A *cool* route to unveil the Higgs boson's secrets

Caterina Vernieri

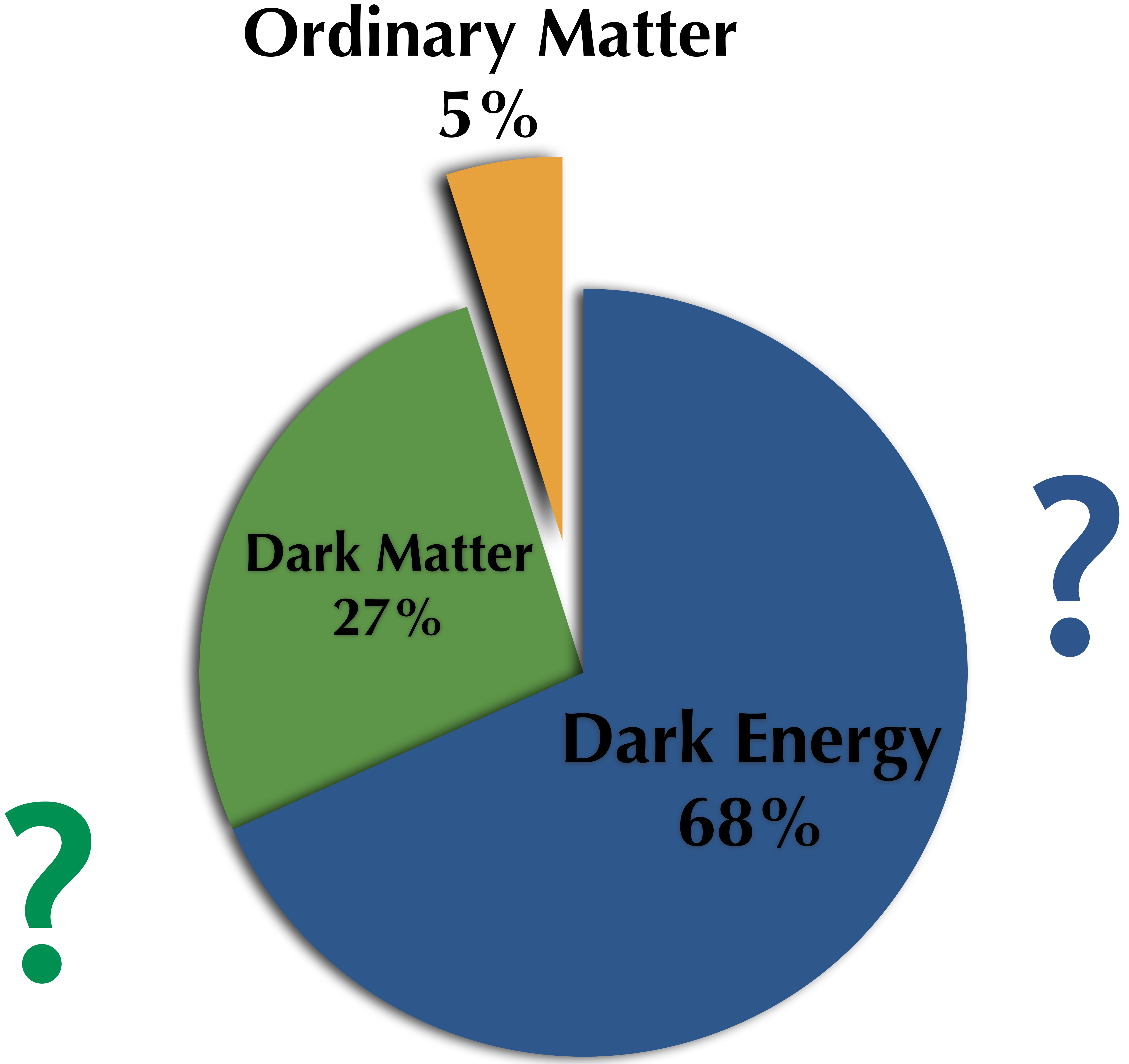
Seminar at University of Wisconsin Madison

December 2, 2021

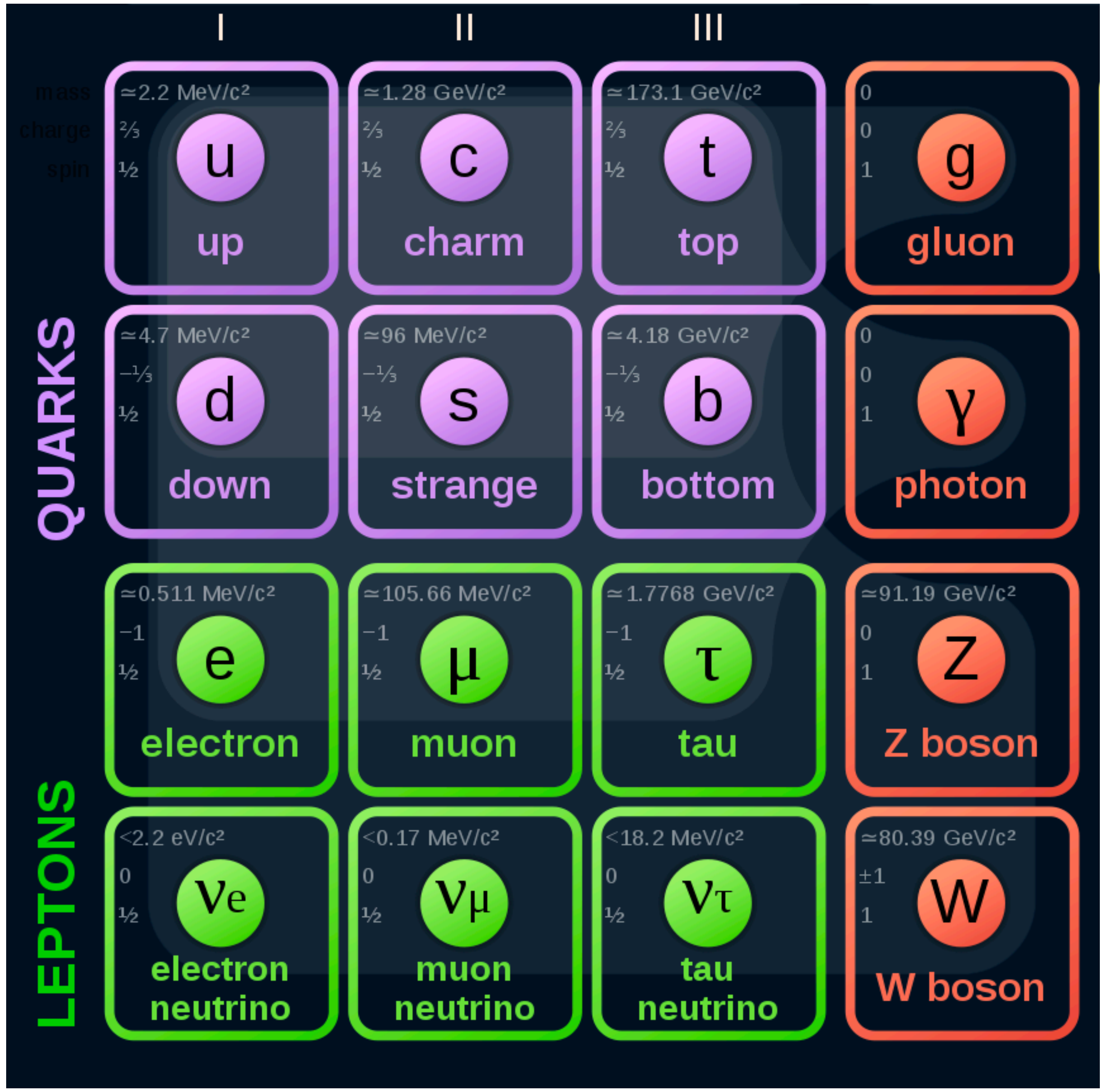
Outline

- The Standard Model and the Higgs boson
  - What we know so far
- Perspectives at the LHC and Future Colliders
  - The Cool Copper Collider

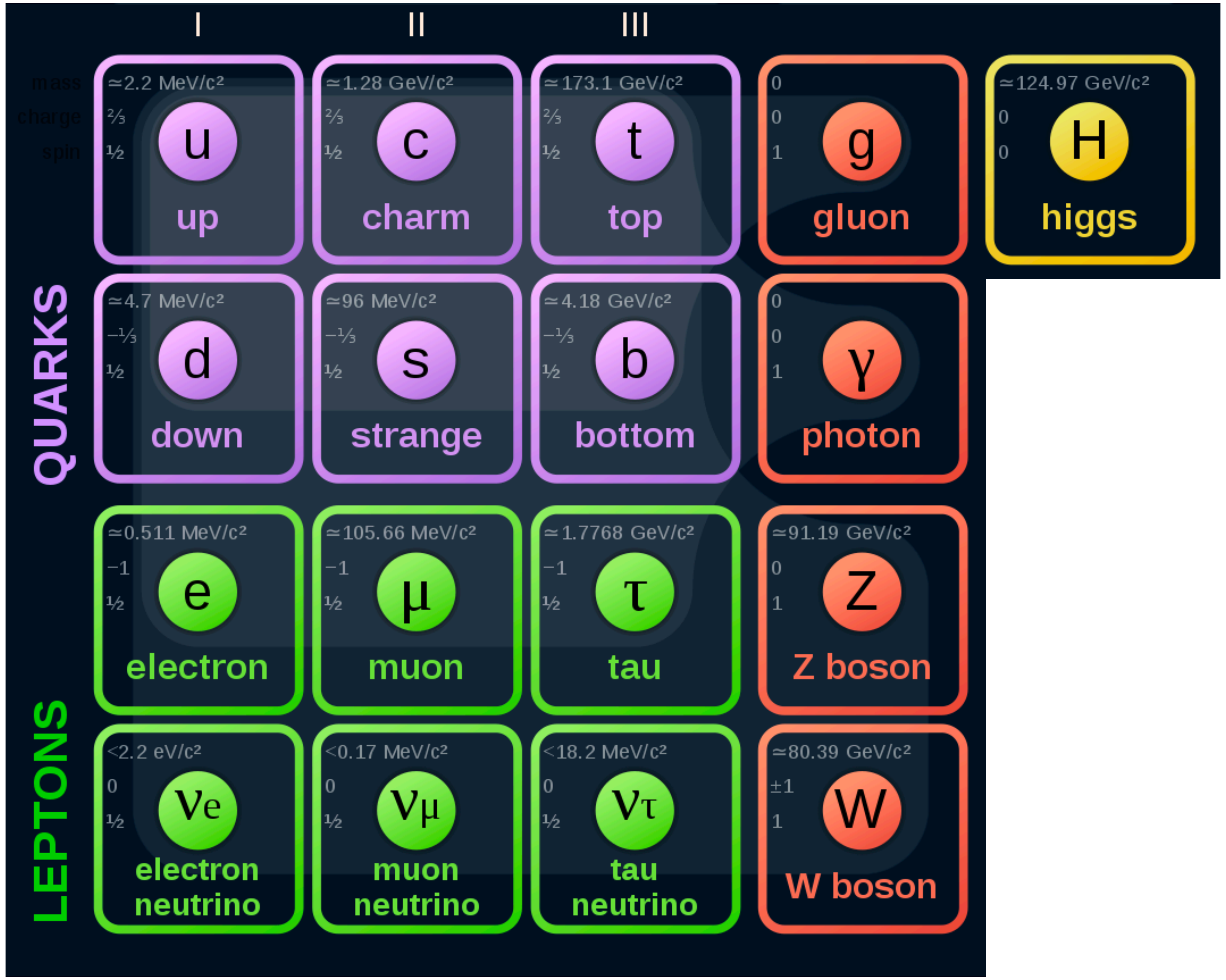
The Standard Model



The Standard Model

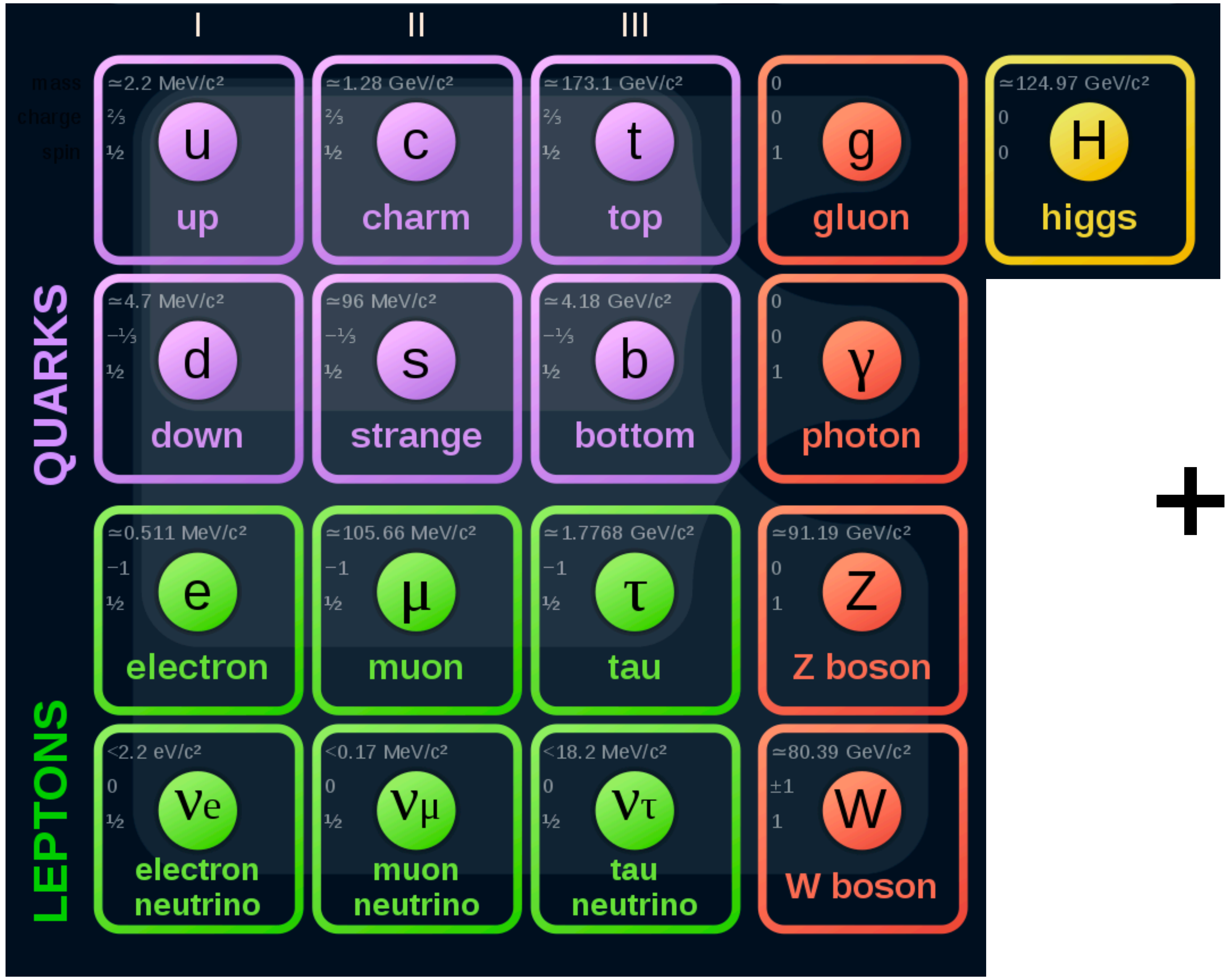


The Standard Model

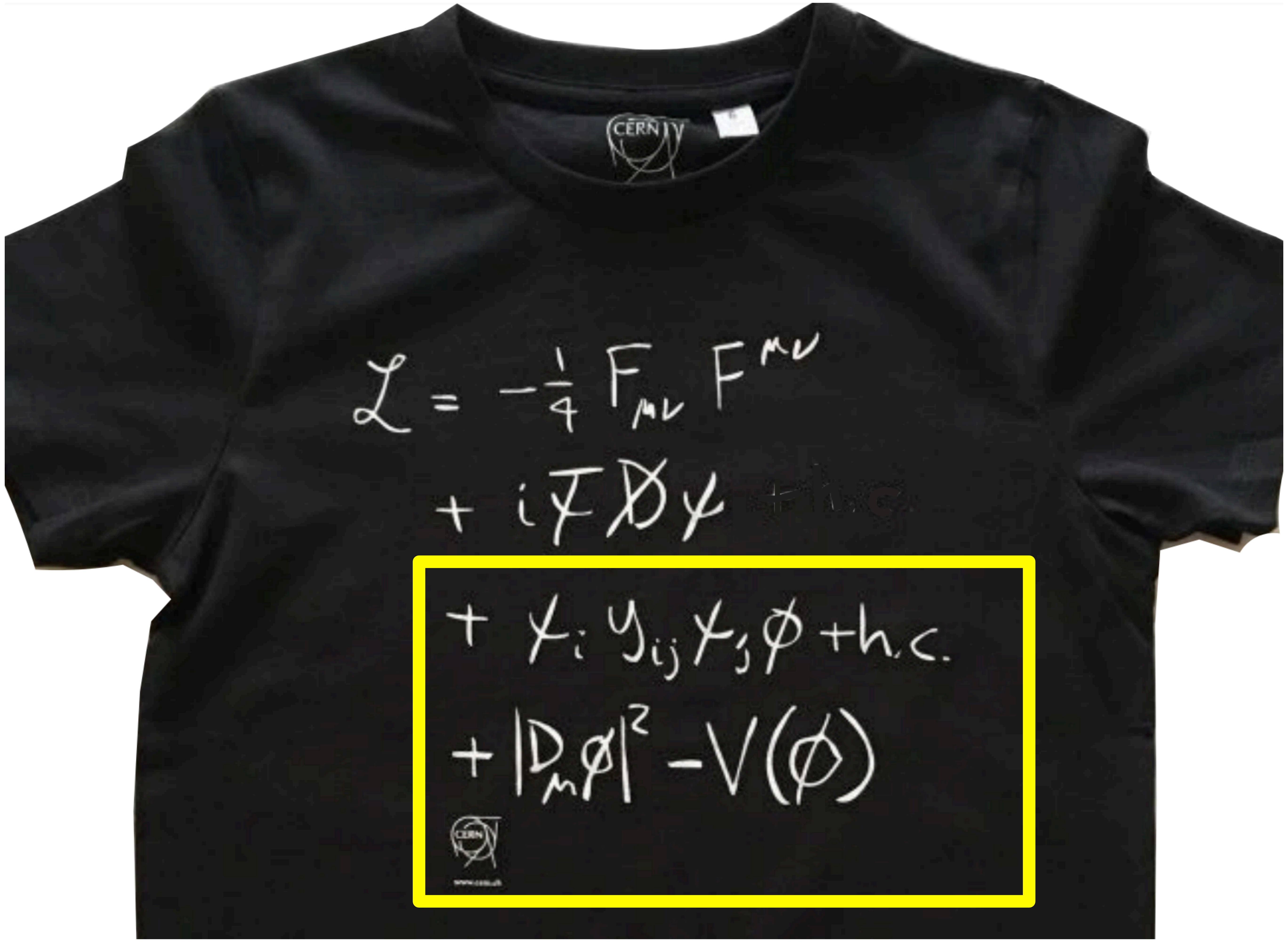



Higgs Boson
self-interaction

The Higgs Boson



+



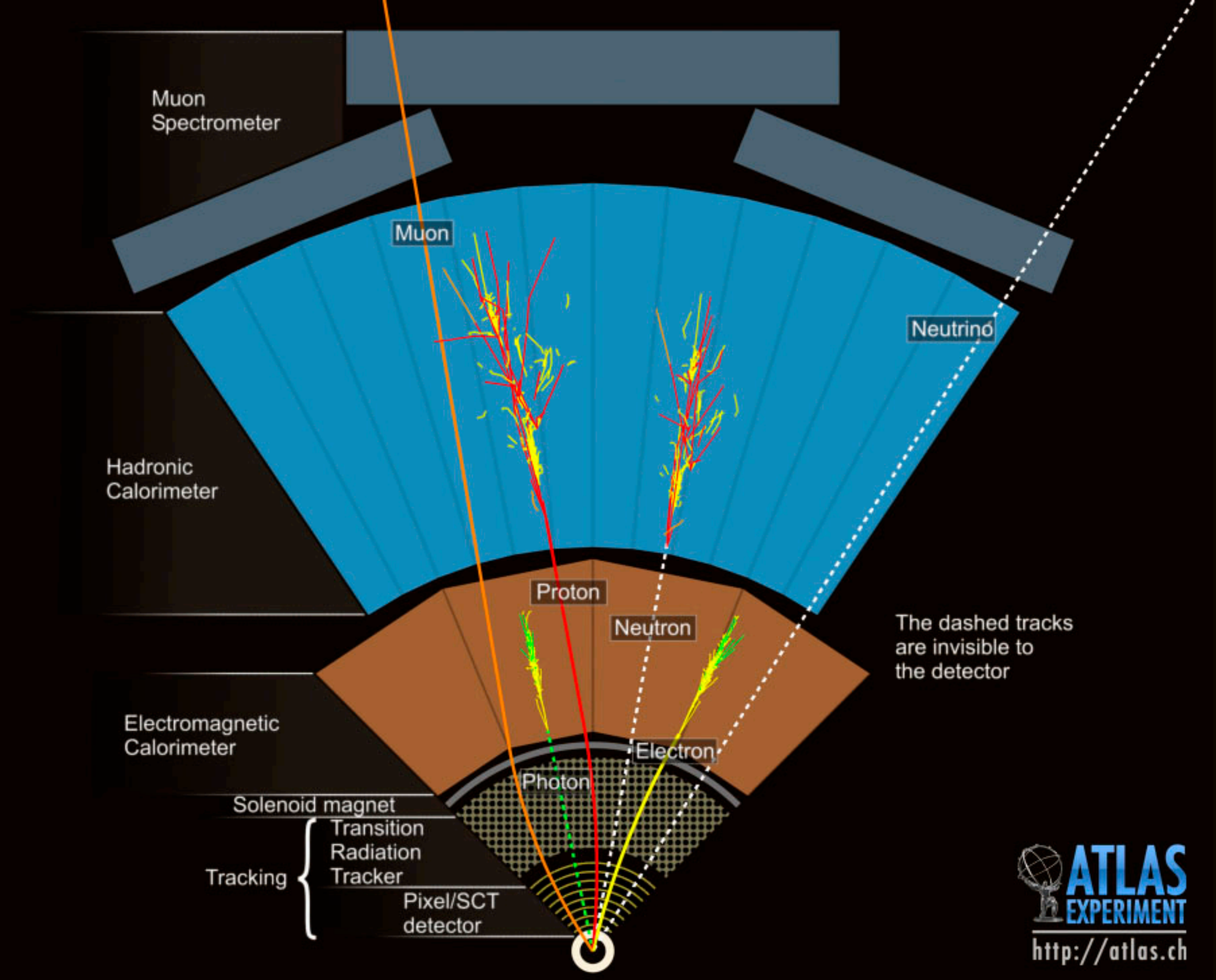
The Large Hadron Collider (LHC)

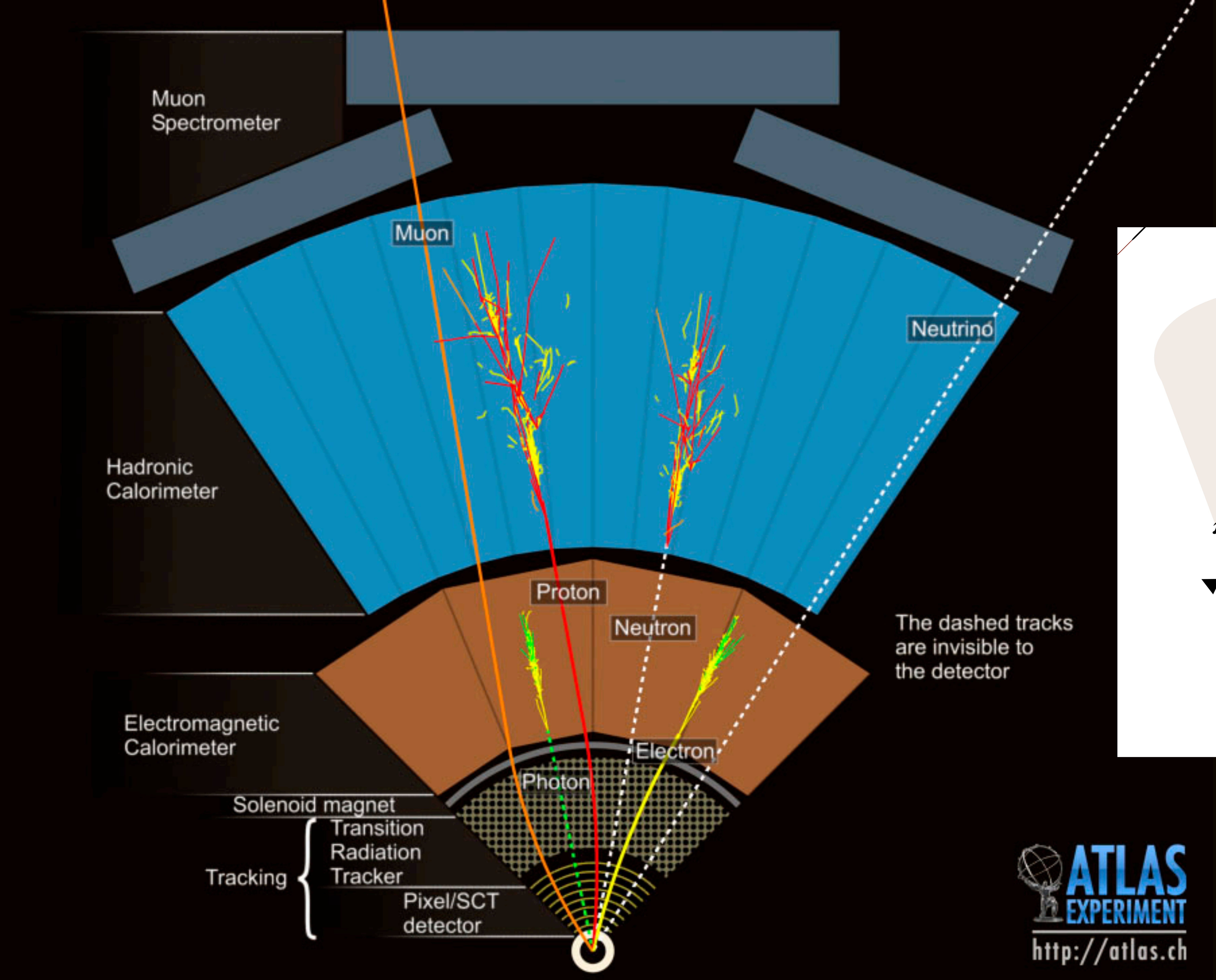
ATLAS

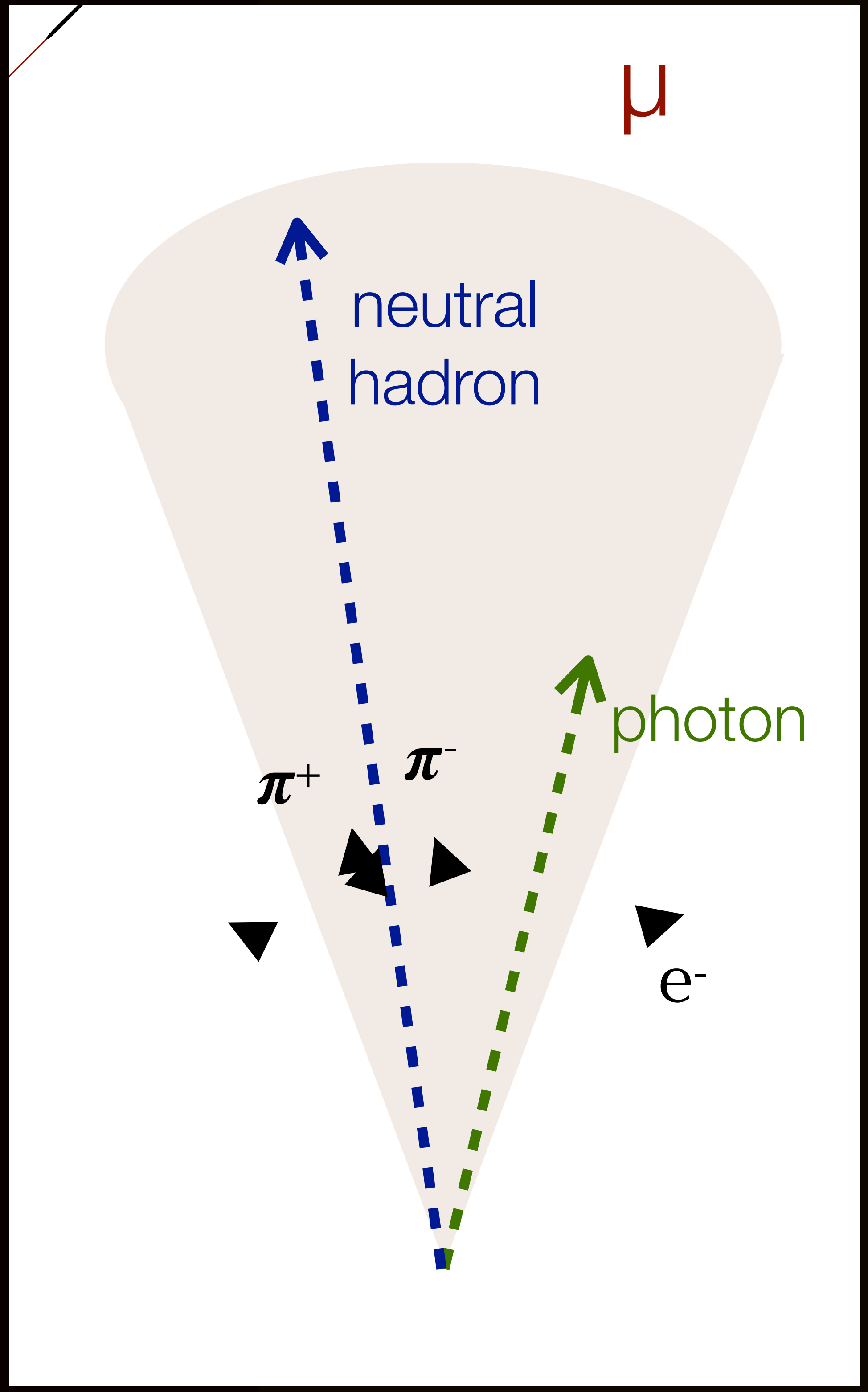
CMS

27 km circumference
100 m underground
energy ~ 13 TeV

← p p →


Muon
Spectrometer
Muon
Hadronic
Calorimeter
Neutrino
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Transition
Radiation
Tracker
Tracking
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

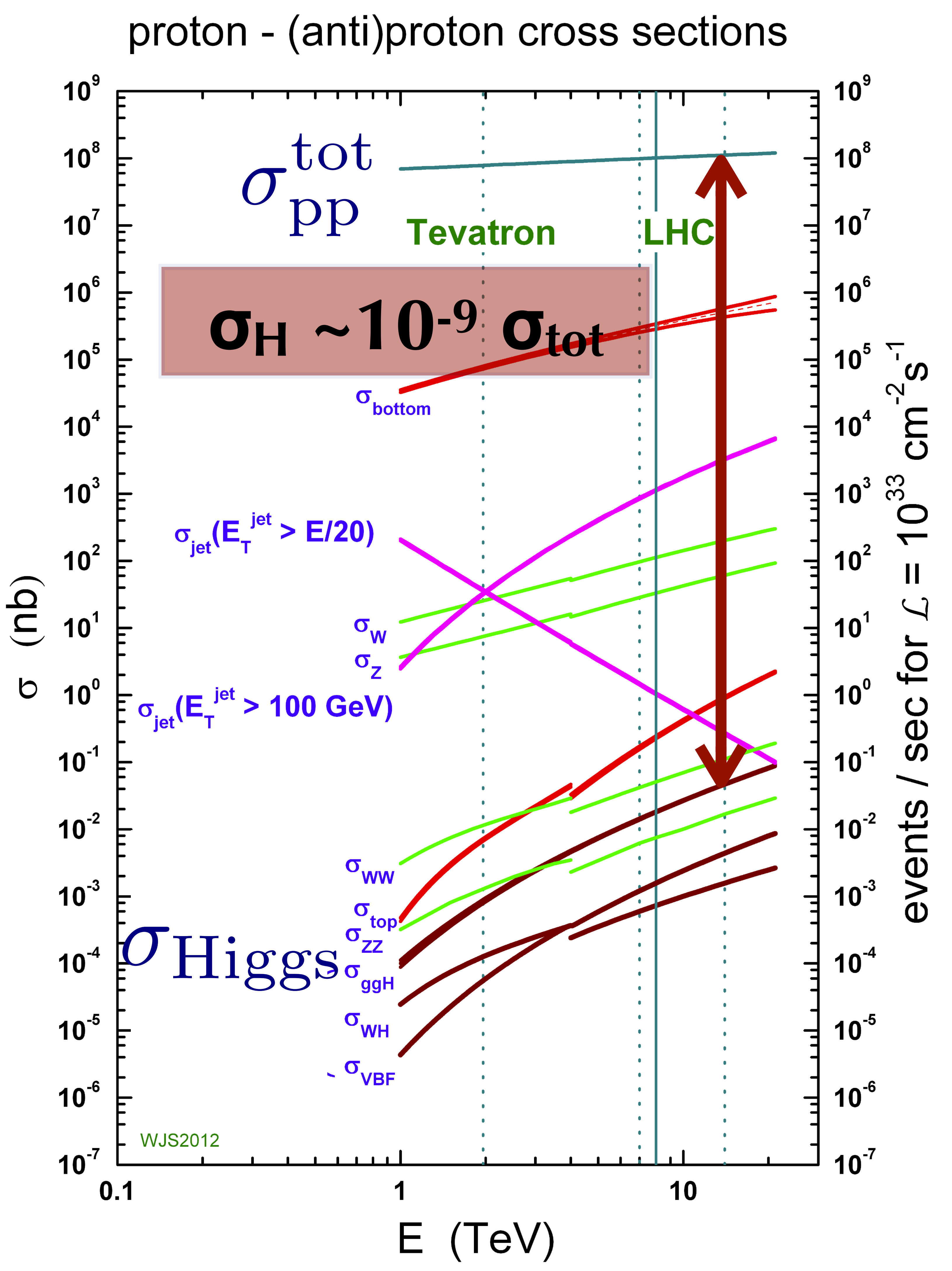

Muon
Spectrometer
Muon
Hadronic
Calorimeter
Neutrino
Proton
Neutron
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Transition
Radiation
Tracker
Tracking
Pixel/SCT
detector
The dashed tracks
are invisible to
the detector
ATLAS
EXPERIMENT
http://atlas.ch


μ
neutral
hadron
photon
π^+
π^-
e^-

Cross section

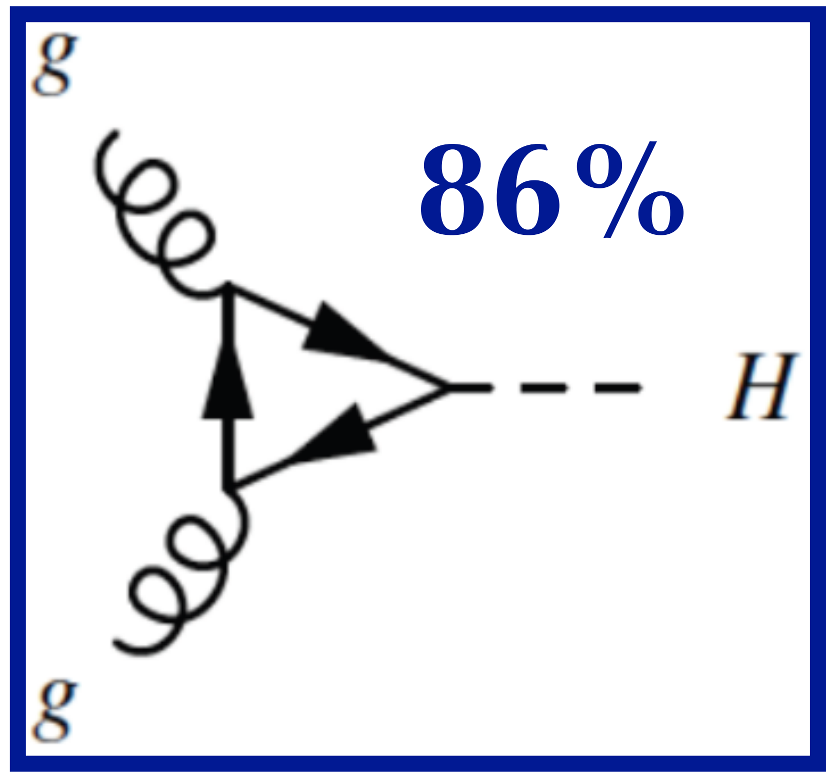
- At the LHC in Run 2 we have ~10^9 pp inelastic interactions/sec
- We record a small selection of collisions (<0.01%)

Storage and computing are limited

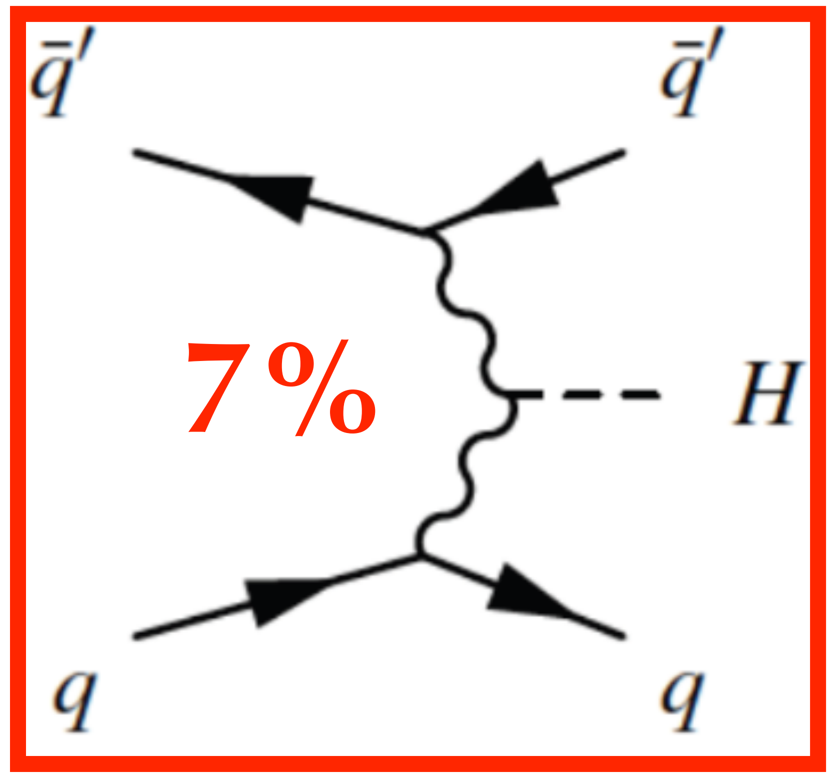



H

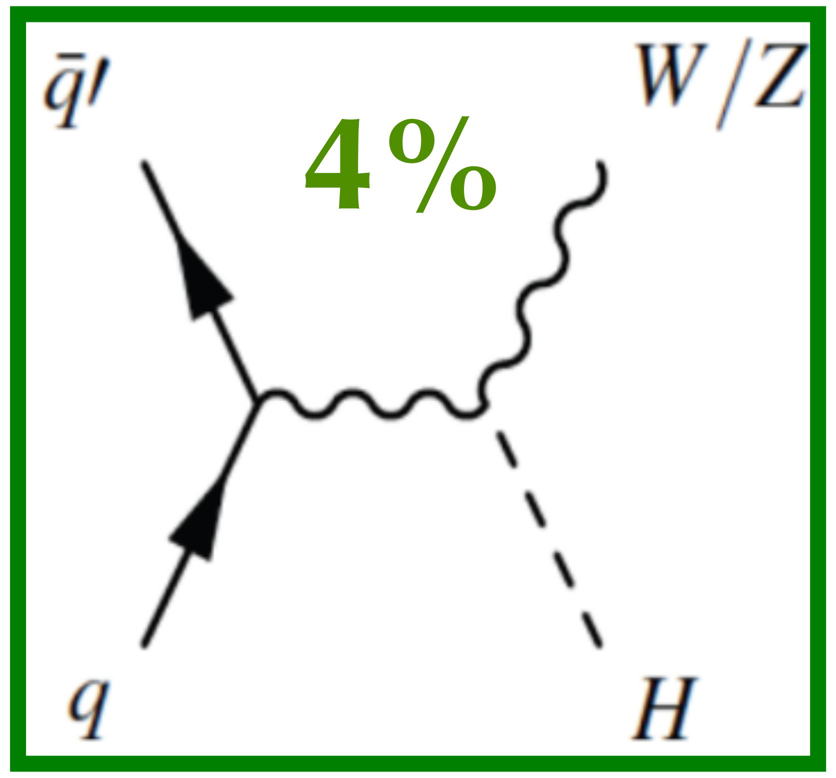
Higgs Boson Production at the LHC



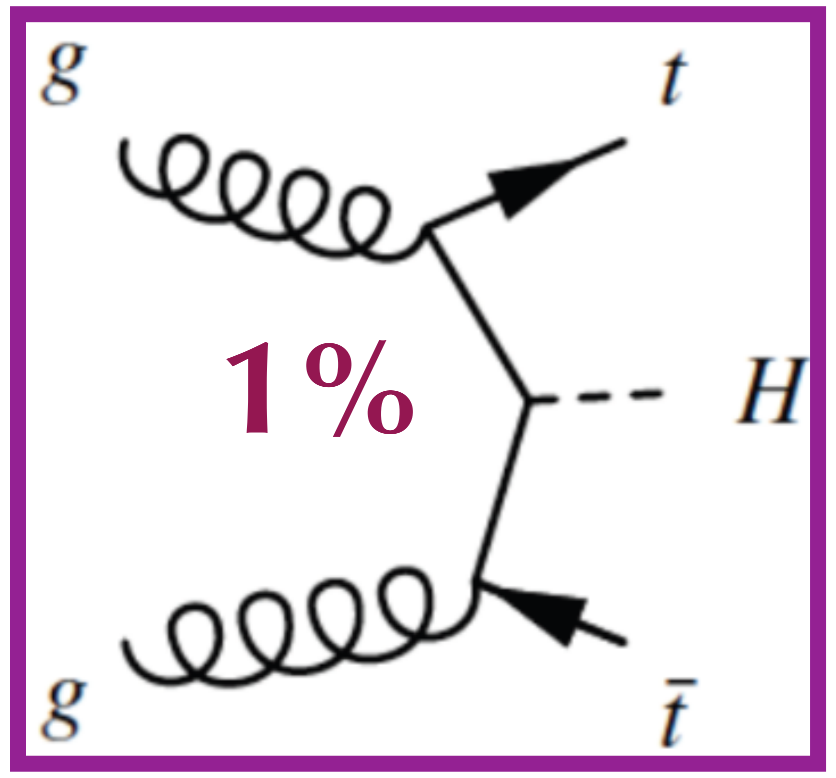
Gluon Fusion



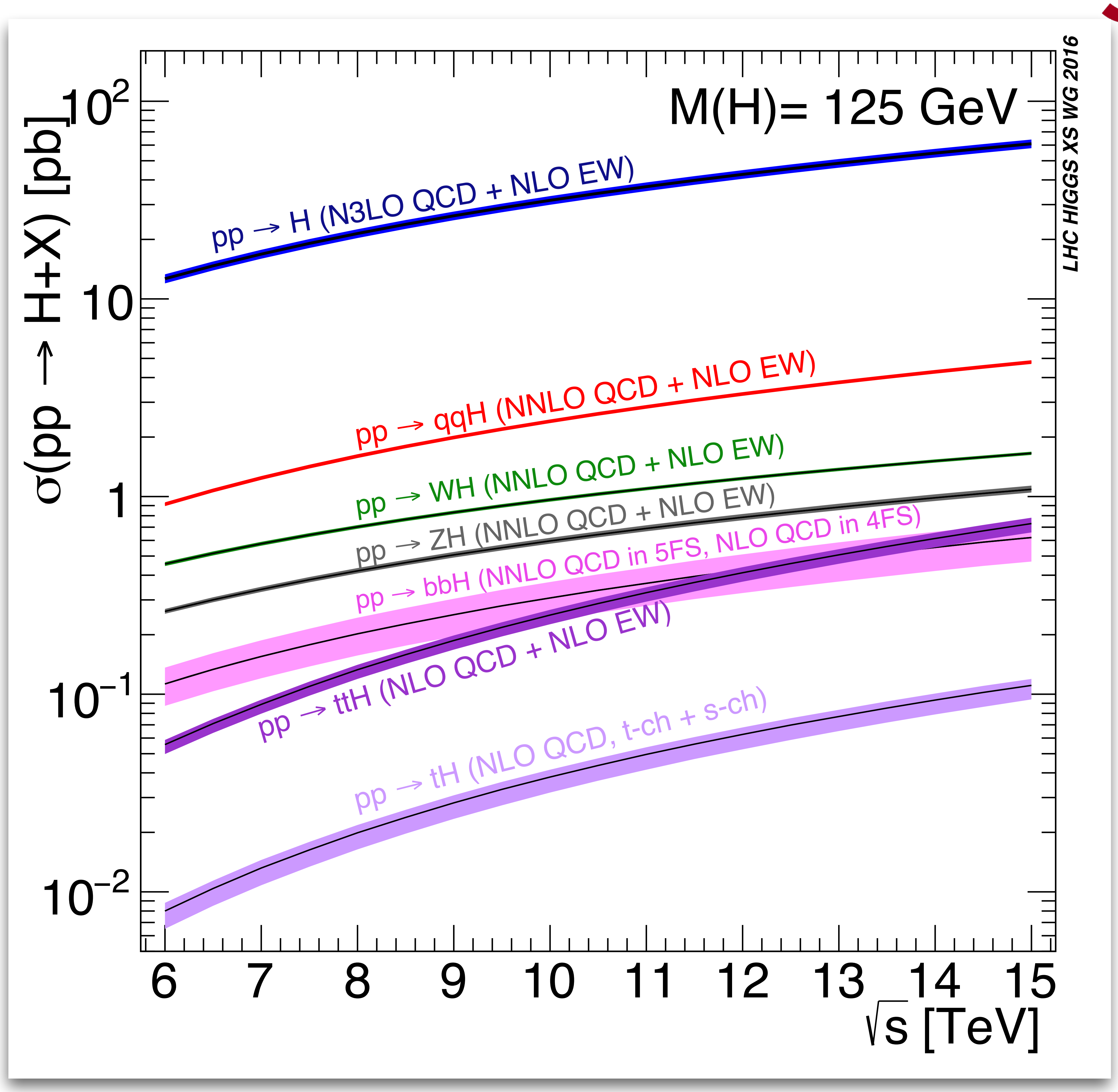
Vector-Boson Fusion



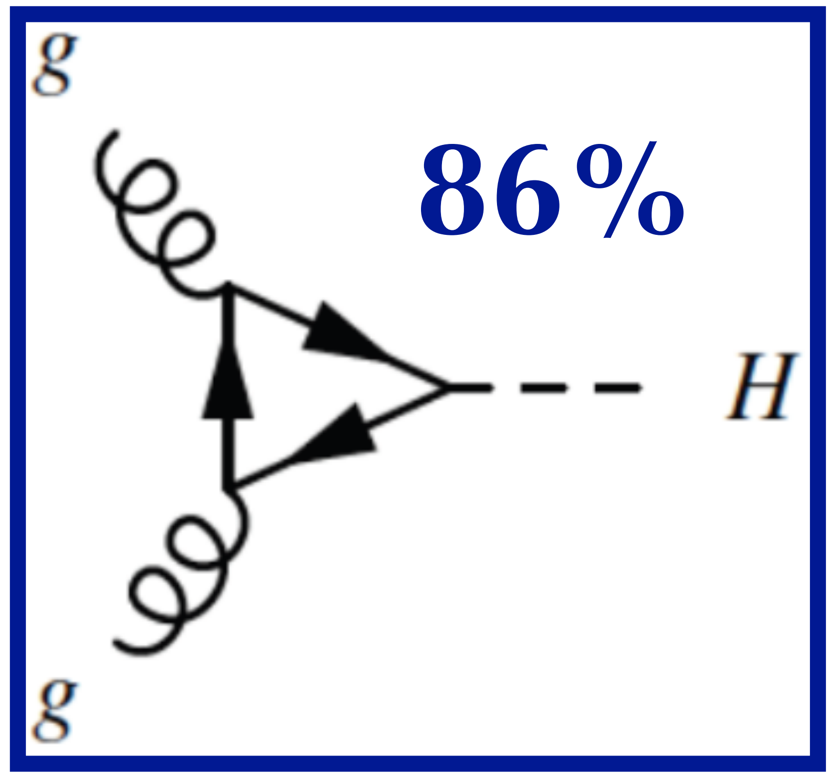
Higgs-strahlung



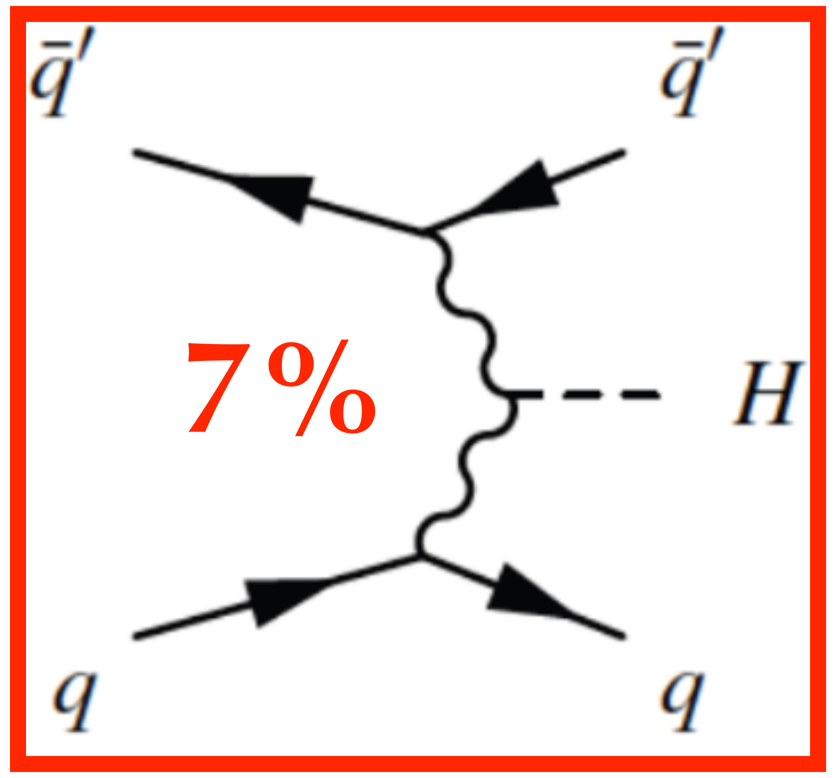
Top Fusion (ttH)



