A “C^3ool” route to unveil the Higgs boson’s secrets

Topic Of The Week · Fermilab · April 25, 2023

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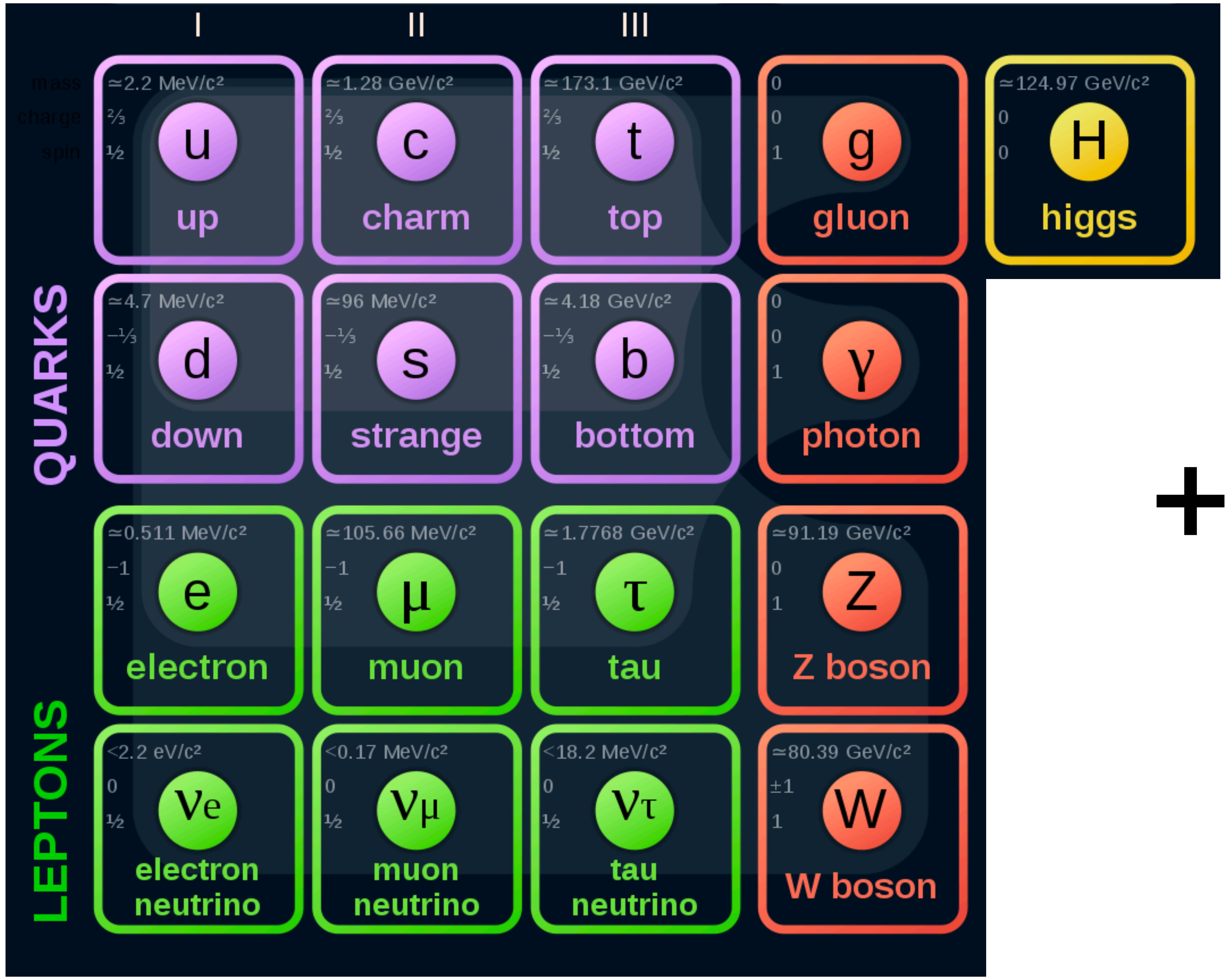
Outline

The Standard Model and the Higgs boson

- What we have learned so far
- Perspectives at the LHC
- Beyond LHC: Higgs Factory and the Cool Copper Collider

The Higgs Boson



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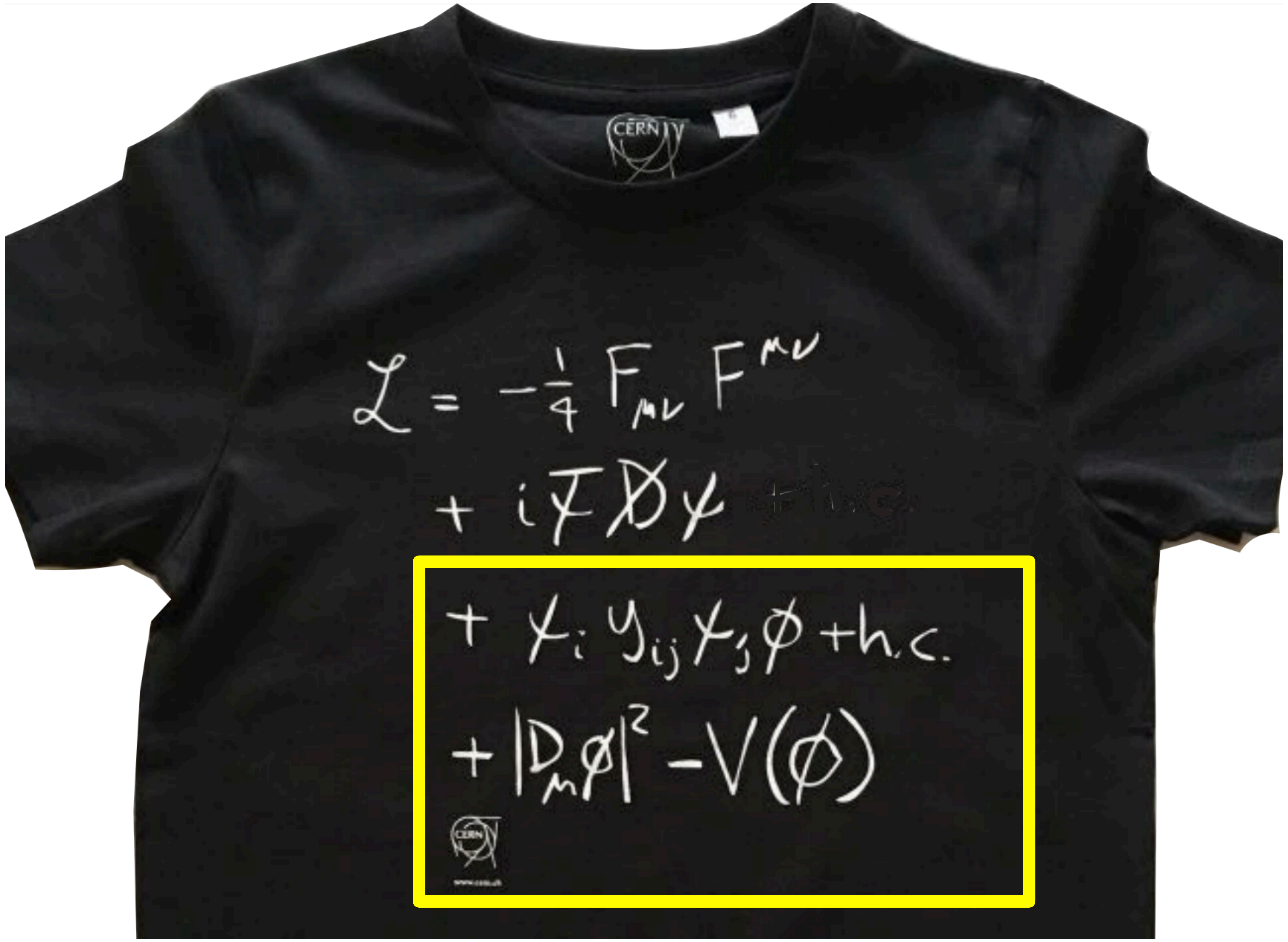
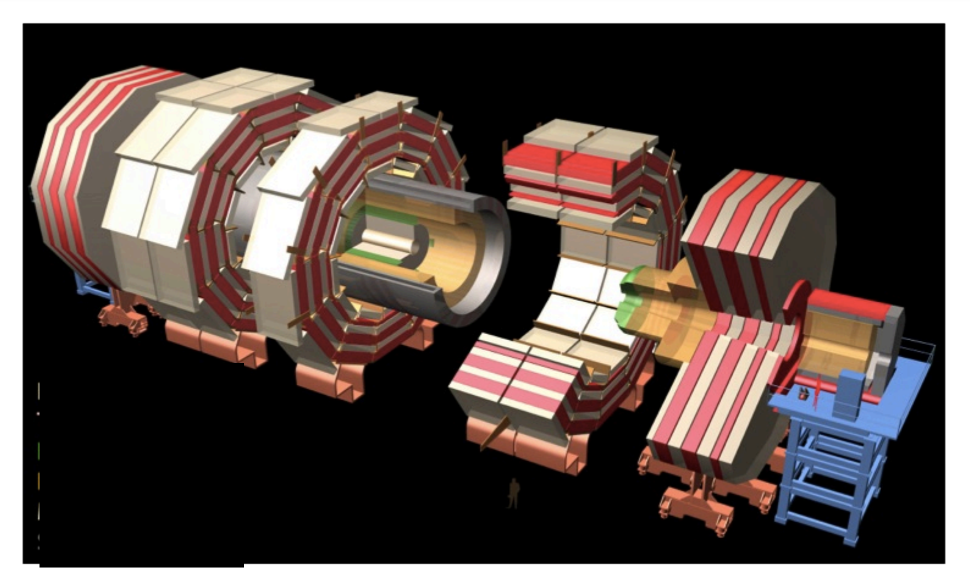
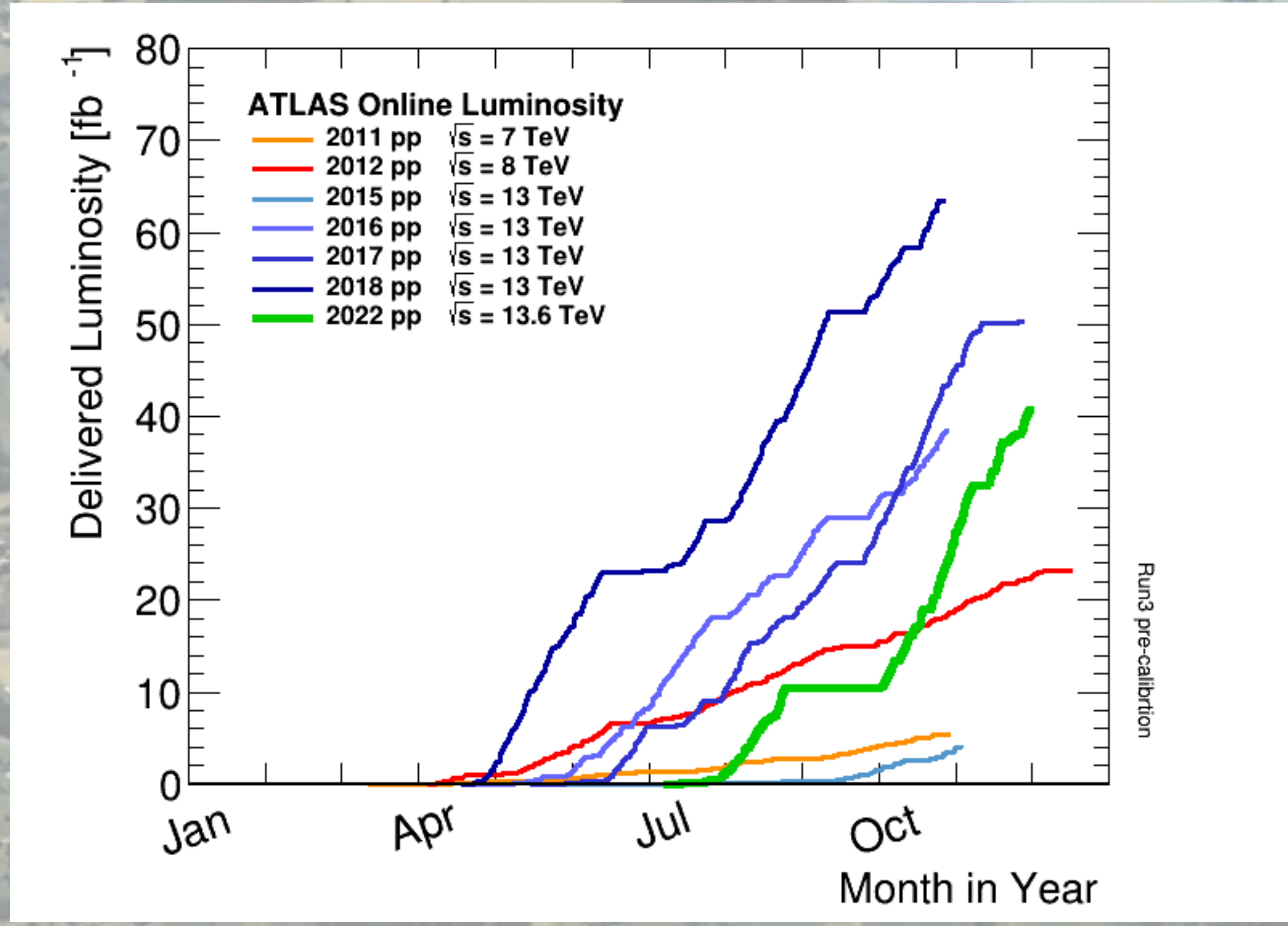


The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC)

LHCb
CERN Prévessin
SPS 7 km
ALICE
LHC 27 km
ATLAS
CMS



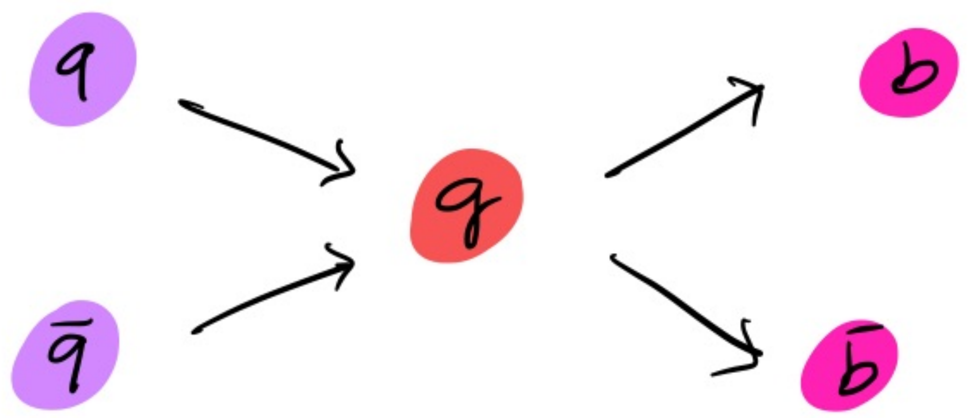


A factor 20x more data than at the time of the Higgs discovery

p p

PROBABILITY

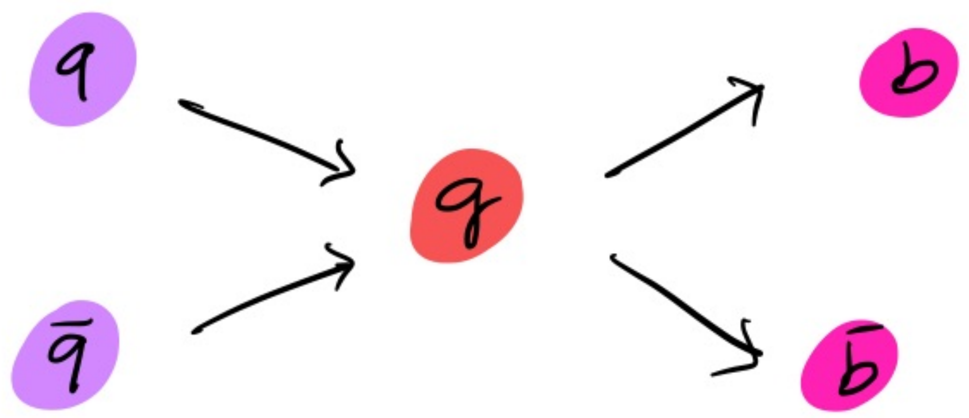
PROBABILITY



bottom

1 in a hundred ***pp collisions***

PROBABILITY



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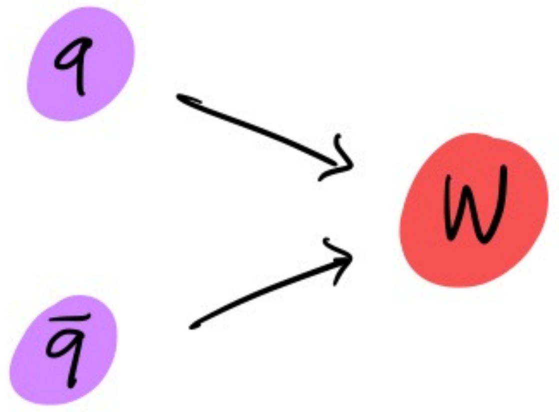
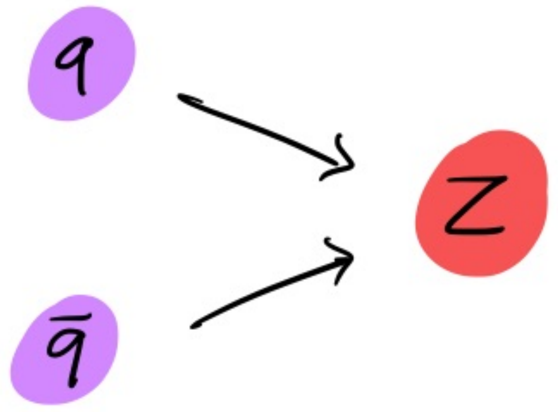
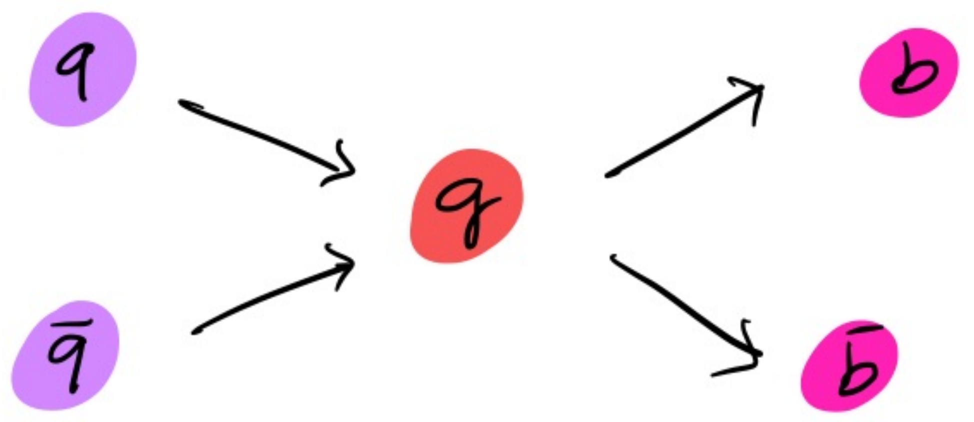




W — 1 in a half a million

Z — 1 in a million

PROBABILITY



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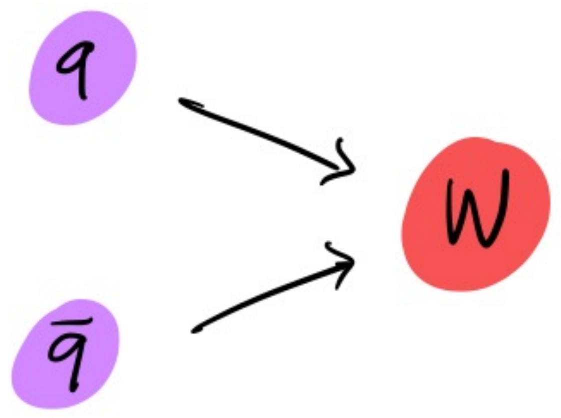

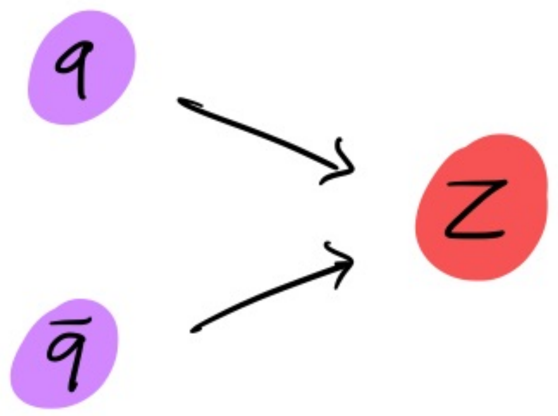

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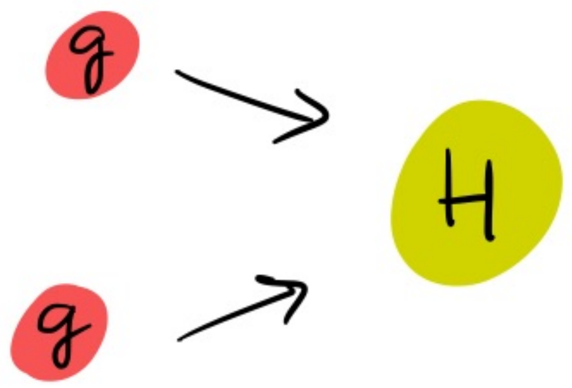
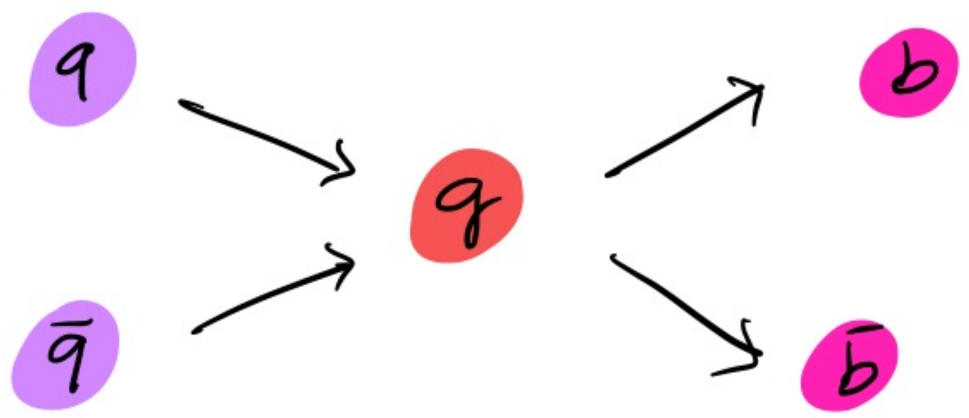


H — **1 in a billion**

PROBABILITY



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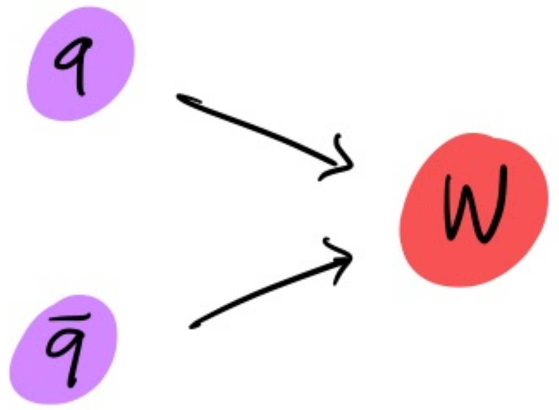

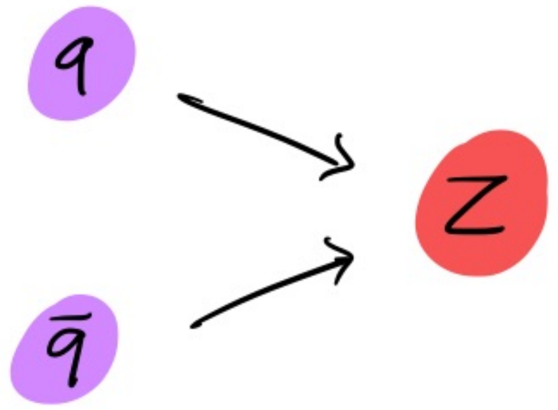

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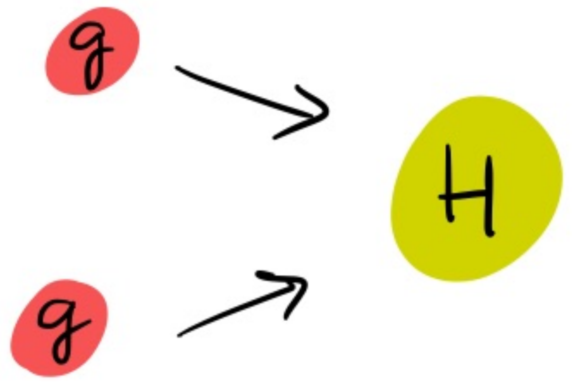
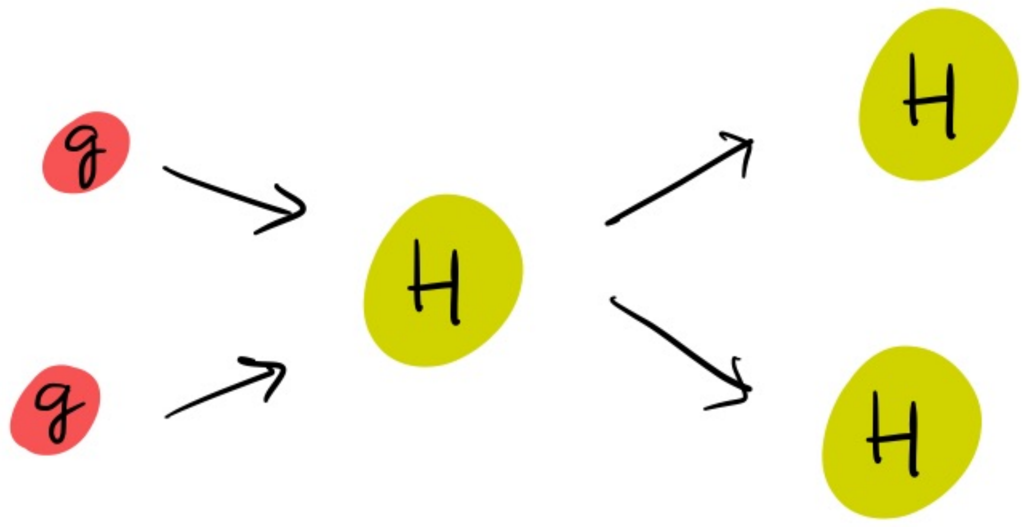
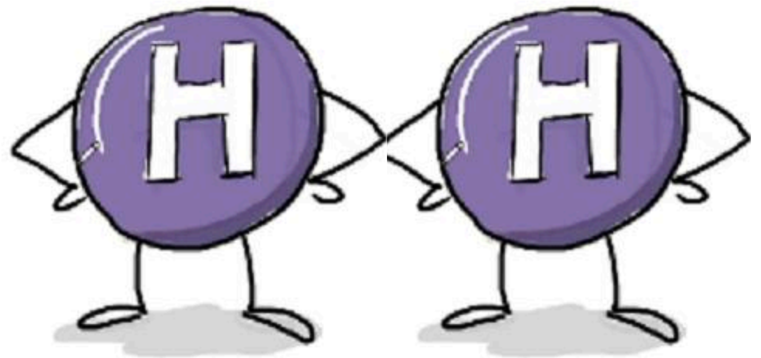


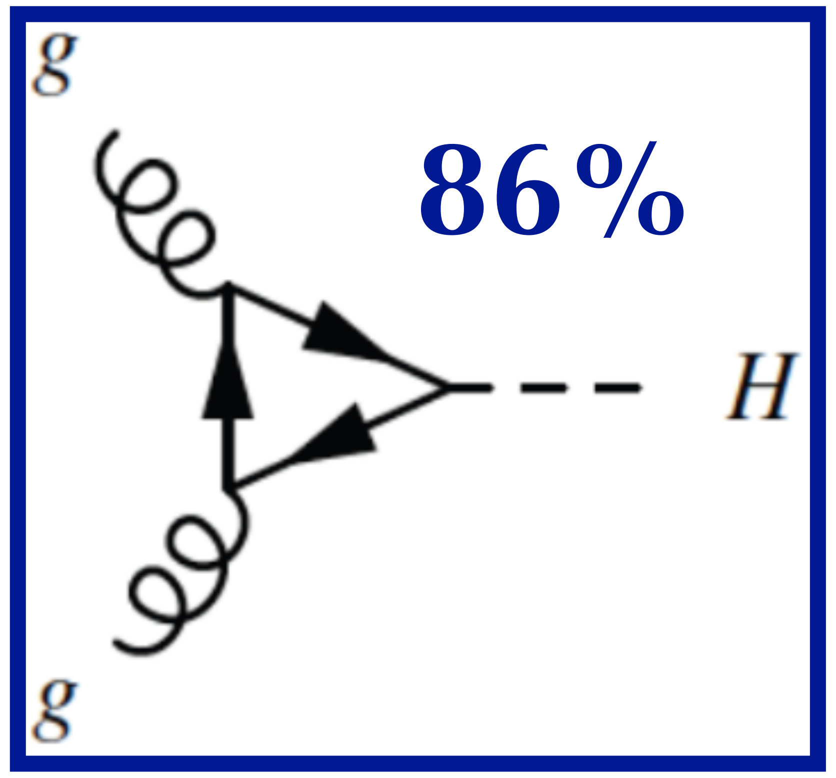
H — **1 in a billion**



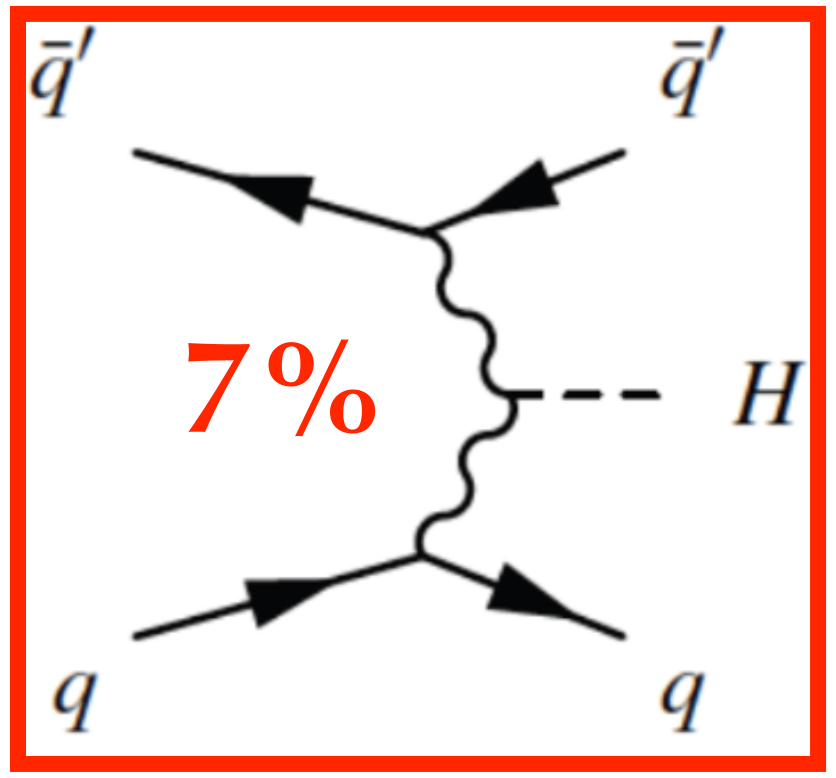
HH — **1 in a trillion**



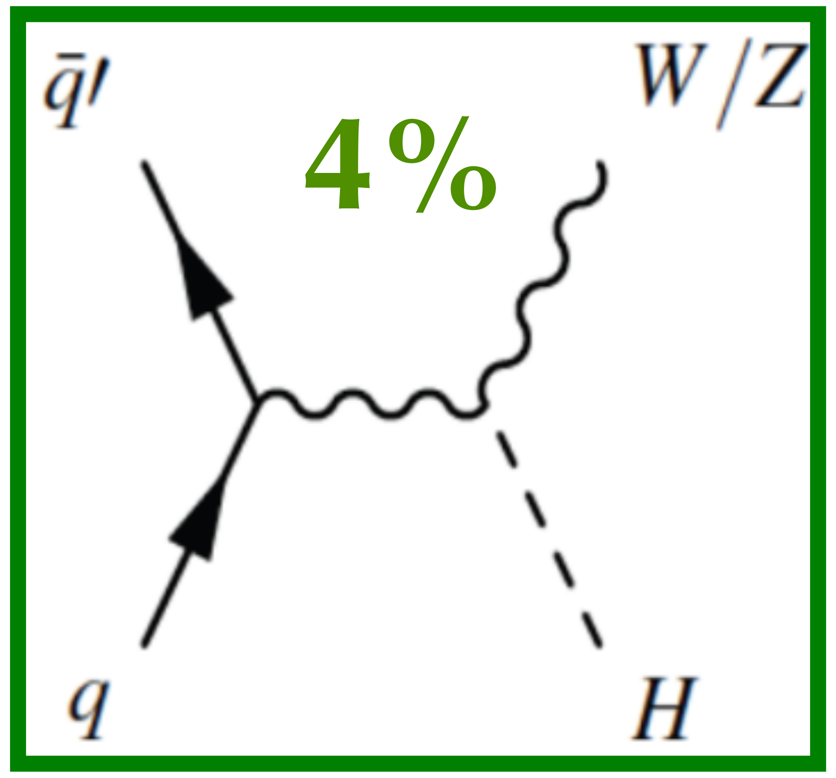
Higgs Boson Production at the LHC



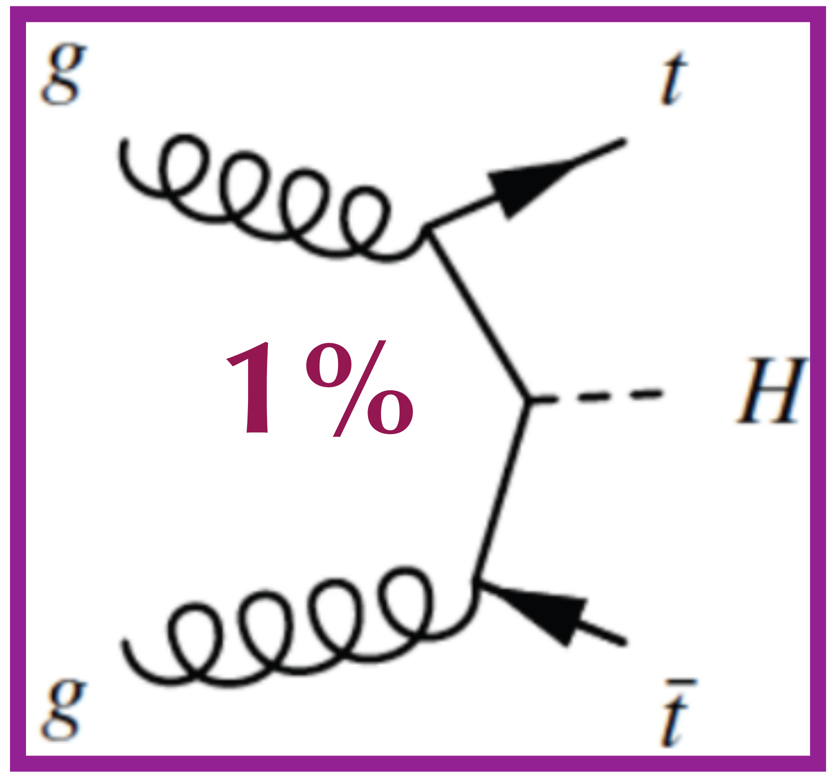
Gluon Fusion



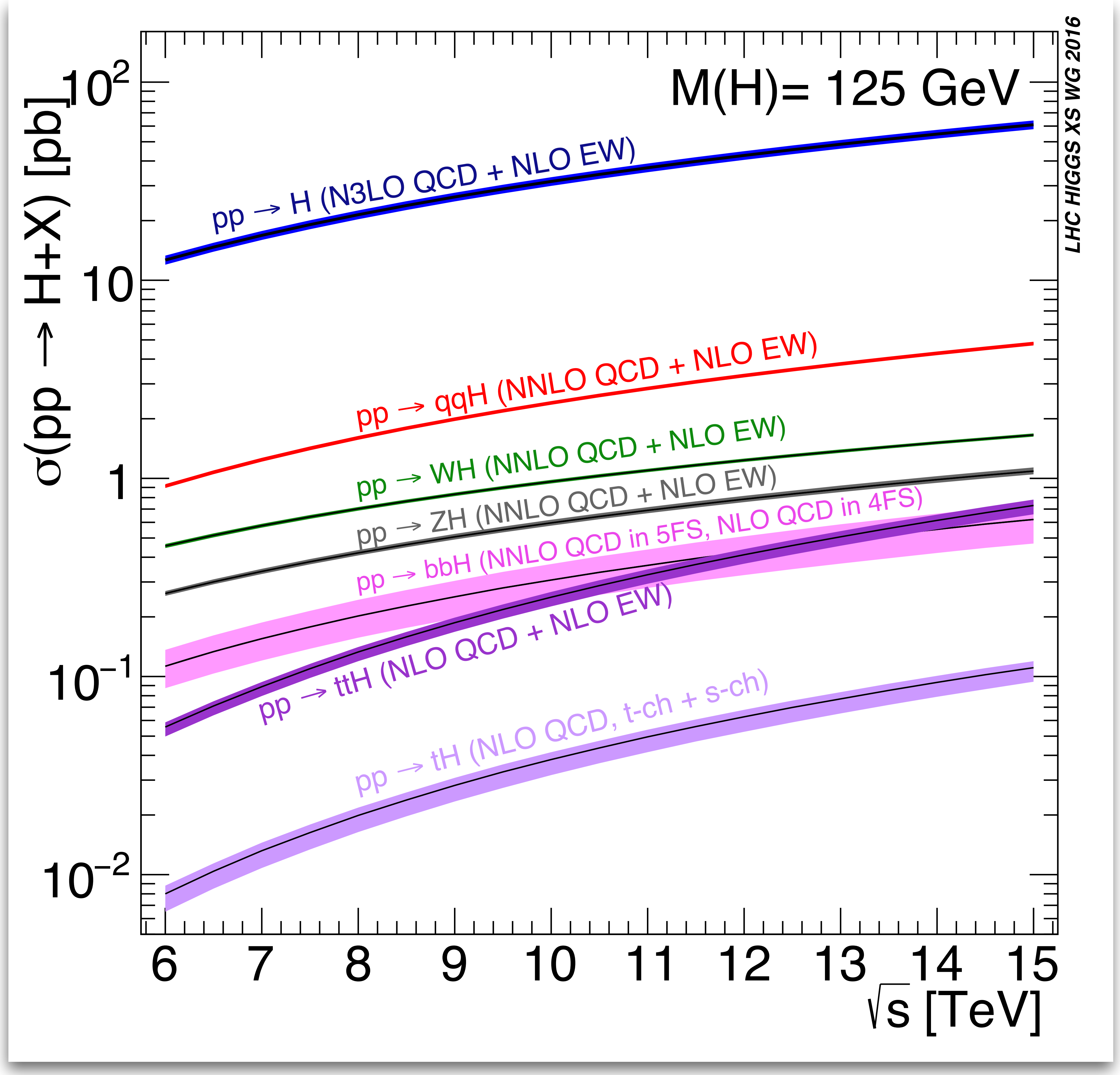
Vector-Boson Fusion



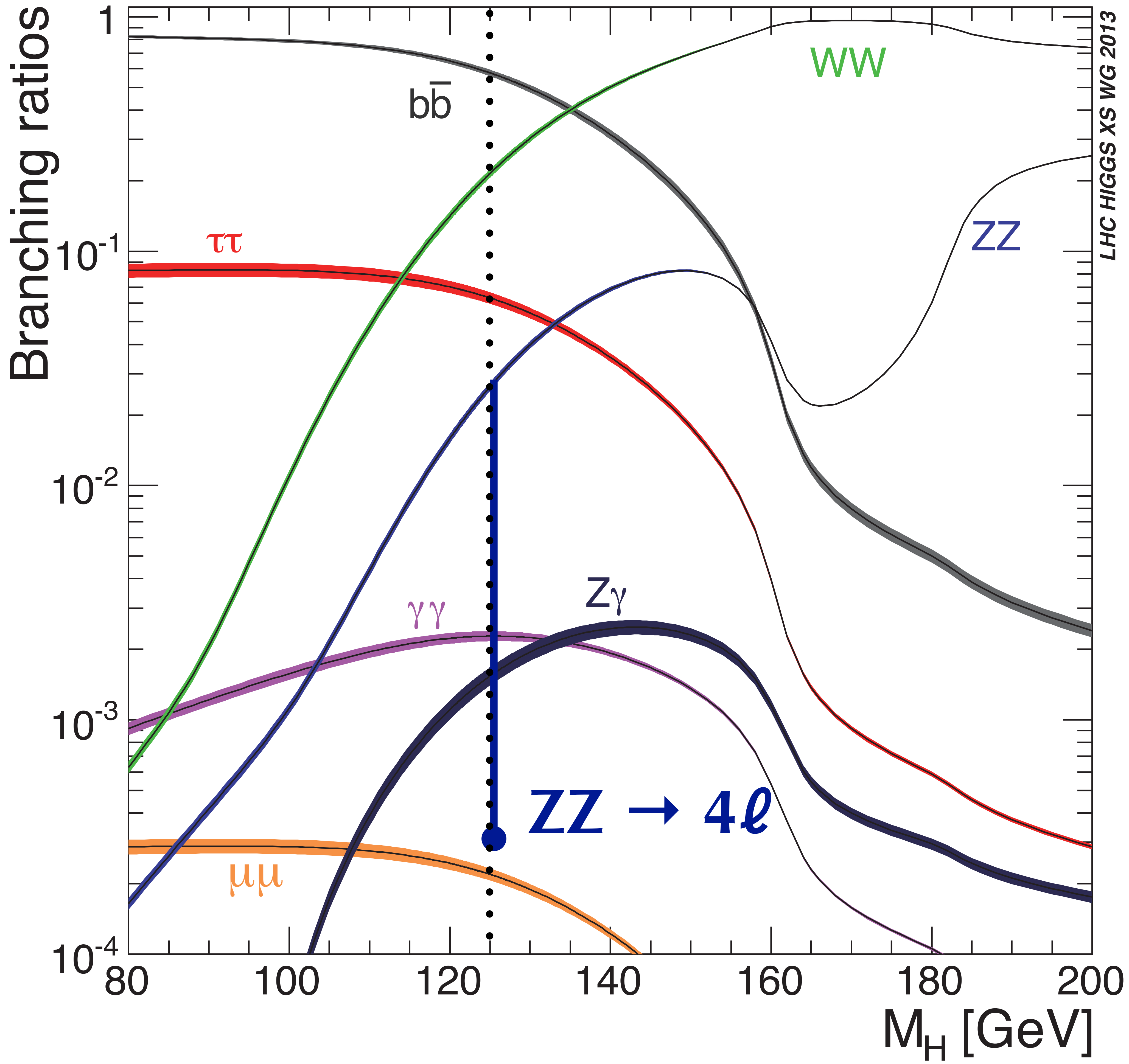
Higgs-strahlung



Top Fusion (ttH)



How does it Decay (m_H = 125 GeV) ?



