Overview on C^3

IAS Program on High Energy Physics (HEP 2024)

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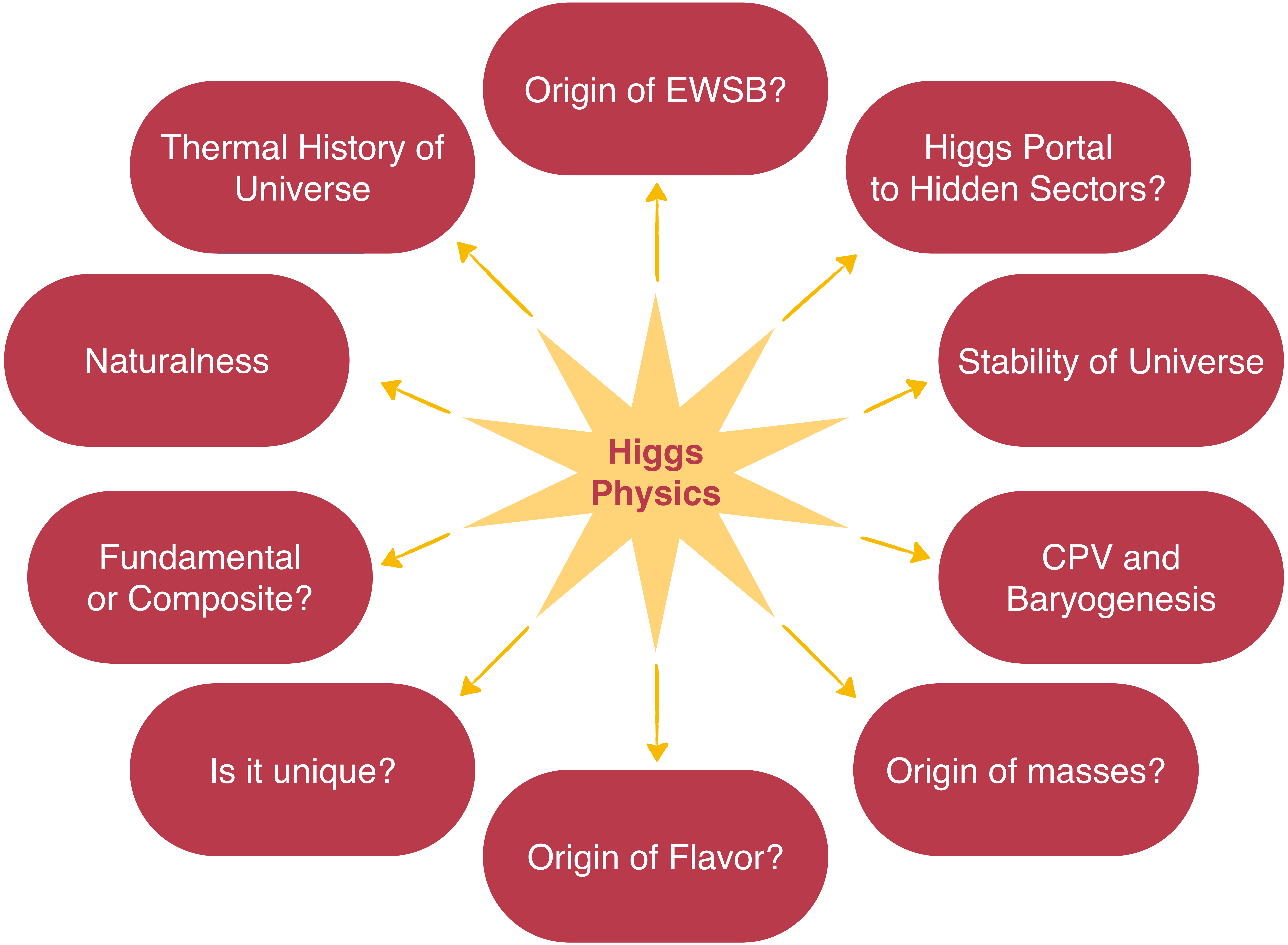
Stanford University
U.S. DEPARTMENT OF ENERGY



Thermal History of Universe

Origin of EWSB?

Higgs Portal to Hidden Sectors?

Naturalness

Higgs Physics

Stability of Universe

Fundamental or Composite?

CPV and Baryogenesis

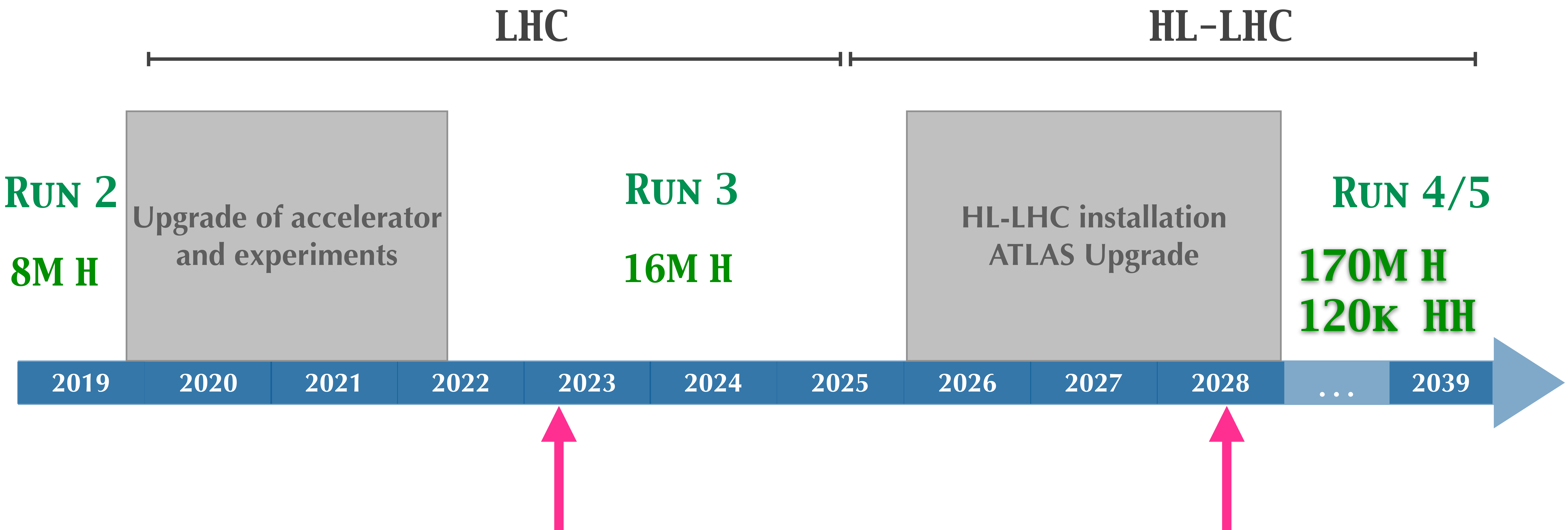
Is it unique?

Origin of Flavor?

Origin of masses?

[The Energy Frontier 2021 Snowmass Report]

LHC → High Luminosity LHC



LHC

HL-LHC

RUN 2

8M H

Upgrade of accelerator and experiments

RUN 3

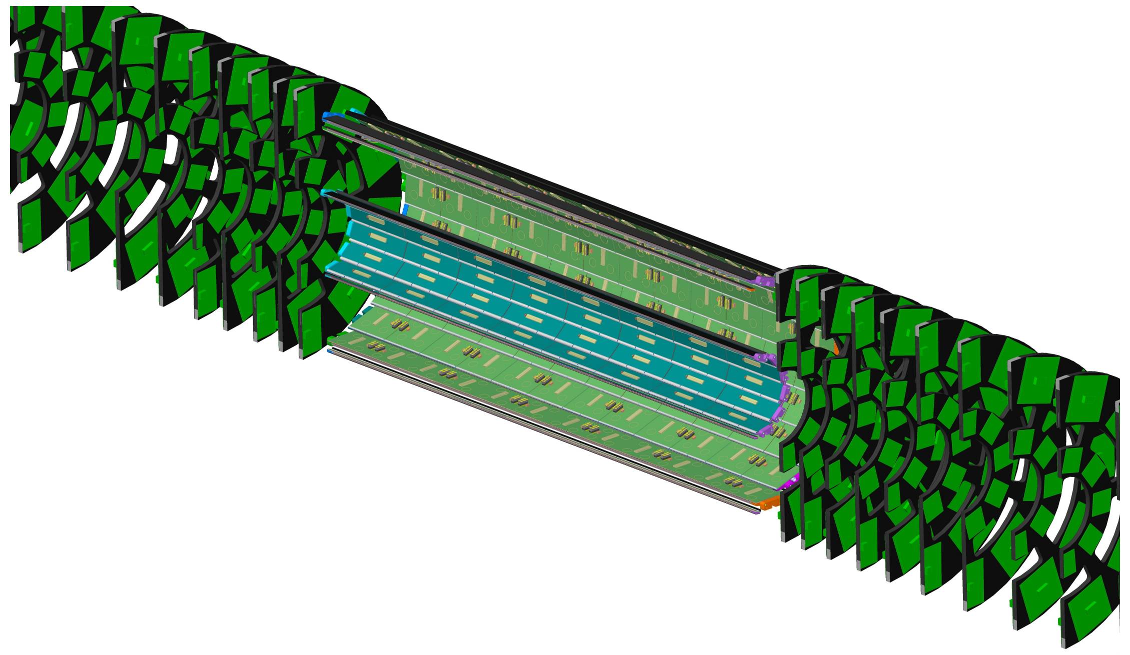
16M H

HL-LHC installation
ATLAS Upgrade

RUN 4/5

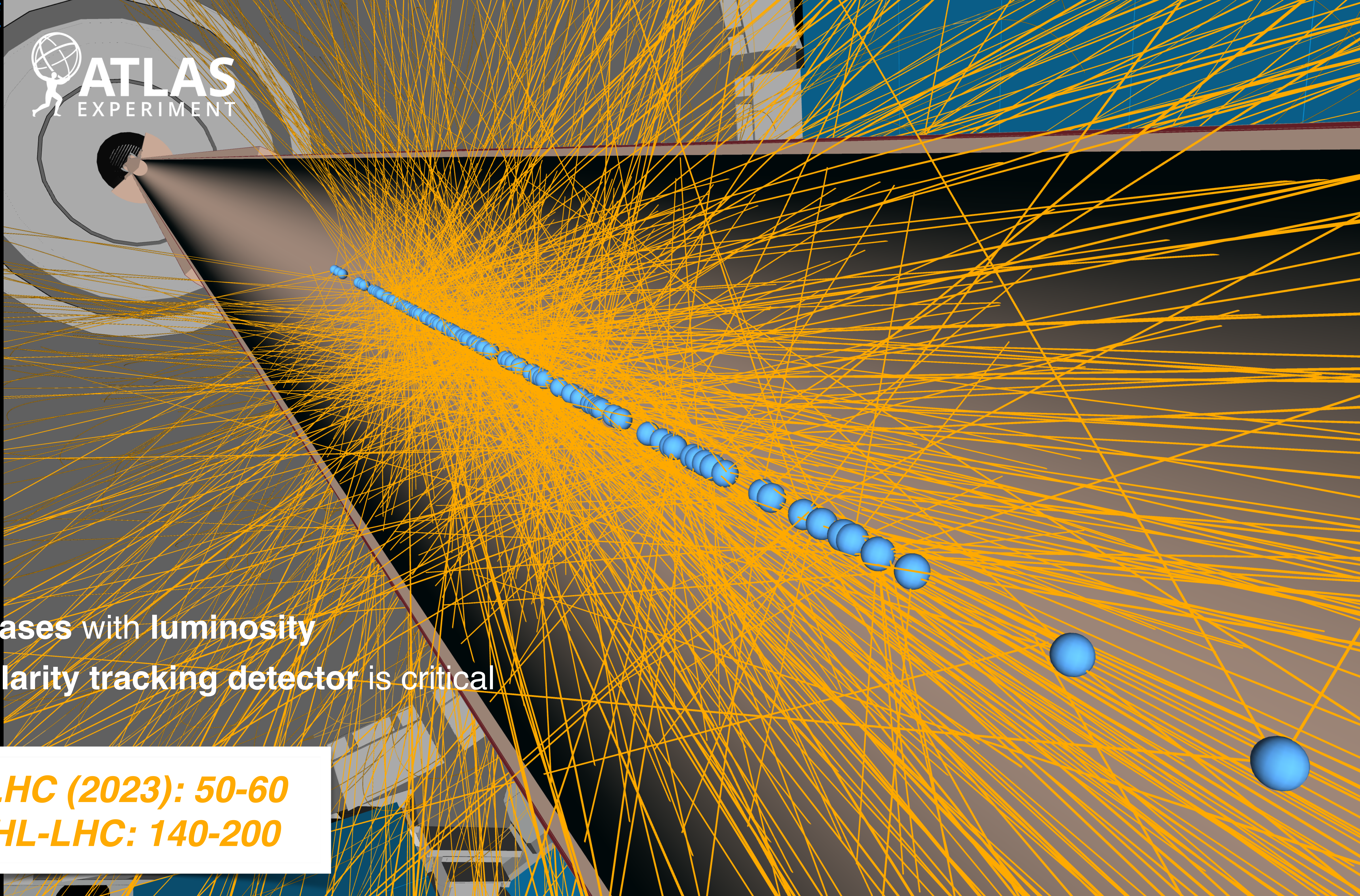
170M H
120K HH

TODAY



Phase-2 HL-LHC detector upgrades are being built

ref



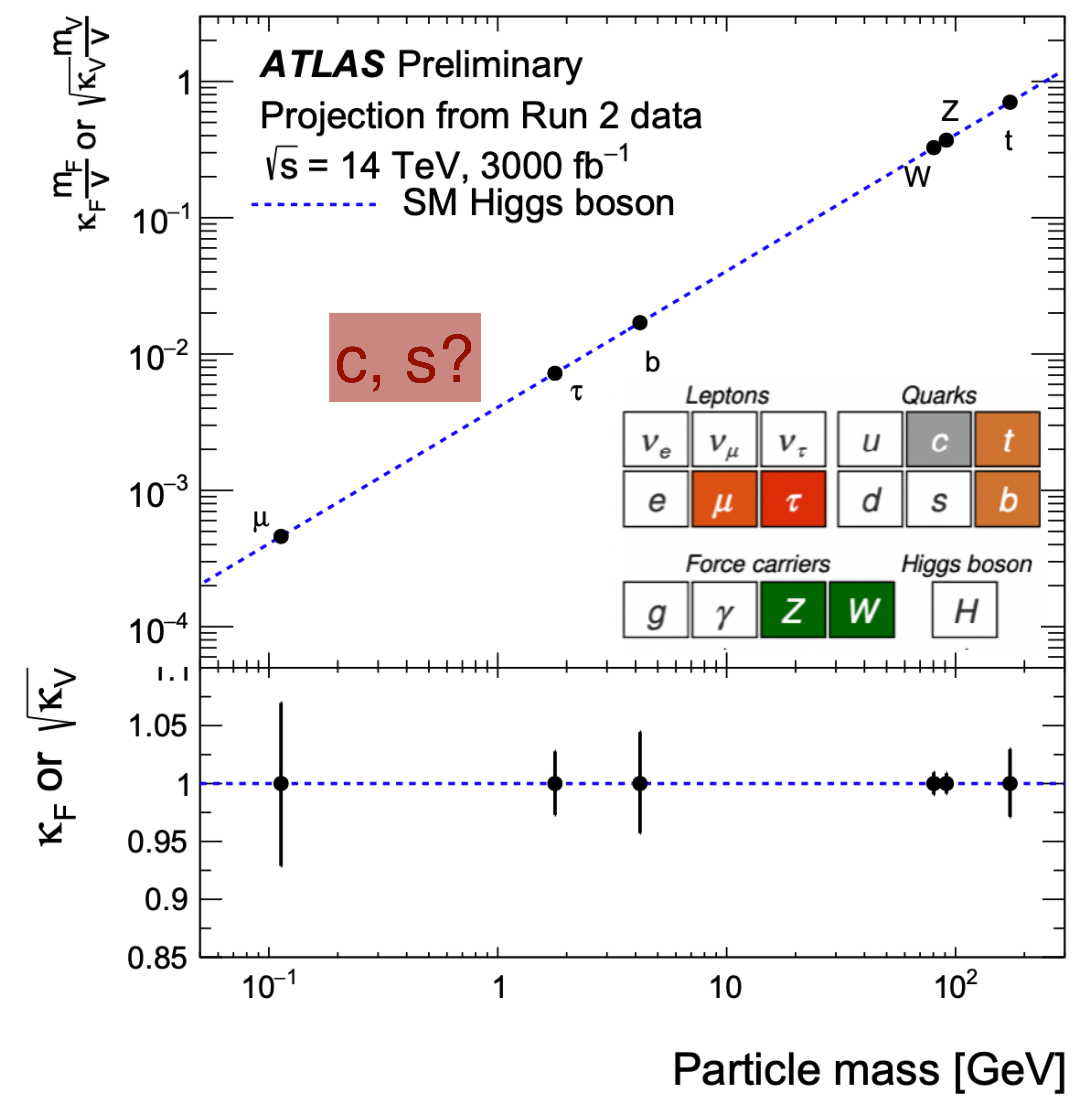
- **Pileup increases** with **luminosity**
  - **High granularity tracking detector** is critical

LHC (2023): 50-60
HL-LHC: 140-200

1902.10229

CERN-LPCC-2018-04

Higgs at HL-LHC



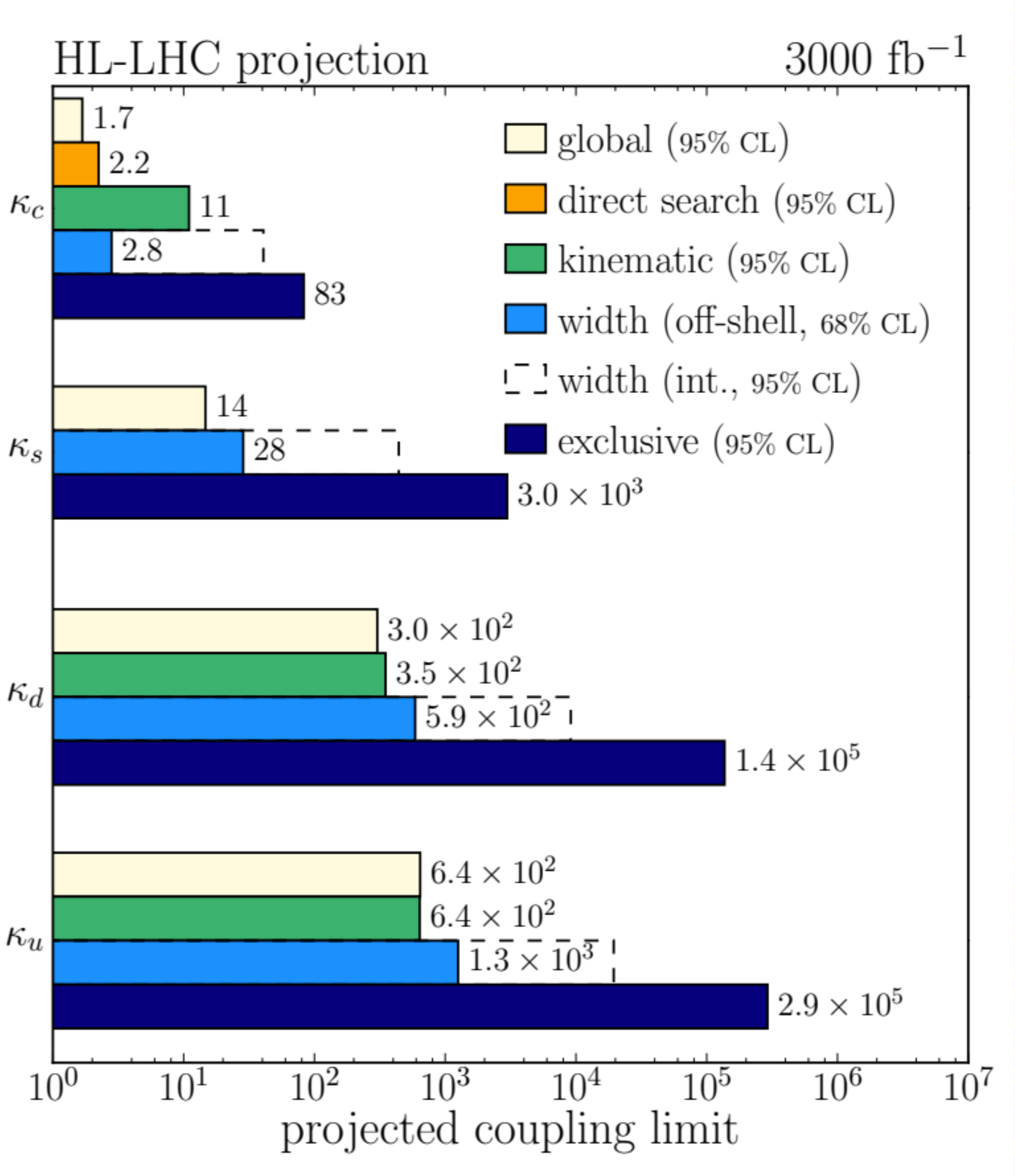
c, s?

The High Luminosity era of LHC will dramatically expand the physics reach for Higgs physics:

- **2-5% precision for many of the Higgs couplings**
- **BUT much larger uncertainties on $Z\gamma$ and charm and ~50% on the self-coupling**

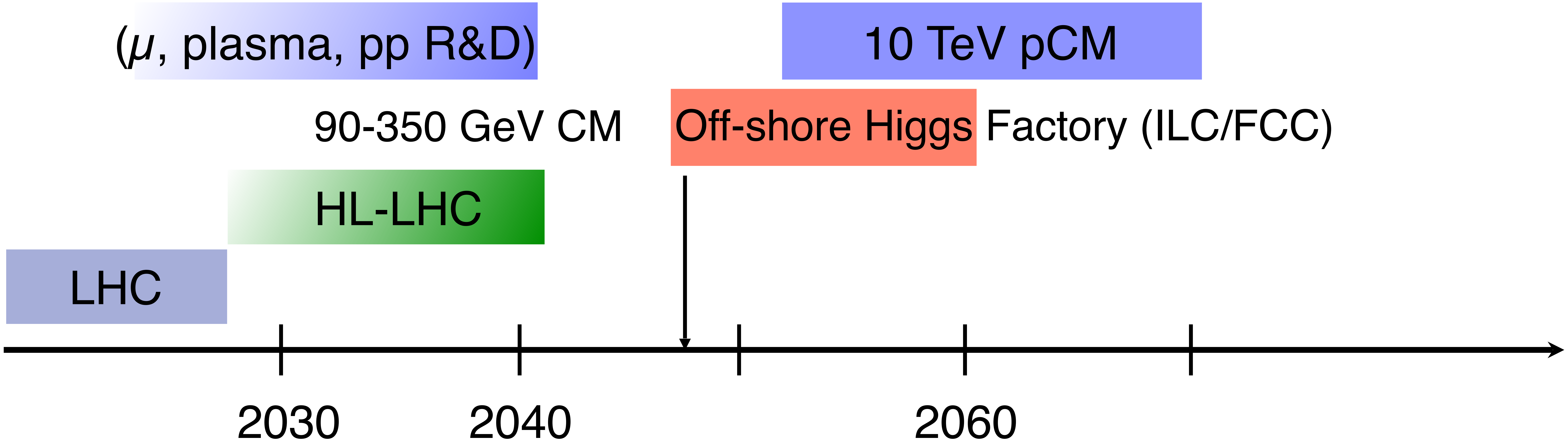
Higgs at HL-LHC

1902.10229
CERN-LPCC-2018-04



Light Yukawa out of reach in the LHC environment

post-P5 roadmap



(*μ*, plasma, pp R&D)

10 TeV pCM

90-350 GeV CM

Off-shore Higgs Factory (ILC/FCC)

HL-LHC

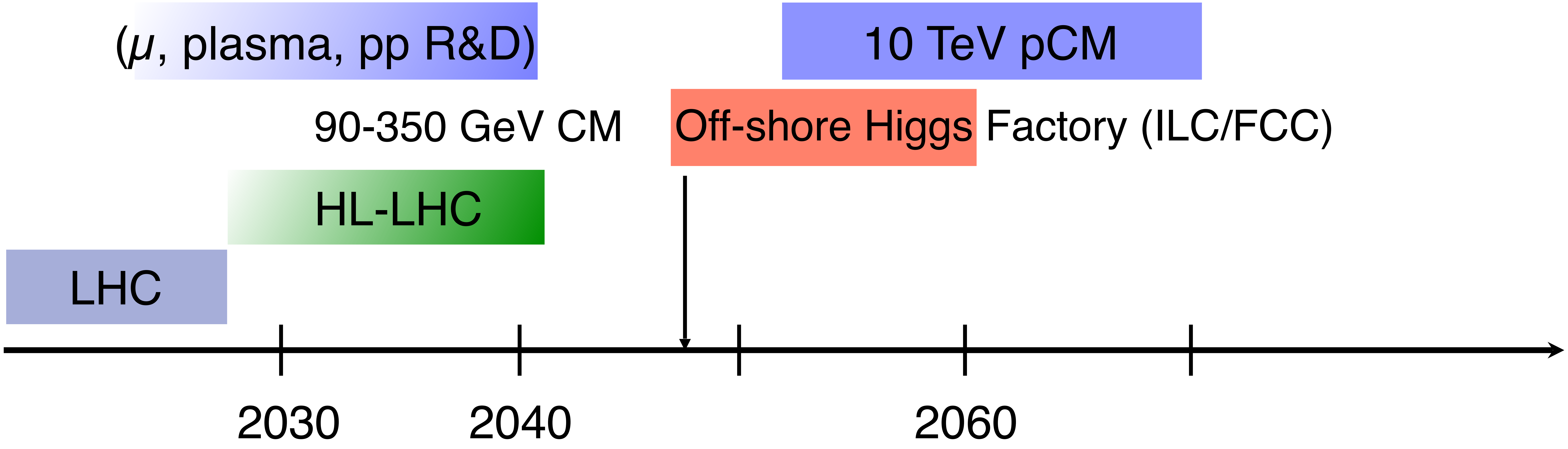
LHC

2030

2040

2060

post-P5 roadmap



(*μ*, plasma, pp R&D)

10 TeV pCM

90-350 GeV CM

Off-shore Higgs Factory (ILC/FCC)

HL-LHC

LHC

2030

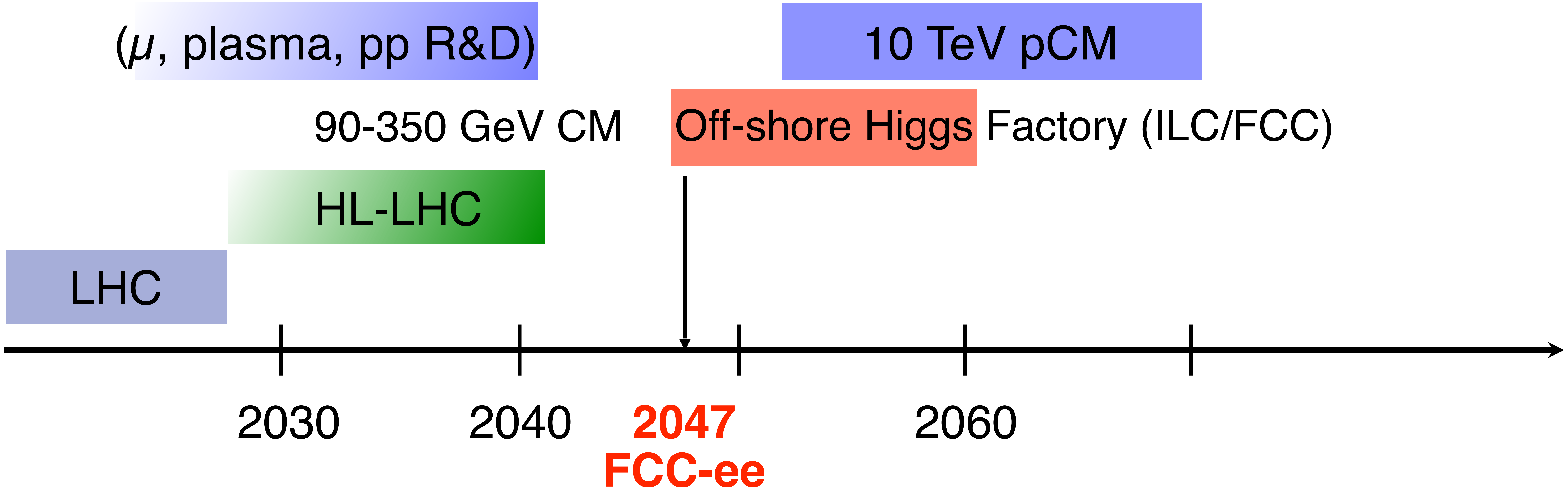
2040

2060

H couplings to: **O(5-10)%** **O(0.1-1)%**

H self-coupling to: **O(50)%** **O(1)%**

post-P5 roadmap



(μ, plasma, pp R&D)

10 TeV pCM

90-350 GeV CM

Off-shore Higgs Factory (ILC/FCC)

HL-LHC

LHC

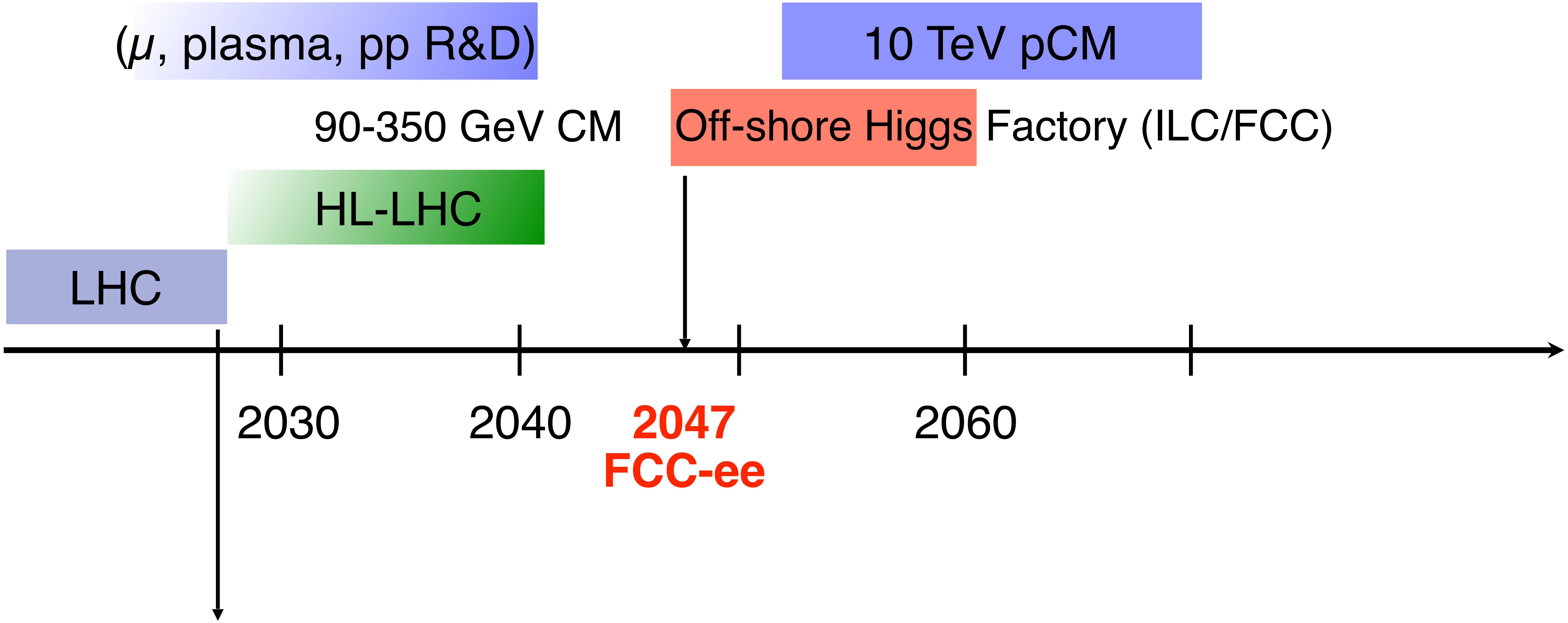
2030

2040

2047
FCC-ee

2060

post-P5 roadmap



(μ, plasma, pp R&D)

10 TeV pCM

90-350 GeV CM

Off-shore Higgs Factory (ILC/FCC)

HL-LHC

LHC

2030

2040

2047

FCC-ee

2060

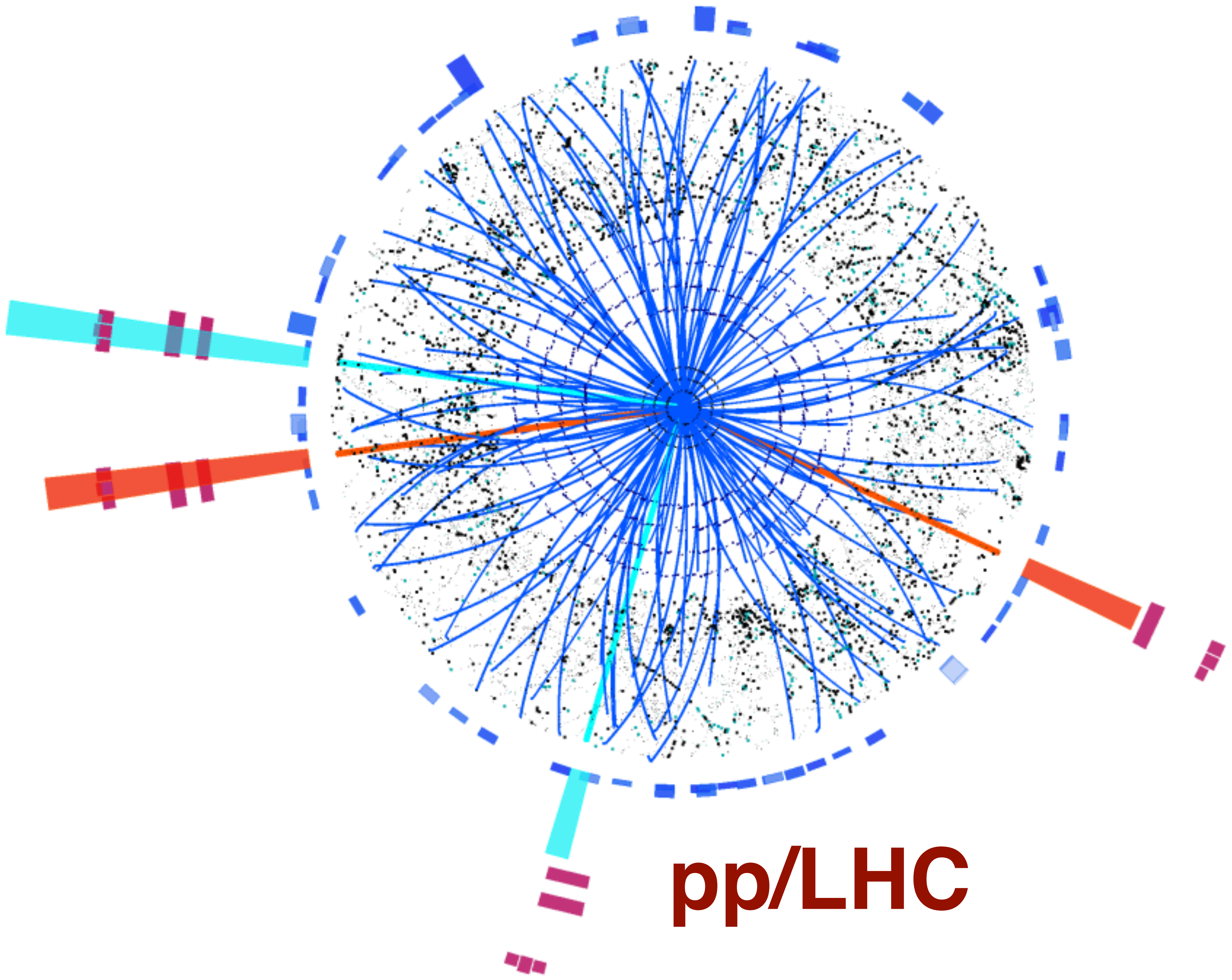
European Strategy for Particle Physics Update

FCC feasibility study report

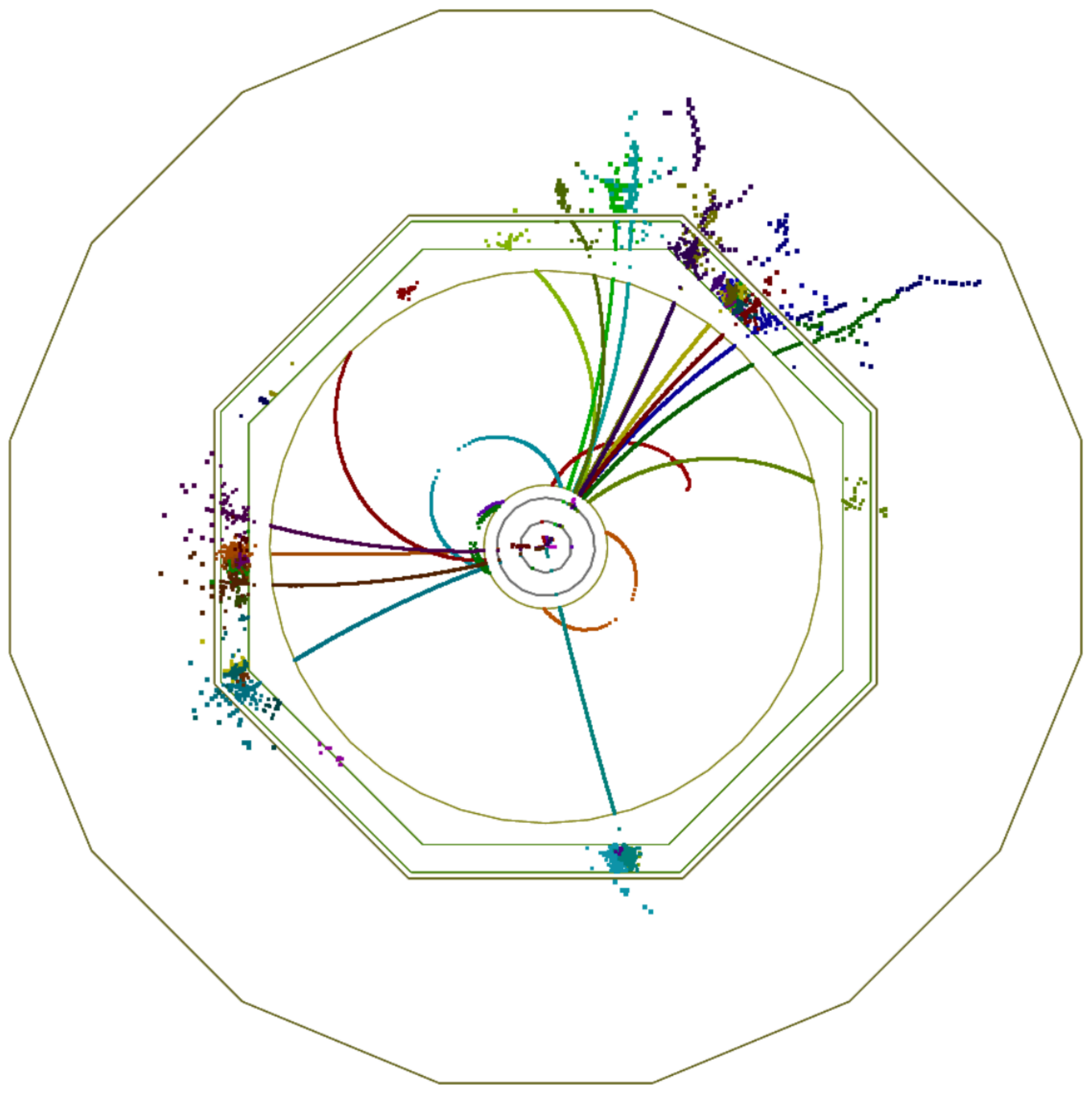
New Panel - mini P5

Why e^+e^-?

- Initial state well defined & polarization ⟹ High-precision measurements
- Higgs bosons appear in 1 in 100 events ⟹ Clean experimental environment and trigger-less readout

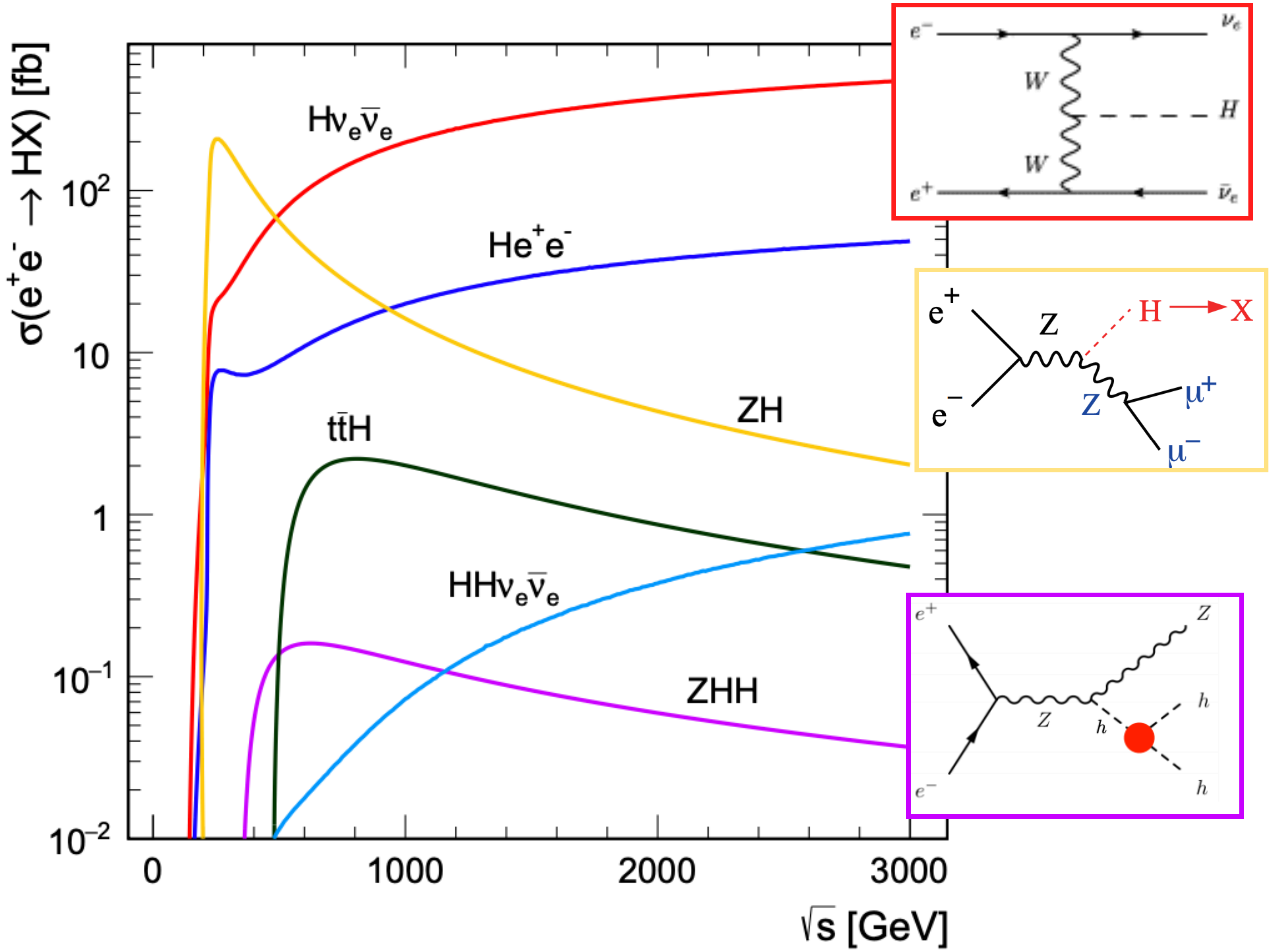


pp/LHC



e^+e^-

Higgs at e^+e^-

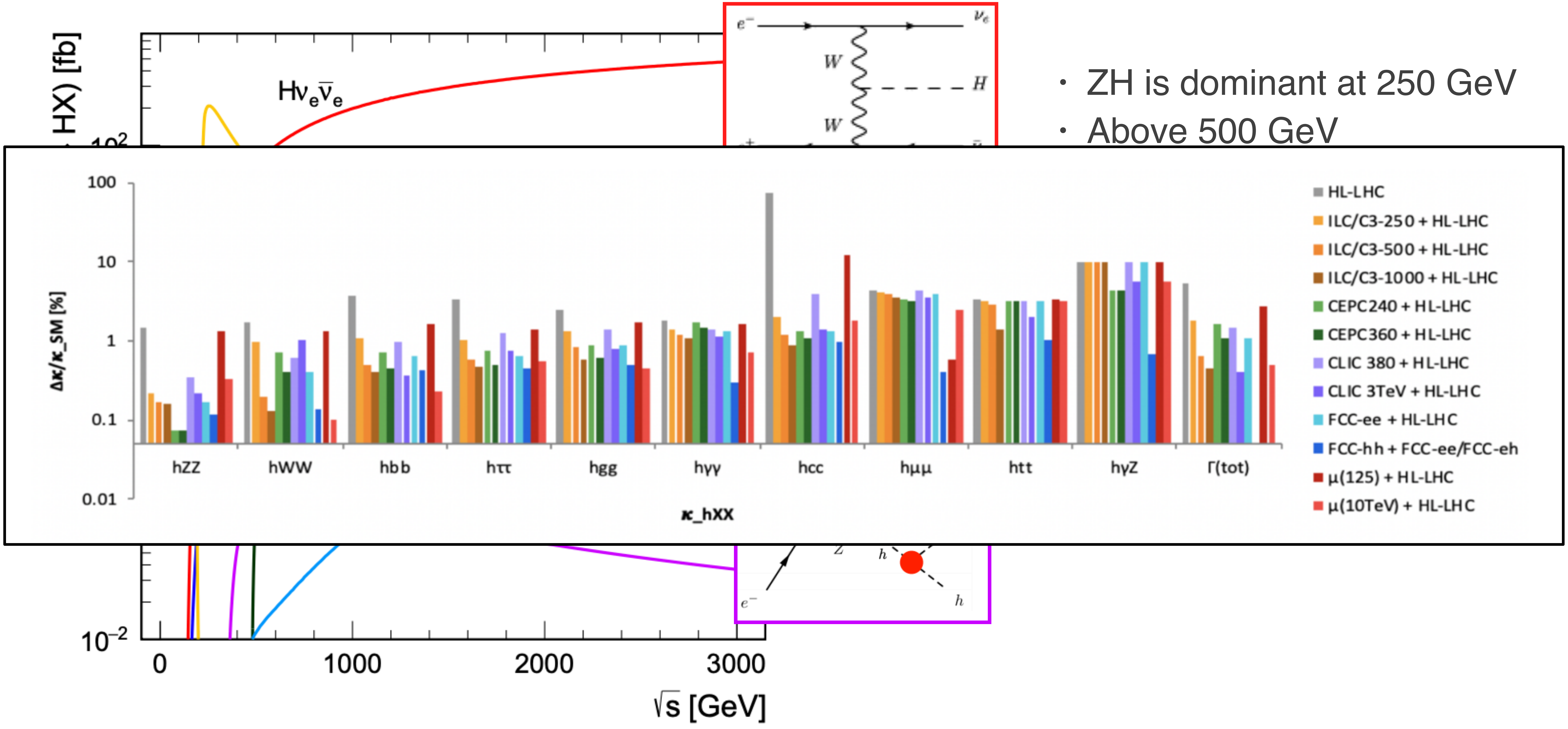


- ZH is dominant at 250 GeV
- Above 500 GeV
  - Hvv dominates
  - ttH opens up
  - **HH accessible with ZHH**

The Energy Frontier 2021 Snowmass Report

Higgs at e⁺e⁻

- ZH is dominant at 250 GeV
- Above 500 GeV



1811.00017
1908.11376
2101.04119

Beyond EFT, is there more?

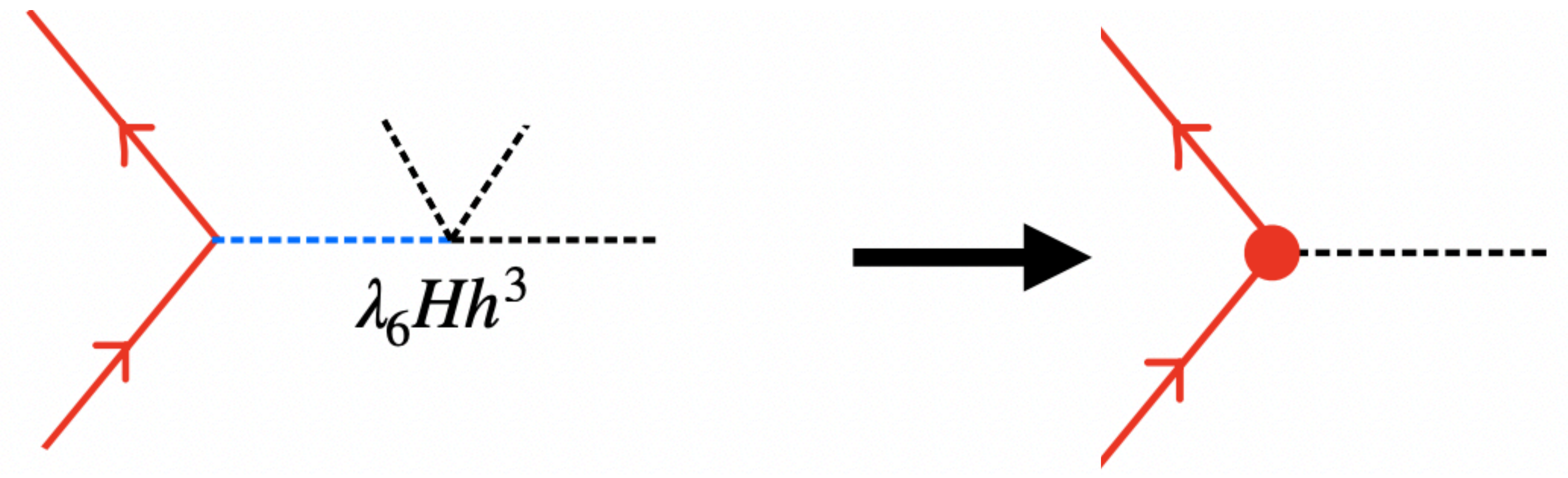
Higgs to strange coupling is an appealing signature to probe new physics

Is the Higgs the source for all flavor?

An option, **Spontaneous Flavor Violation**

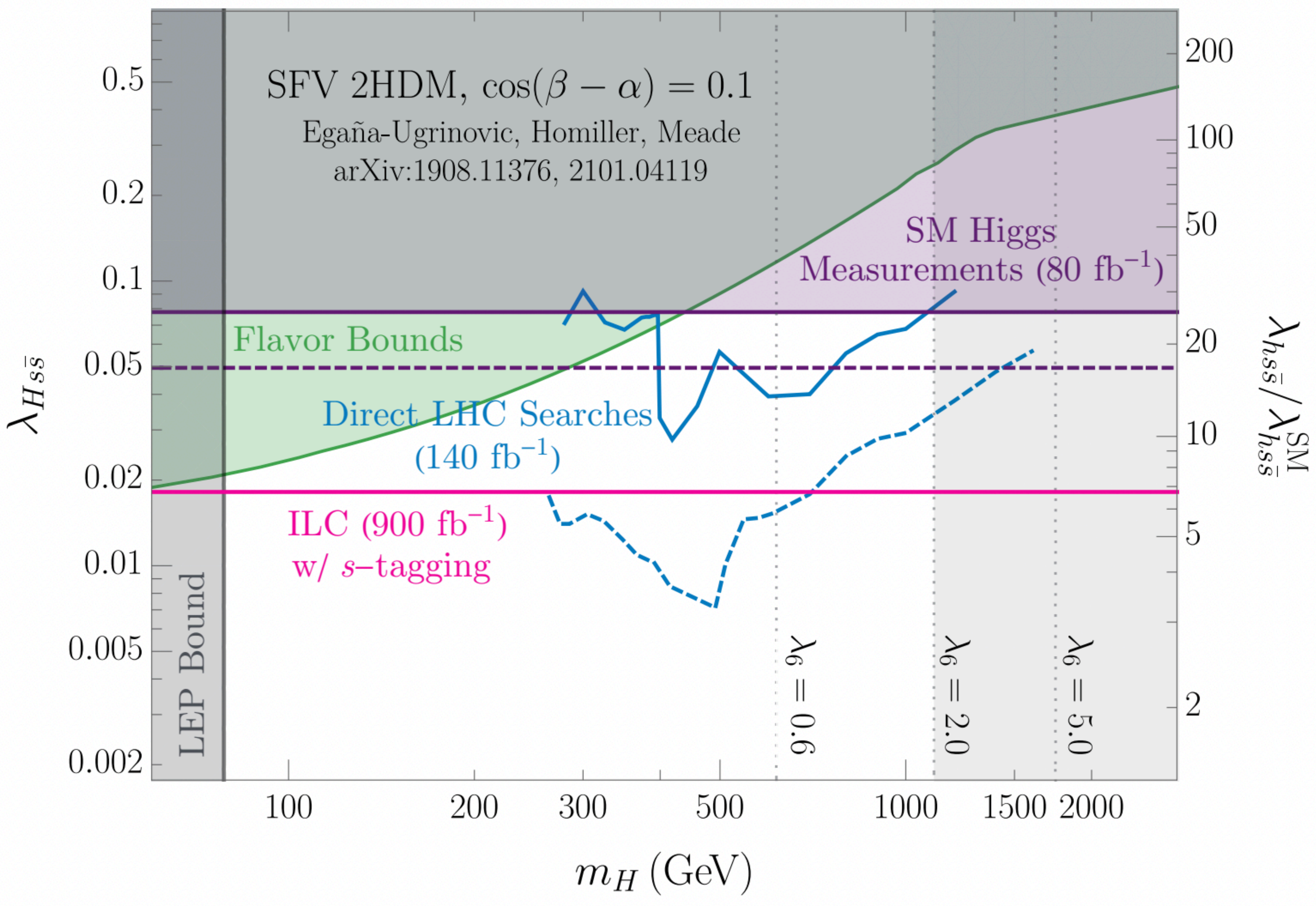
New physics can couple in a strongly flavor dependent way if it is aligned in the down-type quark or up-type quark sectors

- It allows for large couplings of additional Higgs to strange/light quarks
- No flavor-changing neutral currents



$\sim \frac{1}{\Lambda^2}(sh\bar{s})h^2$

P. Meade



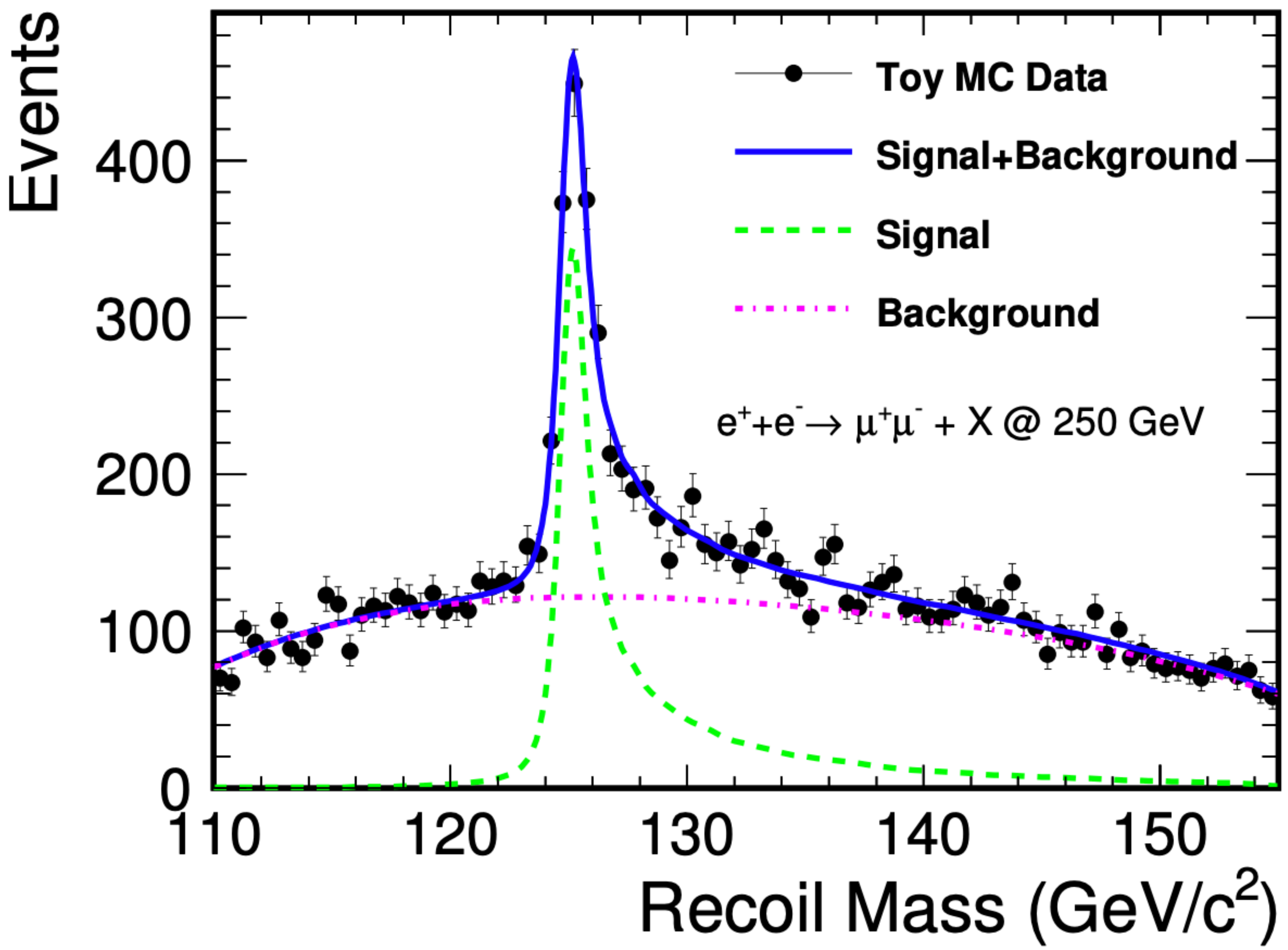
arXiv:2003.01116

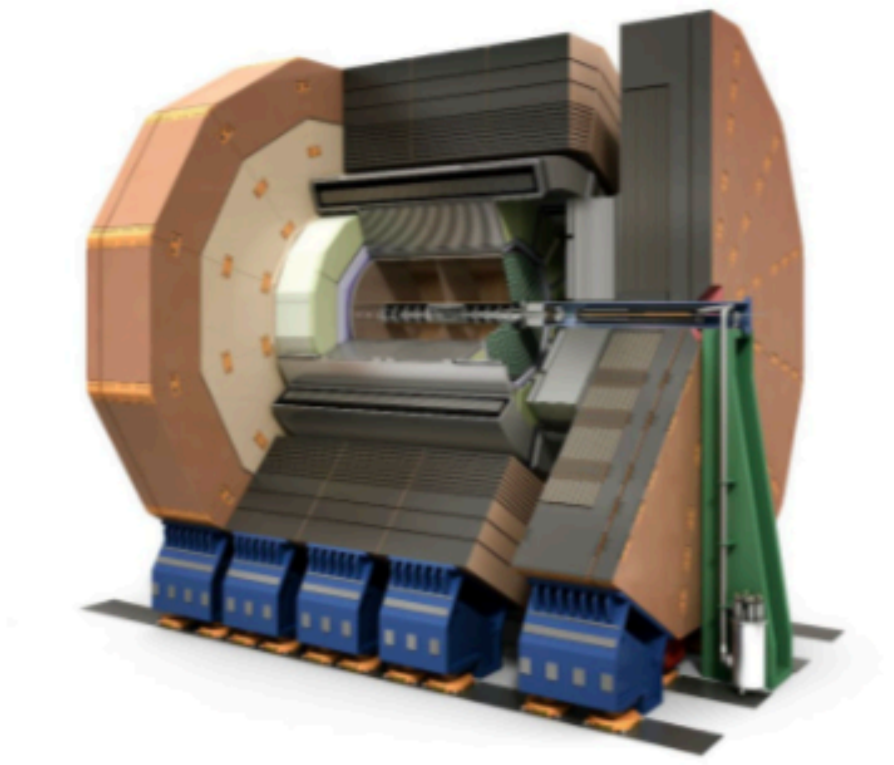
Detectors at future e^+e^-

Stringent detector requirements from ZH reconstruction

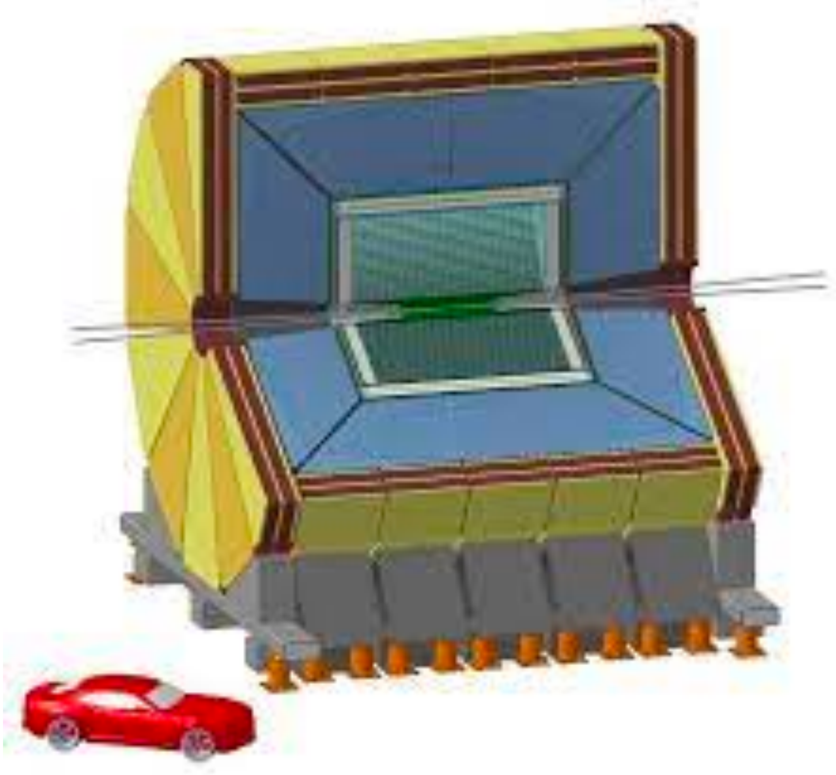
Detector designs at e^+e^- colliders are converging to very similar strategies

- Strong magnetic field 2-5 T
- (Ultra) low material budget tracker (<0.3% X0)
  - Close to the interaction region (10-25 mm)
- High granularity calorimetry
  - Particle Flow reconstruction → plays a big part in many designs