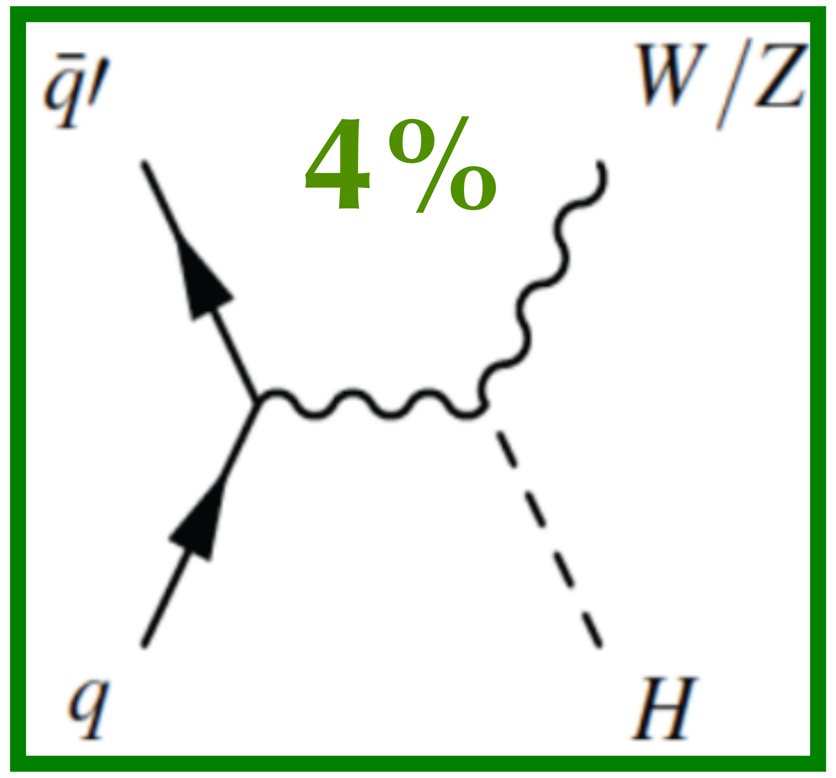
Higgs Boson Production at the LHC



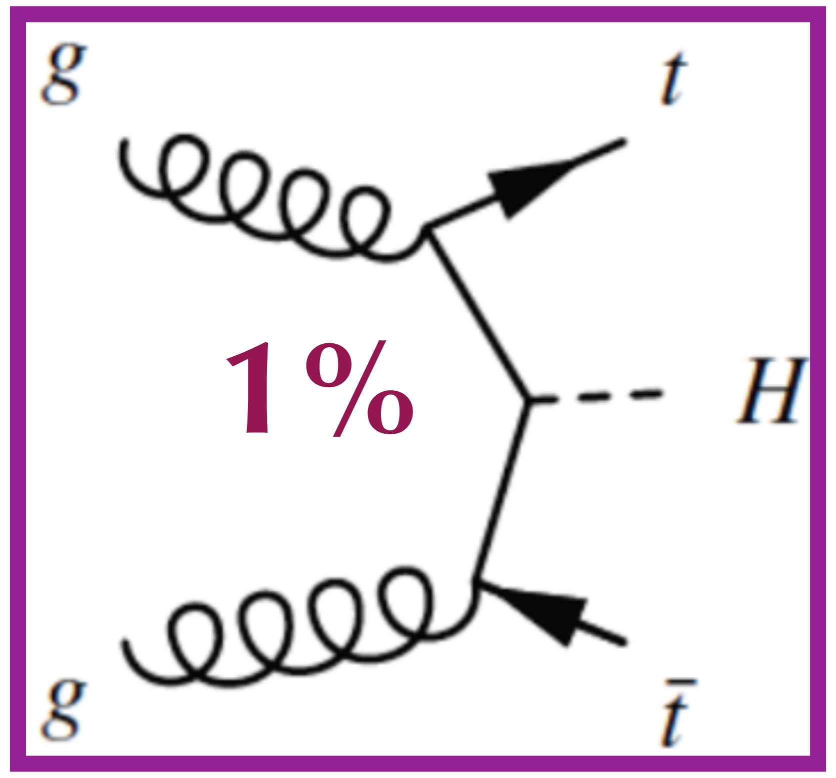
Gluon Fusion



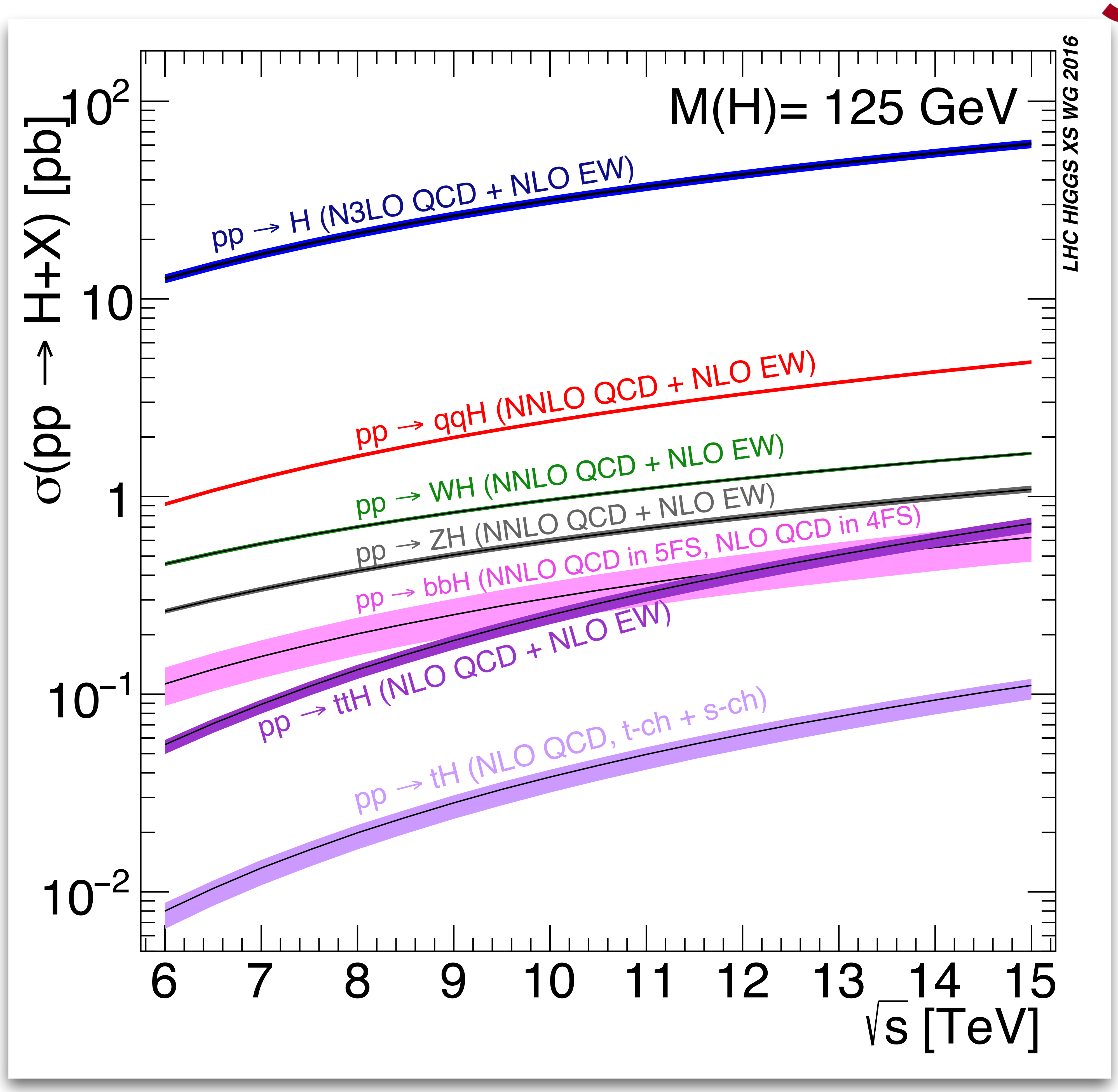
Vector-Boson Fusion



Higgs-strahlung

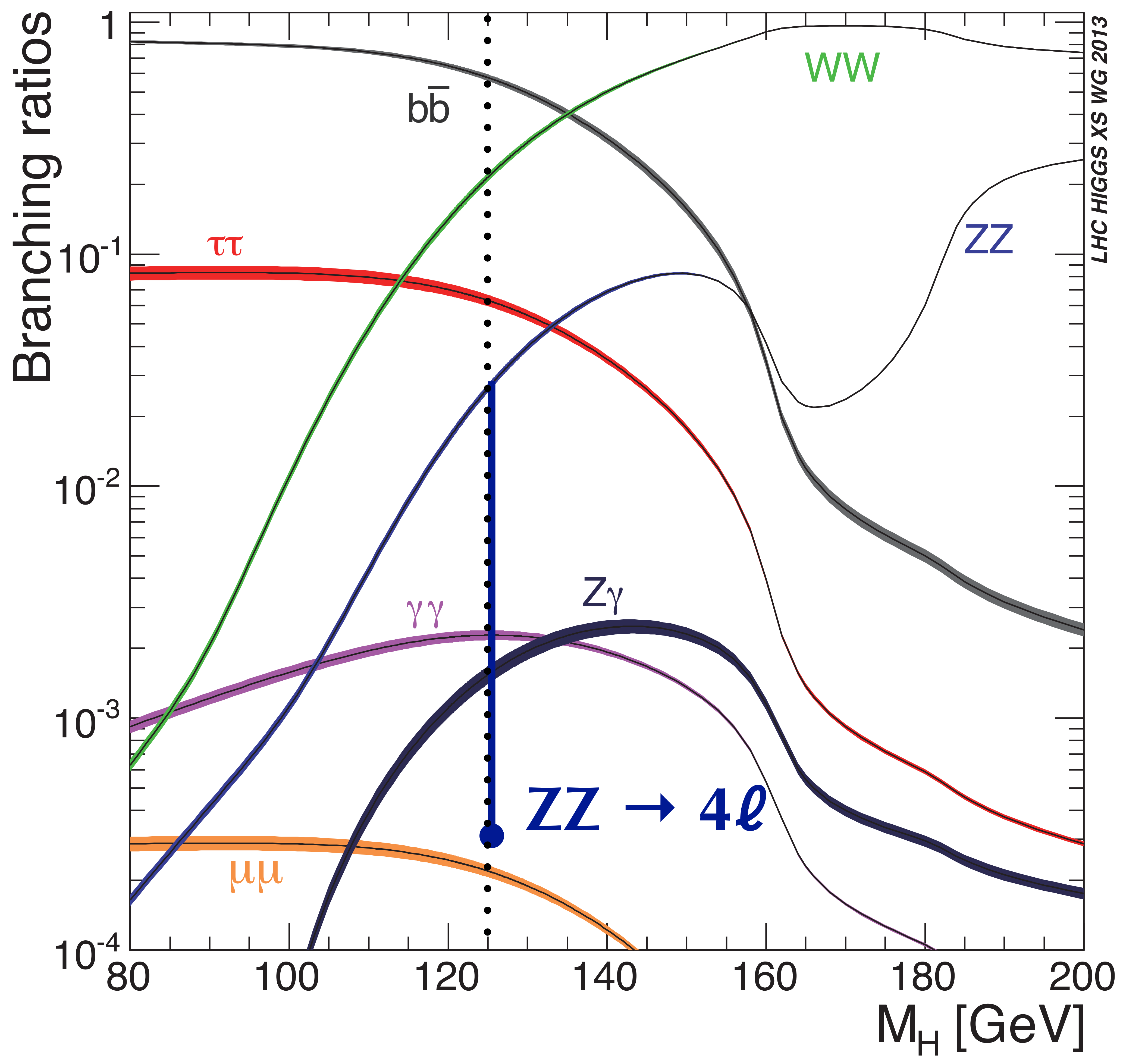


Top Fusion (ttH)

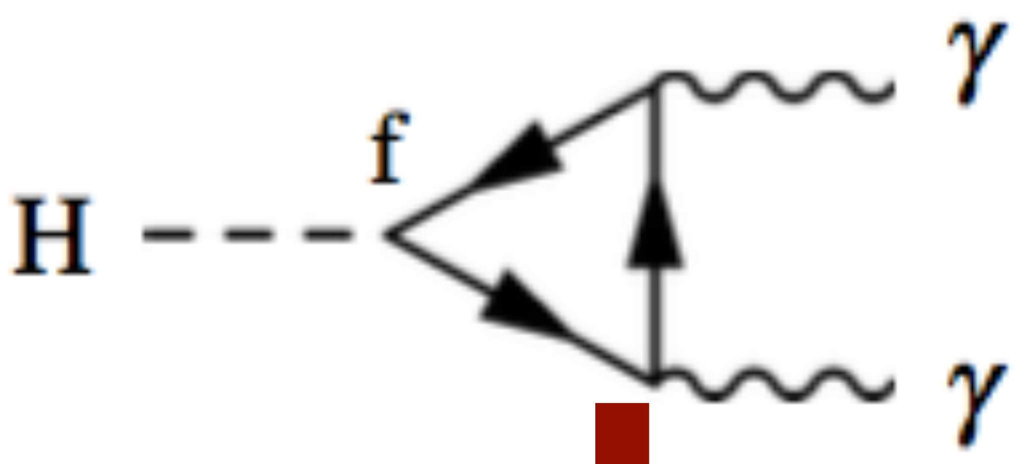


At LHC one every billion collisions we produce a Higgs boson

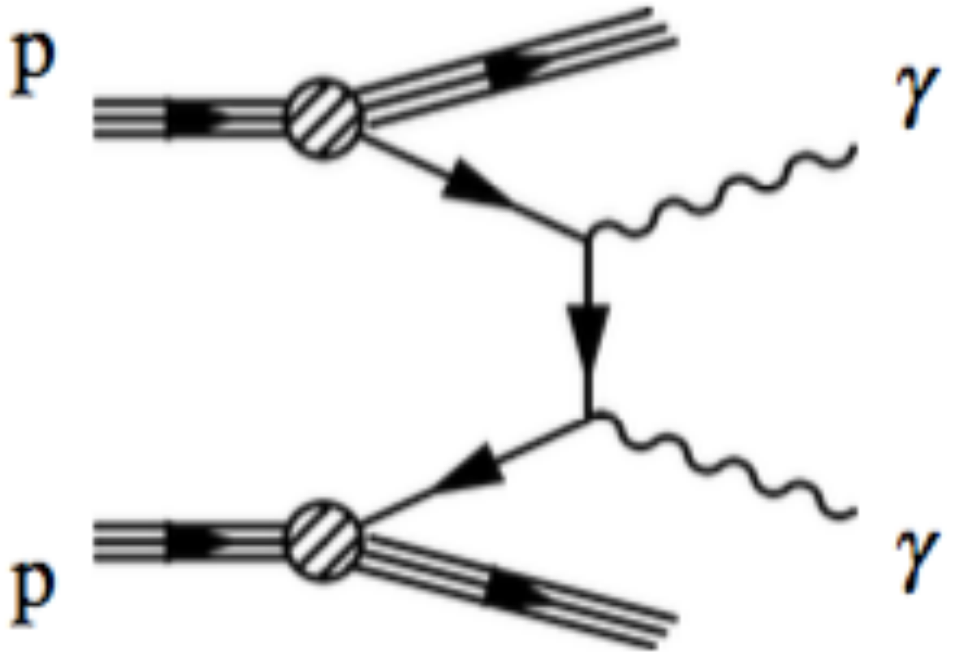
How does it Decay (m_H = 125 GeV) ?

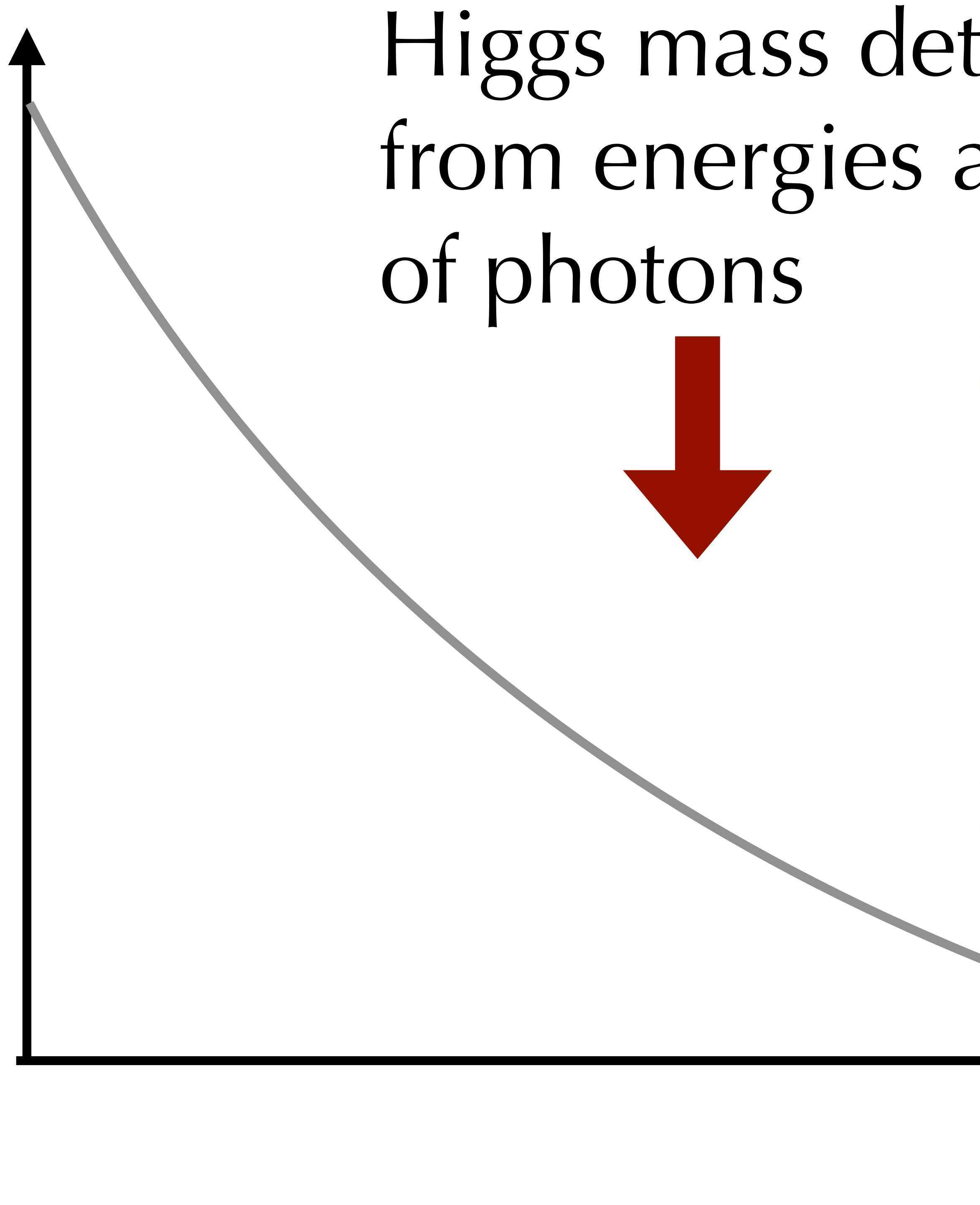


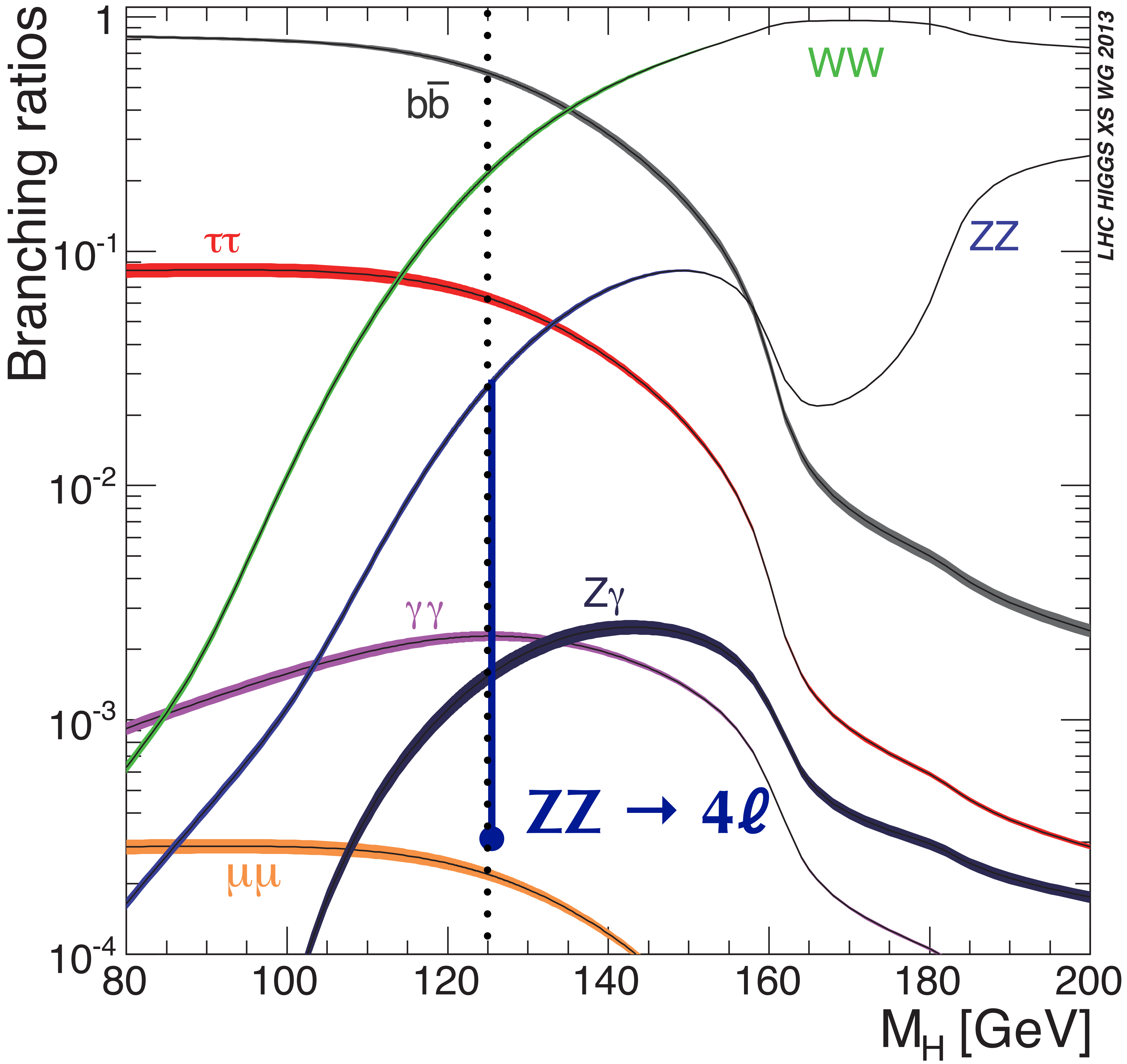
How does it Decay (m_H = 125 GeV) ?



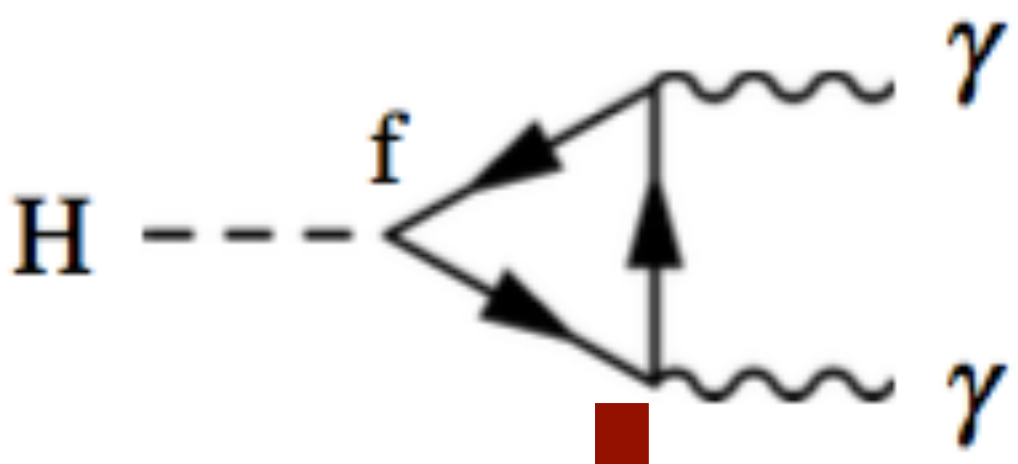
Higgs mass determined from energies and angles of photons



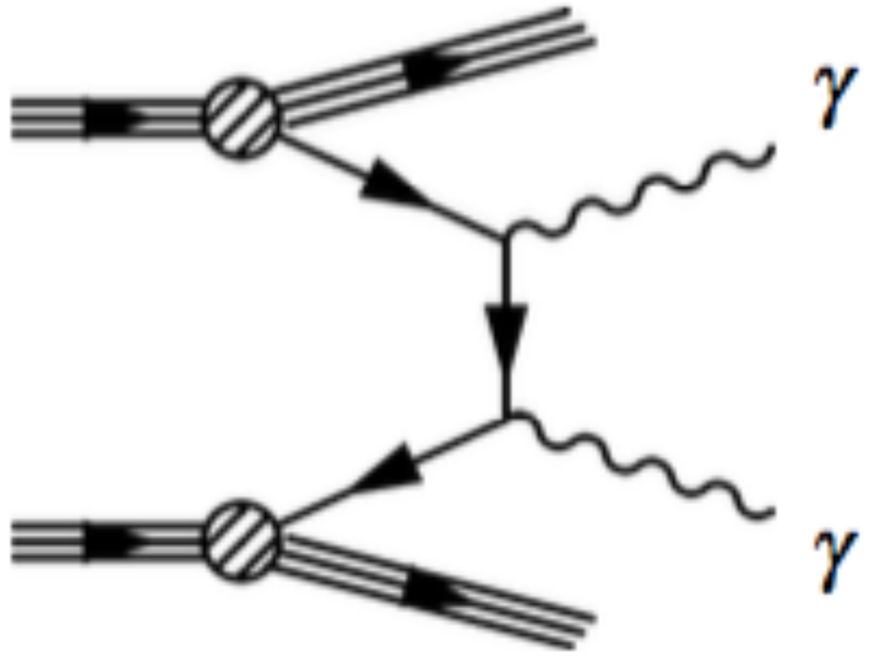


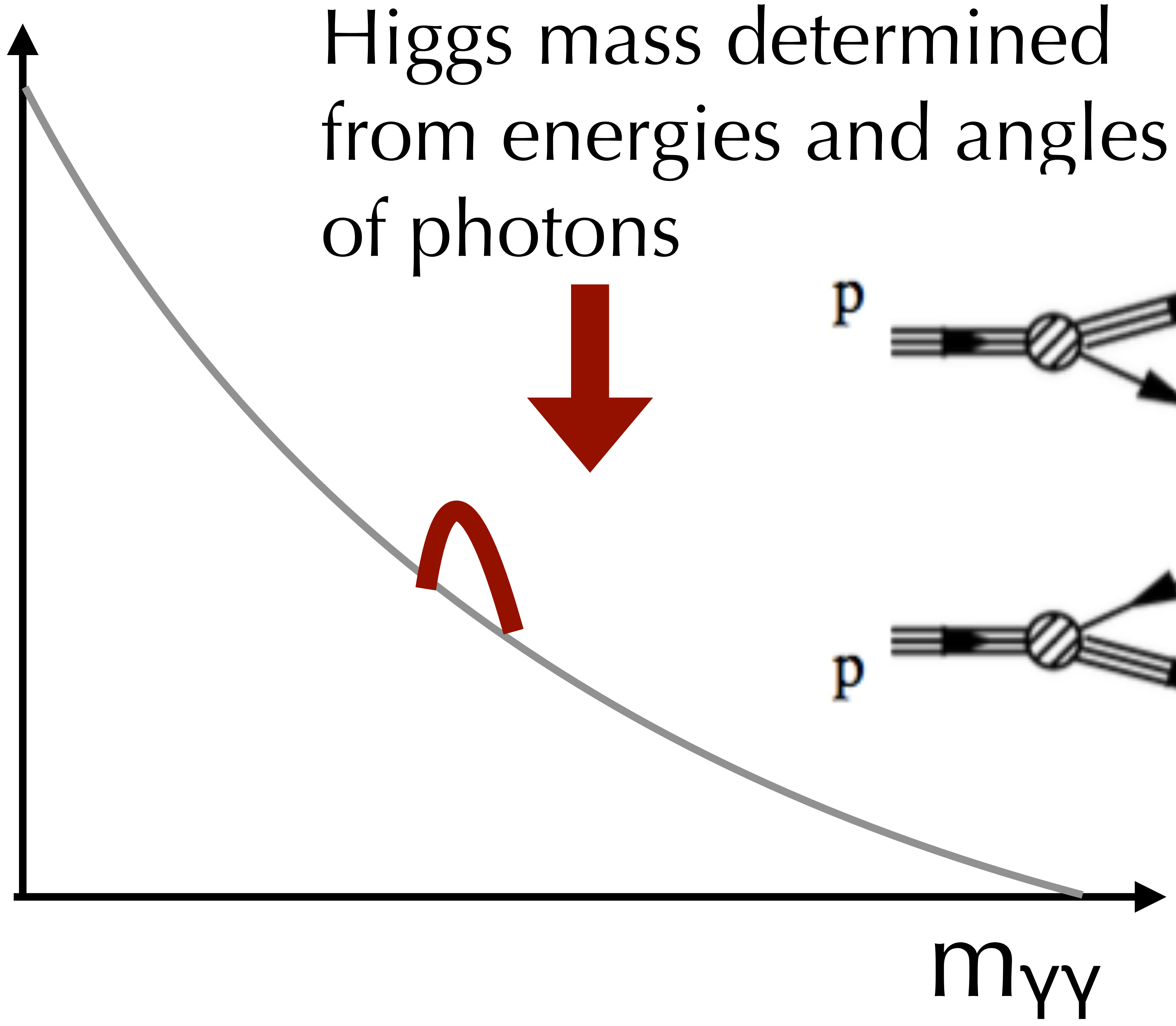


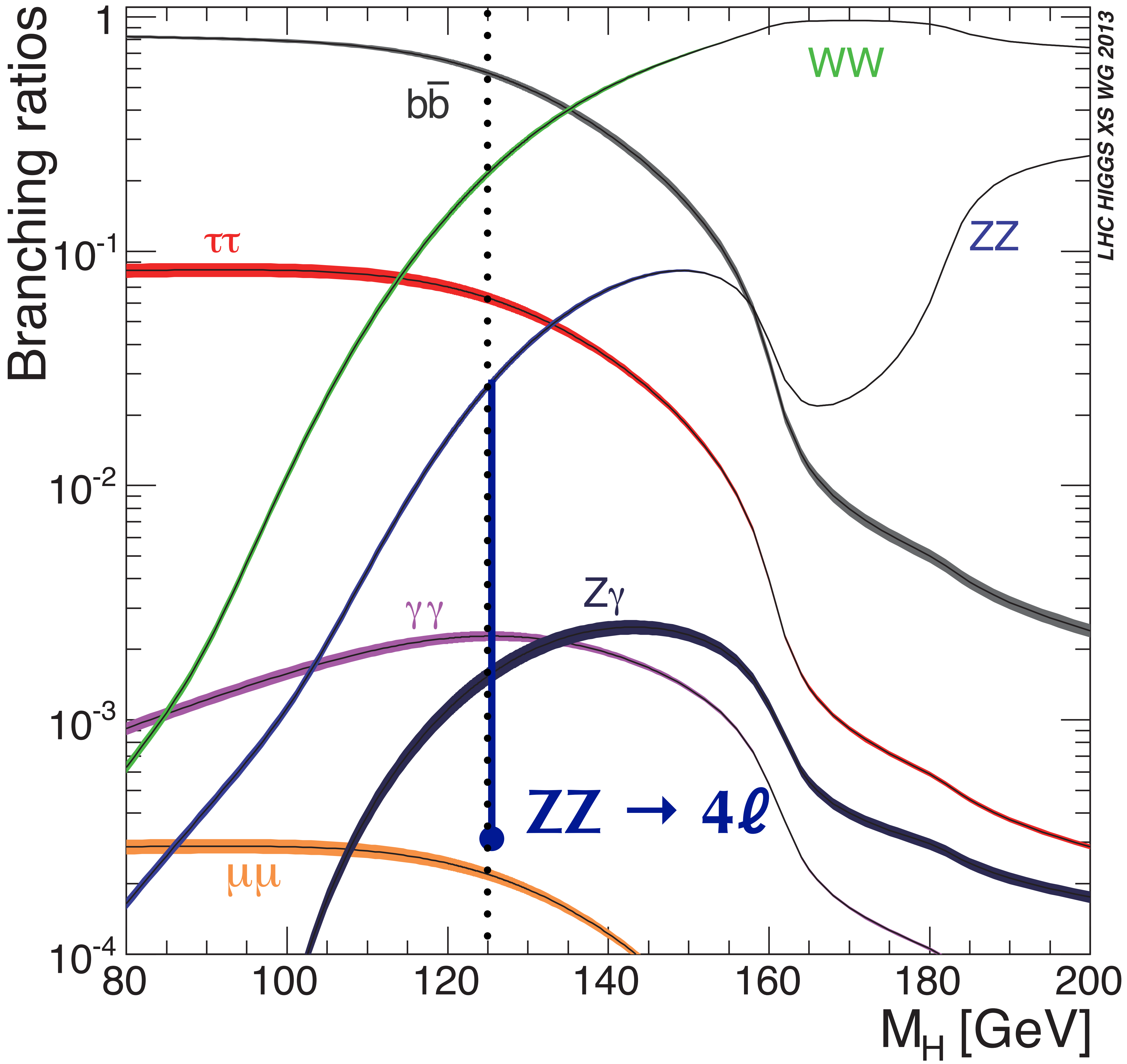
How does it Decay (m_H = 125 GeV) ?



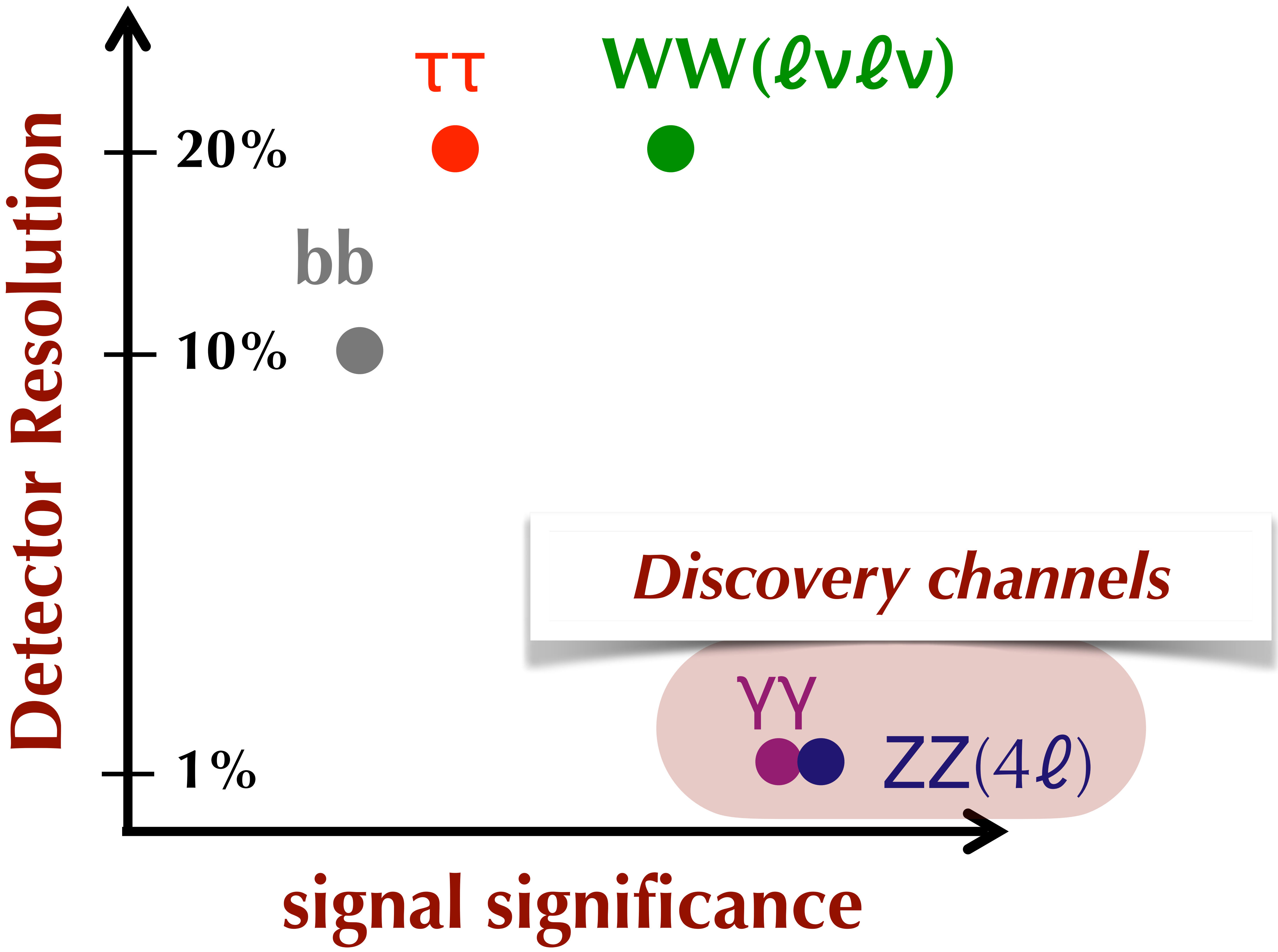
Higgs mass determined from energies and angles of photons

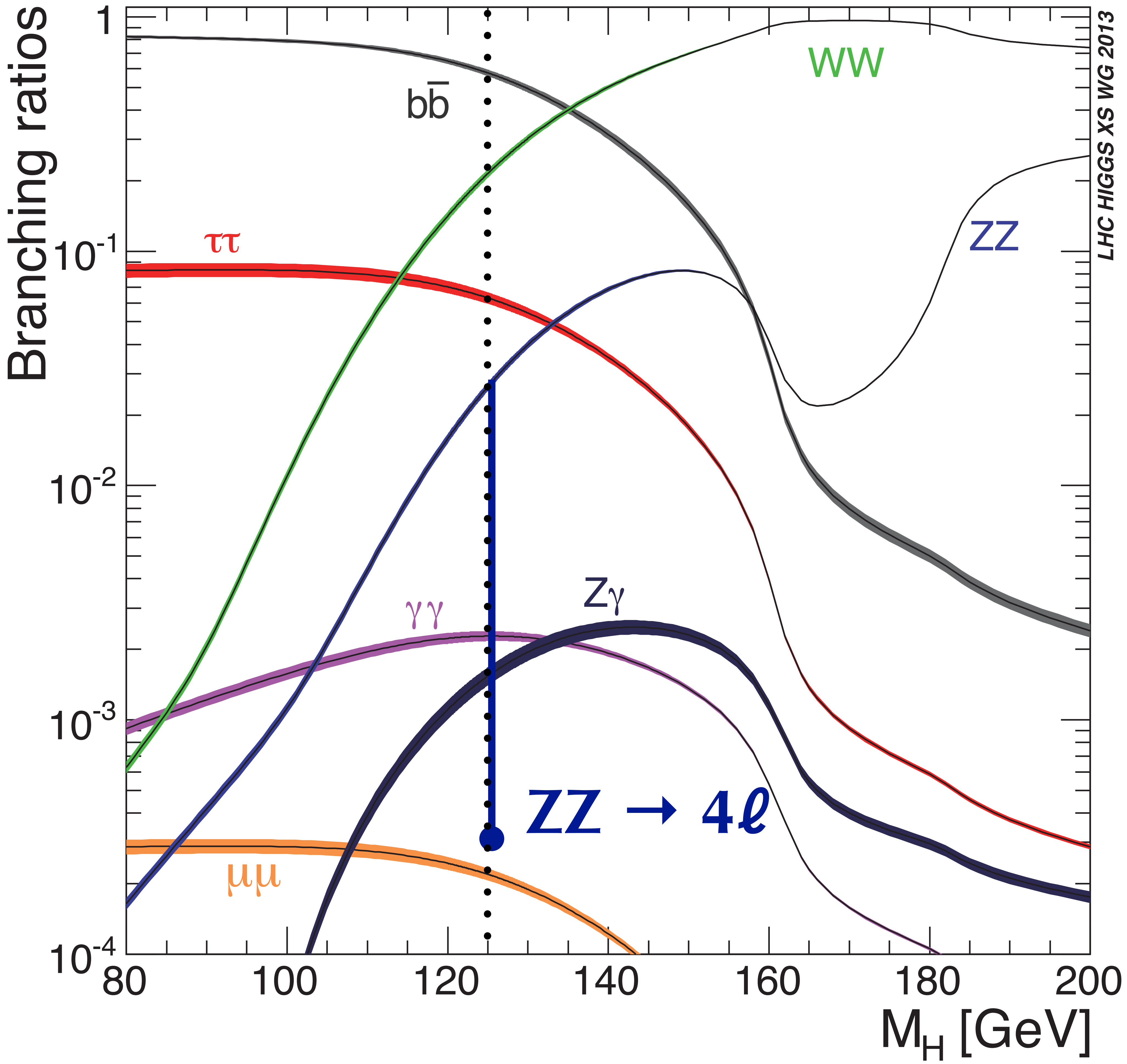






How does it Decay (m_H = 125 GeV) ?





Is it a SM Higgs boson?

