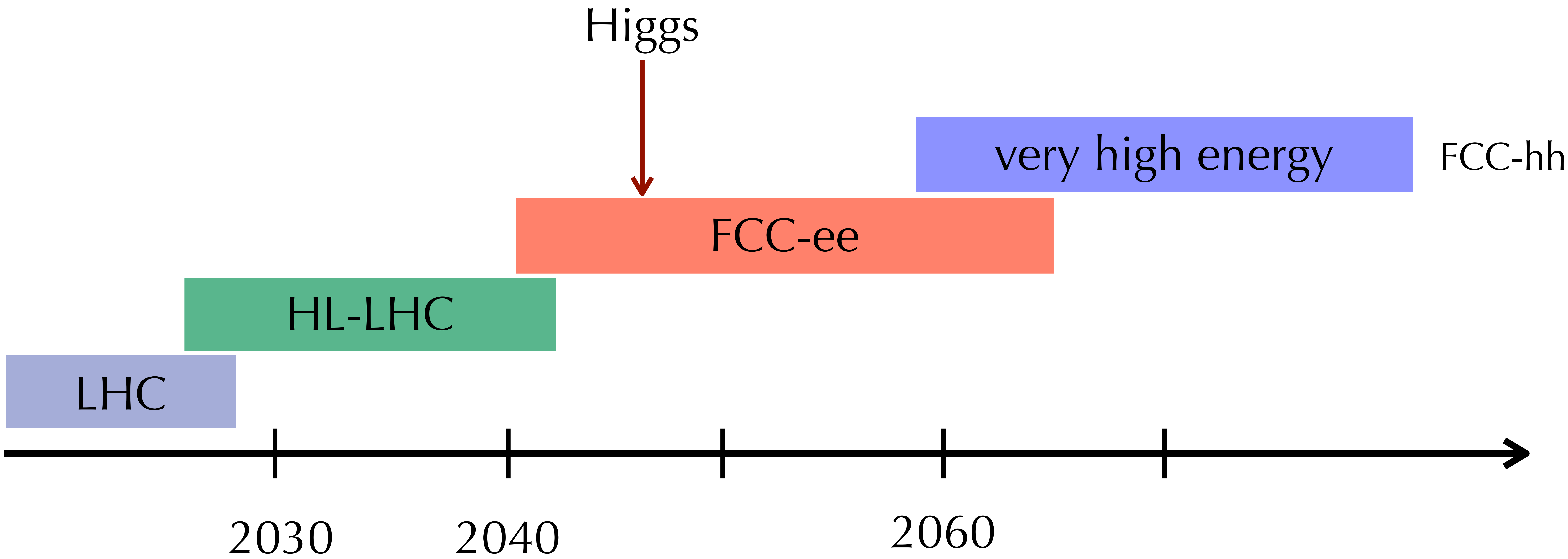
- Direct production of new - heavy ~ O(2 TeV) - particles
- If new particles are too heavy to be produced at the HL-LHC, the resulting modifications to the Higgs couplings could be sizable enough to be detected with precision Higgs coupling measurements.



Wish list beyond HL-LHC:

1. **Establish Yukawa couplings to light flavor —> needs precision**
2. **Establish self-coupling —> needs high energy**

FCC-ee scenario:



H couplings to few % **H couplings to %** **H couplings to ‰**
H self-coupling to %

20 years of FCC-ee

arXiv:2106.13885

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340-350	365	m_H
Lumi/IP (10^{34} cm^{-2}s^{-1})	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics Goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\rightarrow$ H	$10^6 t\bar{t}$ +200k HZ +50k WW $\rightarrow$ H		(6000)

- Multi-year program to test the SM at the Z and WW pole before the Higgs program
  - TeraZ to improve the statistical precision for EWPO observables
  - W mass determination with a precision of 0.5 MeV
  - tt run to improve the determination of the top-Yukawa coupling at FCC-hh (ratio of ttH and ttZ)
- Sensitivity to the self-coupling through ZH and WW→H cross section measurements at 240 and 365 GeV.
- Study the electron-Yukawa coupling with a dedicated run at the Higgs mass with beam energy spread of the order of the Higgs width (4.1 MeV)
  - This run requires to accurately measure the Higgs mass within MeVs
- Extension to 4IP is estimated to give a 1.7 increase in total luminosity

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  - t
- Sens
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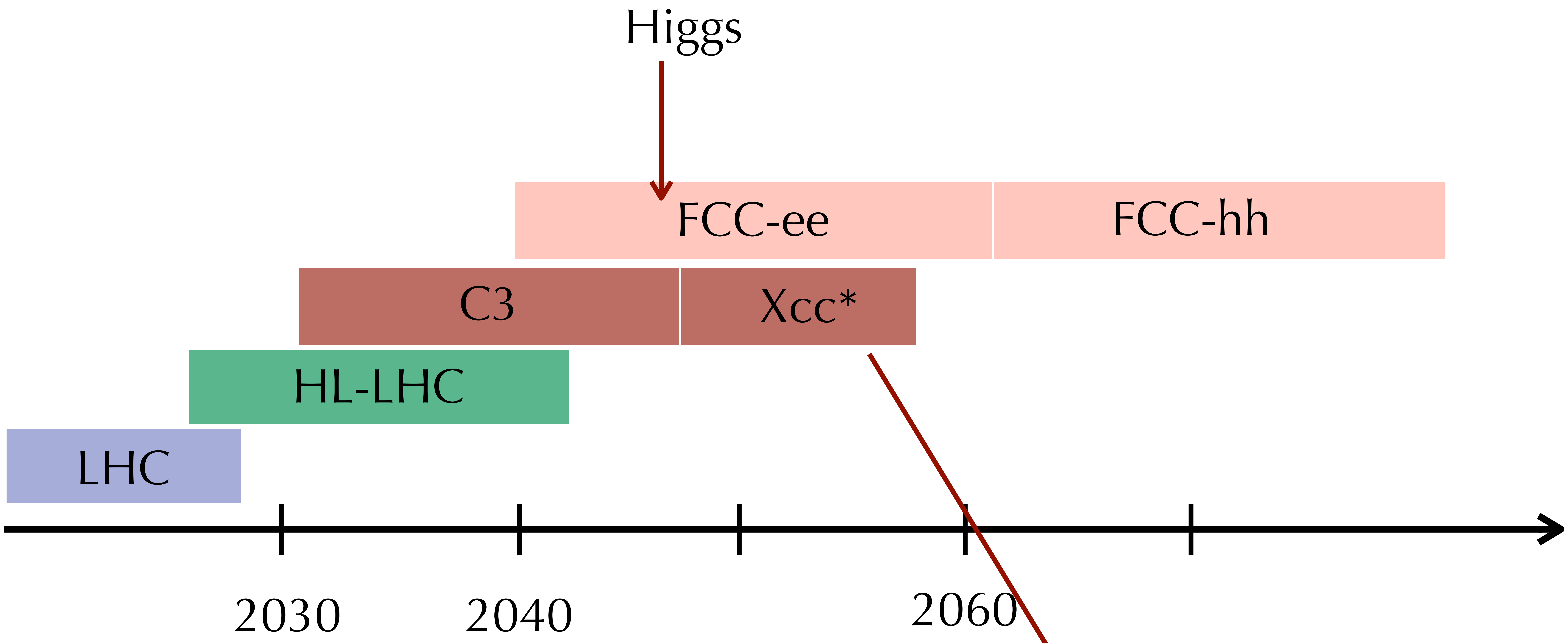
By the end of FCC-ee NO DIRECT access to Higgs top-Yukawa and self-coupling

2-steps C^3 alternative



H couplings to few %   **H couplings to %**   **H couplings to ‰**

H self-coupling to %

* Tim B.

One note on polarization

arXiv:1708.08912

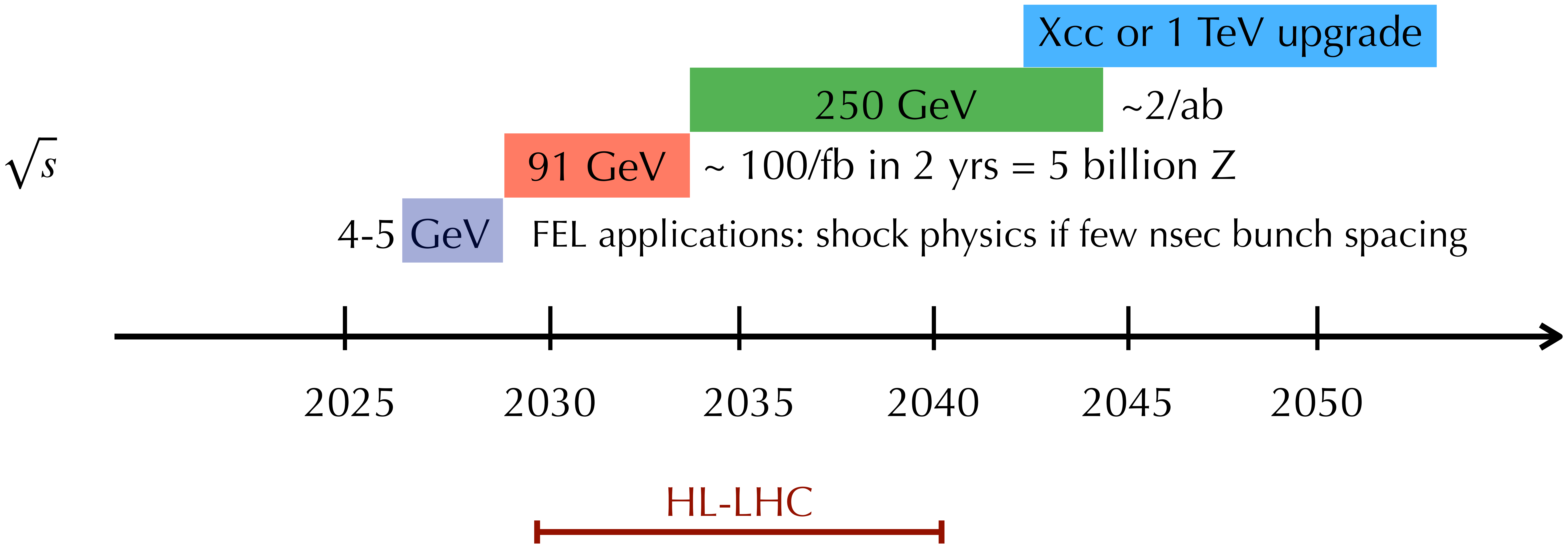
- There are extensive comparisons between the FCC-ee plan and the ILC runs that show they are rather compatible to study the Higgs Boson

- When analyzing Higgs couplings using EFT
  - The measurement of the polarization asymmetry in e+e→ ZH is a very important input to the SMEFT fit
  - 2 ab^{-1} of polarized running is essentially equivalent to 5 ab^{-1} of unpolarized running.

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

2-steps C^3 : best timeline for the physics

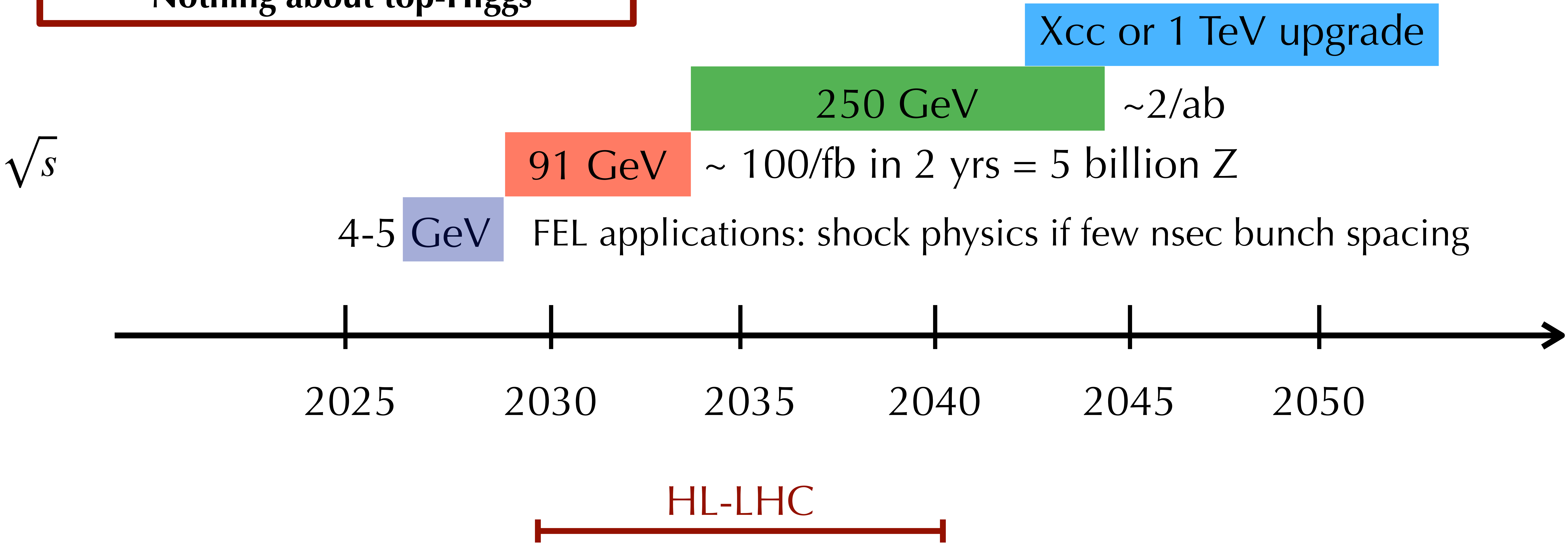
OPTION 1



2-steps C^3 : best timeline for the physics

OPTION 1

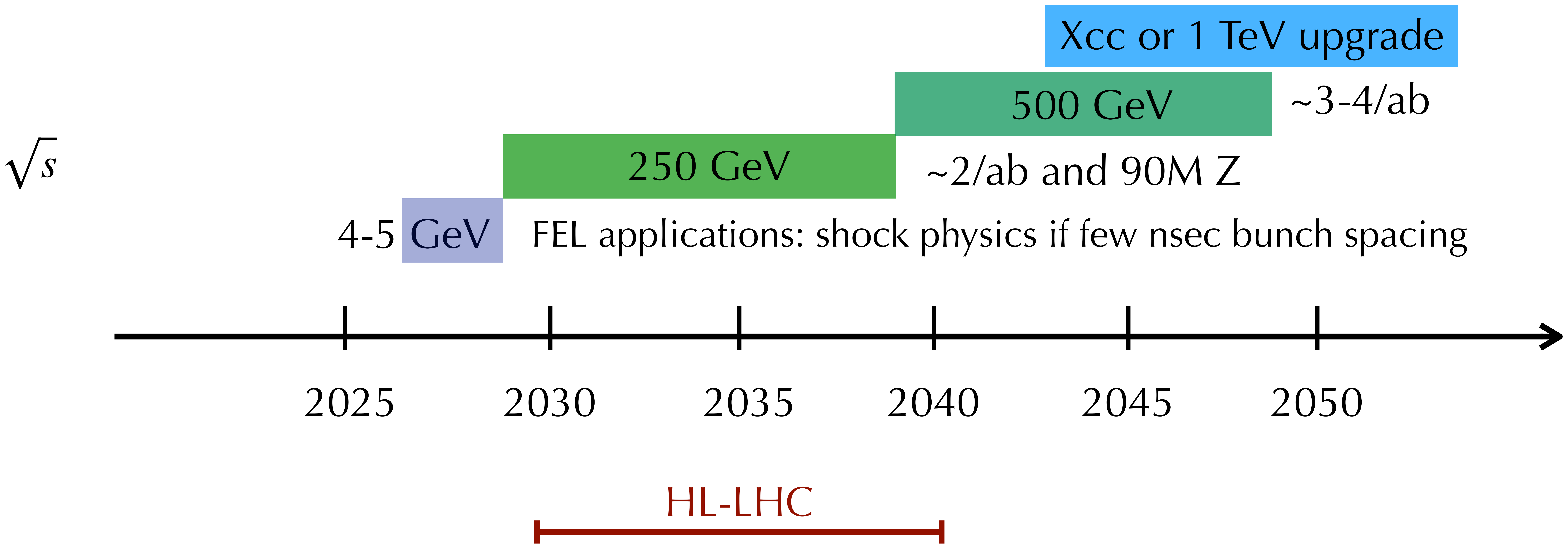
Xcc to test self-coupling
Nothing about top-Higgs