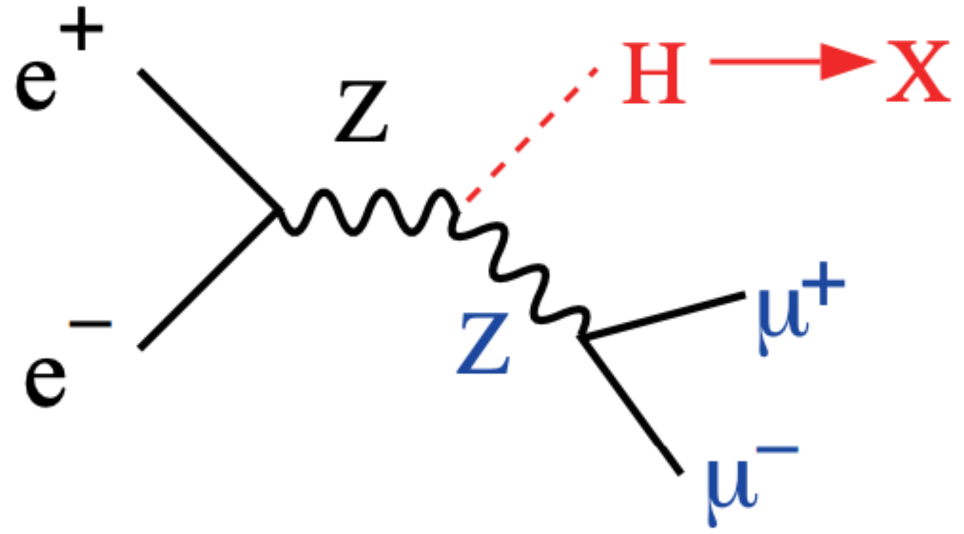




ILD



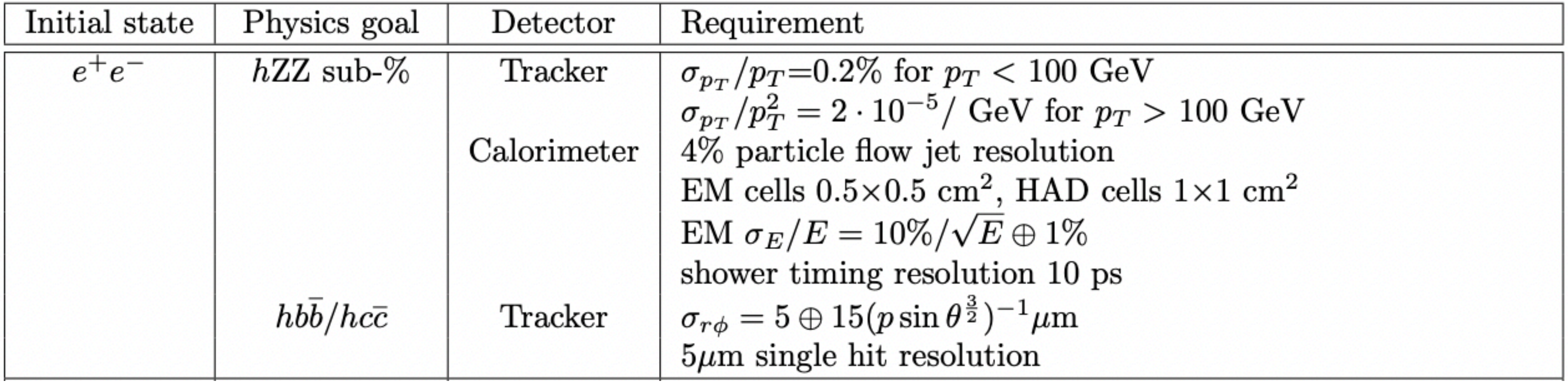
IDEA



Higgs physics as a driver for future detectors R&D

The goal of measuring Higgs properties with sub-% precision translates into ambitious requirements for detectors at e+e-

- Advancing HEP detectors to new regimes of sensitivity
- Building next-generation HEP detectors with novel materials & advanced techniques

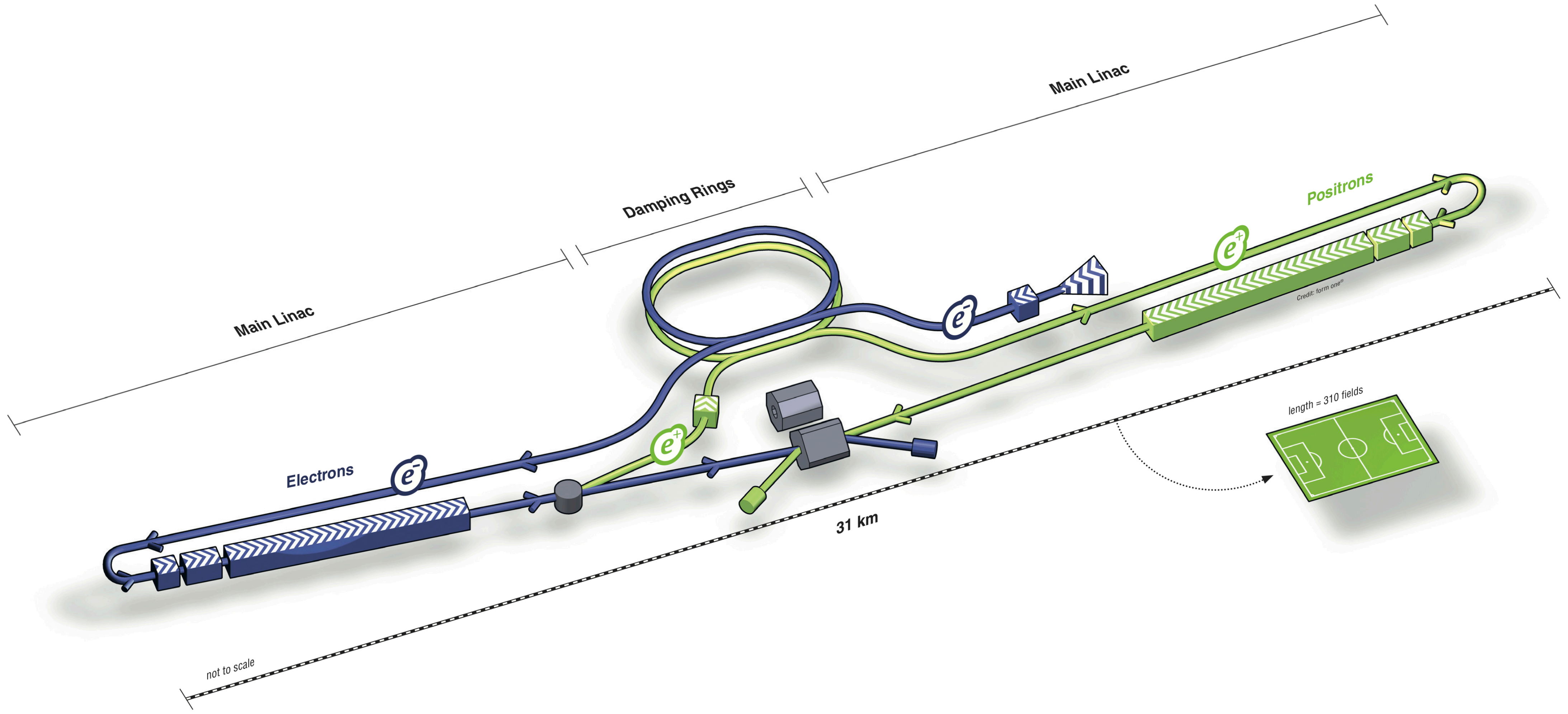


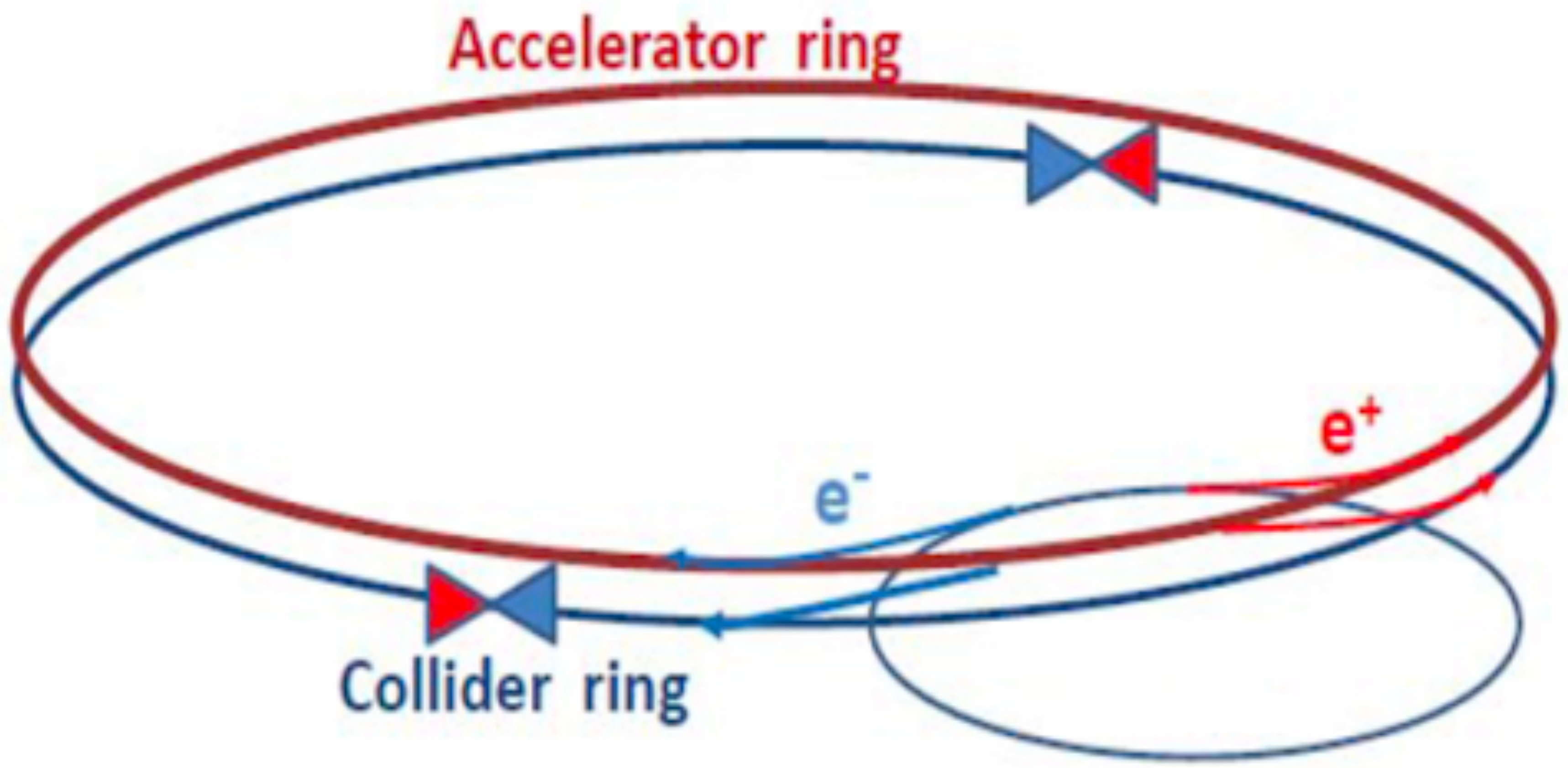
Initial state	Physics goal	Detector	Requirement
e^+e^-	hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV
			$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
		Calorimeter	4% particle flow jet resolution
			EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
			EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
			shower timing resolution 10 ps
	$hb\bar{b}/hc\bar{c}$	Tracker	$\sigma_{r\phi} = 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1} \mu\text{m}$
			5μm single hit resolution

Arxiv:2209.14111 Arxiv:2211.11084 DOE Basic Research Needs Study on Instrumentation

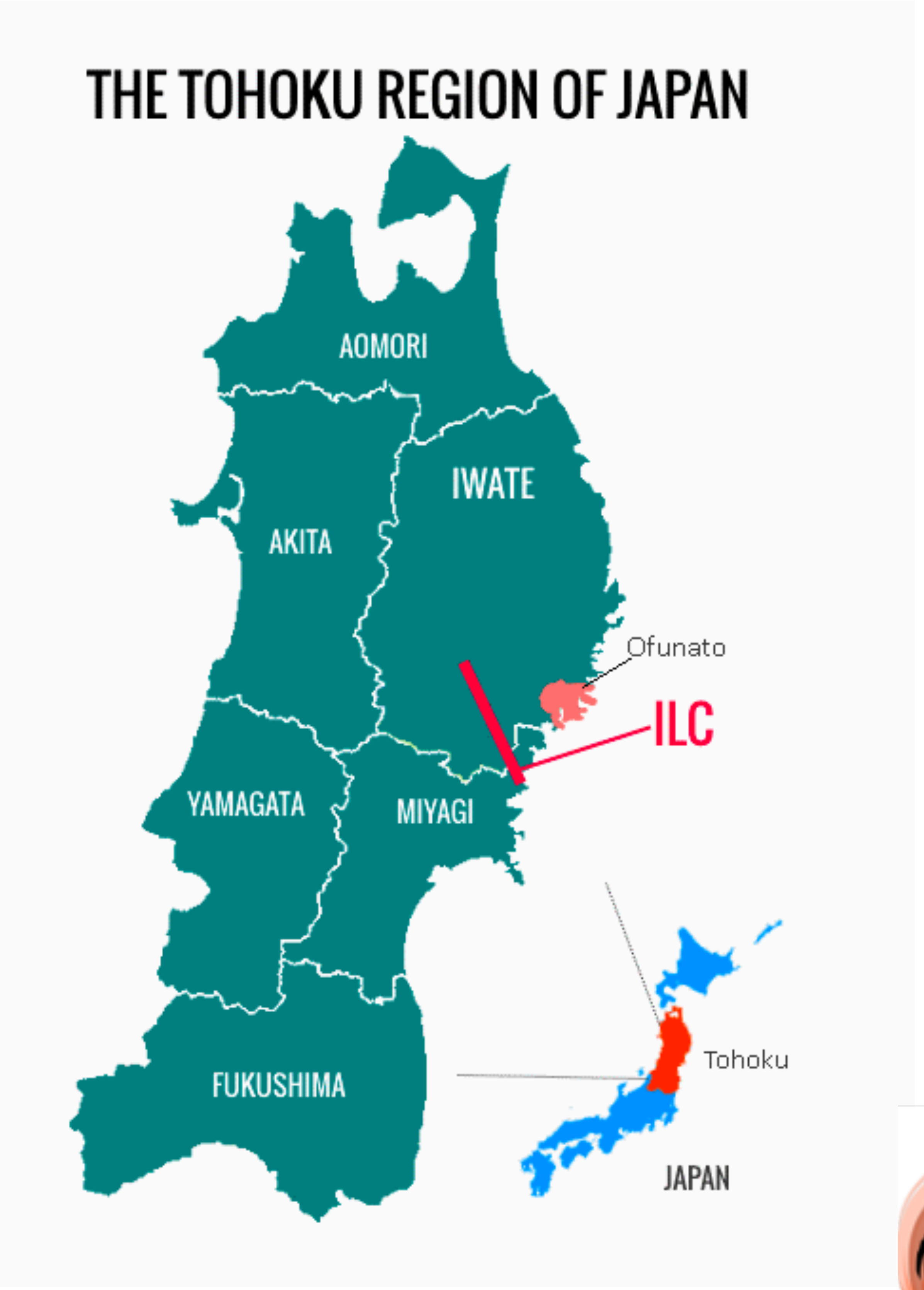
Linear vs. Circular

- **Linear** e^+e^- colliders
  - Reach **higher energies** (~ TeV)
  - Can use **polarized** beams
  - Relatively low radiation
  - Collisions in bunch trains
    - Power pulsing → Significant power saving for detectors
- **Circular** e^+e^- colliders
  - **Highest luminosity** collider at Z/WW/Zh
    - limited by synchrotron radiation above 350– 400 GeV
  - Beam continues to circulate after collision
    - No power pulsing, detectors need active cooling → more material
    - Limits magnetic field in detectors to 2T

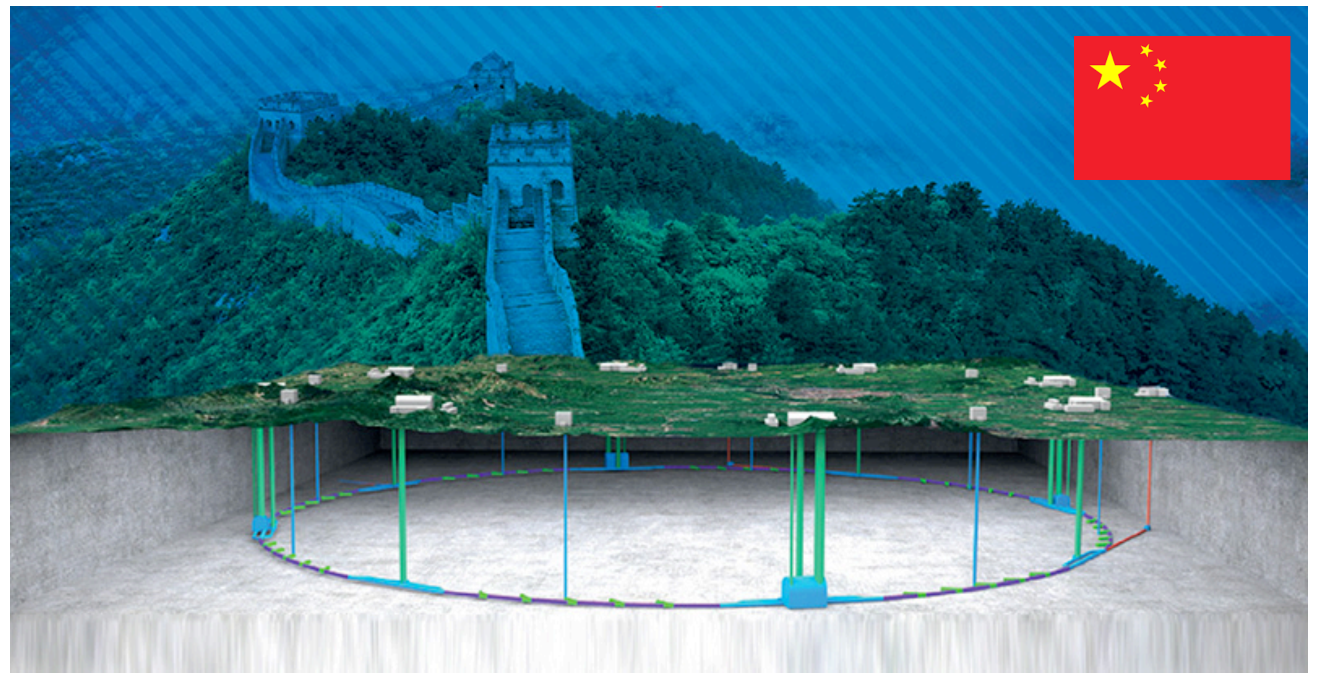




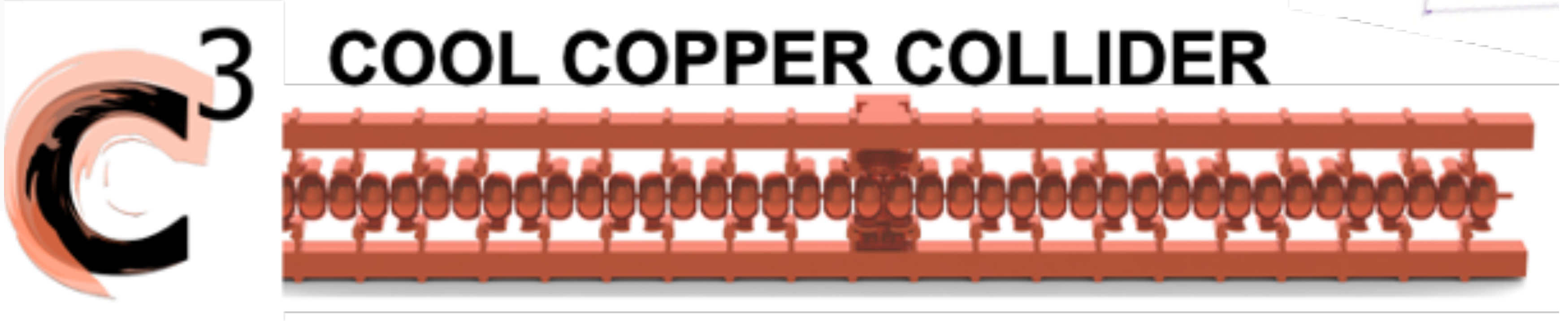
Various proposals …



250/500 GeV



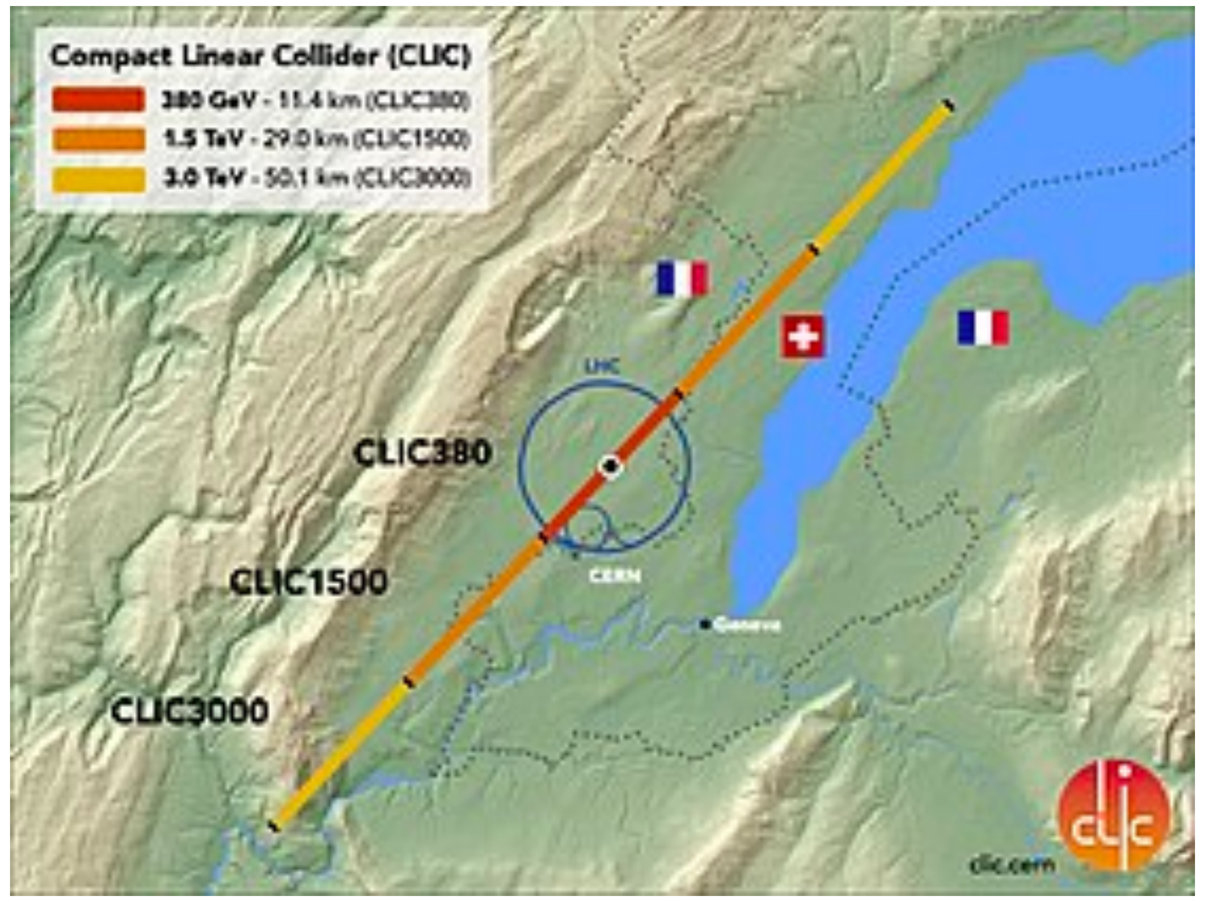
CEPC 240 GeV

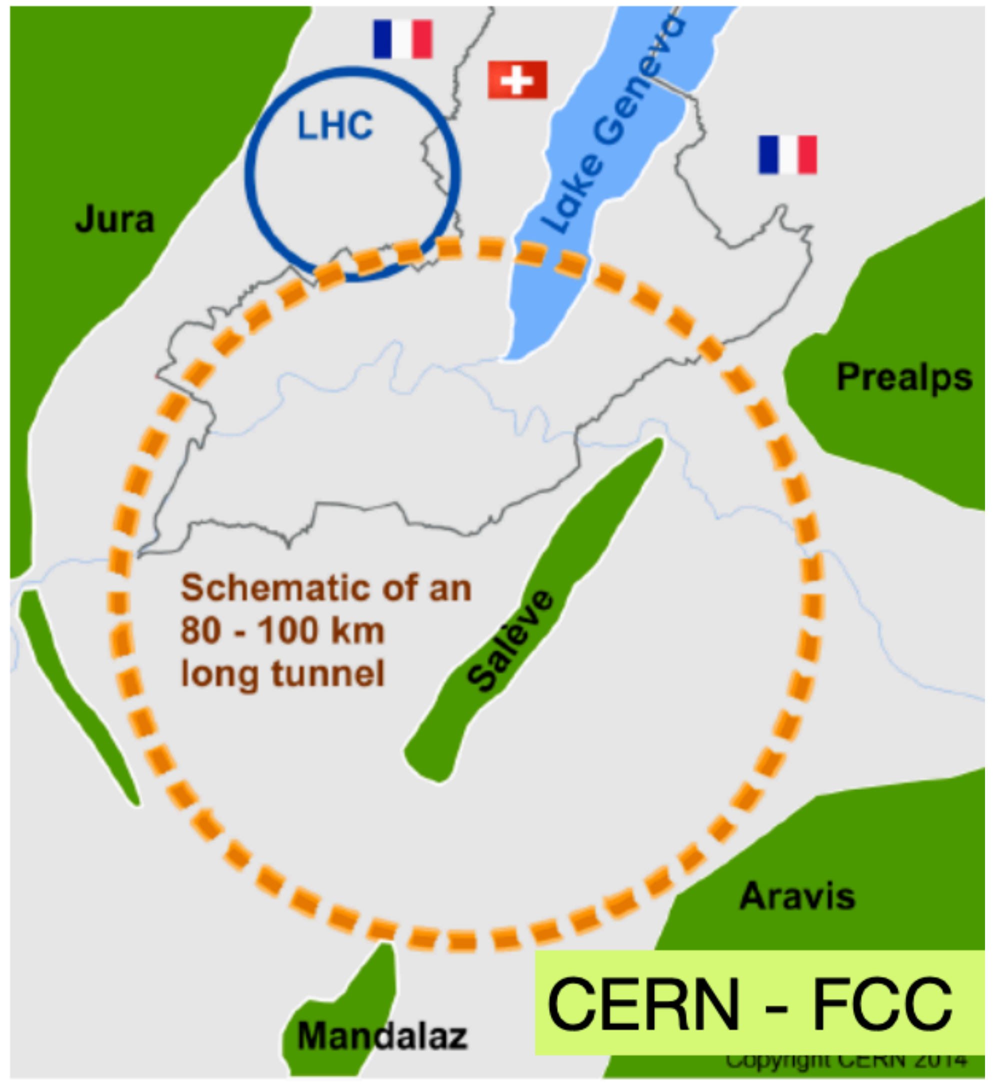


250/550 GeV

… > TeV

CLIC 380/1500/3000 GeV





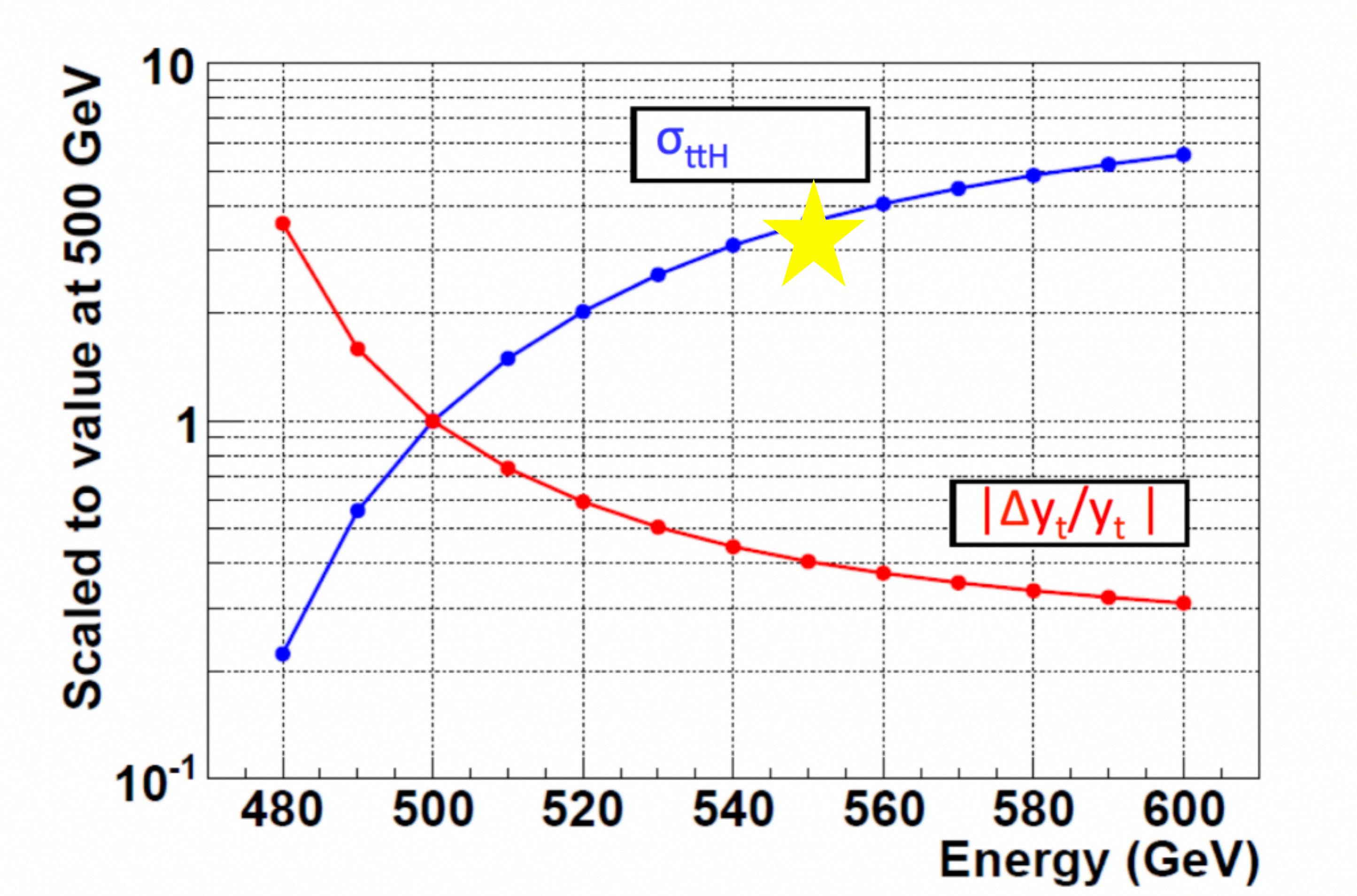
FCC-ee

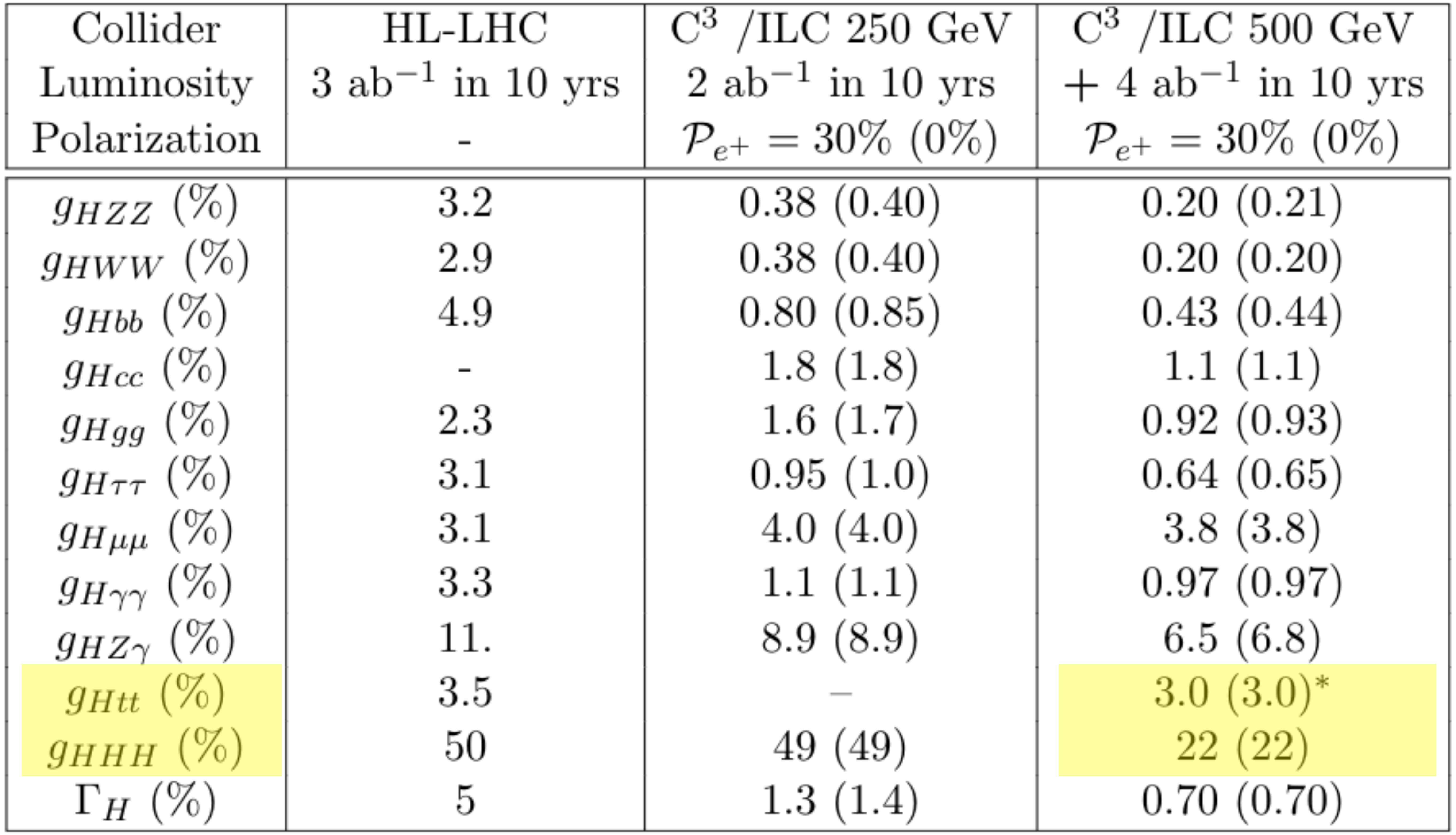
240/365 GeV

arXiv:1908.11299
arXiv:1506.07830

Why 550 GeV?

- We propose **250** GeV with a relatively inexpensive upgrade to **550** GeV on the same 8 km footprint.
- 550 GeV will offer an orthogonal dataset to cross-check a deviation from the SM predictions observed at 250 GeV
- O(20%) precision on the Higgs self-coupling would allow to exclude/ demonstrate at 5σ models of electroweak baryogenesis

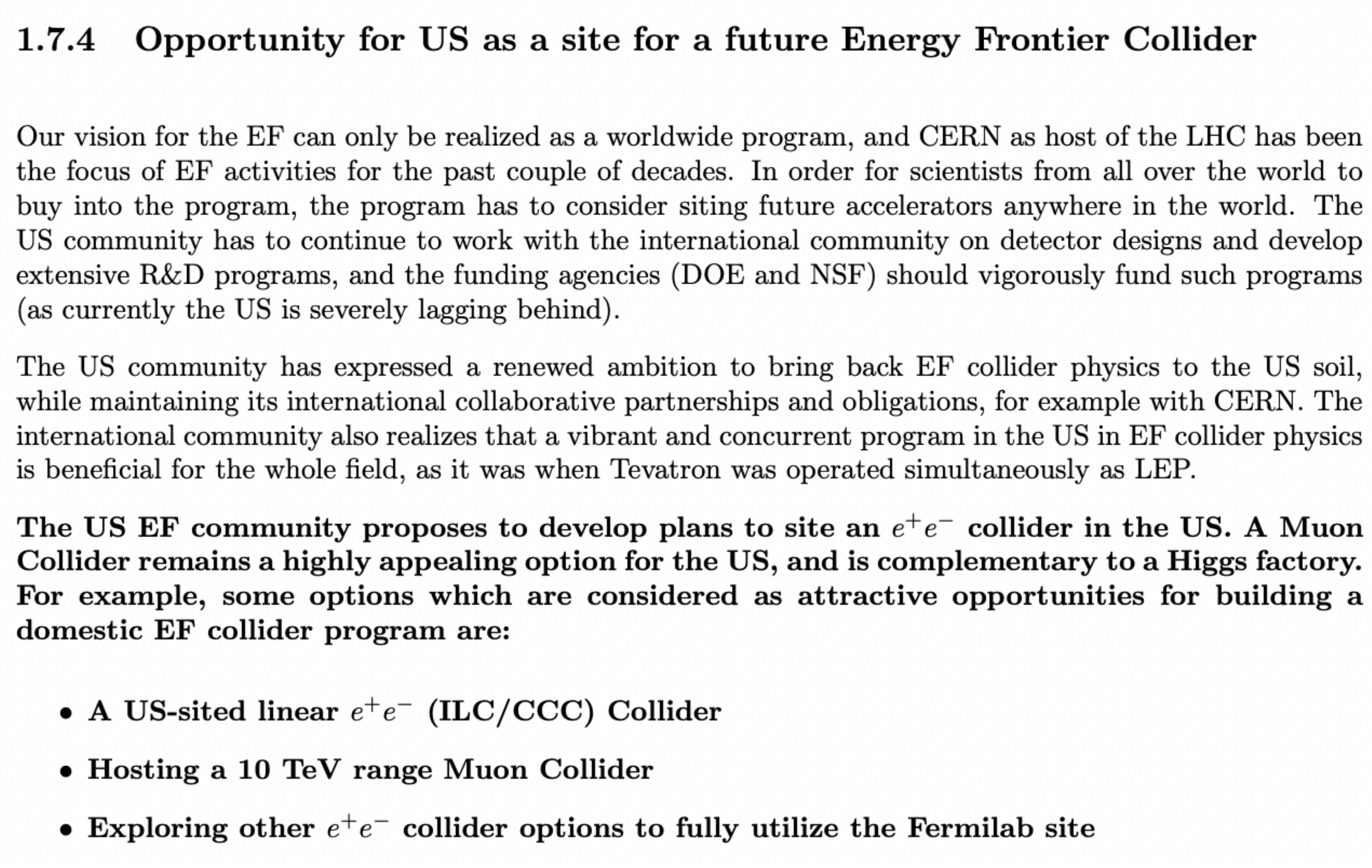




Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80 (0.85)	0.43 (0.44)
g_{Hcc} (%)	-	1.8 (1.8)	1.1 (1.1)
g_{Hgg} (%)	2.3	1.6 (1.7)	0.92 (0.93)
$g_{H\tau\tau}$ (%)	3.1	0.95 (1.0)	0.64 (0.65)
$g_{H\mu\mu}$ (%)	3.1	4.0 (4.0)	3.8 (3.8)
$g_{H\gamma\gamma}$ (%)	3.3	1.1 (1.1)	0.97 (0.97)
$g_{HZ\gamma}$ (%)	11.	8.9 (8.9)	6.5 (6.8)
g_{Htt} (%)	3.5	–	3.0 (3.0)*
g_{HHH} (%)	50	49 (49)	22 (22)
Γ_H (%)	5	1.3 (1.4)	0.70 (0.70)

At Snowmass

- C^3 has been evaluated independently by the Implementation Task Force along with the other proposals
- Strong engagement and support from Energy Frontier



1.7.4 Opportunity for US as a site for a future Energy Frontier Collider

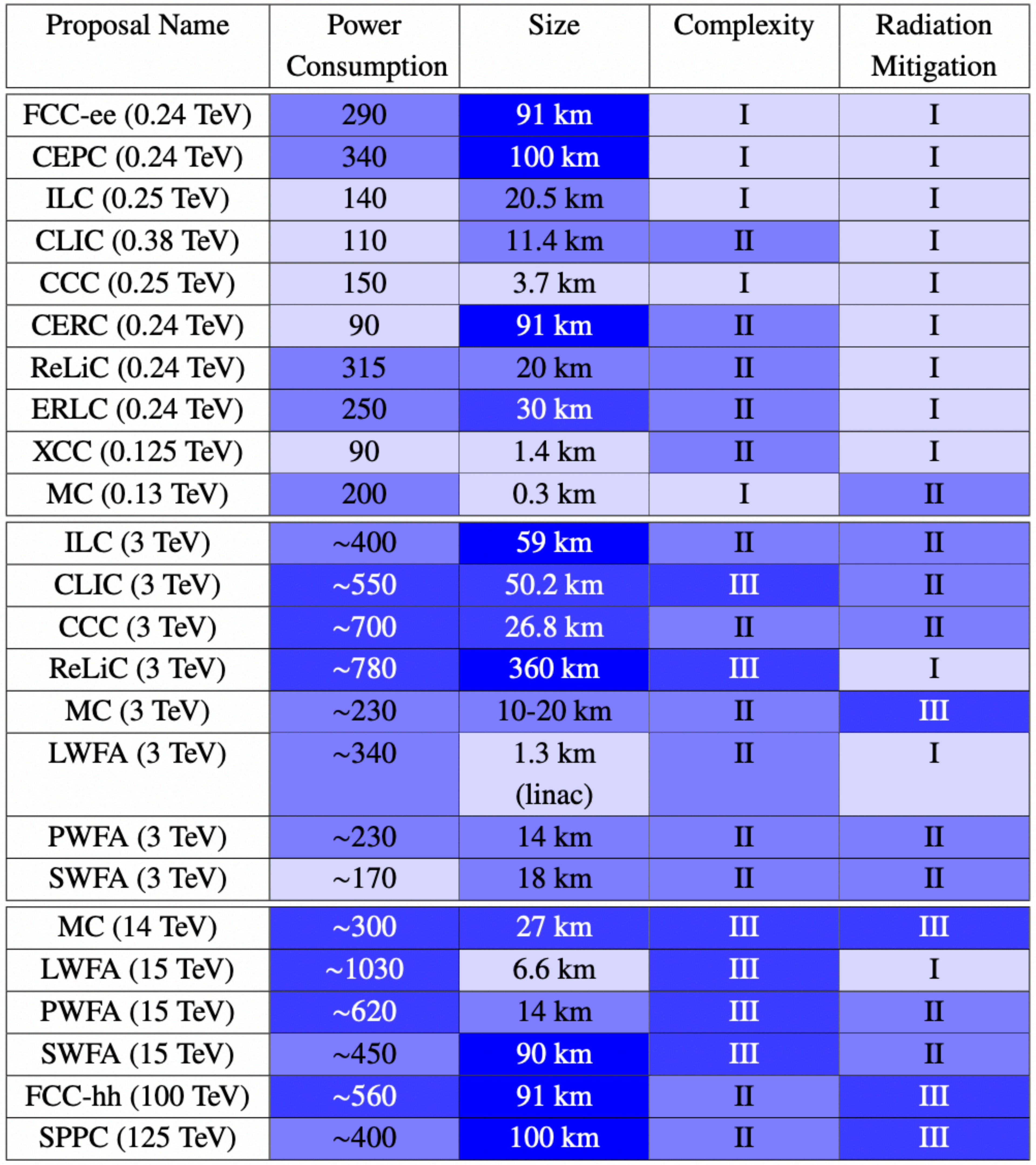
Our vision for the EF can only be realized as a worldwide program, and CERN as host of the LHC has been the focus of EF activities for the past couple of decades. In order for scientists from all over the world to buy into the program, the program has to consider siting future accelerators anywhere in the world. The US community has to continue to work with the international community on detector designs and develop extensive R&D programs, and the funding agencies (DOE and NSF) should vigorously fund such programs (as currently the US is severely lagging behind).

The US community has expressed a renewed ambition to bring back EF collider physics to the US soil, while maintaining its international collaborative partnerships and obligations, for example with CERN. The international community also realizes that a vibrant and concurrent program in the US in EF collider physics is beneficial for the whole field, as it was when Tevatron was operated simultaneously as LEP.

The US EF community proposes to develop plans to site an e^+e^- collider in the US. A Muon Collider remains a highly appealing option for the US, and is complementary to a Higgs factory. For example, some options which are considered as attractive opportunities for building a domestic EF collider program are:

- **A US-sited linear e^+e^- (ILC/CCC) Collider**
- **Hosting a 10 TeV range Muon Collider**
- **Exploring other e^+e^- collider options to fully utilize the Fermilab site**

ArXiv:2211.11084



Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I
CERC (0.24 TeV)	90	91 km	II	I
ReLiC (0.24 TeV)	315	20 km	II	I
ERLC (0.24 TeV)	250	30 km	II	I
XCC (0.125 TeV)	90	1.4 km	II	I
MC (0.13 TeV)	200	0.3 km	I	II
ILC (3 TeV)	~400	59 km	II	II
CLIC (3 TeV)	~550	50.2 km	III	II
CCC (3 TeV)	~700	26.8 km	II	II
ReLiC (3 TeV)	~780	360 km	III	I
MC (3 TeV)	~230	10-20 km	II	III
LWFA (3 TeV)	~340	1.3 km (linac)	II	I
PWFA (3 TeV)	~230	14 km	II	II
SWFA (3 TeV)	~170	18 km	II	II
MC (14 TeV)	~300	27 km	III	III
LWFA (15 TeV)	~1030	6.6 km	III	I
PWFA (15 TeV)	~620	14 km	III	II
SWFA (15 TeV)	~450	90 km	III	II
FCC-hh (100 TeV)	~560	91 km	II	III
SPPC (125 TeV)	~400	100 km	II	III

ArXiv:2208.06030

arXiv:2110.15800

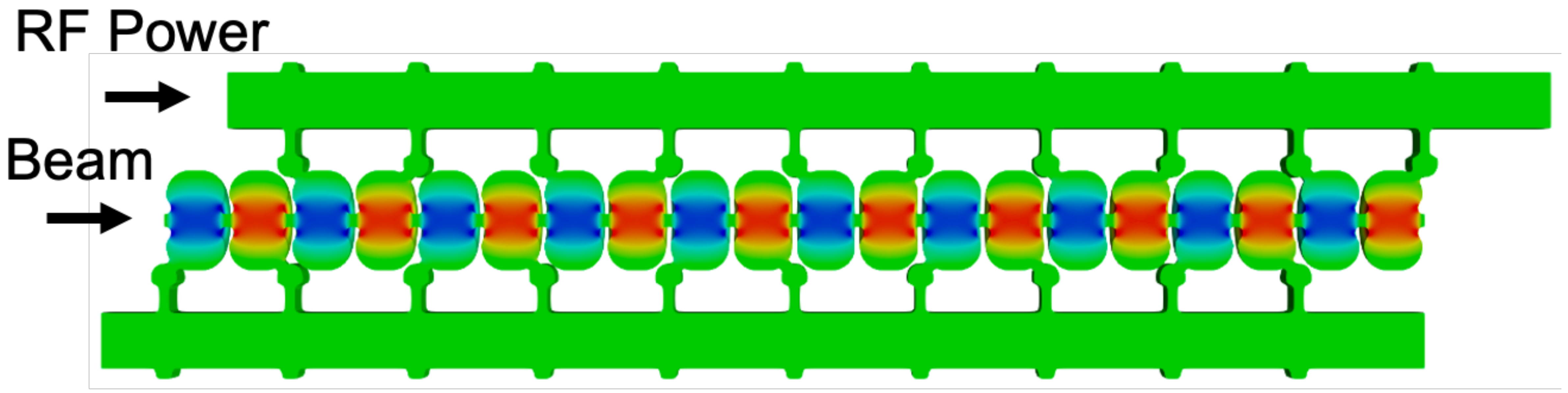
Tantawi, S et al. *PRAB* 23.9 (2020) 092001

C^3 The Cool Copper Collider

C^3 is a new linac **normal conducting technology**

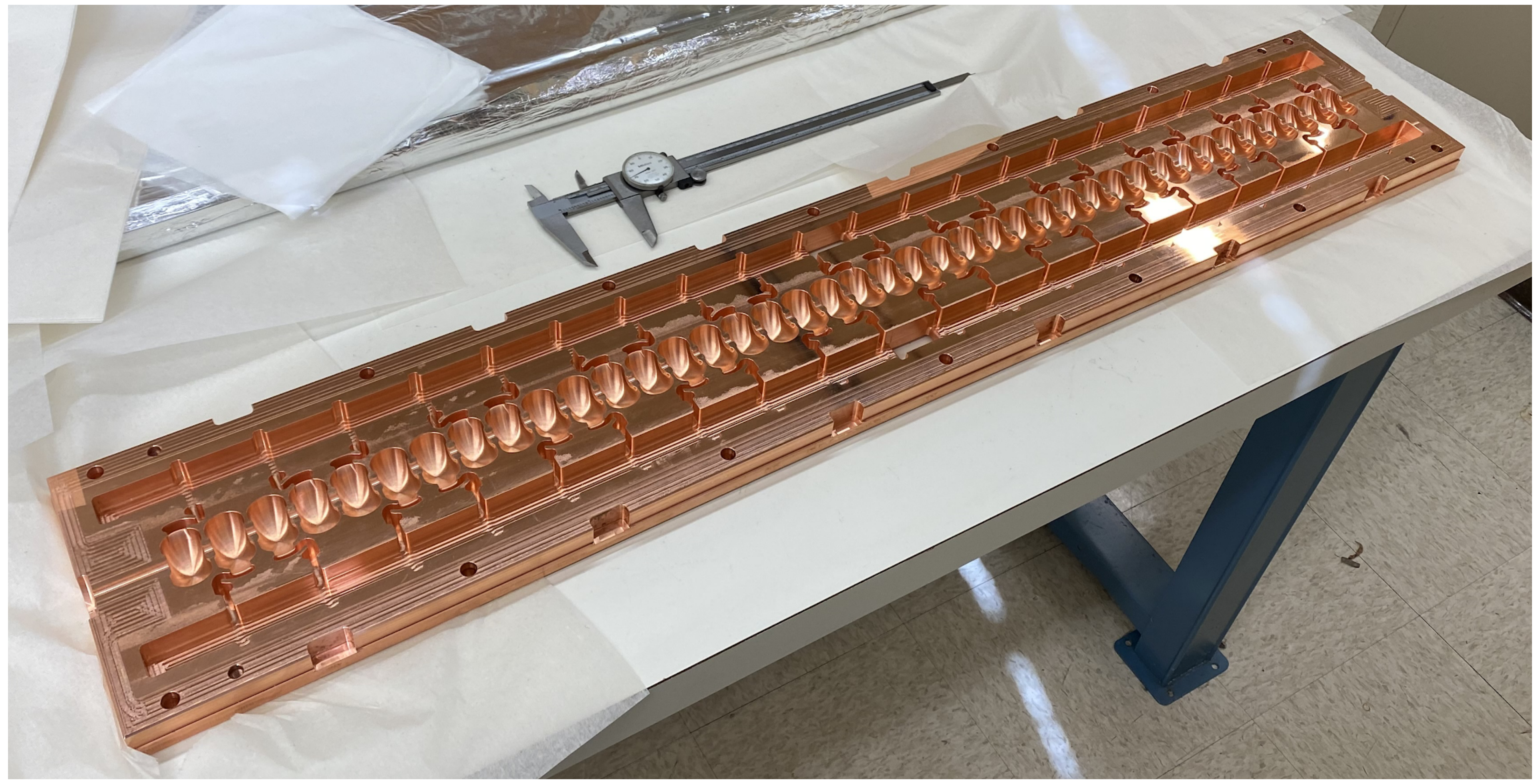
Optimize each cavity for maximum efficiency and lower surface fields

- Relatively small iris such that RF fundamental does not propagate through irises.
- RF power coupled to each cell – no on-axis coupling - required modern super-computing
  - Distributed power to each cavity from a common RF manifold
  - Mechanical realization by modern CNC milling



Electric field magnitude for equal power from RF manifold

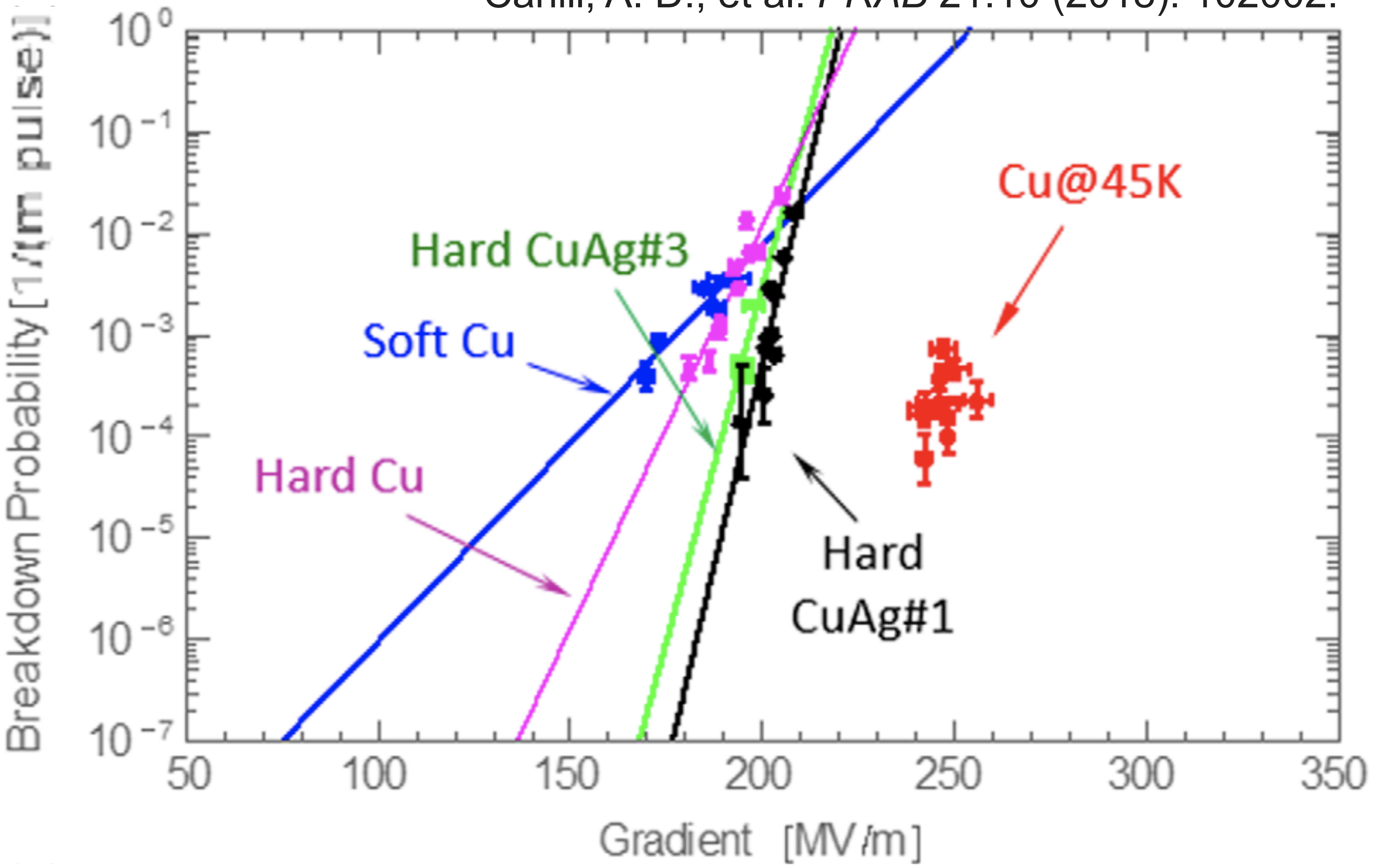
First C^3 structure at SLAC

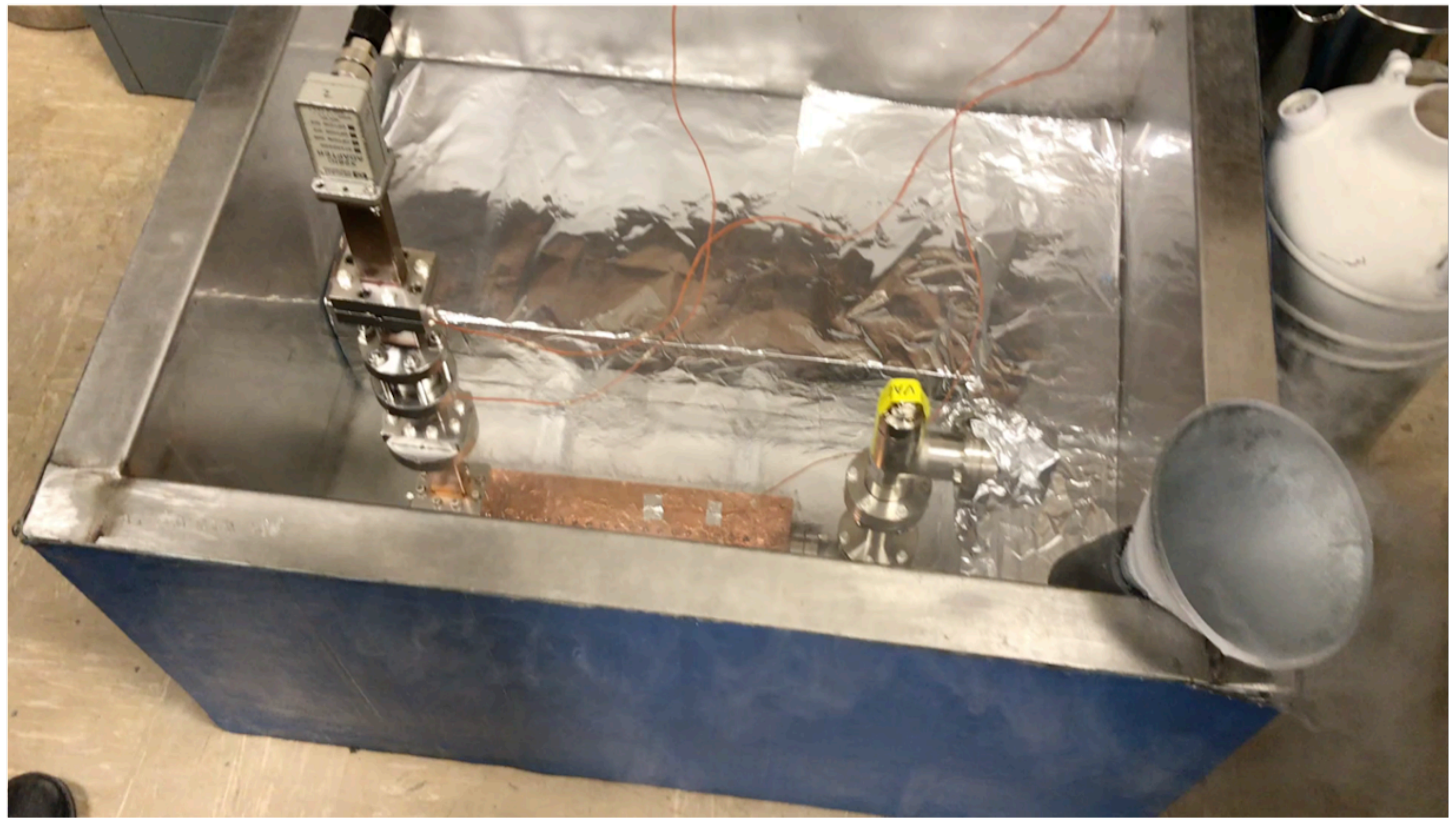


ArXiv:2210.17022

Why cool?

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





Nasr, et al. *PRAB* 24.9 (2021): 093201.