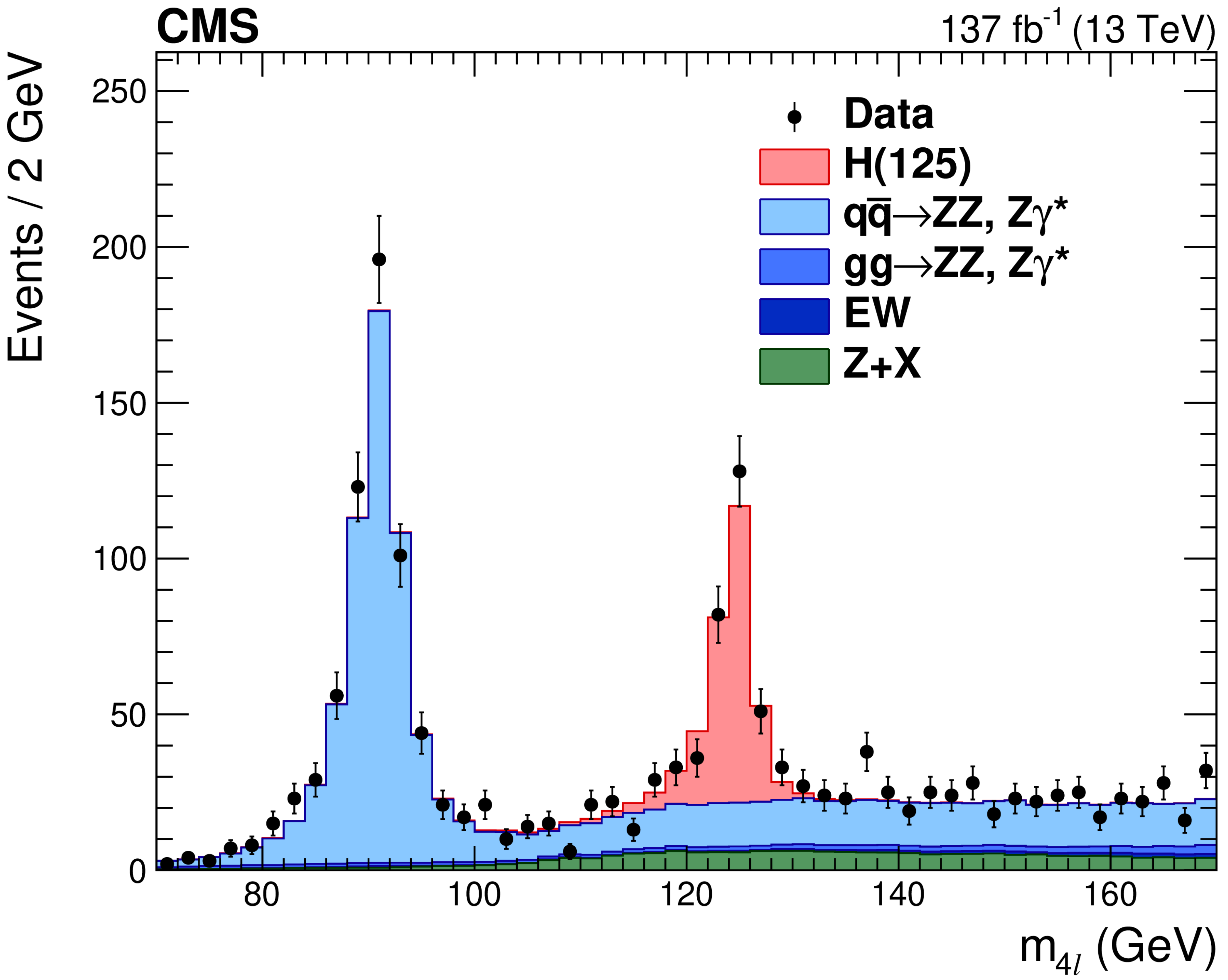
ATLAS-CONF-2020-026
CMS-Eur. Phys. J. C 81 (2021) 488

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

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?

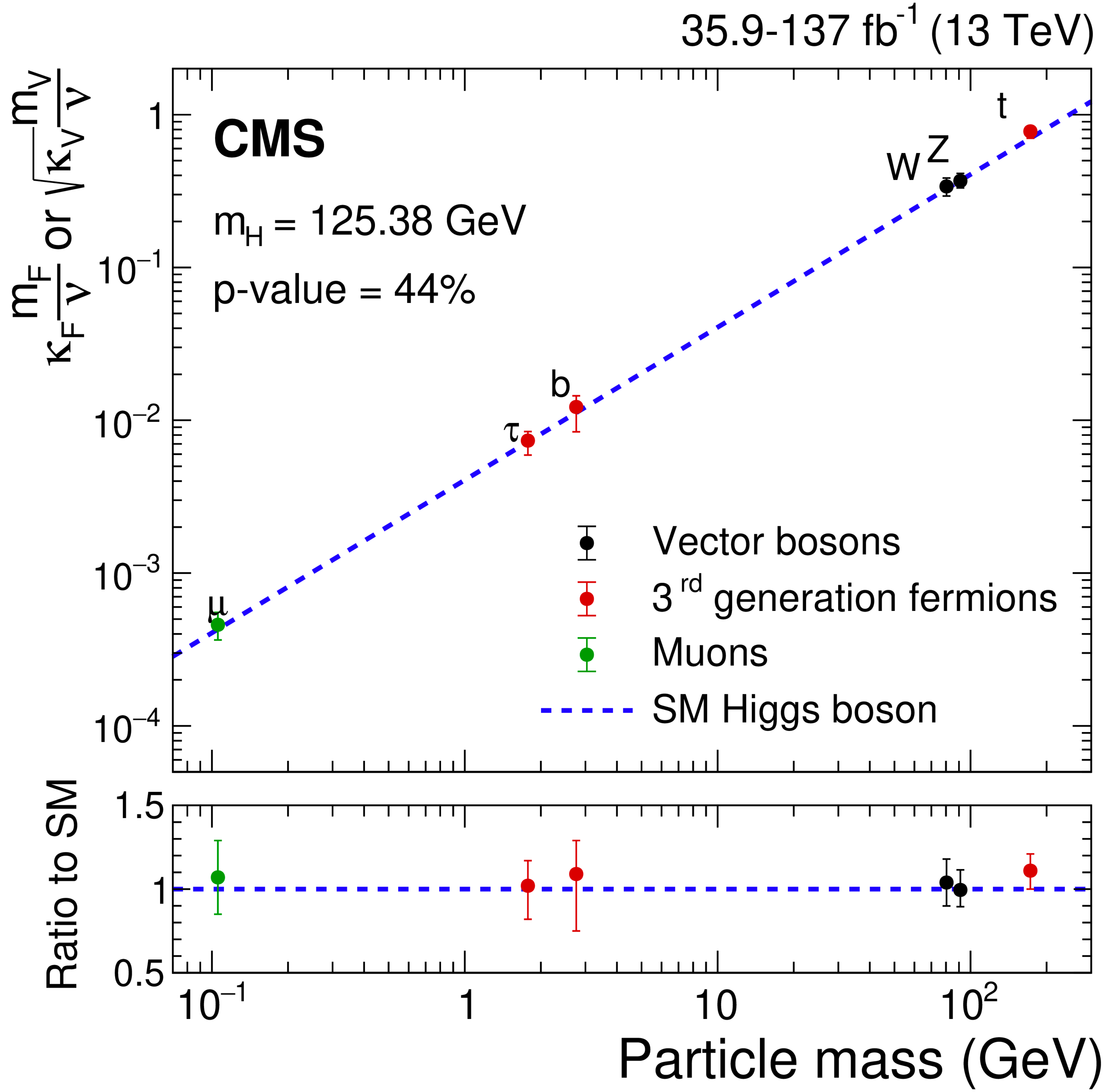


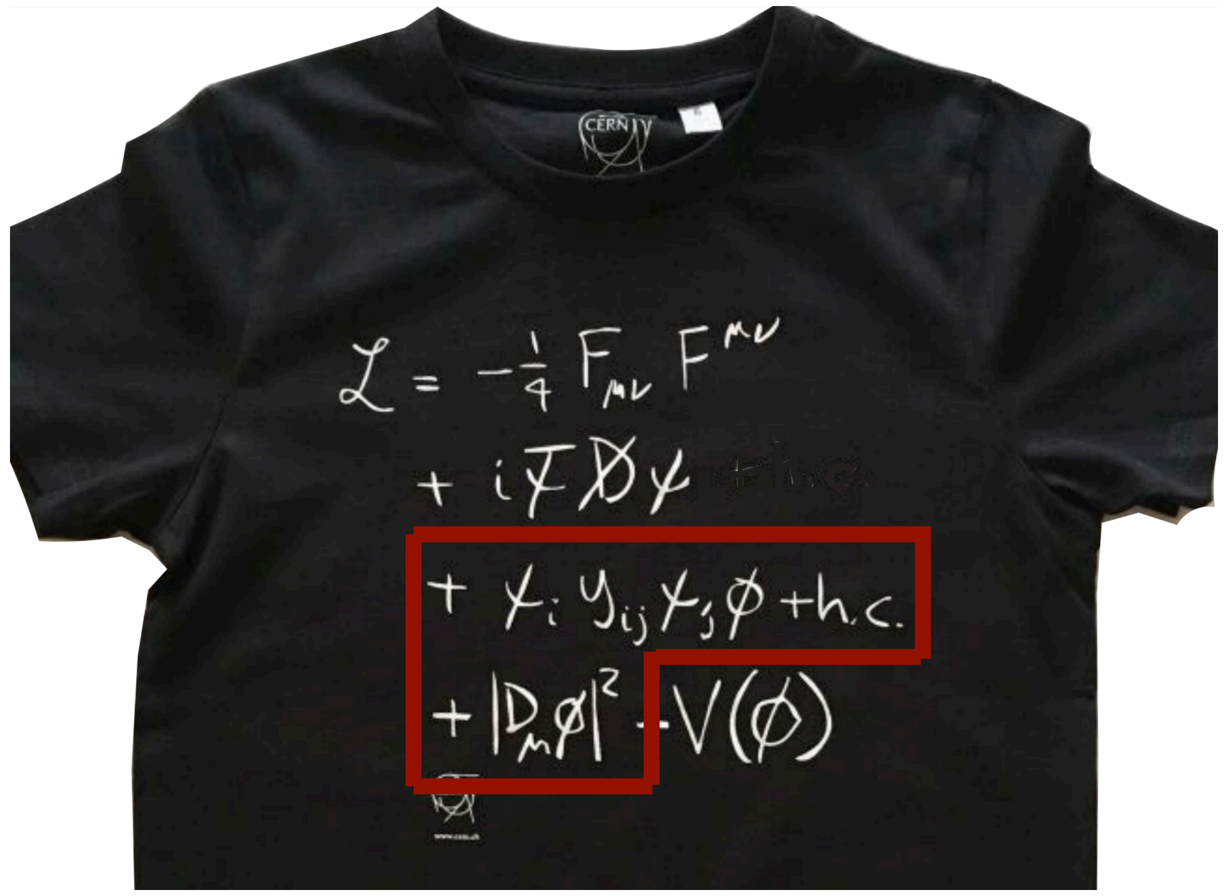
Higgs Boson mass measured with relative uncertainty < 0.2%

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

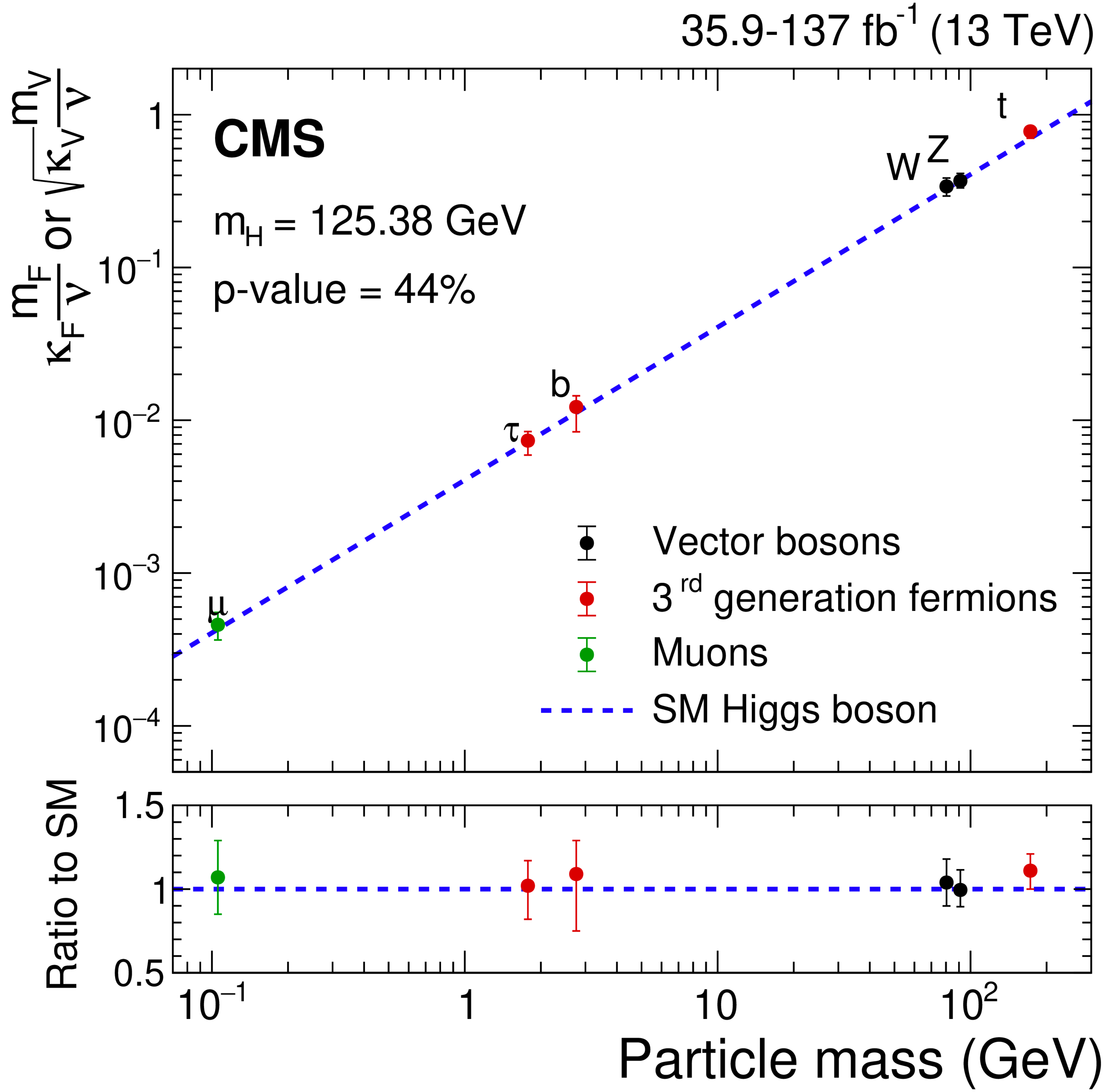
The total calibration uncertainty for **photons** is **0.2%–0.3%**

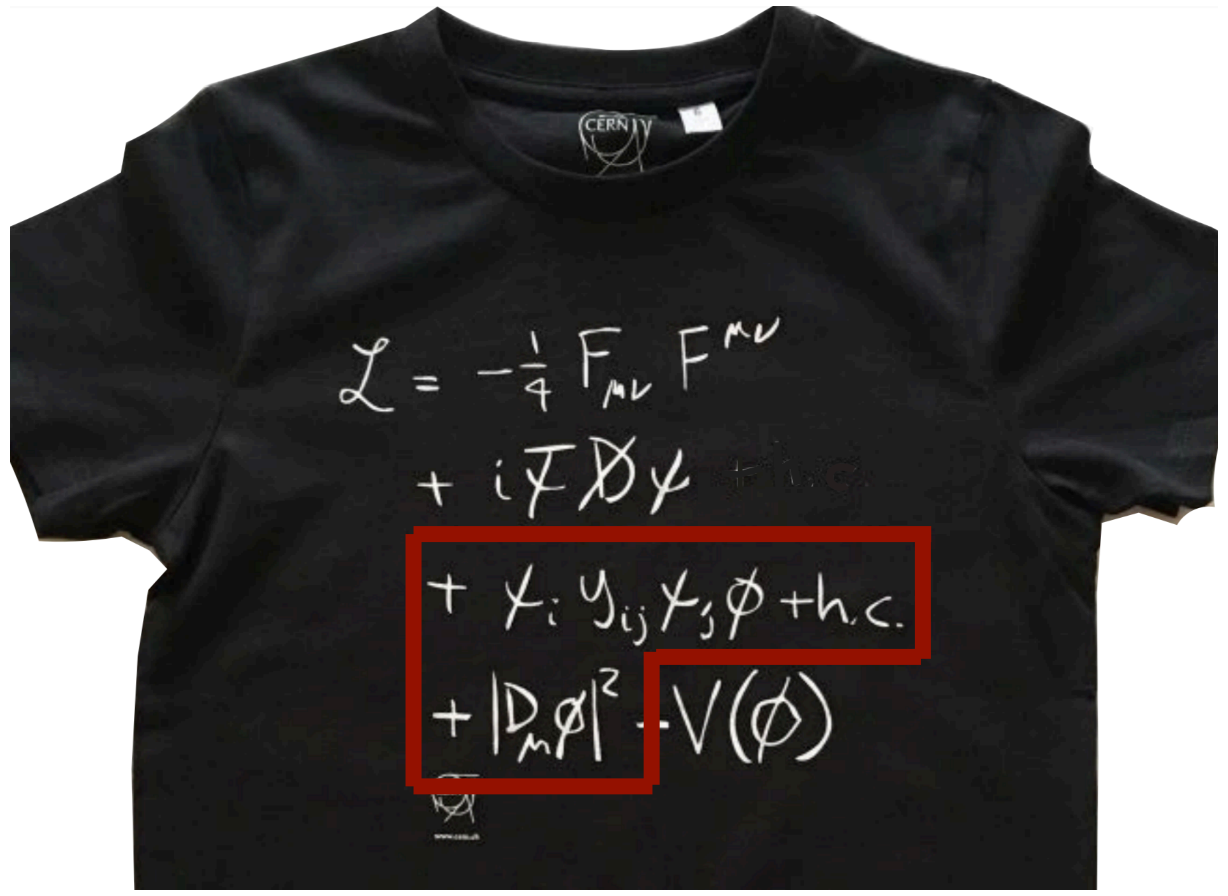
ATLAS-CONF-2019-005
CMS-JHEP 01 (2021) 148





ATLAS-CONF-2019-005
CMS-JHEP 01 (2021) 148

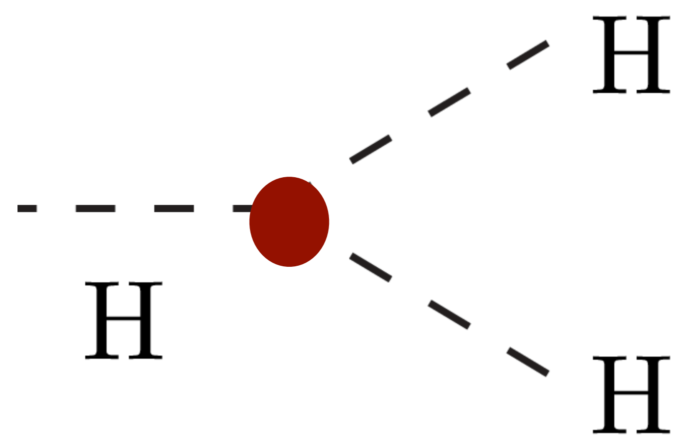




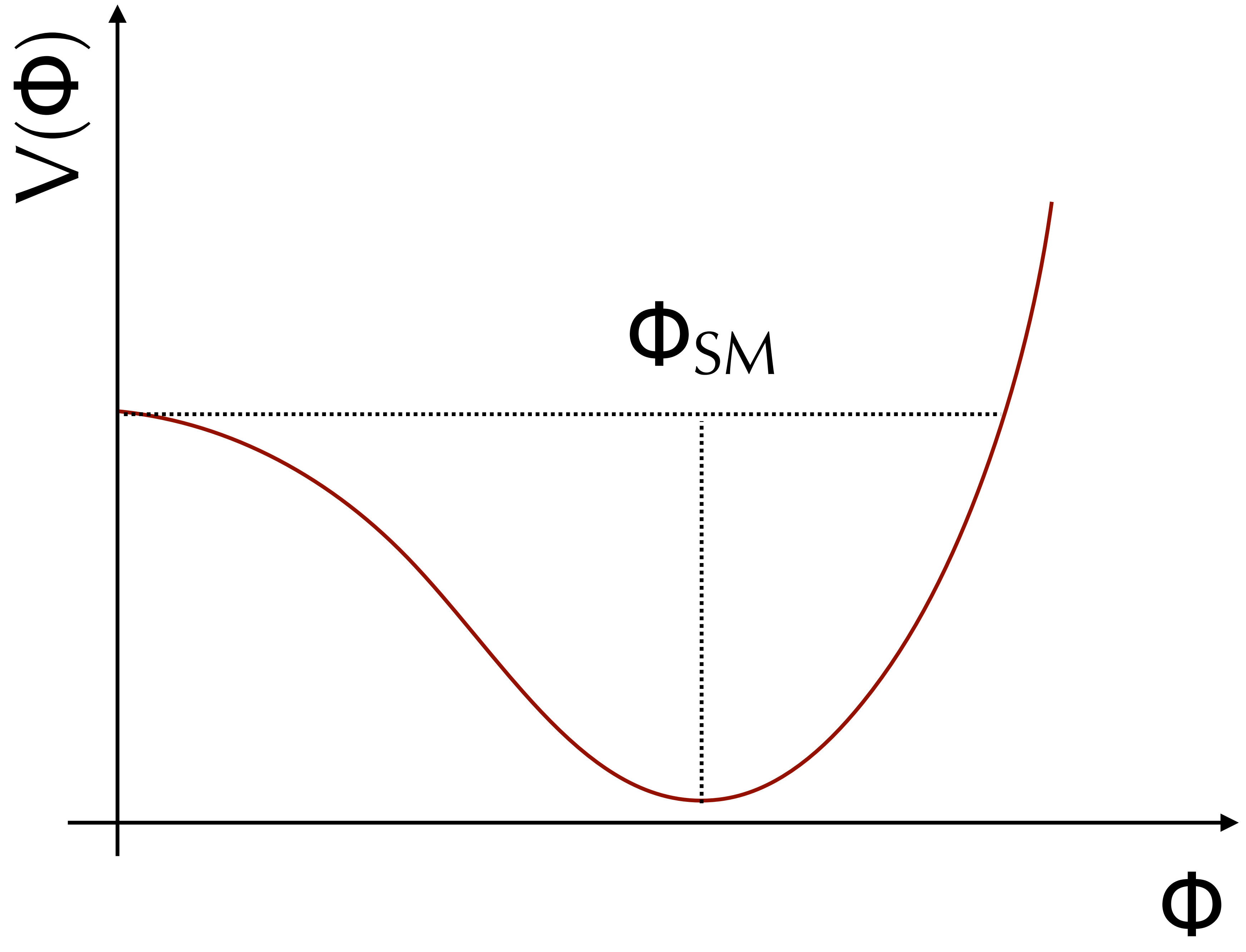
Testing the shape of the potential

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

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



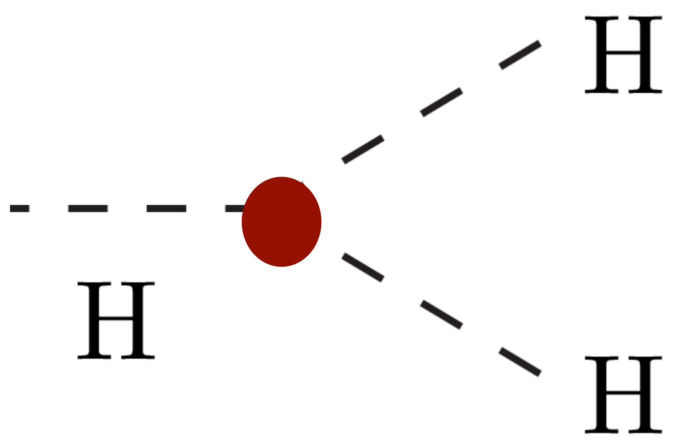
$$\lambda = \frac{m_h^2}{2v^2} = 0.13$$



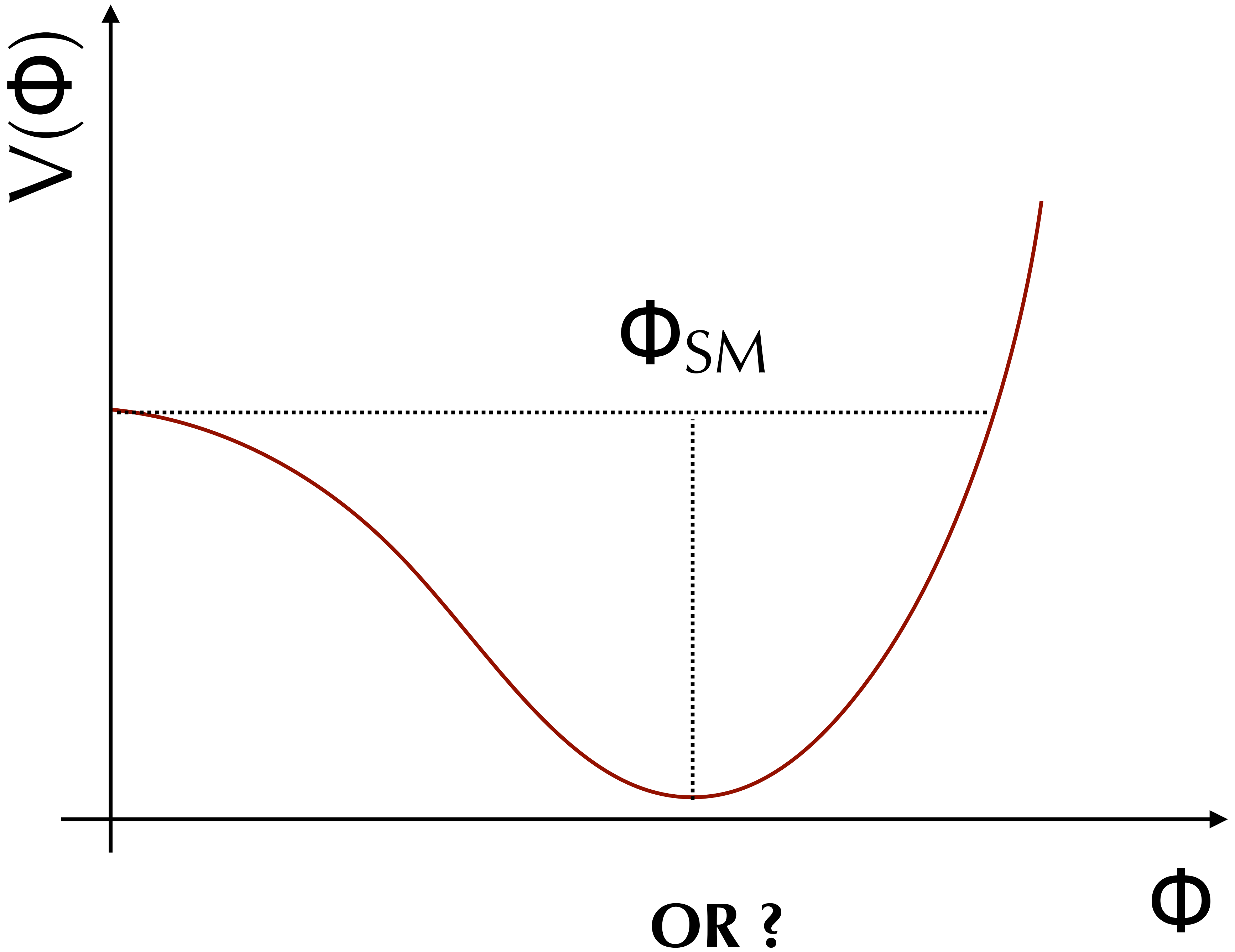
Testing the shape of the potential

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

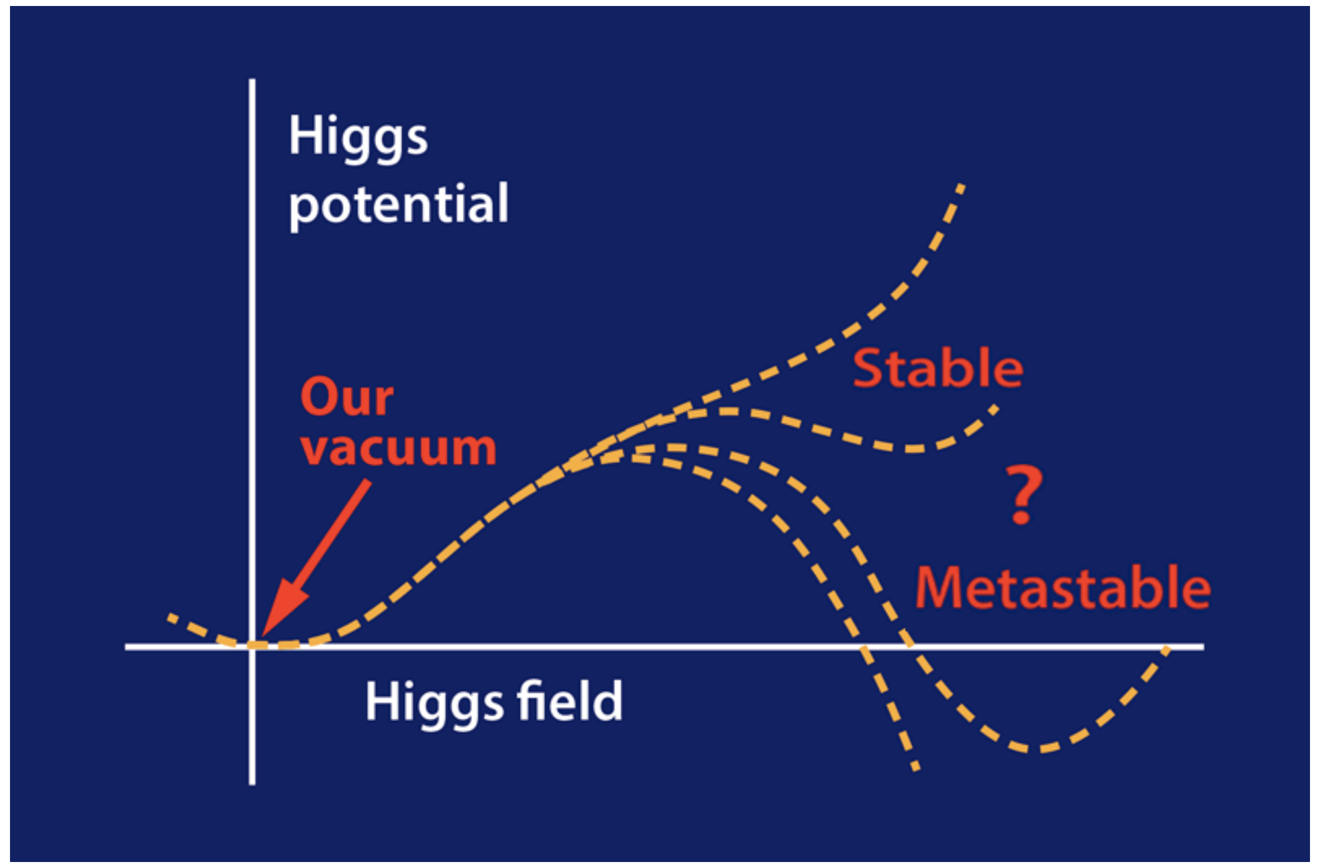
$$V(v+h) = V_0 + \frac{1}{2}m_h^2h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$



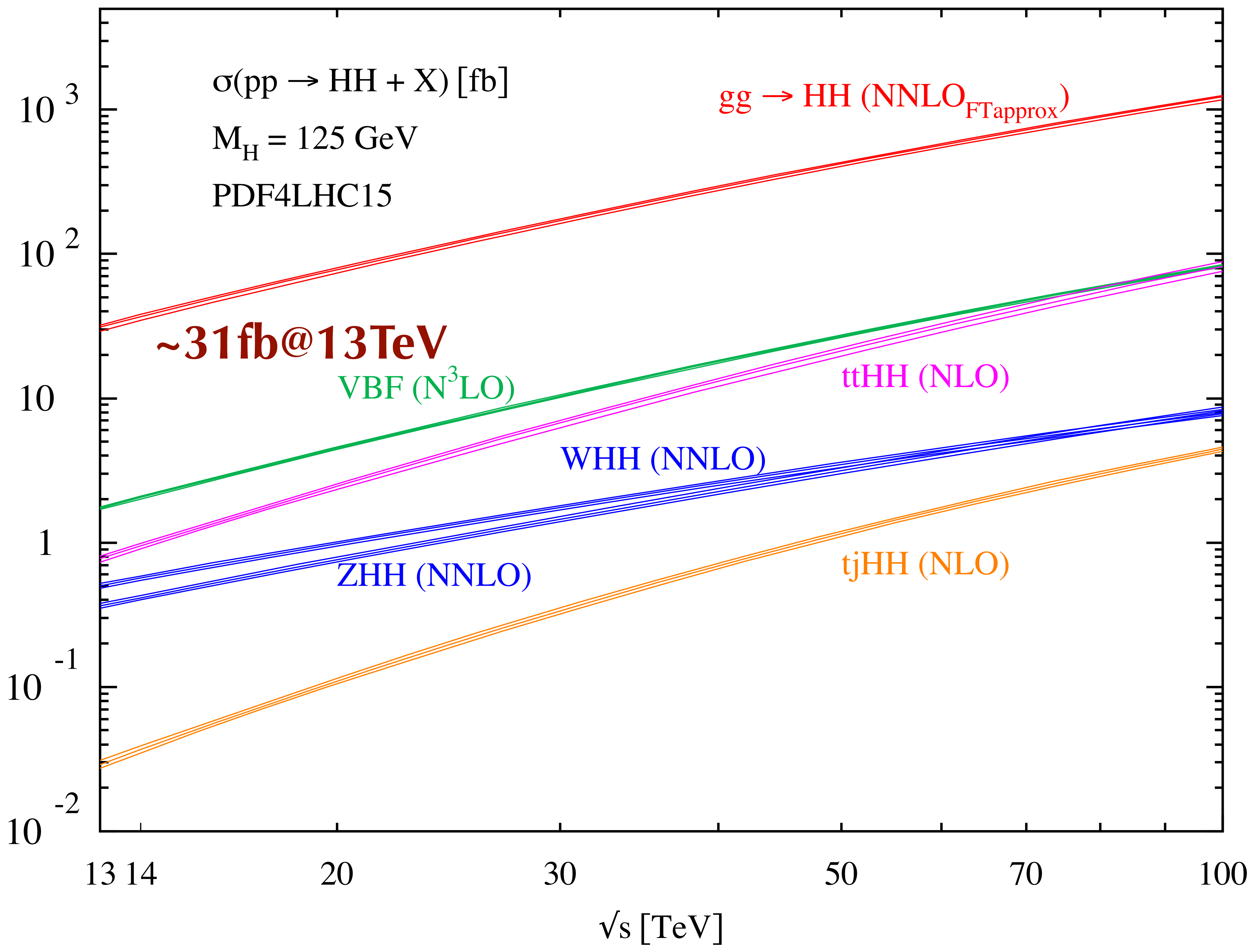
$$\lambda = \frac{m_h^2}{2v^2} = 0.13$$



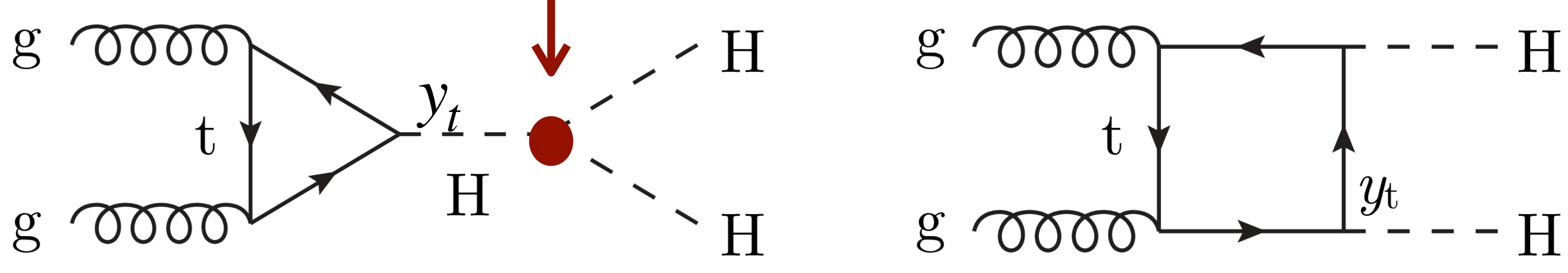
OR ?



Higgs boson self-coupling



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



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

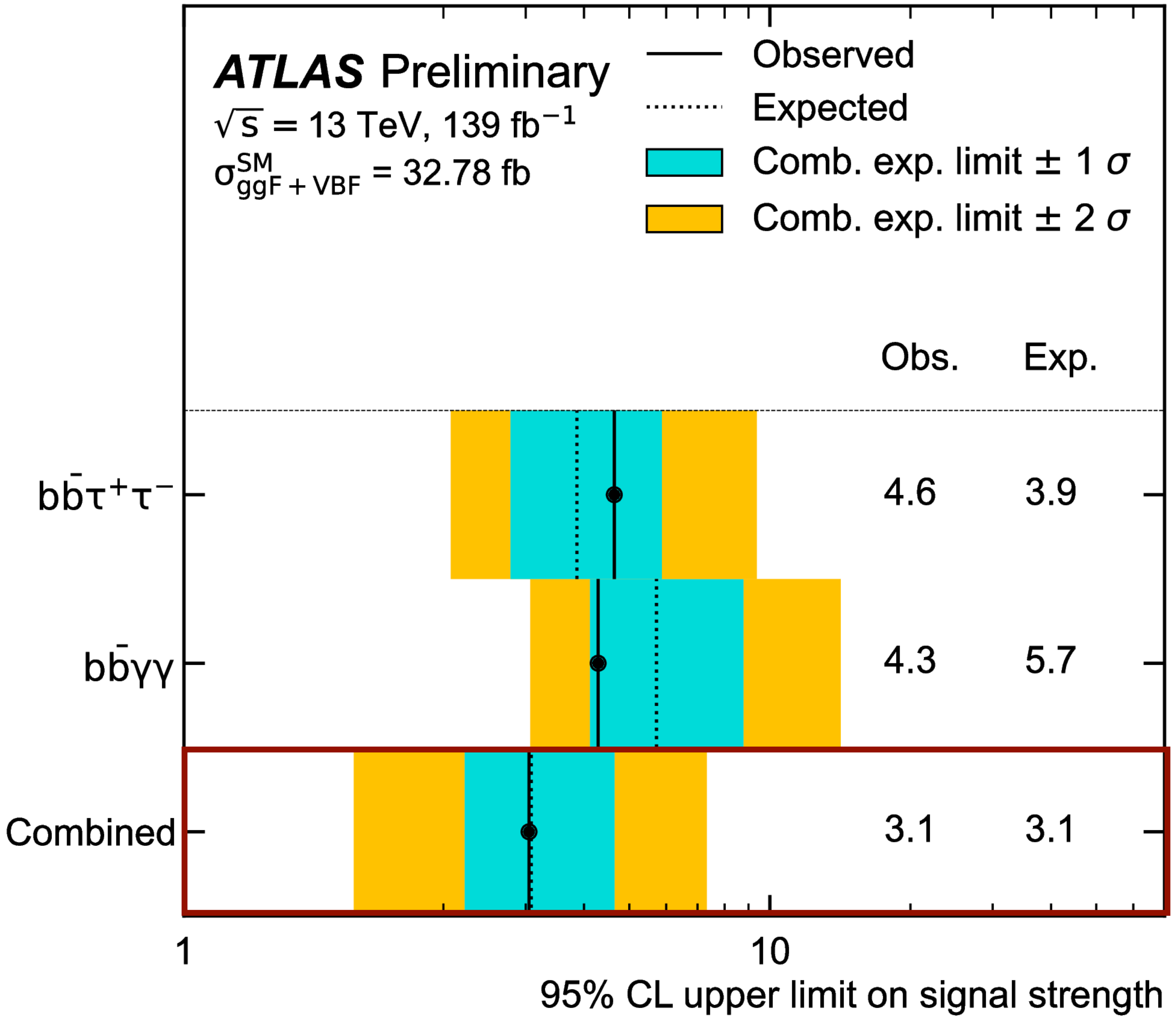
Extremely challenging measurement at the LHC, but **it can be sensitive to large deviations from BSM**: $\kappa_\lambda = \lambda/\lambda_{SM}$

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

Double Higgs Results

Similar sensitivity from several channels to SM HH production

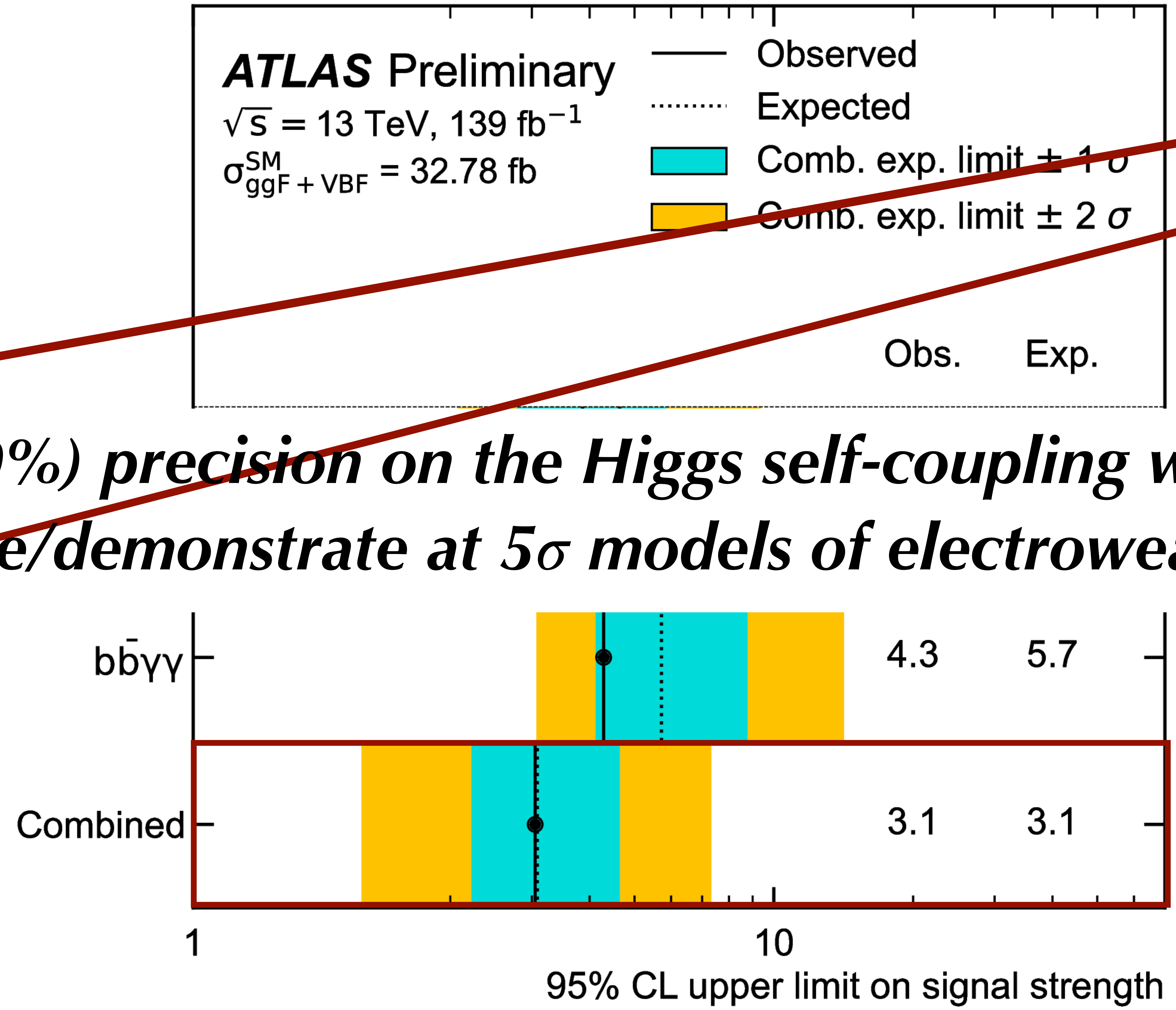
- Best channels are $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$



Double Higgs Results

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

No new particles discovered at the LHC so far…

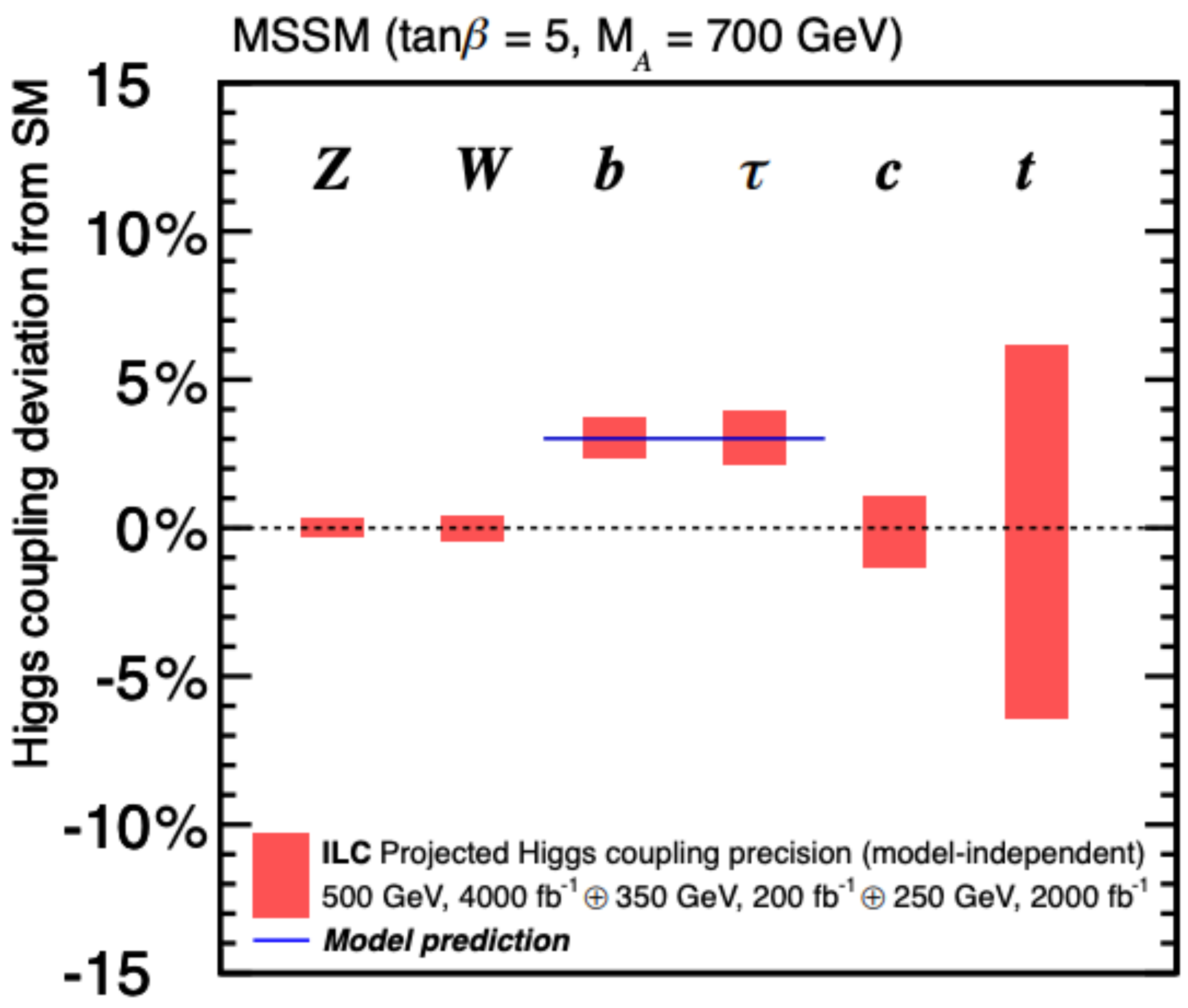
No new particles discovered at the LHC so far…

What's next?

How can we use the Higgs to find new physics?