2-steps C^3 : best timeline for the physics

OPTION 2

* build for 290 GeV



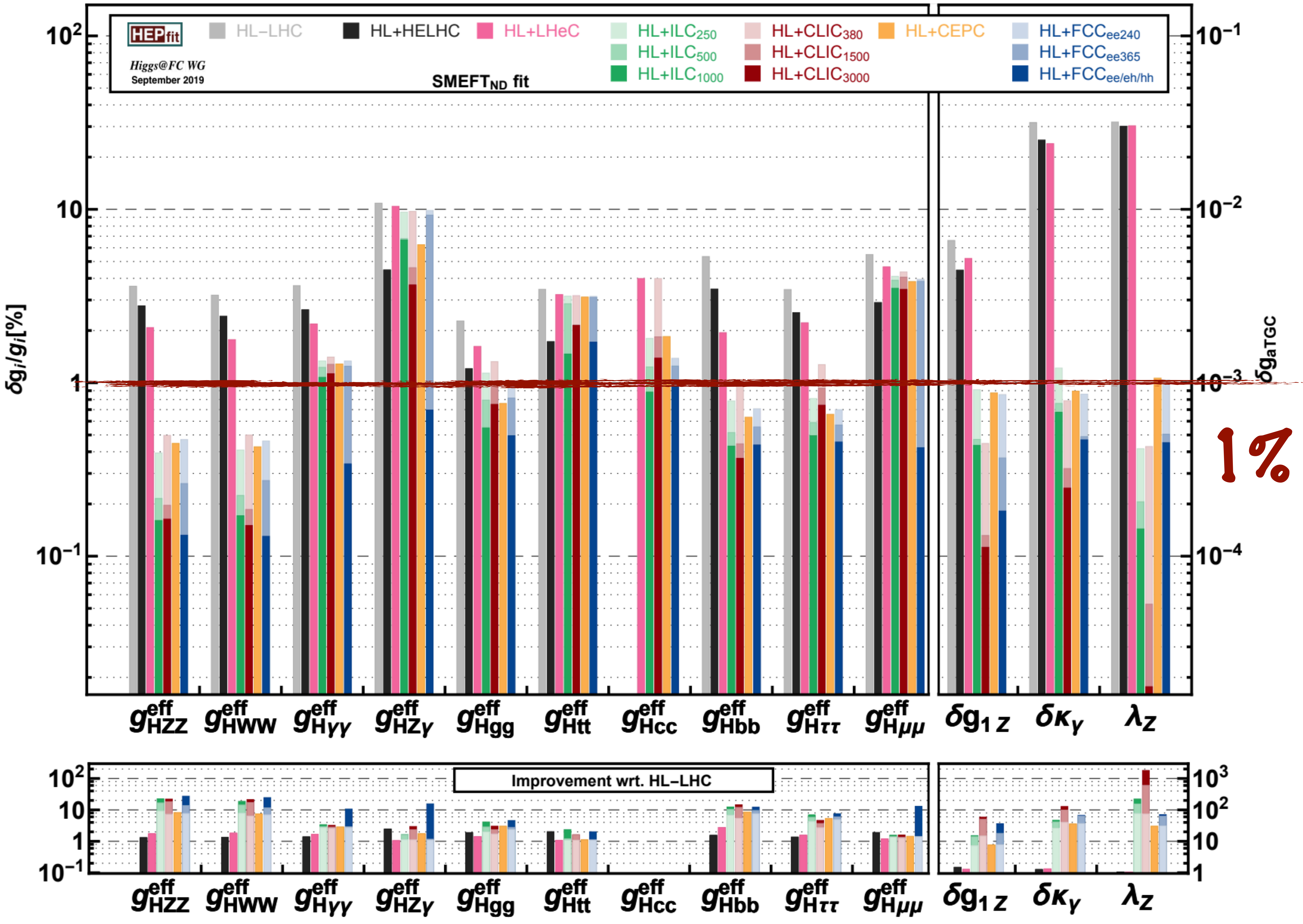
2-steps C³ : best timeline for the physics **OPTION 2**

Access to top-Higgs & HH already at 500 GeV

Higgs @C^3

arXiv:1910.11775,arXiv:1905.03764
arXiv:1908.11299

- The Giga-Z run would serve the purpose to improve an order of magnitude LEP/SLC EWPO measurements
- For the Higgs run C^3 2/ab at 250 GeV :
  - Physics reach should be equivalent to ILC/FCC-ee and complement HL-LHC program
  - **Measure coupling to tau-leptons and charm/bottom** quarks within an accuracy of ~1%
  - **Homework for Snowmass**:
    - evaluate the beam induced backgrounds at C^3 and compare with ILC.
    - Evaluate sensitivity to HH @ 250 GeV
- Run at 125 GeV to study the Higgs-electron coupling is limited by luminosity at C^3
  - **Homework for Snowmass**: evaluate possible ways to increase the luminosity to access that coupling



Higgs self-coupling @ TeV-C^3 or Xcc

arXiv:1910.00012
arXiv:2004.03505

SLAC

The goal for **future machines** beyond the HL-LHC should be to be able to reach at least **5-10%** precision for the Higgs boson self-coupling :

- C^3 **upgrade at high energy** (> 500 GeV) could access the the self-coupling through HH production and top-Higgs Yukawa
- Alternatively if Xcc is a viable opportunity, at $\sqrt{s_{\gamma\gamma}}$ =125 GeV could test the SM prediction for the self-coupling

collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
$CEPC_{240}$	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

Homework for Snowmass

Develop a plan where C^3 could be considered a viable alternatively to FCC-ee to exhaust our wish list for the Higgs sector:

1. ***Establish Yukawa couplings to light flavor***
   - Run at 250 GeV would allow us to access < 1% precision to b/c/tau
   - Electron coupling seems out of reach but to be further investigated the challenges of a high-lumi run at 125 GeV after the 250 GeV
2. **Establish self-coupling** —> TeV-C^3 or Xcc within the same accelerator complex
3. **Electron-yukawa coupling** —> very challenging with a linear complex

Evaluate the beam induced background at C^3 and compare with ILC and CLIC

- Derive correction factors for existing projected sensitivity at ILC 250 GeV and CLIC at 1 TeV for CCC

Roadmap to C^3

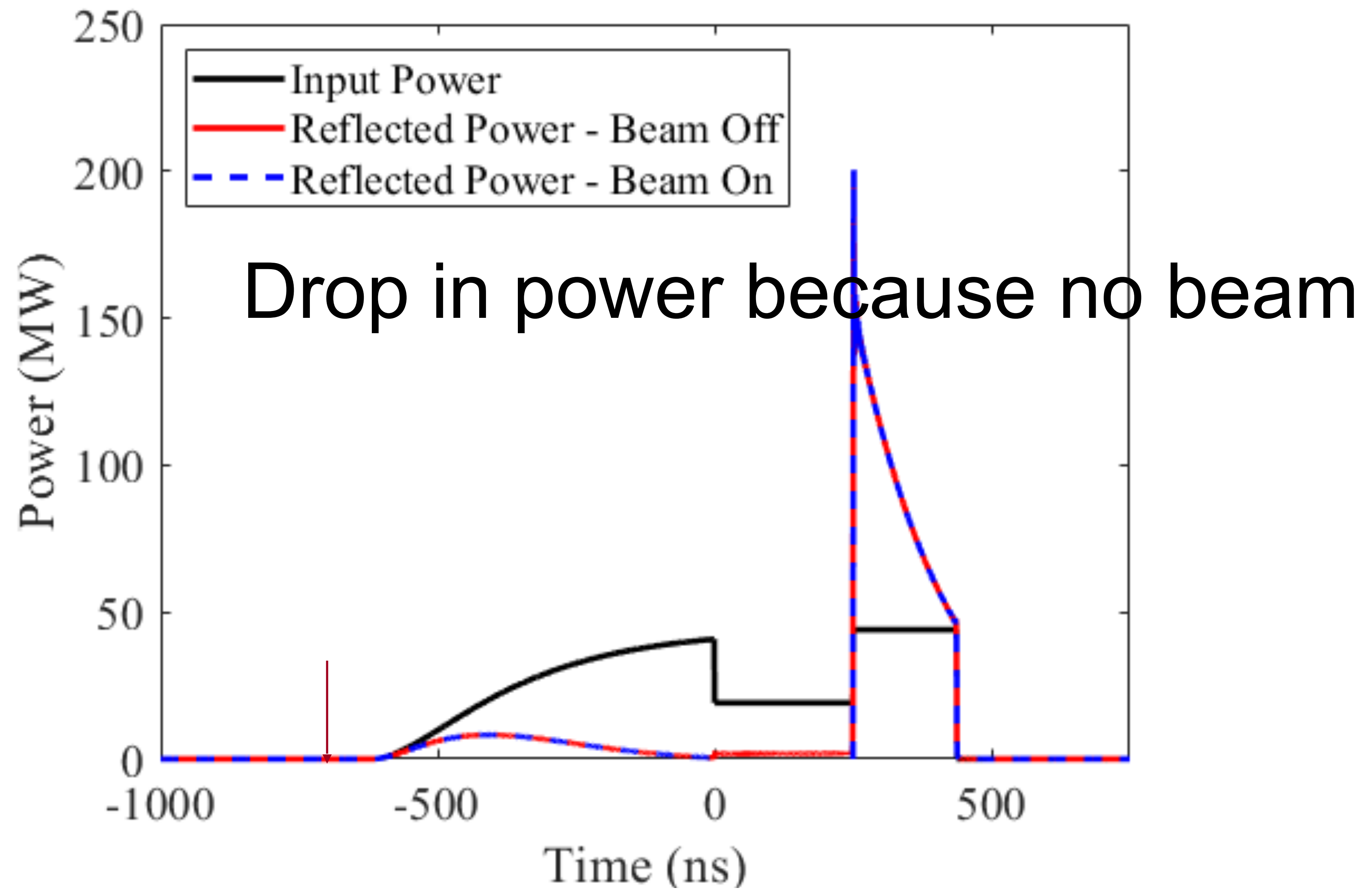
How to get C^3 underway as a project?

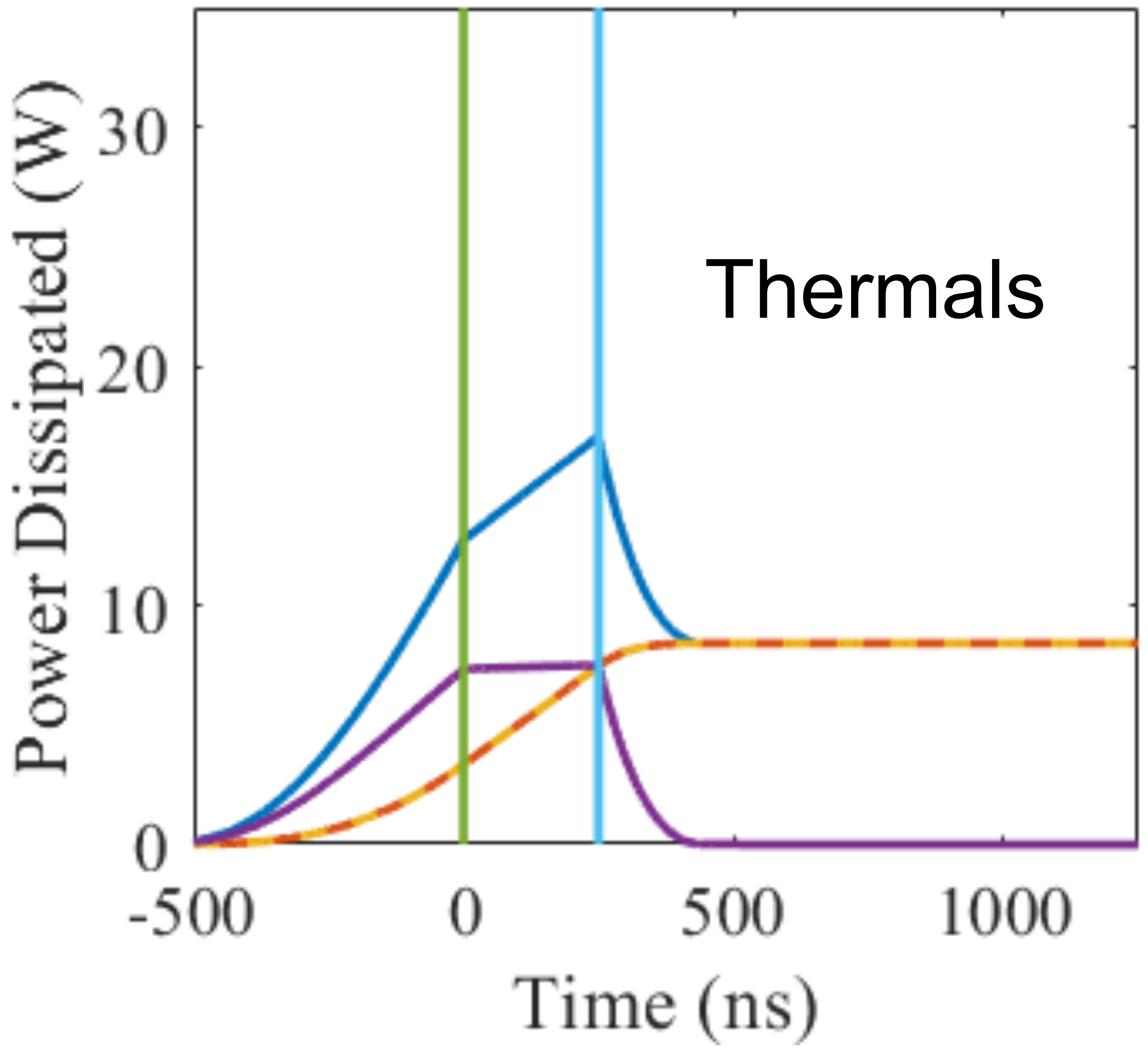
- Timeline that is compatible and competitive on global scale
- The accelerator is built to deliver the Higgs (min. 250 GeV)
  - The run at m_Z would be with lower power / lower gradient, allowing continued development of RF power sources.
- Delivery physics early and often – understanding that the #1 goals is to study the Higgs
- Build a foundation for upgrades – main linac is fixed length upgrade gradient later
- Ultimately a structure operating at 120 MeV/m would be used to reach high energy -> lower energy physics targets could be reached with 70-85 MeV/m
  - Reduced peak power (less $), lower risk (power margin, gradient margin, length margin)
- Utilize commercial options at 50 MW/m to launch program
  - R&D on rf sources would have huge cost reduction impact at higher energy
  - CLIC-k study places rf source cost at 10$/kW

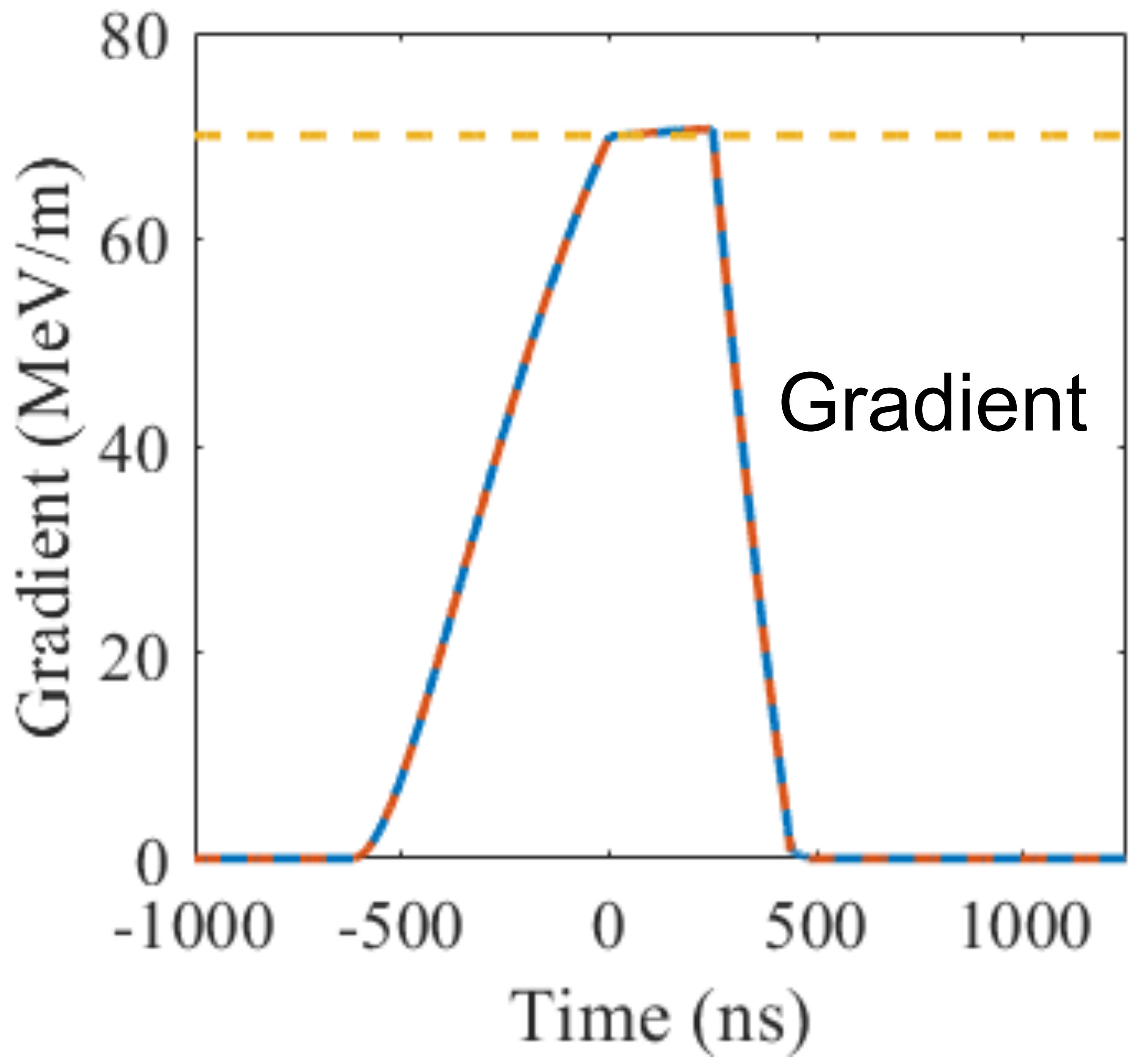
RF Power Requirements

- 70 MeV/m 250 ns Flattop (extendible to 500 ns)
- ~1 microsecond rf pulse, ~44 MW/m
  - Conservative 2.3X enhancement from cryo
- No pulse compression
- Ramp power to reduce reflected power
- Flip phase at output to reduce thermals

- One 50 MW klystron per meter







Comparison of Options

Built from the CLIC-k estimates (units are MCHF ~ M$ ~ ILCU)

pg 196	COM Energy (GeV)	380		250	250	**150**	**257.1429**	257.1429		292	501	130	260
1903.08655			Grad. (MeV/m)	120	85	**70**	**120**	120		70	120	60	120
							UPGRADE	UPGRADE					
		CLIC-K		CCC	CCC	**CCC**	**$10/KW**	$2/KW	CCC			CCC	
Domain	Sub-Domain	MCHF											
	Injectors	175		175	175	**175**			175			175	
Main Beam													
Production	Damping Rings	309		309	309	**309**			309			309	
	Beam Transport	409		409	409	**409**			409			409	
Drive Beam													
Production						**OPTION 1**				**OPTION 2**			
Main Linac Modules	Main Linac	895		208	294	**214**			417			217	
Main Linac													
RF	X-band Klystron	2788											
	C-band Klystron			2083	1471	**1071**	**1071**	214		2086	2086	542	1625
	Beam Delivery	52		52	52	**52**			52			52	
Beam Delivery	Final Focus	22		22	22	**22**			22			22	
	Post-Collision	47		47	47	**47**			47			47	
			Scale by main linac										
Civil	Civil Eng	1479	length	766	1081	**787**			1533			796	
	Electrical	243											
	Surevey Alignment	147											
Infrastructure Services	Cooling	410											
	Transport	36											
	Cryo-plant			208	147	**61**	**154**	154		118	299	61	155
	Safety	114		114	114	**114**			114			114	
Machine Control	Machine Control Inf	131		131	131	**131**			131			131	
	Machine Protec	8		8	8	**8**			8			8	
	Access Safety	23		23	23	**23**			23			23	
	Total Cost M	7288		4556	4283	**3424**	**1225**	368		5444	2385	2906	1780
	Length km	7		2.4	3.3	**2.4**	2.4	2.4		4.6	4.6	2.4	2.4

RF source R&D impact

0.5 klystrons /m

Note: 6X cost per meter vs ILC?

