Roadmap of Particle Physics

International Meeting on
Fundamental Physics - Benasque
13 Sep 2024

Stéphane Willocq
Univ. of Massachusetts,
Amherst

Outline

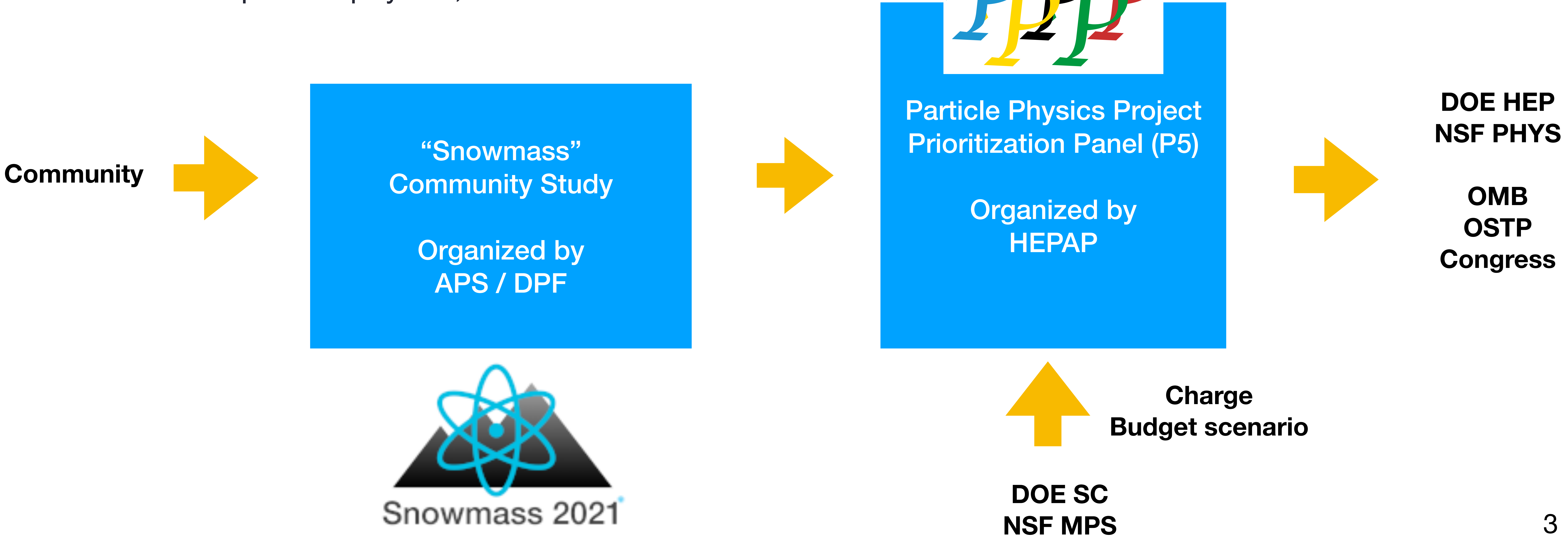
- **US particle physics long-range planning exercise**
  - **Snowmass 2021**
  - **Project prioritization (P5)**
    - Process
    - Recommendations
- **Outstanding physics questions**
  - **Energy frontier**
  - **Intensity frontier**
  - **Cosmic frontier**
- **Summary**

Exploring
the
Quantum
Universe

Important source of information on P5 report for this talk:
Presentation by H. Murayama on 2 Feb 2024 @CERN

US particle physics prioritization

- **Long-range planning for US participation in *global* particle physics:** https://usparticlephysics.org/
  - Broad process to collect community input: “Snowmass” 2021
  - Particle physics project prioritization panel (P5)
    - Report presenting 10-year strategic plan with 20-yr vision for US particle physics, released in Dec 2023



Community

“Snowmass”
Community Study

Organized by
APS / DPF

Snowmass 2021

Particle Physics Project
Prioritization Panel (P5)

Organized by
HEPAP

Charge
Budget scenario

DOE SC
NSF MPS

DOE HEP
NSF PHYS

OMB
OSTP
Congress

US particle physics prioritization

- **Long-range planning for US participation in *global* particle physics:** https://usparticlephysics.org/
  - Broad process to collect community input: “Snowmass” 2021
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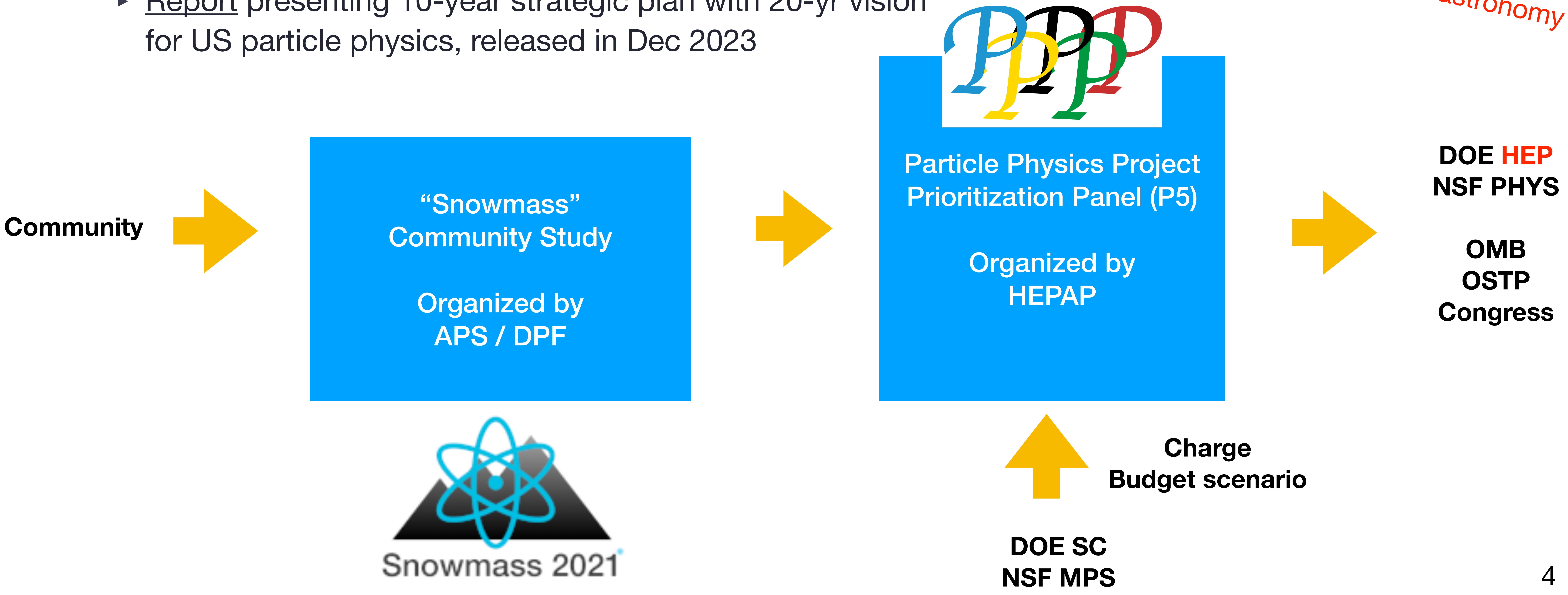
NOTE: separate process carried out for nuclear physics and astronomy



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Snowmass 2021

Particle Physics Project Prioritization Panel (P5)

Organized by HEPAP

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DOE SC
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Snowmass community planning exercise

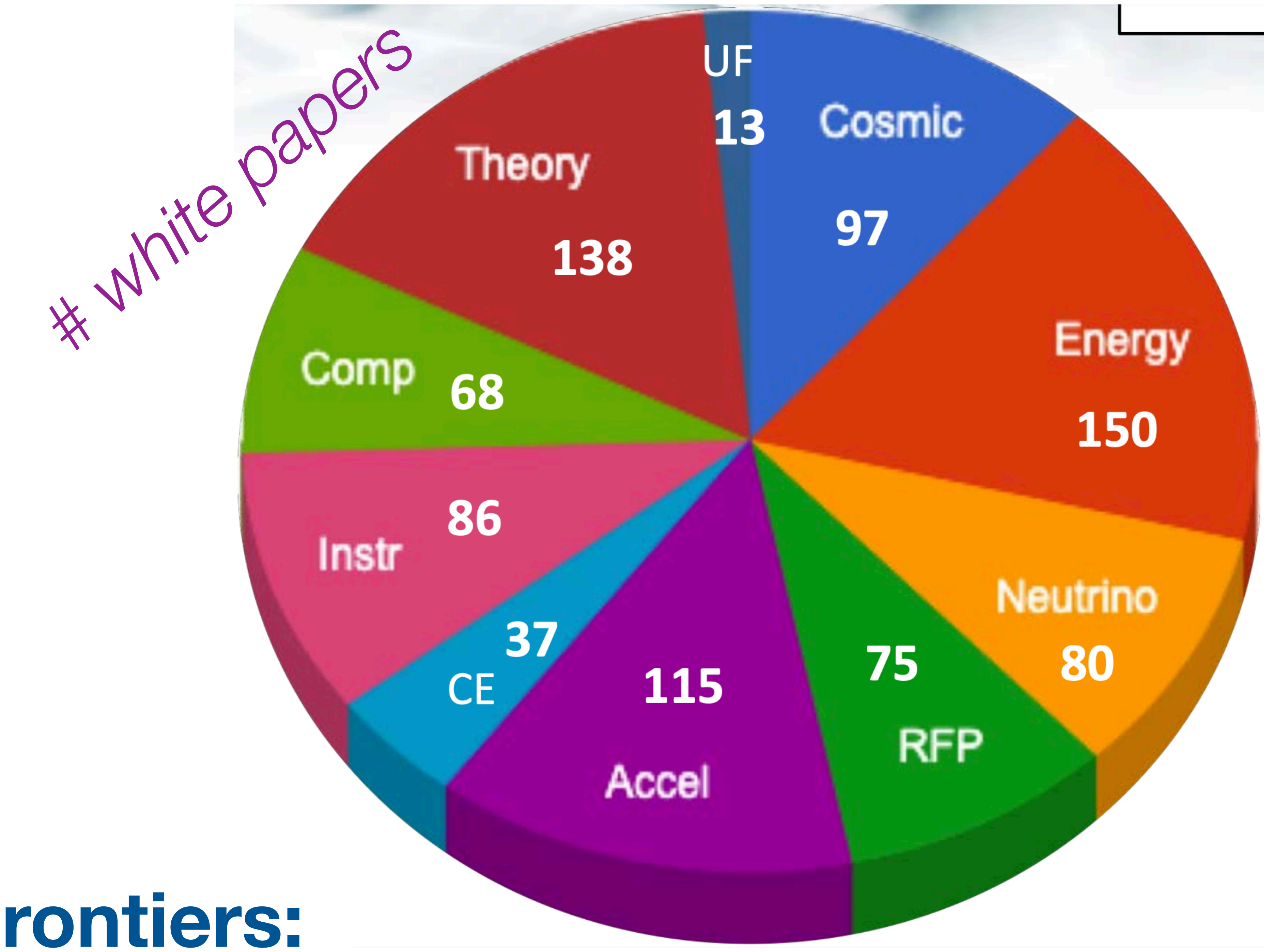
- **US particle physics community gathering** traditionally held in Snowmass, Colorado
- First meeting in 1982 (Snowmass '82 proceedings), organized by Division of Particles & Fields of American Physical Society
    - First US planning exercise open to the community
    - Purpose:
      "*Assess the future of elementary particle physics, to explore the limits of our technological capabilities, and to consider the nature of future major facilities for particle physics in the U.S.*"
- Following meetings:
    - Snowmass '84 on design and utilization of SSC (proceedings)
    - Snowmass '86 on physics of SSC (proceedings)
    - Snowmass '88 on HEP in 1990's (proceedings)
    - Snowmass '90 on research directions for the decade (proceedings)
    - Snowmass '94 on particle astrophysics and cosmology (proceedings)
    - Snowmass '96 on new directions in HEP (proceedings)
    - Snowmass 2001 on future of particle physics (web, proceedings)
    - Snowmass 2005 on linear collider physics and detector (proceedings)

Snowmass community planning exercise

- **Evolving meeting structure**
  - Multi-week workshop format replaced by work and satellite meetings spread over ~1 year
  - Culminating in final meeting with parallel sessions, plenary colloquia, panel discussions, and concluding talks
- **Evolving topics**
  - Initially focused on major accelerator projects
  - Inclusion of broader portfolio with small-, mid-, and large-scale projects, including non-accelerator expts, cosmology
- "**Snowmass on the Mississippi**" 2013 on long-range US HEP plans (agenda)
  - 8 "frontiers" working groups
    - Energy
    - Intensity
    - Cosmic
    - Instrumentation
    - Facilities
    - Computation
    - Education and Outreach
    - Theory

Snowmass 2021 (—> 2022)