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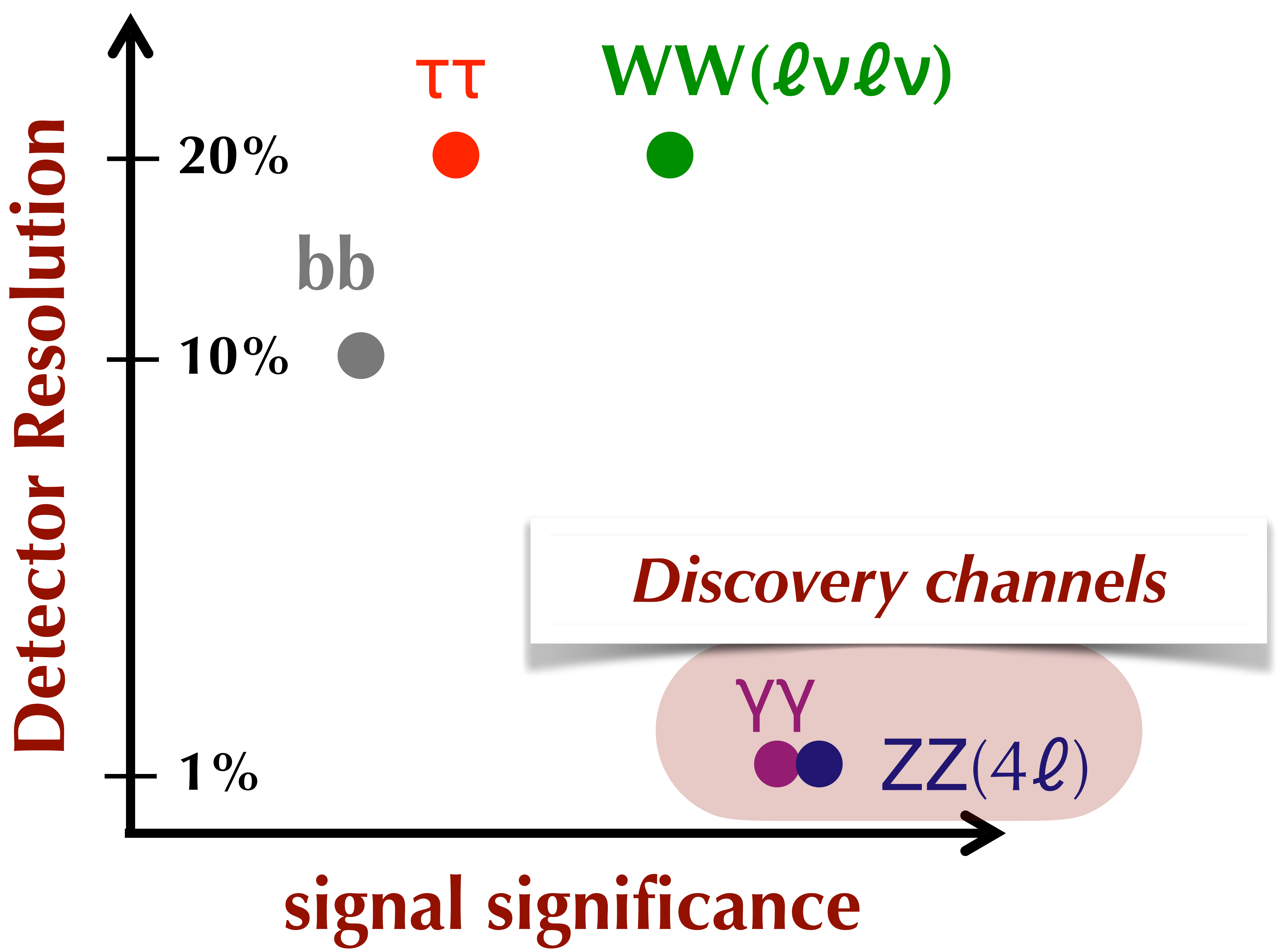
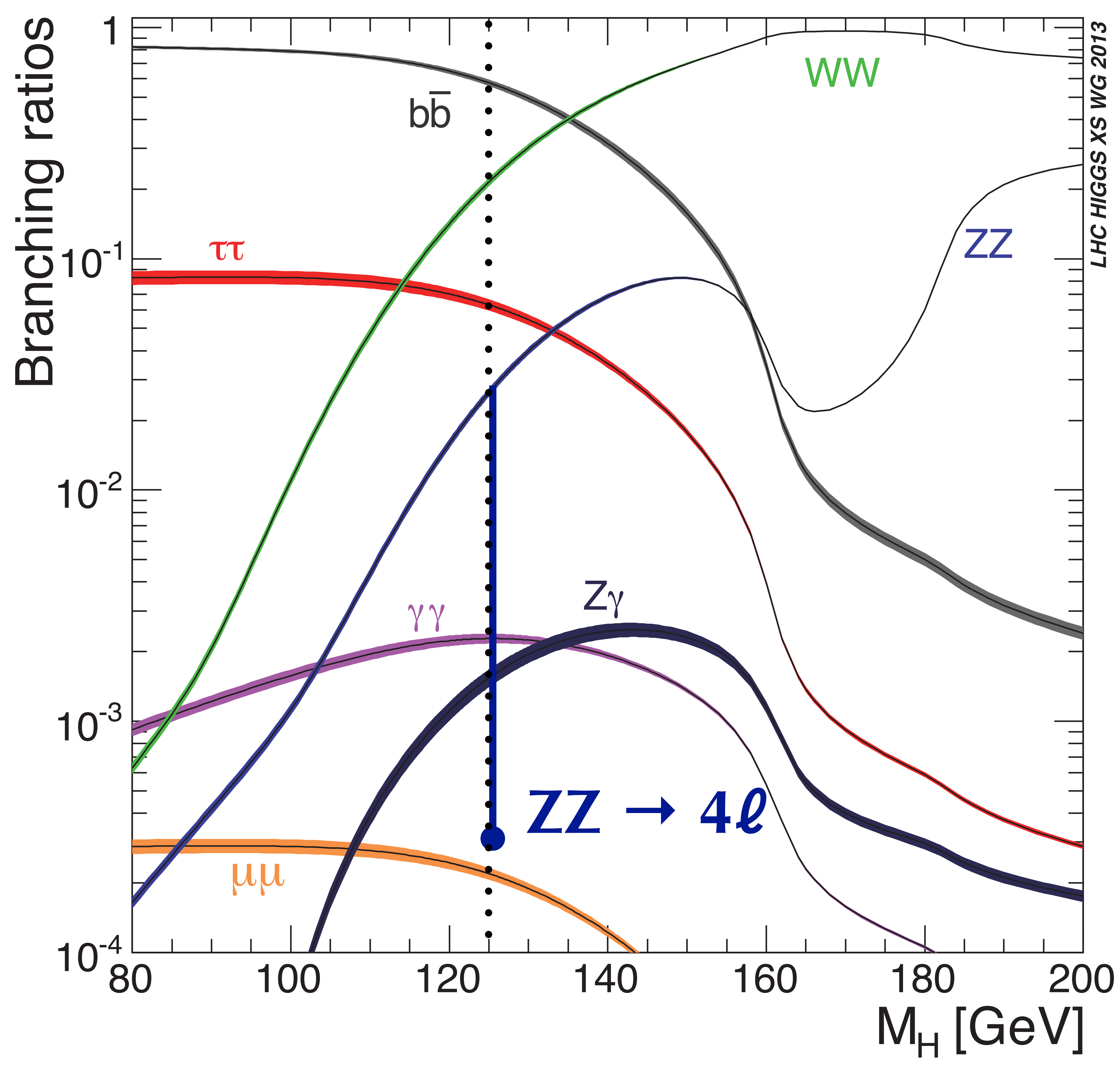
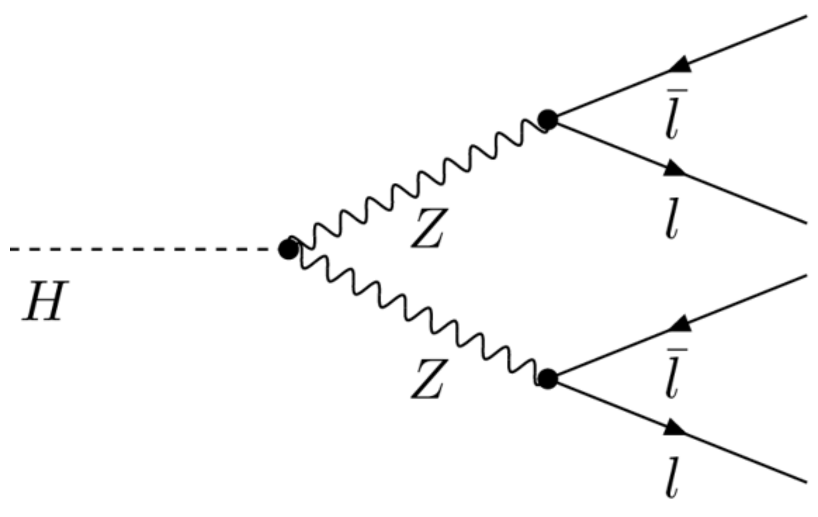
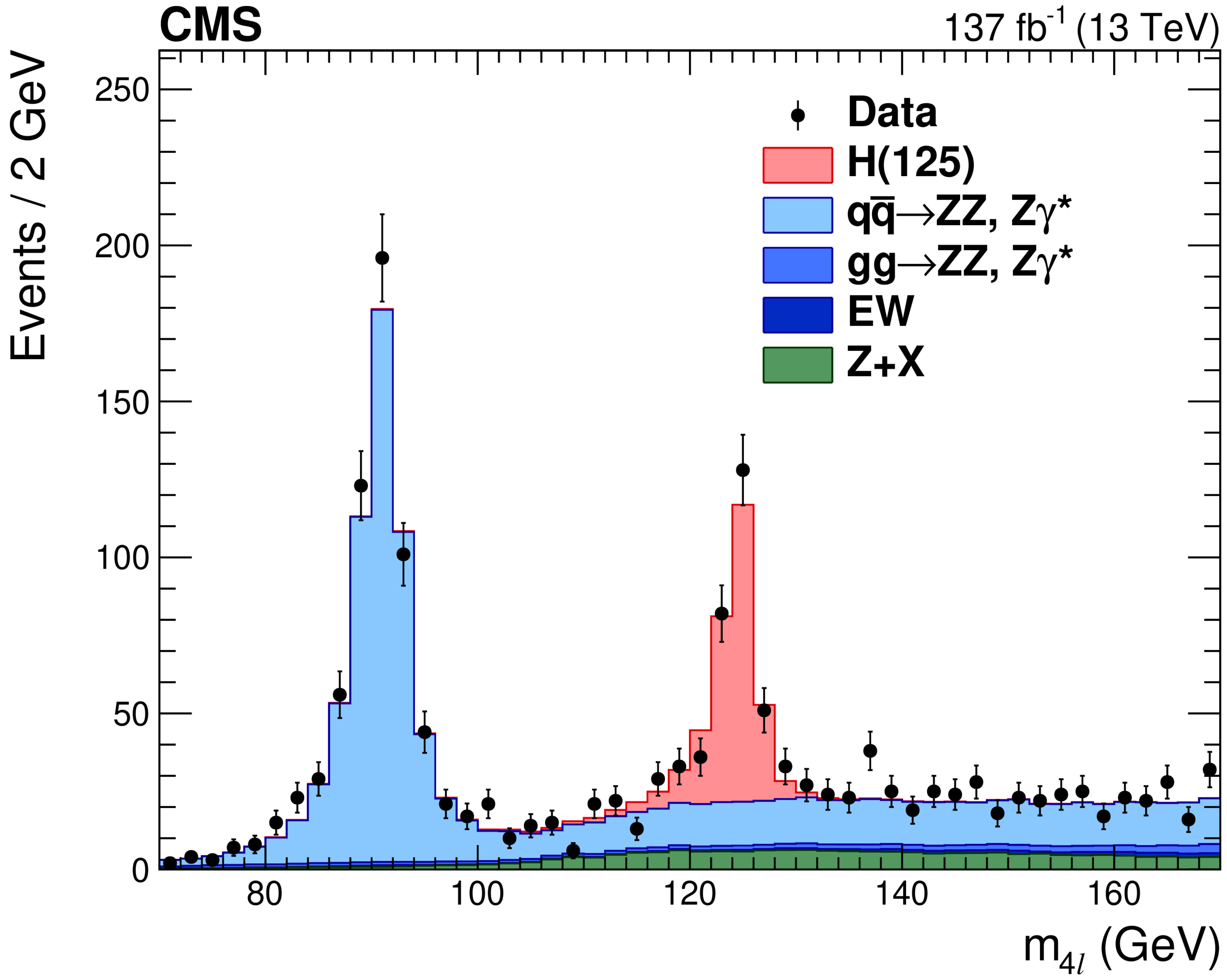




ATLAS-CONF-2020-026
CMS-Eur. Phys. J. C 81 (2021) 488

Higgs mass





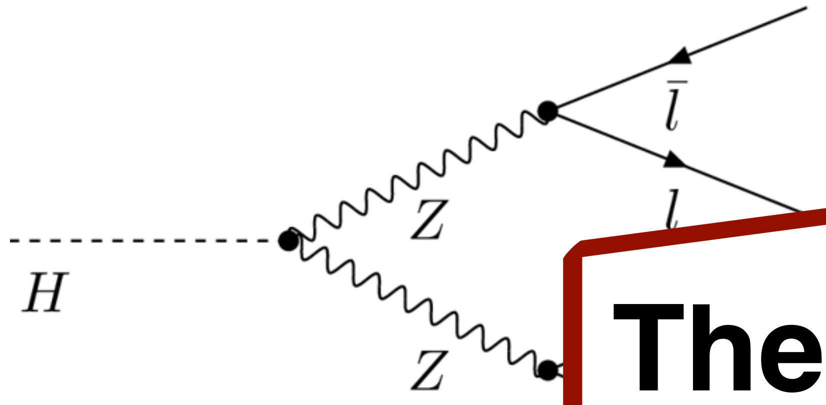
Higgs Boson mass measured with relative uncertainty < 0.2%

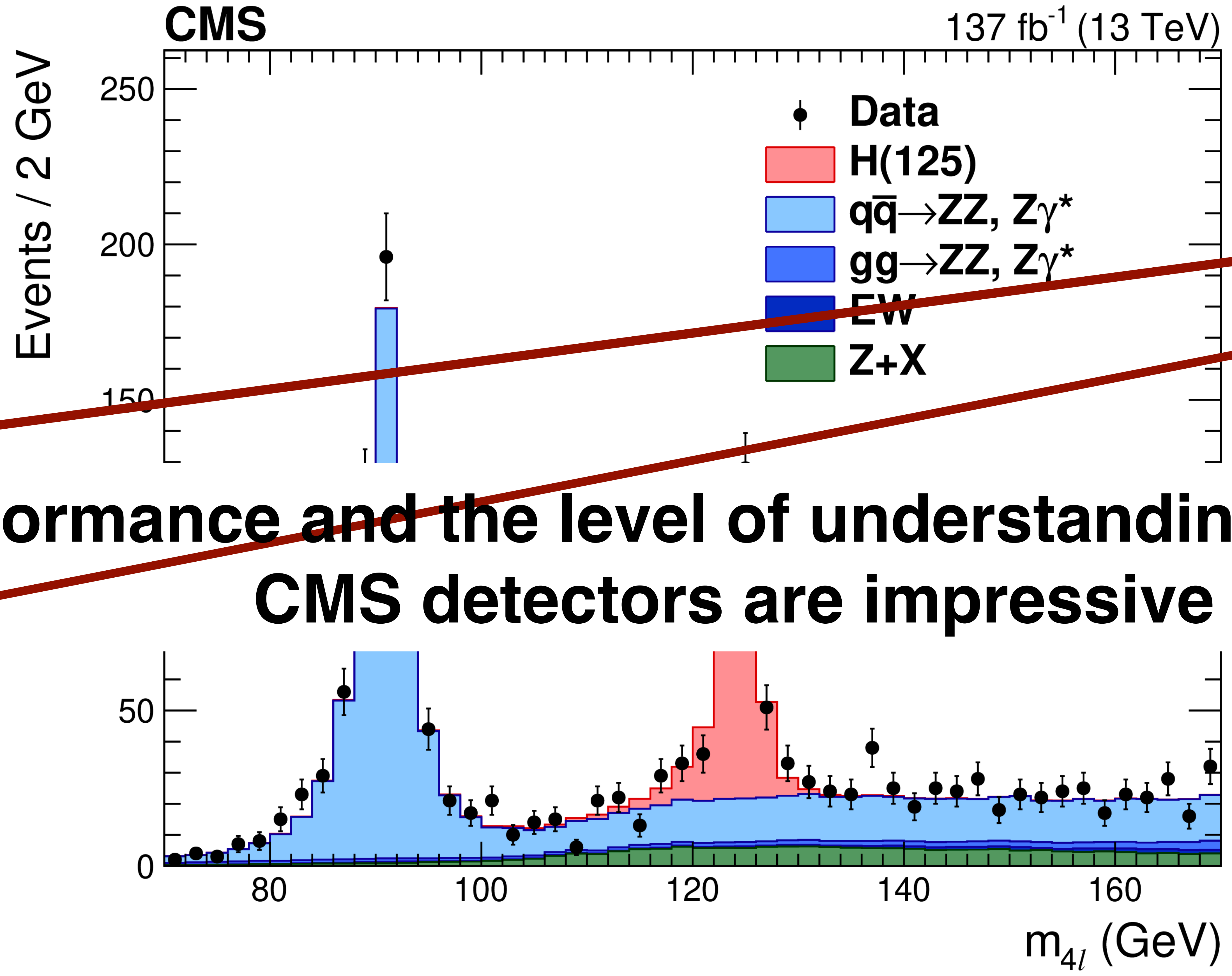
Lepton momentum scale uncertainty is **0.05-0.3%**

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

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

Higgs mass





The performance and the level of understanding of ATLAS and CMS detectors are impressive

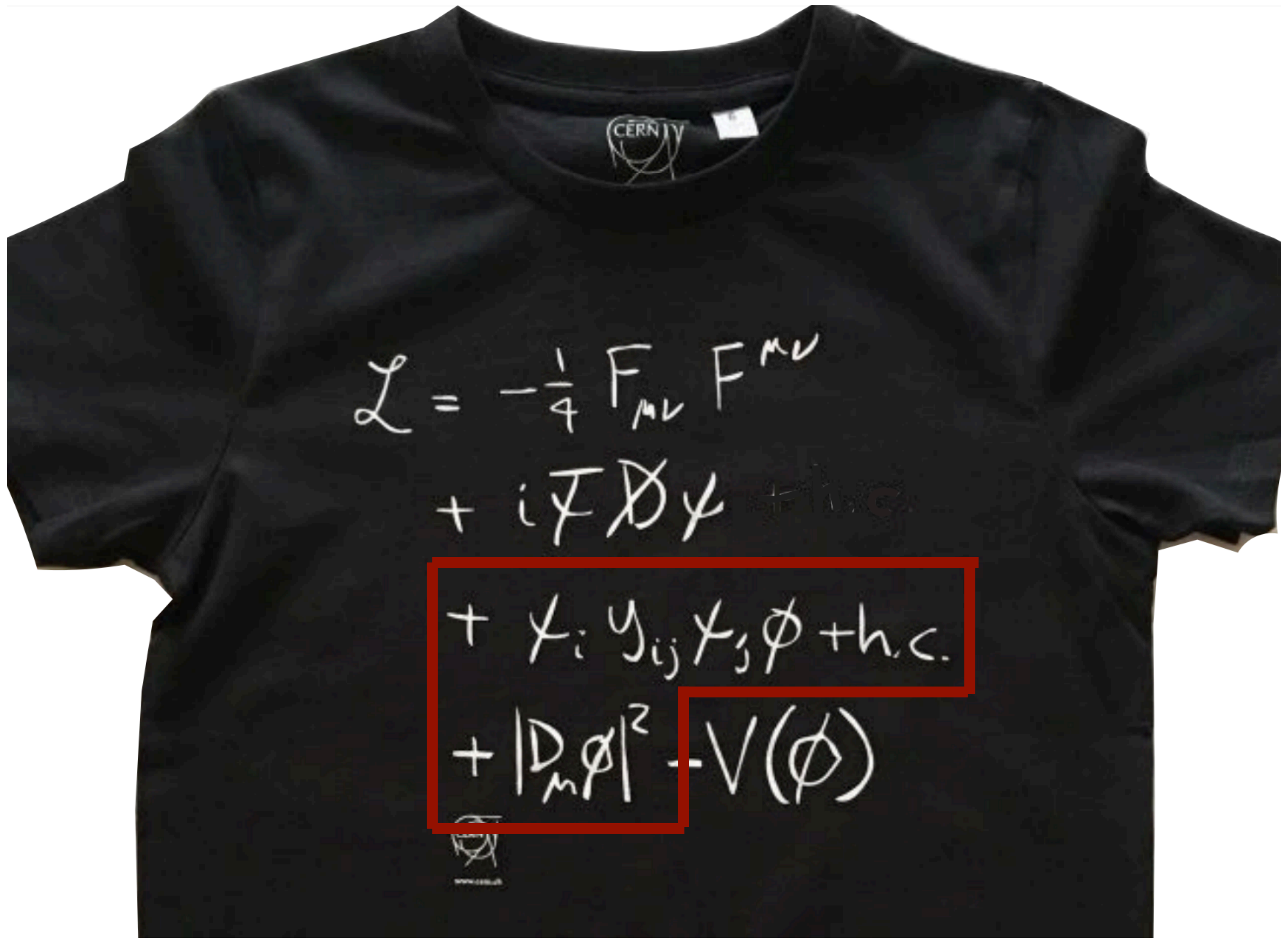
Higgs Boson mass measured with relative uncertainty < 0.2%

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

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

Is it a SM Higgs boson?

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

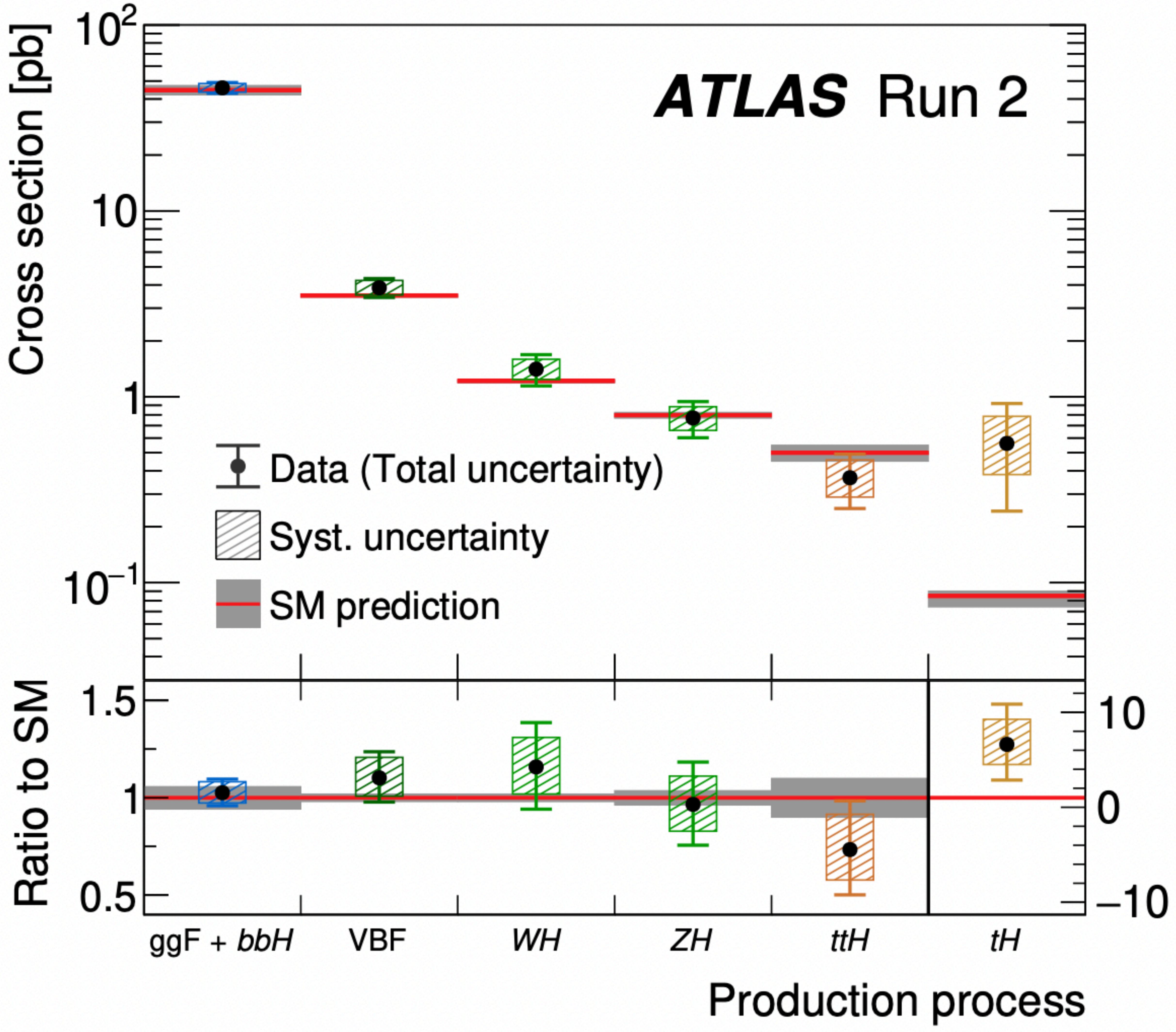


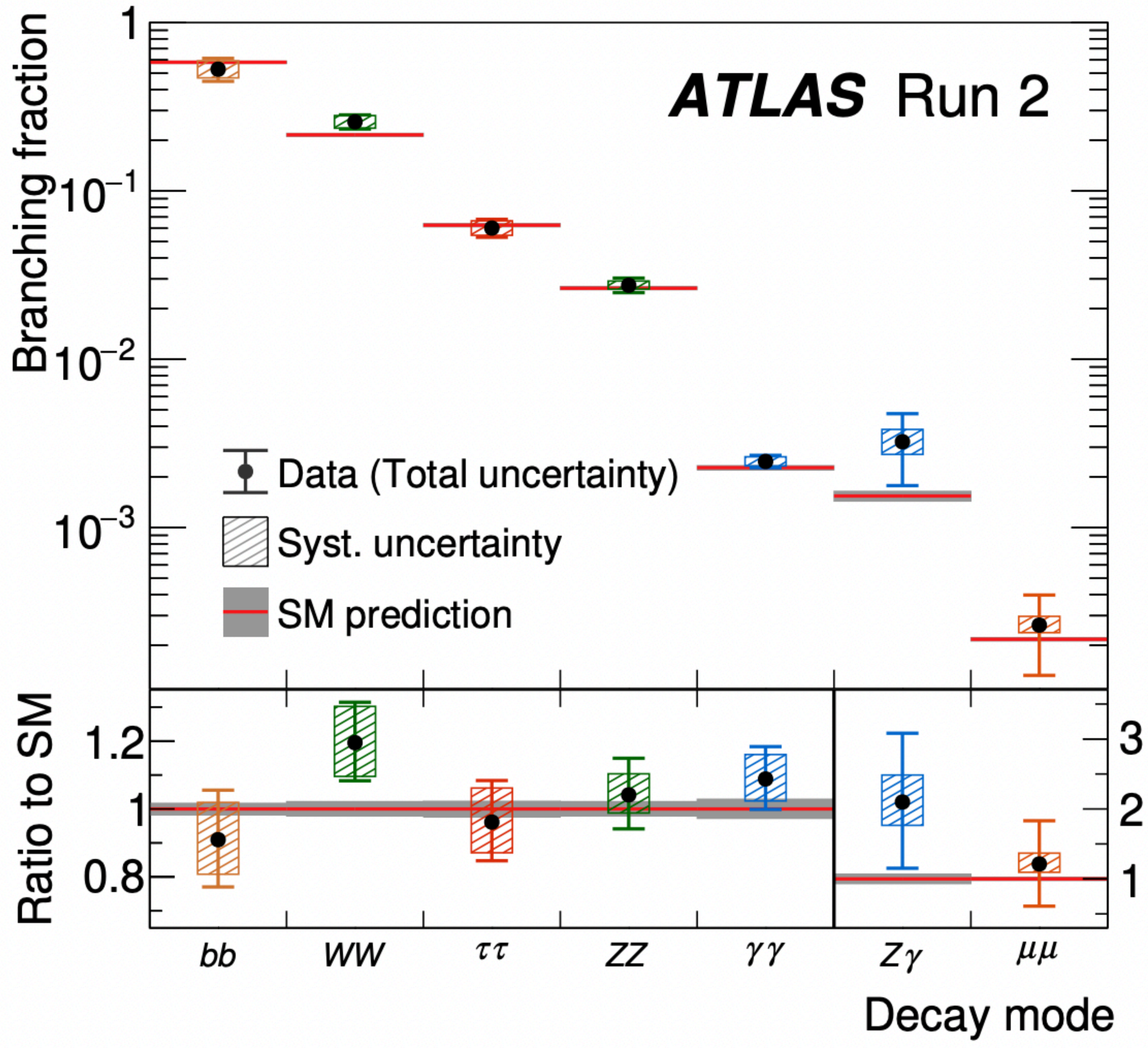
Couplings to W and Z established in Run 1

In Run 2 **first direct confirmation of coupling to all 3rd generation fermions (top/bottom-quarks** and **τ leptons)**

CMS-Nature 607, 60–68 (2022)
ATLAS-Nature 607, 52–59 (2022)

Higgs in 2022





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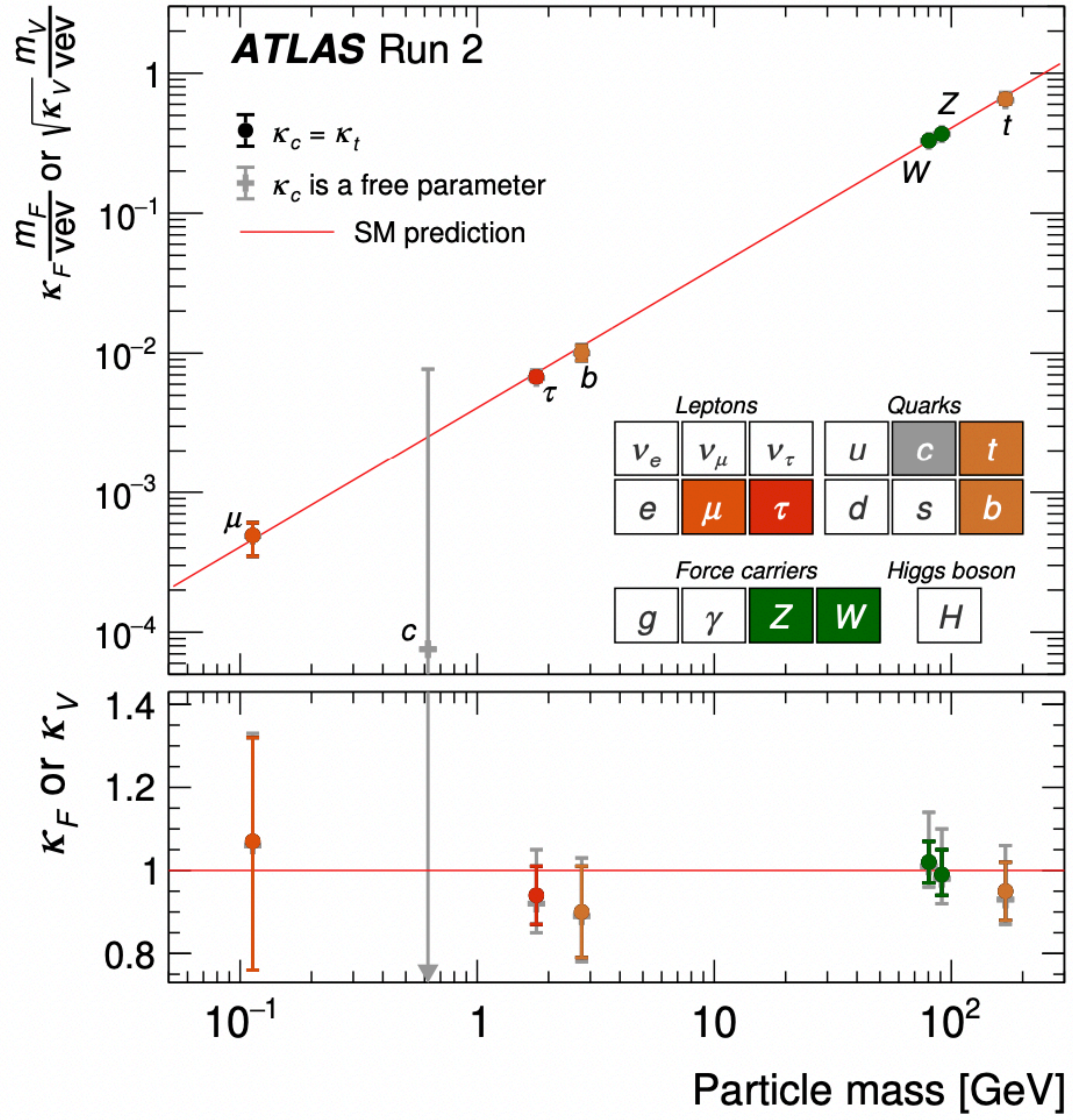


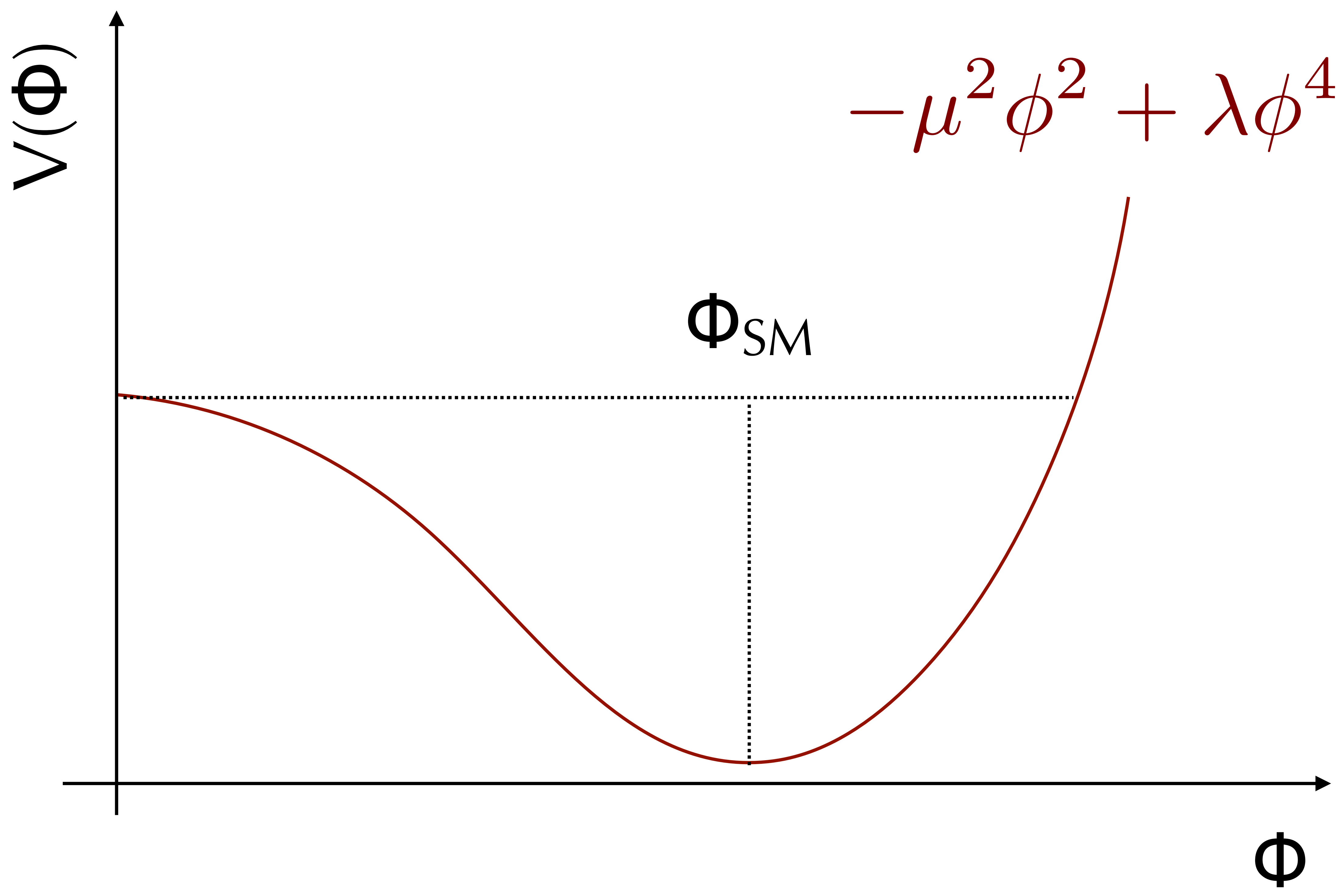
BR(inv.) < 0.17 (0.11)

CMS-PAS-HIG-20-003

|κc|<3.4

CMS-PAS-HIG-21-008

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

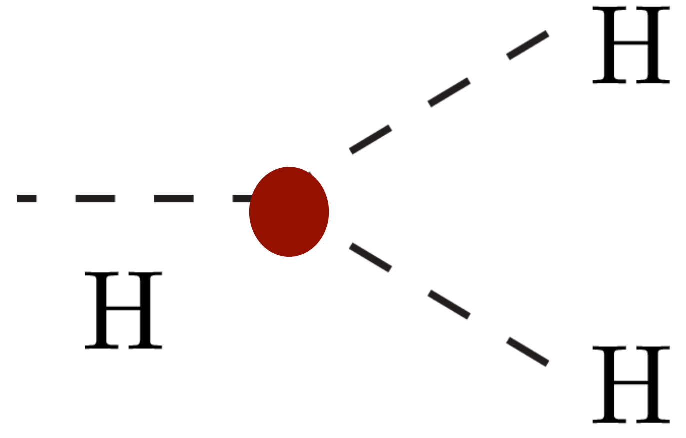


Probing this Higgs Boson potential

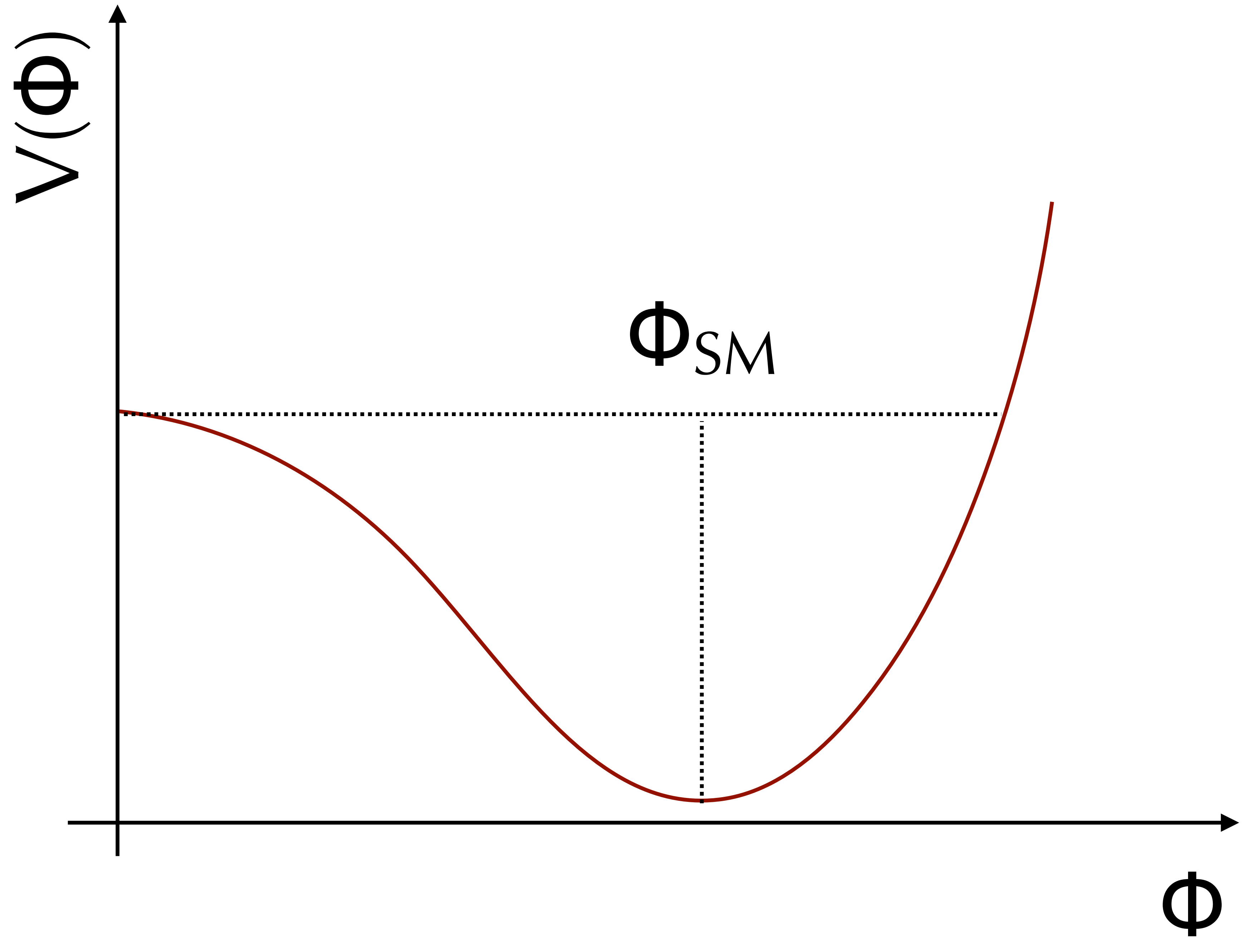
Testing the shape

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

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



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



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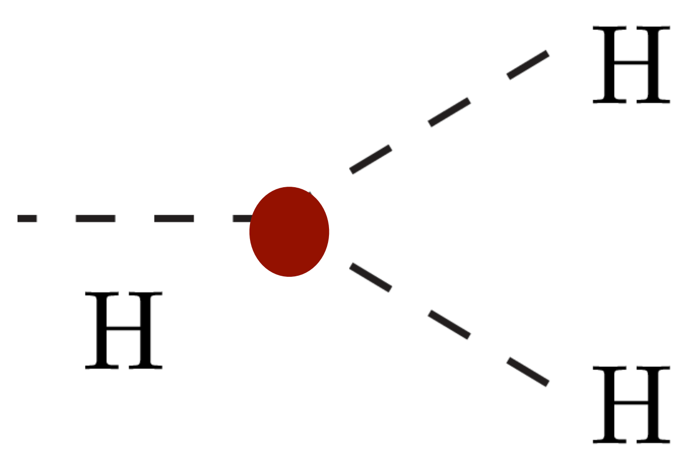

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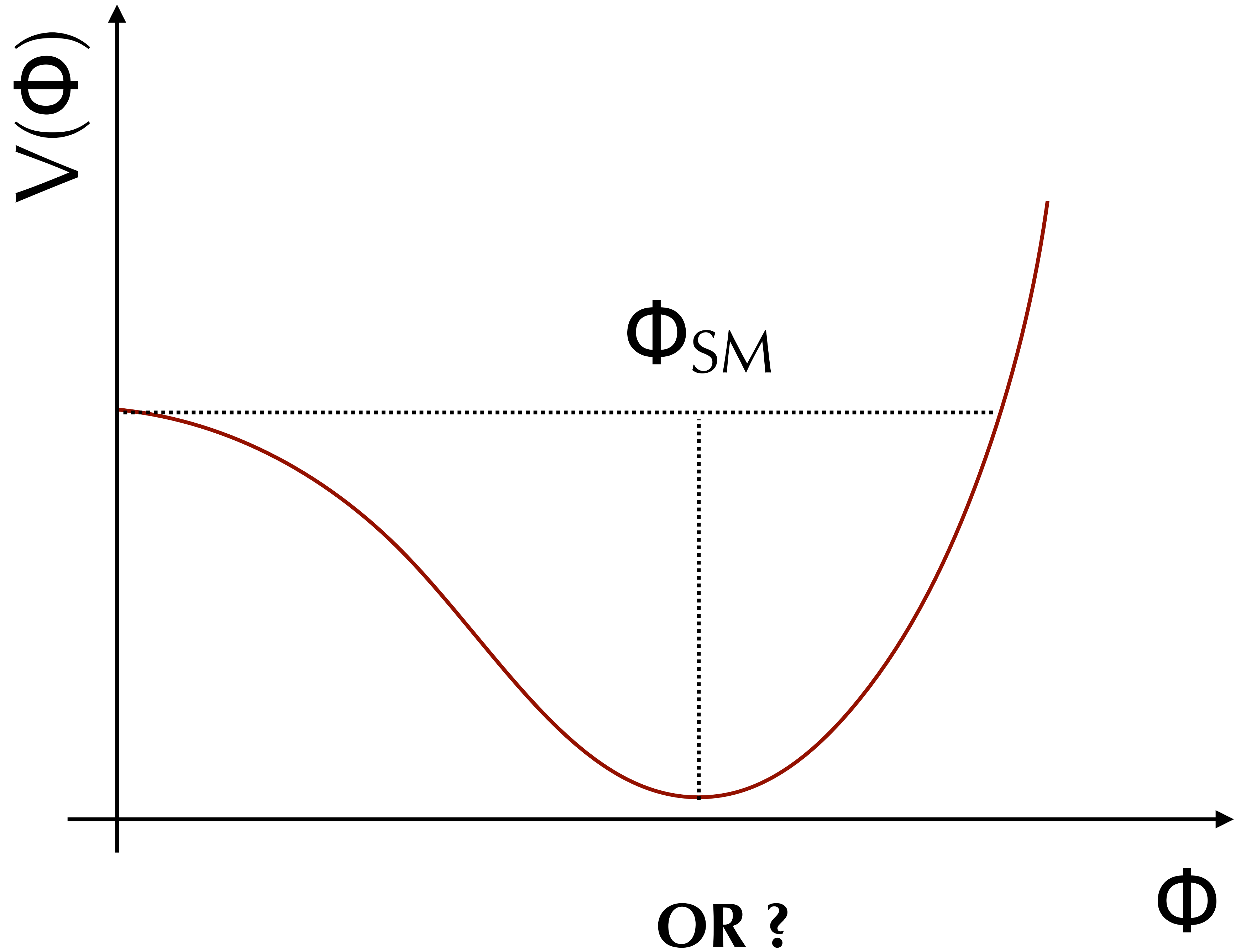
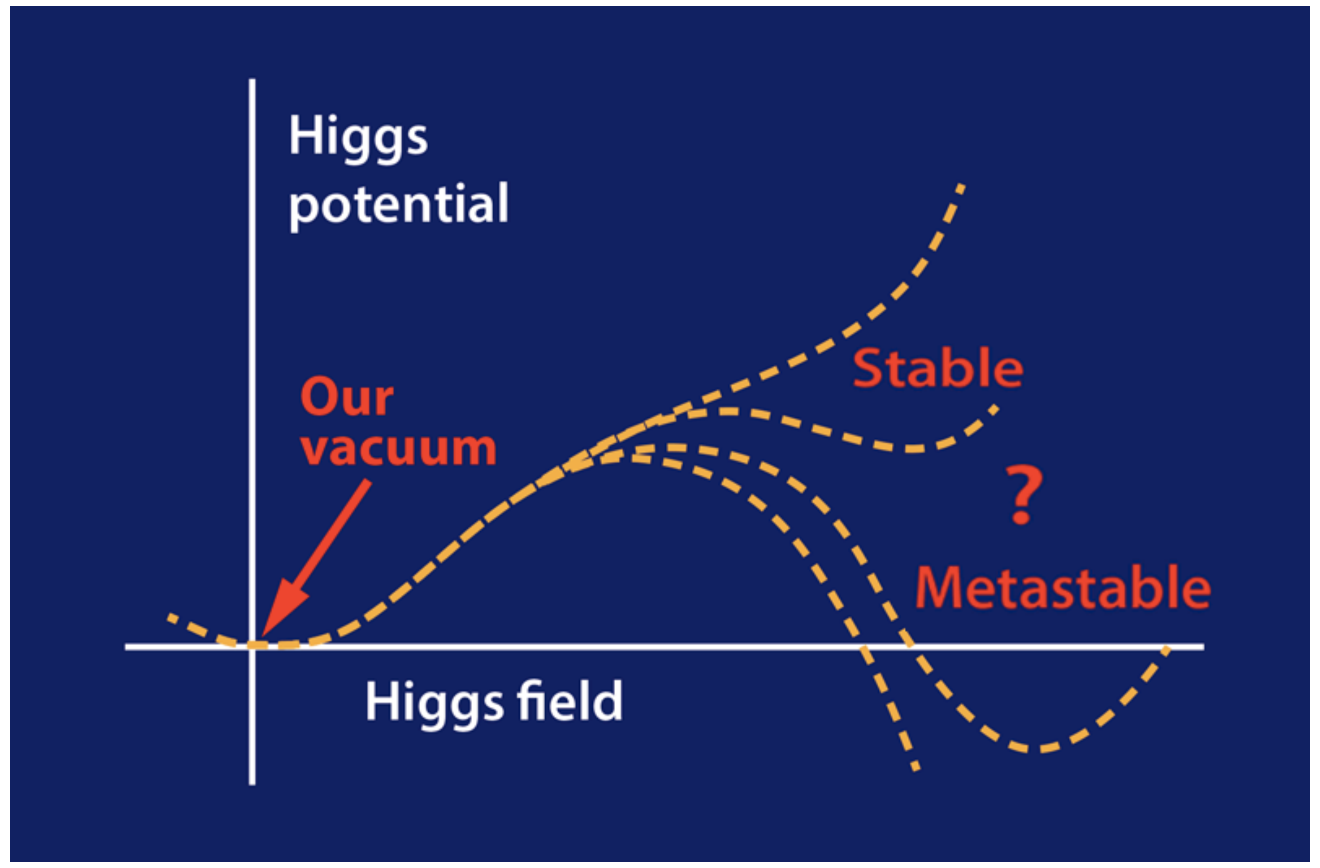
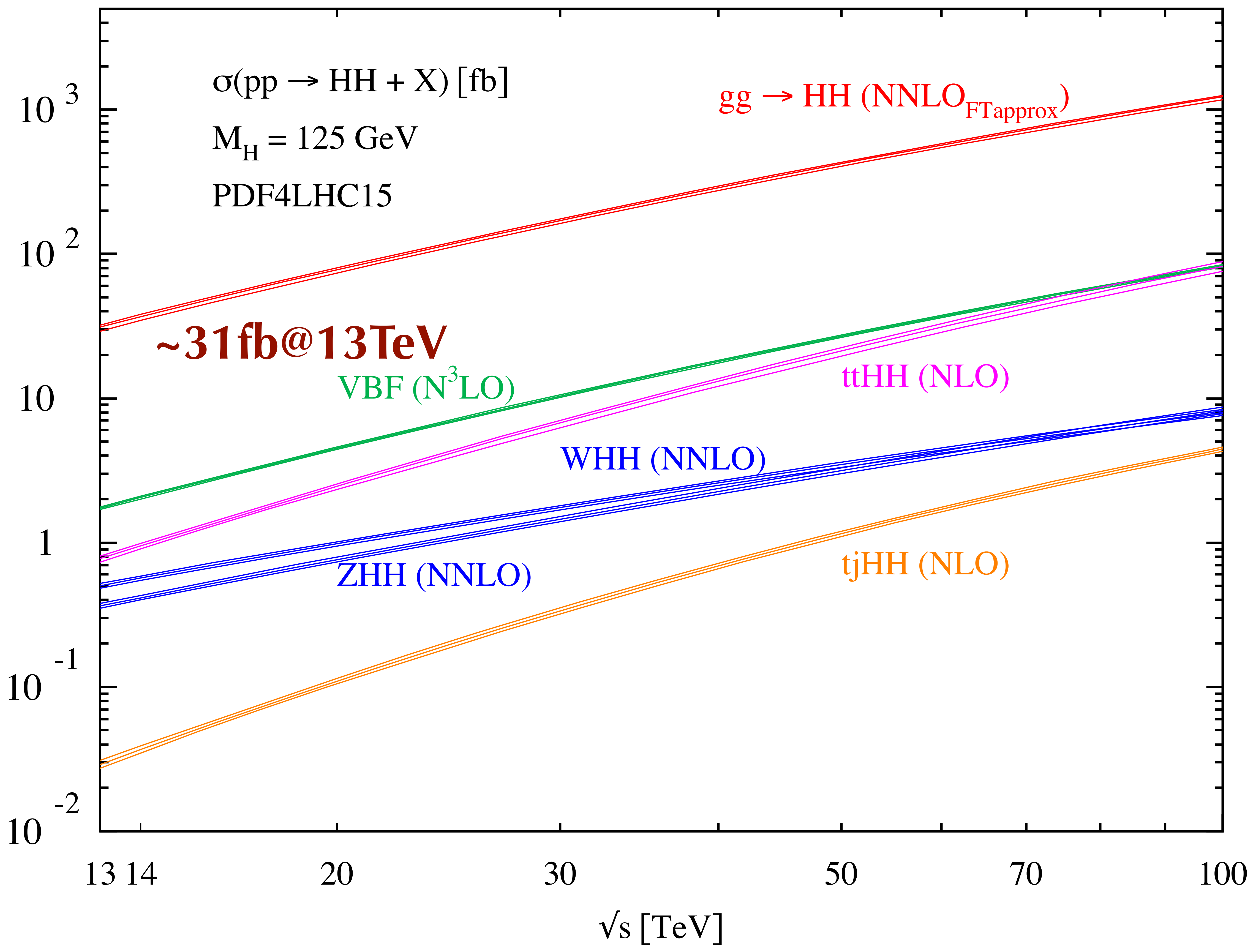


OR ?