Note: Beam power scaled linearly from 2 TeV CoM, increase with longer flat top

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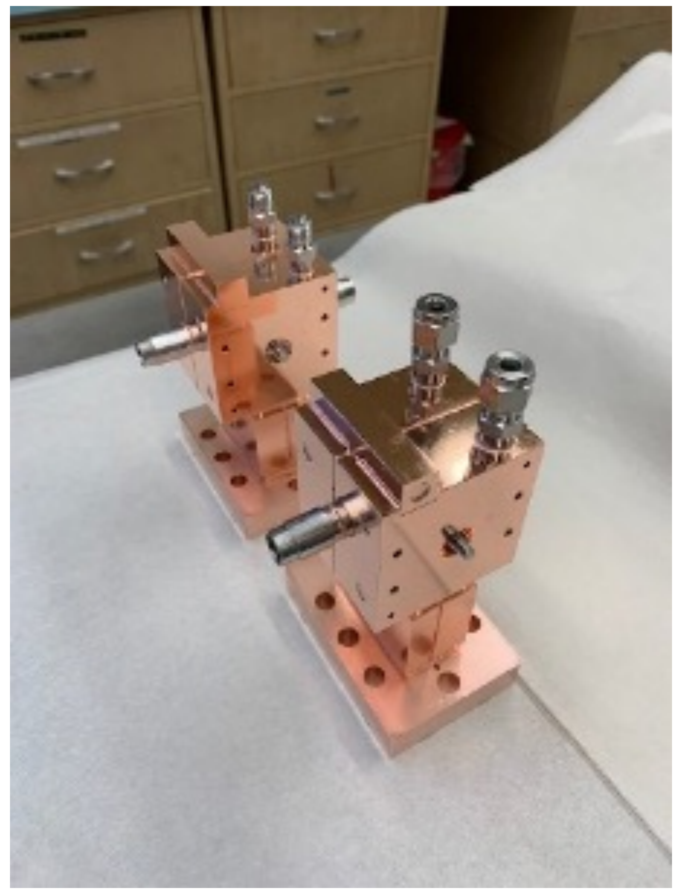
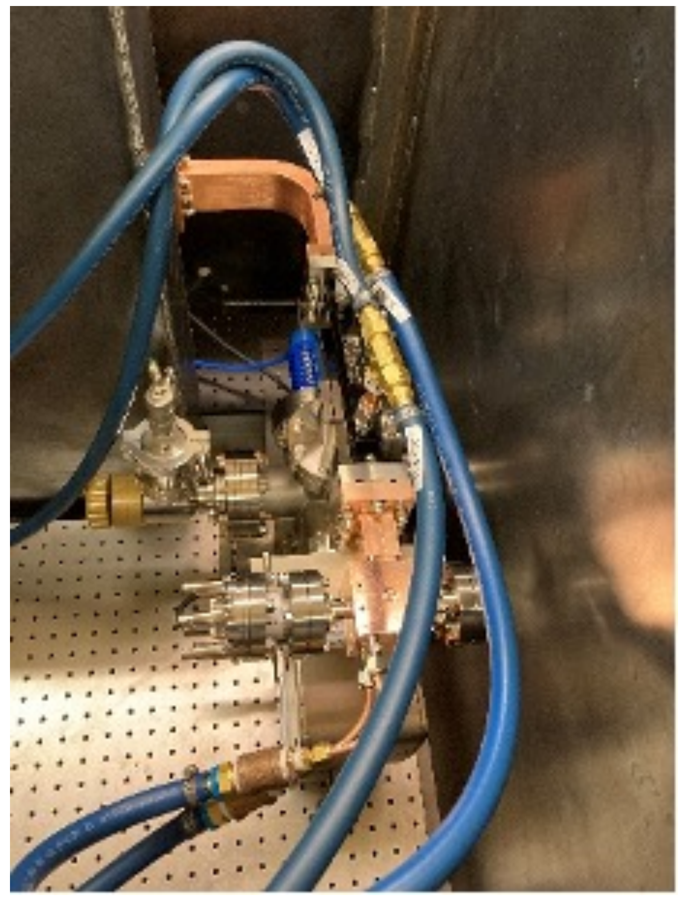
COM Energy		250	250	150	257	257	292	501	130	260
		120	85	70	120	120	70	120	60	120
		CCC	CCC	CCC	$10/KW	$2/KW	CCC		CCC	
				OPTION 1			OPTION 2			
Total Cost	M	4556	4283	3424	1225	368	5444	2385	2906	1780
Length	km	2.4	3.3	2.4	2.4	2.4	4.6	4.6	2.4	2.4

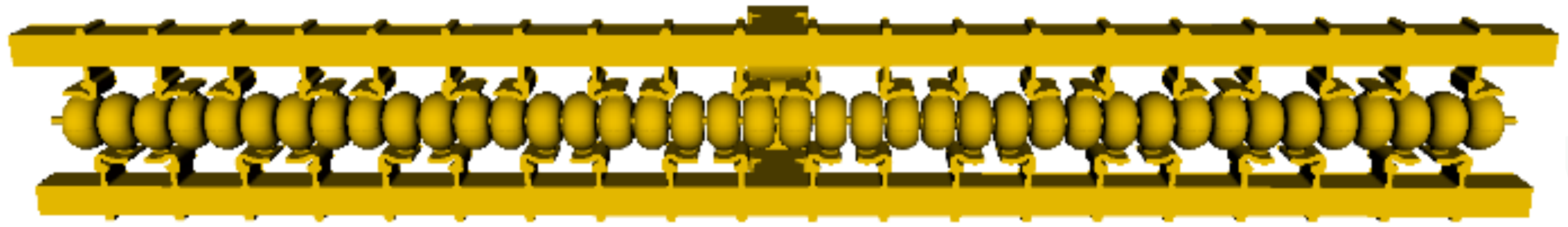
Development of C³ Technology is Ongoing

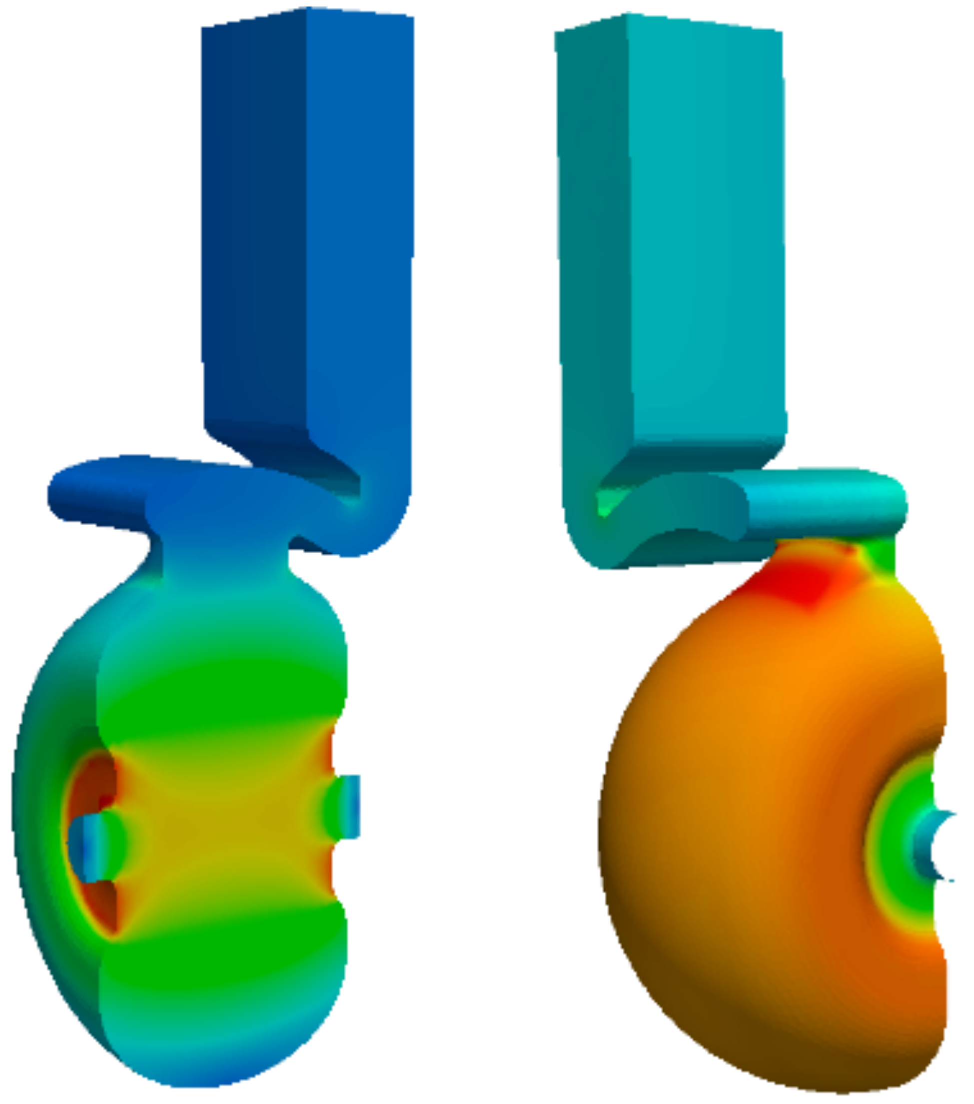
- Key focus - C³ is a practical technology
- Exploring 250 GeV to 2 TeV COM

PRELIMINARY:
LANL Test of single cell SLAC C-band structure

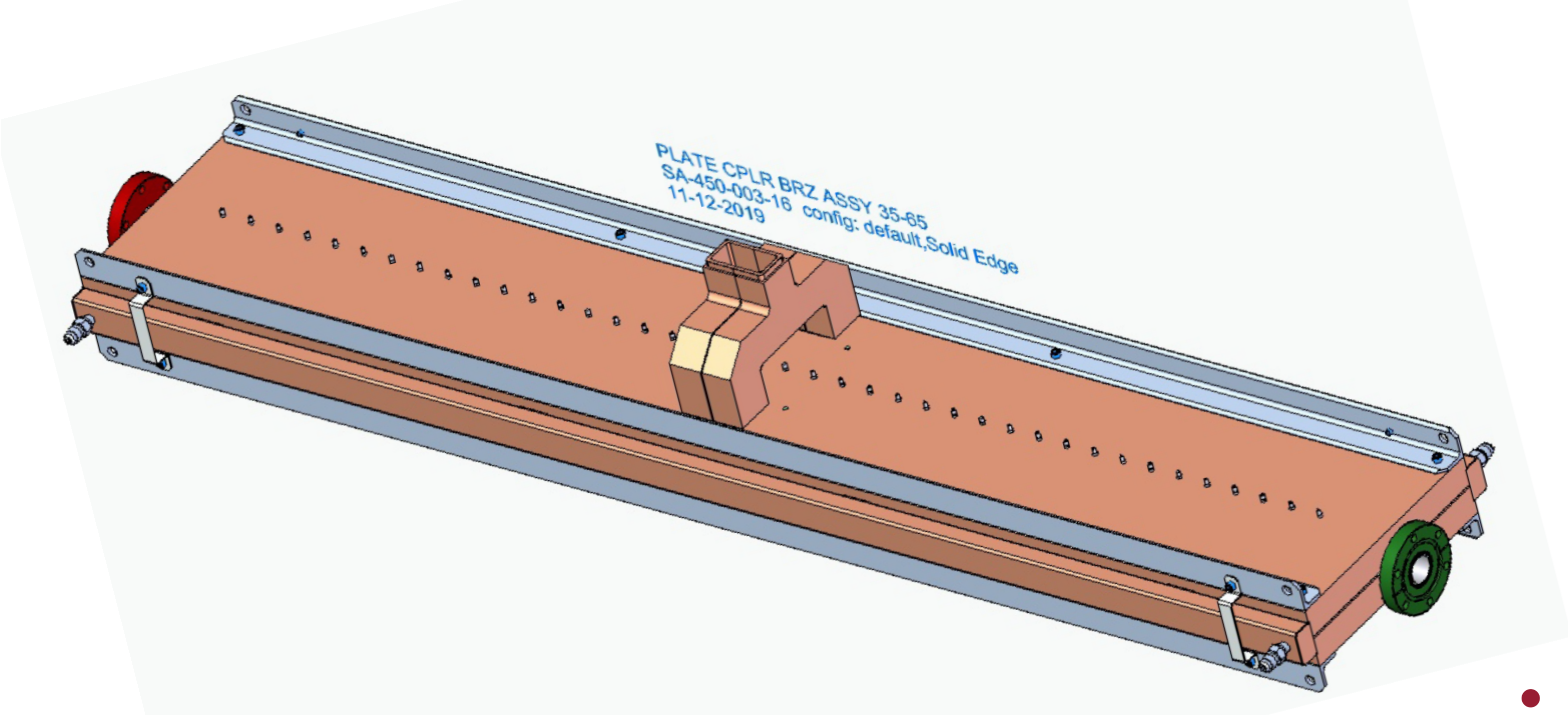
One meter (40-cell) C-band design with reduce peak E and H-field

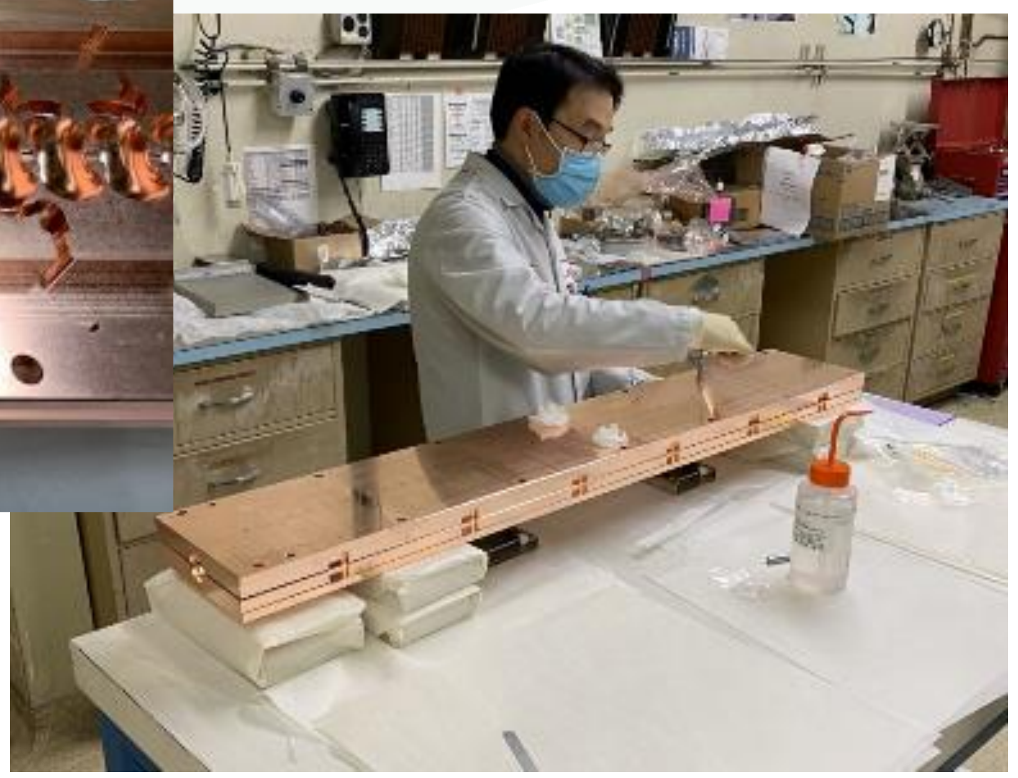




S. Tantawi, and Z. Li

Scaling fabrication techniques in length and including controlled gap





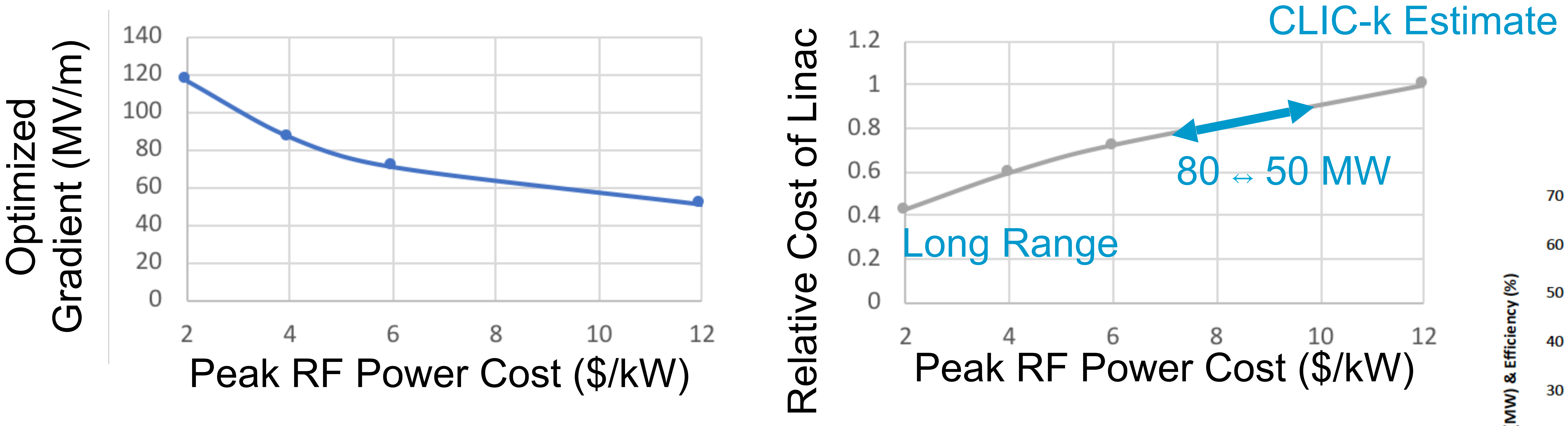
July, 25 2021

- First high gradient test at C-band
- Side coupled, split-cell reduced peak field, reduced phase adv.
- CCC relevant field strengths
- High power in up to 1 microsecond - stay tuned for confirmed numbers!

