C^3: An Advanced Concept for a e^+e^- Linear Collider

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Thanks to Many for Contributions / Discussions

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SLAC NATIONAL ACCELERATOR LABORATORY

Acknowledgements

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October 27, 2021

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

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ABSTRACT

We present a proposal for a cold copper distributed coupling accelerator that can provide a rapid route to precision Higgs physics with a compact 8 km footprint. This proposal is based on recent advances that increase the efficiency and operating gradient of a normal conducting accelerator. This technology also provides an e^+e^- collider path to physics at multi-TeV energies. In this article, we describe our vision for this technology and the near-term R&D program needed to pursue it.

Snowmass Contribution

Snowmass LOI

November, 2 2021

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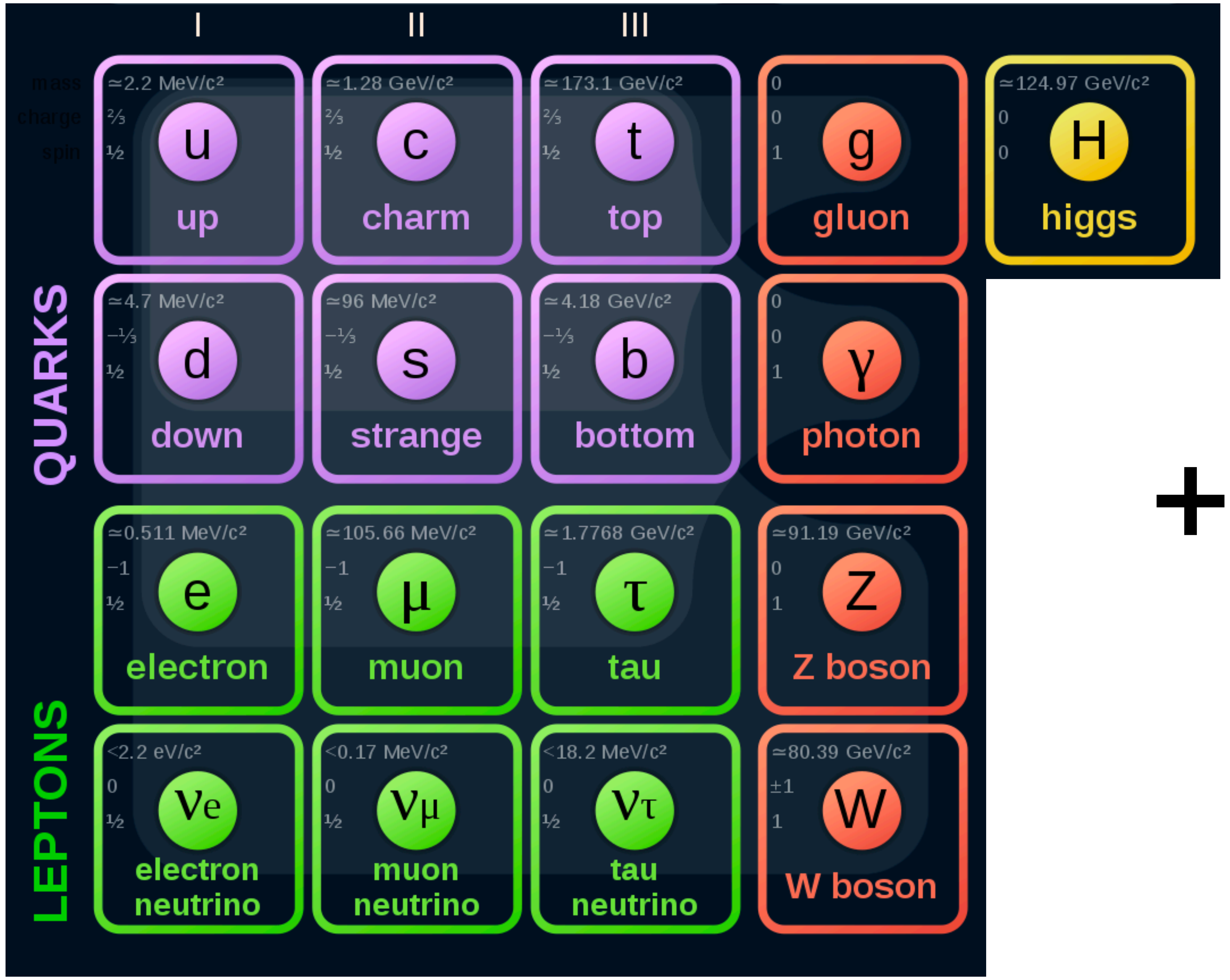
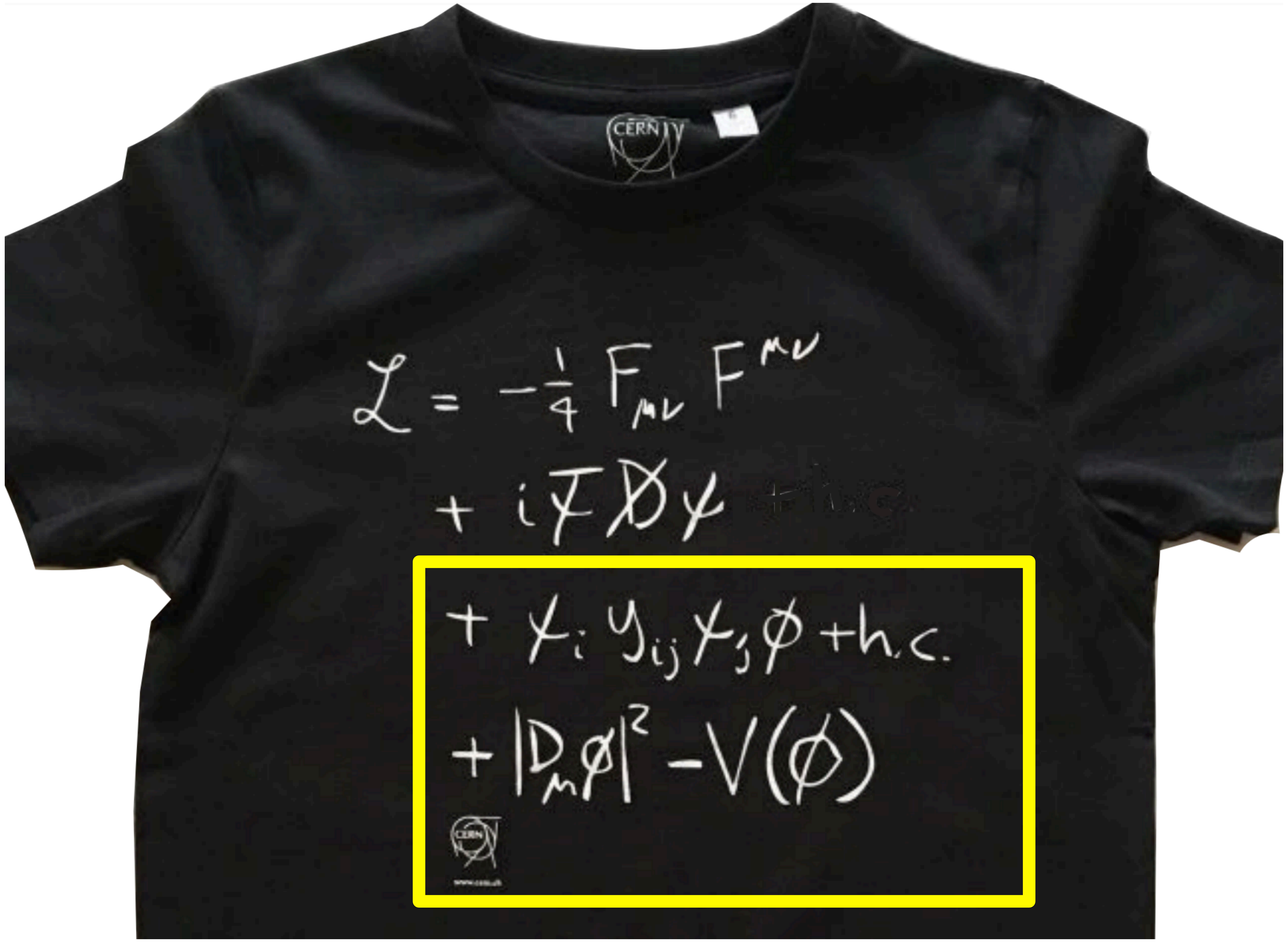
The Higgs Boson



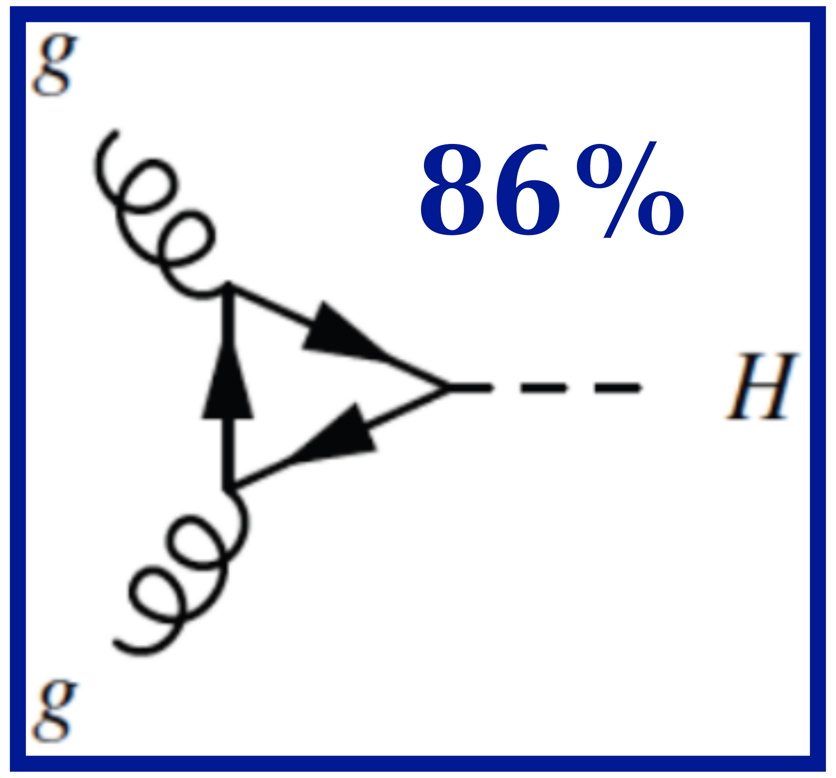
	I	II	III		
mass charge spin QUARKS	≃2.2 MeV/c^2 ⅔ ½ u up	≃1.28 GeV/c^2 ⅔ ½ c charm	≃173.1 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c^2 0 0 H higgs
QUARKS	≃4.7 MeV/c^2 −⅓ ½ d down	≃96 MeV/c^2 −⅓ ½ s strange	≃4.18 GeV/c^2 −⅓ ½ b bottom	0 0 1 γ photon	
LEPTONS	≃0.511 MeV/c^2 −1 ½ e electron	≃105.66 MeV/c^2 −1 ½ μ muon	≃1.7768 GeV/c^2 −1 ½ τ tau	≃91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	≃80.39 GeV/c^2 ±1 1 W W boson	

+

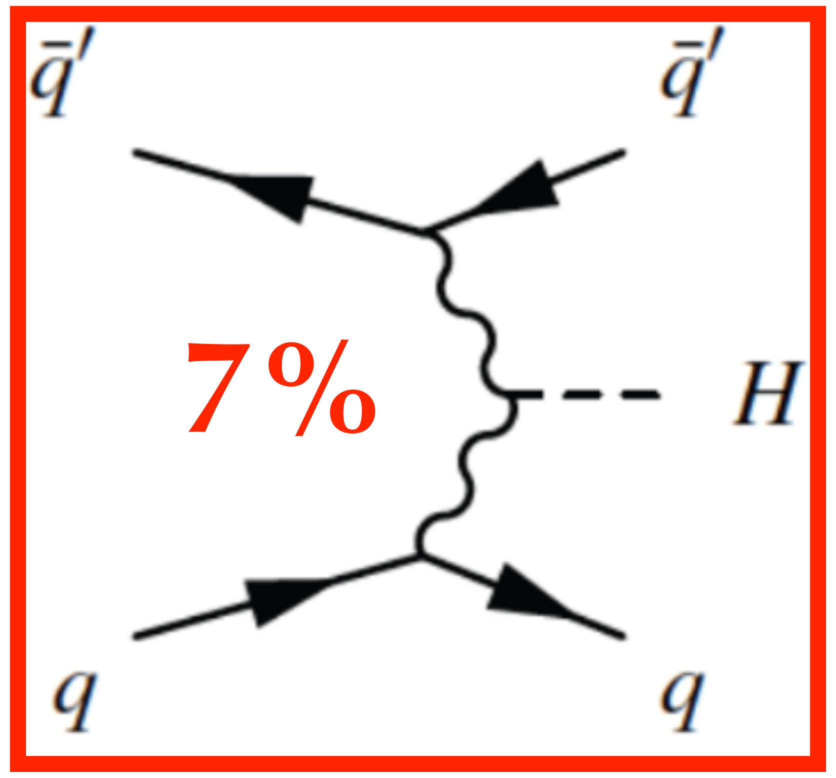


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i\bar{\psi} \not{D} \psi$$
$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

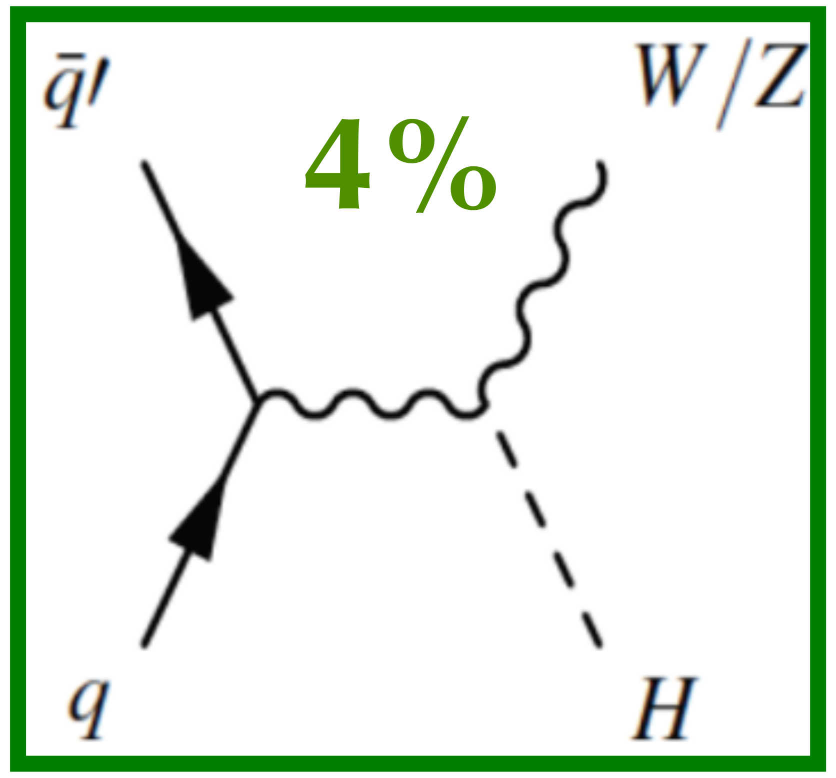
Higgs Boson Production at the LHC



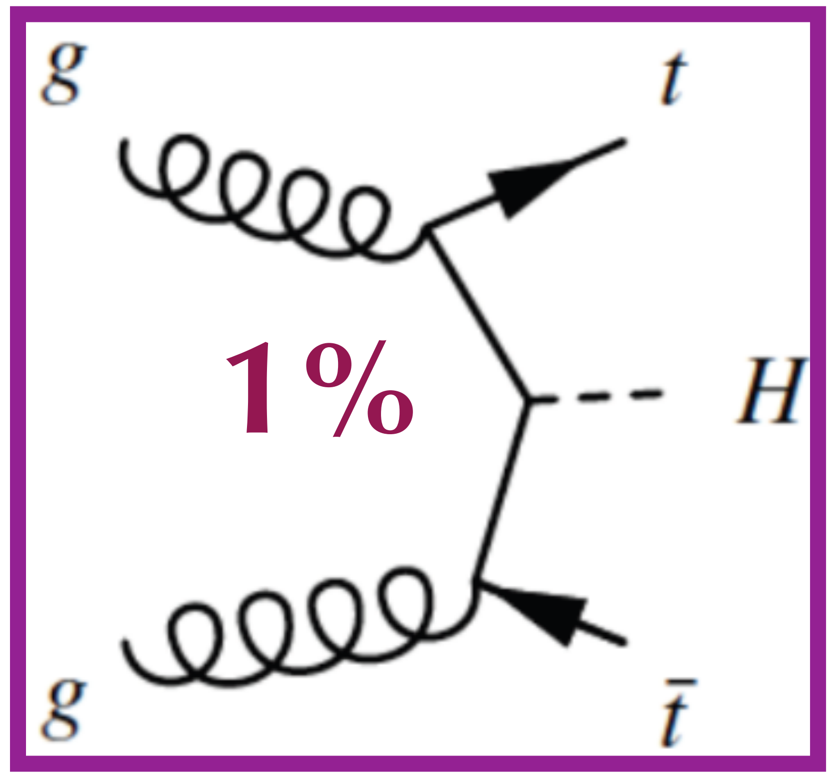
Gluon Fusion



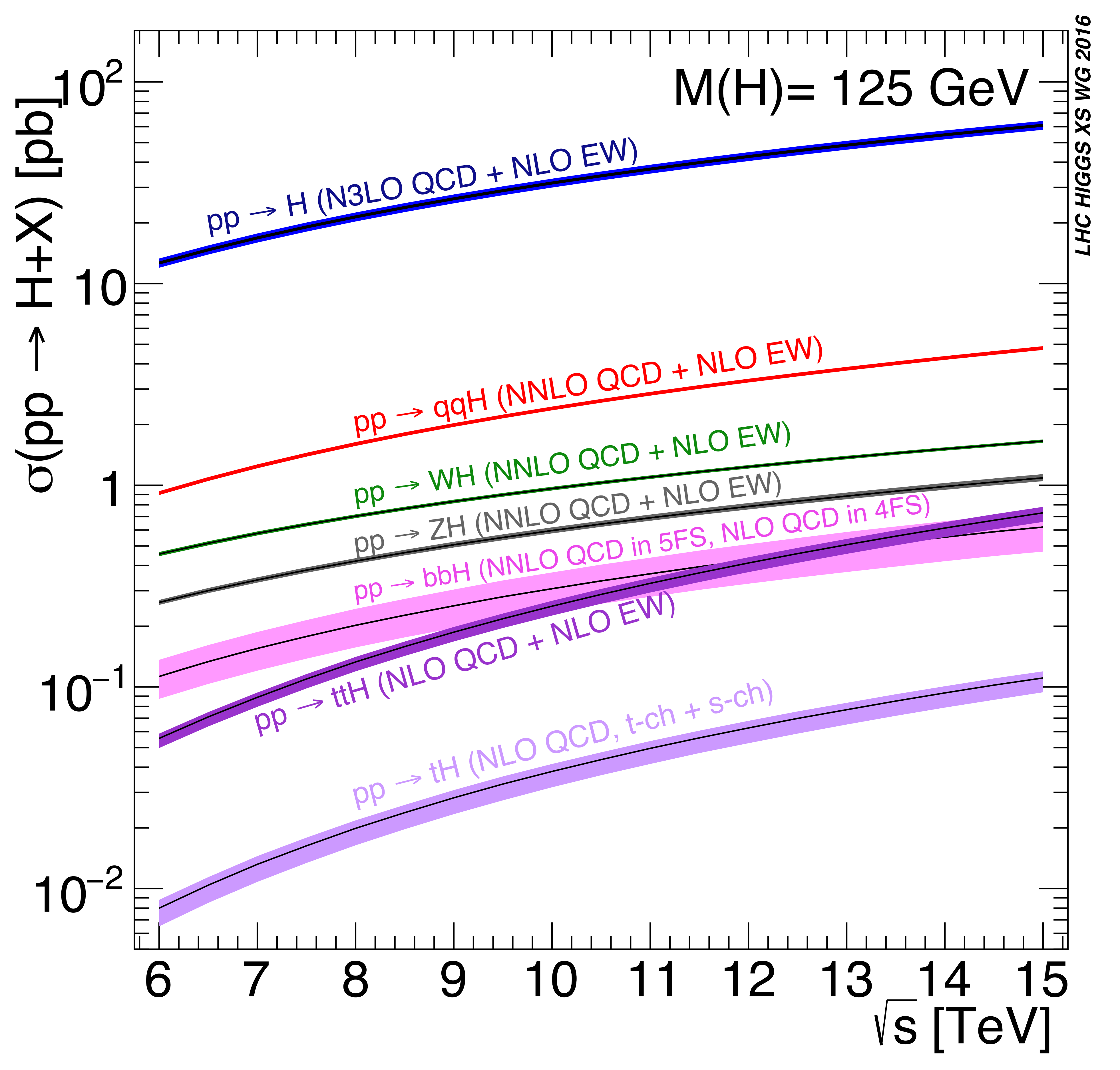
Vector-Boson Fusion



Higgs-strahlung

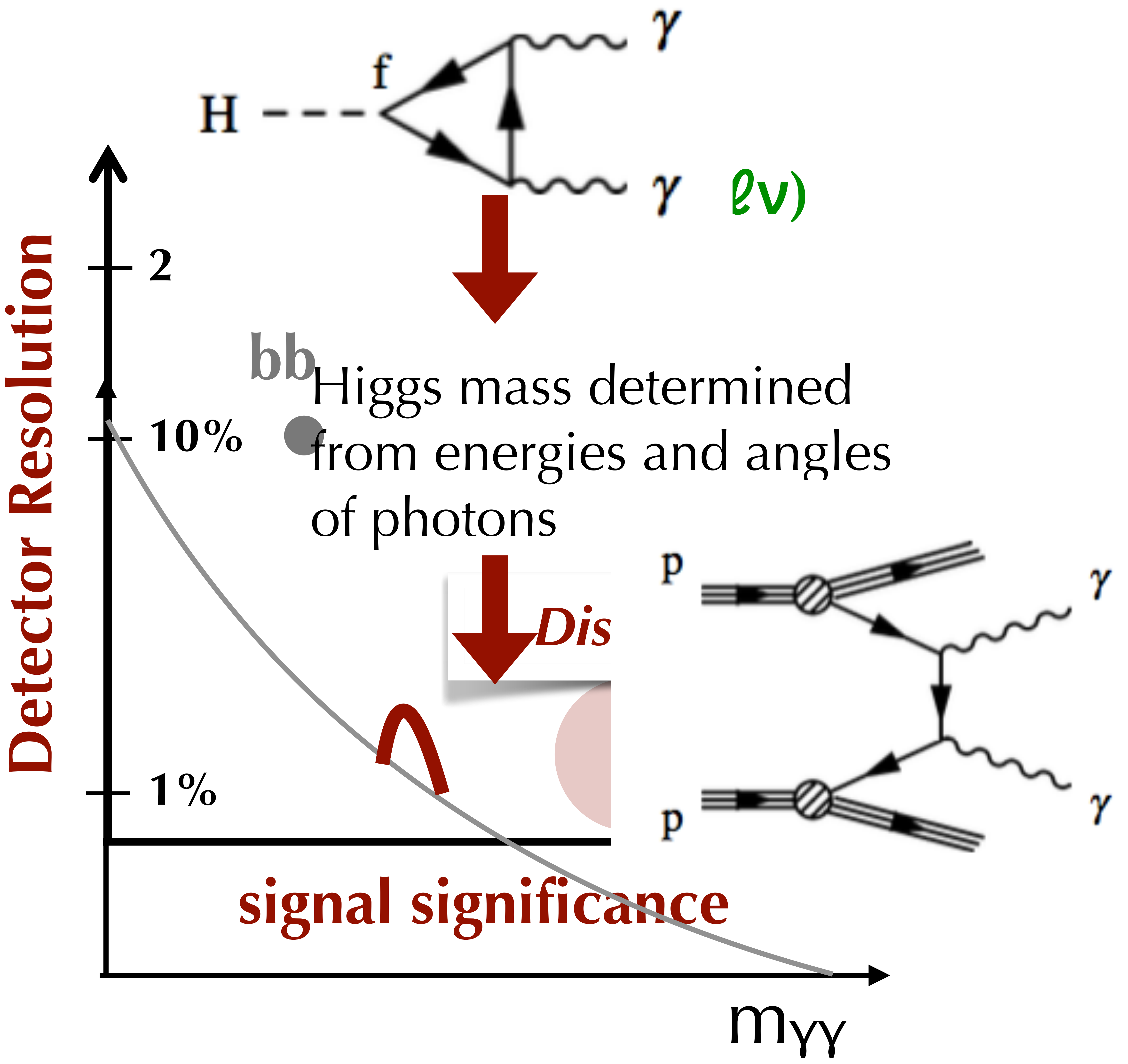


Top Fusion (ttH)

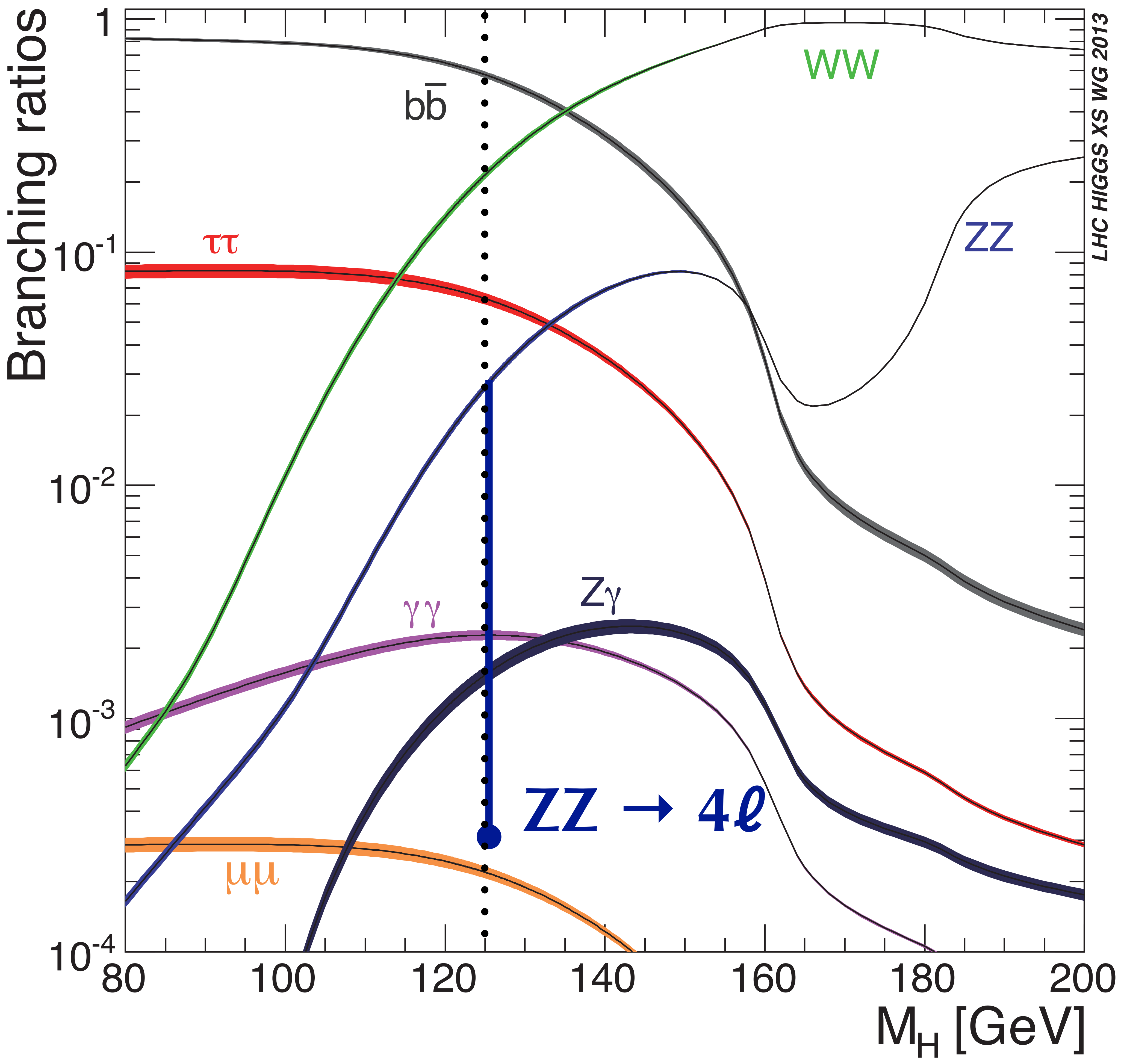


LHC at 13 TeV is producing SM H bosons at a rate of ~ 2000/hr

How does it Decay (m_H = 125 GeV) ?



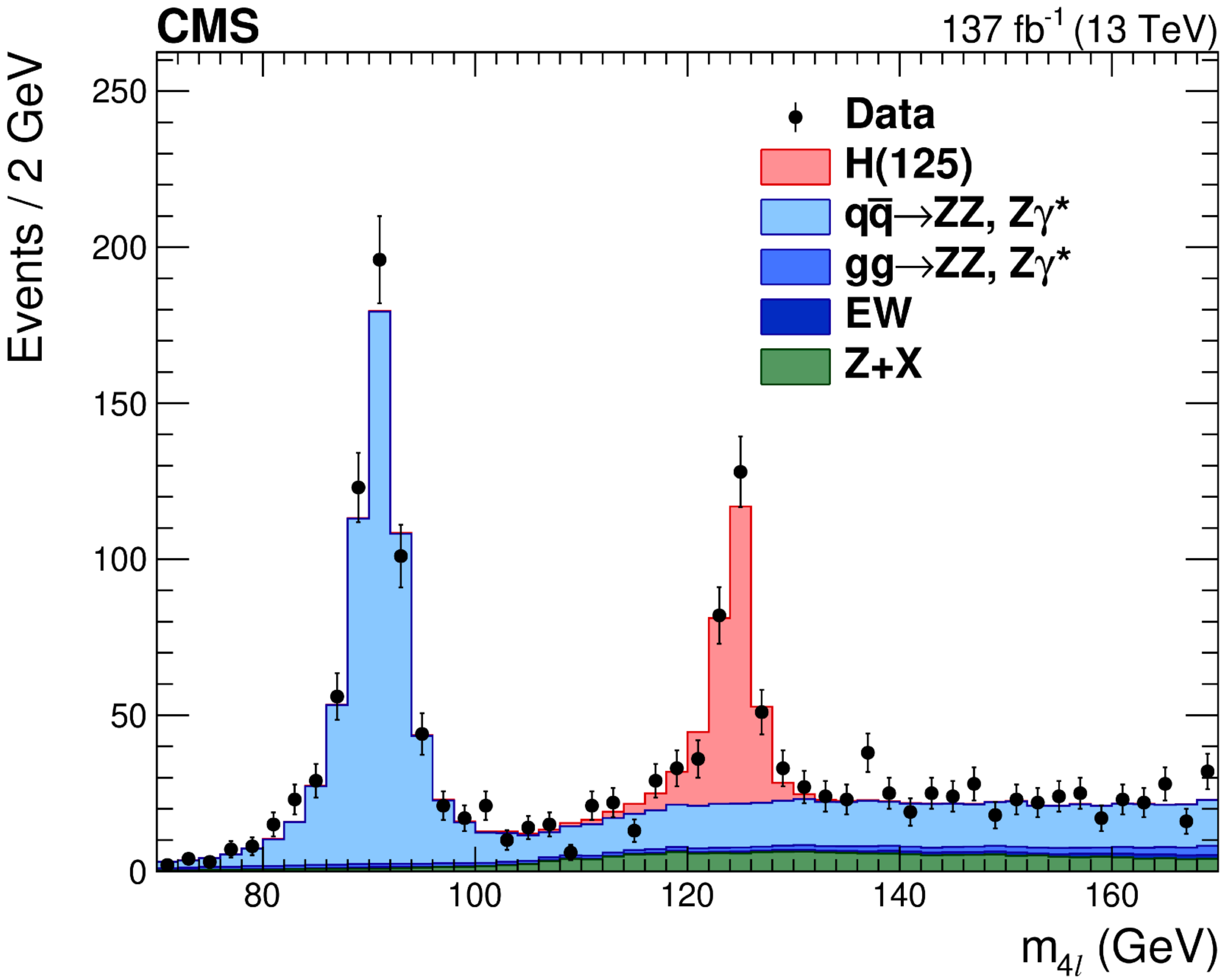
Higgs mass determined from energies and angles of photons



Is it a SM Higgs boson?

ATLAS-CONF-2020-026
CMS-Eur. Phys. J. C 81 (2021) 488

- Mass
- Spin-parity (**0+**)
- Width
- The couplings to fermions and bosons
- Study the self-coupling
- Any non-SM property?