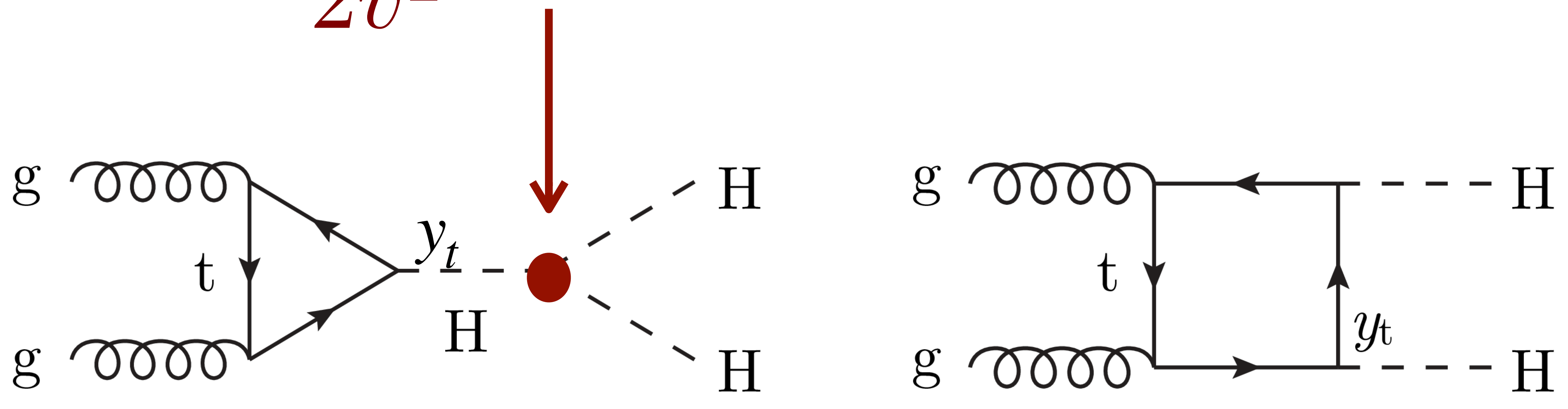


arXiv:1910.00012

Higgs boson self-coupling



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



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

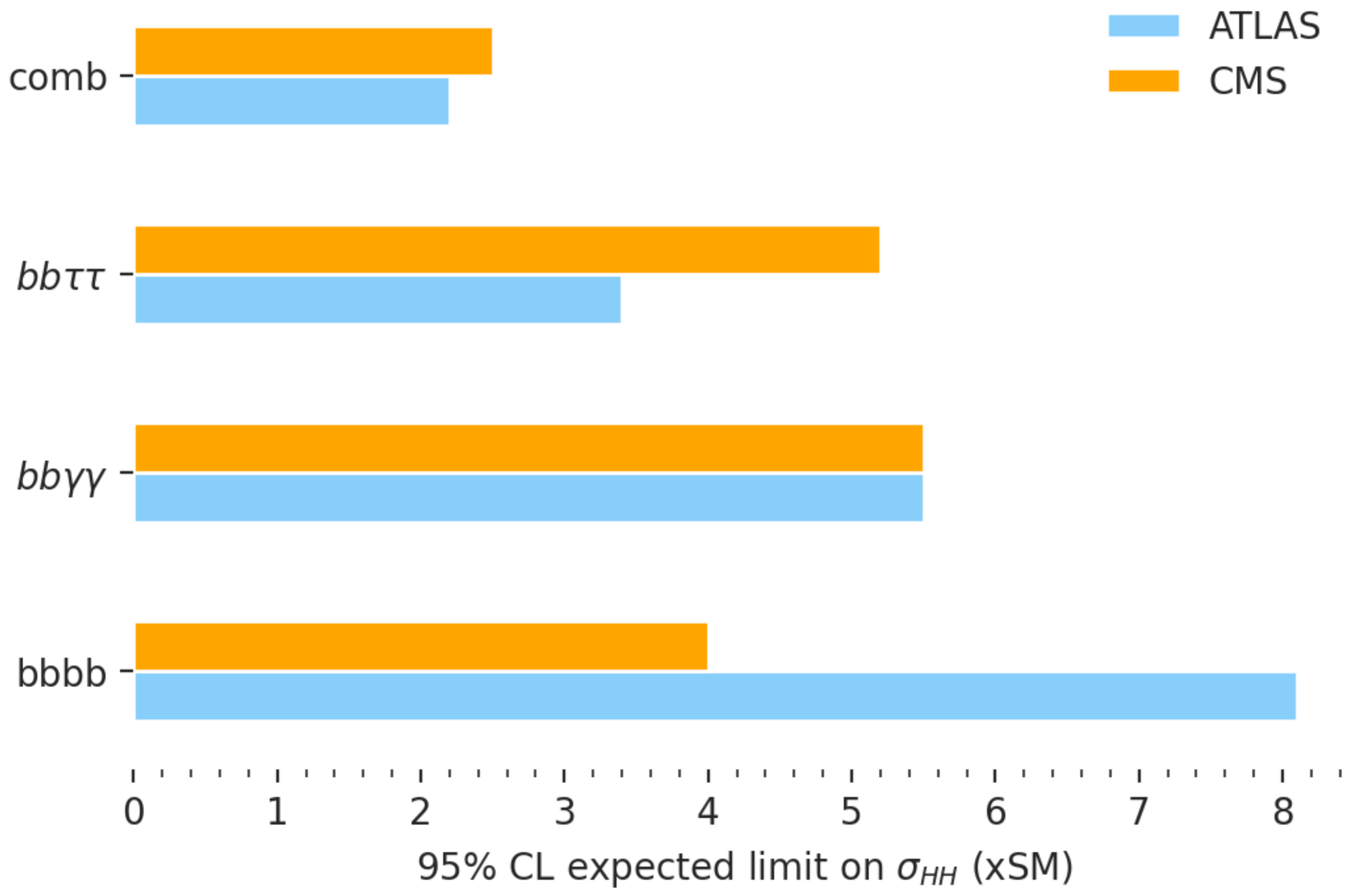
Extremely challenging measurement at the LHC, but **it can be sensitive to large deviations from BSM**: $\kappa_\lambda = \lambda/\lambda_{SM}$

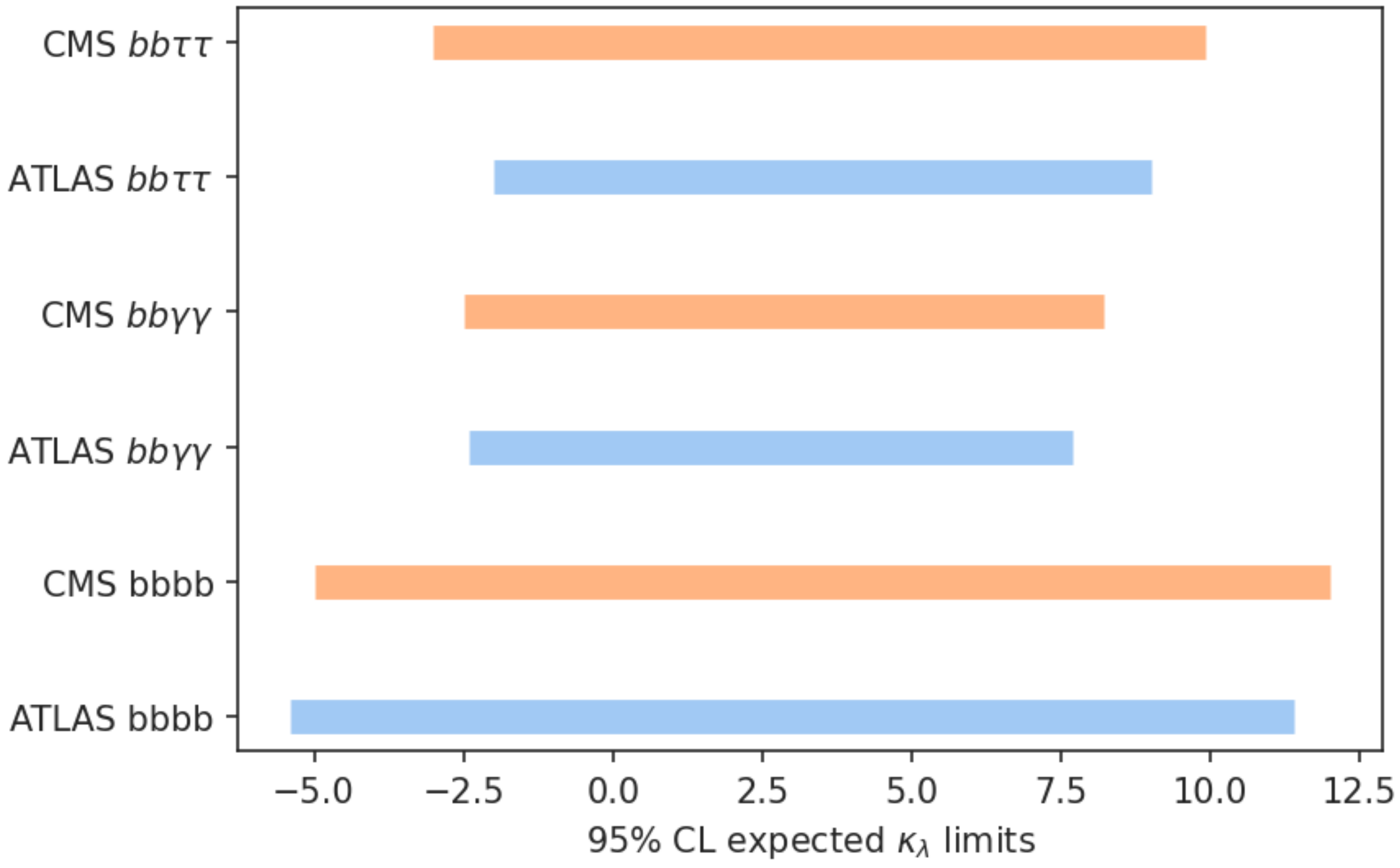

ATLAS
EXPERIMENT
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST
H
γ
γ
H
b
b̄

ArXiv:2209.07510

Double Higgs Results

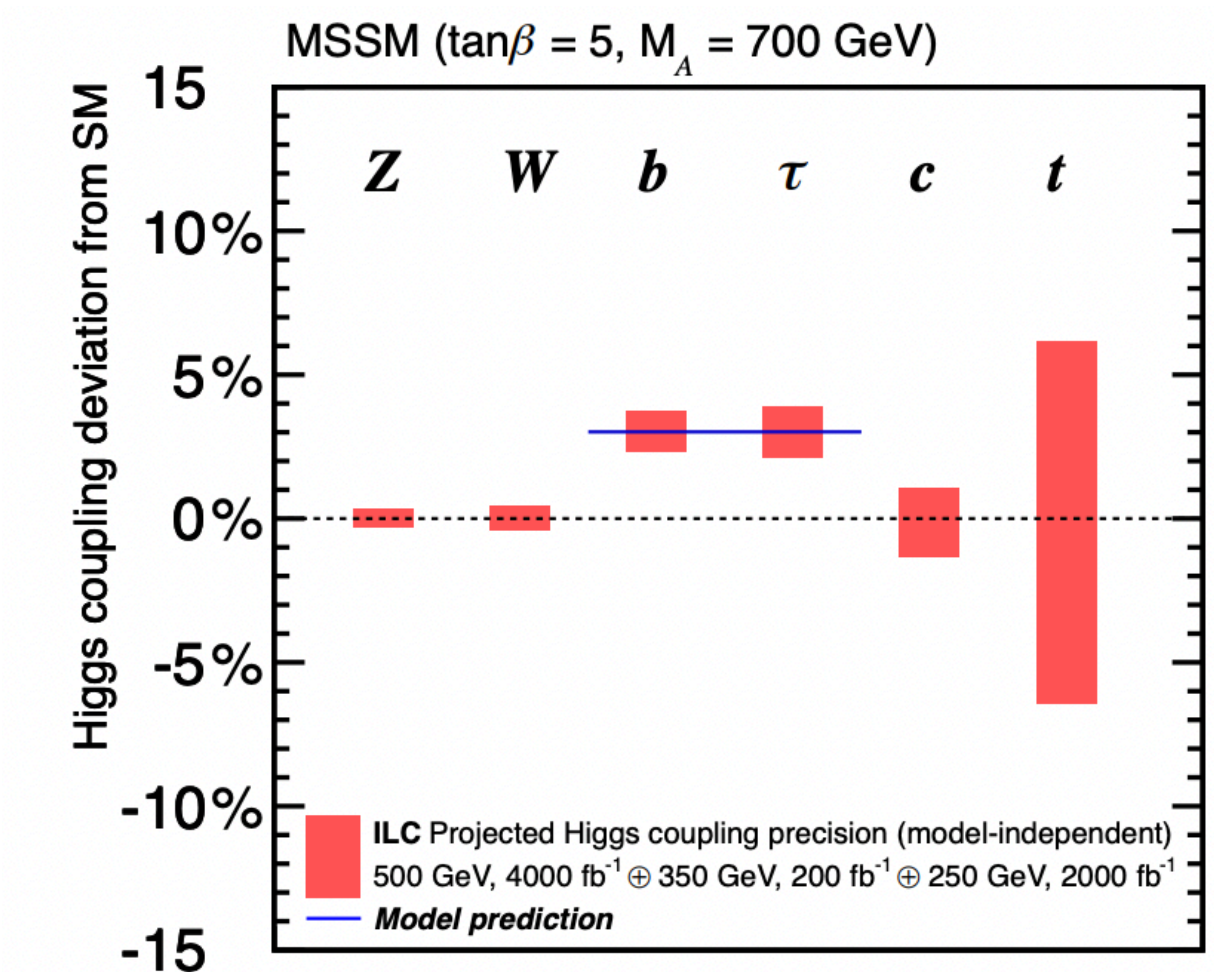
Similar sensitivity from several channels to SM HH production

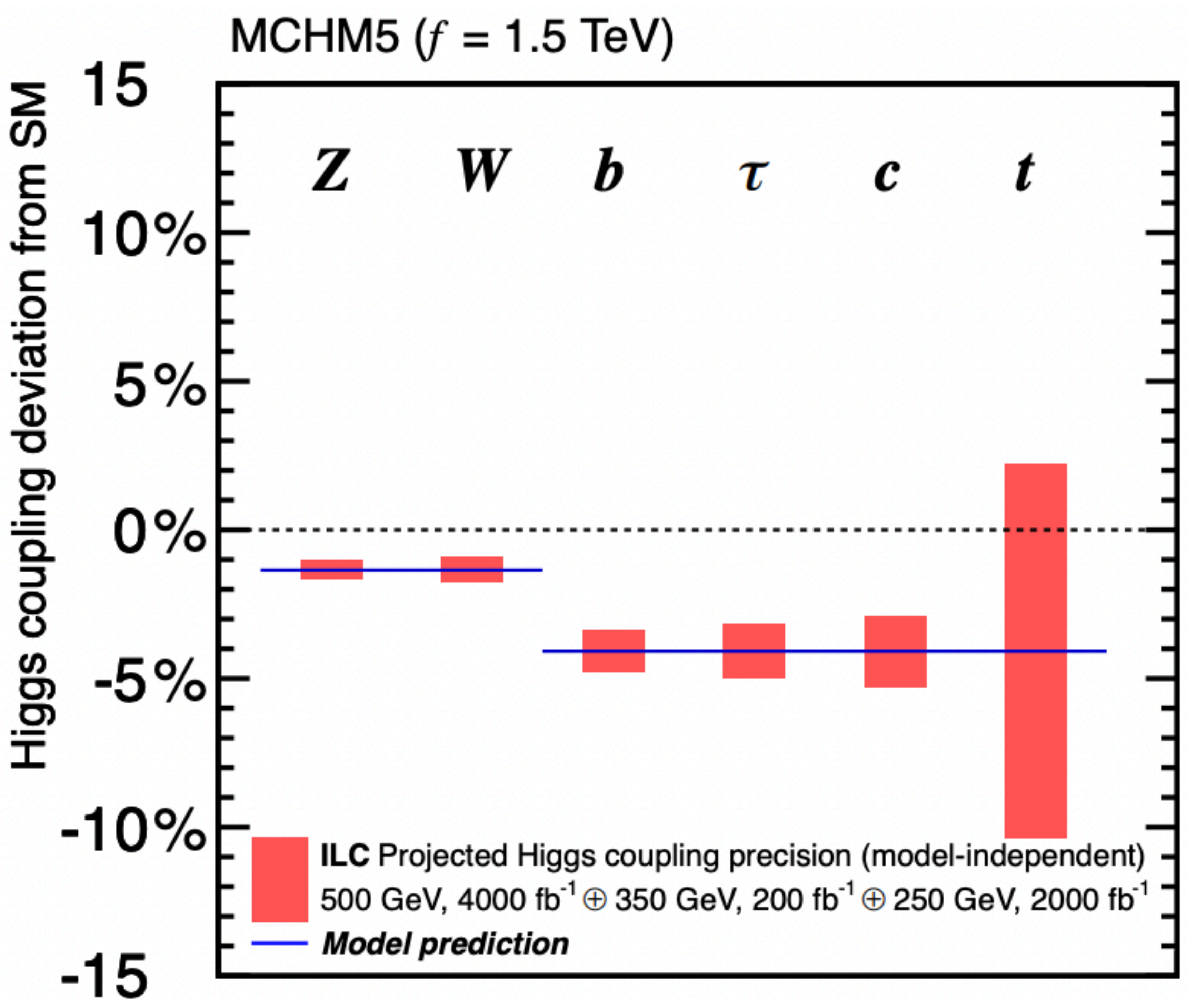




Best channels are $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$

ArXiv:2209.07510





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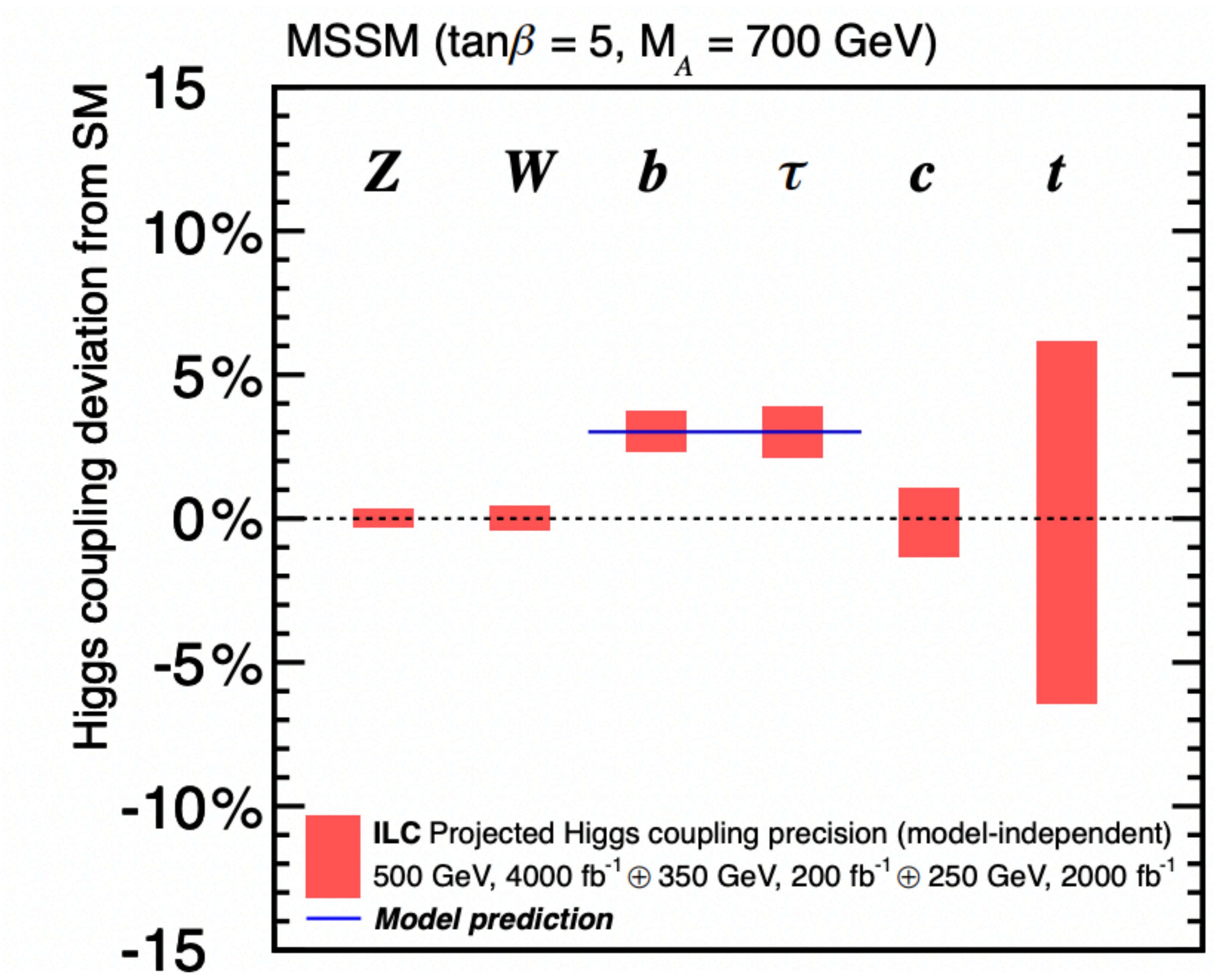
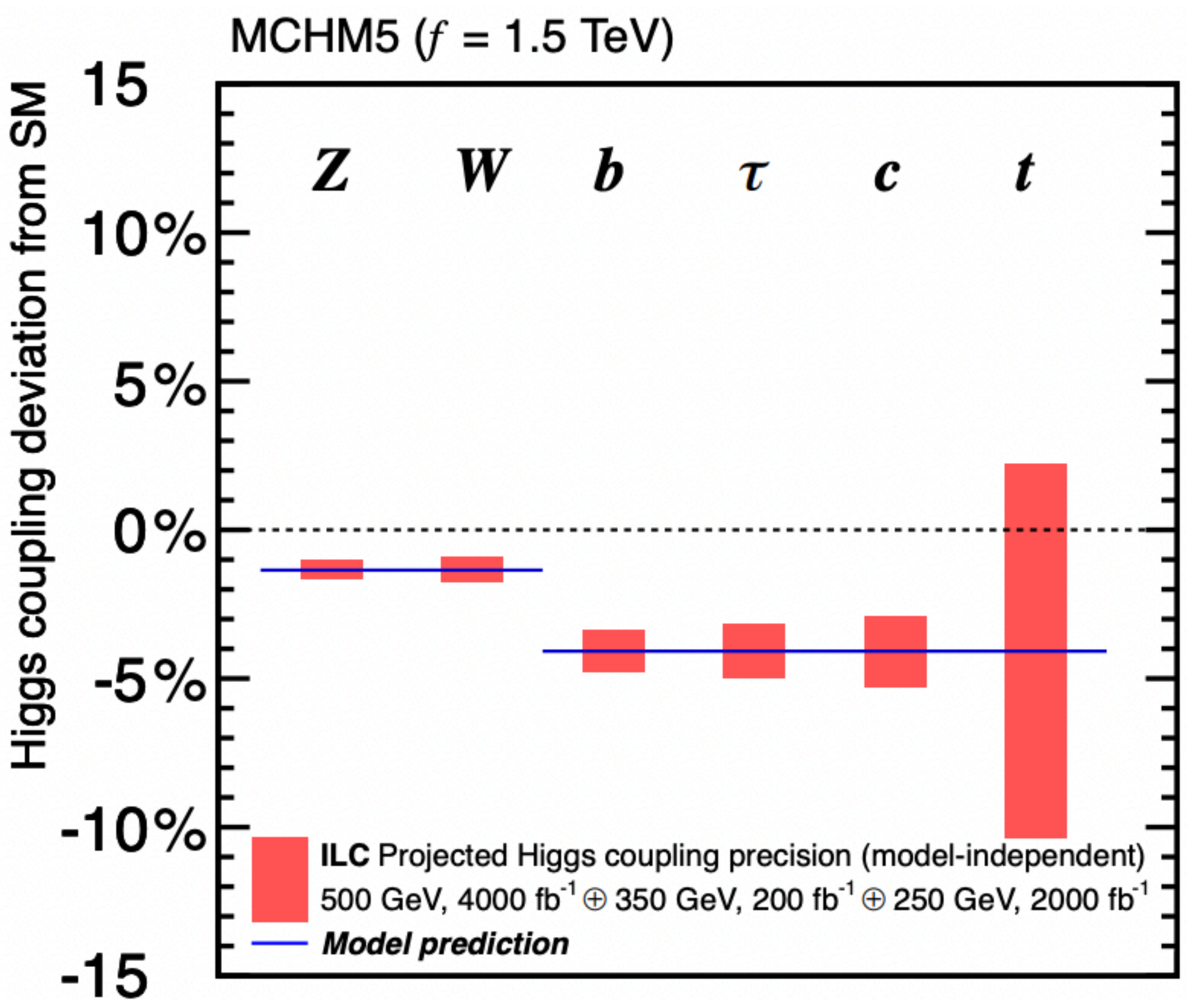
No new particles discovered at the LHC so far…





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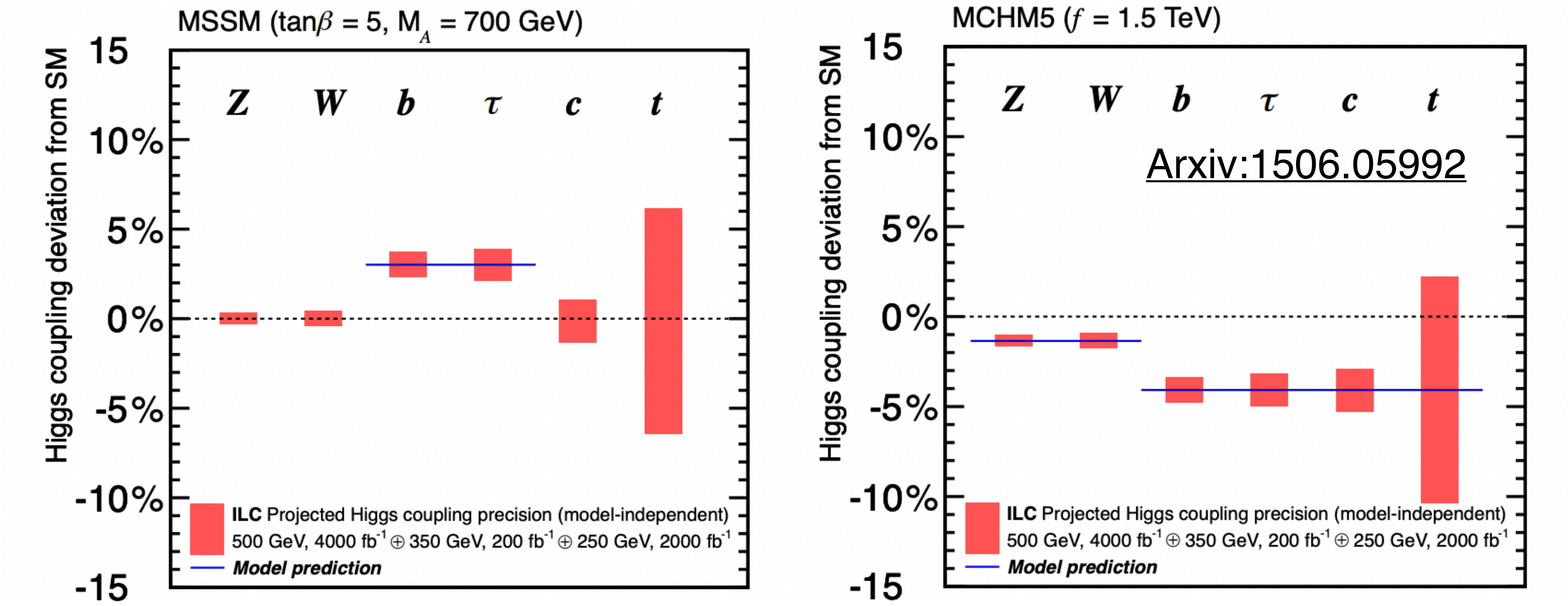
What's next?
How can we use the Higgs to find new physics?



LHC → High Luminosity LHC

LHC | HL-LHC

Run 2
8M H

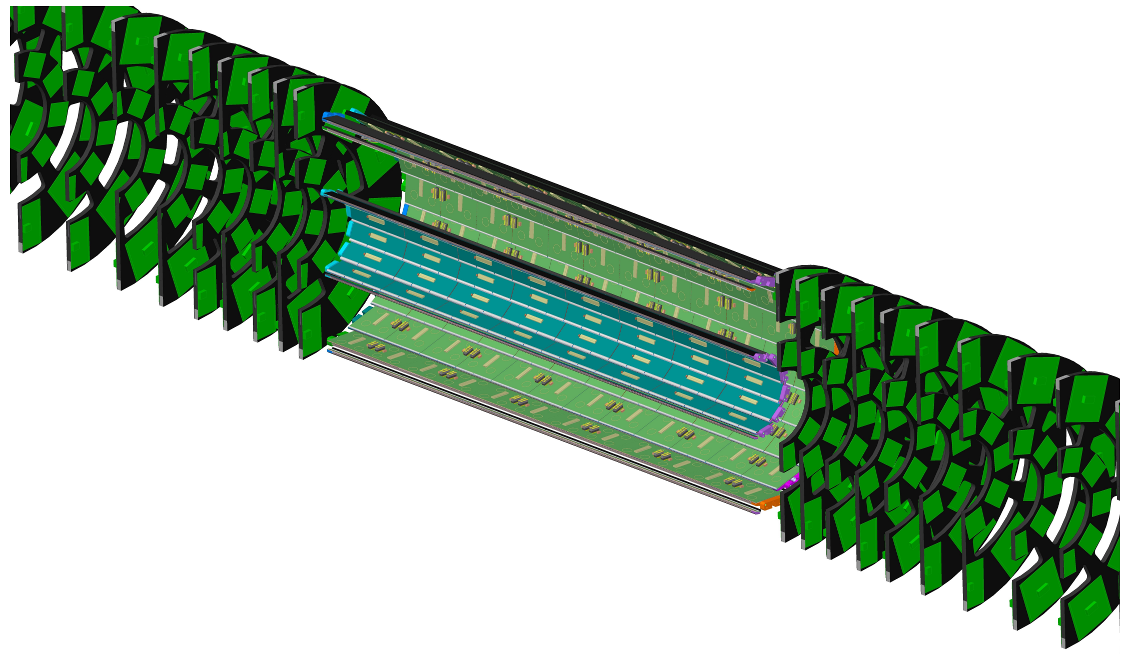
Upgrade of accelerator and experiments

Run 3
16M H

HL-LHC installation
ATLAS Upgrade

Run 4/5
170M H
120k HH

2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | … | 2039

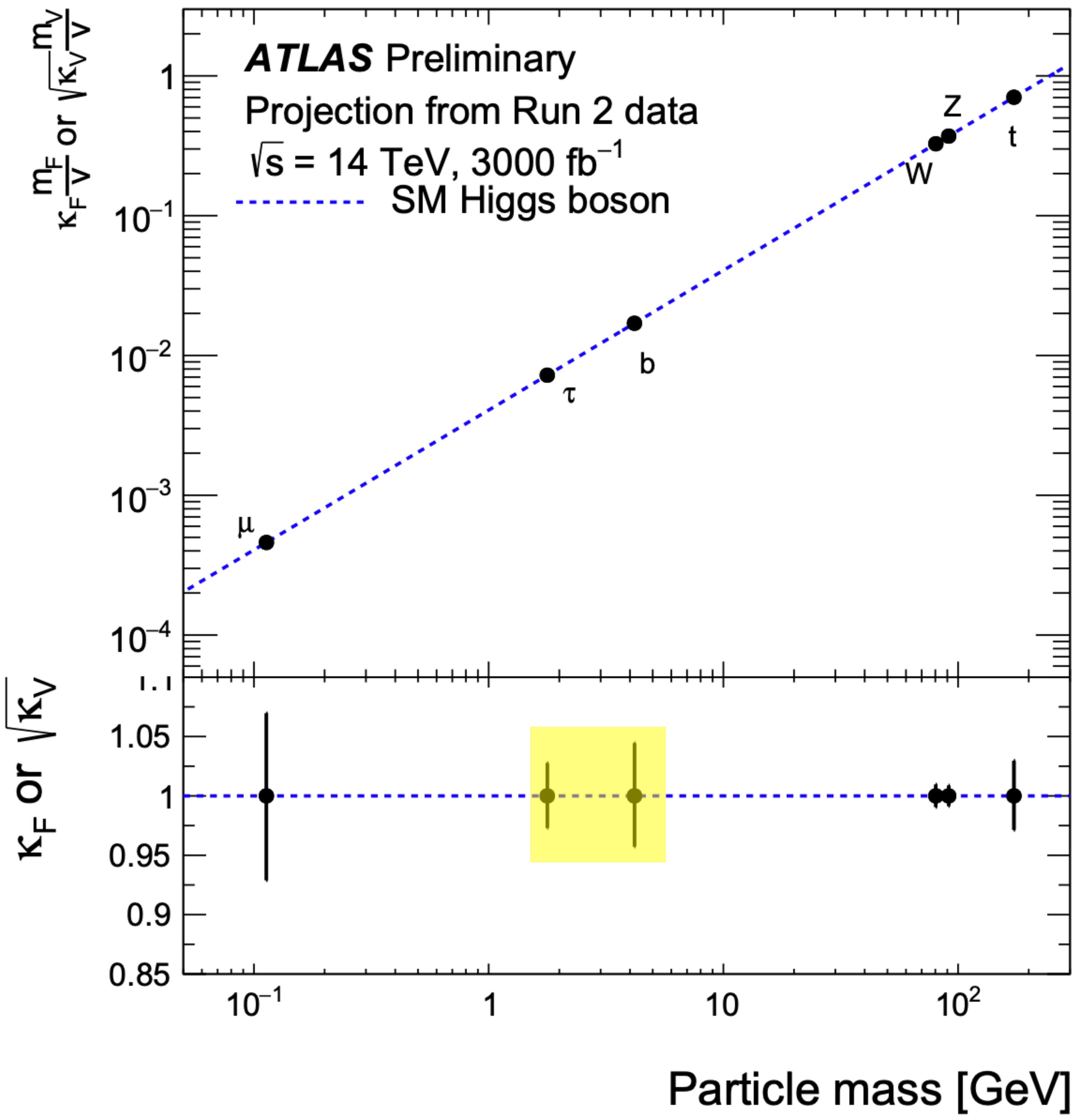


Today

Phase-2 HL-LHC detector upgrades are being built

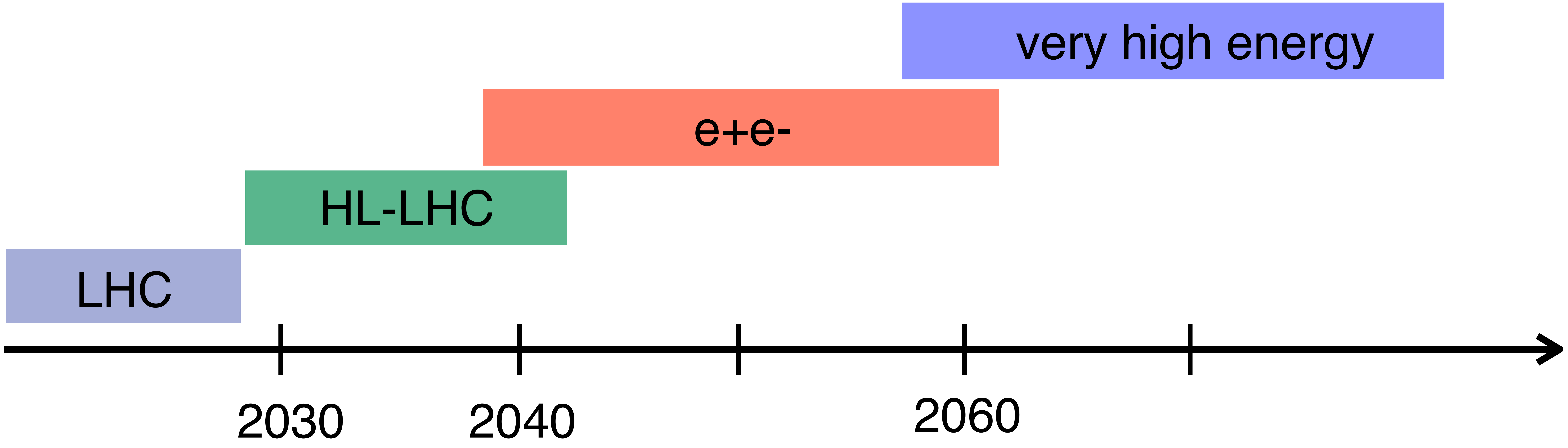
1902.10229

Higgs physics at the HL-LHC



- HL-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

What's next?



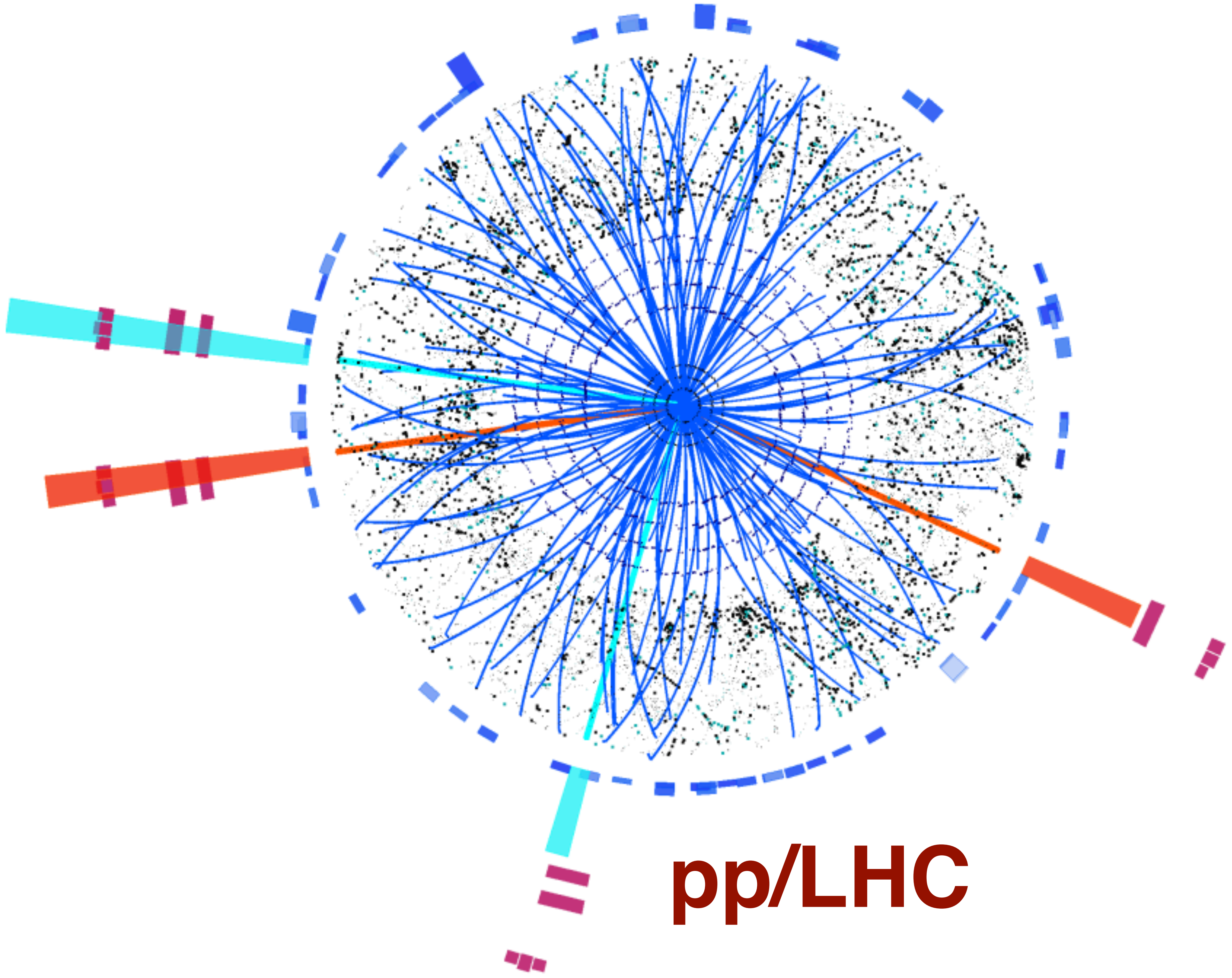
H couplings to: **O(10)%** **O(0.1-1)%** **O(1)‰**

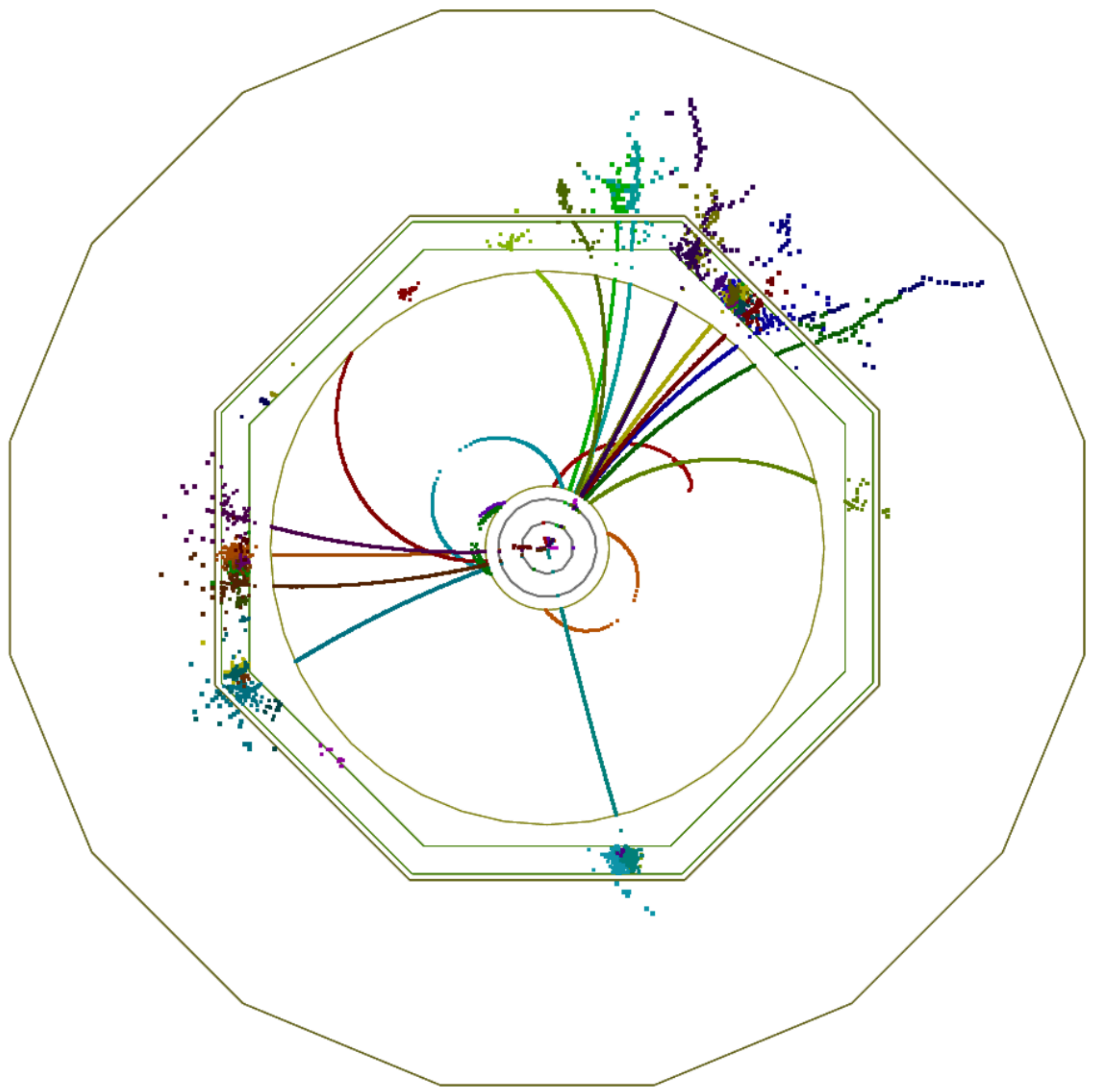
Physics goals beyond HL-LHC:

1. Establish Yukawa couplings to light flavor ⟹ precision & lumi
2. Search for invisible/exotic decays and new Higgs ⟹ precision & lumi
3. Establish self-coupling ⟹ high energy

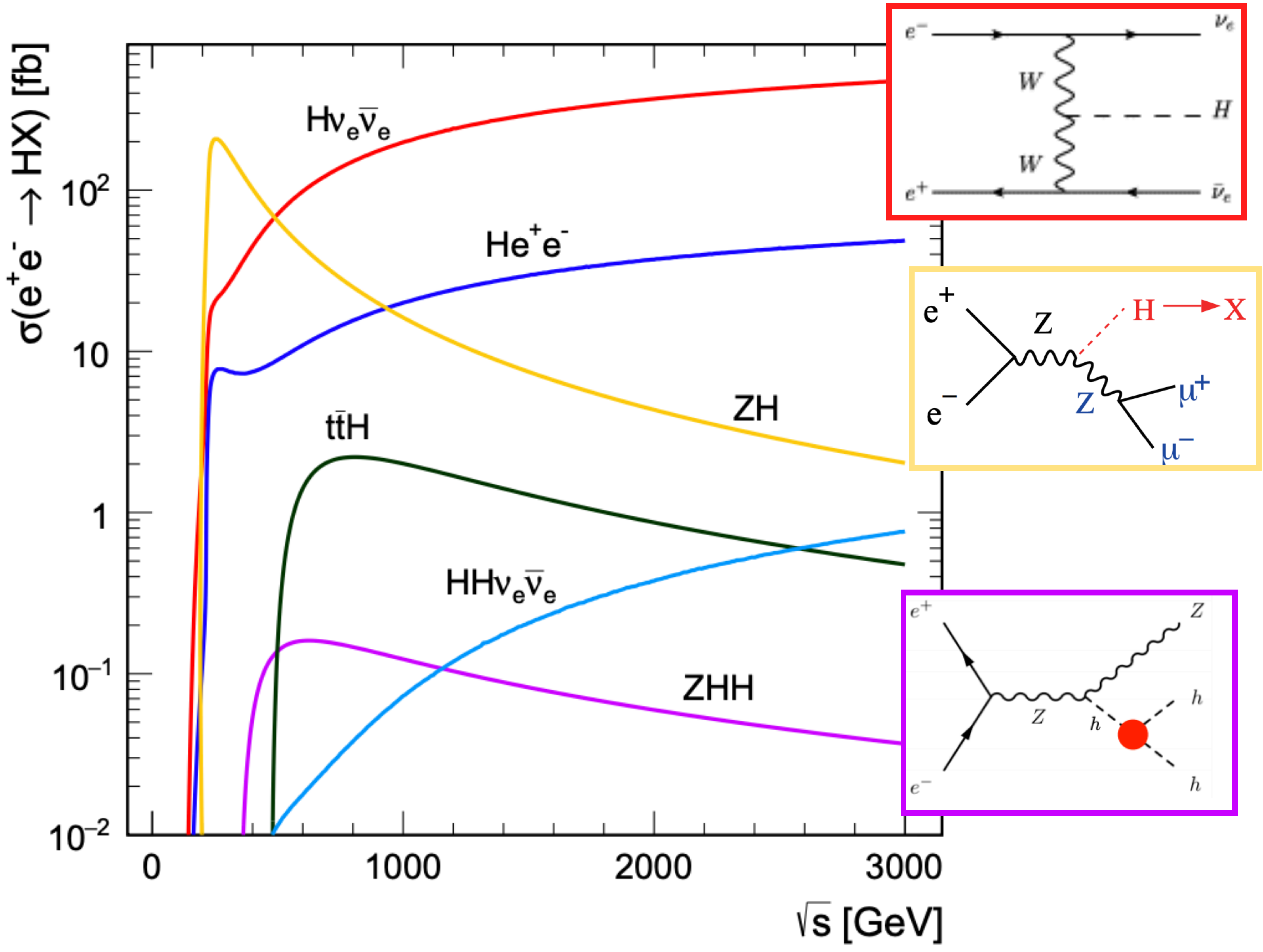
Why e^+e^-?