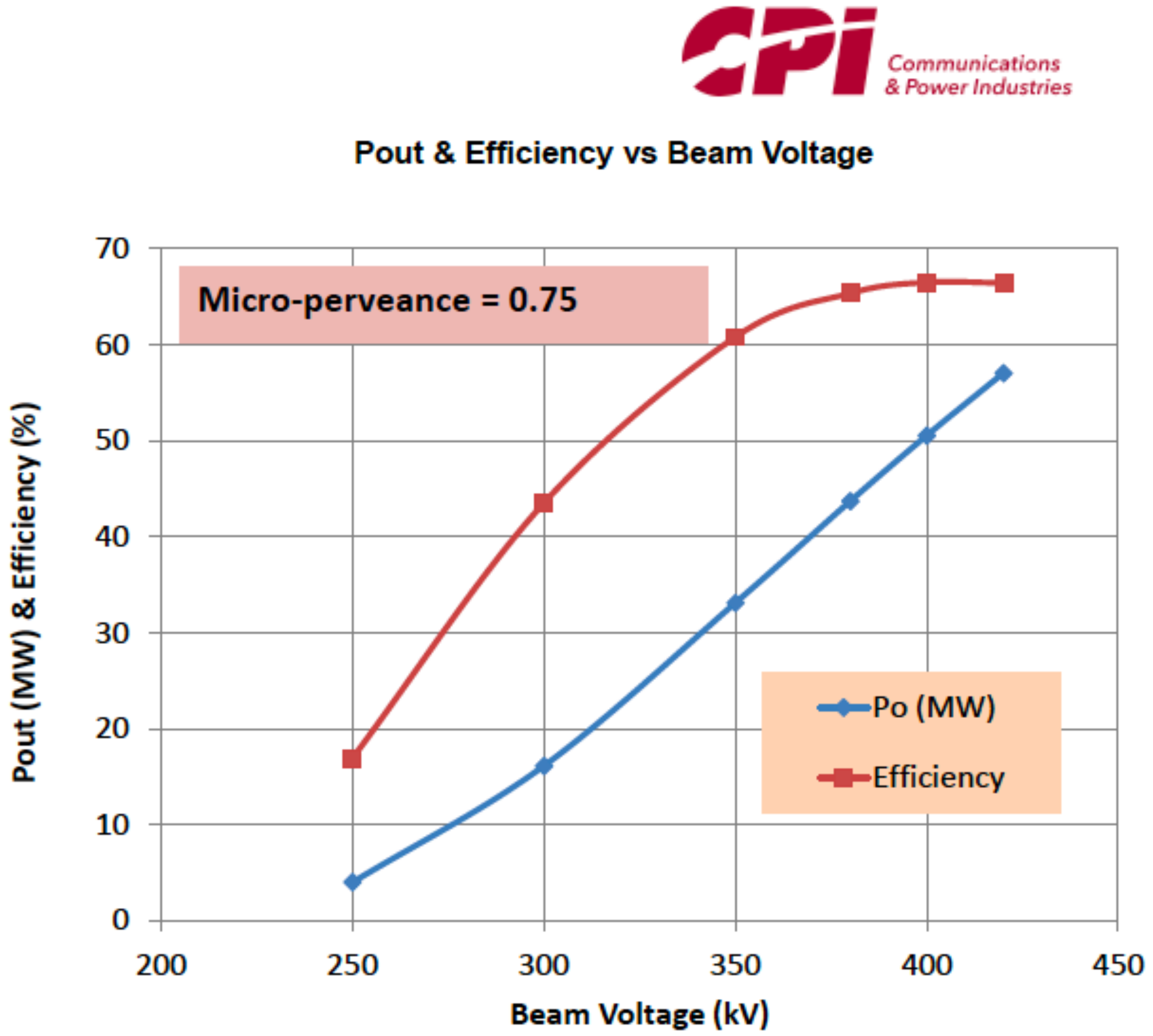
RF Source R&D Remains a Major Focus Over the Timescale of the Next P5

- Optimizing the cost of NCRF technology a fundamental requirement for its implementation for future facilities
- RF source cost is the key driver for gradient and cost – need to focus R&D on reducing source cost

Gradient/Cost Scaling vs RF Source Cost for 2 TeV CoM



Near Term Industry



Understand the Impact on Advanced Collider Concept Enabled by the Goals Defined in the DOE GARD RF Decadal Roadmap

https://science.energy.gov/~/media/hep/pdf/Reports/DOE_HEP_GARD_RF_Research_Roadmap_Report.pdf

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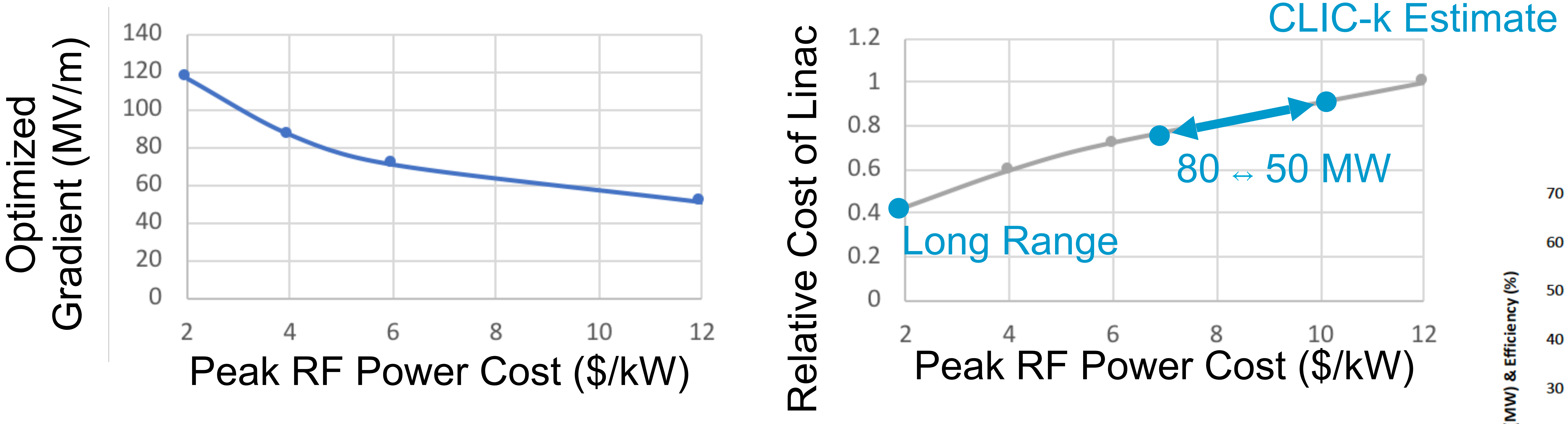

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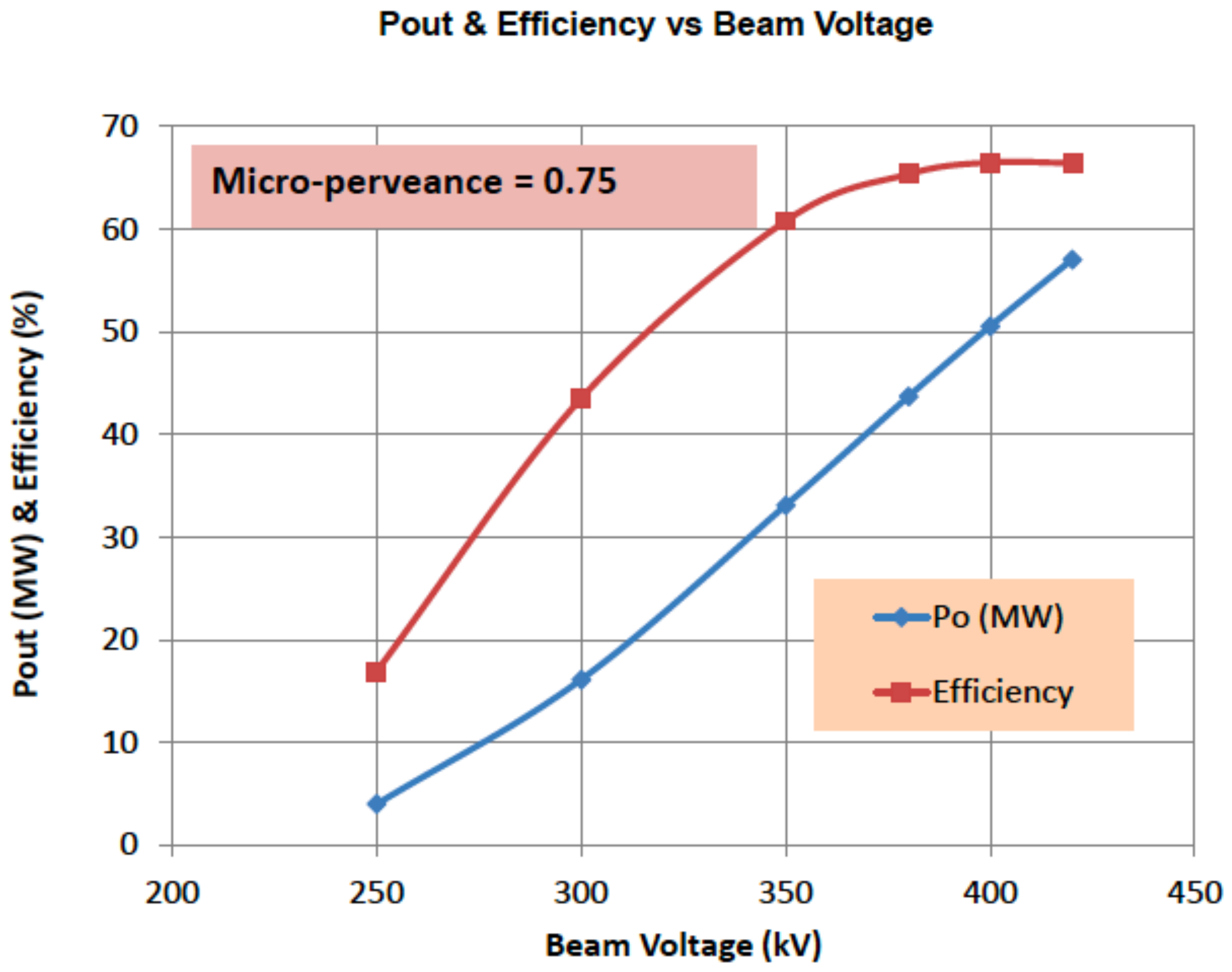

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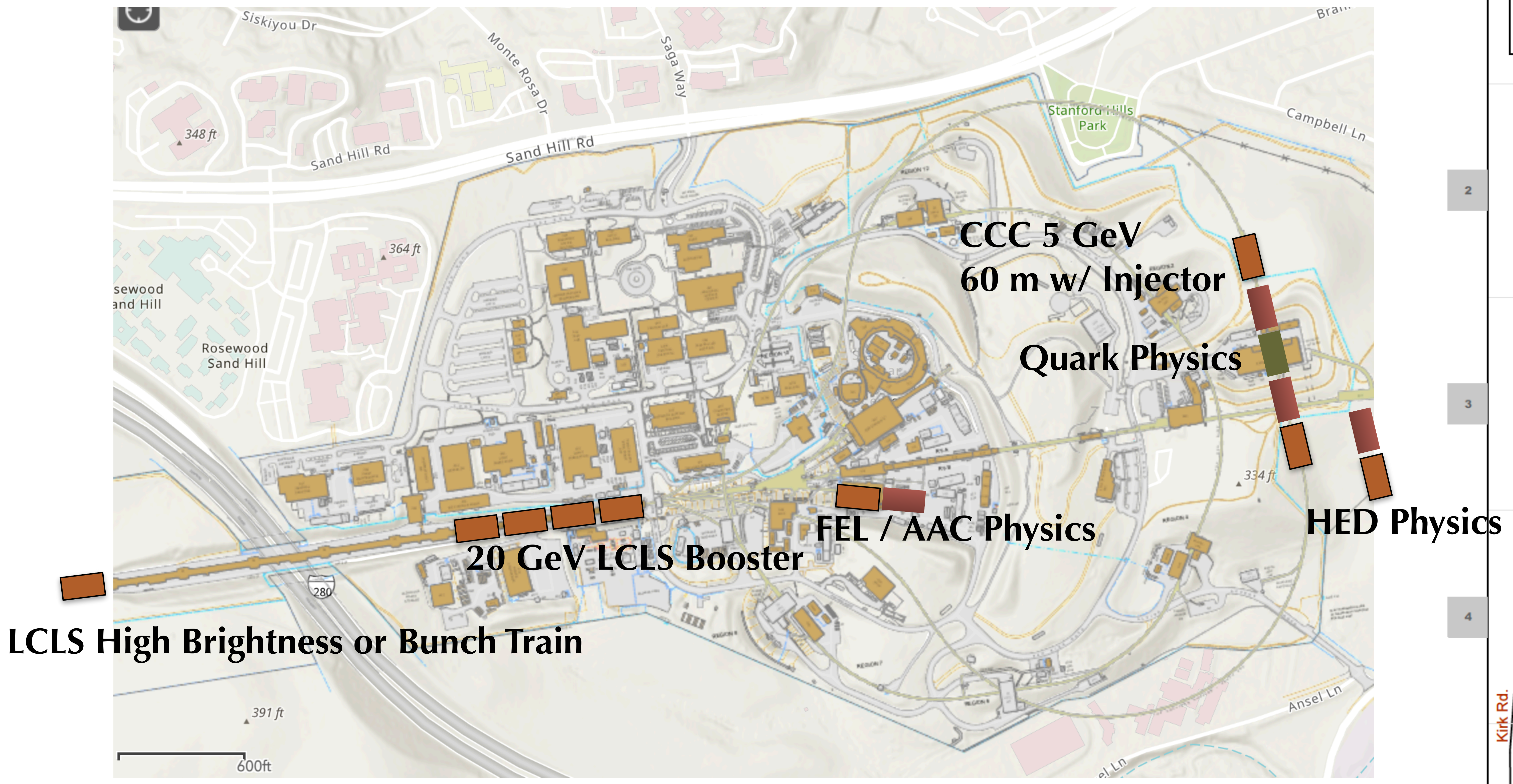
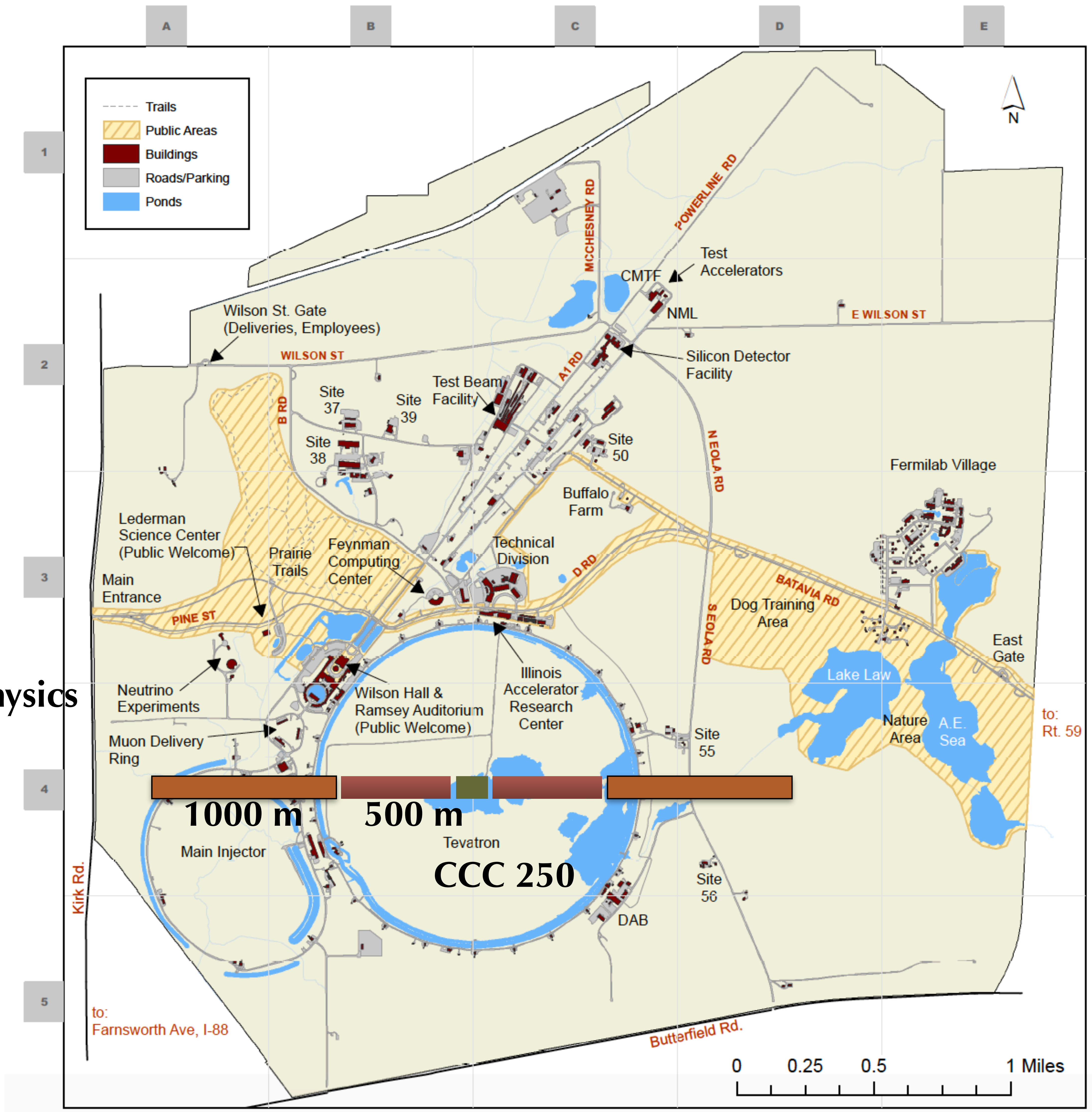
https://science.energy.gov/~/media/hep/pdf/Reports/DOE_HEP_GARD_RF_Research_Roadmap_Report.pdf