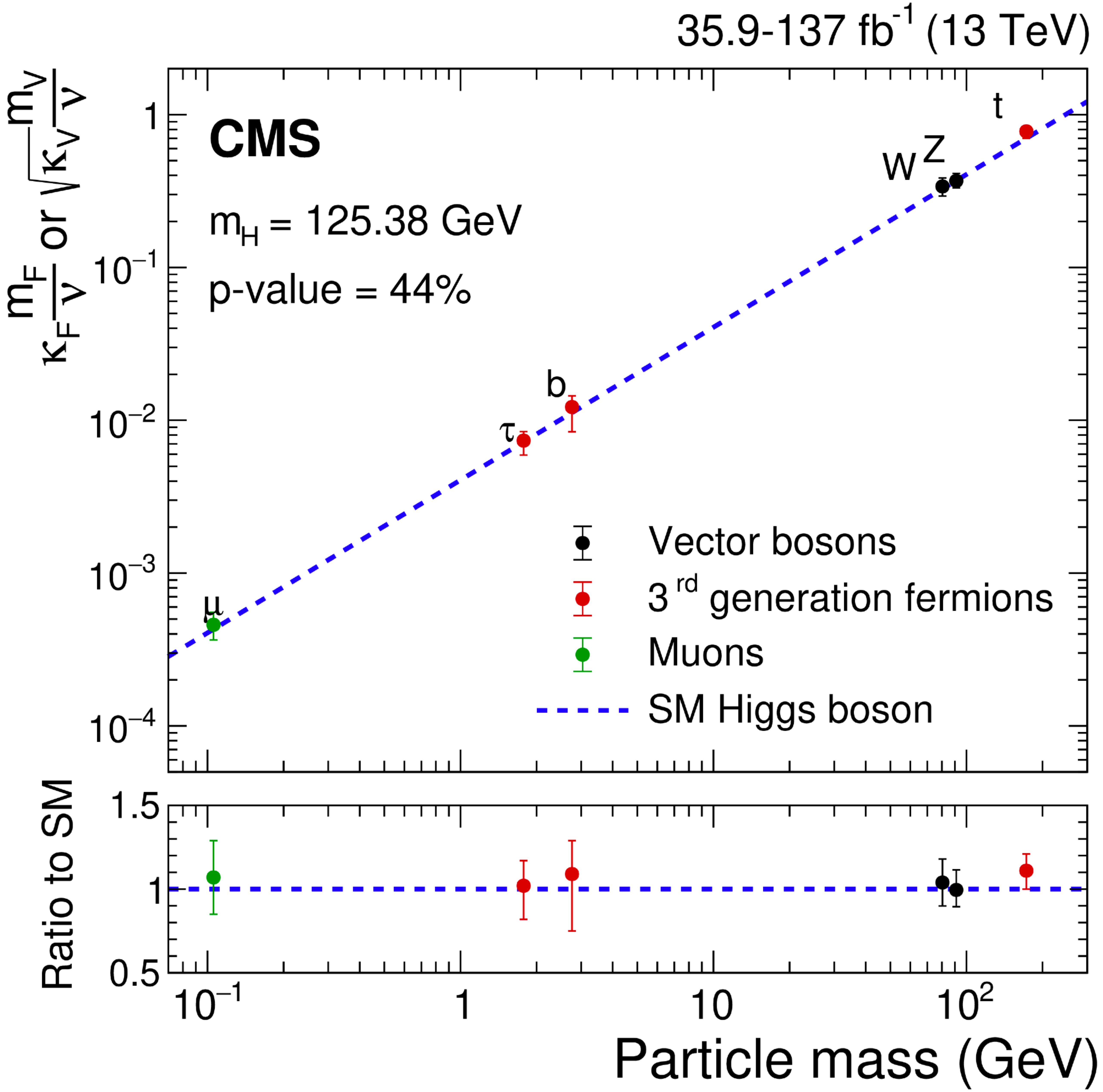
Higgs Boson mass measured with relative uncertainty < 0.2%

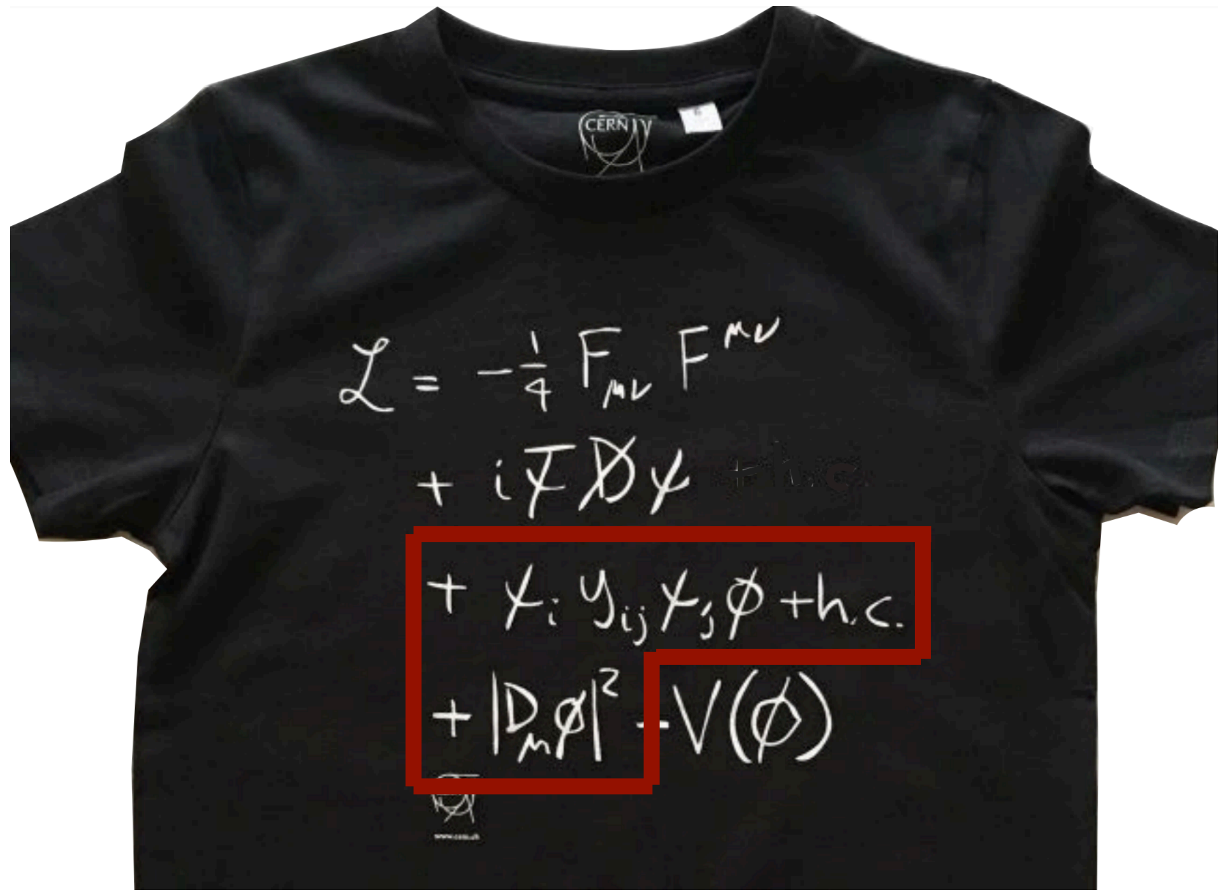
Lepton momentum scale uncertainty is **0.05-0.3%**

The total calibration uncertainty for **photons** is **0.2%–0.3%**

ATLAS-CONF-2019-005

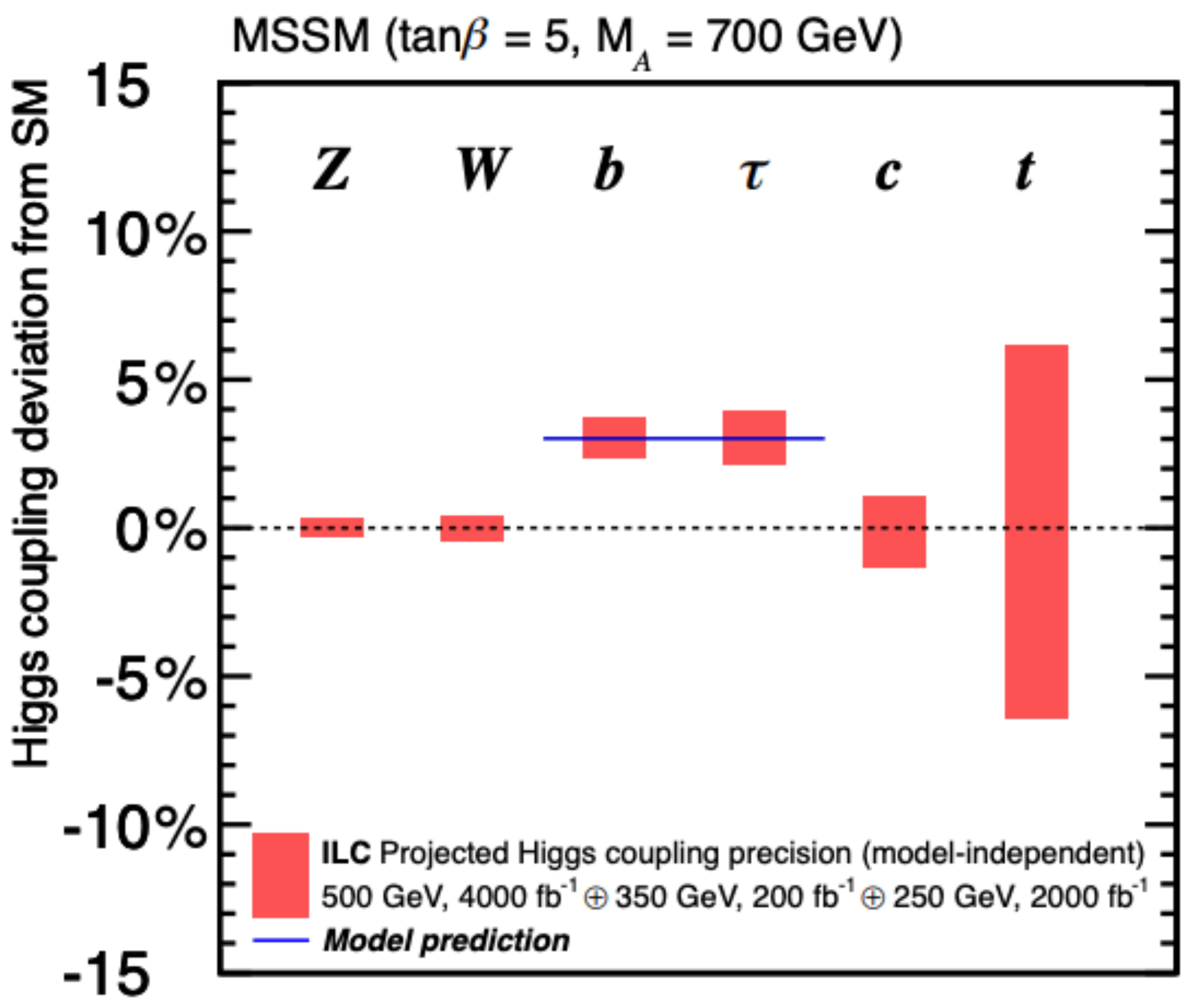
CMS-JHEP 01 (2021) 148





No new particles discovered at the LHC so far…

What's next?
How can we use the Higgs to find new physics?



Arxiv:1506.05992

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

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

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})

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

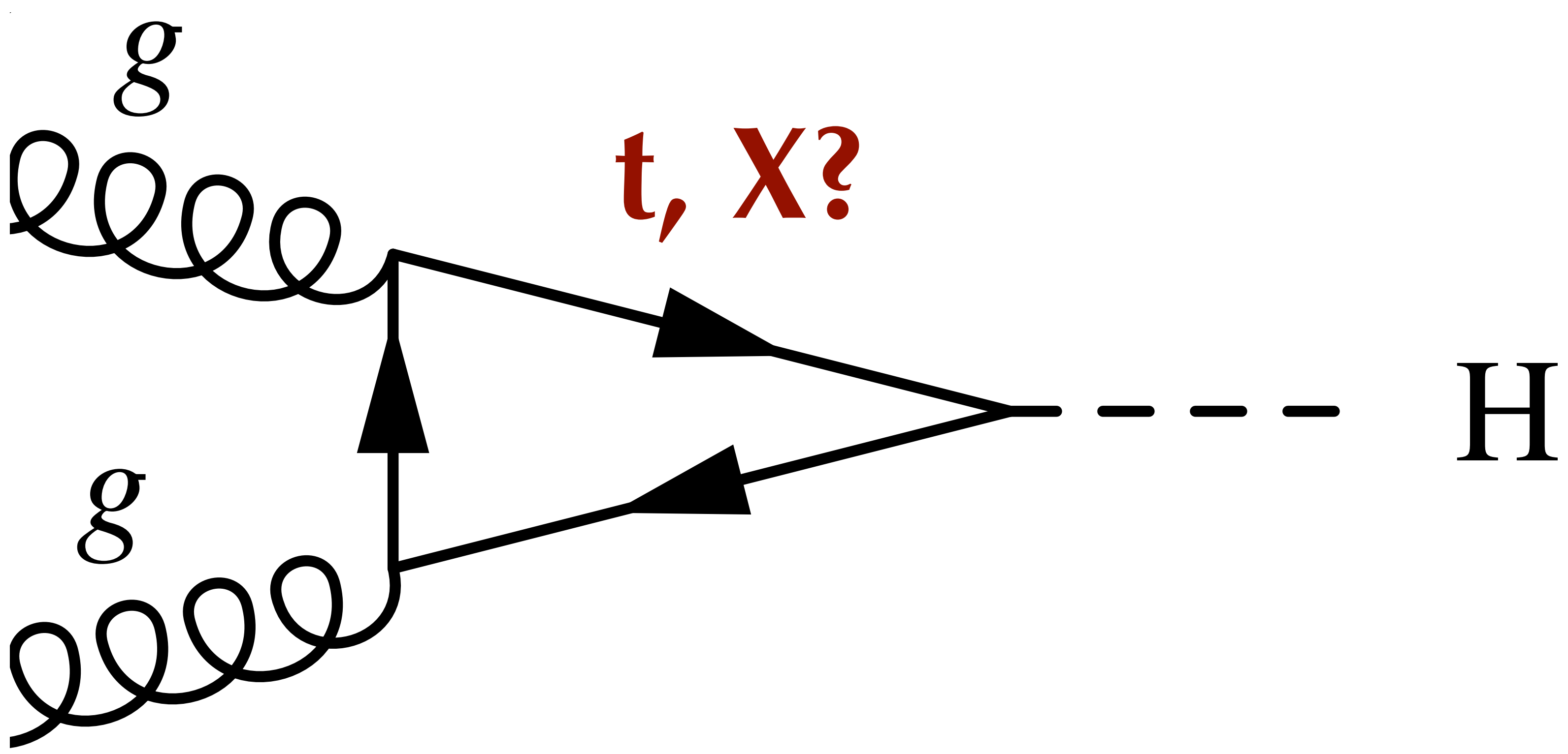
Measurements at **large transferred momentum** (Q) probe large M even if precision is low

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

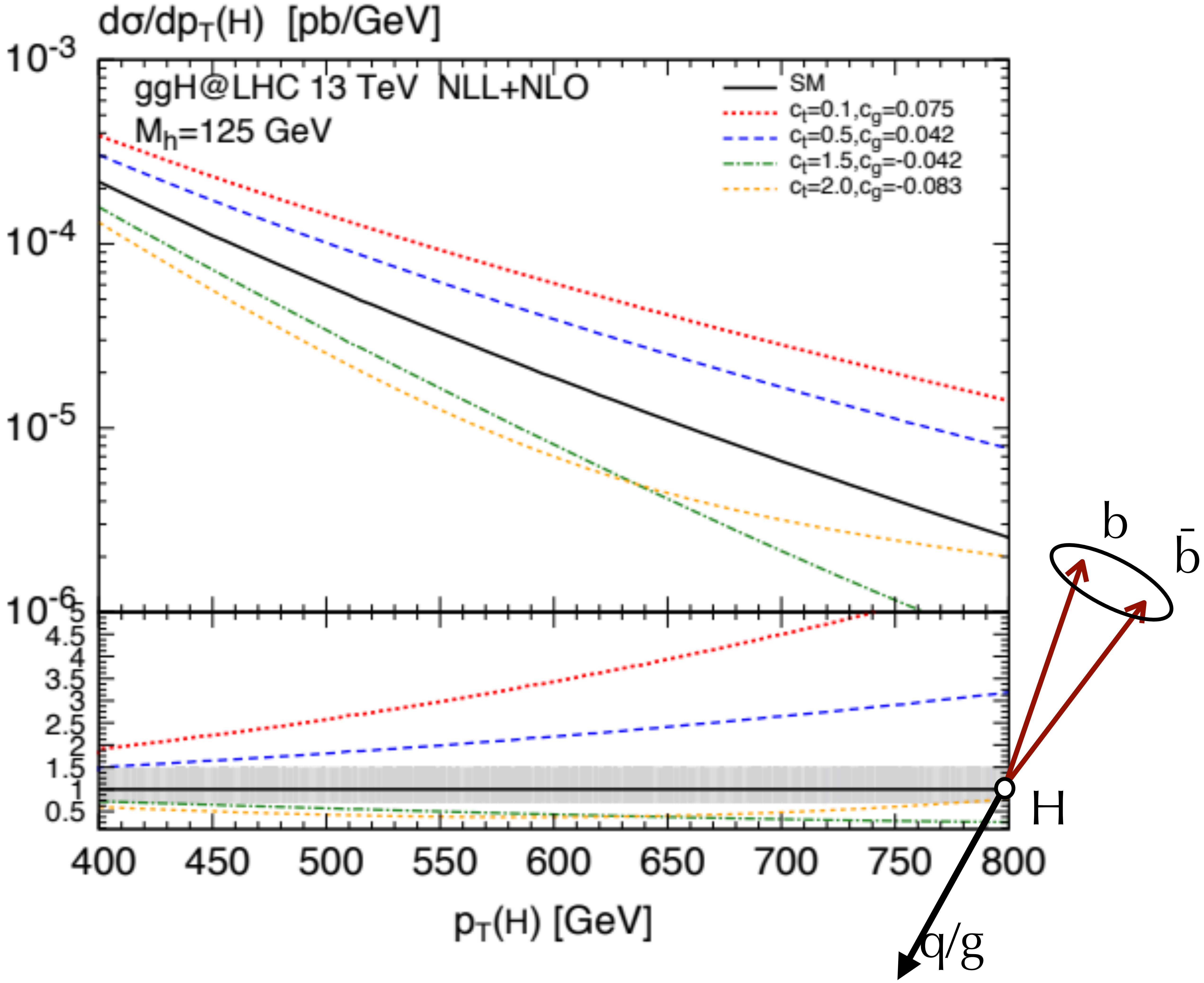
15% effect on δO_Q for M ~ 2.5 TeV

Higgs at high p_T

arXiv:1612.00283
JHEP 10 (2016) 123



At high H p_T we can directly probe **modifications in top quark coupling**



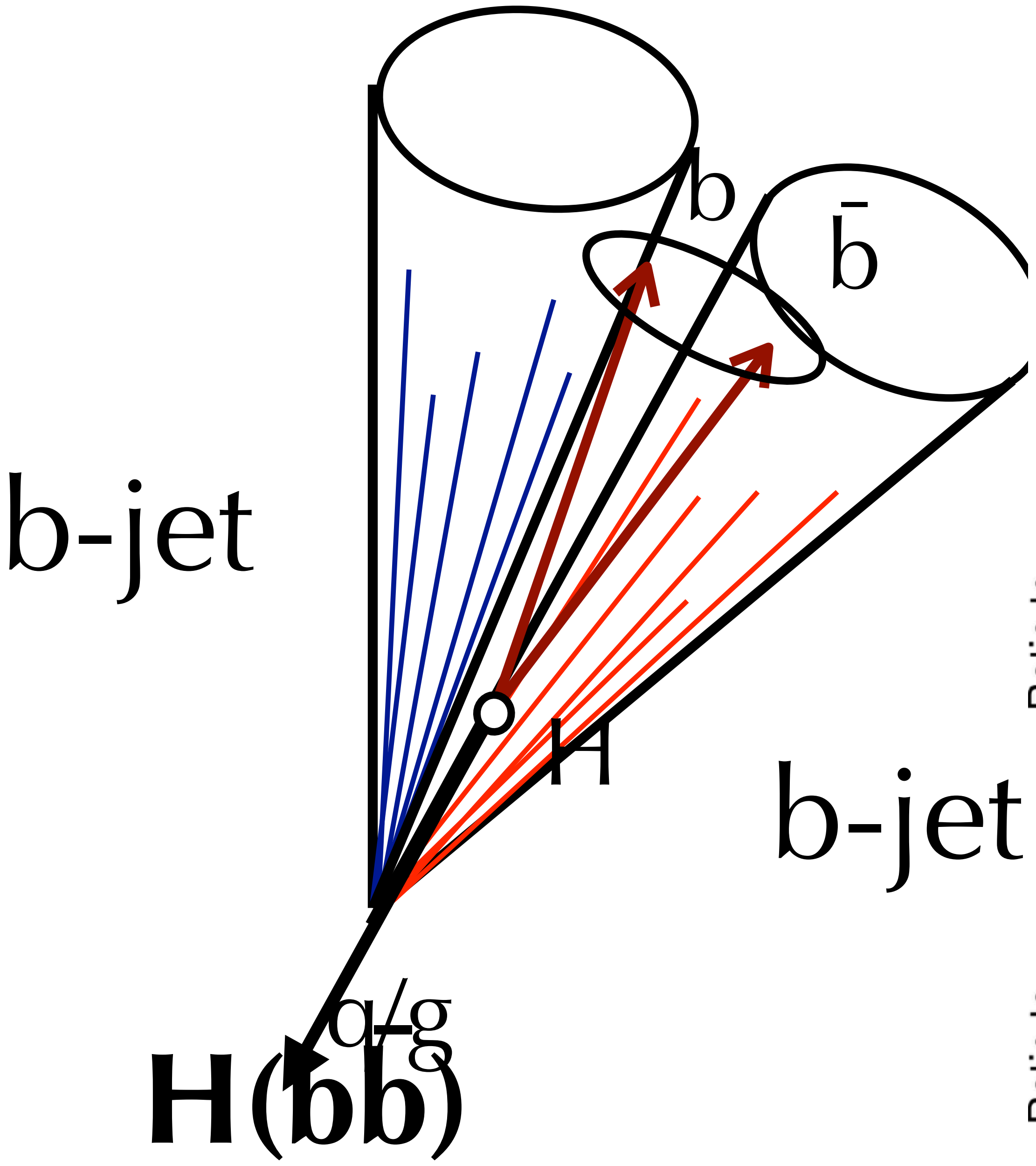
Gluon fusion H to $b\bar{b}$ at high p_T

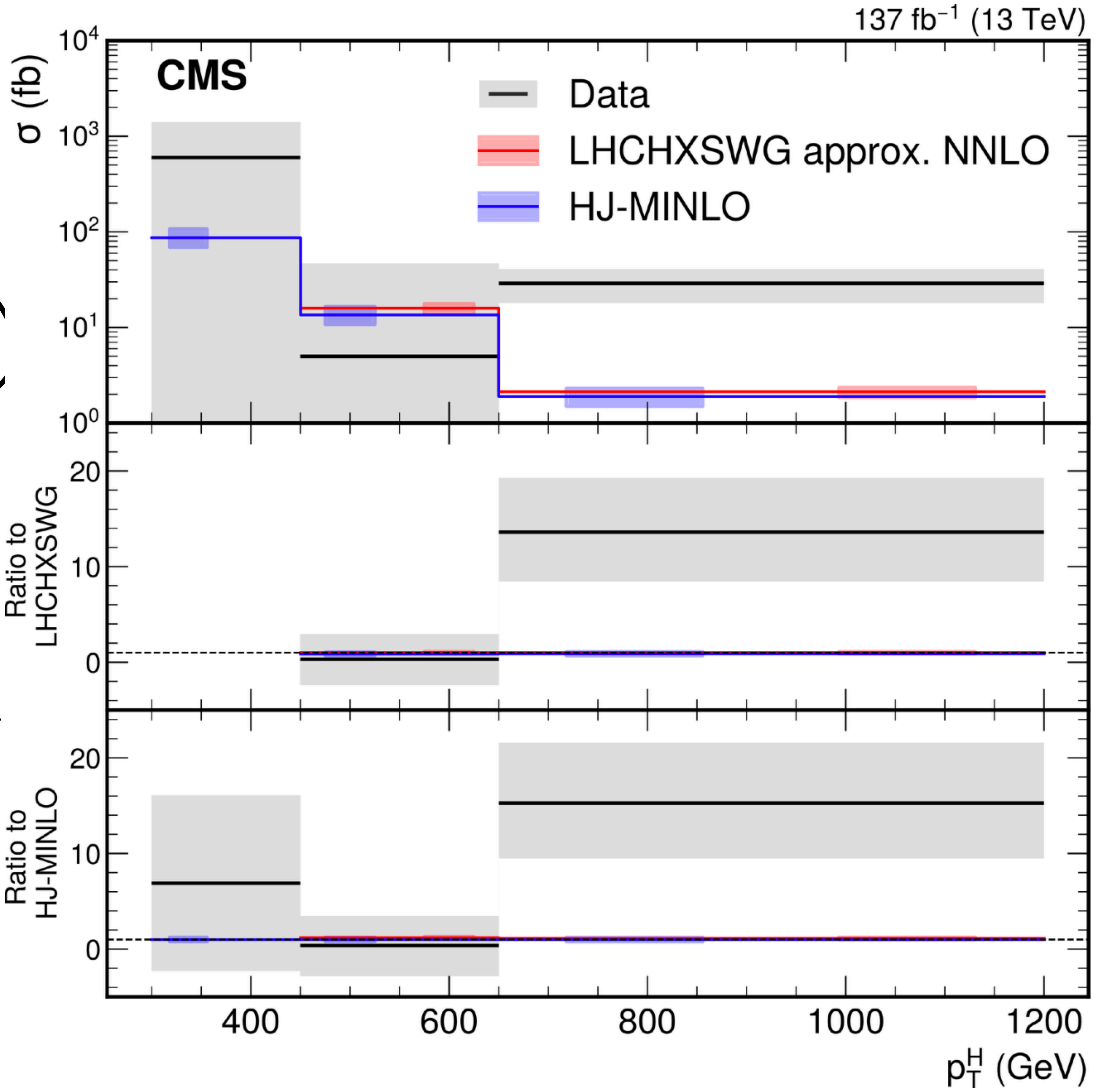
ATLAS-CONF-2021-010
CMS-JHEP 12 (2020) 085

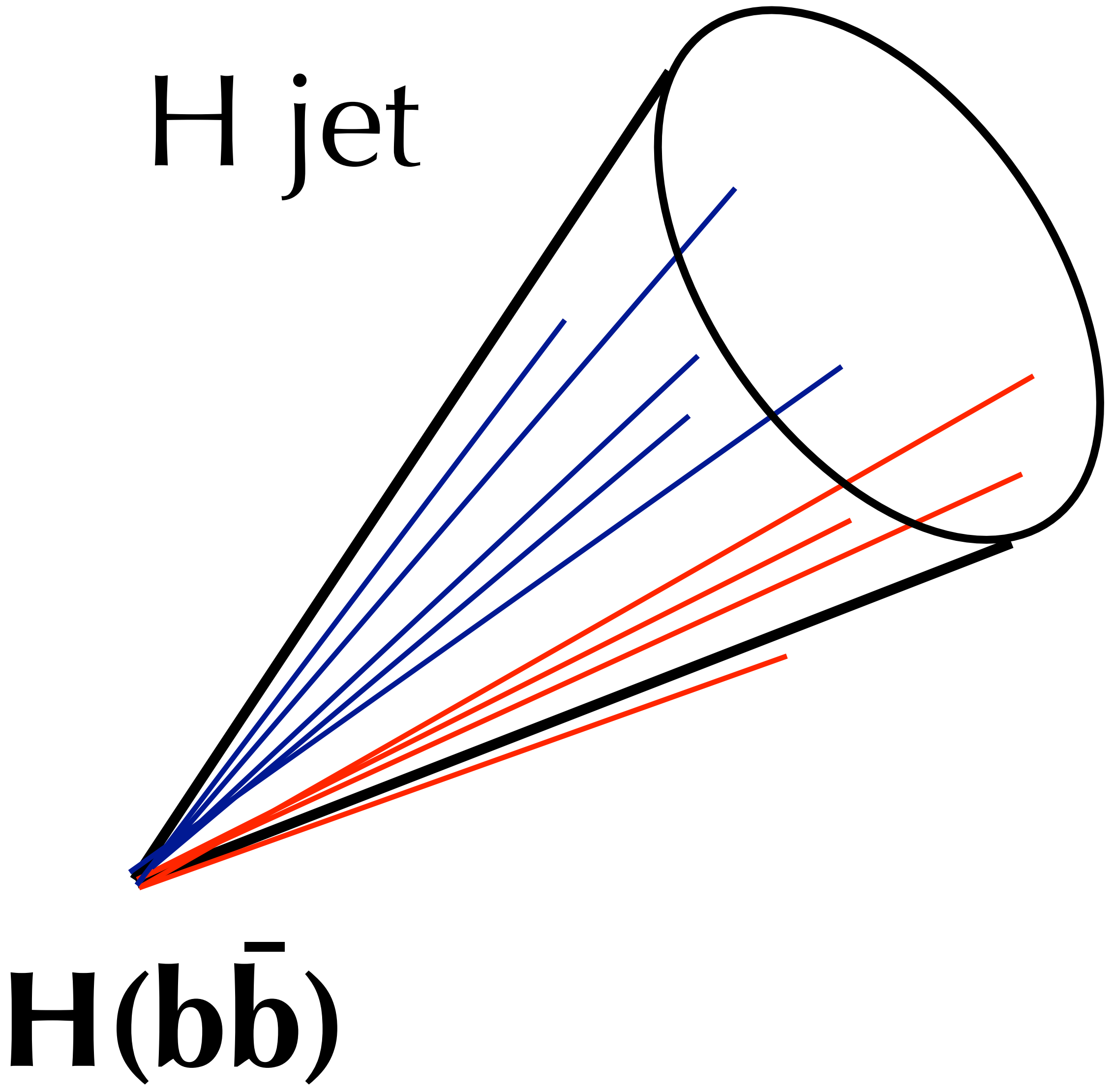
Only handful of events from ZZ and γγ for Higgs p_T >500 GeV, $b\bar{b}$ (and $\tau\tau$) becomes important at high p_T

Measurements made possible thanks to state of the art **boosted event reconstruction techniques** to identify Higgs to $b\bar{b}$

- Full Run 2 result from ATLAS and CMS : ***first look at p_T^H > 1 TeV phase space***



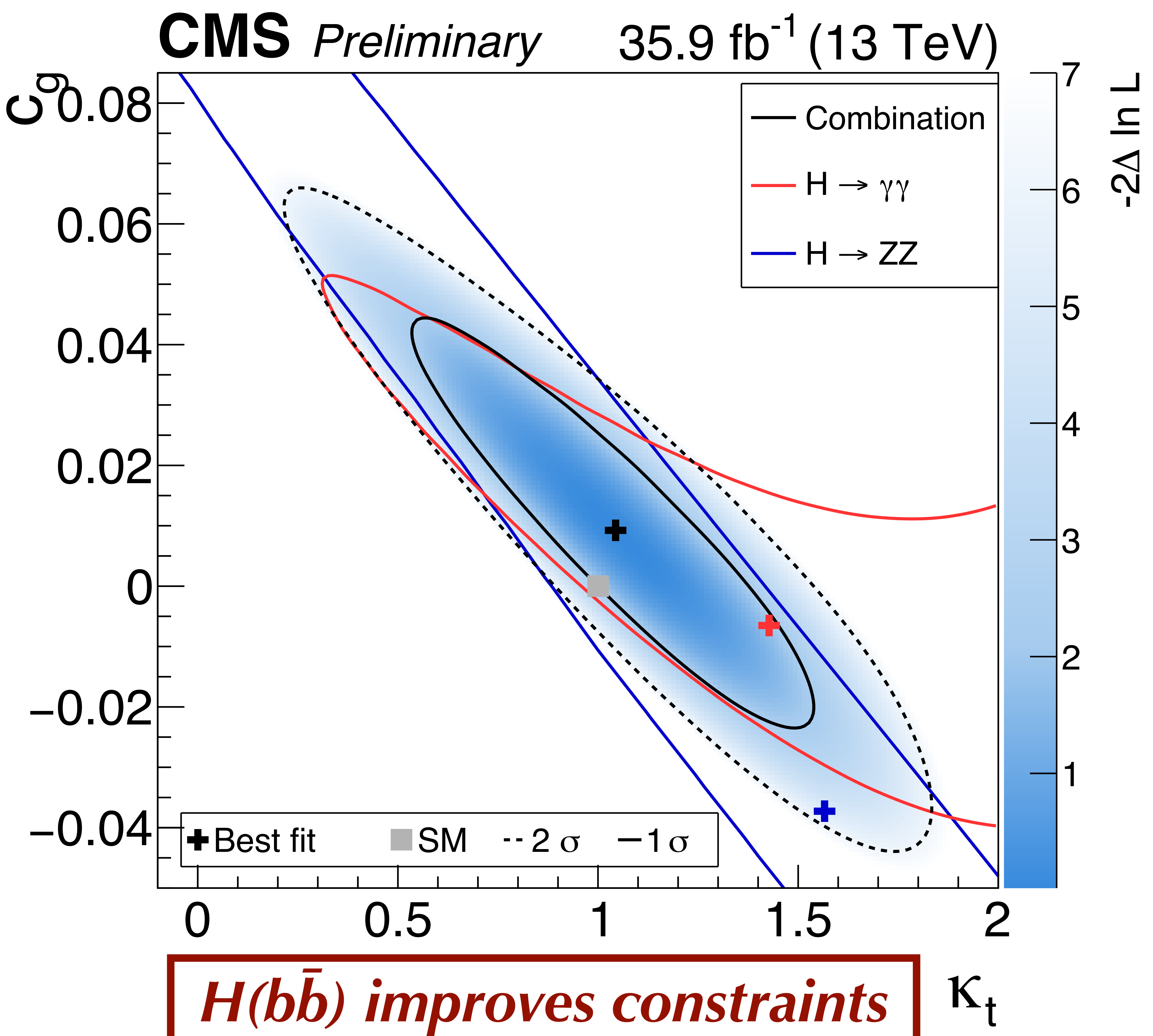


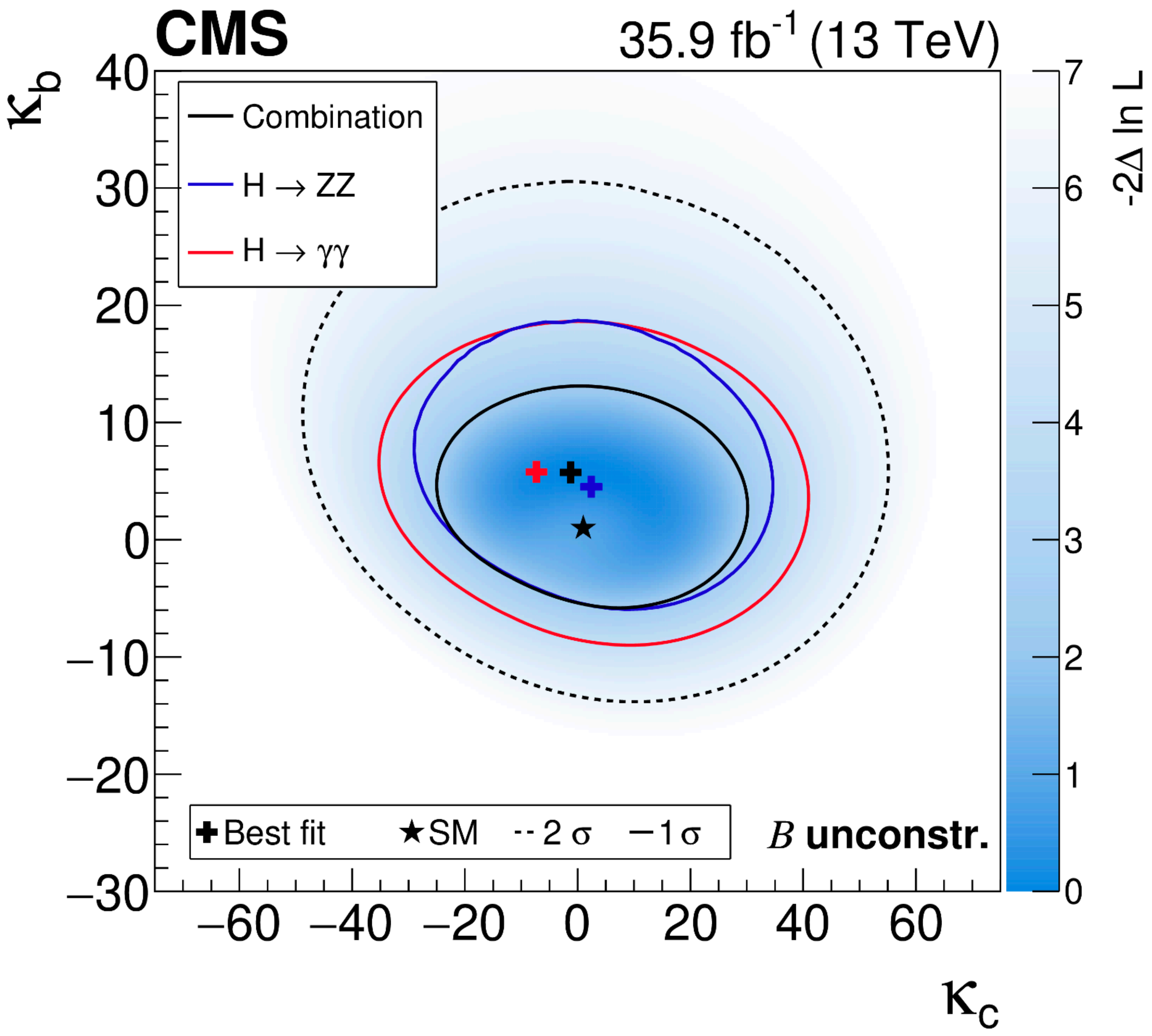


Constraints on the couplings

CMS-Phys. Lett. B 792 (2019) 369

- Indirect access to $H \rightarrow$ cc through differential distributions
  - Similar sensitivity to direct searches