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





Higgs at e+e-

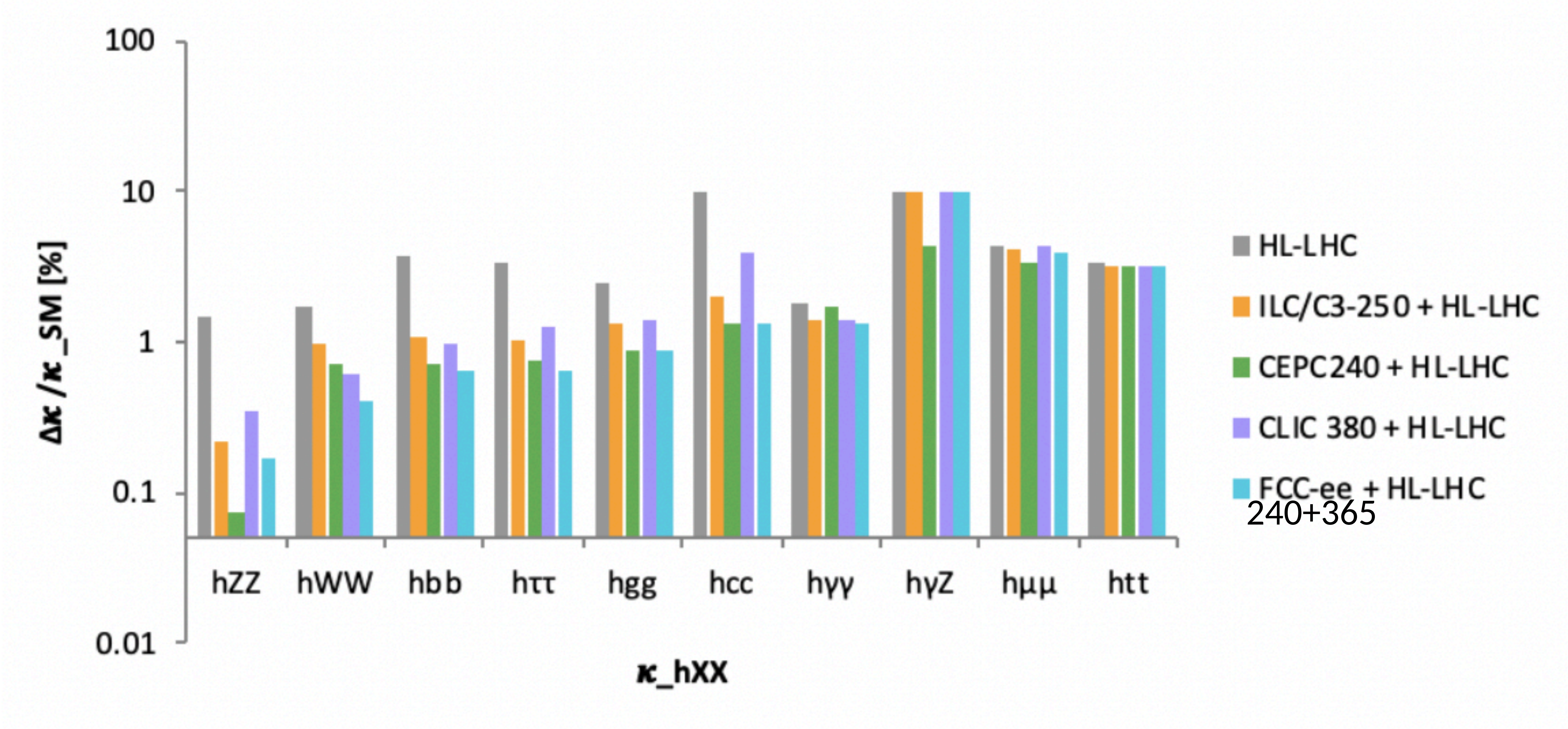


- ZH is dominant at 250 GeV
- Above 500 GeV
  - Hvv dominates
  - ttH opens up
  - **HH accessible with ZHH**

ArXiv:2209.07510

Higgs couplings at future e+e-

- **Coupling to W and Z** would be measured with an accuracy of few 0.1%
- **Coupling to charm and b** quarks could be measured with an accuracy of ~1% at future e+e- machines
- **Couplings to *μ/γ/Zγ*** benefit the most from the large dataset available at HL-LHC



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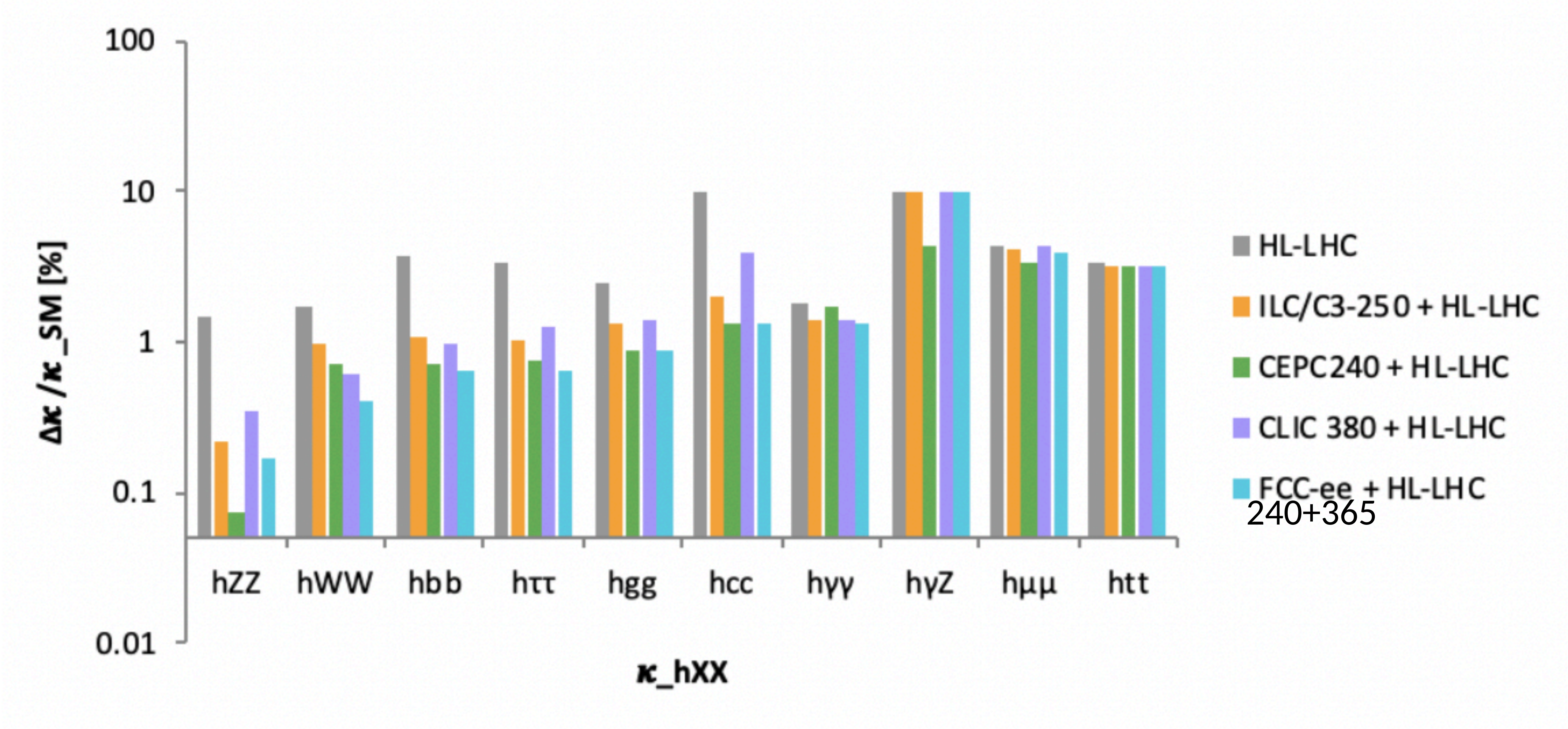


Complementarity between HL-LHC and future colliders (depending on their timeline) **will be the key to explore the Higgs sector**

Physics requirements for detectors

Precision challenges detectors

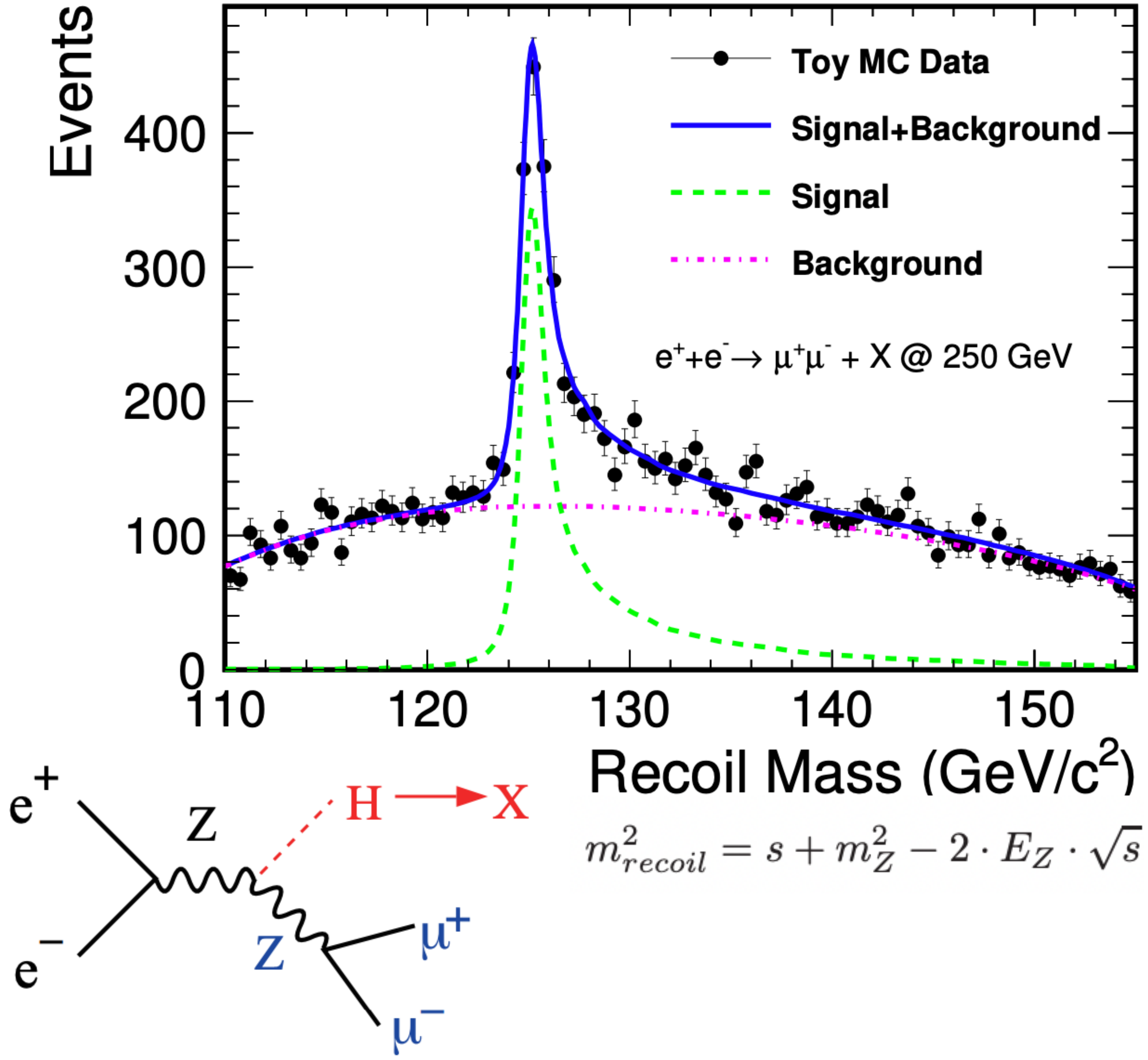
ZH process: Higgs recoil reconstructed from Z →*μμ*

- Drives requirement on charged track momentum and jet resolutions
- Sets need for high field magnets and high precision / low mass trackers
- *Bunch time structure allows high precision trackers with very low X0 at linear lepton colliders*

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)



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

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
- *Bunch time structure allows high precision trackers with very low X0 at linear lepton colliders*

Particle Flow reconstruction

Higgs → bb/cc decays: Flavor tagging & quark charge tagging at unprecedented level

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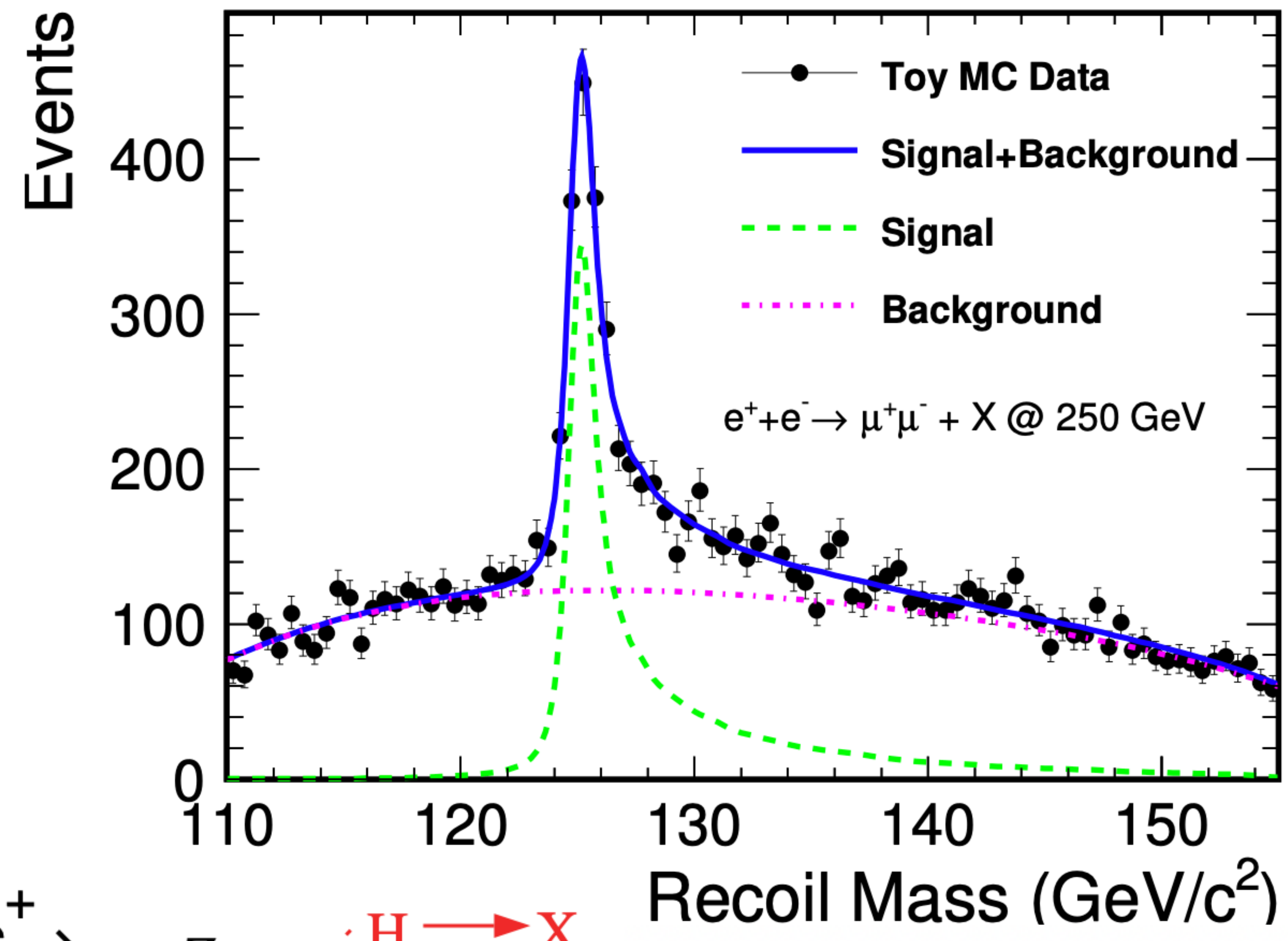
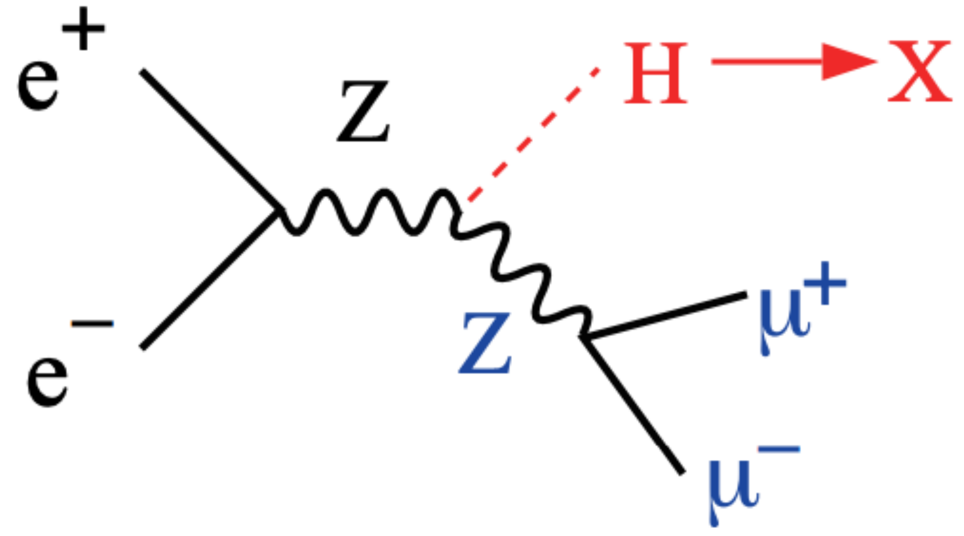




$$m^2_{recoil} = s + m^2_Z - 2 \cdot E_Z \cdot \sqrt{s}$$

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

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	$\sigma_{r\phi} = 5 \oplus 15(p\sin\theta^{\frac{3}{2}})^{-1}\mu$m
			5μm single hit resolution

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

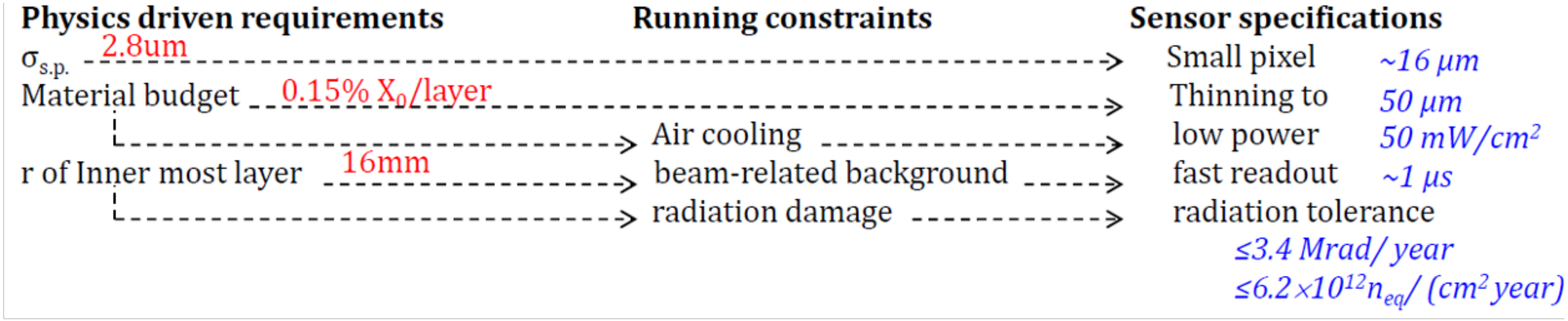
Sensors technology requirements for Vertex Detector

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:

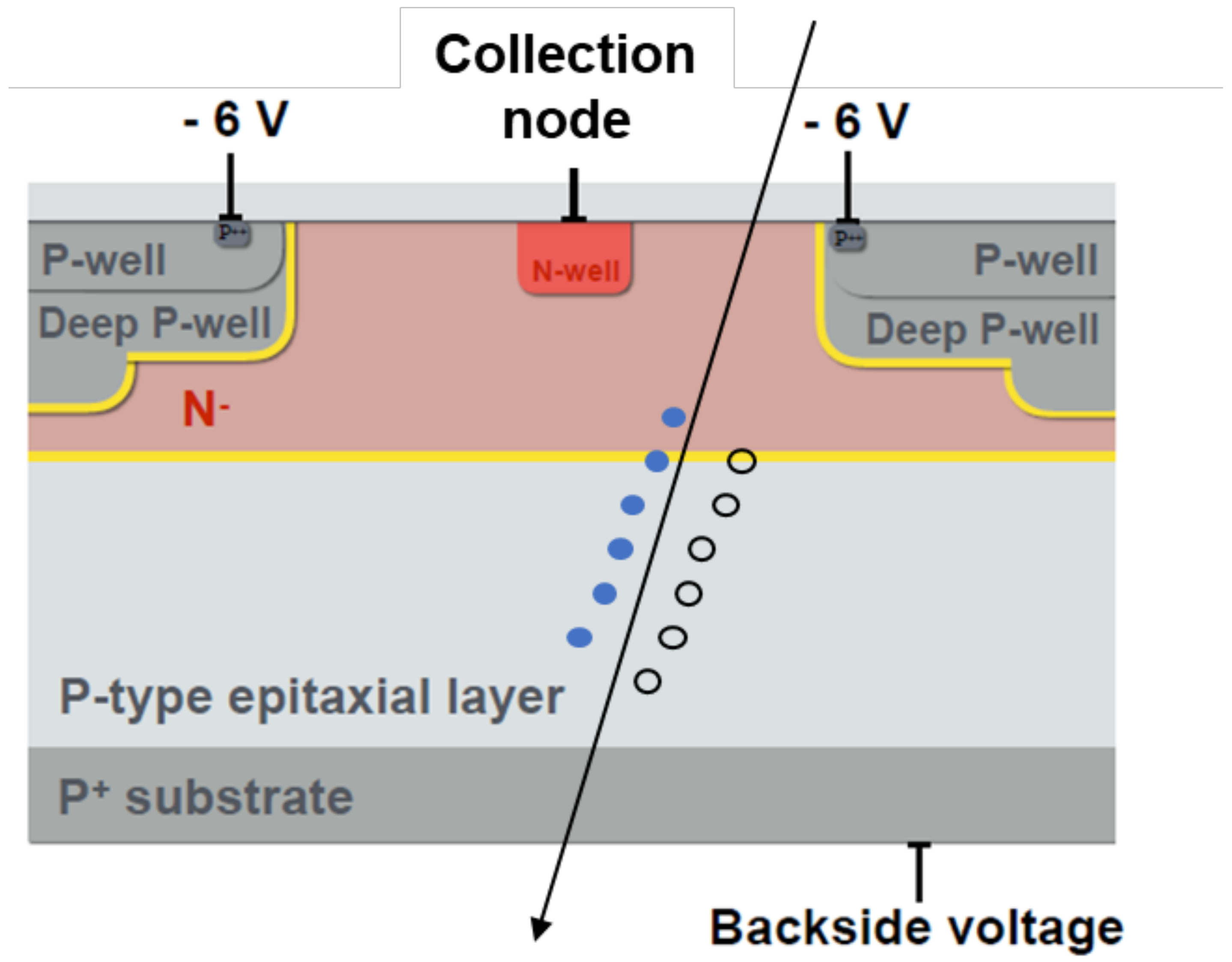
- continuous r/o during the train with power cycling
- delayed after the train → either ~5µm pitch for occupancy or in-pixel time-stamping



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



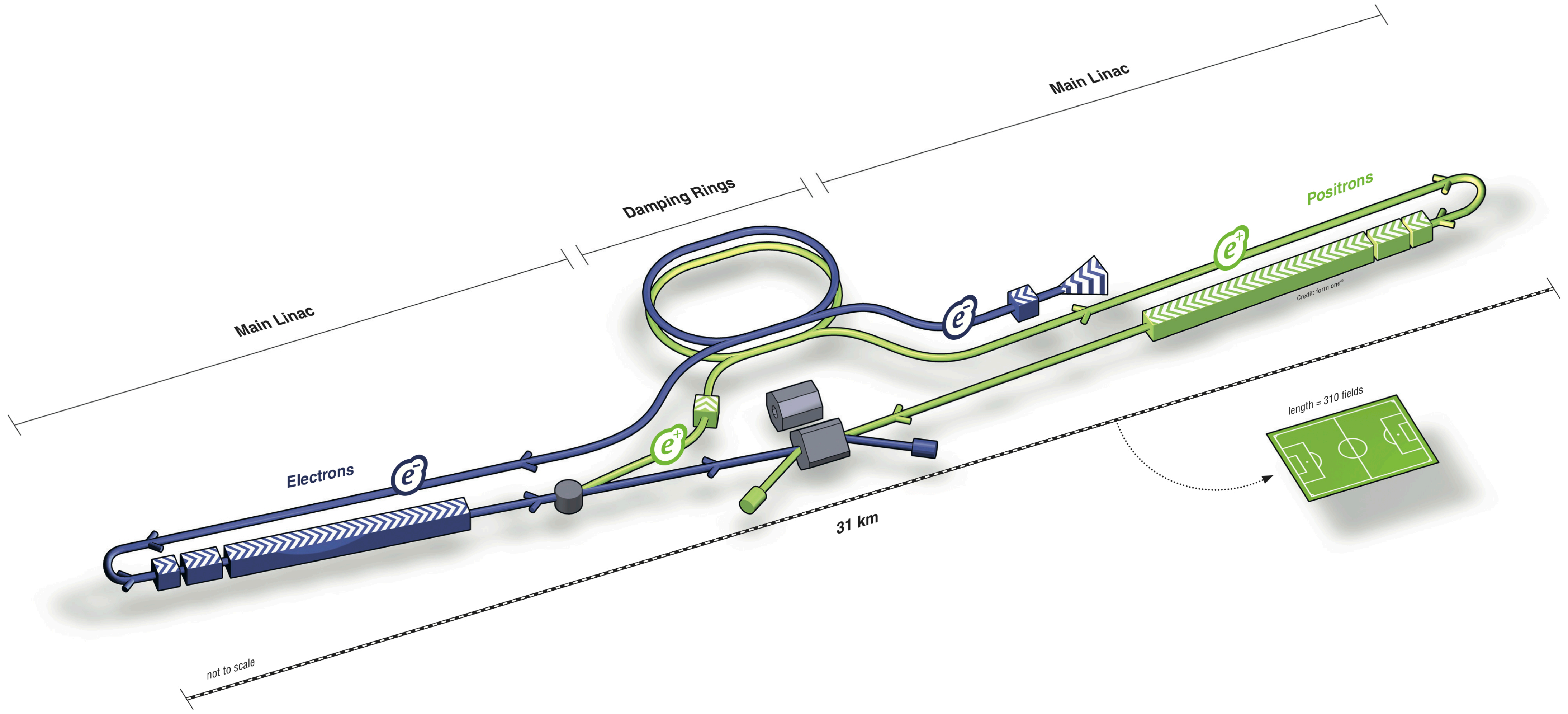
Initial specifications for fast MAPS aka NAPA

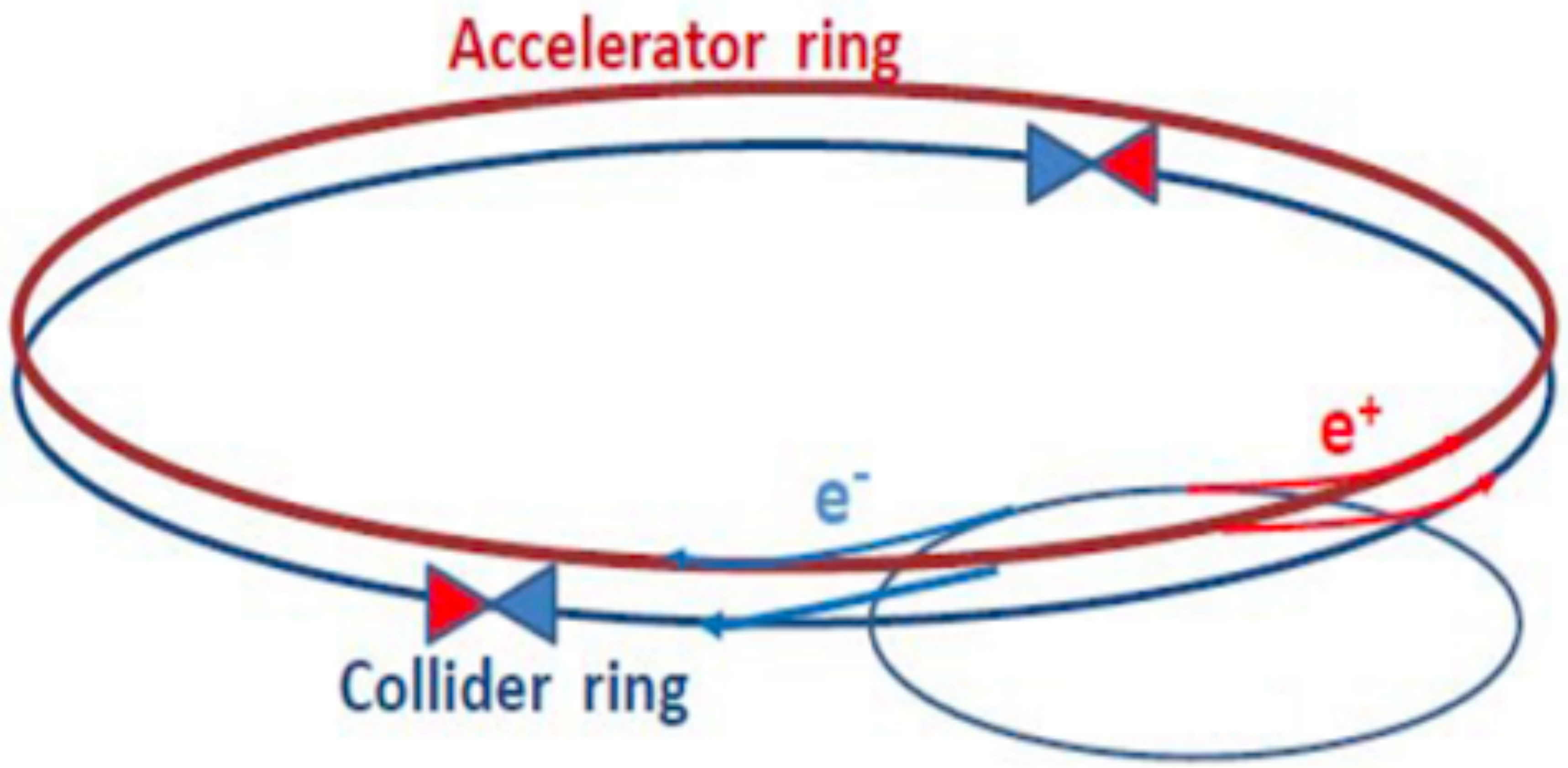
Parameter	Value
Min. Threshold	140 e^-
Spatial resolution	7 μm
Pixel size	25 x 100 μm^2
Chip size	10 x 10 cm^2
Chip thickness	300 μm
Timing resolution (pixel)	~ns
Total Ionizing Dose	100 kRads
Hit density / train	1000 hits / cm^2
Hits spatial distribution	Clusters
Power density	20 mW / cm^2

Table 1: Target specifications for 65 nm prototype.

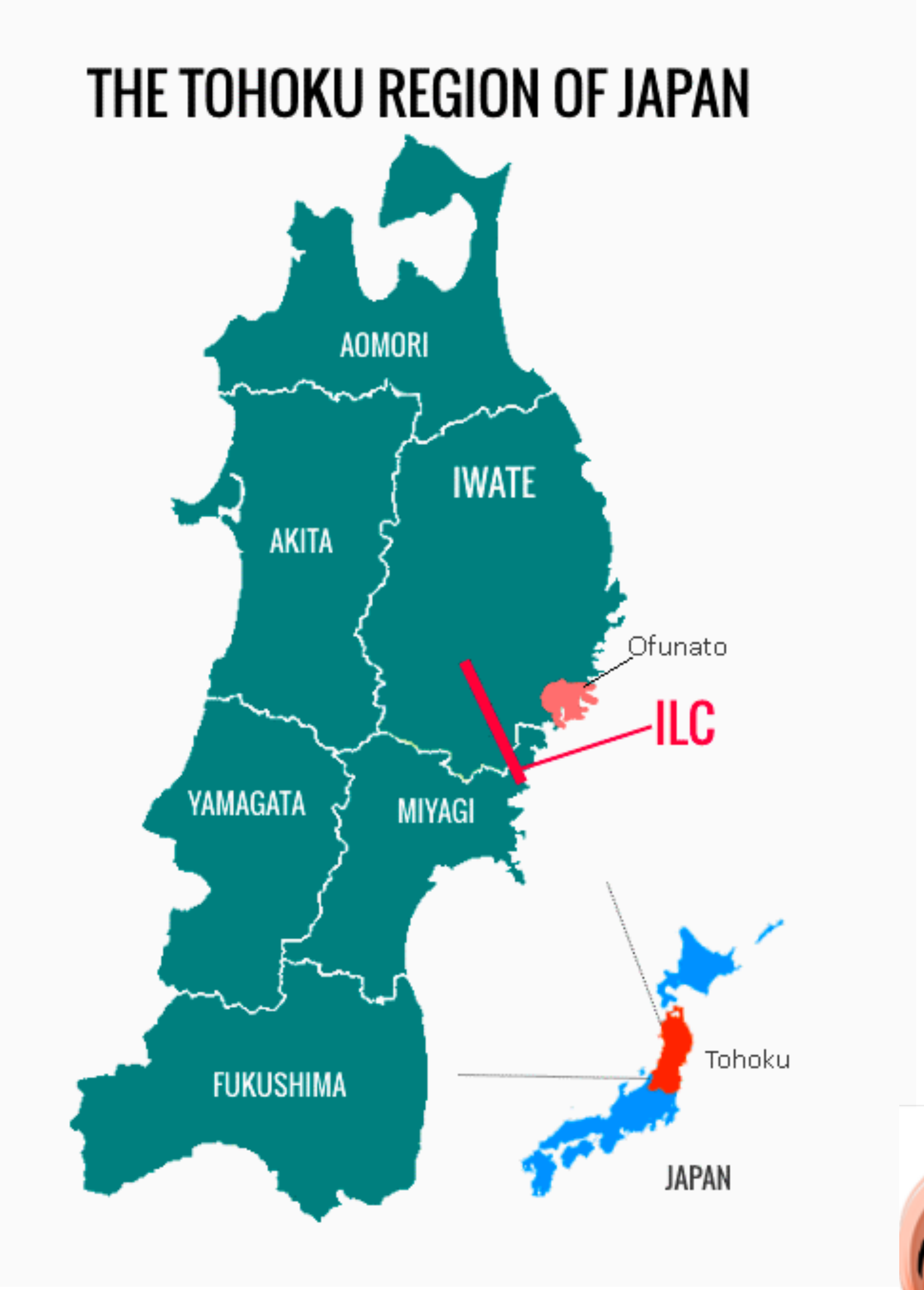
Linear vs. Circular

- **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

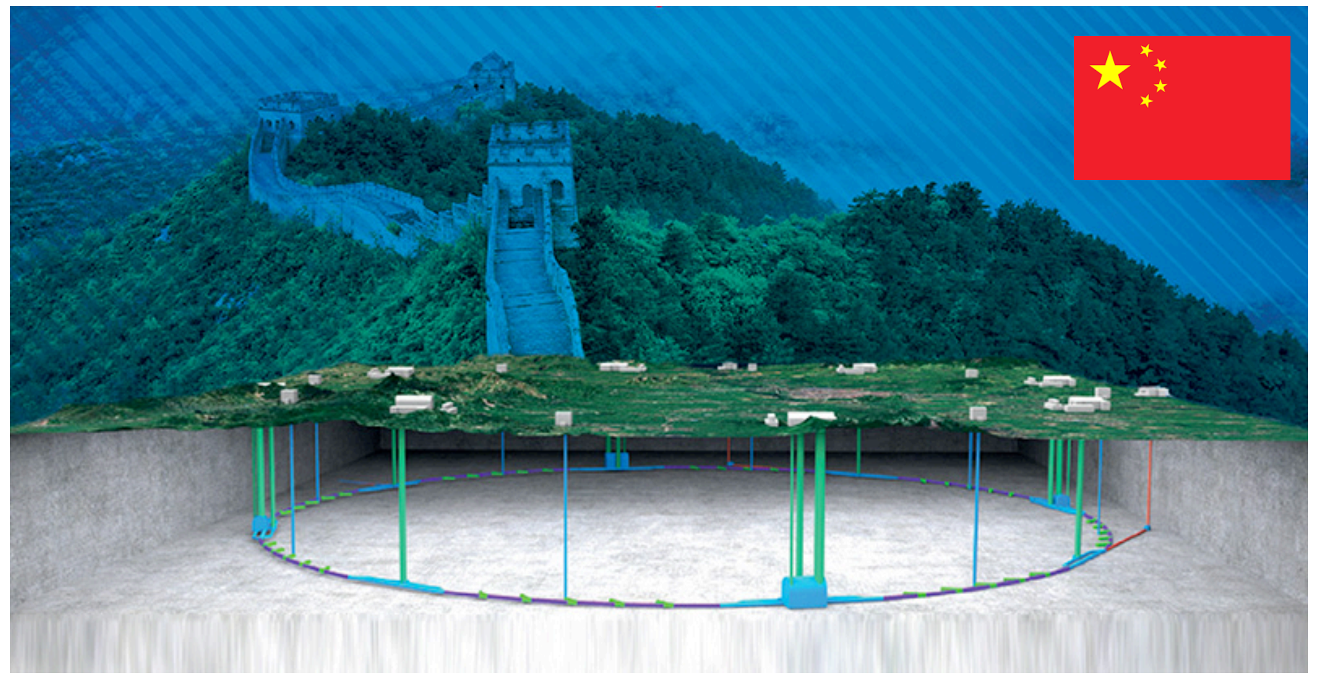




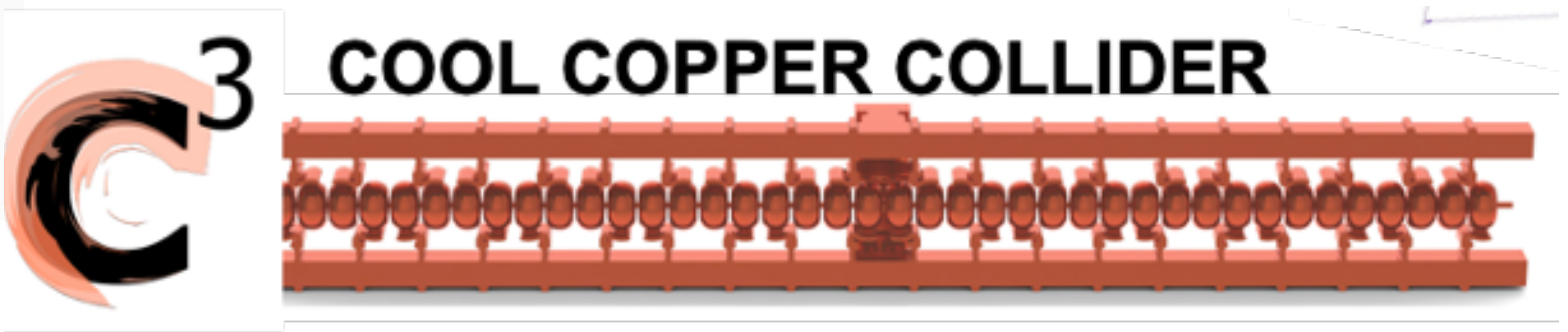
Various proposals …



250/500 GeV



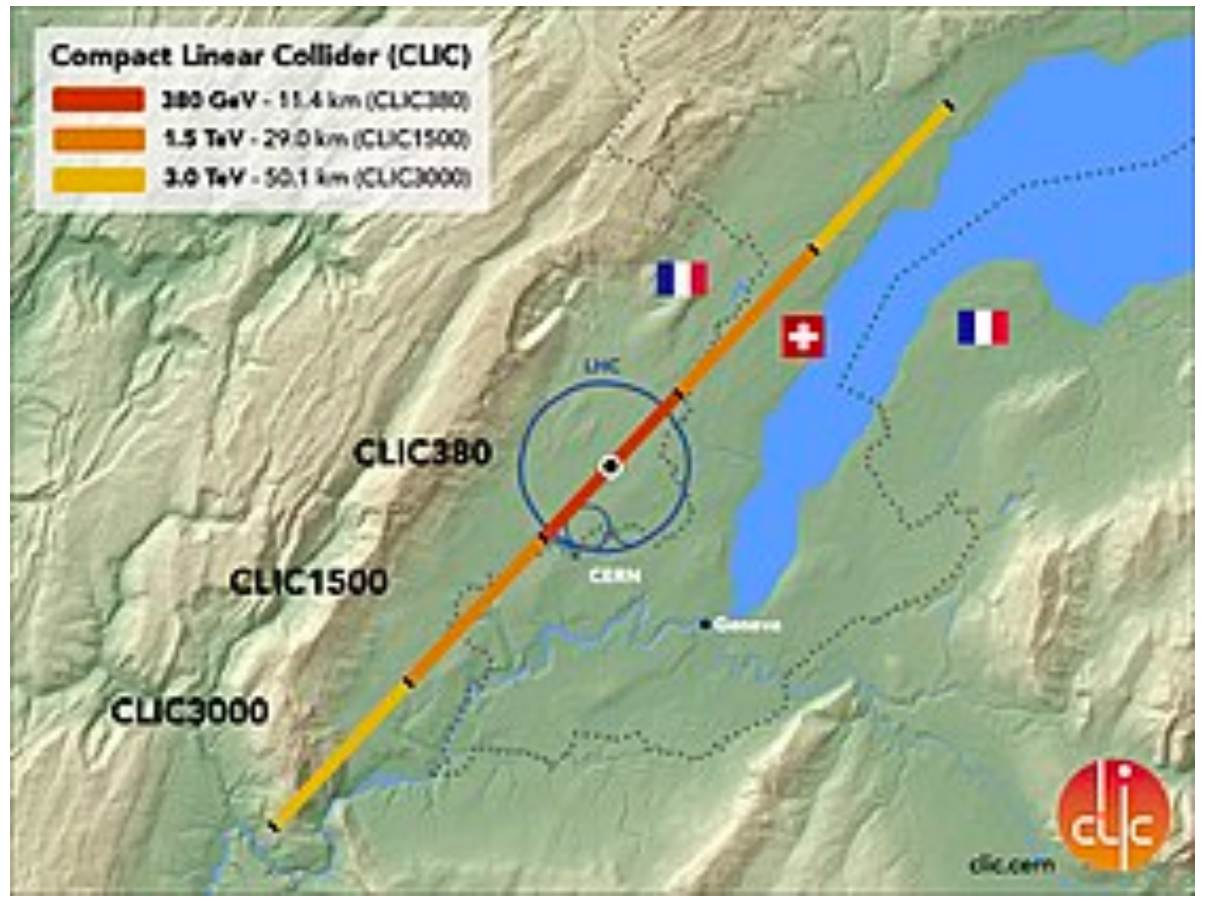
CEPC 240 GeV

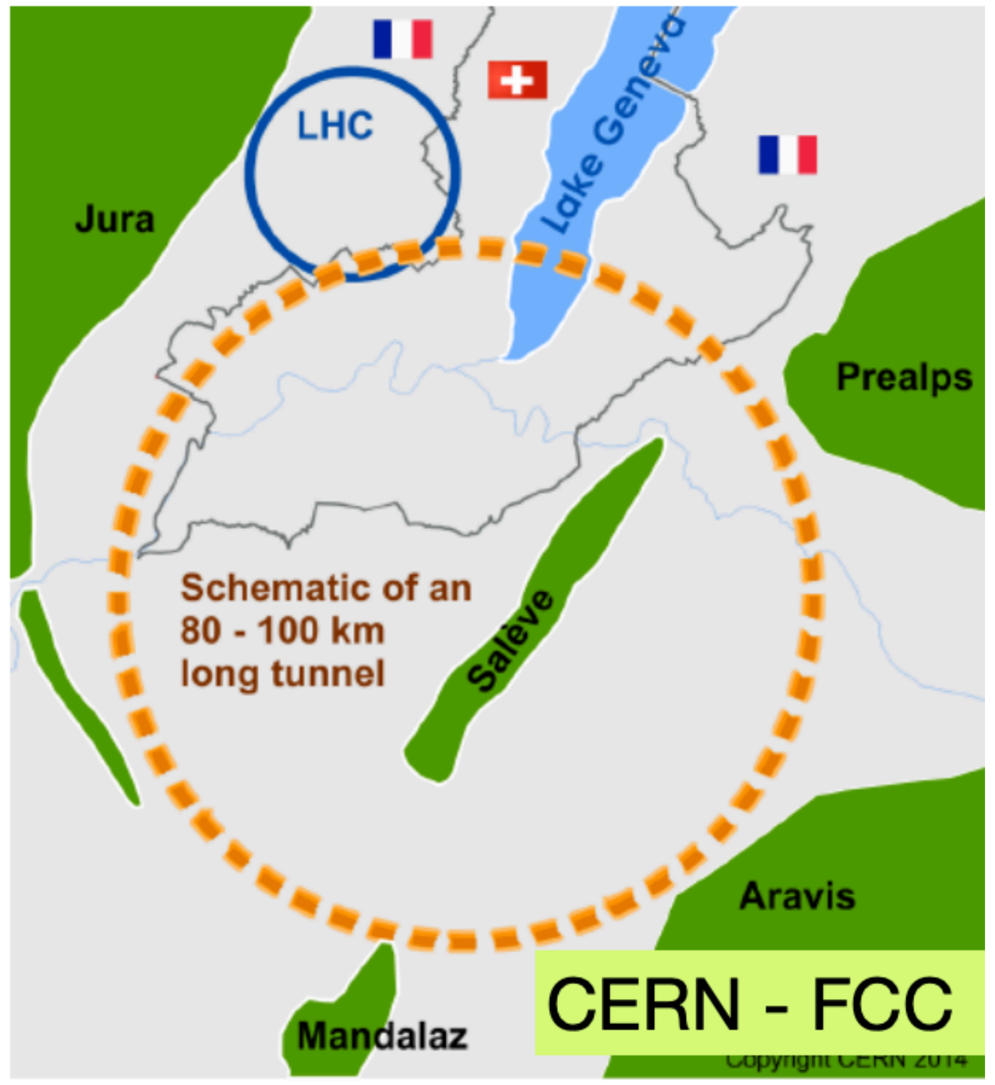


250/550 GeV

… > TeV

CLIC 380/1500/3000 GeV





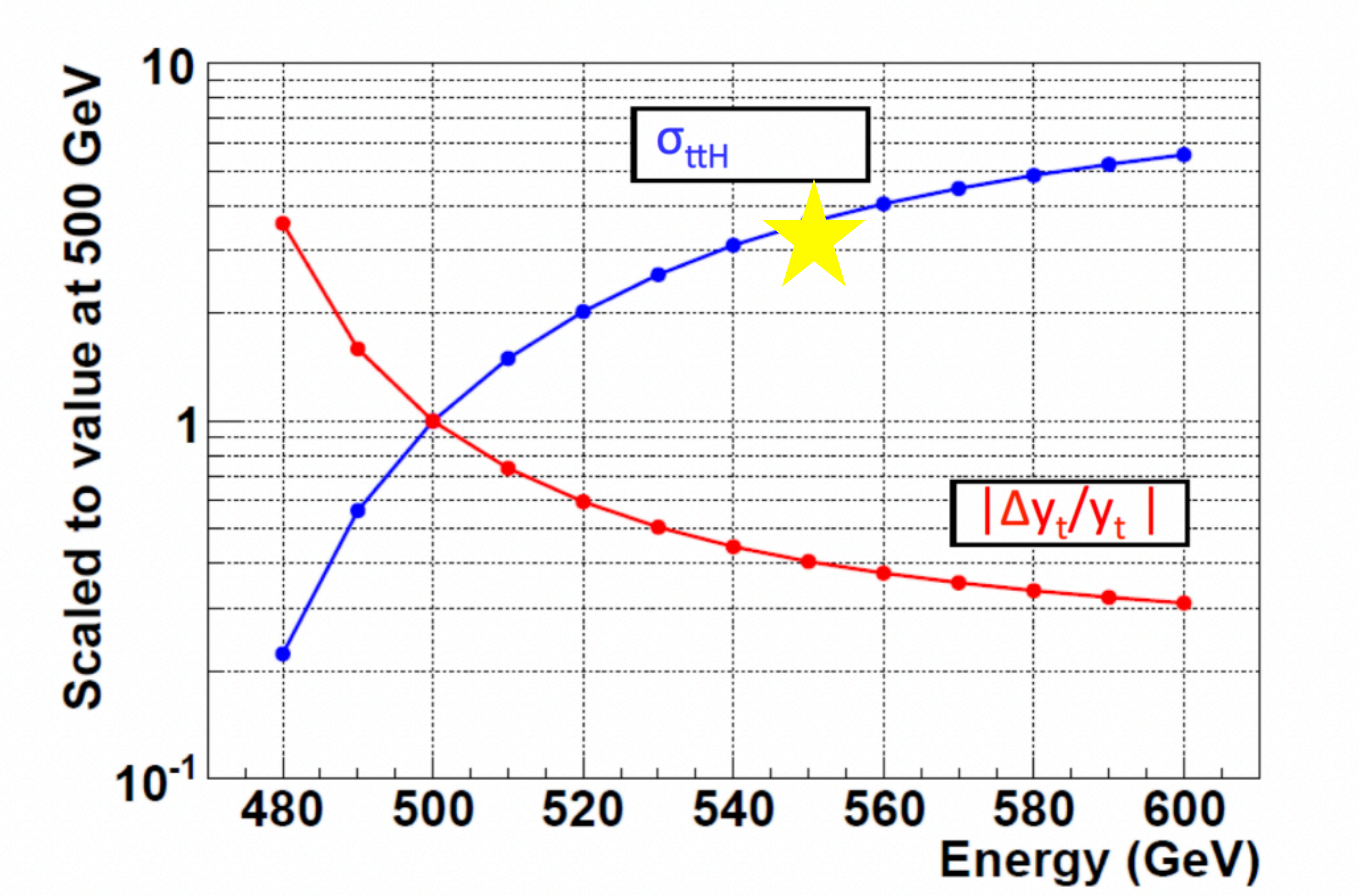
FCC-ee

240/365 GeV

arXiv:1908.11299
arXiv:1506.07830

Why 550 GeV?