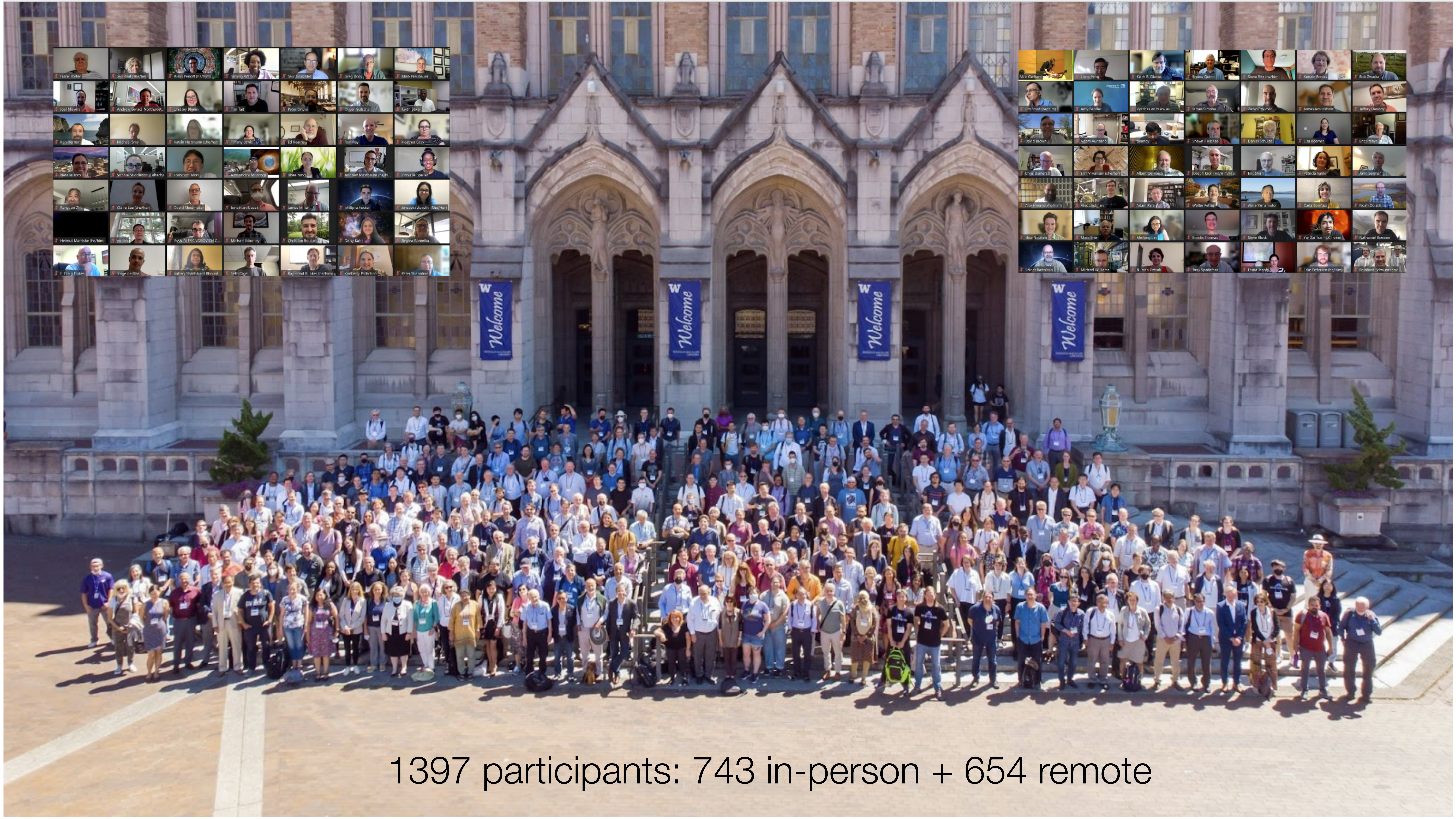
- **Snowmass 2021 community planning exercise** [delayed 1 year by covid] (web, proceedings)
    - 512 white papers —> 79 topical group reports —> 10 frontier summaries (715-page book!)
- **Final meeting**
    - 17-26 July 2022 in Seattle (web)
- **Areas of focus**
    - Science
        - Identify most compelling questions to address
    - Tools and infrastructure
        - Accelerators, detectors, computing, software
        - Theory
    - Human resources
        - Enabling researchers: training, DEI, outreach



Frontiers:

Energy	Instrumentation
Cosmic	Accelerator
Neutrinos	Underground facilities
Rare processes & precision	Computation
	Community engagement
	Theory

Snowmass 2021: Final workshop 17-26 July 2022 in Seattle



1397 participants: 743 in-person + 654 remote

Particle physics project prioritization panel (P5)

HEPAP = High Energy Physics Advisory Panel

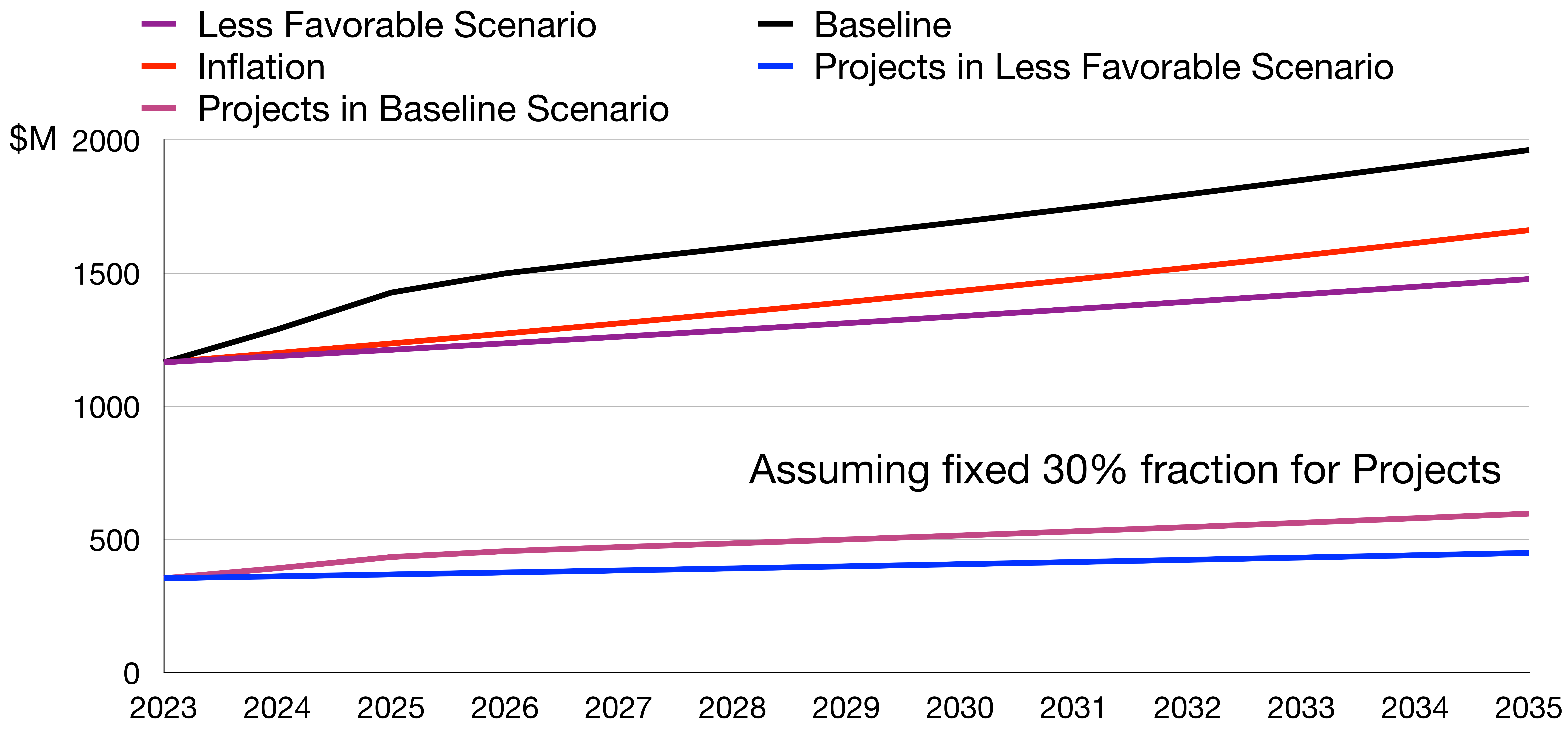
- **What is P5?**
  - Temporary sub-committee of HEPAP which advises US funding agencies (DOE and NSF)
- **P5 charge**
  - Develop a 10-year strategic plan for US particle physics within two budget scenarios
  - Provide a set of prioritized recommendations for US investment in particle physics research
- **Process**
  - Diverse panel of 32 members covering wide range of expertise areas —> panel complete in Jan '23
  - Input sources:
    - Snowmass 2021 community planning
    - Town hall meetings (4 labs + 2 univ.), laboratory visits, and individual communications
    - Funding agencies
    - Sub-committee on costs / risks / schedule
  - Intense panel deliberations with final decisions by consensus —> final report released in Dec '23

P5 members

Shoji Asai (University of Tokyo)
Amalia Ballarino (CERN)
Tulika Bose (Wisconsin–Madison)
Kyle Cranmer (Wisconsin–Madison)
Francis-Yan Cyr-Racine (New Mexico)
Sarah Demers (Yale)
Cameron Geddes (LBNL)
Yuri Gershtein (Rutgers)
Karsten Heeger (Yale) **-** ***Deputy Chair***
Beate Heinemann (DESY)
JoAnne Hewett (SLAC) - HEPAP chair, ex officio until May 2023
Patrick Huber (Virginia Tech)
Kendall Mahn (Michigan State)
Rachel Mandelbaum (Carnegie Mellon)
Jelena Maricic (Hawaii)
Petra Merkel (Fermilab)
Christopher Monahan (William & Mary)
Hitoshi Murayama (Berkeley) **-** ***Chair***
Peter Onyisi (Texas Austin)
Mark Palmer (BNL)
Tor Raubenheimer (SLAC/Stanford)
Mayly Sanchez (Florida State)
Richard Schnee (South Dakota School of Mines & Technology)
Sally Seidel (New Mexico) – interim HEPAP chair, ex officio since June 2023
Seon-Hee Seo (IBS Center for Underground Physics until Sep, Fermilab since Sep)
Jesse Thaler (MIT)
Christos Touramanis (Liverpool)
Abigail Vieregg (Chicago)
Amanda Weinstein (Iowa State)
Lindley Winslow (MIT)
Tien-Tien Yu (Oregon)
Robert Zwaska (Fermilab)

Blue: international members

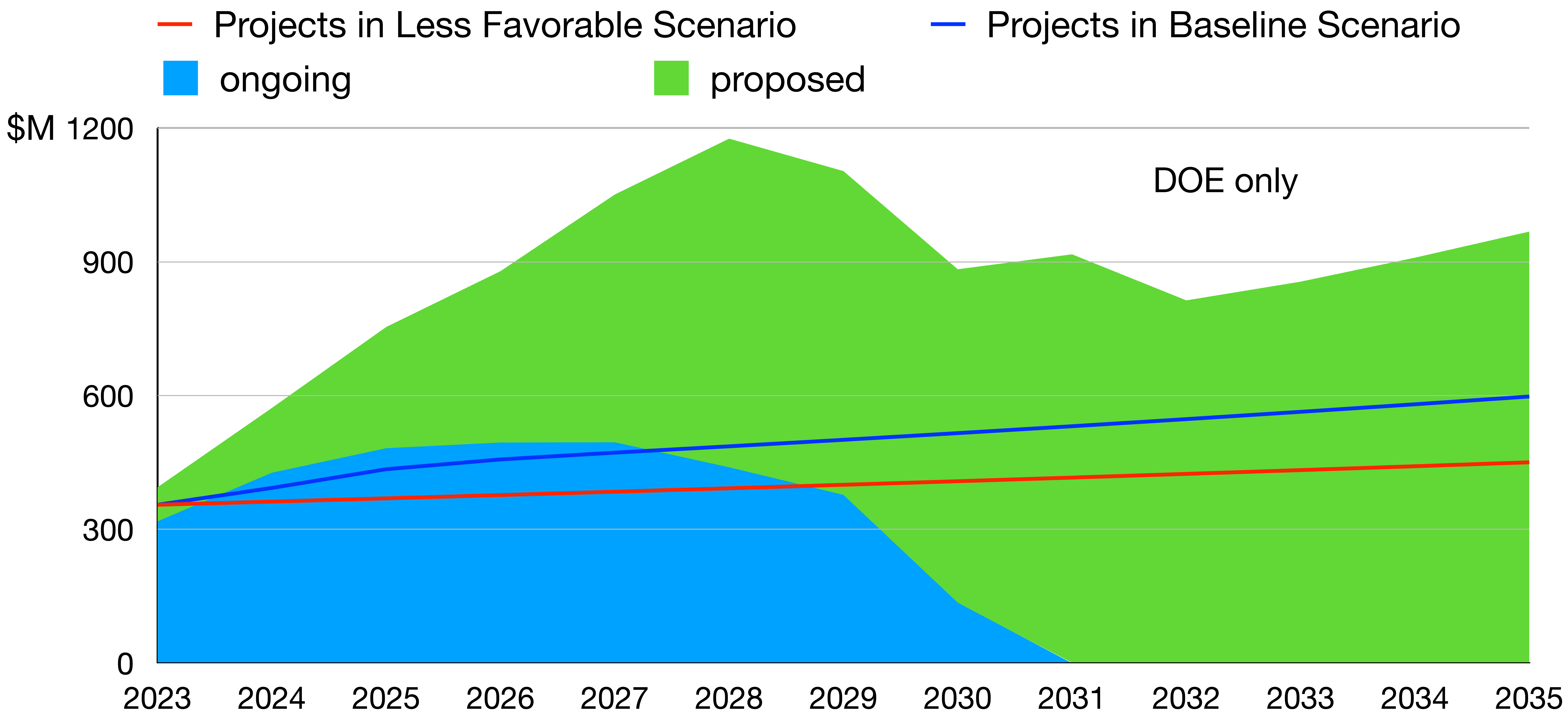
Budget scenarios (overall, including projects)



DOE only

Budget scenarios for projects

Cost of proposals before prioritization (other than excluding on-shore Higgs factory)



P5 sub-committee on costs / risks / schedule

- Costs / risks / schedule sub-committee
  - Crucial input on maturity of cost estimates, risks, and schedule
  - Interacted with project proponents to make independent estimates of costs and schedule, and providing a sort of uncertainty band on those
- Members
  - **Jay Marx (Caltech), Chair**
  - Gil Gilchriese, Matthaeus Leitner (LBNL)
  - Giorgio Apollinari, Doug Glenzinski (Fermilab)
  - Mark Reichanadter, Nadine Kurita, John Seeman (SLAC)
  - Jon Kotcher, Srini Rajagopalan (BNL)
  - Allison Lung (JLab)
  - Harry Weerts (Argonne)