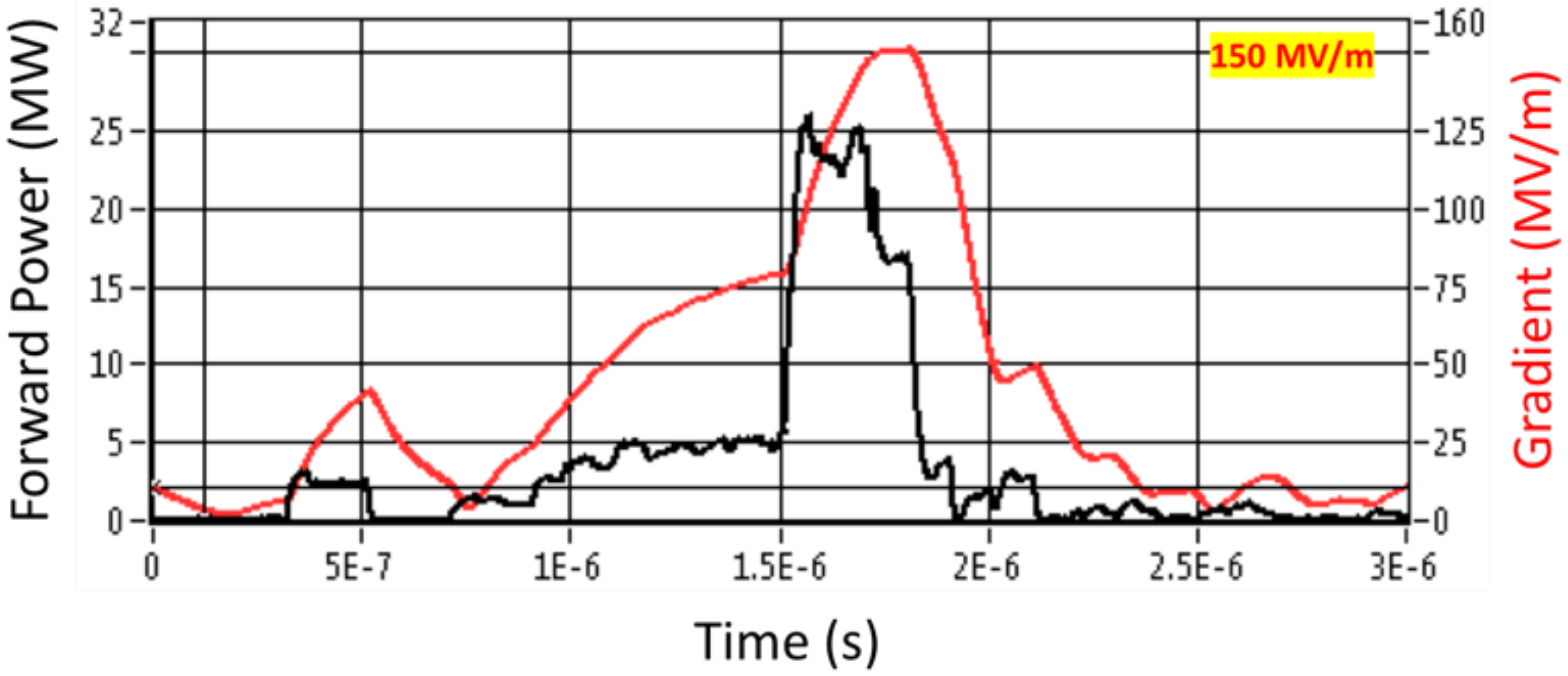
- Cryogenic temperature elevates performance in gradient
  - Increased material strength for gradient
  - Increase electrical conductivity reduces pulsed heating in the material
- Operation at 77 K with liquid nitrogen is simple and practical

arXiv:2110.15800

Expected gradient

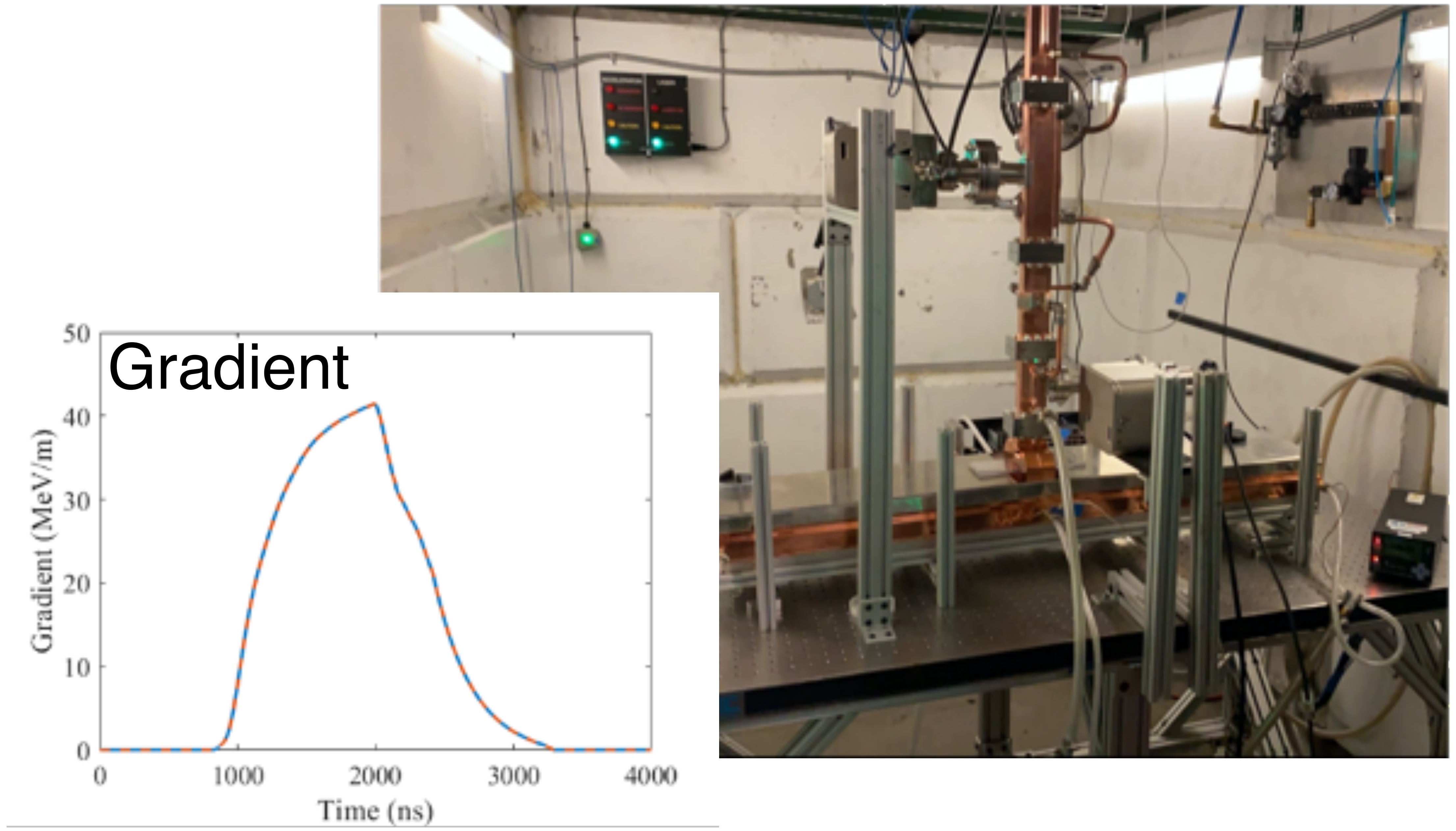
- Robust operations at high gradient: 120 MeV/m
  - Start at 70 MeV/m for C^3-250
- Scalable to multi-TeV operations

High Gradient Operation at 150 MV/m



Cryogenic Operation at X-band

High Power Test at Radiabeam



Accelerator Complex

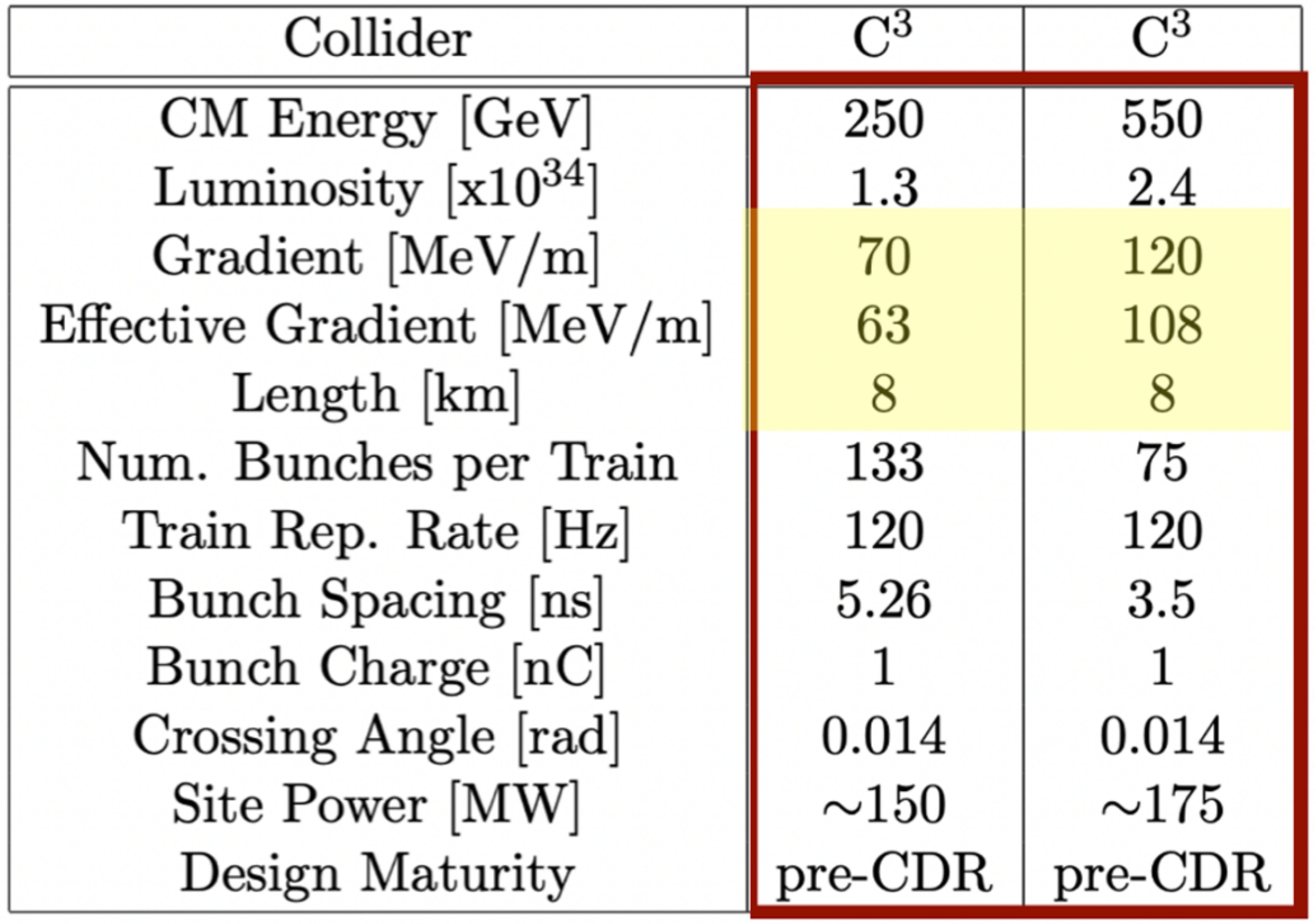
8 km footprint for 250/550 GeV CoM $\Longrightarrow$ 70/120 MeV/m

- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site

Large portions of accelerator complex compatible between LC technologies

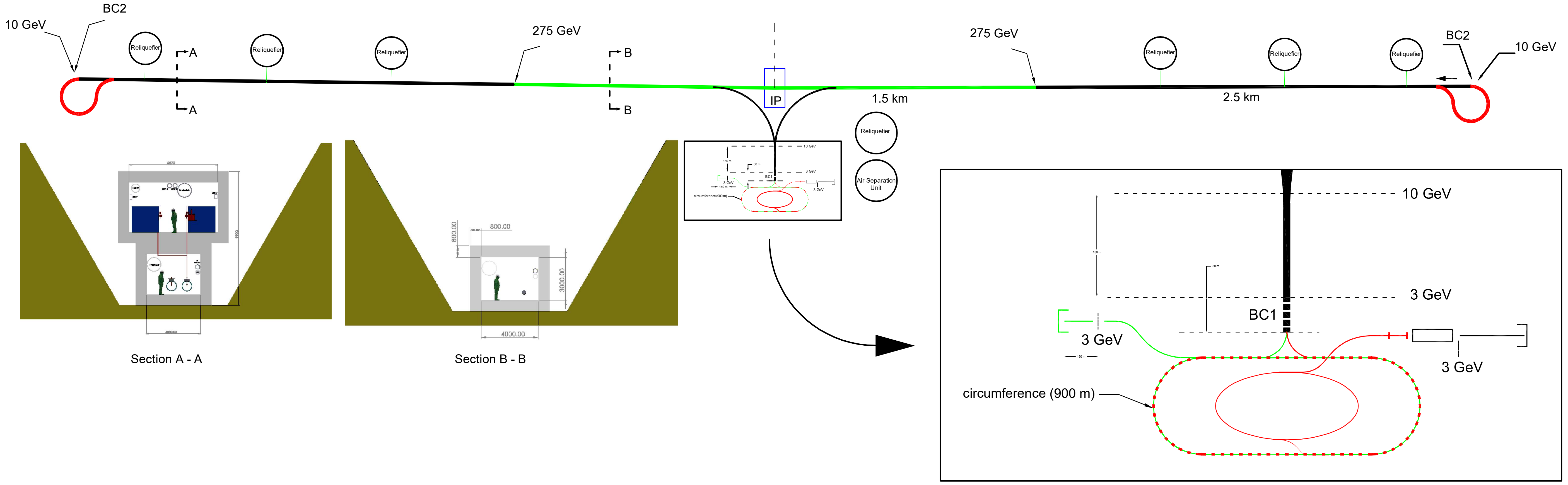
- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline

C^3 Parameters



Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

C^3 - 8 km Footprint for 250/550 GeV



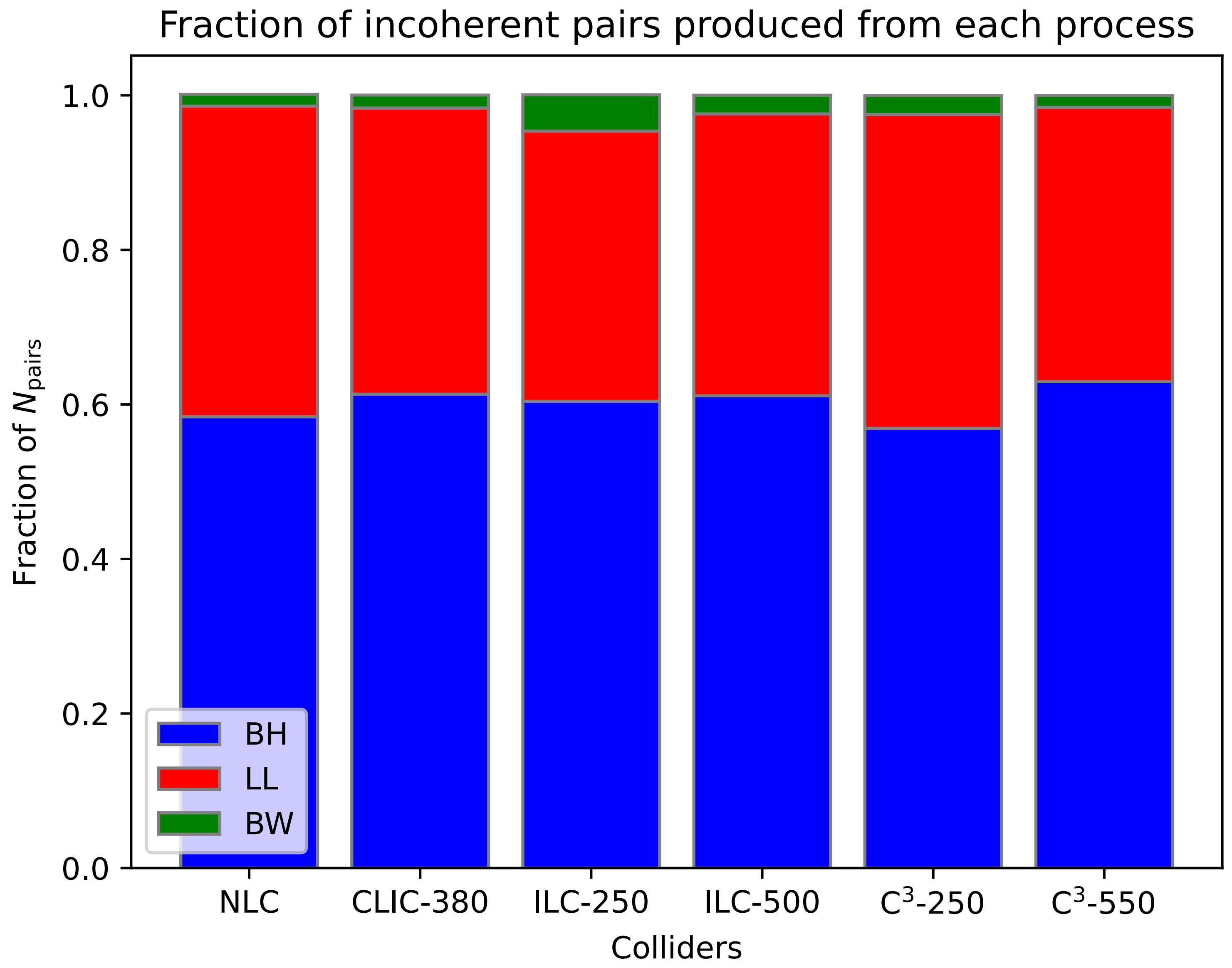
Joint simulation/detector optimization effort with ILC groups
Contacts CV and Lindsey Gray

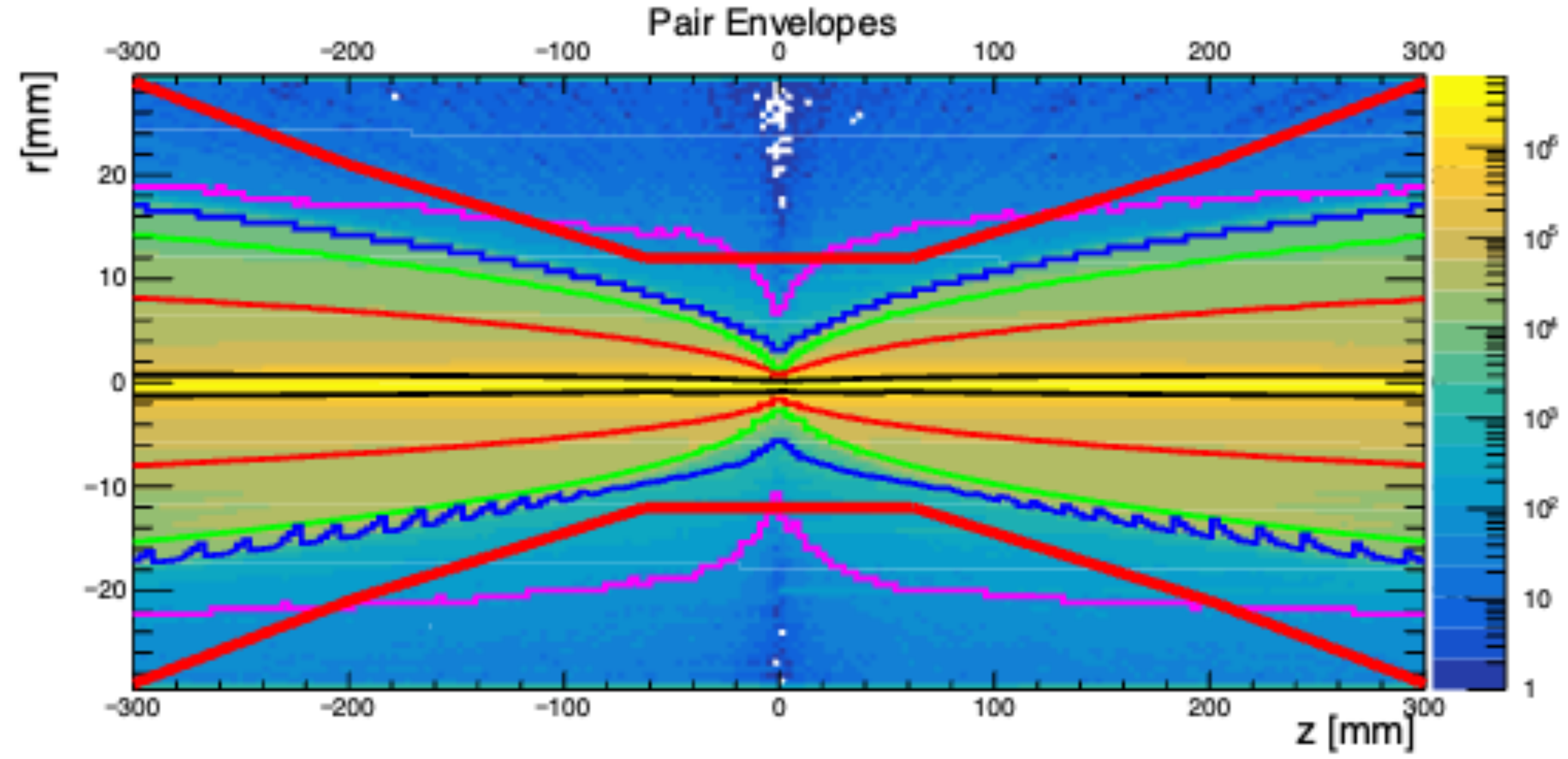
Importance of beam-beam background

The effects of beam-beam interactions have to be careful simulated for physics and detector performance

- Beamstrahlung photons are radiated when the two bunches intersect at the IP and can produce additional background particles
  - Incoherent pair production
    - Bethe-Heitler (BH): interaction of BS photon with a virtual photon
    - Landau-Lifschitz (LL): interaction of two virtual photons
    - Breit-Wheeler (BW): interaction of two BS photons
  - Muon and Hadron photo-production

- Beamstrahlung widens the luminosity spectrum considerably
  - Enables collisions at lower $\sqrt{s}$ and softens initial state constraints → important for kinematic fits,
  - Photoproduced jets affect clustering performance, JER, JES
- High flux in vertex barrel and forward sub detectors
  - Increase in detector occupancy → Impacts detector design



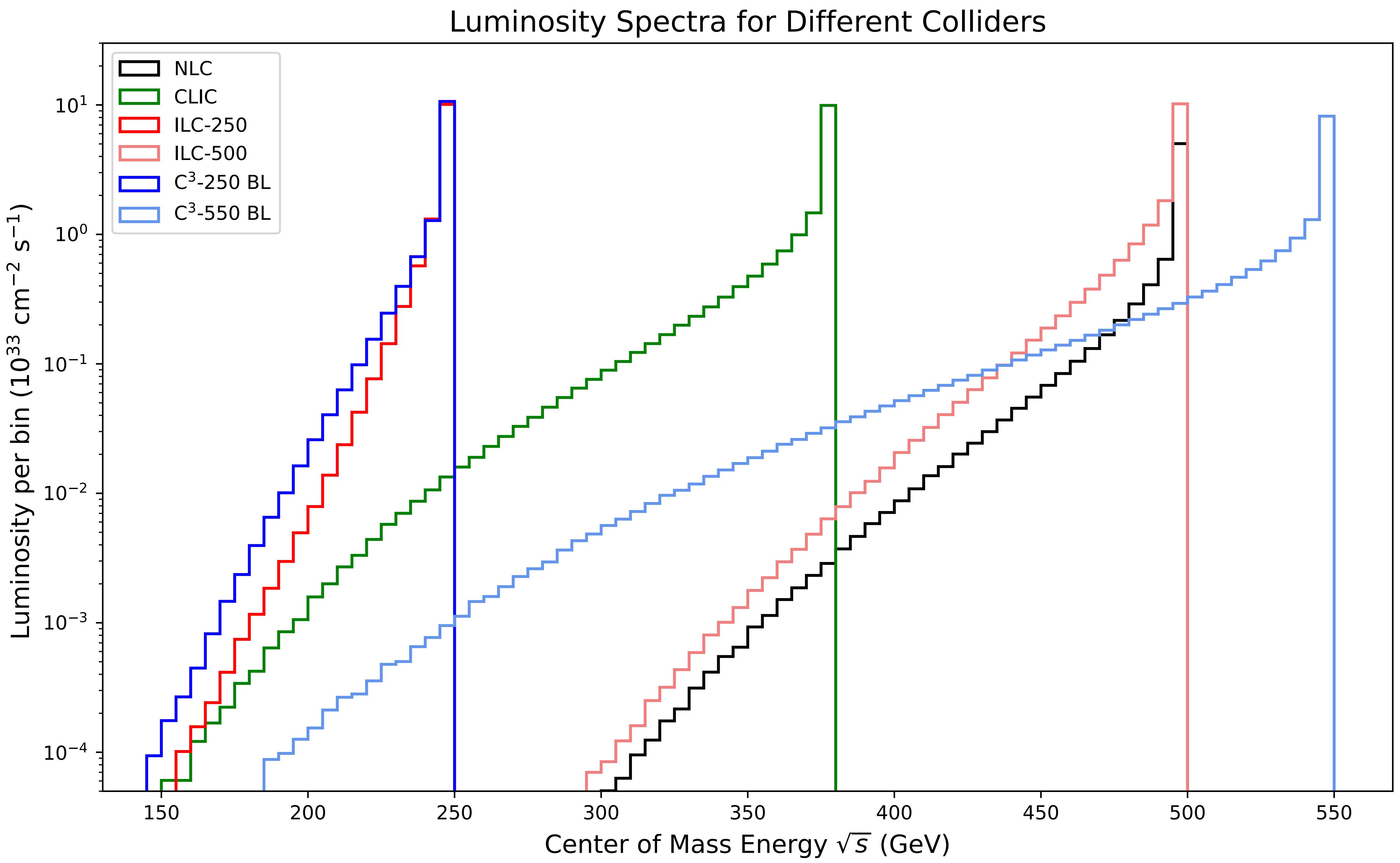


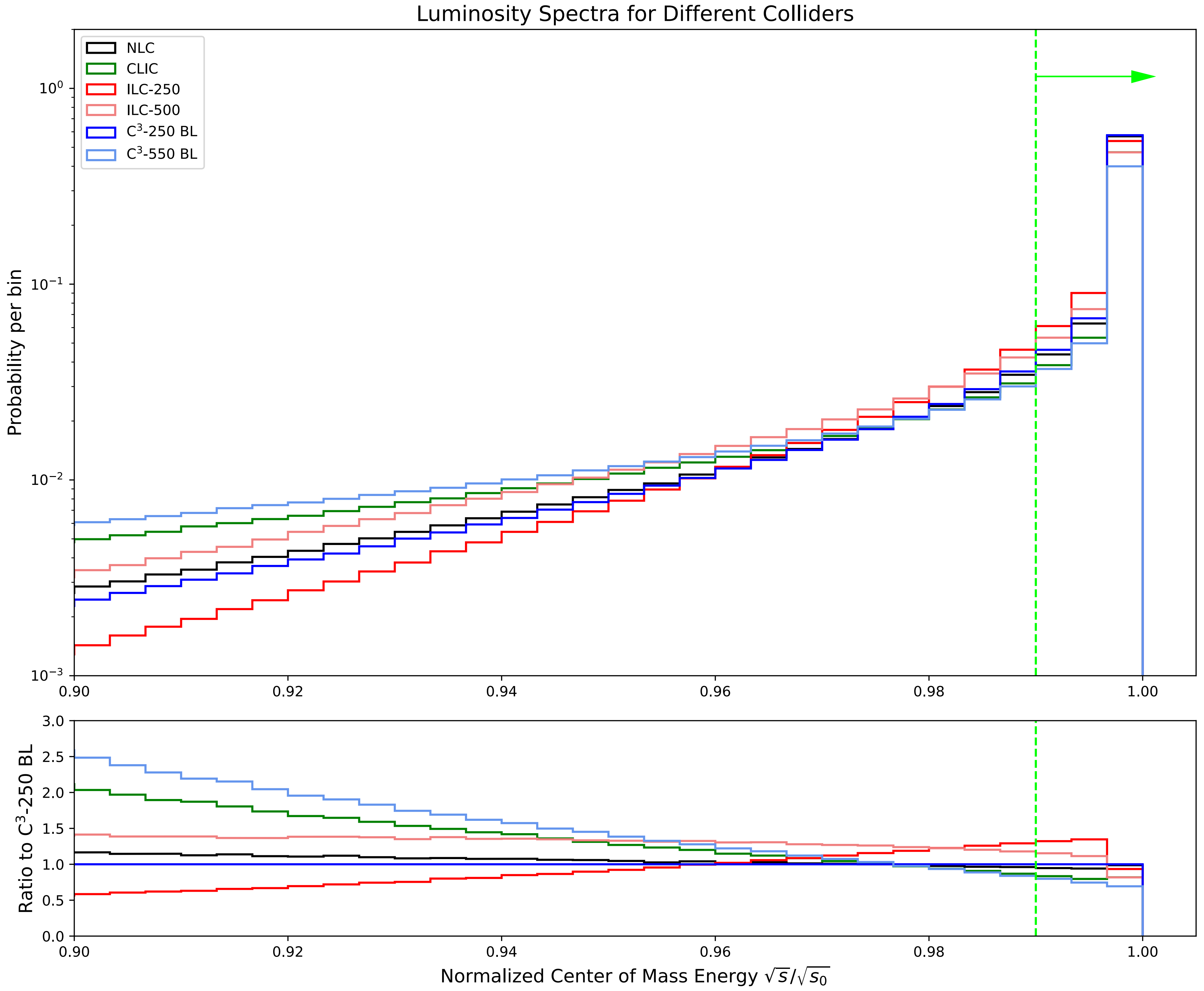
D. Ntounis, manuscript to appear soon

Luminosity Spectra

D. Ntounis, manuscript to appear soon

The emission of Beamstrahlung photons reduces the energy of the colliding beam particles such that a luminosity spectrum is created, with contribution to the luminosity from various $\sqrt{s}$ energies.



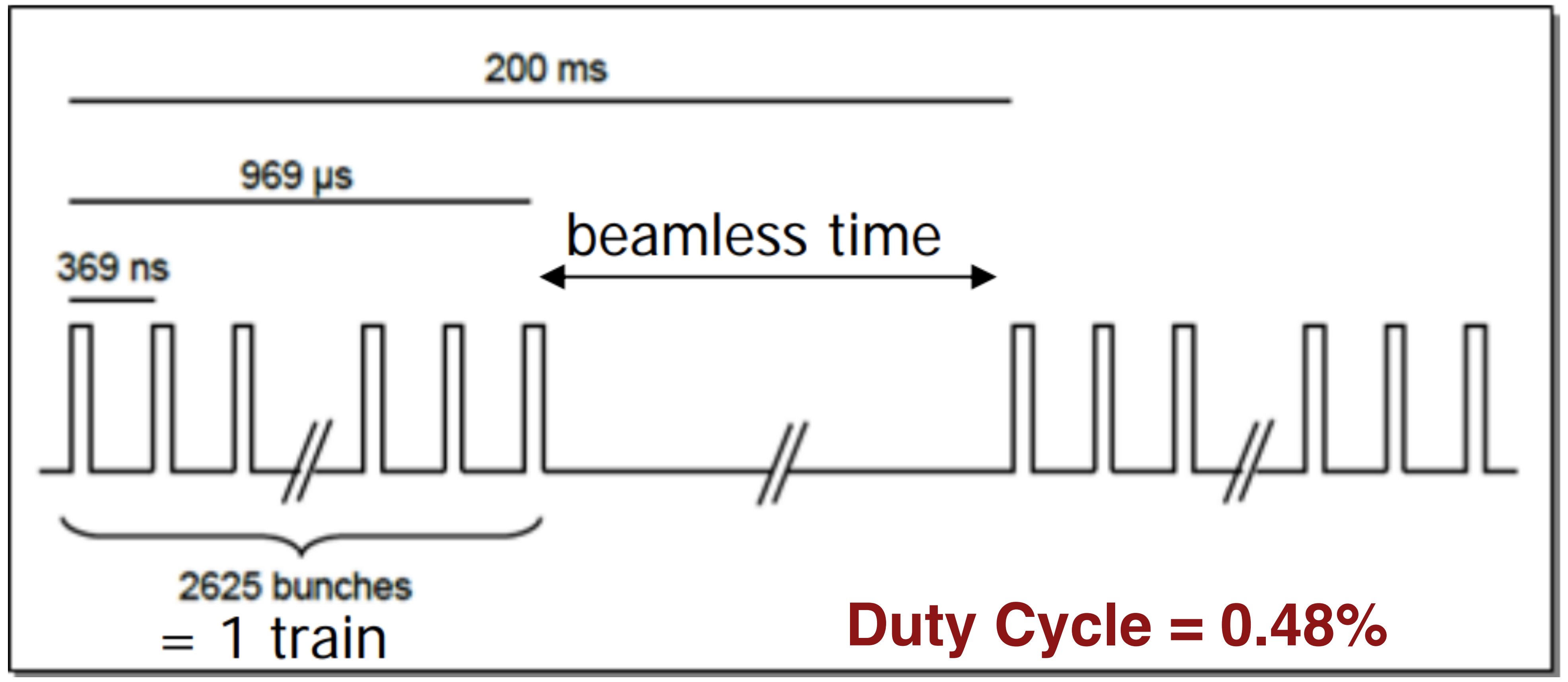


The pair-produced background at C^3 has lower rate and mostly produced in the forward region wrt ILC.
A luminosity enhancement for C^3 is achievable without a significant increase in the beam-beam background rates

General requirement: achieve $\gtrsim 60\,\%$ of luminosity in the top $1\,\%$ of $\sqrt{s}$

Beam Format and Detector Design Requirements

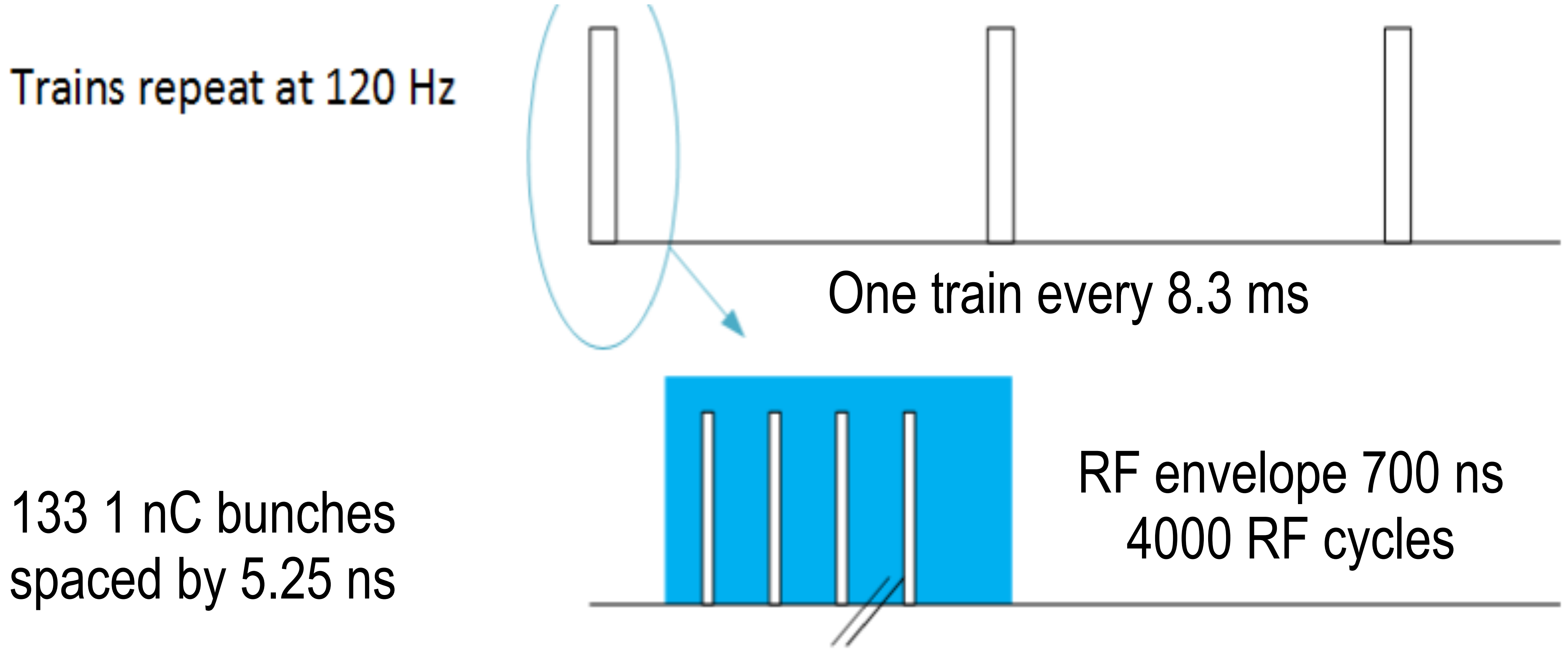
ILC timing structure



Duty Cycle = 0.48%

1 ms long bunch trains at 5 Hz
308ns spacing

C³ timing structure



Trains repeat at 120 Hz

One train every 8.3 ms

133 1 nC bunches
spaced by 5.25 ns

RF envelope 700 ns
4000 RF cycles

Duty Cycle = 0.03 %

Joint simulation/detector optimization effort with ILC groups Common US R&D initiative for future Higgs Factories 2306.13567

- Linear e+e- colliders are characterized by a very low duty cycle
- Power Pulsing can be an additional handle to reduce power consumption and cooling constraint
  - Factor of 100 power saving for FE analog power
- Tracking detectors don't need active cooling
  - Significantly reduction for the material budget

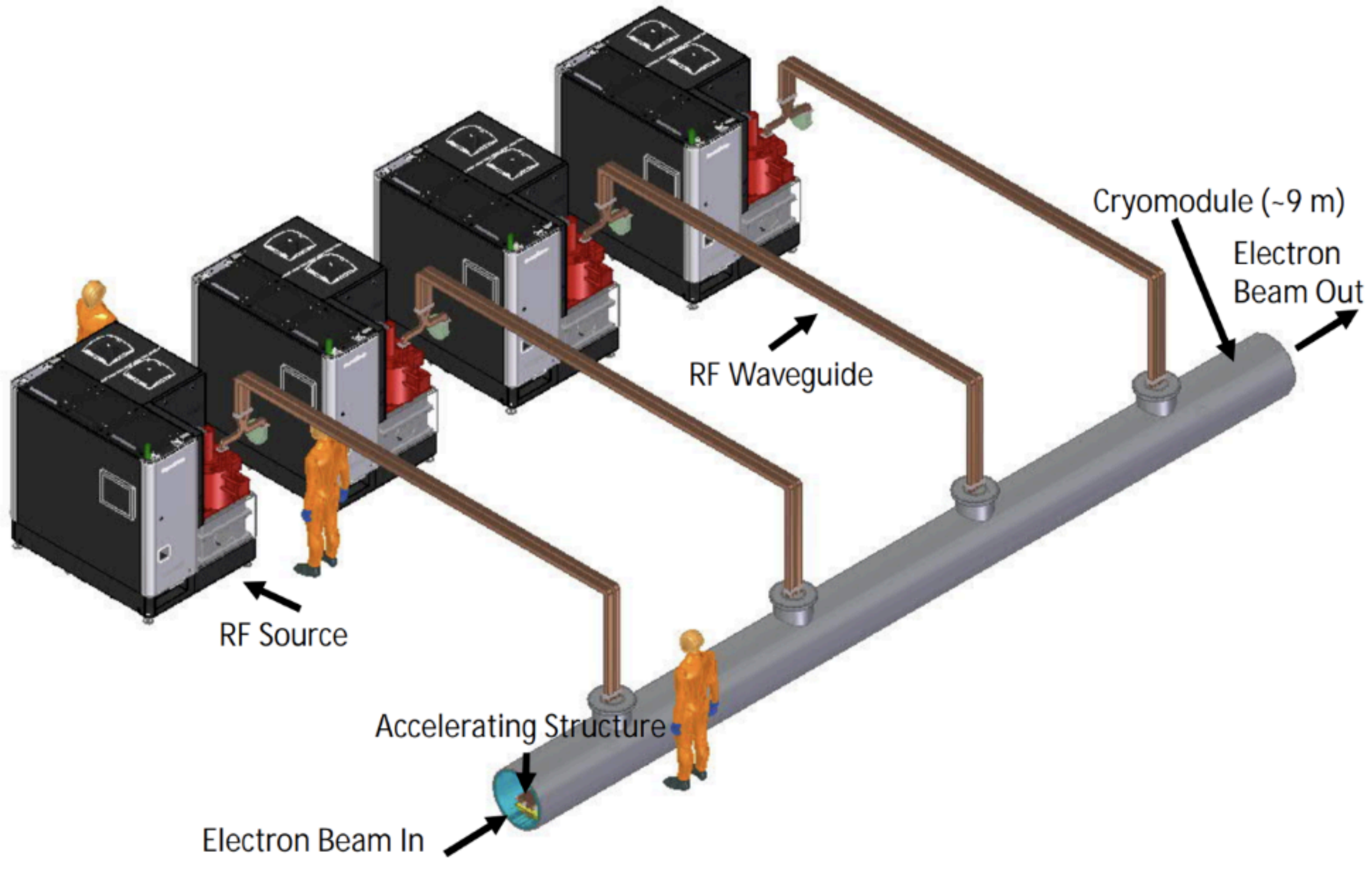
C³ time structure is compatible with ILC-like detector overall design and ongoing optimizations.

Tunnel Layout for Main Linac 250/550 GeV CoM

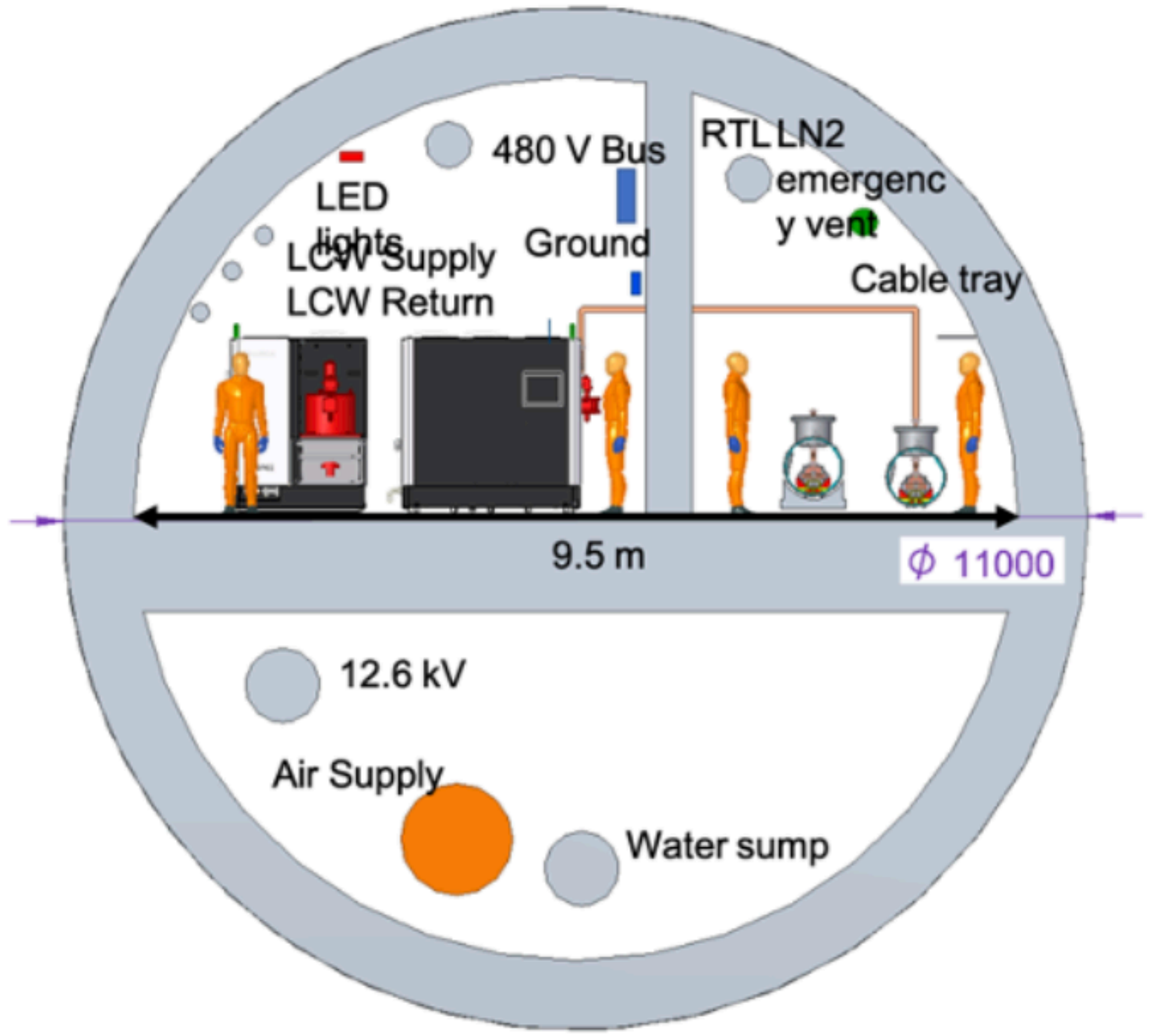
First study looked at 9.5 m inner diameter in order to match ILC costing model

- Must minimize diameter to reduce cost and construction time
- Surface site (cut/cover) provides interesting alternative – concerns with length of site for future upgrade

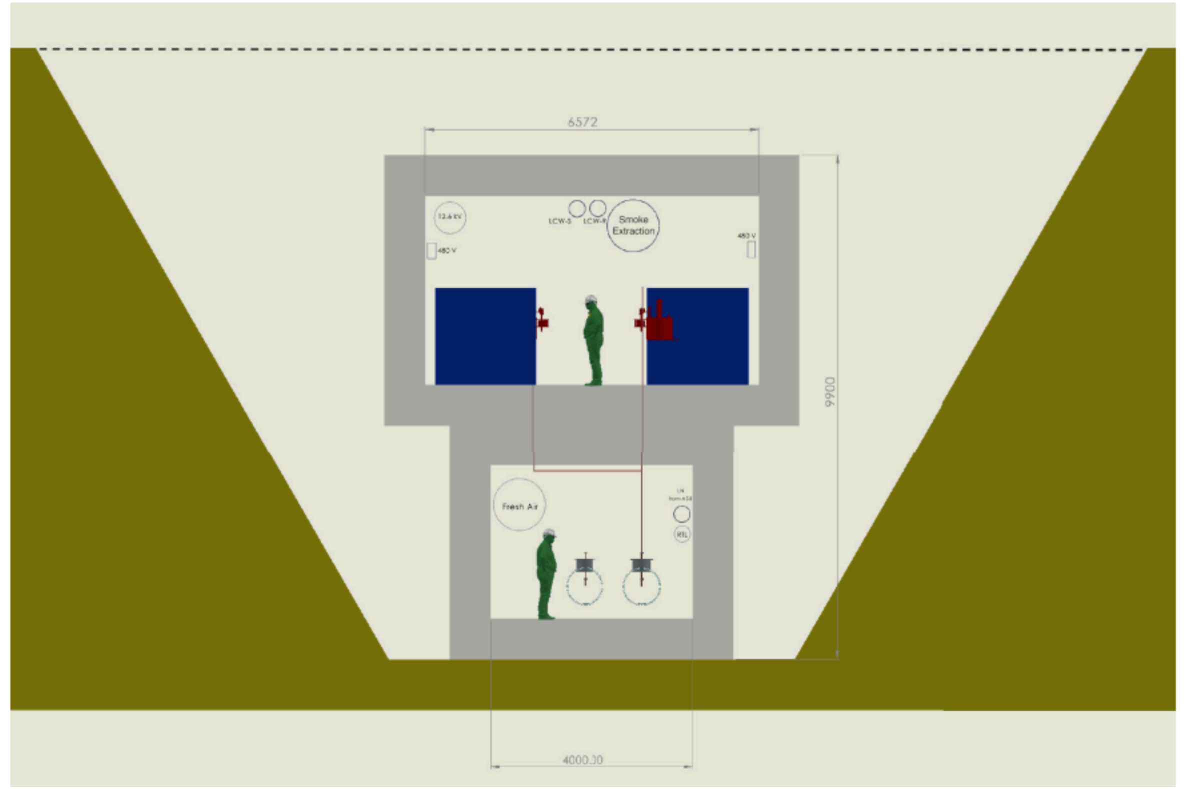
Cryomodule Unit - 9 m
(630 MeV/1 GeV)



Usable Tunnel Width - 9.5 m
(Same tunnel width as ILC)



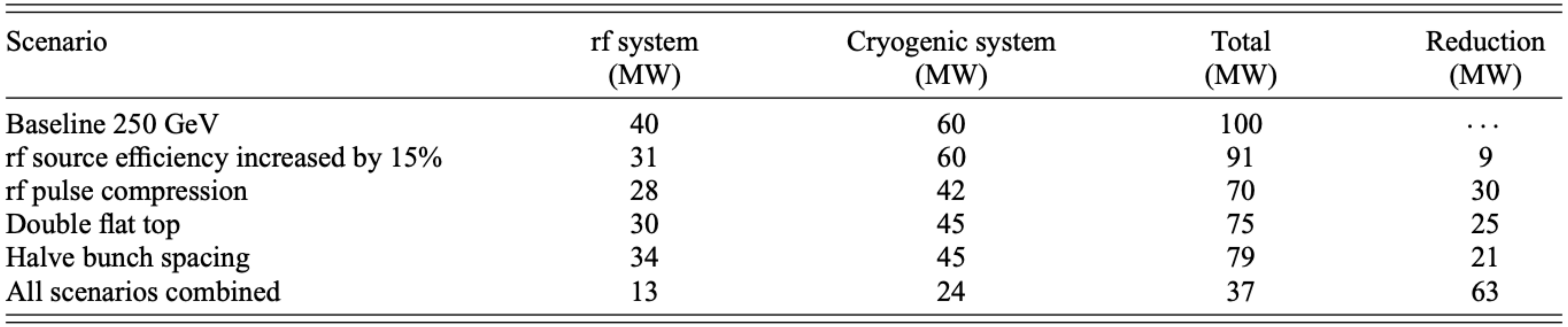
Cut-and-cover



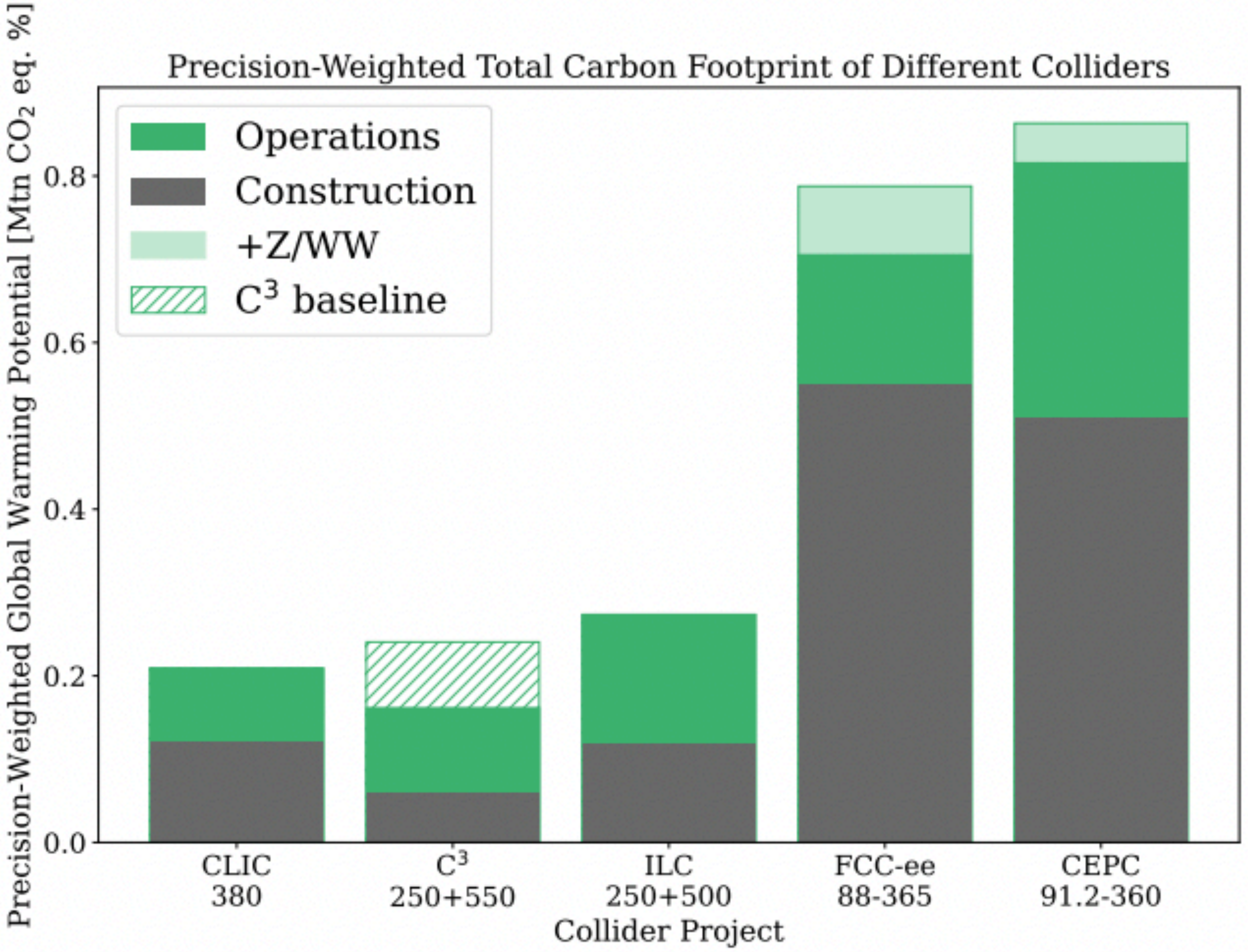
Power Consumption and Sustainability

PRX Energy 2 047001

- Compact footprint < 8 km for both underground and surface sites
- **Sustainability - construction + operations CO_2 emissions per % sensitivity on couplings**
  - Polarization and high energy to account for physics reach
  - Construction CO_2 emissions → minimize excavation and concrete with cut and cover approach
  - Main Linac Operations → limit power, decarbonization of the grid and dedicated renewable sources



Scenario	rf system (MW)	Cryogenic system (MW)	Total (MW)	Reduction (MW)
Baseline 250 GeV	40	60	100	. . .
rf source efficiency increased by 15%	31	60	91	9
rf pulse compression	28	42	70	30
Double flat top	30	45	75	25
Halve bunch spacing	34	45	79	21
All scenarios combined	13	24	37	63



Accelerator Design and Challenges

Accelerator Design

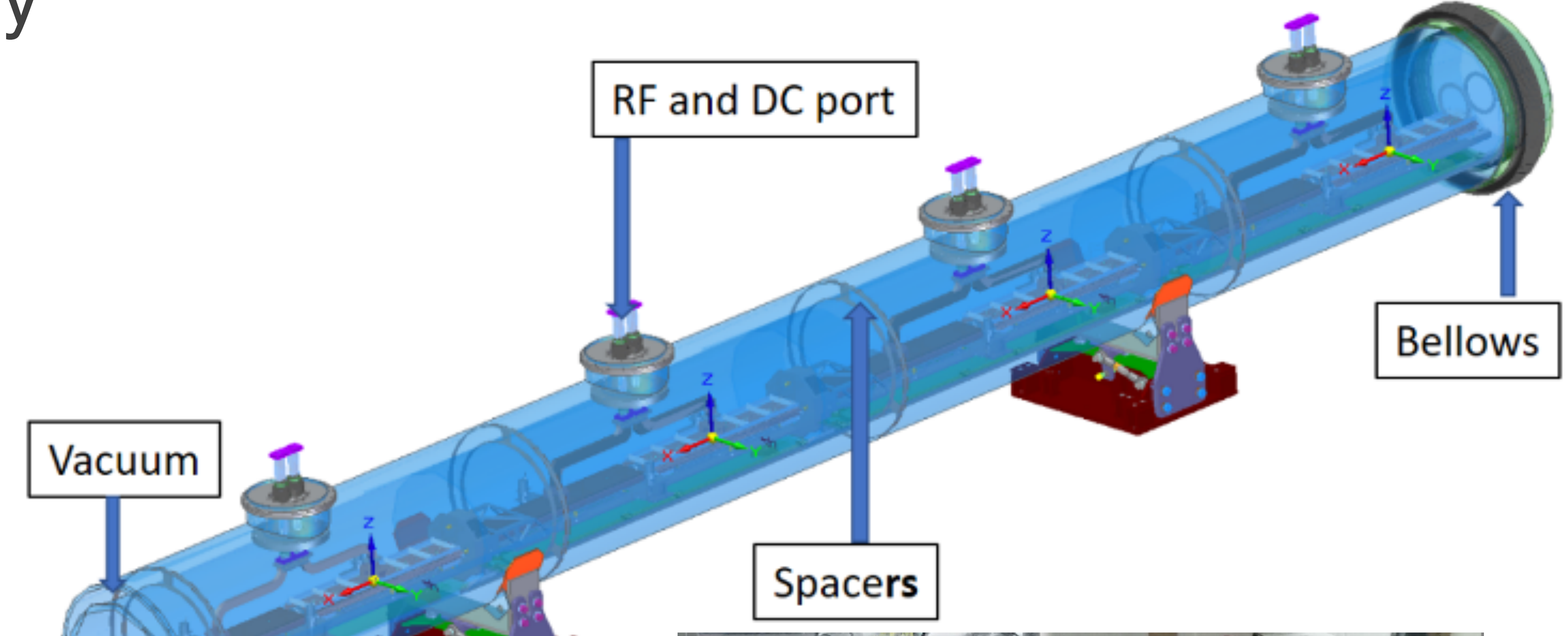
- Engineering and design of prototype cryomodule underway

Focused on challenges identified with community through Snowmass (all underway)

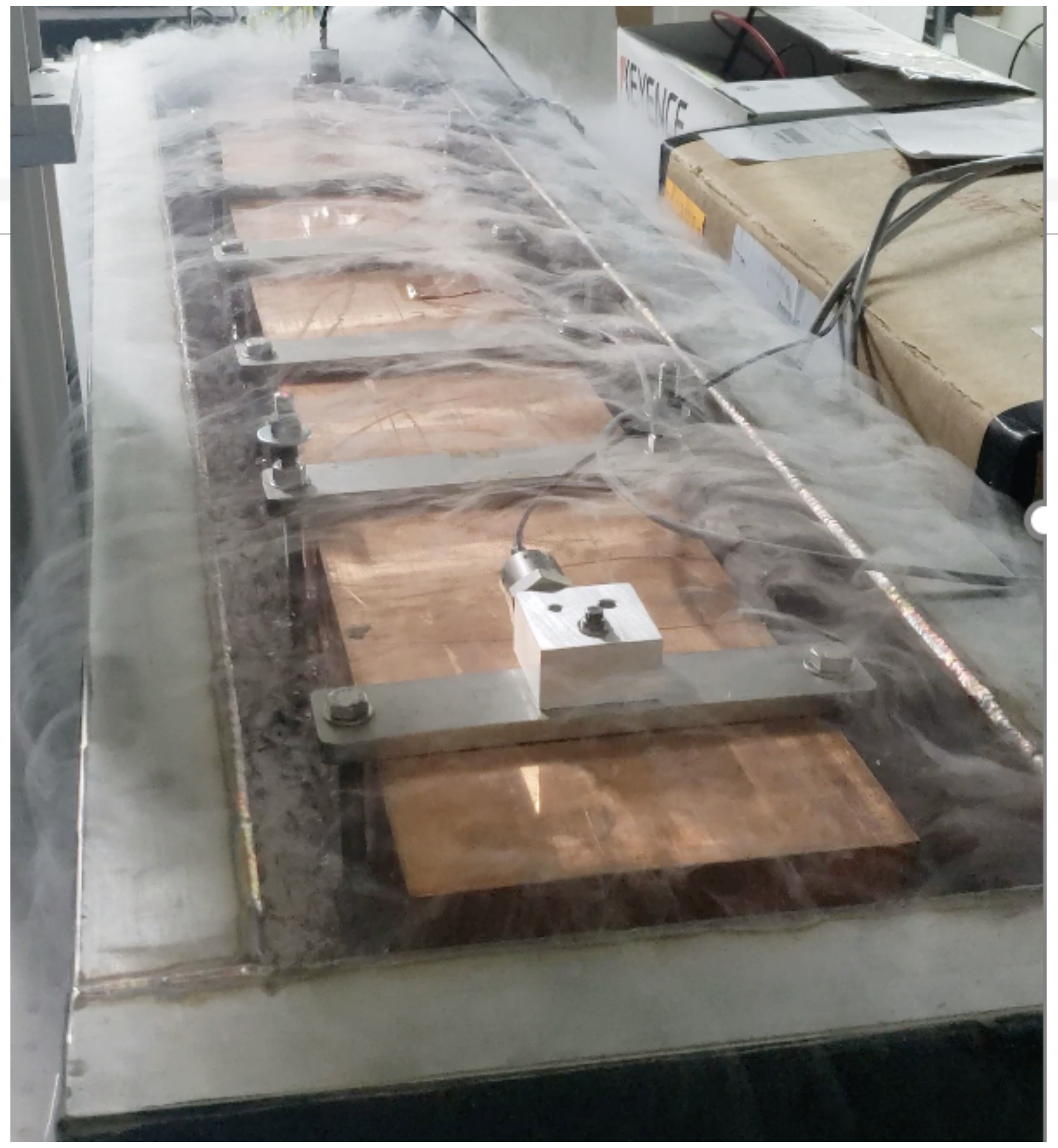
- Gradient – Scaling up to meter scale cryogenic tests
- Vibrations – Measurements with full thermal load
- Alignment – Working towards raft prototype
- Cryogenics – Two-phase flow simulations to full flow tests
- Damping – Materials, design and simulation
- Beam Loading and Stability - Beam test with thermionic gun
- Scalability – Cryomodules and integration

Laying the foundation for a demonstration program to address technical risks beyond CDR level

Cryomodule Concept



Vibration Studies



Recent technical updates

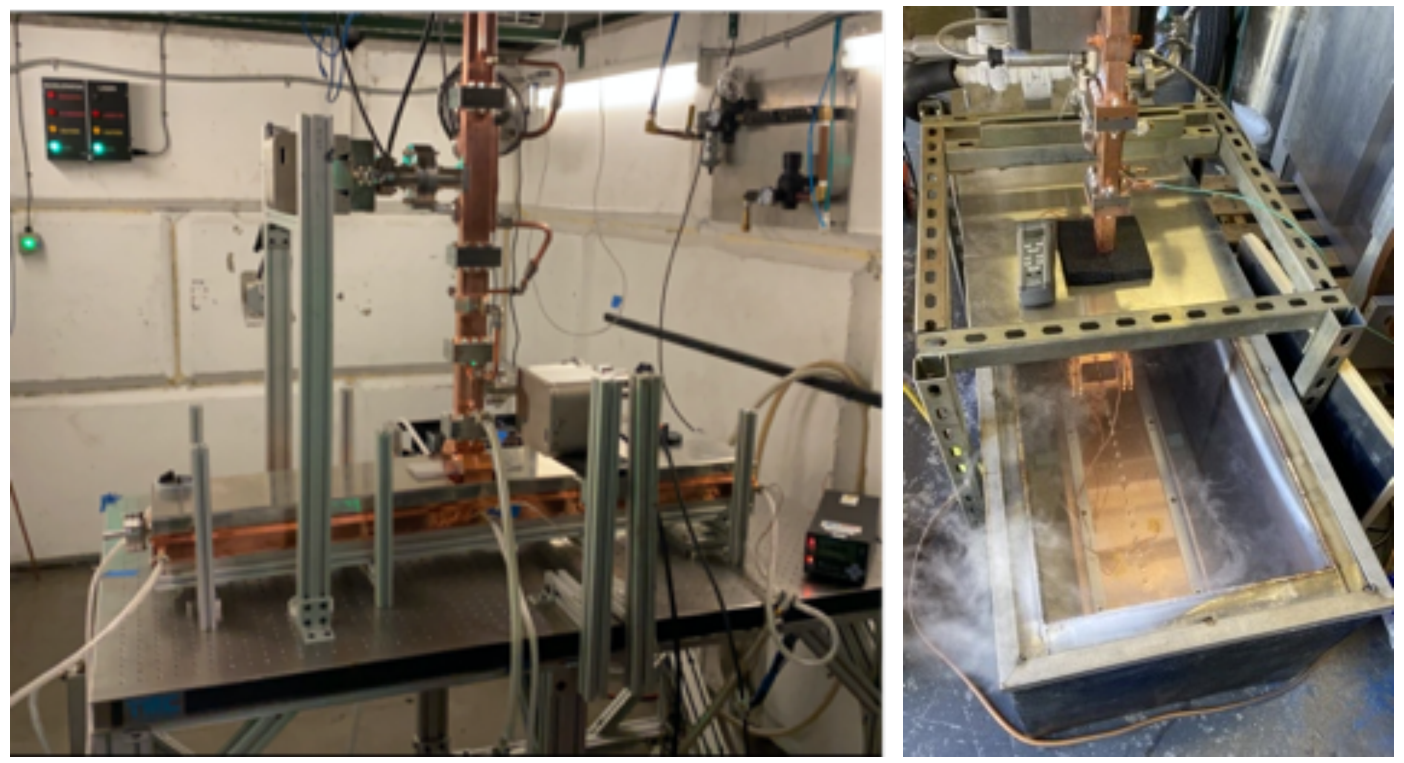
More recent summary of technical progress from Emilio Nanni (link)