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

SLAC

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

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

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

Higs couplings: precision & kinematic

arXiv:1310.8361

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

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

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

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})

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

Higgs couplings: precision & kinematic

SLAC

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

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

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

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})

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

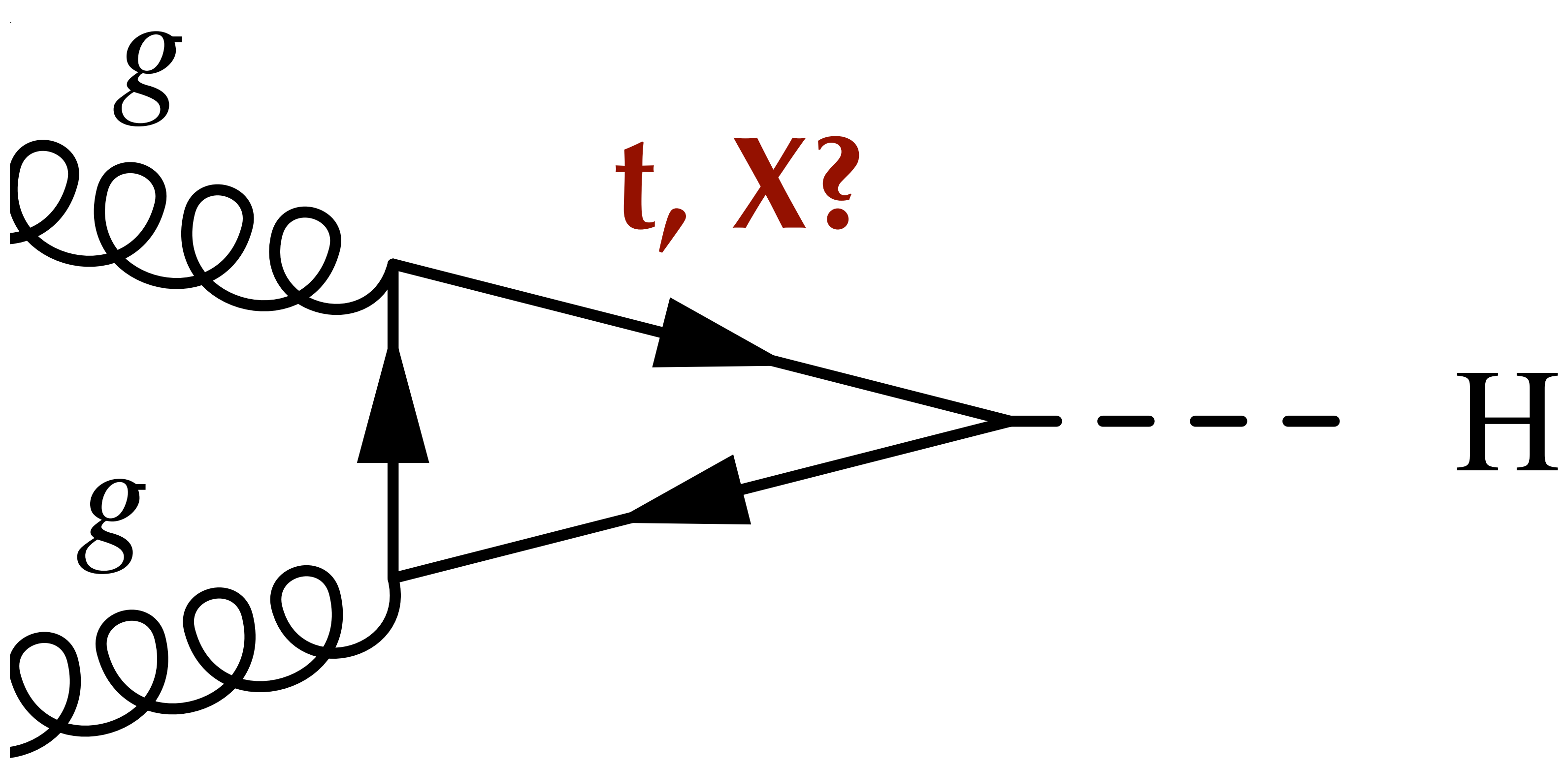
Measurements at **large transferred momentum** (Q) probe large M even if precision is low

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

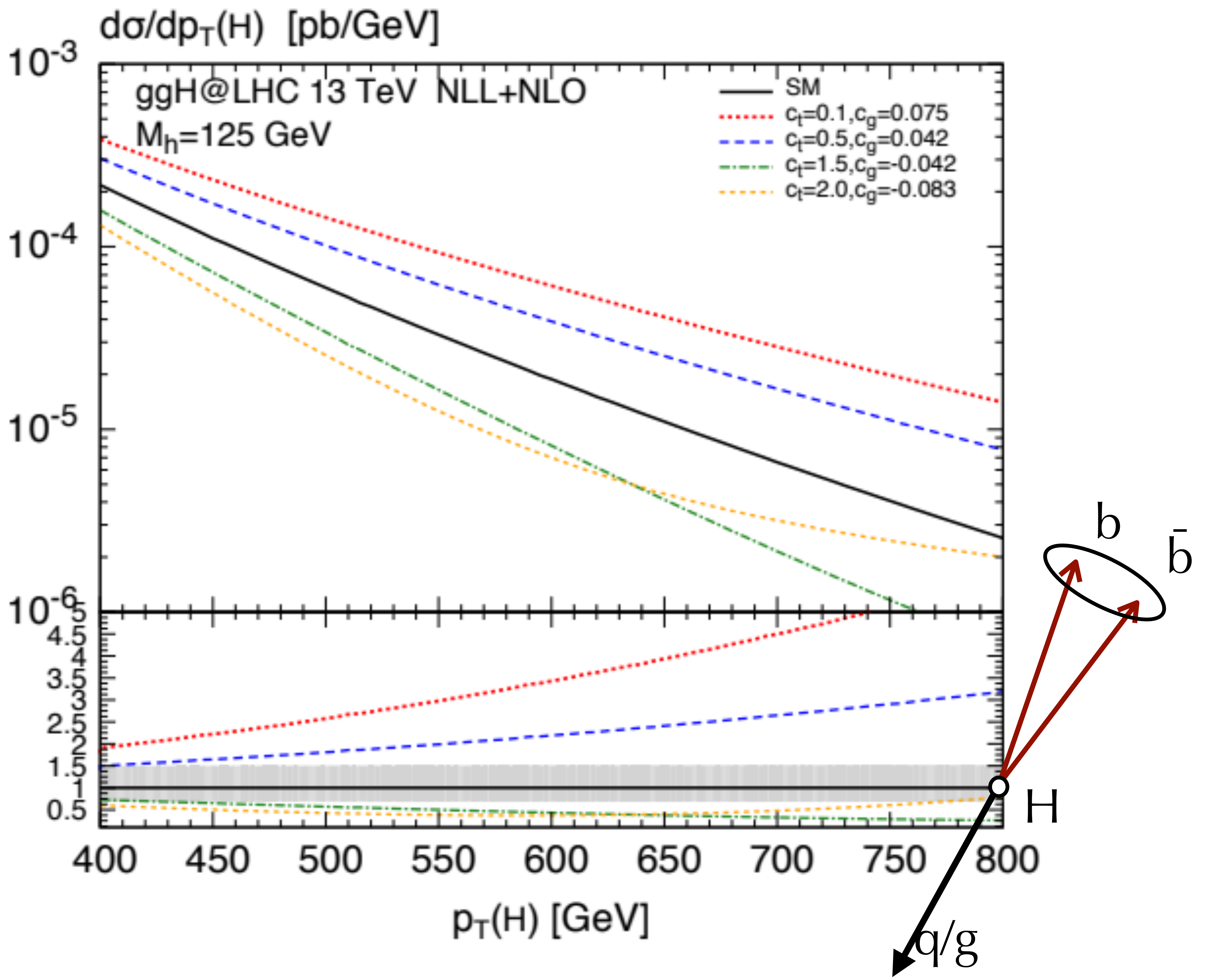
15% effect on δO_Q for M ~ 2.5 TeV

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



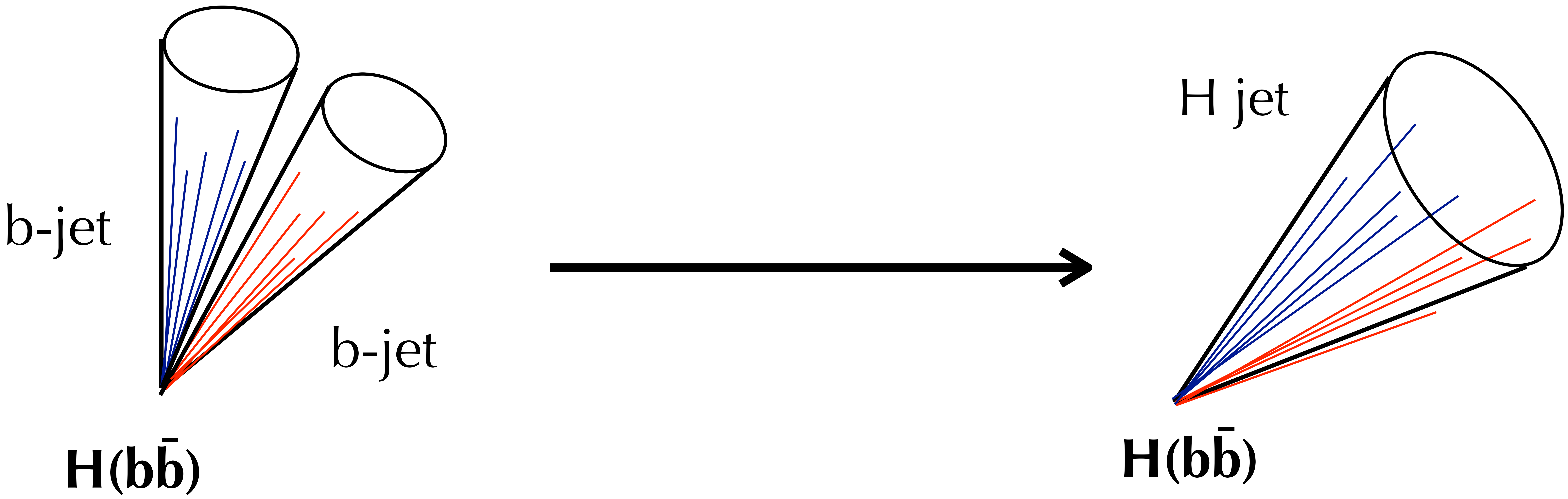
Gluon fusion H to $b\bar{b}$ at high p_T

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***



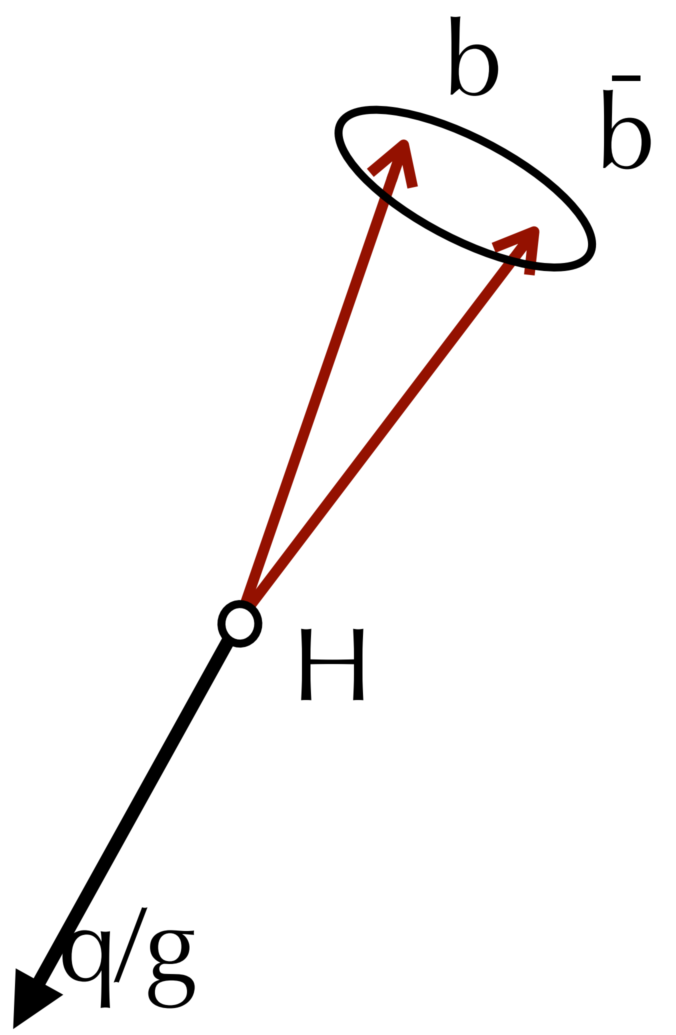
Gluon fusion H to $b\bar{b}$ at high p_T

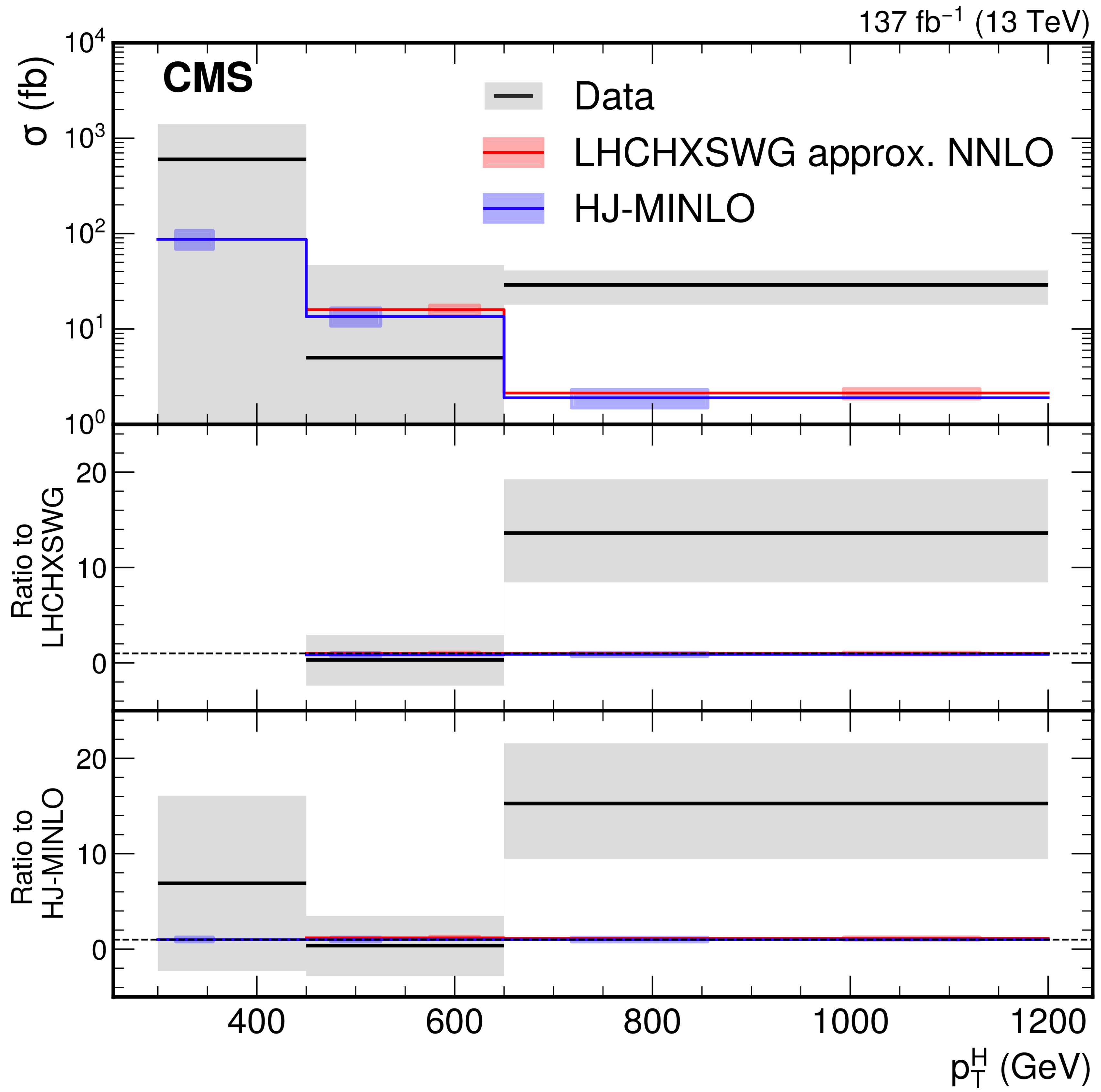
ATLAS-CONF-2021-010
CMS-JHEP 12 (2020) 085

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***

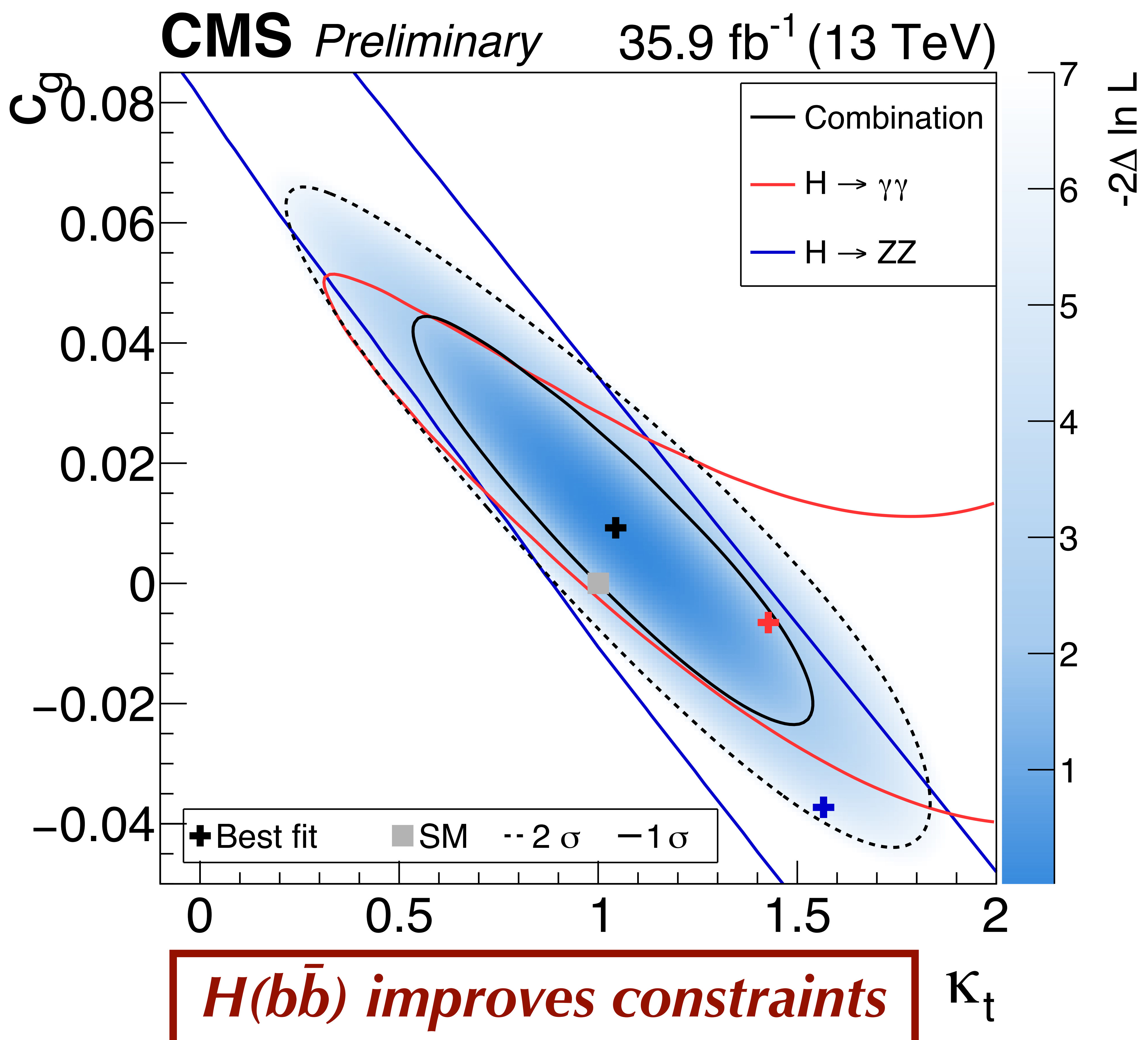


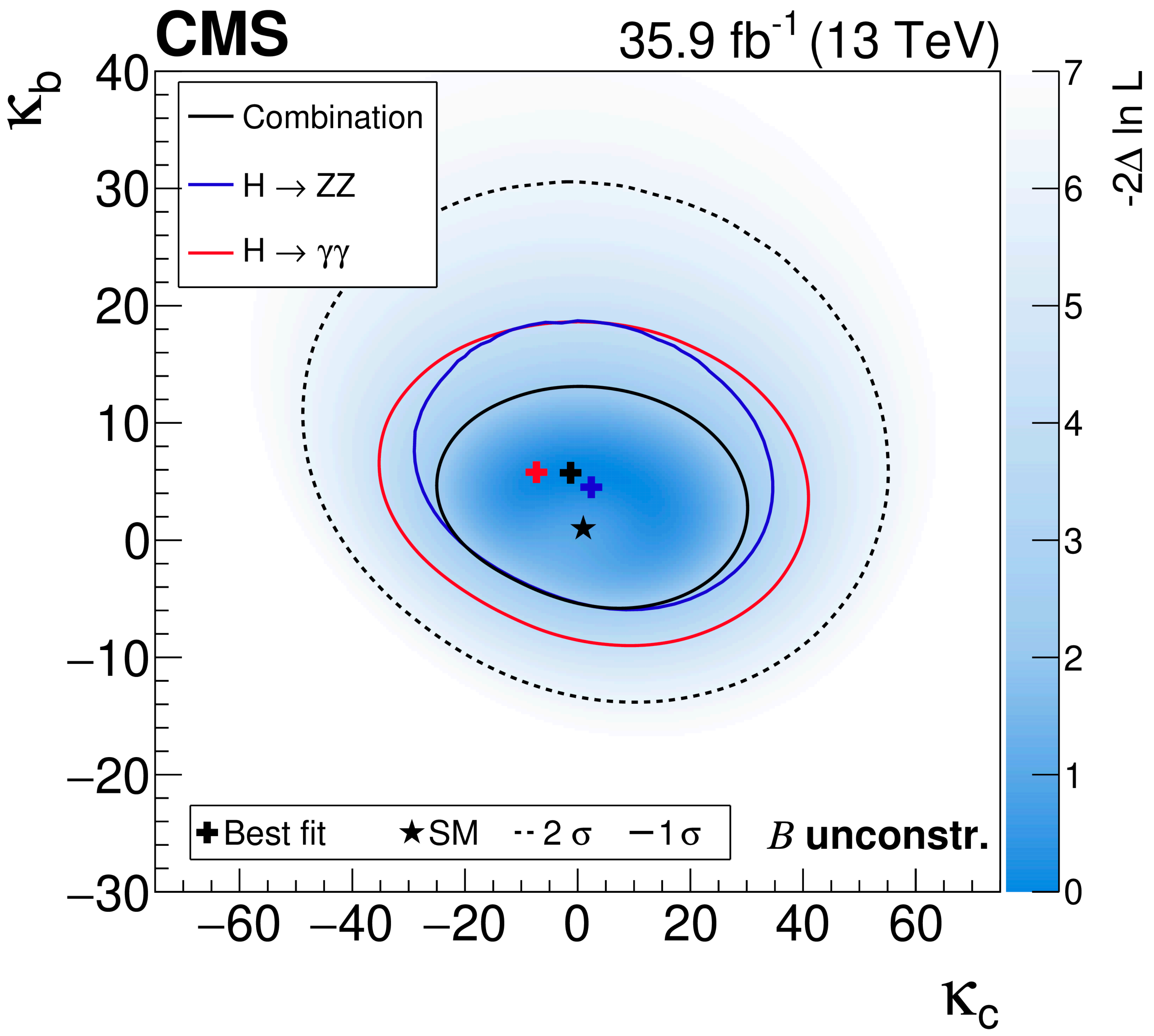


CMS-Phys. Lett. B 792 (2019) 369

Constraints on the couplings

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



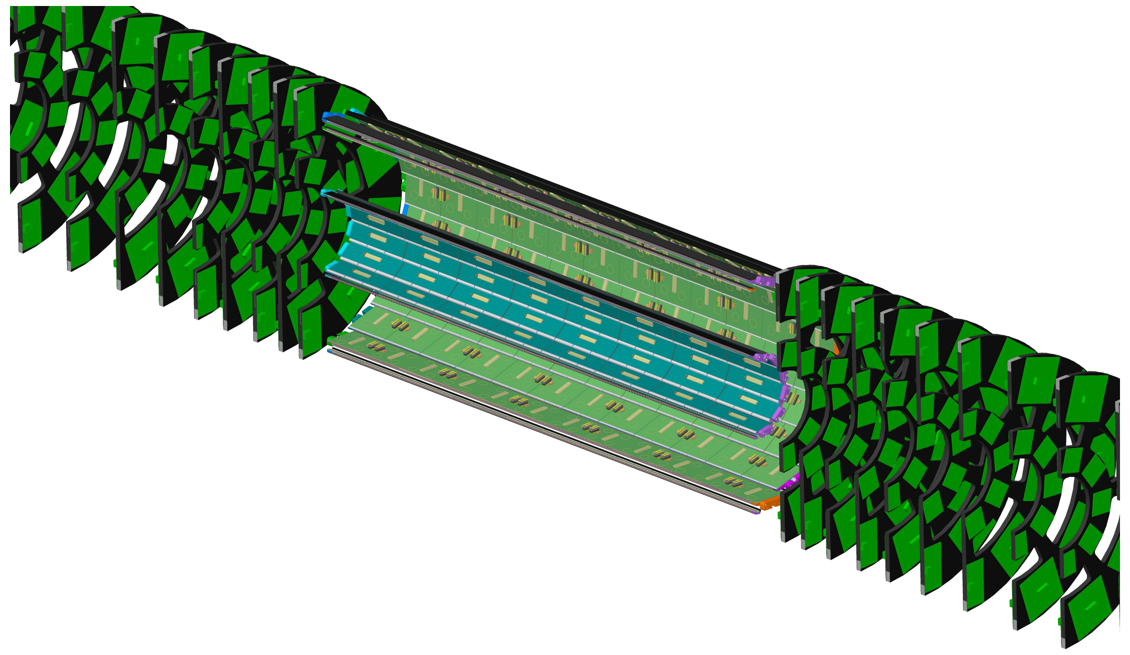


H($b\bar{b}$) improves constraints to new physics by 30%

LHC → High Luminosity LHC

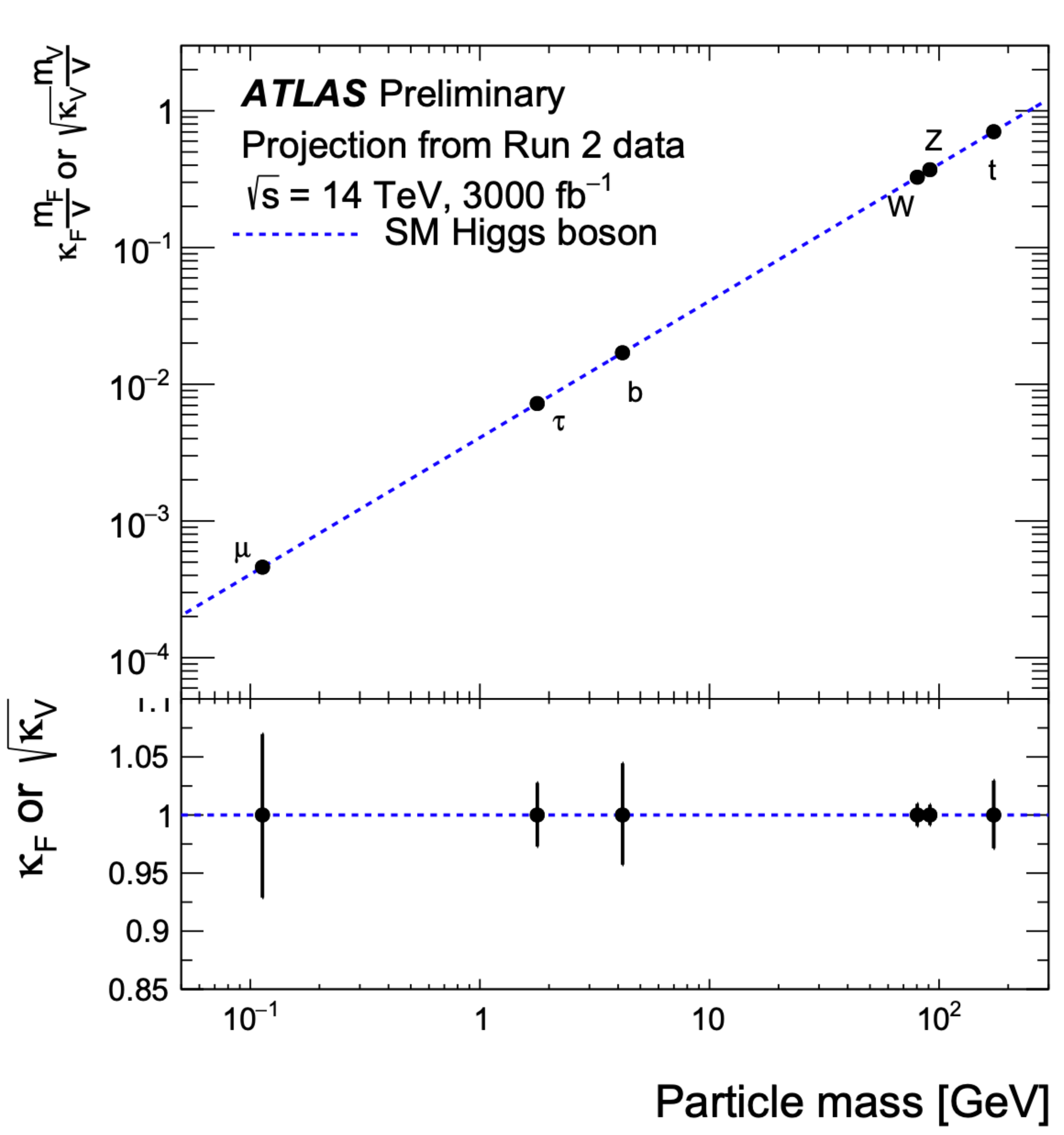
LHC							HL-LHC			
Run 2 8M H	Upgrade of accelerator and experiments			Run 3 16M H			HL-LHC installation ATLAS Upgrade			Run 4 170M H 120k HH
2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	. . . 2037

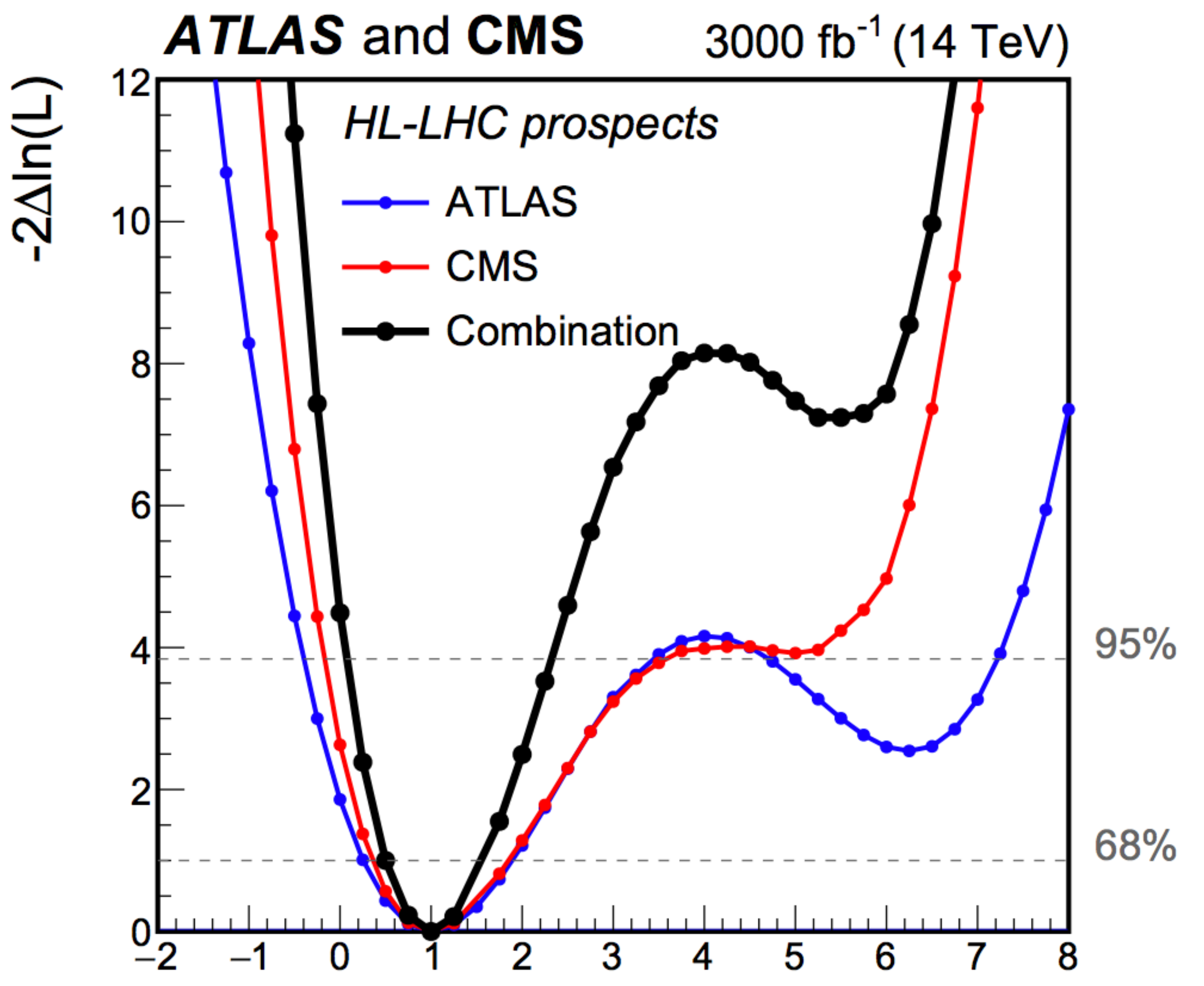
Today



Phase-2 HL-LHC detector upgrades are being built

Higgs physics at the HL-LHC



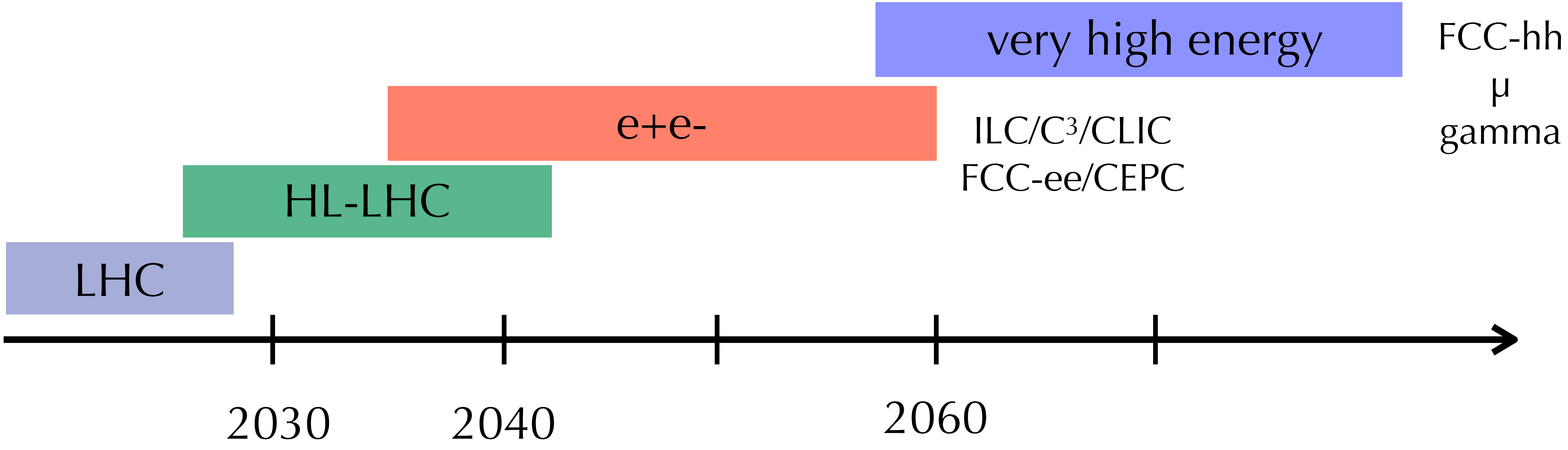


$k_\lambda = \frac{\lambda}{\lambda_{SM}}$

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 $Z\gamma$ and charm and ~50% on the self-coupling**

What's next?

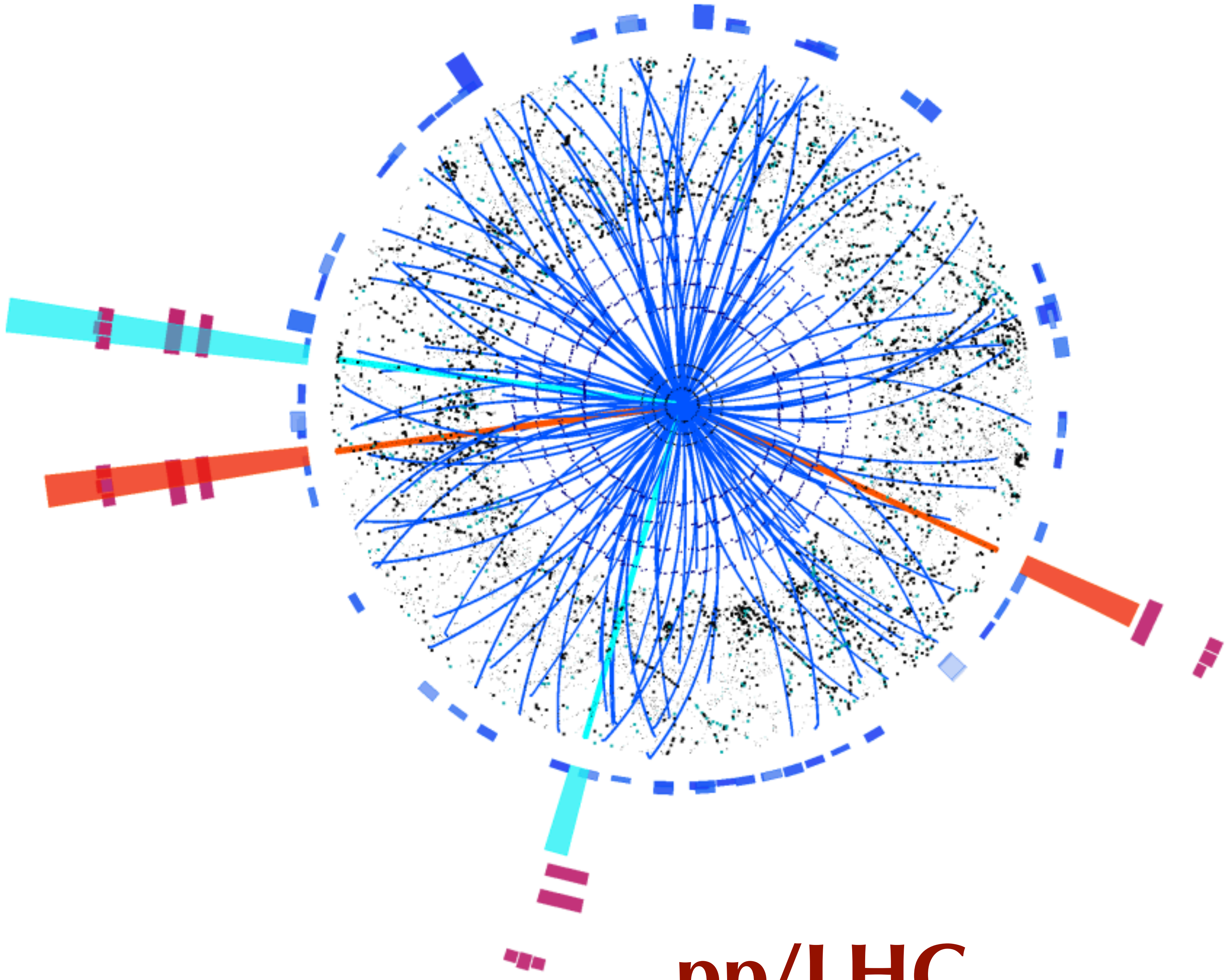


Wish list beyond HL-LHC:

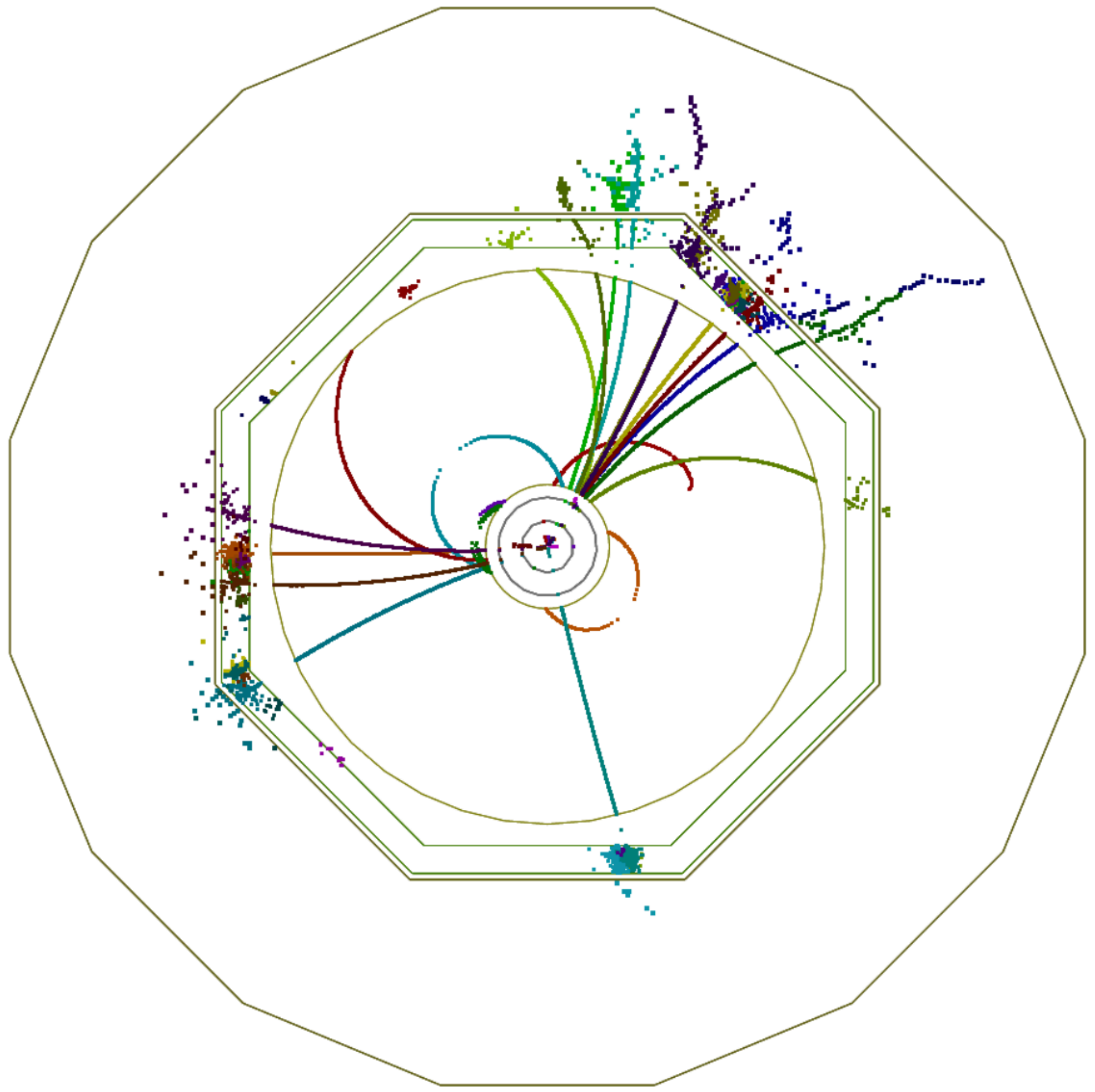
1. **Establish Yukawa couplings to light flavor $\Longrightarrow$ needs precision**
2. **Establish self-coupling $\Longrightarrow$ needs high energy**