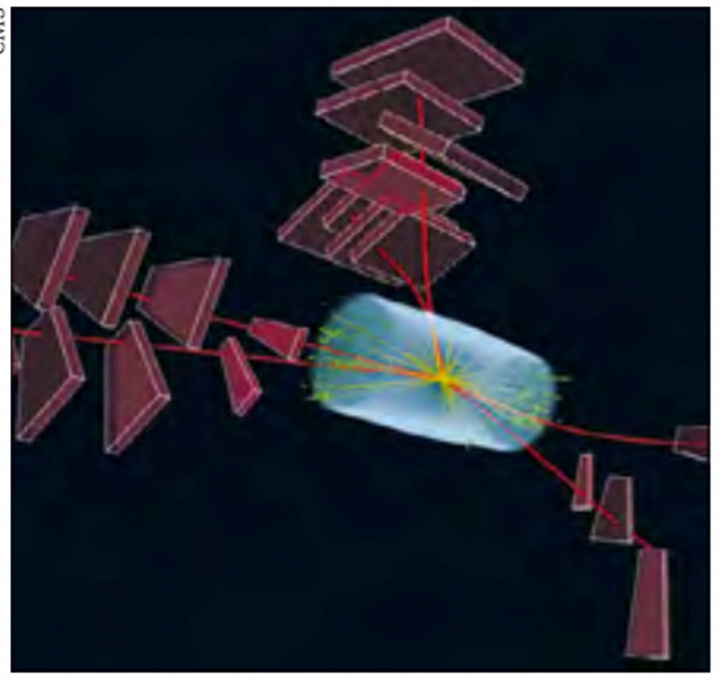
- We propose **250** GeV with a relatively inexpensive upgrade to **550** GeV on the same 8 km footprint.
- 550 GeV will offer an orthogonal dataset to cross-check a deviation from the SM predictions observed at 250 GeV
- O(20%) precision on the Higgs self-coupling would allow to exclude/ demonstrate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

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).

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

Physics ABOUT BROWSE PRESS COLLECTIONS Search articles

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

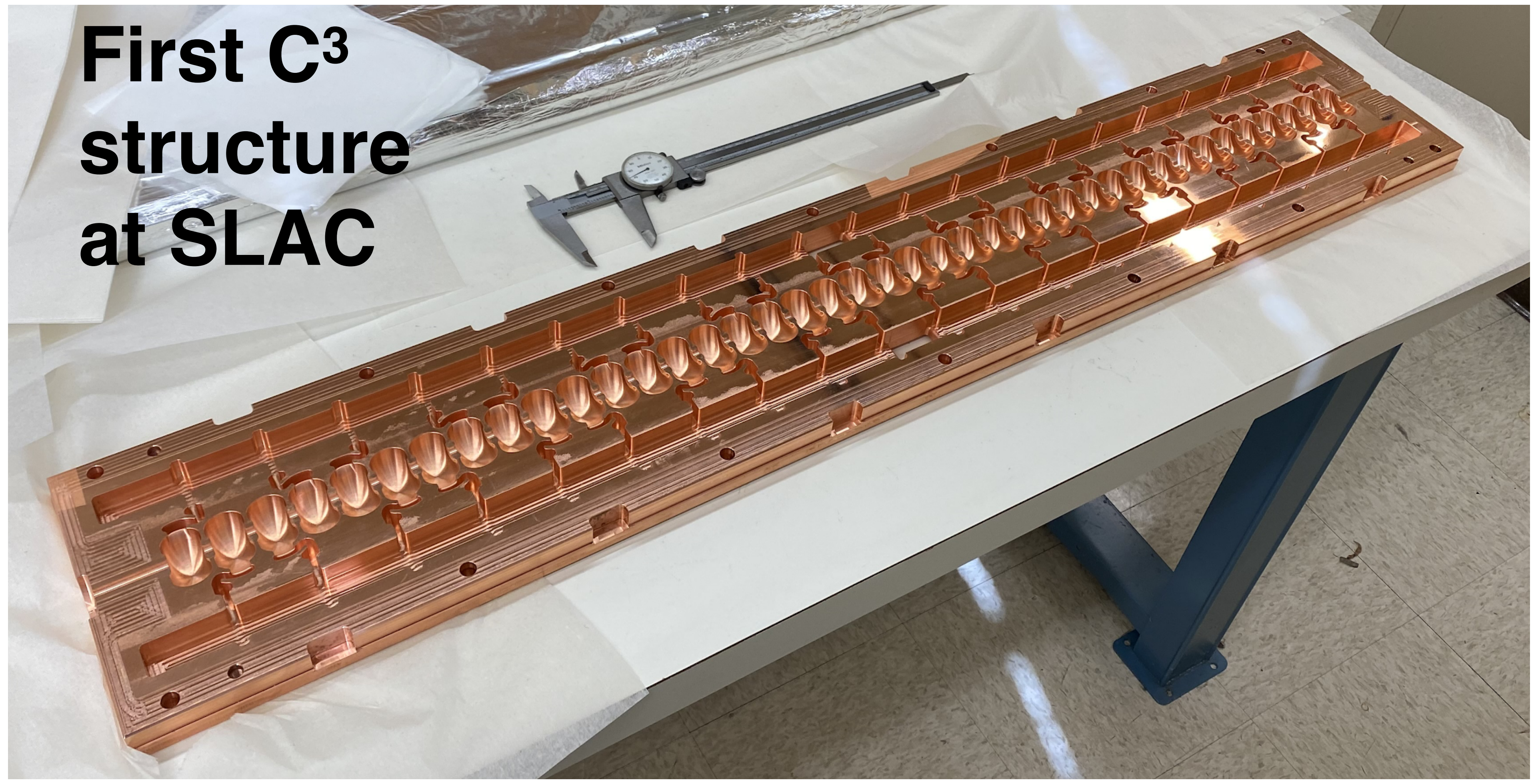
A prototype version of the Cool Copper Collider. The photo shows the central region where the particle beams would pass.

arXiv:2110.15800

C^3 why copper?

C^3 is a new linac **normal conducting technology** based on:

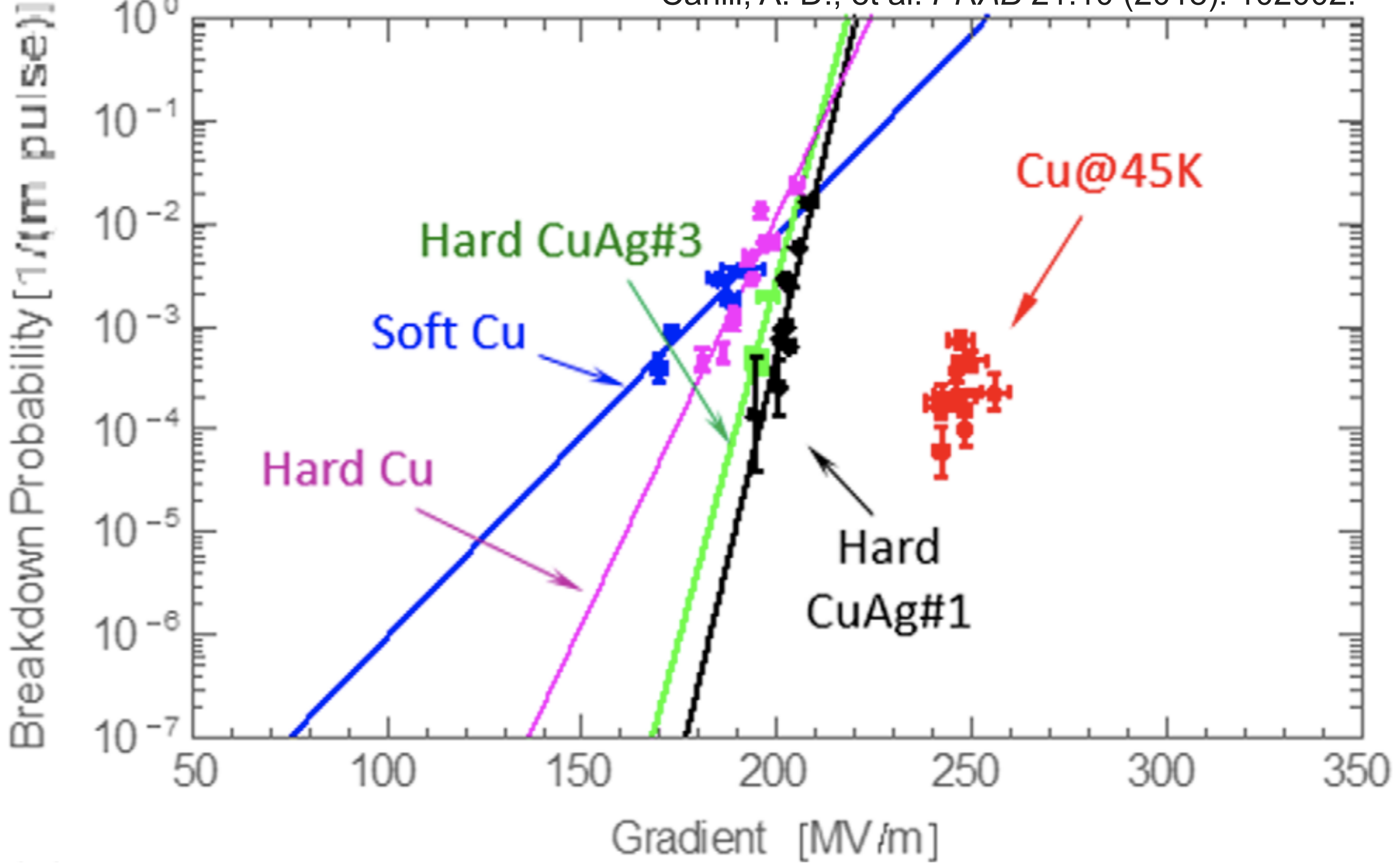
- An ab-initio study of on axis accelerating fields and **cavity breakdown rates** – successful, but with relatively small iris.
  - RF fundamental does not propagate through irises.
- A related discovery of an integrated **RF manifold** delivering proper phase and $1/N_{cavities}$ power to each cavity solves the small iris issue.
  - modern super-computing for solution.
  - Seemingly complex structure can easily and inexpensively be built with **modern CNC Machines**

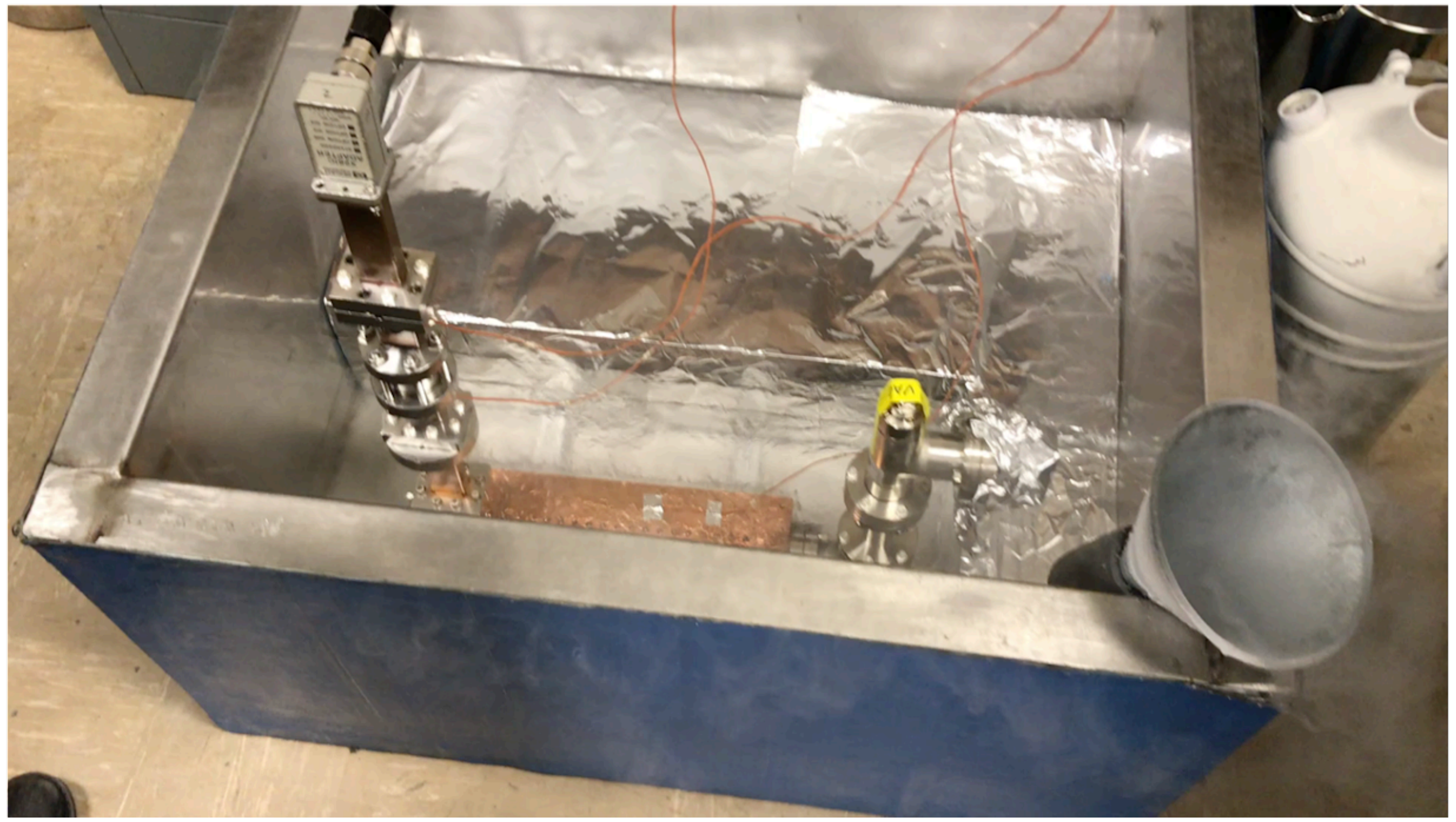


First C^3 structure at SLAC

Why cool?

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





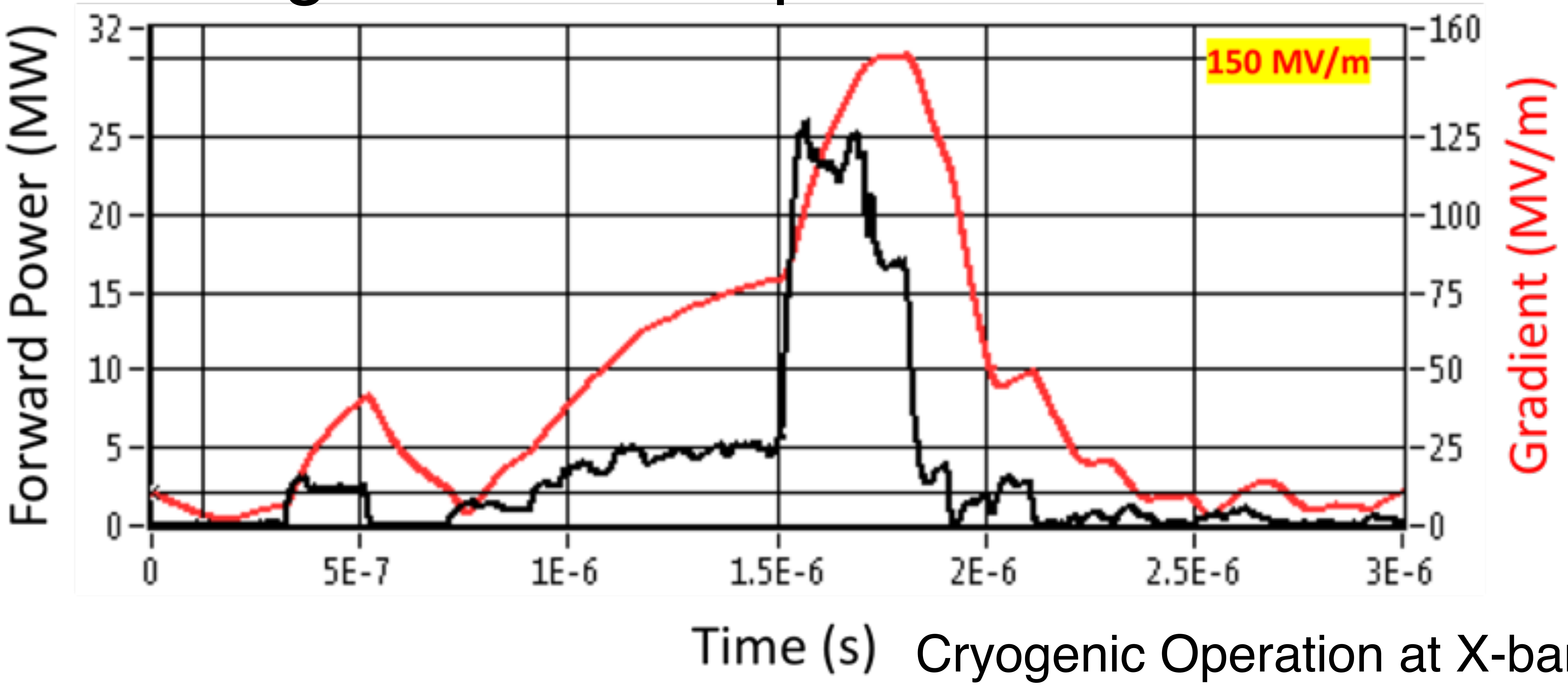
Nasr, et al. *PRAB* 24.9 (2021): 093201.

- Shunt impedance in normal conducting Cu further improved by **running at ~80K LN_2**
- Cryogenic temperature elevates performance in gradient
  - Material strength is key factor
  - Operation at 77 K with liquid nitrogen is simple and practical

C^3 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

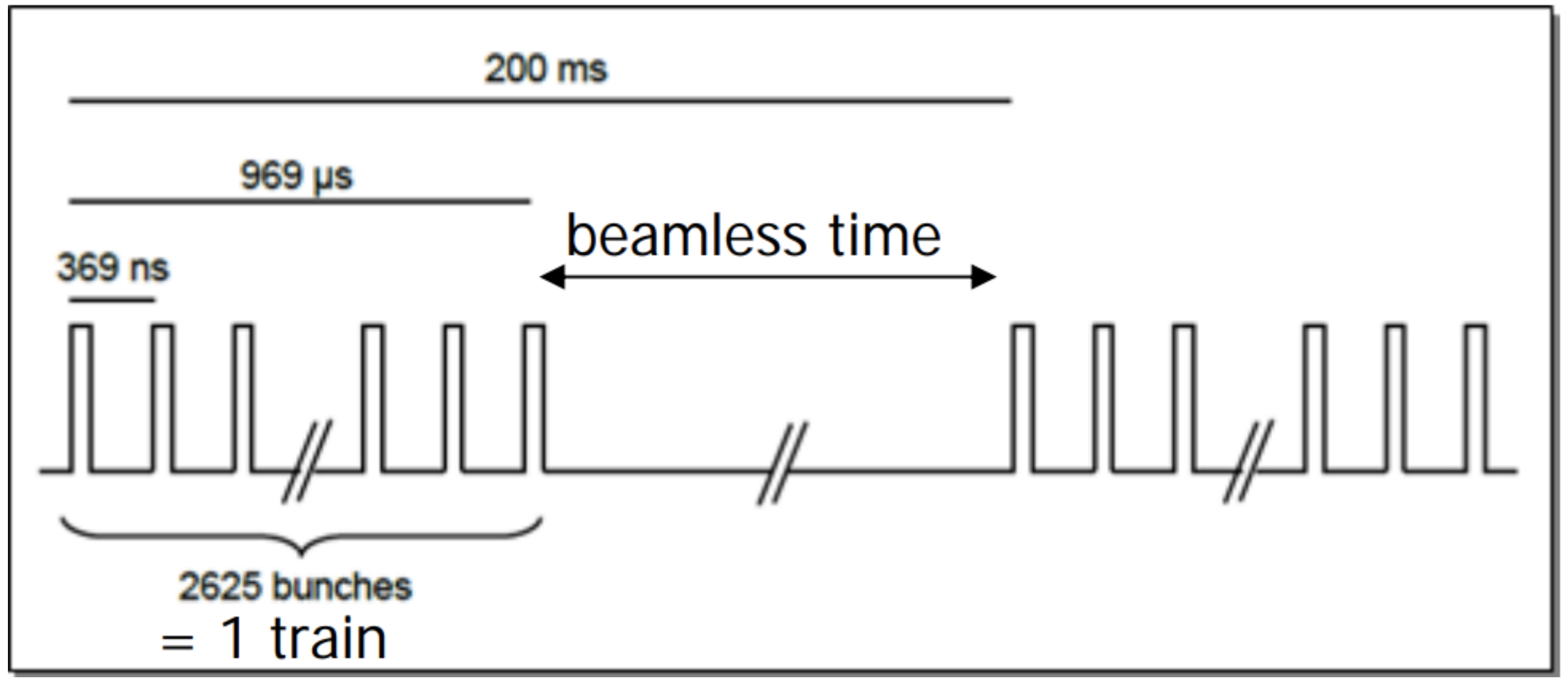
arXiv:2110.15800

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
Site Power [MW]	121	168	125	$\sim$150	$\sim$175
Design Maturity	CDR	CDR	TDR	pre-CDR	pre-CDR

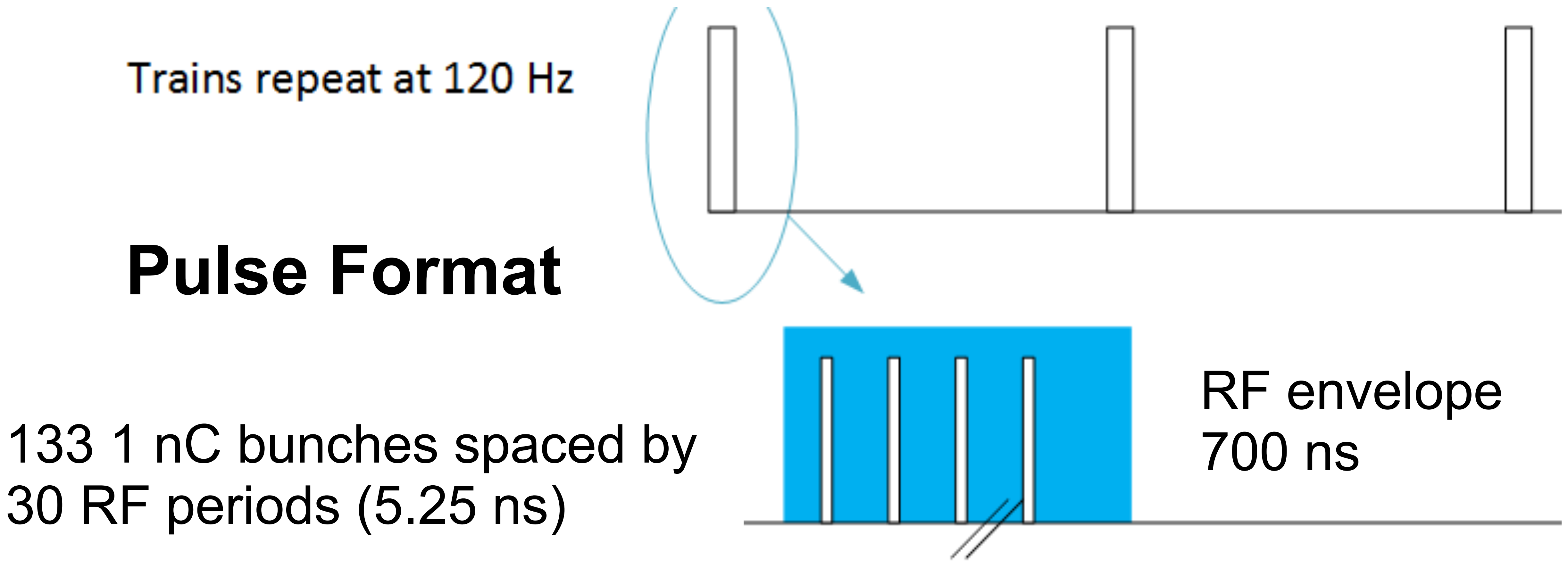
Beam Format and Detector Design Requirements

ILC timing structure



1 ms long bunch trains at 5 Hz
308ns spacing

C³ timing structure



ILC/C³ 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

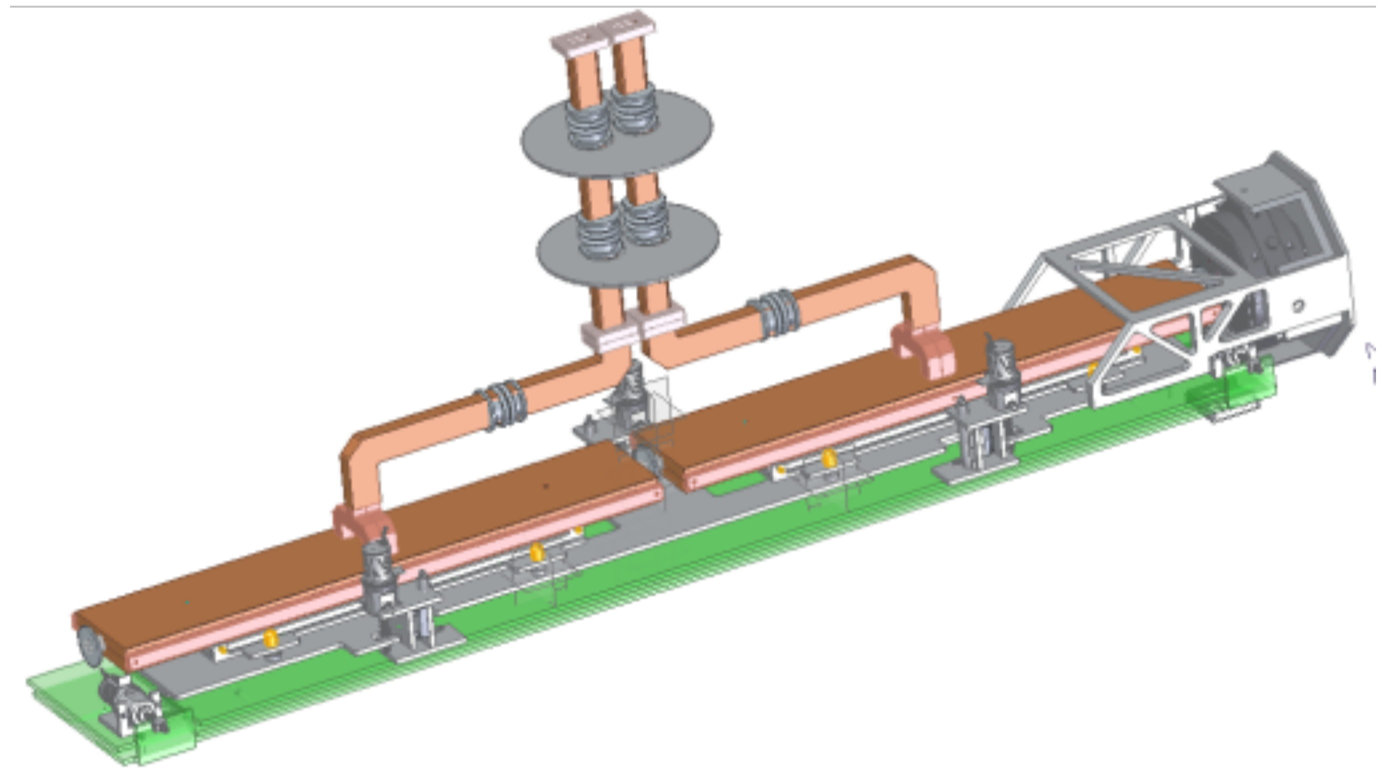
C³ time structure is compatible with ILC-like detector overall design and ongoing optimizations.

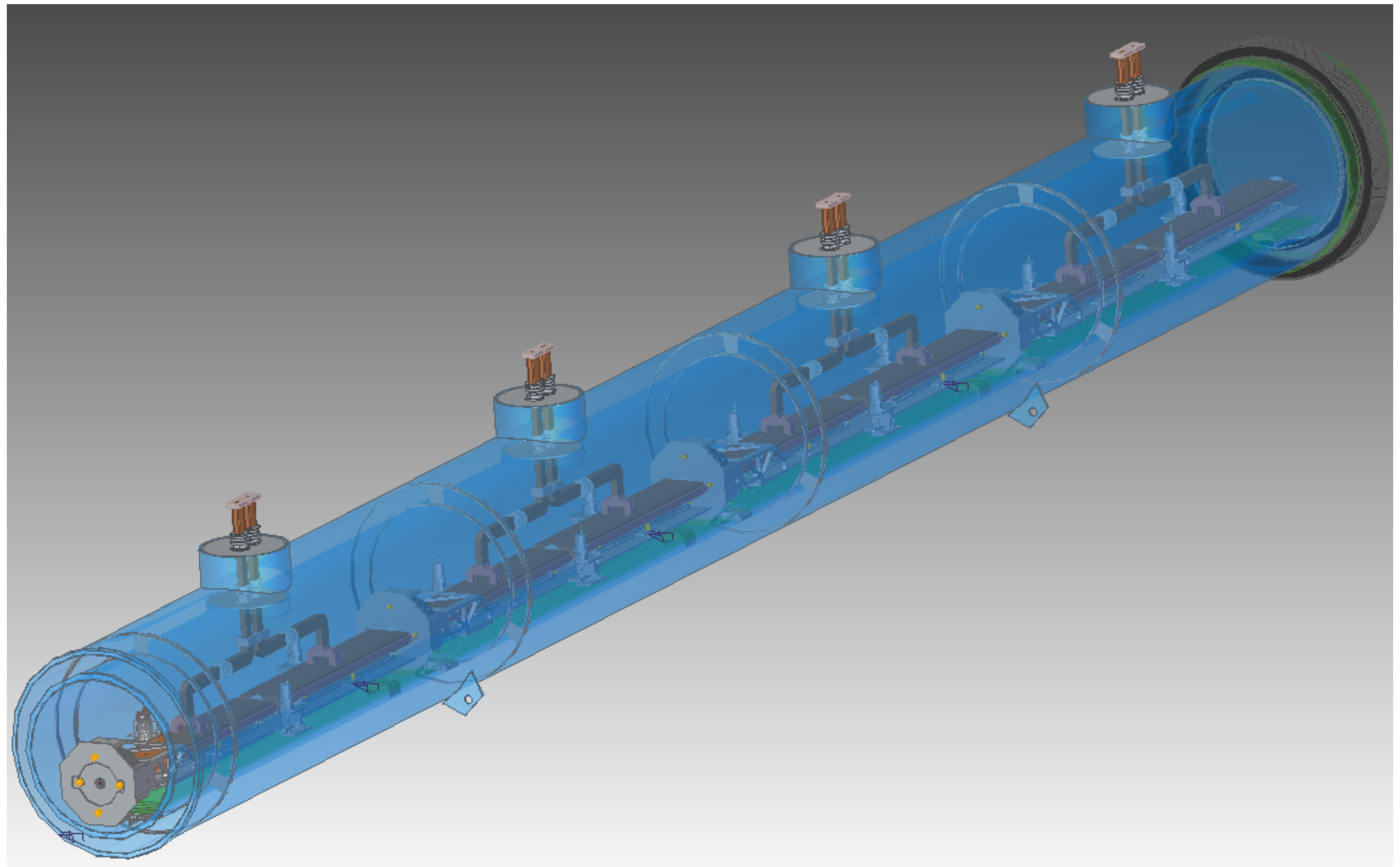
arXiv:2110.15800

Cryomodule Design

Up to 1 GeV of acceleration per 9 m cryomodule; ~90% fill factor with eight 1 m structures

On going development: design of cryomodule for first prototype with two structures.

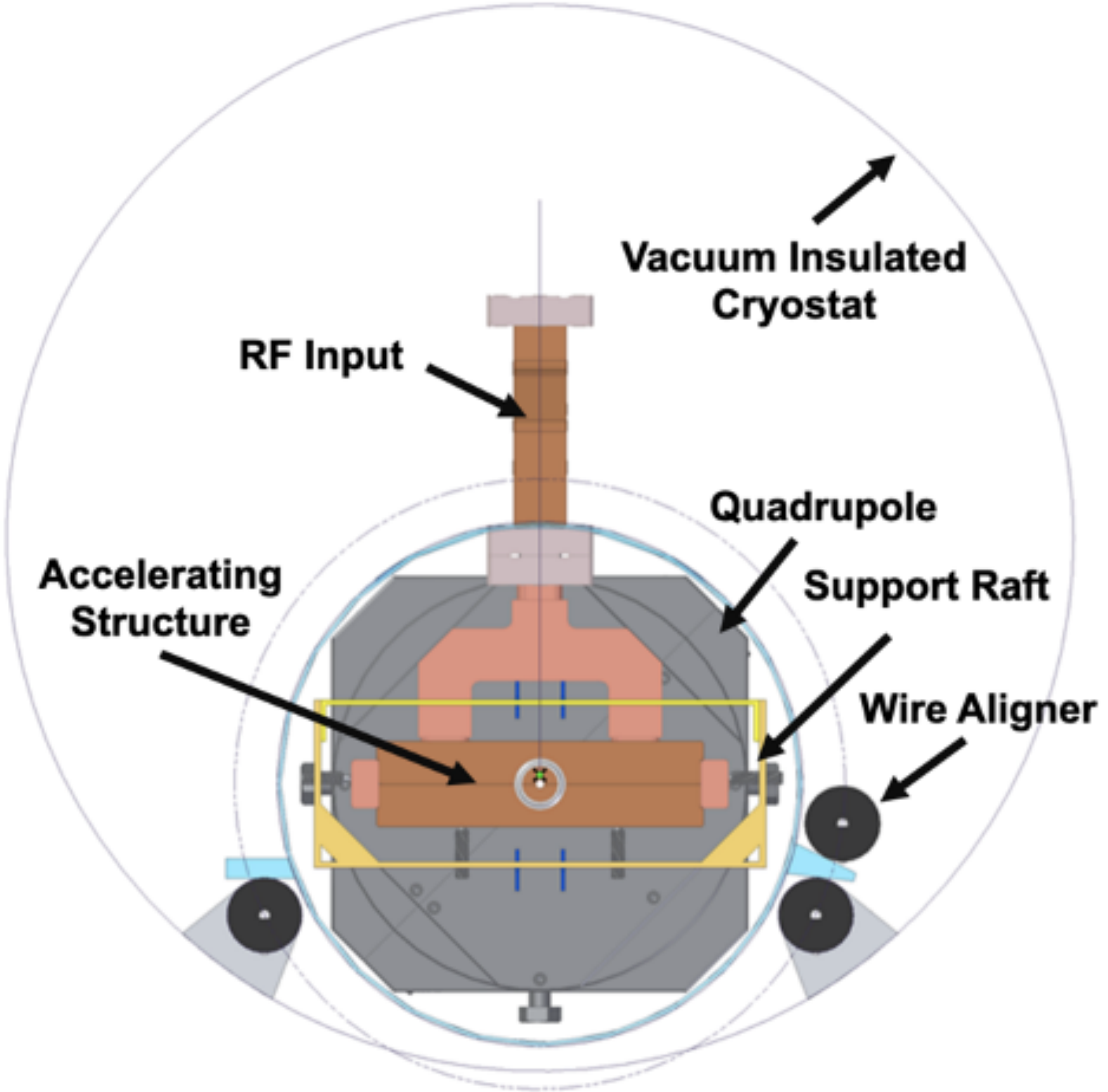




Cryomodule unit - 9 m

630 MeV at 70 MeV/m

1 GeV at 120 MeV/m

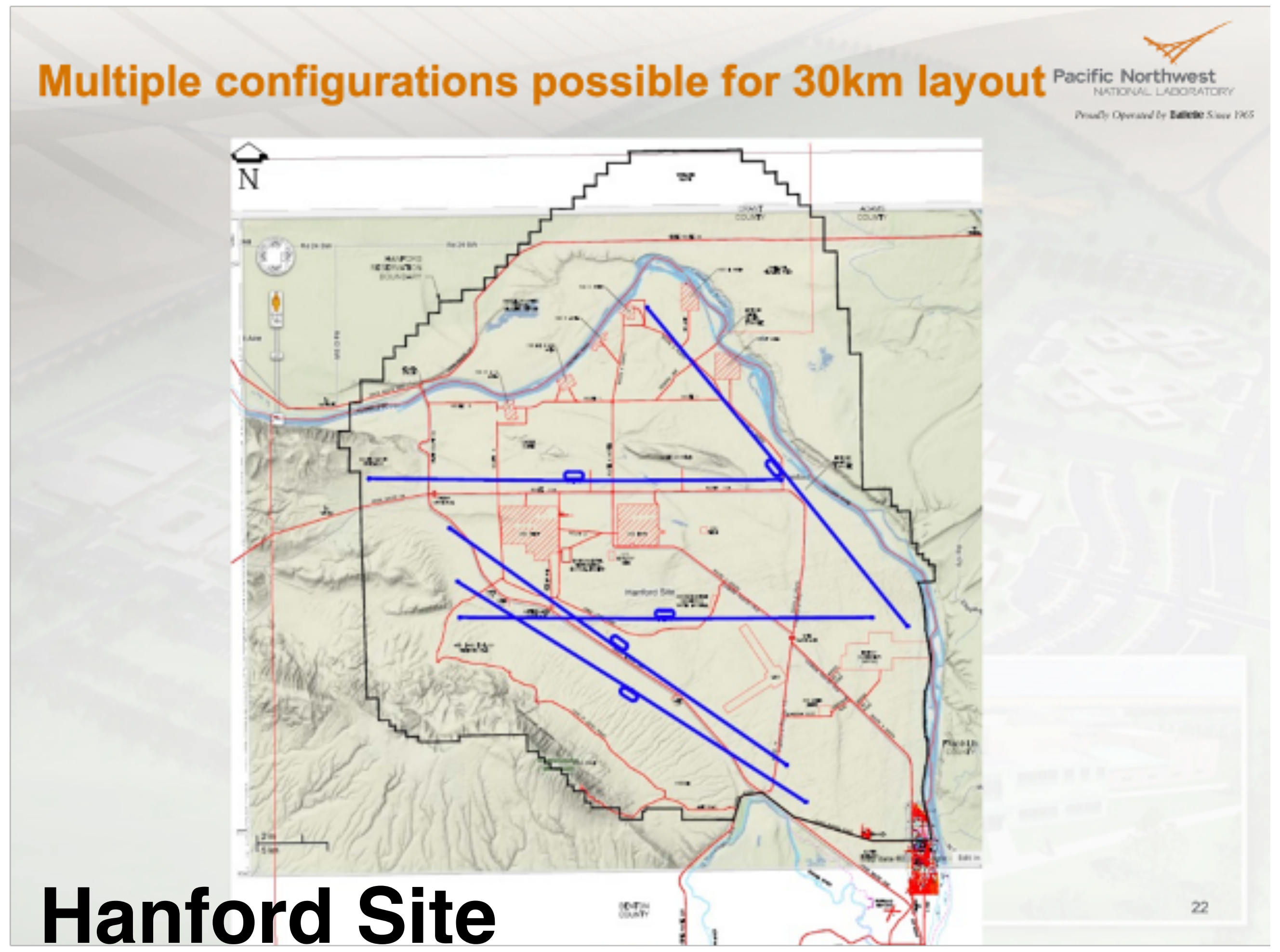


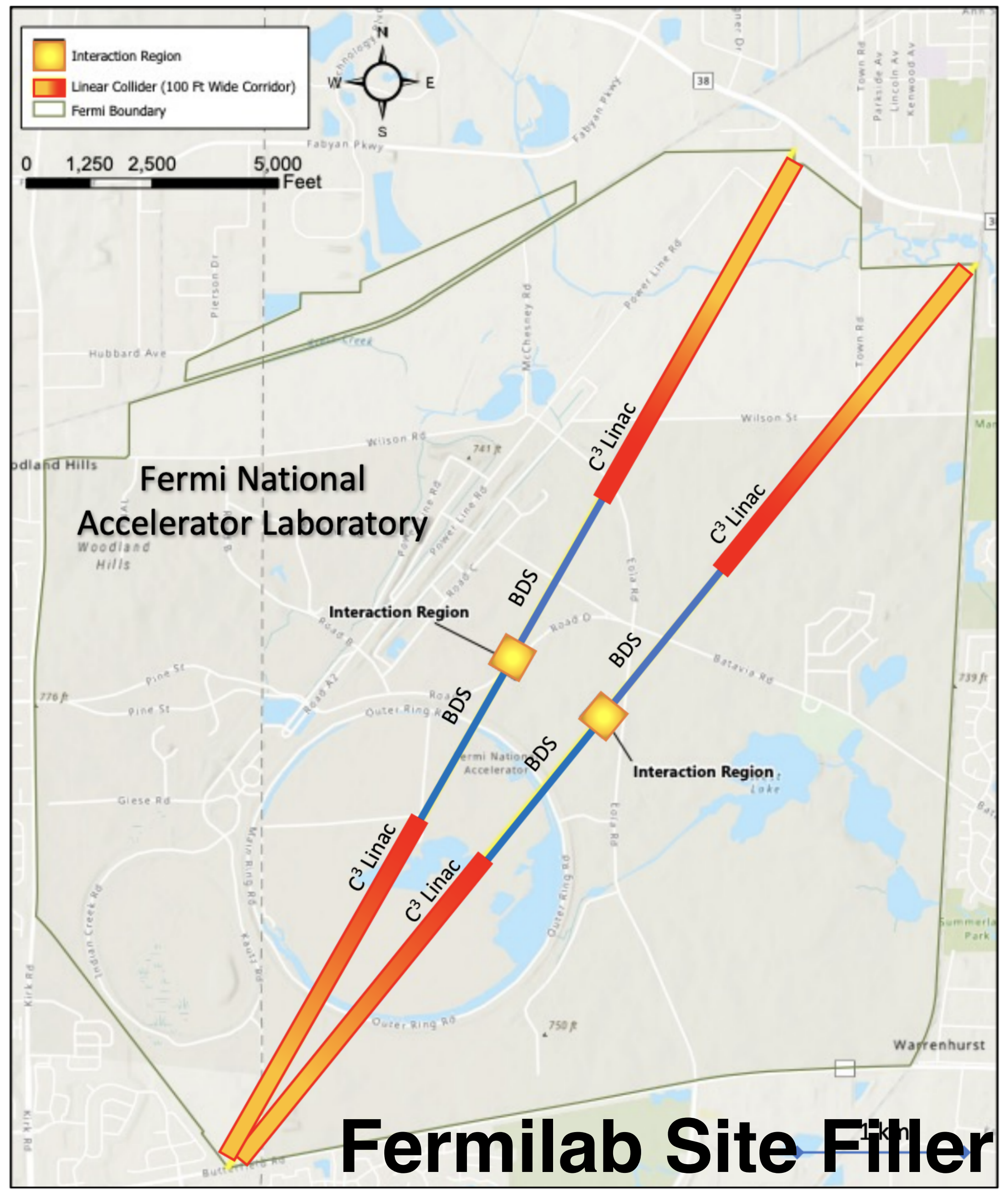
arXiv:2110.15800
arXiv:2203.07646

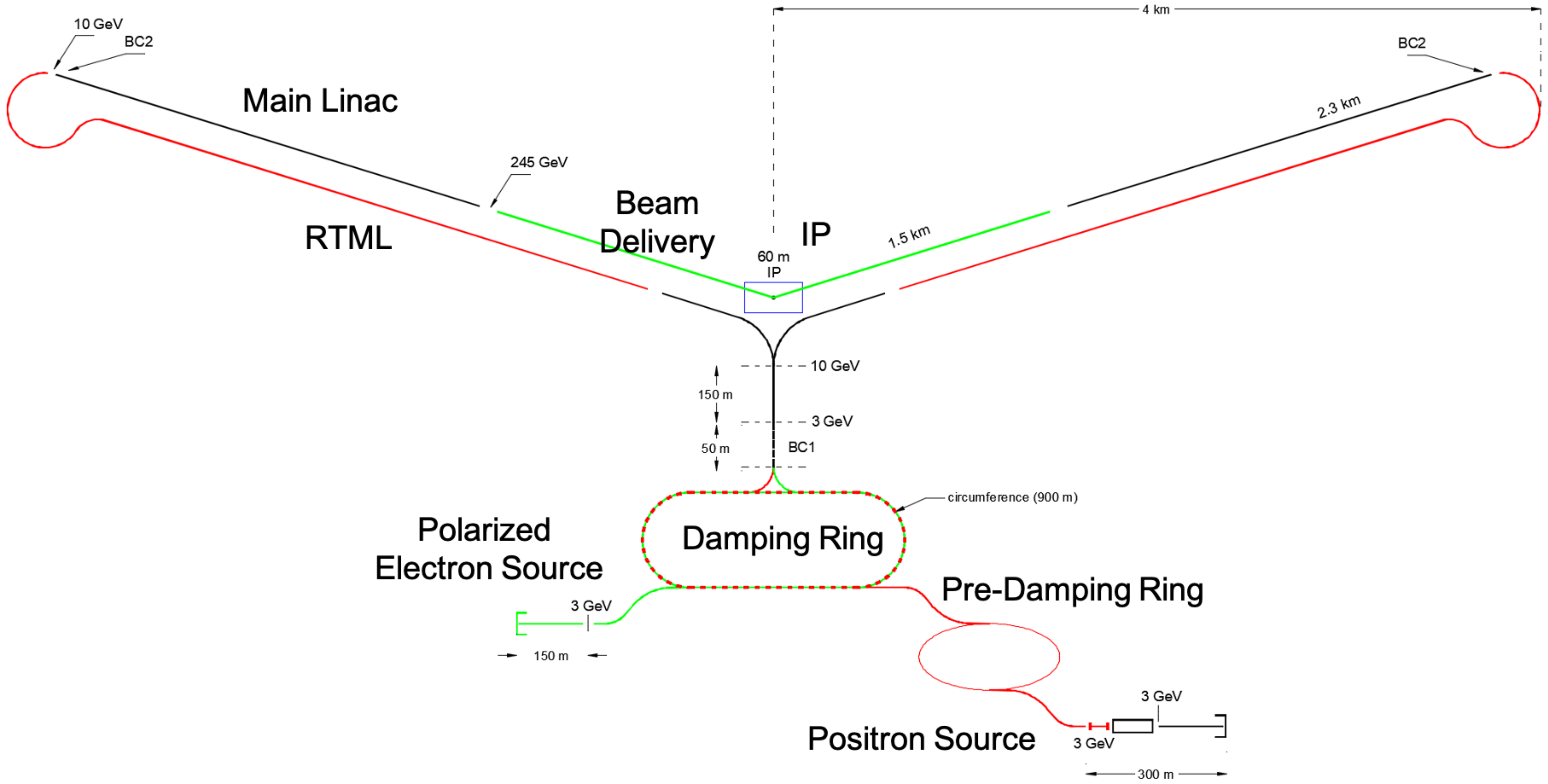
C³ layout

8 km footprint for 250/550 GeV ⟹ 70/120 MeV/m

7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site
Large portions of accelerator complex are compatible between LC technologies