P5 considerations toward decision

- **Considerations**
  - *Ambitious proposals ranked according to scientific merit, design maturity, and fit within budgetary profile constraints*
  - Balance of large-, medium-, and small-scale experiments, and time scales
  - Balance over science drivers
  - Balance of on-shore and off-shore projects
  - Enabling US leadership in core areas of particle physics
  - Current projects vs. future investments
  - Support for theory, accelerator R&D, instrumentation, computing

P5 report: Themes & science drivers

Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

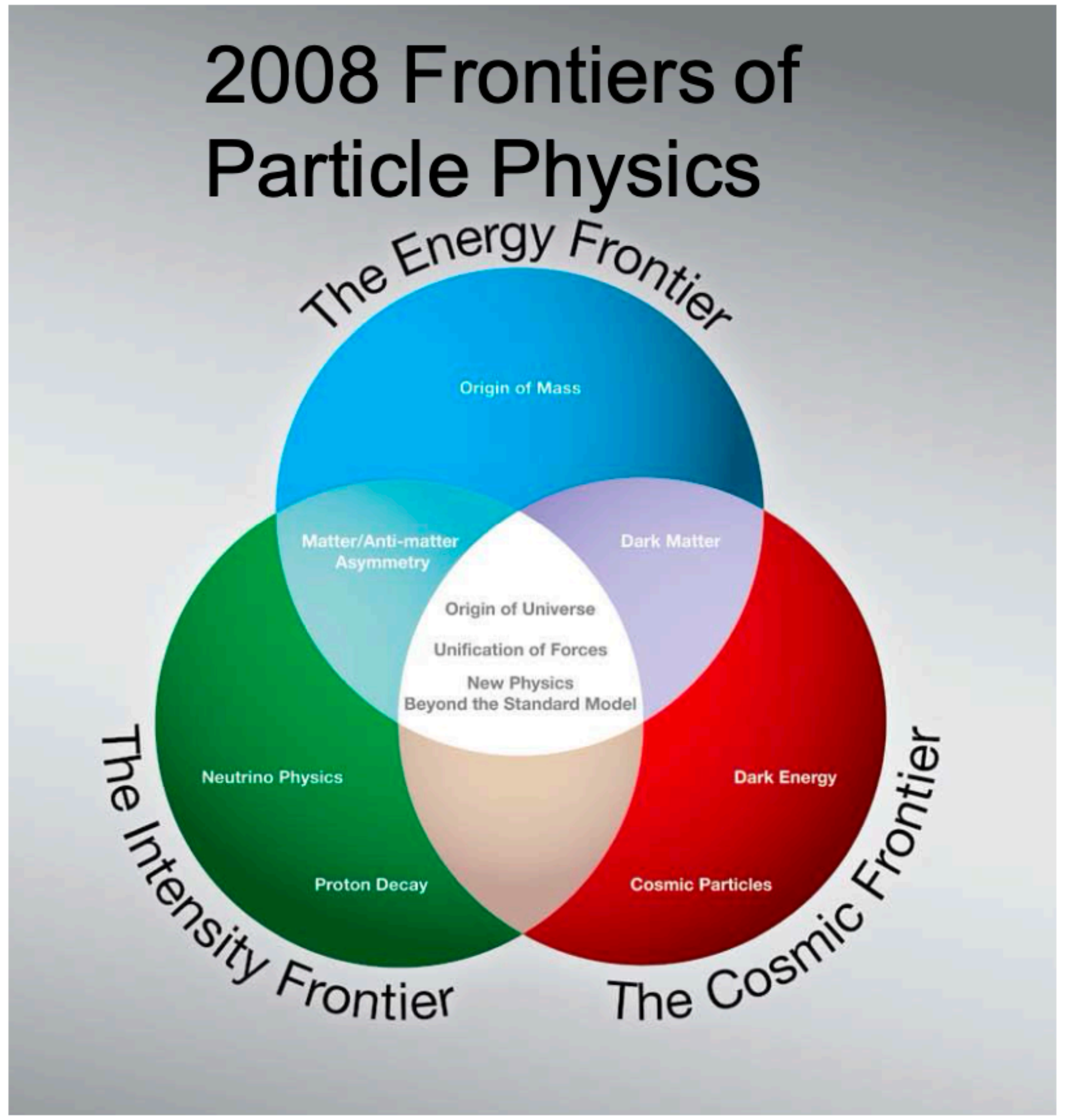
Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

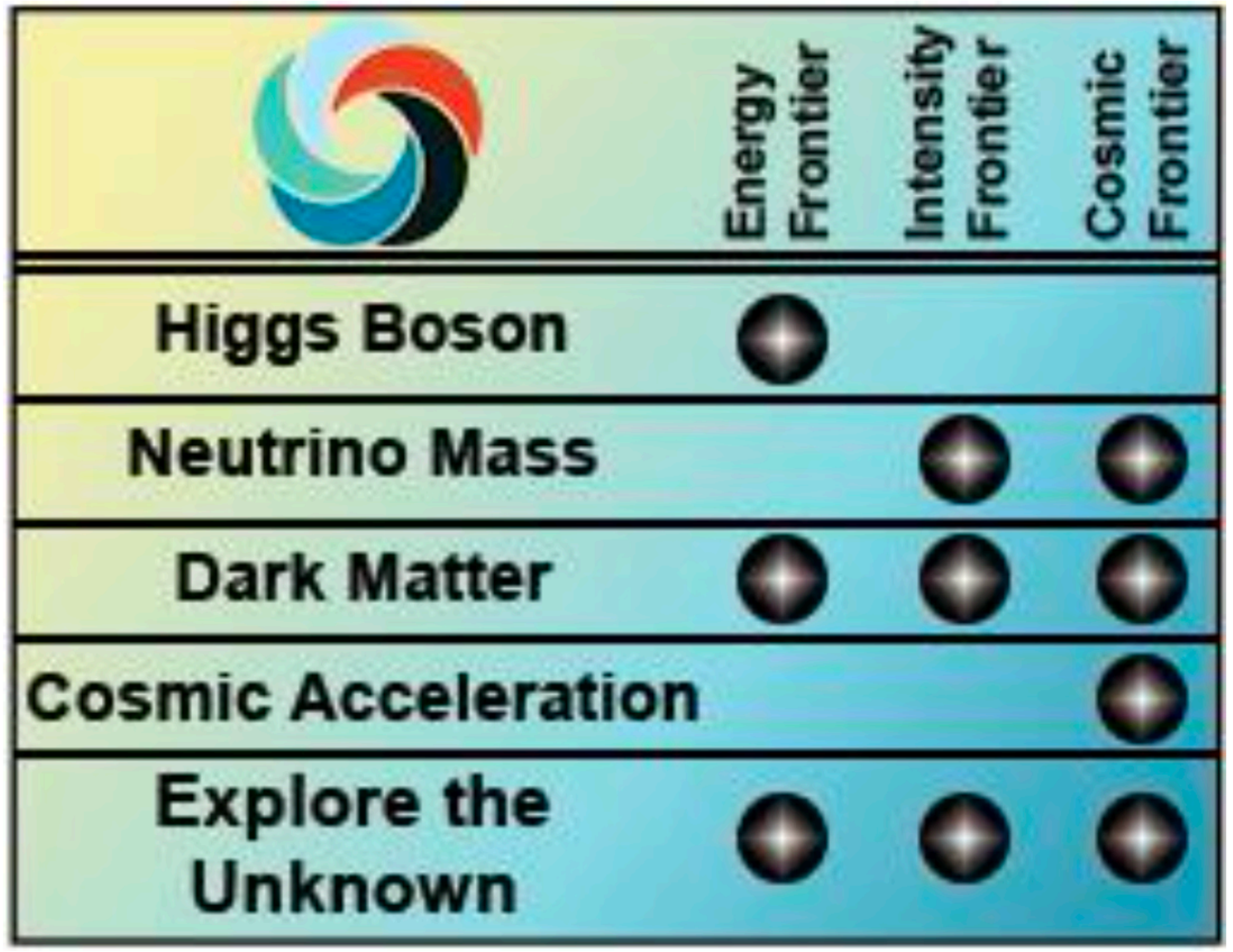
Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

P5 report: Evolution of science drivers

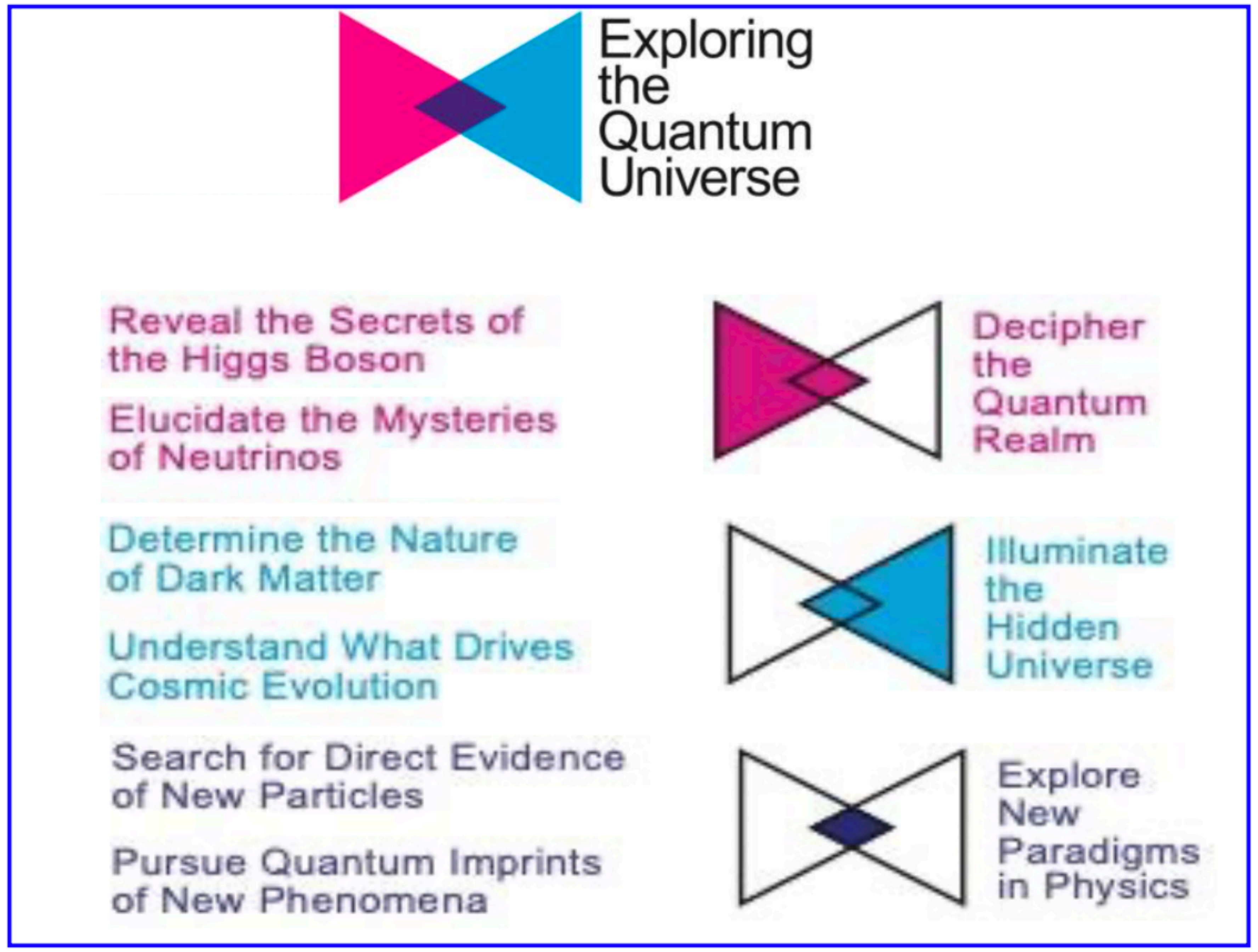


2014 Science Drivers



	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●

2023 Science Drivers



Exploring the Quantum Universe

Reveal the Secrets of the Higgs Boson Elucidate the Mysteries of Neutrinos	Decipher the Quantum Realm
Determine the Nature of Dark Matter Understand What Drives Cosmic Evolution	Illuminate the Hidden Universe
Search for Direct Evidence of New Particles Pursue Quantum Imprints of New Phenomena	Explore New Paradigms in Physics

P5 report: Overview and vision

Exploring the Quantum Universe

We envision a new era of scientific leadership, centered on decoding the quantum realm, unveiling the hidden universe, and exploring novel paradigms. Balancing current and future large- and mid-scale projects with the agility of small projects is crucial to our vision. We emphasize the importance of investing in a highly skilled scientific workforce and enhancing computational and technological infrastructure. Acknowledging the global nature of particle physics, we recognize the importance of international cooperation and sustainability in project planning. We seek to open pathways to innovation and discovery that offer new insights into the mysteries of the quantum universe.