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

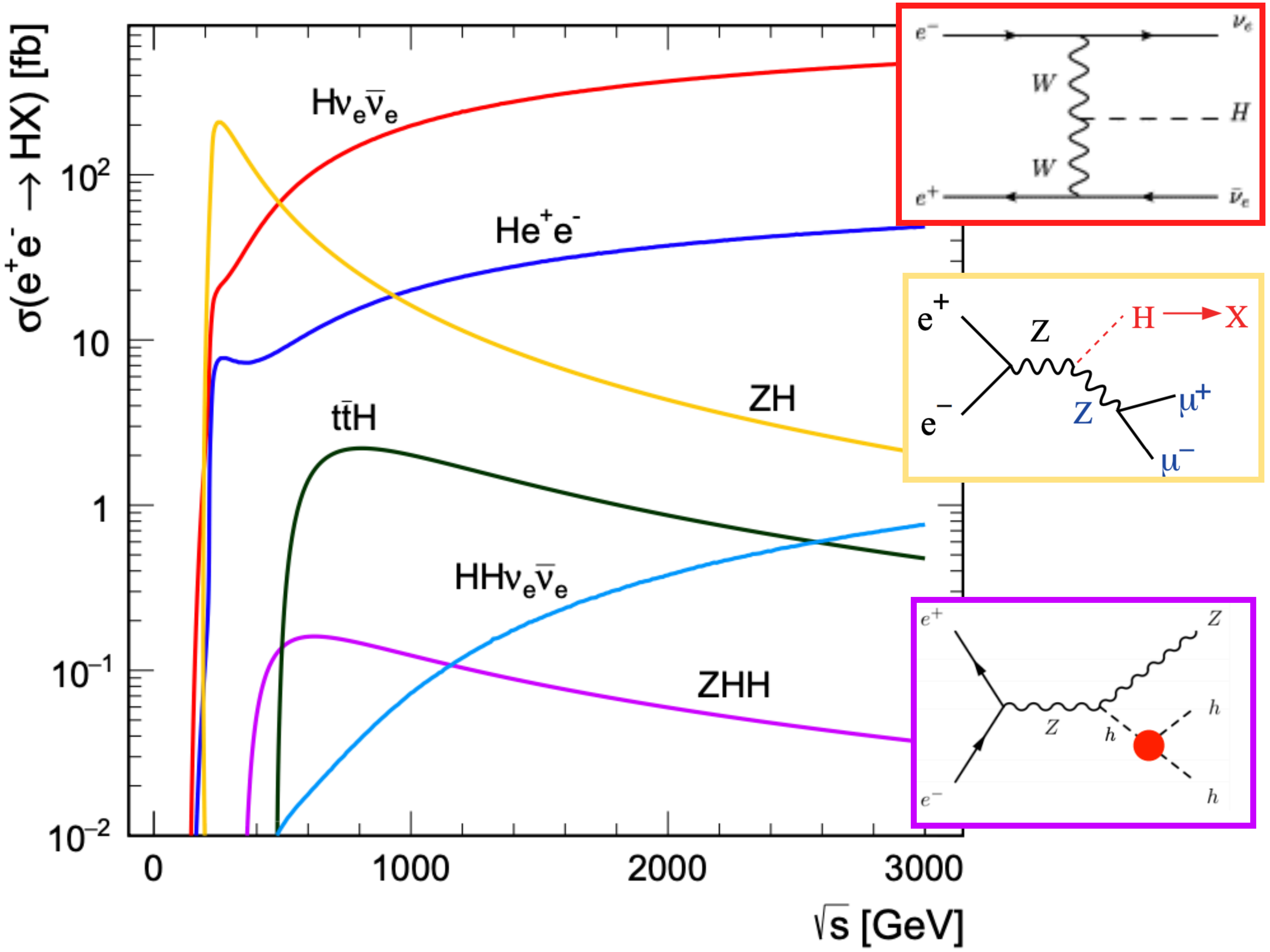


pp/LHC



e^+e^-

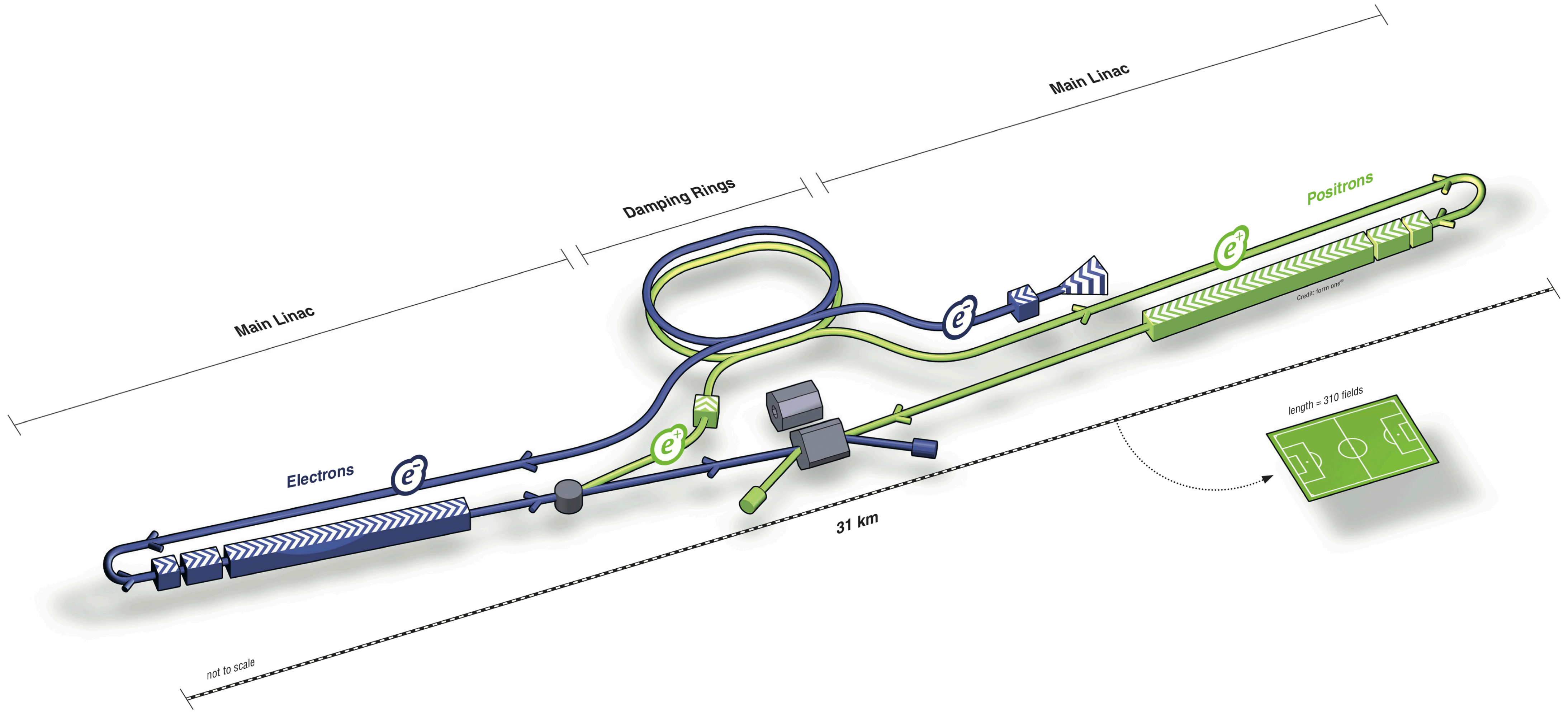
Higgs at e+e-

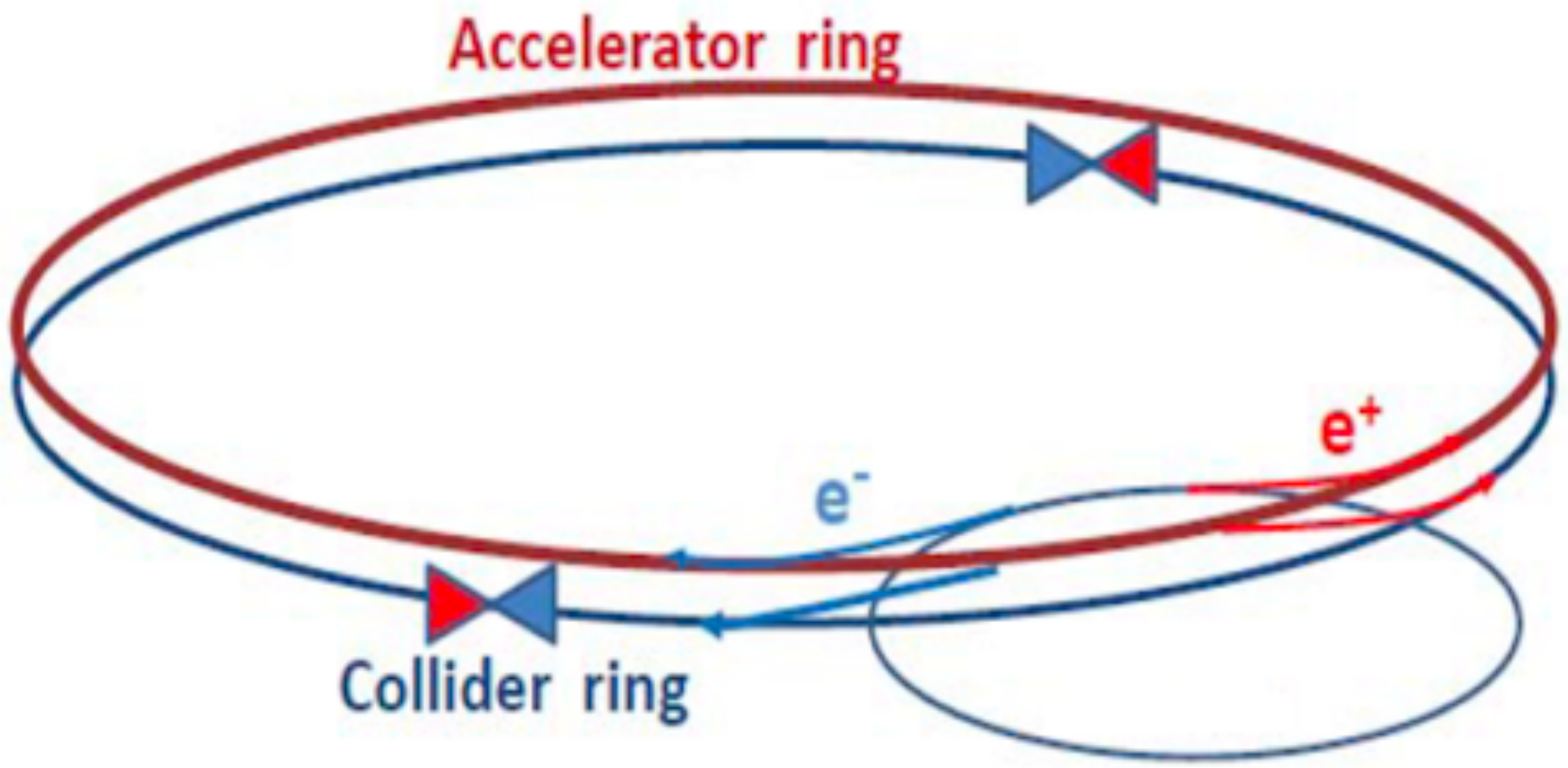


- ZH is dominant at **250 GeV**
- Above **500 GeV**
  - Hvv dominates
  - ttH opens up
  - HH production accessible with ZHH

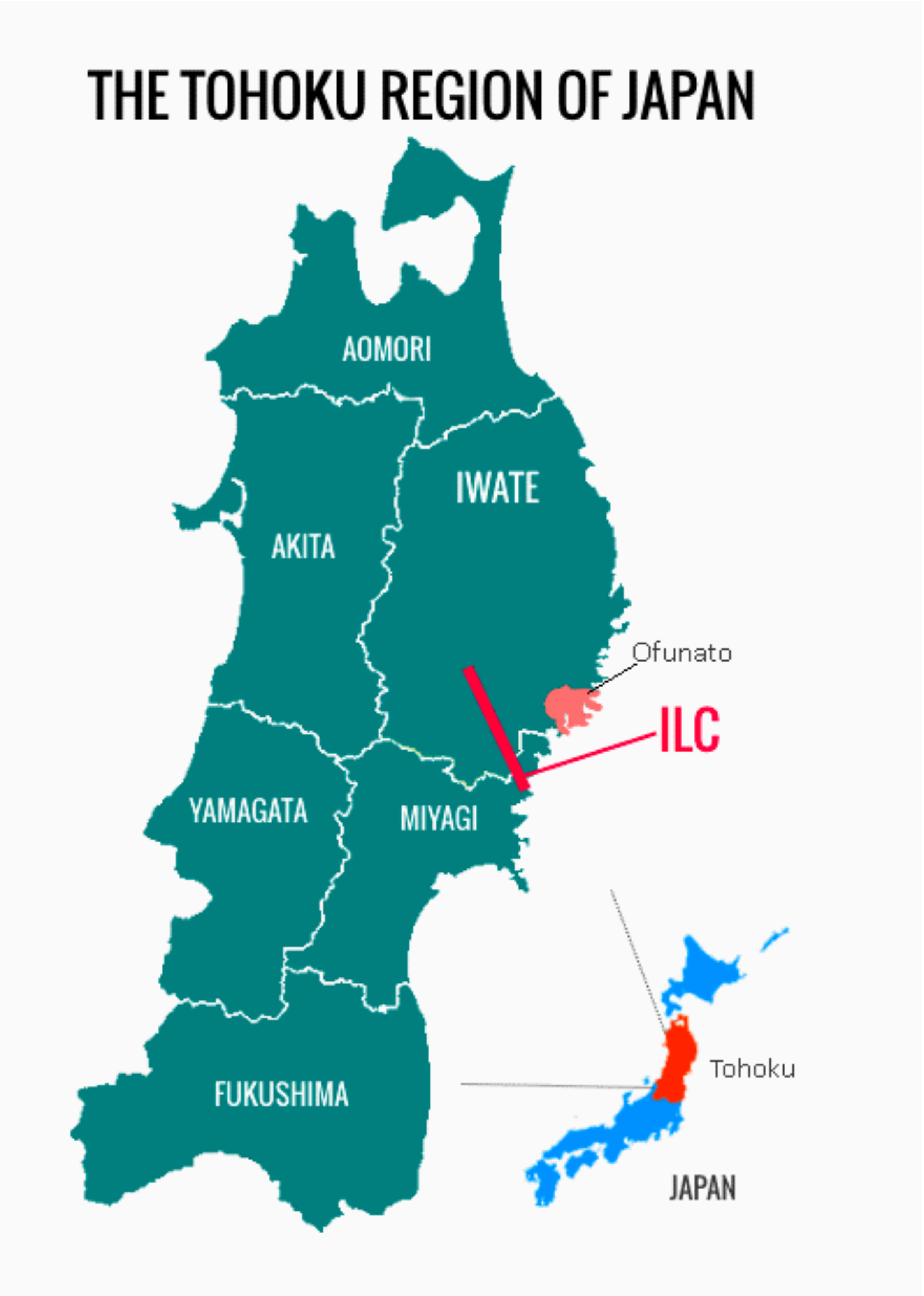
Linear vs. Circular

- **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

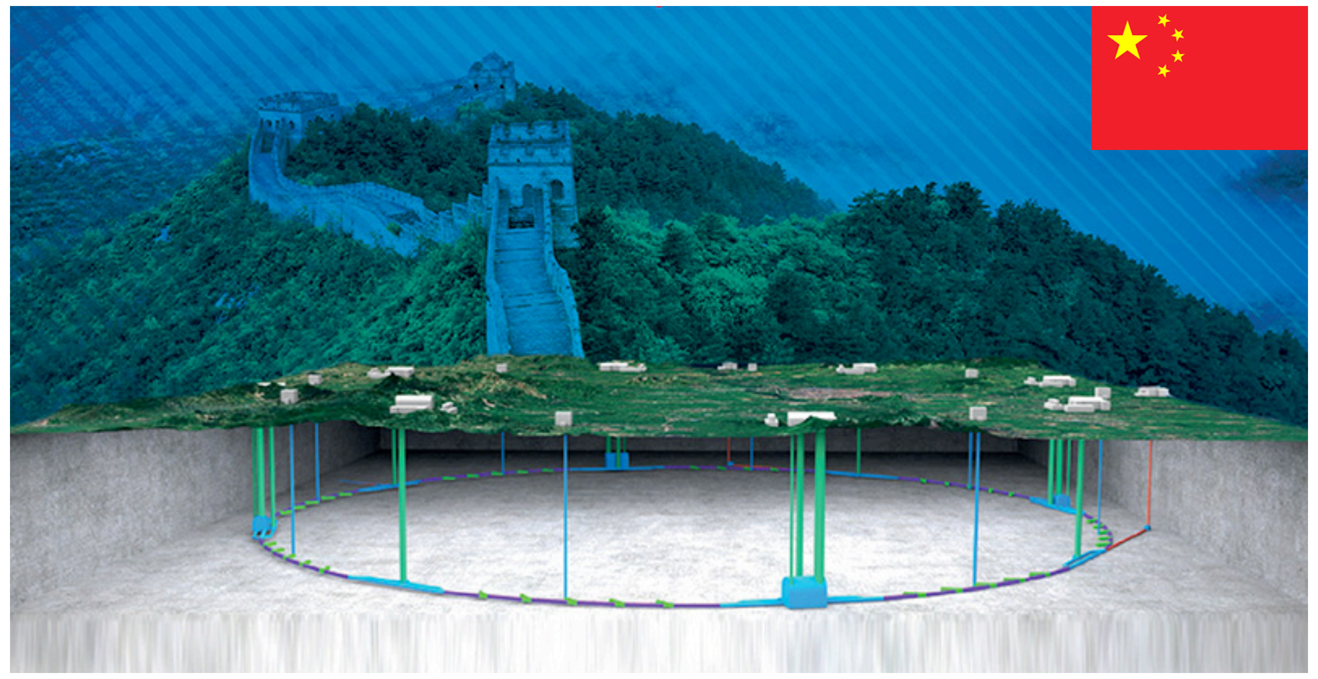




Various proposals …

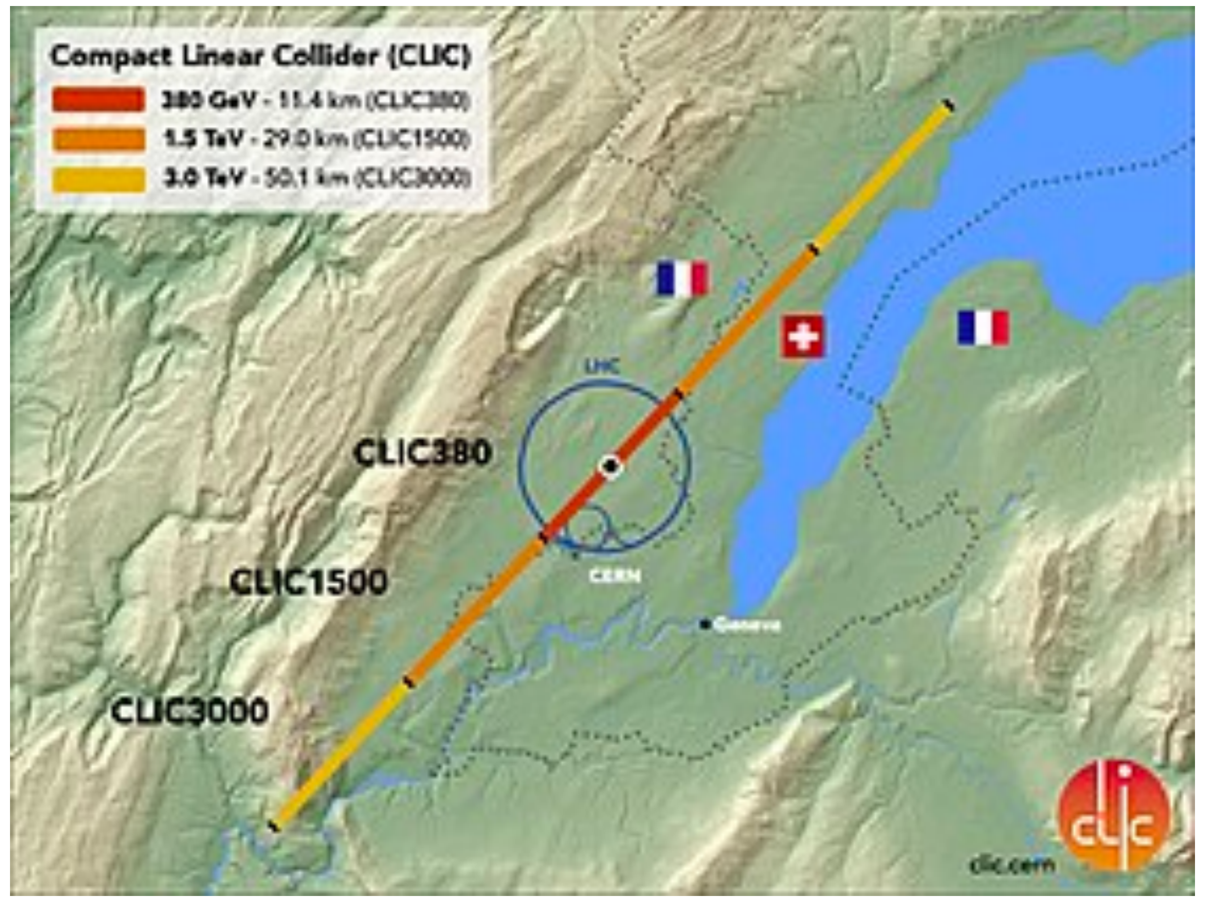


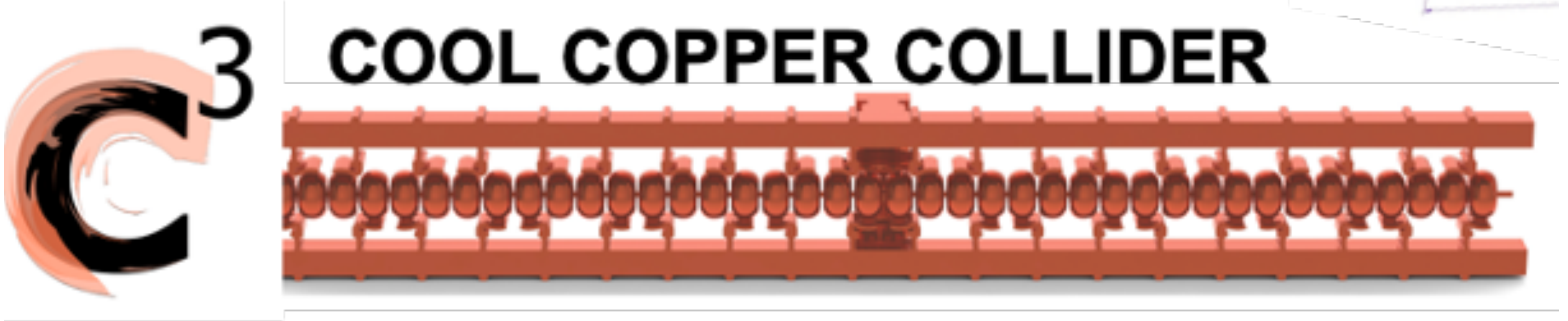
250/500 GeV



CEPC 240 GeV

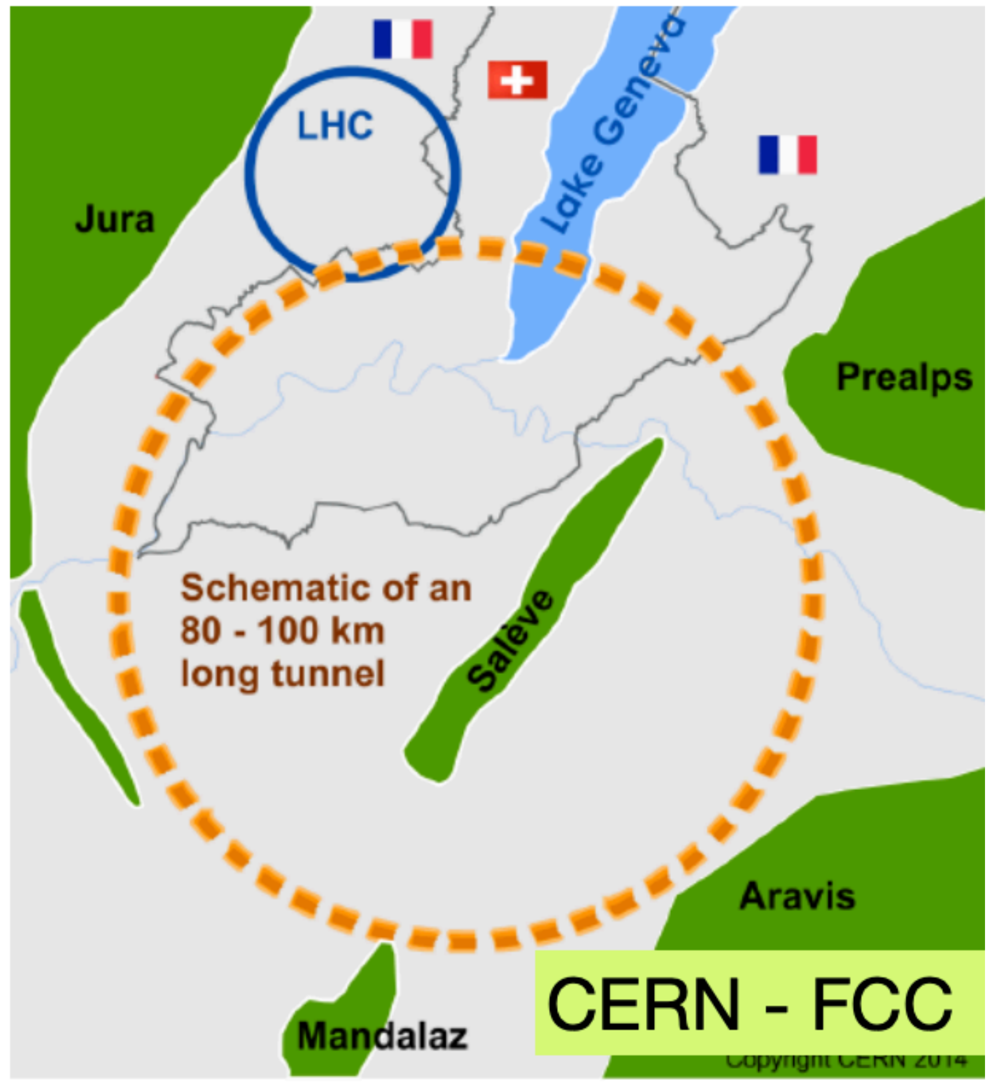
CLIC 380/1500/3000 GeV





250/550 GeV

… > TeV



FCC-ee

240/365 GeV

Why 550 GeV?

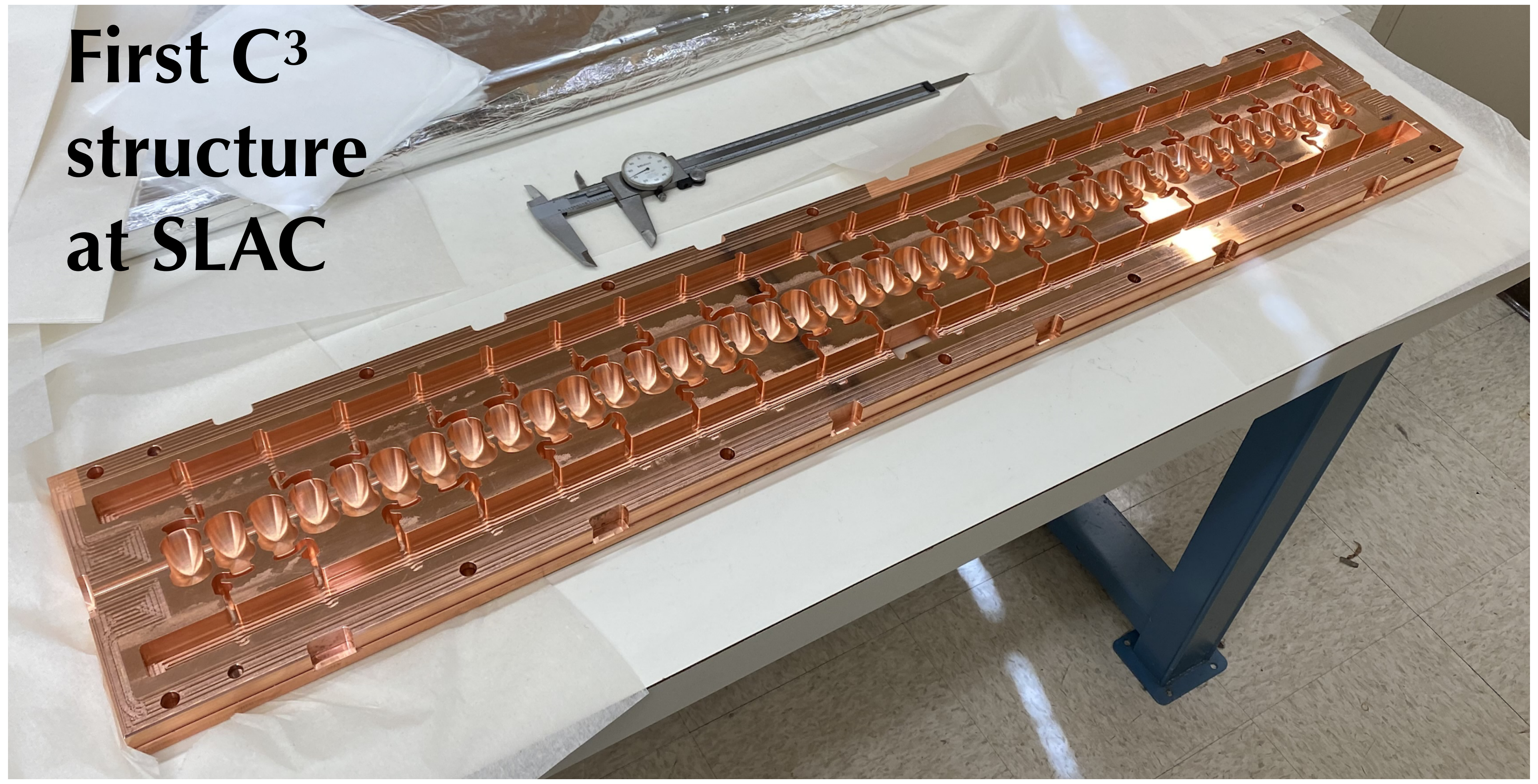
We propose **250** GeV with a relatively inexpensive upgrade to **550** GeV

- 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

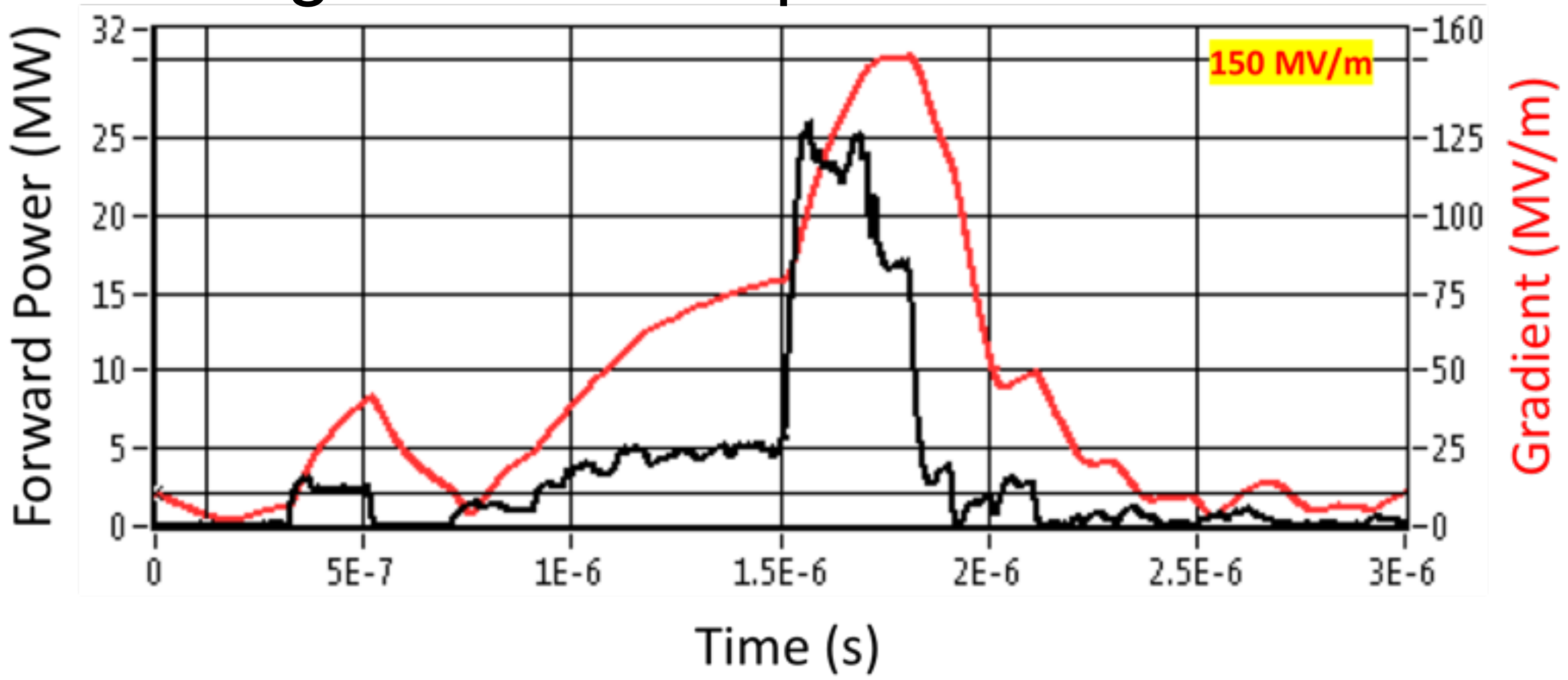
Collider Luminosity Polarization	HL-LHC 3 ab^{-1} in 10 yrs -	C^3 /ILC 250 GeV 2 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)	C^3 /ILC 500 GeV + 4 ab^{-1} in 10 yrs $\mathcal{P}_{e^+} = 30\%$ (0%)
g_{HZZ} (%)	3.2	0.38 (0.40)	0.20 (0.21)
g_{HWW} (%)	2.9	0.38 (0.40)	0.20 (0.20)
g_{Hbb} (%)	4.9	0.80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

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

- C³ is normal conductive accelerator 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



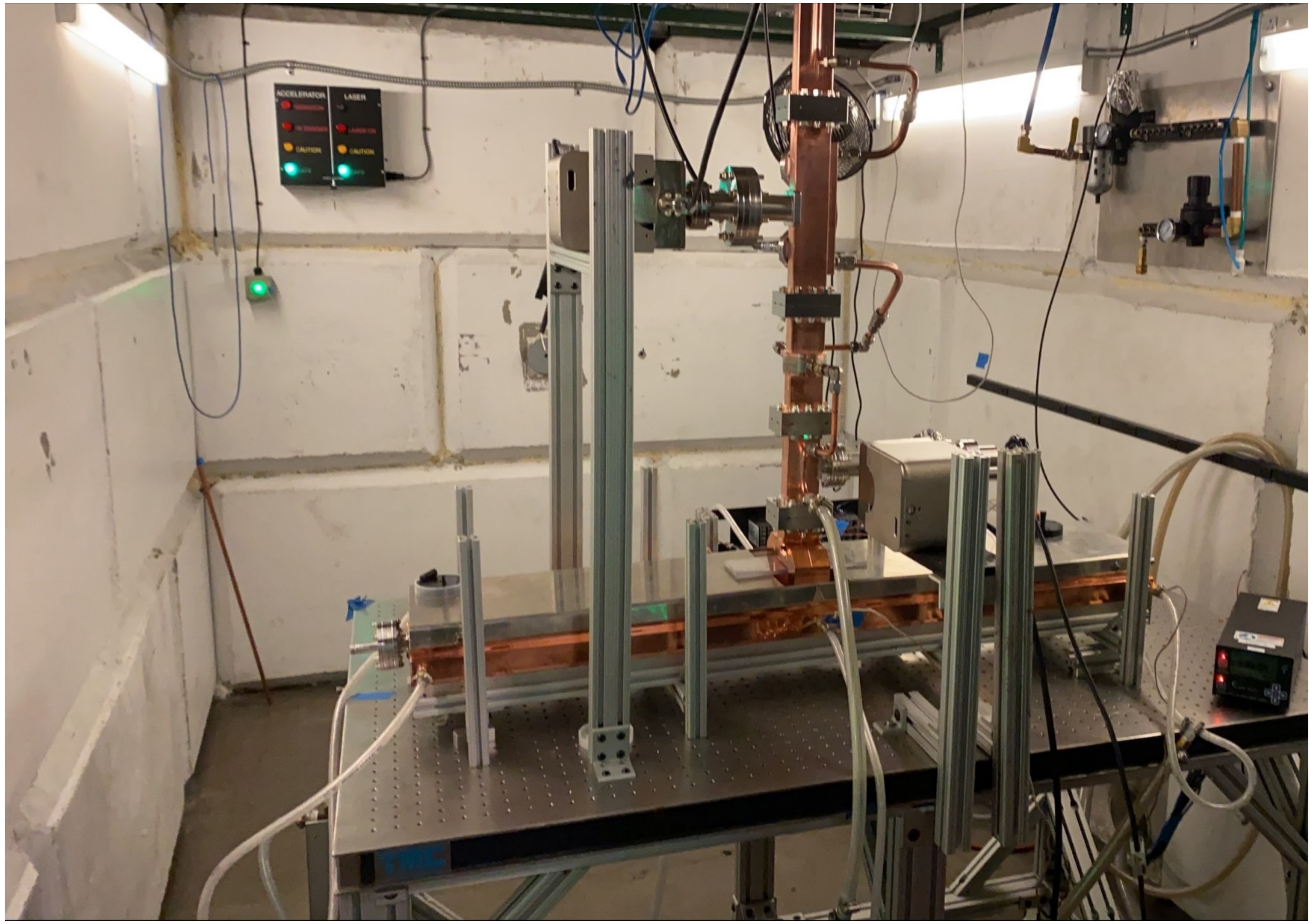
High Gradient Operation at 150 MV/m



Cryogenic Operation at X-band

Ongoing tests

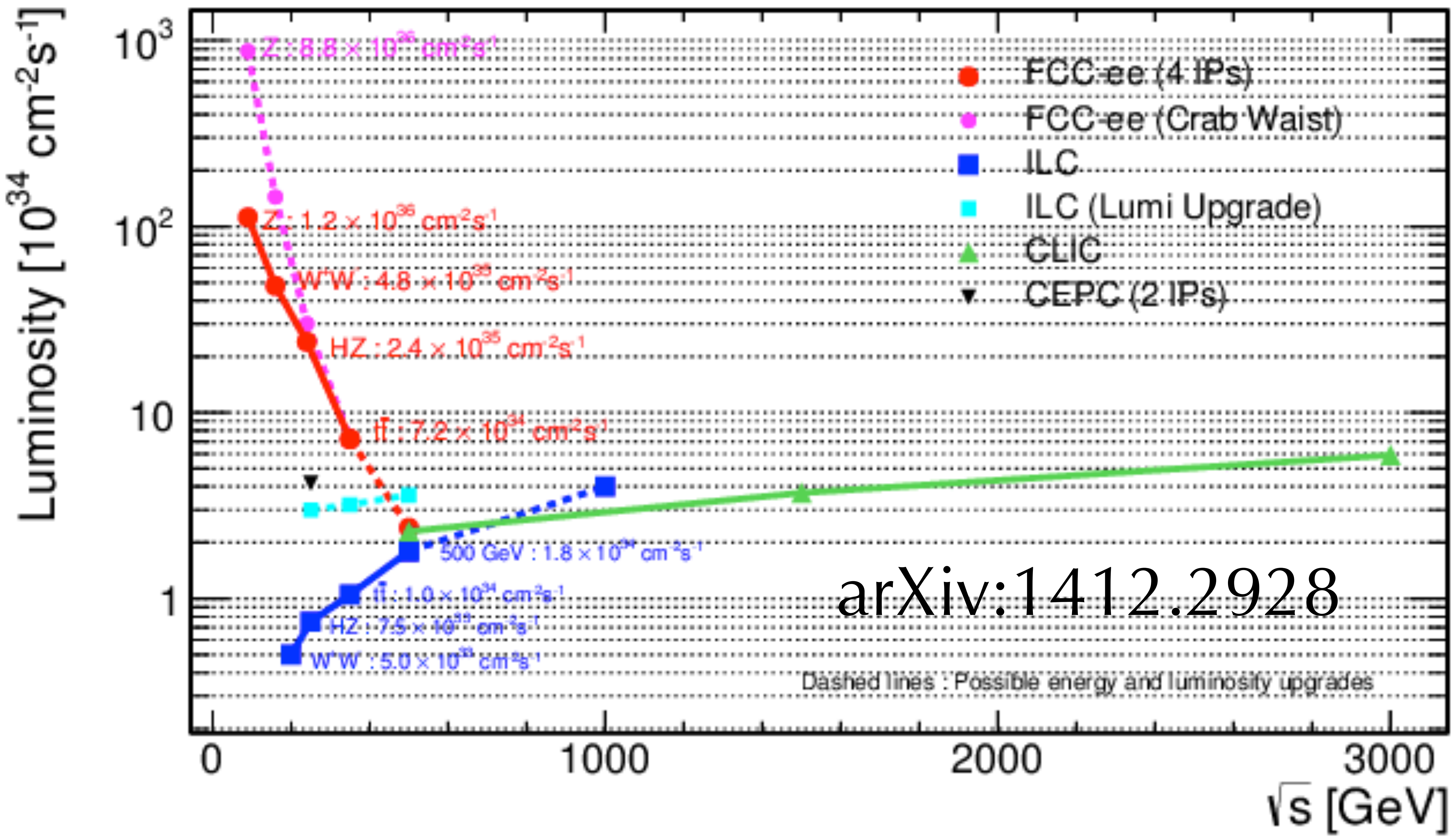
First 300 K high power test in progress



High power test at Radiabeam

Luminosity optimization

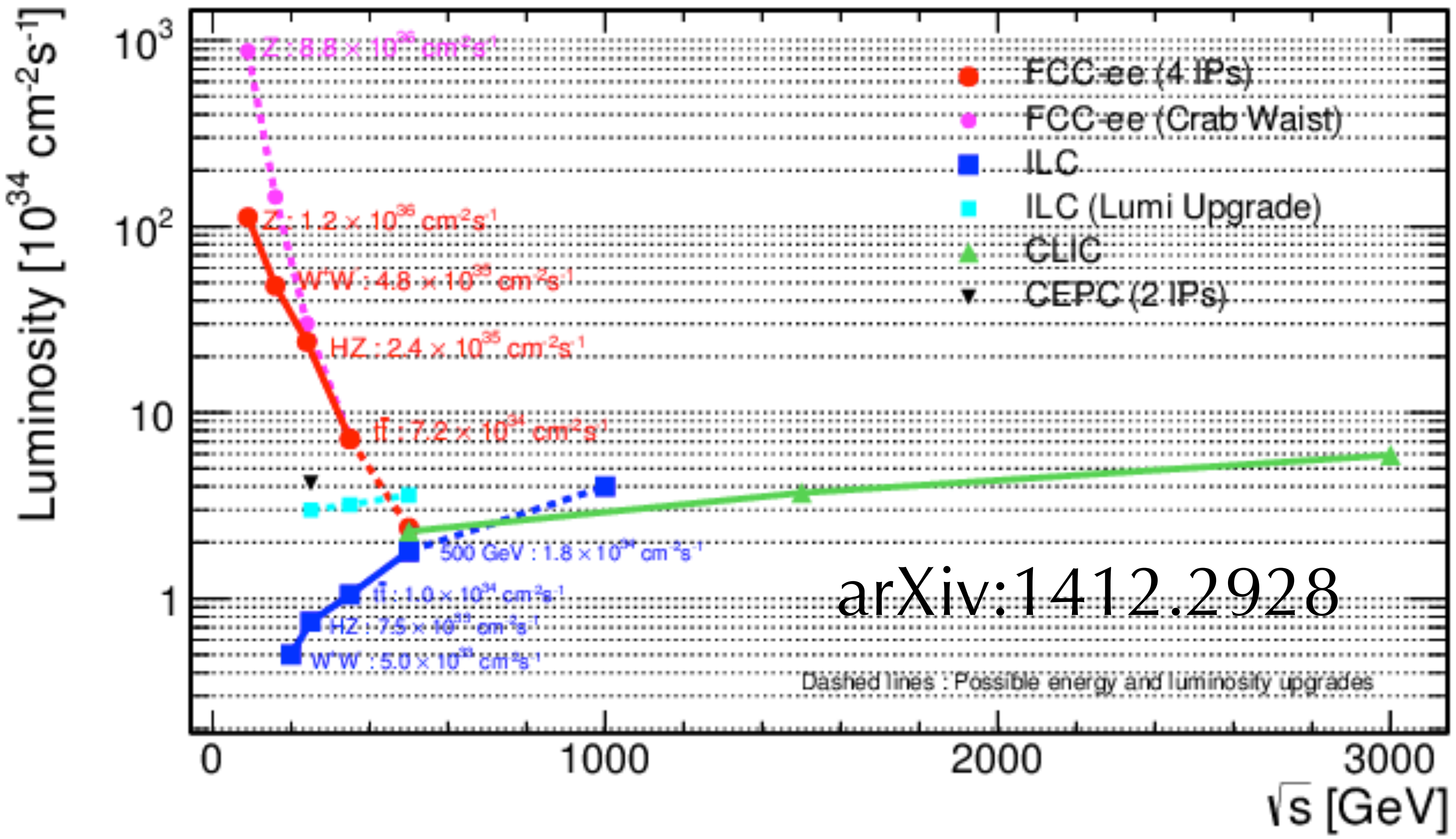
Using established collider designs to inform initial parameters