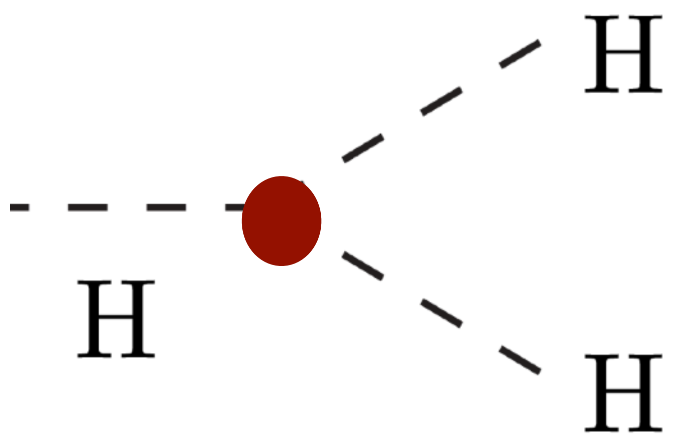


$H(b\bar{b})$ improves constraints to new physics by 30%

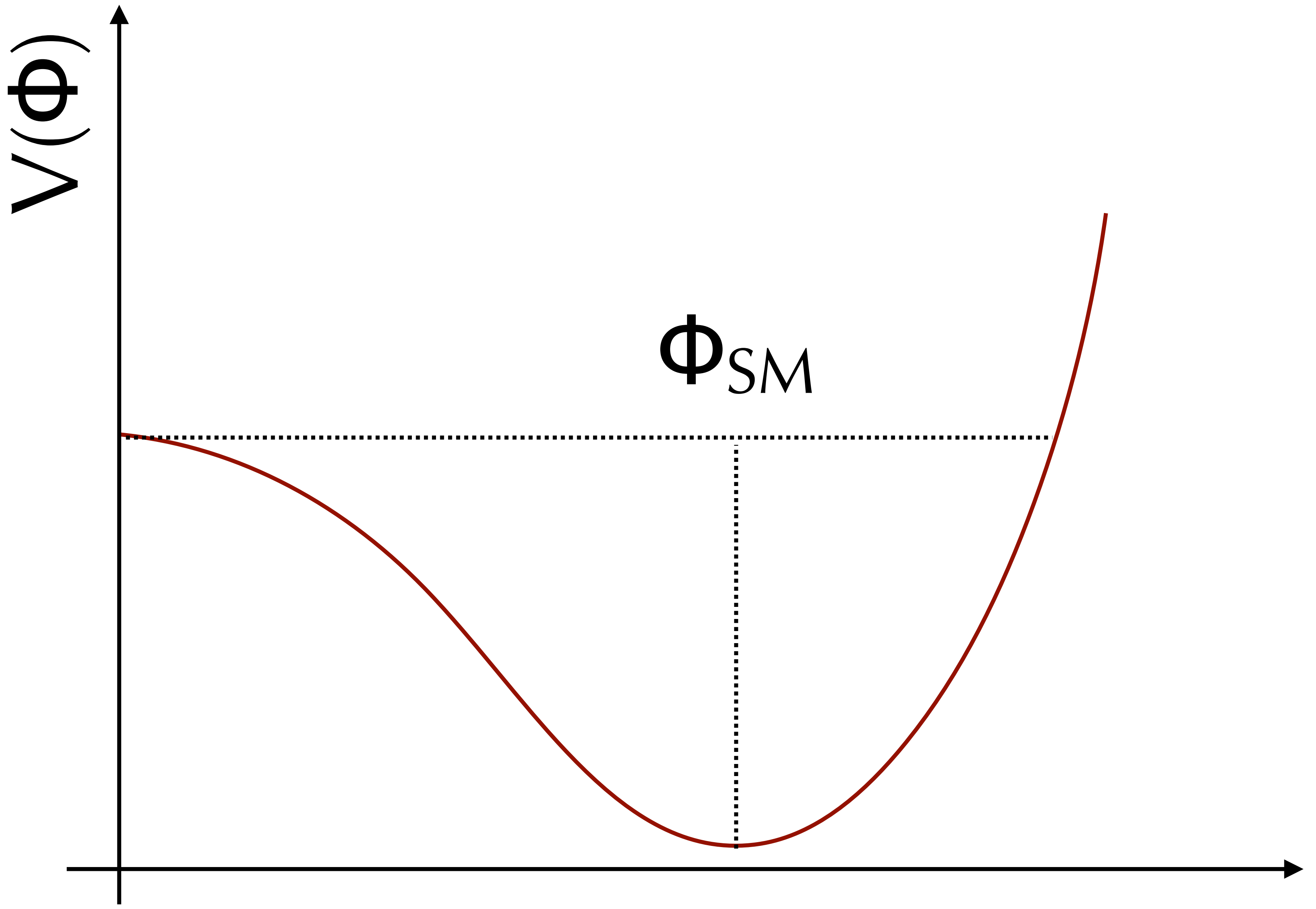
Testing the shape of the potential

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

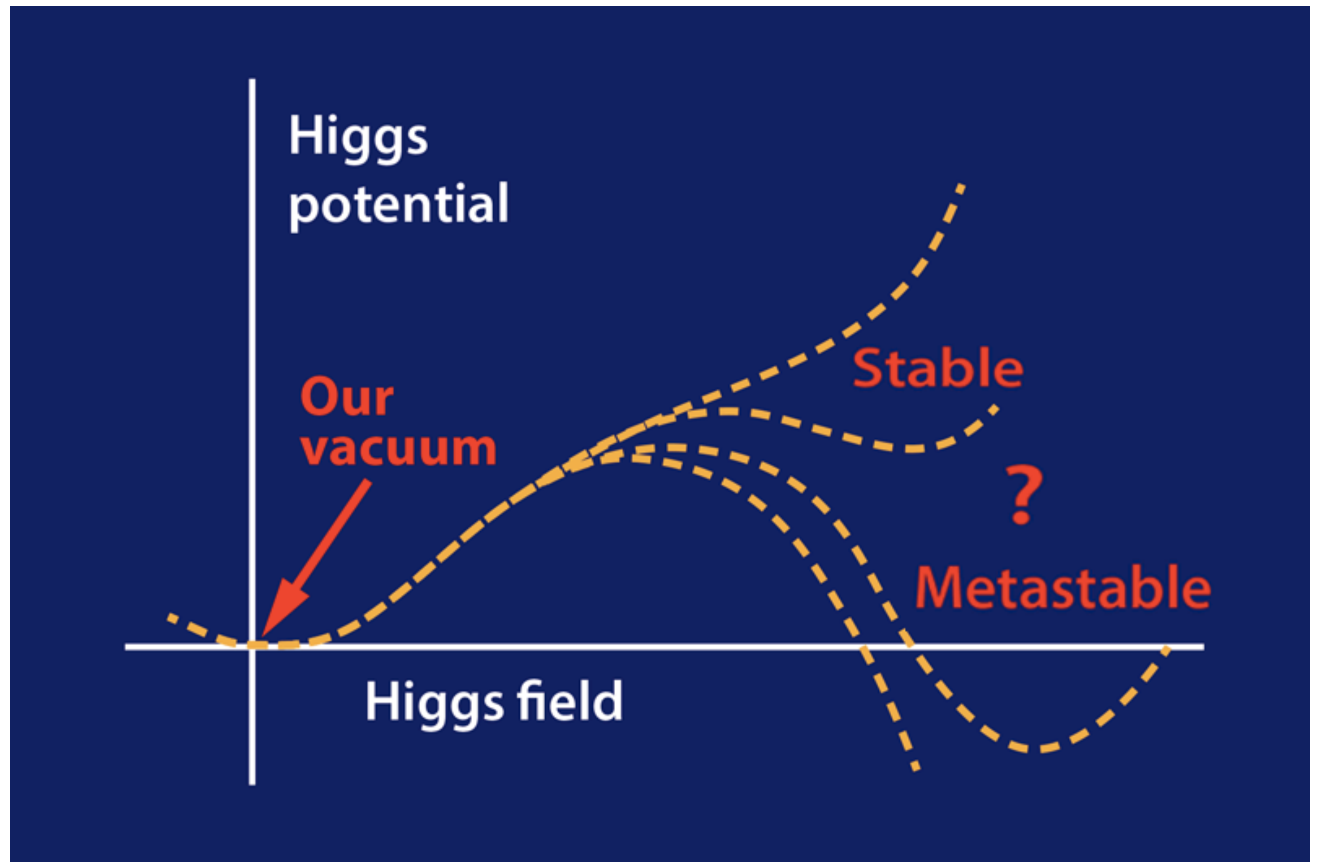
$$V(v+h) = V_0 + \frac{1}{2}m_h^2h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$



$$\lambda = \frac{m_h^2}{2v^2} = 0.13$$

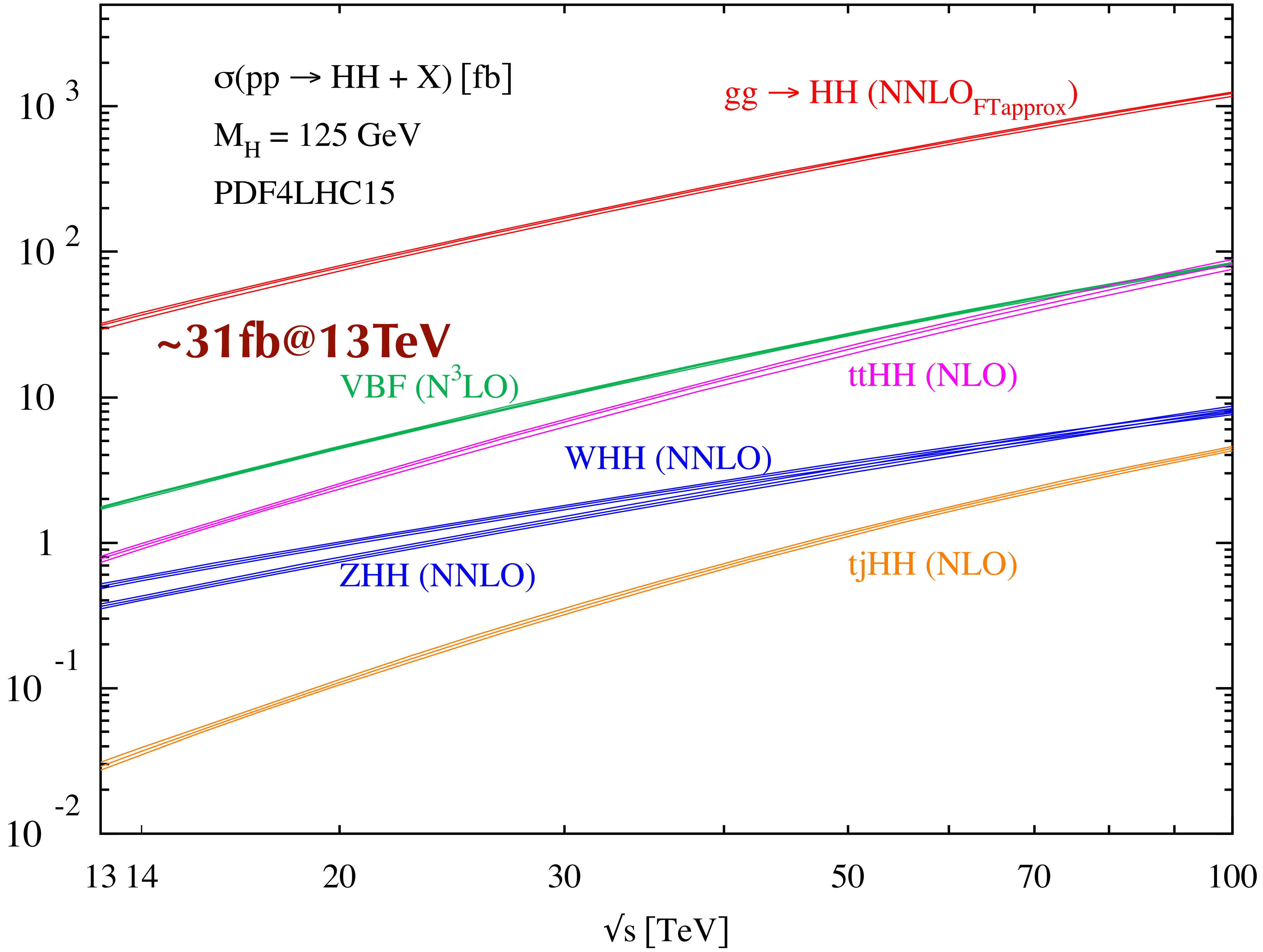


OR ?

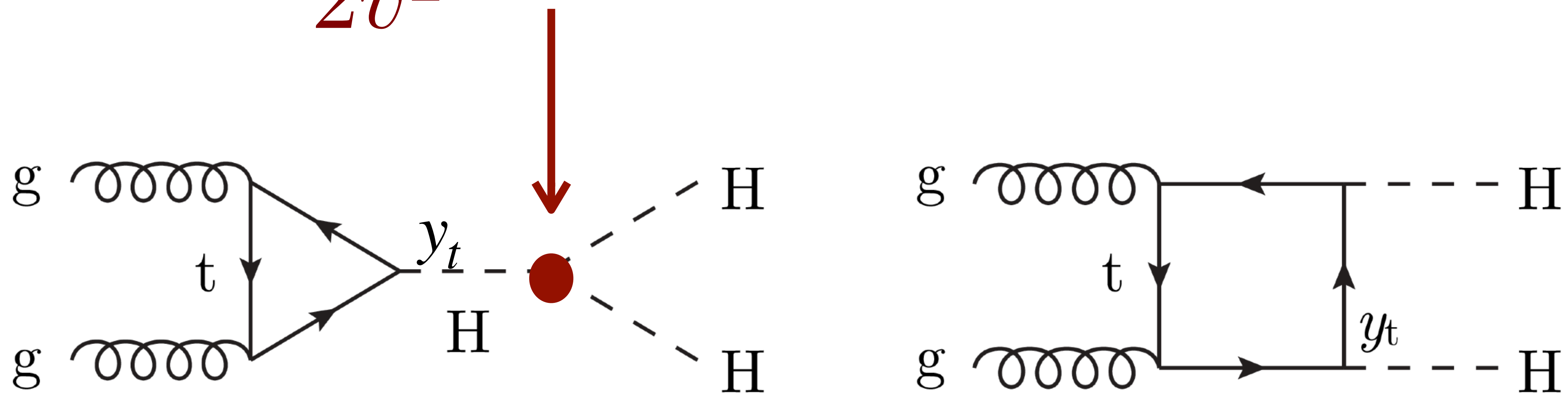


Higgs boson self-coupling

arXiv:1910.00012



$$\lambda = \frac{m_{\mathrm{H}}^2}{2v^2} = 0.13$$



HH production allows to probe the self-coupling: $\Delta\sigma/\sigma \sim \Delta\lambda/\lambda$ **if** $\lambda \sim \lambda_{SM}$

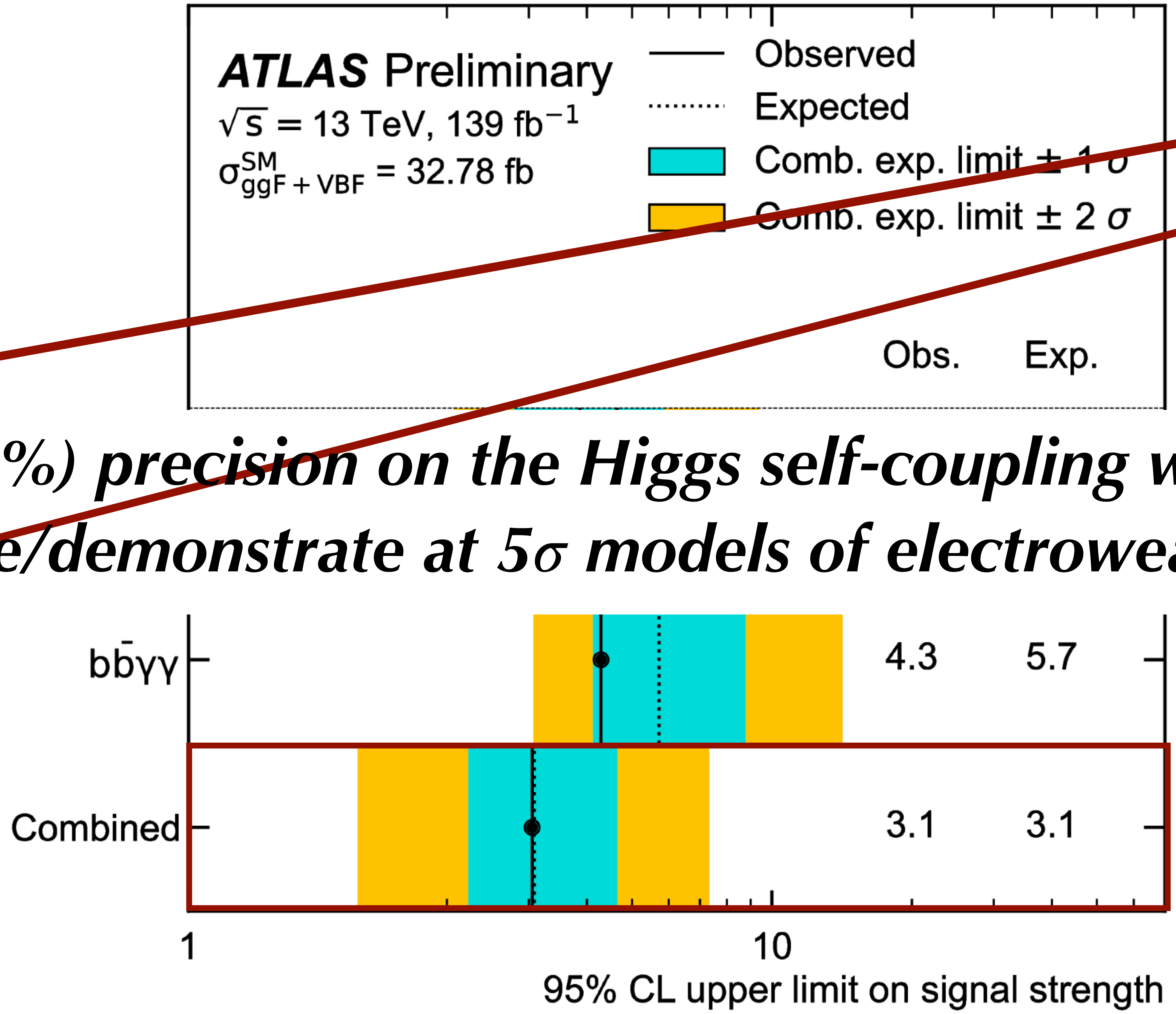
Extremely challenging measurement at the LHC, but **it can be sensitive to large deviations from BSM**: $\kappa_\lambda = \lambda/\lambda_{SM}$

Double Higgs Results

ATLAS-COM-CONF-2021-052
CMS-Phys. Rev. Lett. 122, 121803 (2019)

Similar sensitivity from several channels to SM HH production

- Best channels are $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$



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

LHC → High Luminosity LHC

LHC

HL-LHC

Run 2

8M H

Upgrade of accelerator and experiments

Run 3

16M H

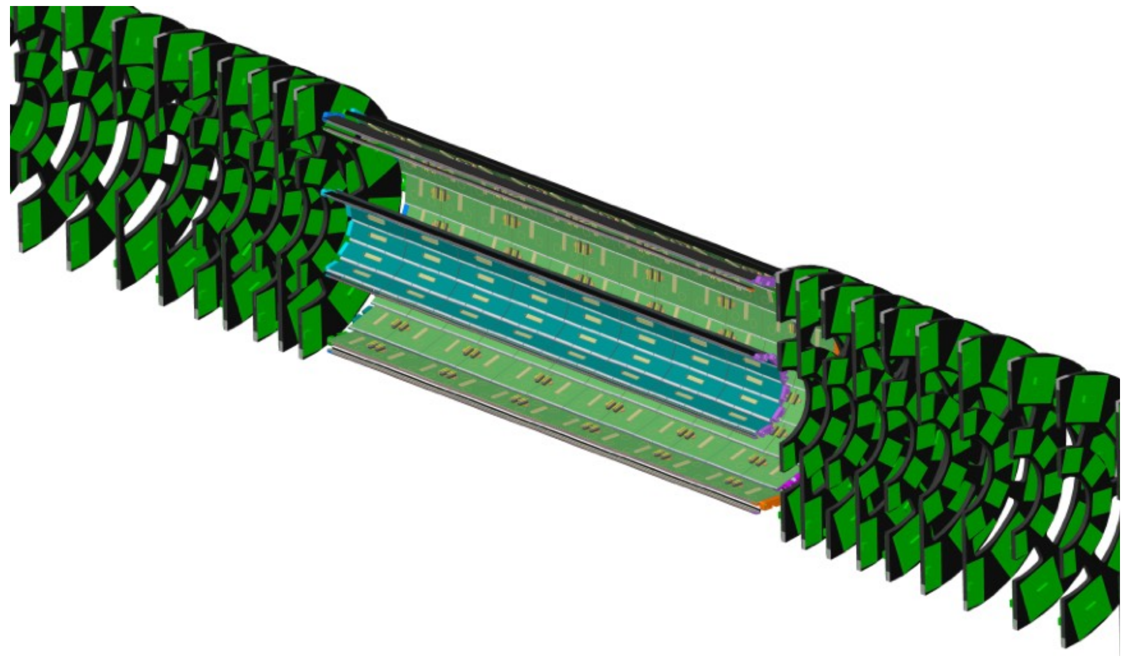
HL-LHC installation
ATLAS Upgrade

Run 4

170M H
120k HH

2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | . . . | 2037

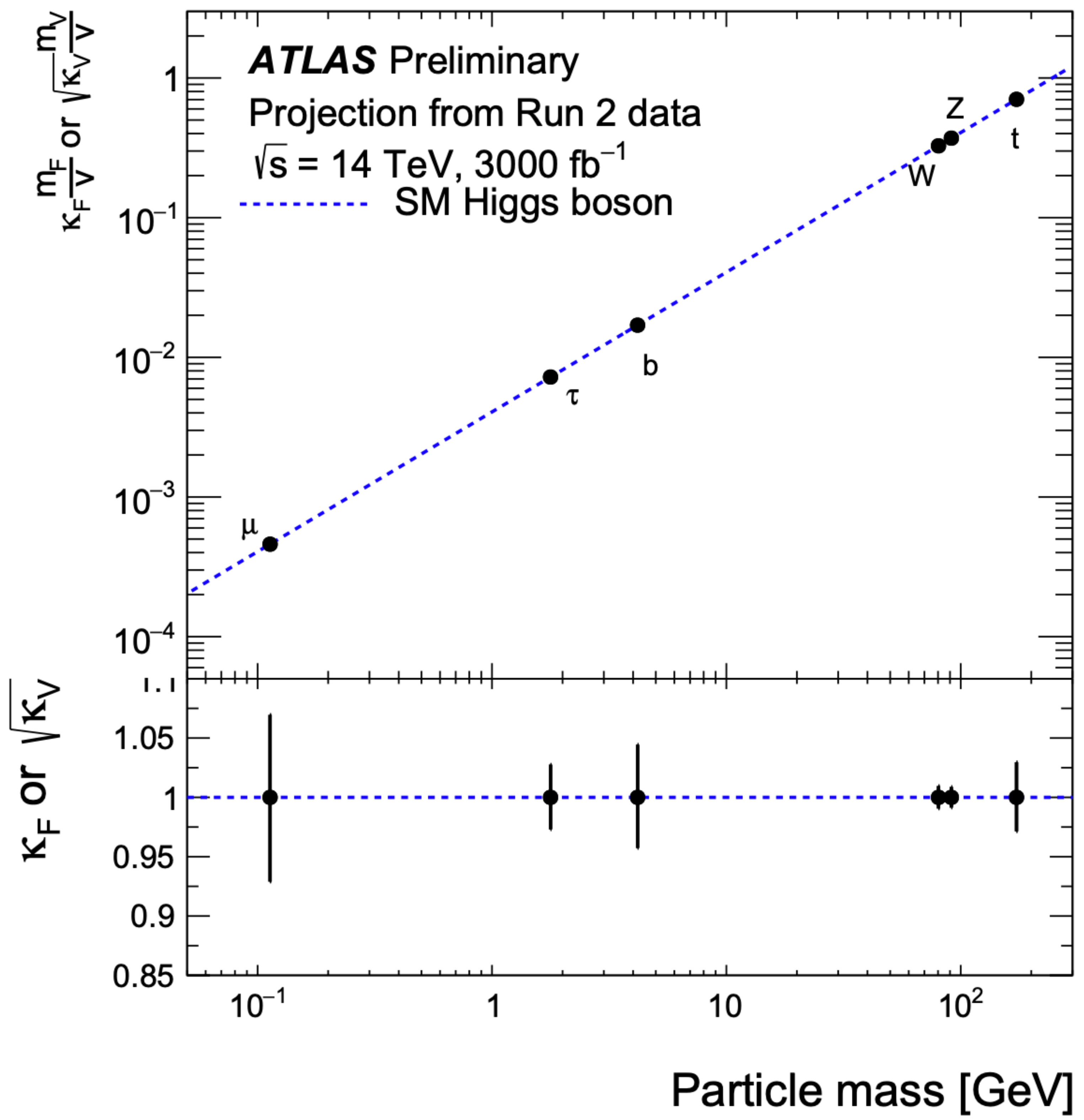
Today

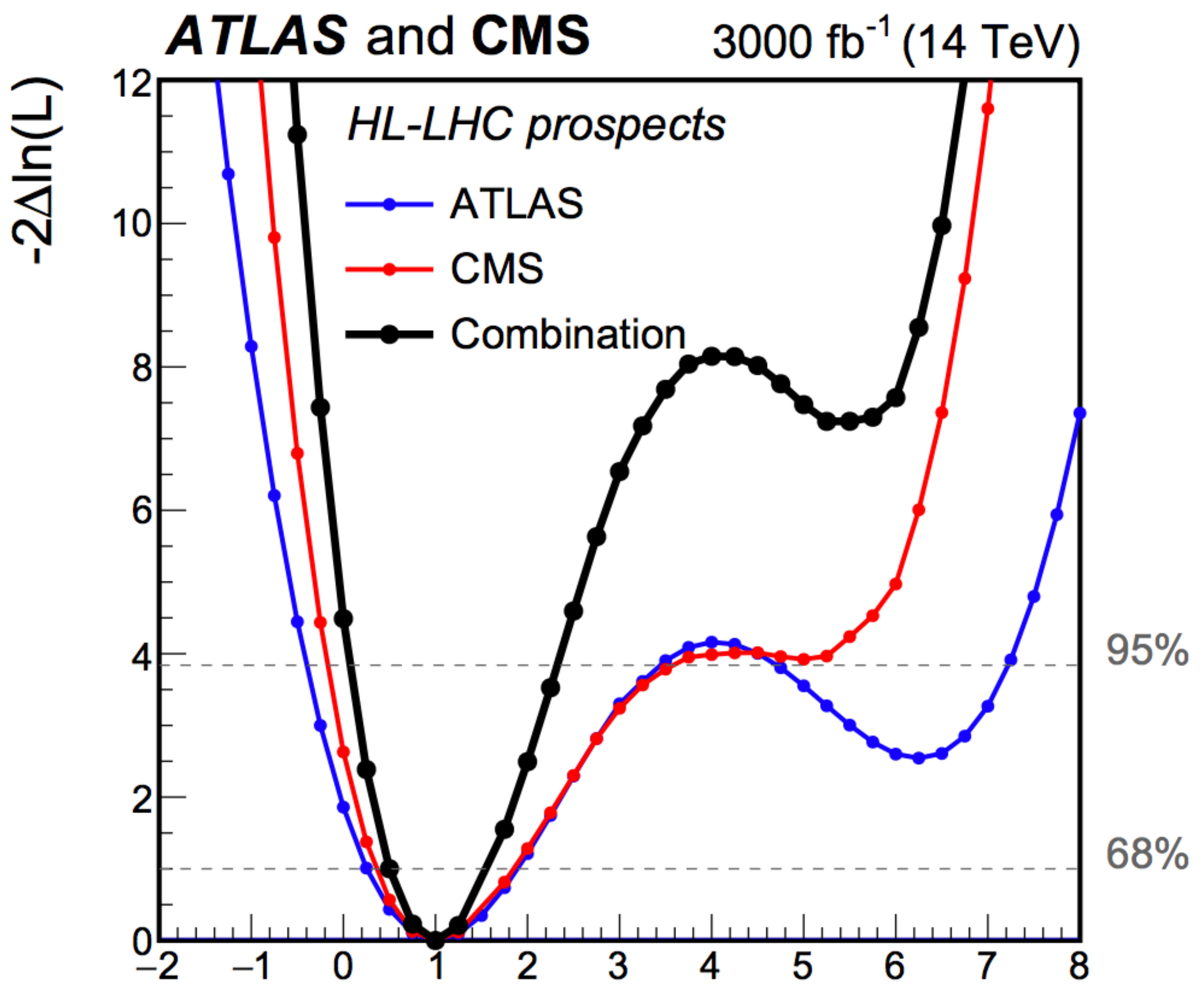


Phase-2 HL-LHC detector upgrades are being built

Higgs physics at the HL-LHC

1902.10229



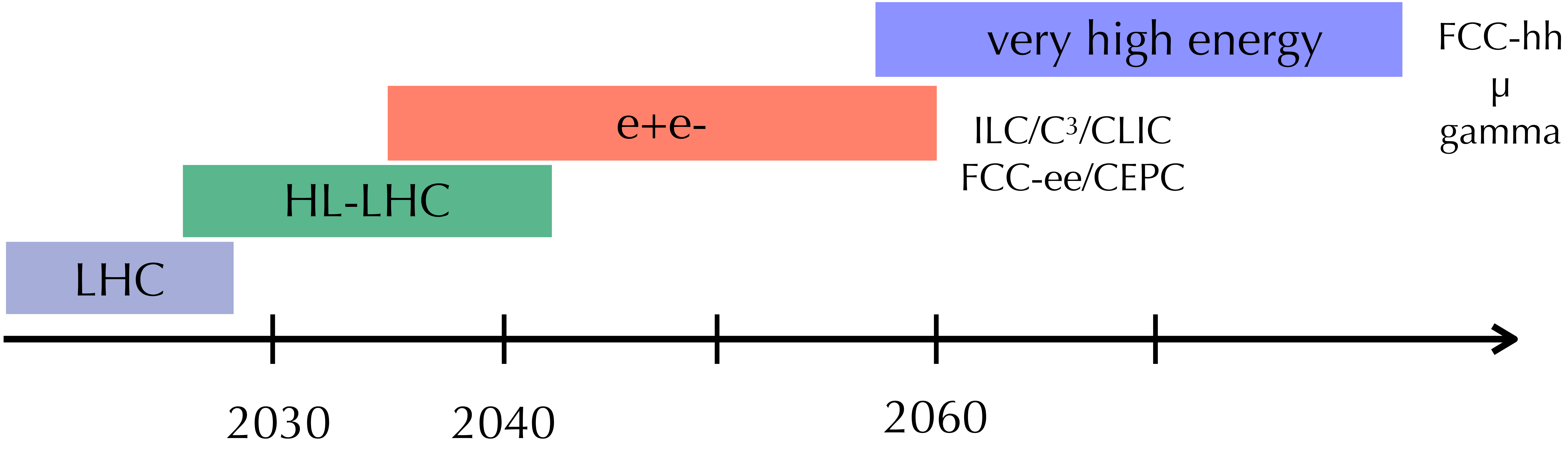


$$k_\lambda = \frac{\lambda}{\lambda_{SM}}$$

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

- **2-4% precision for many of the Higgs couplings**
  - **BUT much larger uncertainties on Zγ and charm and ~50% on the self-coupling**

What's next?