P5 report: Recommendation 1

- **Highest priority on ongoing projects** (no rank-order)
- **Large-scale projects:**
  a. HL-LHC at CERN: upgrades of ATLAS and CMS detectors, and accelerator
  b. Phase-I of DUNE and PIP-II at Fermilab
  c. LSST at Vera Rubin Observatory
- **Mid-scale projects:**
  d. Neutrinos: NOvA, SBN, T2K, IceCube
  e. Dark matter: DarkSide-20k, LZ, SuperCDMS, XENONnT
  f. Cosmic evolution: DESI
  g. New phenomena: Belle II, LHCb, Mu2e

P5 report: Recommendation 2

Exploring the Quantum Universe

- **Exciting new initiatives** (ranked from highest to lowest priority)
  a. Cosmic evolution: CMB-S4 w/ telescopes in Chile and at South Pole
  b. Neutrinos: Phase-II of DUNE at Fermilab
  c. Off-shore Higgs factory: FCC-ee at CERN or ILC in Japan
  d. Third-generation (G3) dark matter direct detection
  e. Second-generation IceCube
- **NSF-specific initiative in multi-messenger astrophysics —> dark matter**
  - Cherenkov Telescope Array (CTA)
  - Next-generation gravitational-wave observatory
  - IceCube-Gen2

P5 report: Recommendation 3

- **Balanced portfolio including mid- and small-scale experiments** (no rank-order)
  - Implement new program at DOE: Advancing Science and Technology through Agile Experiments (ASTAE)
    - Starting with experiments from Dark Matter New Initiatives (DMNI) program, incl. axion searches
  - Continue Mid-Scale Research Infrastructure (MSRI) and Major Research Infrastructure (MRI) programs at NSF
  - Support following experiments:
    - DESI-II for cosmic evolution
    - LHCb upgrade II and Belle II (incl. SuperKEKB) upgrade for quantum imprints
    - Global CTA Observatory for dark matter

P5 report: Recommendation 4

- **Investment in the future** (no rank-order)
    - Vigorous R&D toward cost-effective 10 TeV pCM collider (proton, muon, or wakefield technology) —> ready to build major test/demonstrator facilities within 10 years
    - Enhance research in theory
    - Expand General Accelerator R&D (GARD)
    - Invest in R&D in instrumentation
    - Conduct R&D toward projects in next decade, incl. detectors for ee Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping
    - Support cyberinfrastructure: software tools, R&D in computing, novel data analysis techniques
    - Improve Fermilab accelerator complex (incl. neutrinos, flavor, 10 TeV pCM collider)

P5 report: Recommendation 5

- **Diversity, inclusion, equity & relevance to society**
    - Invest in initiatives to develop workforce, broaden engagement, and ethical conduct
    - Workforce initiatives
        - Incorporate ethics agreements —> expectations for professional conduct
        - Broaden engagement through partnership, training, accessibility programs
        - Conduct work-climate studies
        - Increase support for professionals (scientists, engineers, technicians) at universities
        - Plan dissemination of scientific results to the public, include funding for such activities

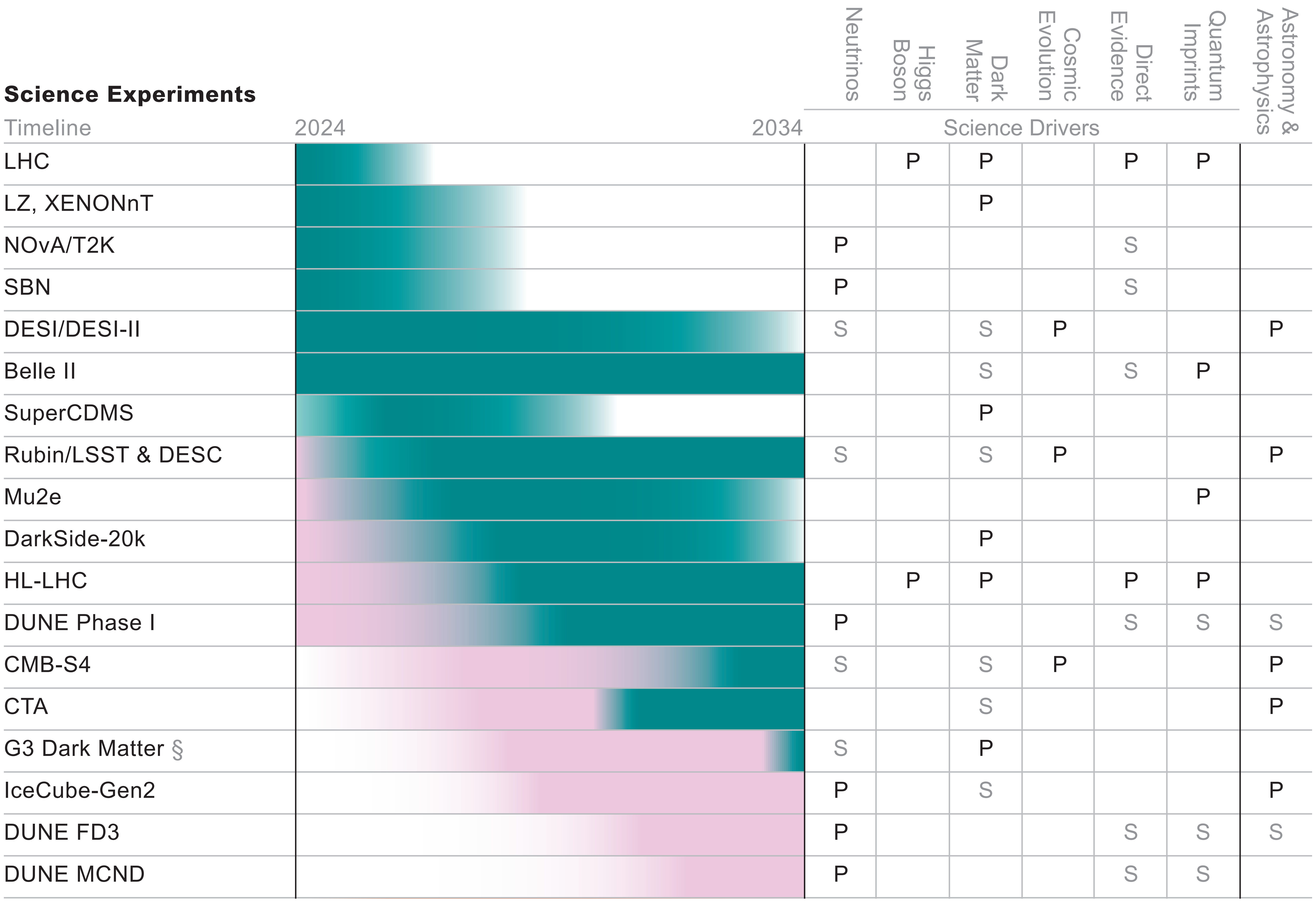
P5 report: Recommendation 6

- **Convene targeted panel to make decision on US accelerator-based program** (without needing to wait for next P5 in ~10 years)
    - Panel charged to consider:
        - Level and nature of US contribution in Higgs factory
        - Mid- and large-scale test and demonstrator facilities in accelerator and collider R&D
        - Plan for evolution of Fermilab accelerator complex

Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: 🟩 Operation 🟪 Construction 🟧 R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion for more favorable budget situations



Science Experiments Timeline	2024 – 2034	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
LHC			P	P		P	P	
LZ, XENONnT				P				
NOvA/T2K		P				S		
SBN		P				S		
DESI/DESI-II		S		S	P			P
Belle II				S		S	P	
SuperCDMS				P				
Rubin/LSST & DESC		S		S	P			P
Mu2e							P	
DarkSide-20k				P				
HL-LHC			P	P		P	P	
DUNE Phase I		P				S	S	S
CMB-S4		S		S	P			P
CTA				S				P
G3 Dark Matter §		S		P				
IceCube-Gen2		P		S				P
DUNE FD3		P				S	S	S
DUNE MCND		P				S	S	

Science Drivers

Figure 1 – Program and Timeline in Baseline Scenario (B)

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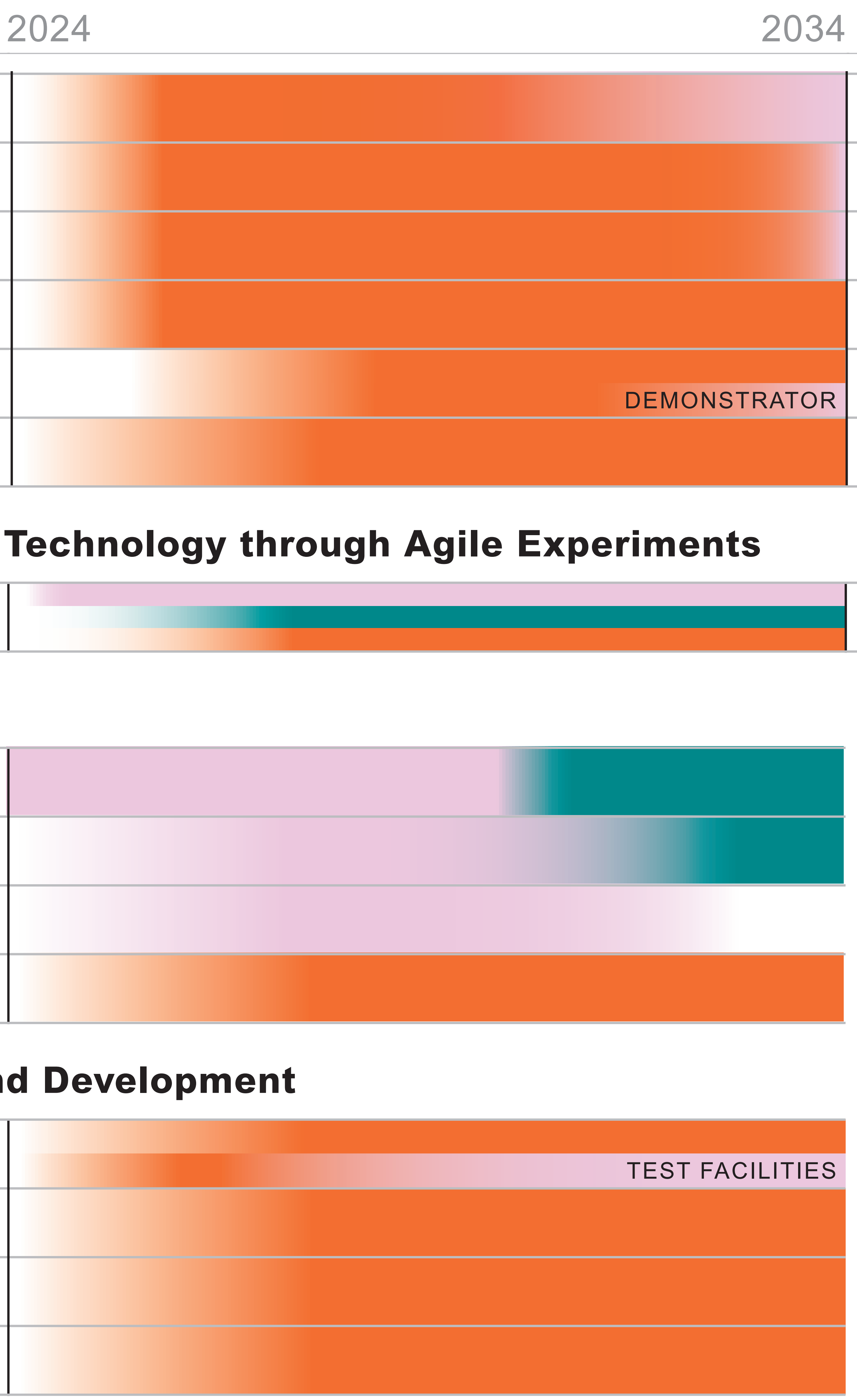


Science Experiments

Science Experiments	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
Higgs factory §		P	S		P	P	
DUNE FD4 §	P				S	S	S
Spec-S5 §	S		S	P			P
Mu2e-II						P	
Multi-TeV §		P	P		P	S	
LIM	S		P	P			P

Science Drivers

Advancing Science and Technology through Agile Experiments

	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
ASTAE §	P	P	P	P	P	P	

Science Enablers

LBNF/PIP-II
ACE-MIRT
SURF Expansion
ACE-BR §, AMF

Increase in Research and Development

GARD §
Theory
Instrumentation
Computing

Approximate timeline of the recommended program within the baseline scenario. Projects in each category are in chronological order. For IceCube-Gen2 and CTA, we do not have information on budgetary constraints and hence timelines are only technically limited. The primary/secondary driver designation reflects the panel's understanding of a project's focus, not the relative strength of the science cases. Projects that share a driver, whether primary or secondary, generally address that driver in different and complementary ways.

The Science

Highlights given on following slides

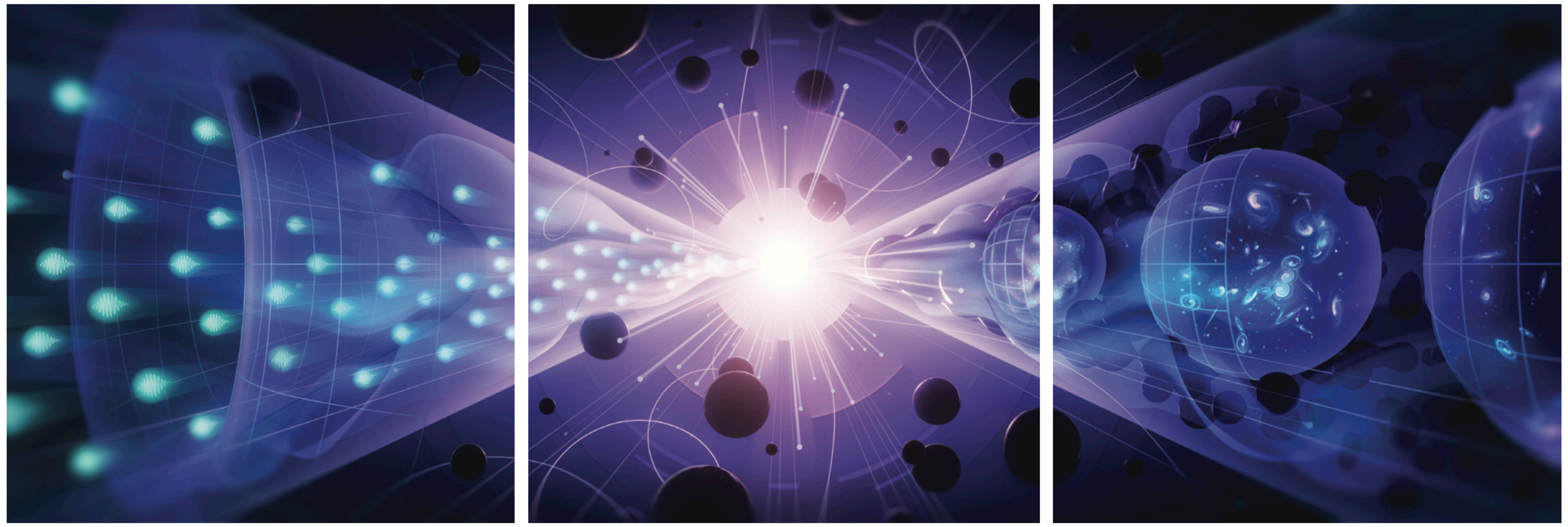
Many interesting topics not covered!