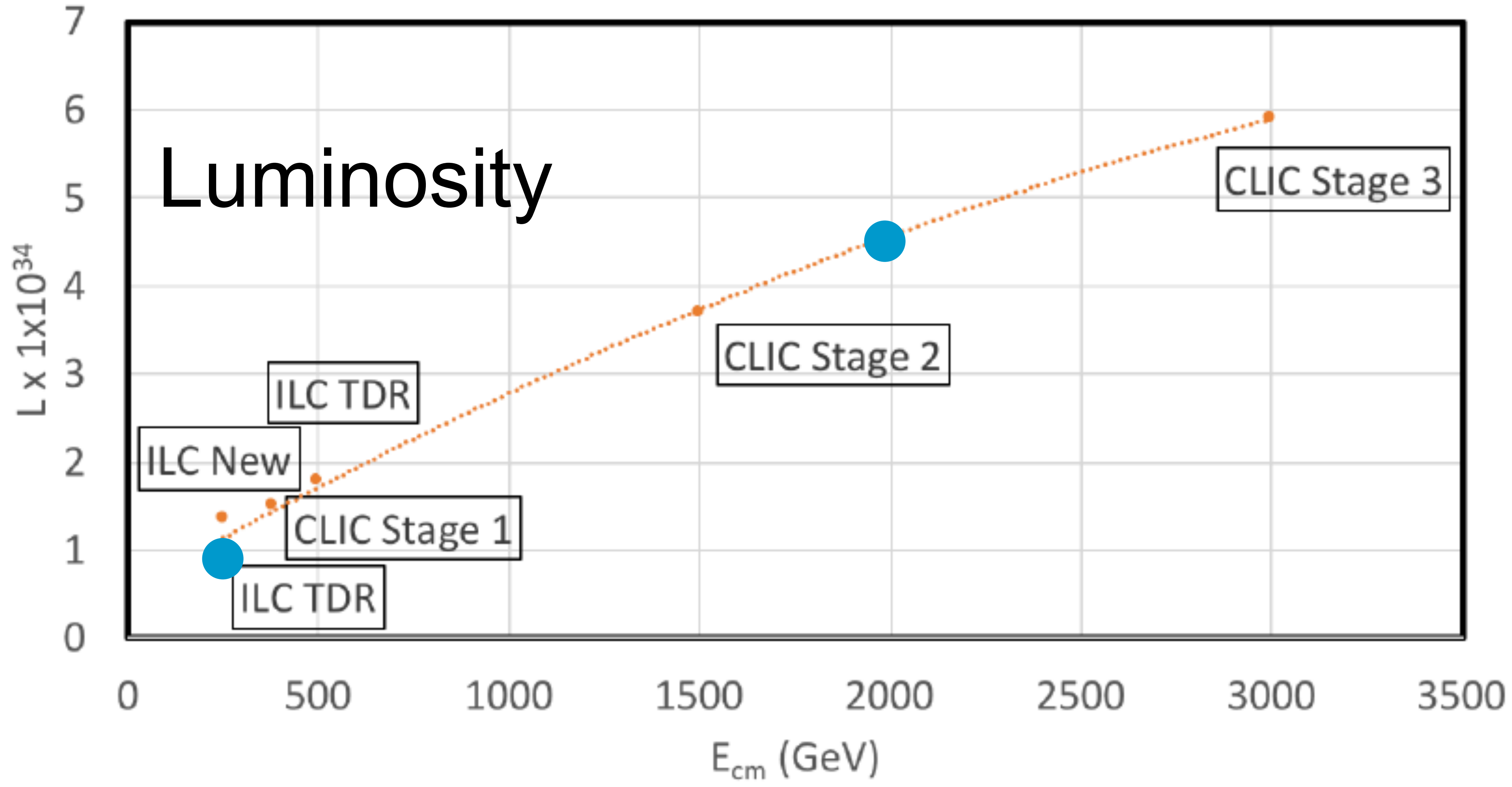
arXiv:1412.2928

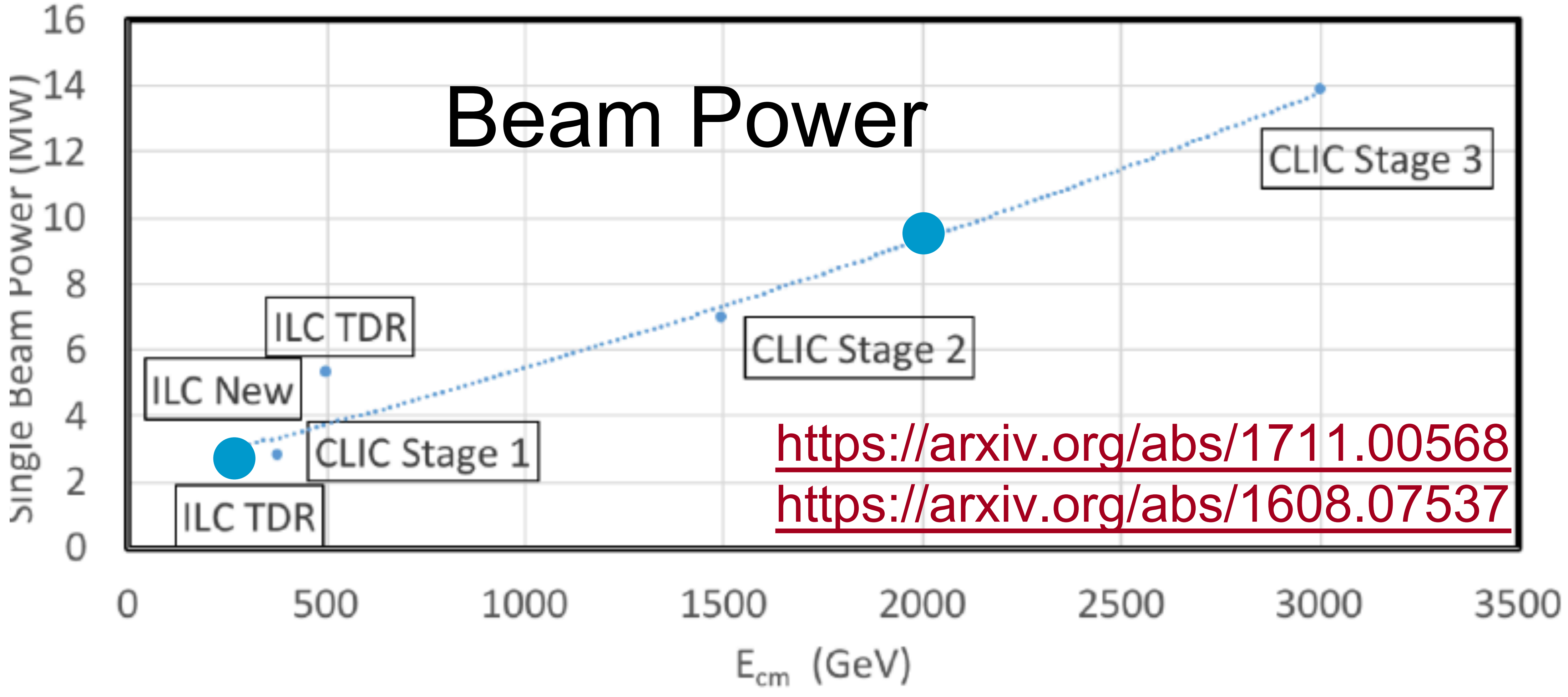
Luminosity optimization

Using established collider designs to inform initial parameters



arXiv:1412.2928





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

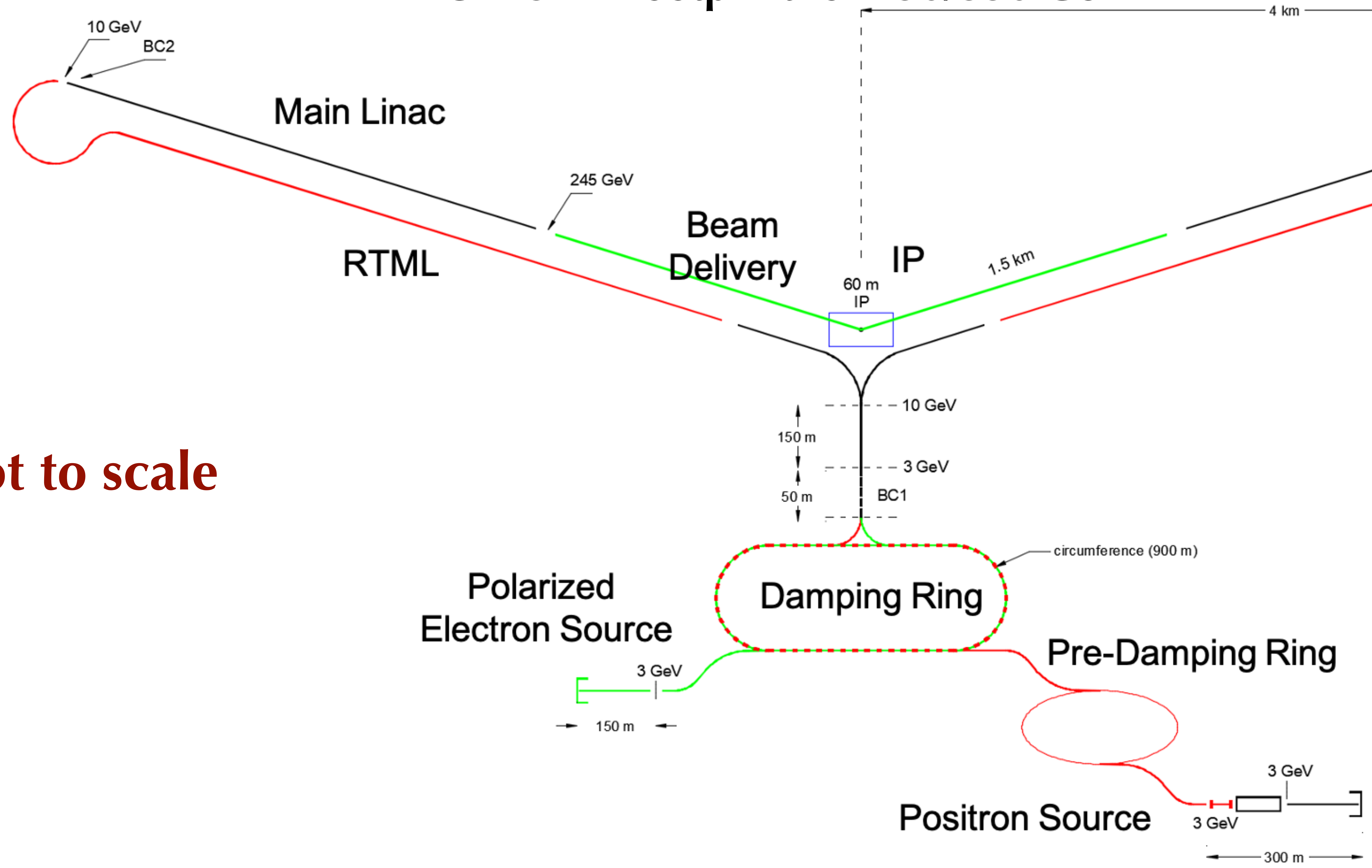
C^3 parameters

arXiv:2110.15800

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	~150	~175

C³ layout

C³ - 8 km footprint for 250/550 GeV

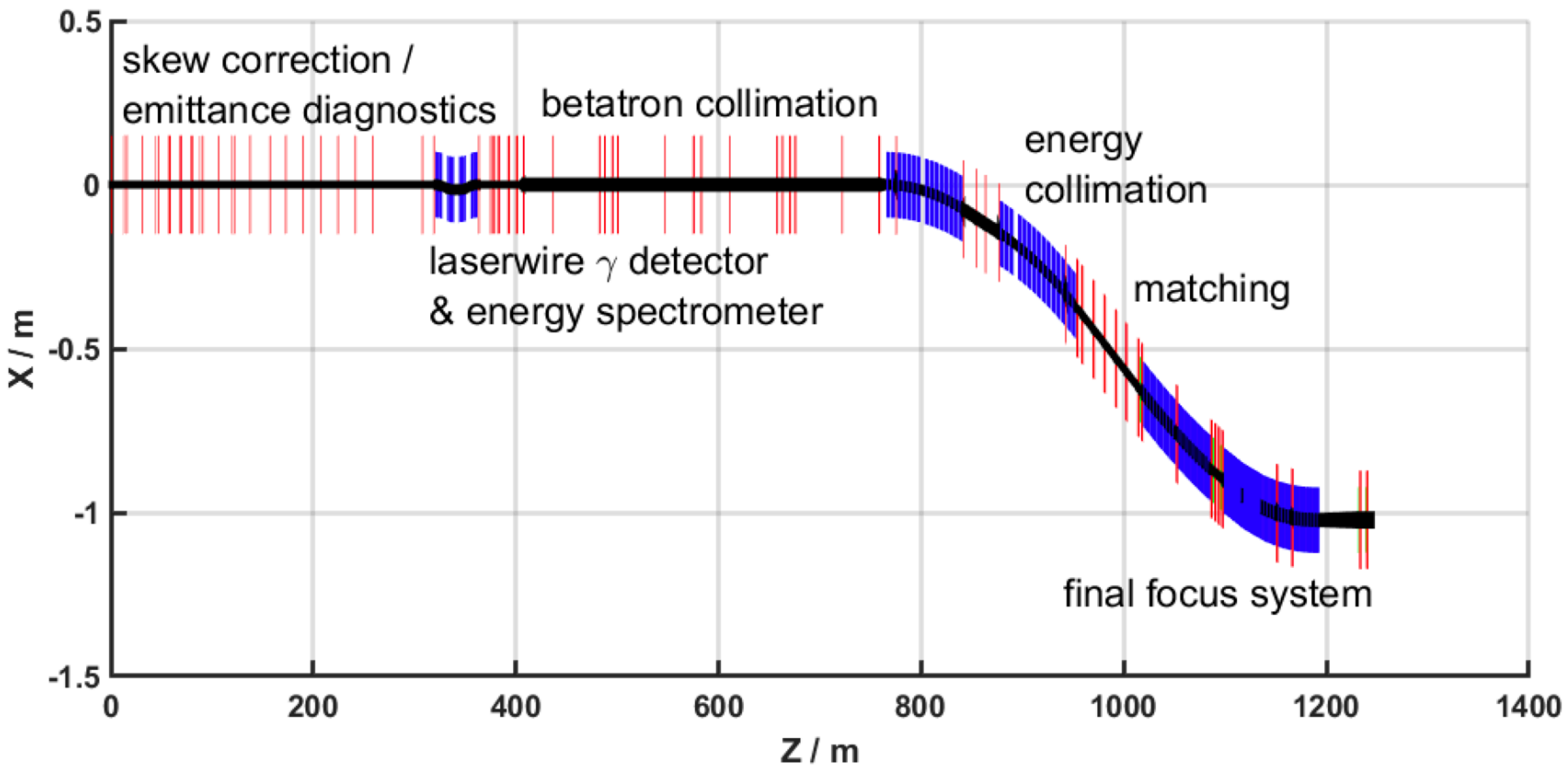


Not to scale

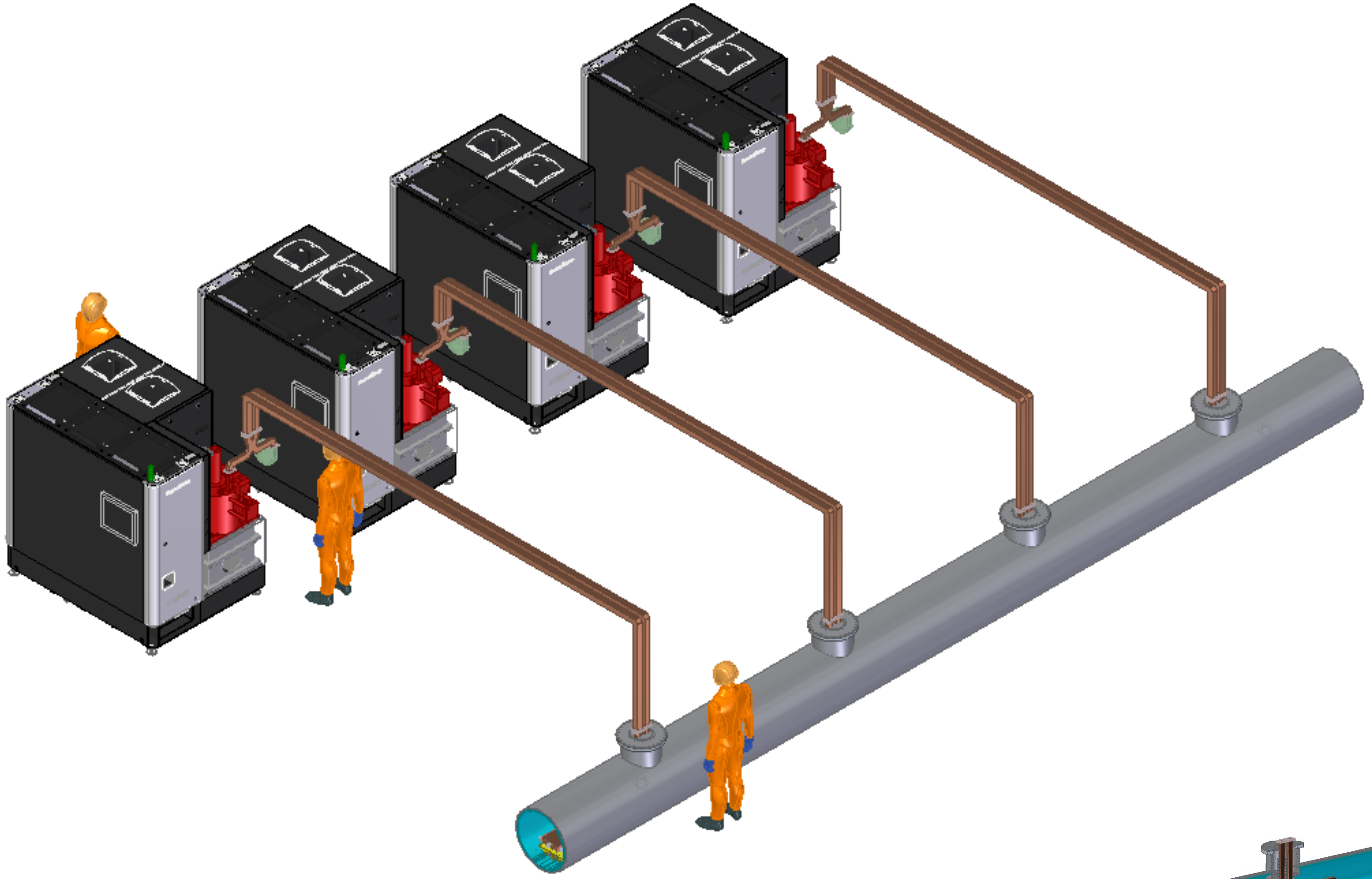
Beam Generation and Delivery Systems for C³

- 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.

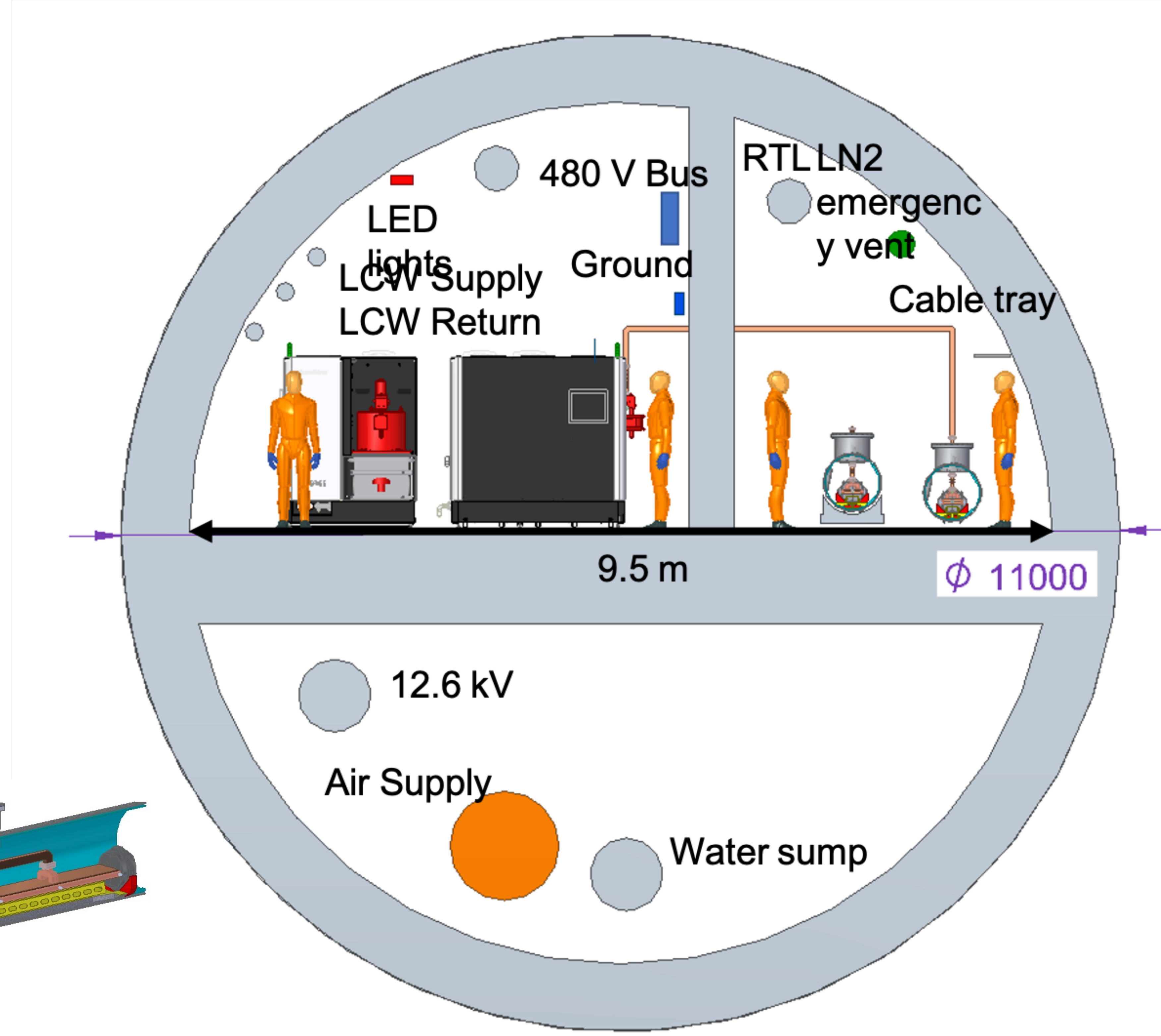
C³ - Investigation of Beam Delivery Adapted from ILC/NLC

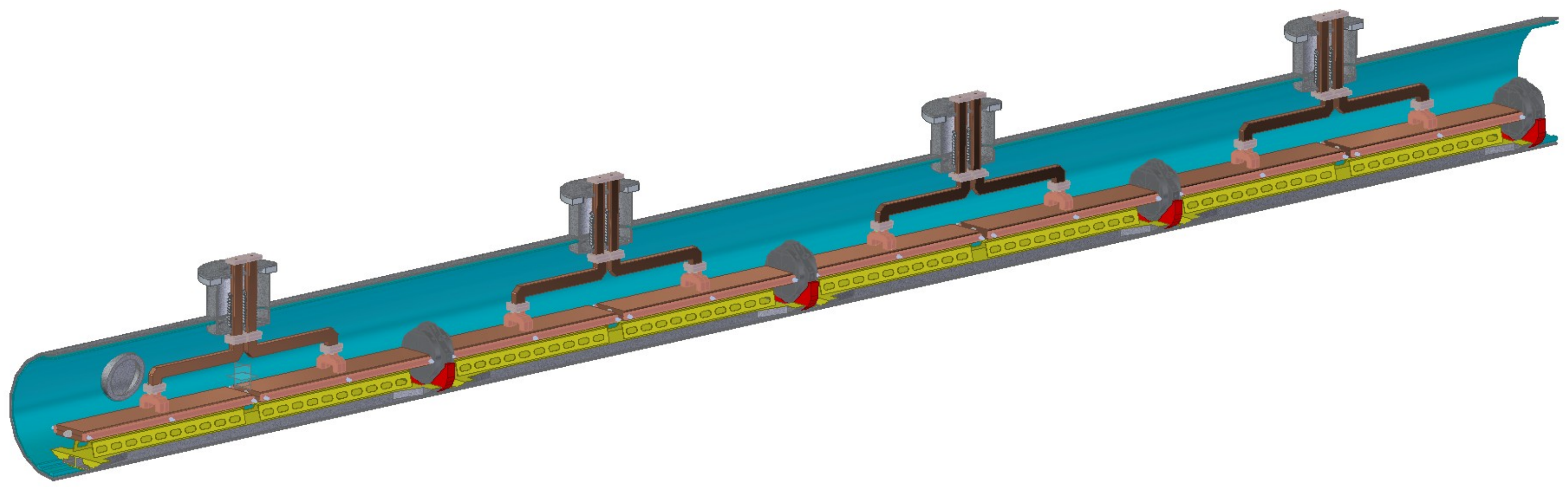


RF system



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





Cryomodule unit - 9 m (630 MeV)

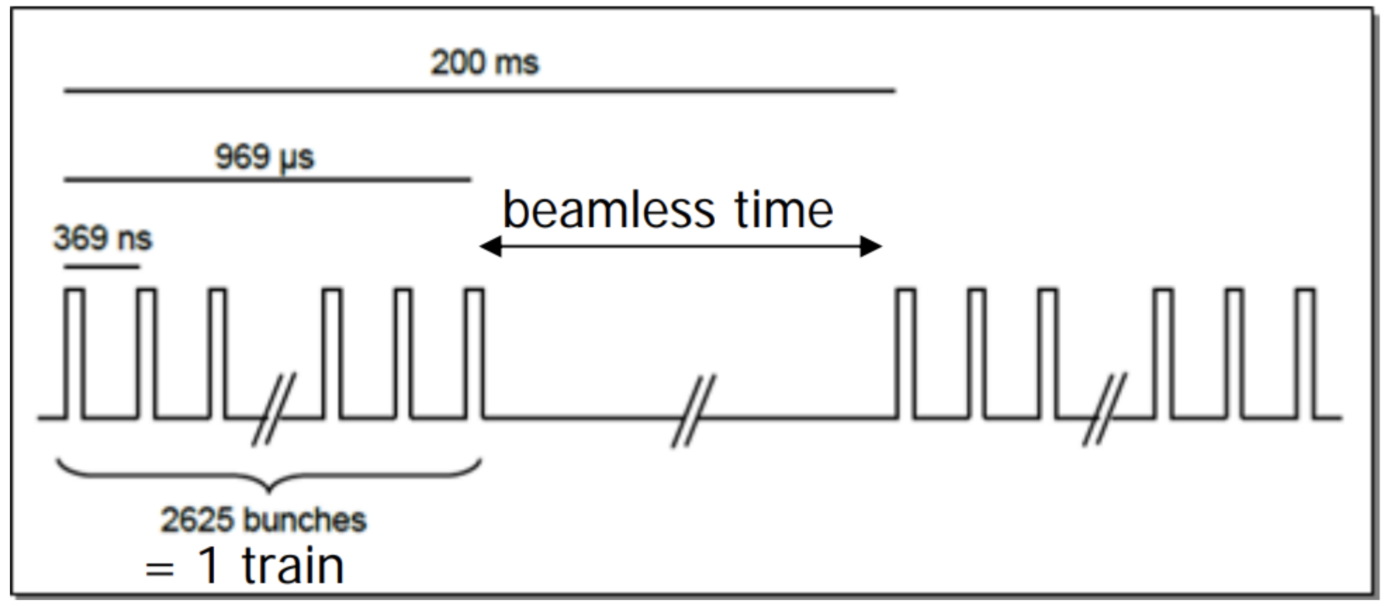
Detector Design Requirements

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

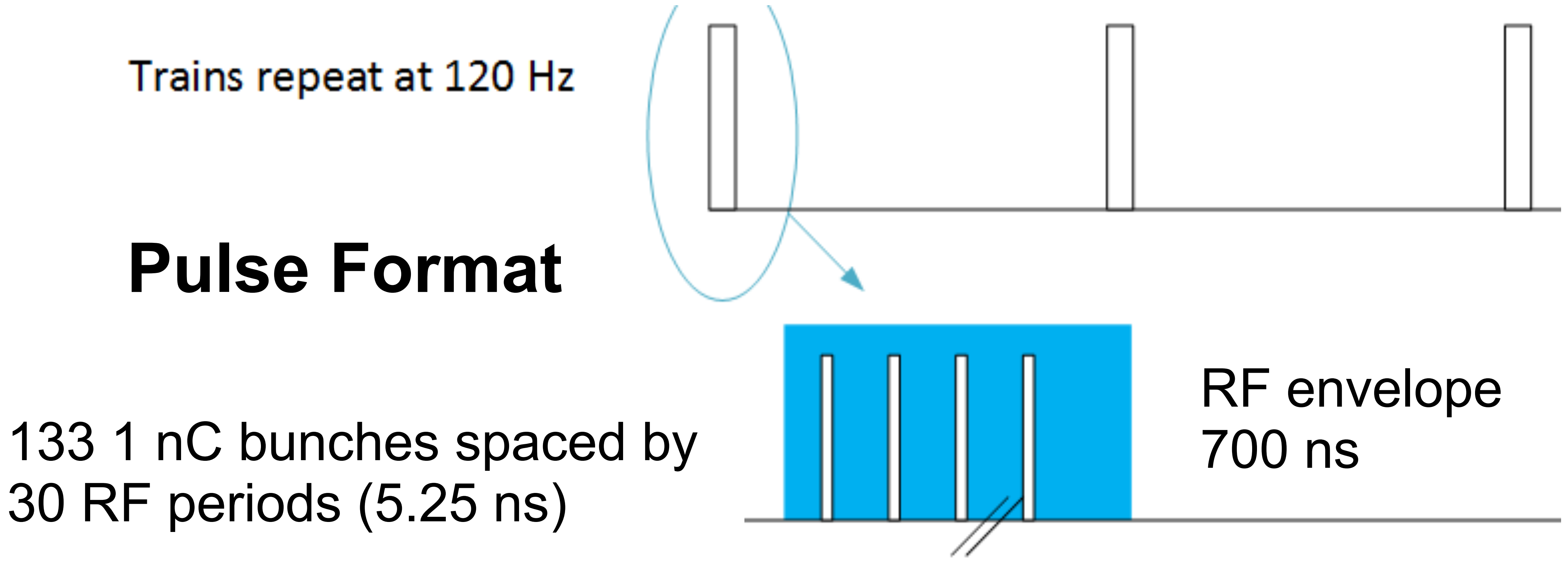
C^3 time structure is compatible with SiD-like detector overall design and ongoing optimizations.

ILC timing structure

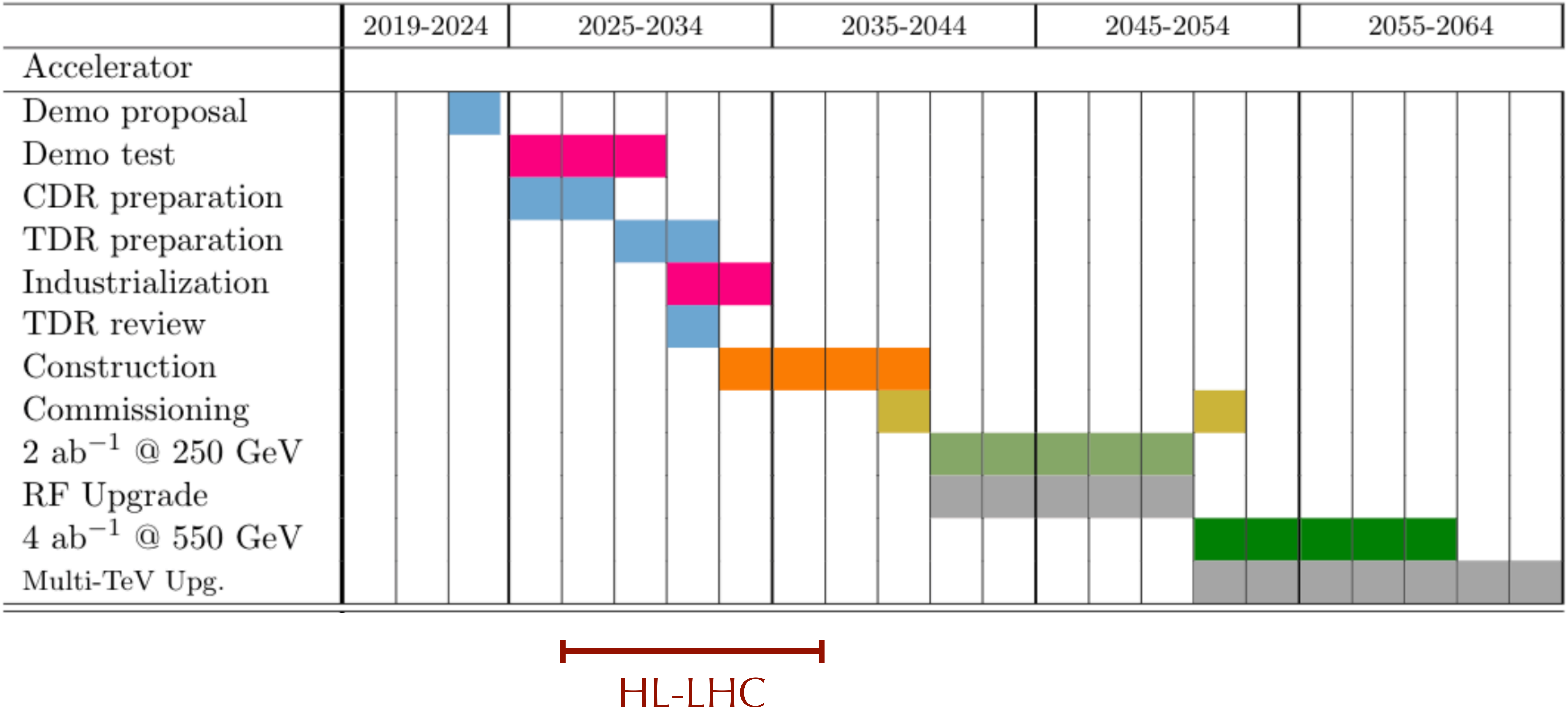


1 ms long bunch trains at 5 Hz
2820 bunches per train
308 ns spacing

C^3 timing structure



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

Next: C^3 Demonstration Facility

- Minimum set of goals
  - **Demonstrate operation of fully engineered and operational cryomodule**
    - Simultaneous operations of at least 3 cryomodules
    - Demonstrate a cryomodule that is close to a production prototype
  - Demonstrate full operational gradient 120 MeV/m (and higher > 155 MeV/m) in single bunch mode
  - Work with industry to develop C-band source unit optimized for installation with Main Linac
- This step is included in our timeline and the cost is O(100 M$).
- This demonstration directly benefits development of compact FELs for photon science
- The development of the other component of the accelerator complex - the sources, damping rings, and beam delivery system - is **synergistic with ILC and CLIC designs**

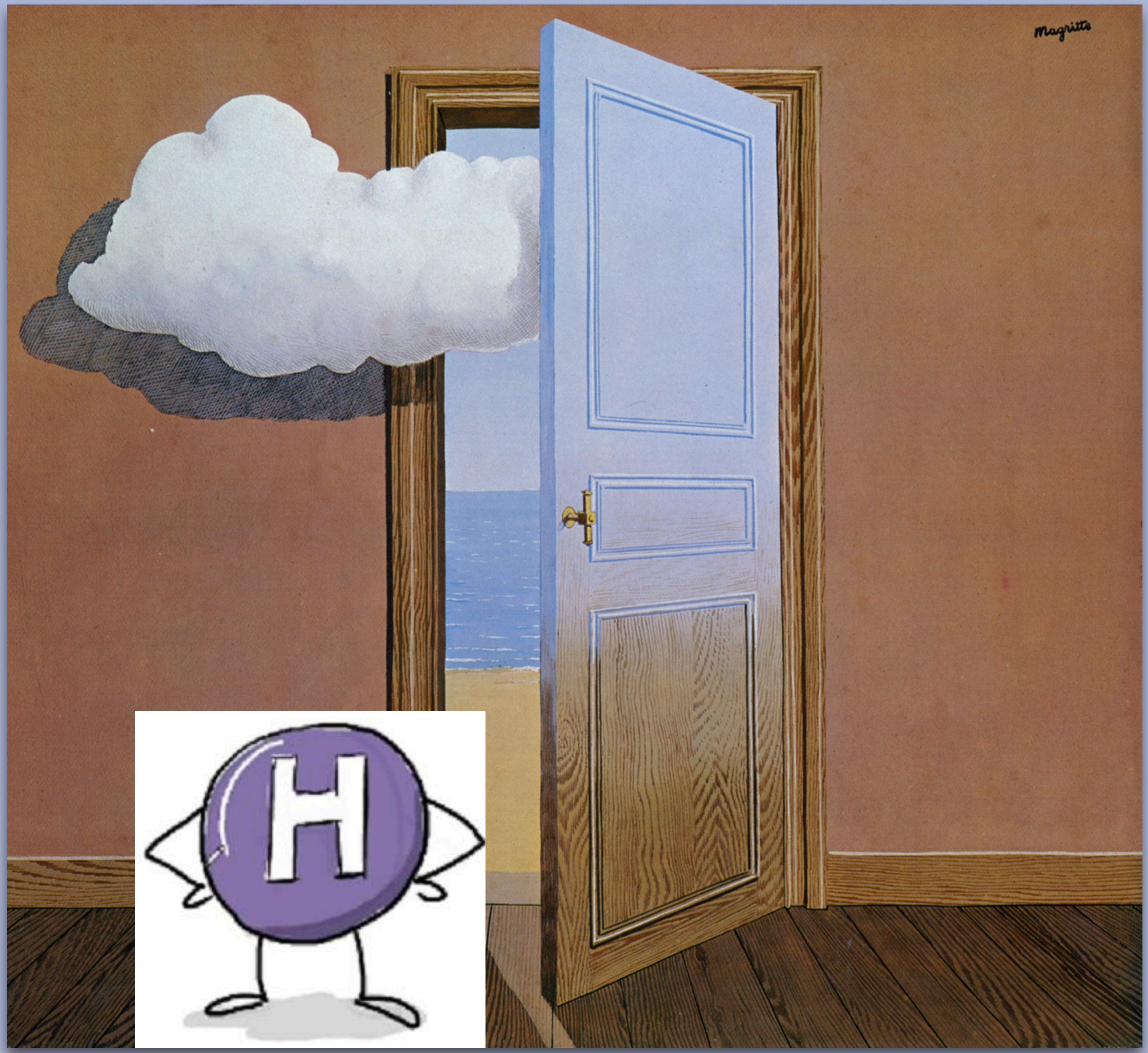
Getting Involved C^3 R&D

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

- The Higgs boson is a central element for the **future colliders**
  - a **new state of matter-energy**
  - a **potential window to Beyond** the Standard Model physics through precision measurements
- 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 can be extended to a 3 TeV e^+e^- collider with capabilities similar to CLIC
- With new ideas, C^3 can provide physics at 10 TeV and beyond



Acknowledgements

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

MEI BAI, TIM BARKLOW, RAINER BARTOLDUS, MARTIN BREIDENBACH*, PHILIPPE GRENIER, ZHIRONG HUANG, MICHAEL KAGAN, ZENGHAI LI, THOMAS W. MARKIEWICZ, EMILIO A. NANNI*, MAMDOUH NASR, CHO-KUEN NG, MARCO ORIUNNO, MICHAEL E. PESKIN*, THOMAS G. RIZZO, ARIEL G. SCHWARTZMAN, DONG SU, SAMI TANTAWI, CATERINA VERNIERI*, GLEN WHITE, CHARLES C. YOUNG

SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025

JOHN LEWELLEN, EVGENYA SIMAKOV

Los Alamos National Laboratory, Los Alamos, NM 87545

JAMES ROSENZWEIG

Department of Physics and Astronomy, University of California, Los Angeles, CA 9009!

BRUNO SPATARO

INFN-LNF, Frascati, Rome 00044, Italy

VLADIMIR SHILTSEV

Fermi National Accelerator Laboratory, Batavia IL 60510-5011

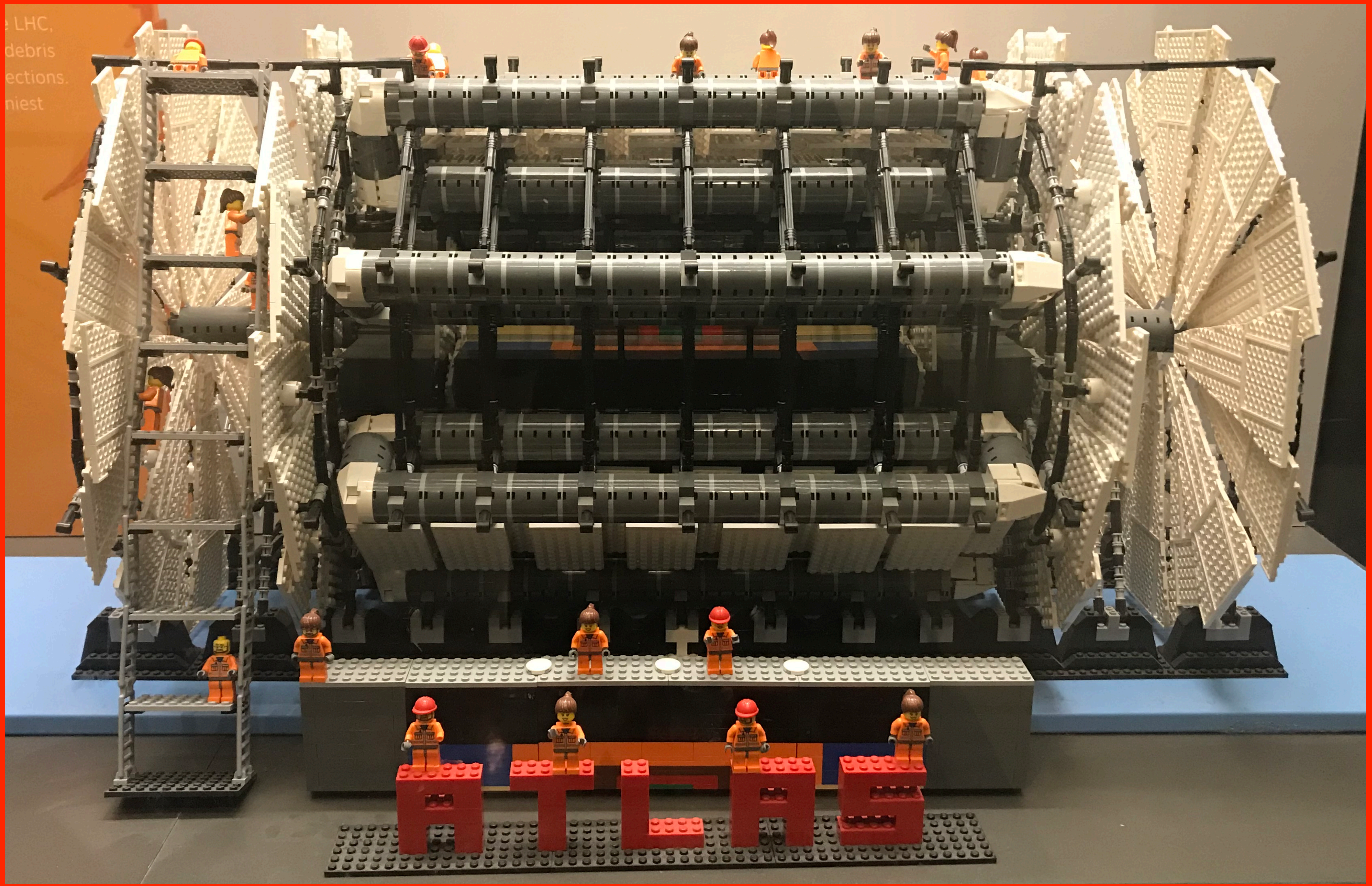
ABSTRACT

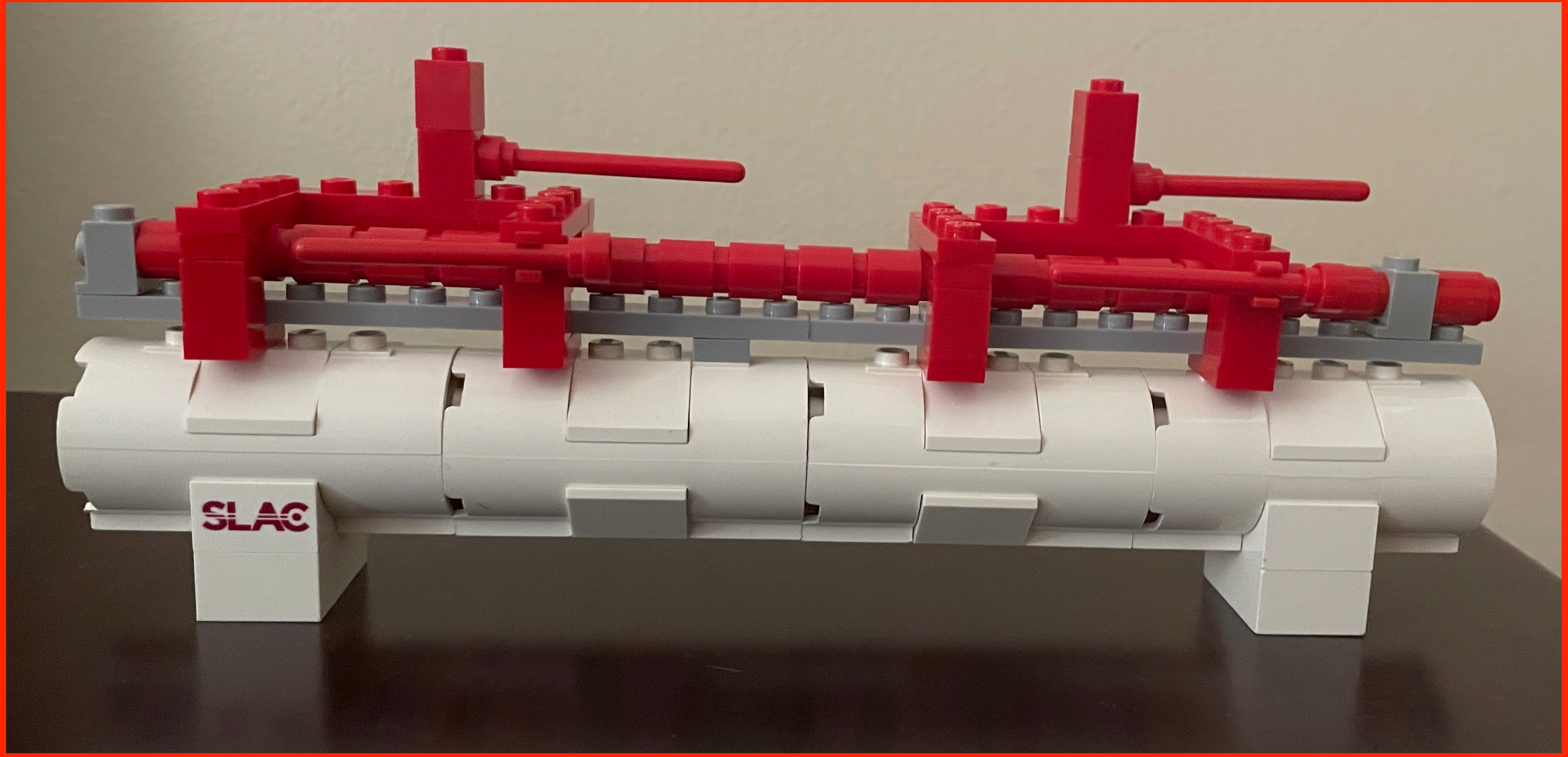
We present a proposal for a cold copper distributed coupling accelerator that can provide a rapid route to precision Higgs physics with a compact 8 km footprint. This proposal is based on recent advances that increase the efficiency and operating gradient of a normal conducting accelerator. This technology 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.

arXiv:2110.15800

Additional Contributors/ Proponents:

Dennis Palmer
Emma Snively
Cici Hanna
Charlotte Whener
Annika Gabriel
Gordon Bowden
Andy Haase
Julian Merrick
Bob Conely
Mitchell Schneider
Radiabeam
Brandon Weatherford