very high energy

FCC-hh
μ
gamma

e+e-

ILC/C^3/CLIC
FCC-ee/CEPC

HL-LHC

LHC

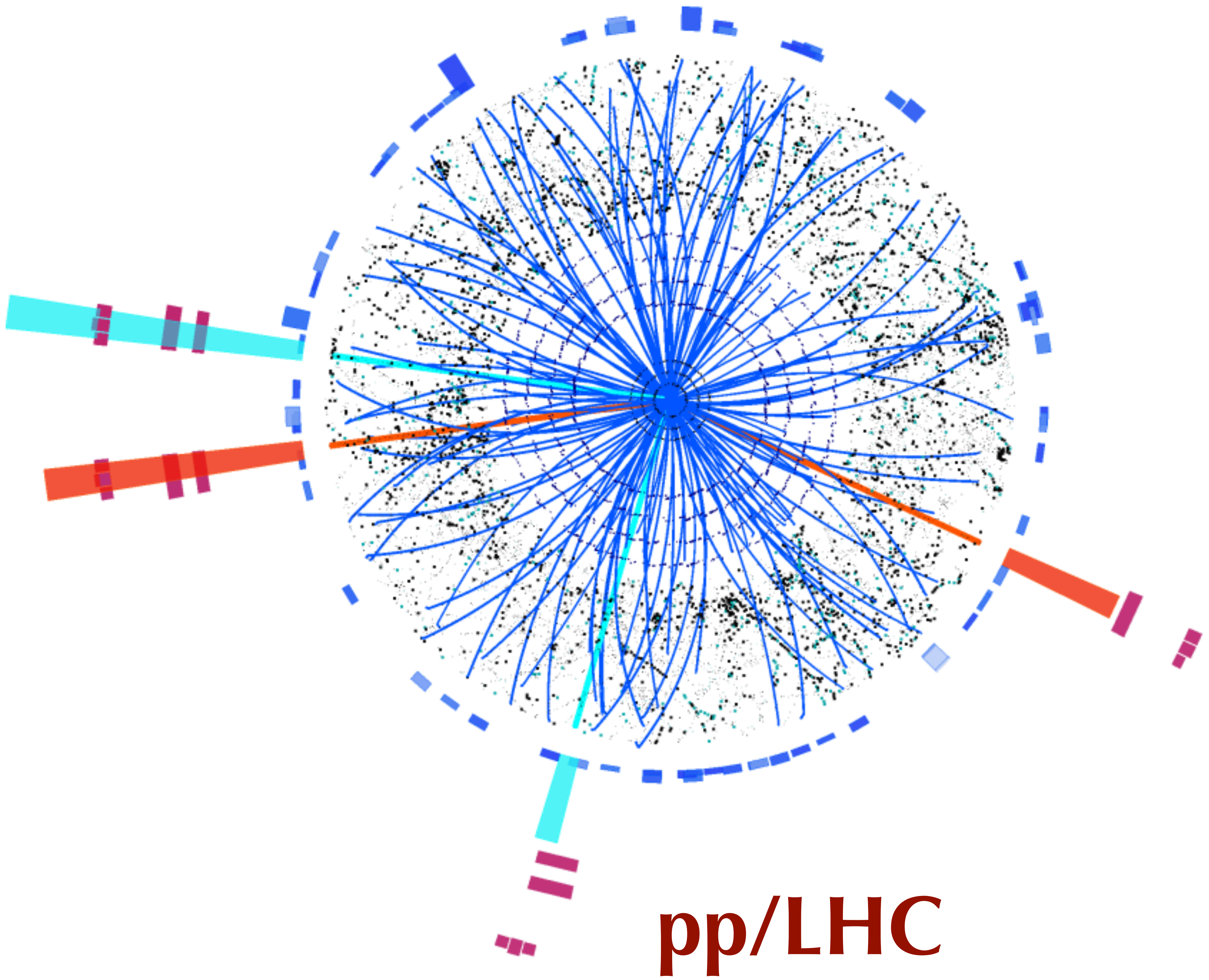
2030 2040 2060

Wish list beyond HL-LHC:

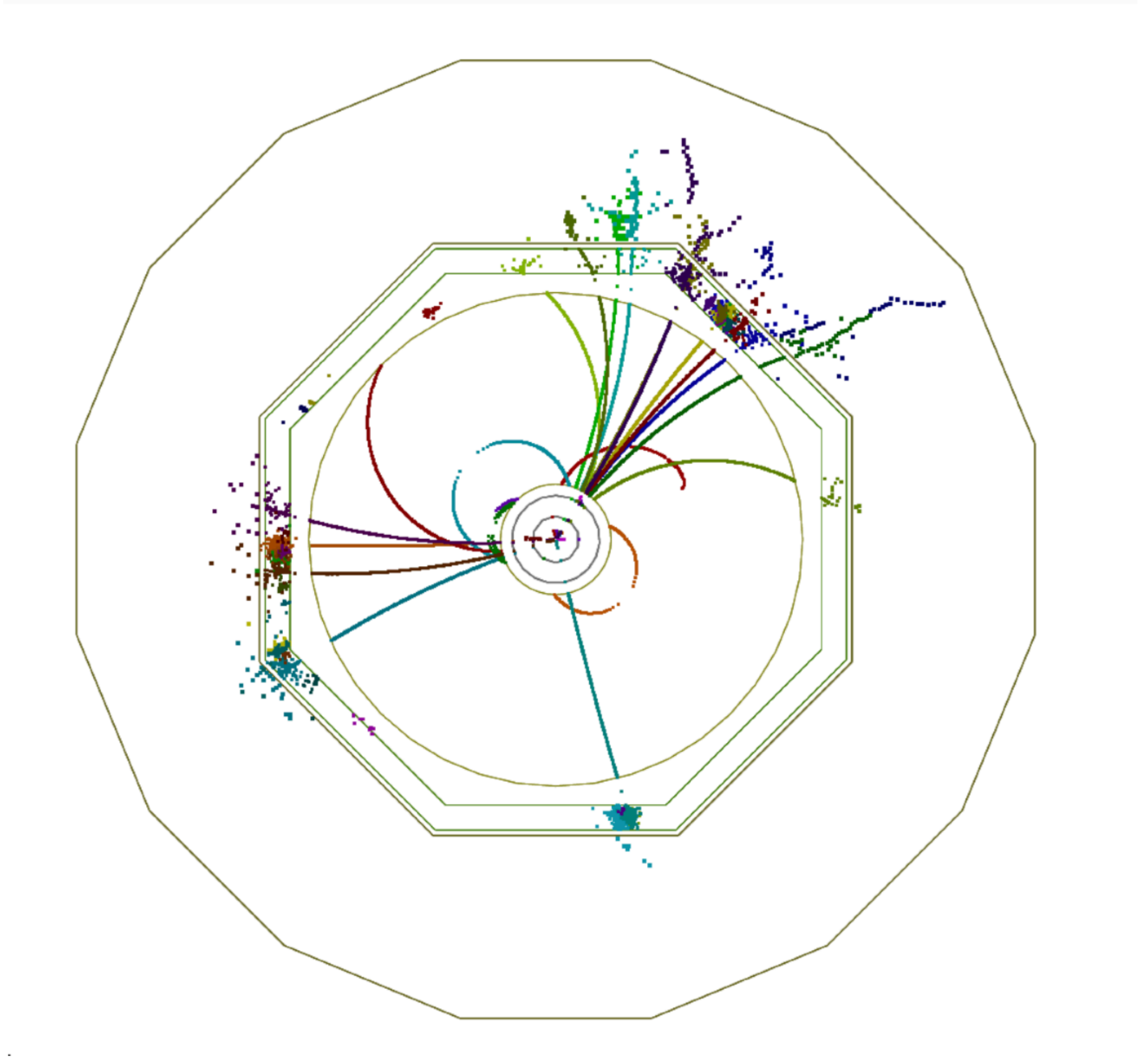
1. **Establish Yukawa couplings to light flavor $\Longrightarrow$ needs precision**
2. **Establish self-coupling $\Longrightarrow$ needs high energy**

Why e^+e^-?

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

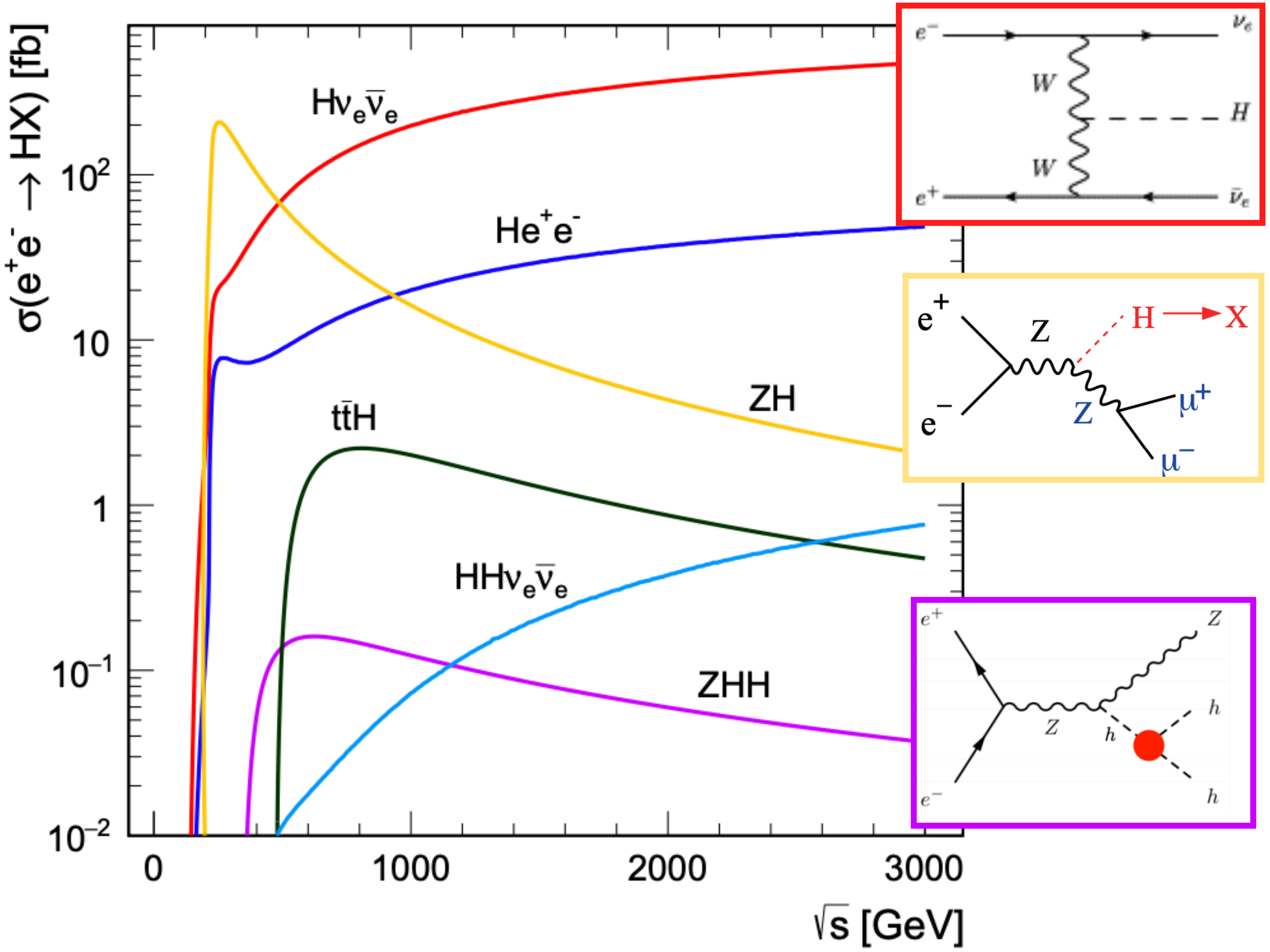


pp/LHC



e^+e^-

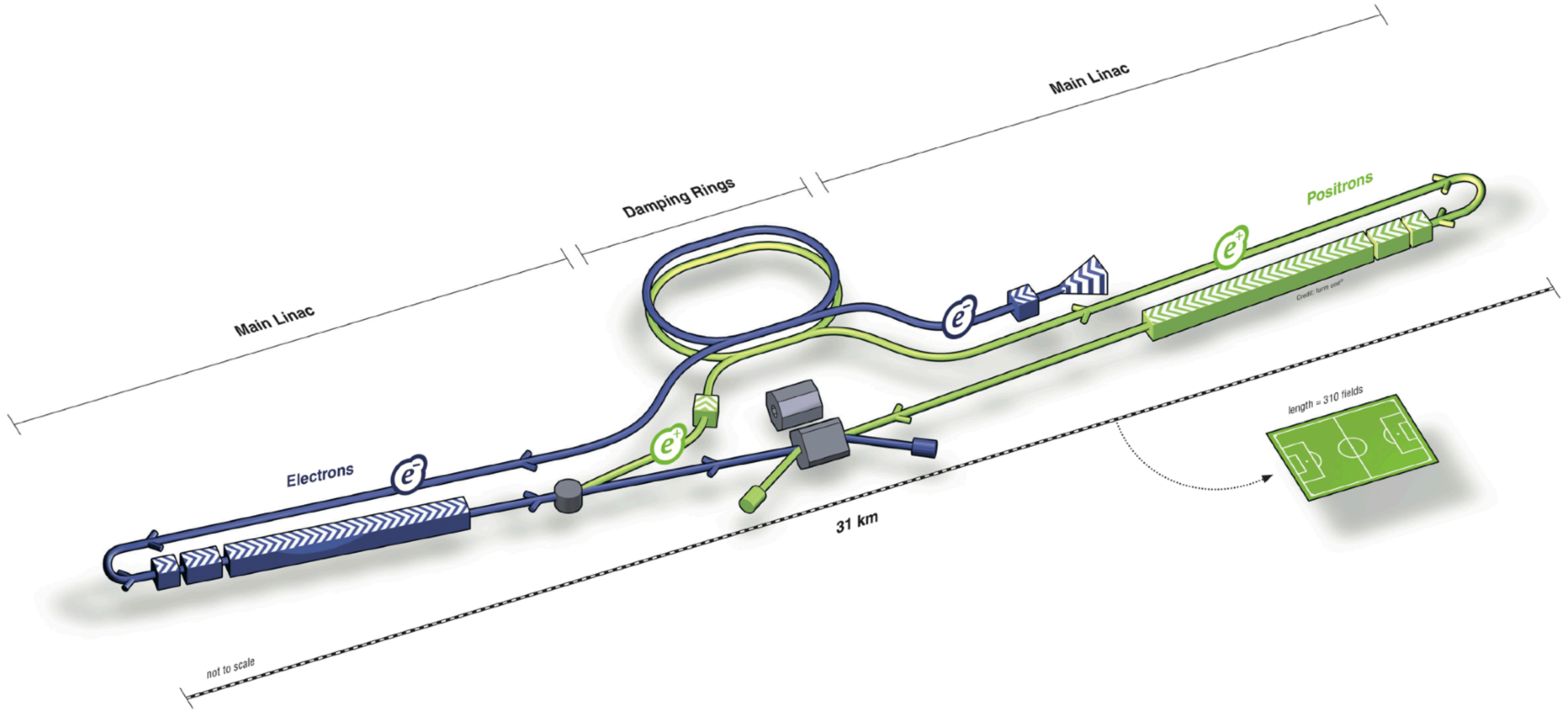
Higgs at e^+e^-

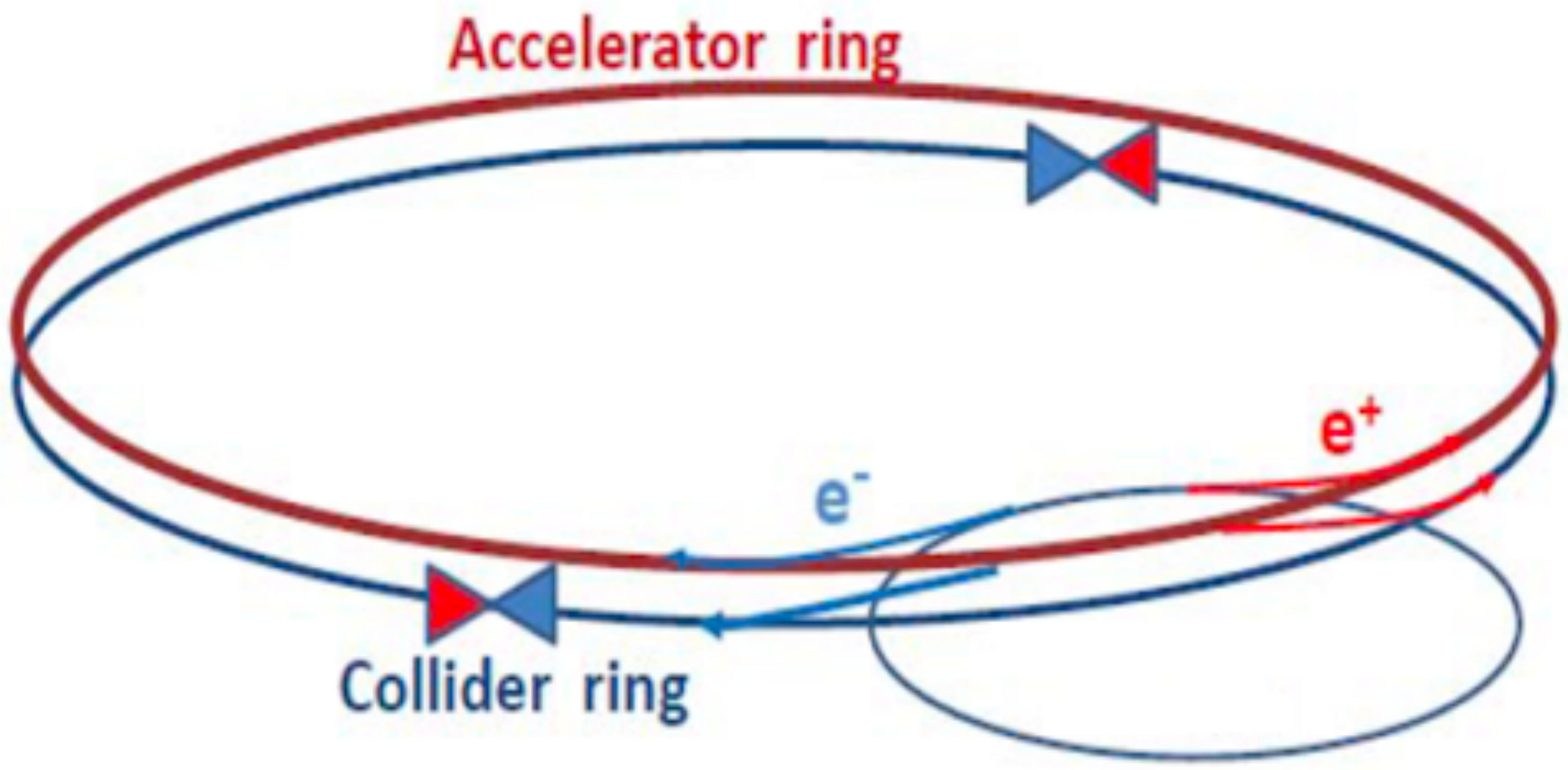


- ZH is dominant at **250 GeV**
- Above **500 GeV**
  - Hνν dominates
  - ttH opens up
  - HH production accessible with ZHH

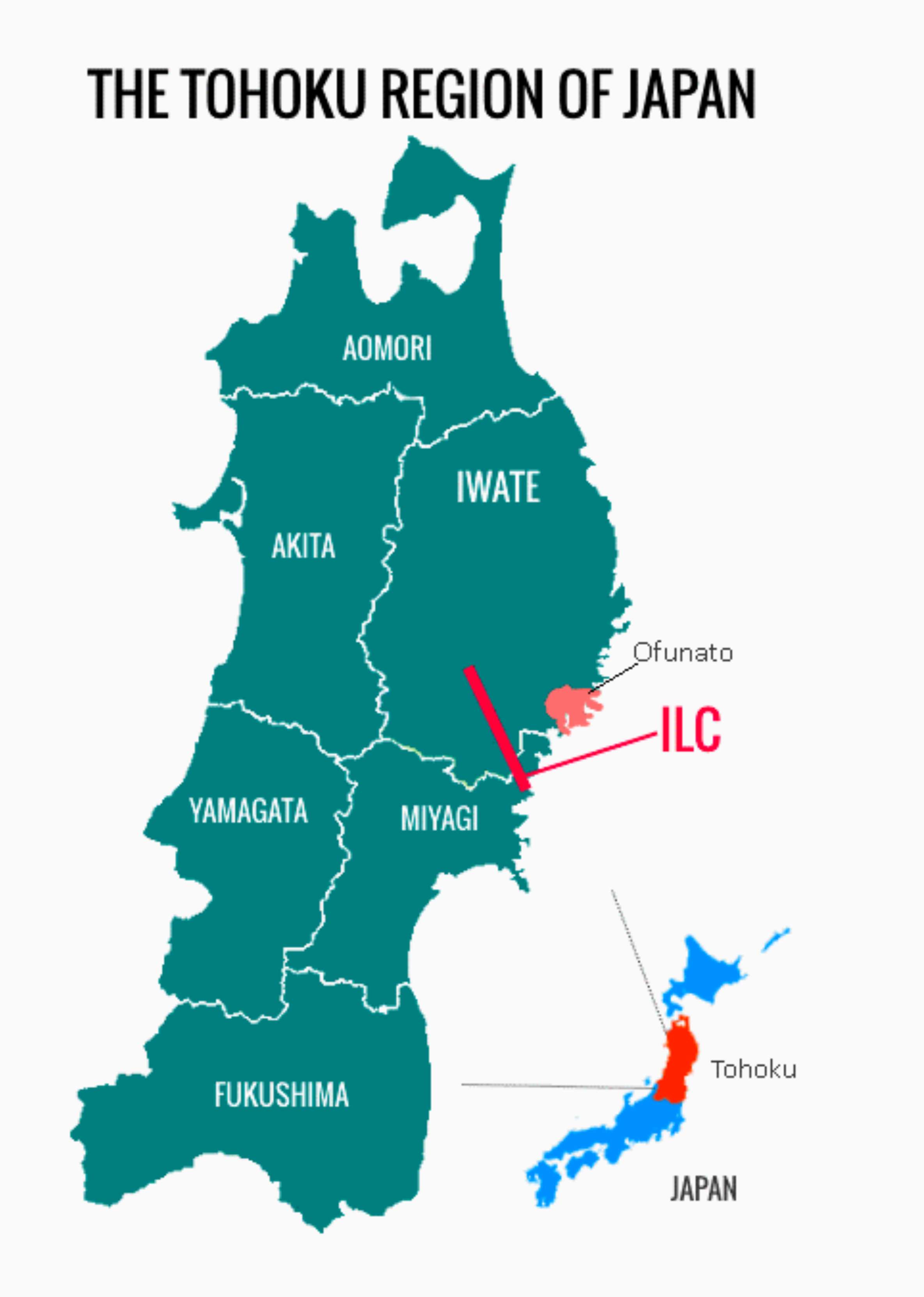
Linear vs. Circular

- **Linear** e^+e^- colliders: ILC, C^3, CLIC
    - Reach higher energies (~ TeV), and can use polarized beams
    - Relatively low radiation
    - Collisions in bunch trains
- **Circular** e^+e^- colliders: FCC-ee, CEPC
    - Highest luminosity collider at Z/WW/Zh
        - limited by synchrotron radiation above 350– 400 GeV
    - Beam continues to circulate after collision

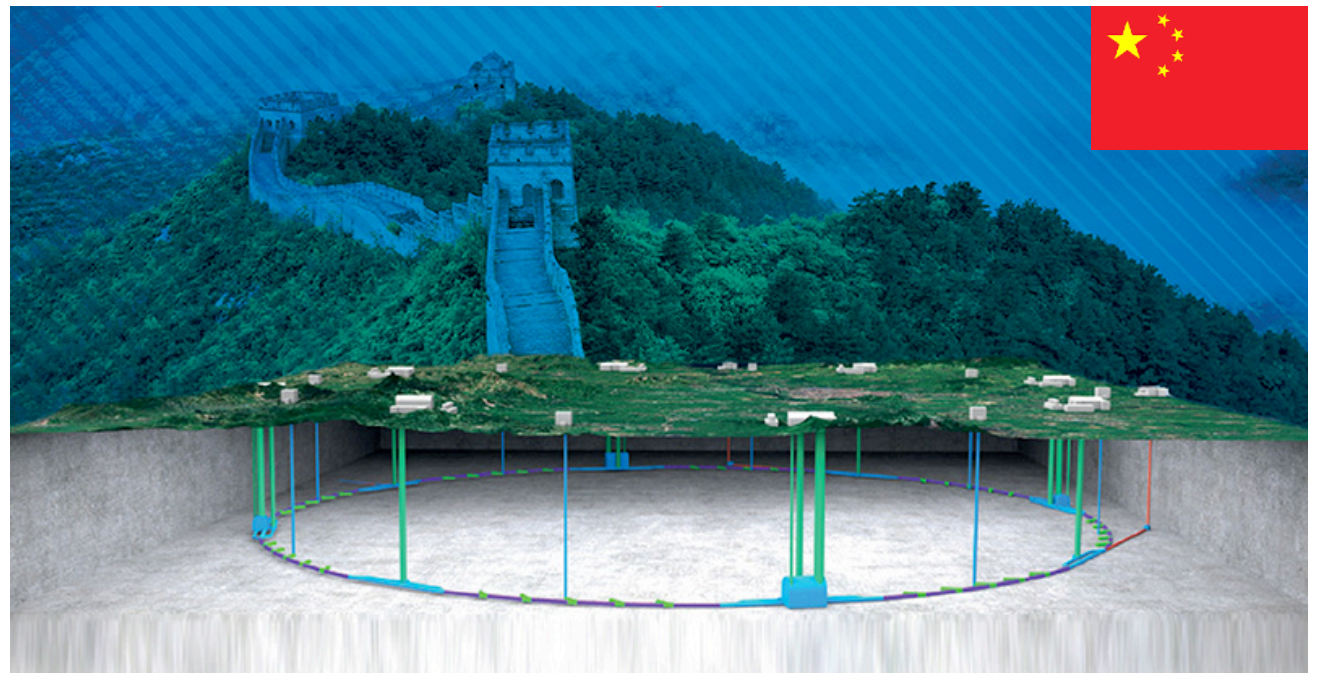




Various proposals …

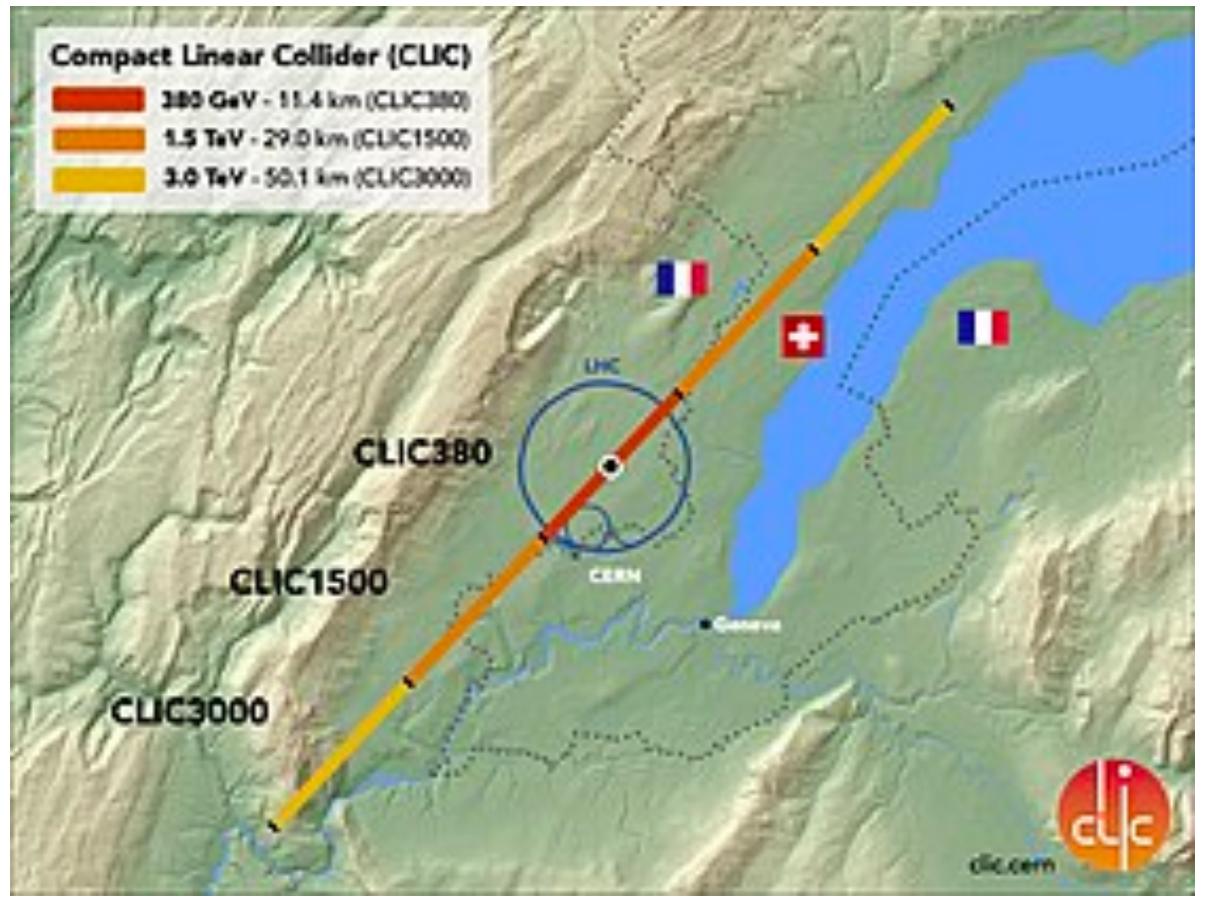


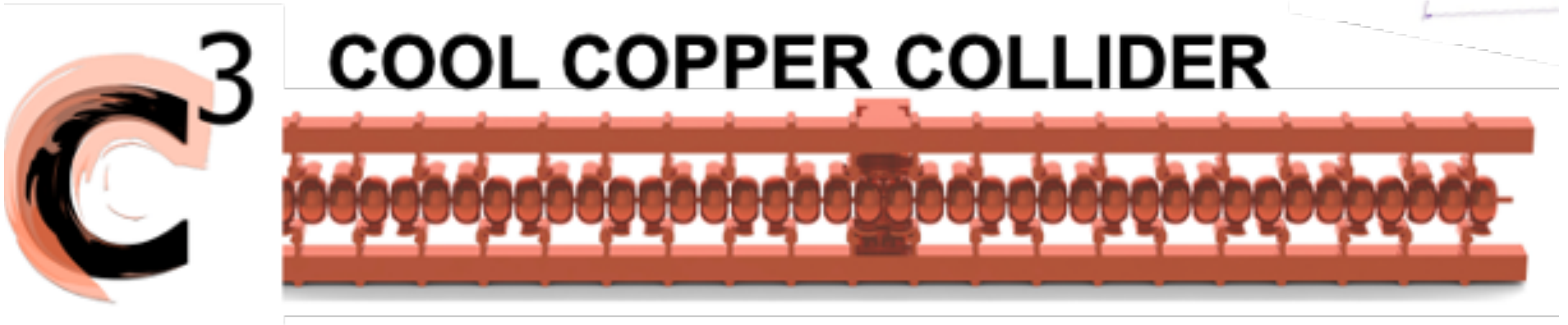
250/500 GeV



CEPC 240 GeV

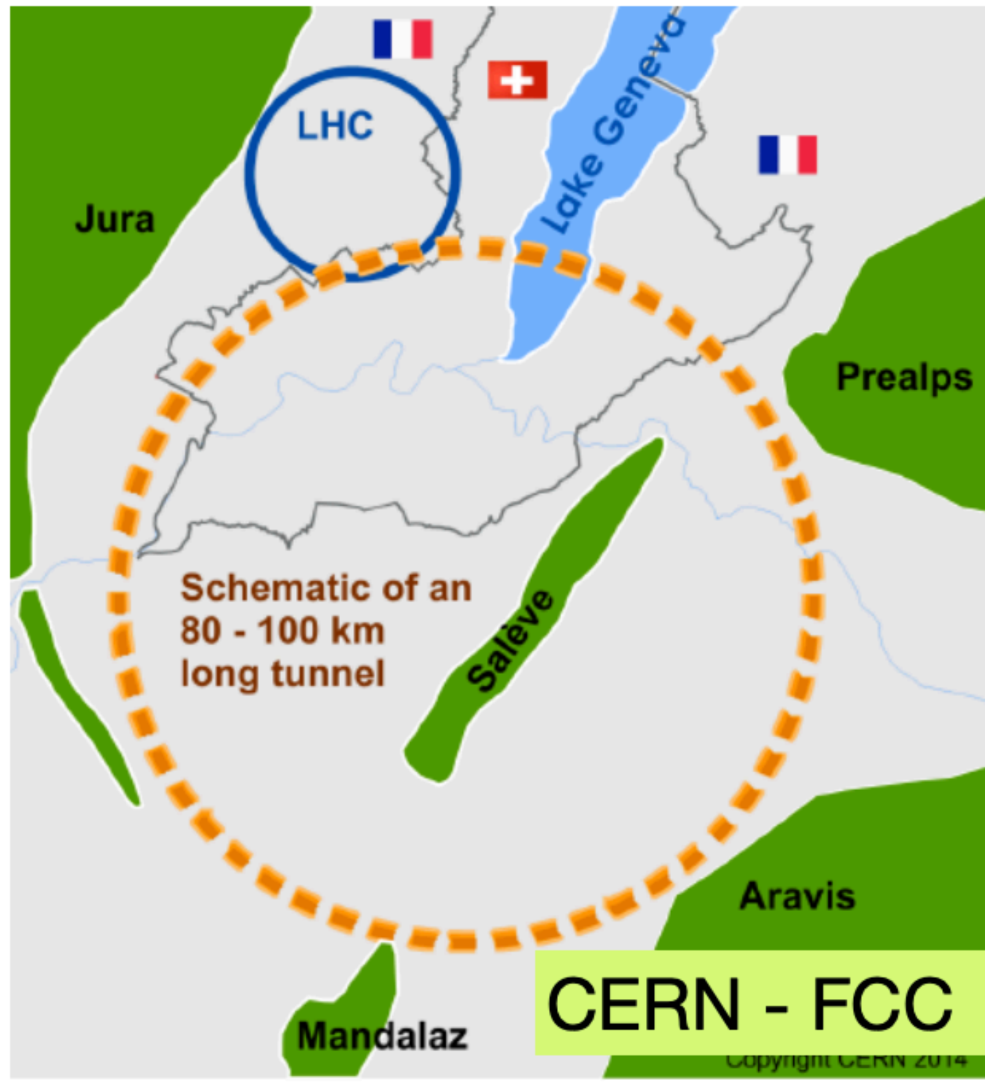
CLIC 380/1500/3000 GeV





250/550 GeV

… > TeV



FCC-ee

240/365 GeV

Luminosity: Starting Point for a High Energy e+e- Linear Collider

- Using established collider designs to inform initial parameters
- Target design at 2 TeV CoM with 9 MW single beam power (~2 MW at 250 GeV CoM)