Refer to excellent talks given earlier at IMFP 2024

for a more complete overview

A broad vision for Particle Physics

- **Elucidate the most fundamental constituents of matter and their interactions, and understand the general physical principles governing them**
    - Deeper tests of **Standard Model** of particle physics
- **Understand the physical principles governing cosmic evolution, space and time**
    - Deeper tests of **ΛCDM Model**
- Explore the Universe at the smallest and largest possible distance scales, and uncover their interconnections
- Discover new paradigms



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

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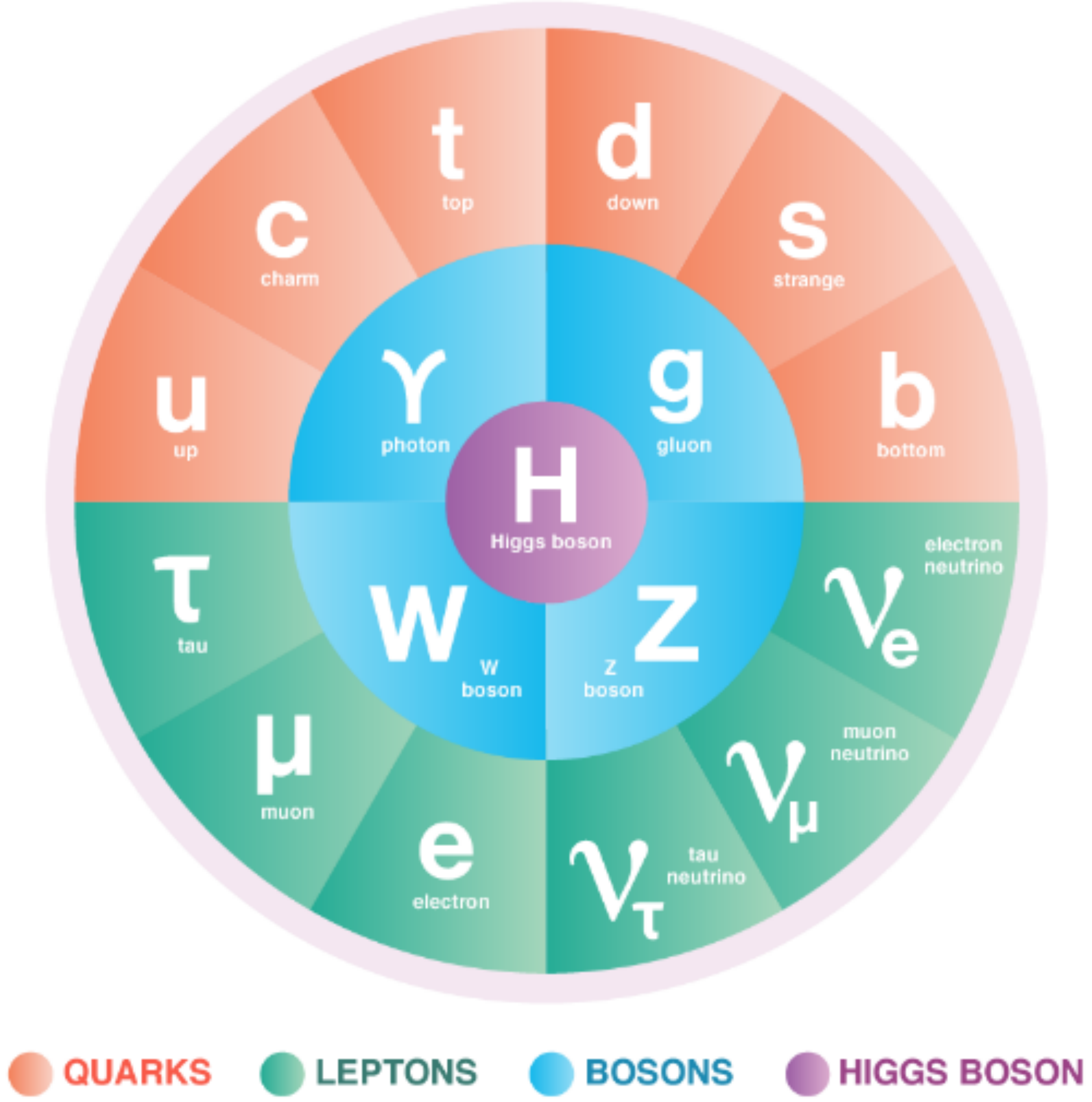
Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

Outstanding questions

- **Standard Model:** astounding success *but incomplete description of Nature*
- ***Fundamental questions that MUST be addressed:***
  - Origin of electroweak scale and electroweak phase transition
  - Higgs boson non-natural? composite?
    part of an extended scalar sector?
  - Flavor puzzle (origin of fermion generations, masses, mixings)
    - Origin of neutrino mass
  - Matter - antimatter asymmetry (CP violation)
  - Nature of dark matter

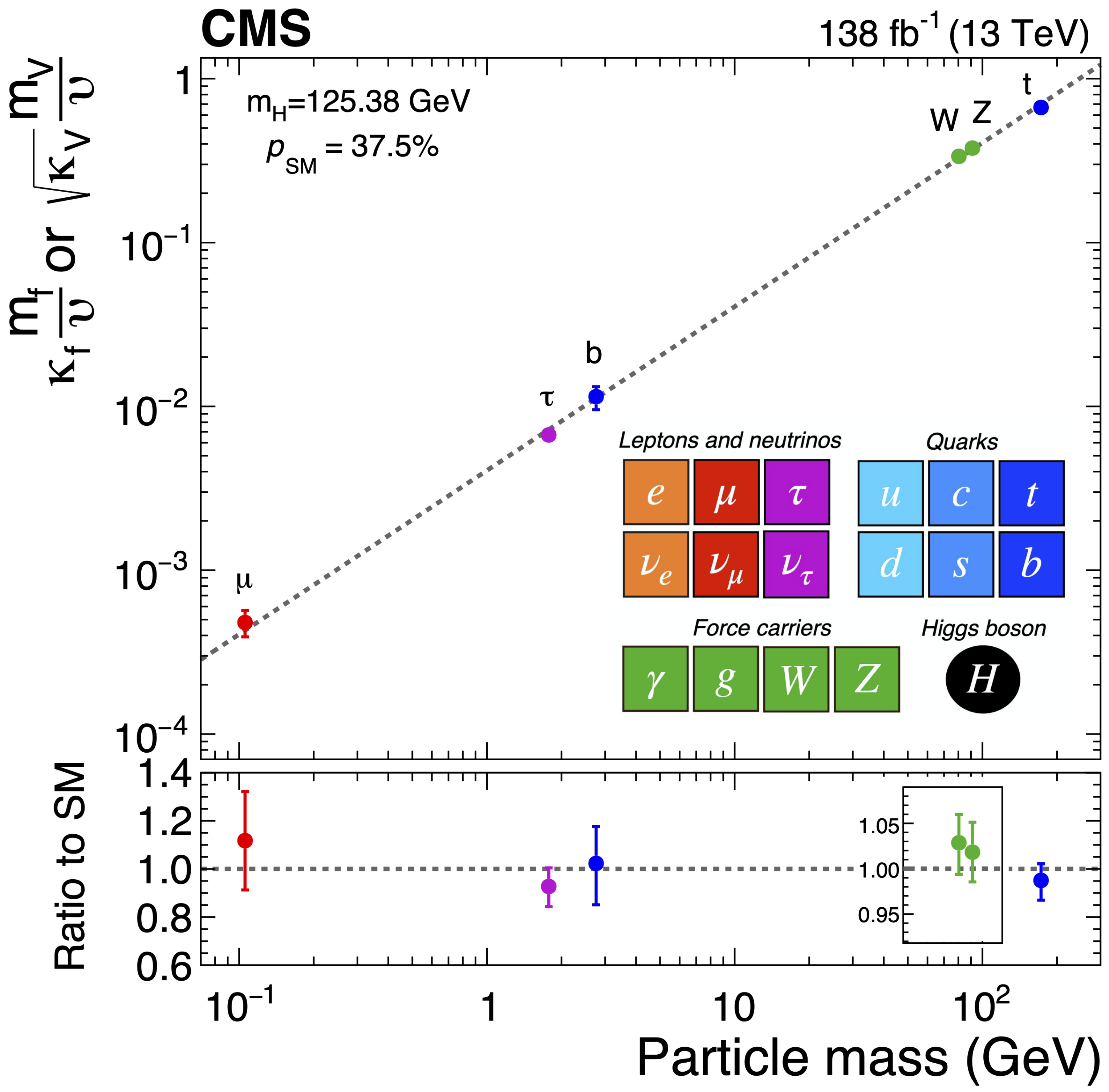


Symmetry magazine

Higgs boson physics

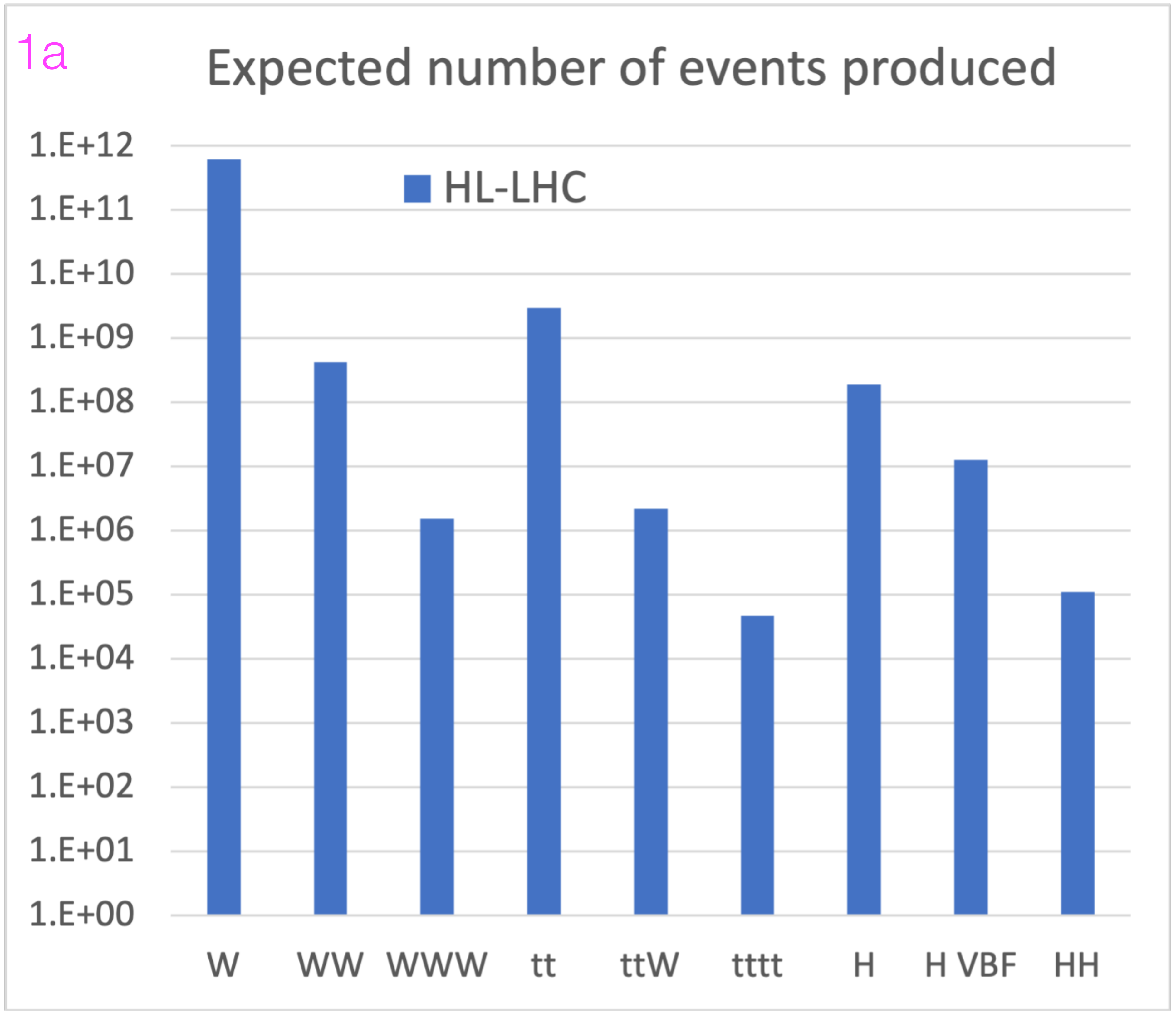
Reveal the Secrets of the Higgs Boson

- **Previous breakthroughs**
  - Discovery via coupling to bosons ($\gamma\gamma, ZZ^*, WW^*$)
  - Established spin-0 scalar nature, mass measured to 0.1%
  - Observation of coupling to 3rd gen. fermions ($\tau^+\tau^-, b\bar{b}, t\bar{t}$)
  - All major production mechanisms observed (ggF, VBF, VH, ttH)
  - Confirmed Electroweak Symmetry Breaking (EWSB)
- **Compelling future program**
  - High-precision measurements, including diff. XS toward high p_T
  - Couplings to lighter fermions (μ, c, s, …)
  - Total width
  - Self-coupling —> Higgs potential, origin of EWSB
  - Searches for additional scalars, exotic decays, portal to hidden sectors



HL-LHC is a Higgs factory (and a W, Z, top, etc. factory)

- **Huge statistical power for heavy particles** Recommendation 1a
    - Number of particles produced for each of ATLAS & CMS with 3,000 fb^{-1} at $\sqrt{s} = 14$ TeV
        - ~600,000,000,000 W bosons
        - ~3,000,000,000 $t\bar{t}$ pairs
        - ~190,000,000 Higgs bosons
        - ~120,000 HH pairs
    - Gives access to “rare” processes
        - ~50,000 $t\bar{t}t\bar{t}$
        - exotic Higgs decays down to BF ~10^{-5} — 10^{-6} (e.g. $H \to aa \to \mu\mu\tau\tau$) + extremely rare Z or top decays