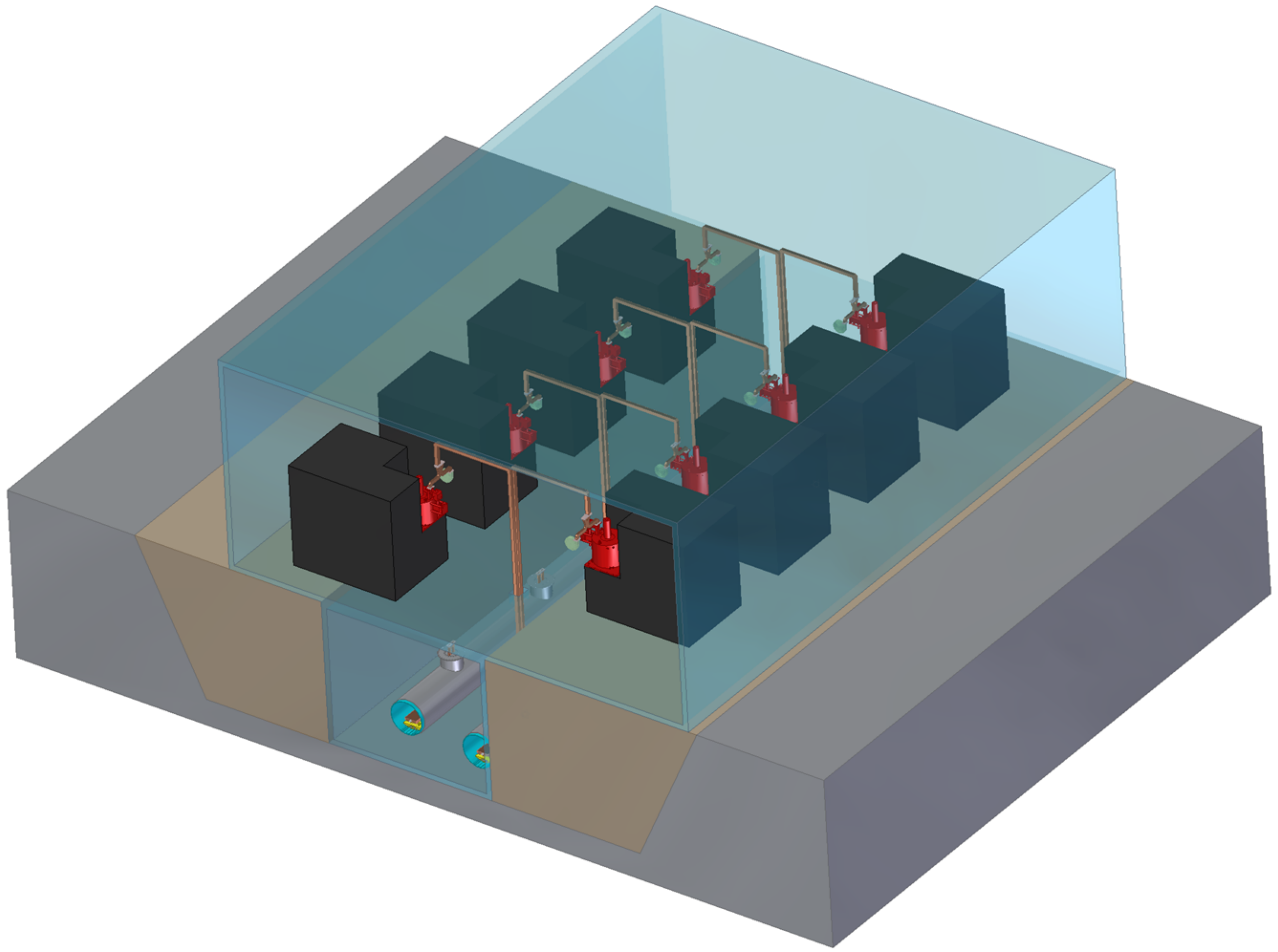


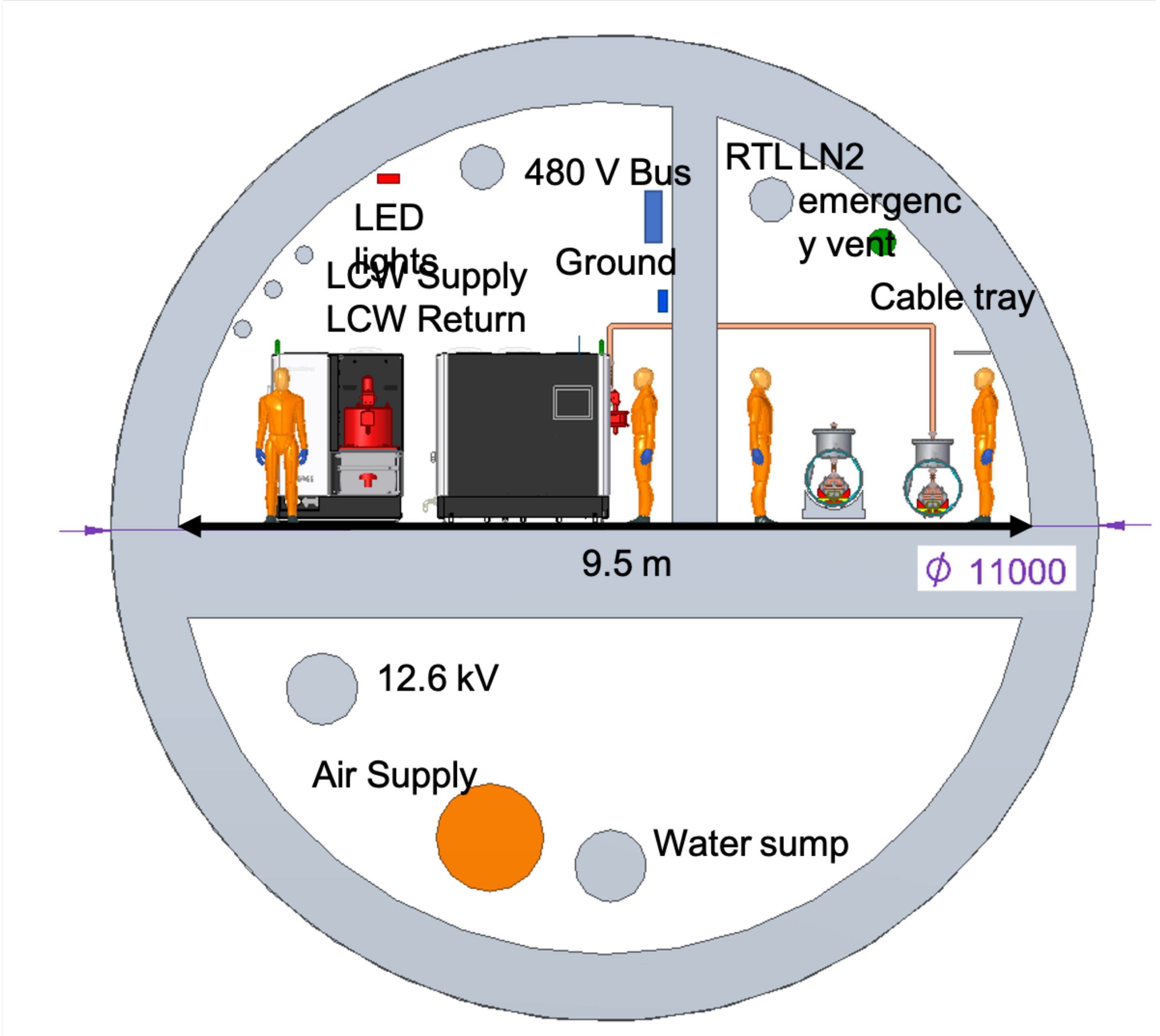




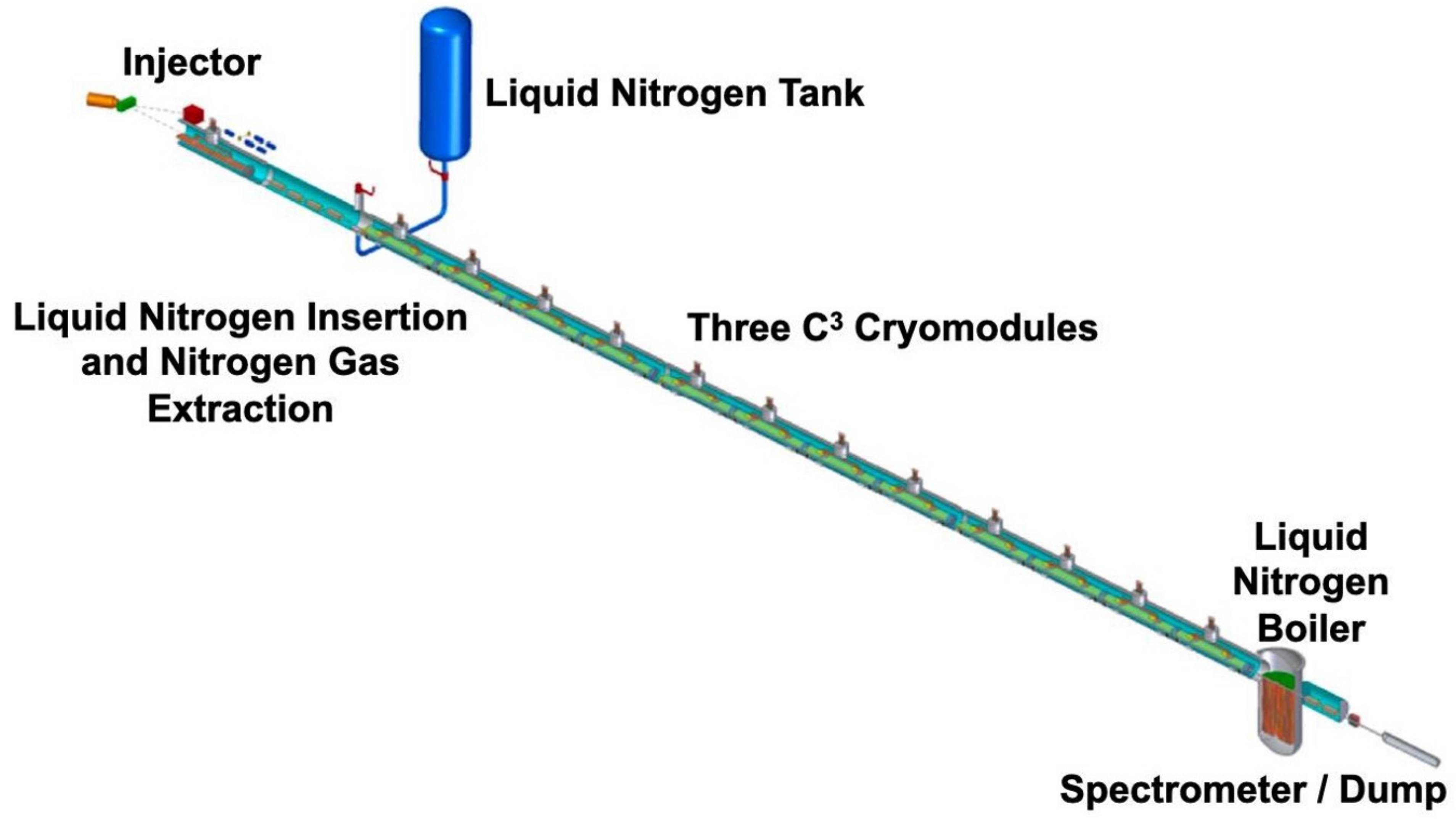
Tunnel Layout for Main Linac 250/550 GeV CoM

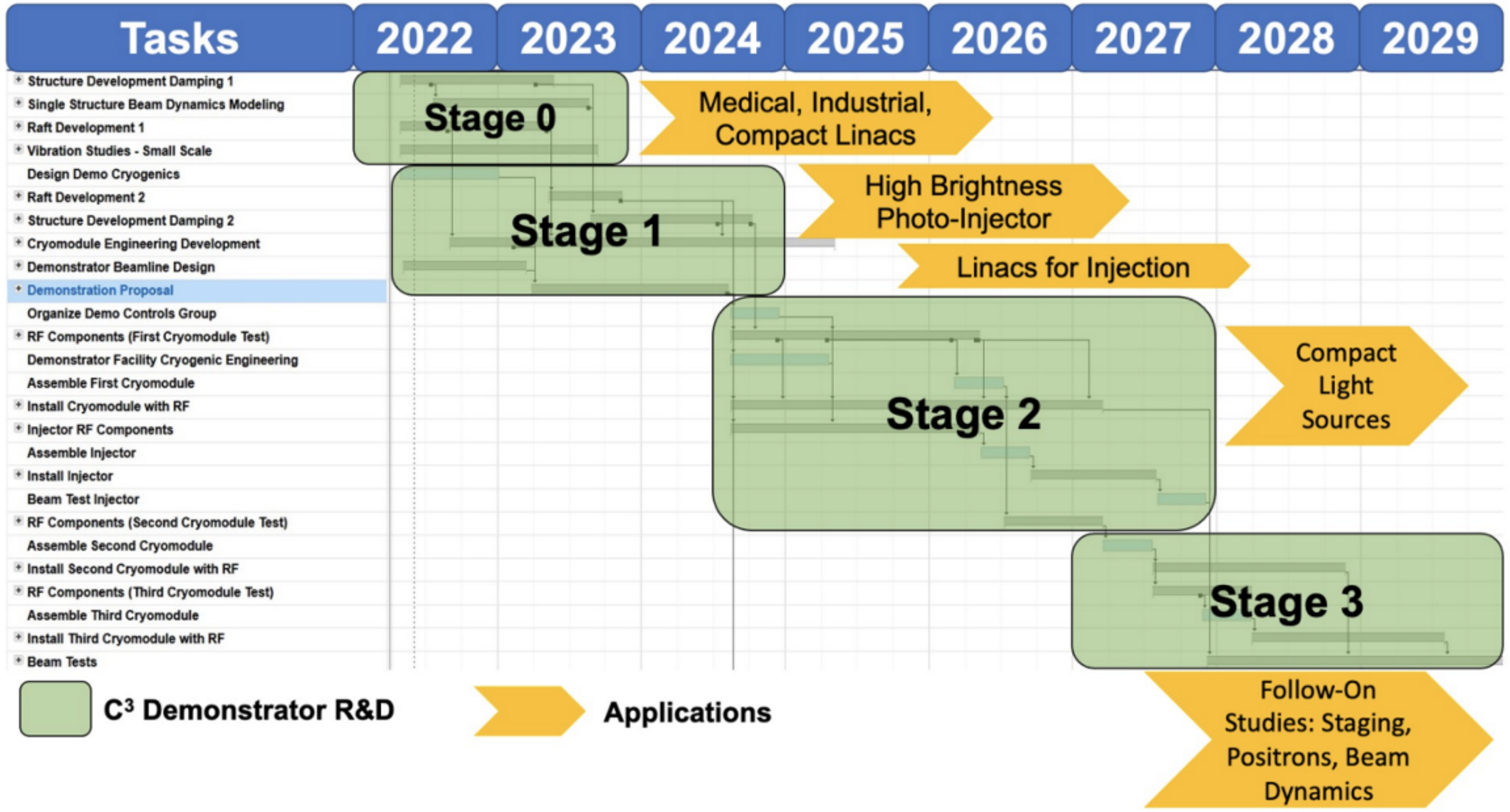
- Need to optimize tunnel layout – first study looked at 9.5 m inner diameter in order to match ILC costing model
  - Must minimize diameter to reduce cost and construction time
- Evaluating both underground and surface sites
  - Underground – less constraints on energy upgrade
  - Surface – lower cost and faster to first physics
- National Lab and Green Field are Possibilities





Next: C^3 Demonstration Facility





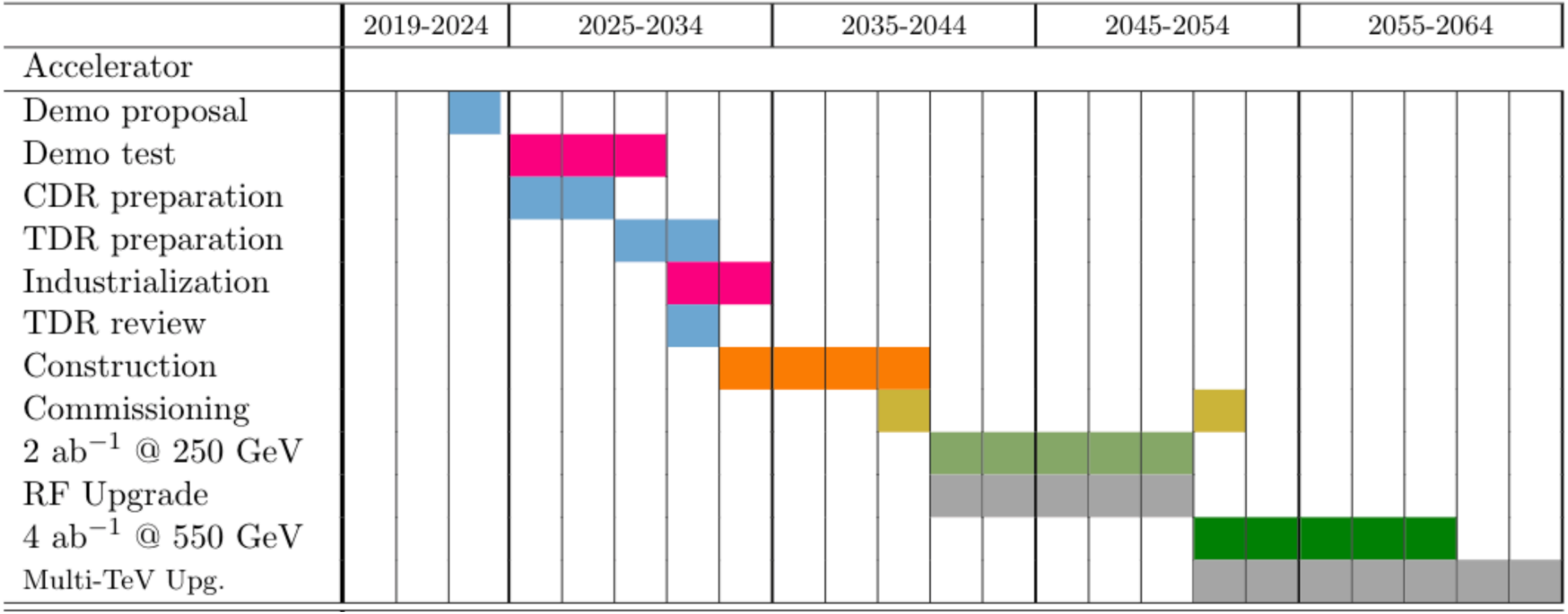
Demonstrate fully engineered cryomodule and then three cryomodules operations:

- ~50 m scale facility
- 3 GeV energy reach

Stage 1 will answer the most pressing technical questions - beam loading, damping, alignment required to complete the engineering to a level appropriate for a **CDR - by 2025**

What's next?

Technically limited timeline of the C^3 proposal



A strong US-based initiative mitigates Global Uncertainty

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

- C^3 has been evaluated independently from 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:

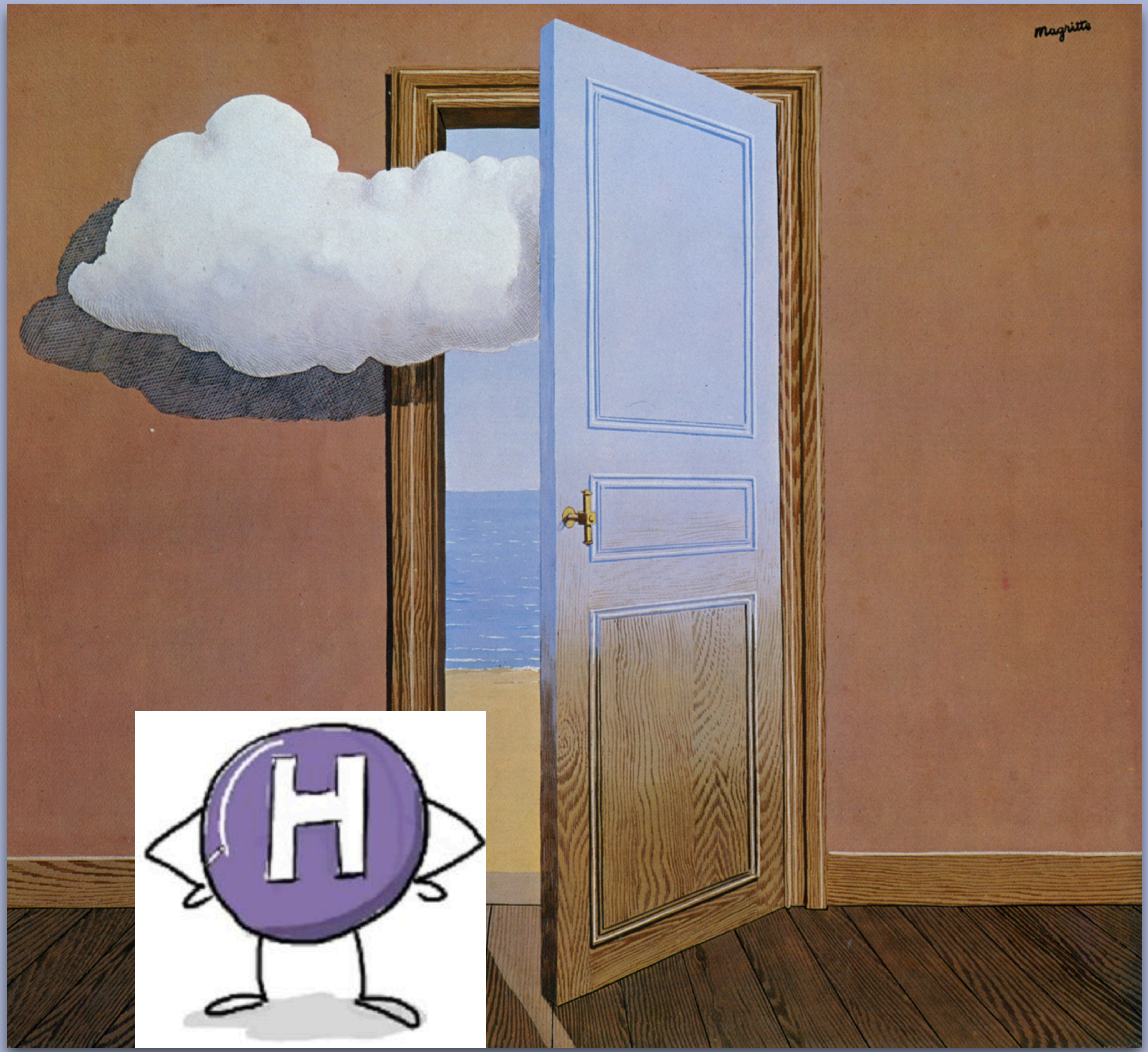
- **A US-sited linear e^+e^- (ILC/CCC) Collider**
- **Hosting a 10 TeV range Muon Collider**
- **Exploring other e^+e^- collider options to fully utilize the Fermilab site**

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

- 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



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Strategy for Understanding the Higgs Physics: The Cool Copper Collider

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C^3 Demonstration Research and Development Plan

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SLAC-PUB-17629
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C^3 : A "Cool" Route to the Higgs Boson and Beyond

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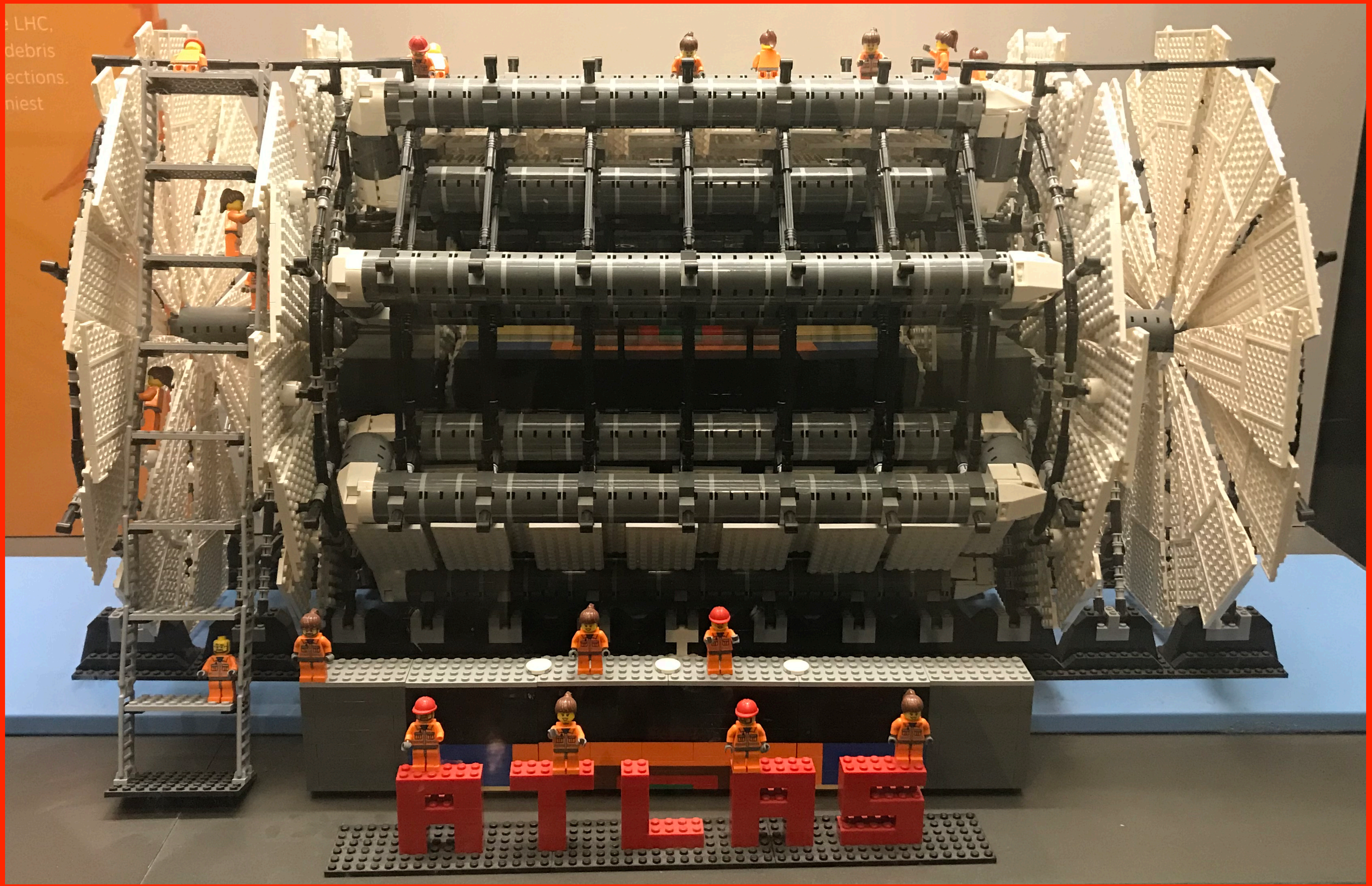
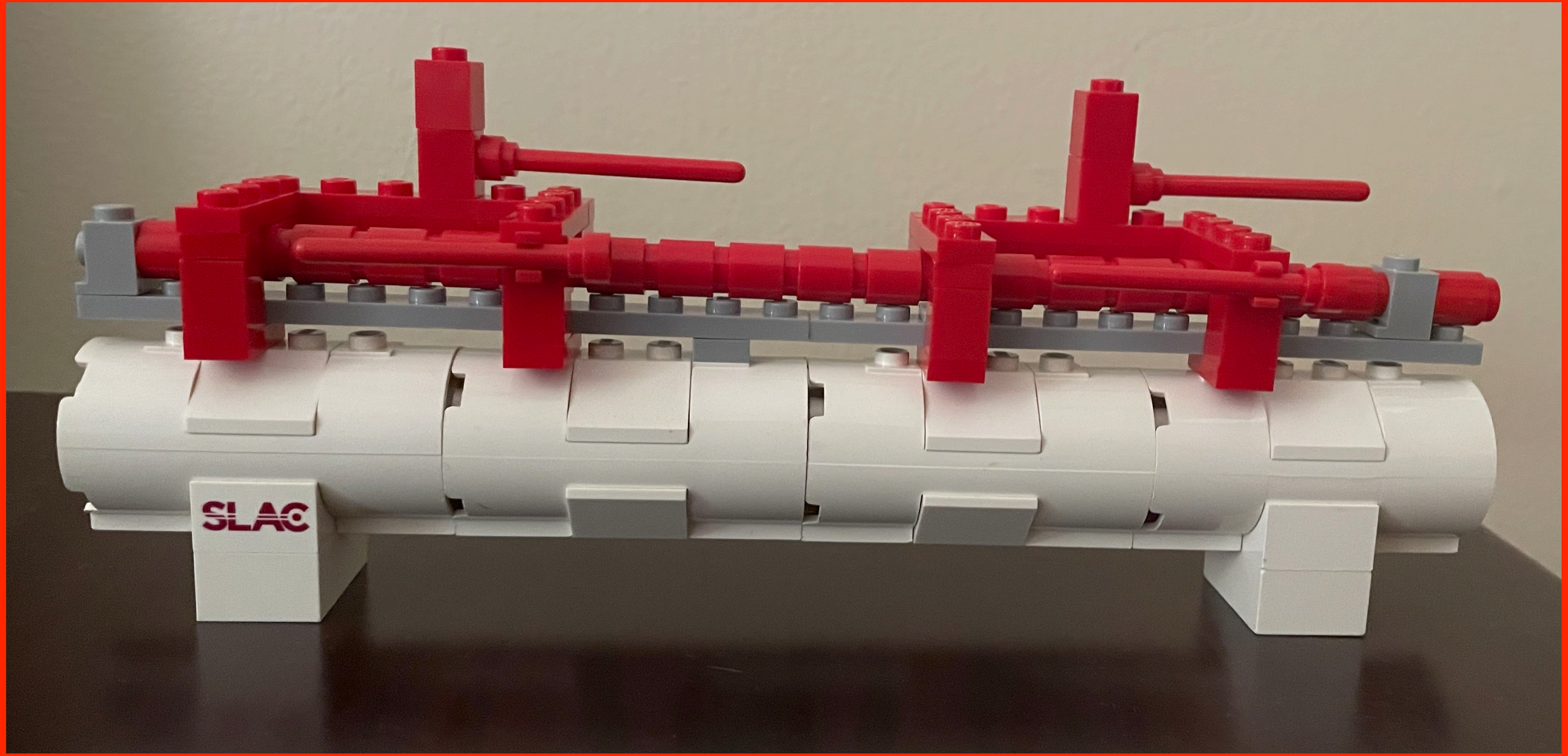
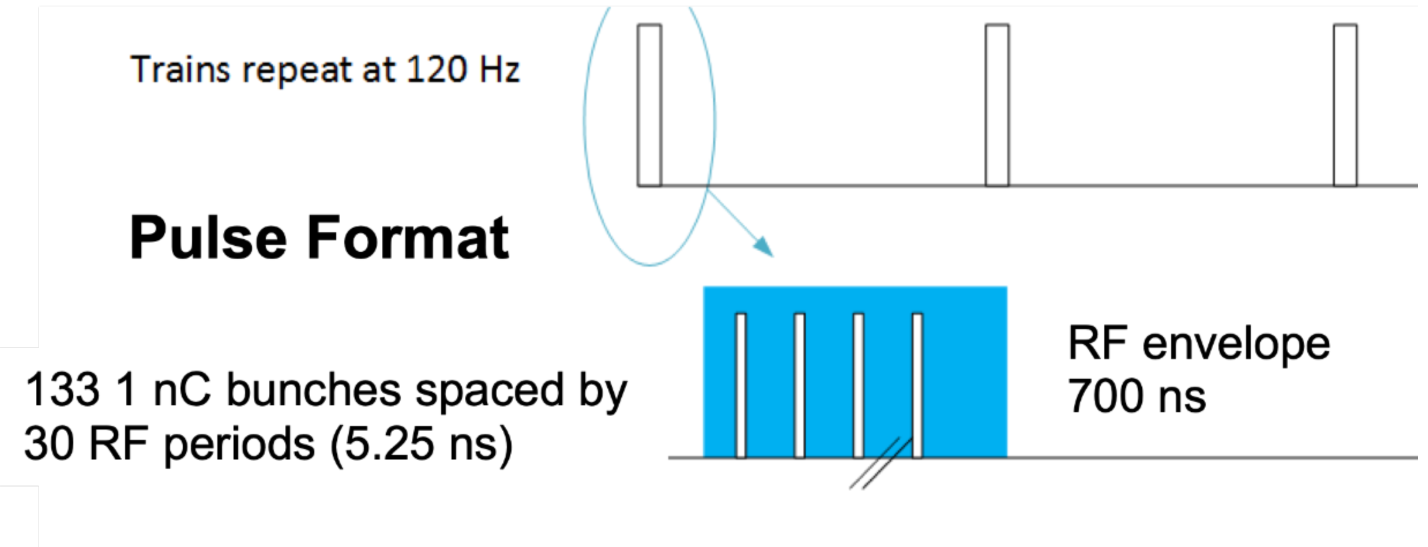
https://indico.slac.stanford.edu/event/7155/





thank you!

Power Consumption and Sustainability



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

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

250 GeV CoM - Luminosity - 1.3x10^{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

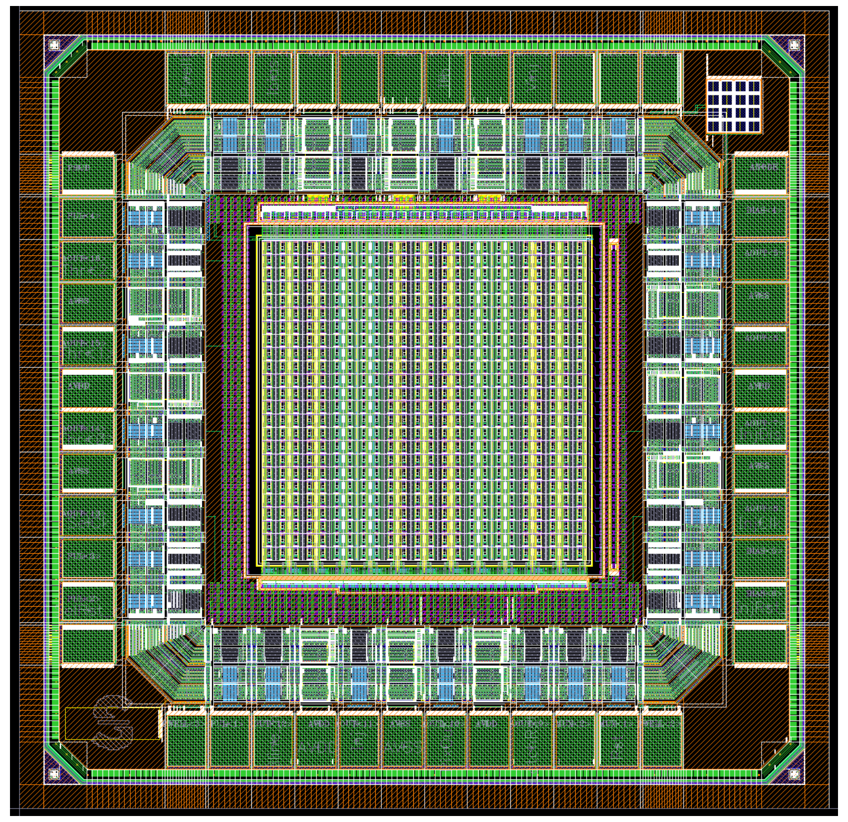
MAPS Detector R&D

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

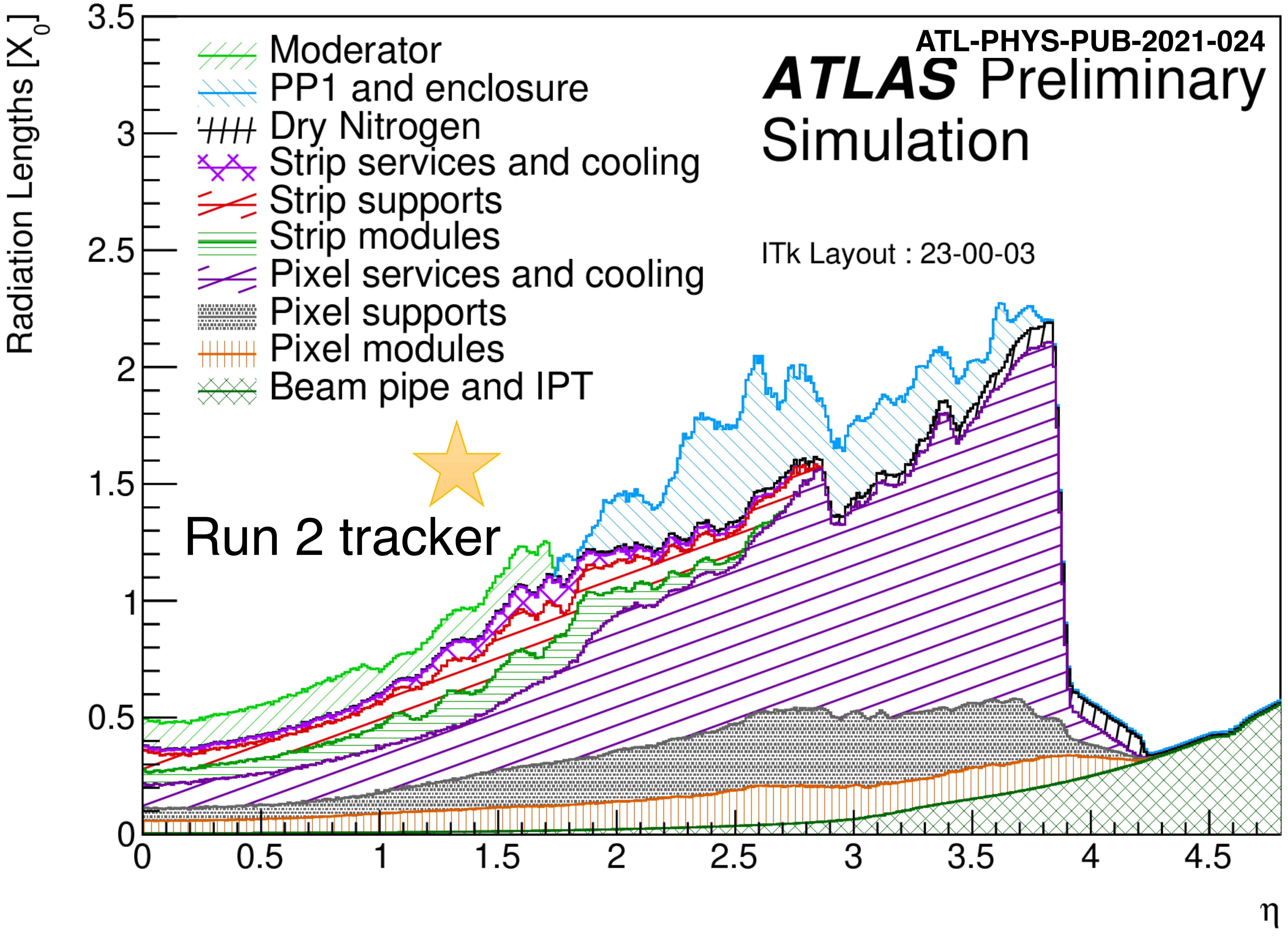
Parameter	Value
Min. Threshold	140 e^-
Spatial resolution	7 μm
Pixel size	25 x 100 μm^2
Chip size	10 x 10 cm^2
Chip thickness	300 μm
Timing resolution (pixel)	$\sim$ns
Total Ionizing Dose	100 kRads
Hit density / train	1000 hits / cm^2
Hits spatial distribution	Clusters
Power density	20 mW / cm^2

Table 1: Target specifications for 65 nm prototype.



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.

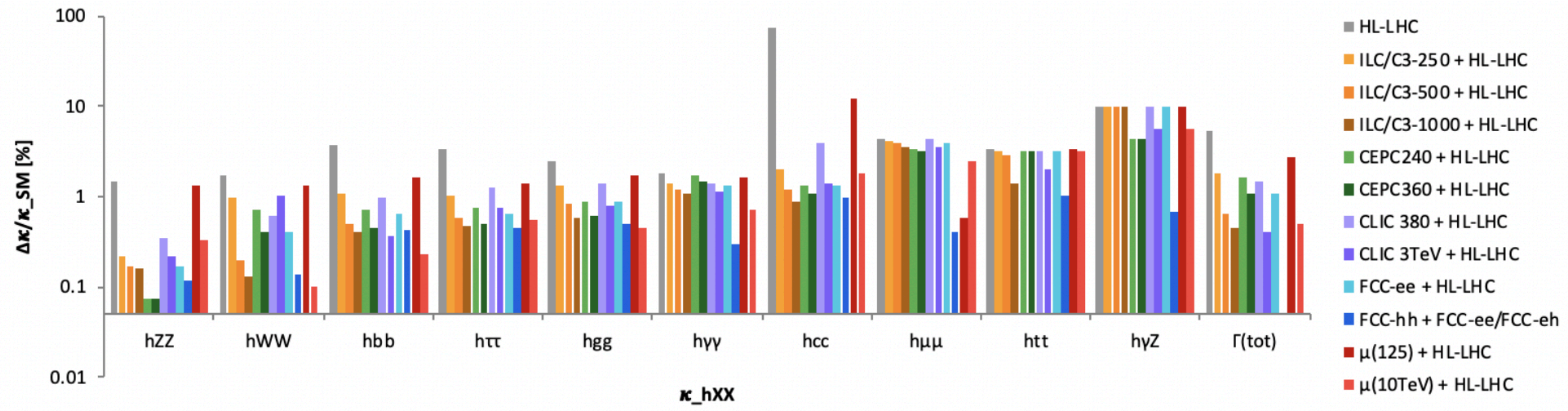
The Higgs self-coupling at future colliders

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

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 C³/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 $e^-_L e^+_R$

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

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 $M \gg v$

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

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

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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

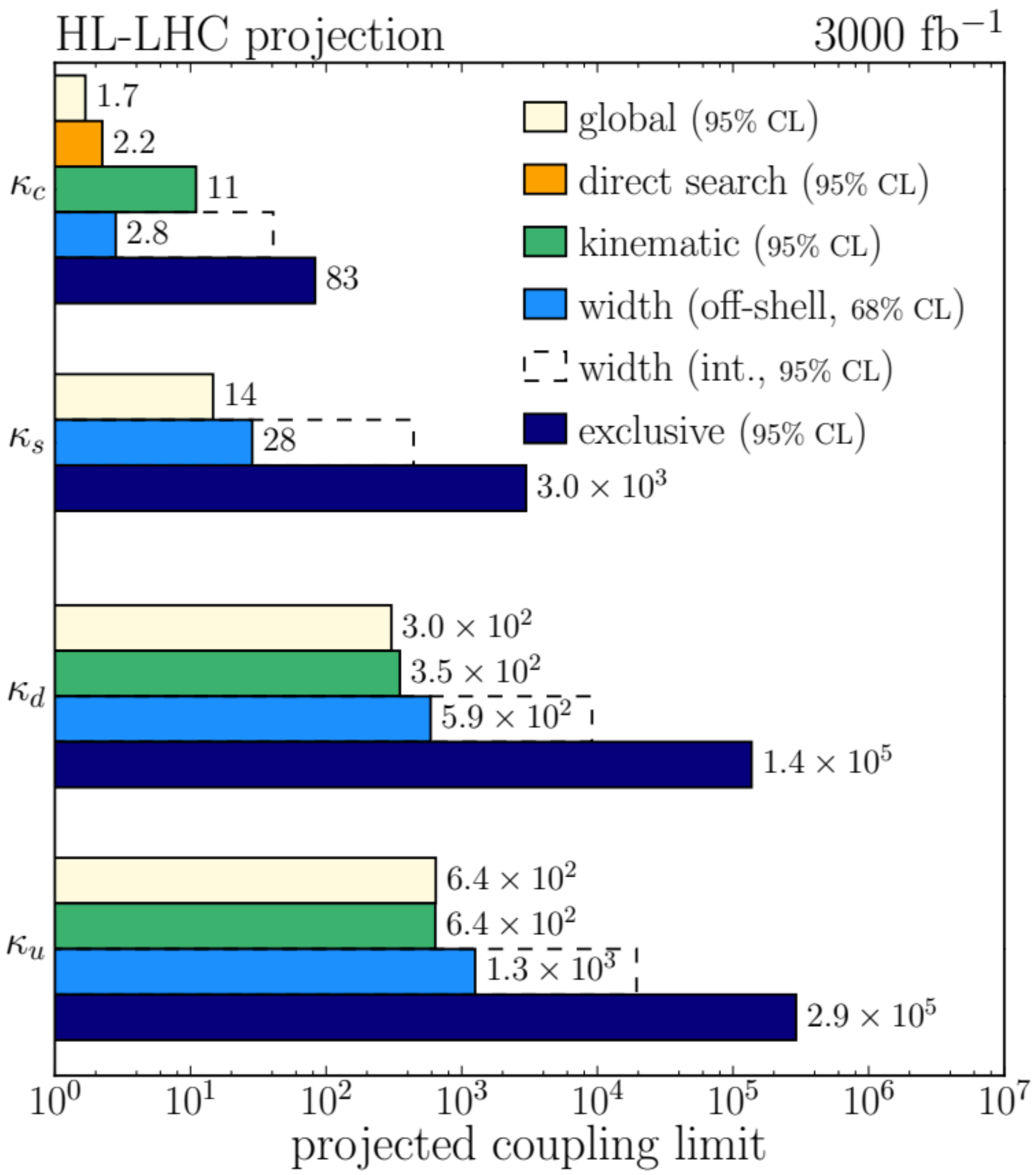
$$\delta O_Q \sim \left(\frac{Q}{M}\right)^2$$

15% effect on δO_Q for M ~ 2.5 TeV

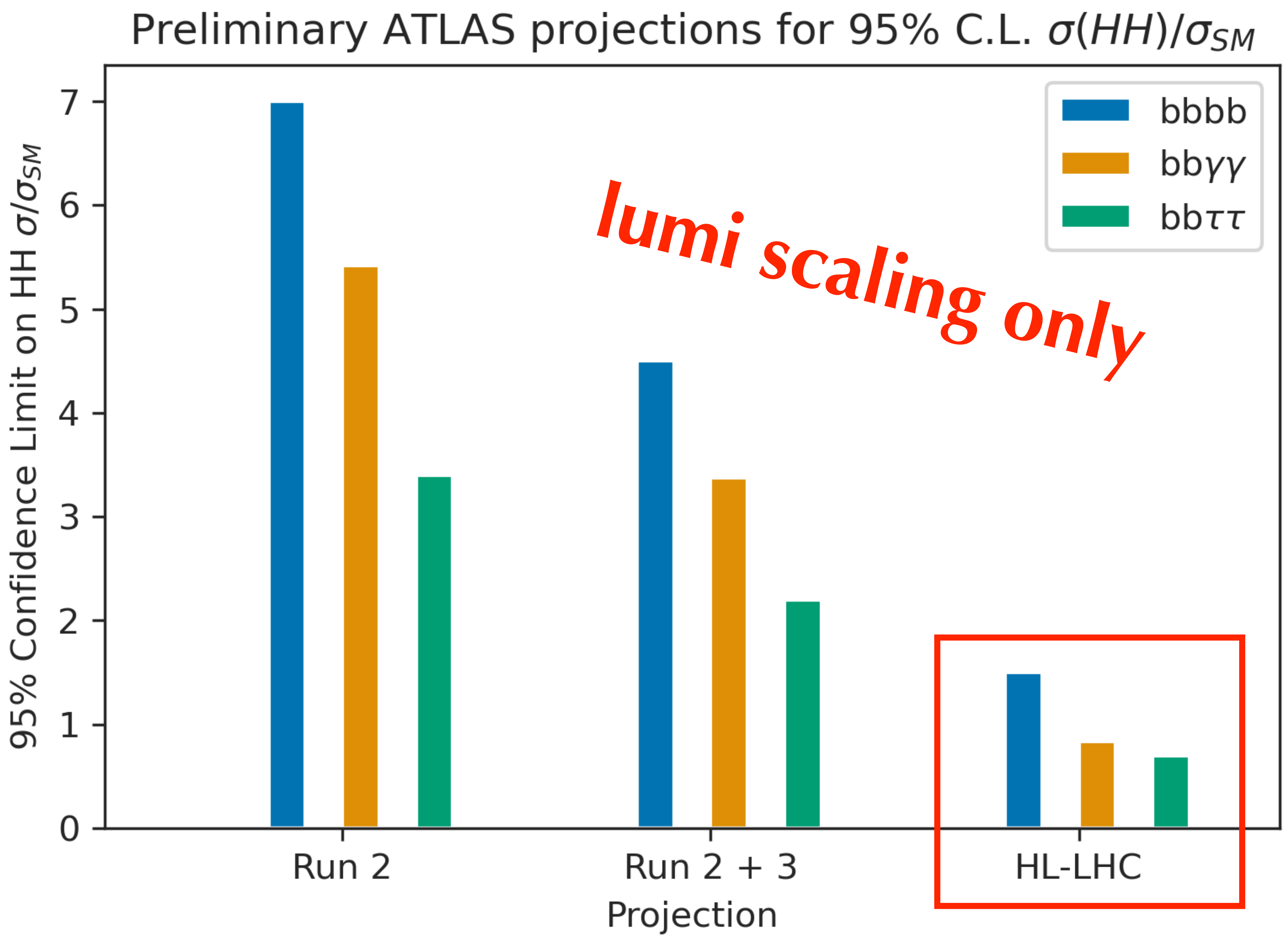
Prospects for light quark couplings at HL-LHC