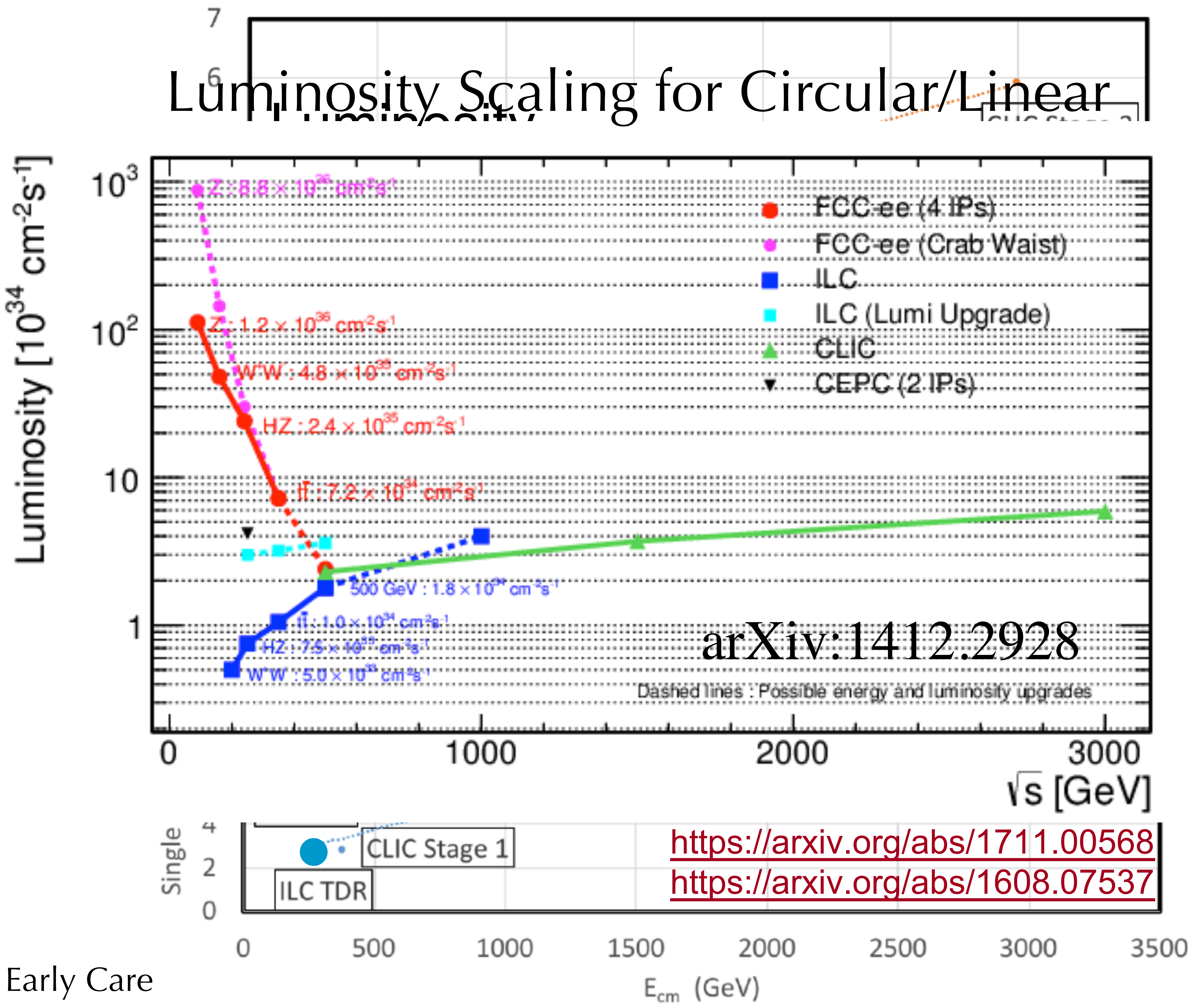
2 TeV CoM

Machine	CLIC	NLC	C^3
Freq (GHz)	12.0	11.4	5.7
a (mm)	2.75	3.9	2.6
Charge (nC)	0.6	1.4	1
Spacing	6	16	19
# of bunches	312	90	75

https://clic-meeting.web.cern.ch/clic-meeting/clictable2010.html

NLC, ZDR Tbl. 1.3,8.3

Luminosity Scaling for Circular/Linear



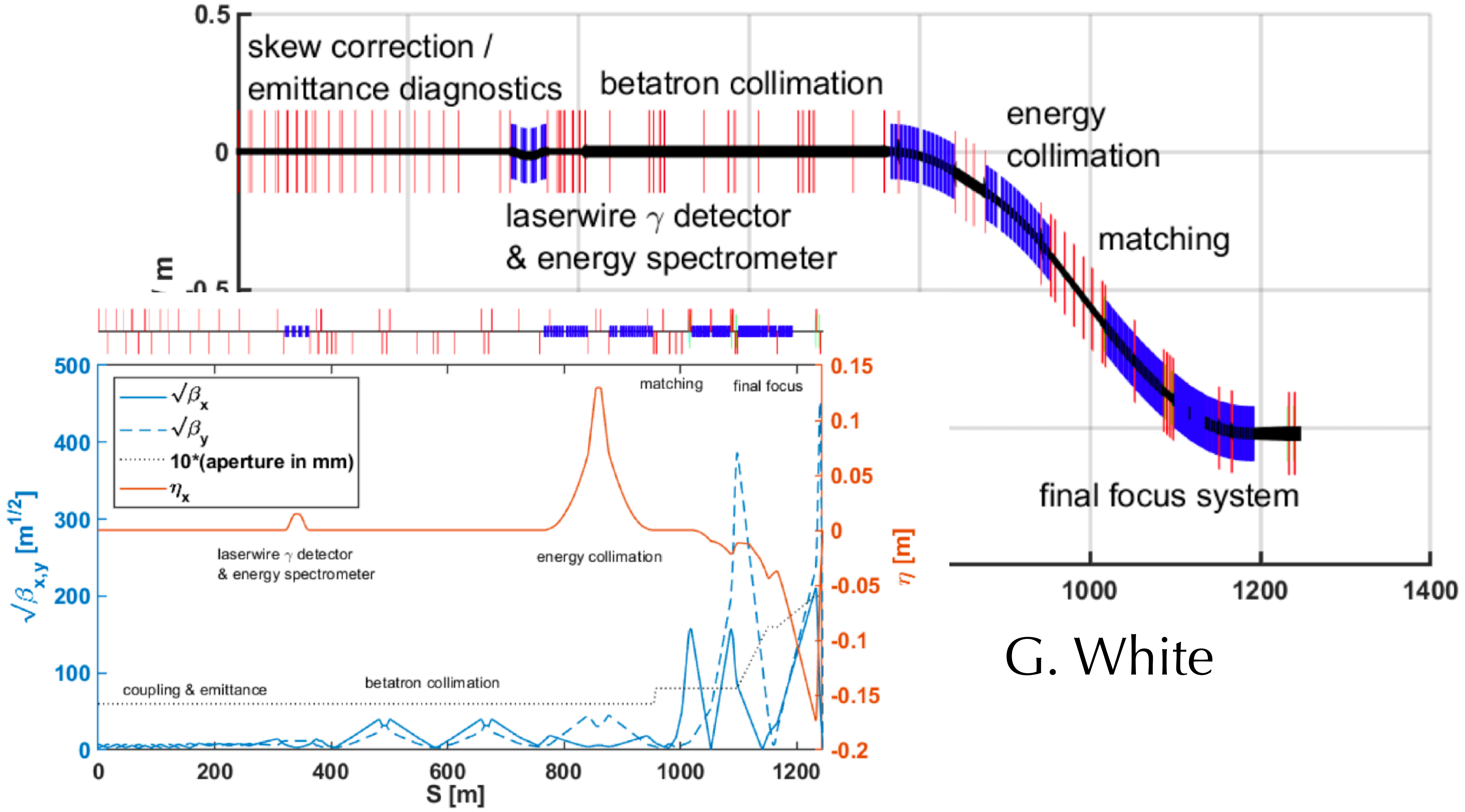
arXiv:1412.2928

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

Leverage the Development of Beam Generation and Delivery Systems for C^3

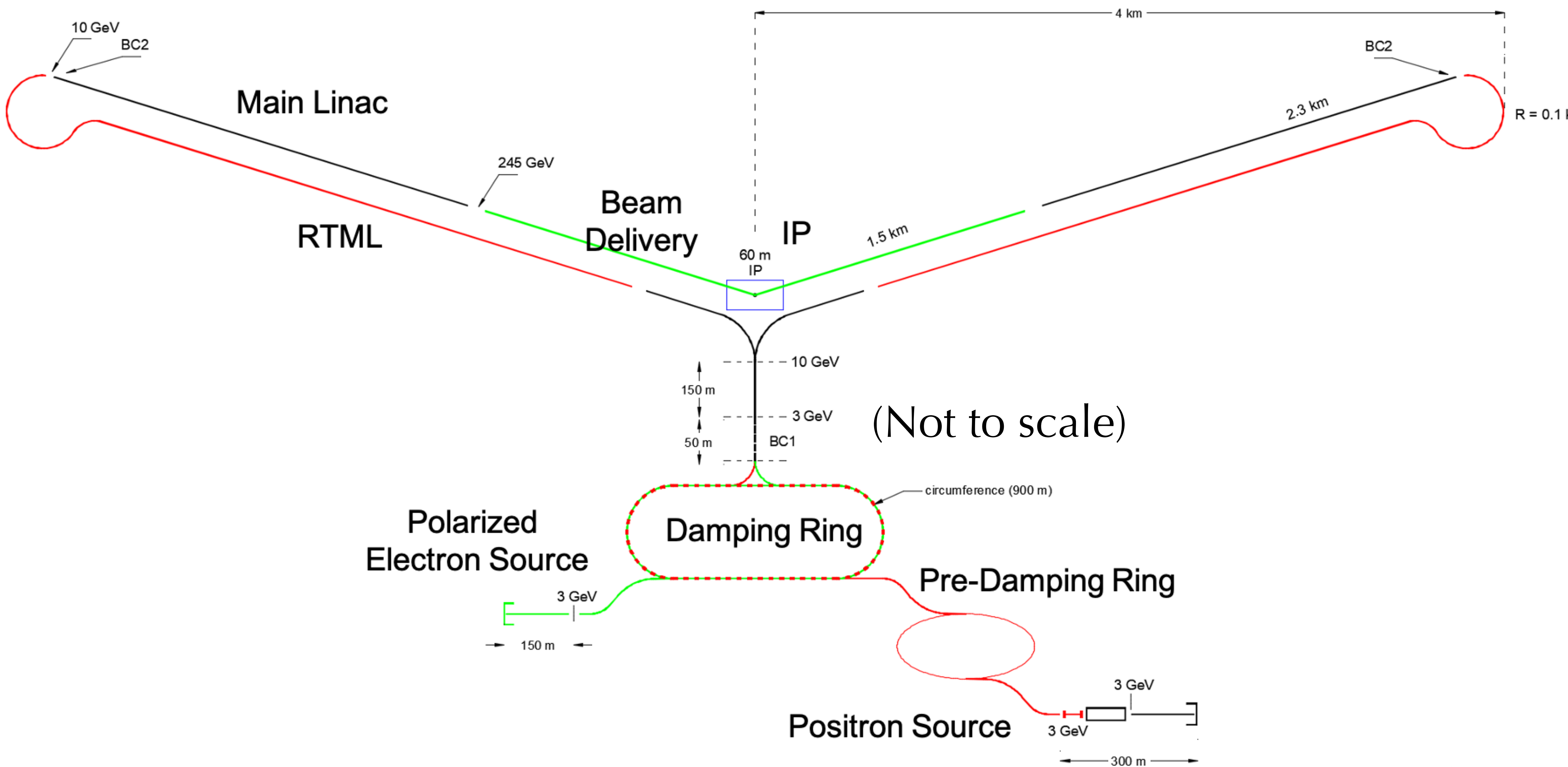
- Large portions of accelerator complex are compatible between LC technologies
  - Beam delivery and IP modified from ILC
  - Damping rings modified from CLIC
  - Injectors to be optimized with CLIC as baseline

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



G. White

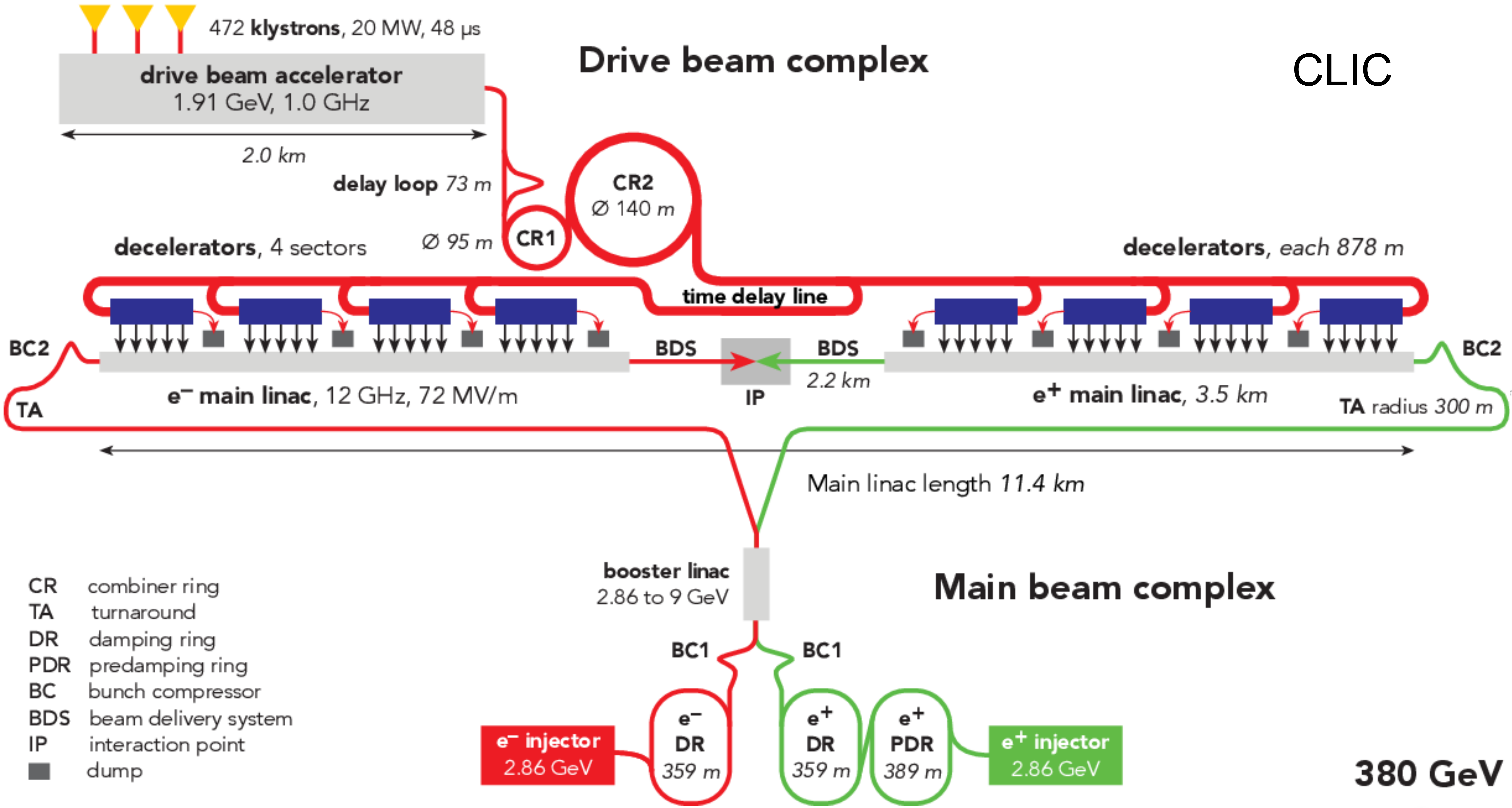
C^3 - 8 km footprint for 250/550 GeV



(Not to scale)

Main Linac Drives the Cost and Scale of Any e+e− Linear Collider

CLIC



CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
■	dump

380 GeV

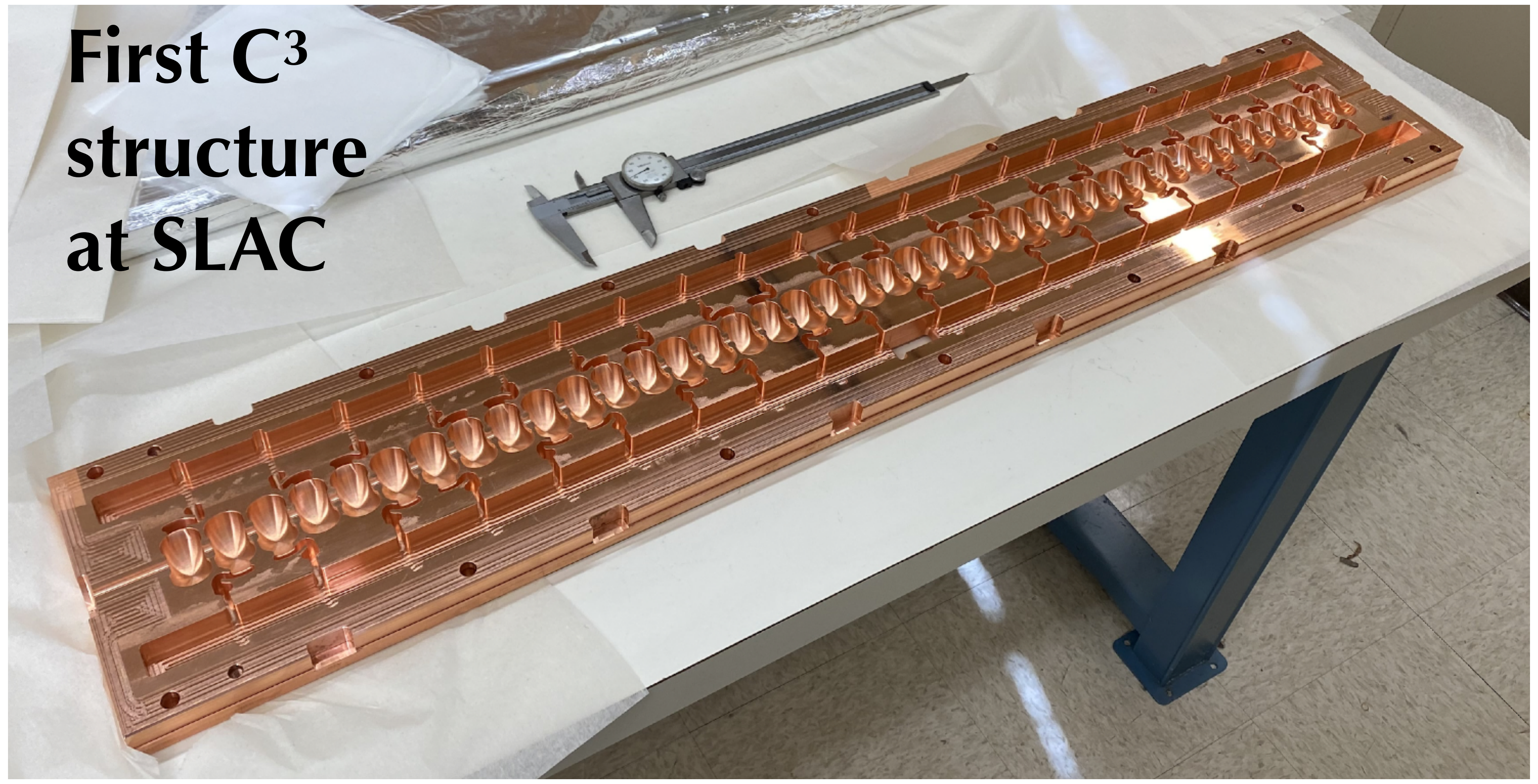
Challenge is Only Exacerbated as We Move to the Multi-TeV Scale

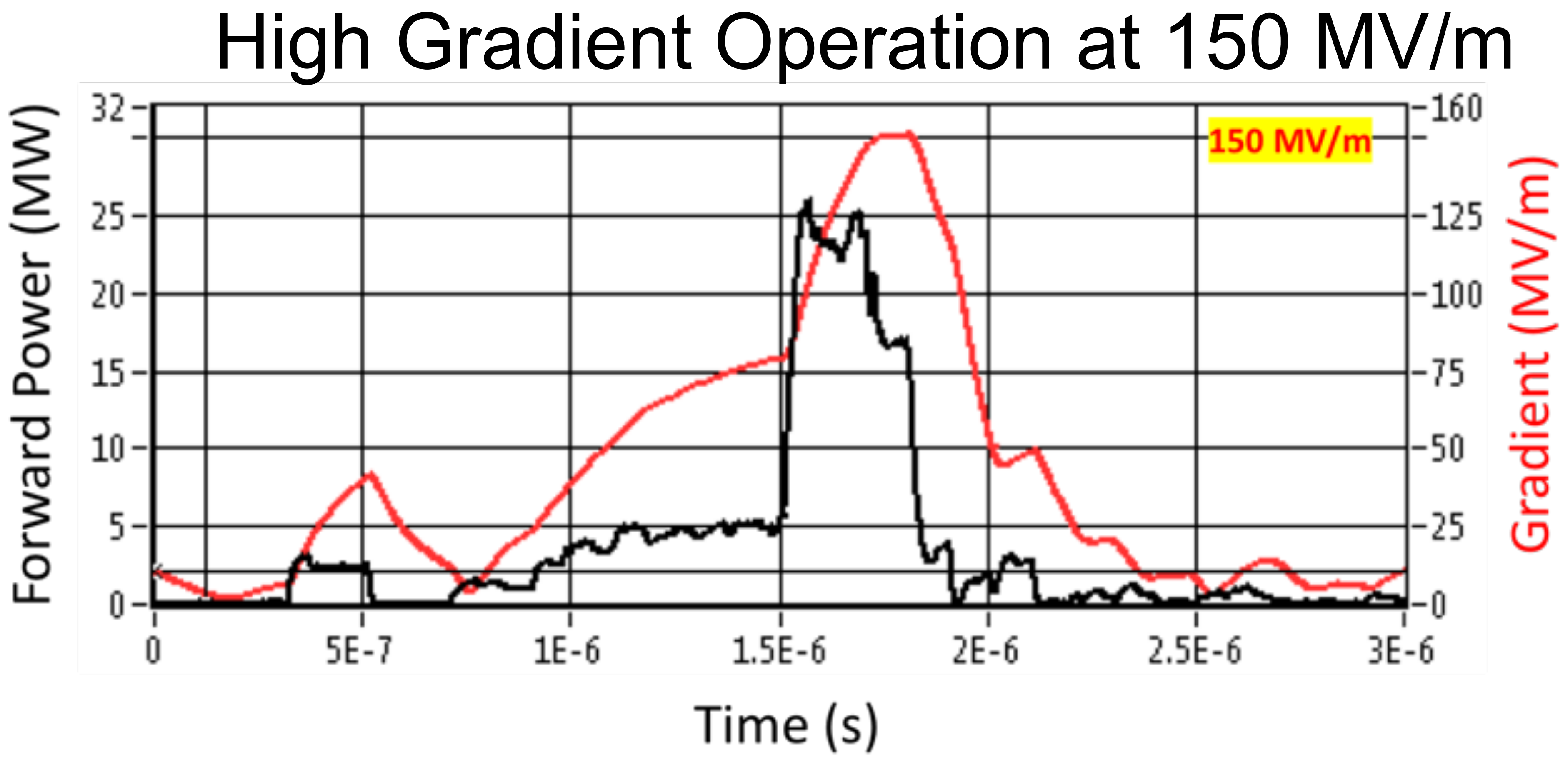
An novel route to a linear e+e- collider…

C^3 - Cool Copper Collider

EF workshop restart C3 LOI Link
UW Seminar Aug. 2021

- C^3 is based on a new SLAC technology
  - dramatically improving efficiency and breakdown rate
- distributed power to each cavity from a common RF manifold
- operation at cryogenic temperatures (LN2 ~80K)
- robust operations at high gradient: 120~MeV/m
- scalable to multi-TeV operation

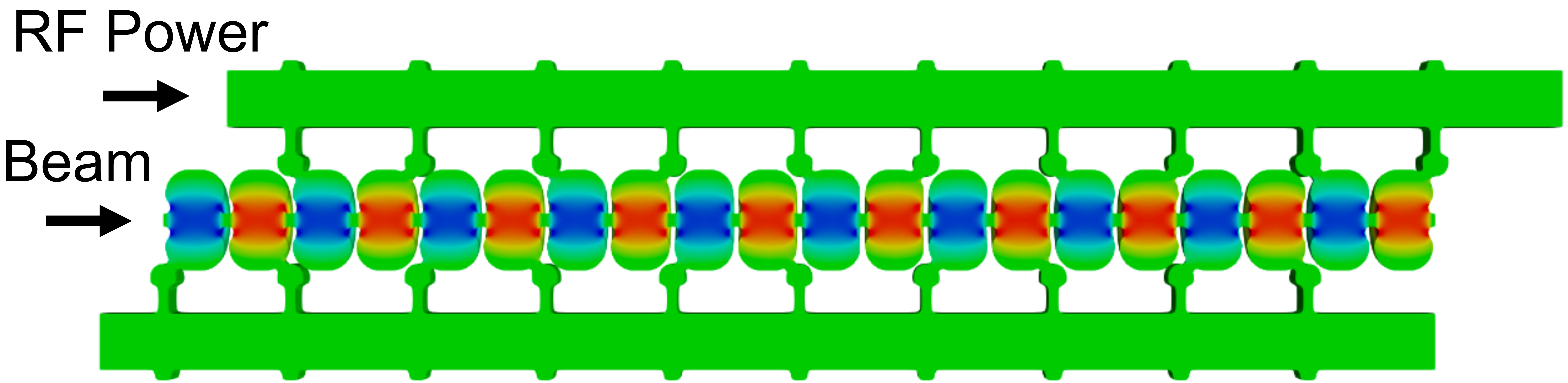

First C^3 structure at SLAC



Cryogenic Operation at X-band

Breakthrough in the Performance of RF Accelerators

- RF power coupled to each cell – no on-axis coupling
- Full system design requires modern virtual prototyping



Electric field magnitude produced when RF manifold feeds alternating cells equally

- Optimization of cell for efficiency (shunt impedance)

$$R_s = G^2/P \text{ [M}\Omega\text{ /m]}$$

- Control peak surface electric and magnetic fields
  - Key to high gradient operation

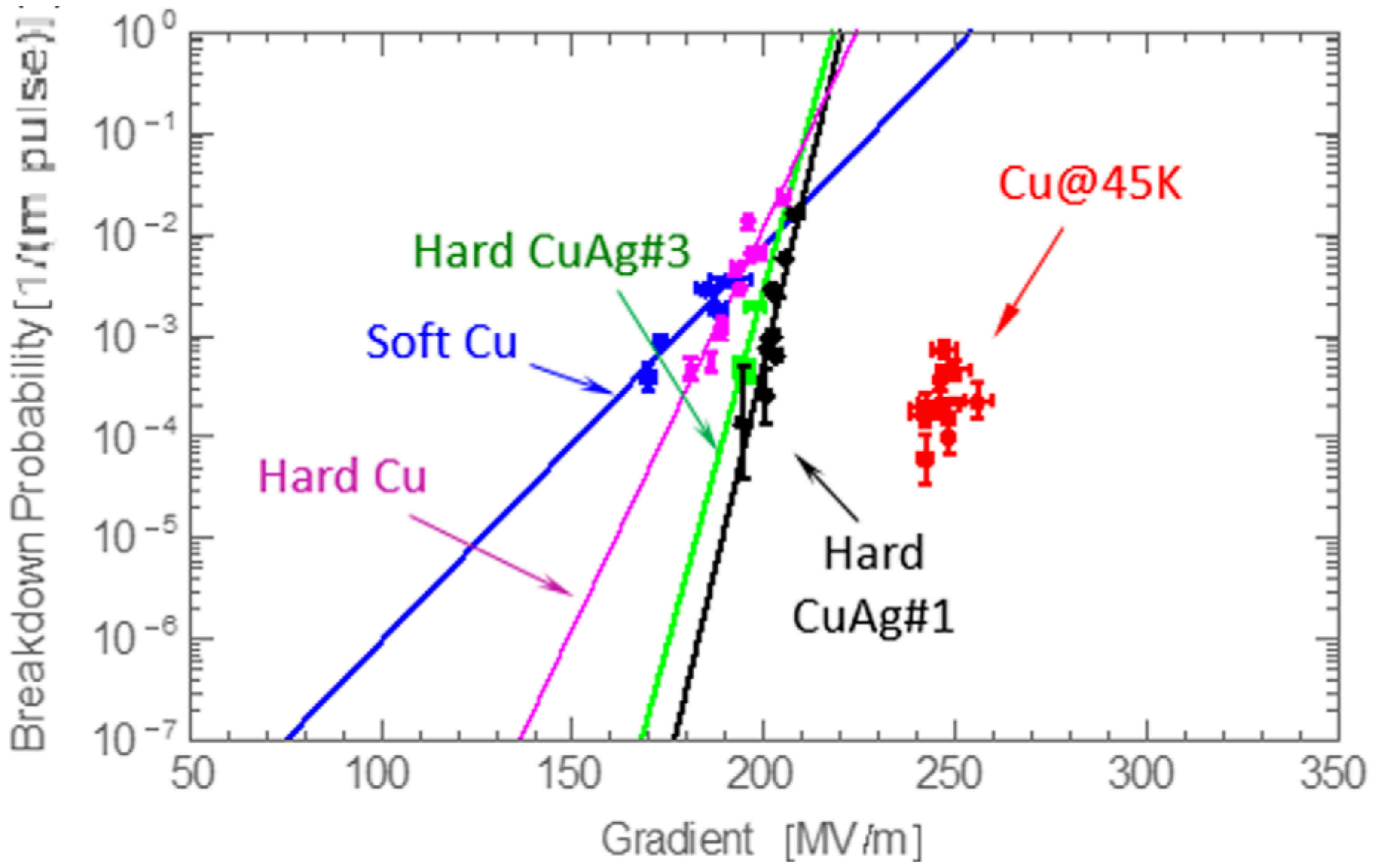
Tantawi, Sami, et al. "Design and demonstration of a distributed-coupling linear accelerator structure." *Physical Review Accelerators and Beams* 23.9 (2020): 092001.

Transformative Impact for High-Gradient Cryo-Copper Accelerators

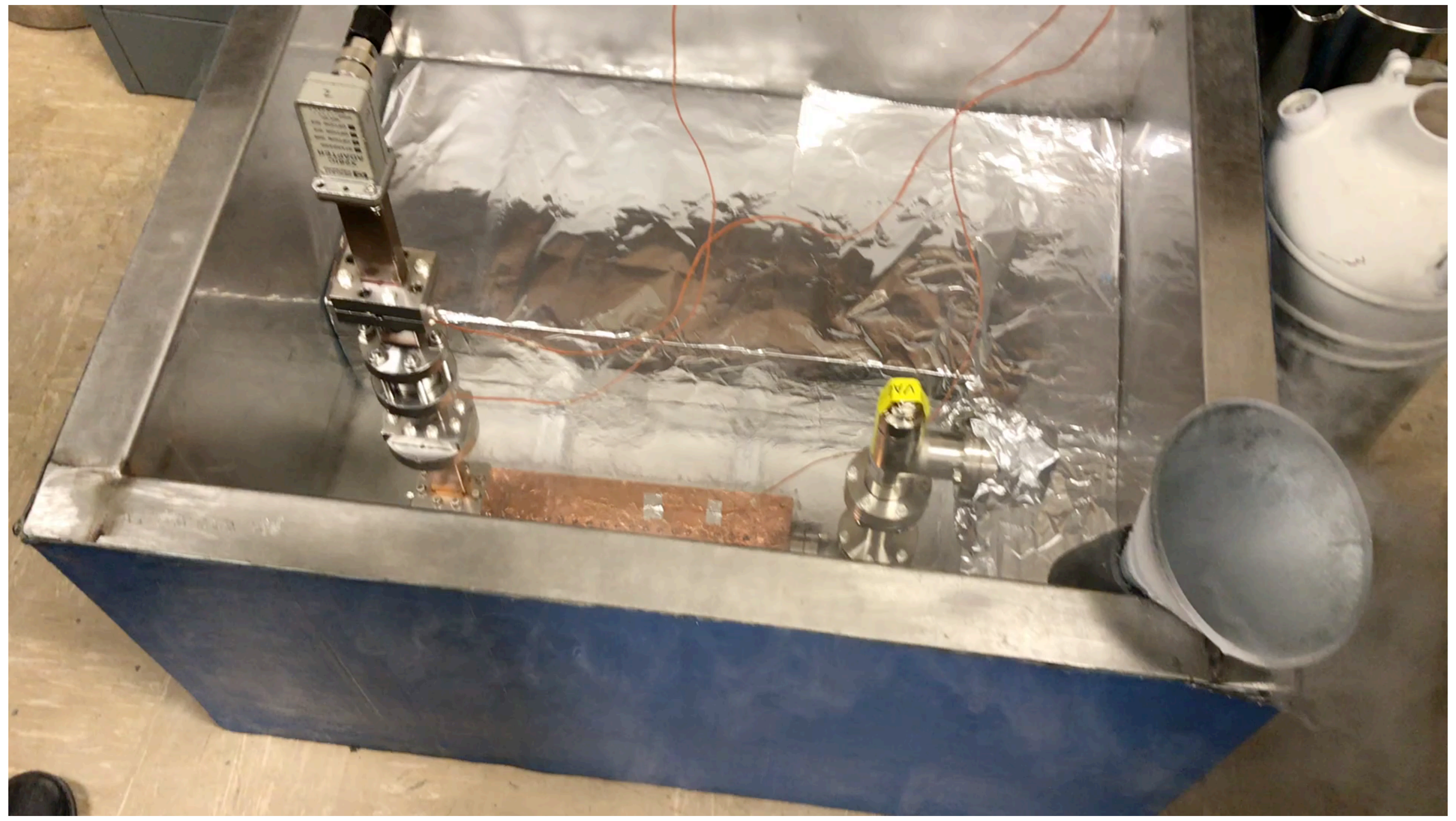
- Cryogenic temperature elevates performance in gradient
  - Material strength is key factor
  - Operation at 77 K with liquid nitrogen is simple and practical
- Large-scale production, large heat capacity, simple handling
  - Small impact on electrical efficiency

$$\eta_{cp} = LN\ Cryoplant$$
$$\eta_{cs} = Cryogenic\ Structure$$
$$\eta_k = RF\ Source$$

$$\frac{\eta_{cs}}{\eta_k}\eta_{cp} \approx \frac{2.5}{0.5}[0.15] \approx 0.75$$



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

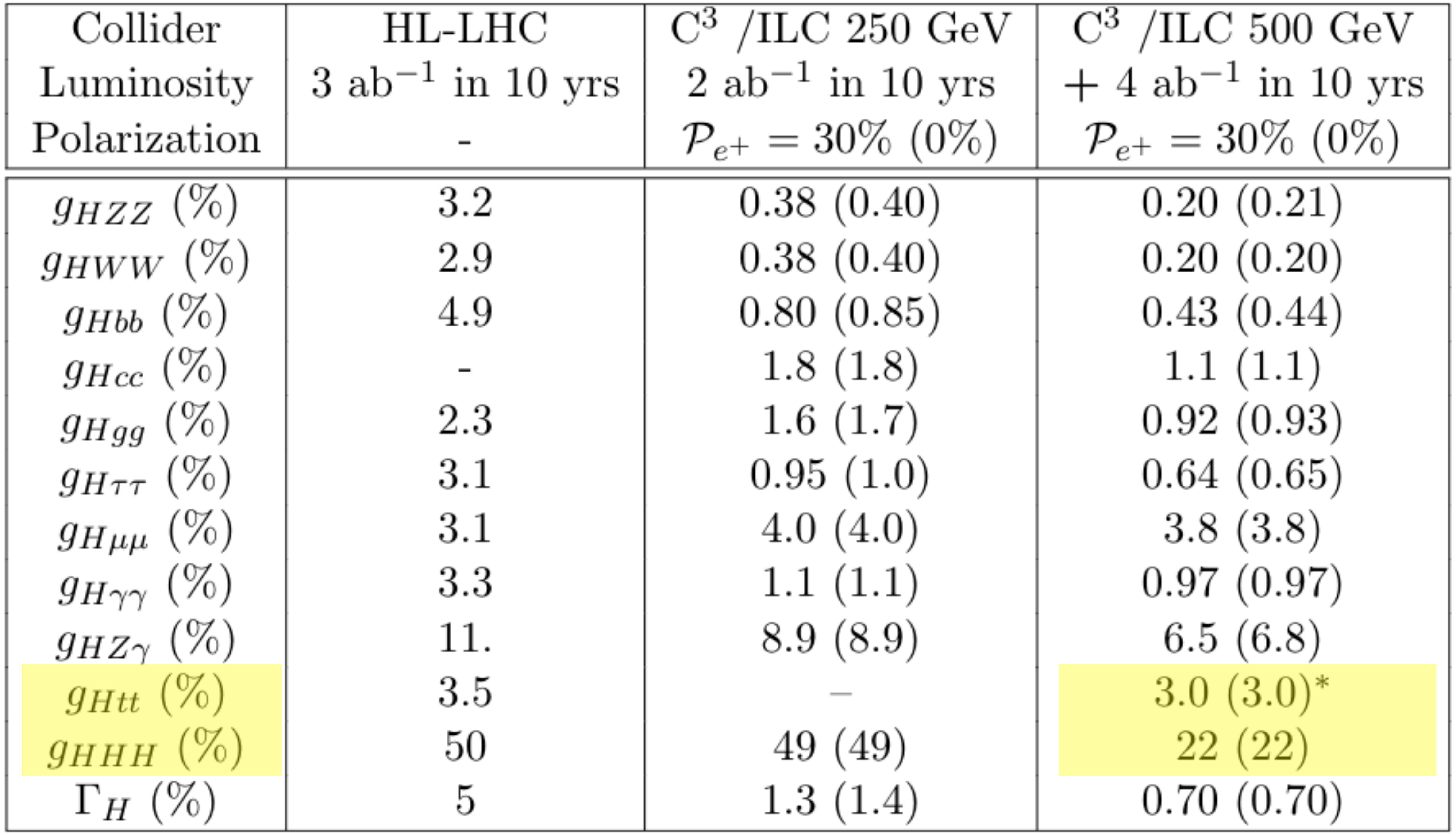


Why 550 GeV?