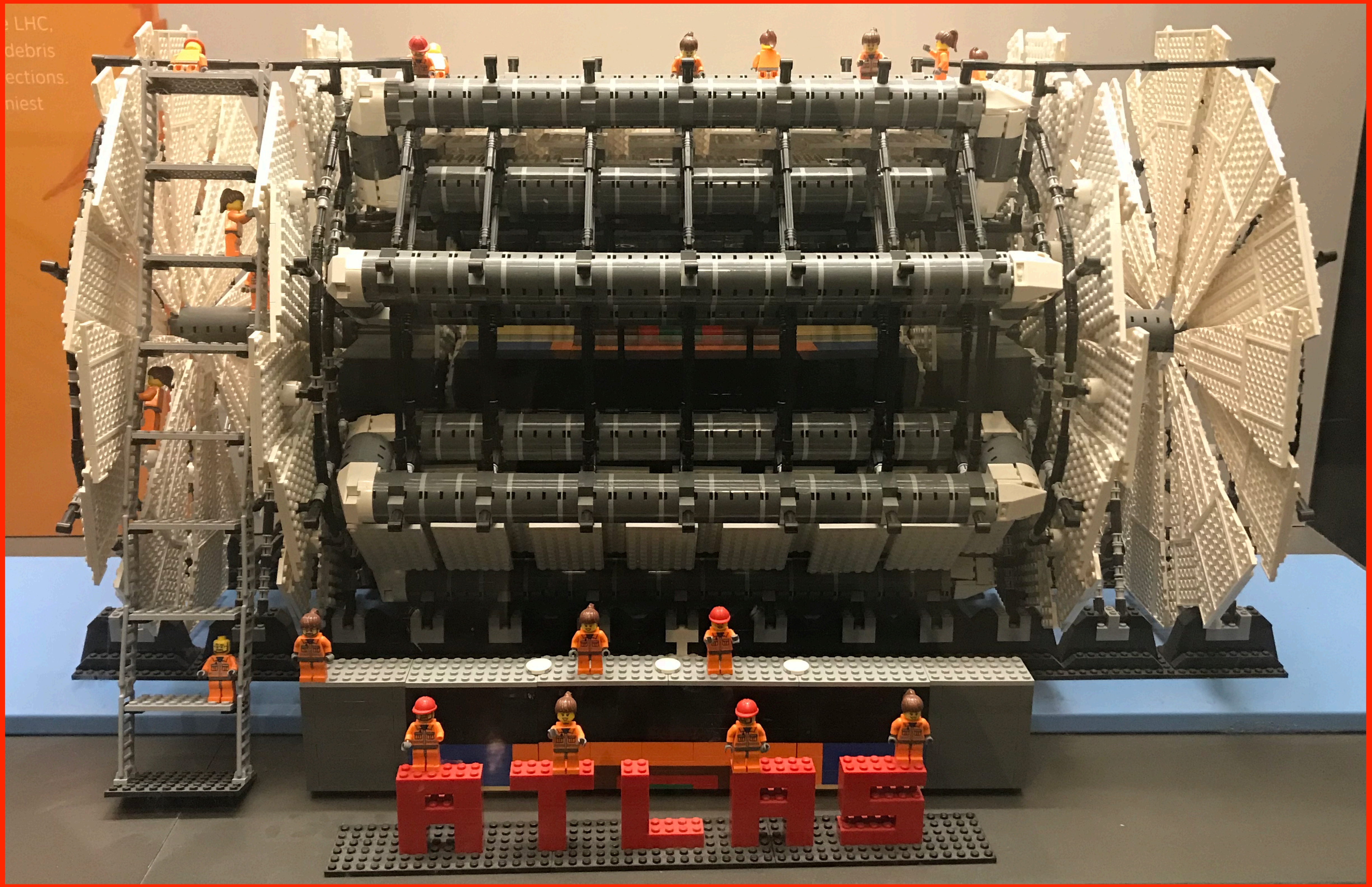
CCC to Scale



CCC 5 GeV
60 m w/ Injector
Quark Physics
HED Physics
FEL / AAC Physics
20 GeV LCLS Booster
LCLS High Brightness or Bunch Train
Sand Hill Rd
Stanford Hills Park
Campbell Ln
Siskiyou Dr
Saga Way
Ansel Ln
600ft



Trails
Public Areas
Buildings
Roads/Parking
Ponds
N
Wilson St. Gate (Deliveries, Employees)
WILSON ST
Test Accelerators
CMTF
NML
E WILSON ST
Silicon Detector Facility
Test Beam Facility
Site 37
Site 39
Site 38
Site 50
Fermilab Village
Buffalo Farm
Lederman Science Center (Public Welcome)
Main Entrance
PINE ST
Prairie Trails
Feynman Computing Center
Technical Division
Dog Training Area
BATAVIA RD
East Gate
Lake Law
Nature Area
A.E. Sea
to: Rt. 59
Neutrino Experiments
Wilson Hall & Ramsey Auditorium (Public Welcome)
Illinois Accelerator Research Center
Muon Delivery Ring
Site 55
1000 m
500 m
Main Injector
Tevatron
CCC 250
Site 56
DAB
Kirk Rd.
to: Farnsworth Ave, I-88
Butterfield Rd.
0 0.25 0.5 1 Miles



Extra

Luminosity

- Beam parameters chosen to match CLIC/ILC
- Is this enough? We can push harder (especially at low energy)
-

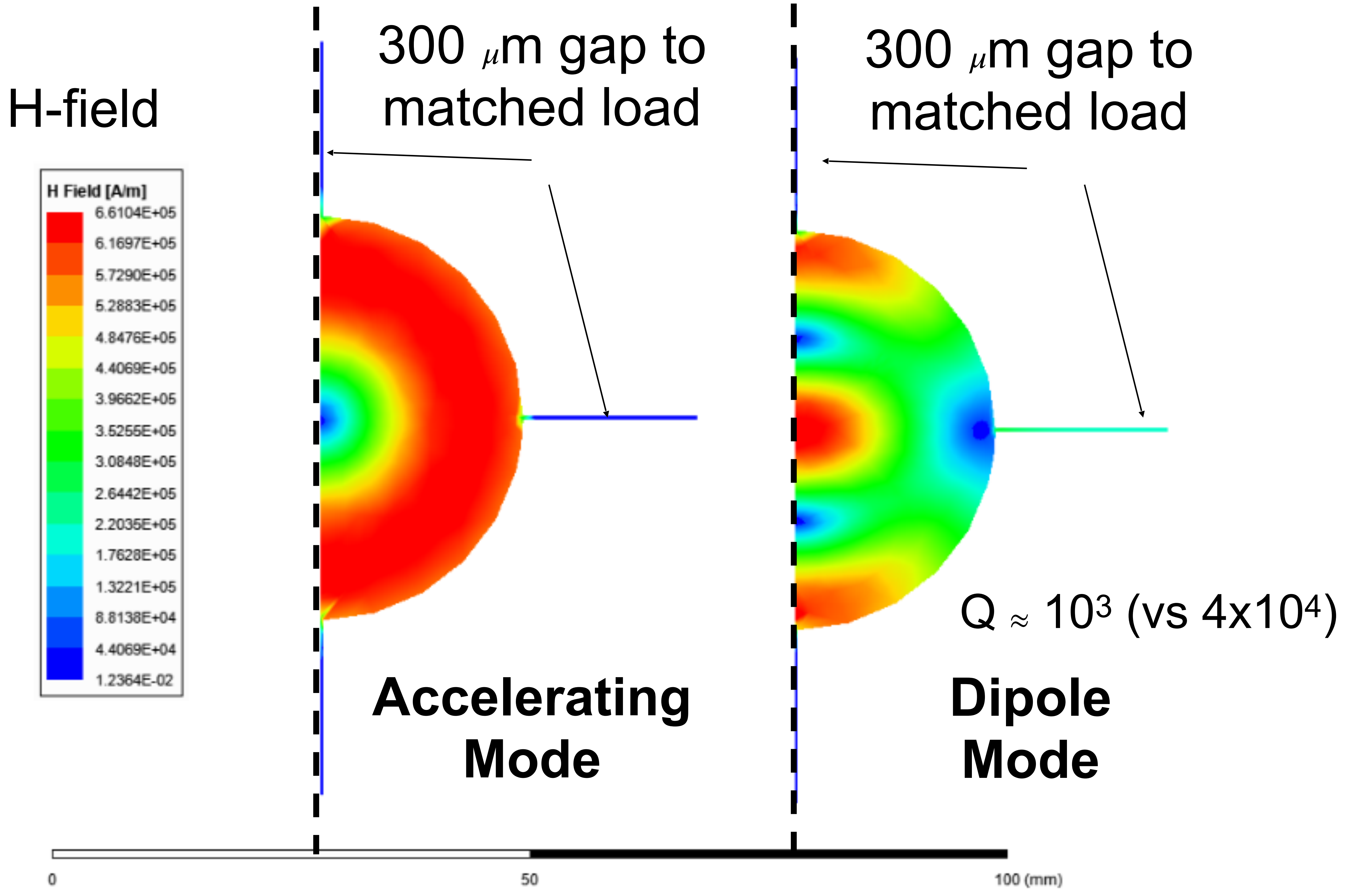
CCC	91 GeV	0.4	1E+34	cm-2s-1	4000	1E+30	cm-2s-1	4000	microb-1*s-1	6.40E+10	microb-1	0.064	ab-1
CCC	125 GeV	0.75	1E+34	cm-2s-1	7500	1E+30	cm-2s-1	7500	microb-1*s-1	1.20E+11	microb-1	0.12	ab-1
CCC	250 GeV	1.5	1E+34	cm-2s-1	15000	1E+30	cm-2s-1	15000	microb-1*s-1	2.40E+11	microb-1	0.24	ab-1
CCC	2 TeV	4.5	1E+34	cm-2s-1	45000	1E+30	cm-2s-1	45000	microb-1*s-1	5.3946E+11	microb-1	0.5394(	ab-1

High Luminosity C^3

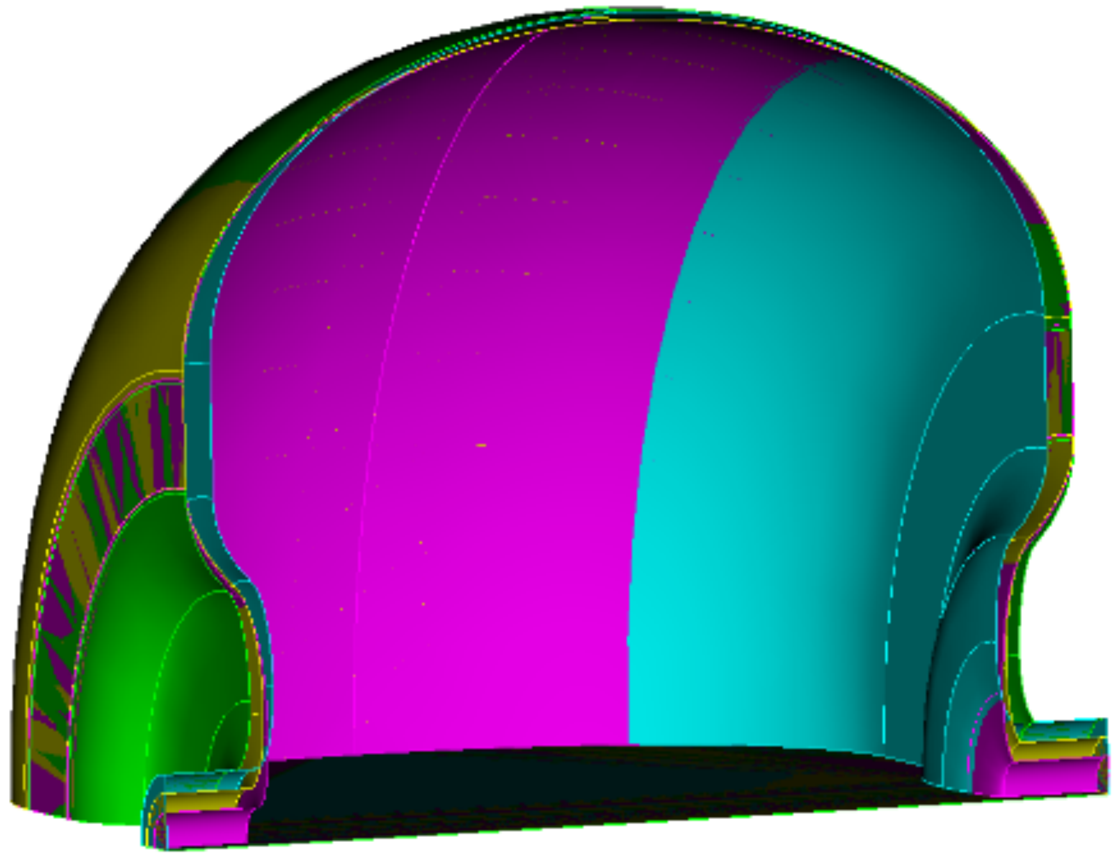
- One thing we miss from FCC-ee - S-channel H
- Requires very high luminsity
- Can we push CCC to the extremes?

- 125 GeV CoM at low gradient (60 MeV/m)
- 1000 Hz, 500 ns flat top
  - 100% thermal load > 250 GeV CoM
- Single Beam Power 18.75 MW
- 300 x 1 nC bunches
- 1.125 ab^-1/yr
  - Need 10-20 ab^-1

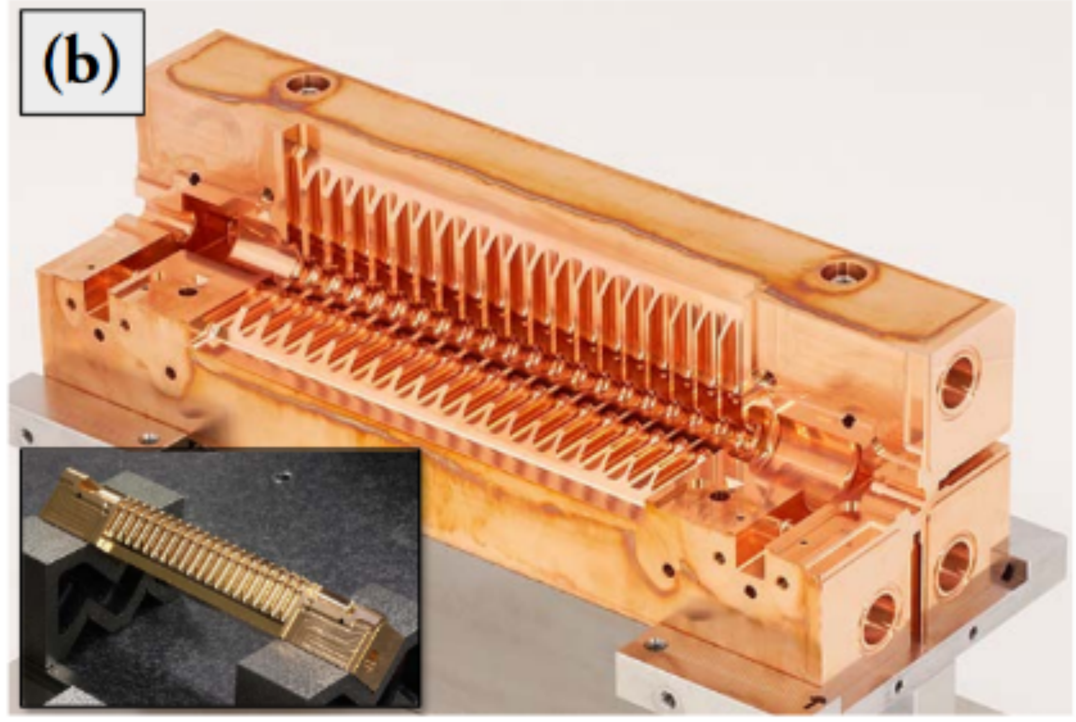
- Individual cell feeds necessitate adoption of split-block assembly
- Perturbation due to joint does not couple to accelerating mode
- Exploring gaps in quadrature to damp higher order mode