Recent technical updates

High Accelerating Gradients Cryogenic Operation

RadiaBeam

More recent tests, new results to appear soon



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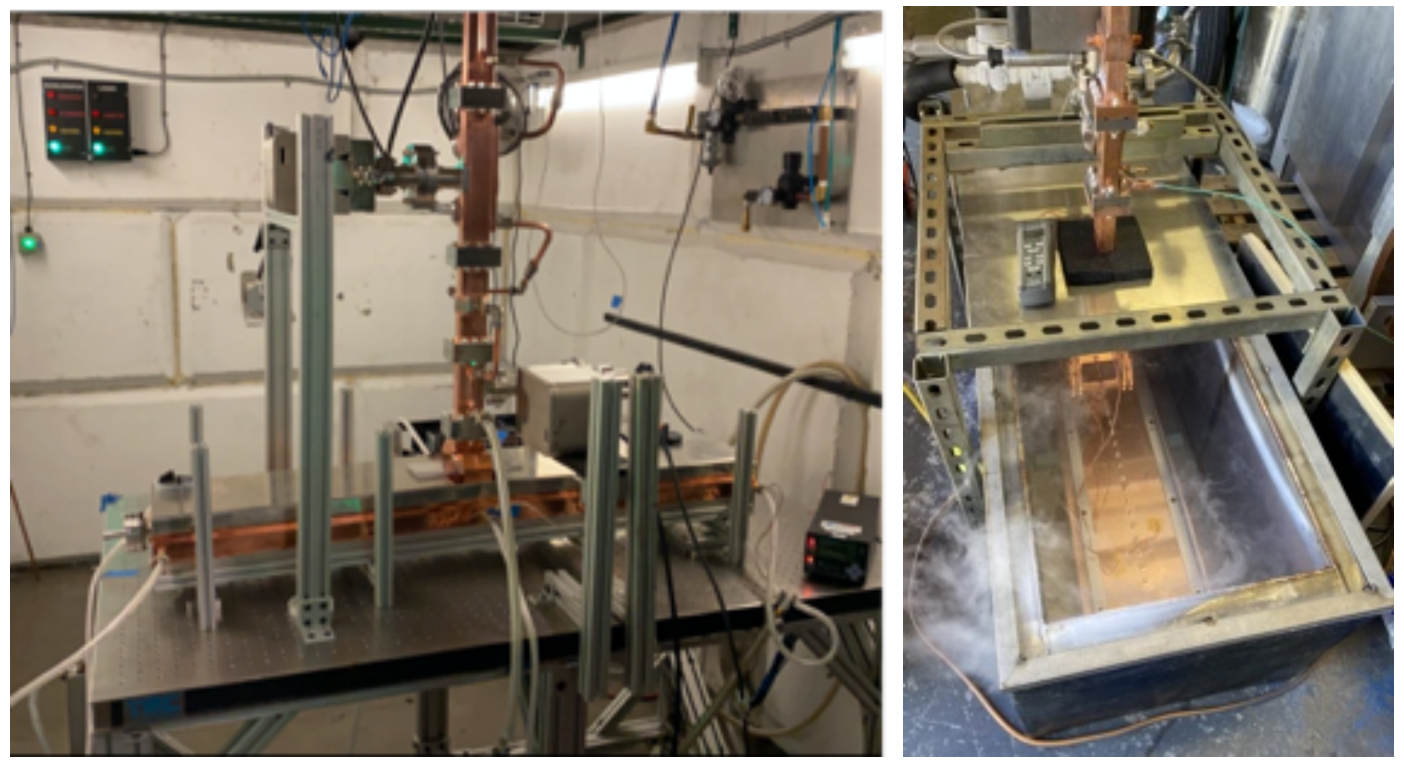
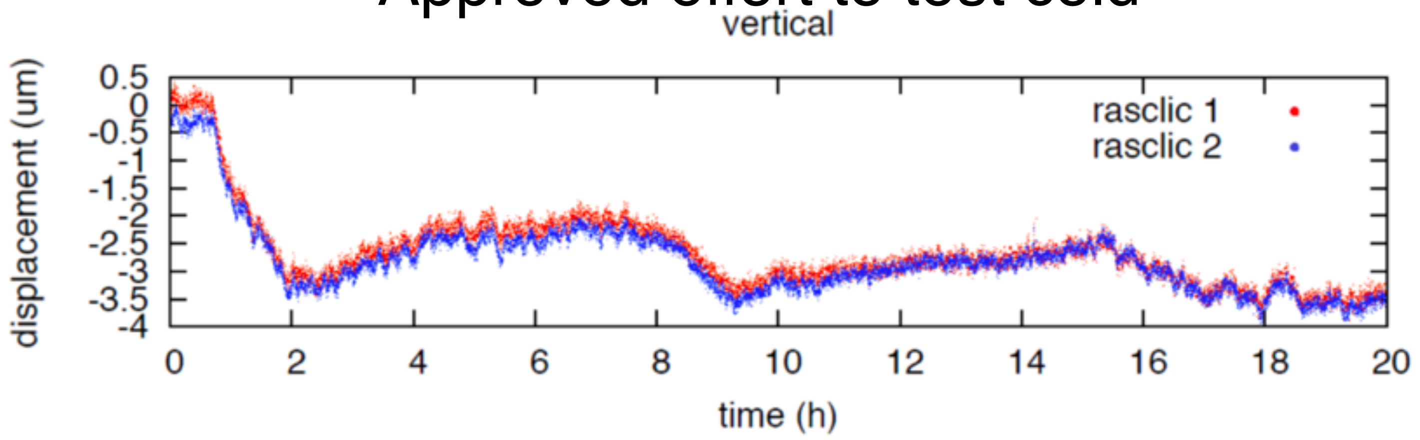


Precision Short and Long Range Alignment

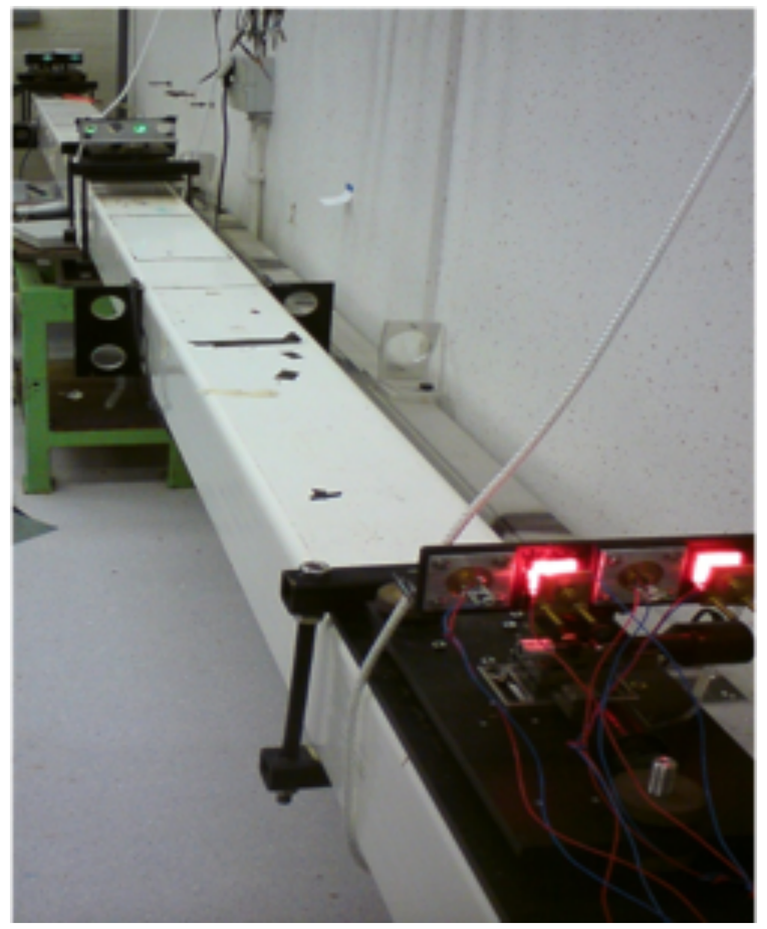
100 nm resolution

Approved effort to test cold



Nikhef

H. Van Der Graaf



Tested in LN and meets specs pre-alignment

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Recent technical updates

High Accelerating Gradients Cryogenic Operation

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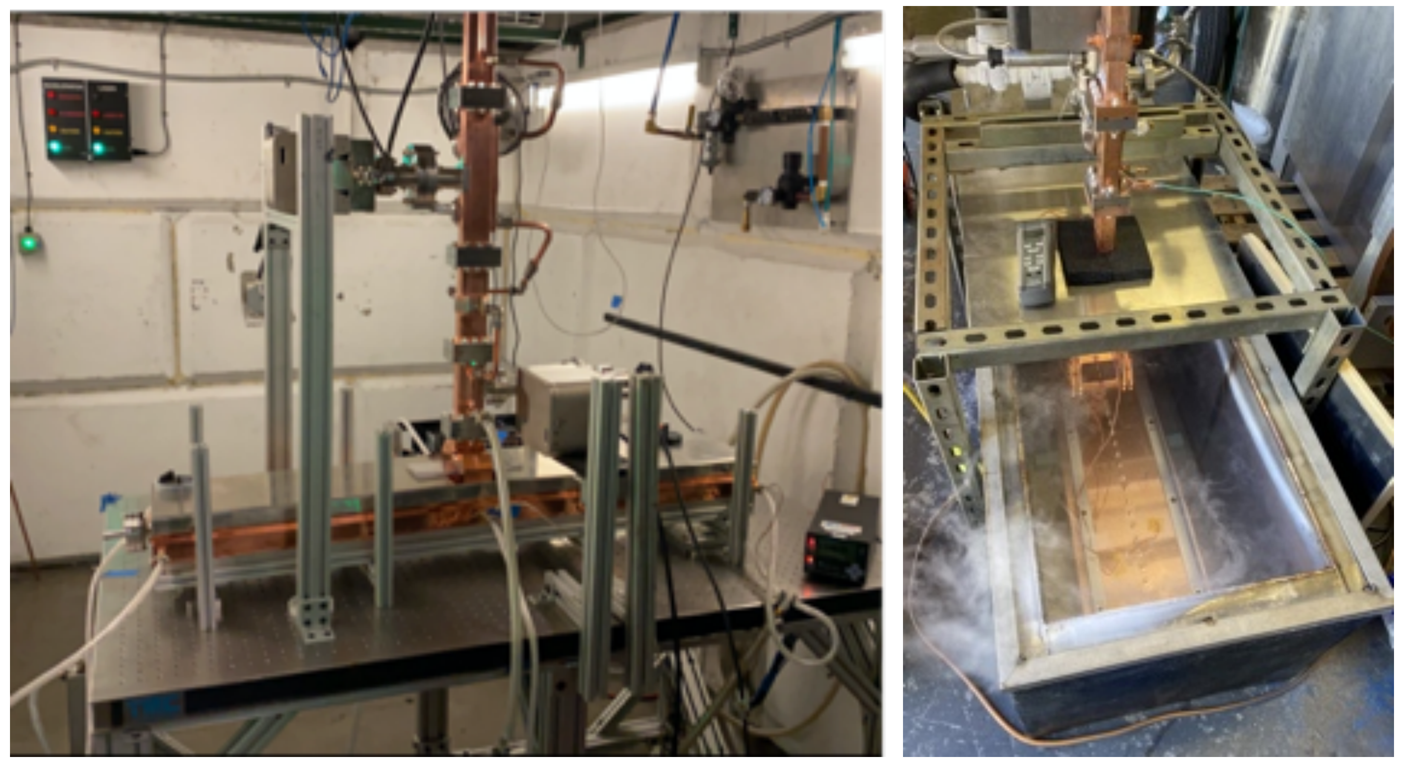
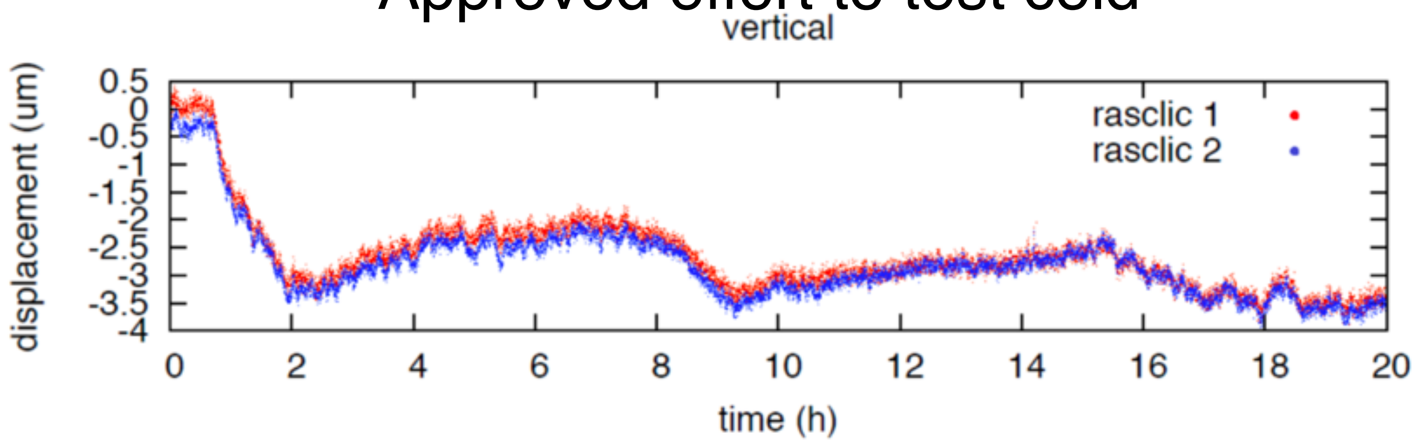


Glen White

Precision Short and Long Range Alignment

100 nm resolution
Approved effort to test cold



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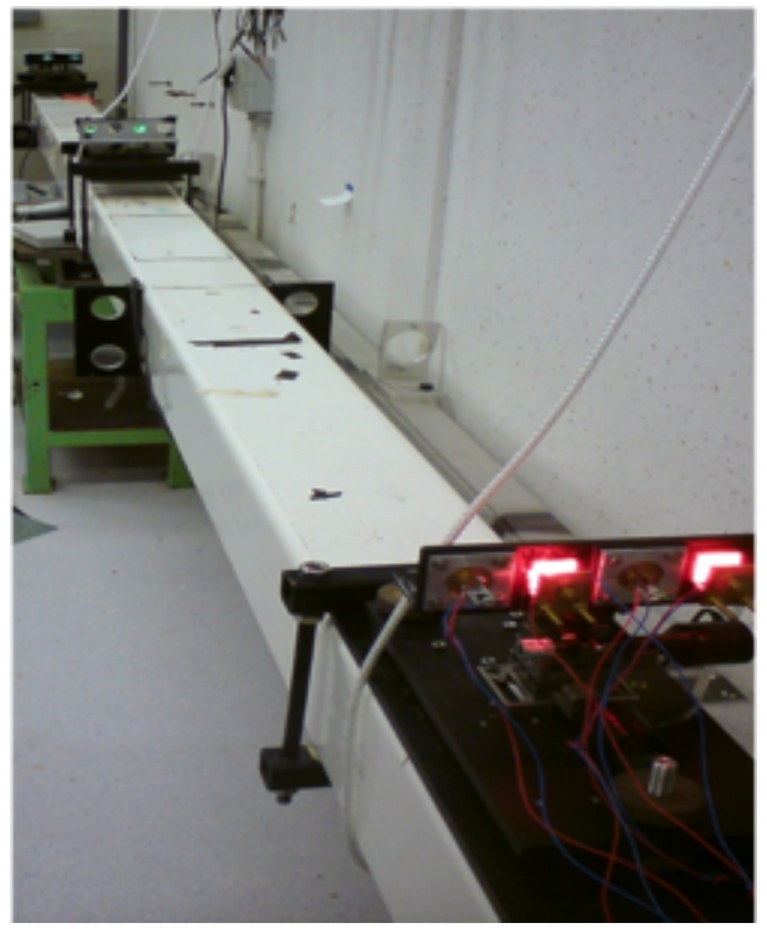
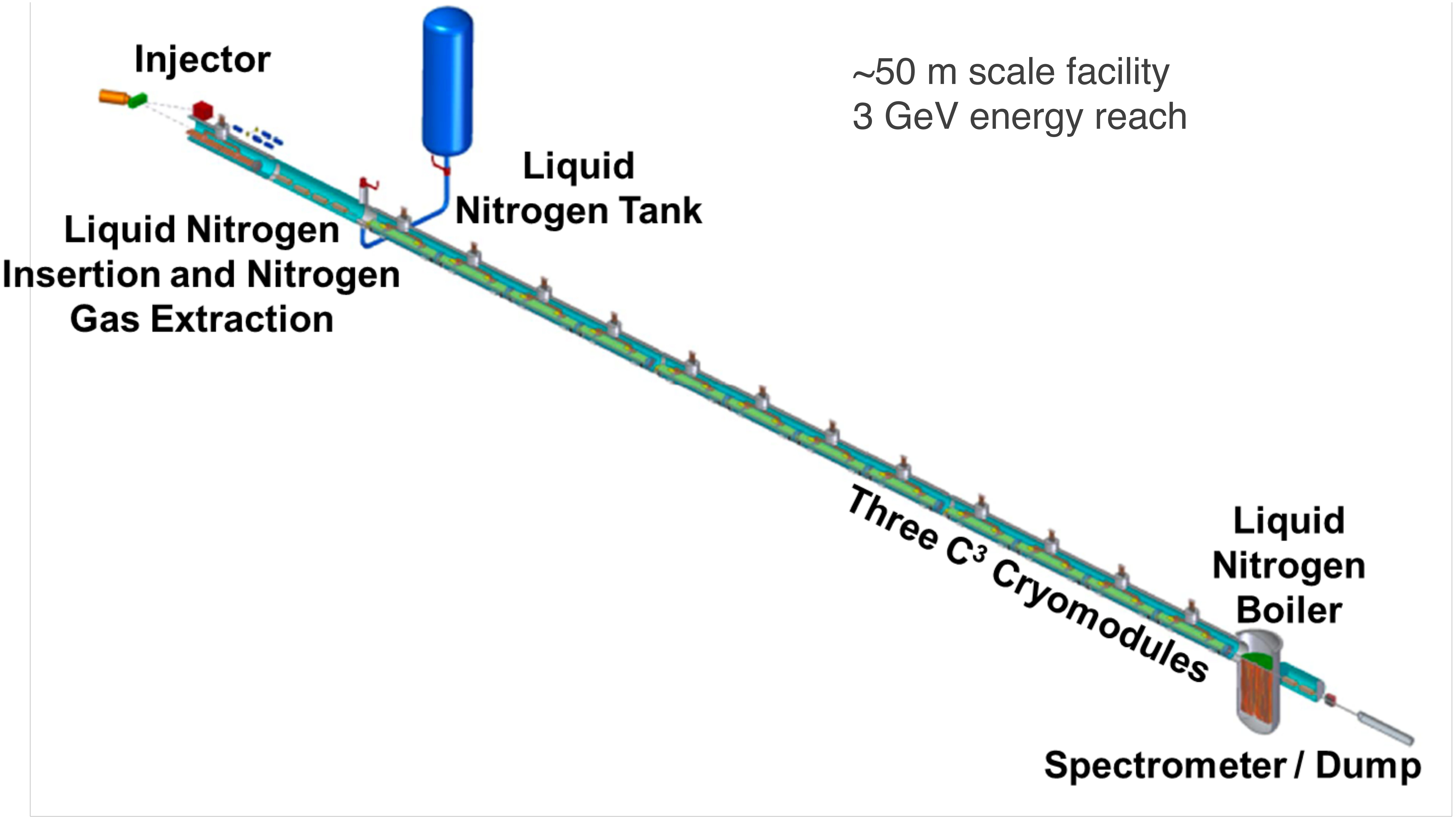


Alignment Parameters	Units	Value
Raft Components	µm	5
Short Range (~10m)	µm	30
Long Range (>200m)	µm	1000
Structure Vert. Vibration	µm	9
Quad Vert. Vibration	nm	15
BPM Resolution	µm	0.1
BPM-Quad Alignment	µm	2

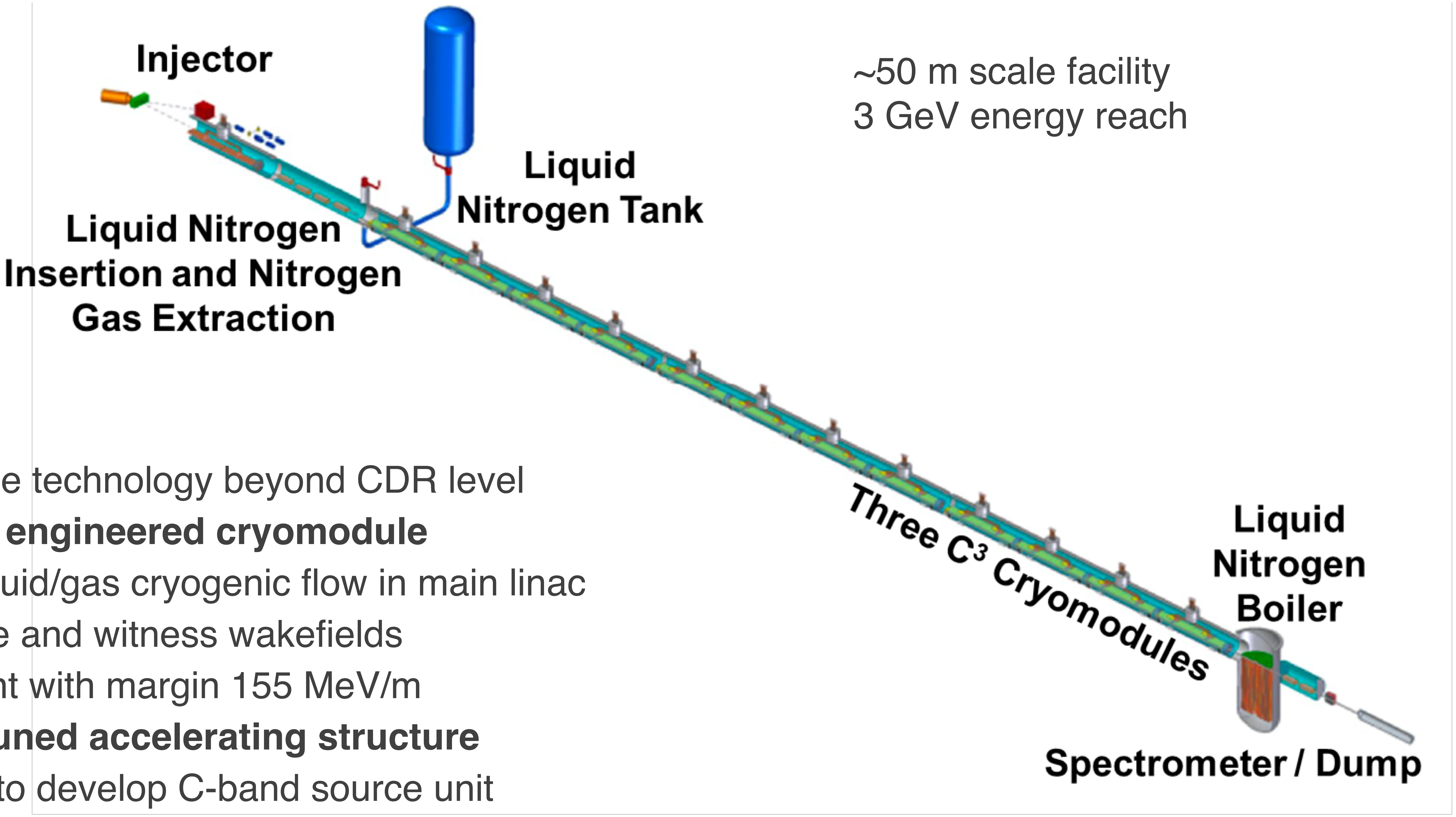
More recent summary of technical progress from Emilio Nanni (link)

The Complete C^3 Demonstrator



~50 m scale facility
3 GeV energy reach

The Complete C^3 Demonstrator

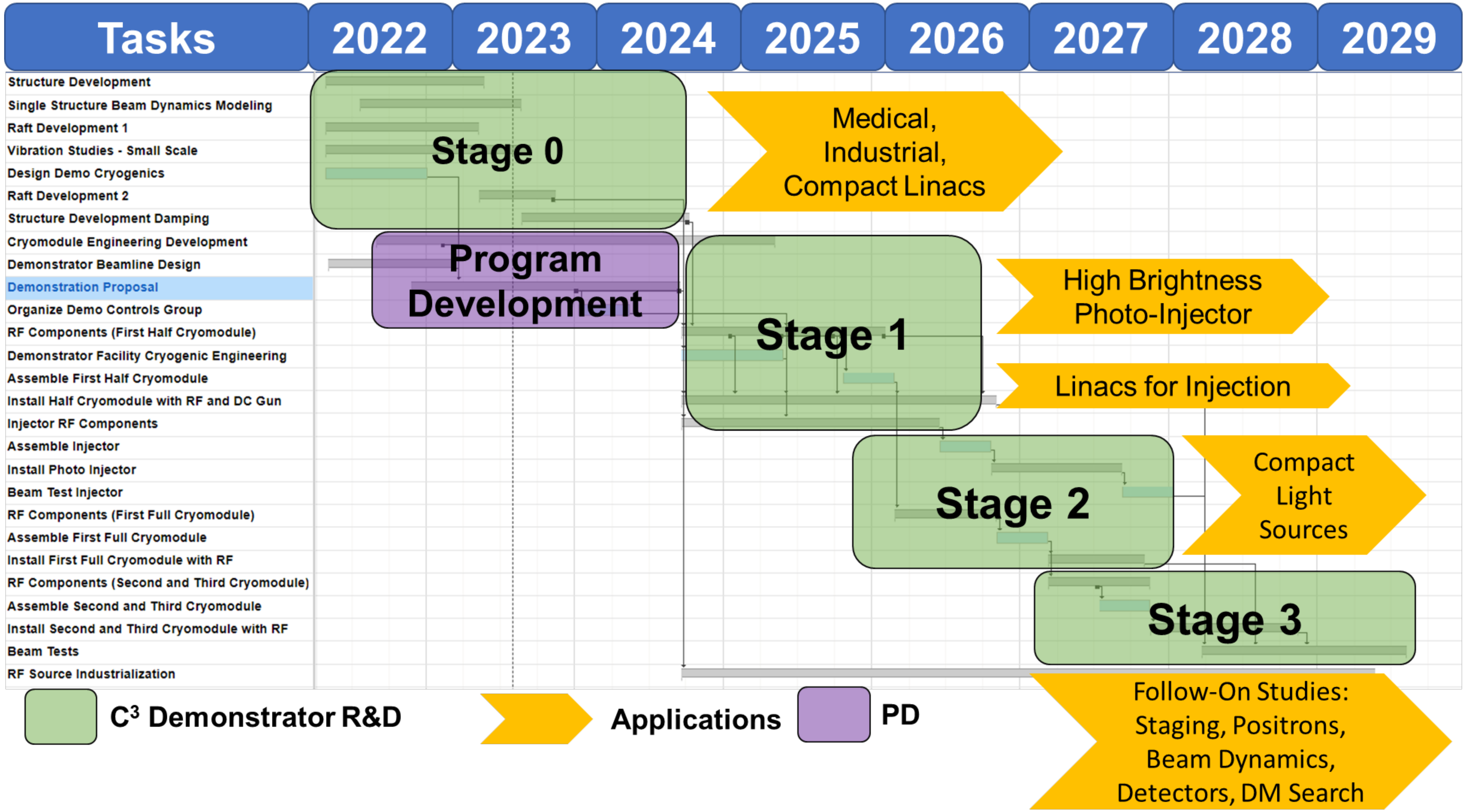


~50 m scale facility
3 GeV energy reach

R&D needed to advance technology beyond CDR level

- **Demonstrate fully engineered cryomodule**
- Demonstrate full liquid/gas cryogenic flow in main linac
- Multi-Bunch: Induce and witness wakefields
- Operational gradient with margin 155 MeV/m
- **Fully damped-detuned accelerating structure**
- Work with industry to develop C-band source unit optimized for installation with main linac

Demonstration R&D Plan Timeline *



Tasks	2022	2023	2024	2025	2026	2027	2028	2029

- Structure Development
- Single Structure Beam Dynamics Modeling
- Raft Development 1
- Vibration Studies - Small Scale
- Design Demo Cryogenics
- Raft Development 2
- Structure Development Damping
- Cryomodule Engineering Development
- Demonstrator Beamline Design
- Demonstration Proposal
- Organize Demo Controls Group
- RF Components (First Half Cryomodule)
- Demonstrator Facility Cryogenic Engineering
- Assemble First Half Cryomodule
- Install Half Cryomodule with RF and DC Gun
- Injector RF Components
- Assemble Injector
- Install Photo Injector
- Beam Test Injector
- RF Components (First Full Cryomodule)
- Assemble First Full Cryomodule
- Install First Full Cryomodule with RF
- RF Components (Second and Third Cryomodule)
- Assemble Second and Third Cryomodule
- Install Second and Third Cryomodule with RF
- Beam Tests
- RF Source Industrialization

Stage 0

Medical, Industrial, Compact Linacs

Program Development

Stage 1

High Brightness Photo-Injector

Linacs for Injection

Stage 2

Compact Light Sources

Stage 3

Follow-On Studies: Staging, Positrons, Beam Dynamics, Detectors, DM Search

🟩 **C³ Demonstrator R&D**

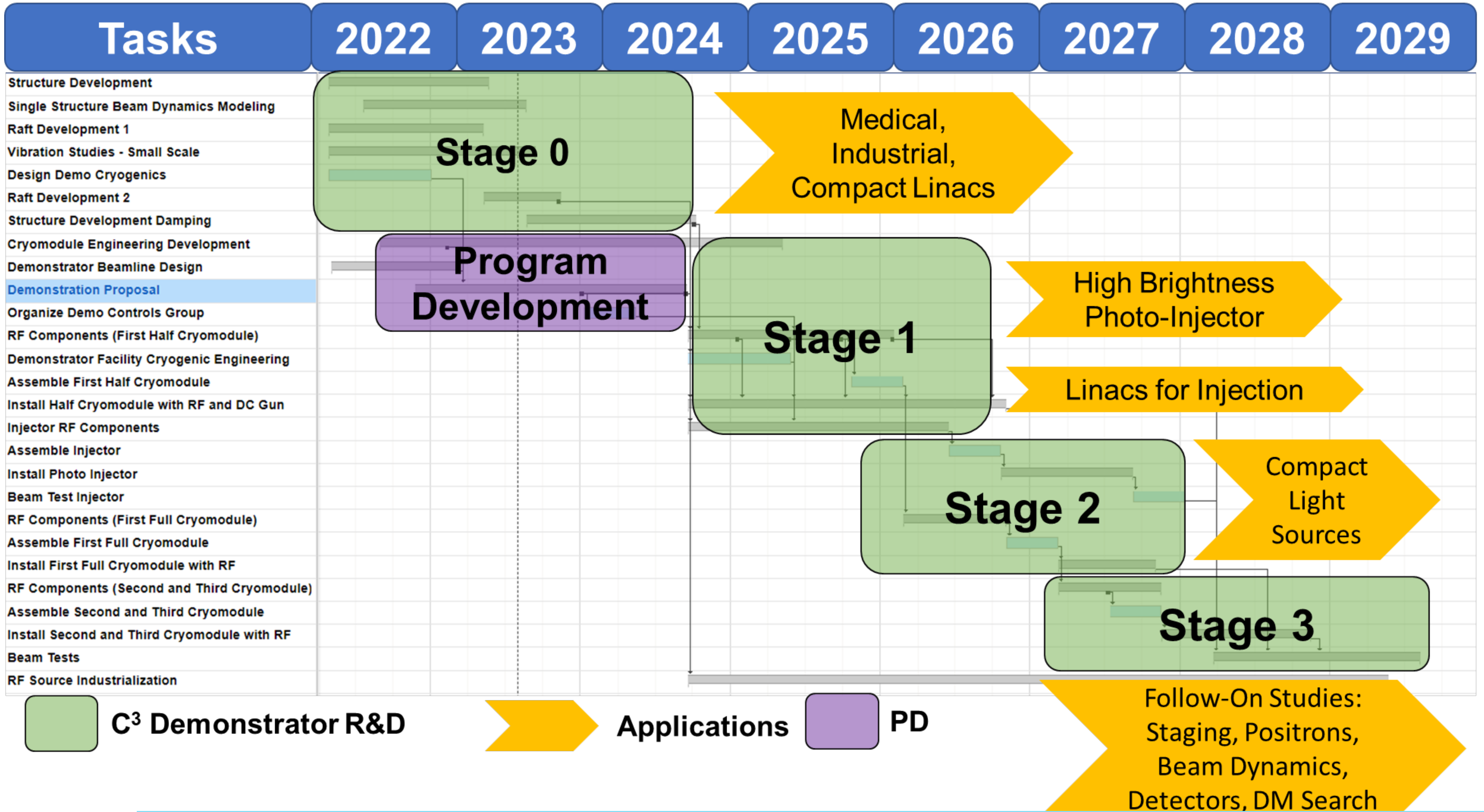
Applications

🟪 **PD**

Area Recommendation 8 P5 report

* Technically Limited

Demonstration R&D Plan Timeline *



Tasks | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

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Install First Full Cryomodule with RF
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Assemble Second and Third Cryomodule
Install Second and Third Cryomodule with RF
Beam Tests
RF Source Industrialization

Stage 0

Medical, Industrial, Compact Linacs

Program Development

Stage 1

High Brightness Photo-Injector

Linacs for Injection

Stage 2

Compact Light Sources

Stage 3

Follow-On Studies: Staging, Positrons, Beam Dynamics, Detectors, DM Search

🟩 C³ Demonstrator R&D

Applications

PD

Area Recommendation 8 P5 report

Stage 1/2 will answer the most pressing technical questions - beam loading, damping, alignment required to complete the engineering to a level appropriate for a **CDR**

* Technically Limited

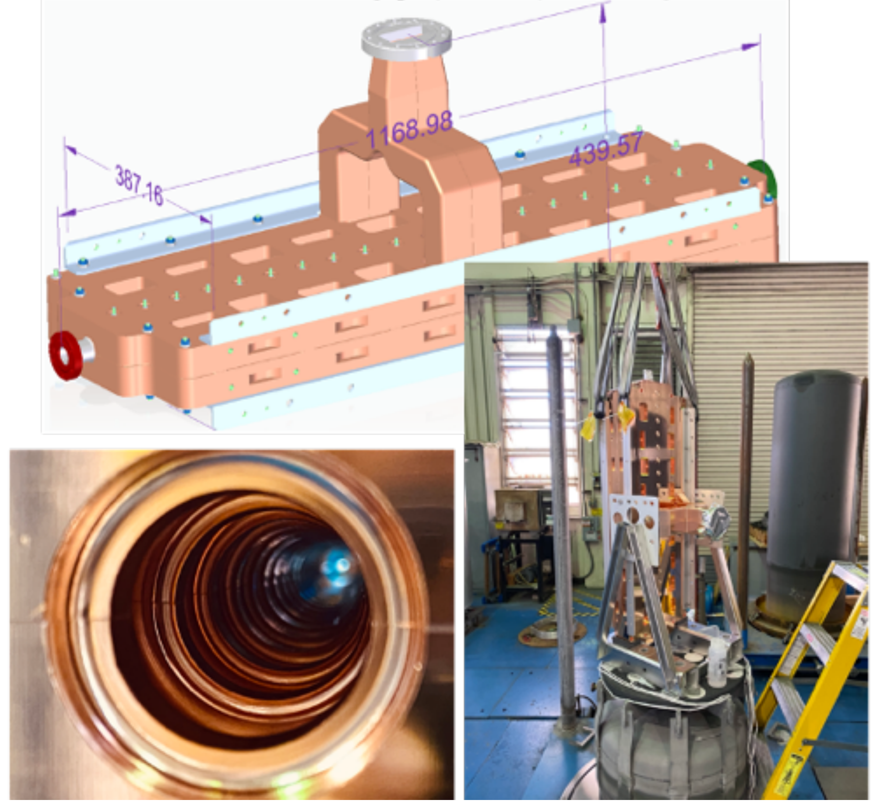
Synergies with Future Colliders

RF Accelerator Technology Essential for All Near-Term Collider Concepts

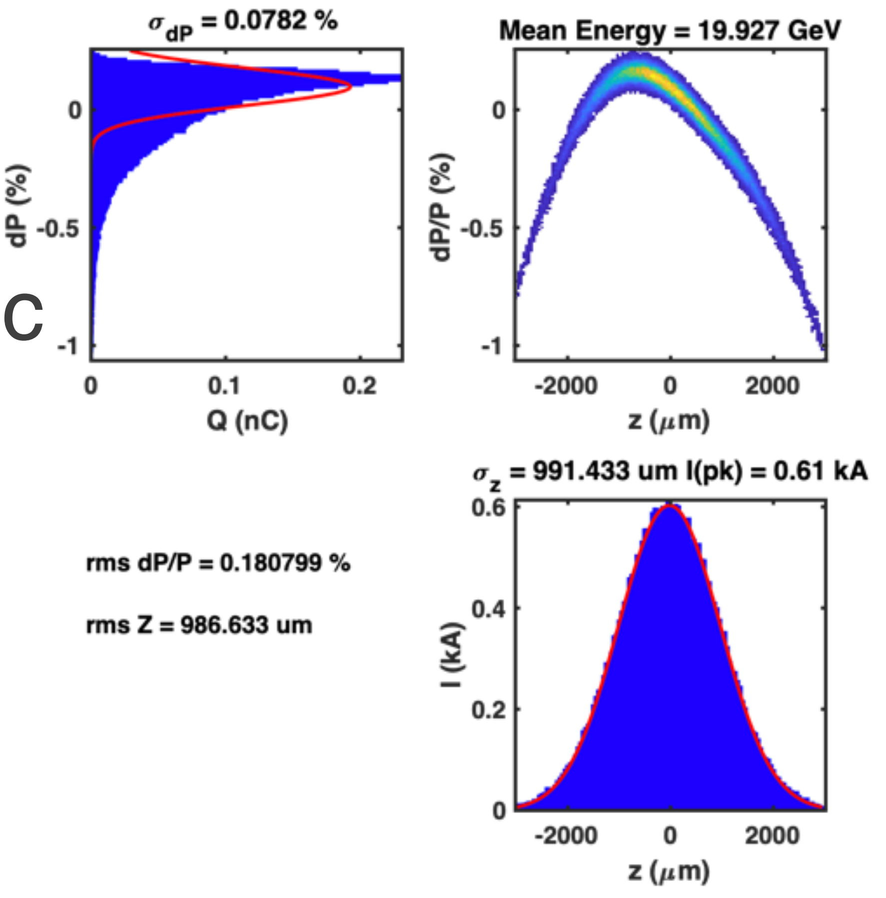
C^3 Demo is positioned to contribute synergistically or directly to all near-term collider concepts

- CLIC - components, damping, fabrication techniques
- ILC - options for electron driven positron source based C^3 technology
- Muon Collider - high gradient cryogenic copper cavities in cooling channel, alternative linac for acceleration after cooling
- AAC - C^3 Demo utilized for staging, C^3 facility multi-TeV energy upgrade reutilizing tunnel, $\gamma\gamma$ colliders
- FCC-ee - common electron and positron injector linac from 6 to 20 GeV
  - **reduce length 3.5X OR reduce rf power 3.5X**

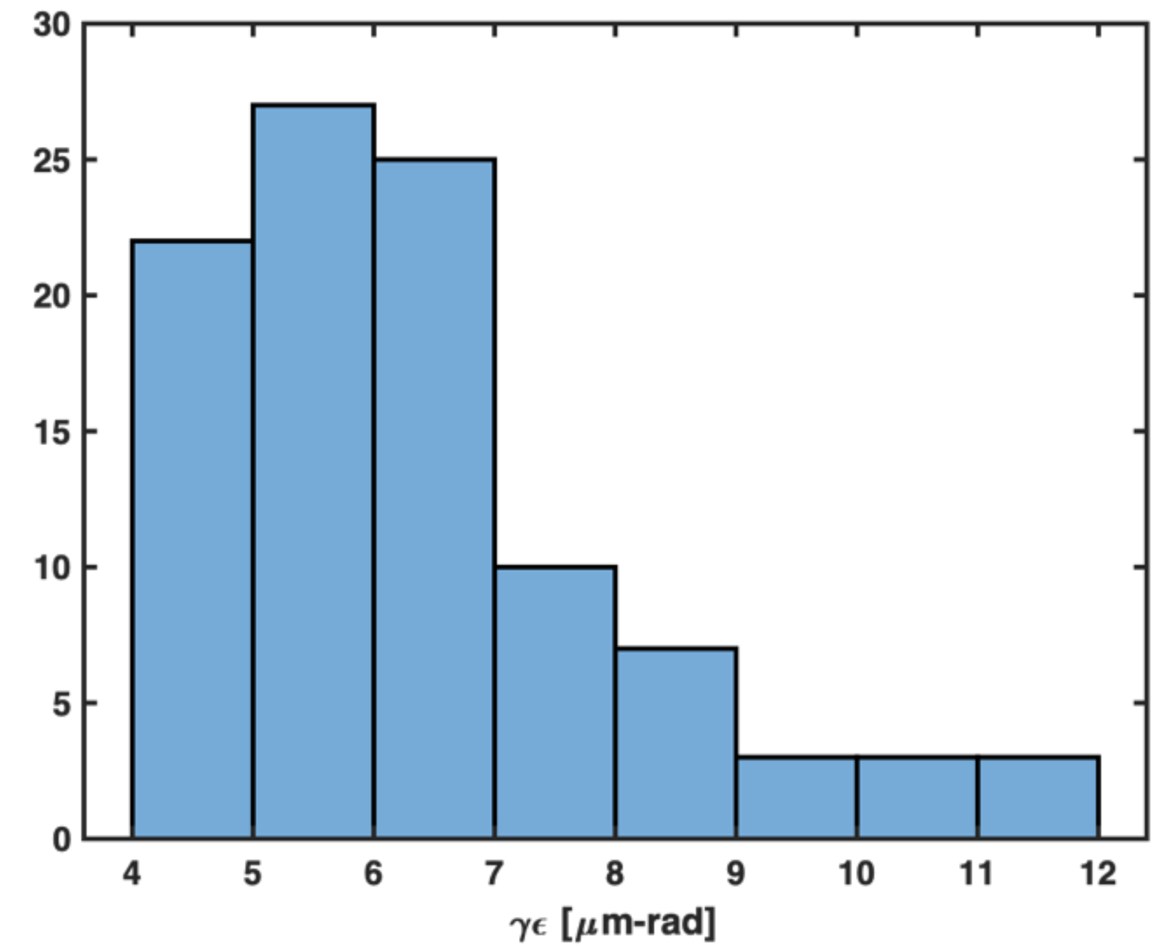
Wide Aperture S-band Injector Linac
$a/\lambda = 0.125$



- Planned test at Argonne
- Tracking with Lucretia includes longitudinal and transverse wakes, chromatic effects etc
- Error study is 100 seeds, 100 μm element offsets, 300 μrad element rolls (rms)
  - No corrections applied



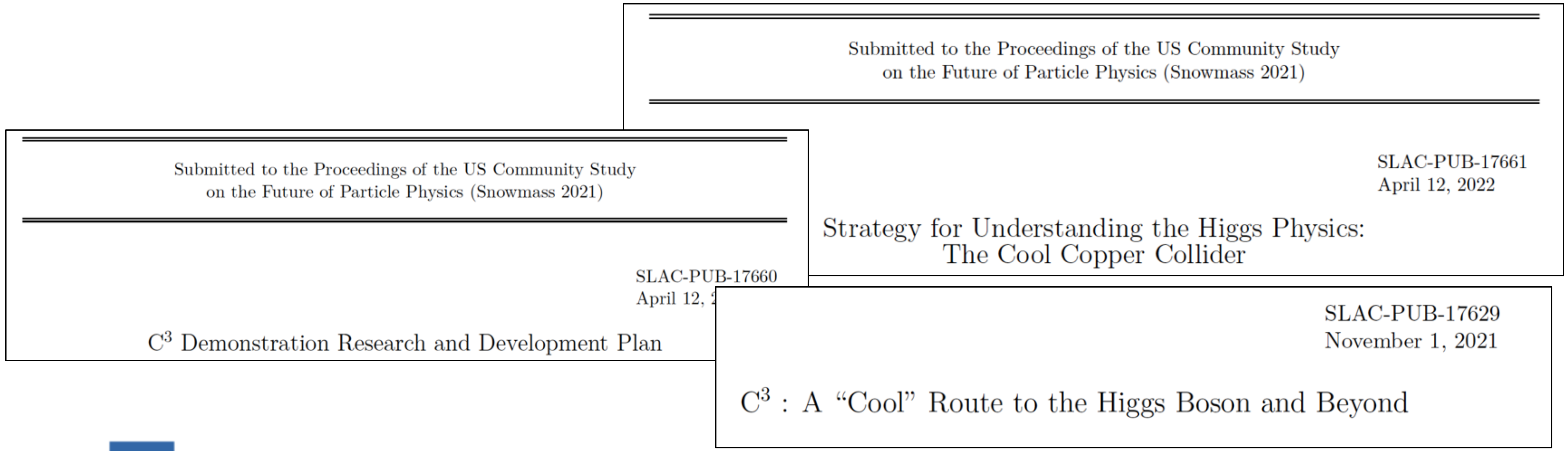
90% seeds < 8 um-rad with lattice errors



C^3 cryomodule provides significant improvements to size and sustainability of FCC-ee high energy linac
C^3 Demo timeline needs to be compatible with selection of FCC-ee injector

Acknowledgements

WEBSITE web.slac.stanford.edu/c3/



Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

SLAC-PUB-17661
April 12, 2022

Strategy for Understanding the Higgs Physics:
The Cool Copper Collider

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

SLAC-PUB-17660
April 12,

C^3 Demonstration Research and Development Plan

SLAC-PUB-17629
November 1, 2021

C^3 : A "Cool" Route to the Higgs Boson and Beyond

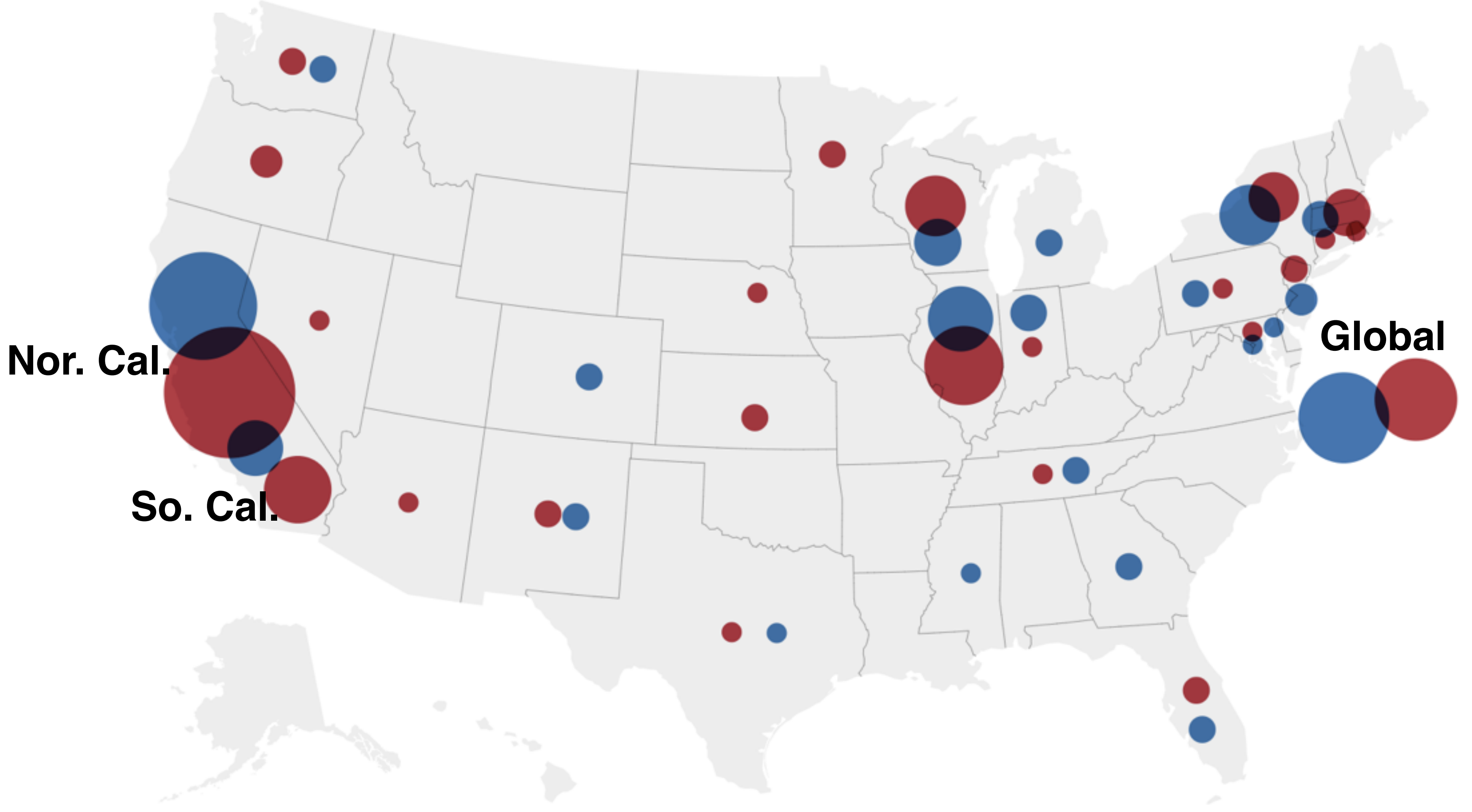
Community Workshops:

Virtual, Fermilab, SLAC, LANL & Cornell University

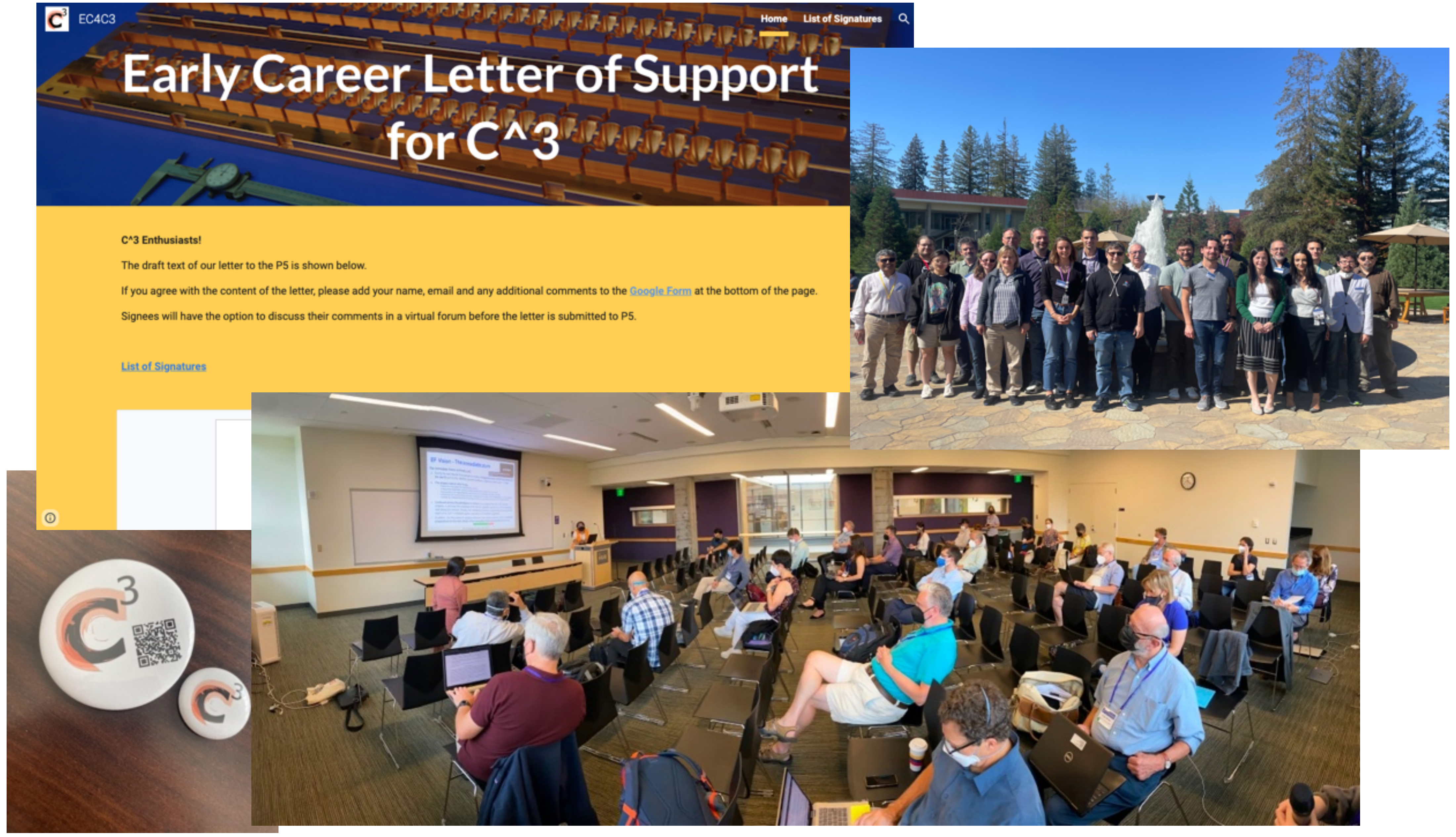
220 Participants 60 Institutions

🟦 **>150 Supporters of Early Career Letter to P5**

🟥 **>170 Endorsers from >40 Institutions at Snowmass**



https://sites.google.com/view/ec4c3



Early Career Letter of Support for C^3

C^3 Enthusiasts!

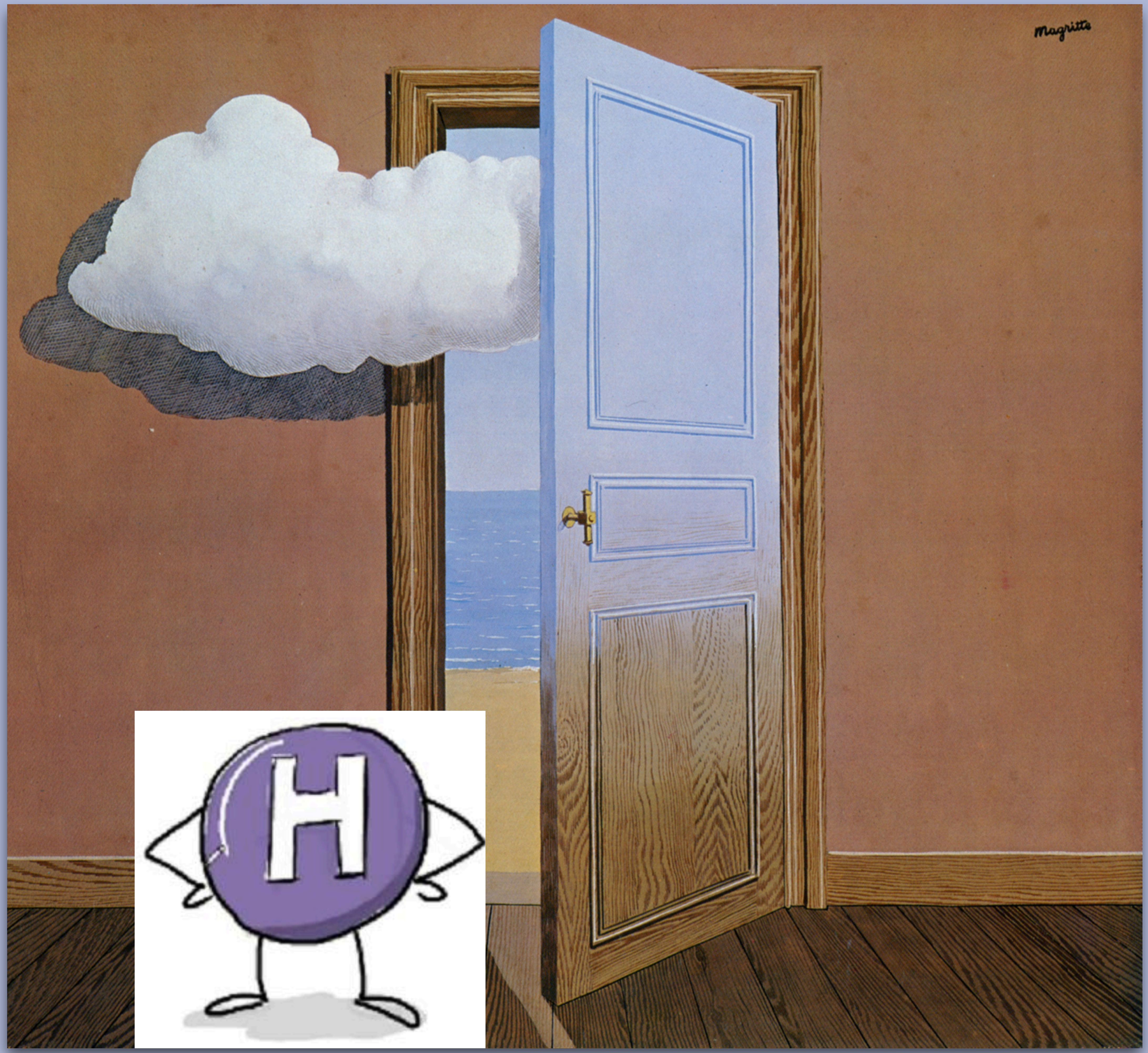
The draft text of our letter to the P5 is shown below.

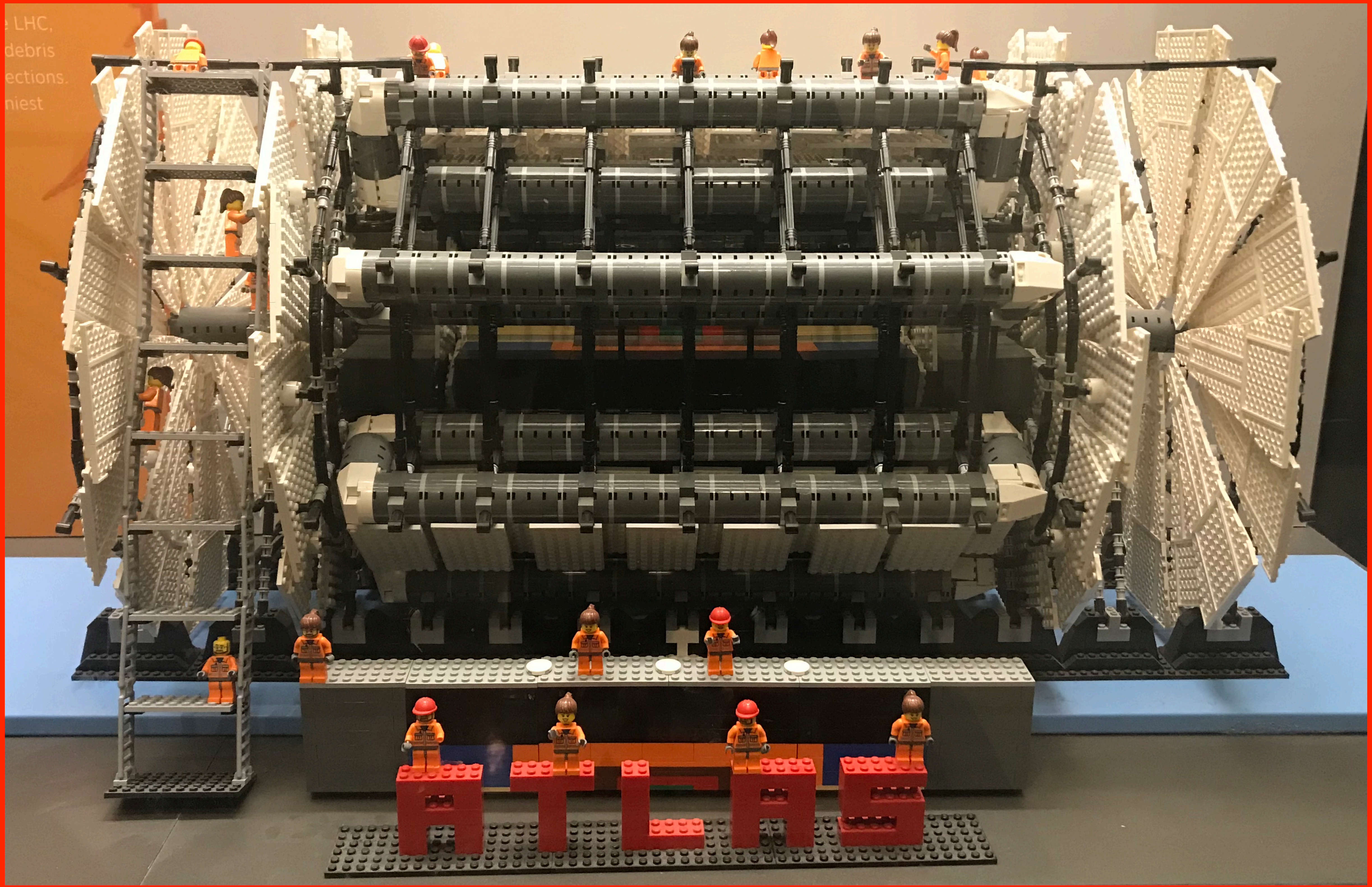
If you agree with the content of the letter, please add your name, email and any additional comments to the Google Form at the bottom of the page.