SLAC-PUB-17629

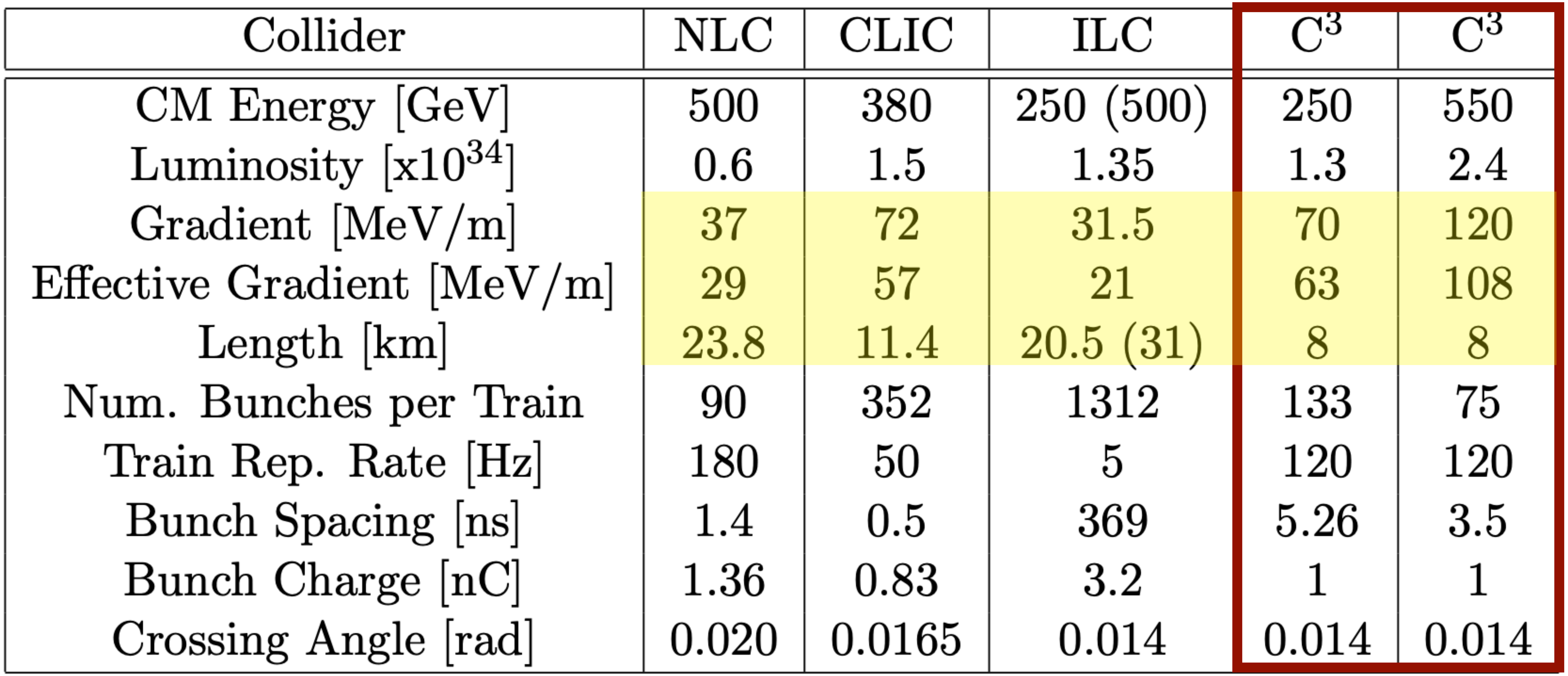
We propose **250** GeV with a relatively inexpensive upgrade to **550** GeV

- An **orthogonal dataset** at 550 GeV to cross-check a deviation from the SM predictions observed at 250 GeV
- From 500 to 550 GeV a factor 2 improvement to the **top-Yukawa** coupling
- O(20%) precision on the Higgs **self-coupling** would allow to exclude/demonstrate at 5σ models of electroweak baryogenesis



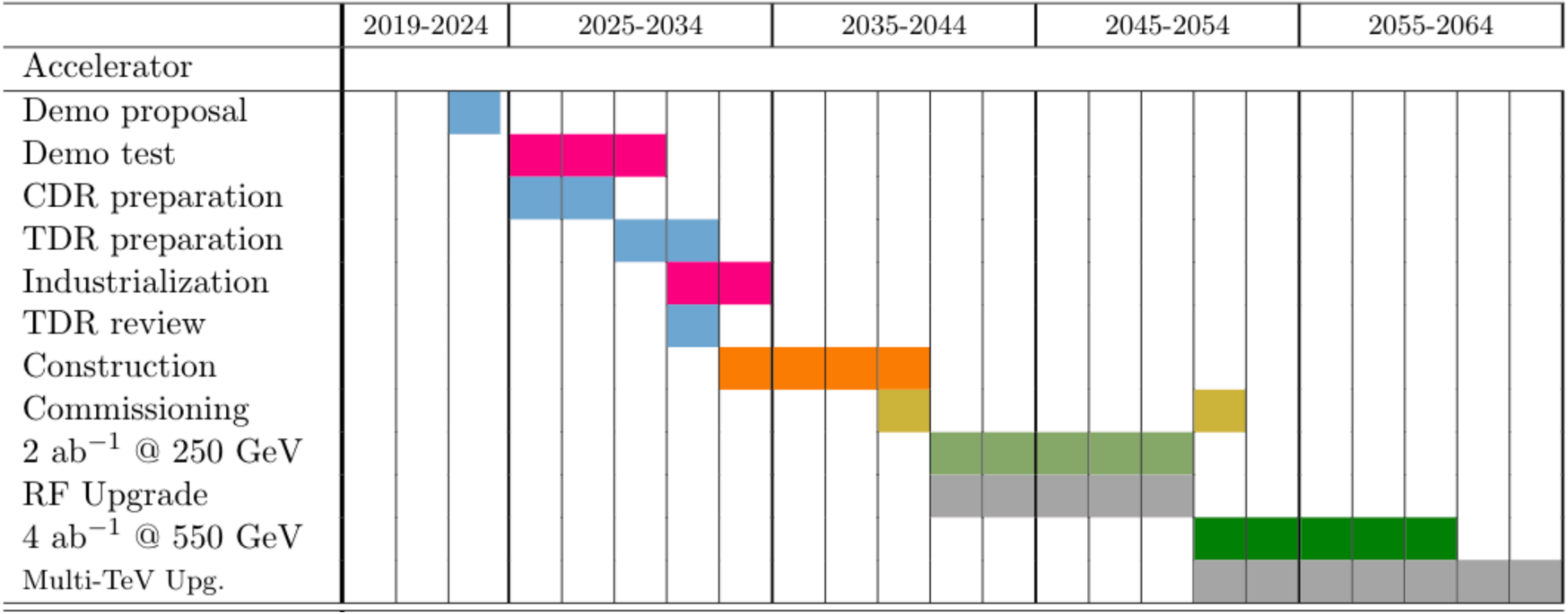
Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80 (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)

C^3 parameters



Collider	NLC	CLIC	ILC	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
Luminosity [x10^{34}]	0.6	1.5	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Length [km]	23.8	11.4	20.5 (31)	8	8
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014

C^3 timeline



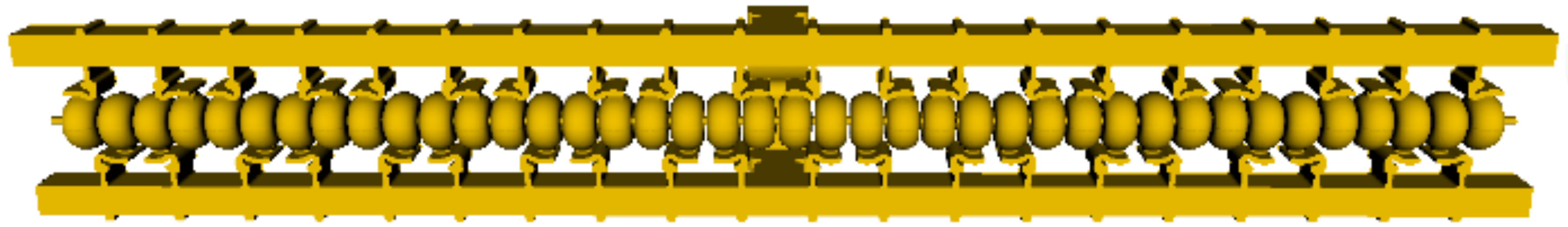
	2019-2024			2025-2034					2035-2044					2045-2054					2055-2064				
Accelerator																							
Demo proposal			🟦																				
Demo test				🟪	🟪	🟪																	
CDR preparation				🟦	🟦																		
TDR preparation						🟦	🟦																
Industrialization							🟪	🟪														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

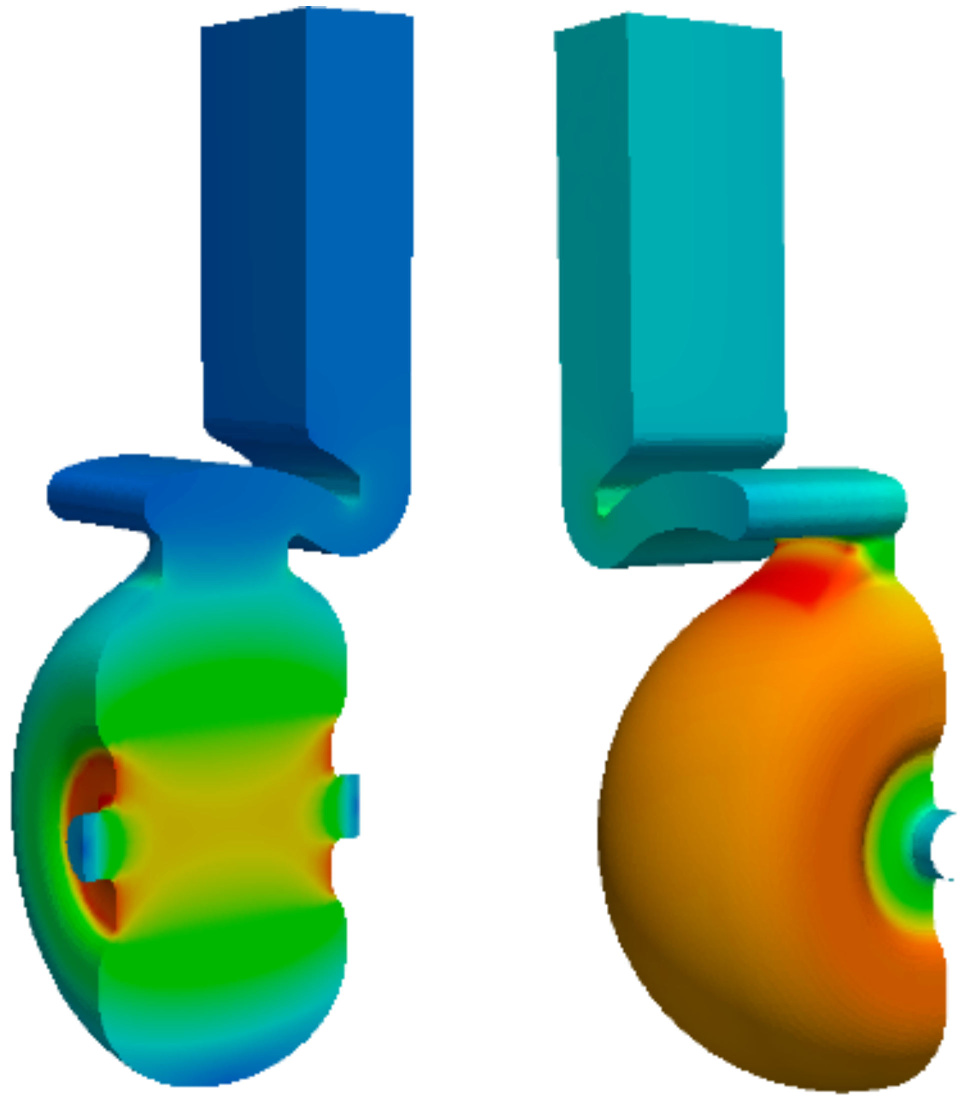
HL-LHC

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

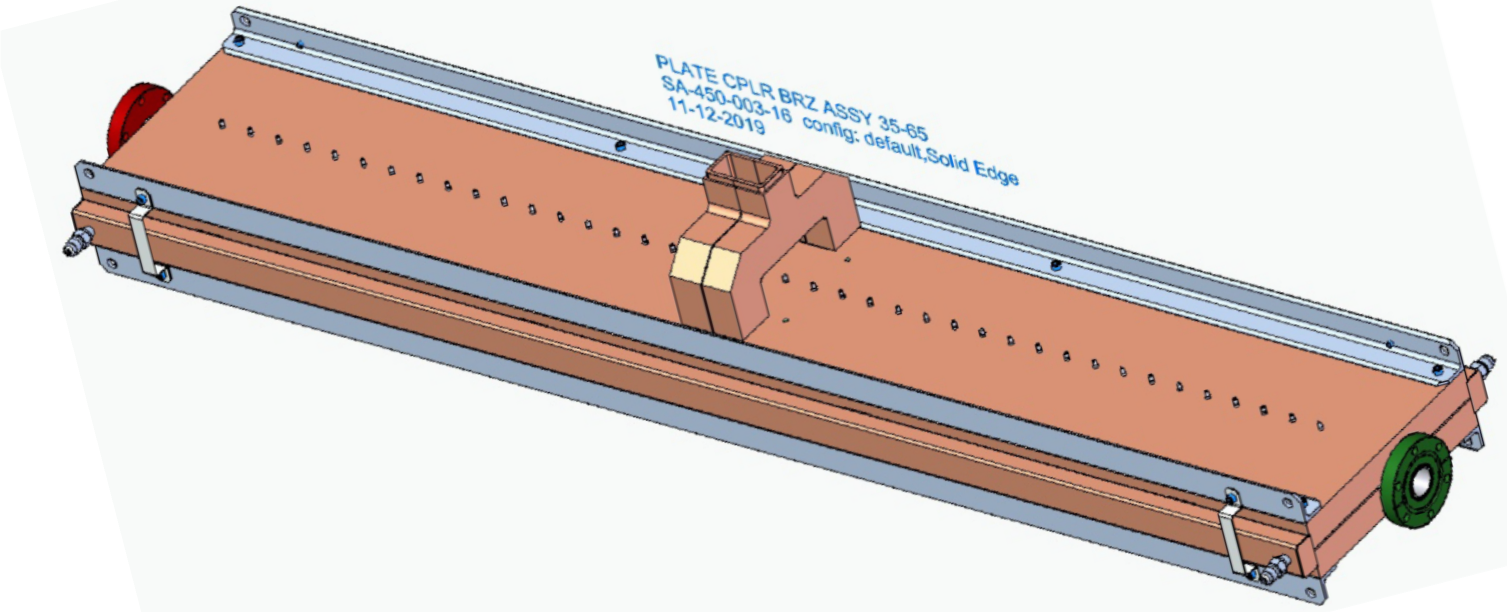
One meter (40-cell) C-band design with reduce peak E and H-field

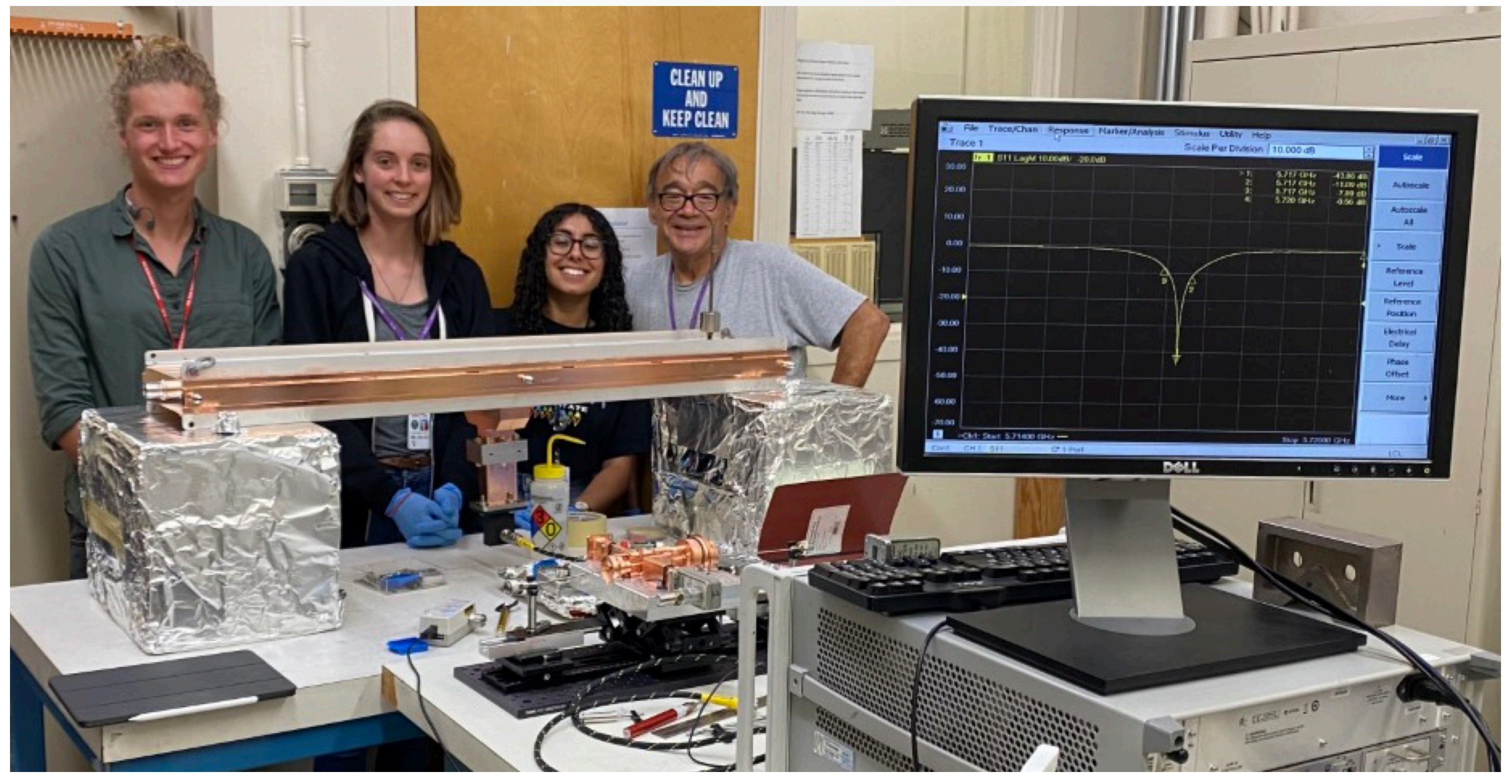




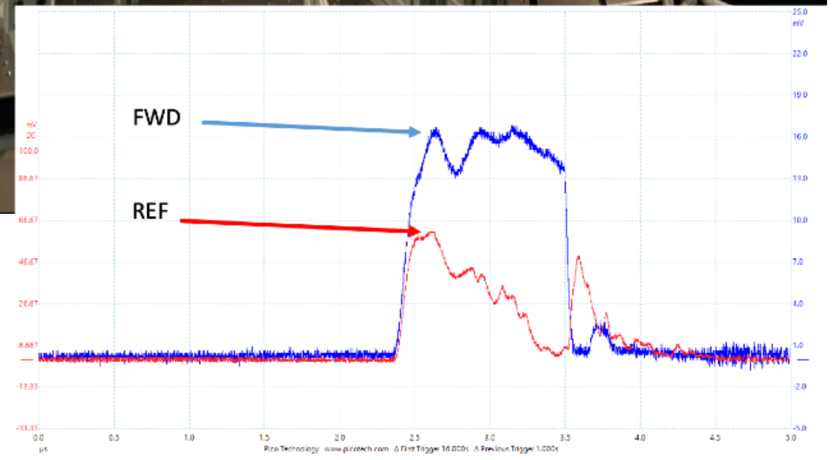
Z. Li, S. Tantawi

Scaling fabrication techniques in length and including controlled gap





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

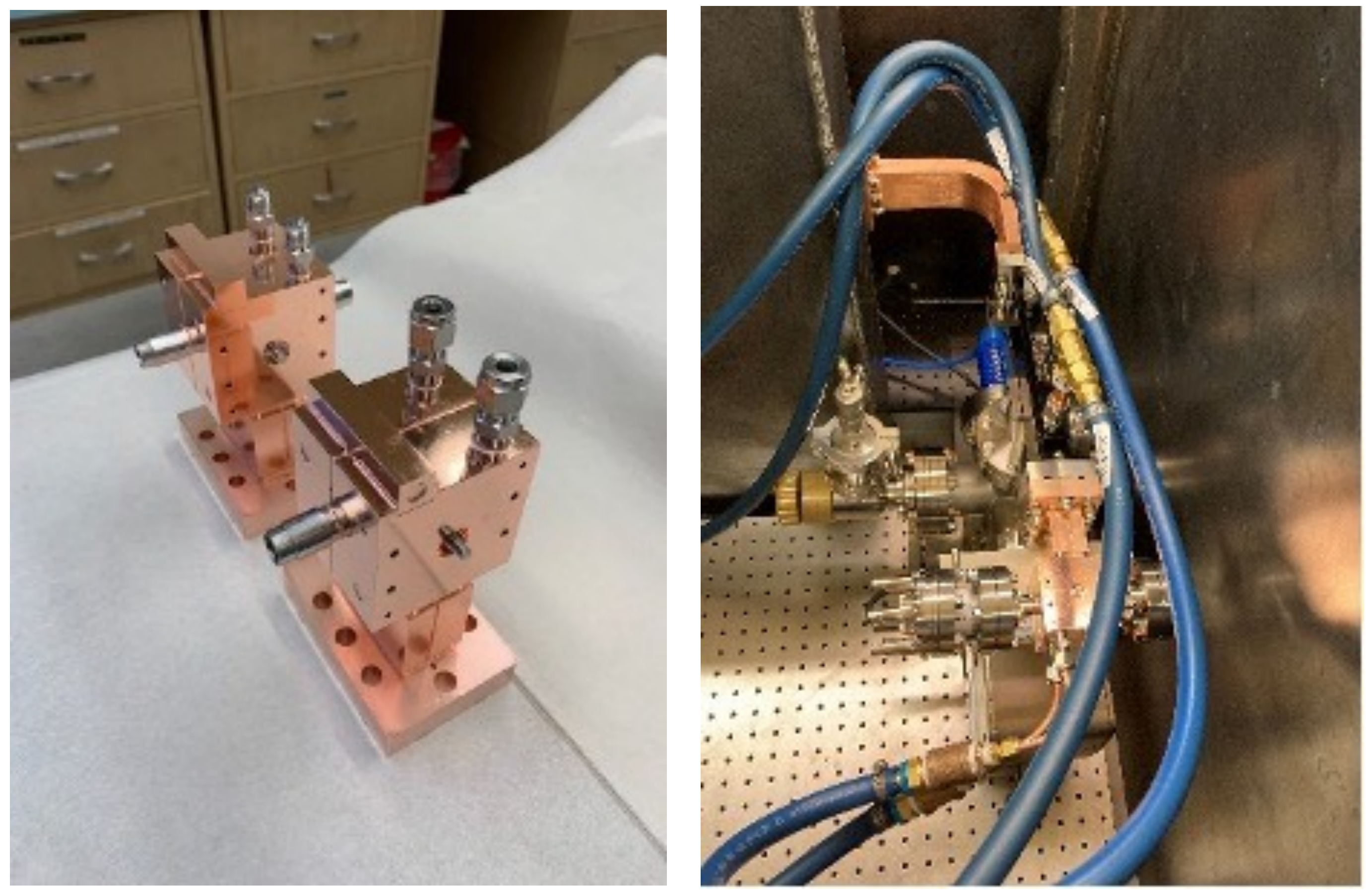


High power test at Radiabeam

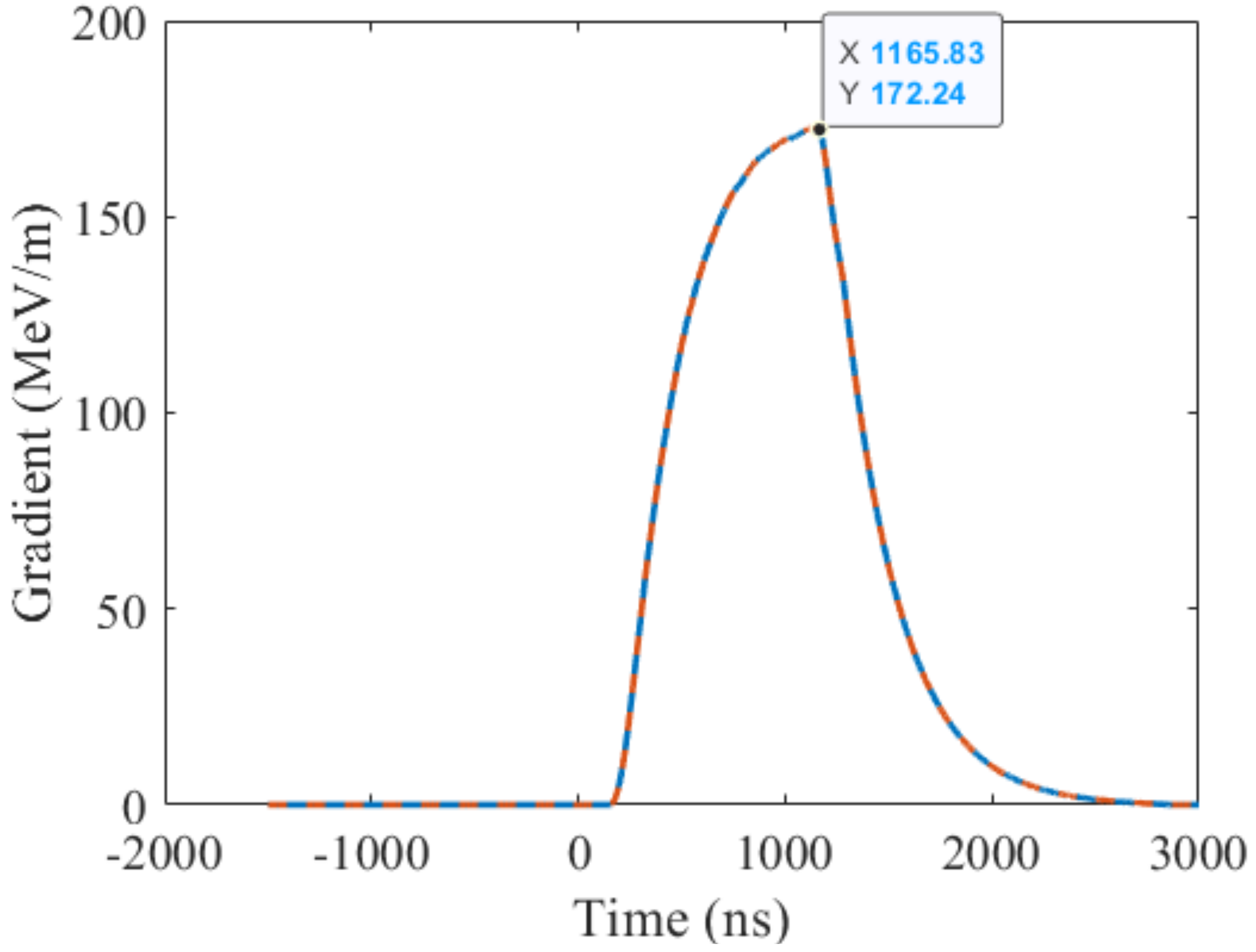
Performance of Single-Cavity Structure Prototypes

- First high gradient test at C-band
- Side coupled, split-cell reduced peak field, reduced phase adv.
- Exceed ultimate C3 field strengths
- High power in up to 1 microsecond - break down rate statistics collected and being prepared for release

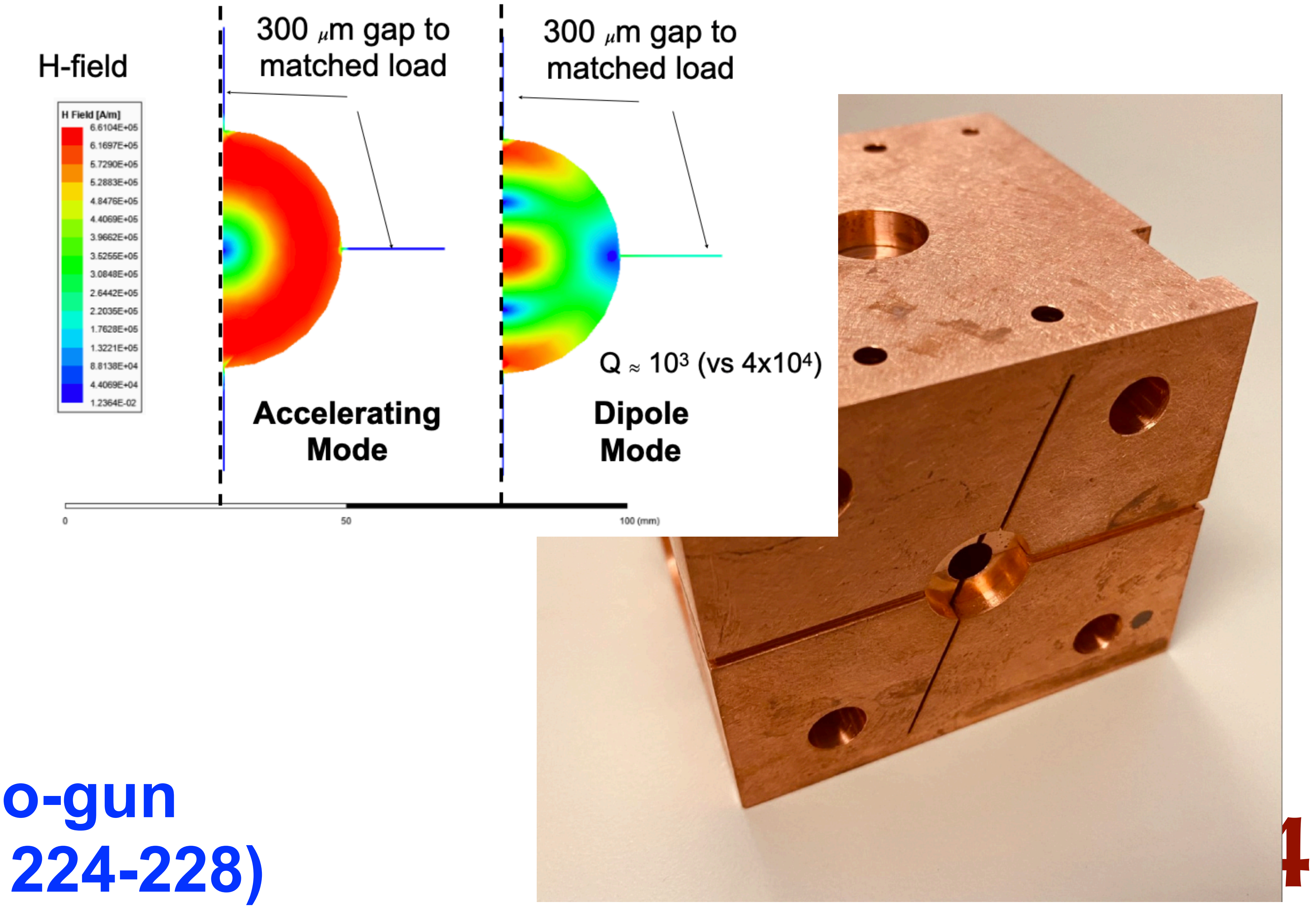
LANL Test of single cell SLAC C-band structure