CERN-LPCC-2018-04

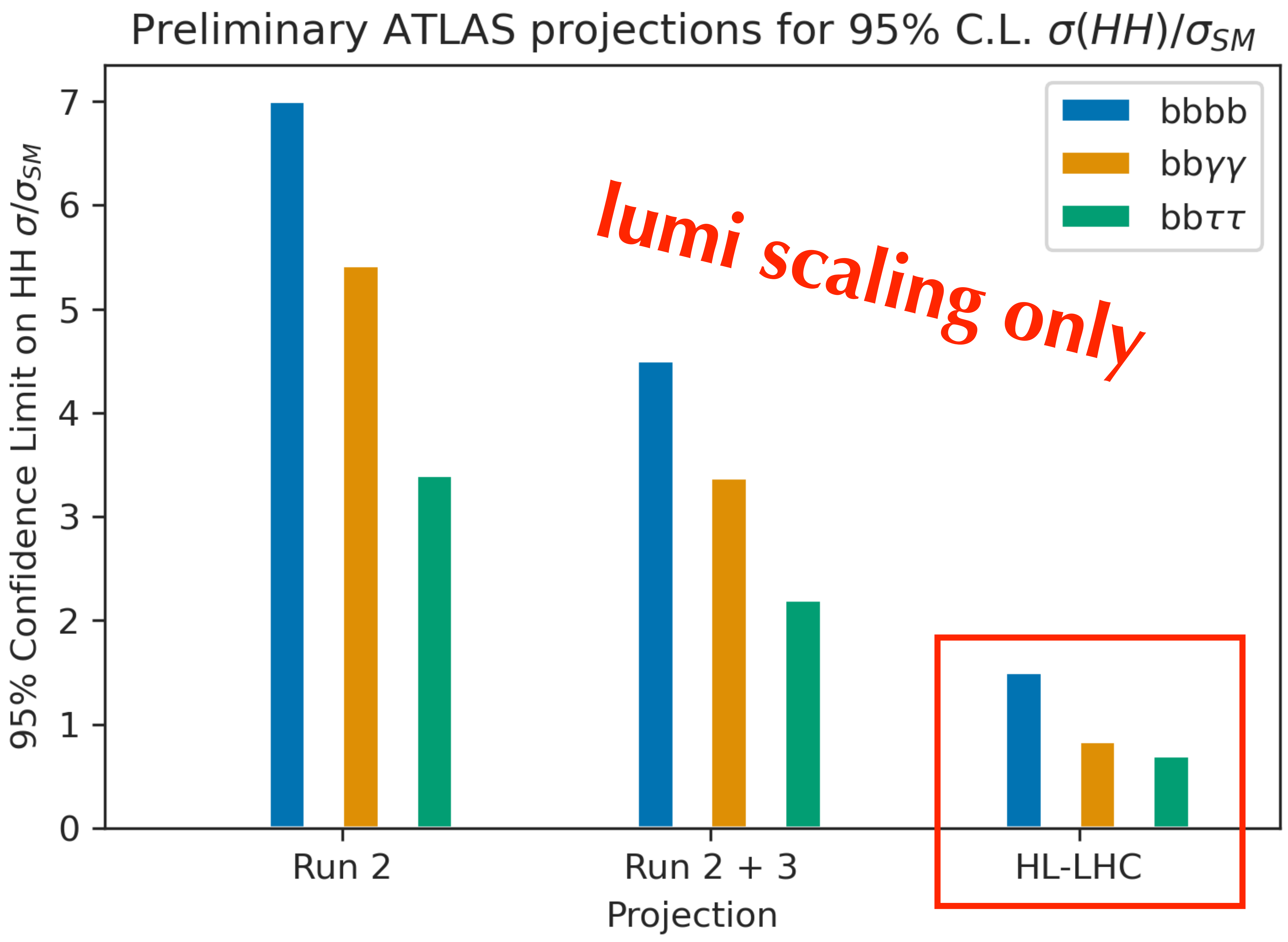
- Exclusive decays to γ+meson include contributions from light quark Yukawa couplings
- Interpretation of Higgs width constraint: direct measurement and via off-shell
- Interpretation of kinematic distributions
- Direct search for H→cc
- Global fit of all Higgs couplings (assuming no other BSM decays)

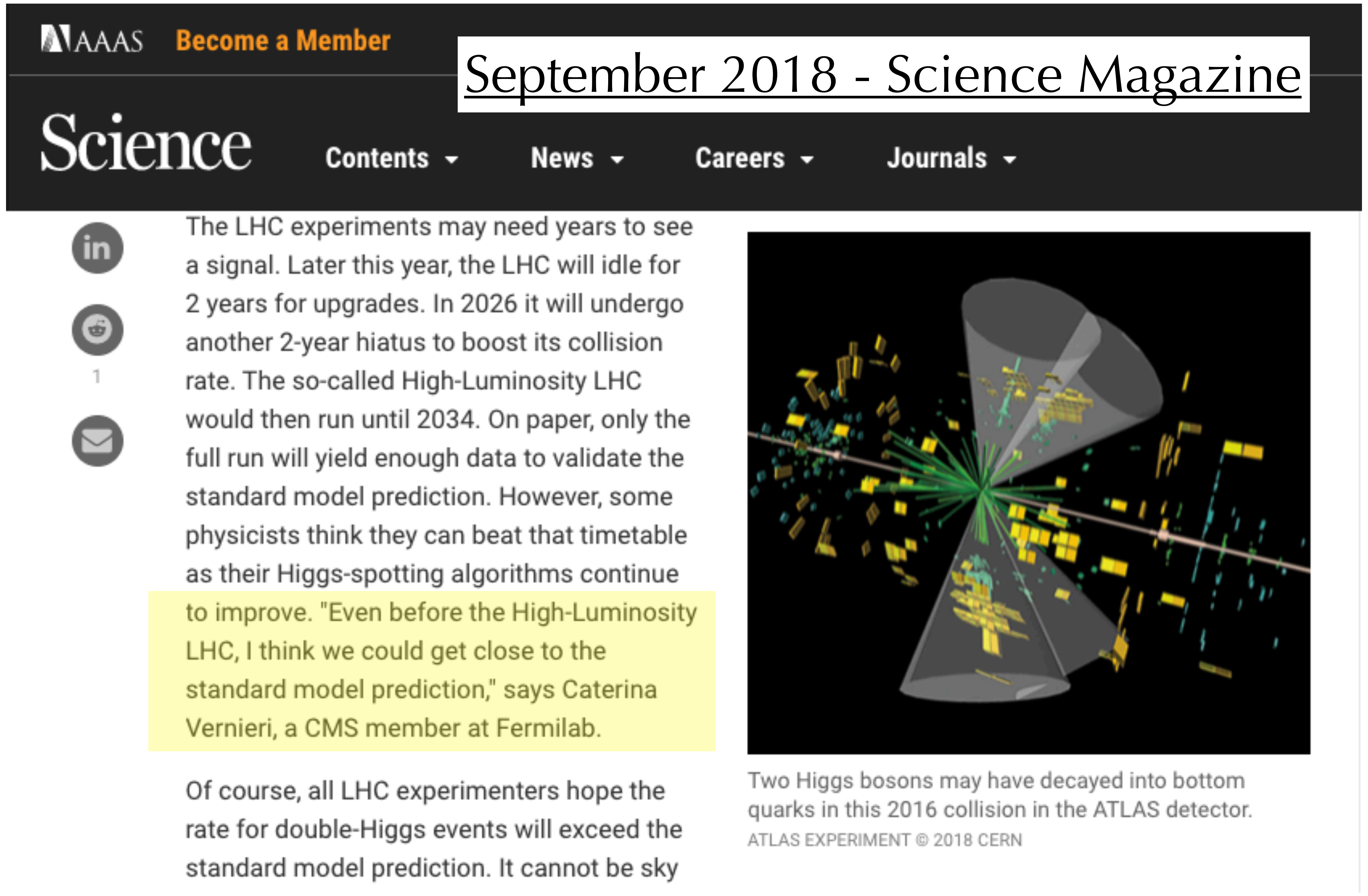


HH prospects



HH prospects





September 2018 - Science Magazine

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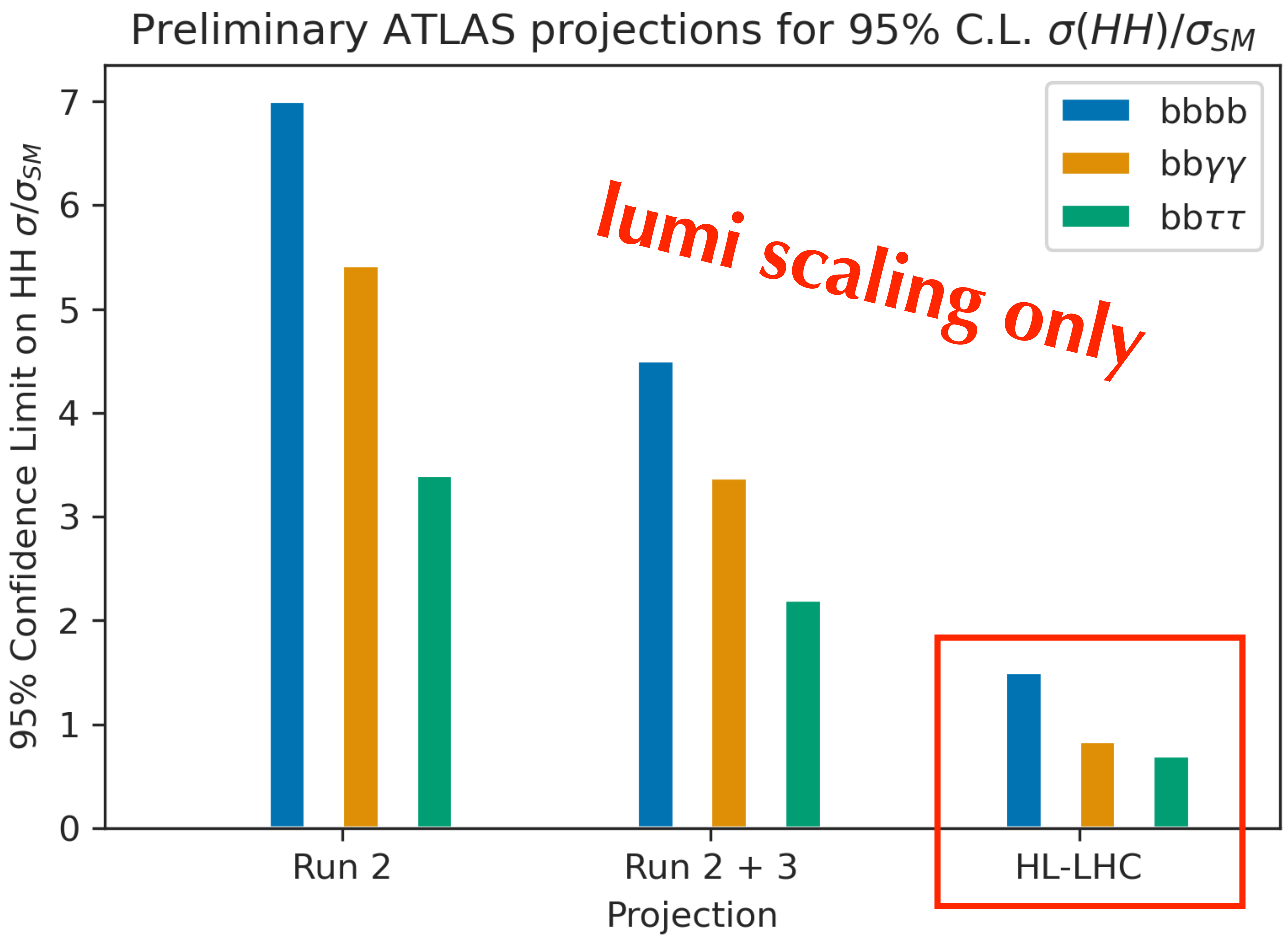
The LHC experiments may need years to see a signal. Later this year, the LHC will idle for 2 years for upgrades. In 2026 it will undergo another 2-year hiatus to boost its collision rate. The so-called High-Luminosity LHC would then run until 2034. On paper, only the full run will yield enough data to 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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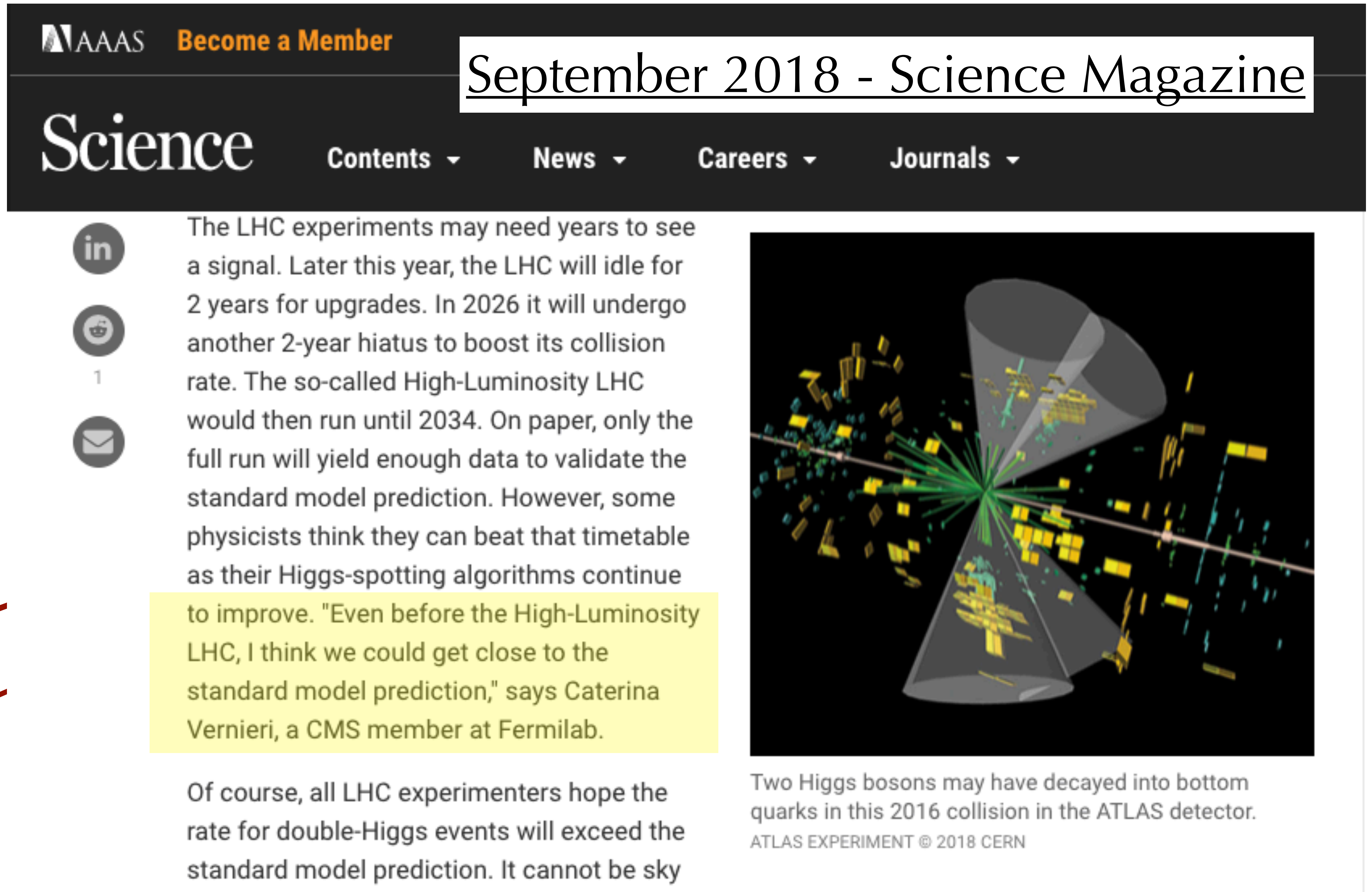
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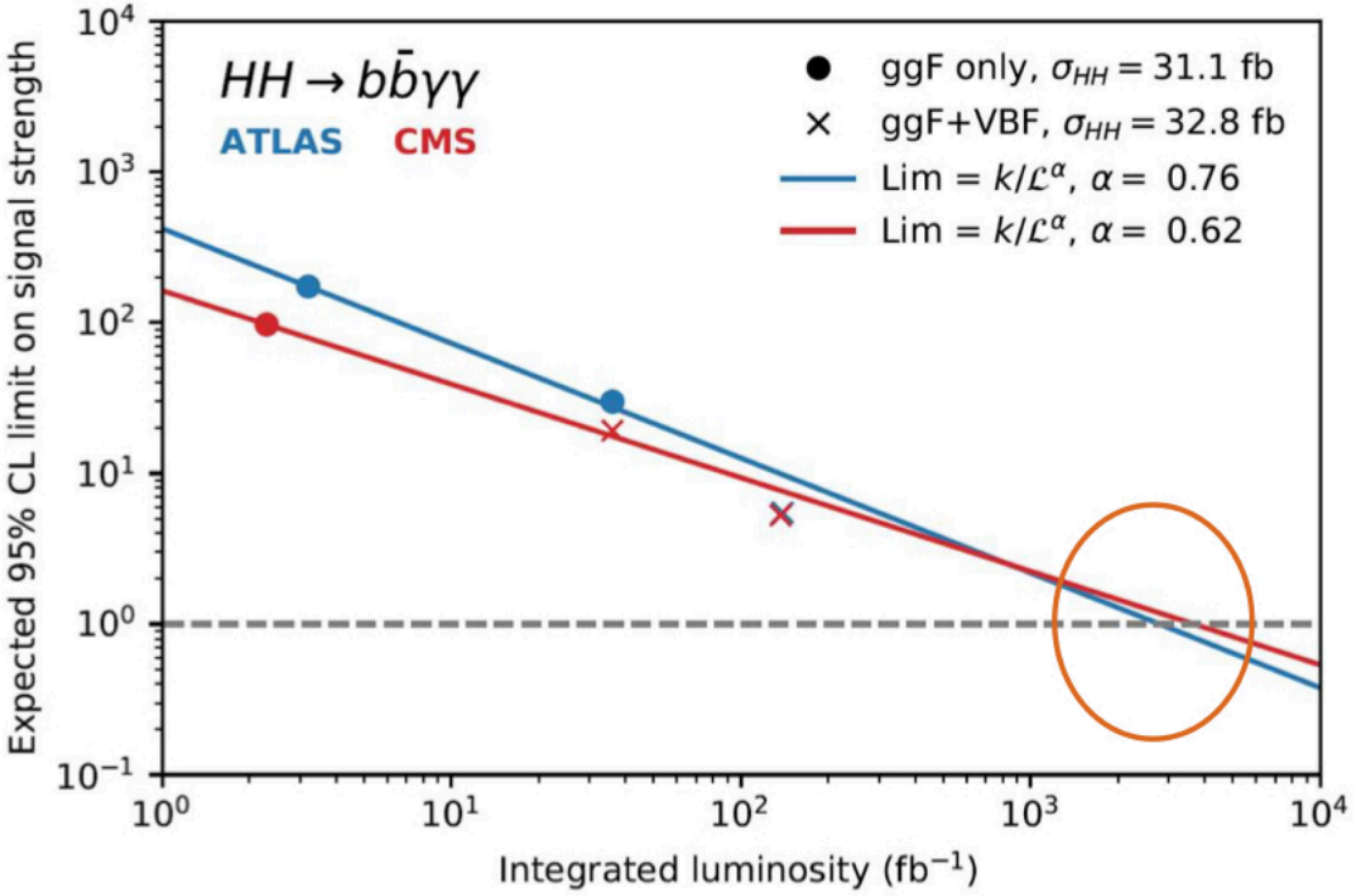
Two Higgs bosons may have decayed into bottom quarks in this 2016 collision in the ATLAS detector.
ATLAS EXPERIMENT © 2018 CERN

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



$HH \rightarrow b\bar{b}\gamma\gamma$
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})

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.

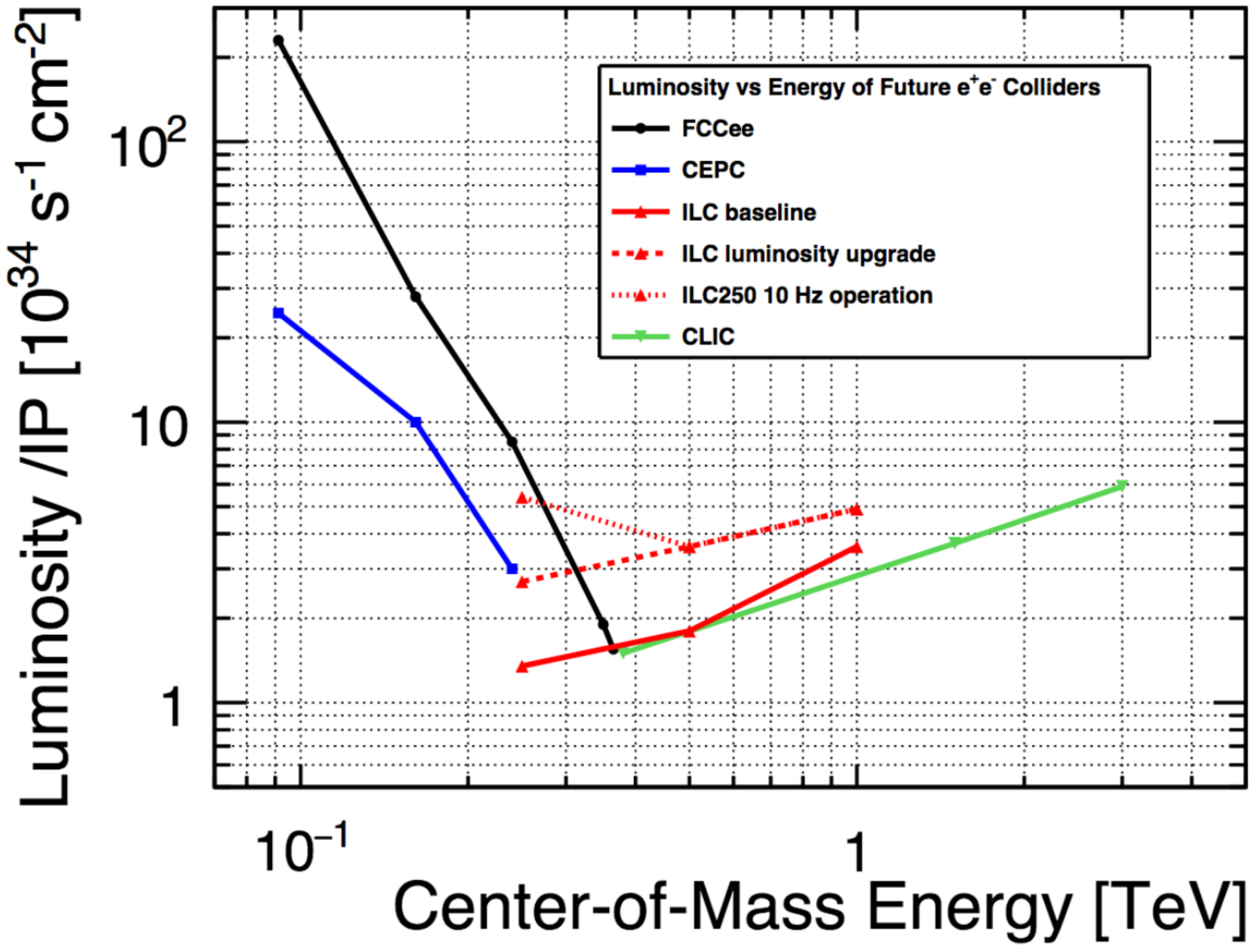
Physics Process	Measured Quantity	Critical System	Physical Magnitude	Required Performance
Zhh $Zh \to q\bar{q}b\bar{b}$ $Zh \to ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs coupling Higgs mass $B(h \to WW^*)$ $\sigma(e^+e^- \to \nu\bar{\nu}W^+W^-)$	Tracker and Calorimeter	Jet Energy Resolution $\Delta E/E$	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

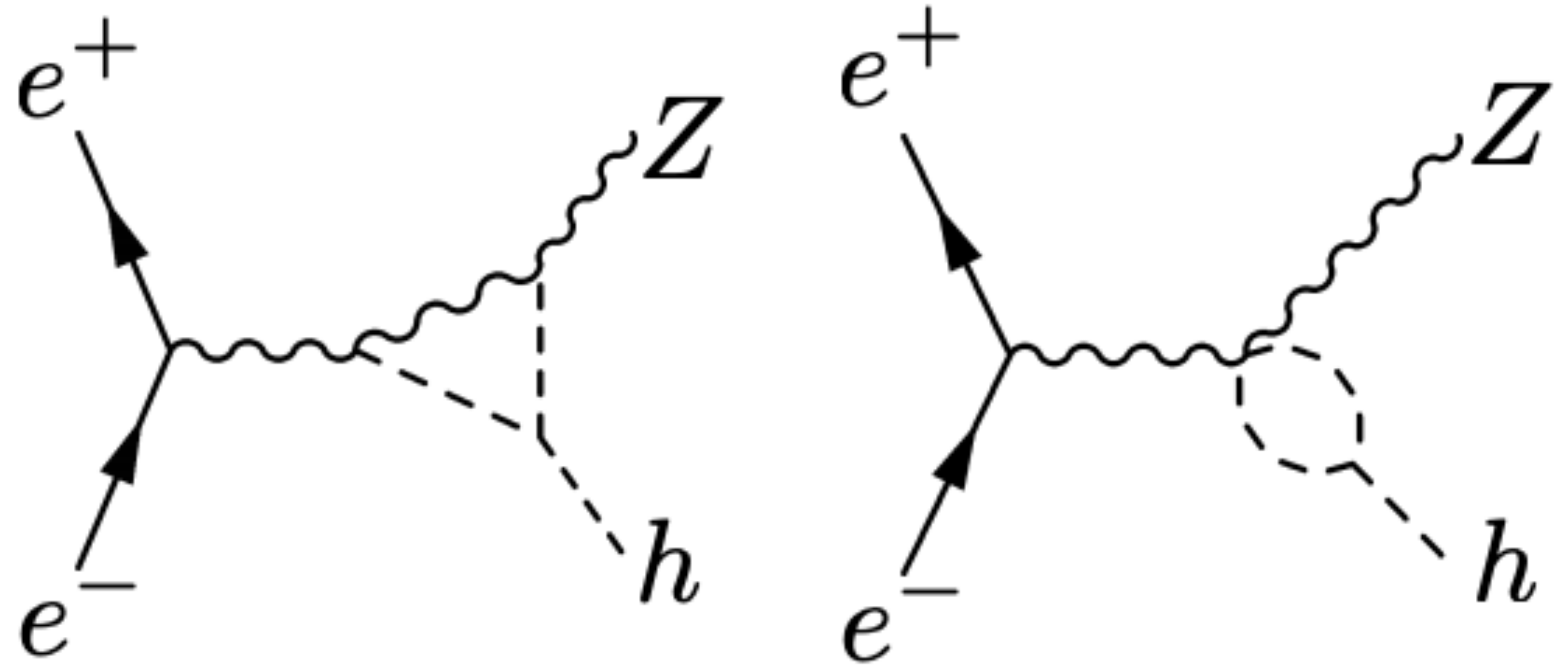
- **Linear** colliders : ILC, CLIC
  - Only possible way towards high-energy with leptons
  - Polarized collisions possible
  - The time structure and low radiation background provides an environment which allows us to consider **very light, low power detector structures**
- **Circular** colliders :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

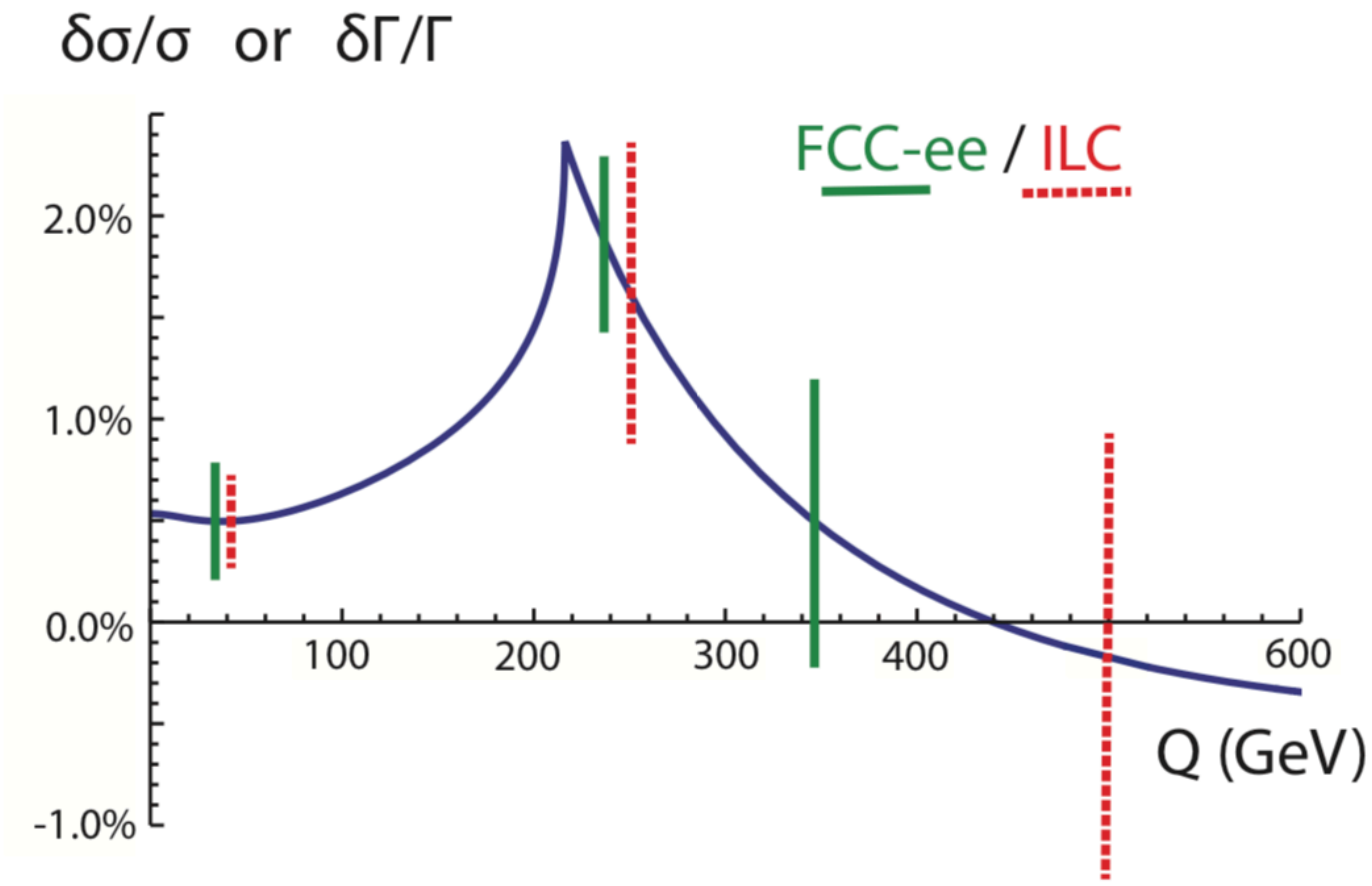


Self-coupling at e+e-

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

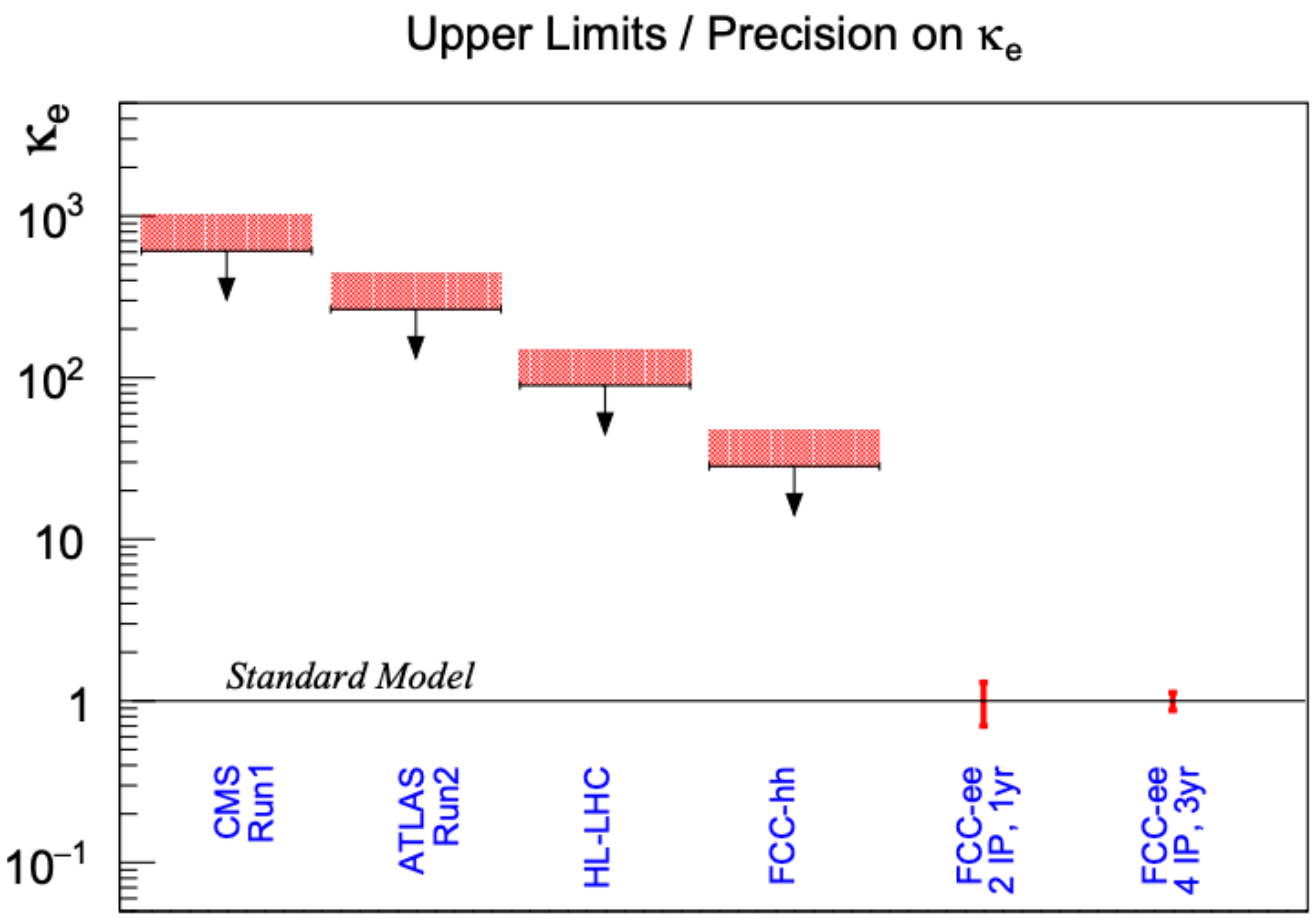
- Relative enhancement of the e+e– → ZH cross-section and the H→W+W– partial width
- Need multiple Q^2 to identify the effects due to the self-coupling





Higgs at e+e-

1912.11871

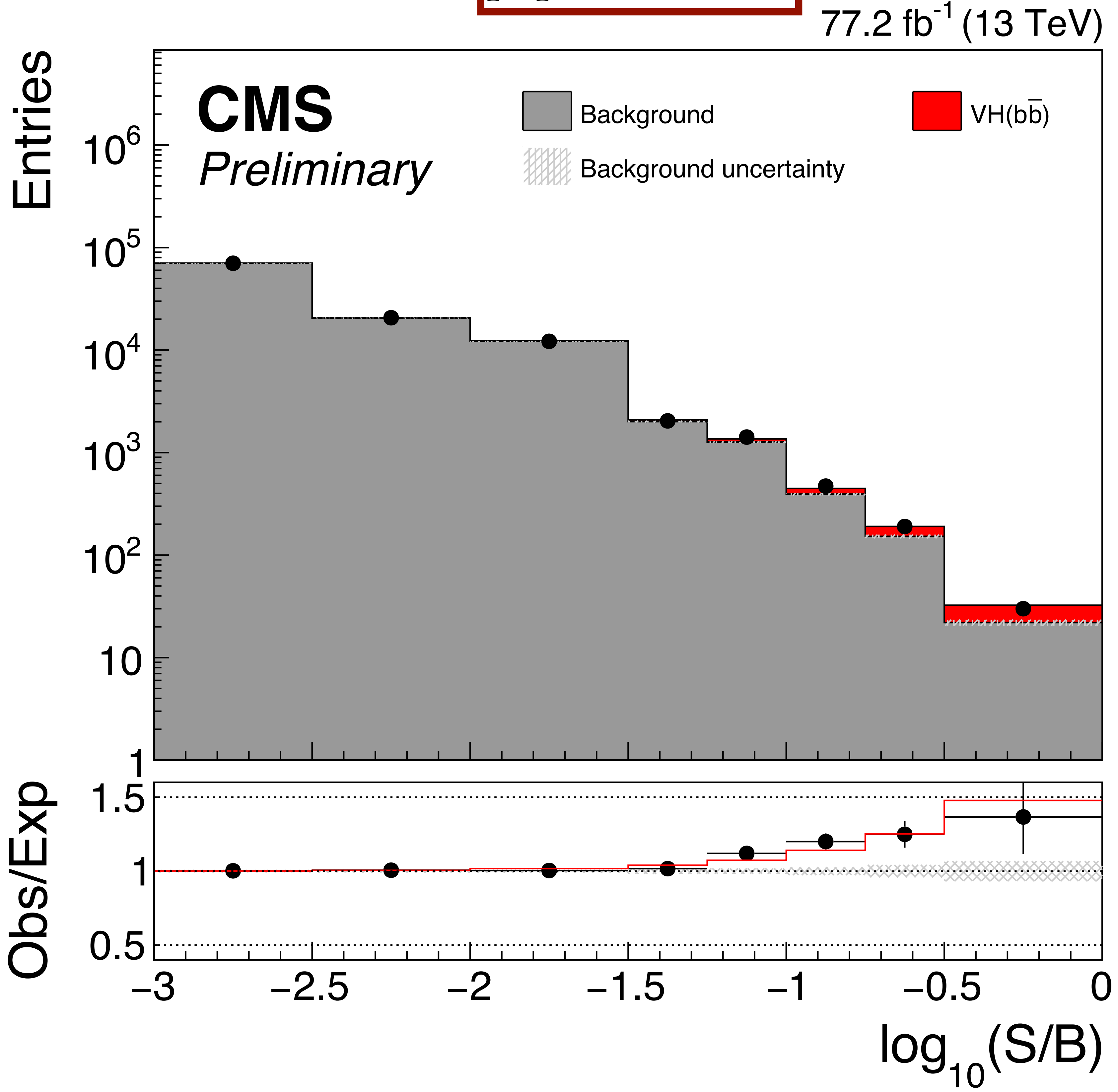


- Circular lepton colliders - FCC-ee - provide the highest luminosities at lower centre-of-mass energies
  - Unique opportunity to measure the Higgs boson coupling to electrons through the resonant production process $e^+e^- \to H$ at $\sqrt{s} = 125$ GeV
  - FCC-ee running at H pole-mass with 20/ab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

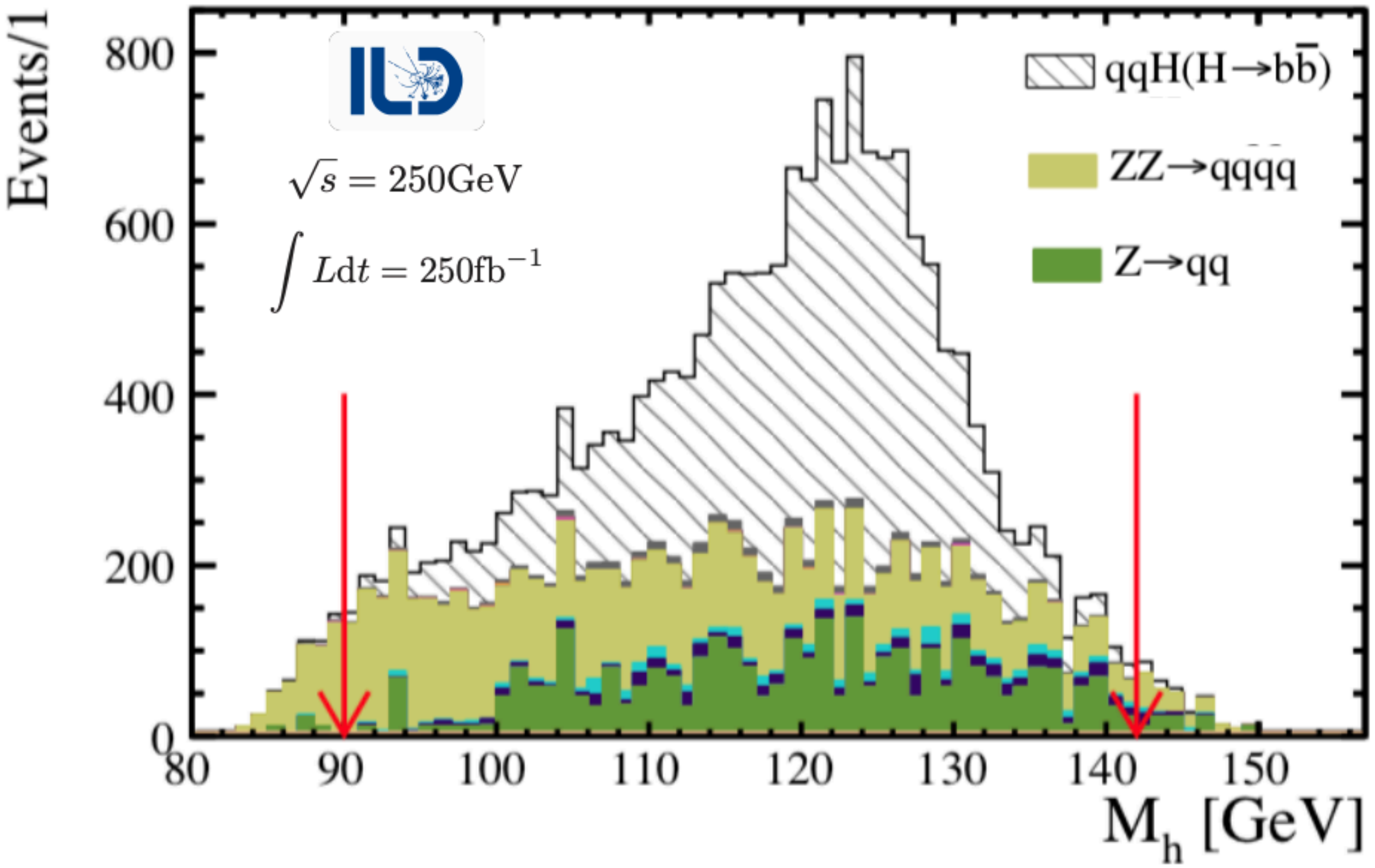
One example: $H(b\bar{b})$

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

pp LHC



e+e- ILC

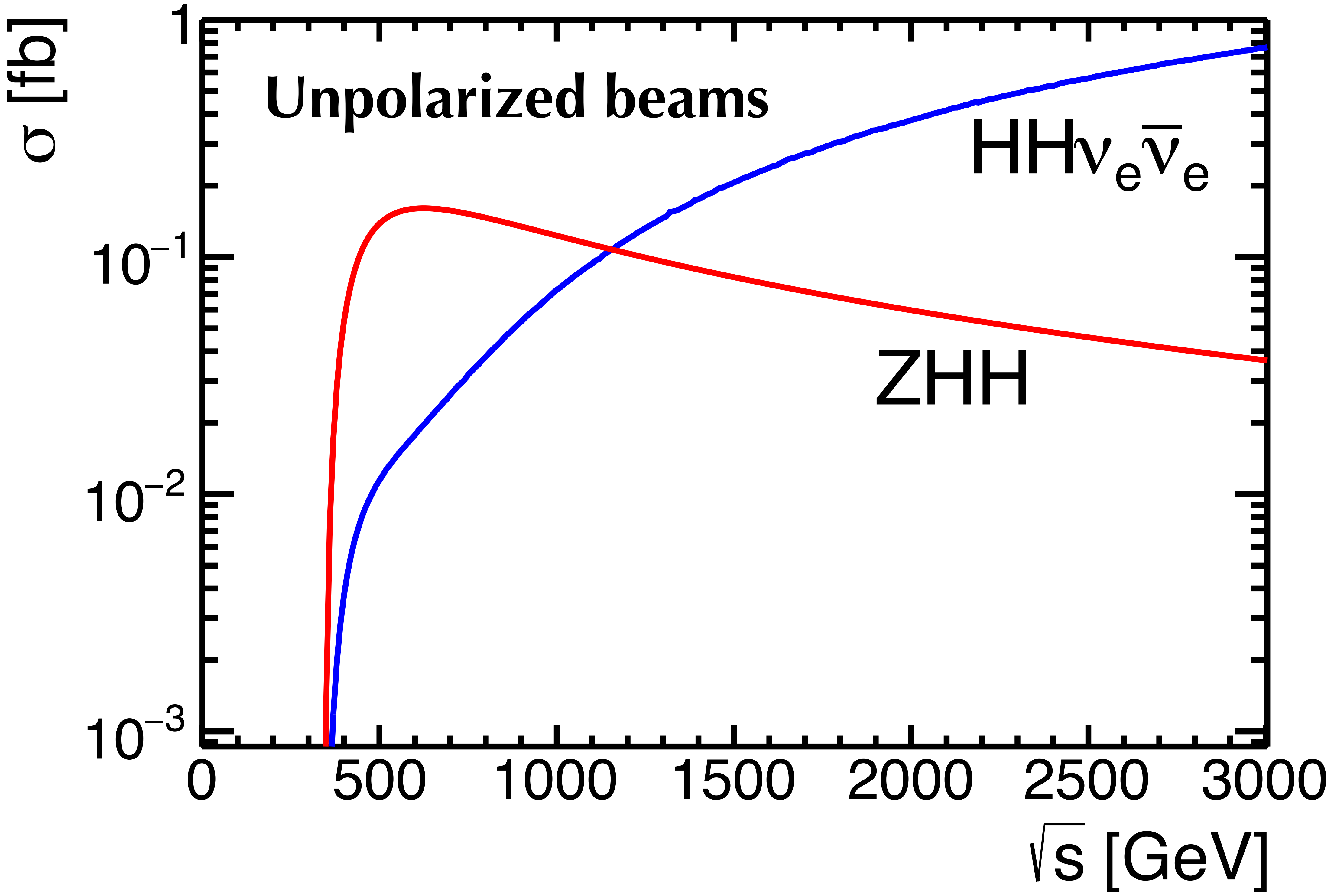


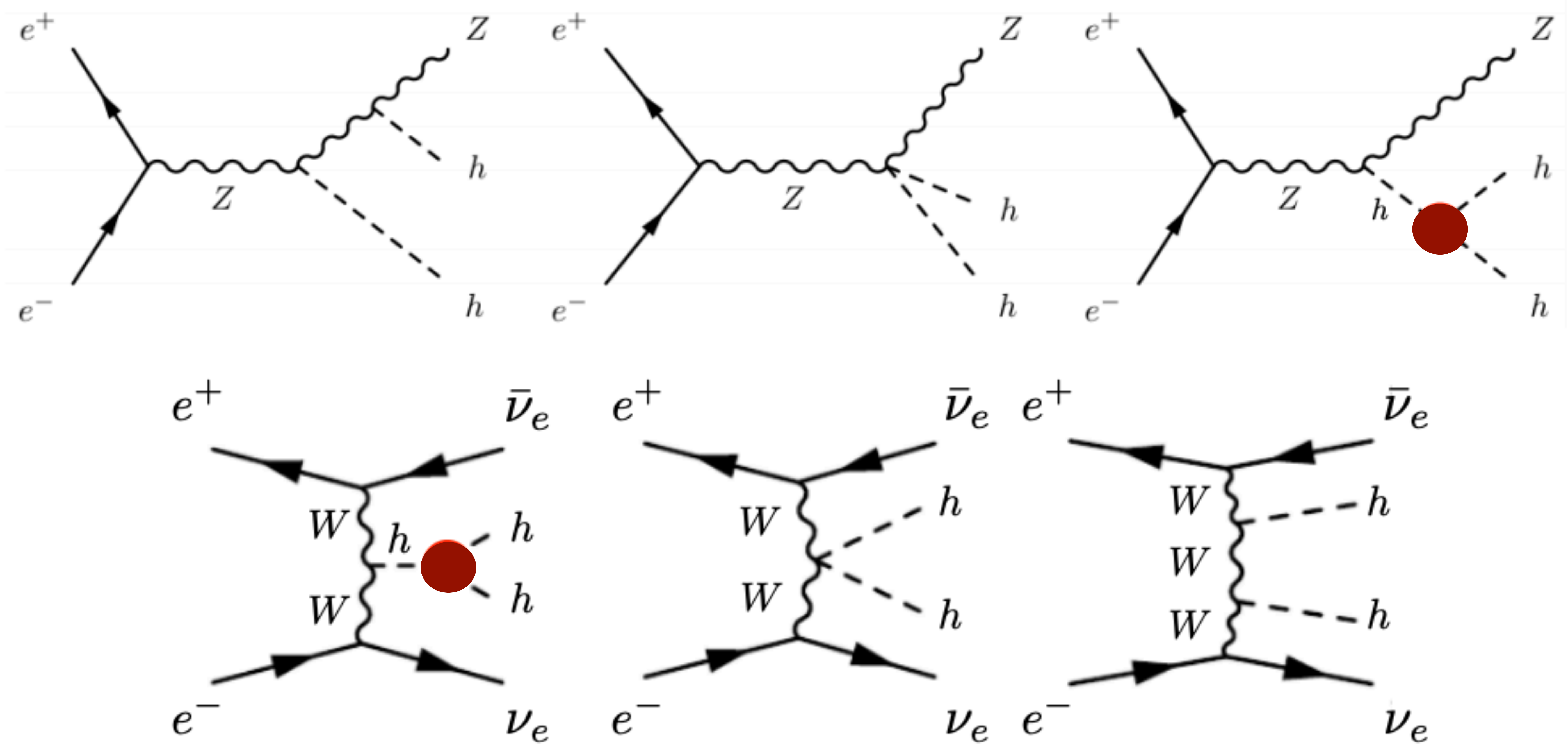
# of Higgs produced: **~4M** **~400**

4.8σ (VH only) **5.2σ**

HH at future e+e- colliders

Review in Physics (2020) 100045



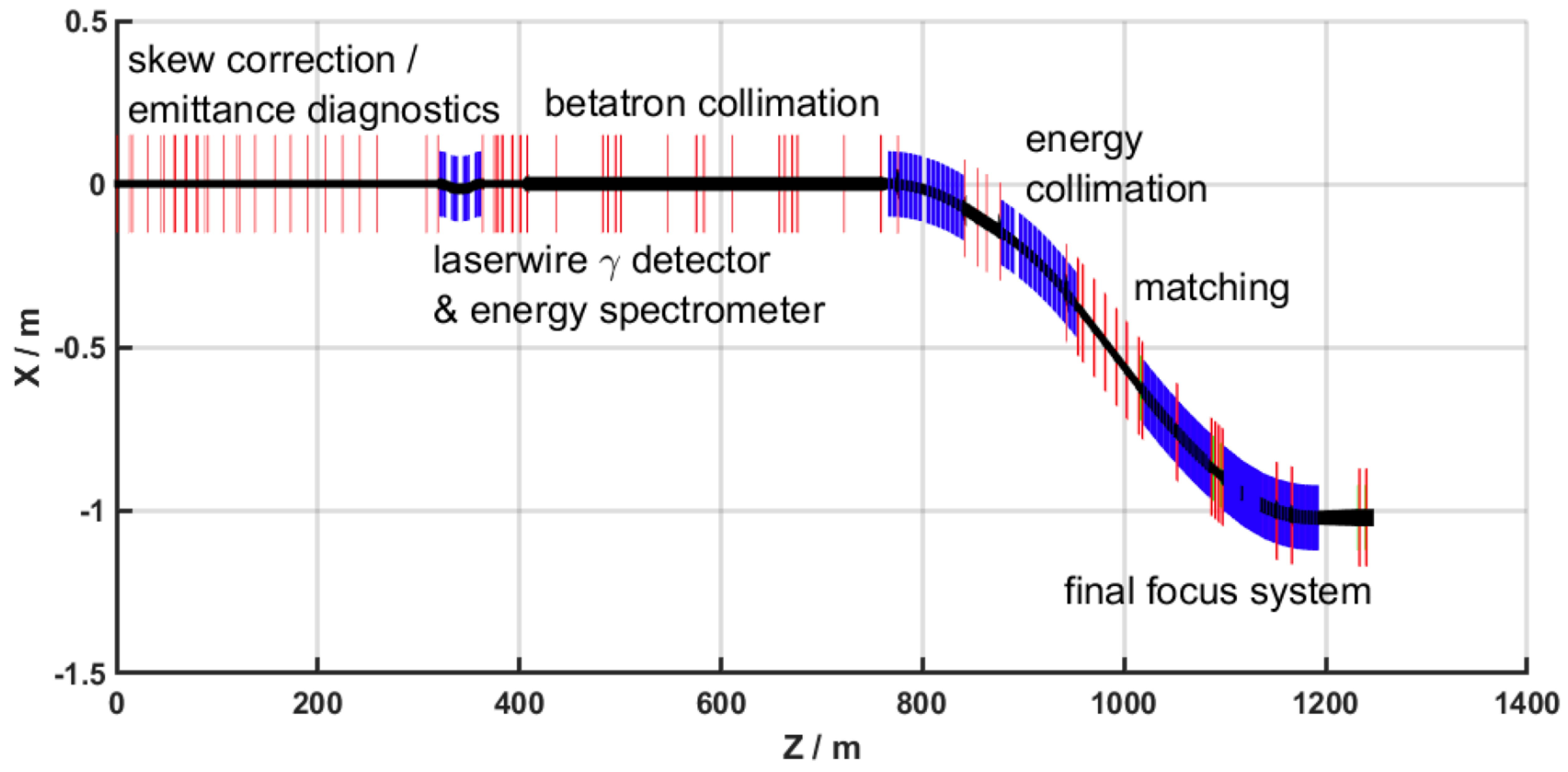


- The self-coupling can be probed at e+e- through HH with ZHH ~500GeV and vvHH ≥1TeV
  - **HHvv** requires $e_L^- e_R^+$, the use of polarized beams could increase the cross-section by a factor ~2

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.