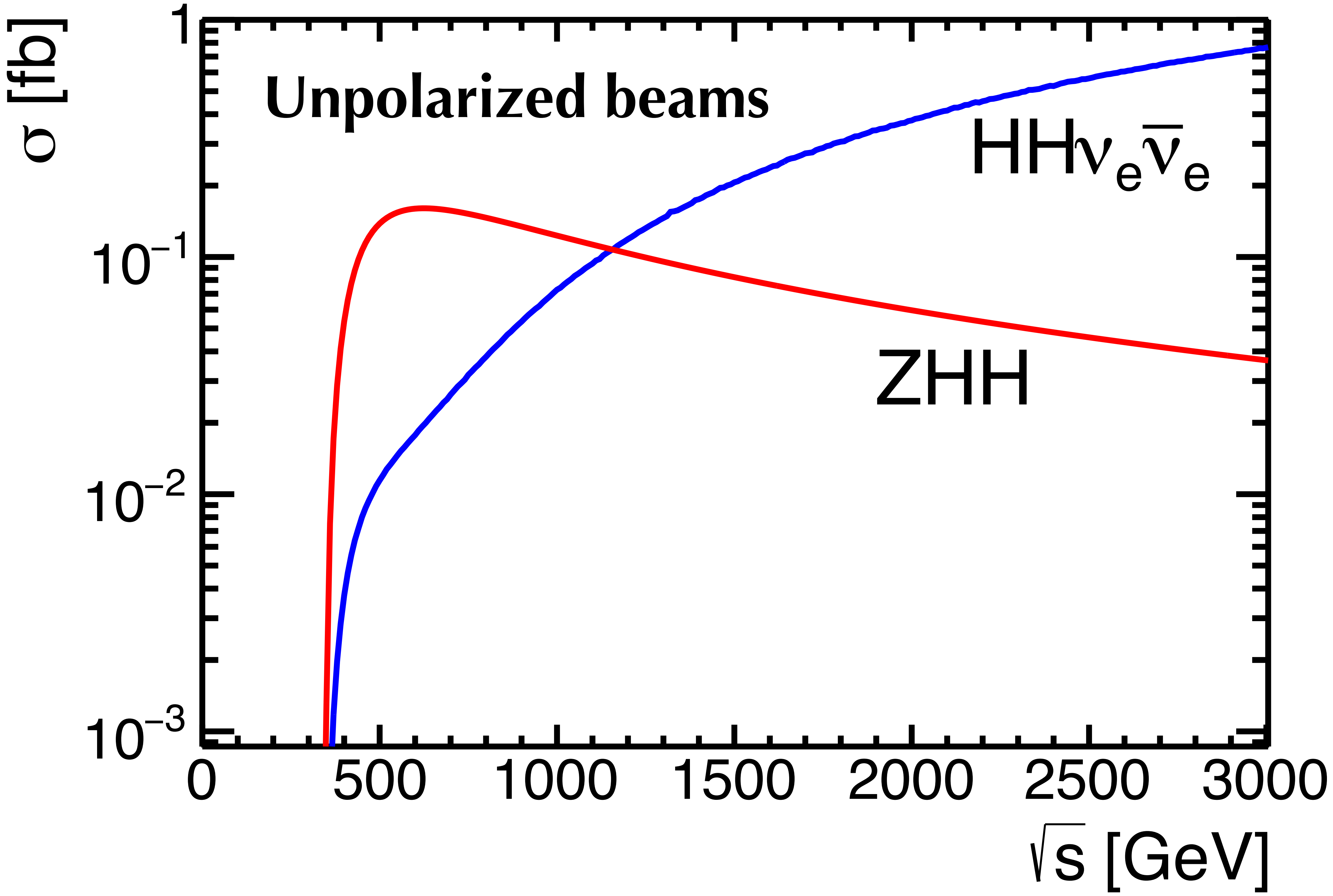


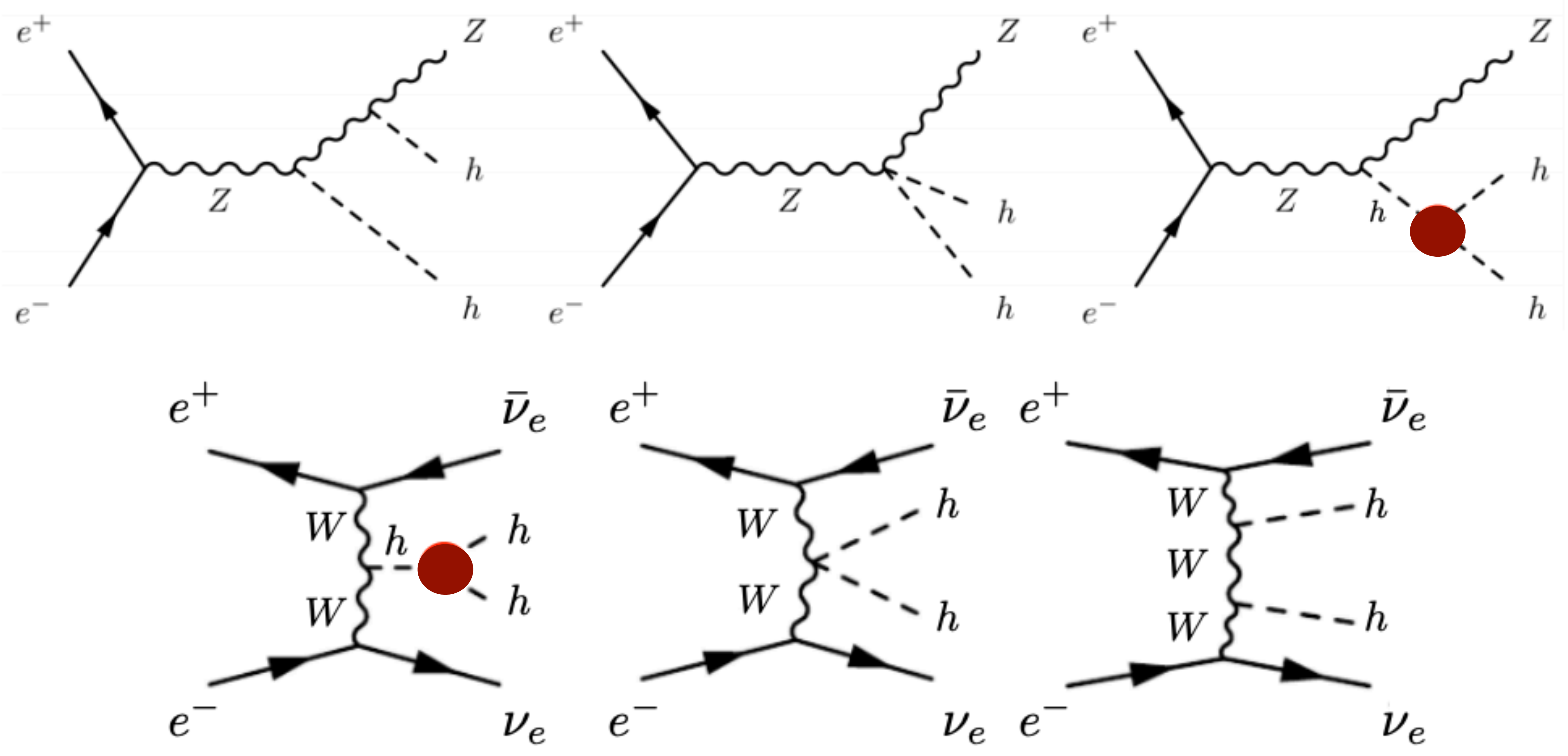


Extra

HH at future e+e- colliders

Review in Physics (2020) 100045





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

Which precision on the self-coupling is needed?

arXiv:1910.00012

Bronze 100%

Silver 25–50%

Gold 5–10%

Platinum 1%

Sensitivity to:

models where we expect new particles of few hundred GeV mass

mixing of the Higgs boson with a heavy scalar with a mass of order 1 TeV

loop diagram effects created by any new particle with strong coupling to the H

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

Which precision on the self-coupling is needed?

arXiv:1910.00012

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

Sensitivity to:

mo

mix

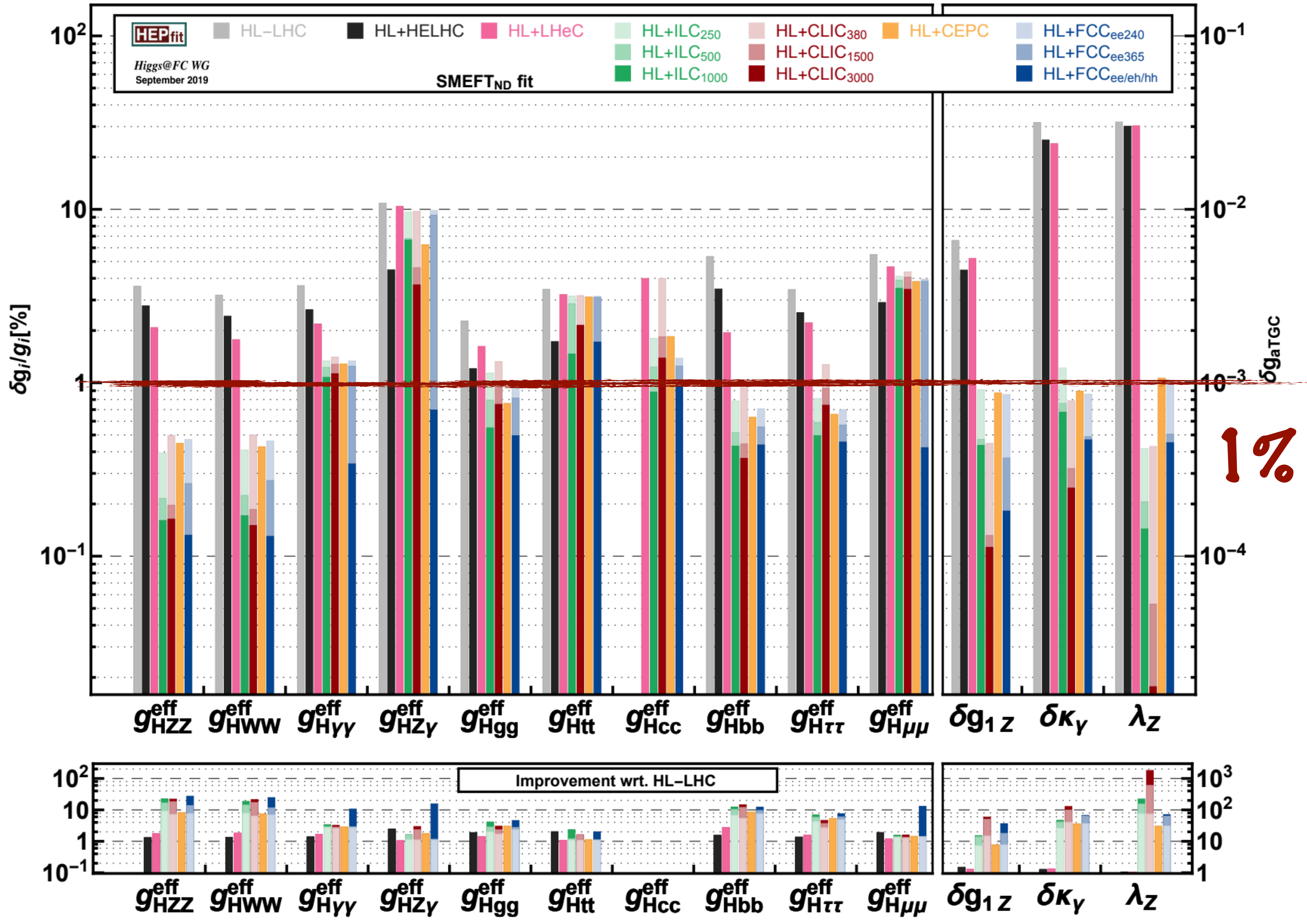
loo

Interplay between precisions inference and direct searches for new particles.

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

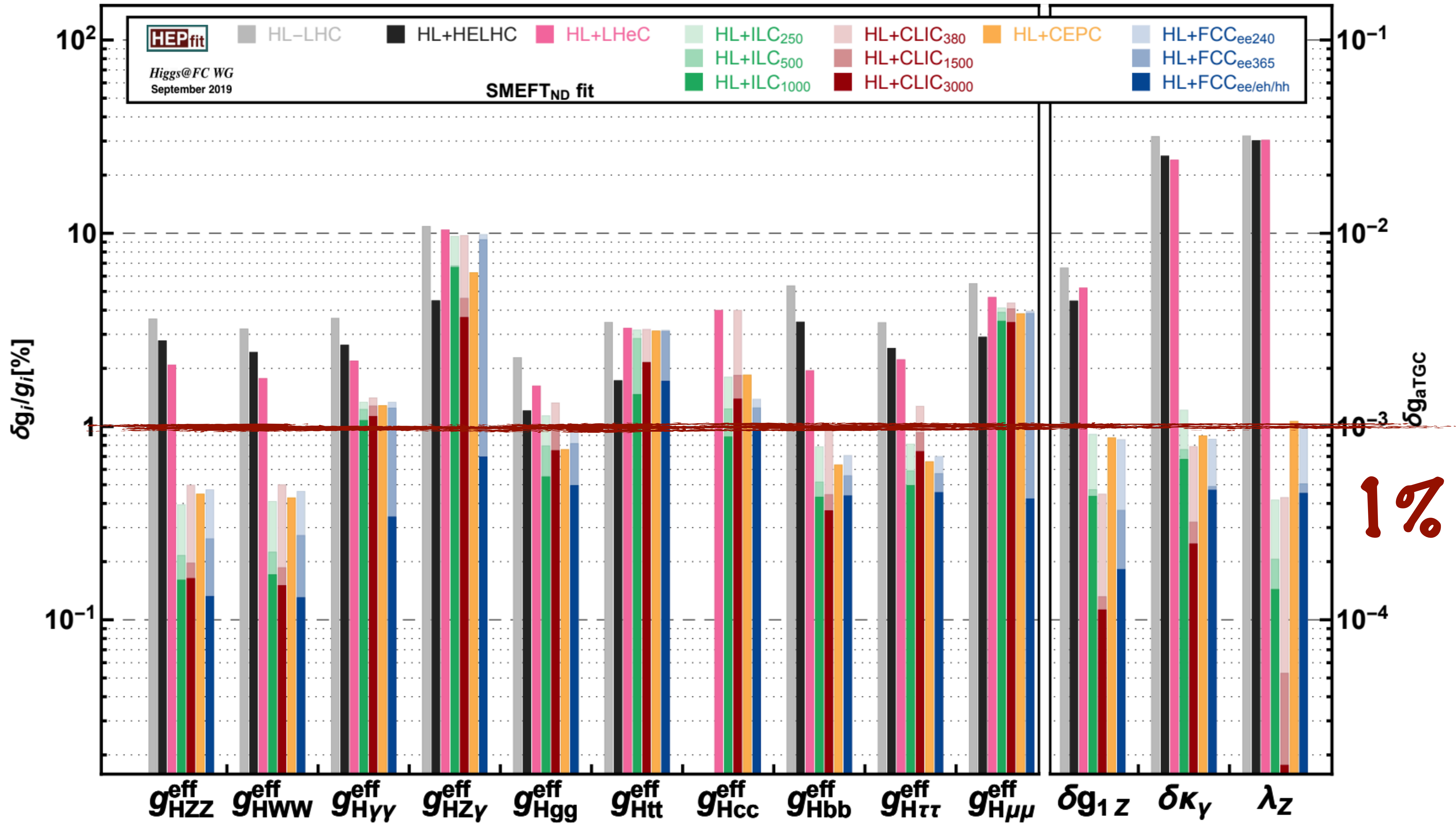
Higgs couplings at future colliders

- **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 and not really improved at future colliders



Higgs couplings at future colliders

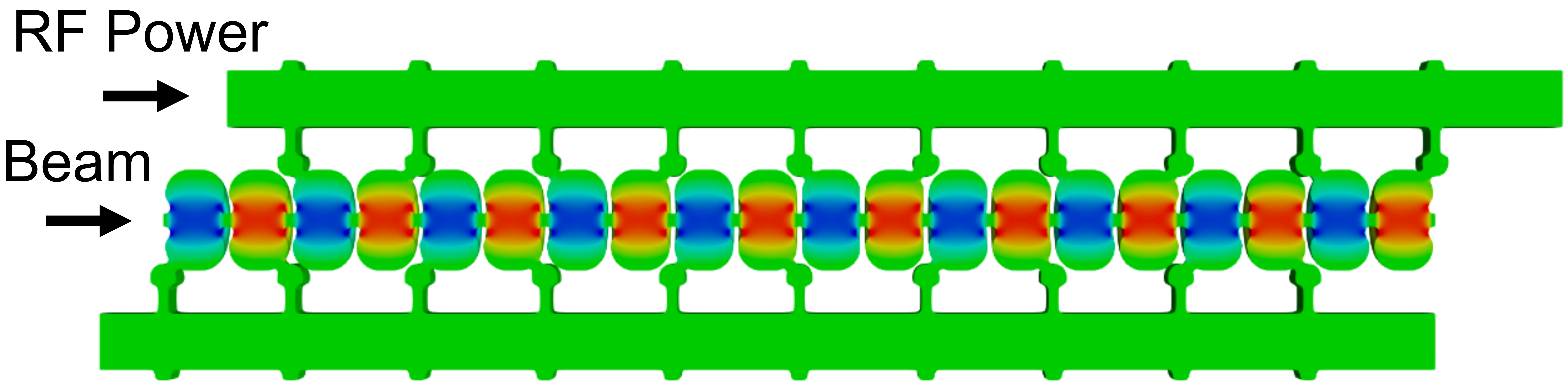
- **Coupling to W and Z** would be measured with an accuracy of few 0.1%
- **Coupling to charm and b** quarks could be measured with an accuracy of ~1% at future e+e- machines
- **Couplings to μ/γ/Zγ** benefit the most from the large dataset available at HL-LHC and not really improved at future colliders



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

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

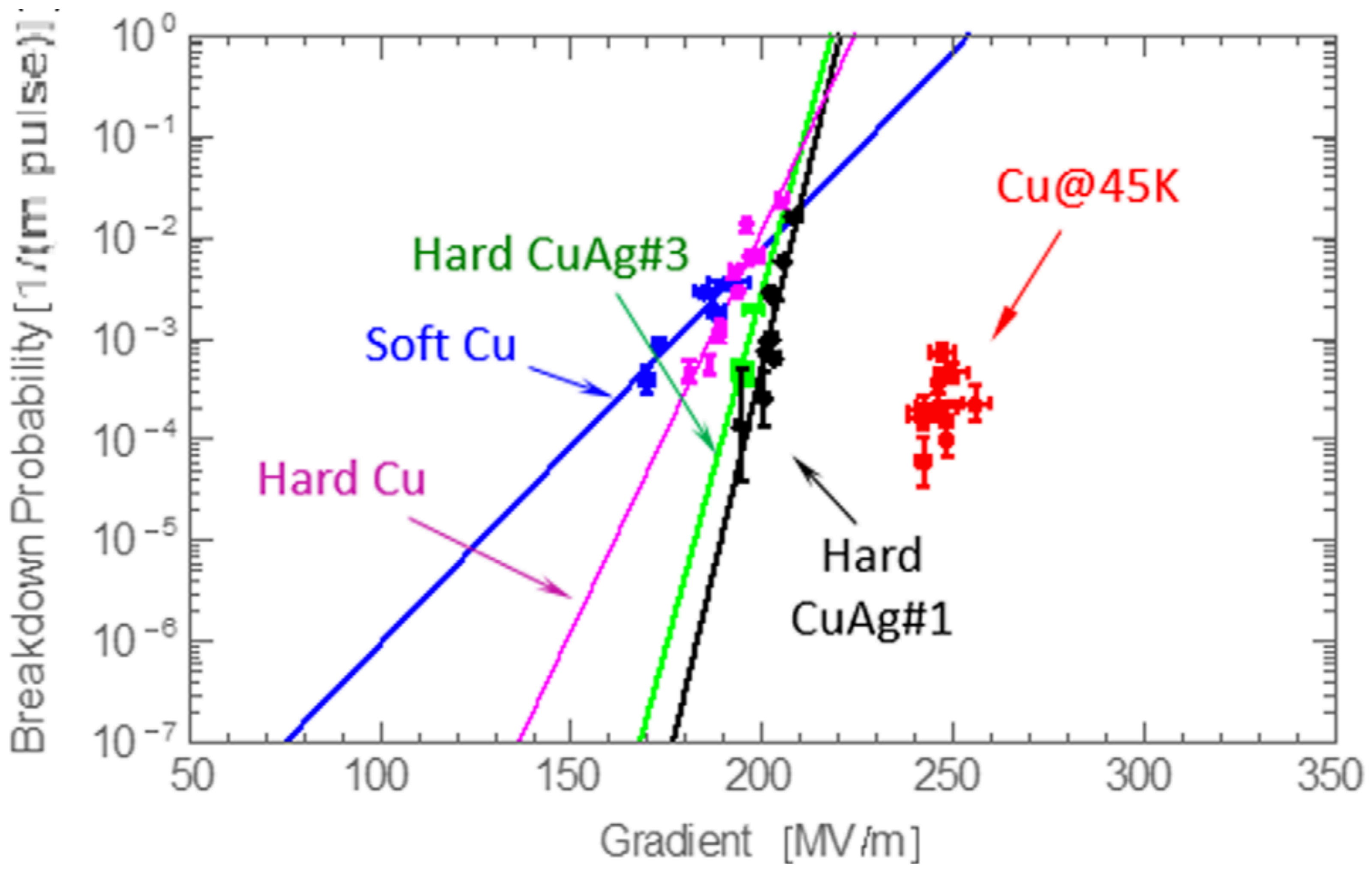
Tantawi, Sami, et al. "Design and demonstration of a distributed-coupling linear accelerator structure." *Physical Review Accelerators and Beams* 23.9 (2020): 092001.

Transformative Impact for High-Gradient Cryo-Copper Accelerators

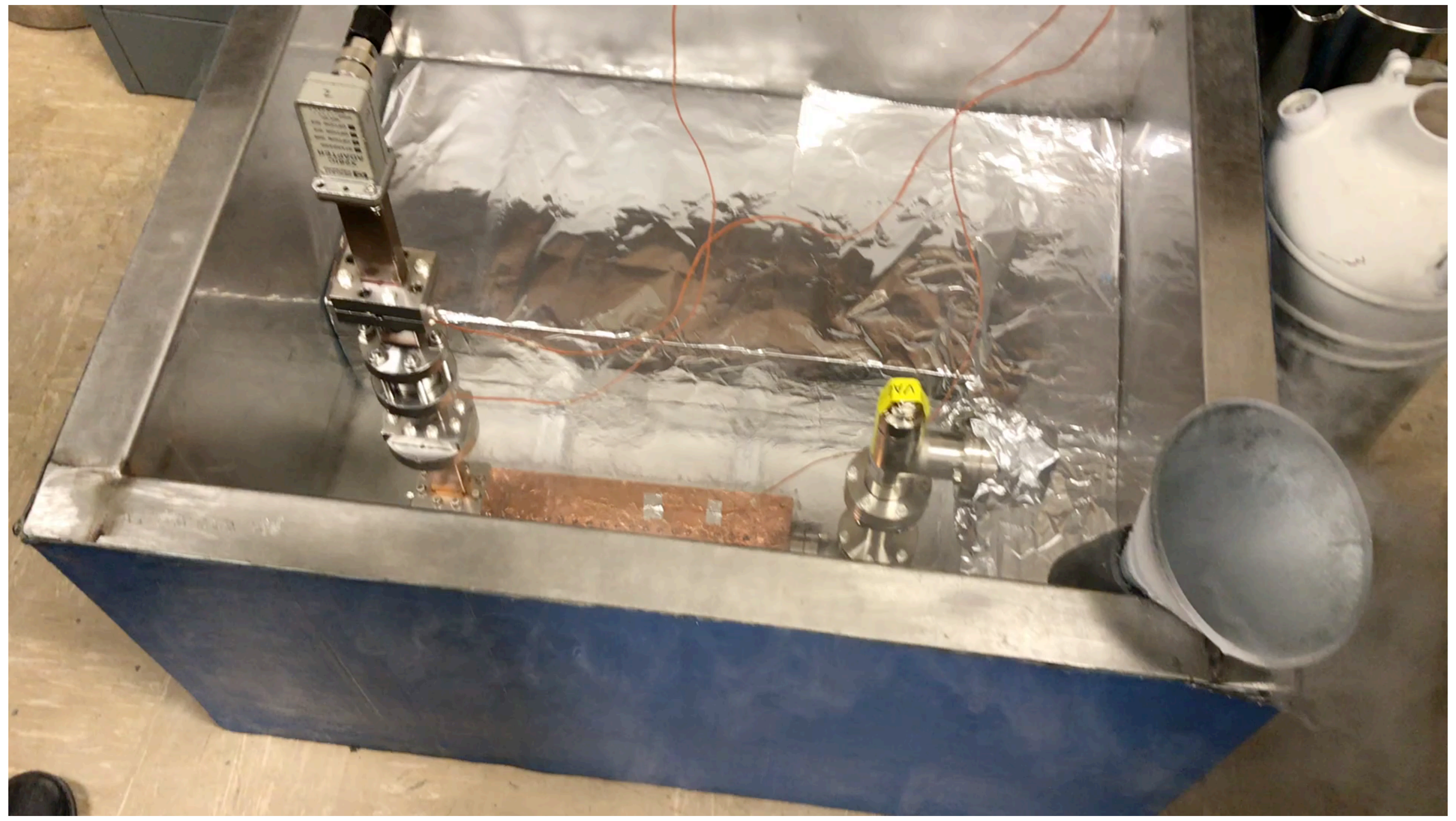
- Cryogenic temperature elevates performance in gradient
  - Material strength is key factor
  - Operation at 77 K with liquid nitrogen is simple and practical
- Large-scale production, large heat capacity, simple handling
  - Small impact on electrical efficiency

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

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



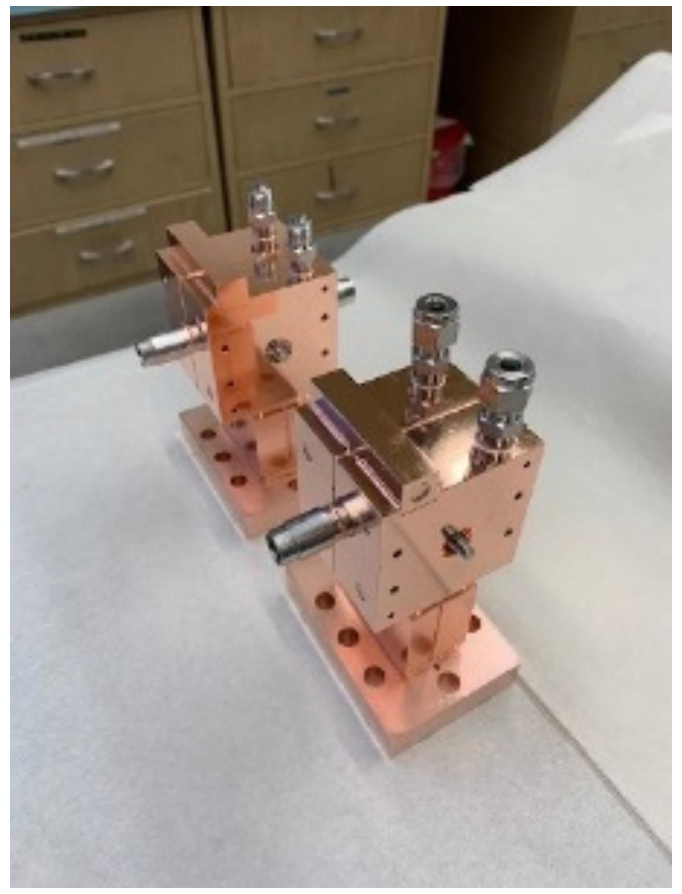
Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.

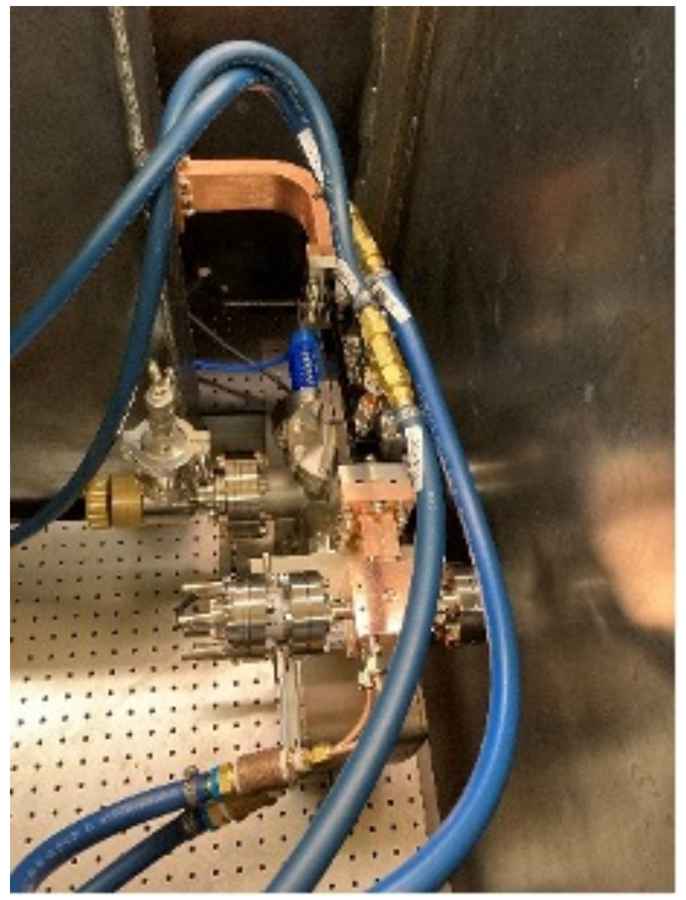


Performance of Single-Cavity Structure Prototypes

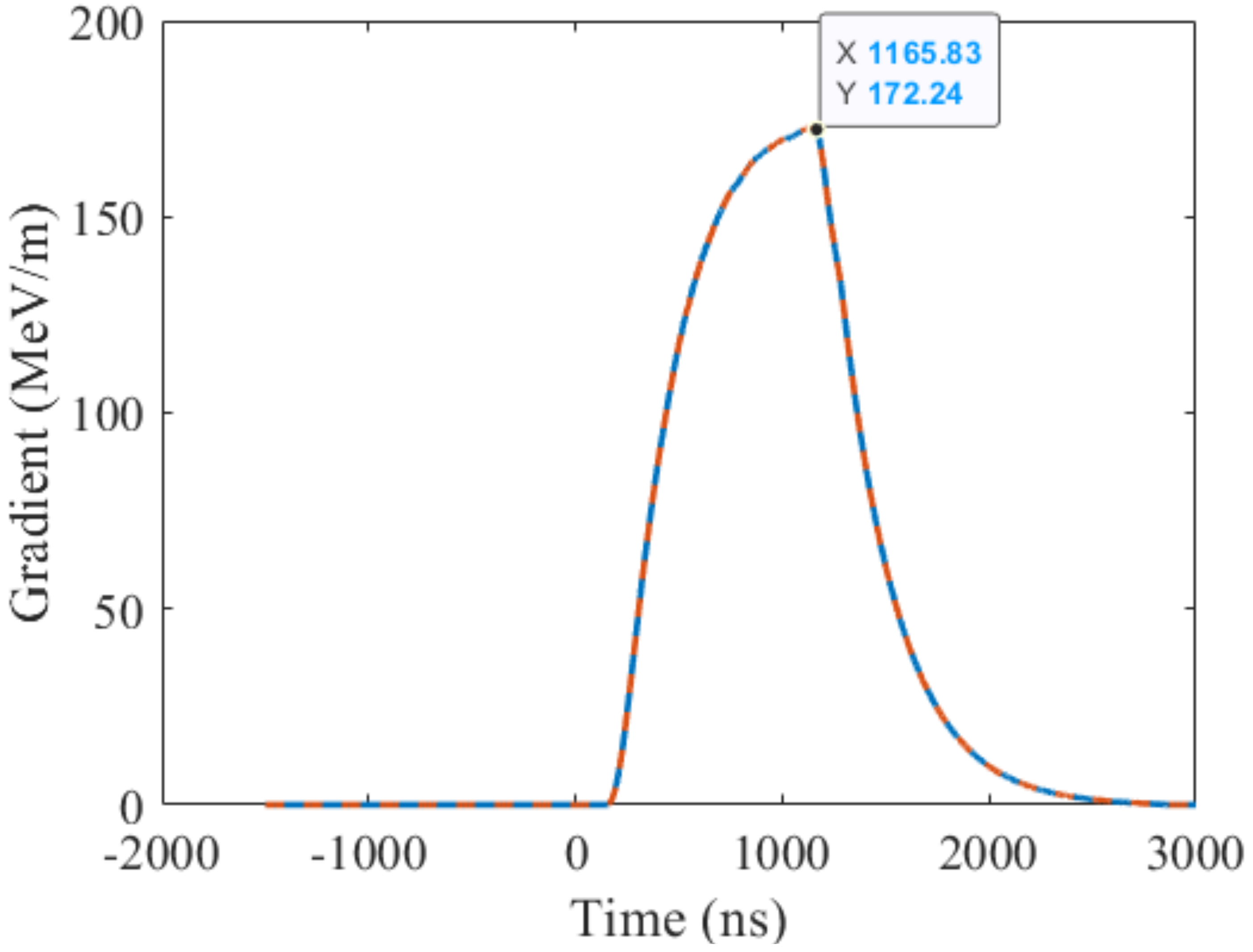
- First high gradient test at C-band
- Side coupled, split-cell reduced peak field, reduced phase adv.
- Exceed ultimate C^3 field strengths
- High power in up to 1 microsecond - break down rate statistics collected and being prepared for release

LANL Test of single cell SLAC C-band structure



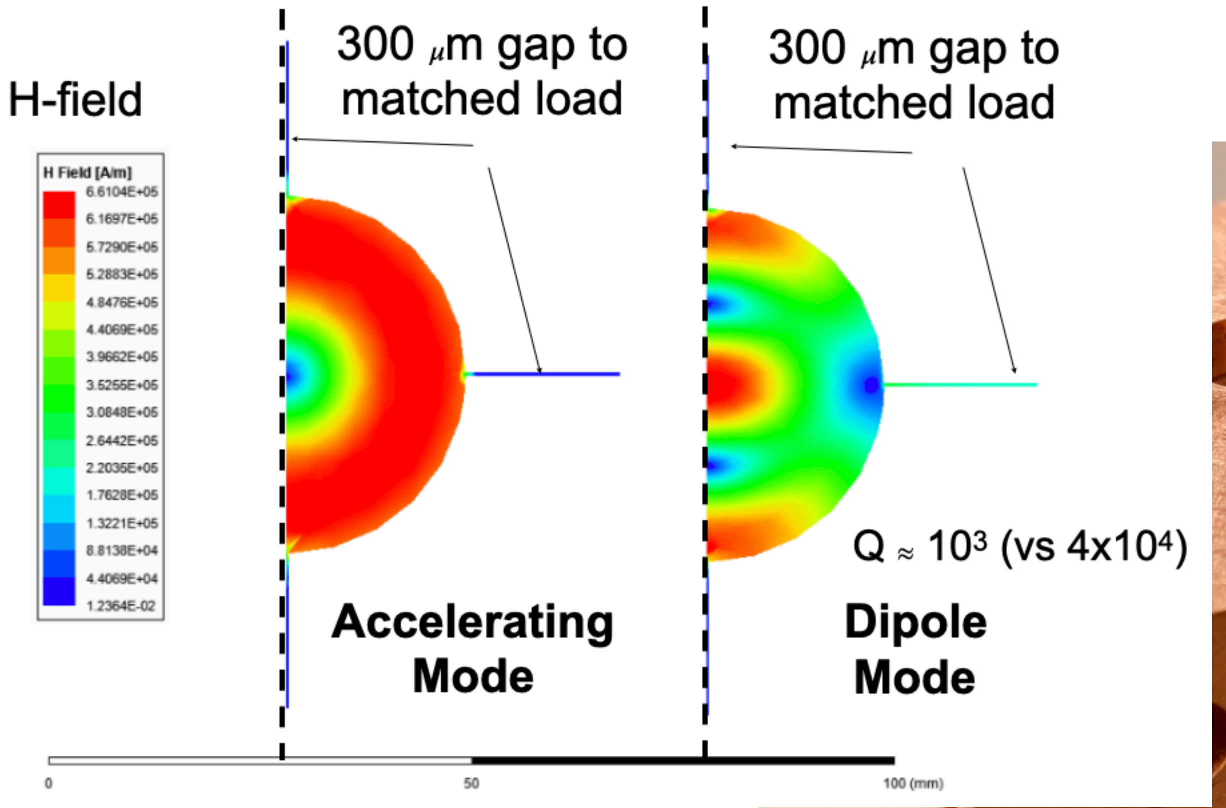


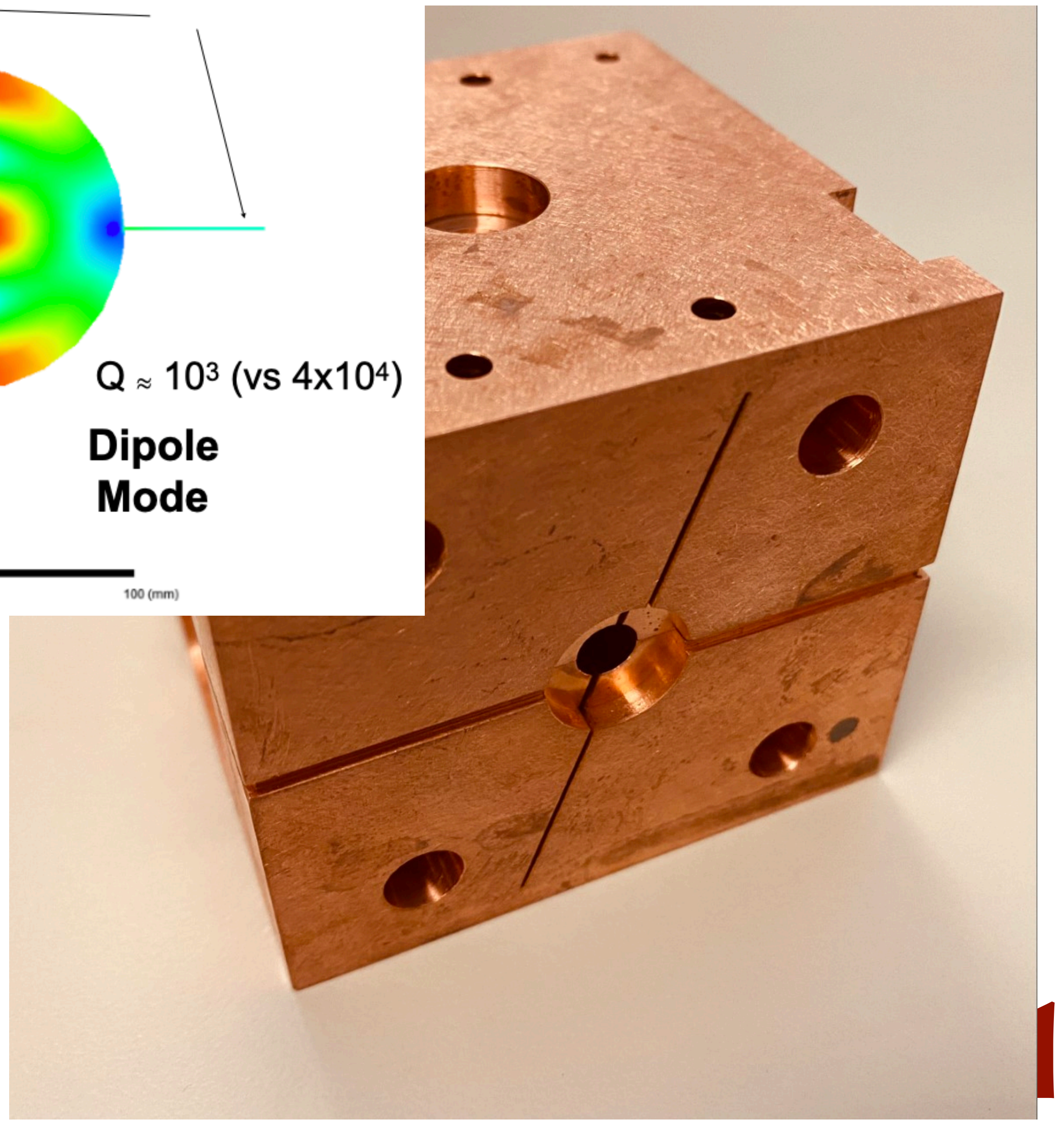
Structure Exceeds 120 MeV/m for 500 ns @ Room Temp BDR Data Collected



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

Slot Damping Prototype Working on NiCr Coating

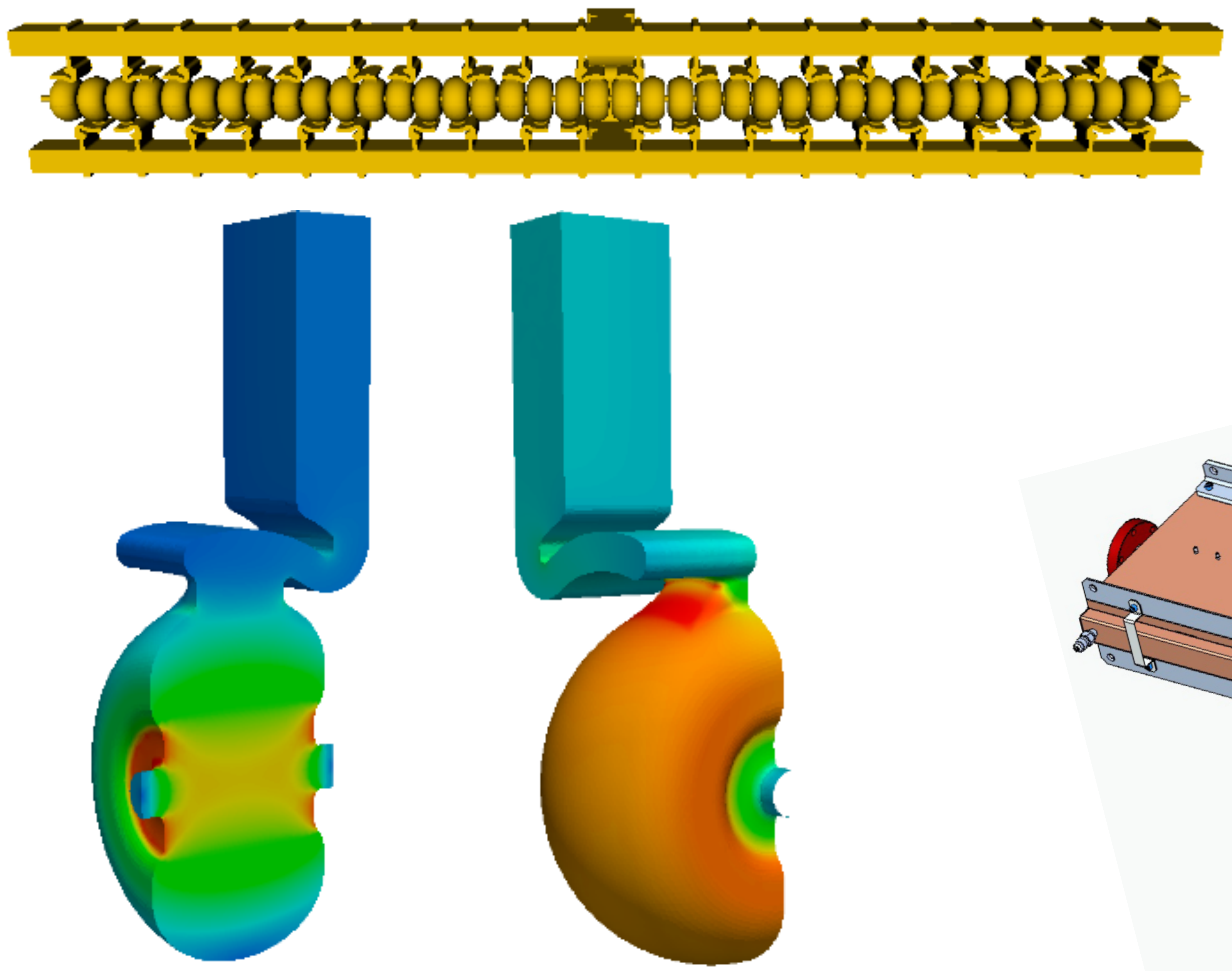




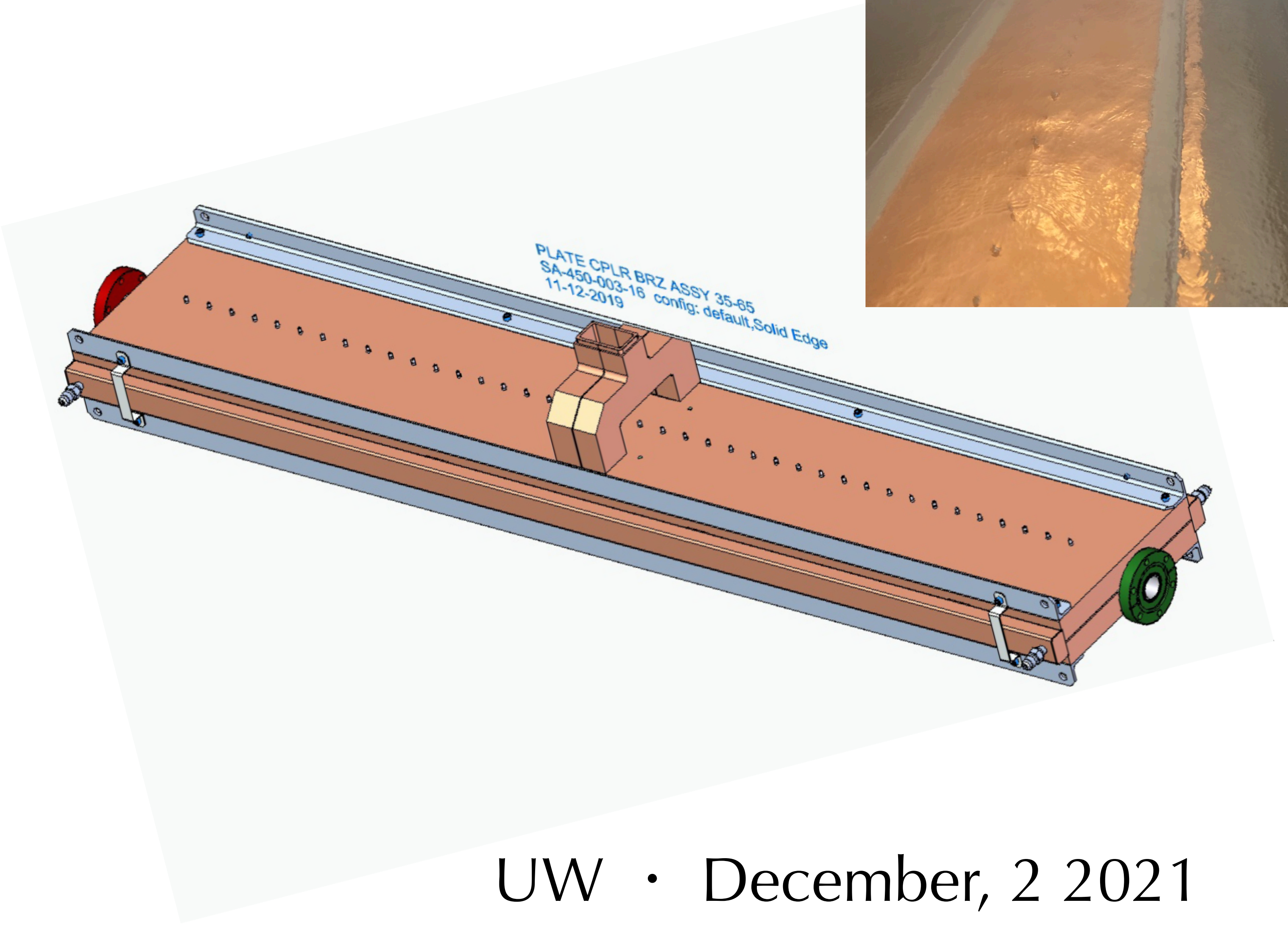
Development of C³ Accelerating Structure

- Incorporates two key technical advances: Distributed Coupling and Cryo-Copper RF
- Envision meter-scale accelerating structures, technology demonstration underway
- Implement optimized rf cavity designs to control peak surface fields

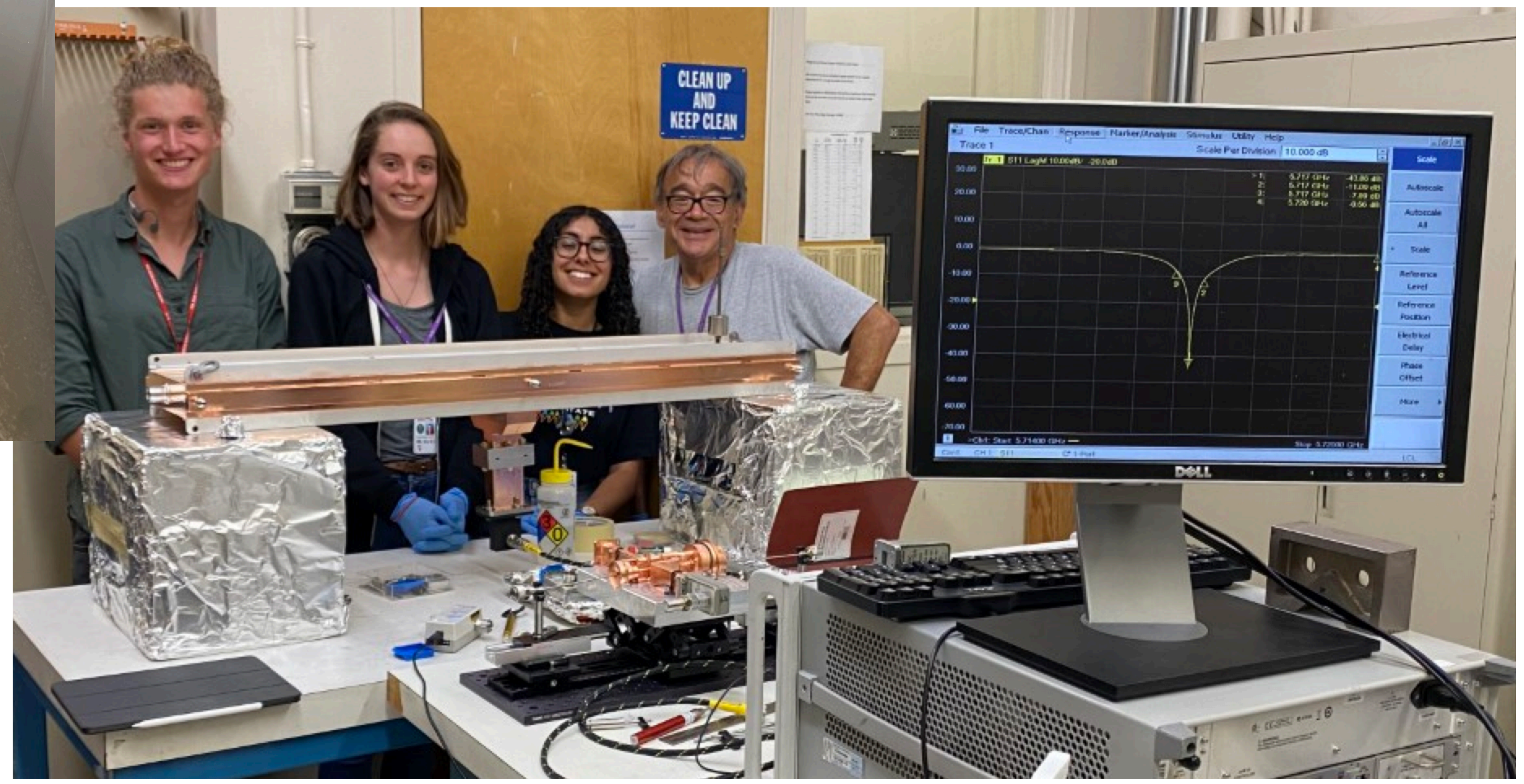
One meter (40-cell) C-band design with reduce peak E and H-field