- **HL-LHC allows exploration at both energy frontier <u>and</u> intensity frontier**

Reveal the Secrets of the Higgs Boson

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Determine the Nature of Dark Matter

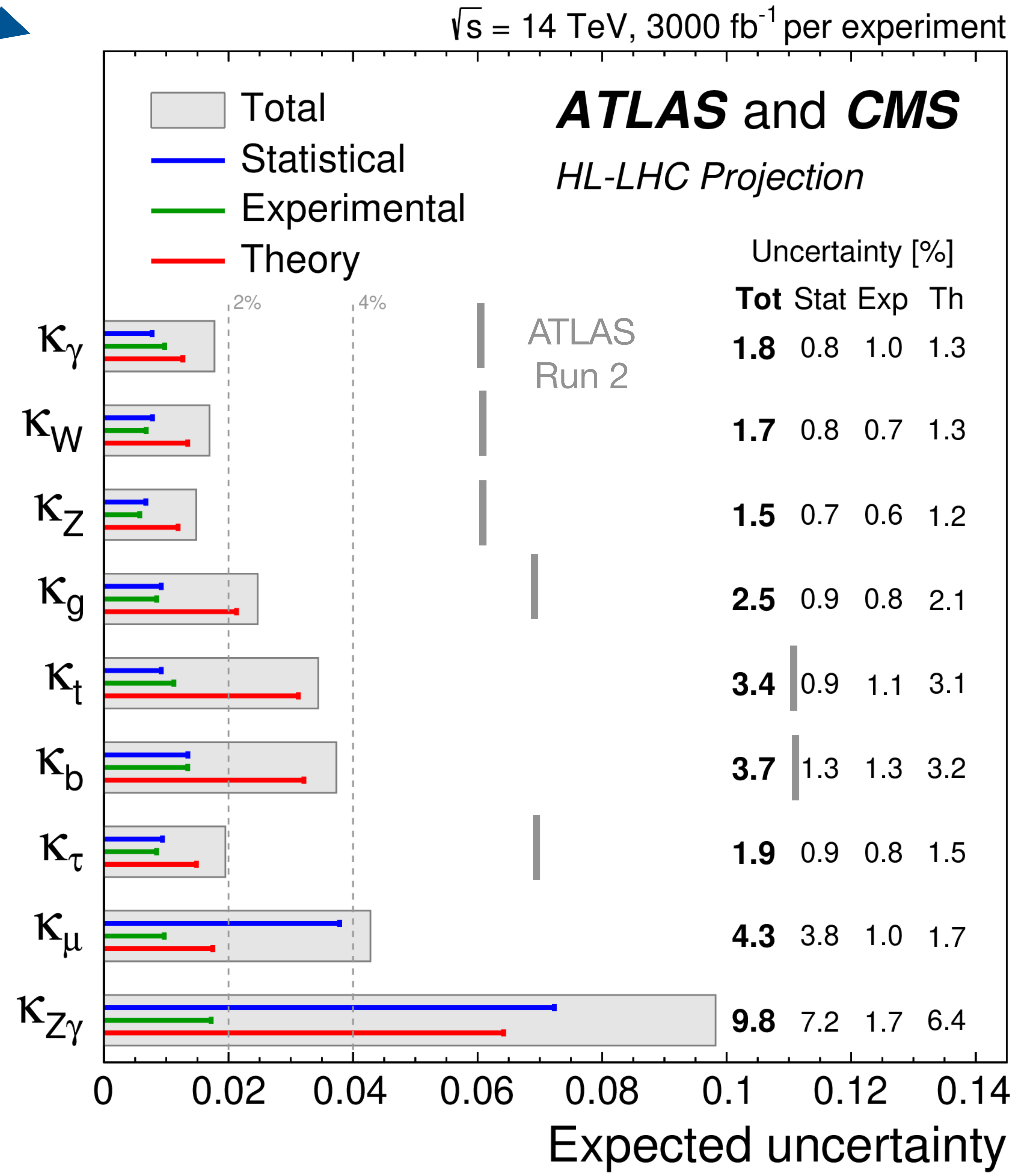
Higgs couplings @HL-LHC

CERN-2019-007 (YR18)

- Combination of ATLAS and CMS measurements extrapolated from (early) Run 2 analyses

- Precision on tree-level coupling modifiers (κ_i)

  - 1.5 - 1.8% for couplings to bosons (γ, W, Z)
  - 1.9 - 4.3% for couplings to fermions (μ, τ, b, t)



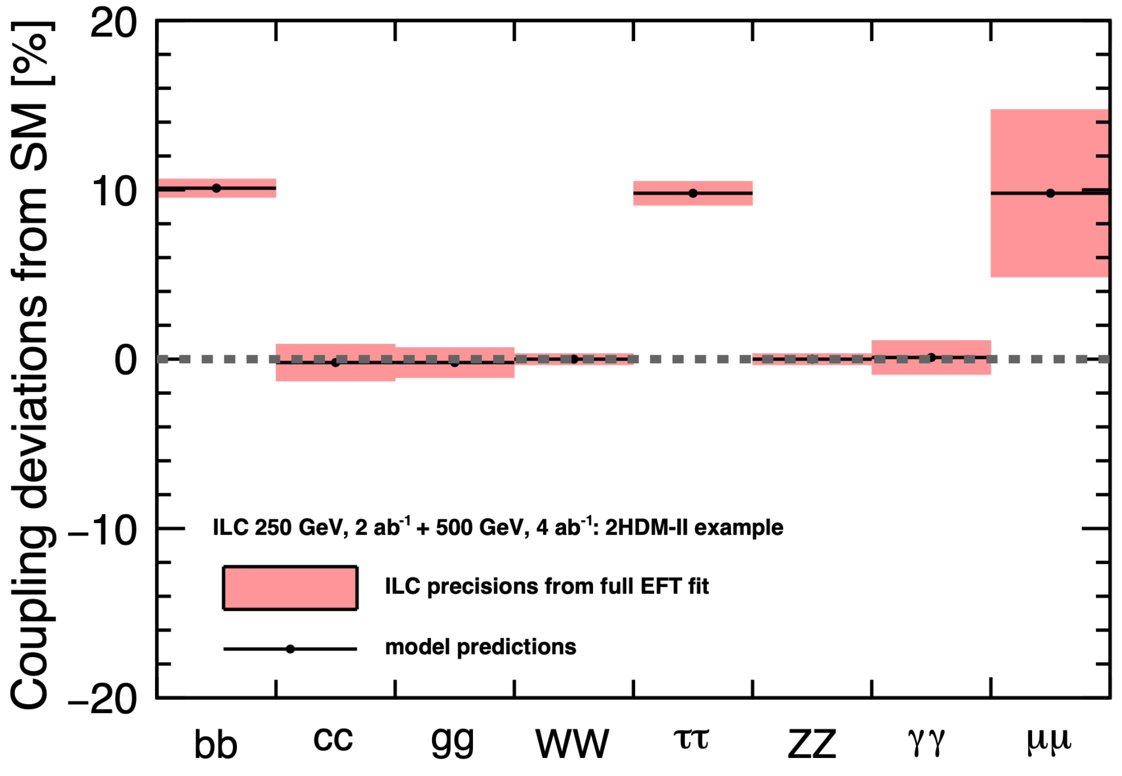
Impact of precision on BSM @HL-LHC

- **Higgs couplings deviations** depend on BSM scenario

Sally Dawson (LHCP 2024)

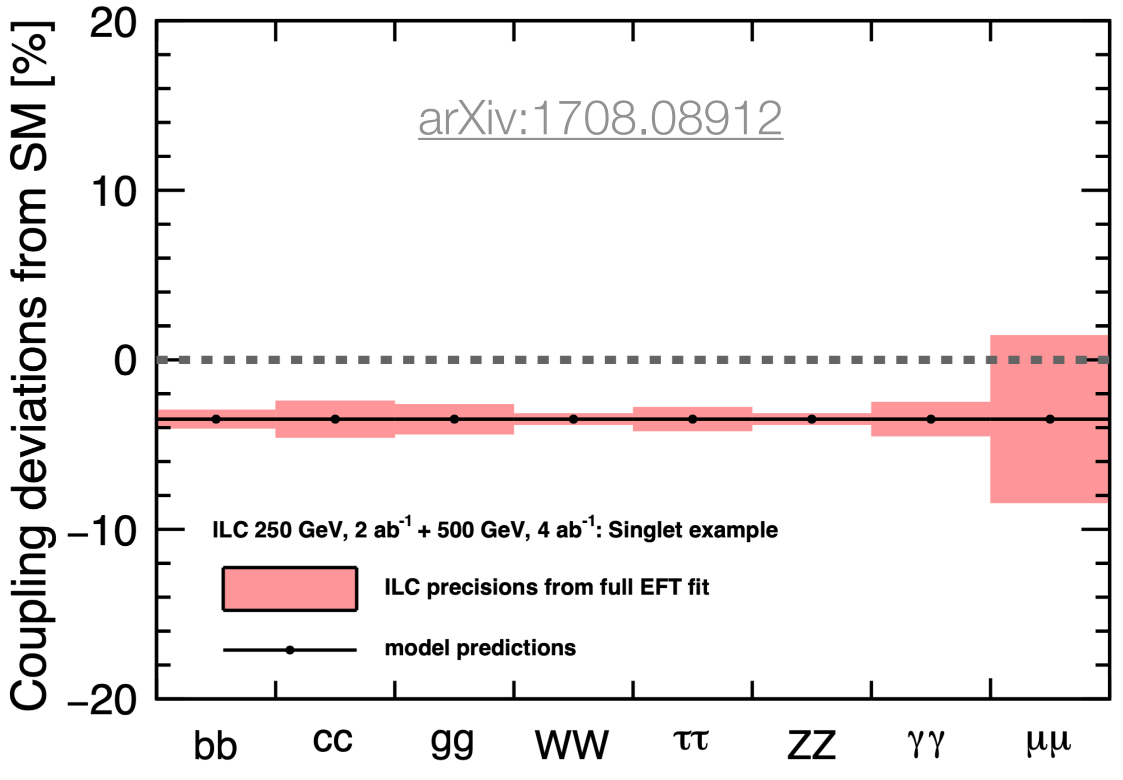
2HDM Type-II

$m_A = 600\ \text{GeV},\ \tan\beta = 7$



Extra Higgs singlet

$m_X = 2.8\ \text{TeV}, \text{max allowed mixing}$

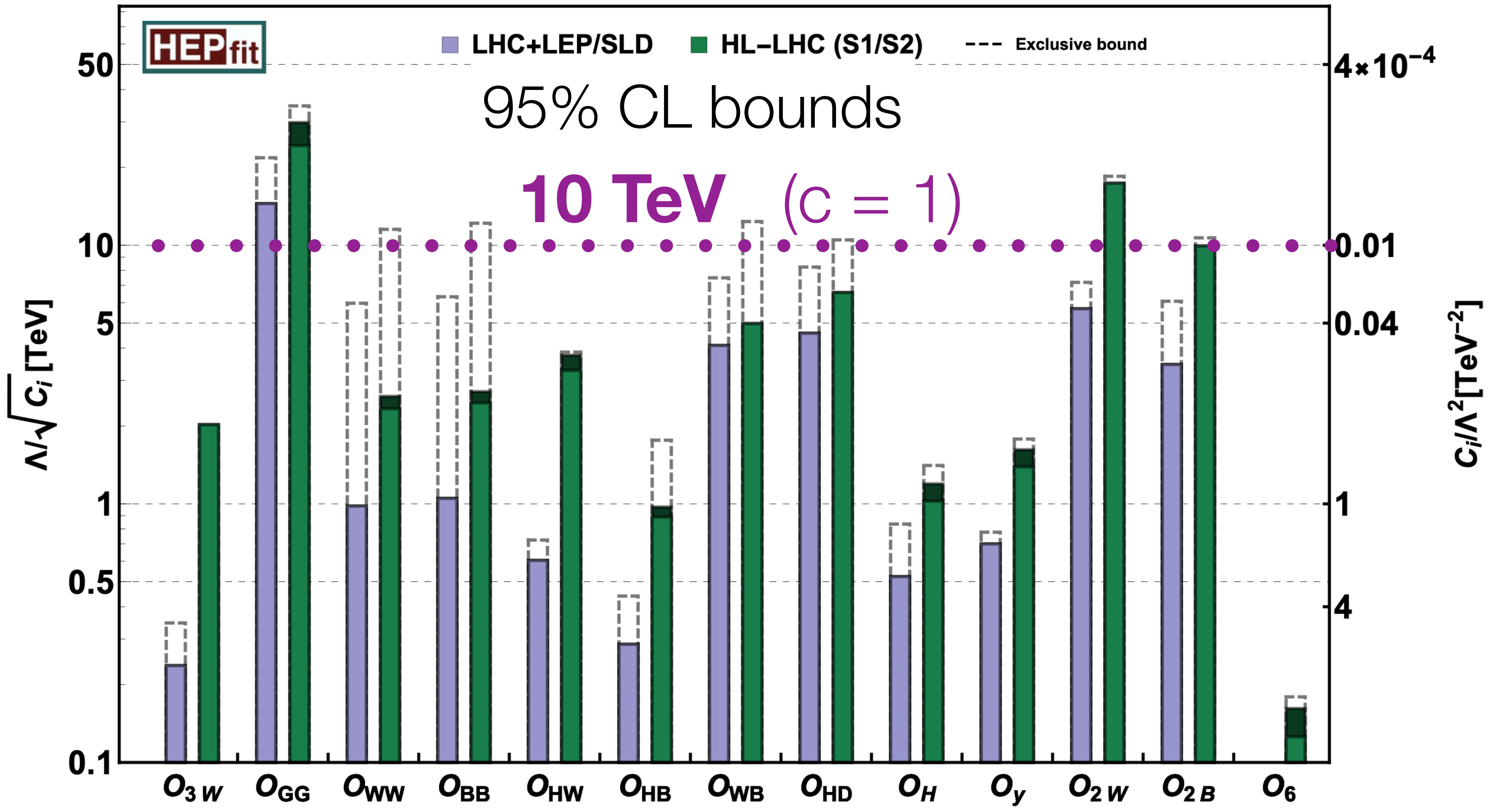


- **Generic Higgs coupling deviations**

$$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right) \simeq 1.6\,\%\left(\frac{2\ \text{TeV}}{\Lambda}\right)^2$$

but mapping between precision and energy scale is highly model dependent

- **Dim-6 EFT w/ Higgs + EW**
  - Large impact of tree-level $\mathcal{O}_{GG,WW,BB}$ on SM loop-induced $gg \to H$ or $H \to \gamma\gamma$ $\Lambda \gtrsim 30$ TeV $(c = 1)$
  - Also strong impact from Drell-Yan measurements on $\mathcal{O}_{2W,2B}$