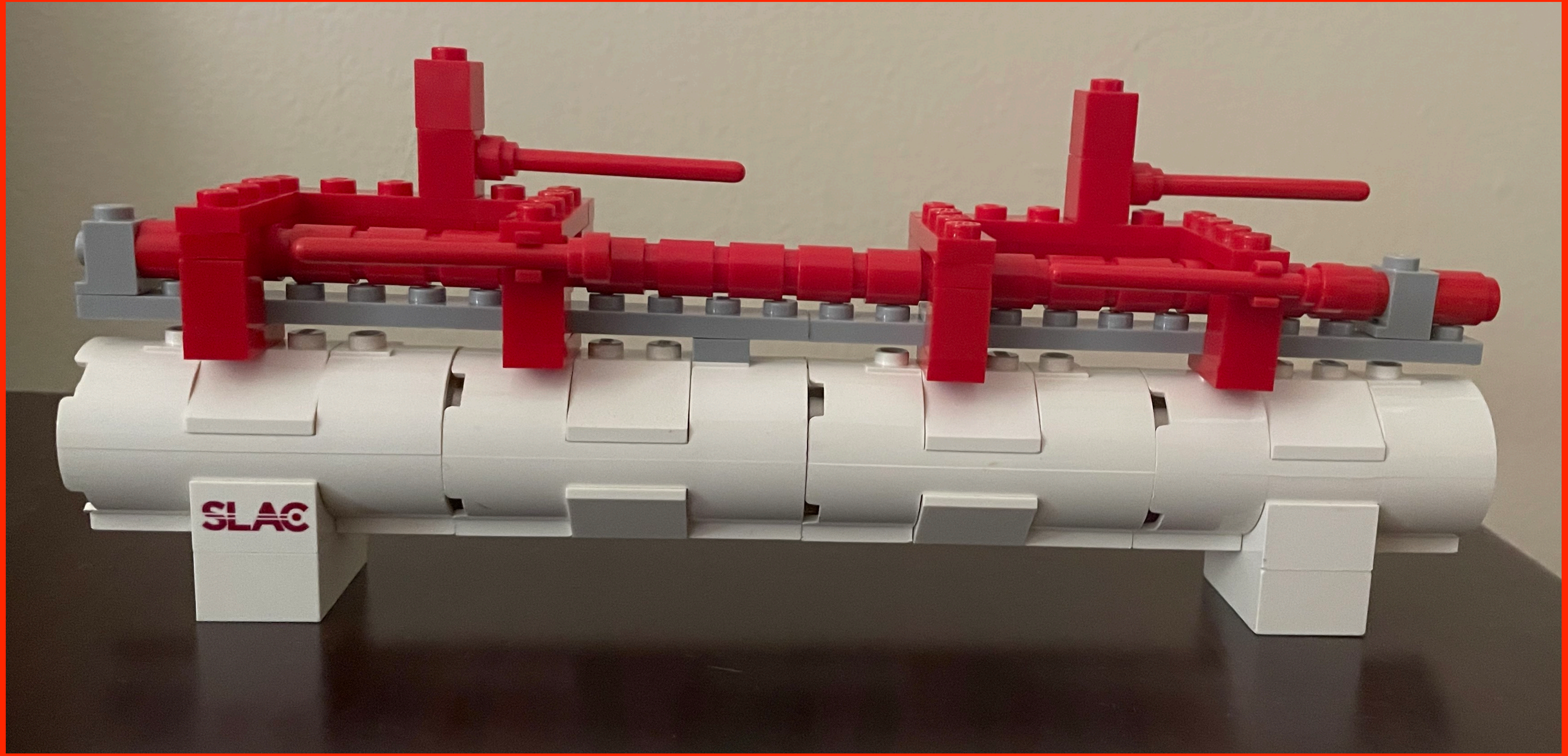
Signees will have the option to discuss their comments in a virtual forum before the letter is submitted to P5.

List of Signatures

- The Higgs boson is our most recent advance in the understanding of the fundamental particles
    - a **new state of matter-energy**
    - a **potential window to Beyond** the Standard Model through precision measurements
        - a possible relation between Higgs and dark matter, baryogenesis and inflation
- Collider physics is essential to explore the property of the Higgs Boson and EWSB
    - Higgs plays a central element for the **future colliders**
    - C^3 can provide a rapid route to precision Higgs physics with a compact footprint



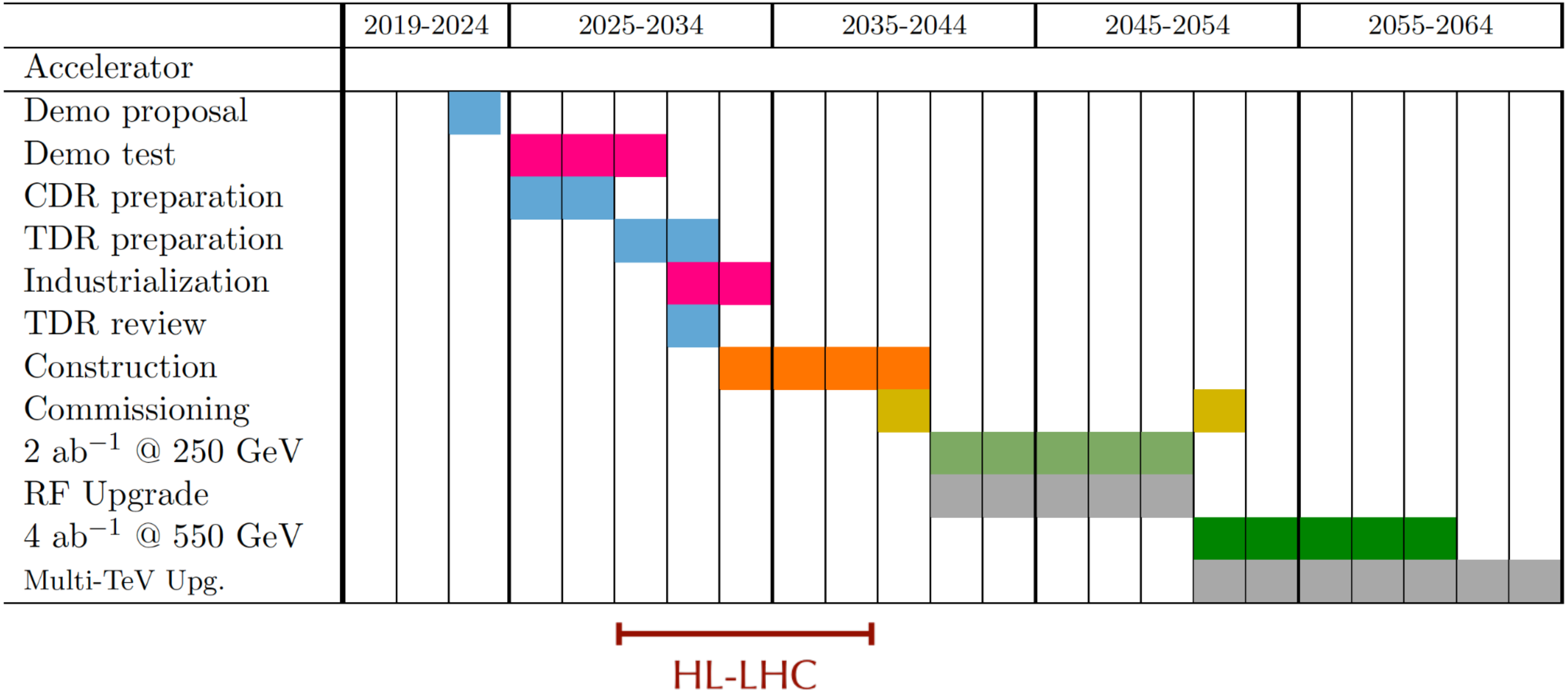




thank you!

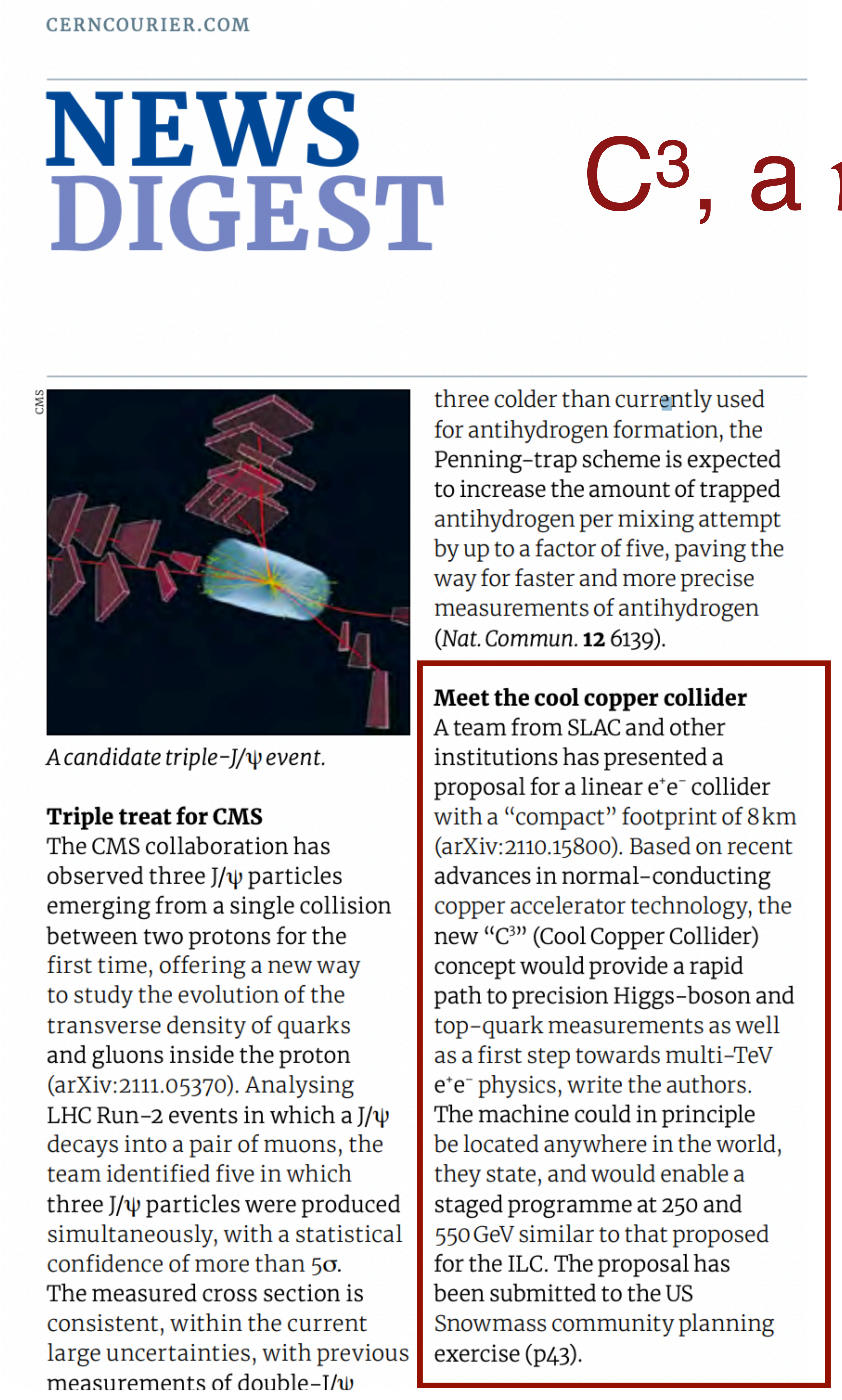
Technical Timeline for 250/550 GeV CoM

Energy upgrade in parallel to operation with installation of additional RF power sources



	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, a *novel* route to a linear e^+e^- collider



CERNCOURIER.COM

NEWS DIGEST

CMS

A candidate triple-J/ψ event.

Triple treat for CMS
The CMS collaboration has observed three J/ψ particles emerging from a single collision between two protons for the first time, offering a new way to study the evolution of the transverse density of quarks and gluons inside the proton (arXiv:2111.05370). Analysing LHC Run-2 events in which a J/ψ decays into a pair of muons, the team identified five in which three J/ψ particles were produced simultaneously, with a statistical confidence of more than 5σ. The measured cross section is consistent, within the current large uncertainties, with previous measurements of double-J/ψ

three colder than currently used for antihydrogen formation, the Penning-trap scheme is expected to increase the amount of trapped antihydrogen per mixing attempt by up to a factor of five, paving the way for faster and more precise measurements of antihydrogen (*Nat. Commun.* **12** 6139).

Meet the cool copper collider
A team from SLAC and other institutions has presented a proposal for a linear e^+e^- collider with a "compact" footprint of 8 km (arXiv:2110.15800). Based on recent advances in normal-conducting copper accelerator technology, the new "C^3" (Cool Copper Collider) concept would provide a rapid path to precision Higgs-boson and top-quark measurements as well as a first step towards multi-TeV e^+e^- physics, write the authors. The machine could in principle be located anywhere in the world, they state, and would enable a staged programme at 250 and 550 GeV similar to that proposed for the ILC. The proposal has been submitted to the US Snowmass community planning exercise (p43).

RESEARCH NEWS

A "Retro" Collider Design for a Higgs Factory

October 6, 2022 • *Physics* 15, 155

The Cool Copper Collider is a new proposal for a Higgs-producing linear collider that would be more compact than other collider designs.

Emilio Nanni/SLAC

A prototype version of the Cool Copper Collider. The photo shows the central region where the particle beams would pass.

https://physics.aps.org/articles/v15/155

arXiv:2003.01116

Physics requirements for detectors

Precision challenges detectors

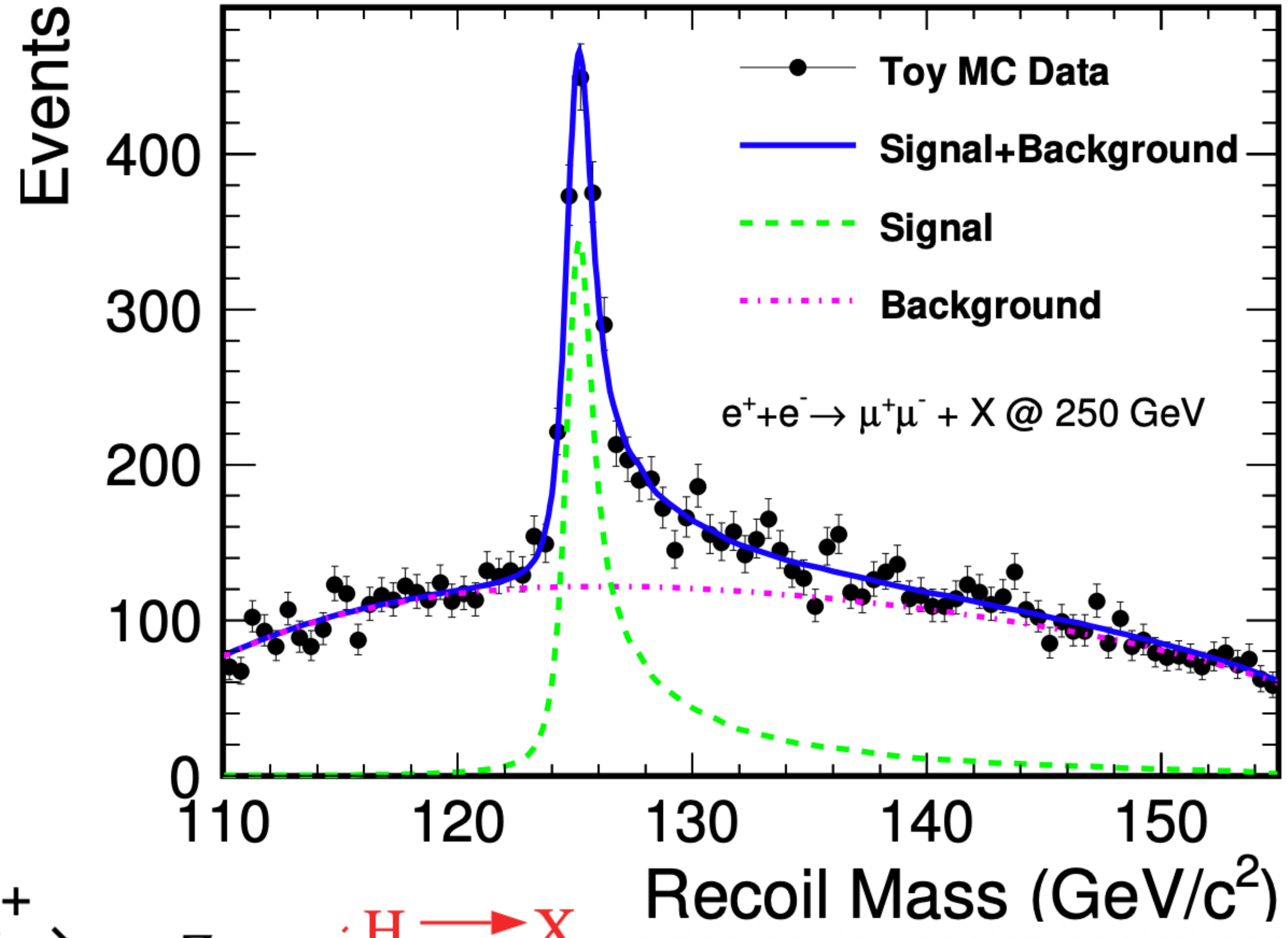
ZH process: Higgs recoil reconstructed from Z →*μμ*

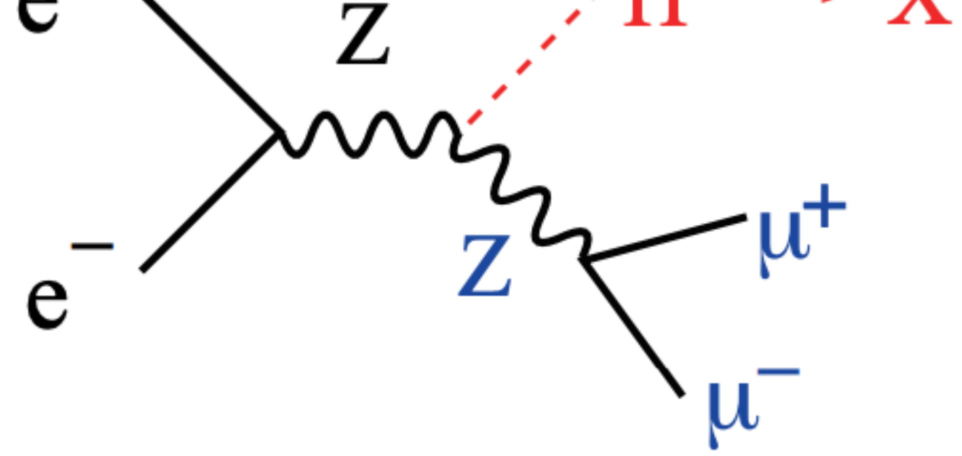
- ○ Drives requirement on charged track momentum and jet resolutions
- ○ Sets need for high field magnets and high precision / low mass trackers

Particle Flow reconstruction

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% X0) for vertex detector
- ○ Sensors will have to be less than 75 *μ*m thick with at least 5 *μ*m hit resolution (17-25*μ*m pitch)





$$m^2_{recoil} = s + m^2_Z - 2 \cdot E_Z \cdot \sqrt{s}$$

arXiv:2003.01116

Physics requirements for detectors

Precision challenges detectors

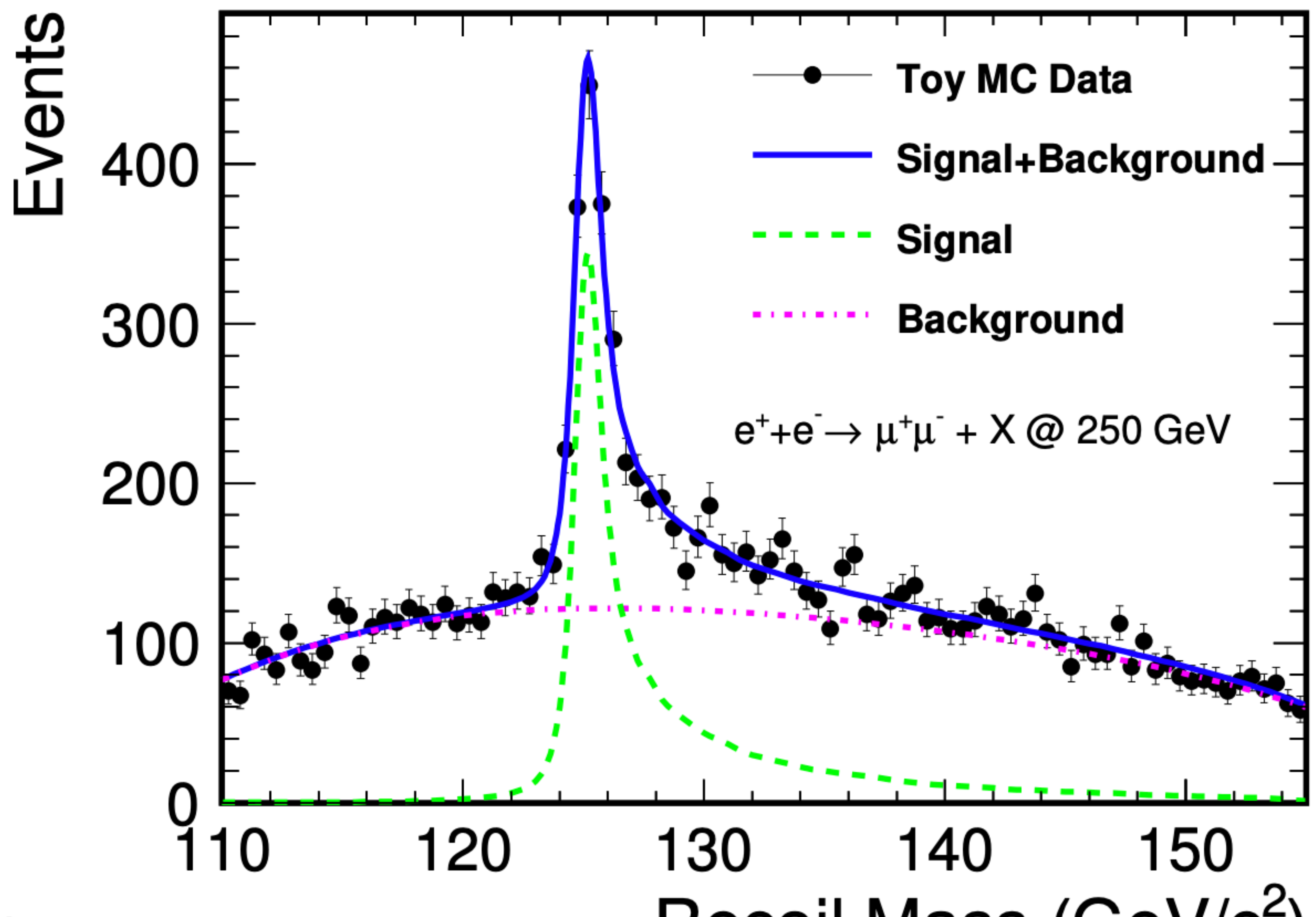
ZH process: Higgs recoil reconstructed from Z →$\mu\mu$

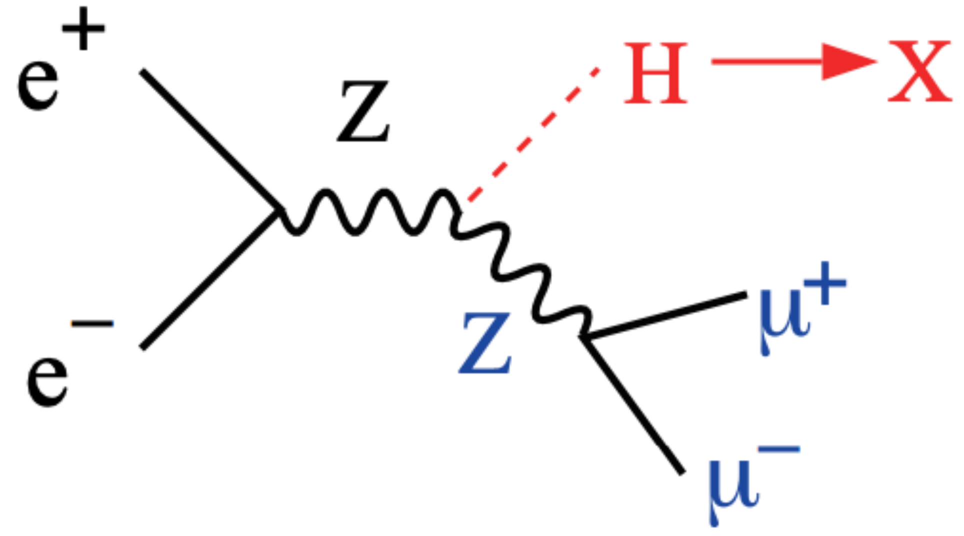
- Drives requirement on charged track momentum and jet resolutions
- Sets need for high field magnets and high precision / low mass trackers

Particle Flow reconstruction

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% X0) for vertex detector
- Sensors will have to be less than 75 μm thick with at least 5 μm hit resolution (17-25μm pitch)





$$m^2_{recoil} = s + m^2_Z - 2 \cdot E_Z \cdot \sqrt{s}$$

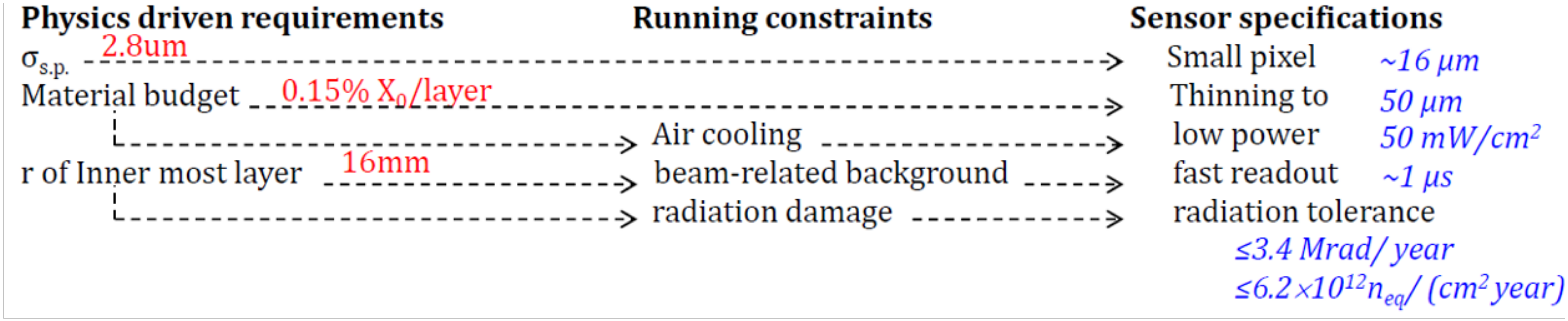
Need new generation of ultra low mass vertex detectors with dedicated sensor designs

Sensors technology requirements for Vertex Detector

Several technologies are being studied to meet the physics performance

Sensor’s contribution to the total material budget of vertex detector is 15-30%

Sensors will have to be less than 75 μm thick with at least 3-5 μm hit resolution (17-25 μm pitch) and low power consumption



Physics driven requirements **Running constraints** **Sensor specifications**

$\sigma_{s.p.}$ 2.8um → Small pixel ~16 μm

Material budget 0.15% X_0/layer → Thinning to 50 μm

→ Air cooling → low power 50 mW/cm^2

r of Inner most layer 16mm → beam-related background → fast readout ~1 μs

→ radiation damage → radiation tolerance

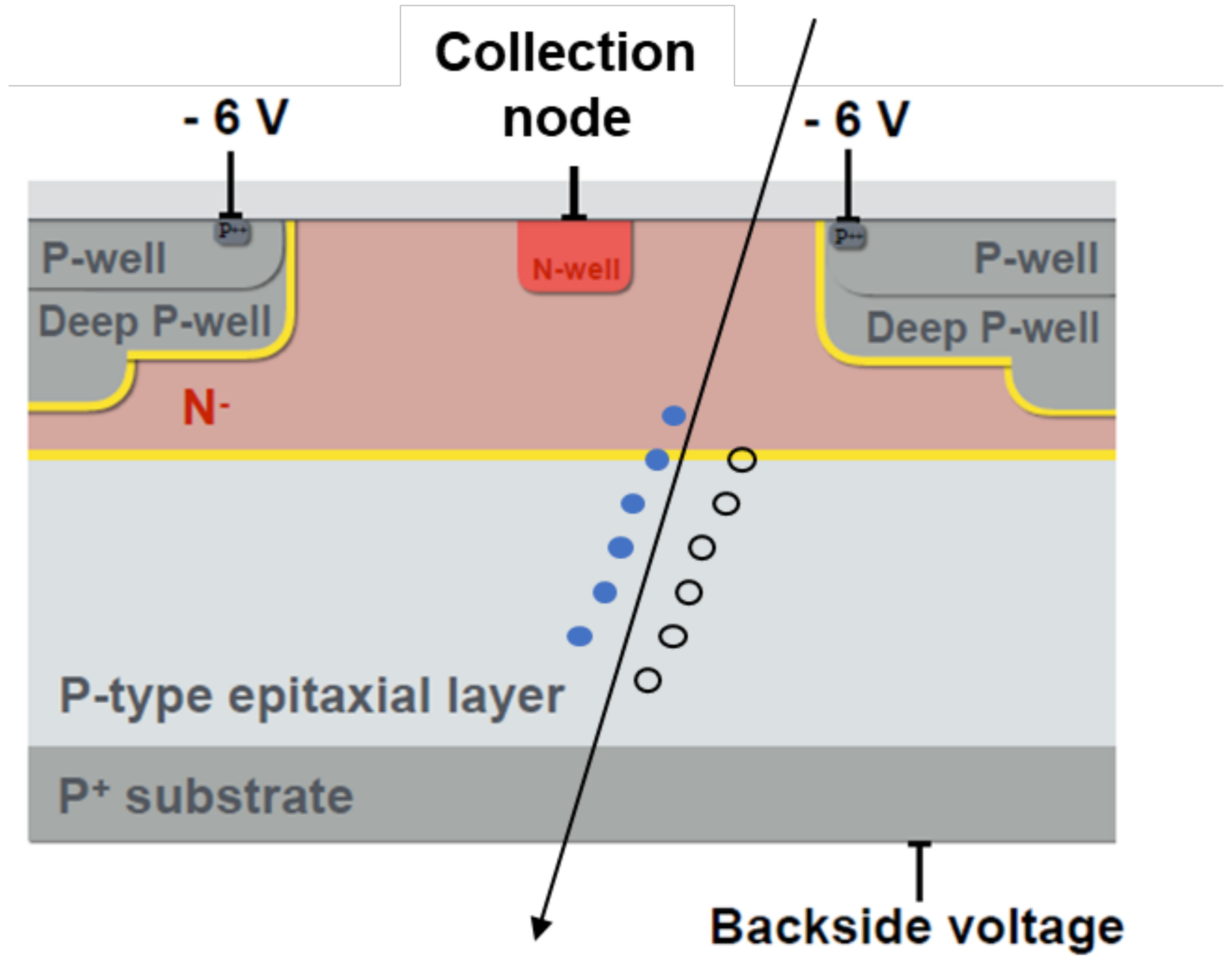
≤ 3.4 Mrad/ year

$\leq 6.2 \times 10^{12} n_{eq}/ (cm^2\ year)$

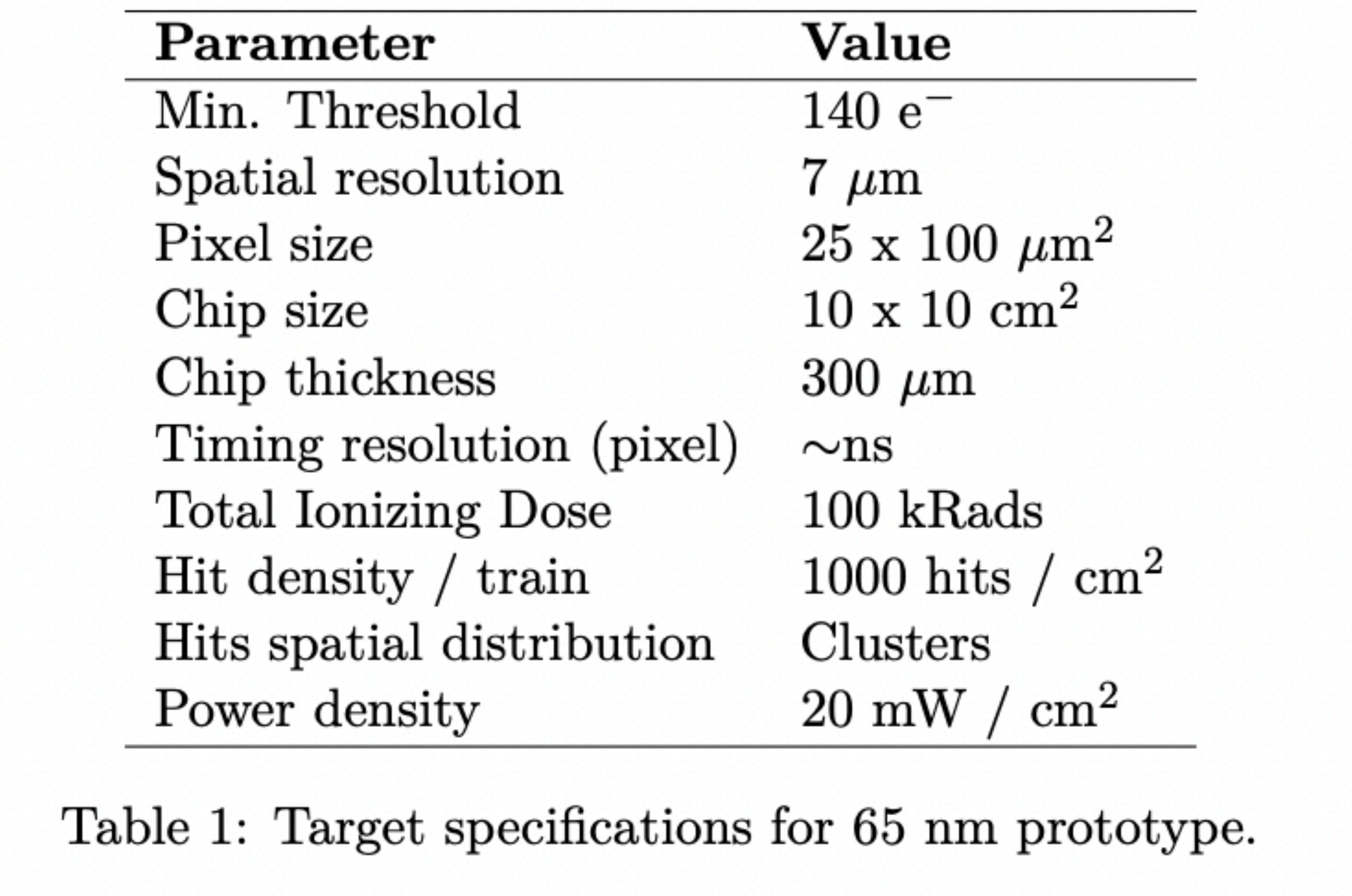
MAPS

Monolithic Active Pixel Sensors (MAPS) for high precision tracker and high granularity calorimetry

- Monolithic technologies have the potential for providing higher granularity, thinner, intelligent detectors at lower overall cost.
- Significantly lower material budget: sensors and readout electronics are integrated on the same chip
  - Eliminate the need for bump bonding : thinned to less than 100μm
  - Smaller pixel size, not limited by bump bonding
  - Lower costs : implemented in standard commercial CMOS processes



Initial specifications for fast MAPS aka NAPA



Parameter	Value
Min. Threshold	140 e^-
Spatial resolution	7 μm
Pixel size	25 x 100 μm^2
Chip size	10 x 10 cm^2
Chip thickness	300 μm
Timing resolution (pixel)	~ns
Total Ionizing Dose	100 kRads
Hit density / train	1000 hits / cm^2
Hits spatial distribution	Clusters
Power density	20 mW / cm^2

Table 1: Target specifications for 65 nm prototype.

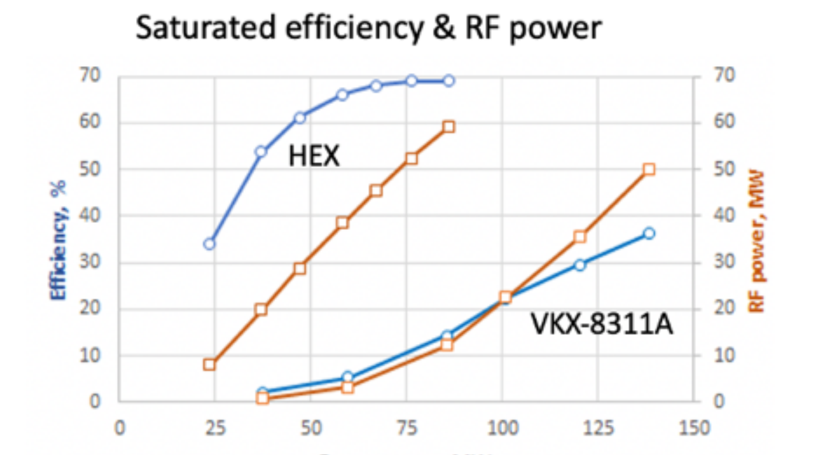
Global Contributions

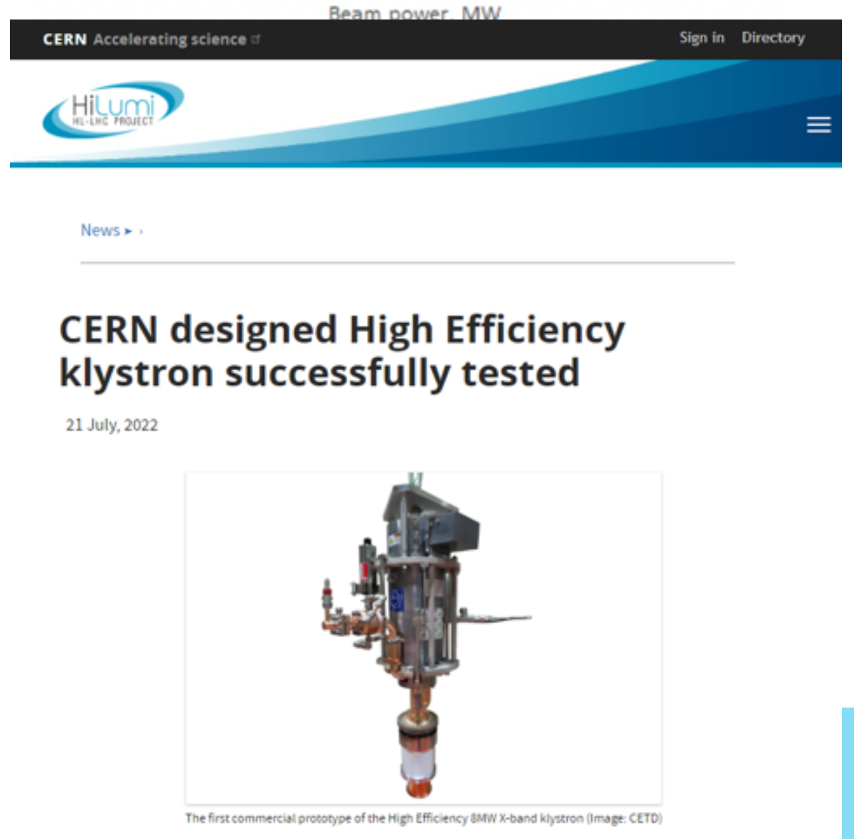
C3 Technical Timeline Only Possible with the Exceptional Progress of ILC and CLIC

- Benefit from injector complex and beam delivery concepts
- Continue to benefit from technological improvement by ILC and CLIC

High Efficiency RF Sources (CLIC)

Retro-fit High Efficiency 50 MW, 12 GHz klystron (CERN/CPI).

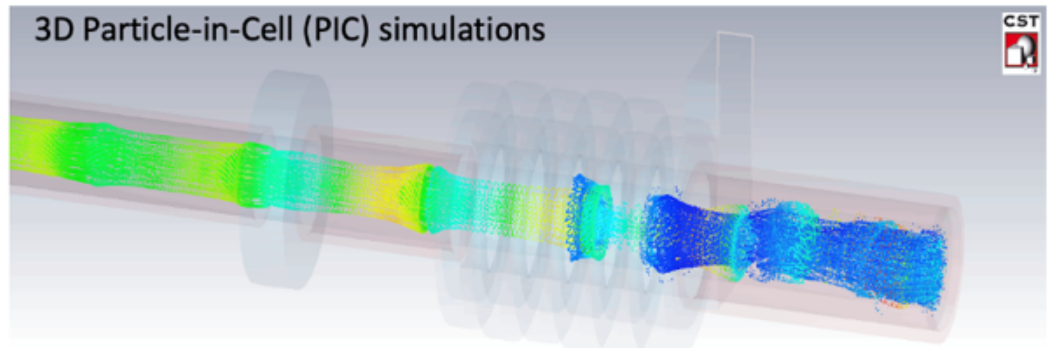

Saturated efficiency & RF power

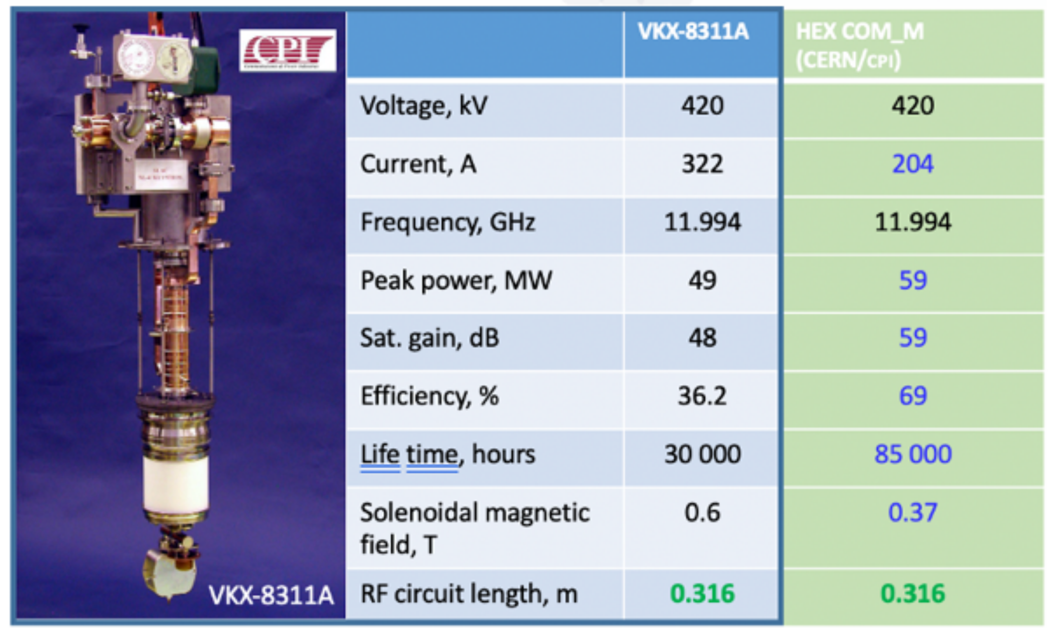


CERN designed High Efficiency klystron successfully tested

21 July, 2022

The first commercial prototype of the High Efficiency 8MW X-band klystron (Image: CETD)

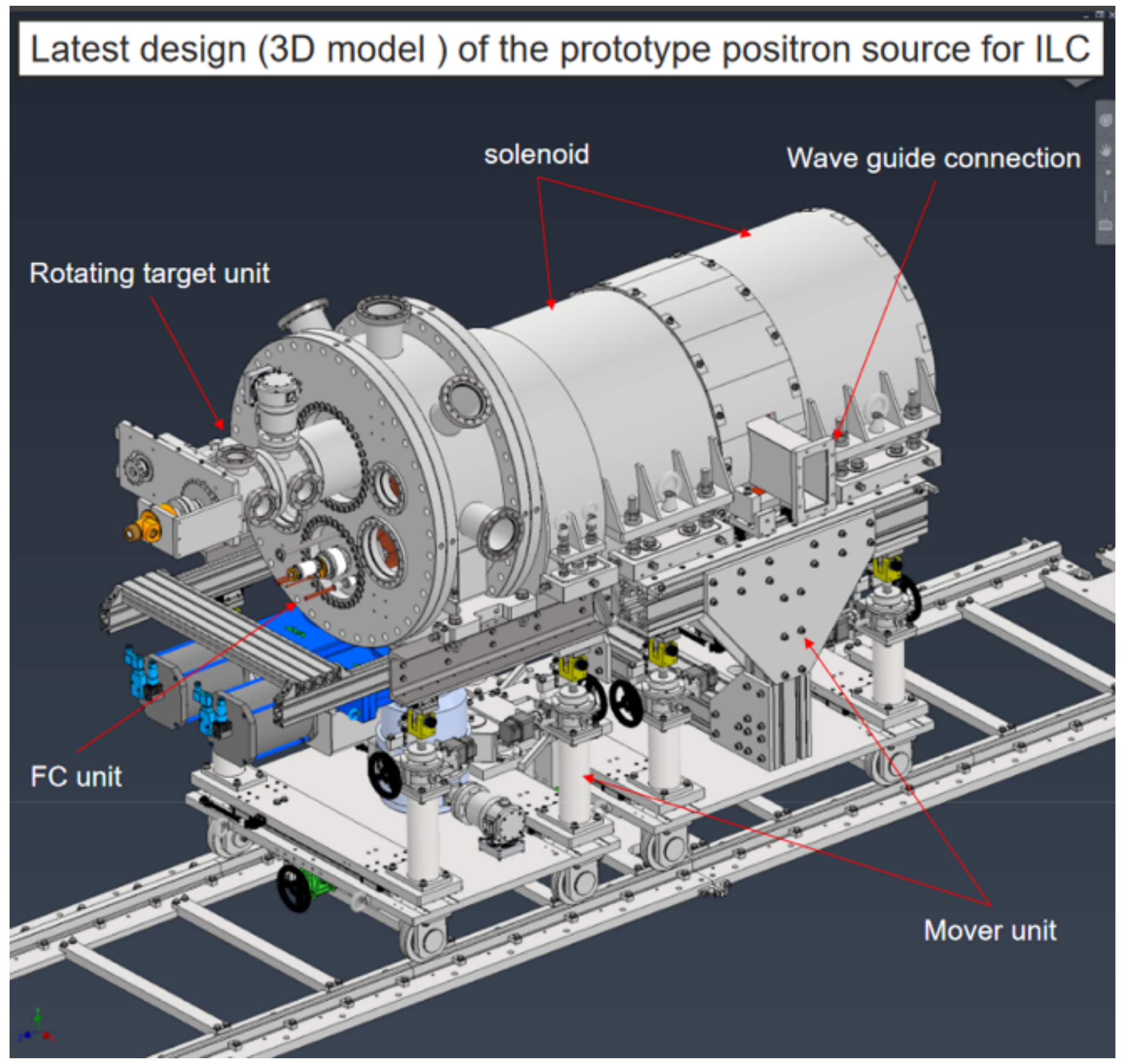

3D Particle-in-Cell (PIC) simulations



	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	59
Efficiency, %	36.2	69
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.37
RF circuit length, m	0.316	0.316

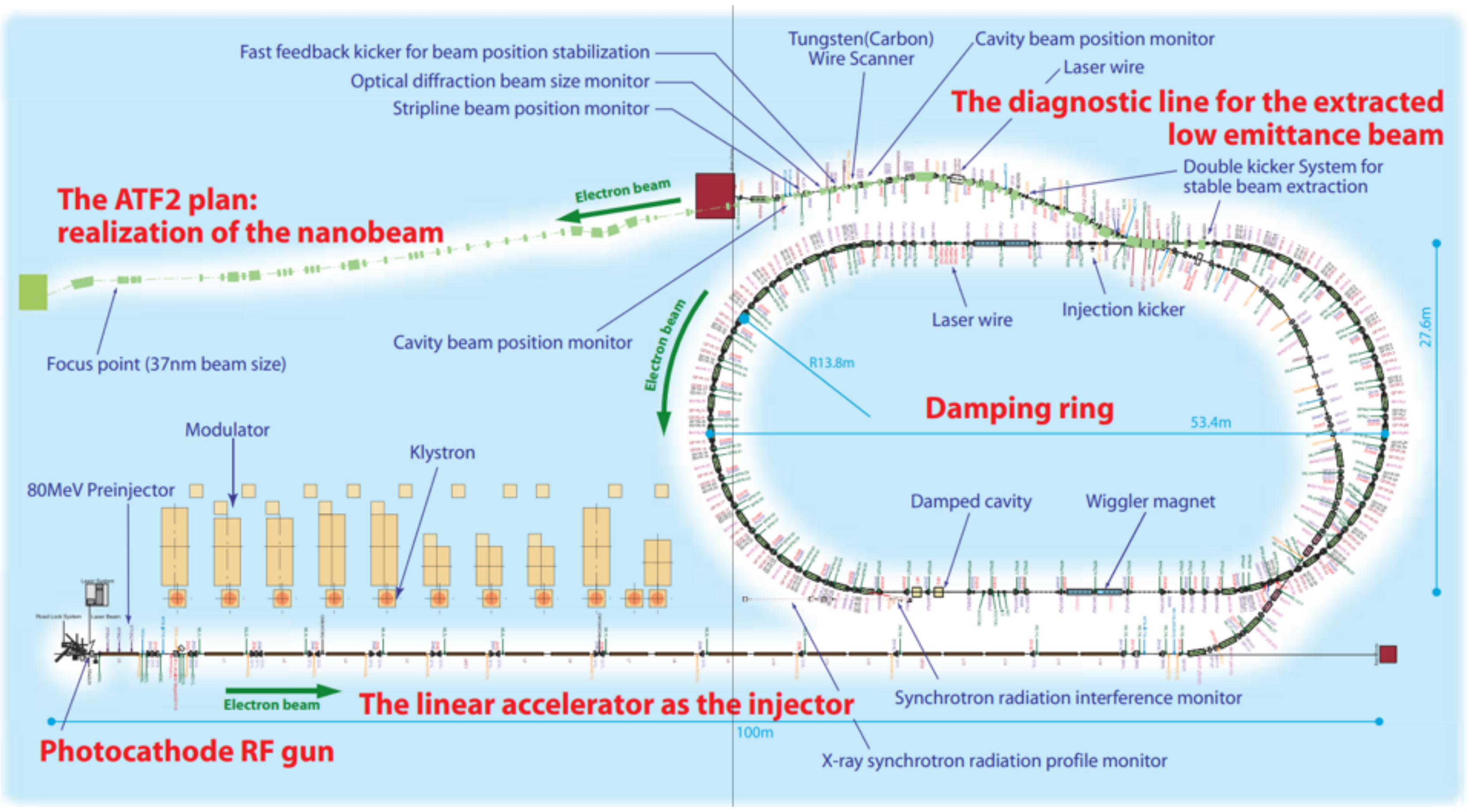
I. Sarchev, CERN

Electron Driven Positron Source


Latest design (3D model) of the prototype positron source for ILC

Courtesy of Y. Enomoto

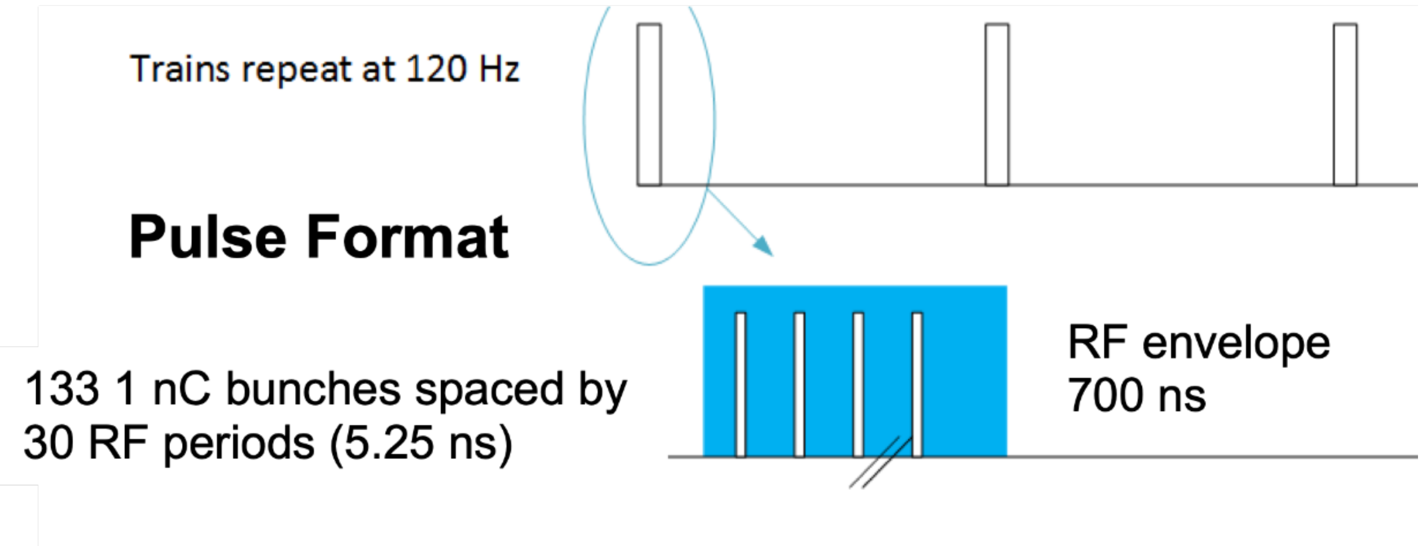
Nanobeams for IP (ATF)



https://www-atf.kek.jp/atf/

Vibrant International Community for Future Colliders is Essential
National Future Colliders R&D in the US to Optimize Efforts

Power Consumption and Sustainability



Trains repeat at 120 Hz

Pulse Format

133 1 nC bunches spaced by 30 RF periods (5.25 ns)

RF envelope 700 ns

Temperature (K)	77
Beam Loading (%)	45
Gradient (MeV/m)	70
Flat Top Pulse Length (μs)	0.7
Cryogenic Load (MW)	9
Main Linac Electrical Load (MW)	100
Site Power (MW)	~150

250 GeV CoM - Luminosity - 1.3×10^{34}

Parameter	Units	Value
Reliquification Plant Cost	M$/MW	18
Single Beam Power (125 GeV linac)	MW	2
Total Beam Power	MW	4
Total RF Power	MW	18
Heat Load at Cryogenic Temperature	MW	9
Electrical Power for RF	MW	40
Electrical Power For Cryo-Cooler	MW	60
Accelerator Complex Power	MW	~50
Site Power	MW	~150

Compatibility with Renewables
Cryogenic Fluid Energy Storage

Highview Power

Intermittent and variable power production from renewables mediated with commercial scale energy storage and power production

MAPS Detector R&D

Monolithic Active Pixel Sensors (MAPS) for high precision tracker and high granularity calorimetry

- Monolithic technologies have the potential for providing higher granularity, thinner, intelligent detectors at lower overall cost.
- Significantly lower material budget: sensors and readout electronics are integrated on the same chip
  - Eliminate the need for bump bonding : thinned to less than 100μm
  - Smaller pixel size, not limited by bump bonding
  - Lower costs : implemented in standard commercial CMOS processes
- SLAC is part of the existing CERN WP 1.2 collaboration
- R&D efforts towards a wafer-scale MAPS on TowerJazz 65 nm

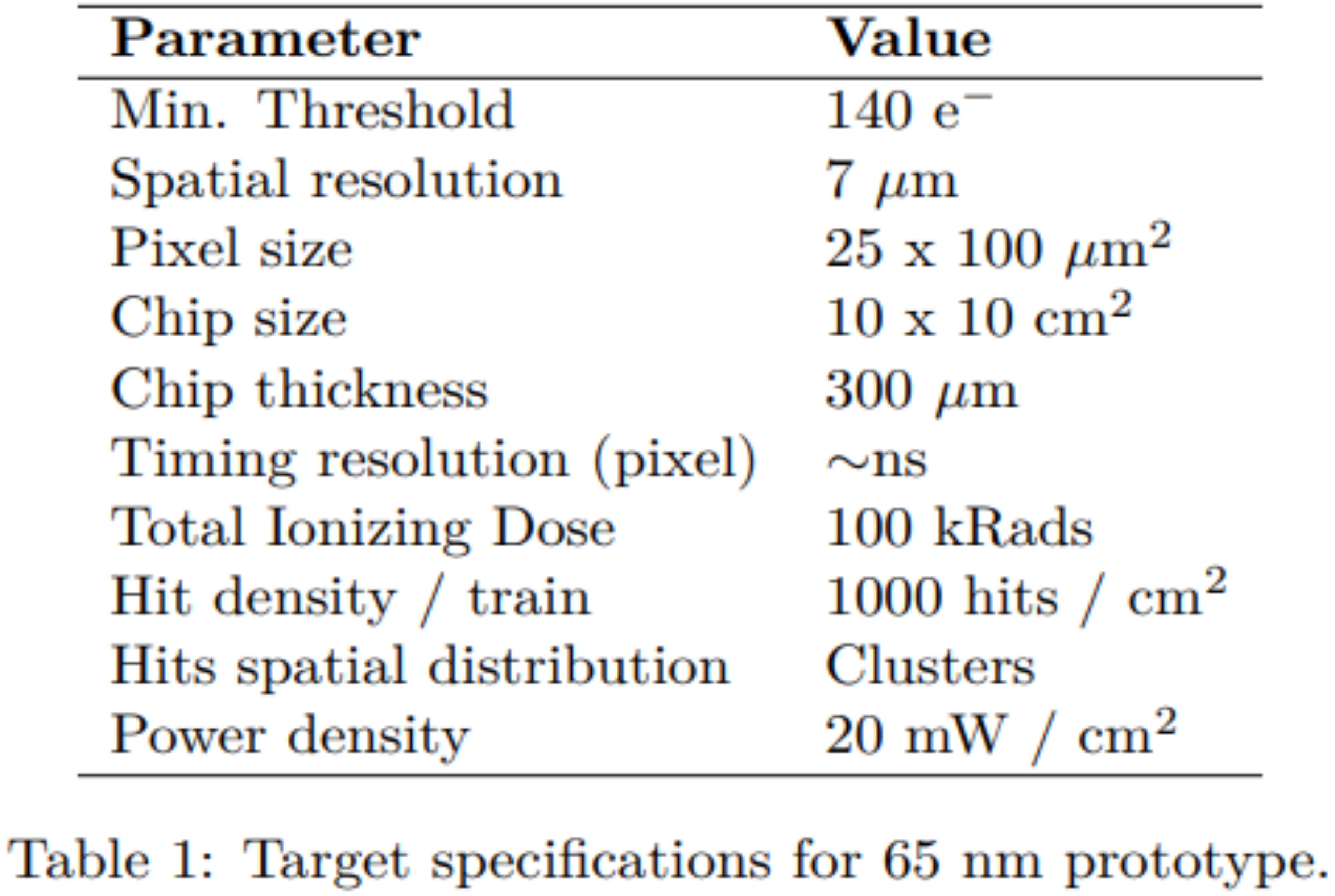


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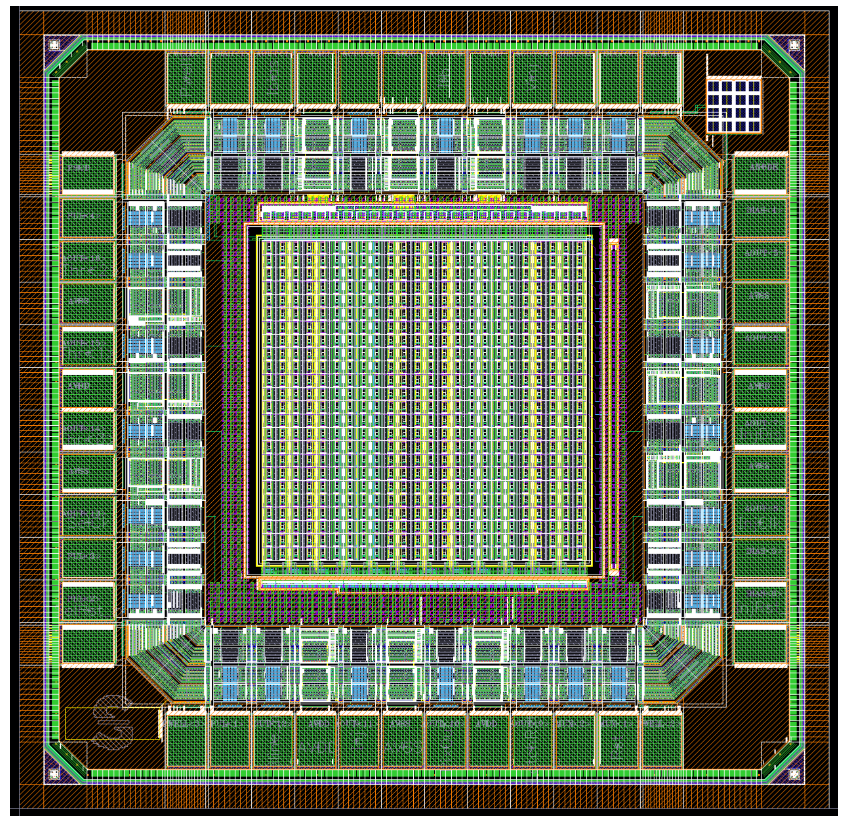
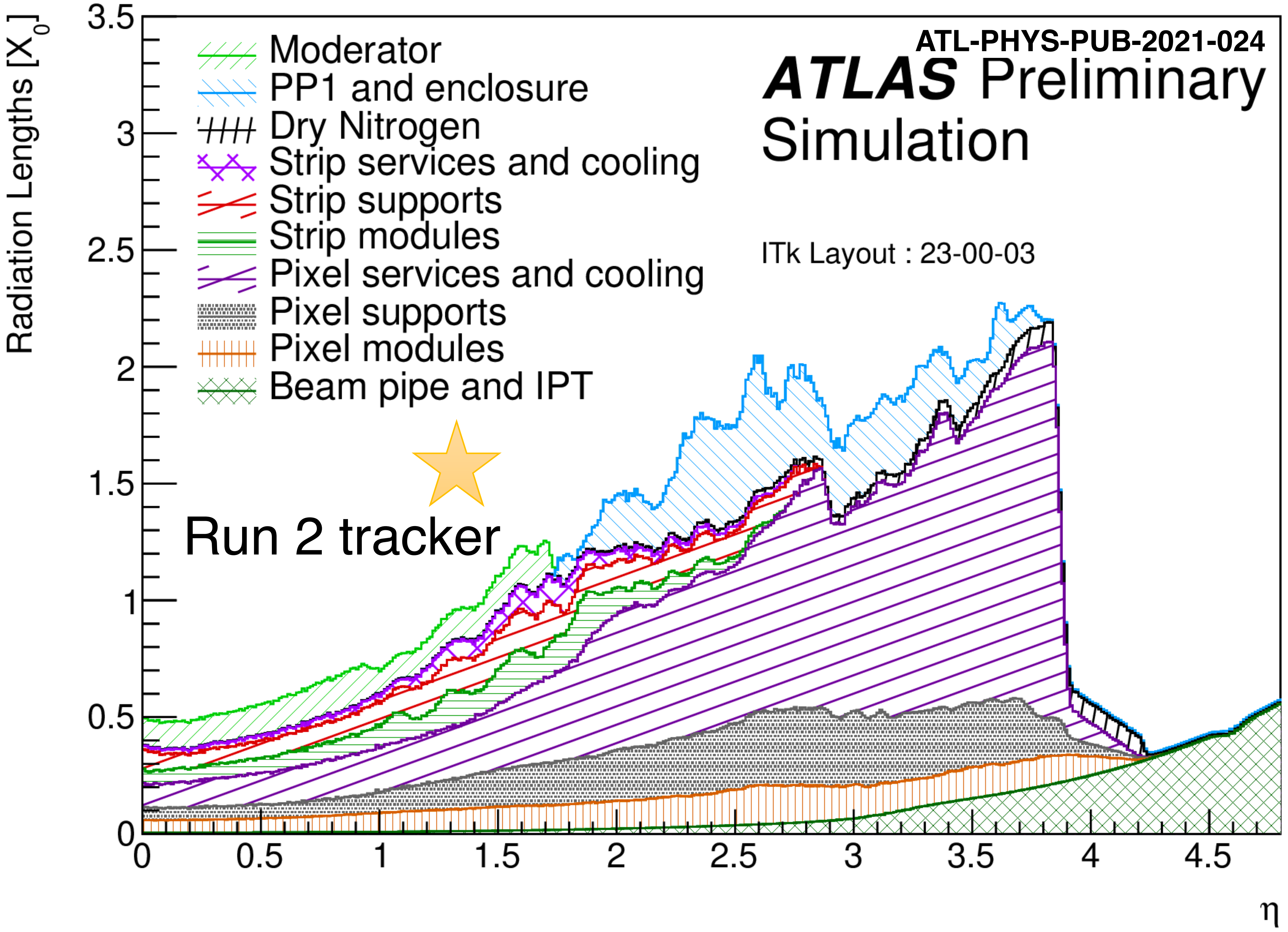
Table 1: Target specifications for 65 nm prototype.