Z. Li, S. Tantawi



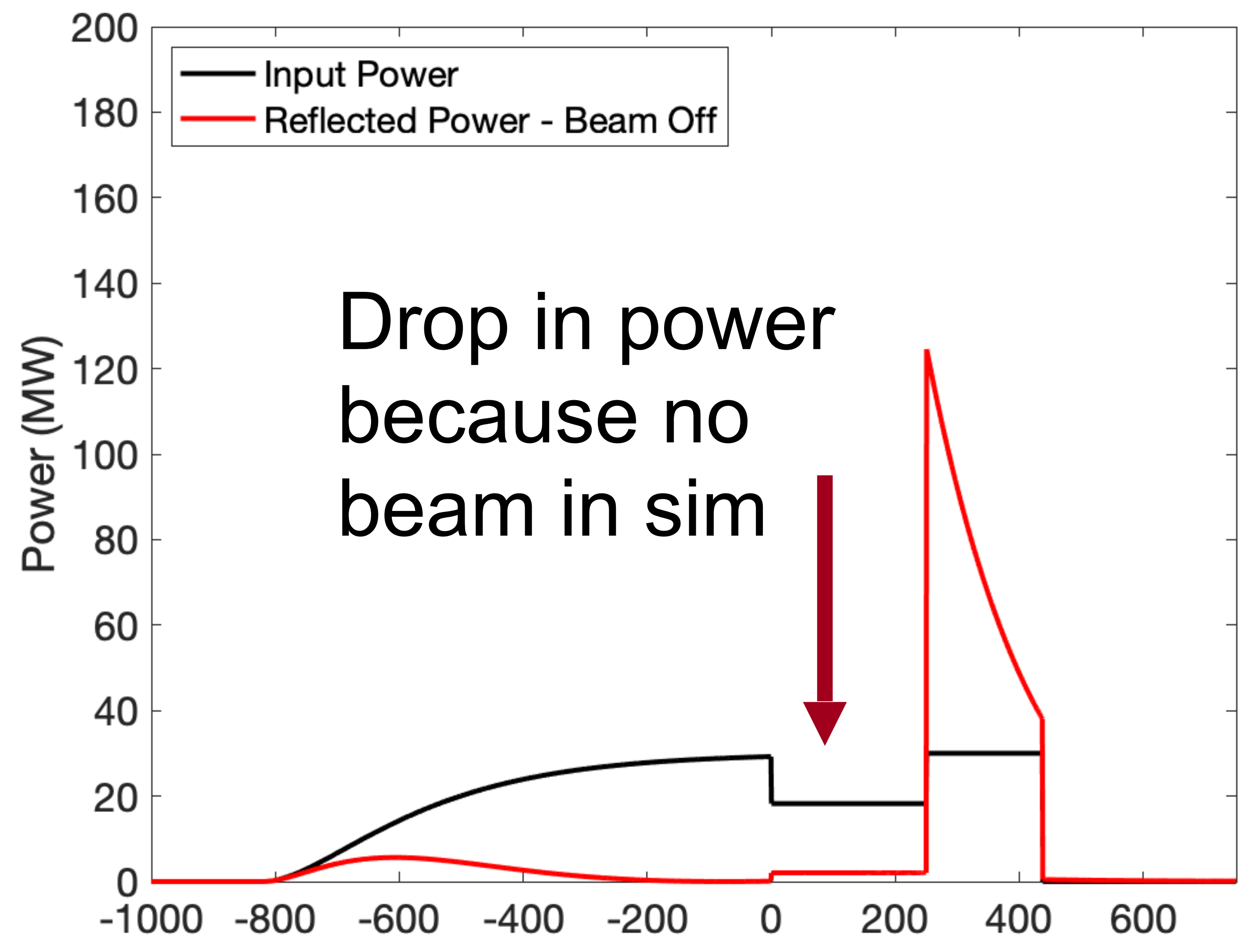
Scaling fabrication techniques in length and including controlled gap; tuned and confirmed performance at 77 K

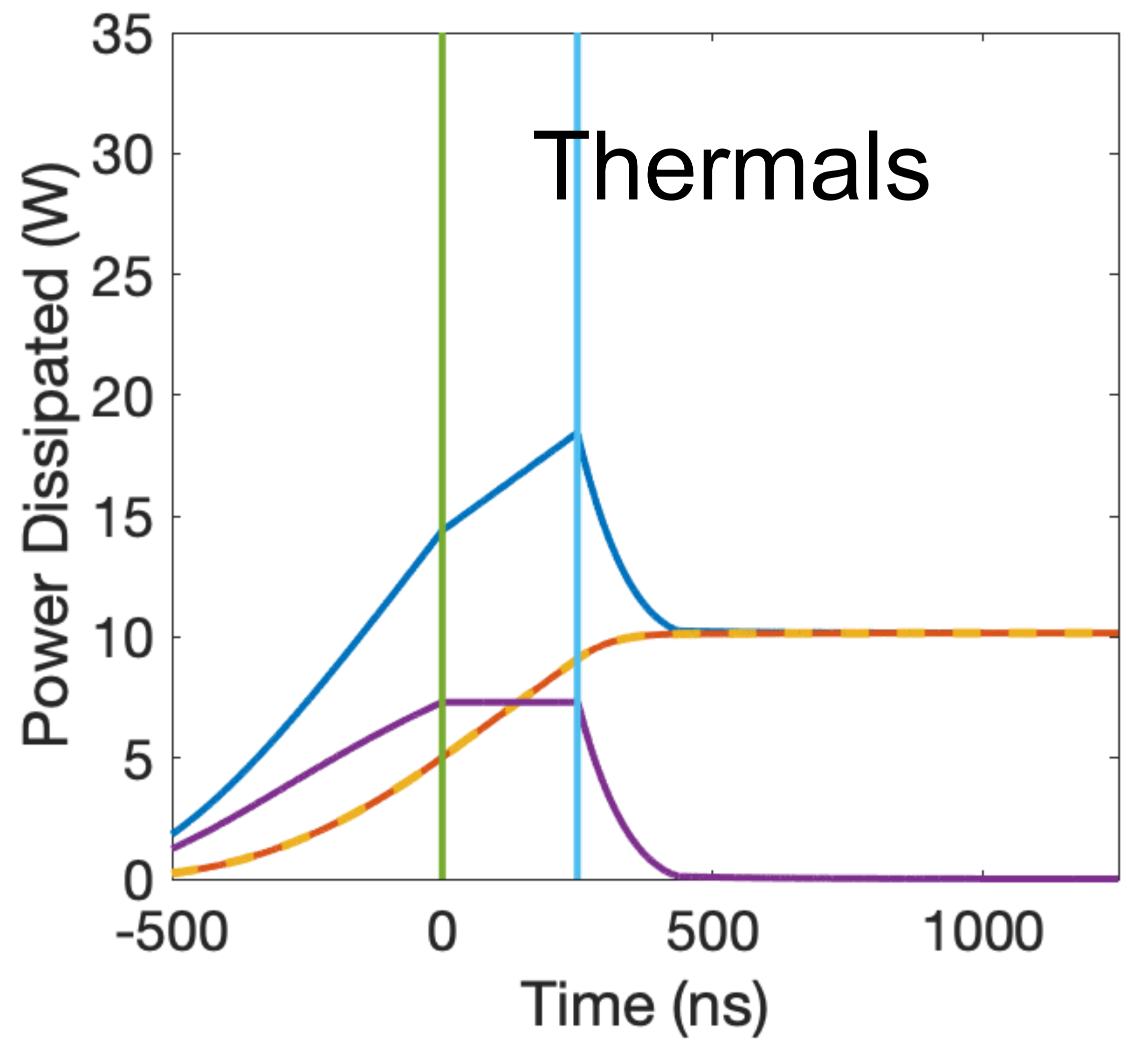


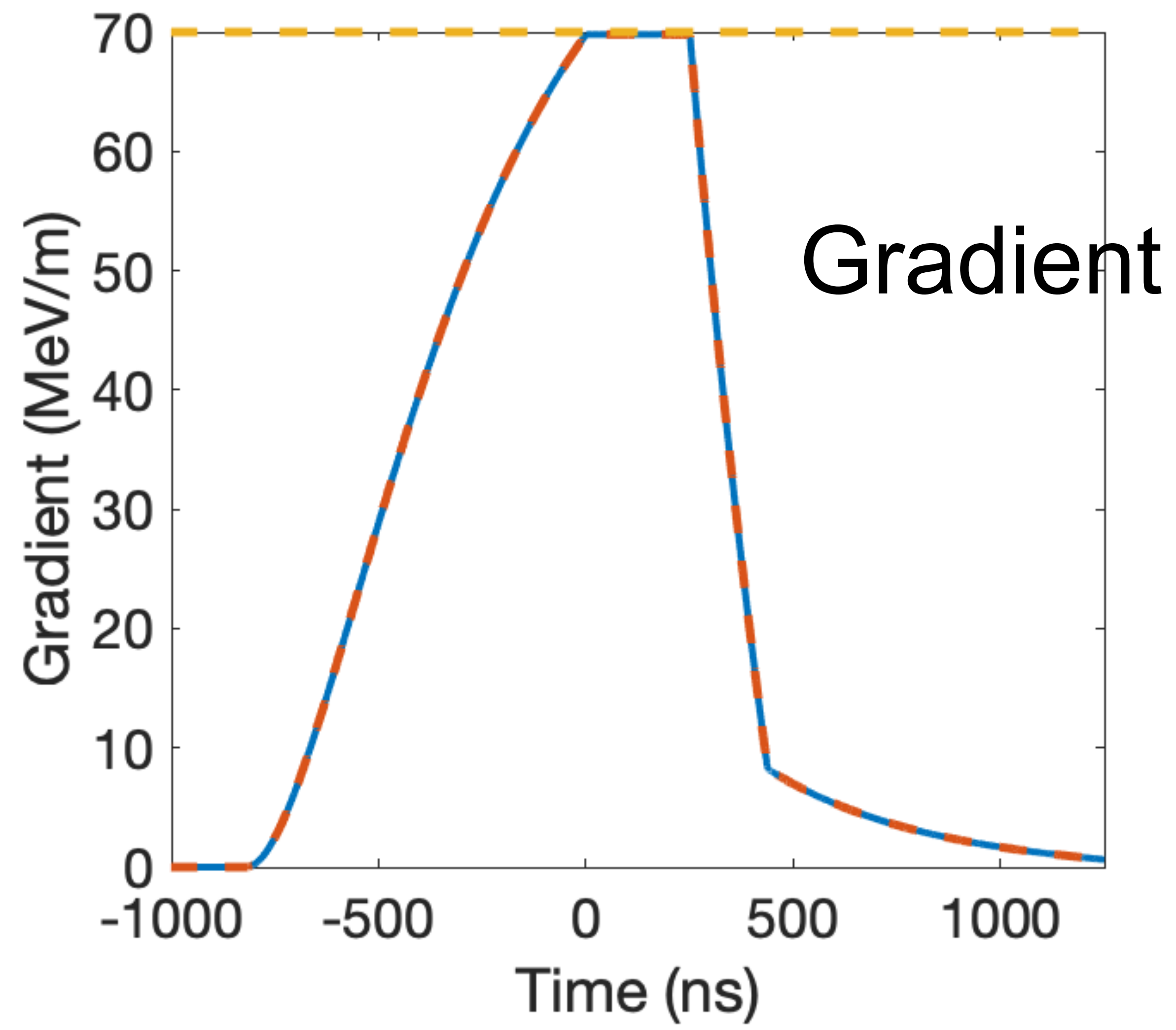
RF Power Requirements

- 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

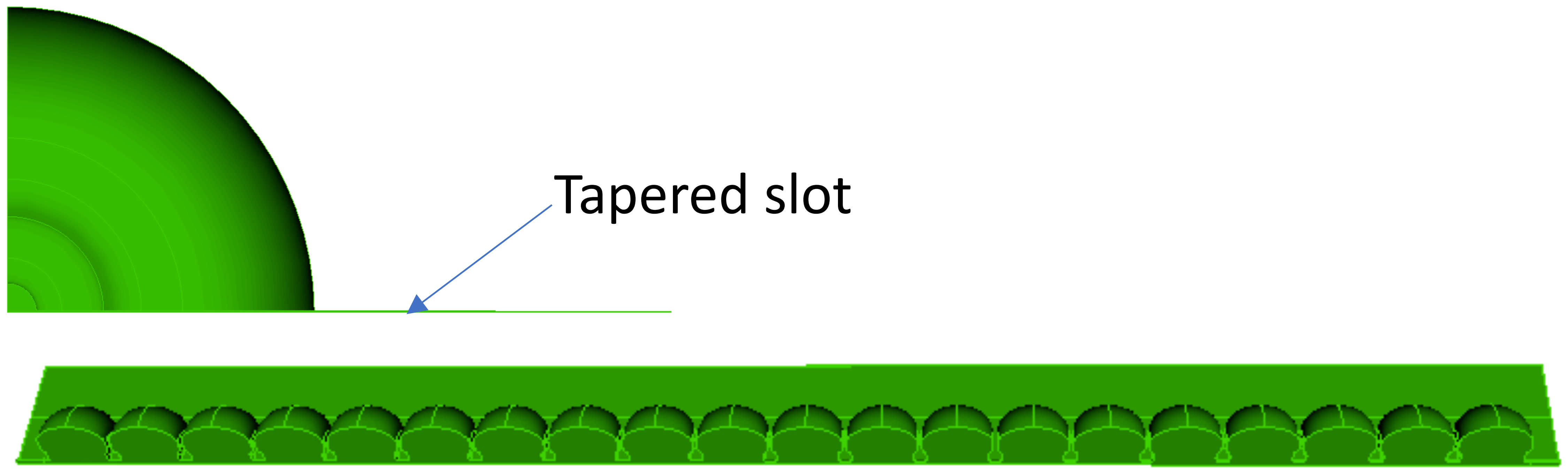


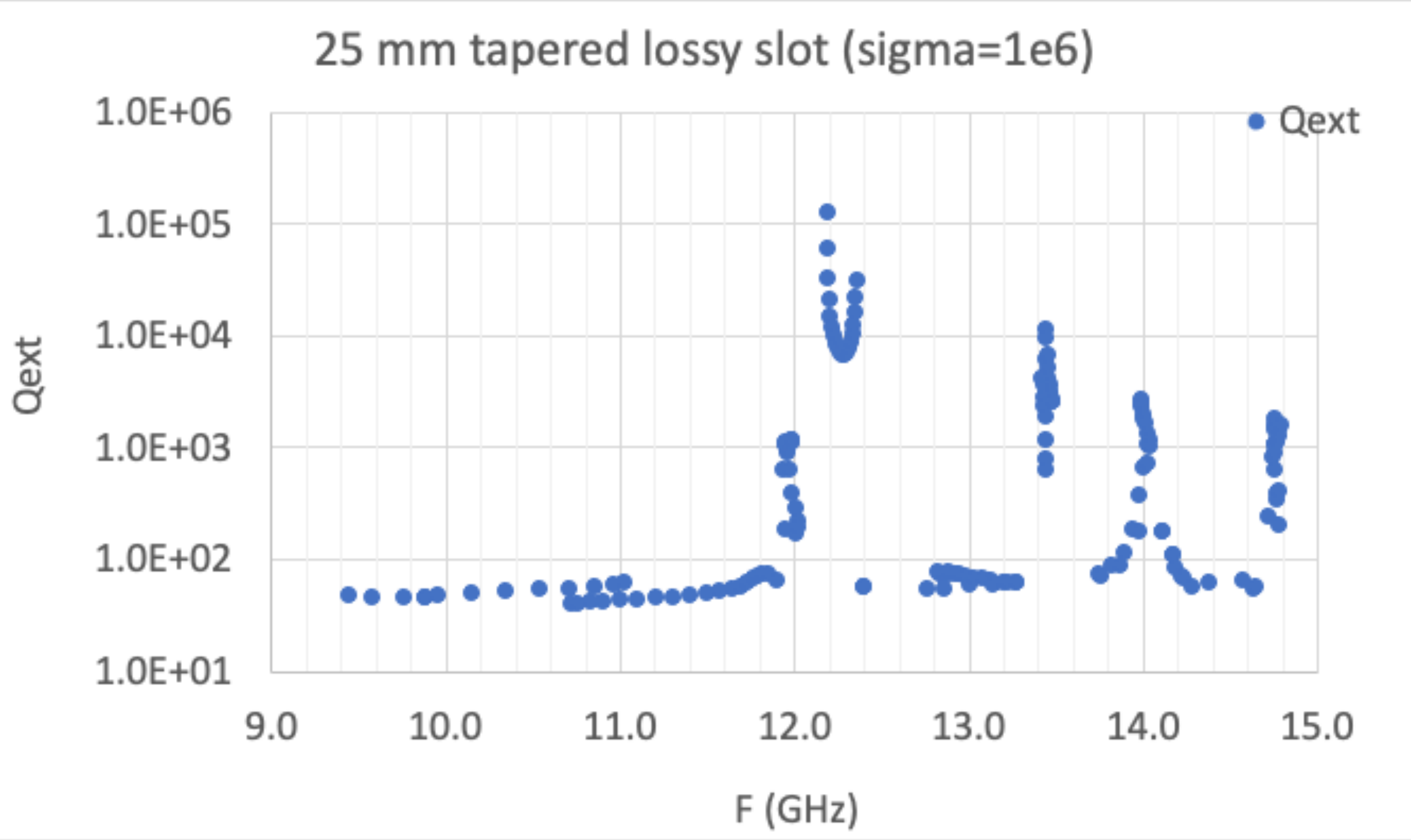


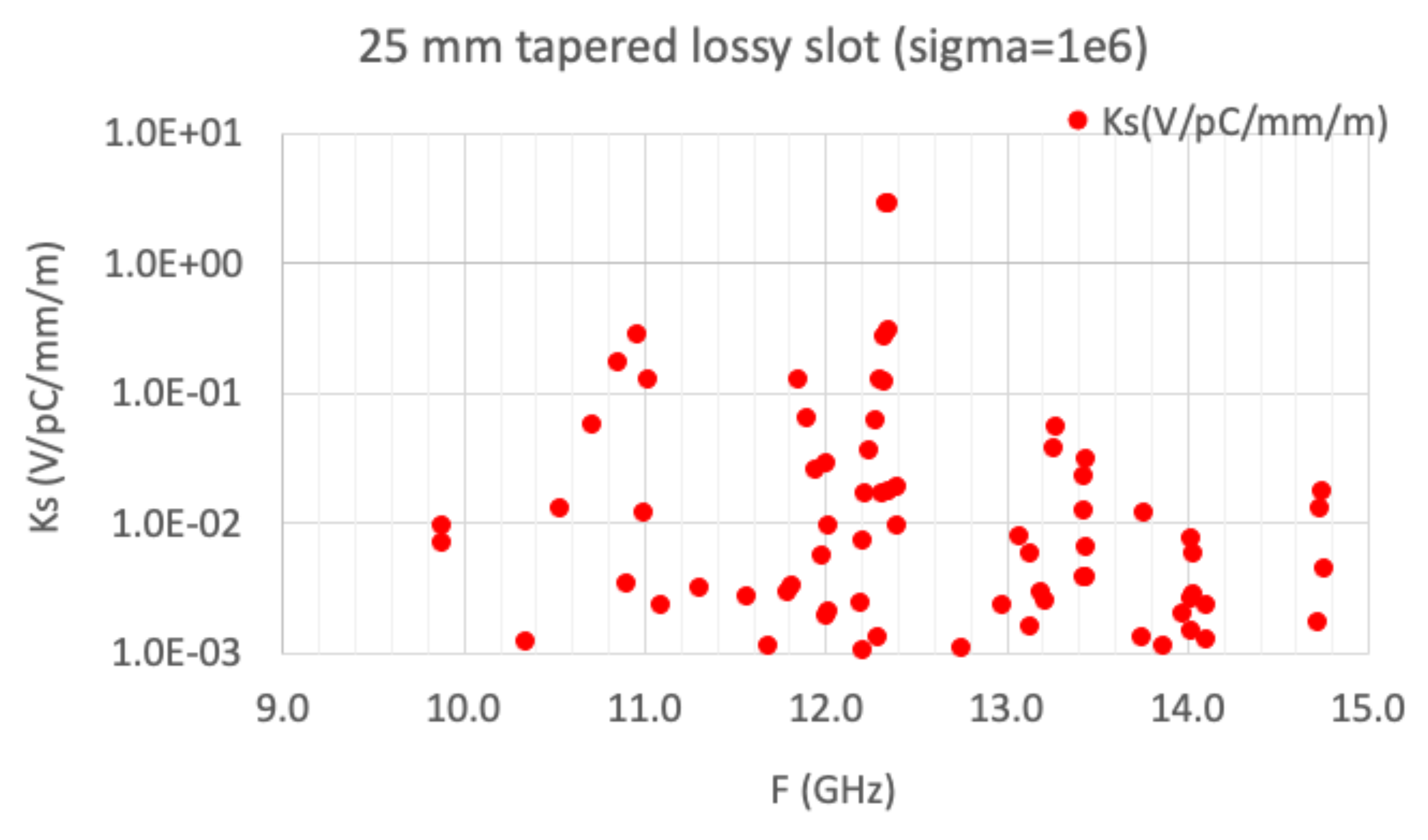


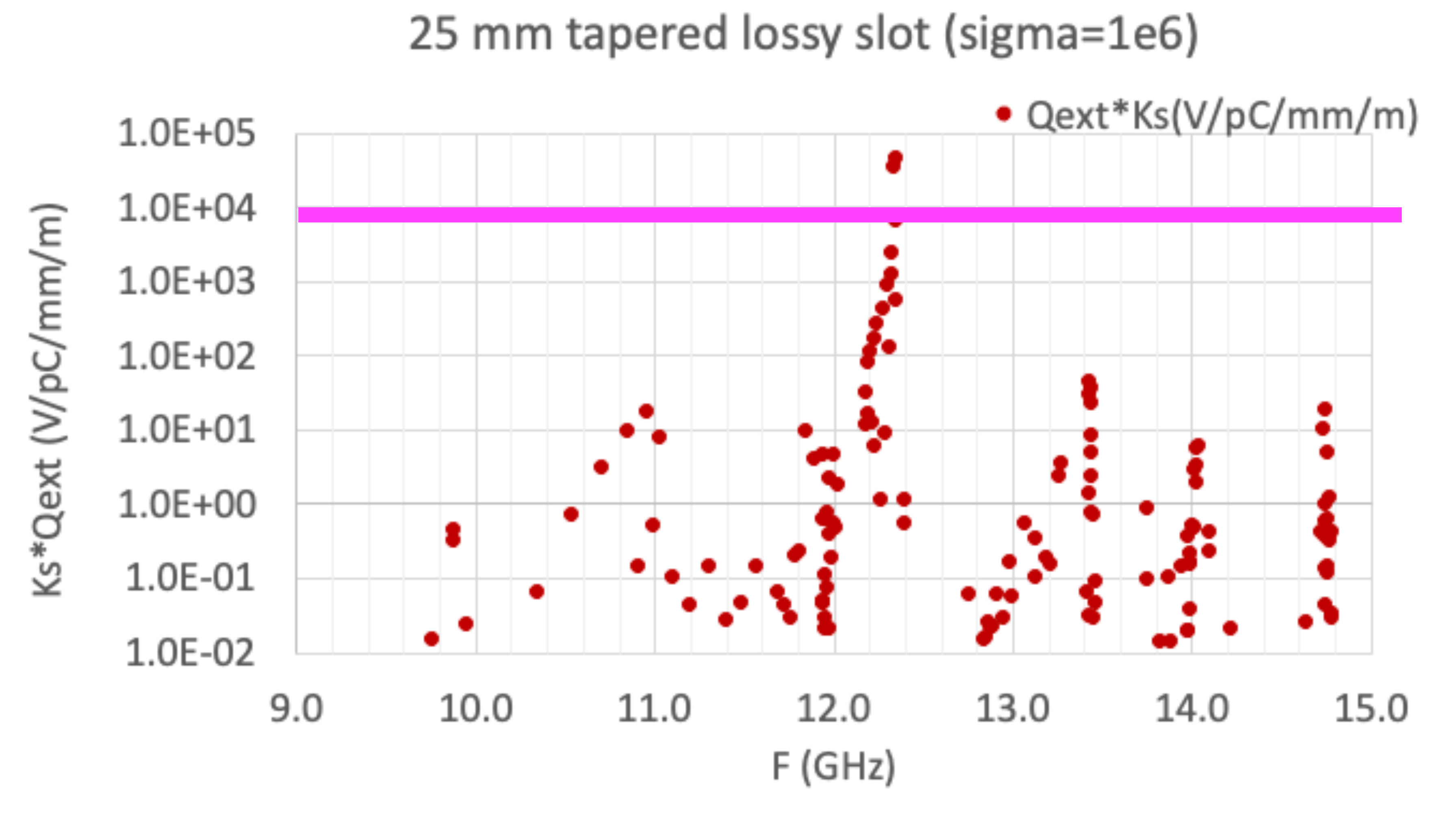
HOM Damping with Tapered Lossy Slot - Preliminary - Z. Li

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







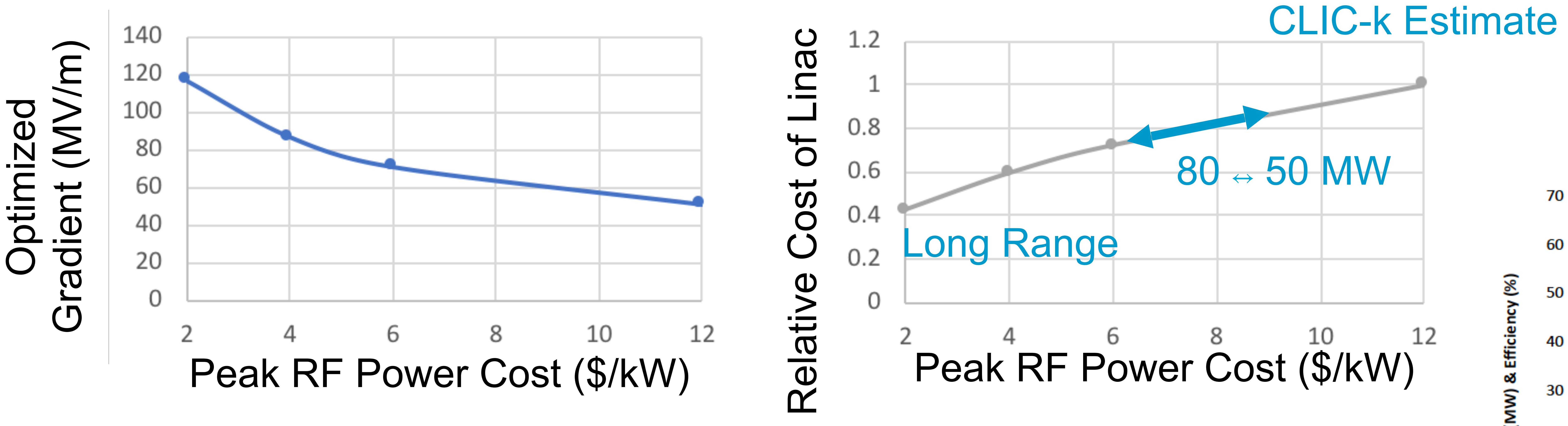


Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m

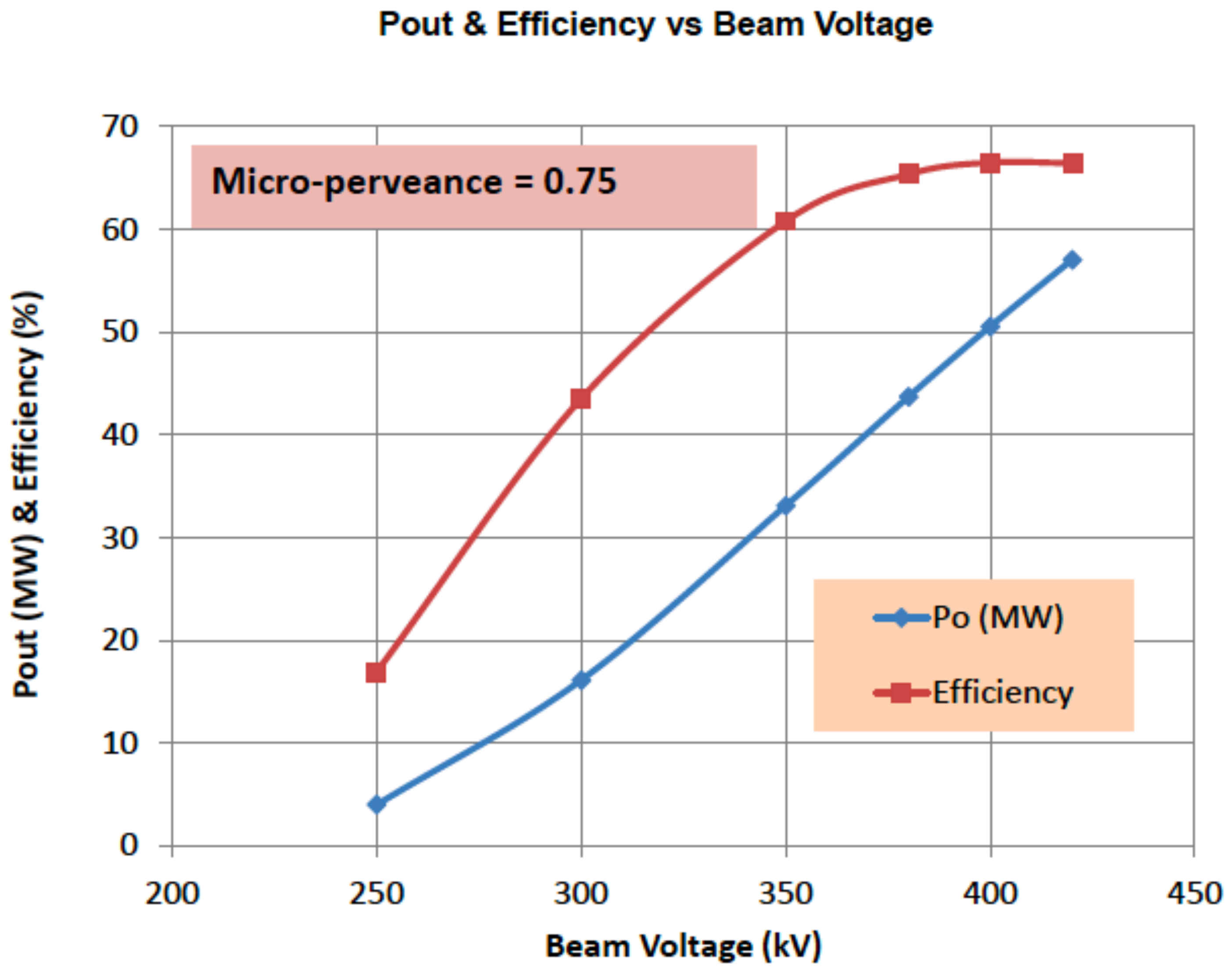
RF Source R&D Remains a Major Focus Over the Timescale of the Next P5

- 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



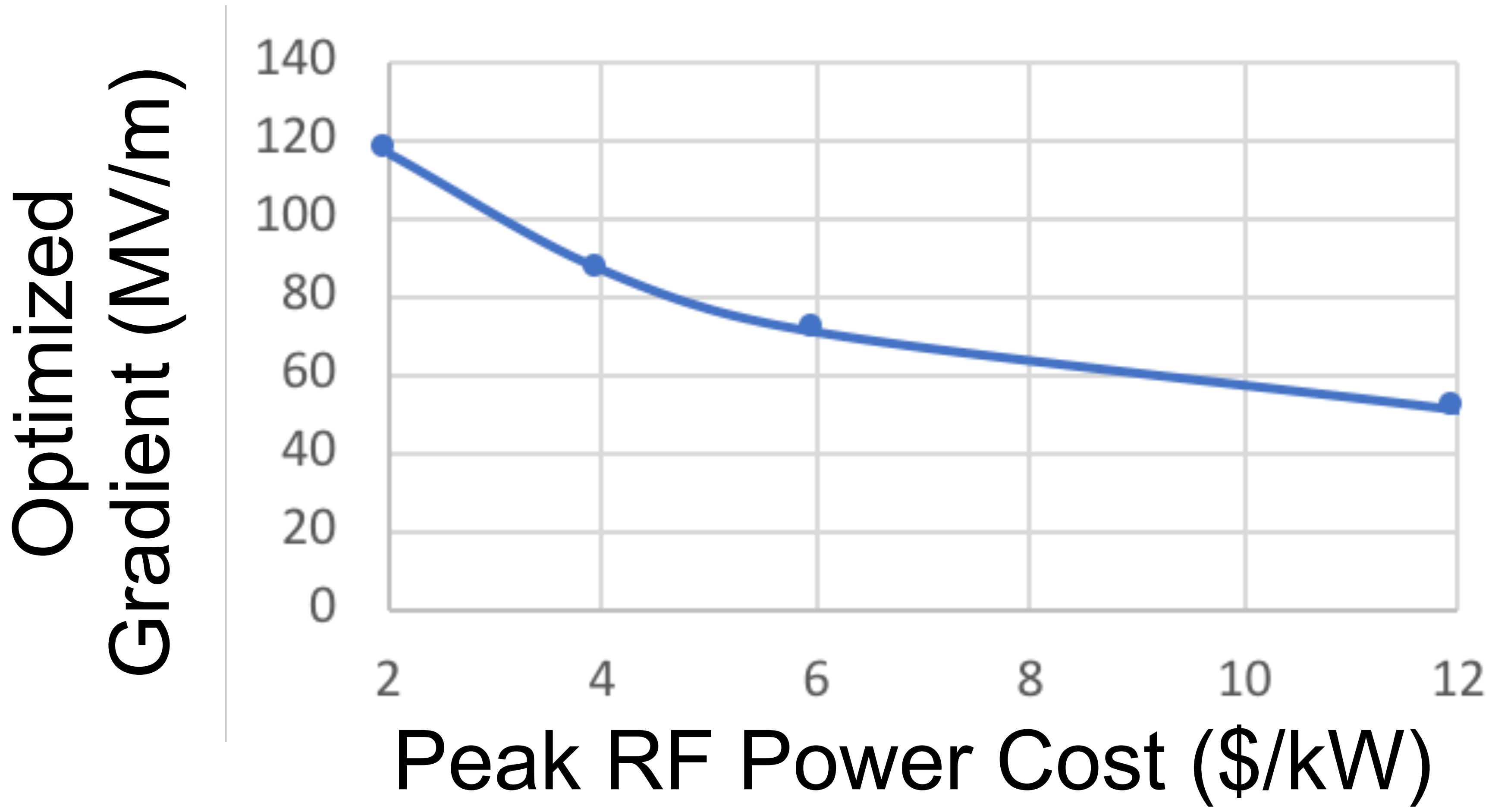
Understand the Impact on Advanced Collider Concept Enabled by the Goals Defined in the DOE GARD RF Decadal Roadmap

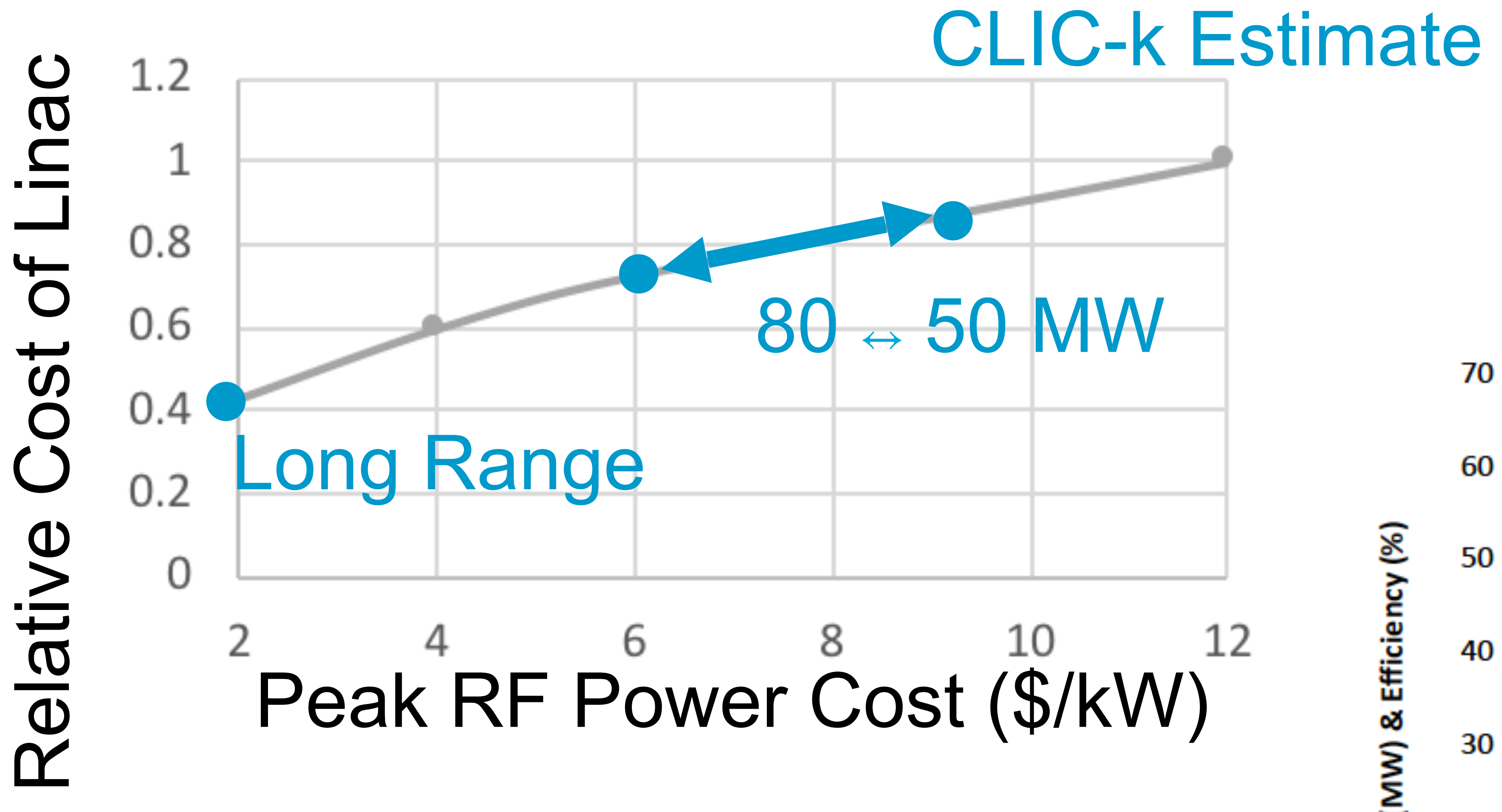
https://science.energy.gov/~/media/hep/pdf/Reports/DOE_HEP_GARD_RF_Research_Roadmap_Report.pdf

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

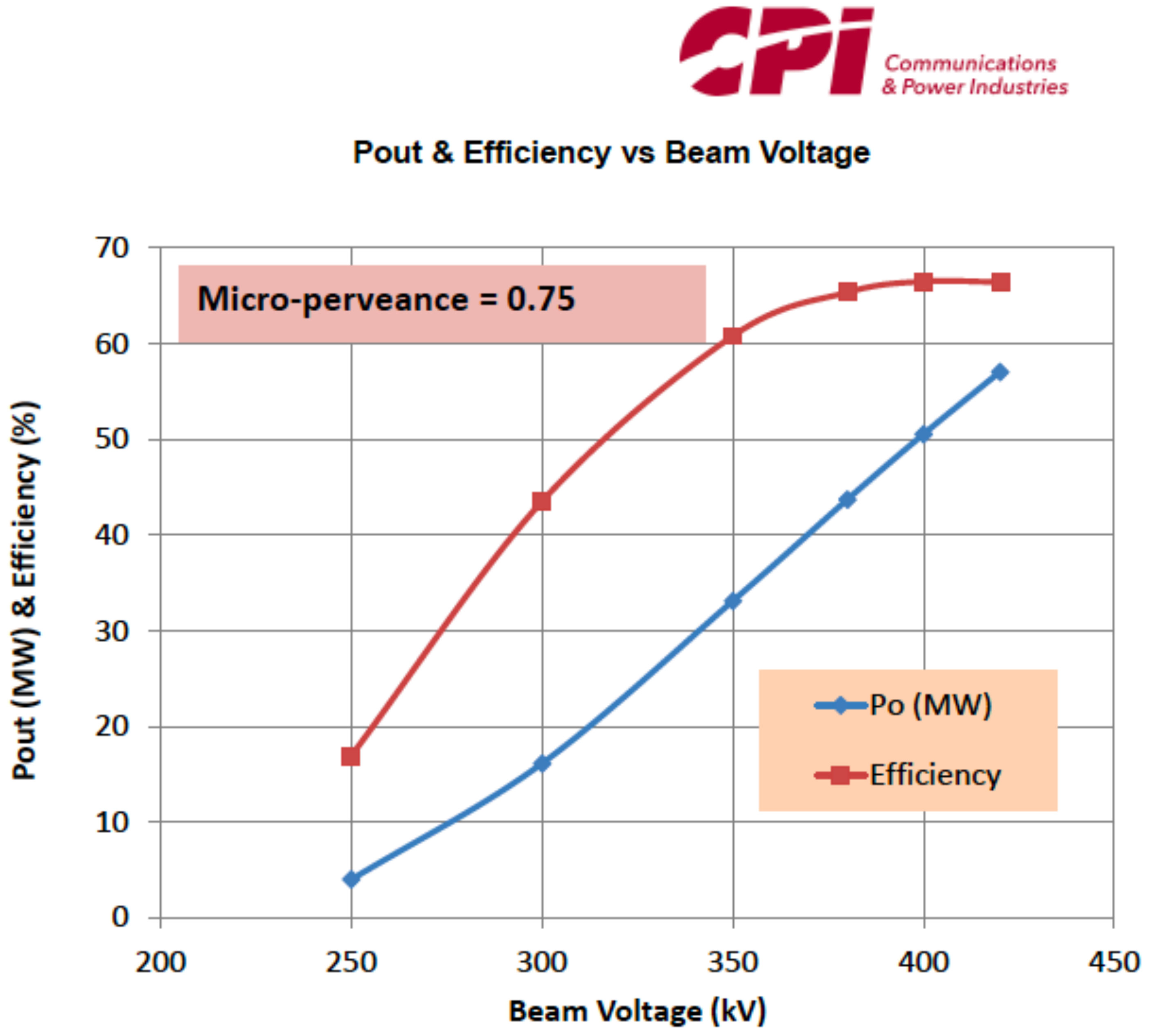
- Optimizing the cost of NCRF technology a fundamental requirement for its implementation for future facilities
- RF source cost is the key driver for gradient and cost – need to focus R&D on reducing source cost

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

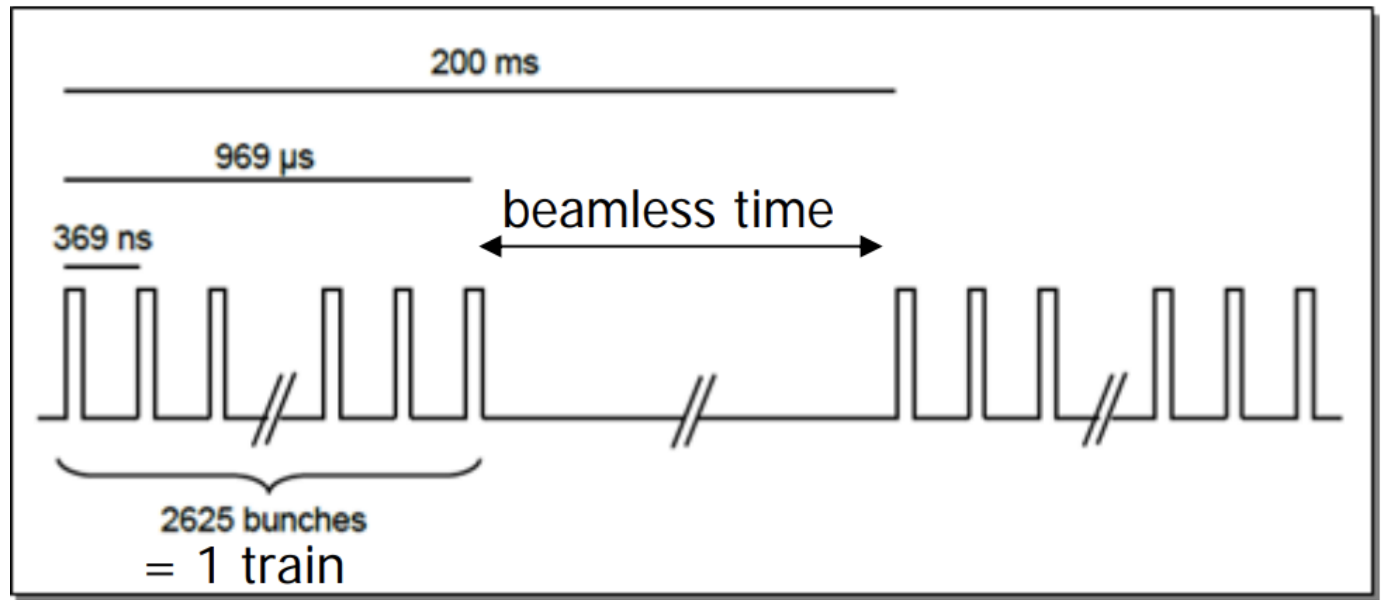
ILC timing structure: Fraction of a percent duty cycle

- **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

C³ 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

C³ timing structure