Design of Detuned Cavities



Quadrant Structure



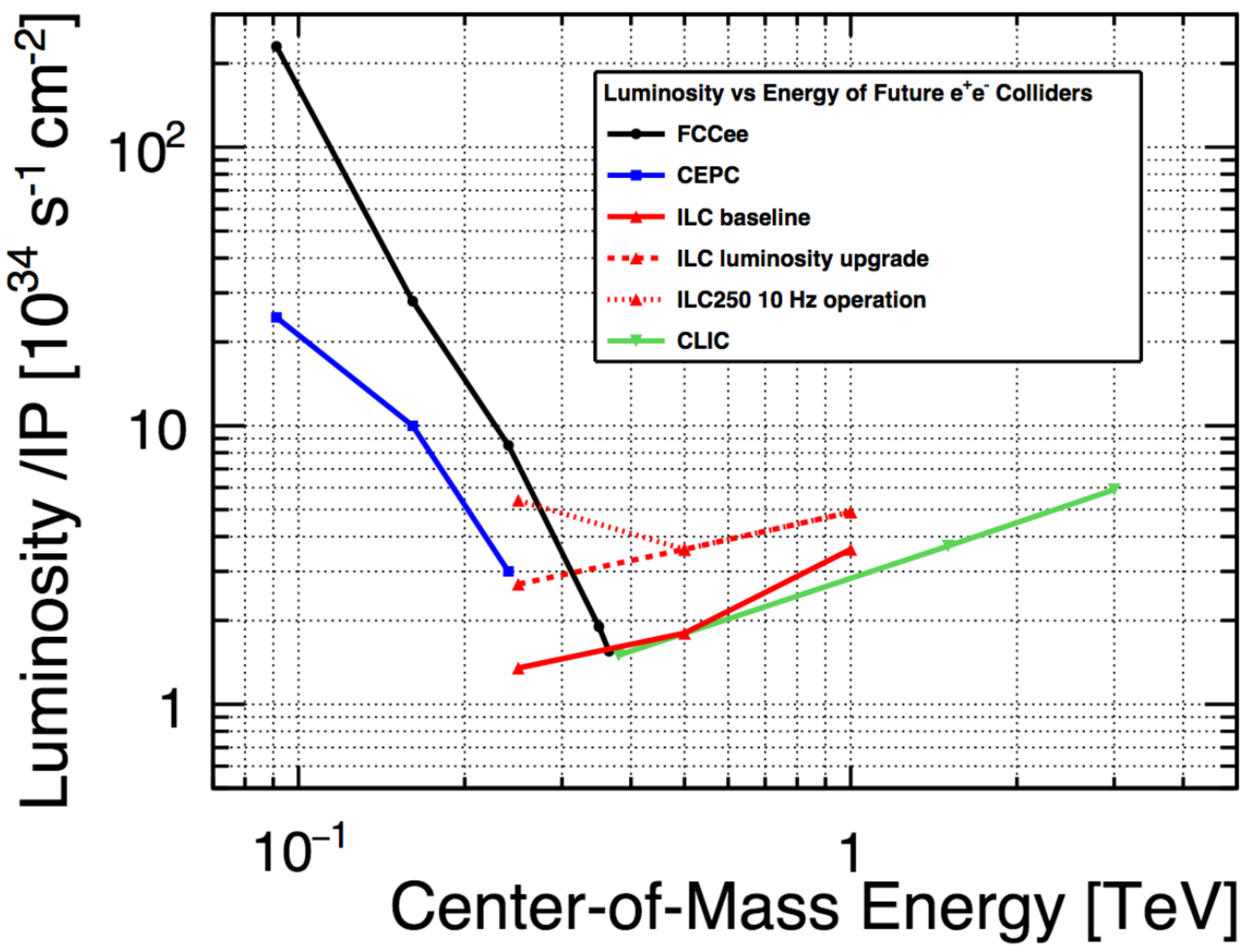
Abe et al., PASJ, 2017, WEP039

Linear & Circular Collider - Detector Impact

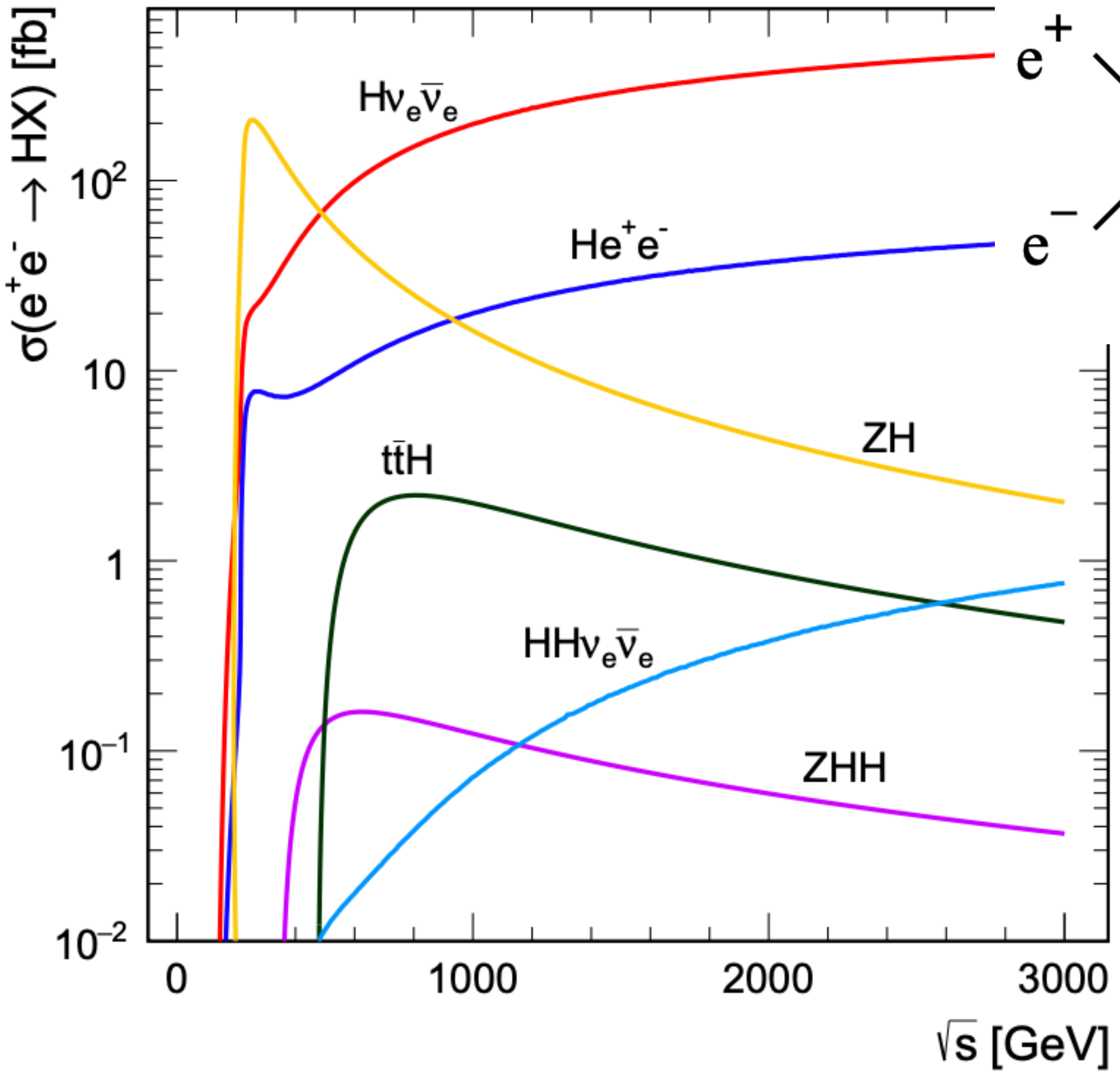
- **Linear** colliders : ILC, CLIC
  - Only possible way towards high-energy with leptons
  - Polarized collisions possible
  - The time structure and low radiation background provides an environment which allows us to consider **very light, low power detector structures**

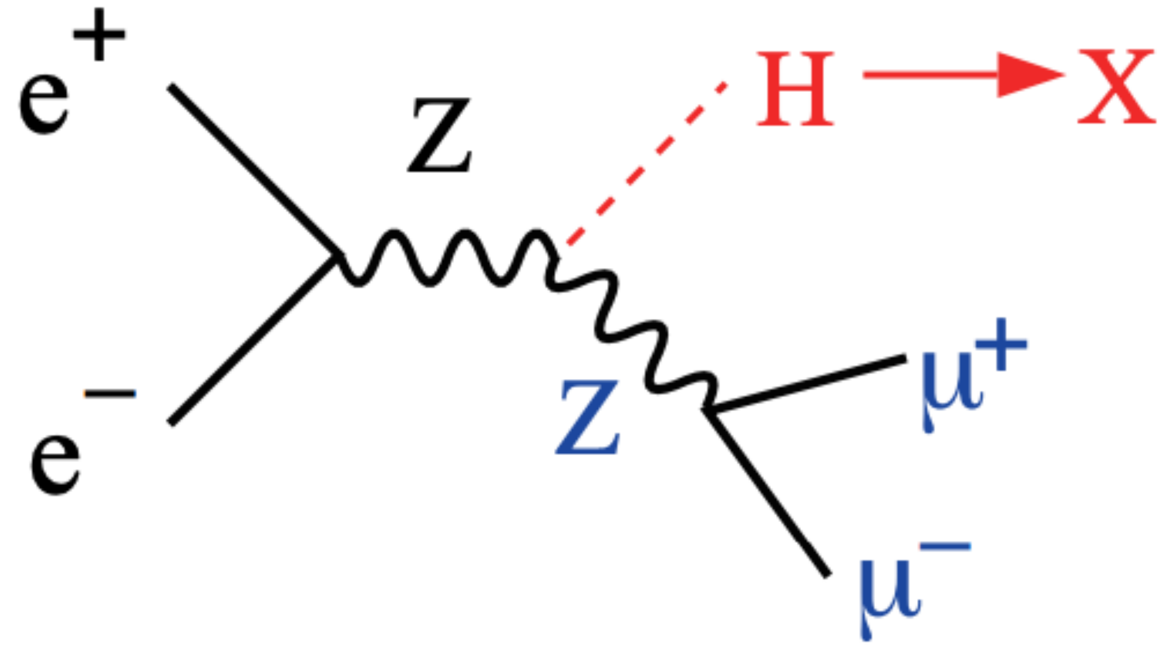
- **Circular** colliders : FCC, CEPC
  - Highest luminosity at Z pole/WW/ZH, but strongly limited by synchrotron radiation above 350– 400 GeV
  - The interaction rates (up to 100 kHz at the Z pole) put strict constraints on the event size and readout speed
  - Due to beam crossing angle, solenoid magnetic field is limited to 2 T to avoid a significant impact on the luminosity
  - Trackers must achieve good resolution without power pulsing

- Linear colliders allow lower mass Si pixel and strip trackers



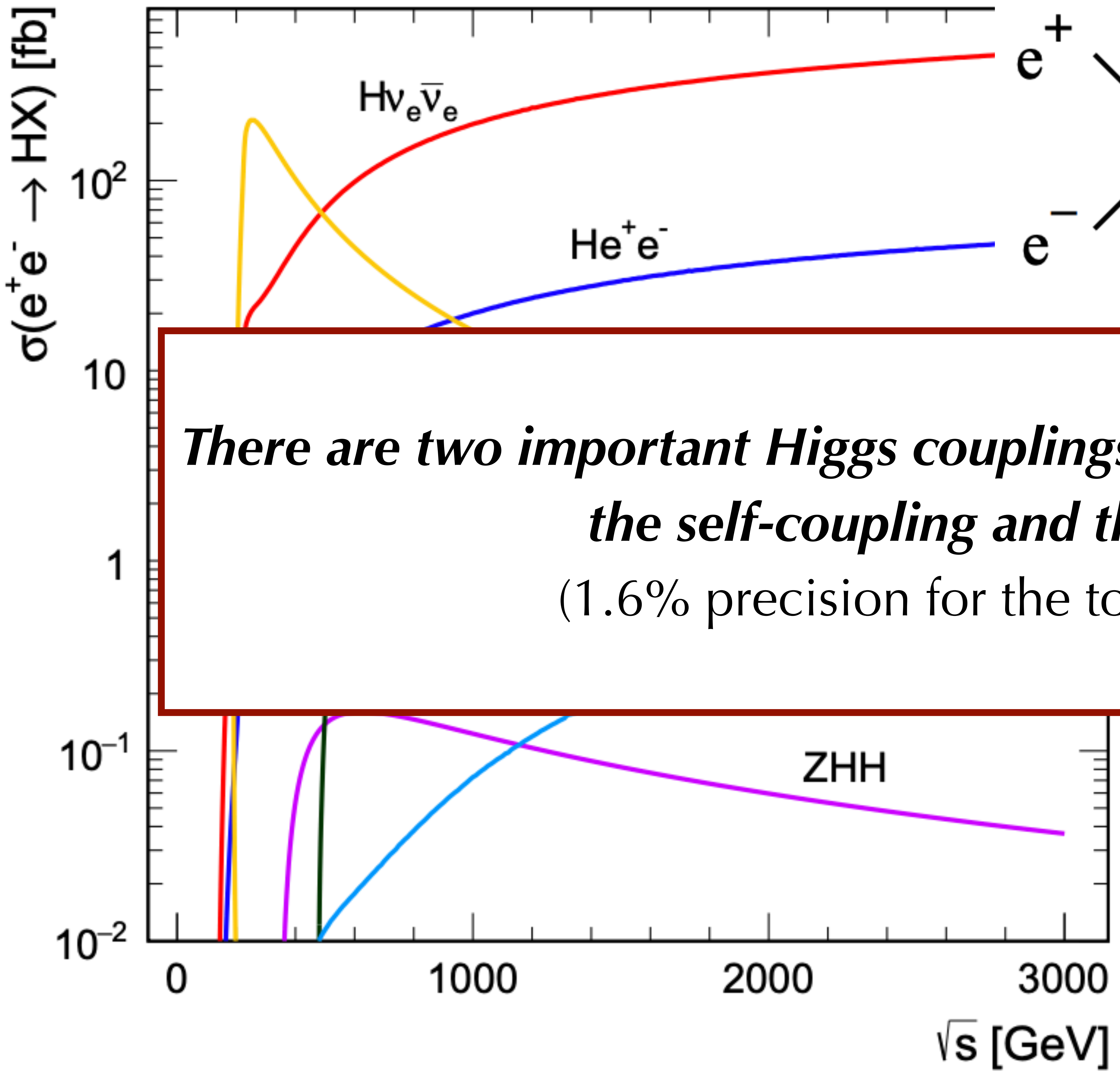
Higgs at e+e-

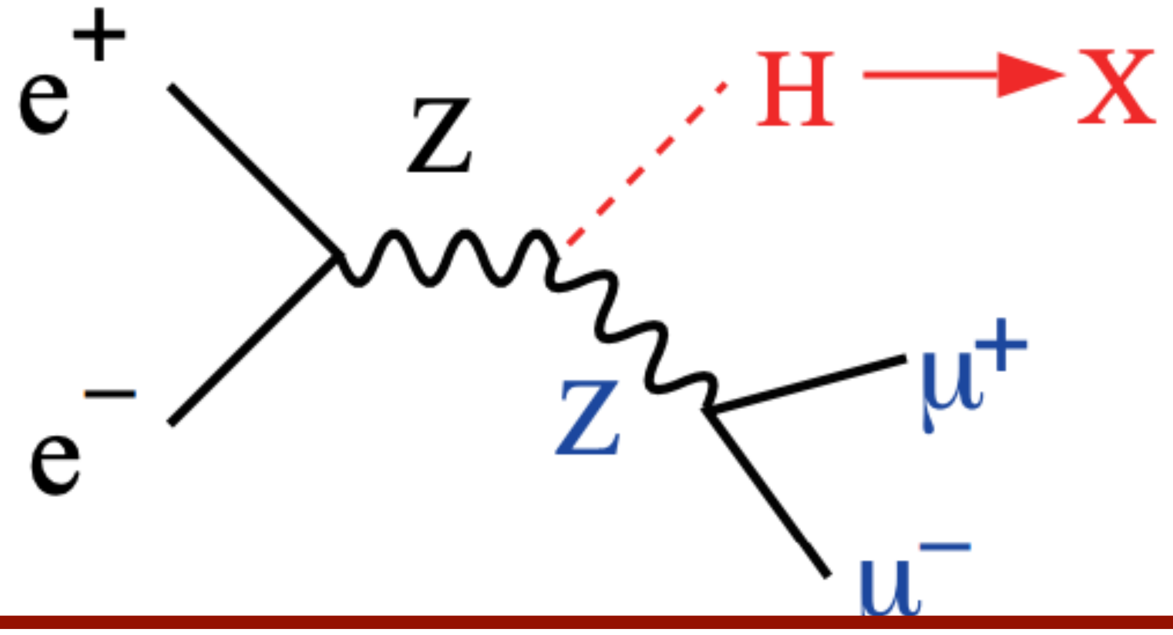




- ZH is the dominant production mode for √s ~ 250 GeV
- The well defined initial states allows to tag the Higgs boson without looking into its decay with **"recoil" technique**
  - Measurement of the inclusive ZH cross section at 0.5-1%
  - Recoil technique observes all final state, including all invisible and exotic decay modes
    - **ZH is key for the determination of the absolute Higgs couplings**
- Clean environment for **excellent b- and c-tagging performance**: Hbb/cc/gg separation

Higgs at e+e-





There are two important Higgs couplings that cannot be measured directly below 500 GeV — the self-coupling and the Higgs-top quark Yukawa coupling

(1.6% precision for the top quark Yukawa coupling at ILC 1 TeV)