Material Budget

Lower material budget than ATLAS ID, from 1.6 → 0.6 X_0 at η ~1



- **Evaporative CO_2** cooling system with titanium pipes
- **Carbon structures** for local supports.
- Optimized number of readout cables using **link sharing**
- Innovative **Serial Powering scheme** in the pixels.

A strong US-based initiative mitigates Global Uncertainty

The Snowmass Energy Frontier discussions have unequivocally highlighted the following theme:

- The US community advocates for an active role in planning for future colliders
  - Investigate the possibility of an Higgs factory and the R&D for a future muon collider in the US
  - Given global uncertainties, consideration should be given to the timely realization of a domestic Higgs factory, in case none of the currently proposed options will be realized.
- Future colliders will set unique challenges in detector design to achieve our ambitious physics goals

The investment in detector and collider R&D for lepton facilities in the US should start now

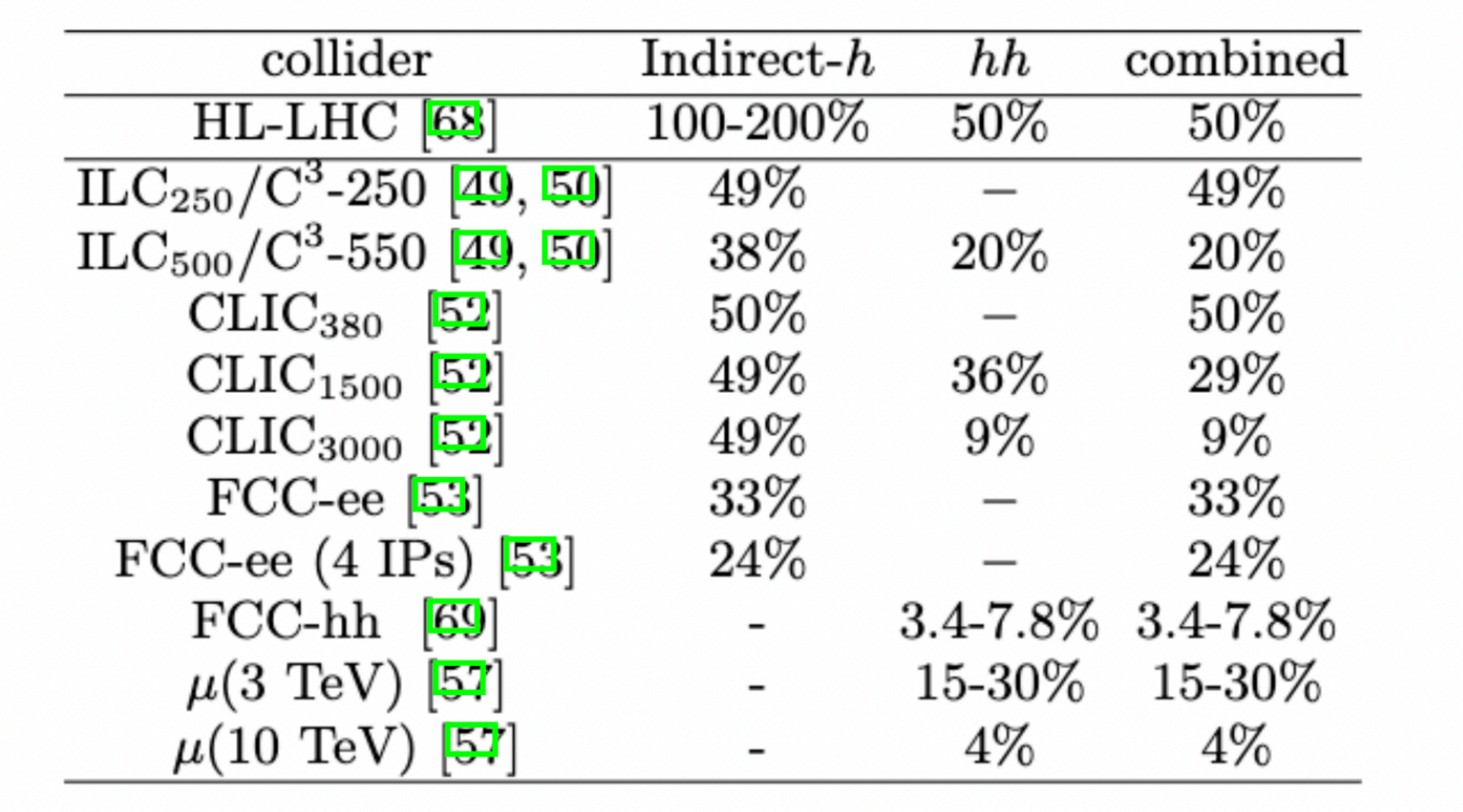
- A parallel effort with the LHC to enable a future e+e– precision electroweak program and a high-energy machine
- **Such a domestic R&D program would grow the US accelerator & detector workforce and strengthen the international community, regardless of where the next big project will be realized**

The opportunity to work on fundamental problems and technological challenges is a key element to motivate students and early career scientists

- A US-based future collider R&D program will give the impetus to make particle physics program attractive to the young and future generations of scientists in the US.

The Higgs self-coupling at future colliders

arXiv:1910.00012
arXiv:2004.03505



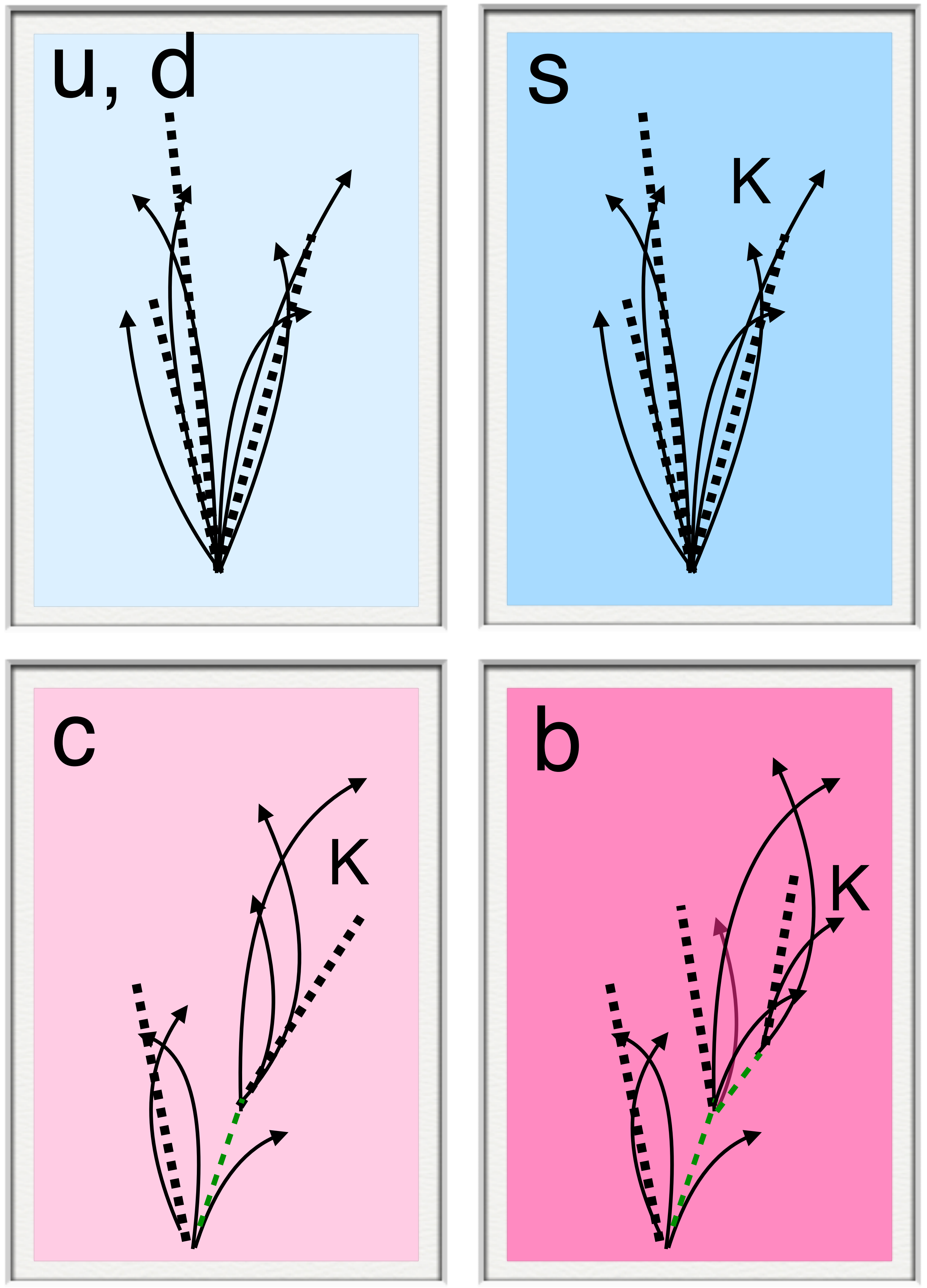
collider	Indirect-h	hh	combined
HL-LHC [68]	100-200%	50%	50%
ILC$_{250}$/C^3-250 [49, 50]	49%	–	49%
ILC$_{500}$/C^3-550 [49, 50]	38%	20%	20%
CLIC$_{380}$ [52]	50%	–	50%
CLIC$_{1500}$ [52]	49%	36%	29%
CLIC$_{3000}$ [52]	49%	9%	9%
FCC-ee [53]	33%	–	33%
FCC-ee (4 IPs) [53]	24%	–	24%
FCC-hh [69]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [57]	-	15-30%	15-30%
μ(10 TeV) [57]	-	4%	4%

O(20%) precision on the Higgs self-coupling would allow to exclude/demonstrate at 5σ models of electroweak baryogenesis

2101.04119
2203.07535

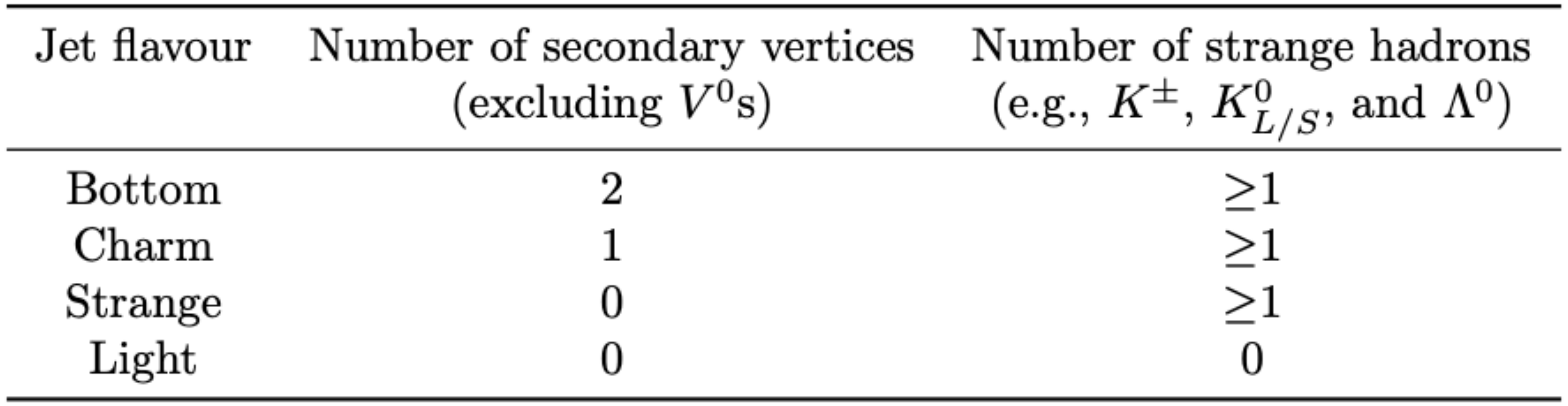
s-tagging

Tagging strange is a challenging but not impossible task for future detectors at e^+e^-



- As b,c, and s jets contain at least one strange hadron
- Strange quarks mostly hadronize to prompt kaons which carry a large fraction of the jet momentum
- Strange hadron reconstruction:
  - $K^\pm$ PID
  - K^0_L PF (neutral)
  - $K^0_S \rightarrow \pi^+\pi^-$ (~70%) / $\pi^0\pi^0$ (~30%)
  - $\Lambda^0 \rightarrow p\pi^-$ (~65%)

Distinctive two-prong vertices topology

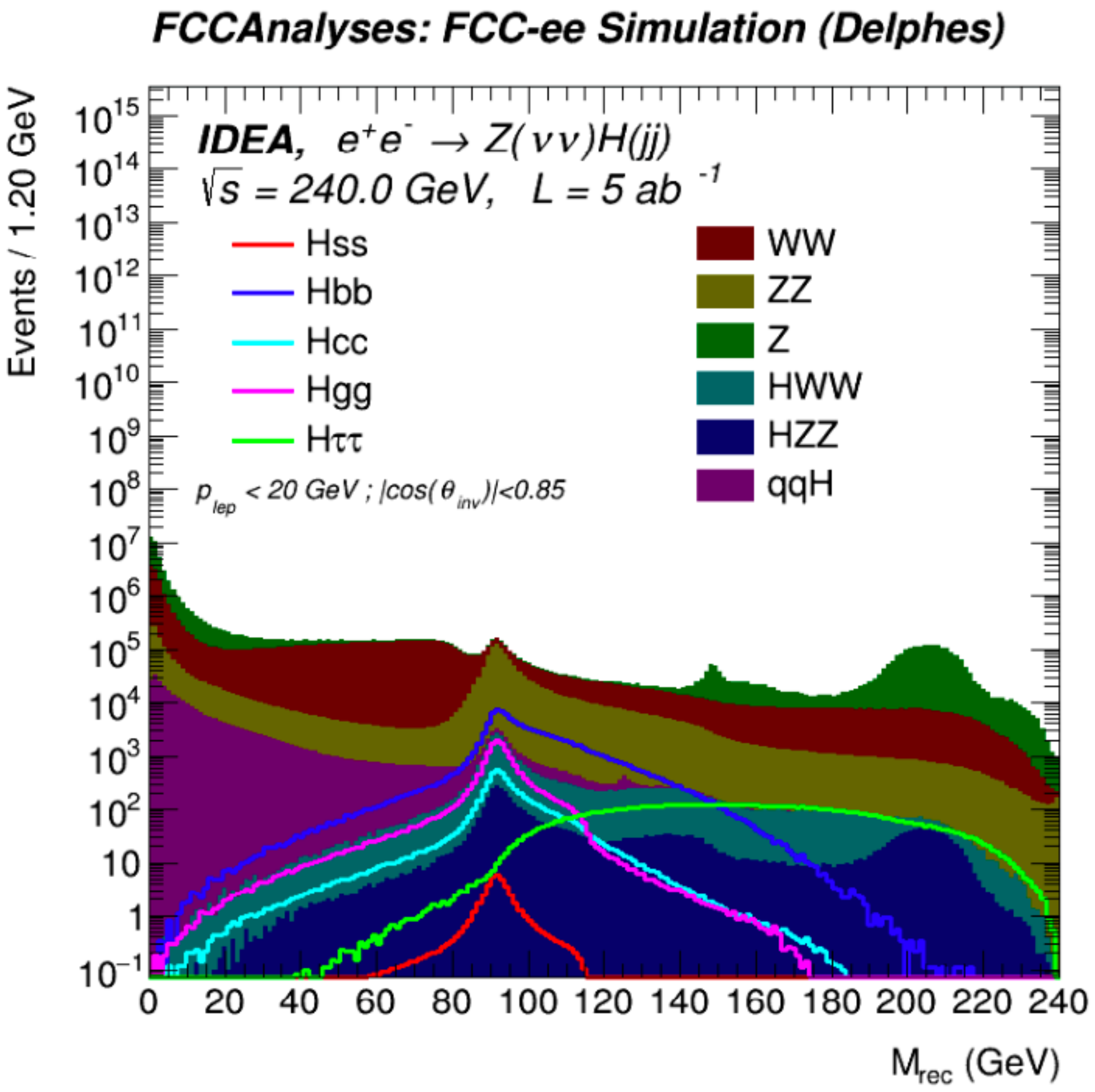


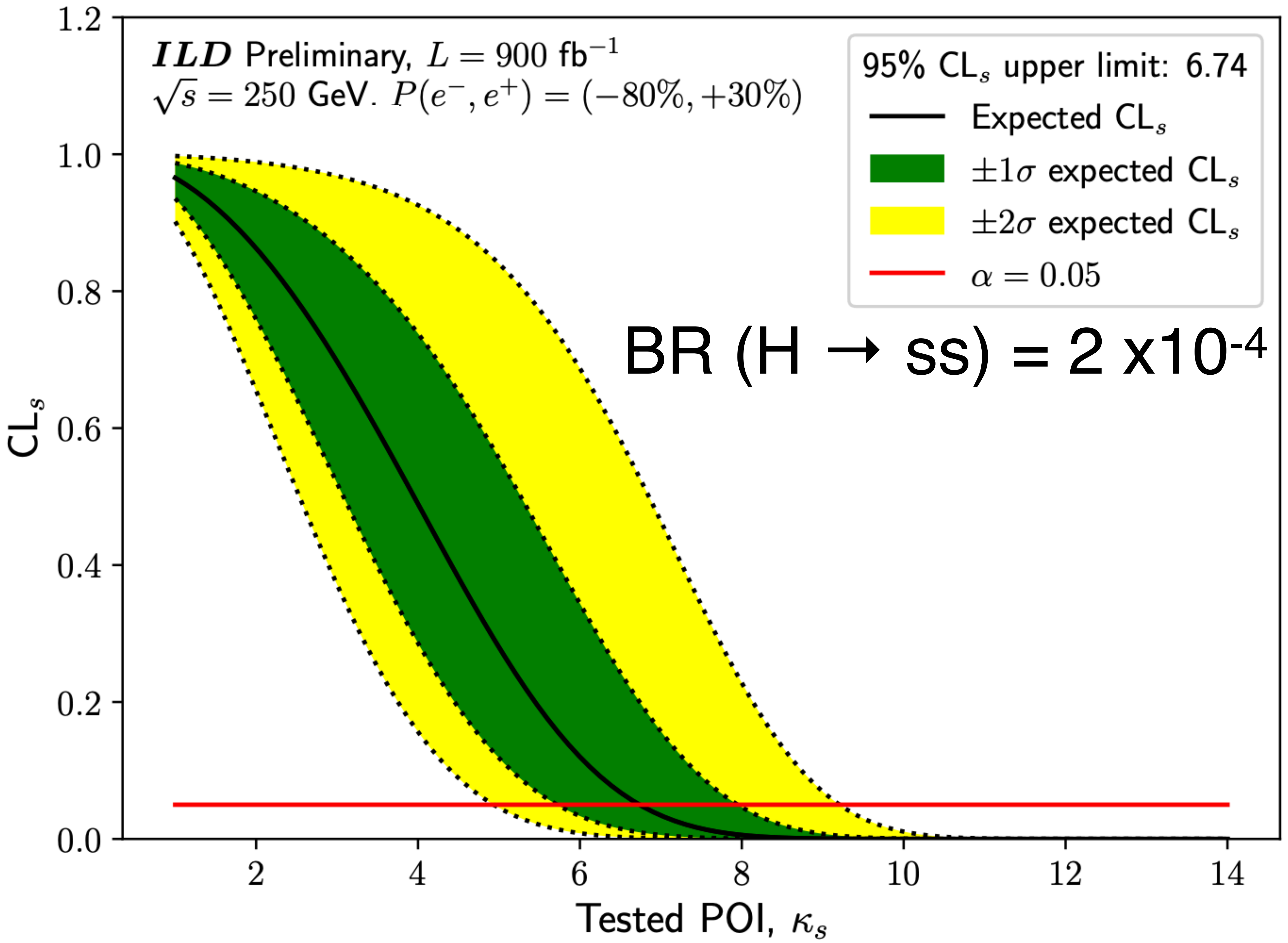
Jet flavour	Number of secondary vertices (excluding V^0s)	Number of strange hadrons (e.g., $K^\pm$, $K^0_{L/S}$, and Λ^0)
Bottom	2	≥1
Charm	1	≥1
Strange	0	≥1
Light	0	0

Constraints on s-coupling

Compatible results for both FCC and ILC like analyses

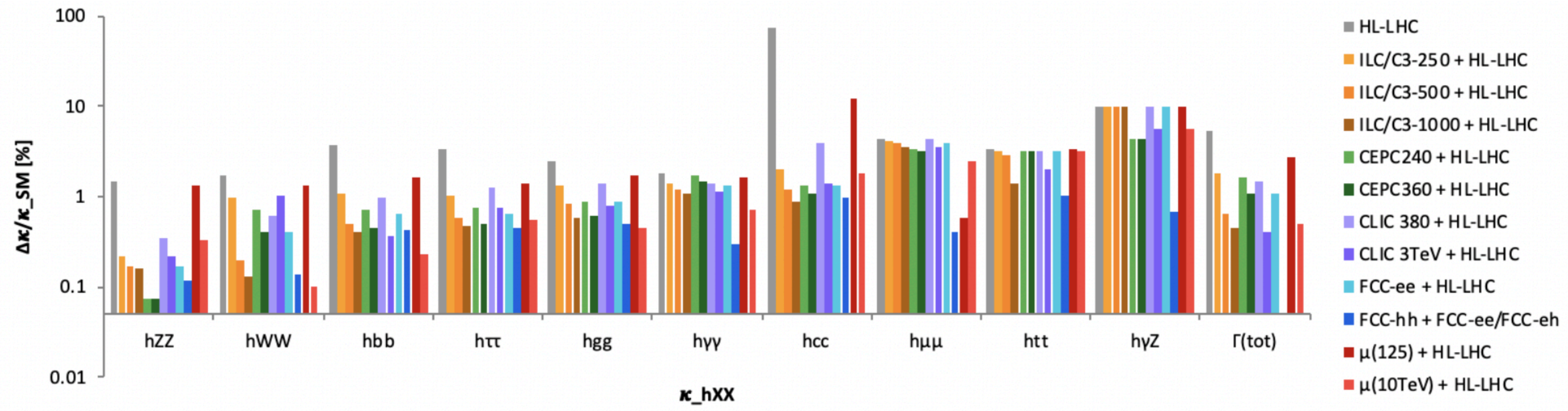
- ILD combined limit of $\kappa_s < 6.74$ at 95% CL with 900/fb at 250 GeV (i.e. half dataset)
  - No PID worsen the results by 8%
- FCC for Z(vv) only sets a limit of $\kappa_s < 1.3$ at 95% CL with 5/ab at 250 GeV and 2 IPs





BR (H → ss) = 2 x10^{-4}

Higgs couplings at future machines



- The Zγ interaction remains difficult to measure at all future machines
- Higher energy collision is required (factor 2 from 500 to 550 GeV e+e-) to further constraints the Higgs-top coupling
- These results are based on the κ_0 scenario of the ESG (combined with projections for HL-LHC results) and do not allow for BSM decays

One note on polarization

arXiv:1708.08912
arXiv:1801.02840

- There are extensive comparisons between the FCC-ee plan and the C^3/ILC runs that show they are rather **compatible to study the Higgs Boson**
- When analyzing Higgs couplings with SMEFT, 2 ab^{-1} of polarized running is essentially equivalent to 5 ab^{-1} of unpolarized running.
  - **Electron polarization is essential** for this. But, there is almost no difference in the expectation with and without positron polarization.
  - Positron polarization allows more cross-checks of systematic errors. We may wish to add it later.
  - Positron polarization brings a large advantage in multi-TeV running, where the most important cross sections are from $e^-_L e^+_R$

	2/ab-250	+4/ab-500	5/ab-250	+ 1.5/ab-350
coupling	pol.	pol.	unpol.	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

Higgs couplings: precision & kinematic

arXiv:1310.8361

The **EFT formalism summarizes** deviations that might appear in a very wide class of models beyond the SM

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{M^2}\sum_k \mathcal{O}_k$$

Assuming new physics at some scale $M \gg v$

Higgs couplings: precision & kinematic

arXiv:1310.8361

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Assuming new physics at some scale $M \gg v$

Sub-percent level measurements can test TeV-scale new physics effect

- If E~m_H and M~1 TeV, the effects of **dim-6** (8) operators are of the order of **few %** (10^{-4})

$$\delta O \sim \left(\frac{v}{M}\right)^2 \sim 6\,\% \left(\frac{\mathrm{TeV}}{M}\right)^2$$

Higgs couplings: precision & kinematic

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$$\delta O \sim \left(\frac{v}{M}\right)^2 \sim 6\,\%\left(\frac{\mathrm{TeV}}{M}\right)^2$$

Measurements at **large transferred momentum** (Q) probe large M even if precision is low

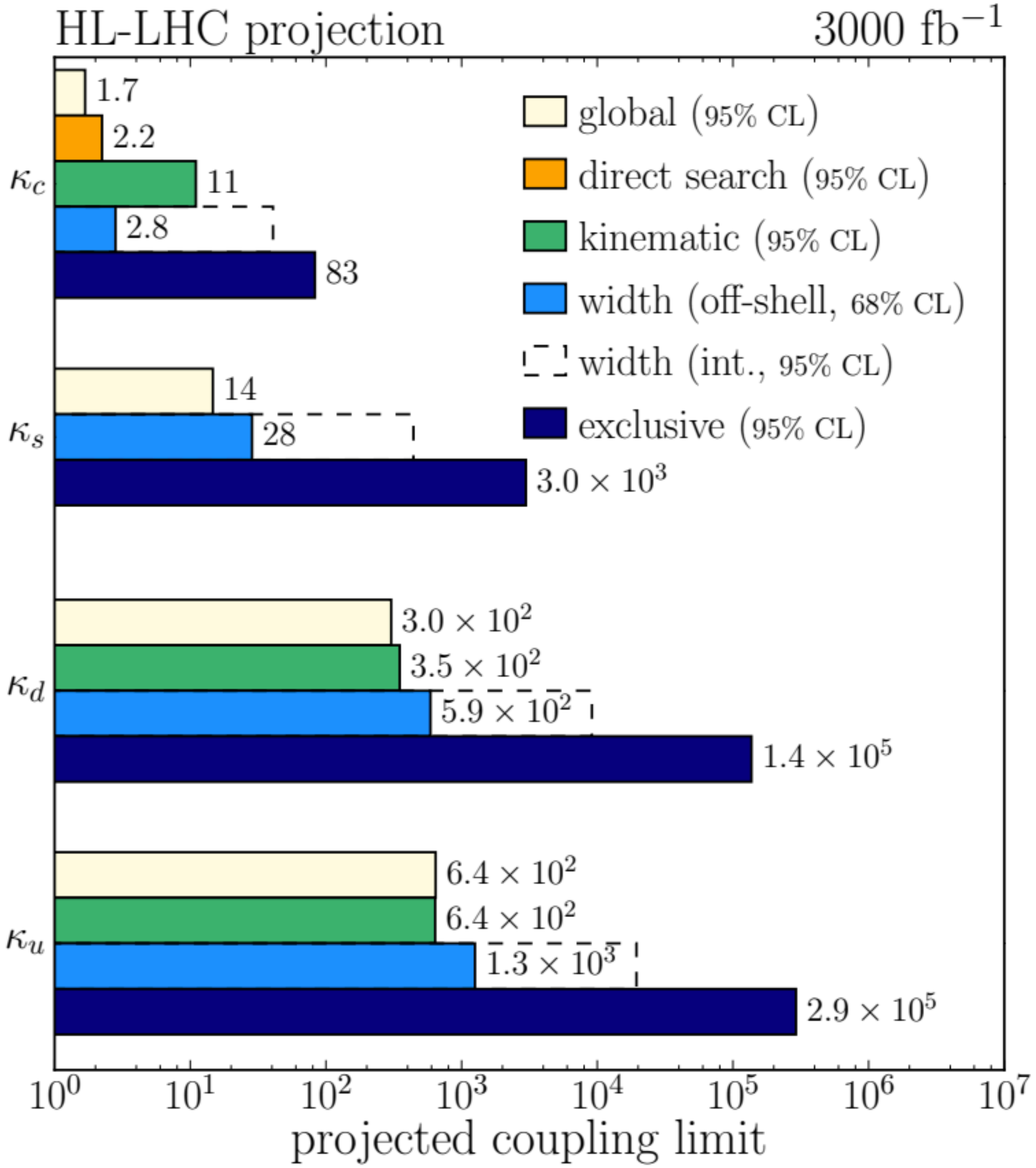
$$\delta O_Q \sim \left(\frac{Q}{M}\right)^2$$

15% effect on δO_Q for M ~ 2.5 TeV

Prospects for light quark couplings at HL-LHC

CERN-LPCC-2018-04

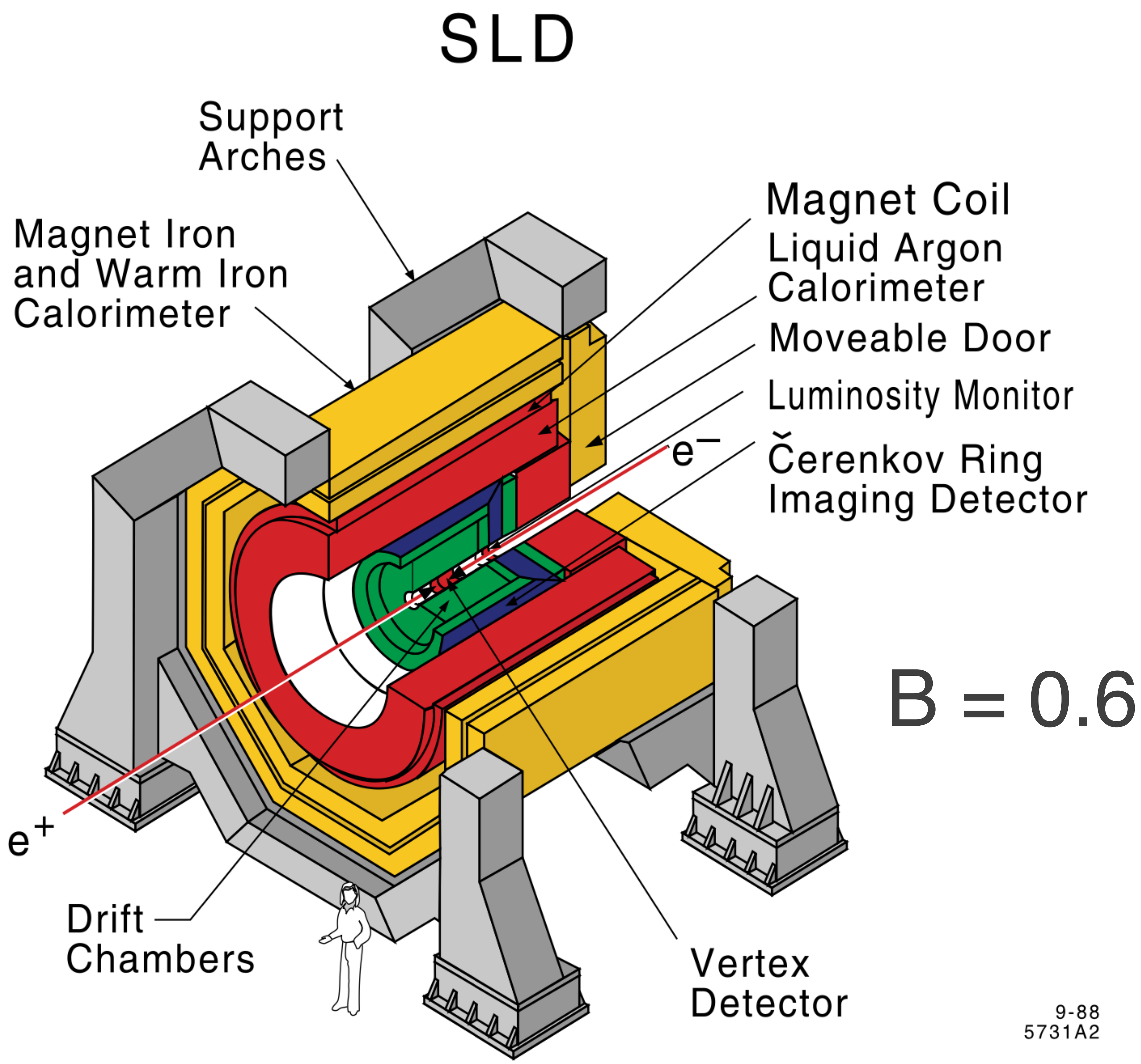
- Exclusive decays to γ+meson include contributions from light quark Yukawa couplings
- Interpretation of Higgs width constraint: direct measurement and via off-shell
- Interpretation of kinematic distributions
- Direct search for H→cc
- Global fit of all Higgs couplings (assuming no other BSM decays)



PRL 85 (2000), 5059
SLAC-R-520

s-tagging in the past

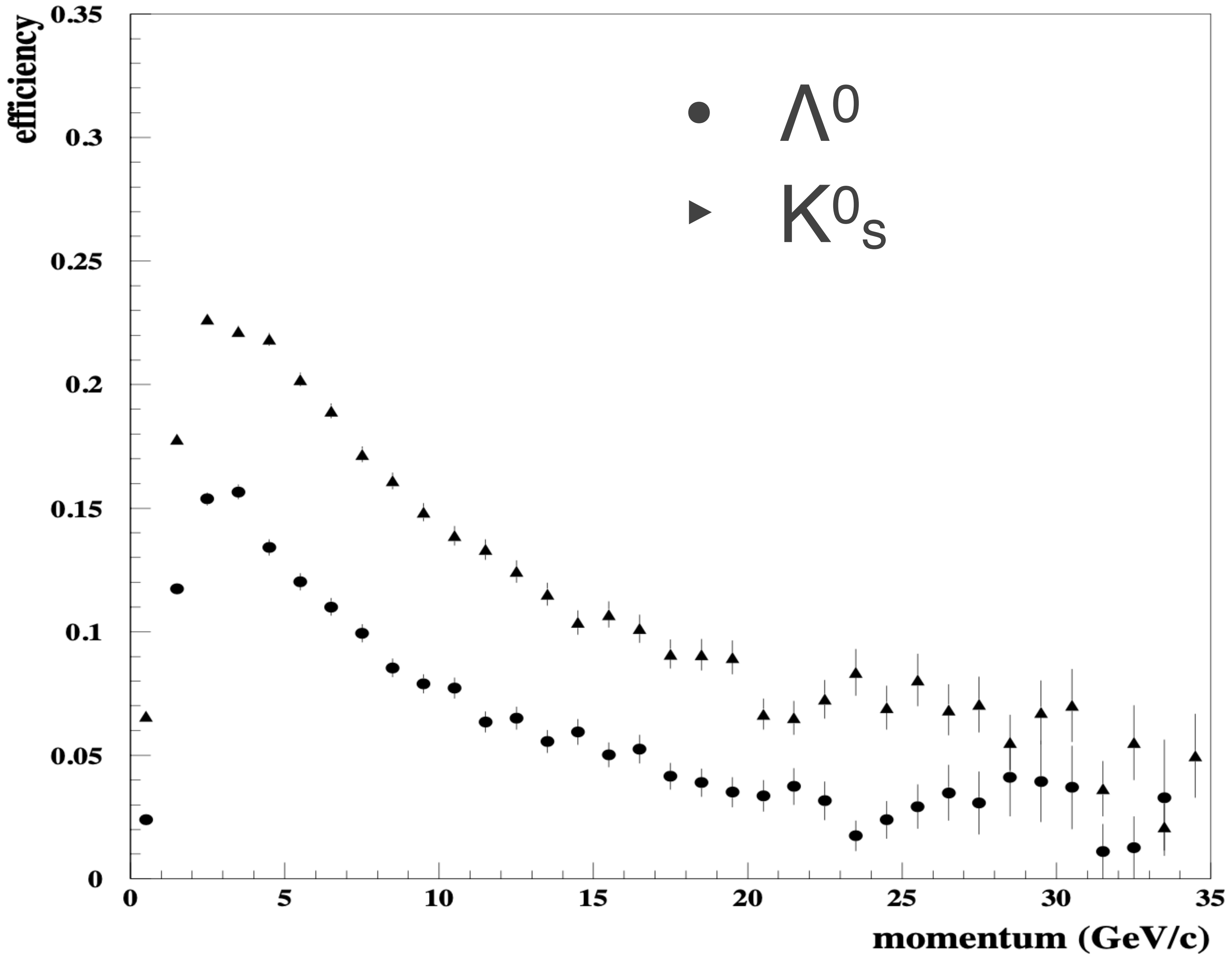
SLD at SLC (e+e- at the Z) measured asymmetry in $Z \to s\bar{s}$



B = 0.6 T

A Cherenkov Ring Imaging Detector combined with a drift chamber and vertex detector

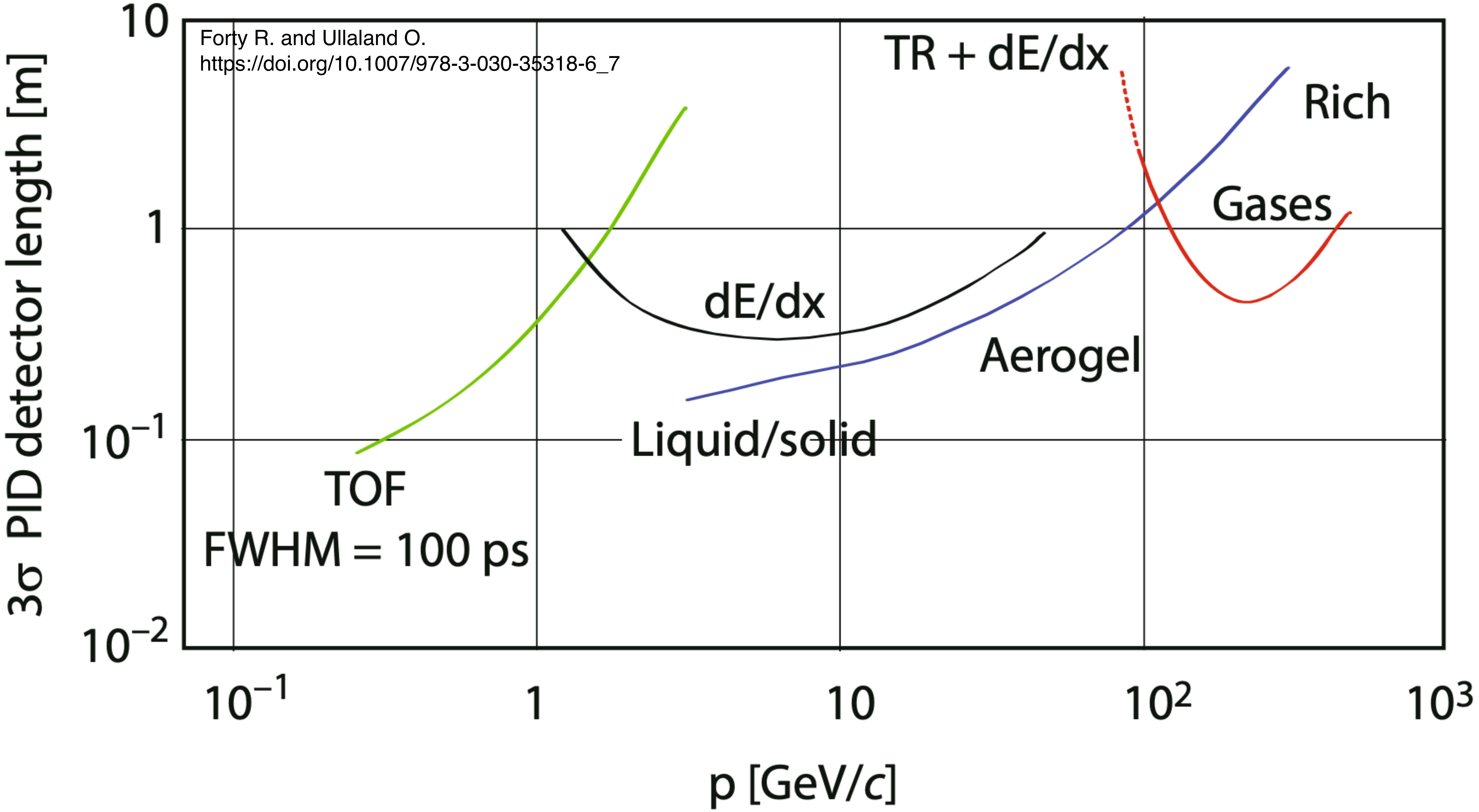
- CRID only available for $K^{\pm}$ with $p_T > 9$ GeV with a selection efficiency (purity) of 48% (91.5%)
- K^0_S efficiency (purity) of 24% (90.7 %)



1912.04601
e2019-900045-4

Particle ID for s-tagging

Combining different strategies for optimal PID performance across a wide p_T range



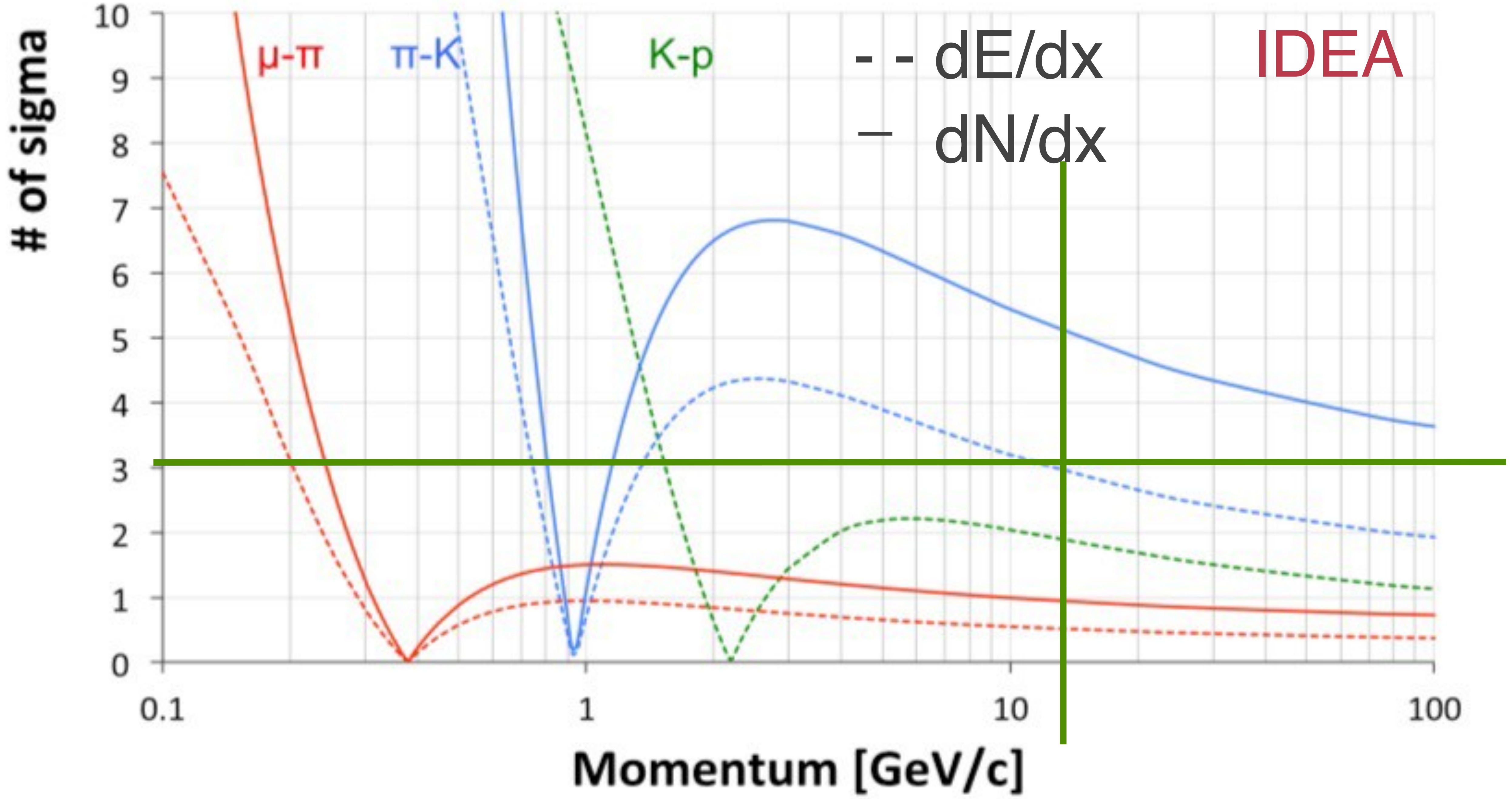
Forty R. and Ullaland O.
https://doi.org/10.1007/978-3-030-35318-6_7

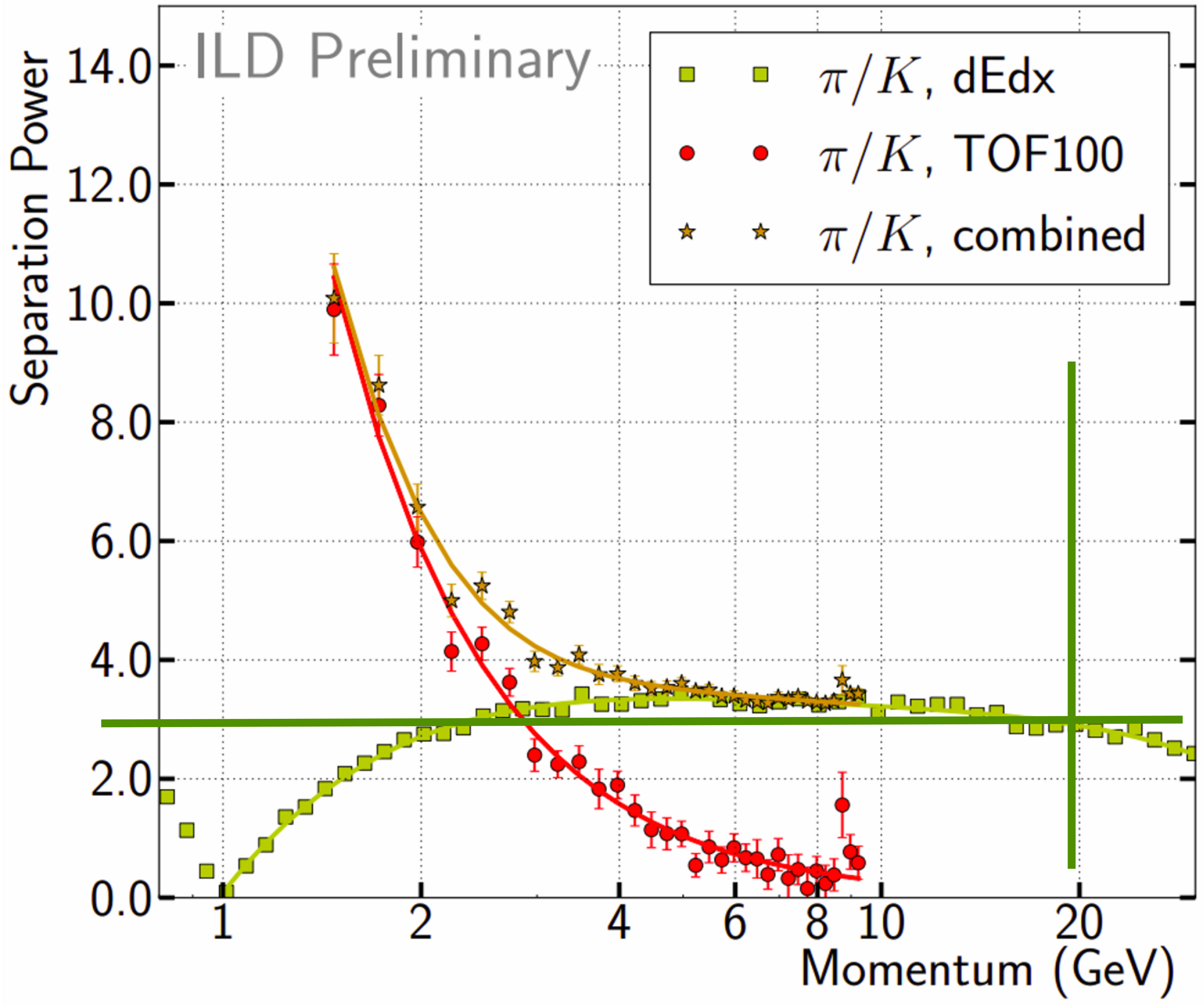
1912.04601
e2019-900045-4

Particle ID for s-tagging

Combining different strategies for optimal PID performance across a wide p_T range

- dE/dx from silicon (< 5 GeV) and large gaseous tracking detectors (< 30 GeV)
- < 5 GeV, time-of-flight (i.e. 100 ps from ECAL)



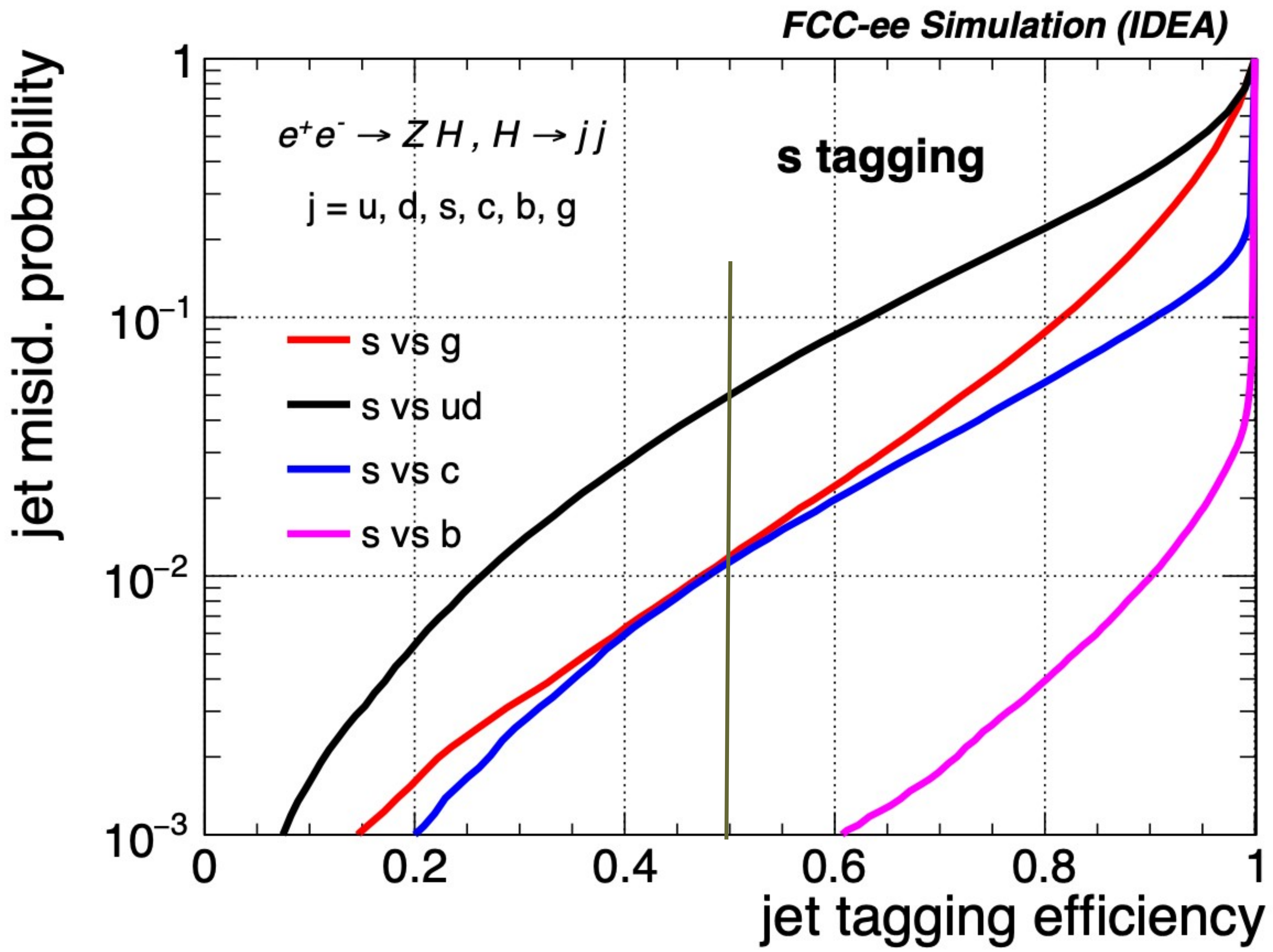


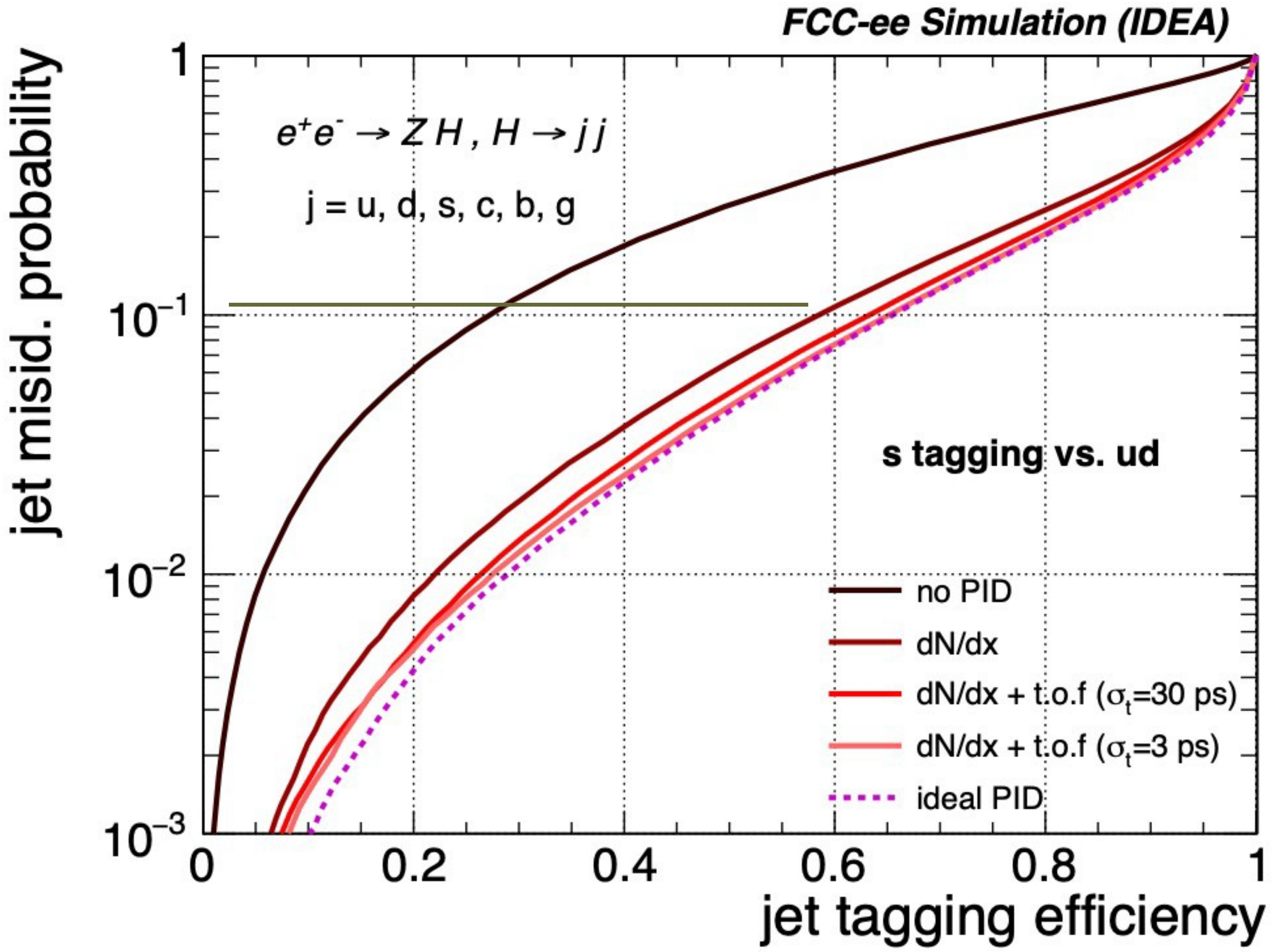
PRD 101 056019 (2020)
EPJ C 82 646 (2022)
L. Gouskos @FCC week

Strange tagging performance 1/2

IDEA-like detector and Particle cloud graph neural network (fast sim)

- Both TOF and dN/dx ($3\sigma < 30$ GeV) included as inputs
- No PID to PID with dN/dx → at fixed mistag, efficiency doubles



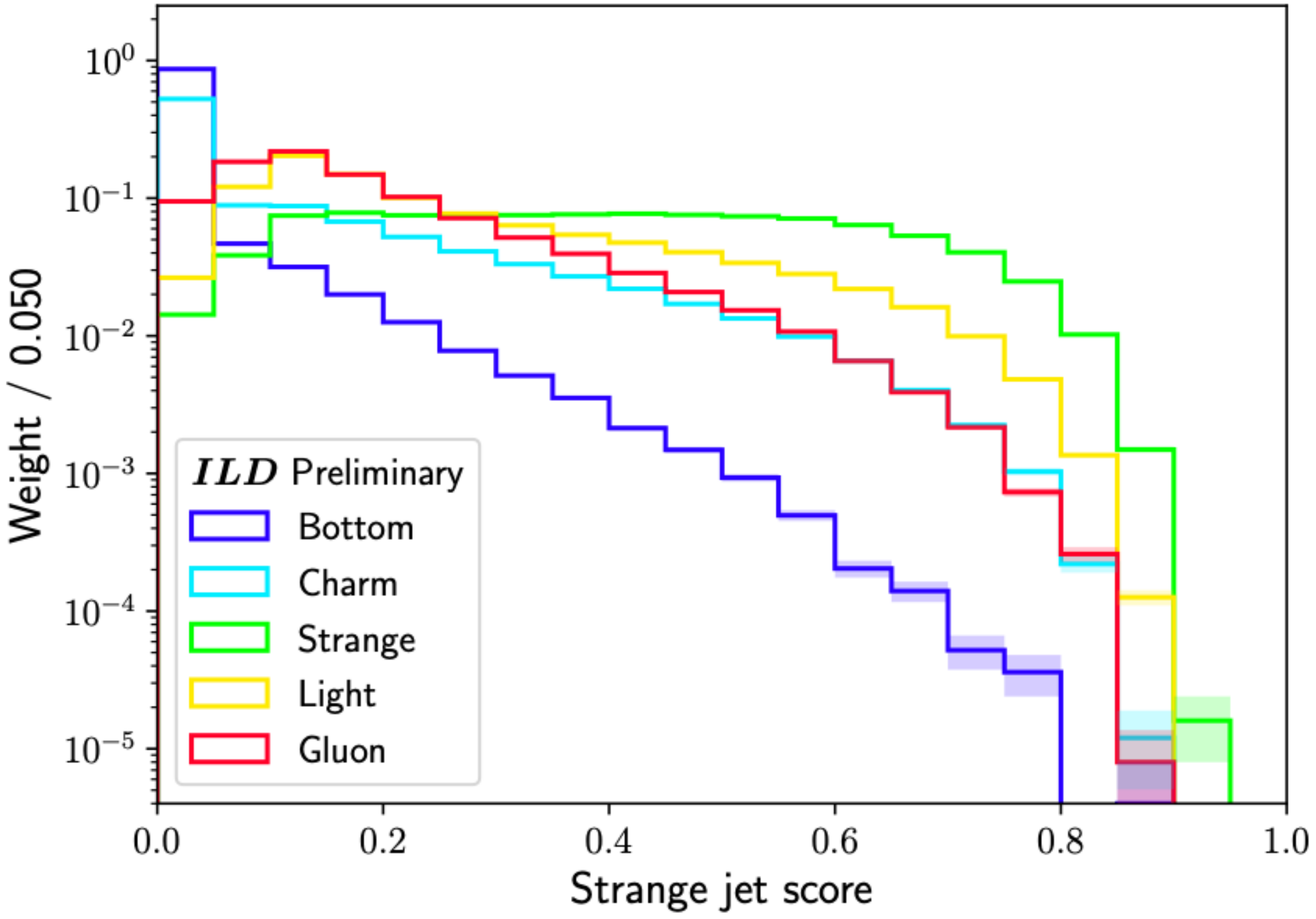


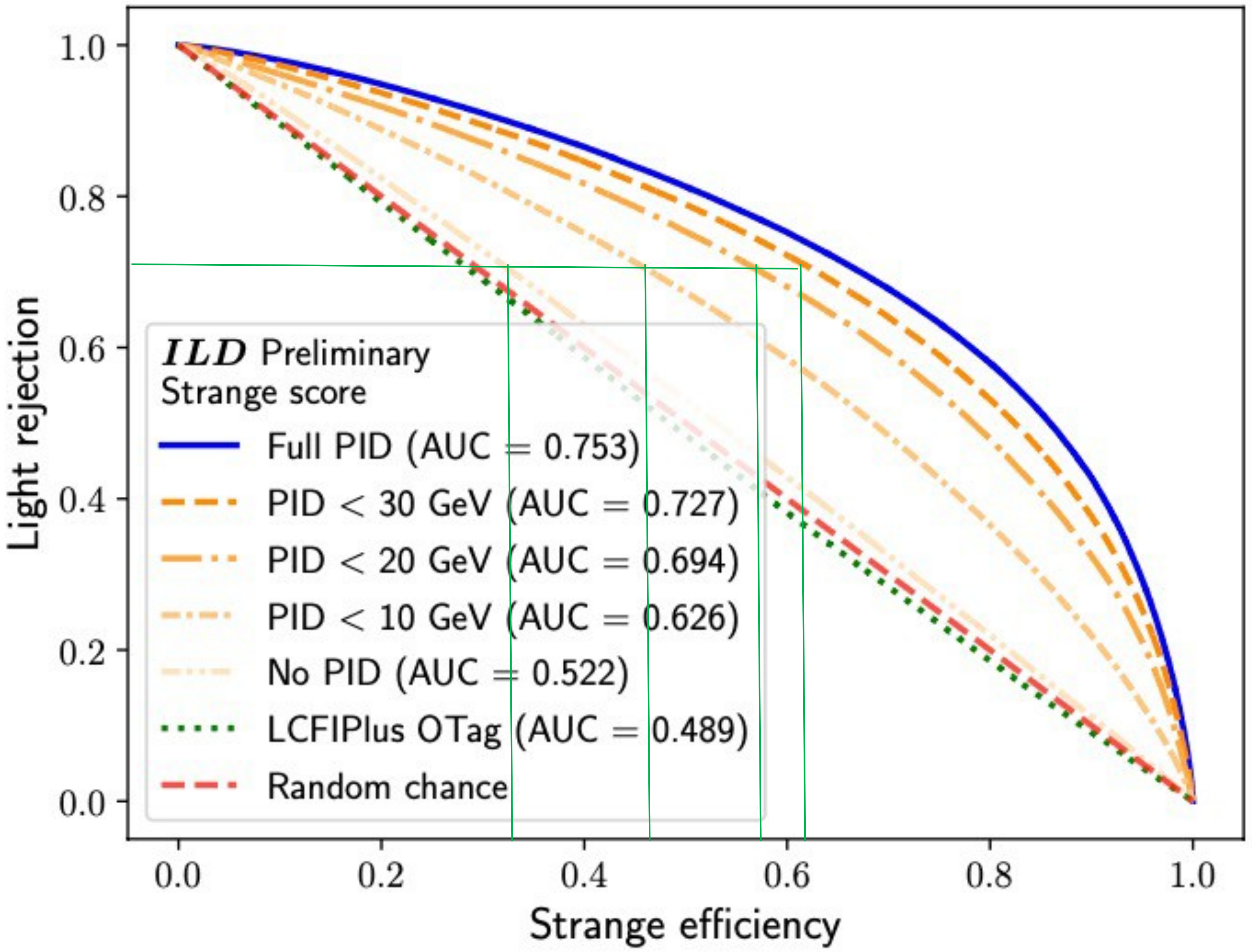
WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	9%	20%	6%	0.4%