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



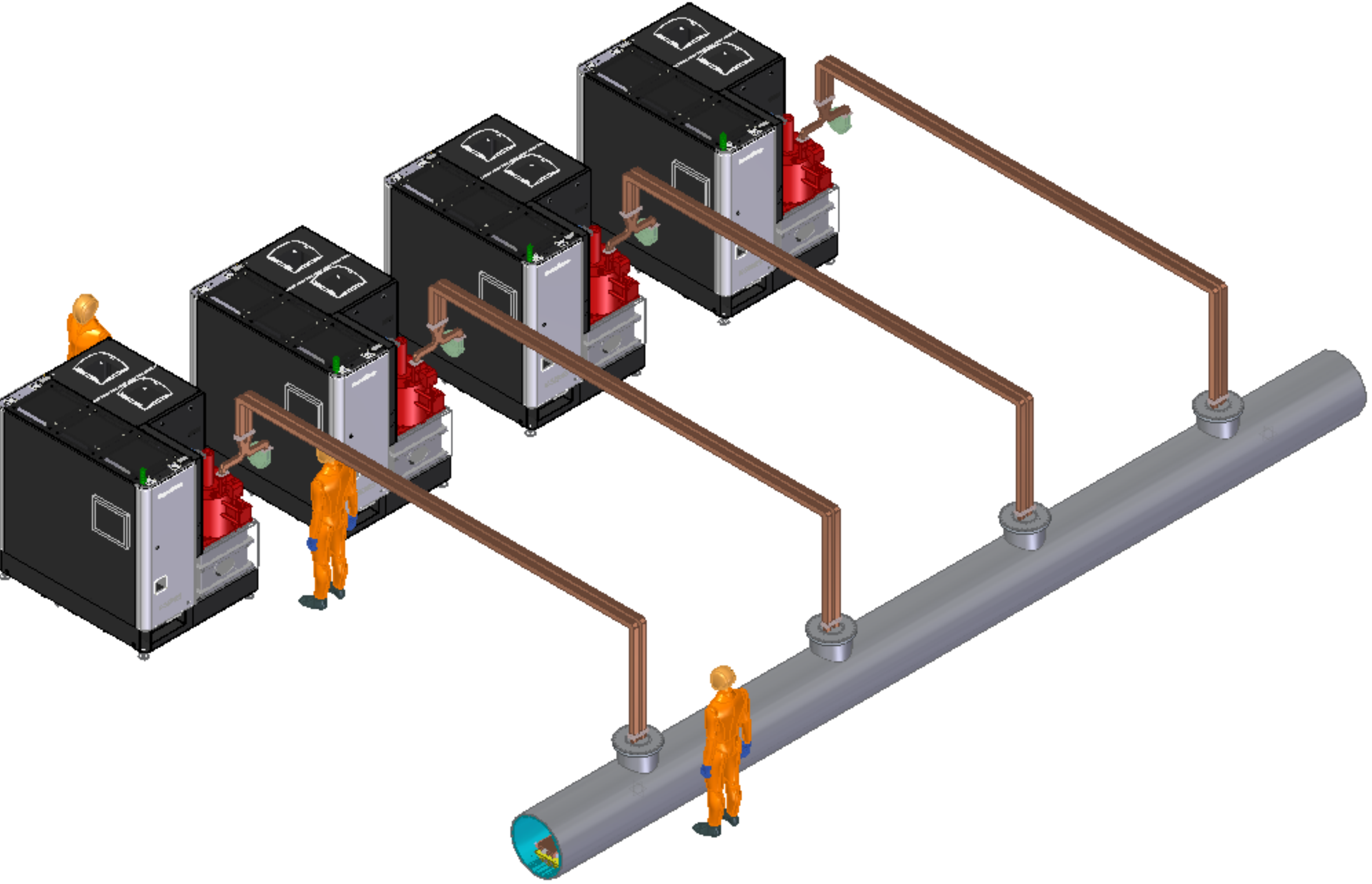
Slot Damping Prototype Working on NiCr Coating



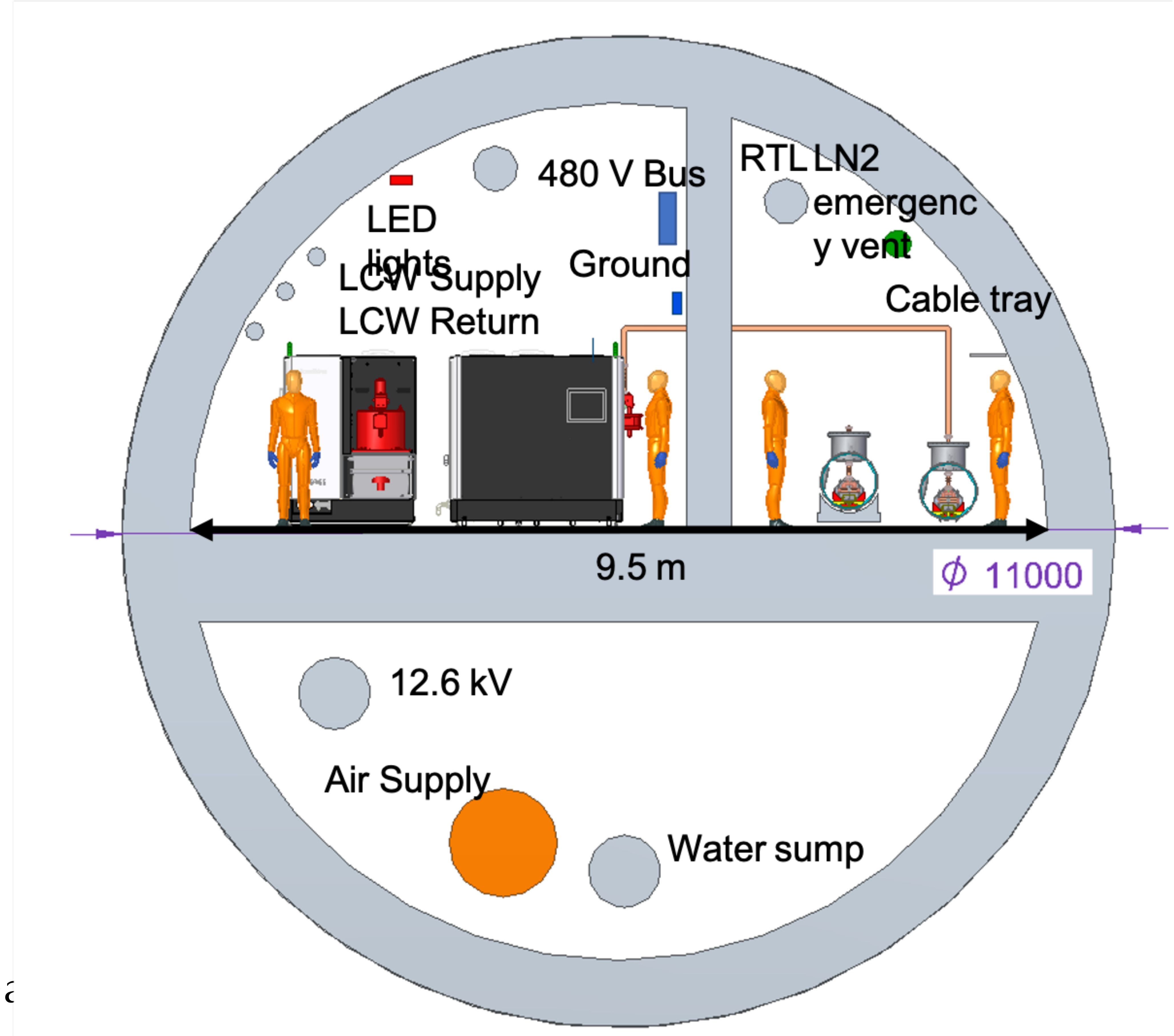
Very promising for polarized cryo-gun (Rosenzweig, et al. NIM 909 (2018): 224-228)

Tunnel Layout for 250 GeV CoM

- Cryomodule unit - 9 m (630 MeV)

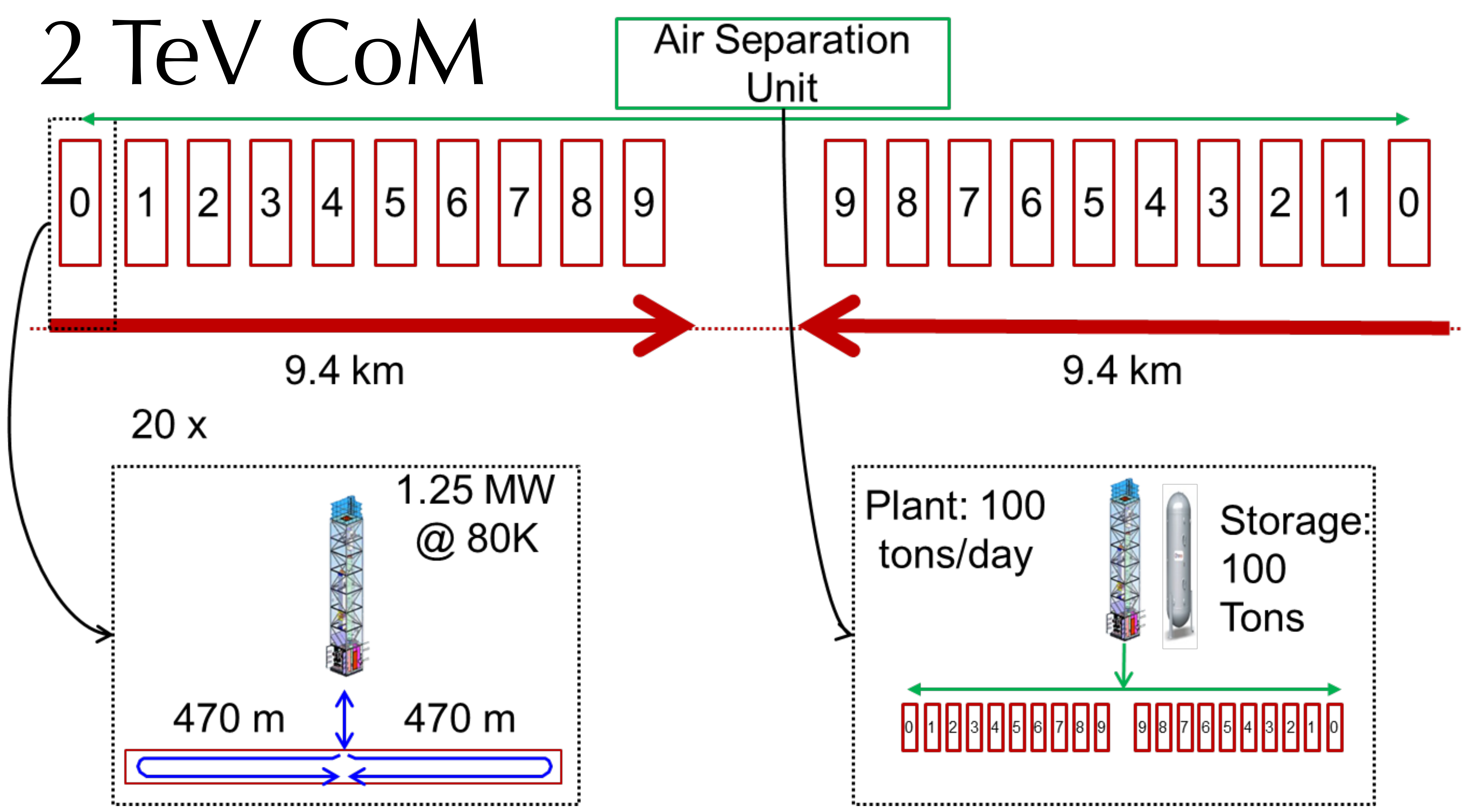


Usable Tunnel Width - 9.5 m
(Same tunnel width as ILC)



Cryomodule Design Scalable from 250 GeV to multi-TeV

- X-band structure test demonstrated full average power over short length (0.25 m)
- Cryomodule design developed for cryoplant layout to cool 1.2 MW/km thermal load at 77K



2 TeV CoM

Air Separation Unit

0 1 2 3 4 5 6 7 8 9

9 8 7 6 5 4 3 2 1 0

9.4 km

9.4 km

20 x

1.25 MW @ 80K

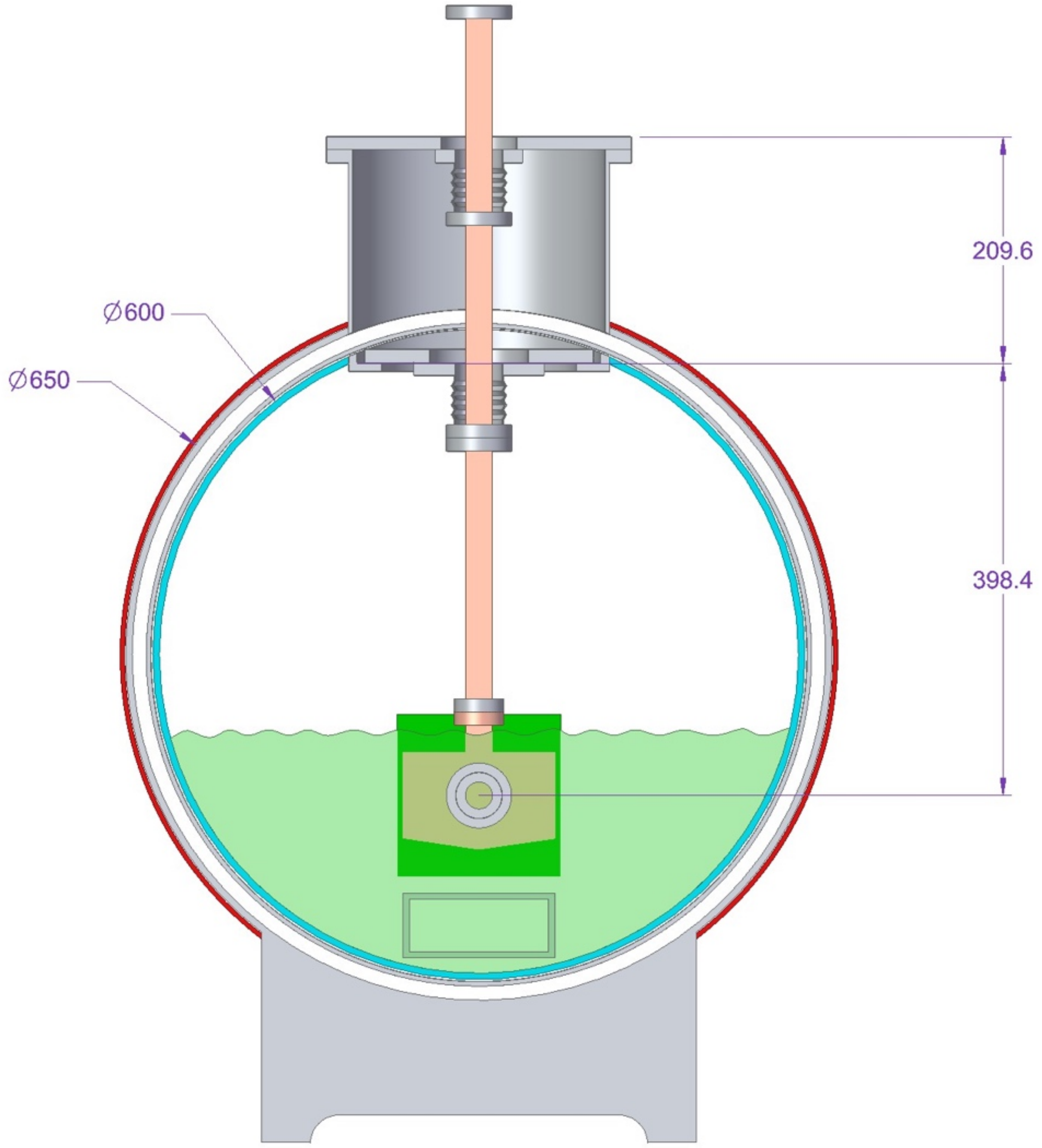
470 m

470 m

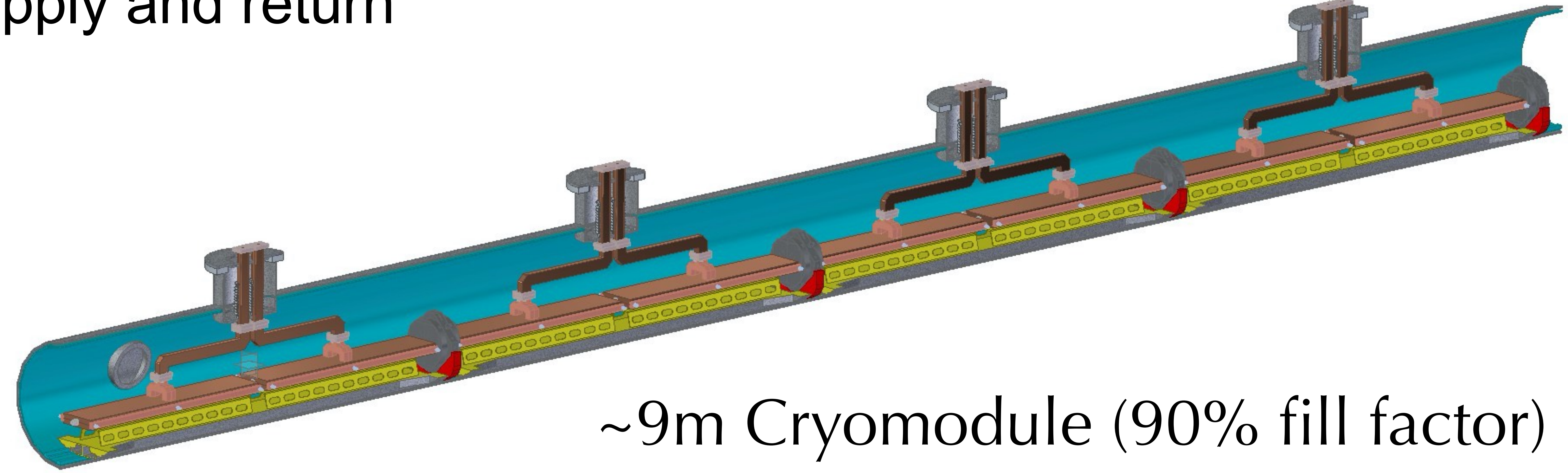
Plant: 100 tons/day

Storage: 100 Tons

0 1 2 3 4 5 6 7 8 9 9 8 7 6 5 4 3 2 1 0



Shared nitrogen supply and return



~9m Cryomodule (90% fill factor)

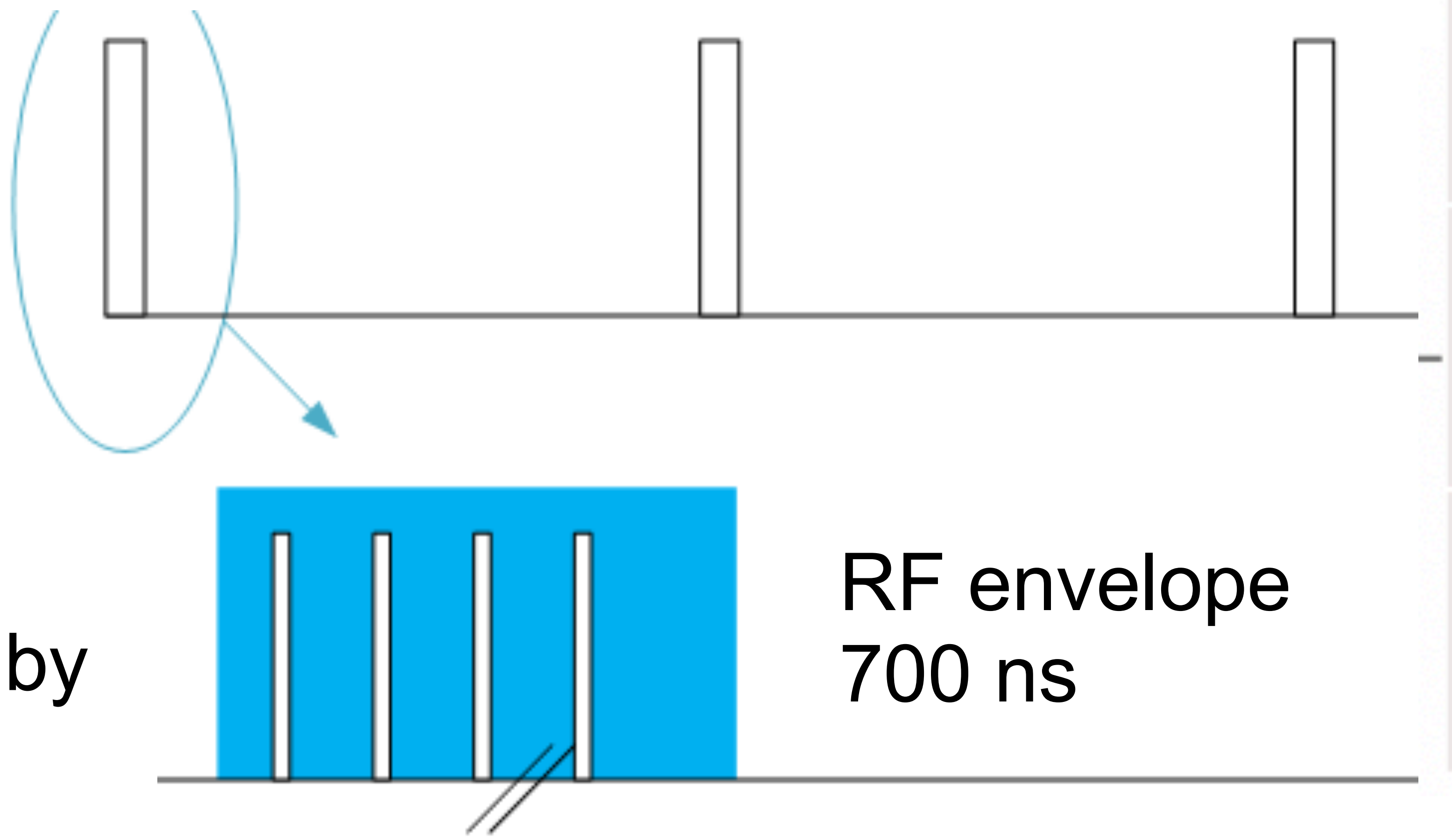
Oriunno, Breidenbach

Summary of Parameters for 250 GeV Conceptual Design

Luminosity - 1.3x10^34

Temperature (K)	77
Beam Loading (%)	45
Gradient (MeV/m)	70
Flat Top Pulse Length (μs)	0.7
Cryogenic Load @ 77K (MW)	9
Electrical Load (MW)	100

Parameter (250 GeV CoM)	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



Trains repeat at 120 Hz

Pulse Format

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

RF envelope
700 ns

Demonstration Facility

- We are proposing a demonstration facility to carry out a “string test” of three C^3 cryomodules.
- Minimum requirement for Demo Facility:
  - Demonstrate operation of fully engineered and operational cryomodule
    - Will iterate on cryomodule design (min. 3 cryomodules)
  - Demonstrate operation during cryogenic flow equivalent to main linac at full liquid/gas flow rate
  - Operation with a multi-bunch photo injector - high charges bunches to induce wakes, tunable delay witness bunch to measure wakes
  - Demonstrate full operational gradient 120 MeV/m (and higher) in single bunch mode (1GeV)
  - **Fully damped-detuned accelerating structure**
  - Work with industry to develop C-band source unit (3 vendors for klystron / 3 vendors for modulator and integration)
- This step is included in our timeline. The cost is O(100) M$.
  - This demonstration directly benefits development of compact FELs for photon science.
- The other elements needed for a linear collider - the sources, damping rings, and beam delivery system - already have mature designs created for the ILC and CLIC.
  - Our current baseline uses these directly although we will look for further cost-optimizations for the specific needs of the C^3

Getting Involved C^3 R&D

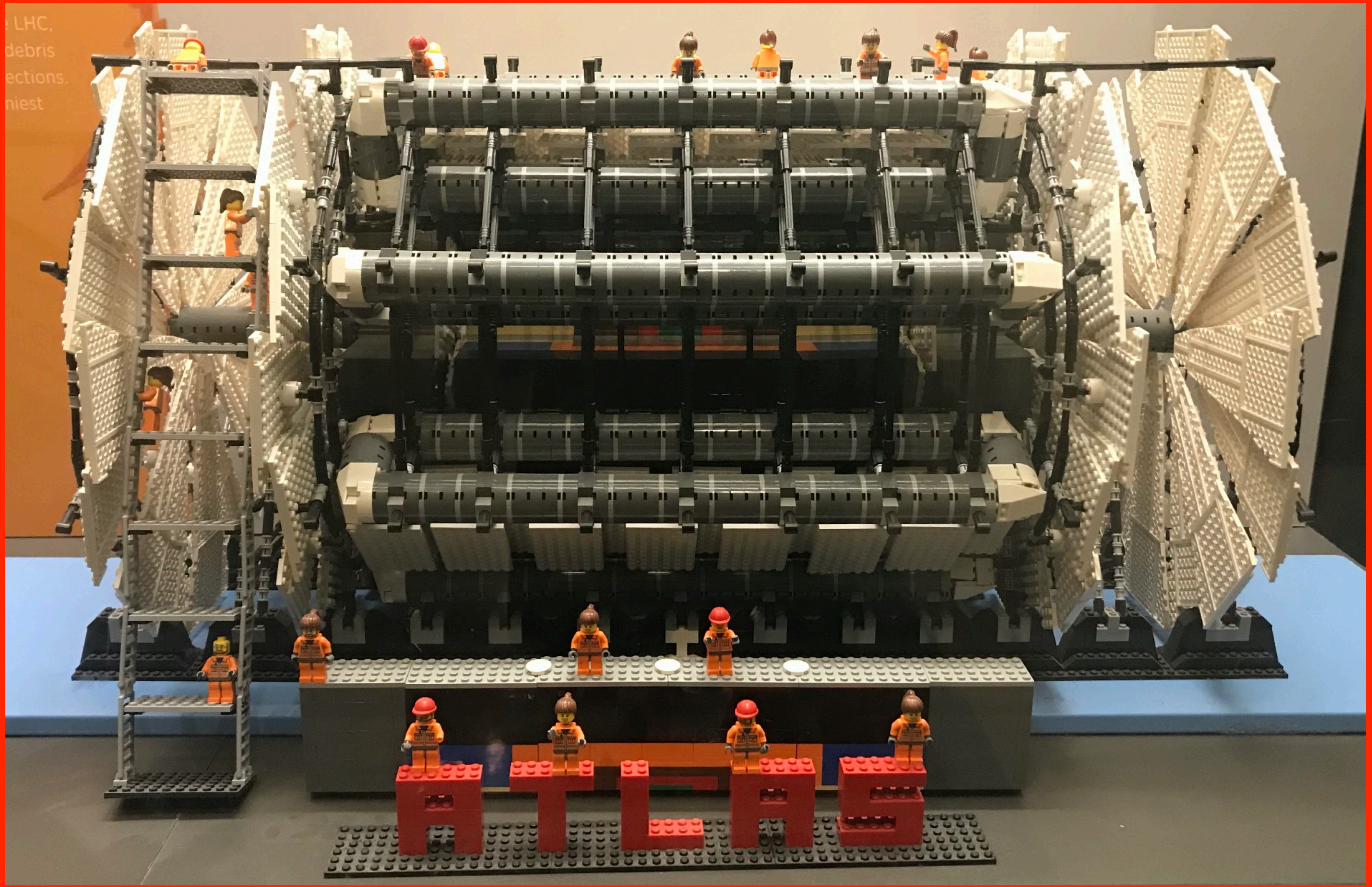
C^3 R&D, System Design and Project Planning are ongoing

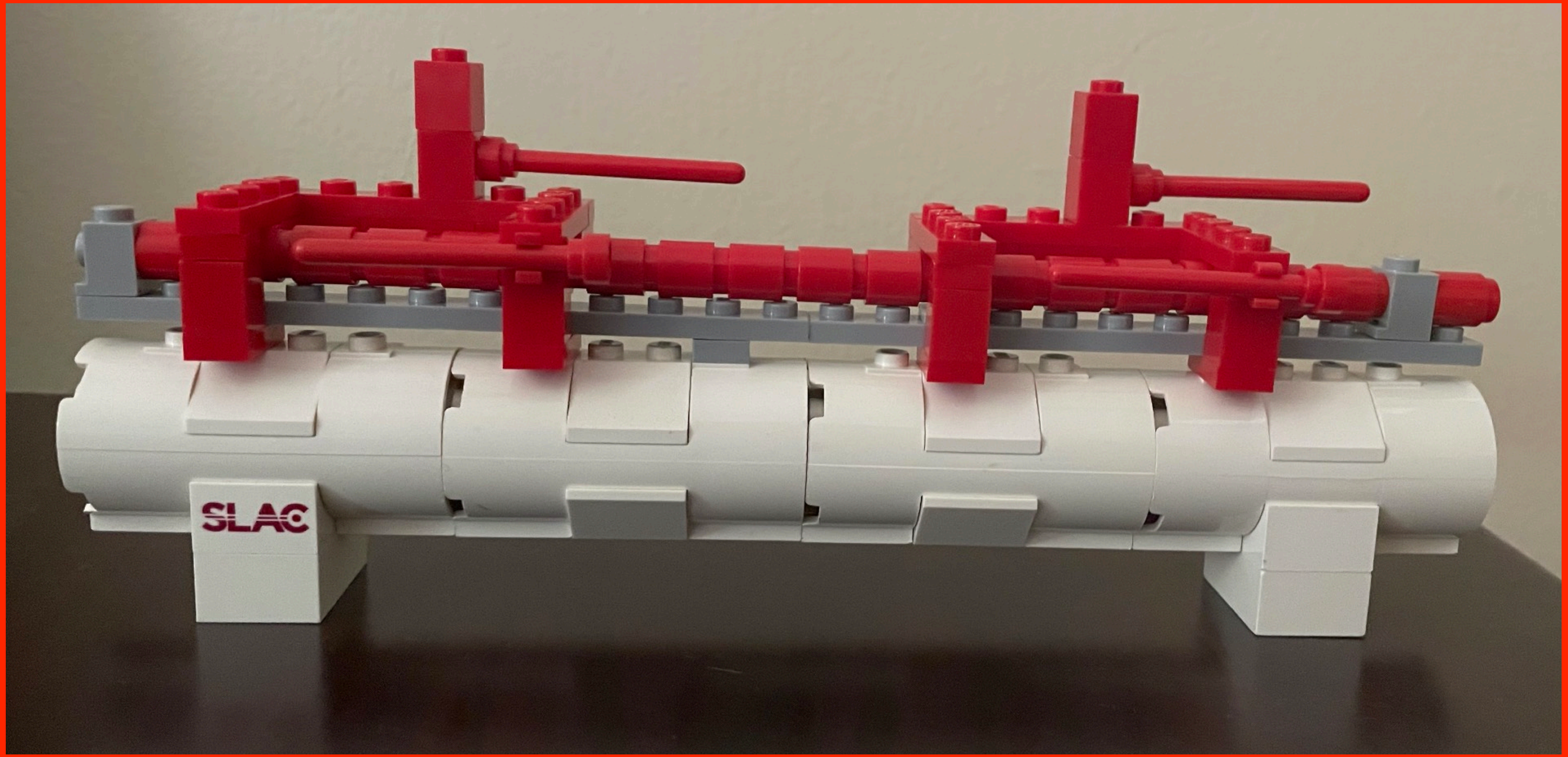
- Early career scientists should drive the agenda for an experiment they will build/use
- Many opportunities for other institutes to collaborate on:
  - (SiD) detector optimization, background studies, beam dynamics, vibrations and alignment, cryogenics, rf engineering, controls, etc
- Research opportunities at SLAC for short-long term:
  - Undergraduate Research Opportunities
    - DOE SULI https://science.osti.gov/wdts/suli
  - Graduate Research Opportunities
    - DOE SCGSR https://science.osti.gov/wdts/scgsr

High Energy Physics: Caterina Vernieri caterina@slac.stanford.edu
Accelerator Science: Emilio Nanni nanni@slac.stanford.edu

Conclusions

- C^3 can provide a rapid route to precision Higgs physics with a compact 8 km footprint
  - ***Higgs physics run by 2040***
  - ***Possibly, a US-hosted facility***
- C^3 time structure is compatible with SiD-like detector overall design and ongoing optimizations.
- C^3 can be quickly and inexpensively upgraded to 550 GeV
- C^3 can be extended to a 3 TeV e^+e^- collider with capabilities similar to CLIC
- With new ideas, the C^3 lab can provide physics at 10 TeV and beyon
- May be possible to do physics at an intermediate stage in the construction at 91 GeV
  - We do not consider this a part of our baseline, but we mention the possibility in case there is community interest for a Giga-Z (2 yrs) program.