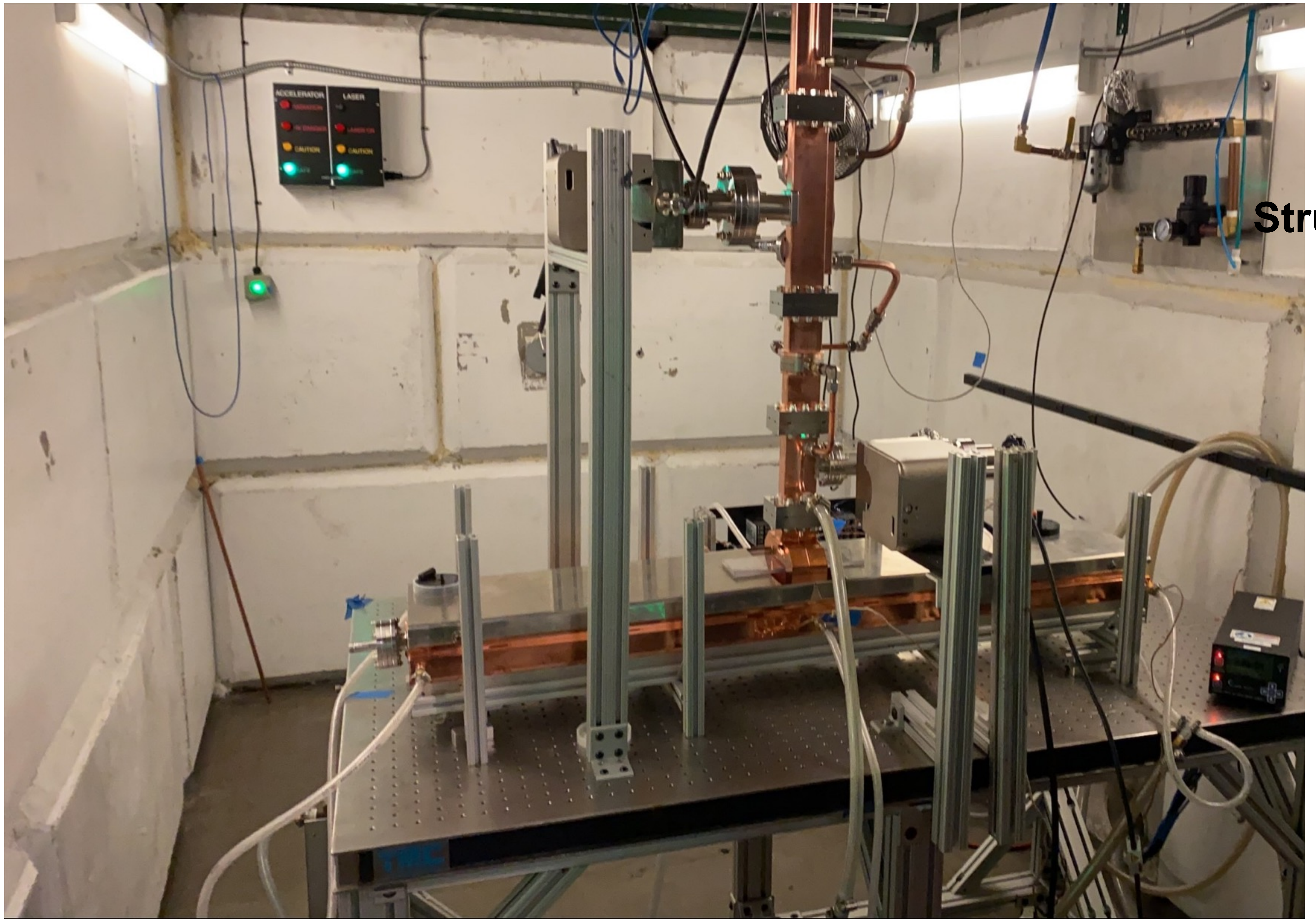
C^3 - Investigation of Beam Delivery Adapted from ILC/NLC



Next: C^3 Demonstration Facility

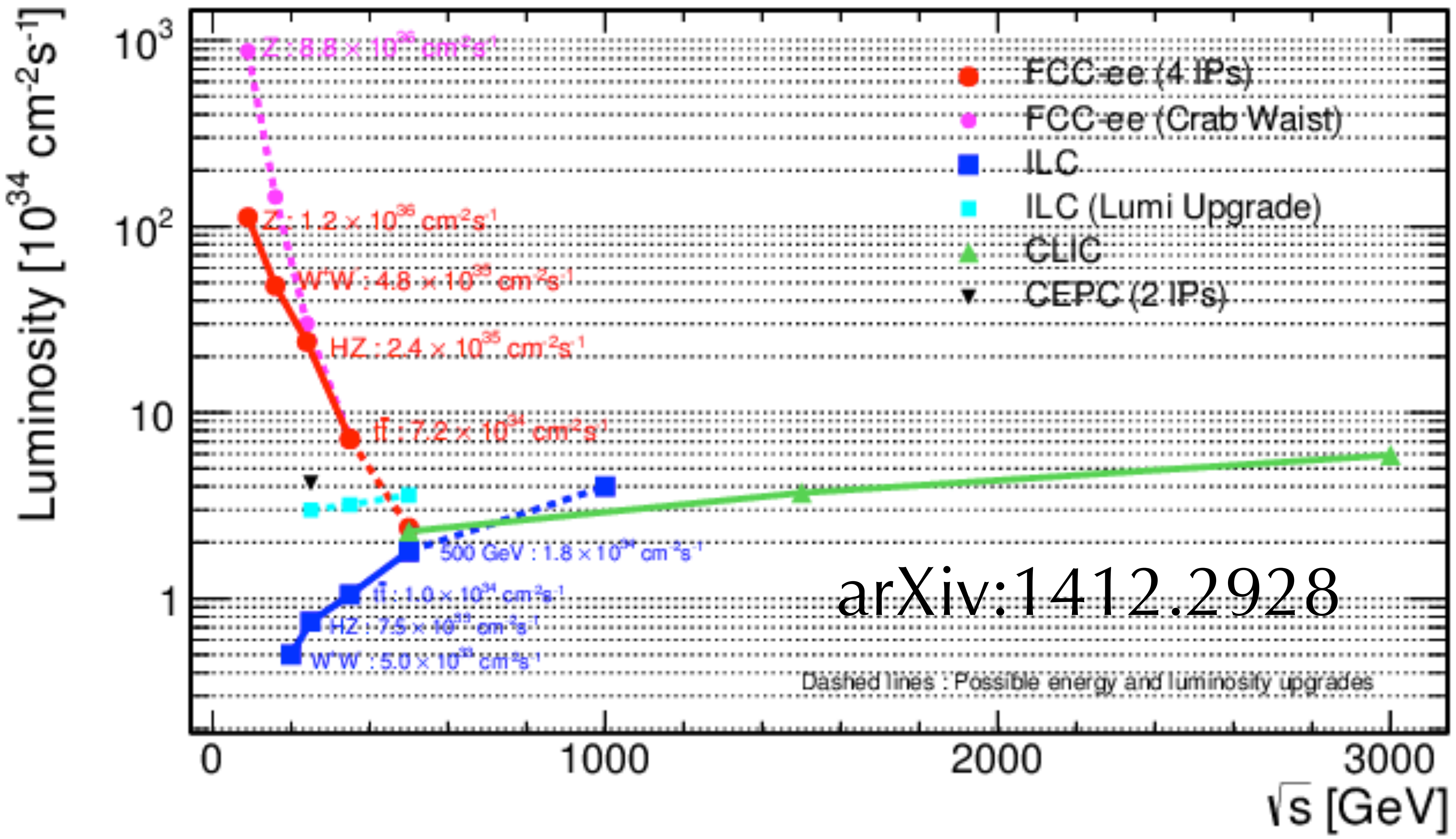
		Time Frame	Key R&D	Synergy and Spin-Offs
	Stage 0	Ongoing	Fundamental structure R&D with prototype structure demonstration with beam and corresponding industrialization	Cost effective compact linacs for medical, security and industrial applications (irradiation with electrons, x-rays)
	Stage 1	2022-2024	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.*)
CDR	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
TDR	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.*

Latest tests



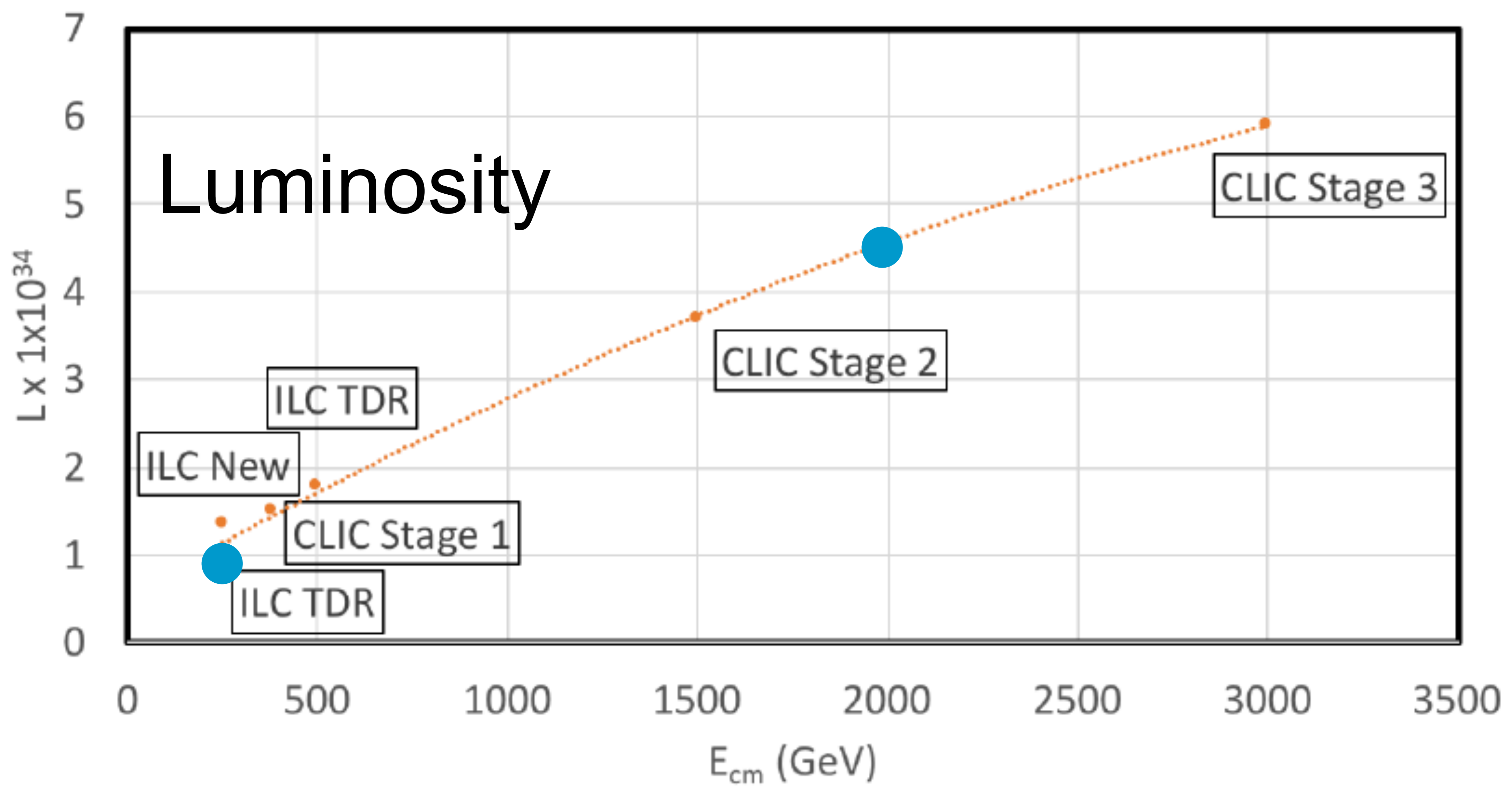
Structure in test stand at radiabeam

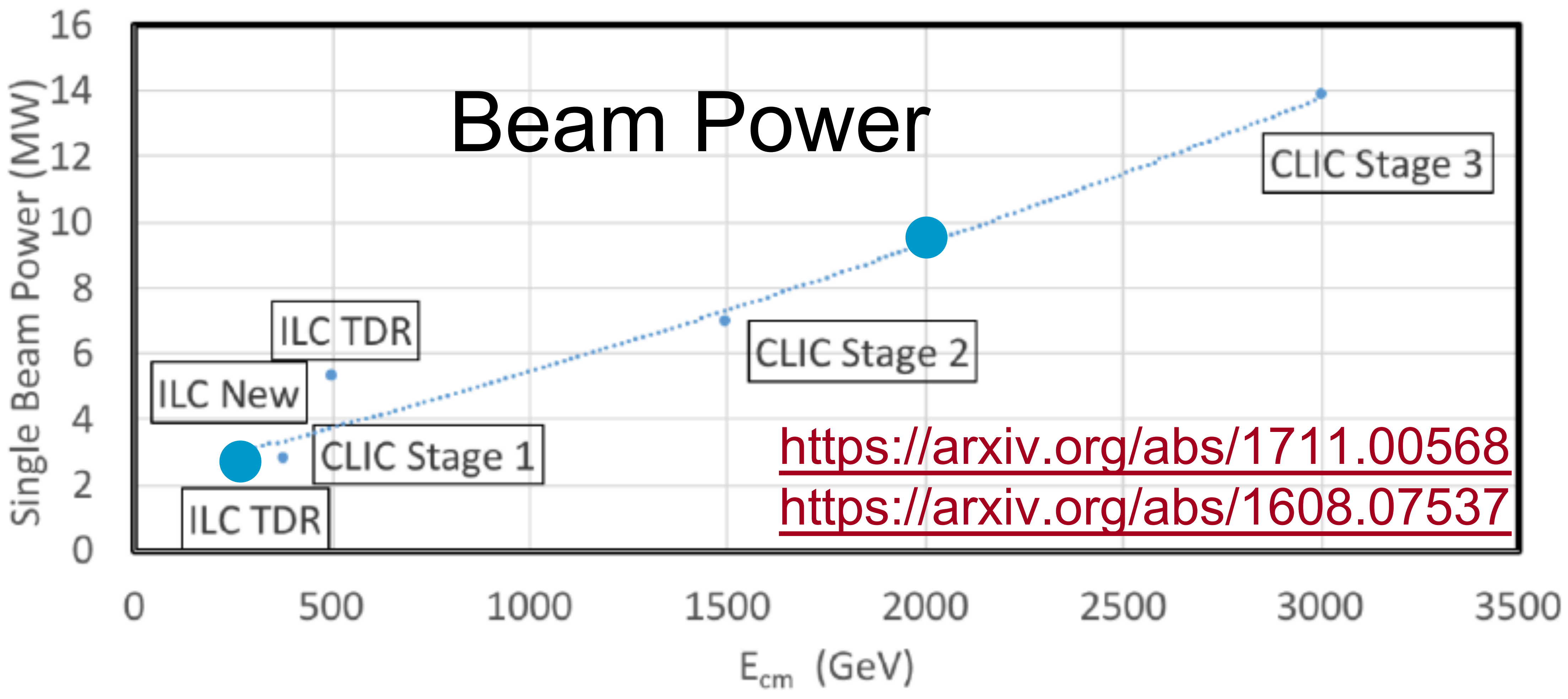
Using established collider designs to inform initial parameters



Luminosity optimization

Using established collider designs to inform initial parameters



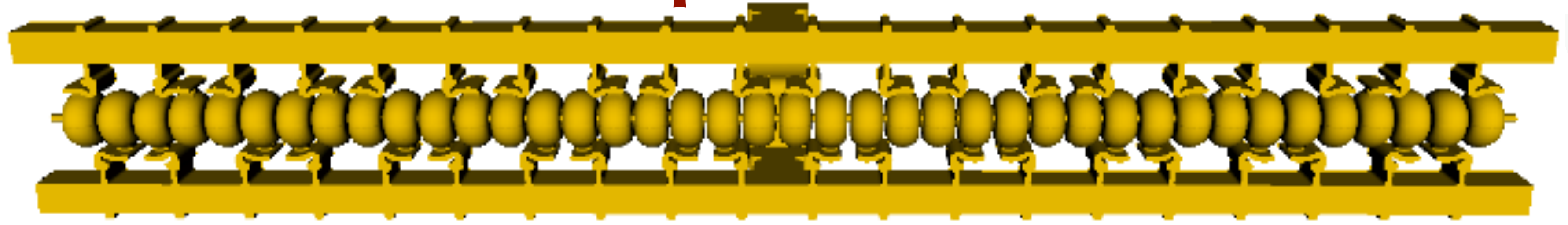


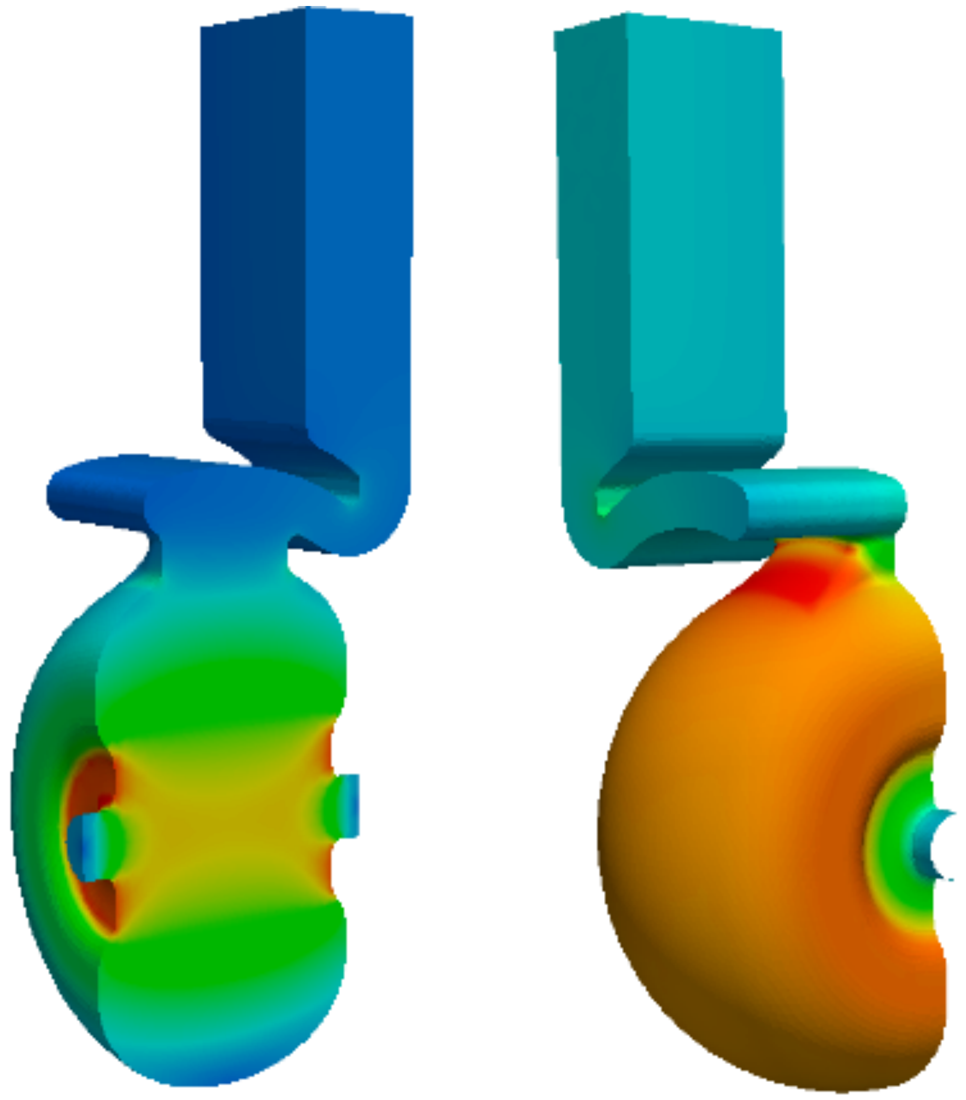
https://arxiv.org/abs/1711.00568
https://arxiv.org/abs/1608.07537

Development of C³ 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

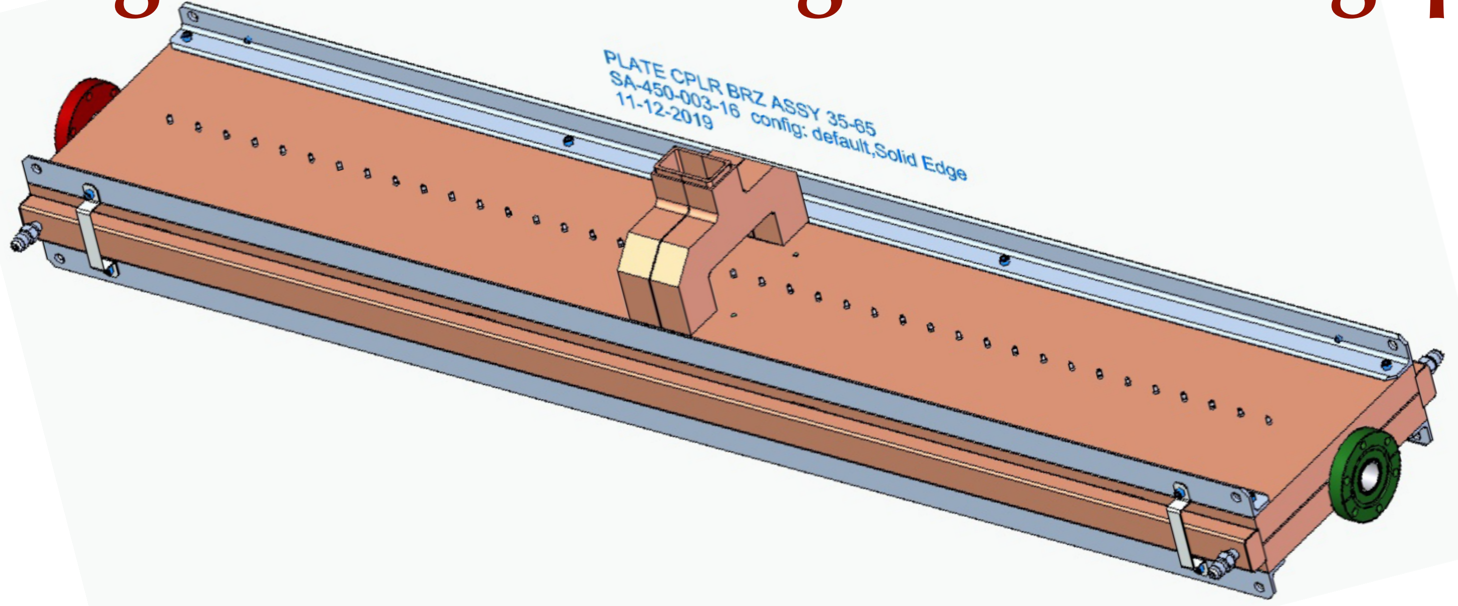
One meter (40-cell) C-band design with reduce peak E and H-field

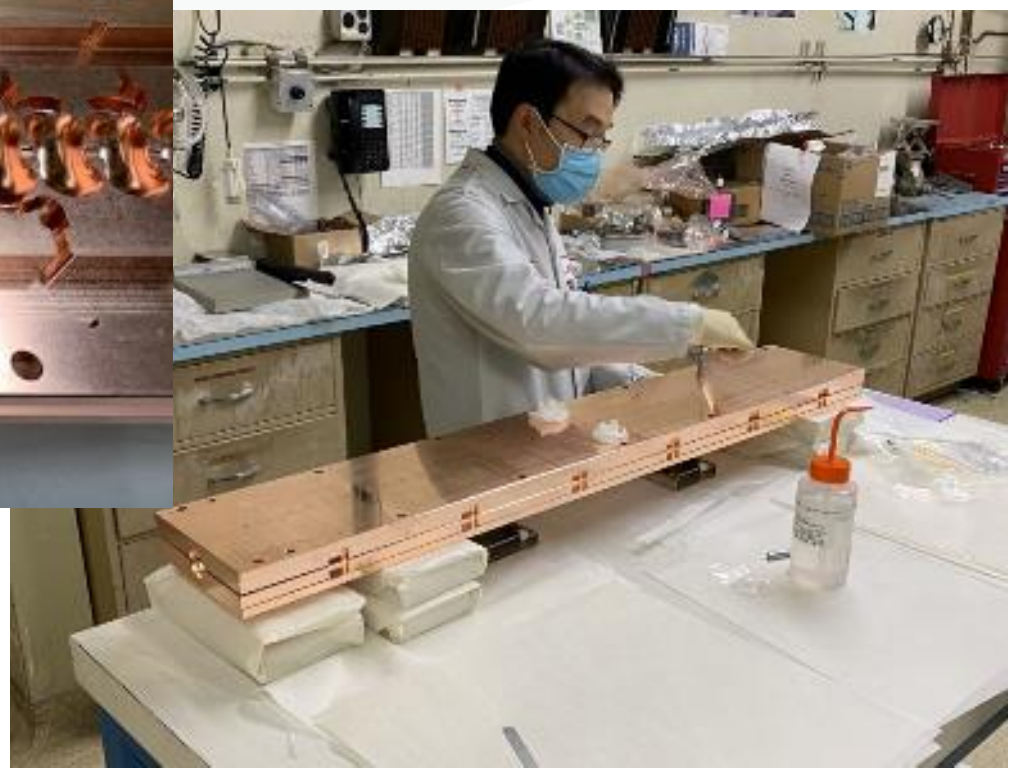




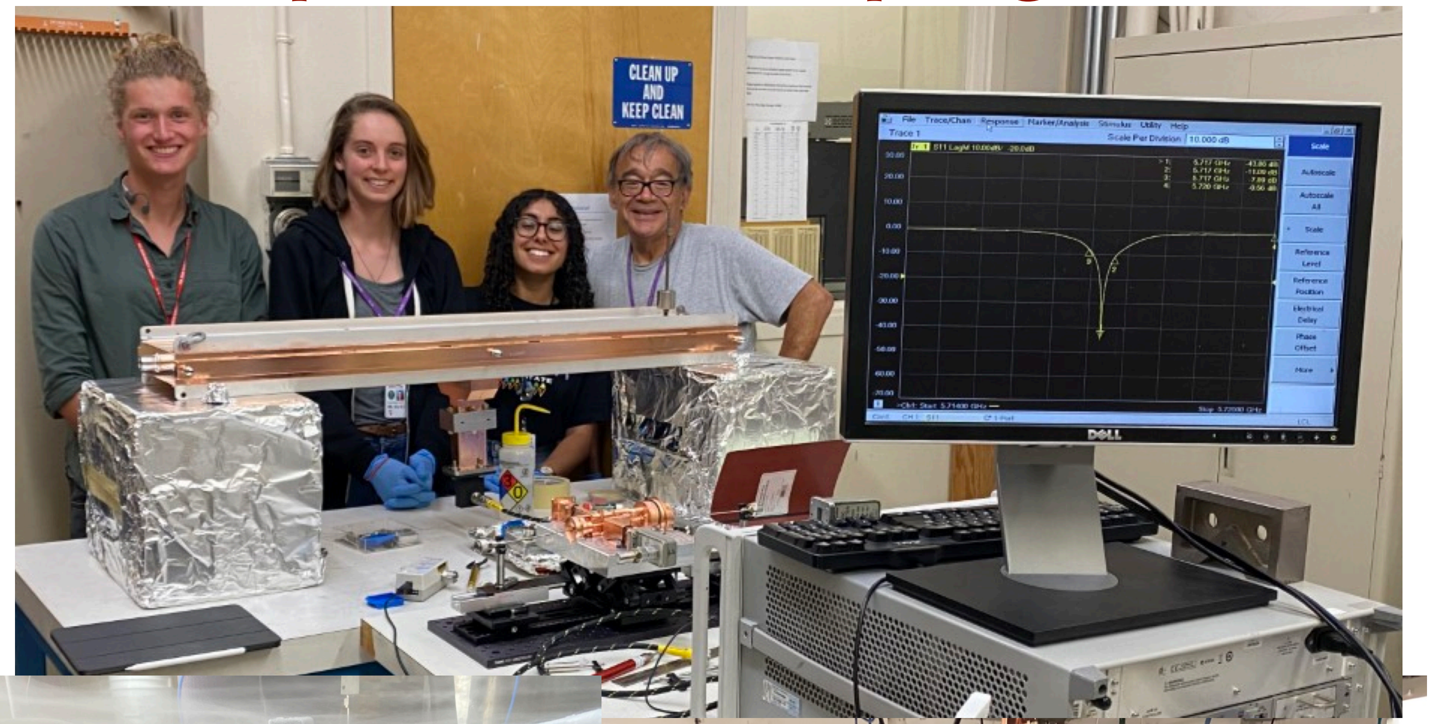
Z. Li, S. Tantawi

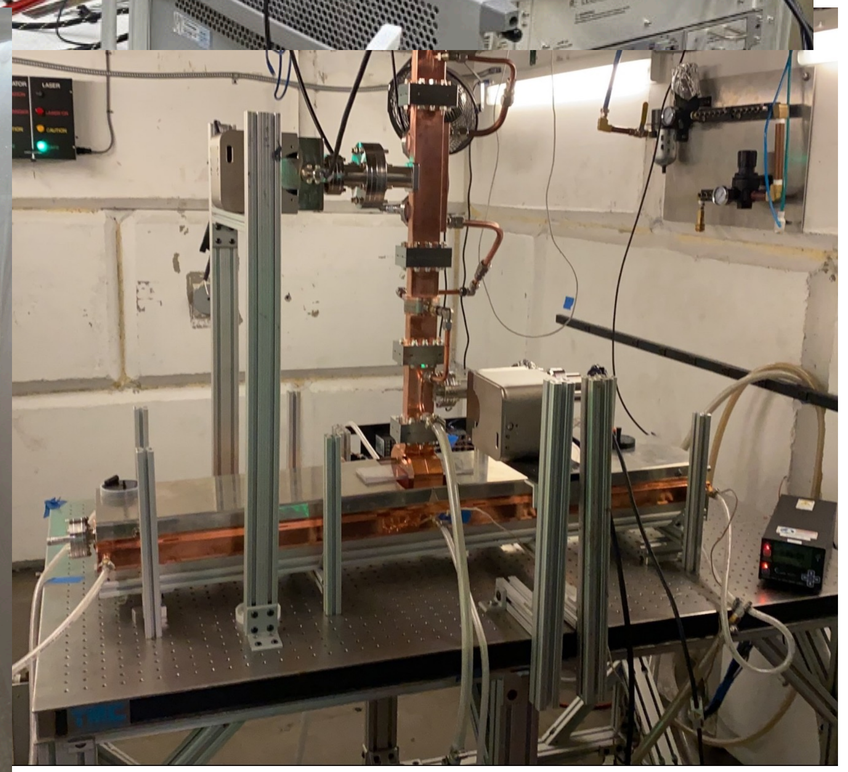
Scaling fabrication techniques in length and including controlled gap





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

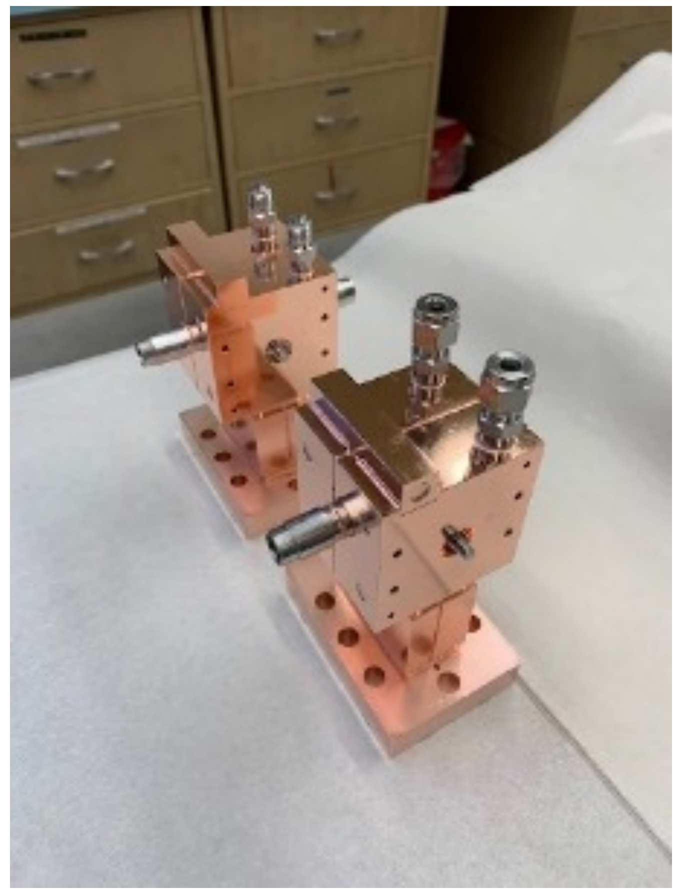
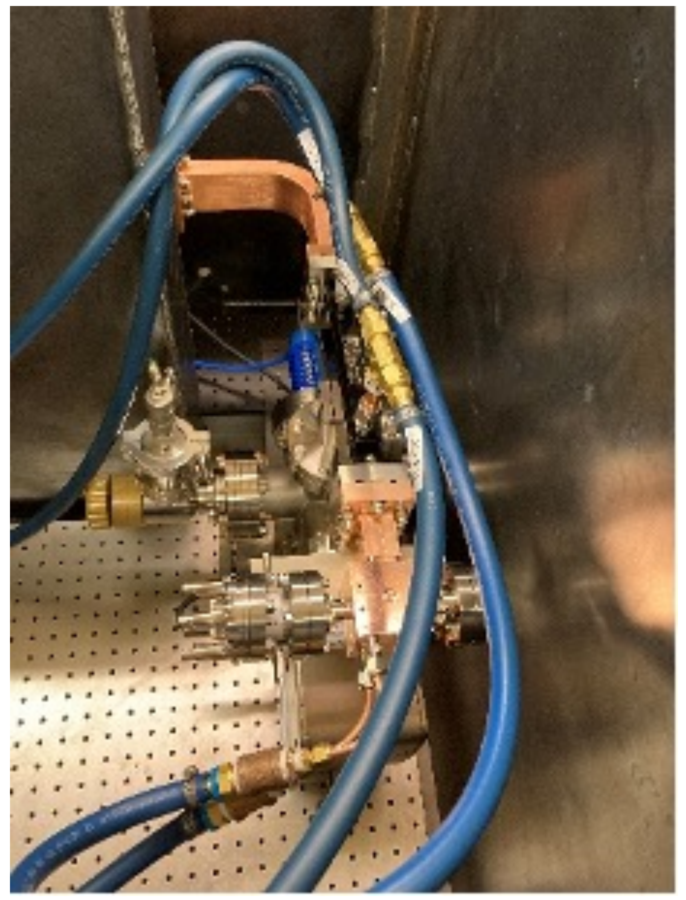




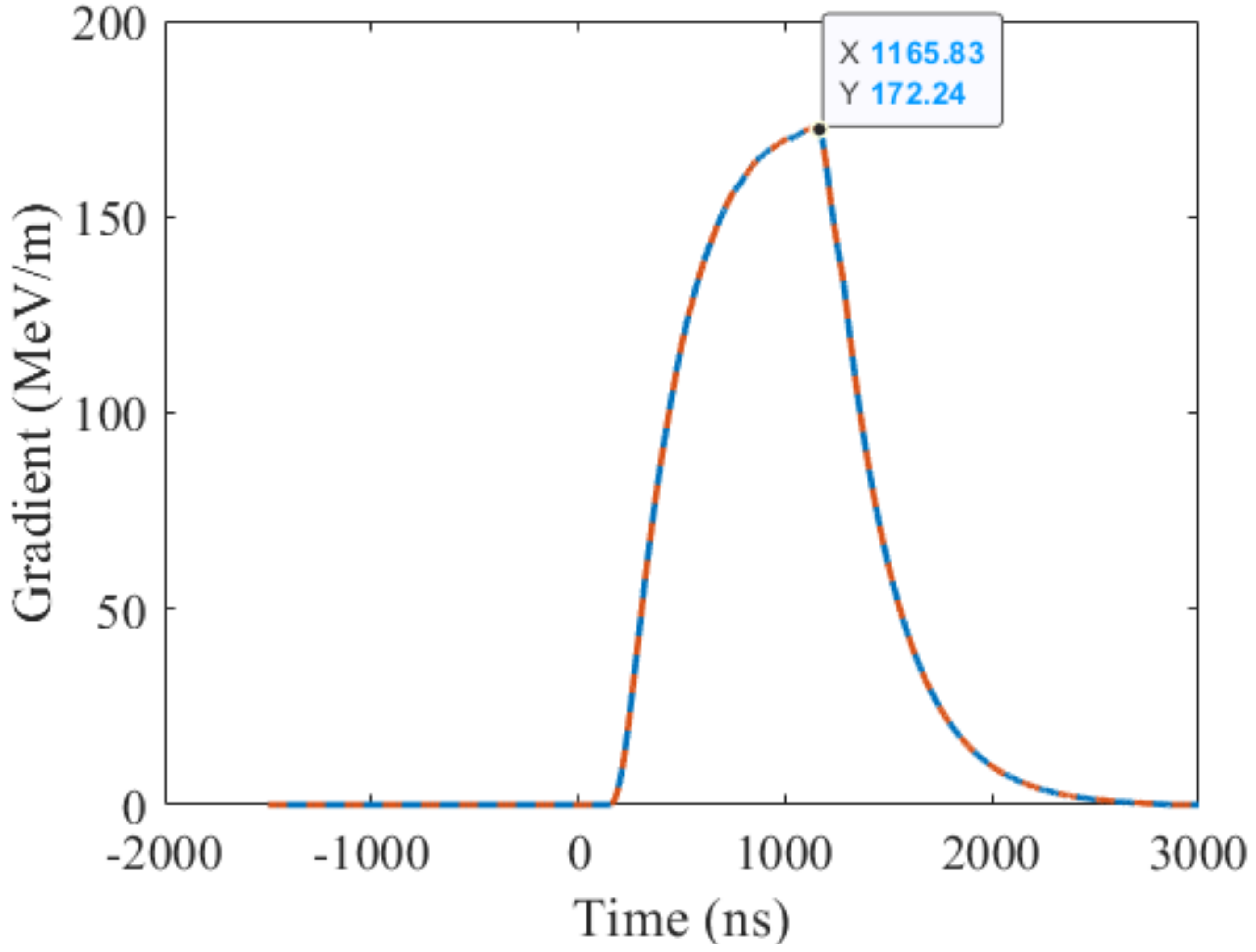
Performance of Single-Cavity Structure Prototypes

- 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

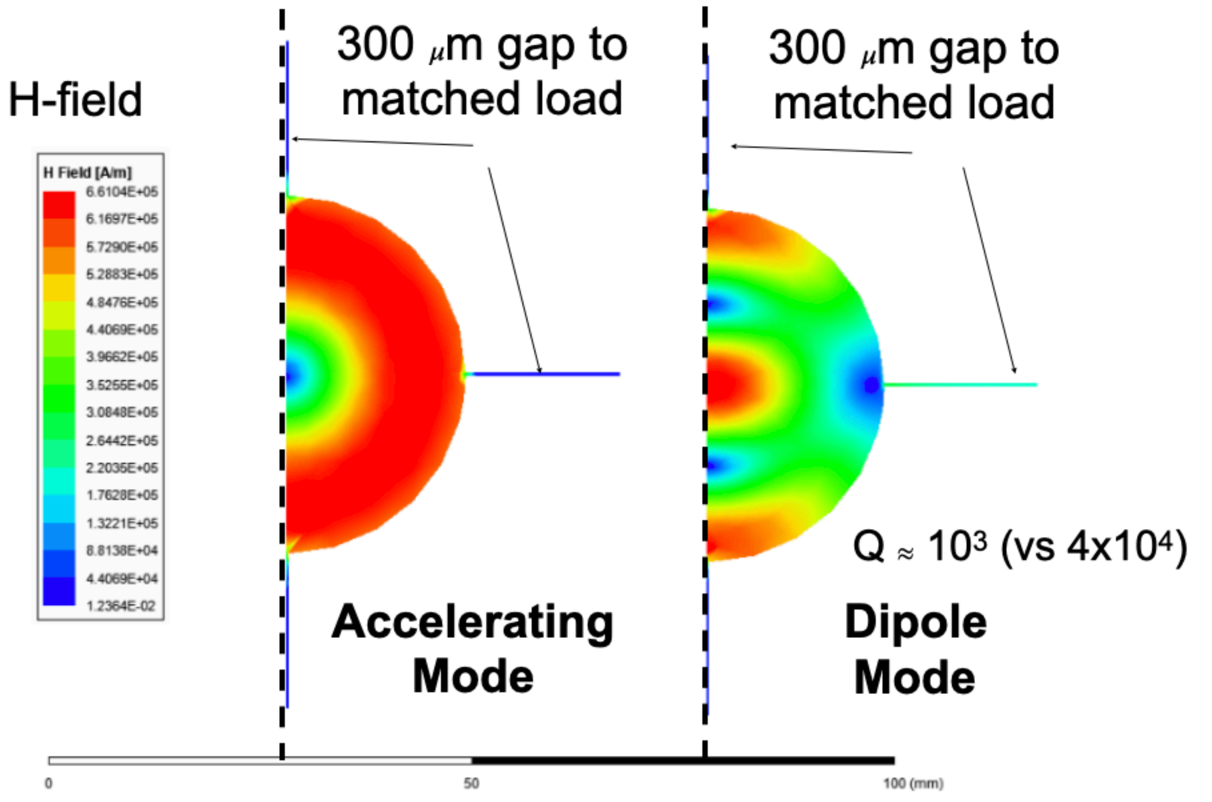
LANL Test of single cell SLAC C-band structure

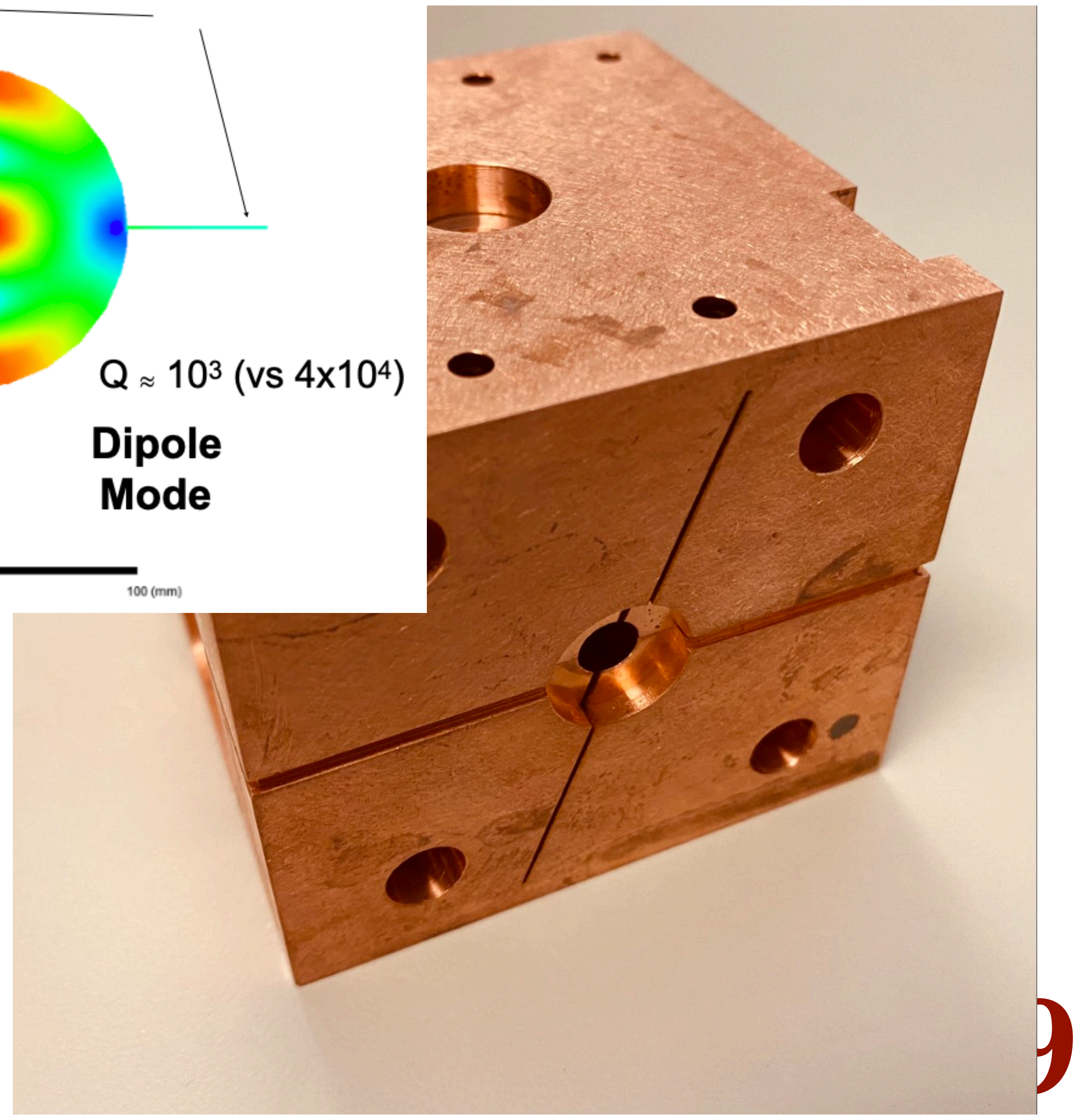



Structure Exceeds 120 MeV/m for 500 ns @ Room Temp BDR Data Collected



Slot Damping Prototype Working on NiCr Coating





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