Strange tagging performance 2/2

ILD-like detector with full simulation and Recurrent NN

- Includes PDG-based PID → assuming perfect detector capability
- At 50% s-tag efficiency, 90% background rejection
- No PID to PID < 10 (30) GeV → at fixed mistag, 1.5x (2x) efficiency



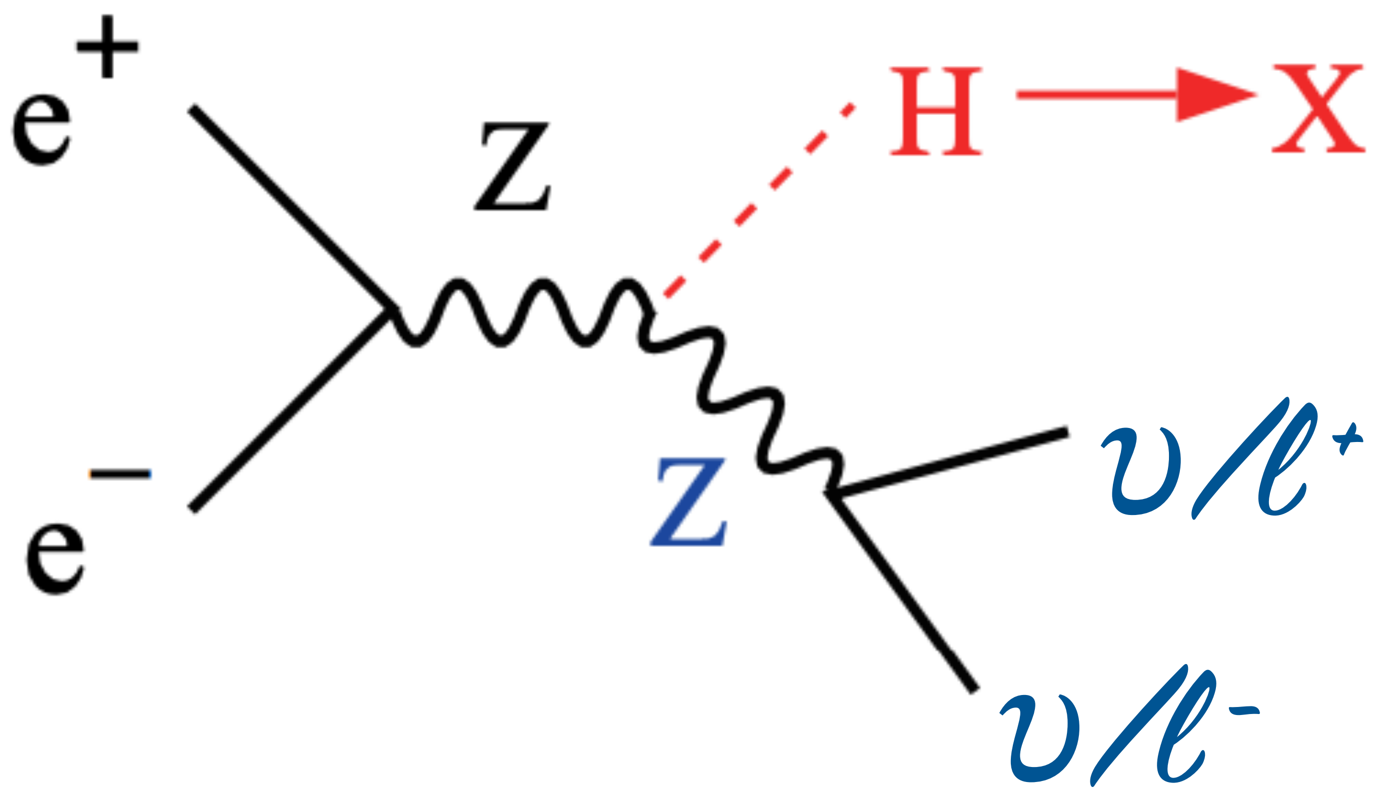


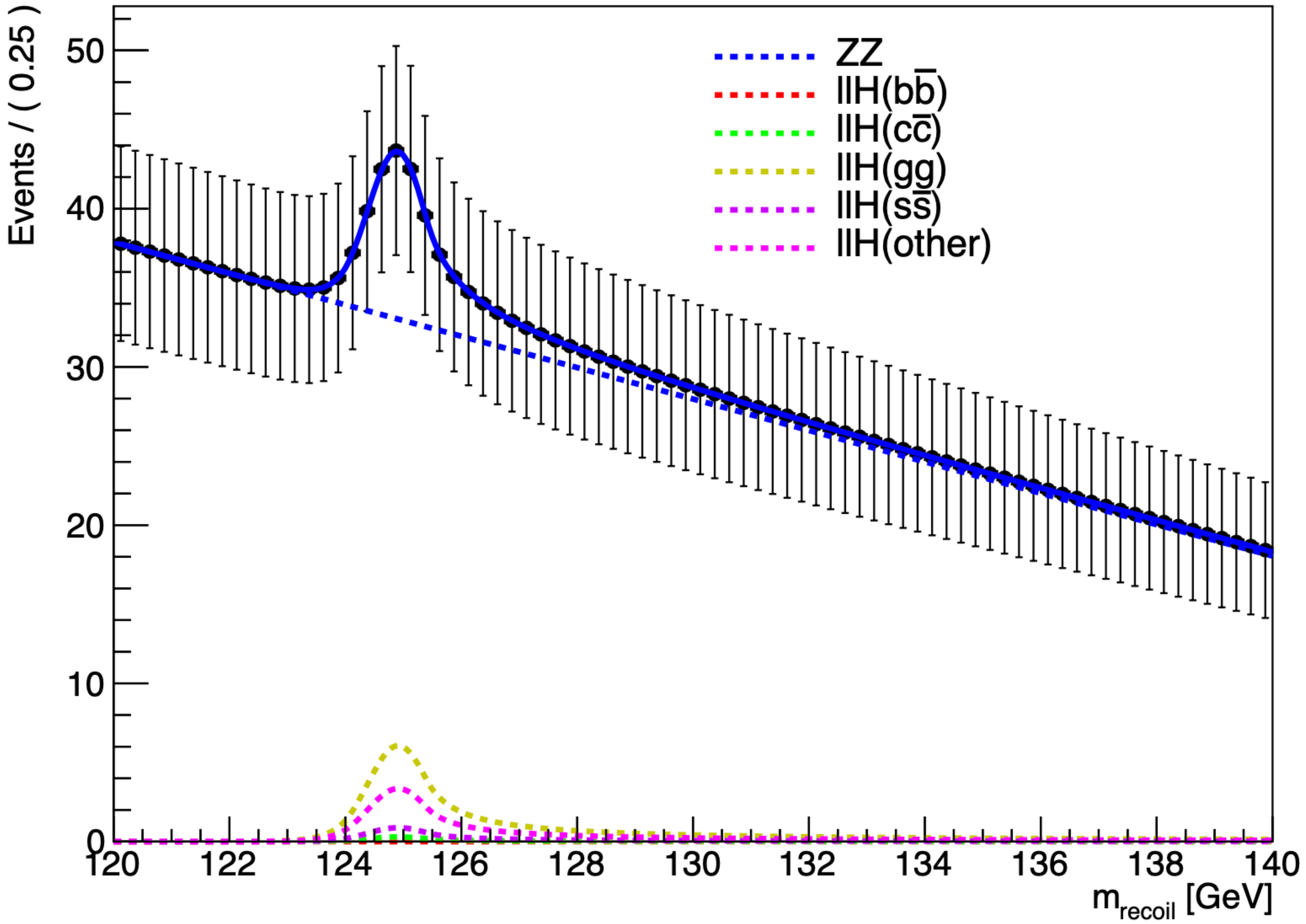
arXiv:2203.07622
L. Gouskos @FCC week

Analysis strategy to target H → ss

Exploit Z boson reconstruction in the ZH associated mode

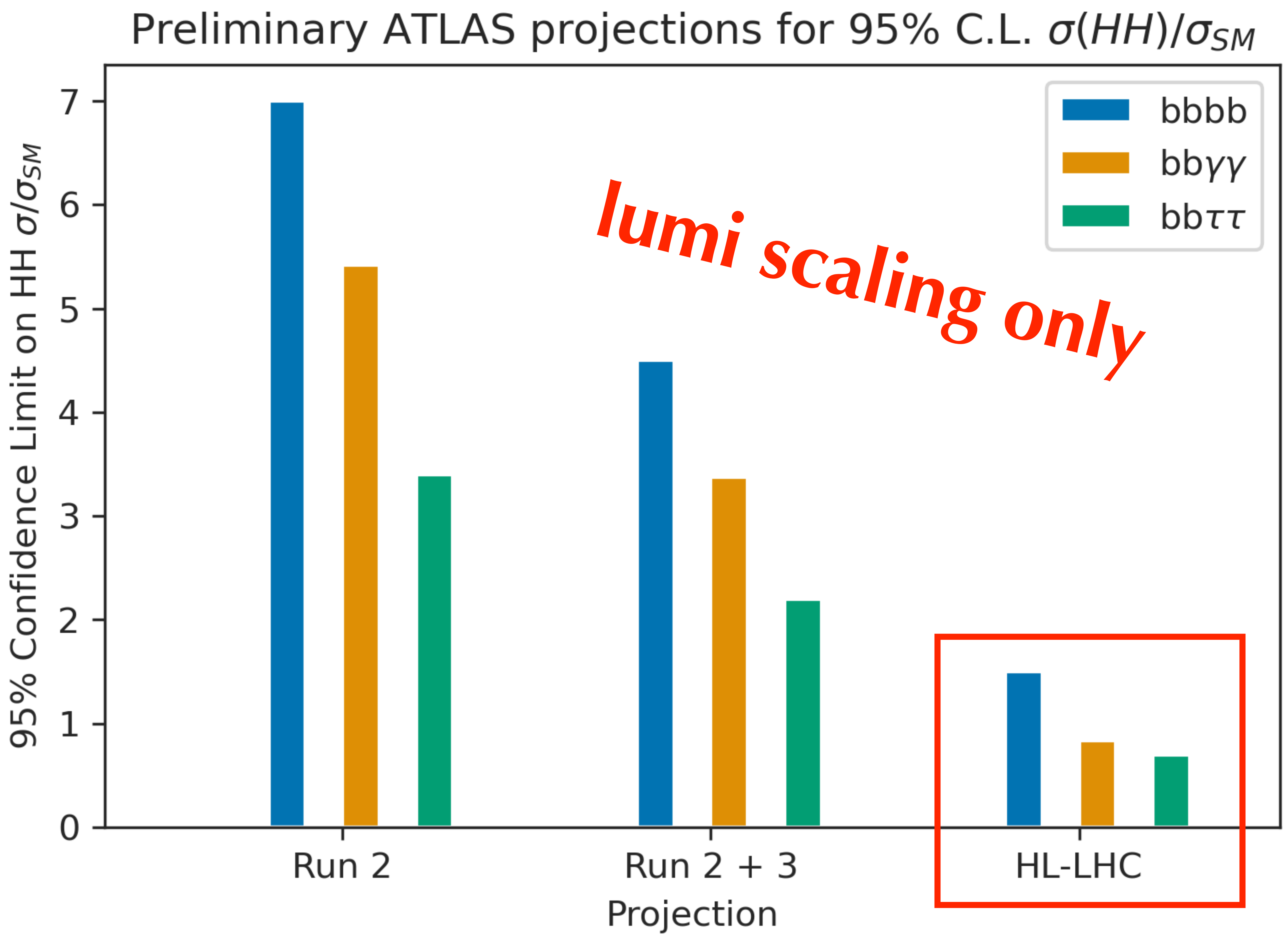
- At 250 GeV the total Zh cross section can be extracted independently of the Higgs boson's detailed properties by counting events with an identified Z boson
- Looking at 0 or 2 leptons Z decay modes





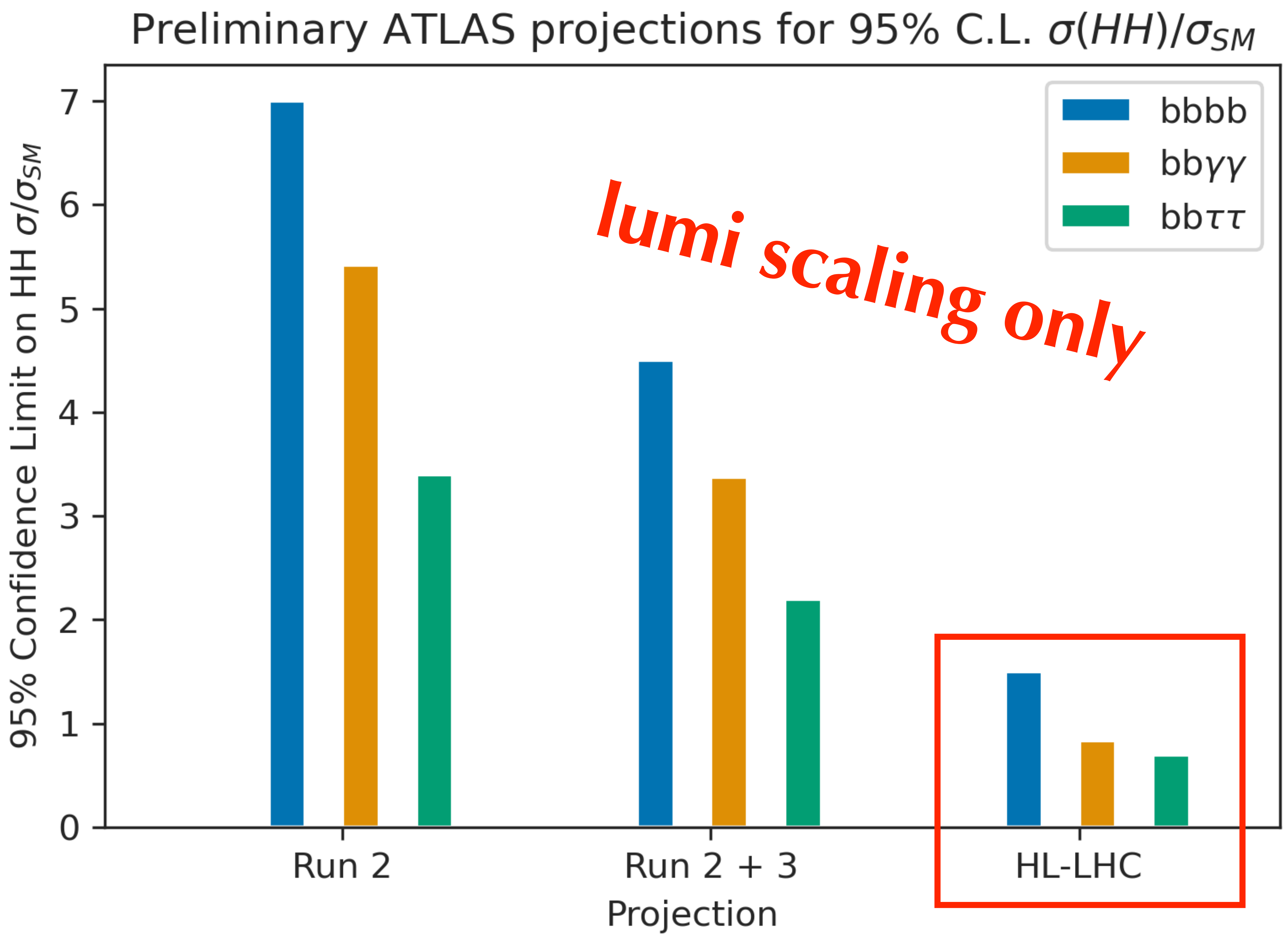
$$M_{\rm rec} = \sqrt{(\sqrt{s} - E_Z)^2 - \vec{p}_Z^{\,2}}$$

HH prospects

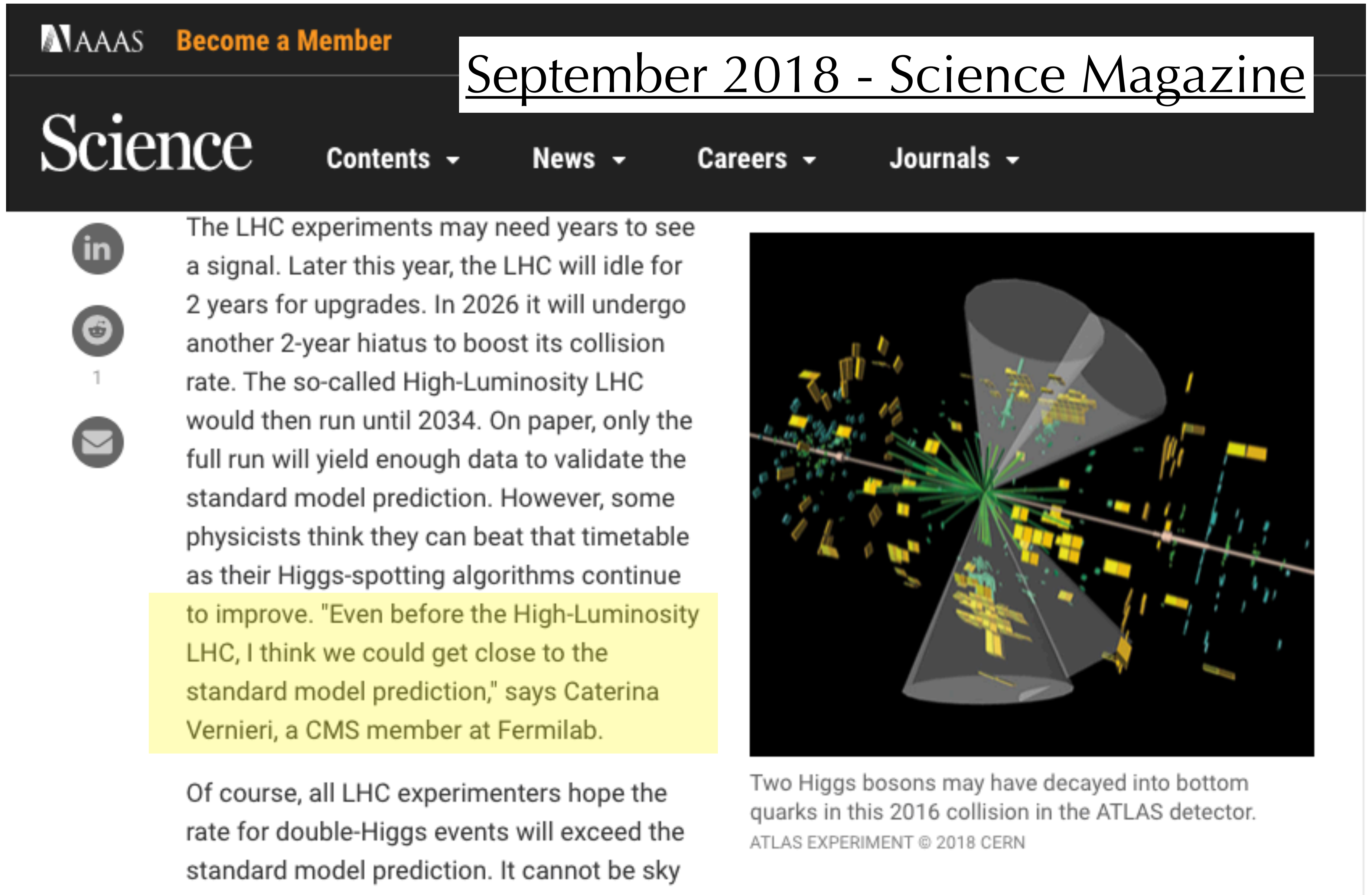


Caterina Vernieri

HH prospects



lumi scaling only



September 2018 - Science Magazine

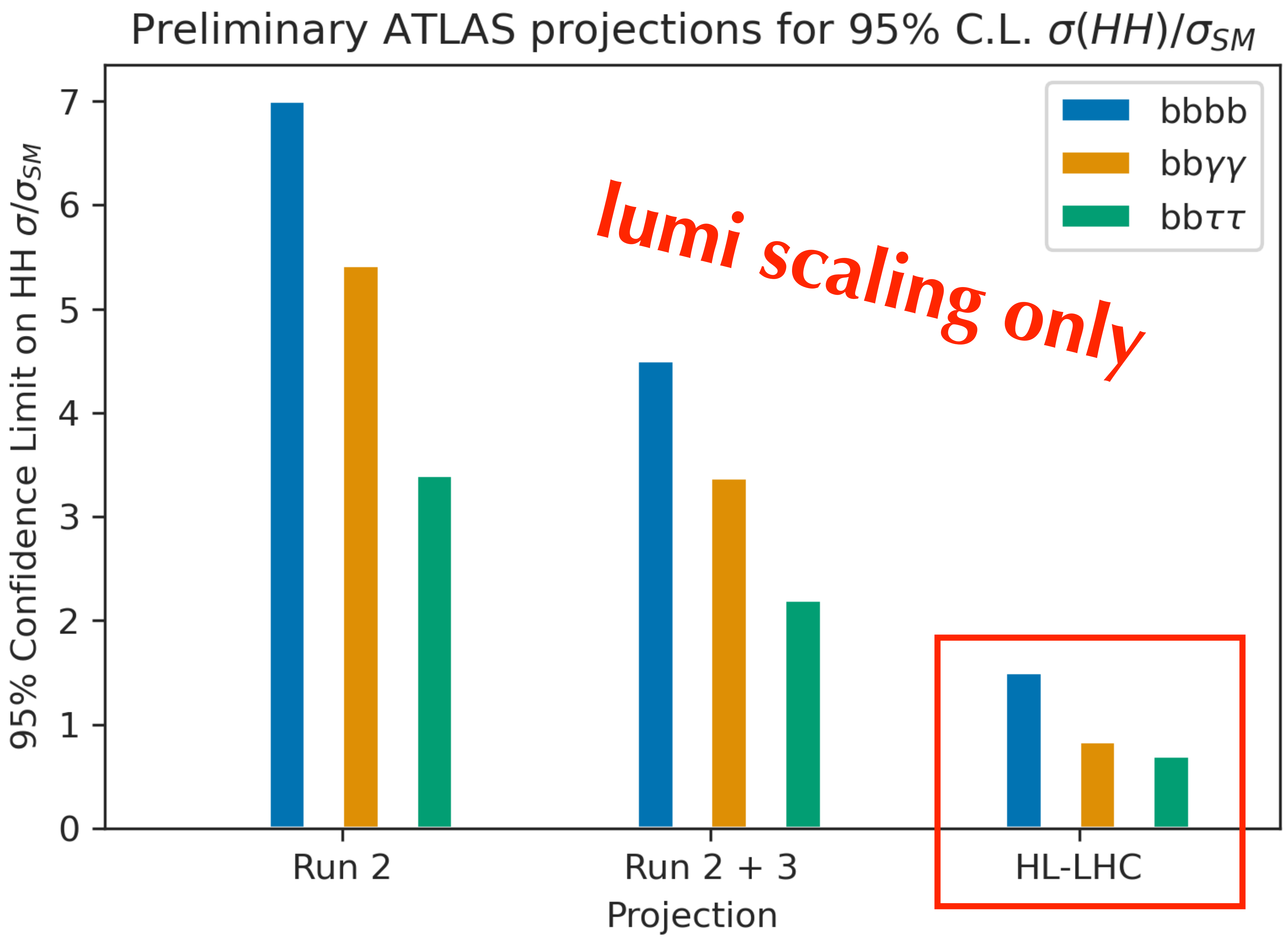
The LHC experiments may need years to see a signal. Later this year, the LHC will idle for 2 years for upgrades. In 2026 it will undergo another 2-year hiatus to boost its collision rate. The so-called High-Luminosity LHC would then run until 2034. On paper, only the full run will yield enough data to validate the standard model prediction. However, some physicists think they can beat that timetable as their Higgs-spotting algorithms continue to improve. "Even before the High-Luminosity LHC, I think we could get close to the standard model prediction," says Caterina Vernieri, a CMS member at Fermilab.

Of course, all LHC experimenters hope the rate for double-Higgs events will exceed the standard model prediction. It cannot be sky

Two Higgs bosons may have decayed into bottom quarks in this 2016 collision in the ATLAS detector.

ATLAS EXPERIMENT © 2018 CERN

HH prospects



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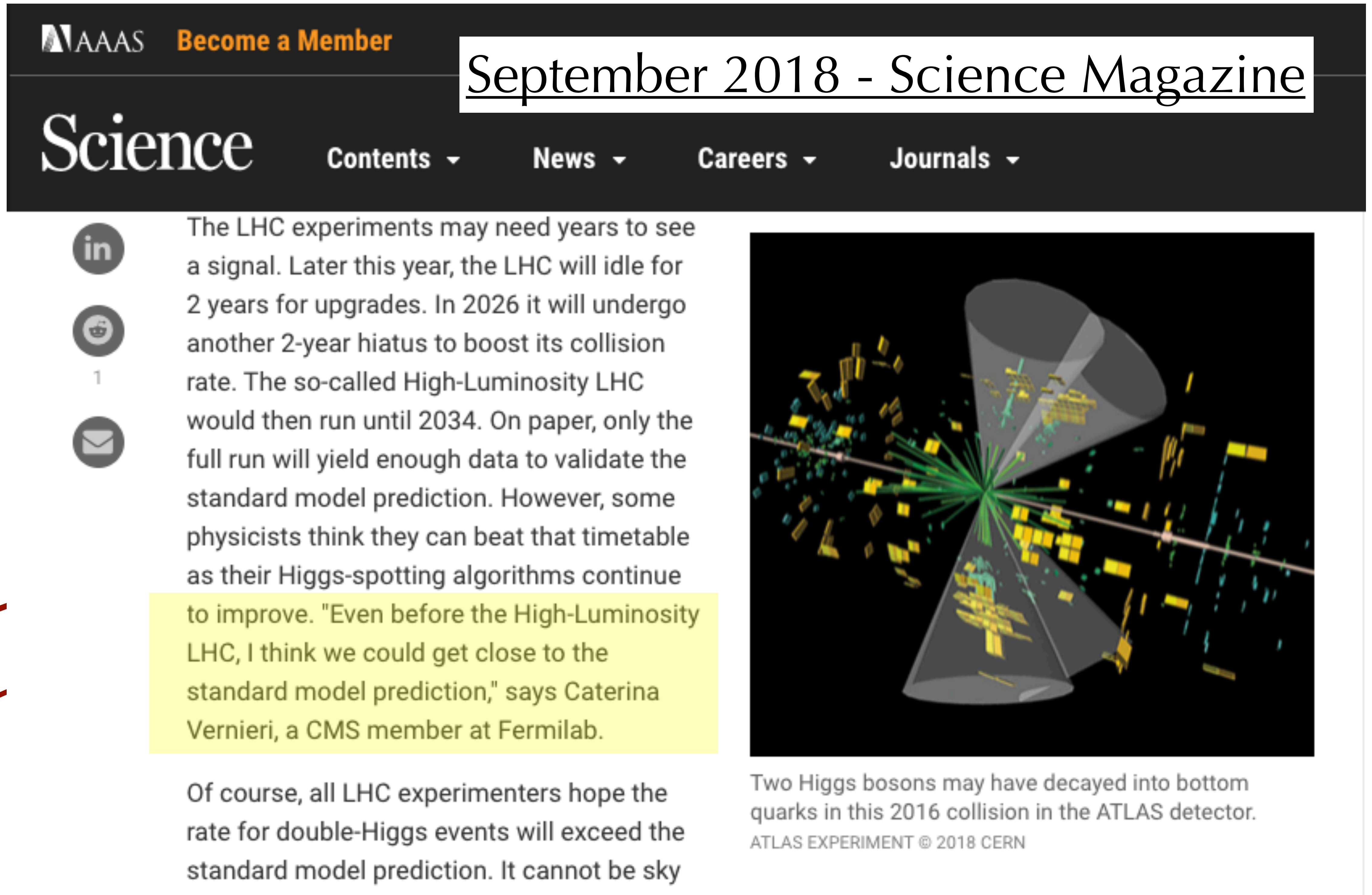

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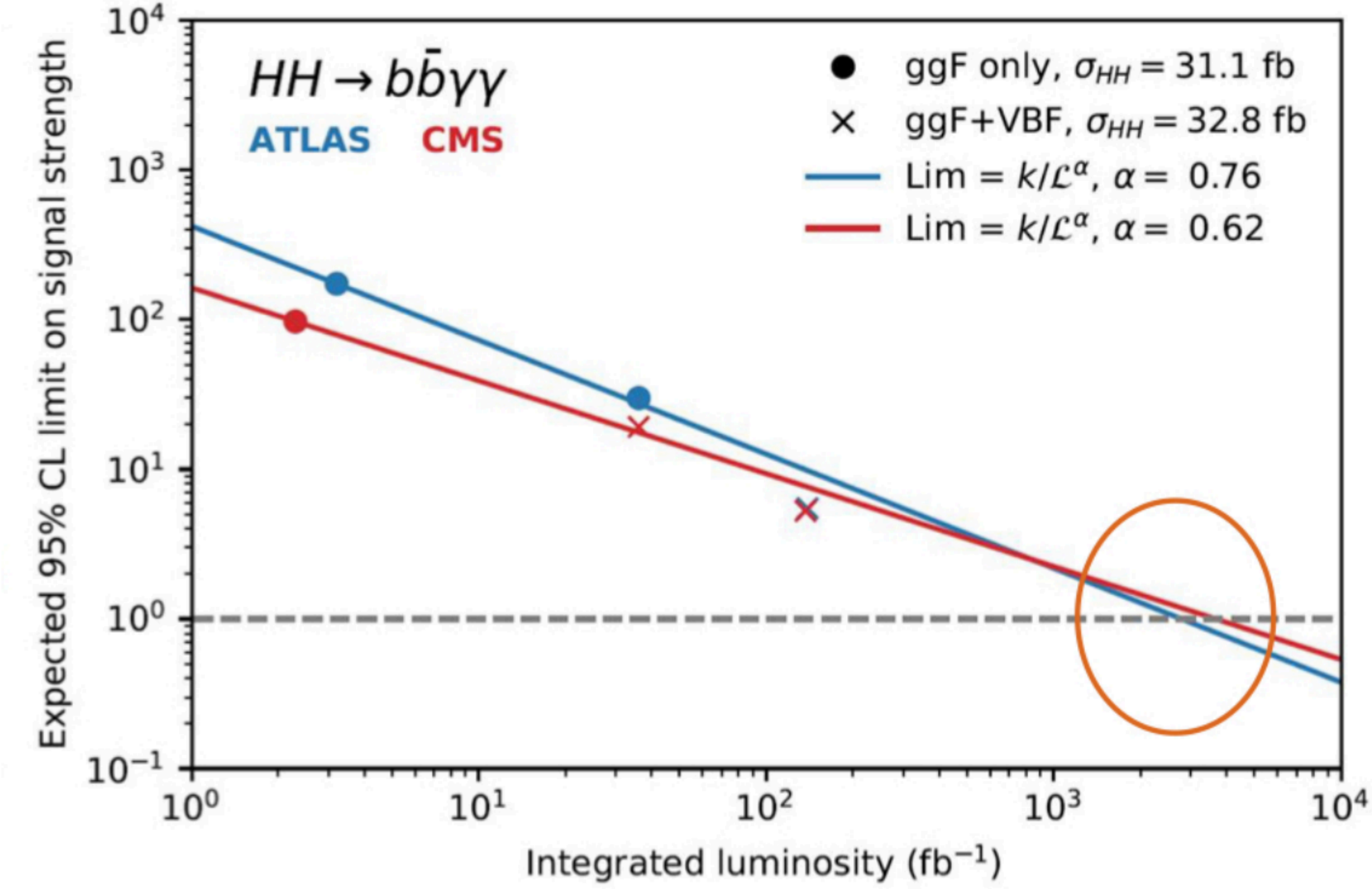
Two Higgs bosons may have decayed into bottom quarks in this 2016 collision in the ATLAS detector.

ATLAS EXPERIMENT © 2018 CERN

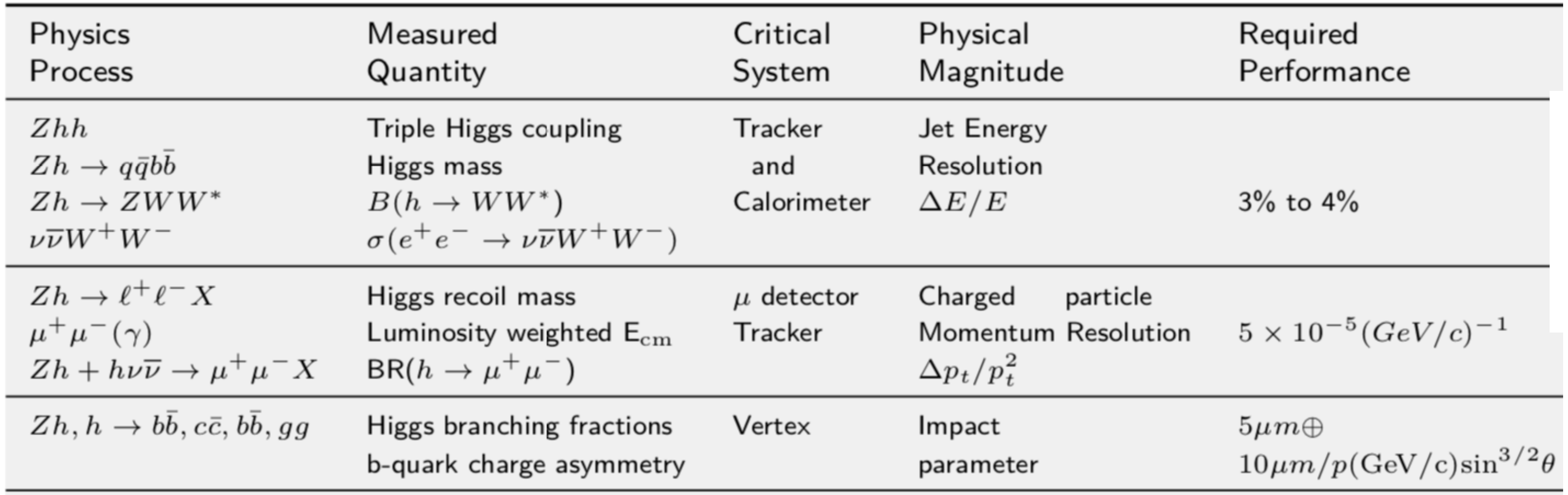
With Full Run 2 data - significant analyses improvements on top of additional data

Combination of the best channels could get us close to test the SM hypothesis at the end of Run 3


$HH \to b\bar{b}\gamma\gamma$
ATLAS
CMS
● ggF only, $\sigma_{HH} = 31.1$ fb
× ggF+VBF, $\sigma_{HH} = 32.8$ fb
Lim = $k/\mathcal{L}^{\alpha}$, $\alpha =$ 0.76
Lim = $k/\mathcal{L}^{\alpha}$, $\alpha =$ 0.62
Expected 95% CL limit on signal strength
Integrated luminosity (fb^{-1})
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

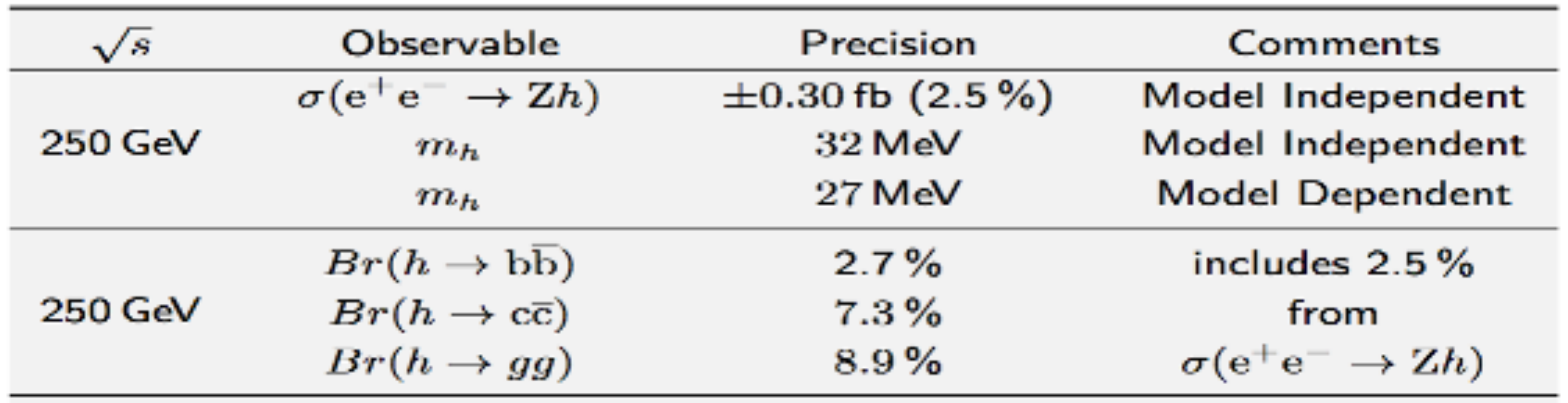
Physics requirements for e+e-

- The ZH process, with the recoiling Higgs reconstructed from the Z →ll drives the requirement on charged track momentum resolution
  - High field magnets and high precision/low mass trackers
- Flavour tagging & quark charge tagging will be available at an unprecedented level
  - new generation of vertex detectors with dedicated sensor designs to address the modest, but challenging, ILC backgrounds.
  - soft beamstrahlung pairs create high occupancies that demand fast readouts, requiring extra power.



Physics Process	Measured Quantity	Critical System	Physical Magnitude	Required Performance
Zhh $Zh \to q\bar{q}b\bar{b}$ $Zh \to ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs coupling Higgs mass $B(h \to WW^*)$ $\sigma(e^+e^- \to \nu\bar{\nu}W^+W^-)$	Tracker and Calorimeter	Jet Energy Resolution $\Delta E/E$	3% to 4%
$Zh \to \ell^+\ell^- X$ $\mu^+\mu^-(\gamma)$ $Zh + h\nu\bar{\nu} \to \mu^+\mu^- X$	Higgs recoil mass Luminosity weighted E_{cm} BR$(h \to \mu^+\mu^-)$	μ detector Tracker	Charged particle Momentum Resolution $\Delta p_t/p_t^2$	$5 \times 10^{-5}(GeV/c)^{-1}$
$Zh, h \to b\bar{b}, c\bar{c}, b\bar{b}, gg$	Higgs branching fractions b-quark charge asymmetry	Vertex	Impact parameter	$5\mu m \oplus$ $10\mu m/p(\mathrm{GeV}/c)\sin^{3/2}\theta$

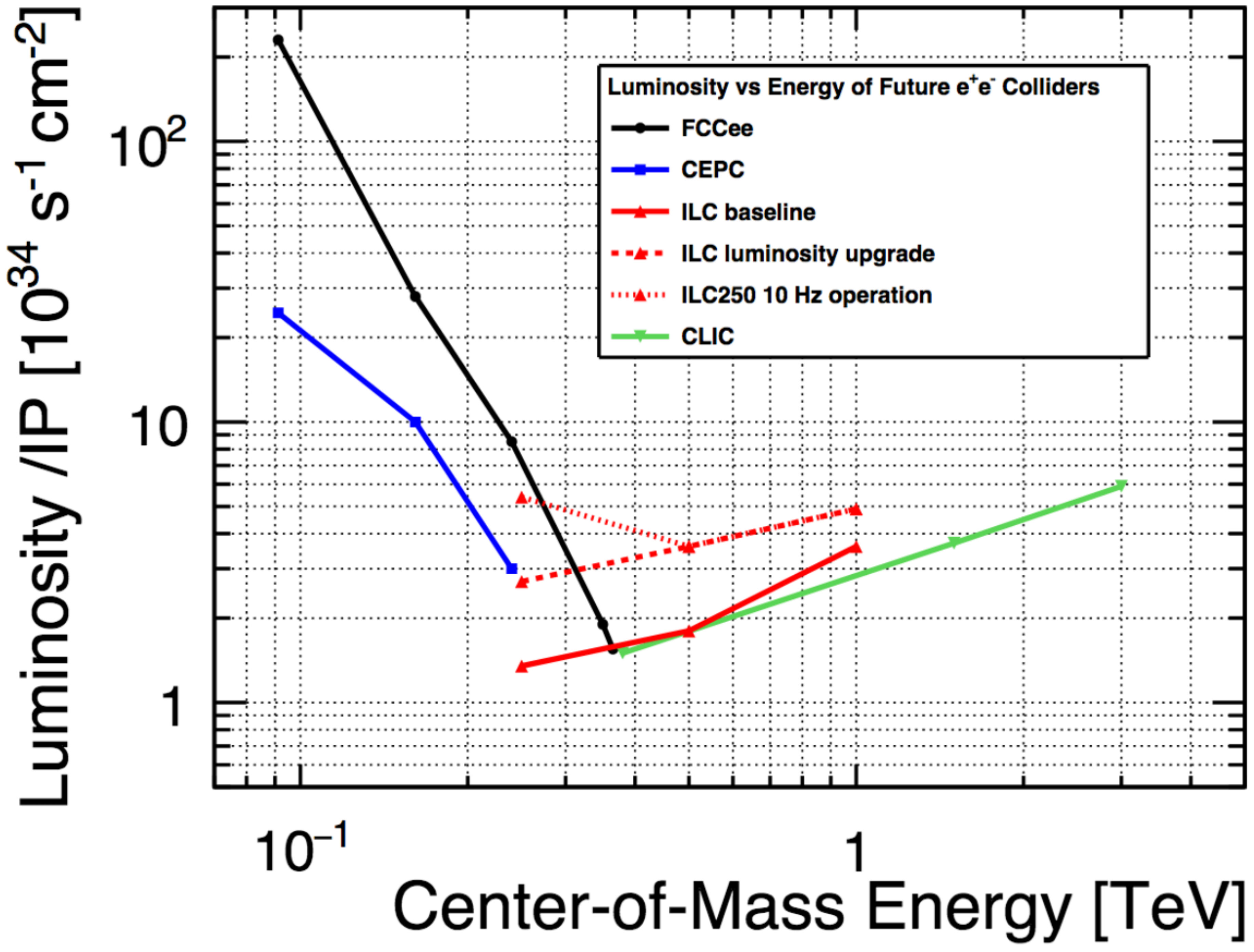
arXiv:2003.01116



$\sqrt{s}$	Observable	Precision	Comments
250 GeV	$\sigma(e^+e^- \to Zh)$	±0.30 fb (2.5 %)	Model Independent
	m_h	32 MeV	Model Independent
	m_h	27 MeV	Model Dependent
250 GeV	$Br(h \to b\bar{b})$	2.7 %	includes 2.5 % from $\sigma(e^+e^- \to Zh)$
	$Br(h \to c\bar{c})$	7.3 %	
	$Br(h \to gg)$	8.9 %	

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



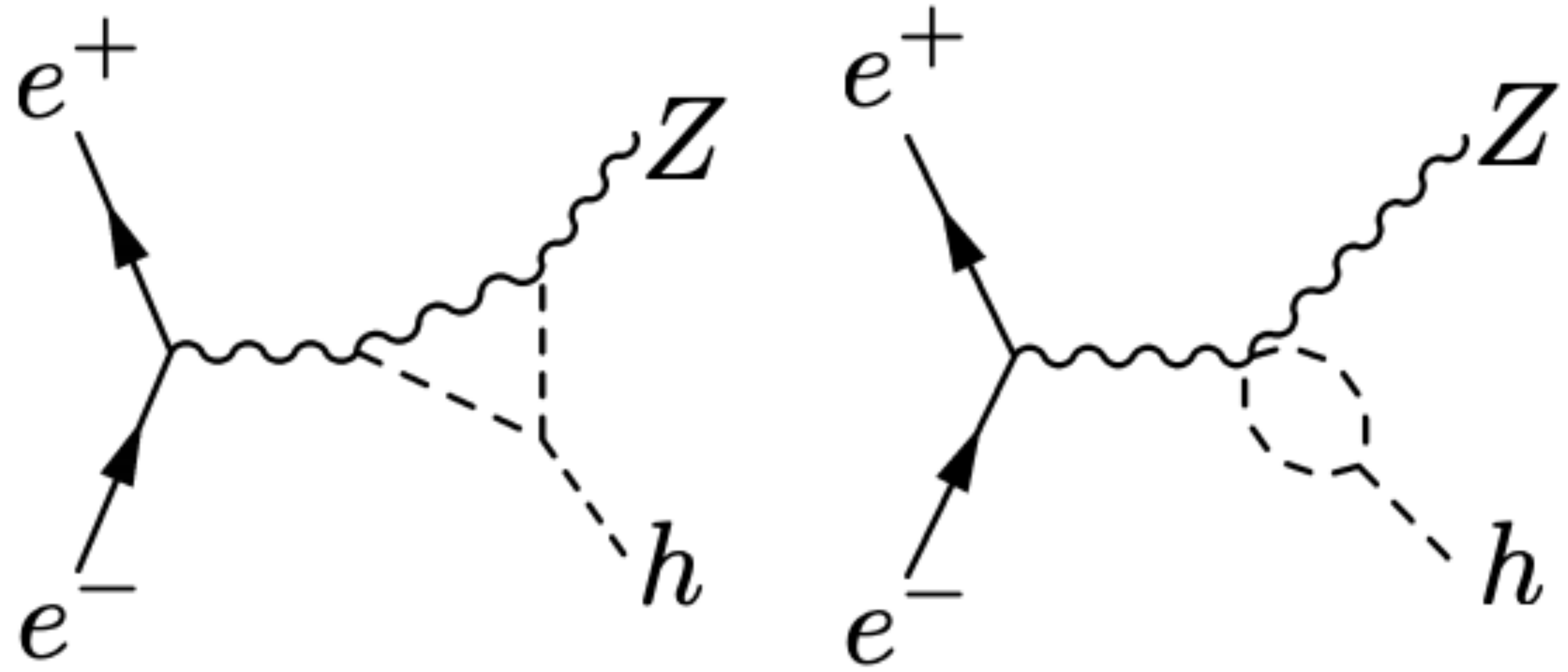
Caterina Vernieri

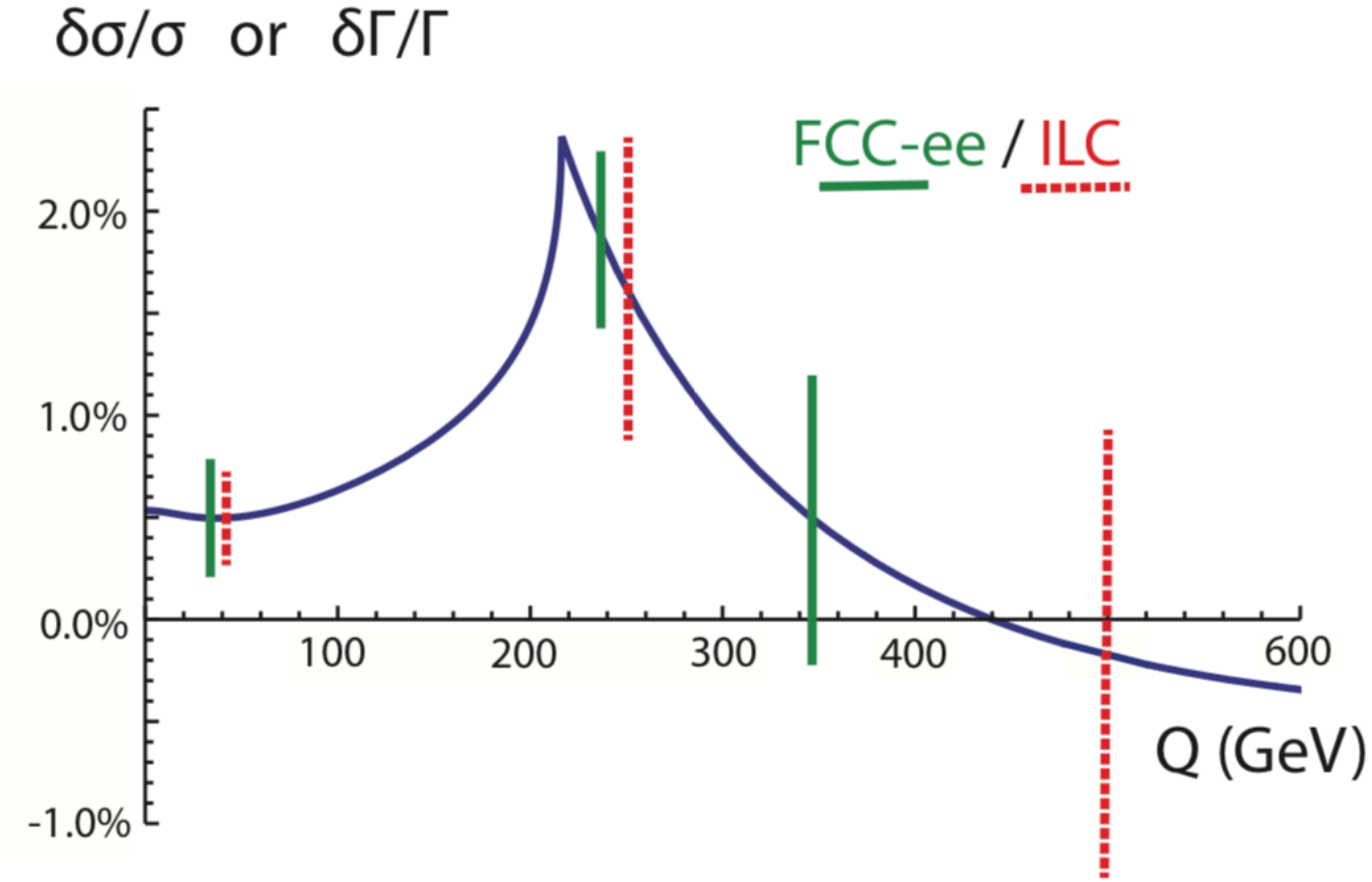
Self-coupling at e+e-

arXiv:1312.3322
arXiv:1910.00012

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

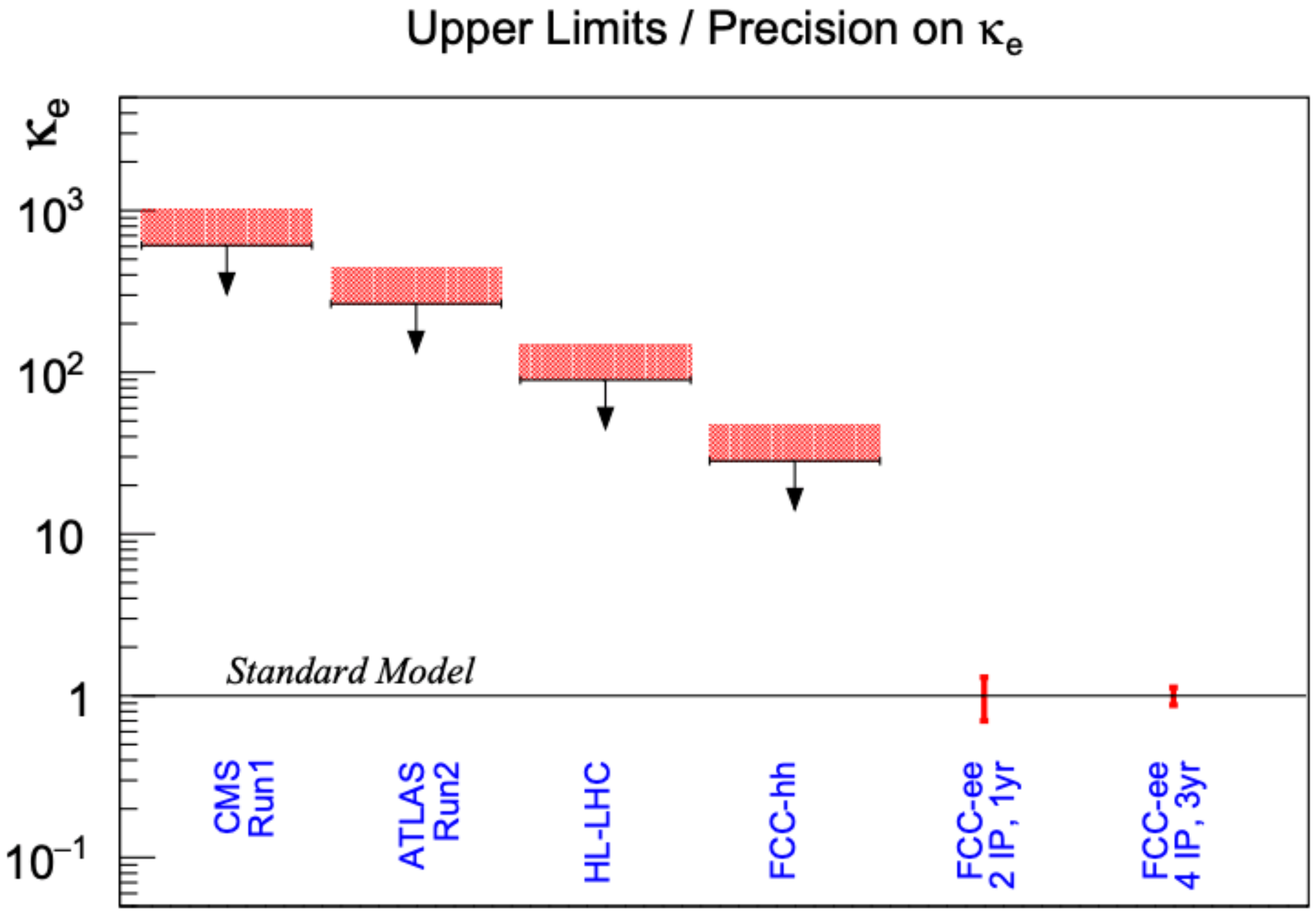
- Relative enhancement of the e+e– → ZH cross-section and the H→W+W– partial width
- Need multiple Q^2 to identify the effects due to the self-coupling





Higgs at e^+e^-

1912.11871

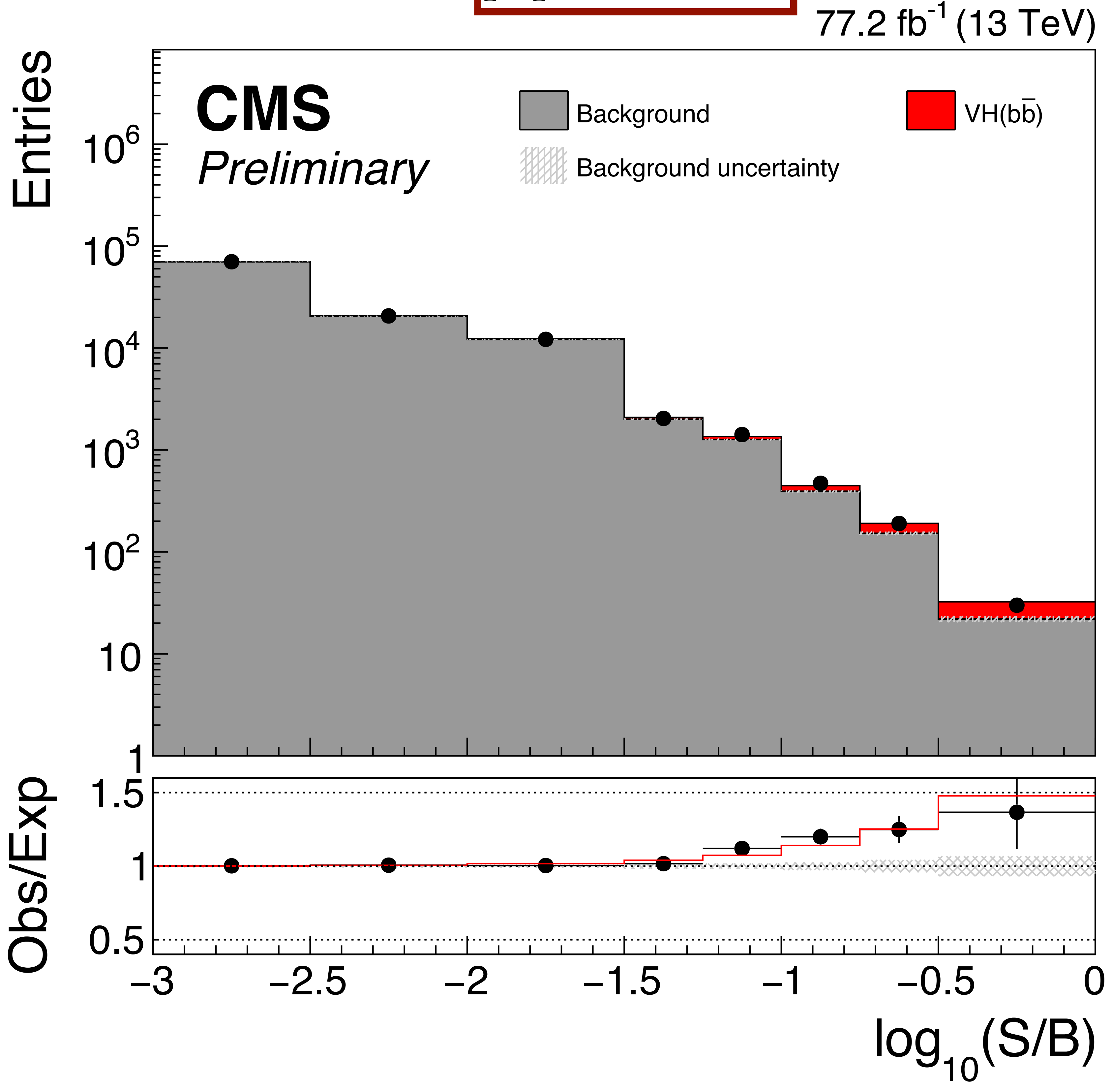


- Circular lepton colliders - FCC-ee - provide the highest luminosities at lower centre-of-mass energies
  - Unique opportunity to measure the Higgs boson coupling to electrons through the resonant production process $e^+e^- \rightarrow H$ at $\sqrt{s} = 125$ GeV
  - FCC-ee running at H pole-mass with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