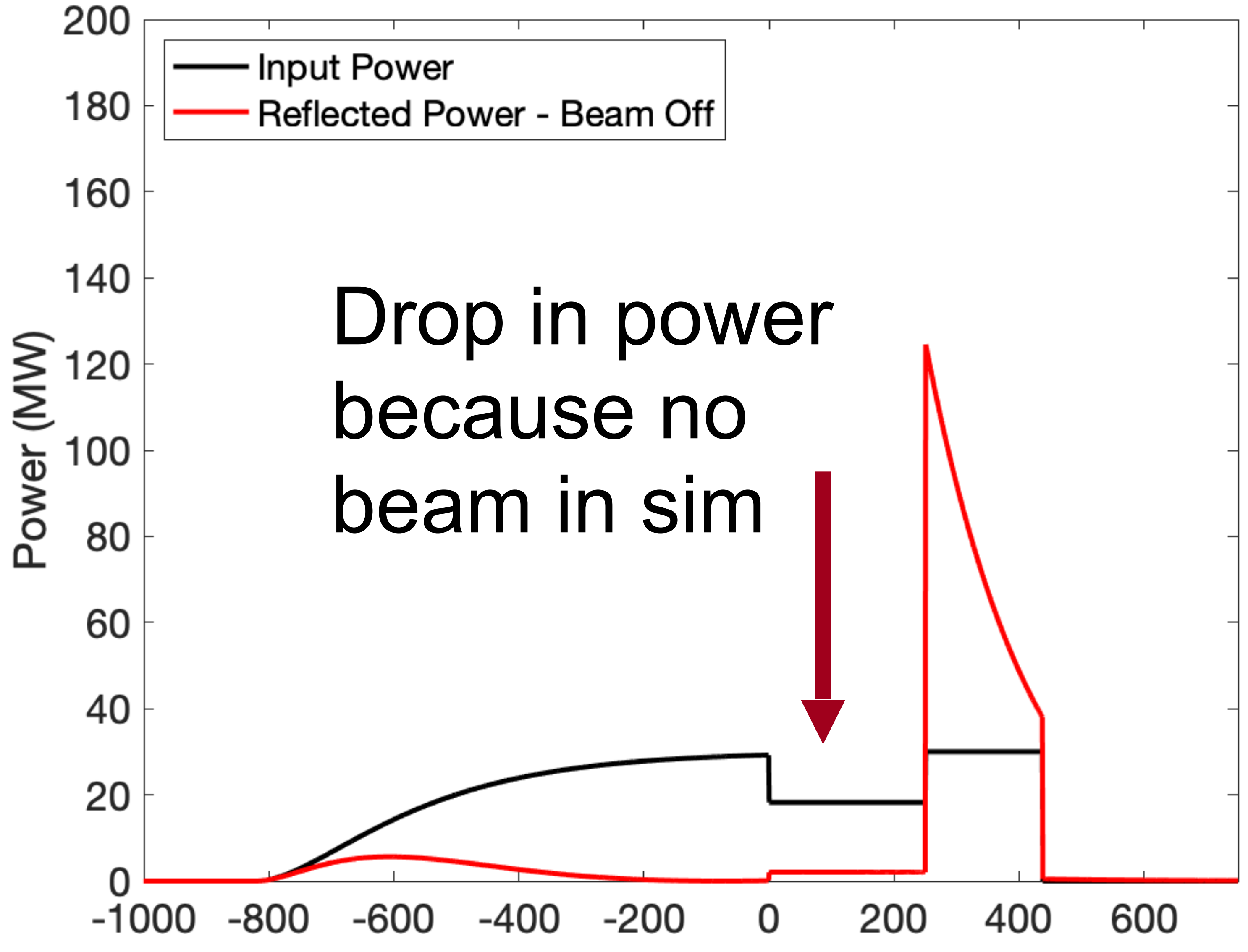


Extra

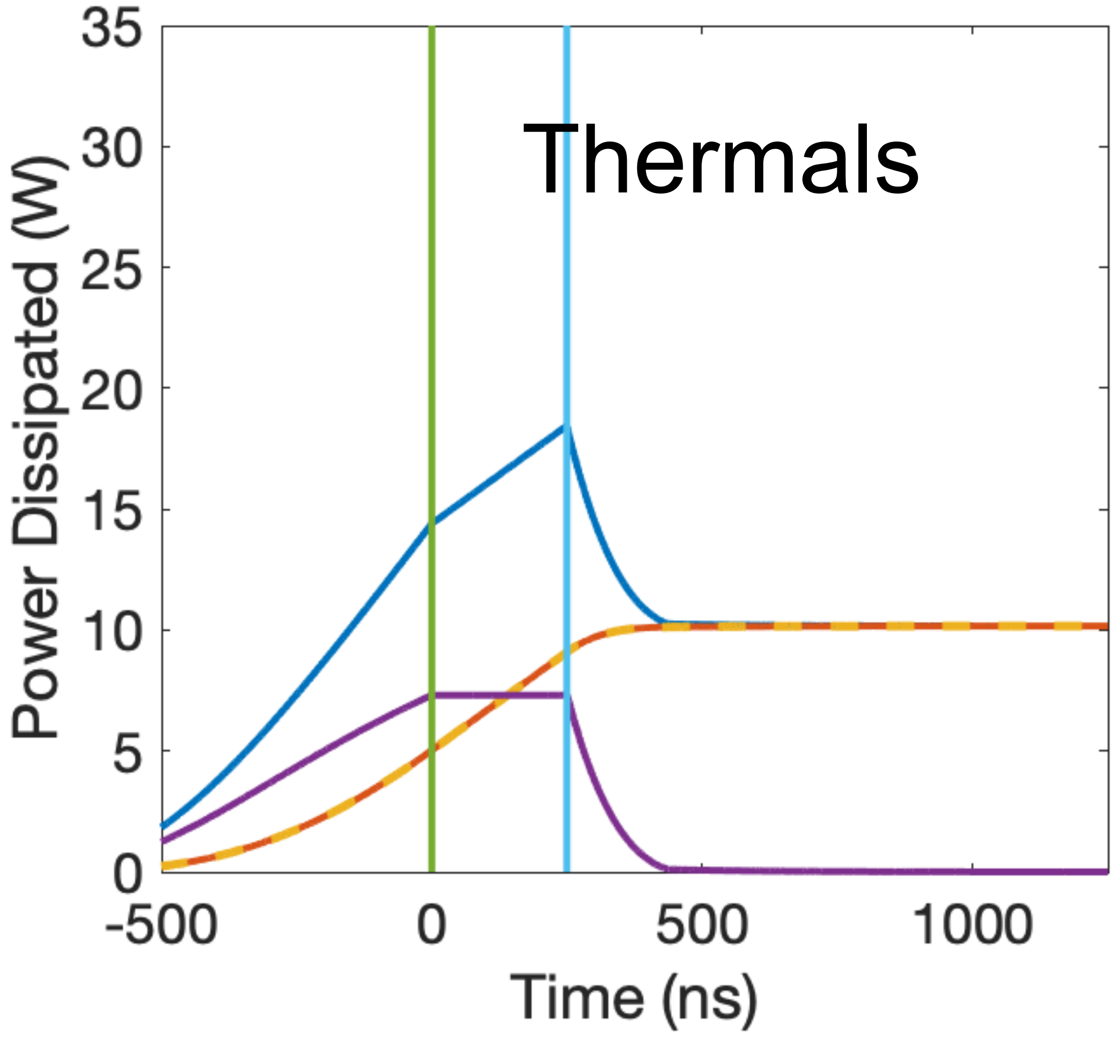
RF Power Requirements

- 70 MeV/m 250 ns Flattop (extendible to 700 ns)
- ~1 microsecond rf pulse, ~30 MW/m
  - Conservative 2.3X enhancement from cryo
- No pulse compression
- Ramp power to reduce reflected power
- Flip phase at output to reduce thermals

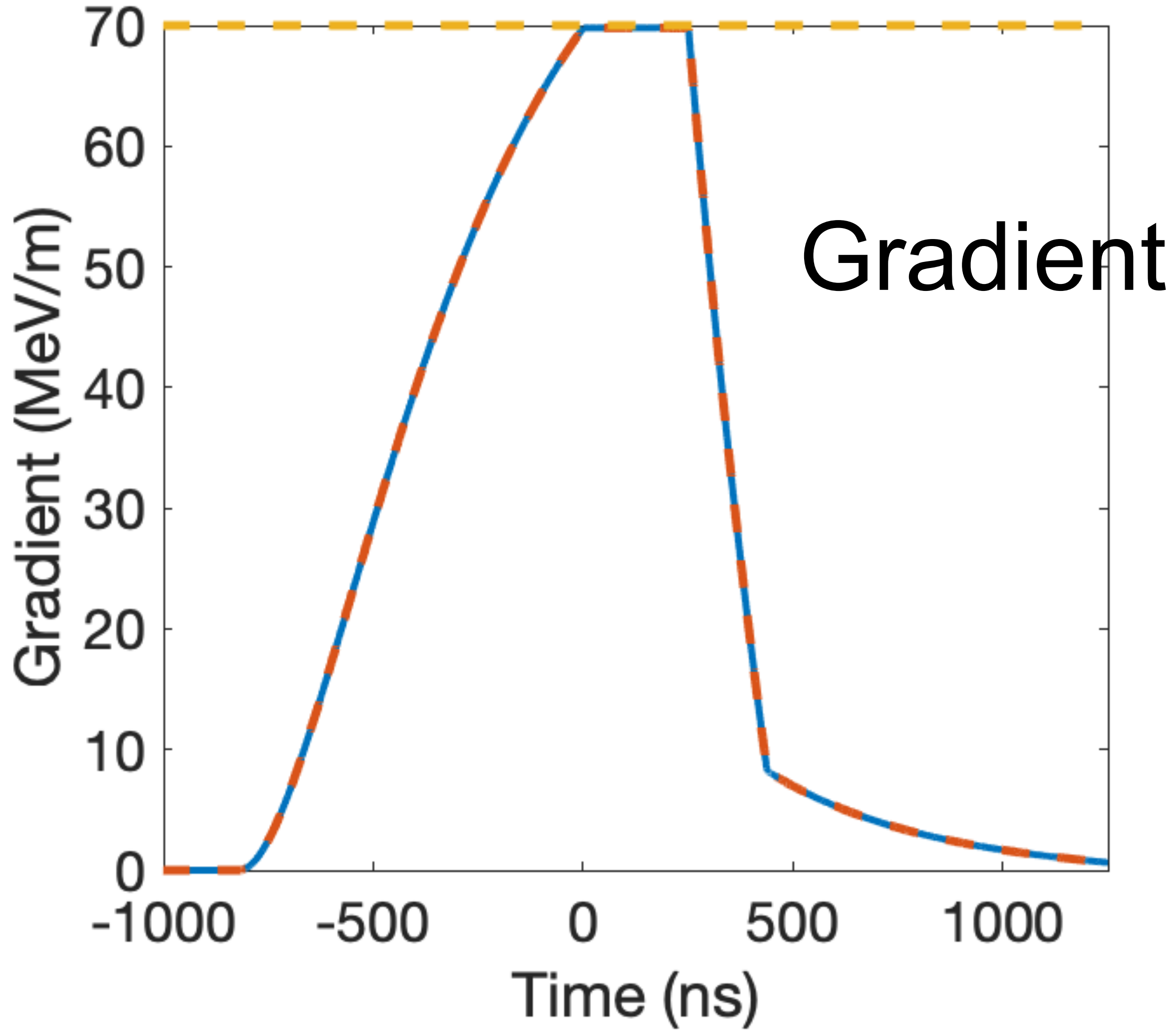
- One 65 MW klystron every two meters -> Matches CLIC-k rf module power



Drop in power because no beam in sim



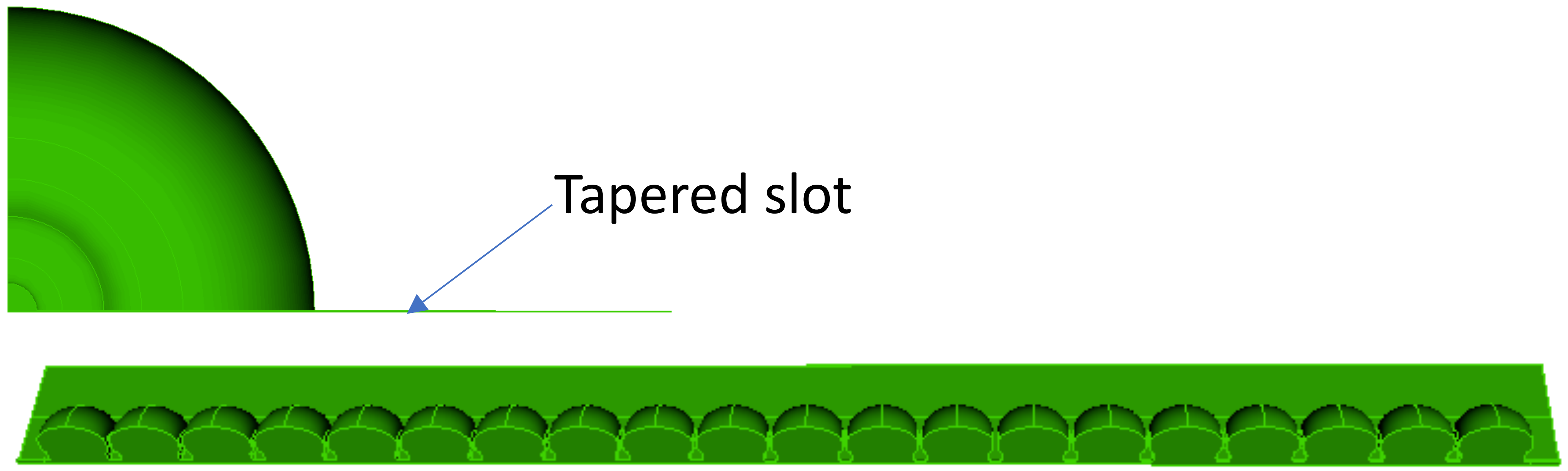
Thermals

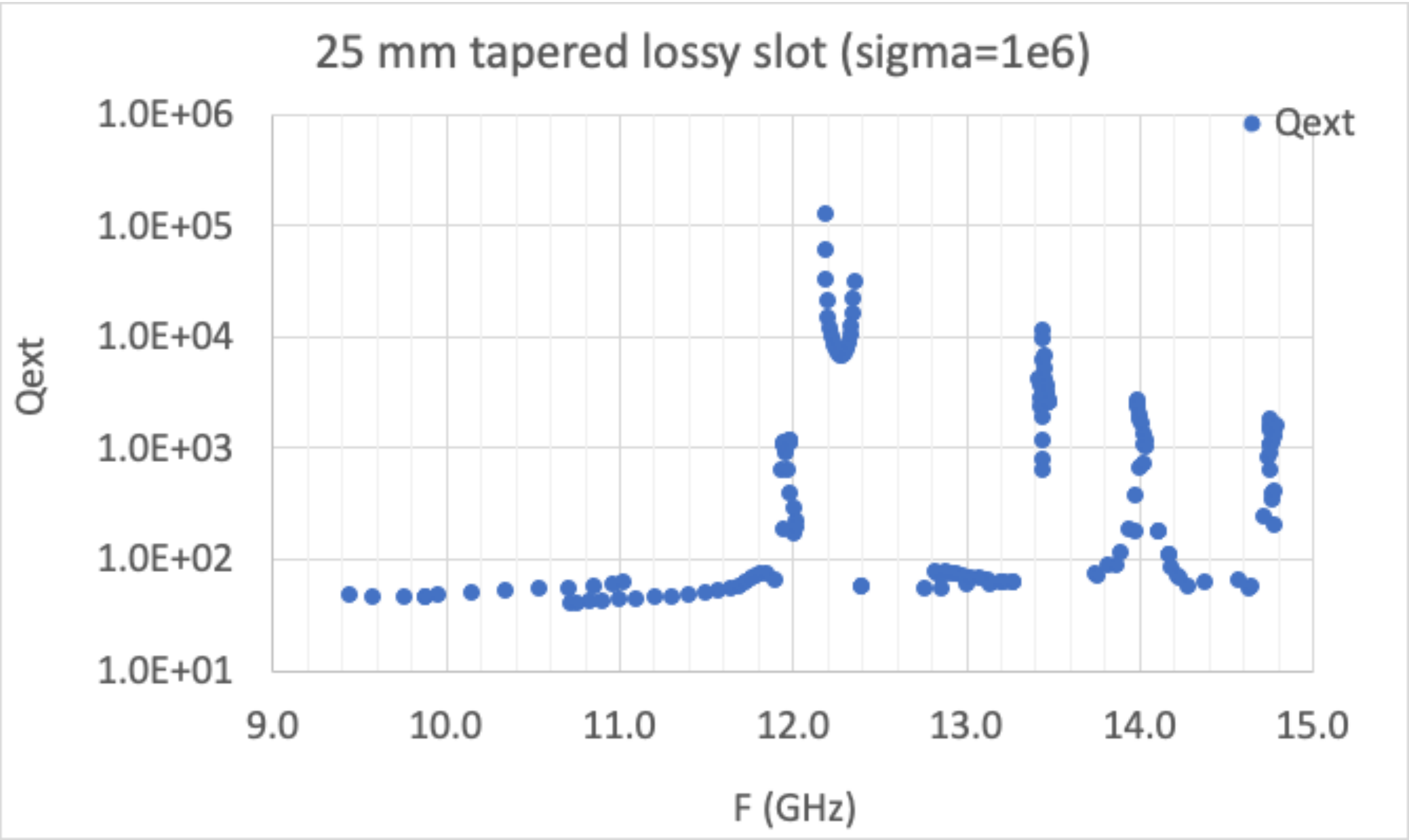


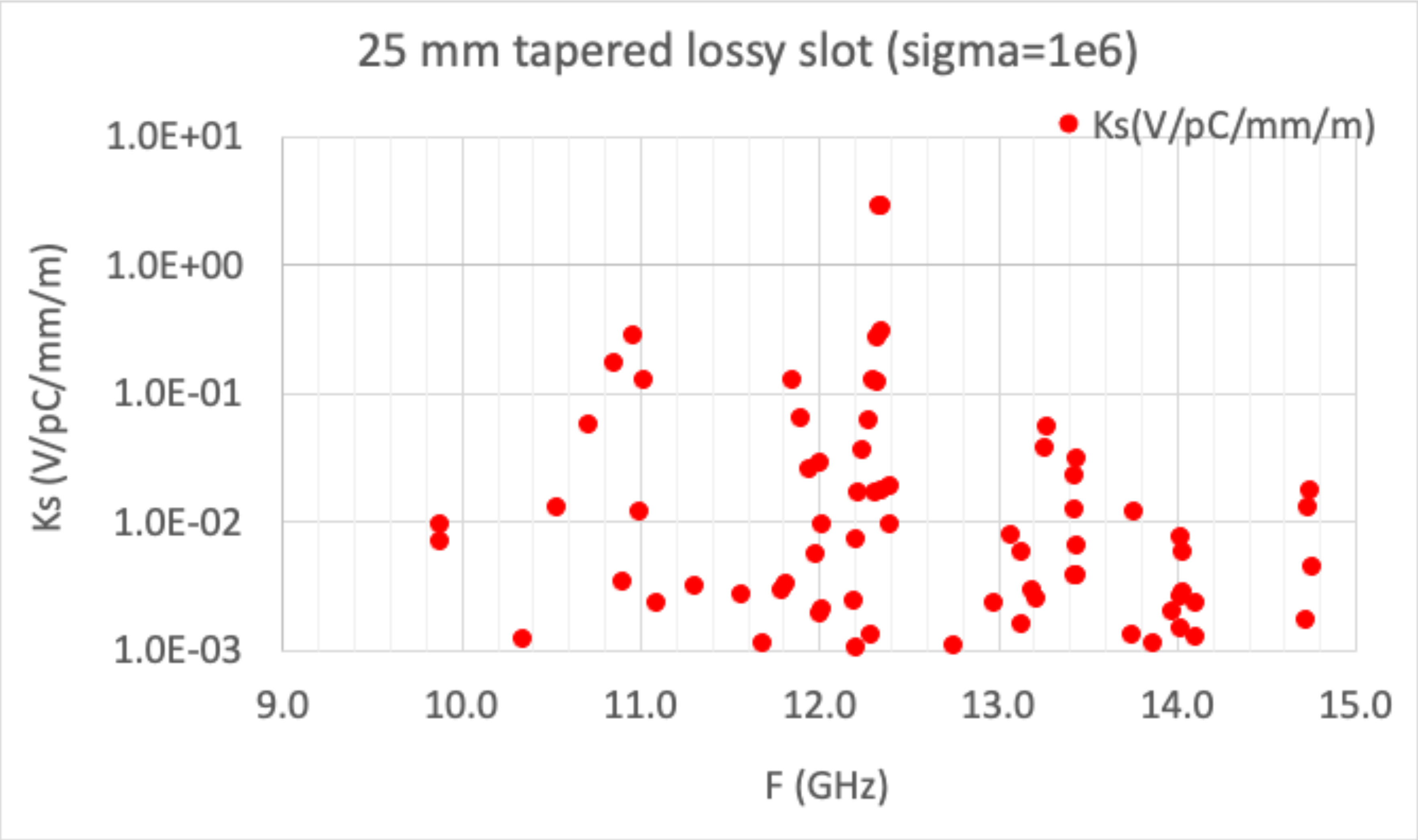
Gradient

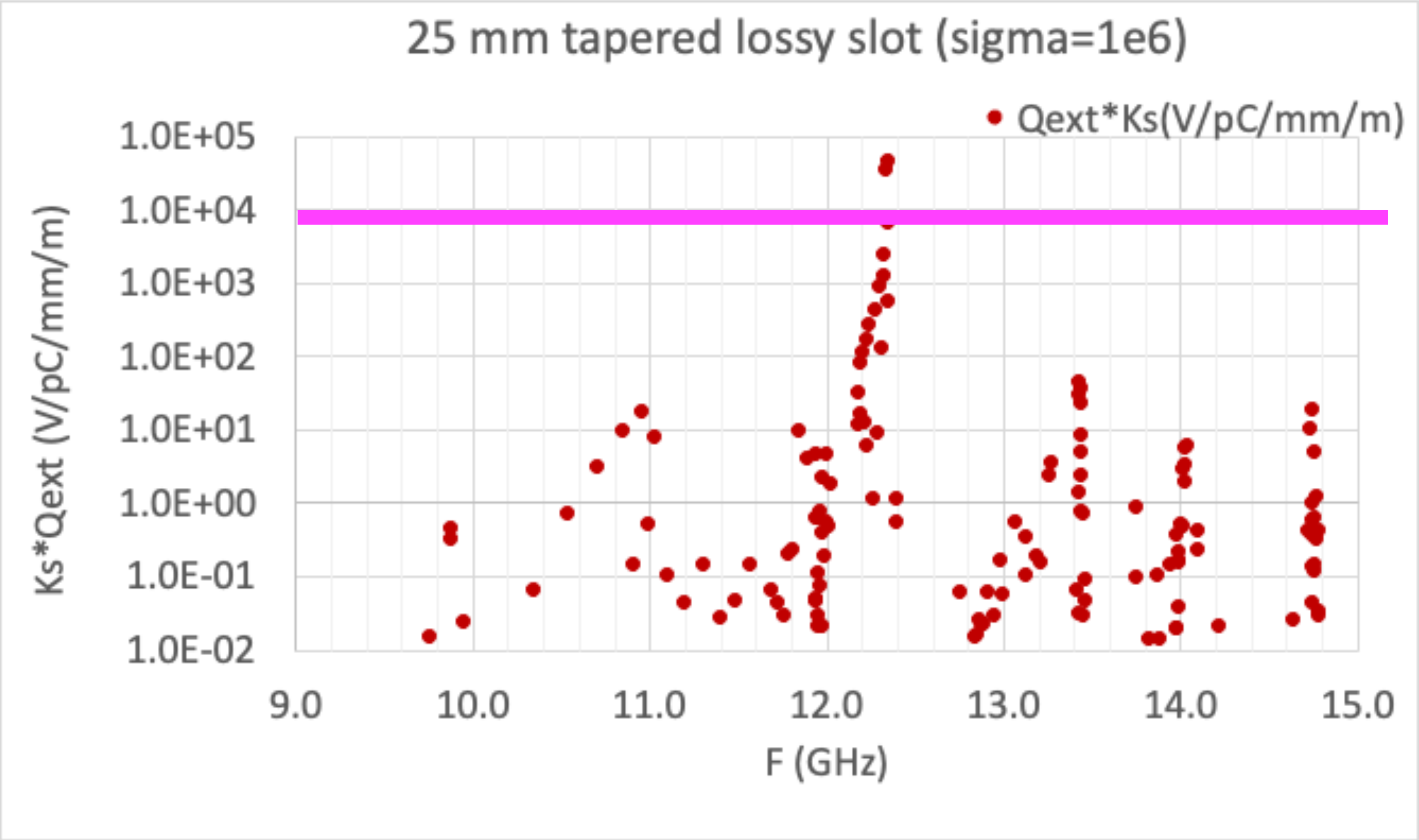
HOM Damping with Tapered Lossy Slot - Preliminary - Z. Li

- Slot surface conductivity: 1e6
- Tapered slot height: from 300 micron to 100 micron







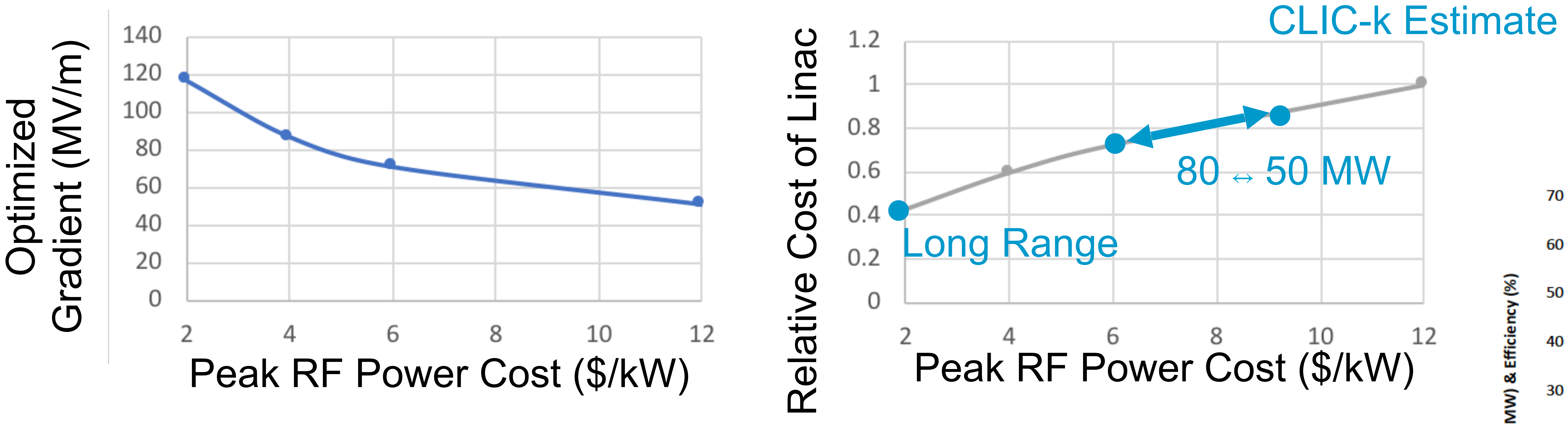


Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m

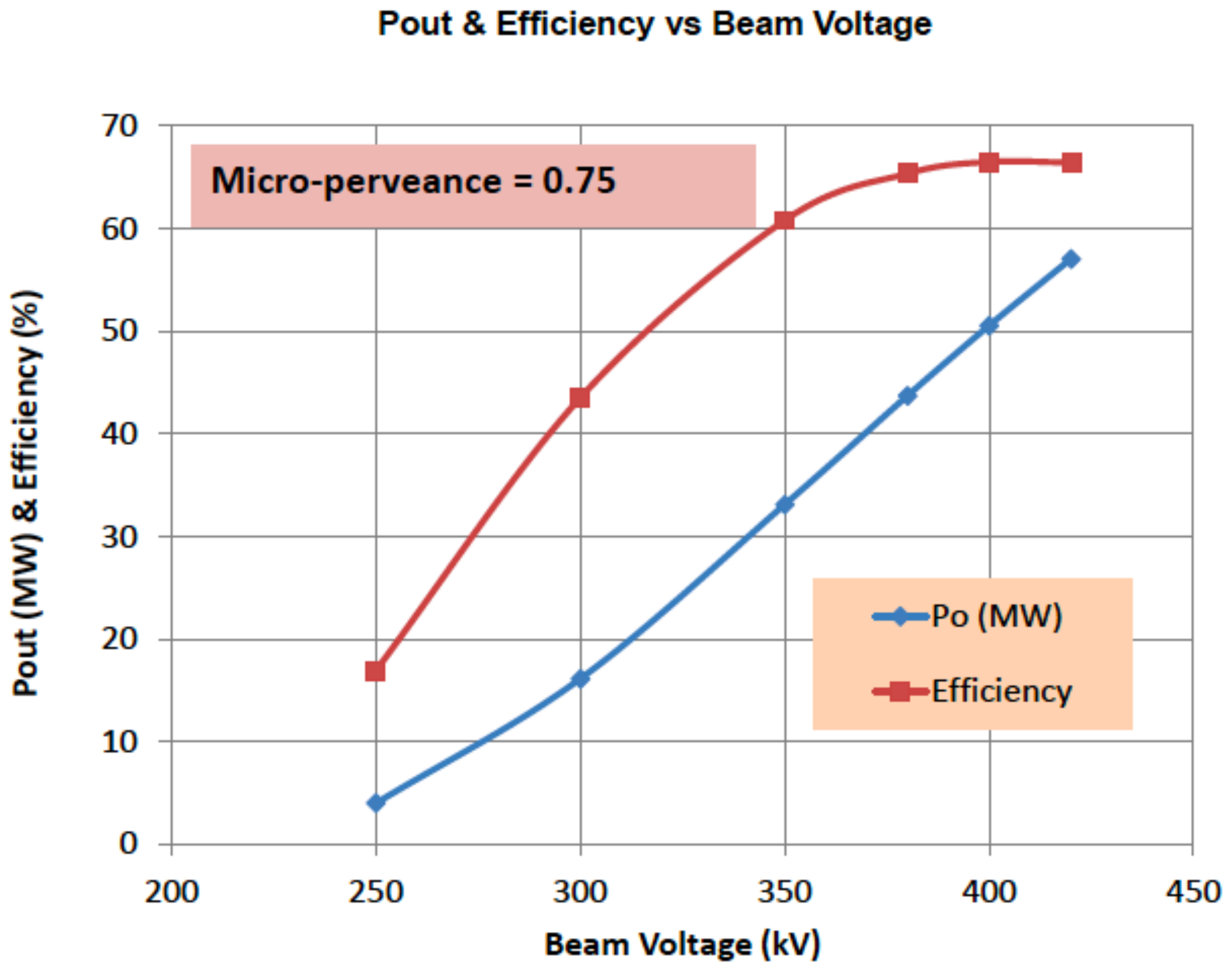
RF Source R&D Remains a Major Focus Over the Timescale of the Next P5

- 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

Detector Design Requirements

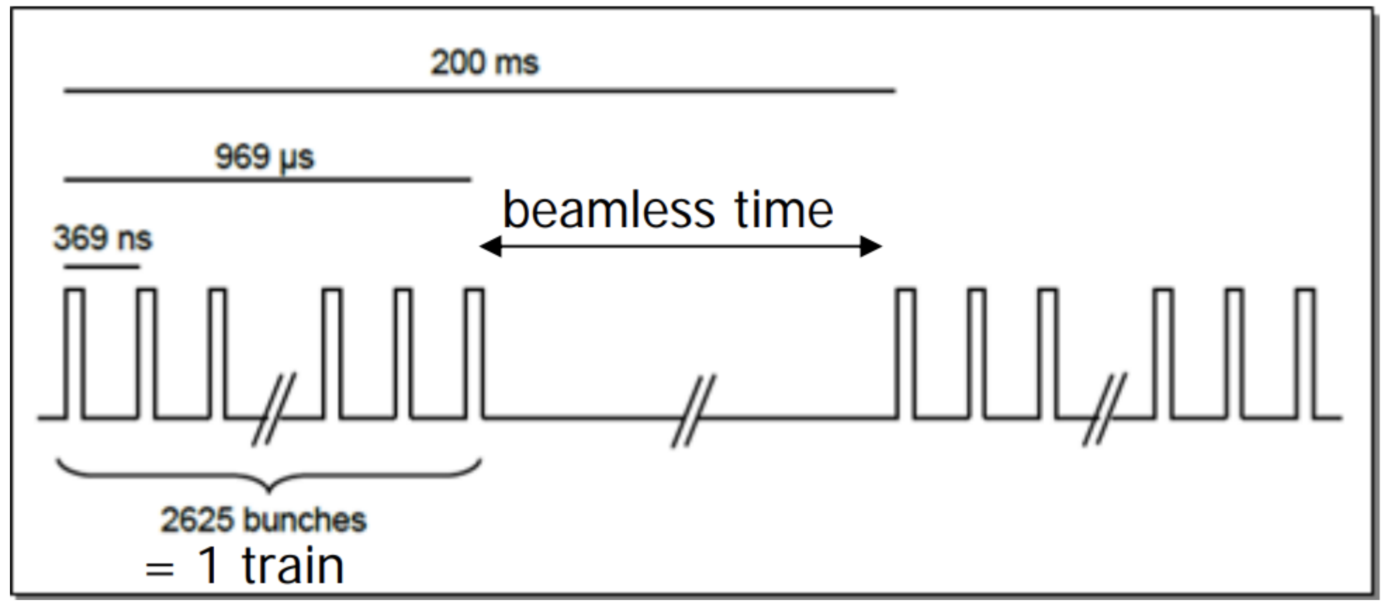
ILC timing structure: Fraction of a percent duty cycle

- **Power pulsing possible**, significantly reduce heat load
    - Factor of 50-100 power saving for FE analog power
- Tracking detectors **don't need active cooling**
    - Significantly reduction for the material budget
- **Triggerless readout** is the baseline

C^3 time structure is compatible with SiD-like detector overall design and ongoing optimizations.

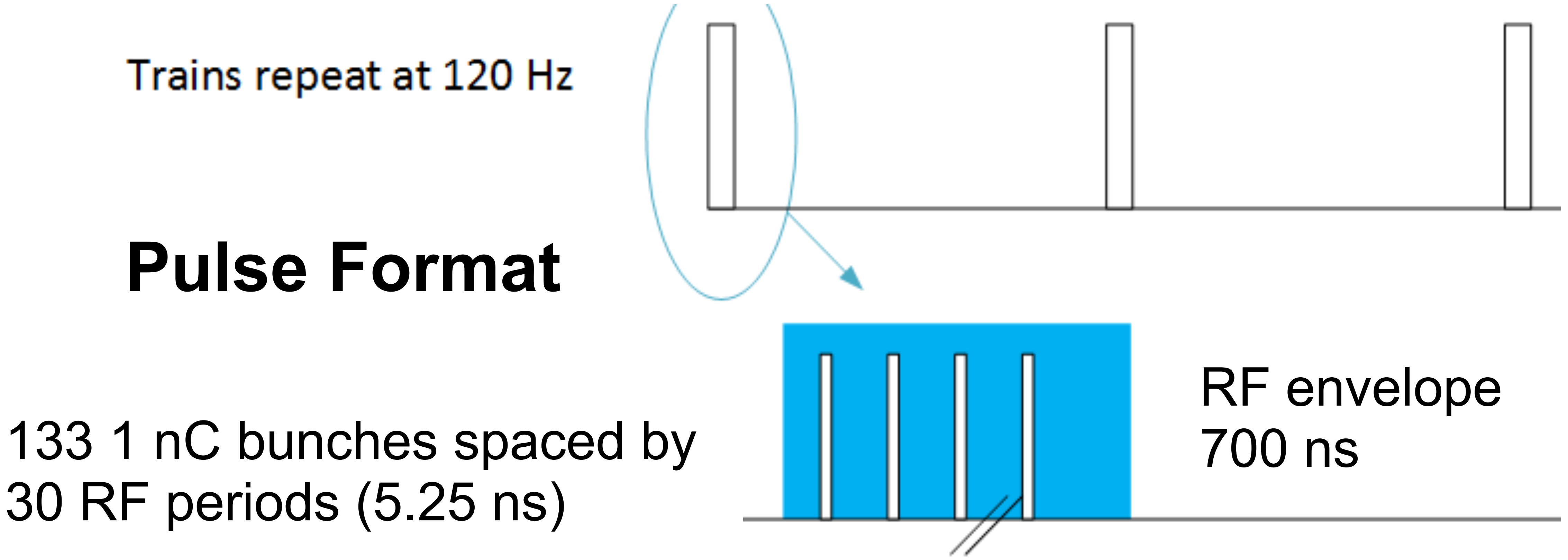
Collider	ILC	CCC
σ_z	300 μm	100 μm
β_x	8.0 mm	13 mm
β_y	0.41 mm	0.1 mm
ϵ_x	500 nm/rad	900 nm/rad
ϵ_y	35 nm/rad	20 nm/rad
N bunches	1312	133
Repetition rate	5 Hz	120 Hz
Crossing angle	0.014	0.020
Crab angle	0.014/2	0.020/2

ILC timing structure



1 ms long bunch trains at 5 Hz
2820 bunches per train
308ns spacing

C^3 timing structure



Trains repeat at 120 Hz

Pulse Format

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

RF envelope 700 ns