CERN-2019-007 (YR18)

exclusive bounds on single operator

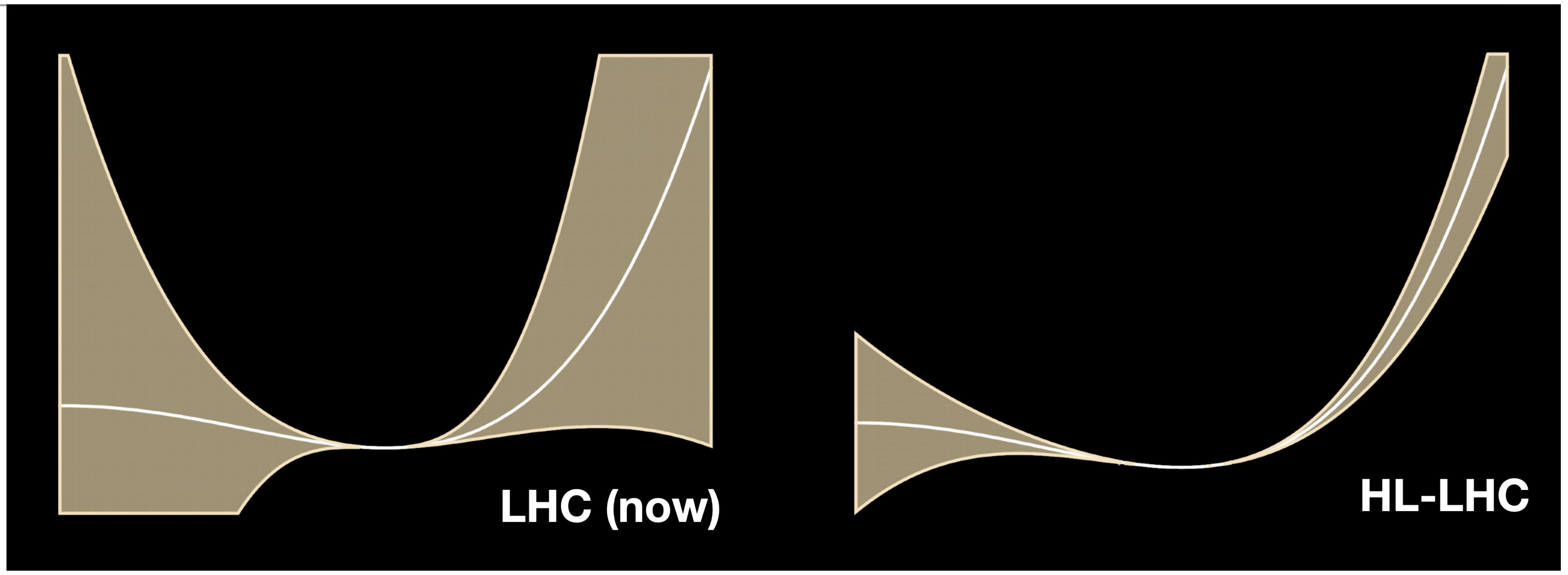
bounds from global fit

Higgs potential

EW phase transition resp. for baryon asymmetry? Vacuum stable?

N. Craig (Dec 2022)

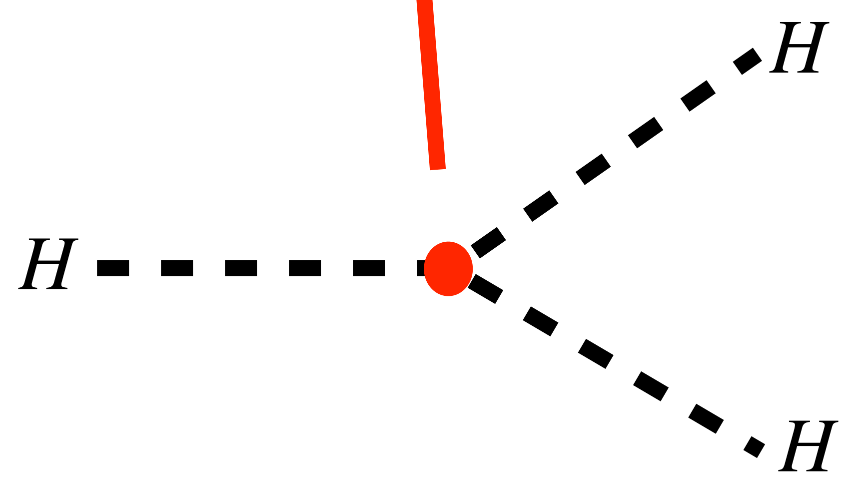
- **Measurement of Higgs potential a *science driver* for HL-LHC,** largely unconstrained so far
- Shape of potential key to understand **EW phase transition in early universe**
- Shape of potential determines **vacuum stability**

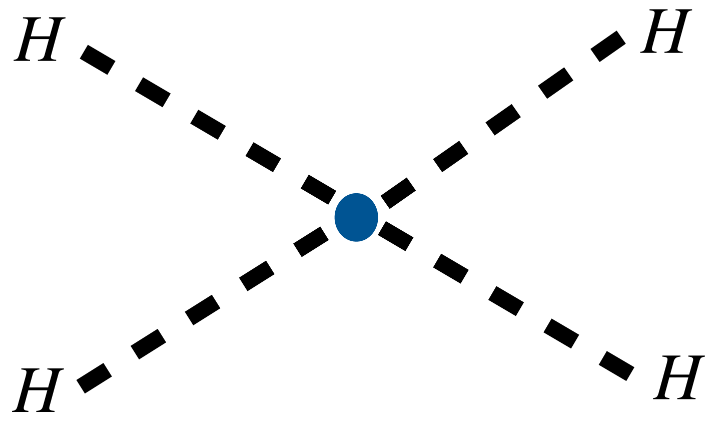


$$V(H) = \frac{1}{2}m_H^2H^2 + \lambda_3 vH^3 + \frac{\lambda_4}{4}H^4$$

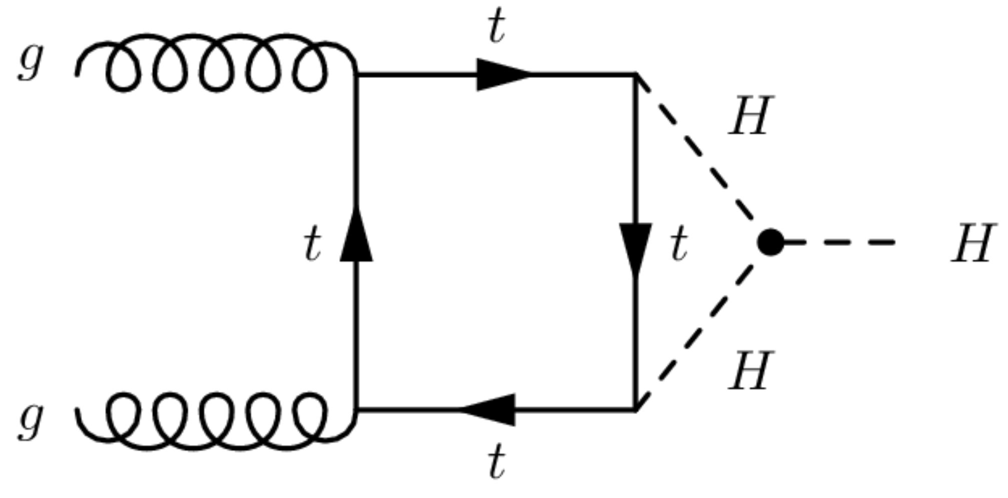
$$\lambda_3^{\mathrm{SM}} = \lambda_4^{\mathrm{SM}} = \frac{m_H^2}{2v^2}$$

Higgs mass already measured at LHC with ~per-mill precision



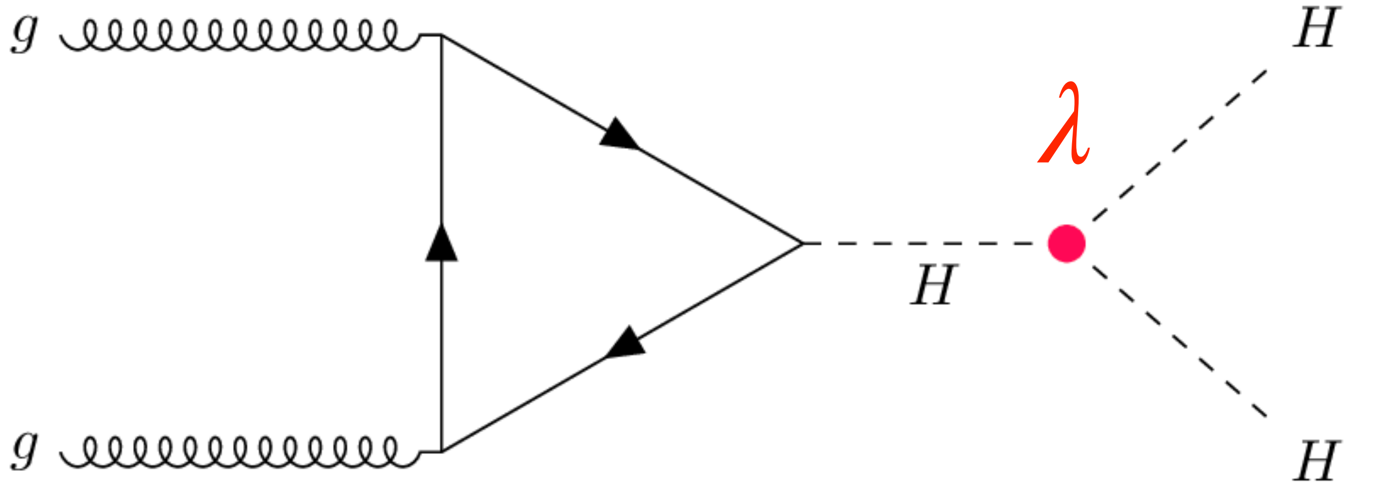


- Cubic (aka tri-linear) coupling λ ($\equiv \lambda_3$) via Higgs pair production
- Single Higgs measurements sensitive to λ via higher-order corrections



Higgs self-coupling @HL-LHC

- Tri-linear coupling λ directly accessible via Higgs pair production
- $pp \to HH$ cross section 3 orders of mag. lower than single Higgs
- Improved trackers and ML key for HH studies (e.g. b tagging)

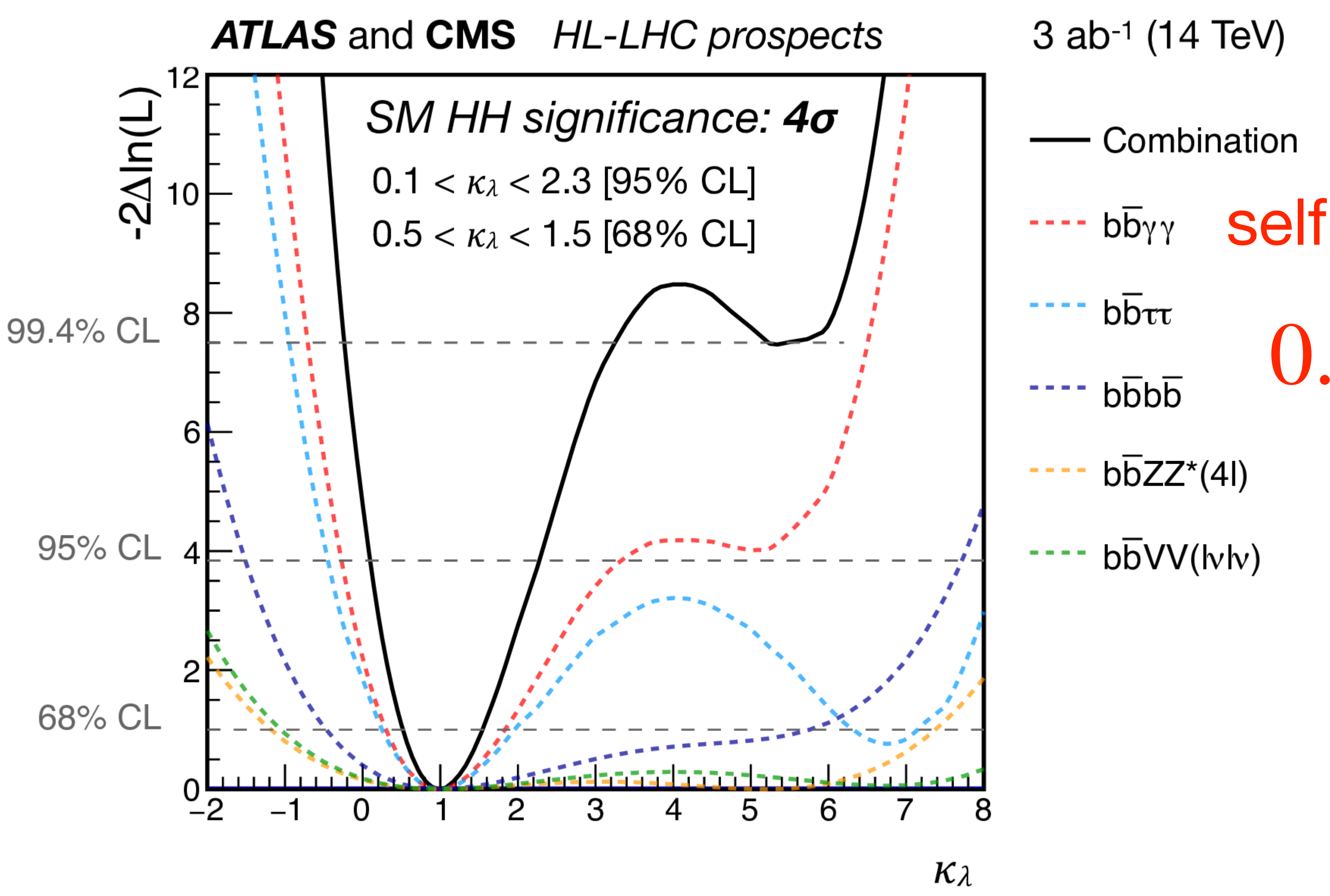


destructive interference with box diagram

- **ATLAS+CMS Yellow Report 2018**

  $pp \to HH$ significance = 4.0 σ (4.5 σ stat only)