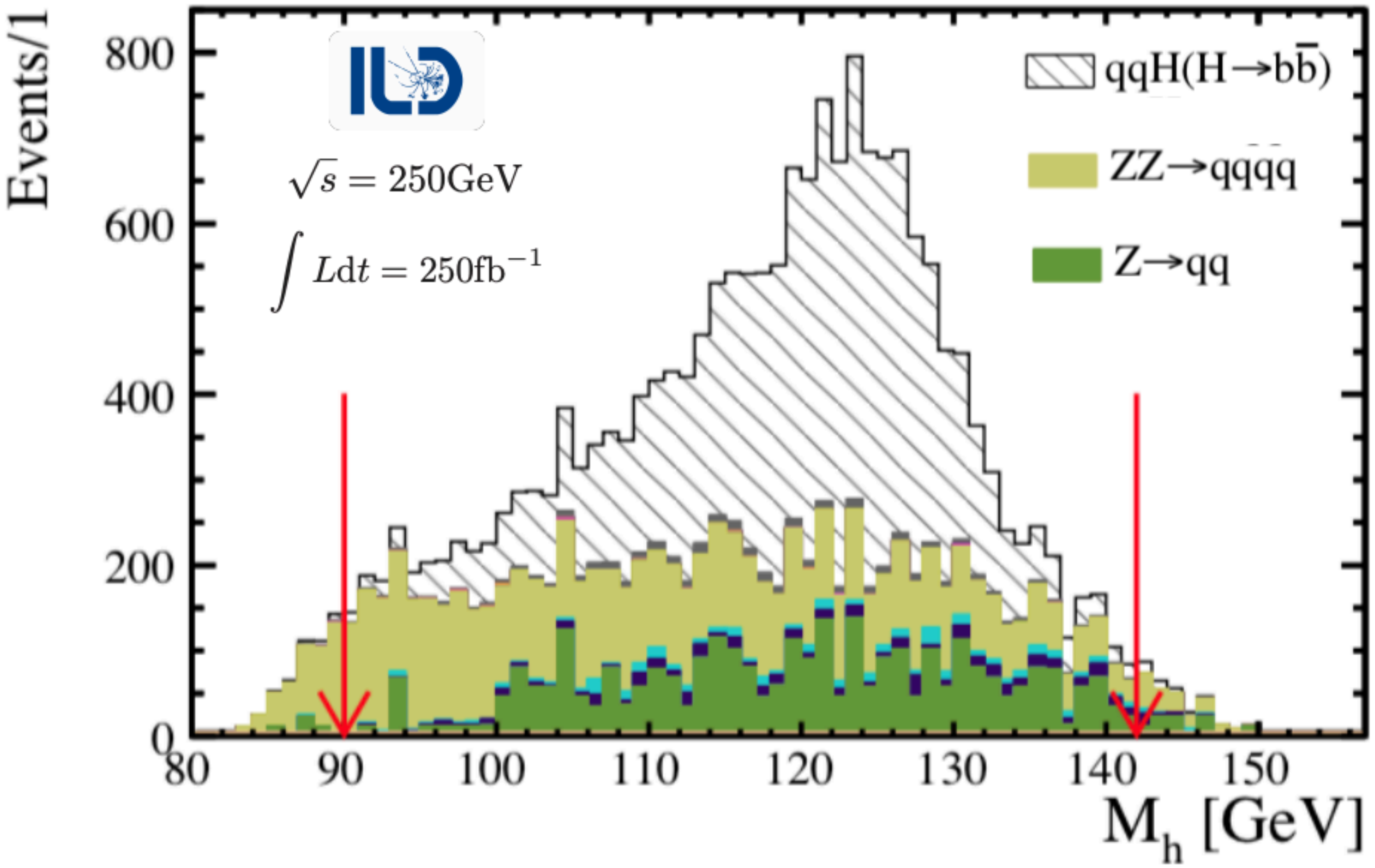
One example: $H(b\bar{b})$

CMS-PRL 120 (2018) 231801
ATLAS-Phys. Lett. B 786 (2018) 59
Ogawa, thesis

pp LHC



e+e- ILC

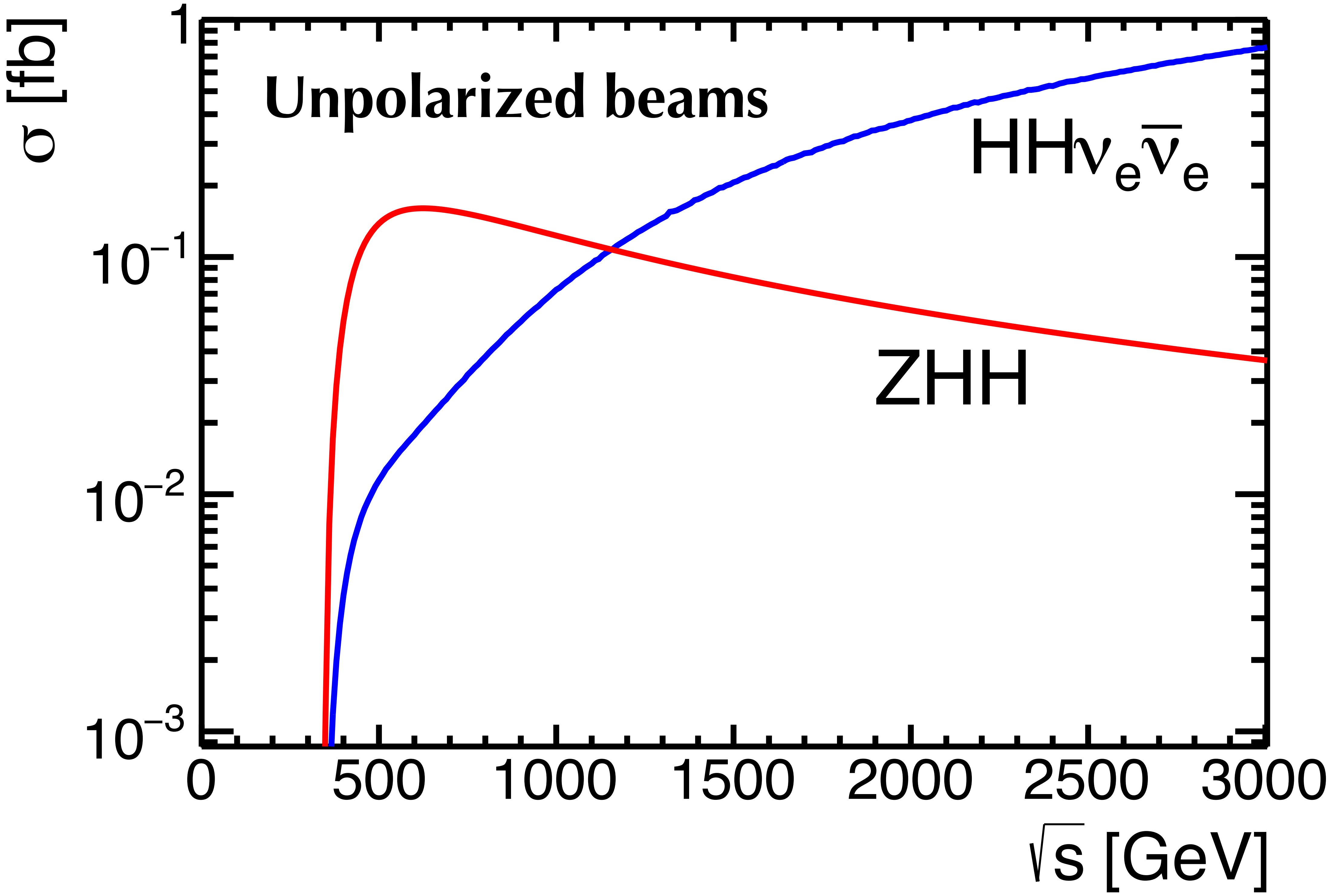


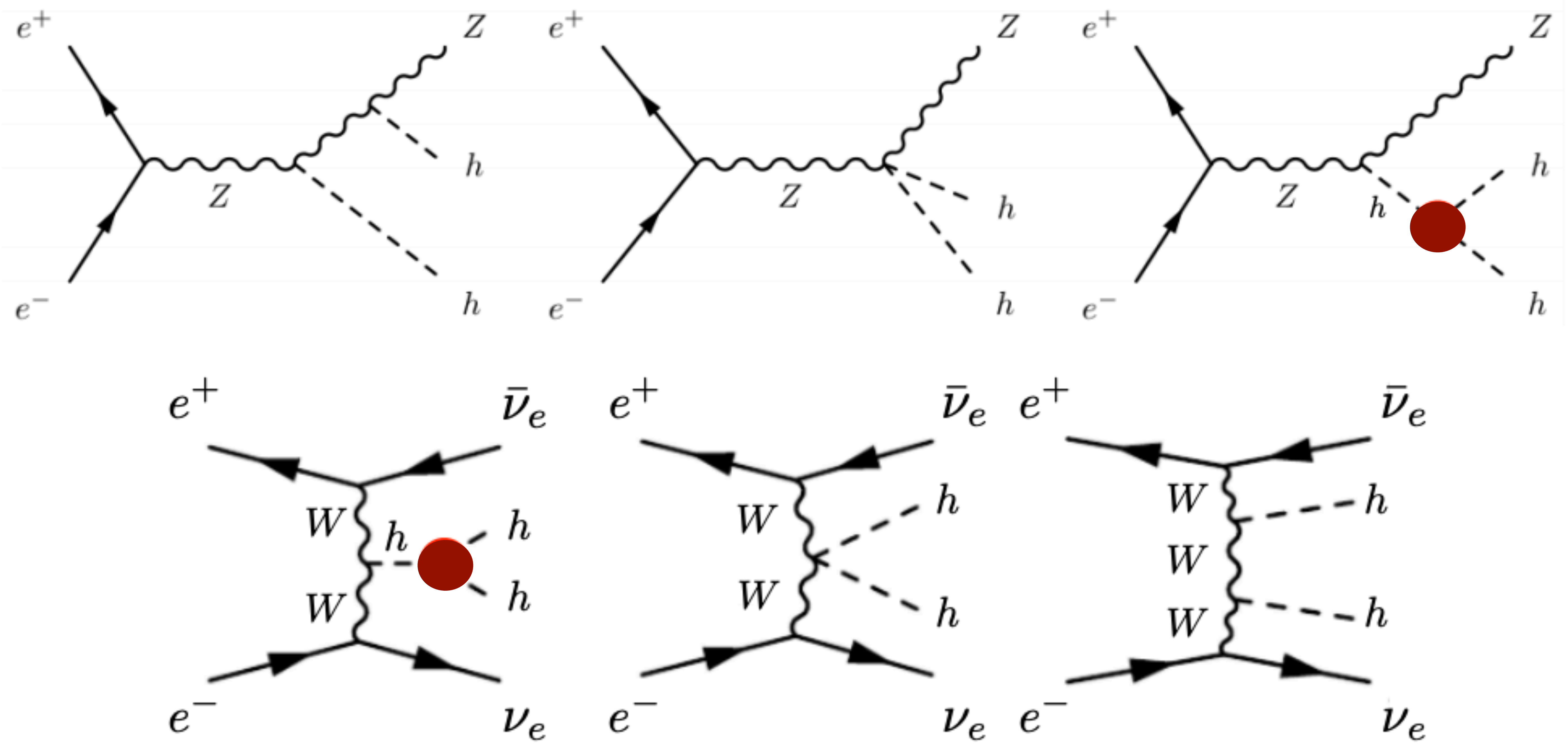
# of Higgs produced: **~4M** **~400**

4.8σ (VH only) **5.2σ**

HH at future e+e- colliders

Review in Physics (2020) 100045



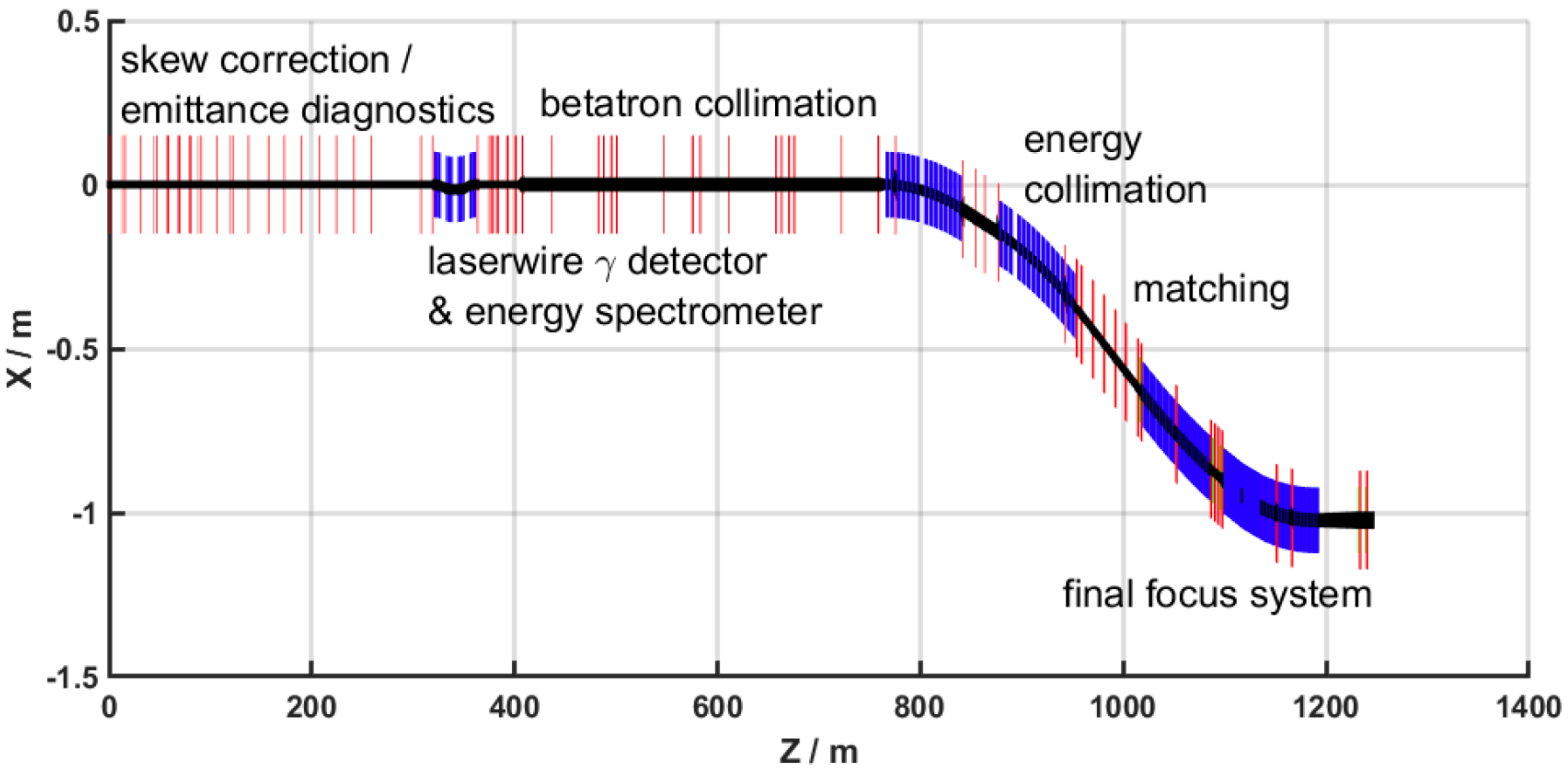


- The self-coupling can be probed at e+e- through HH with ZHH ~500GeV and **νν**HH ≥1TeV
  - **HHνν** requires $e_L^- e_R^+$, the use of polarized beams could increase the cross-section by a factor ~2

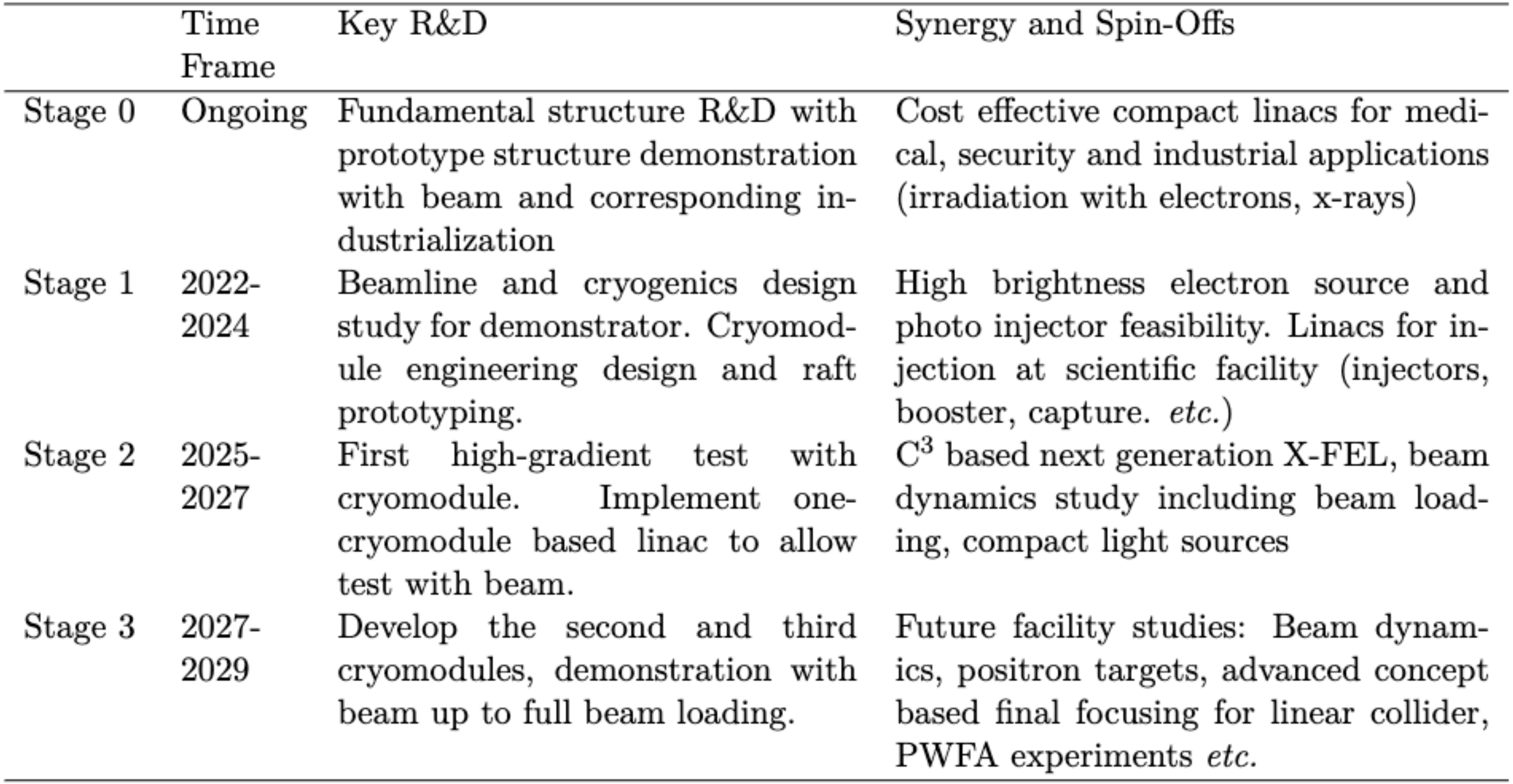
Beam Generation and Delivery Systems for C^3

- No positron polarization.
  - No upstream polarization measurement, but downstream polarization and energy measurement for both beams.
- Large portions of **accelerator complex are compatible between LC technologies**
  - Beam delivery and IP modified from ILC
  - Damping rings modified from CLIC
  - Injectors to be optimized with CLIC as baseline
  - There is a possibility of a high brightness, polarized
    - RF gun which might eliminate the e- damping ring, but that is not in the cost models.

C^3 - Investigation of Beam Delivery Adapted from ILC/NLC



Next: C^3 Demonstration Facility

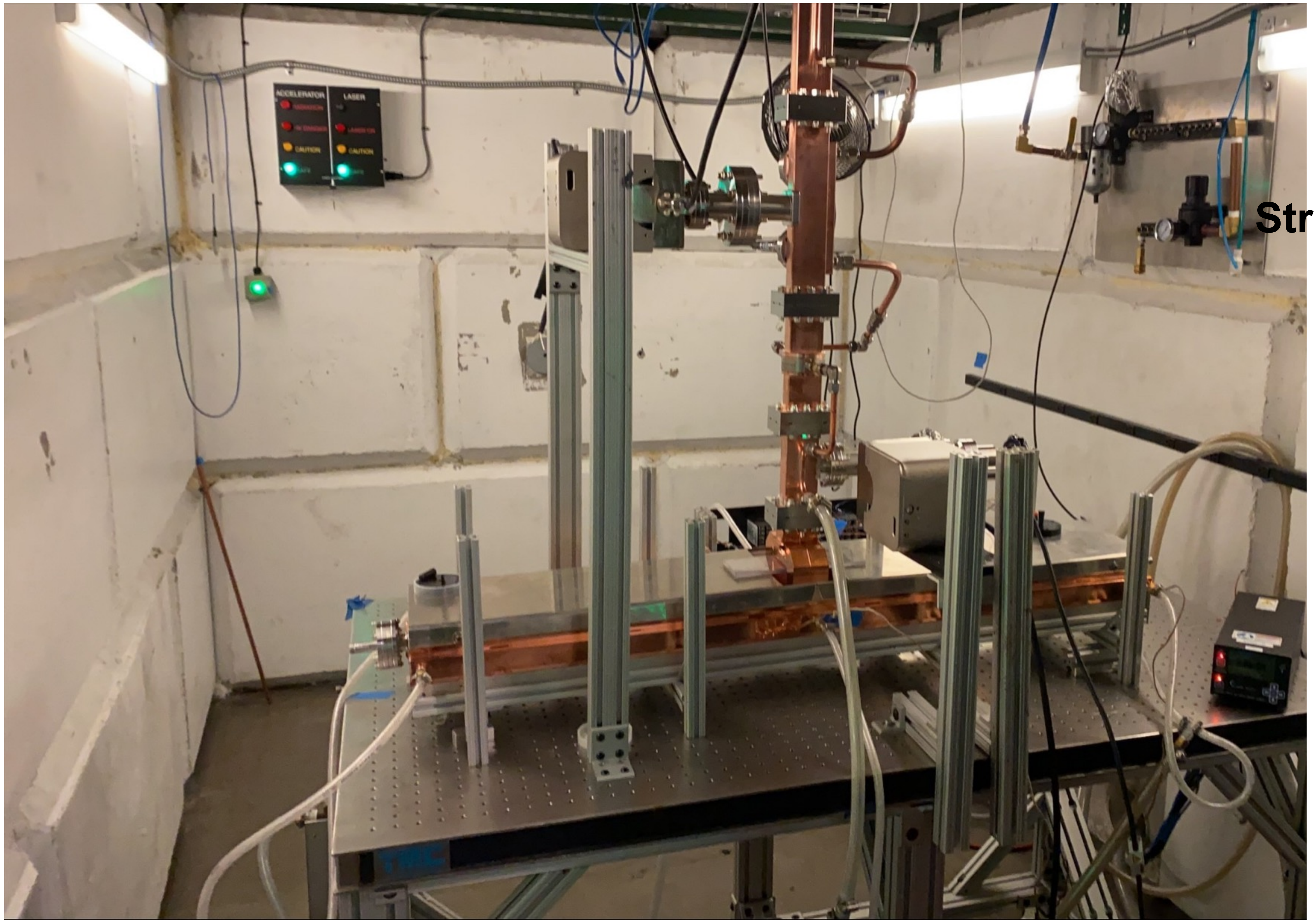


	Time Frame	Key R&D	Synergy and Spin-Offs
Stage 0	Ongoing	Fundamental structure R&D with prototype structure demonstration with beam and corresponding industrialization	Cost effective compact linacs for medical, security and industrial applications (irradiation with electrons, x-rays)
Stage 1	2022-2024	Beamline and cryogenics design study for demonstrator. Cryomodule engineering design and raft prototyping.	High brightness electron source and photo injector feasibility. Linacs for injection at scientific facility (injectors, booster, capture. *etc.*)
Stage 2	2025-2027	First high-gradient test with cryomodule. Implement one-cryomodule based linac to allow test with beam.	C^3 based next generation X-FEL, beam dynamics study including beam loading, compact light sources
Stage 3	2027-2029	Develop the second and third cryomodules, demonstration with beam up to full beam loading.	Future facility studies: Beam dynamics, positron targets, advanced concept based final focusing for linear collider, PWFA experiments *etc.*

CDR

TDR

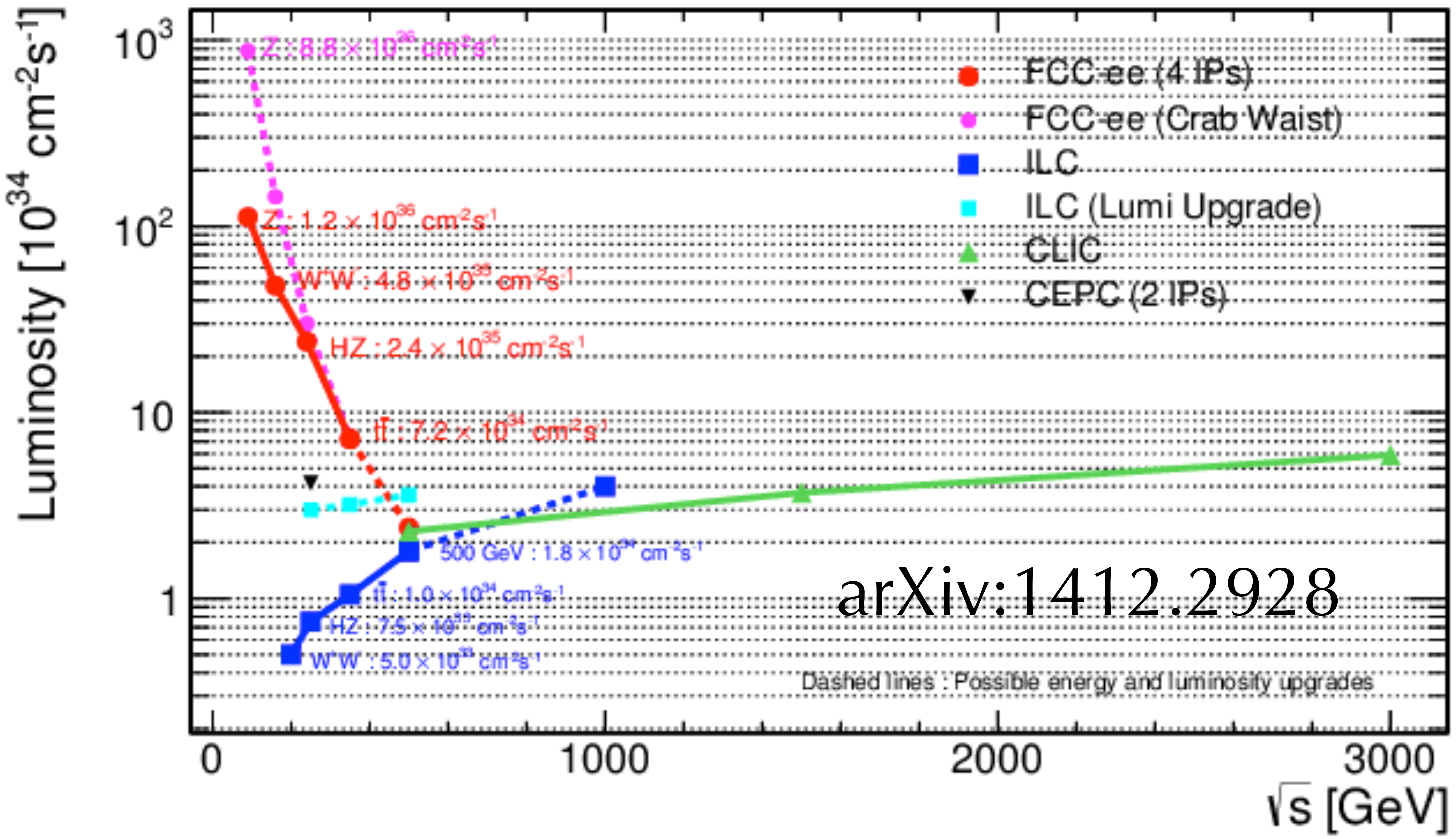
Latest tests



Structure in test stand at radiabeam

Luminosity optimization

Using established collider designs to inform initial parameters

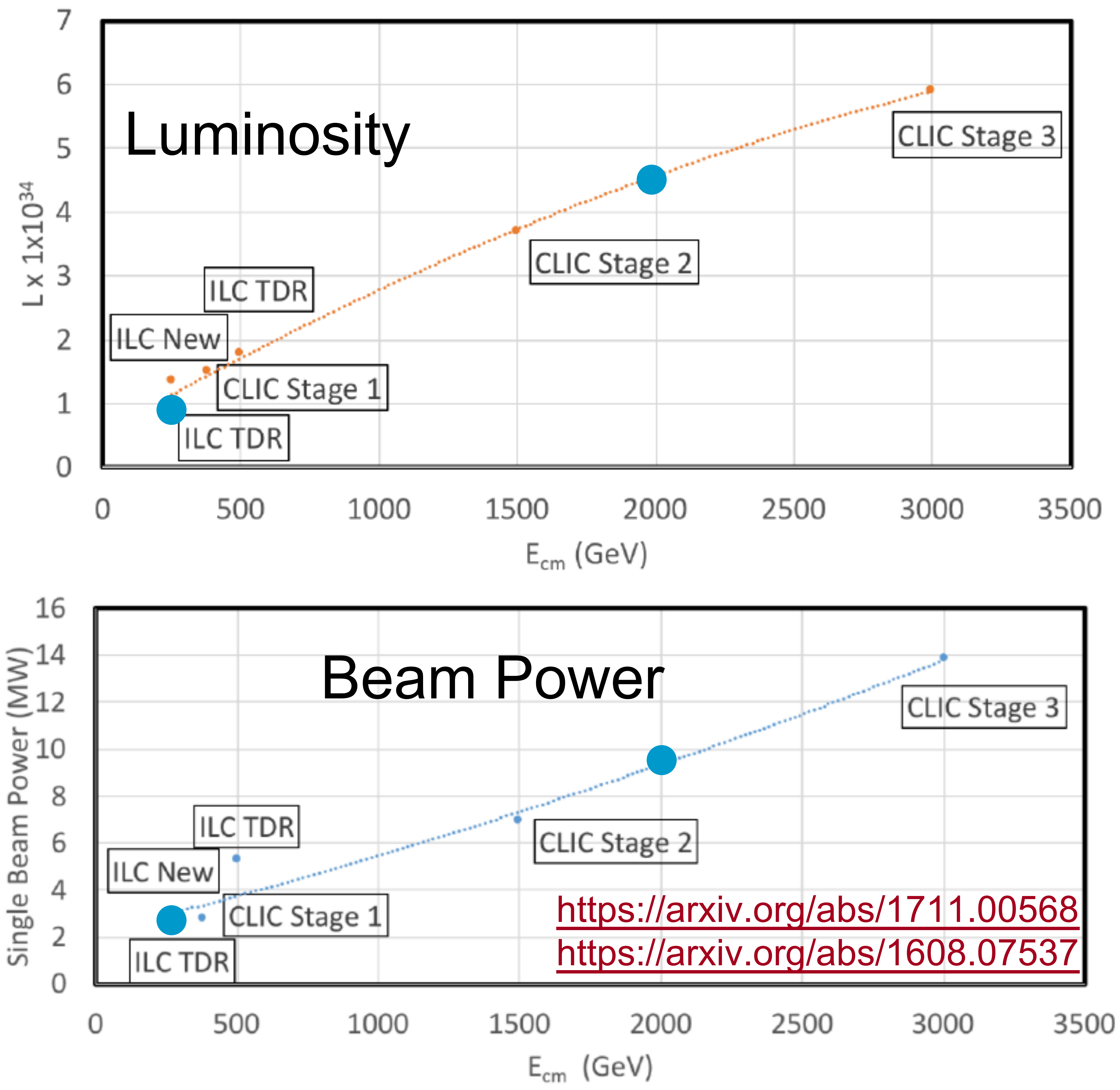


arXiv:1412.2928

Caterina Vernieri

Luminosity optimization

Using established collider designs to inform initial parameters

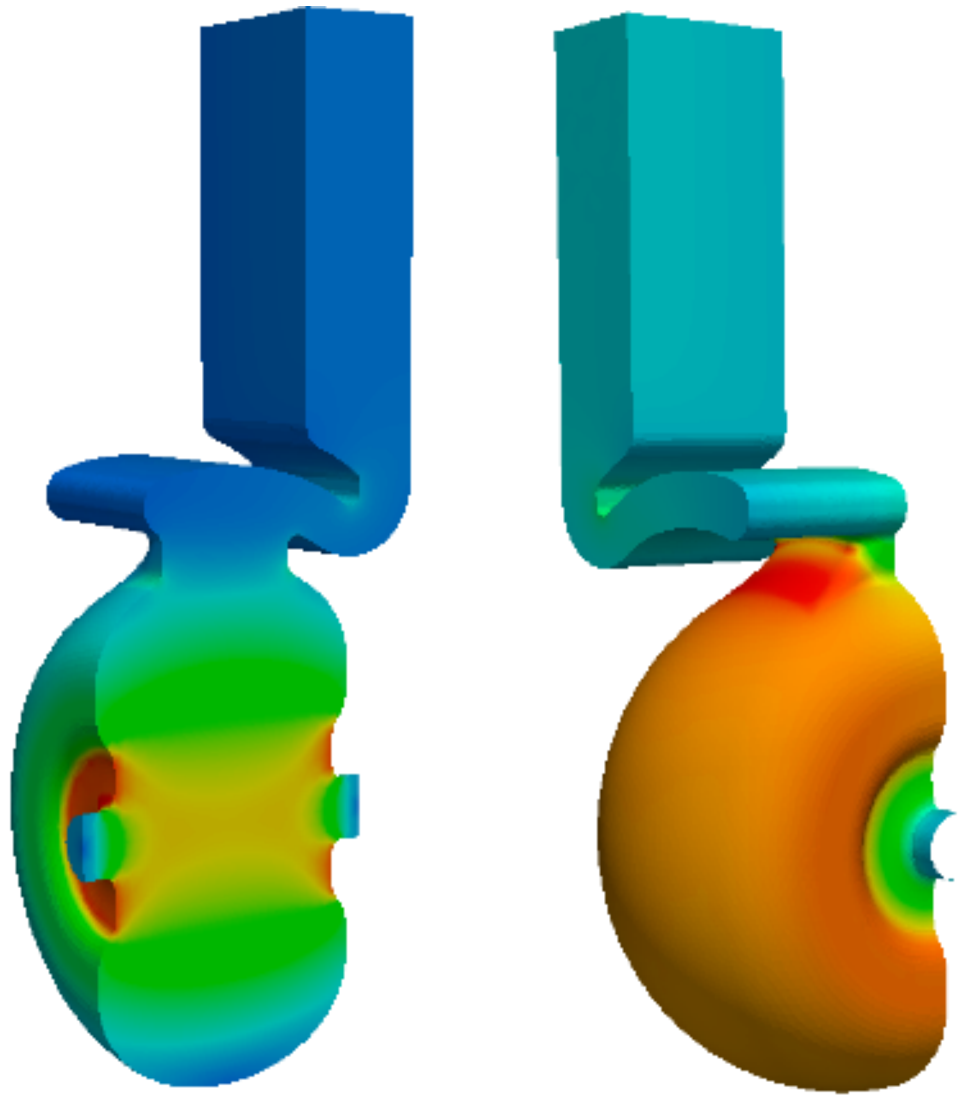


https://arxiv.org/abs/1711.00568
https://arxiv.org/abs/1608.07537

Development of C^3 Accelerating Structure

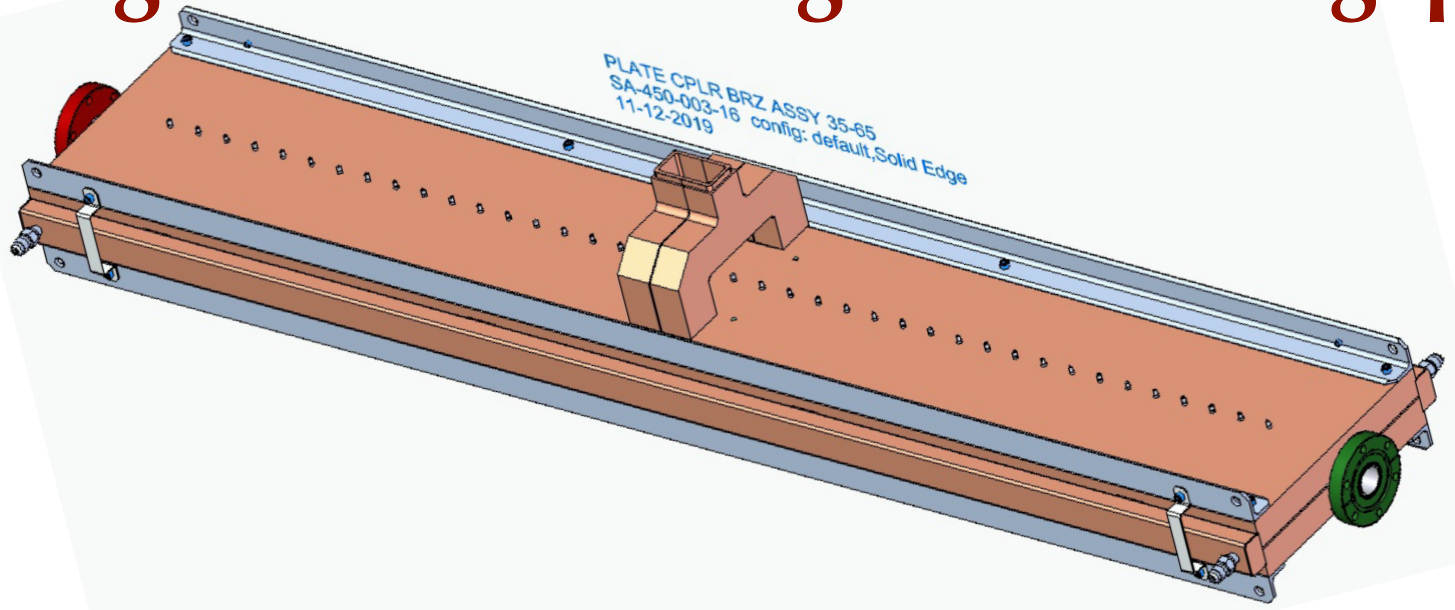
- Two Key Technical Advances: Distributed Coupling and Cryo-Copper RF
- Envision meter-scale accelerating structures, technology demonstration underway
- Implement most high-gradient advances

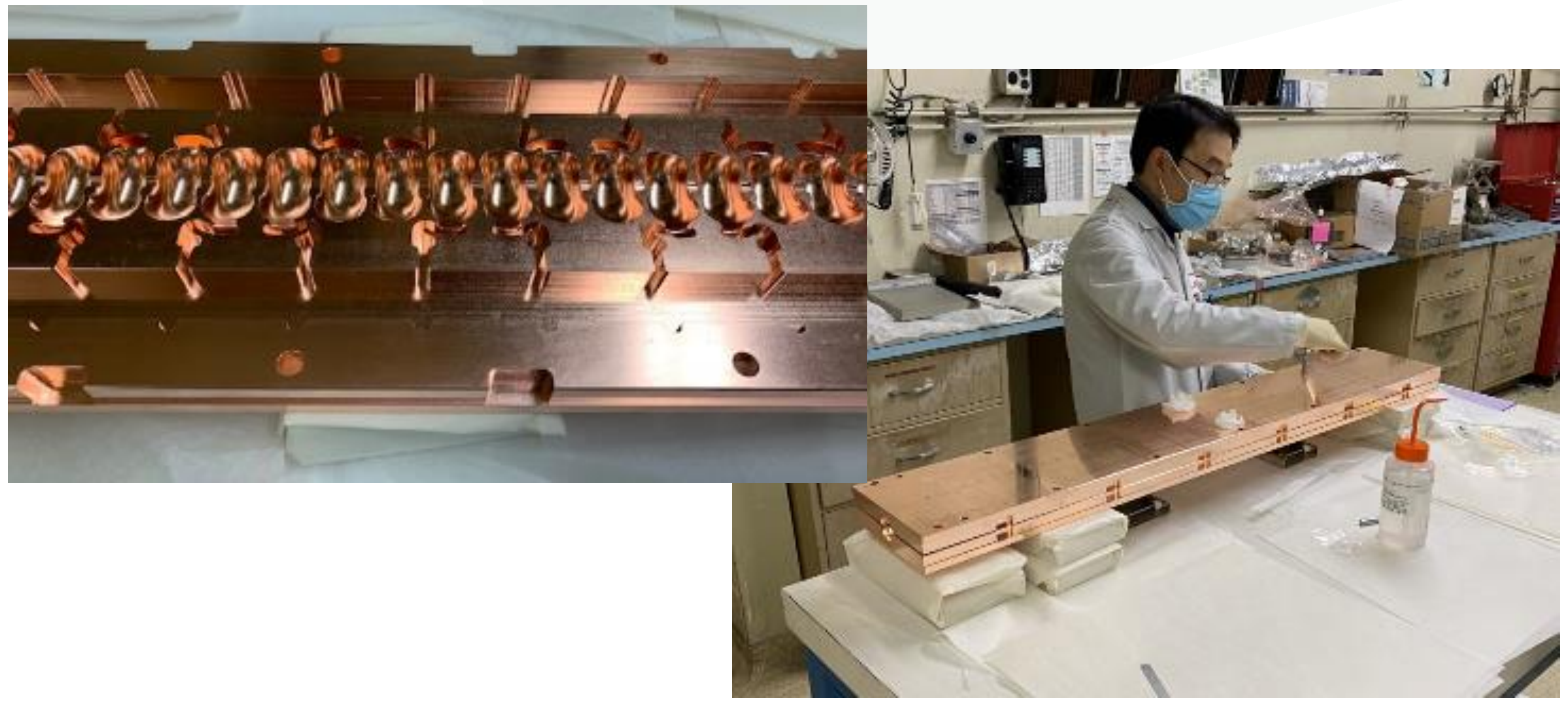
One meter (40-cell) C-band design with reduce peak E and H-field



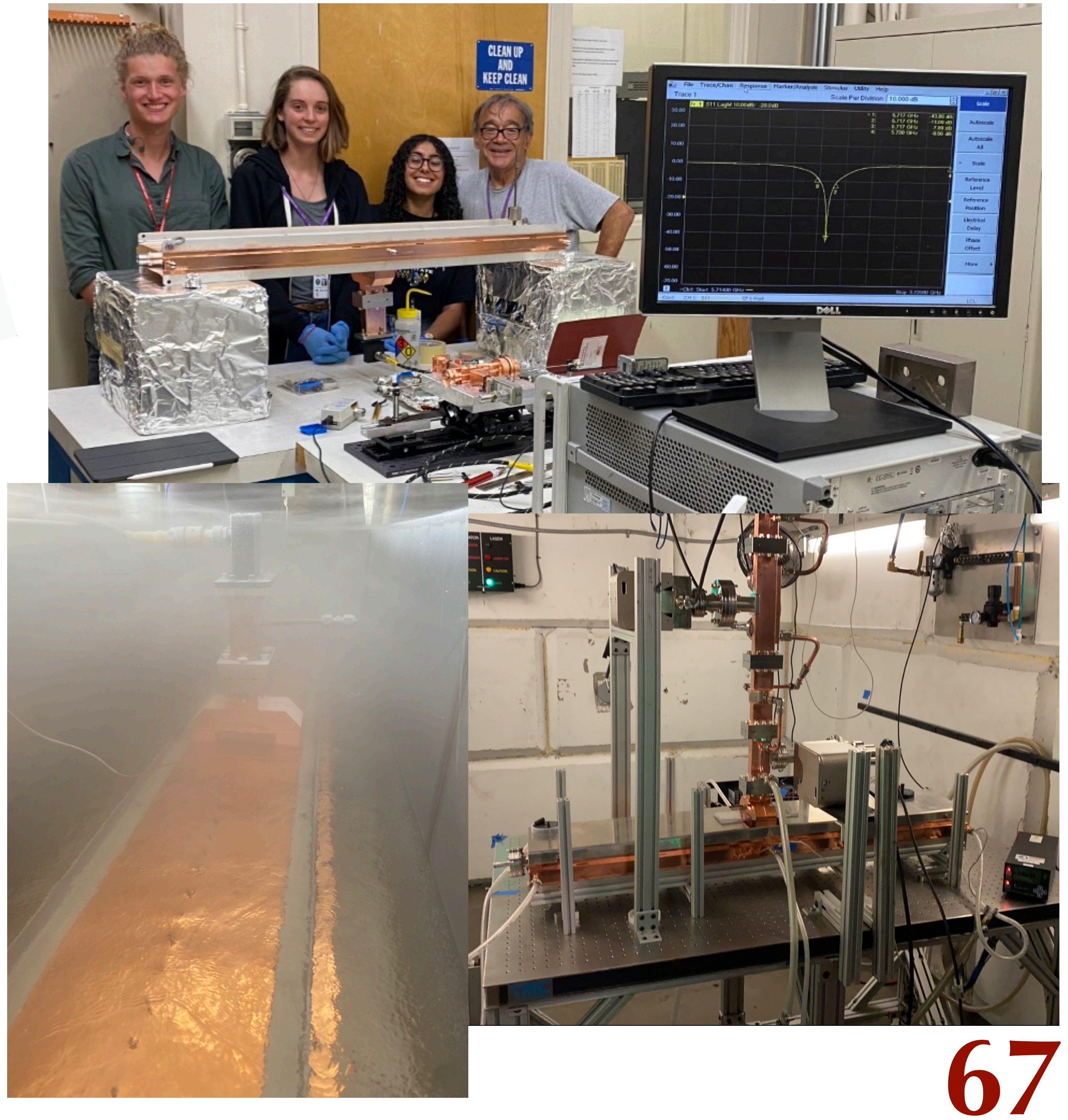
Z. Li, S. Tantawi

Scaling fabrication techniques in length and including controlled gap





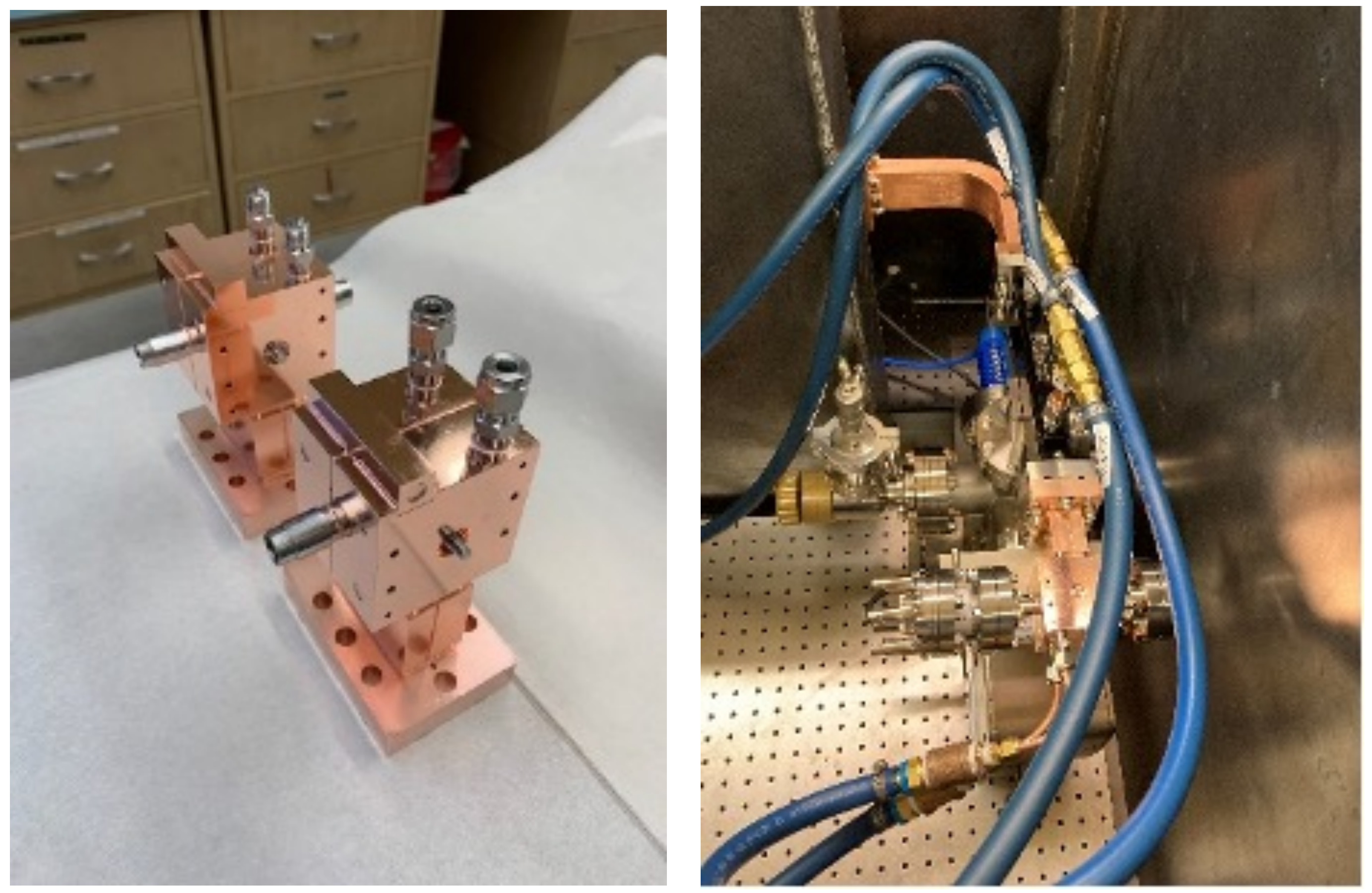
Tuned, confirmed 77K performance, first 300k high power test in progress



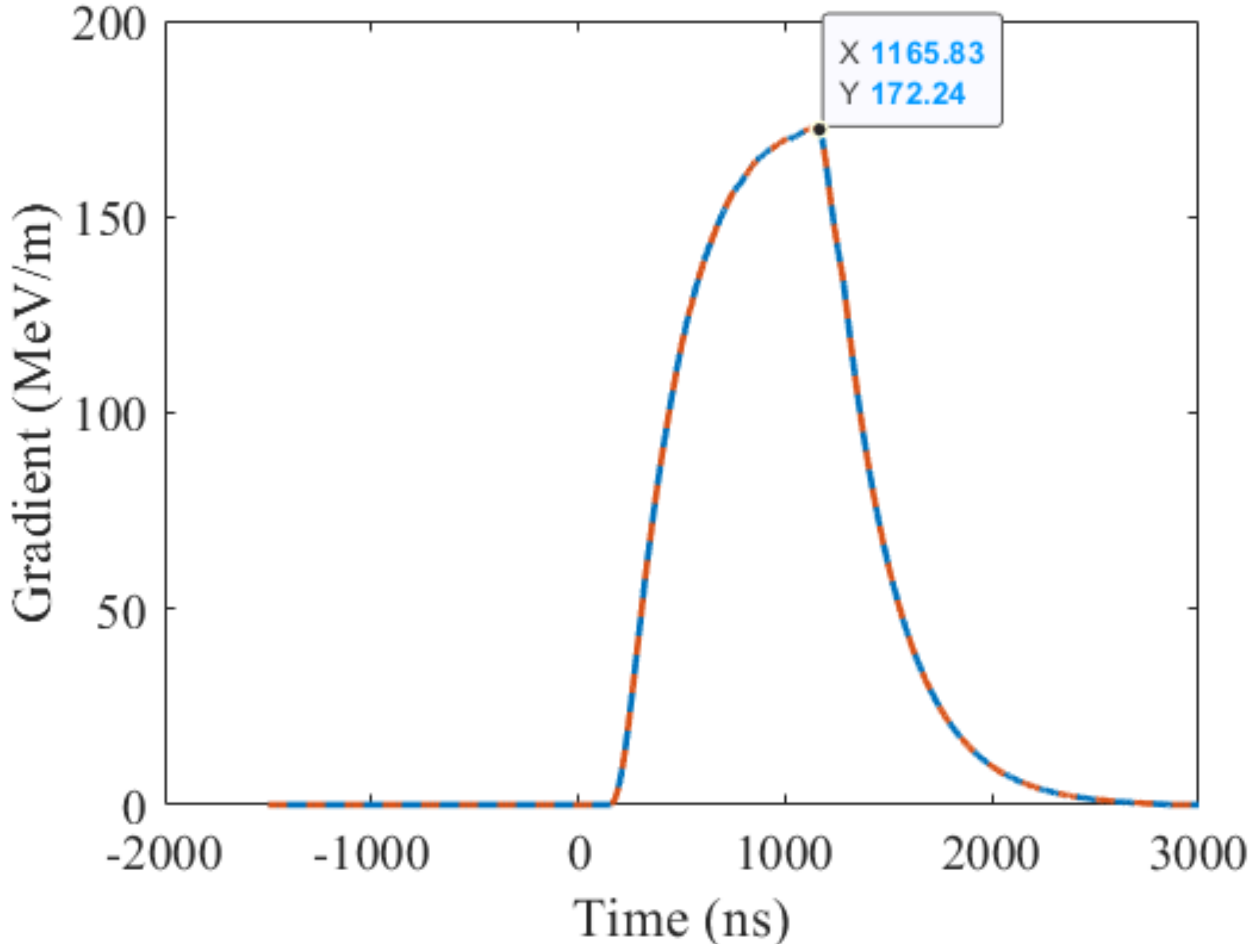
Performance of Single-Cavity Structure Prototypes

- First high gradient test at C-band
- Side coupled, split-cell reduced peak field, reduced phase adv.
- Exceed ultimate C^3 field strengths
- High power in up to 1 microsecond - break down rate statistics collected and being prepared for release

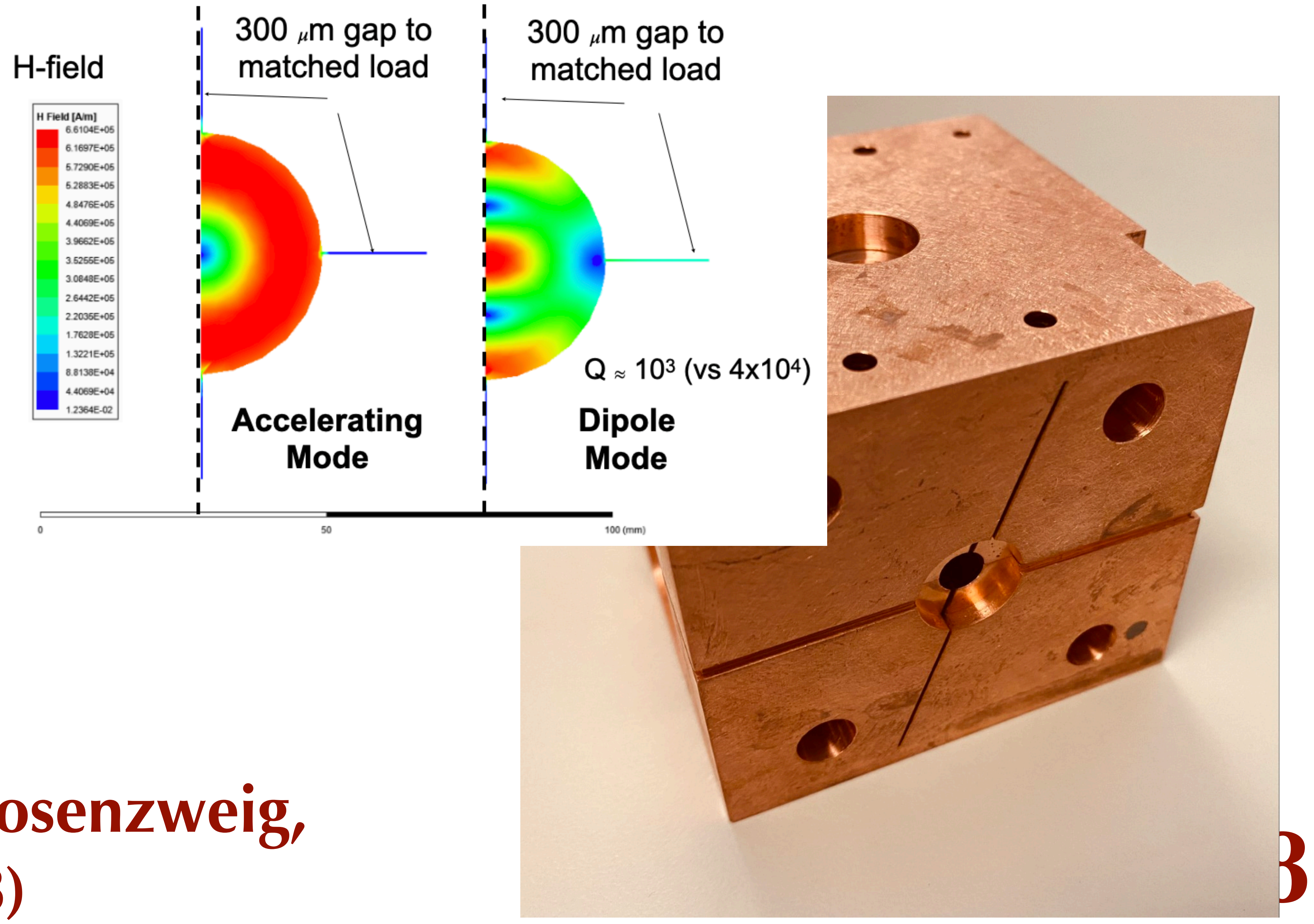
LANL Test of single cell SLAC C-band structure



Structure Exceeds 120 MeV/m for 500 ns @ Room Temp BDR Data Collected



Slot Damping Prototype Working on NiCr Coating



Very promising for polarized cryo-gun (Rosenzweig, et al. NIM 909 (2018): 224-228)

Incoherent Pair Production

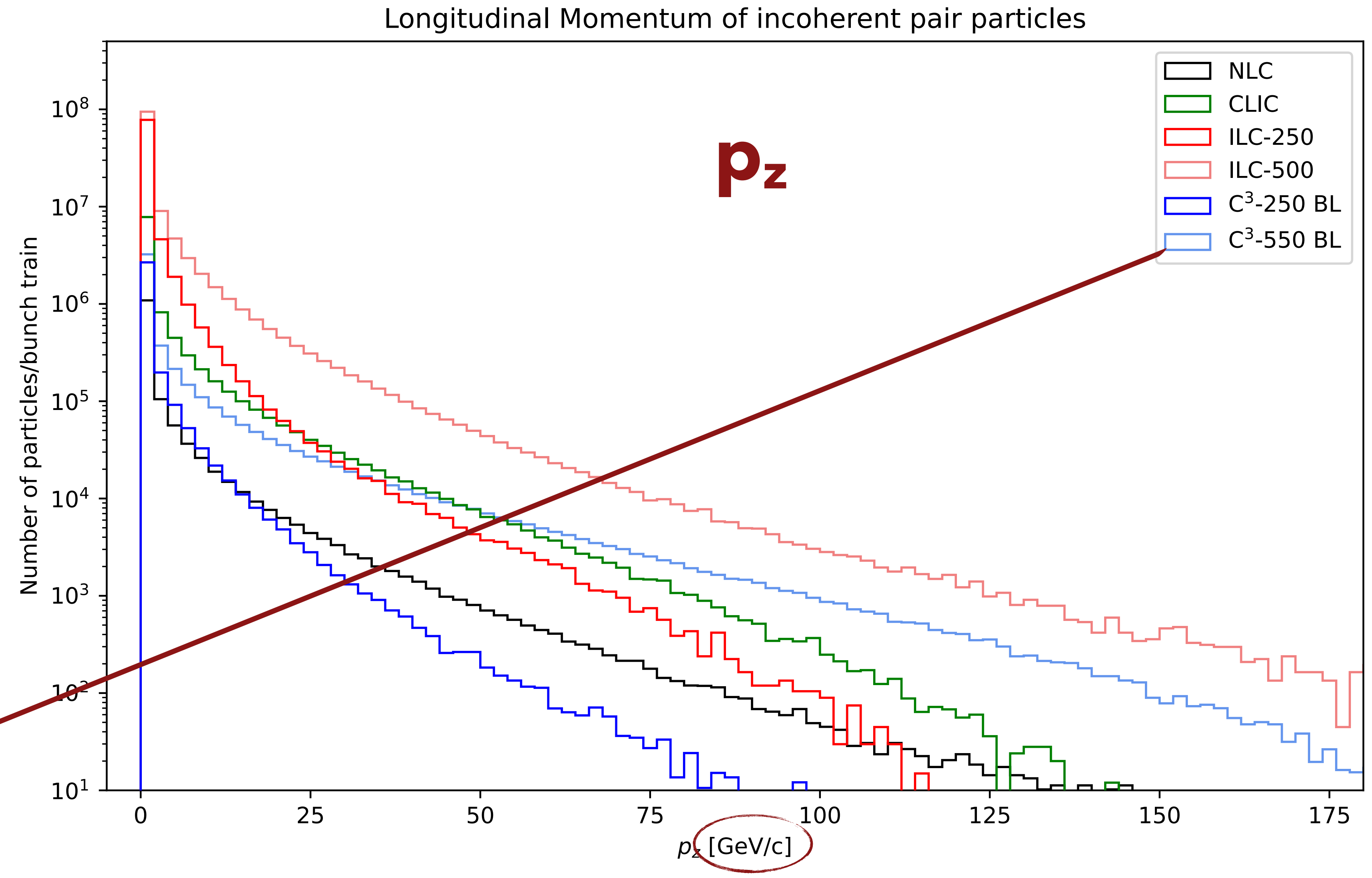
D. Ntounis, manuscript to appear soon

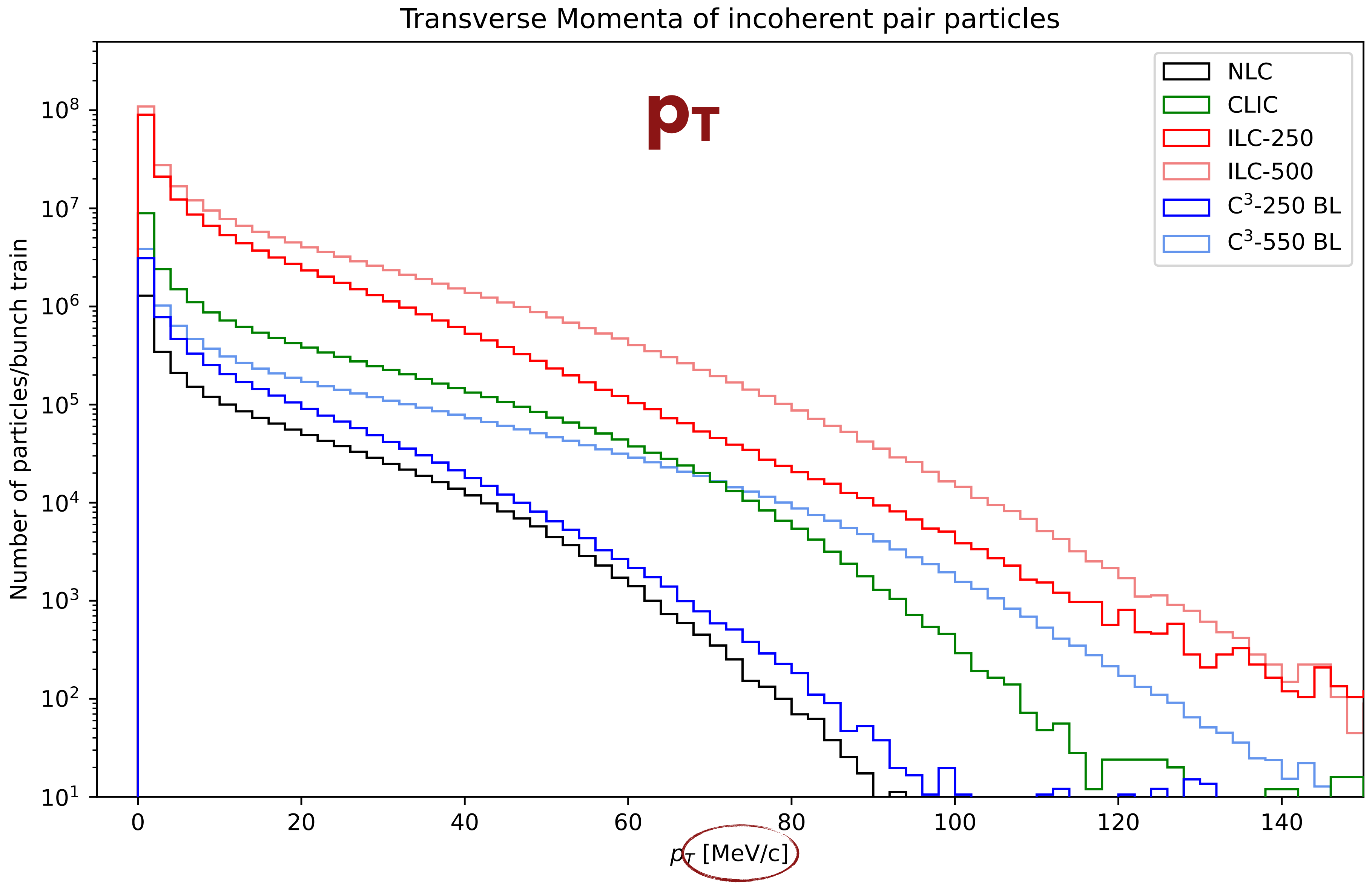
Incoherently produced pair particles are typically low-energetic and boosted in the forward direction.

Assuming a common per-bunch-train readout scheme, the expected number of such pair particles produced per bunch train is $\langle N_{\text{incoh}} \rangle \cdot n_b$.

The energy and momentum spectra are shown assuming this normalization.

Coherent pairs/pairs from trident cascade are negligible for HFs at sub-TeV energies!


Longitudinal Momentum of incoherent pair particles


Transverse Momenta of incoherent pair particles