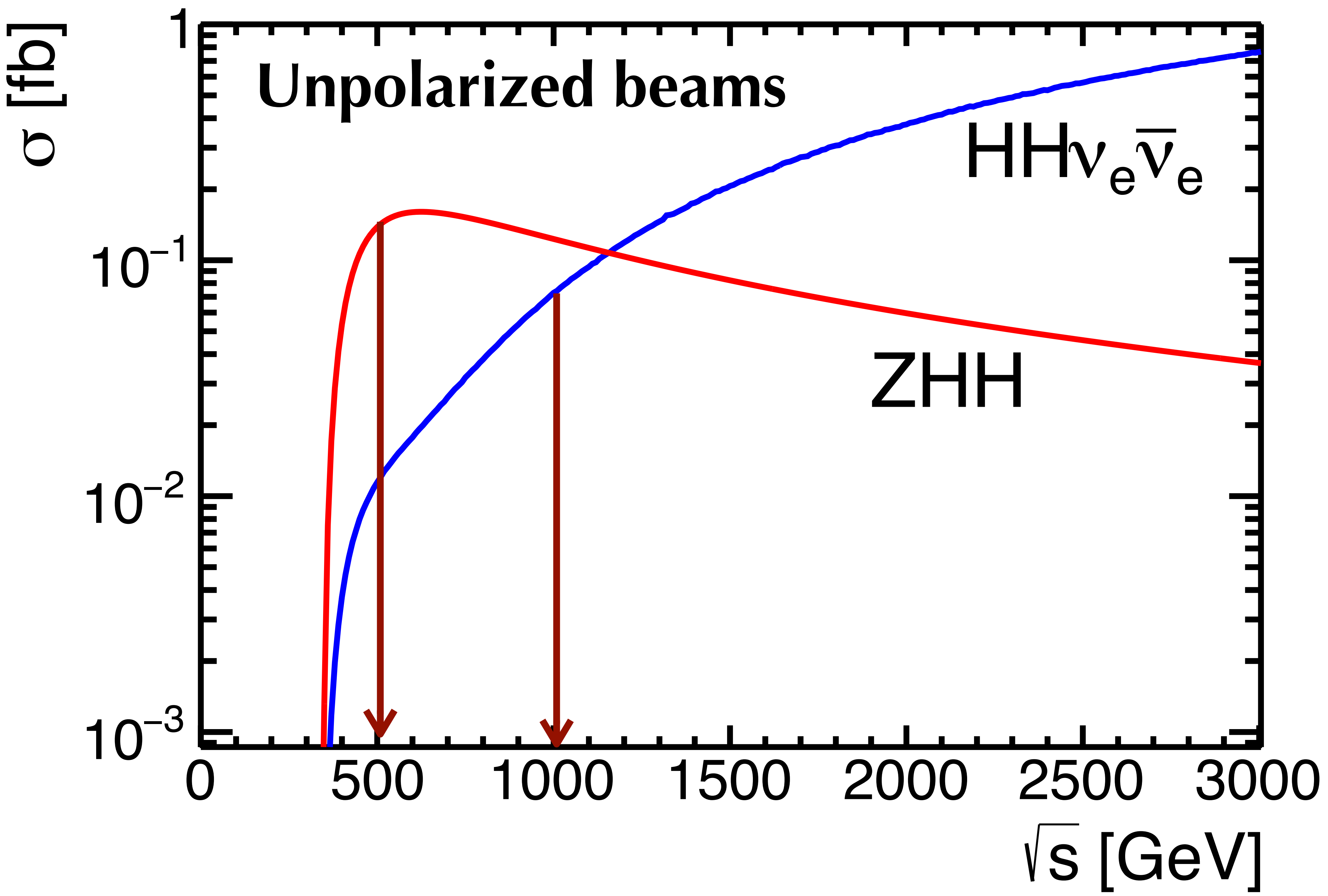
invisible and exotic decay modes

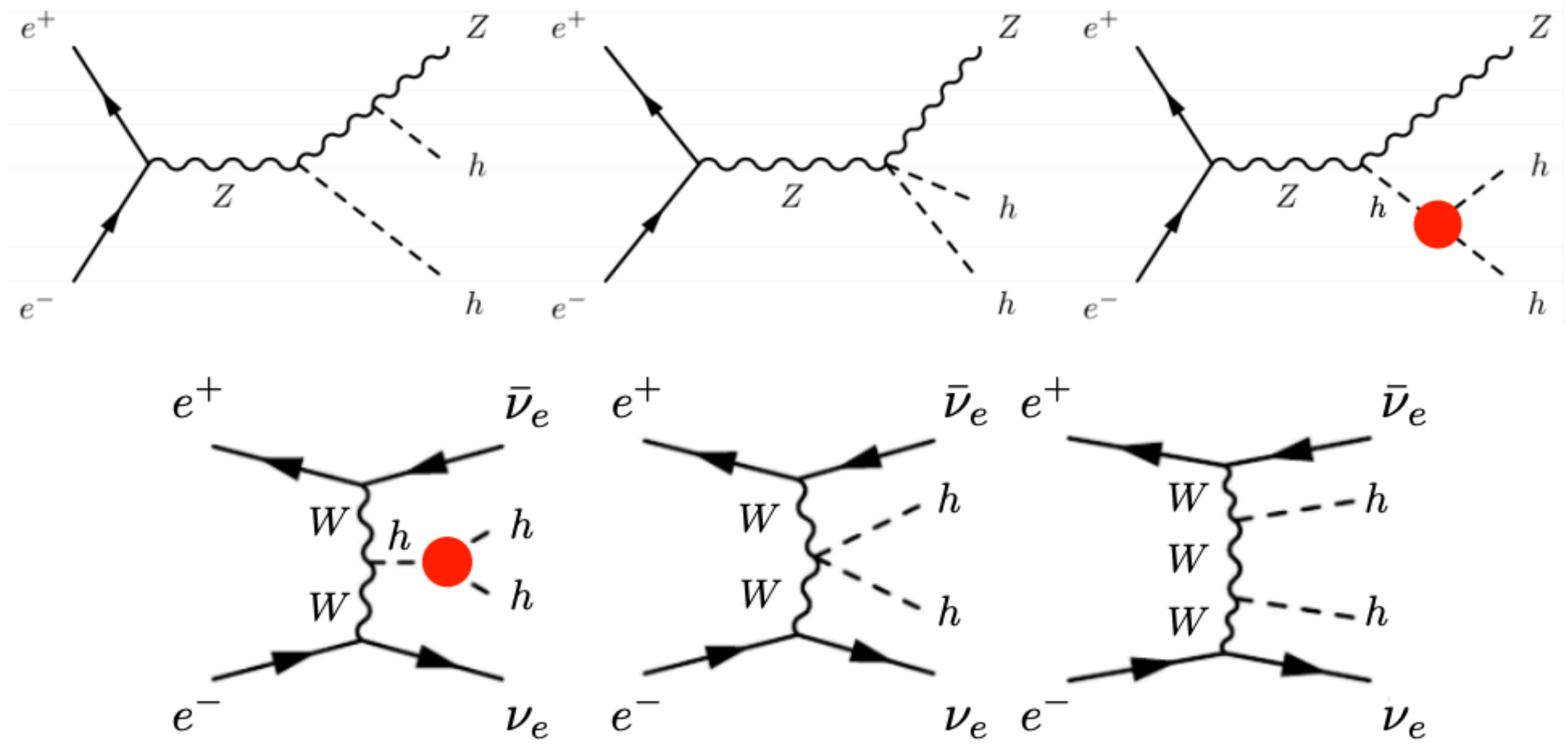
- **ZH is key for the determination of the absolute Higgs couplings**

- Clean environment for **excellent b- and c-tagging performance**: Hbb/cc/gg separation

HH at future e+e- colliders

arXiv:1910.00012



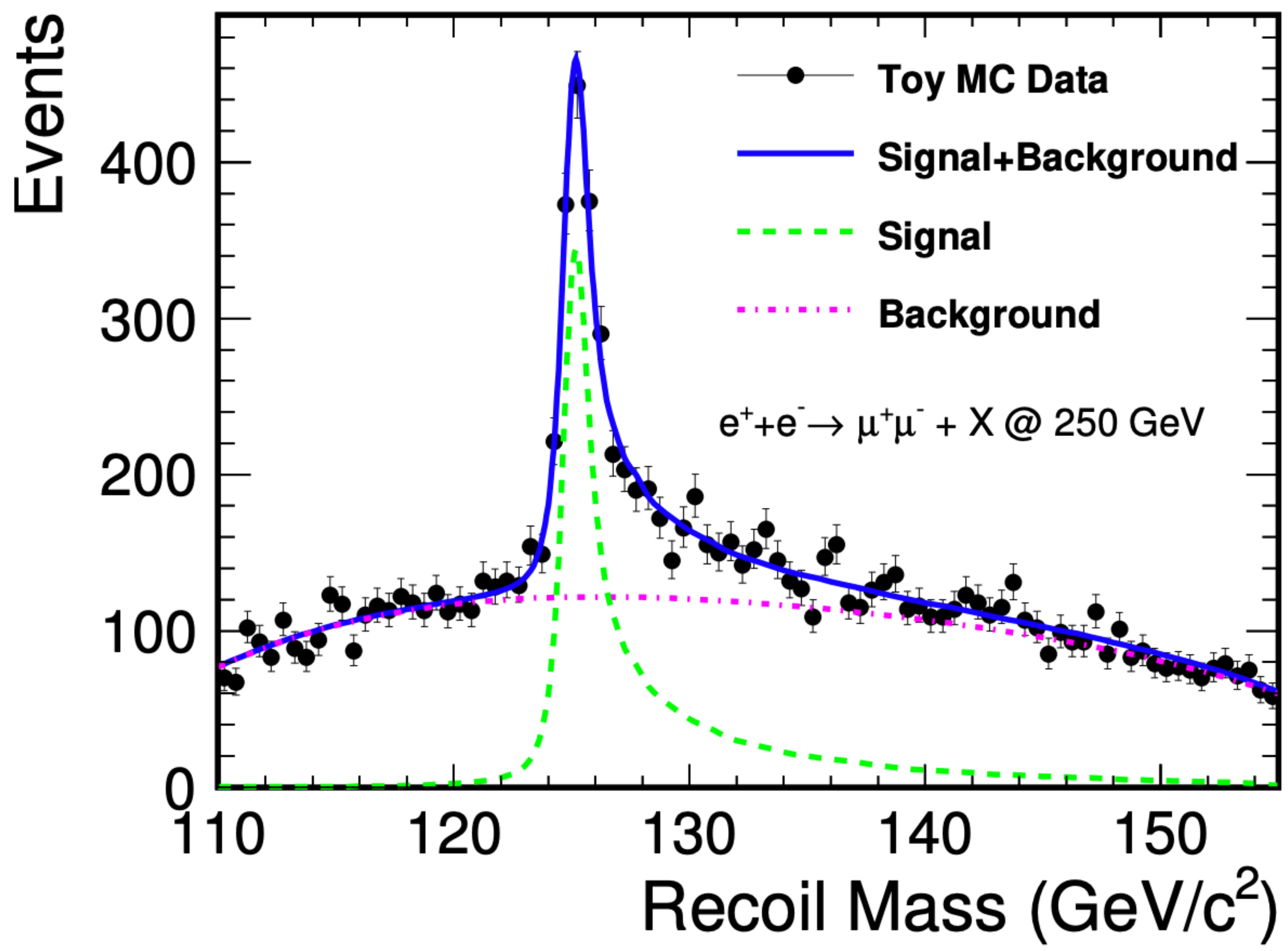


- The self-coupling can be probed at e+e- through double Higgs with ZHH ~500GeV and **vv**HH ≥1TeV
  - **HHvv** requires $e_L^- e_R^+$, the use of polarized beams could increase the cross-section by a factor ~2
- For **ZHH** / **HHvv** processes there is a constructive/deconstructive interference between diagrams with and without the self- coupling
  - No matter what is the sign of the deviation of the Higgs self-coupling from its SM value, one process is always enhanced

Physics requirements for tracking detectors at e+e-

ILC TDR Vol. 4
arXiv:2003.01116

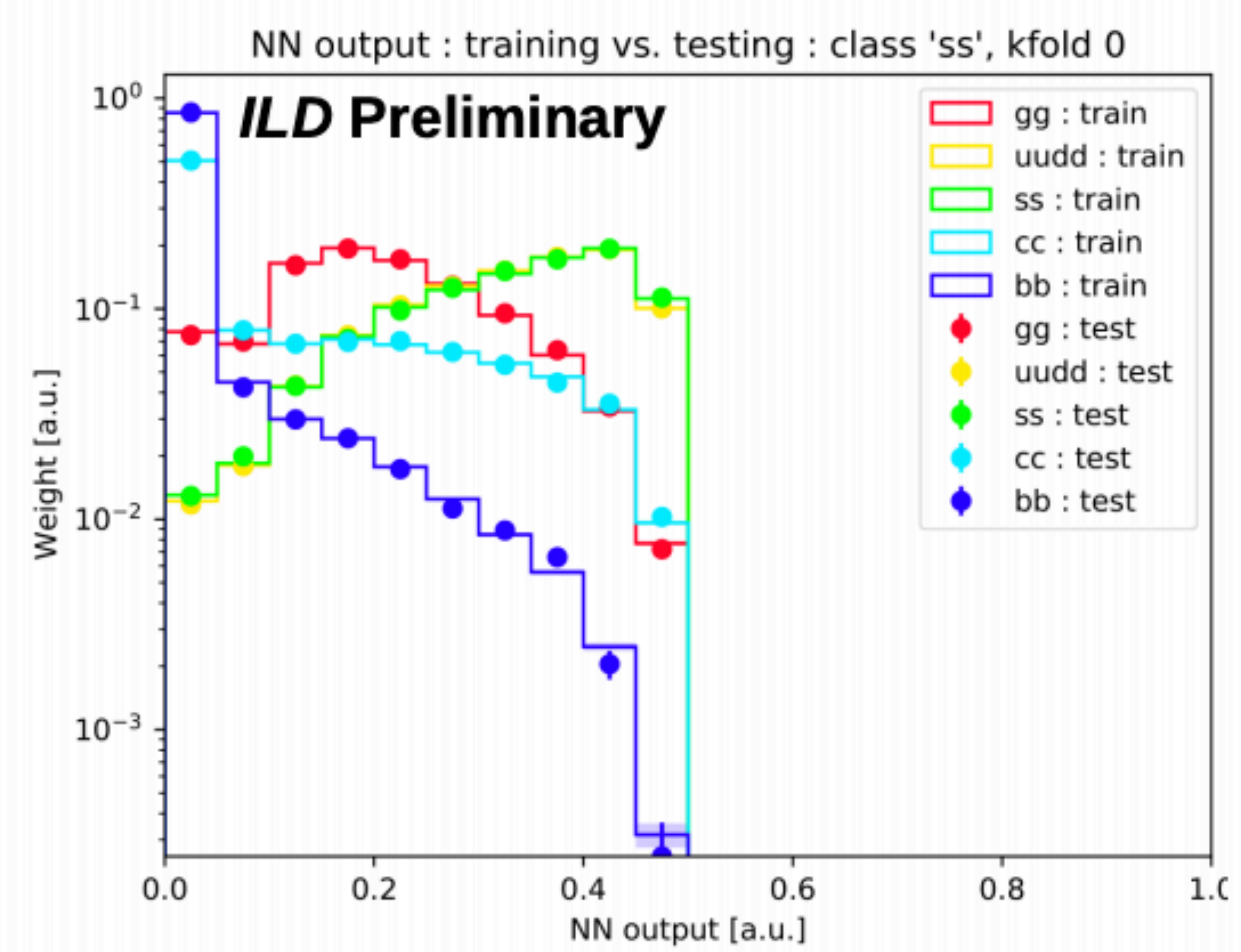
- **ZH process**: Higgs recoil reconstructed from Z →μμ
  - Drives requirement on charged track momentum and jet resolutions
  - Sets need for high field magnets and high precision / low mass trackers
  - Bunch time structure allows high precision trackers with very low X_0 at **linear lepton colliders**
- **Higgs → bb/cc decays**: Flavor tagging & quark charge tagging at unprecedented level
  - Drives requirement on charged track impact parameter resolution → low mass trackers near IP
    - <0.3% X0 per layer (ideally 0.1% X_0) for vertex detector
    - Sensors will have to be less than 75 μm thick with ~ 5 μm hit resolution (17-25μm pitch)

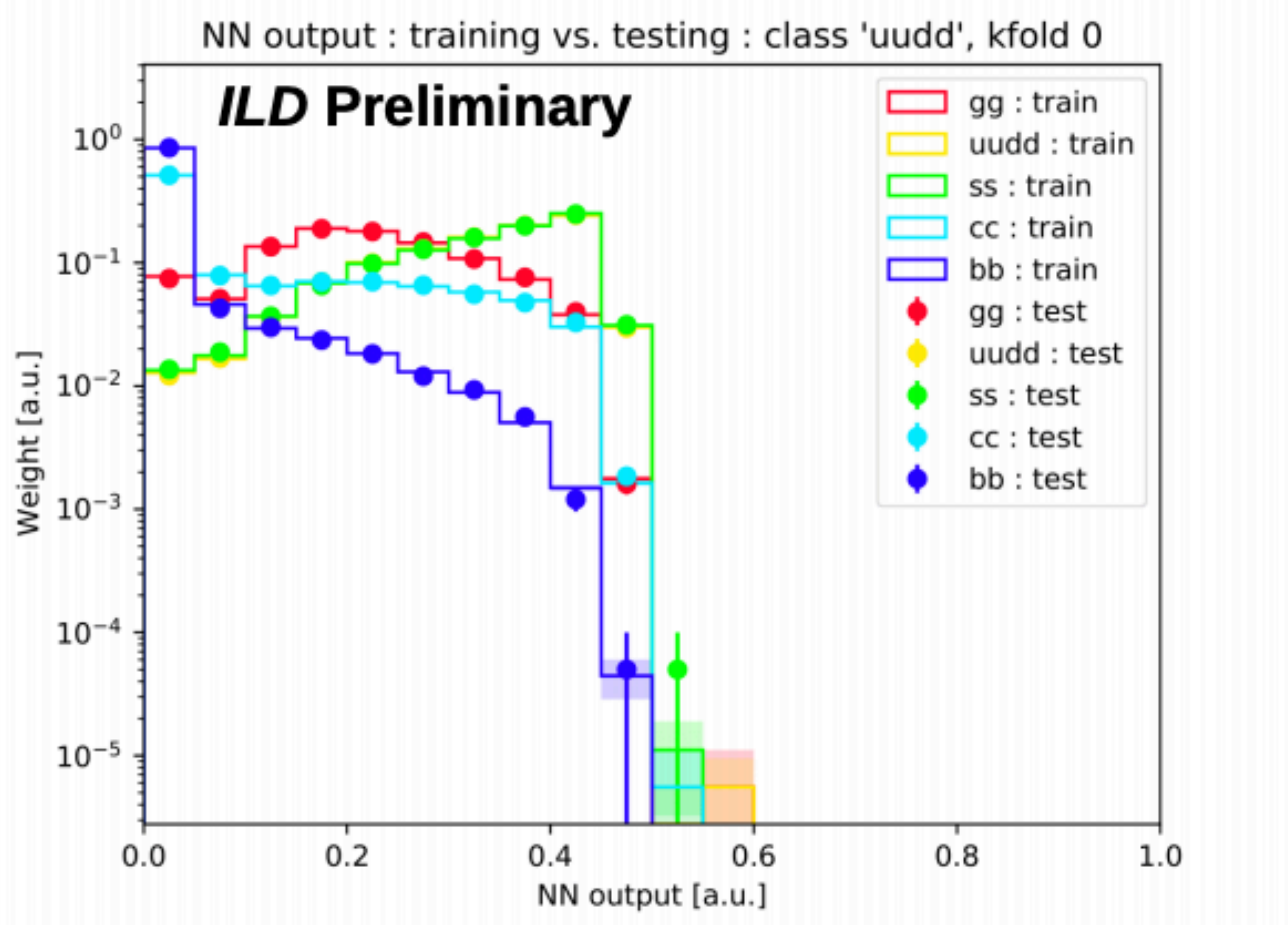


Need new generation of ultra low mass vertex detectors with dedicated sensor designs

Strange coupling

- Evaluate sensitivity to H→ss/H→cs
  - some BSM models allow for the 1st & 2nd generation fermion masses to be an additional source of EW symmetry breaking





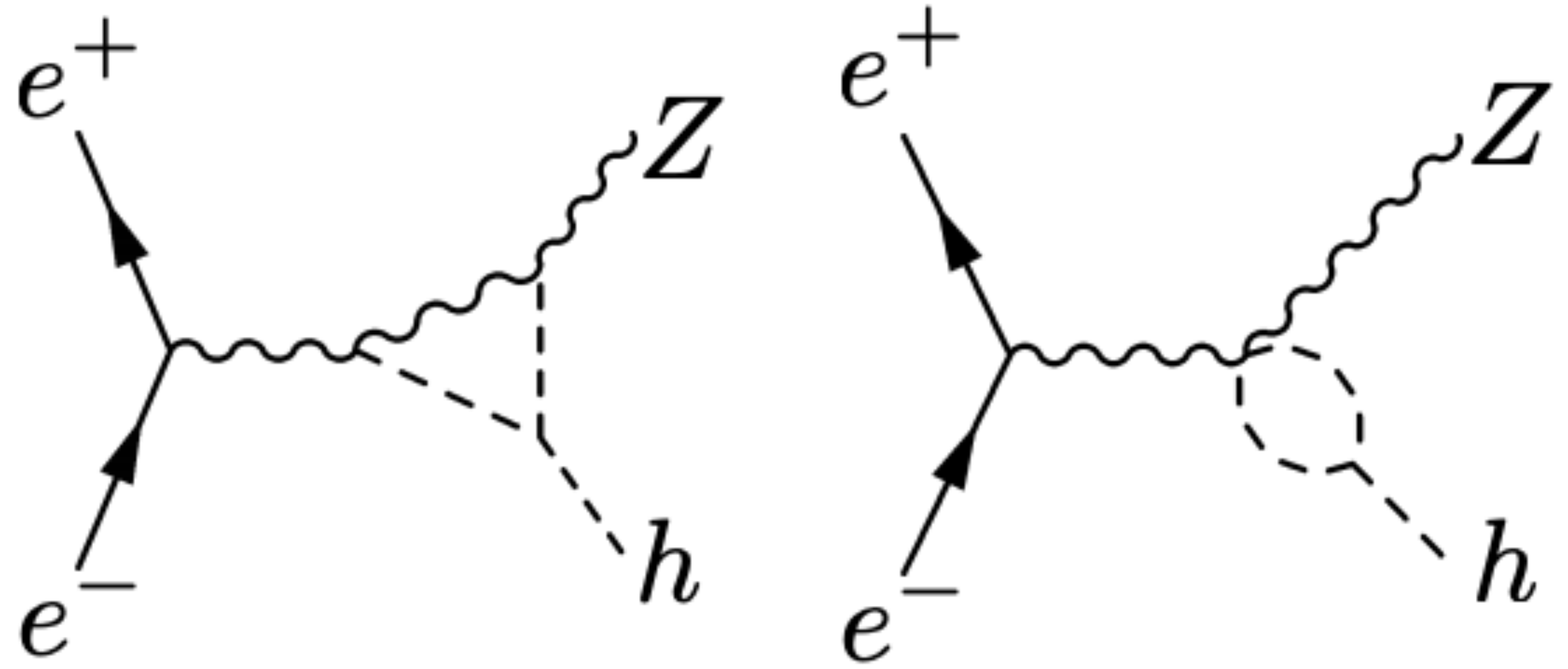
Currently: reasonable separation possible for b, c, g, s+u/d
Separation of strange and light jets is very challenging

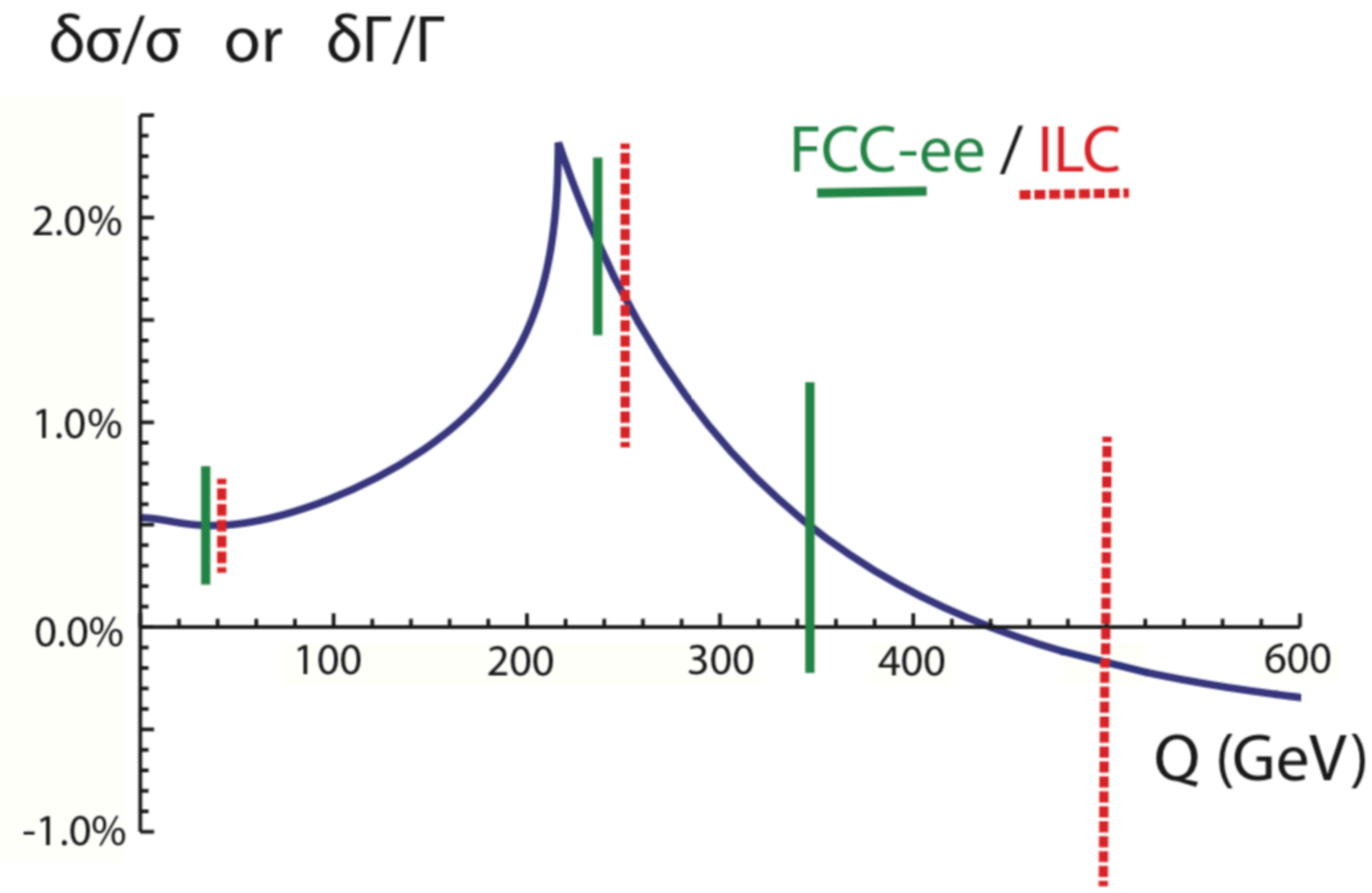
LOI submitted (w Valentina, Ariel, Su Dong)

Self-coupling at e+e-

The self-coupling could be determined also through single Higgs processes

- Relative enhancement of the e+e− → ZH cross-section and the H→W+W− partial width
- Need multiple Q^2 to identify the effects due to the self-coupling





Which precision on the self-coupling is needed?

arXiv:1910.00012




Bronze 100% | **Silver 25–50%** | **Gold 5–10%** | **Platinum 1%**

Sensitivity to models with the largest new physics effects, in which new particles of few hundred GeV mass appear in tree diagrams or as s-channel resonances

Sensitivity to mixing of the Higgs boson with a heavy scalar with a mass of order 1 TeV (i.e. electroweak baryogengesis)

Sensitivity to a broad class of loop diagram effects that might be created by any new particle with strong coupling to the H

Sensitivity to typical quantum corrections to the Higgs self-coupling generated by loop diagrams

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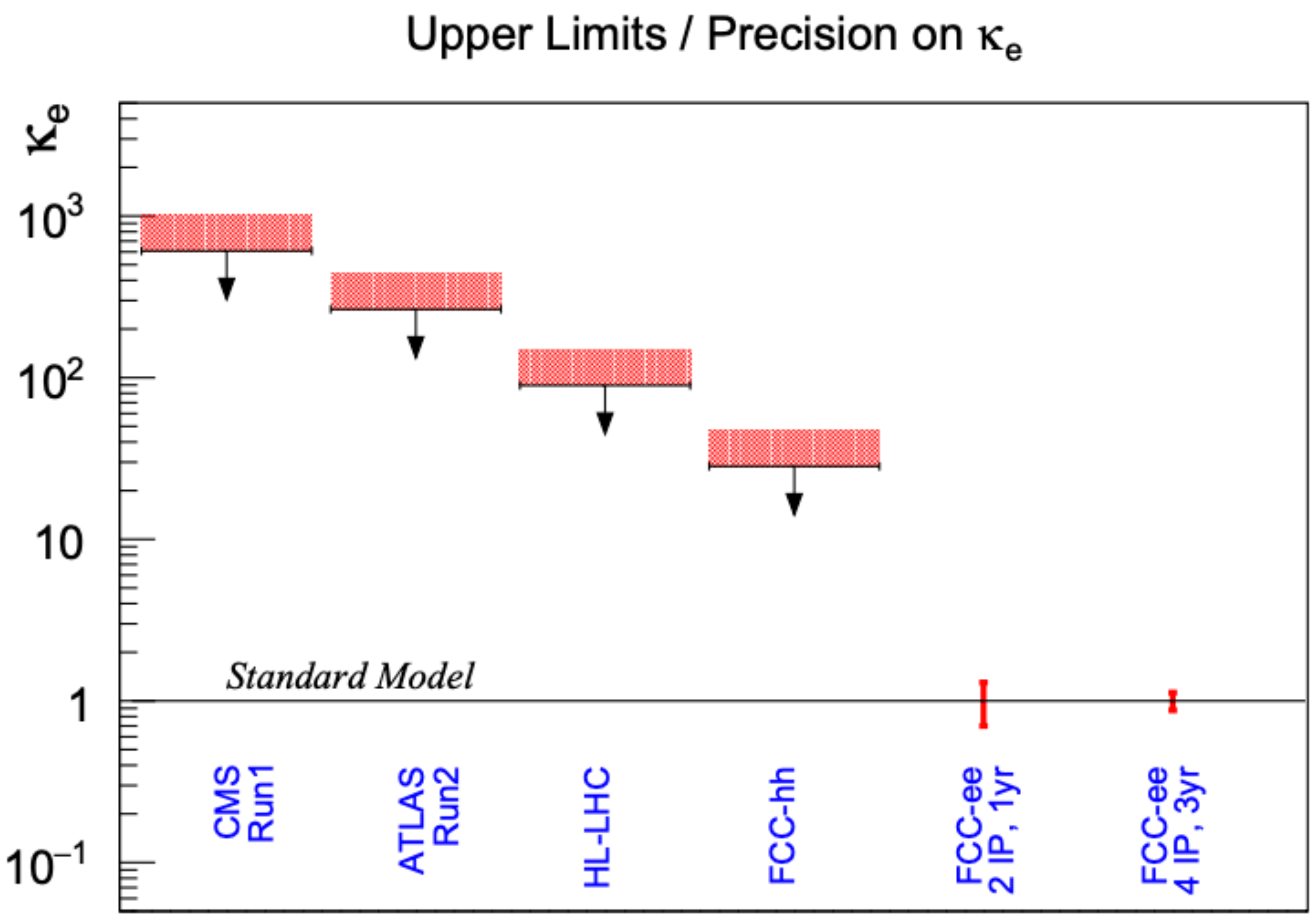
Interplay between precisions inference and direct searches for new particles

Higgs at e+e-

1912.11871



- Circular lepton colliders - FCC-ee - provide the highest luminosities at lower centre-of-mass energies
  - Unique opportunity to measure the Higgs boson coupling to electrons through the resonant production process $e^+e^- \rightarrow H$ at $\sqrt{s}$ = 125 GeV
  - FCC-ee running at H pole-mass with 20/ab would produce O(30.000) H's reaching SM sensitivity
    - Requires control of beam-energy spread

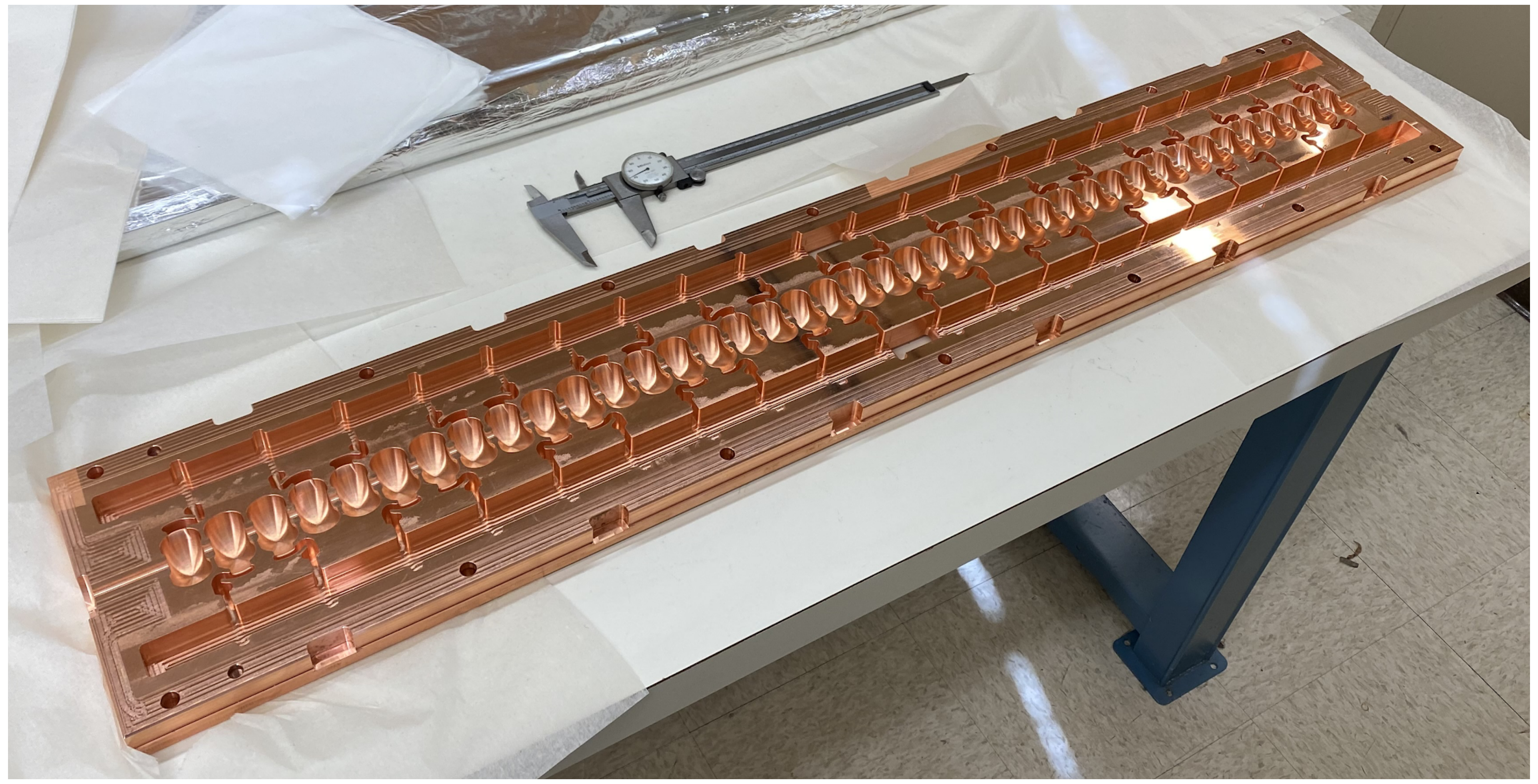
C3 - Cool Copper Collider

More Details See: Bane et al., *ArXiv* 1807.10195 (2018)
C^3 Colloquium: https://sites.slac.stanford.edu/colloquium/node/159
C3 LOI Link

SLAC

- SLAC technology for normal conducting accelerator at cryogenic temperature
- Aim to achieve high gradient (110 MeV/m real footprint) on short timescale
- Potential for high brightness polarized sources to eliminate damping rings
- Scalable technology optimizing for multi-TeV operation

First C3 structure at SLAC



Timeline:

2 years - meter scale, wakefield damping, cryogenics
4 years - modular GeV units
Target operation in parallel w/ HL-LHC