CERN-2019-007 (YR18)



self-coupling modifier

$$0.52 < \kappa_\lambda < 1.5$$

(68% Cl)

Higgs self-coupling @HL-LHC

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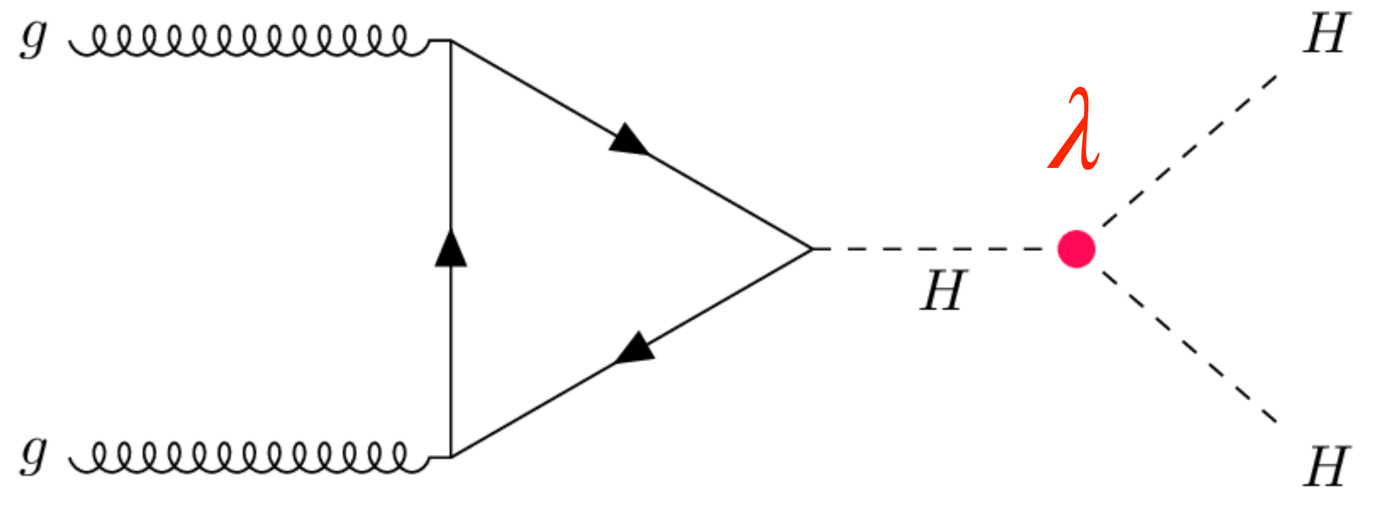

destructive interference with box diagram

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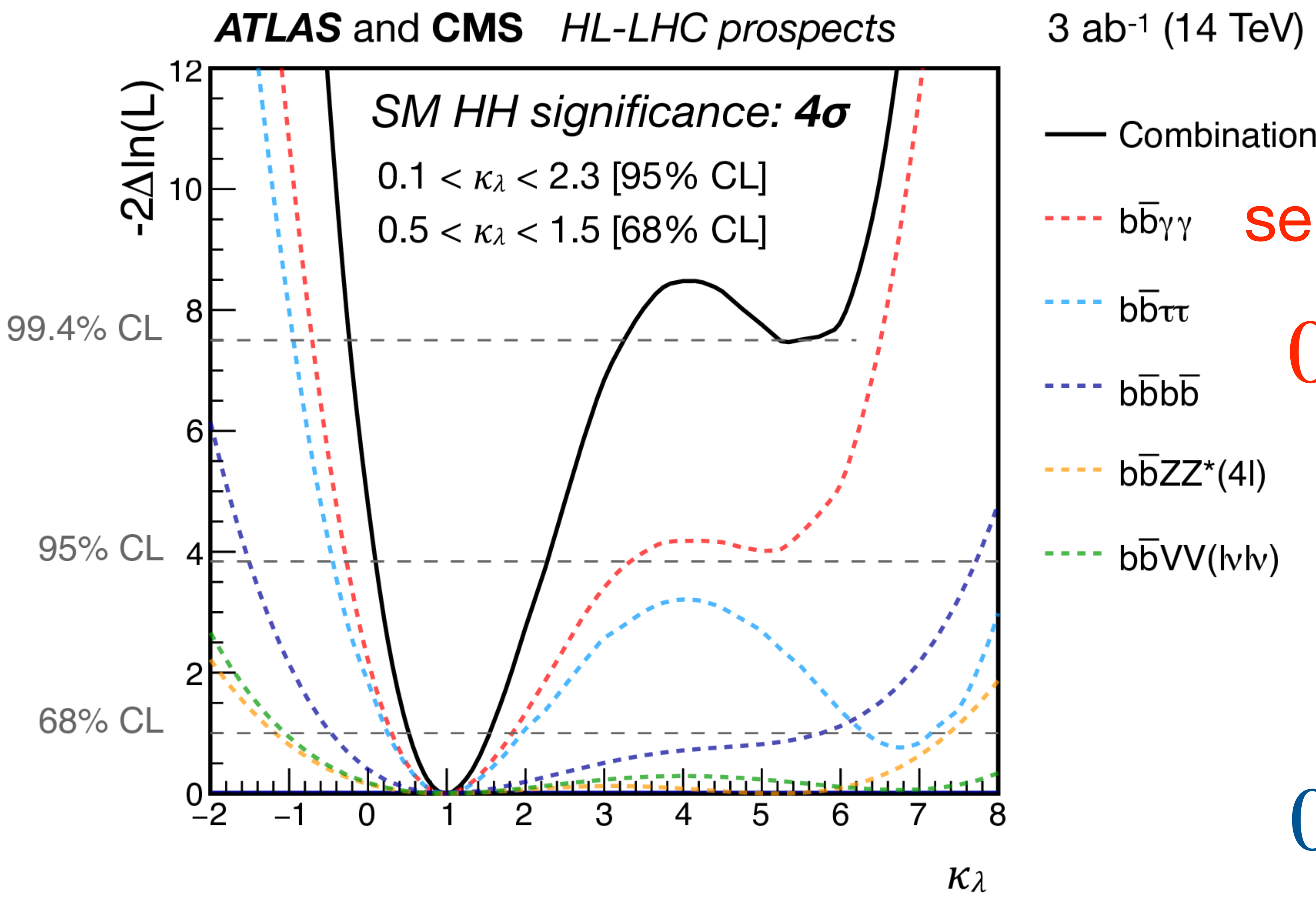
CERN-2019-007 (YR18)



self-coupling modifier

$$0.52 < \kappa_\lambda < 1.5$$

(68% Cl)

ATLAS-PHYS-PUB-2018-053

ATLAS only

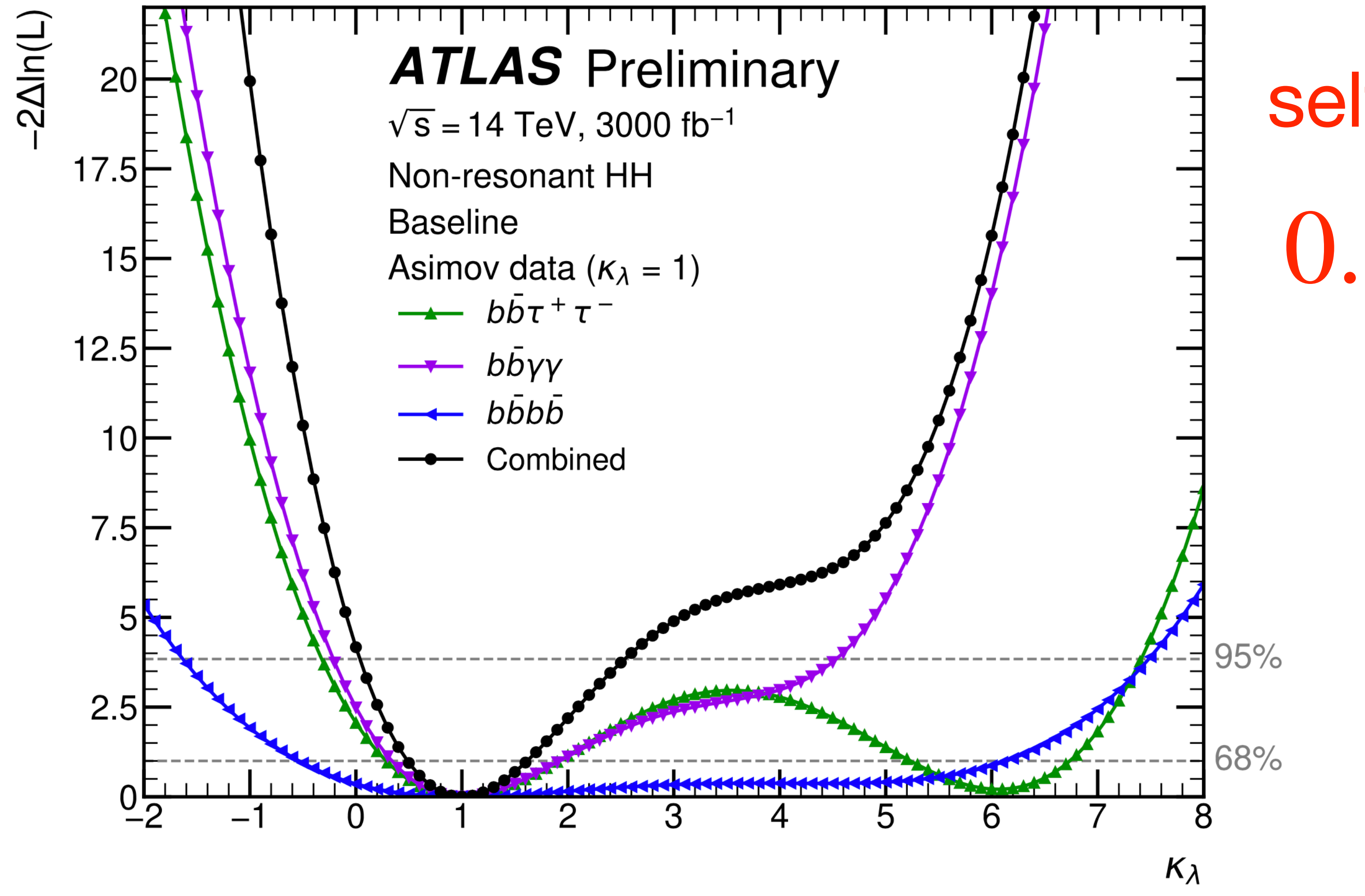
$$0.25 < \kappa_\lambda < 1.9$$

- **ATLAS update after Snowmass 2021**

  Extrapolated from **full** Run 2 $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$

  $pp \rightarrow HH$ significance = 3.4 σ (4.9 σ stat only)

ATLAS-PHYS-PUB-2022-053



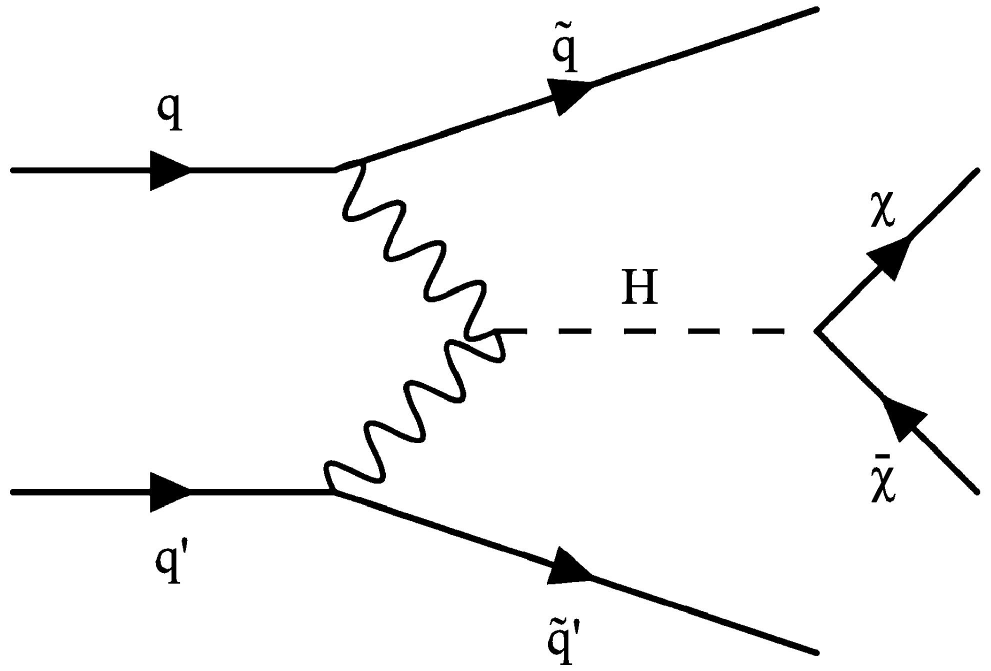
self-coupling mod.

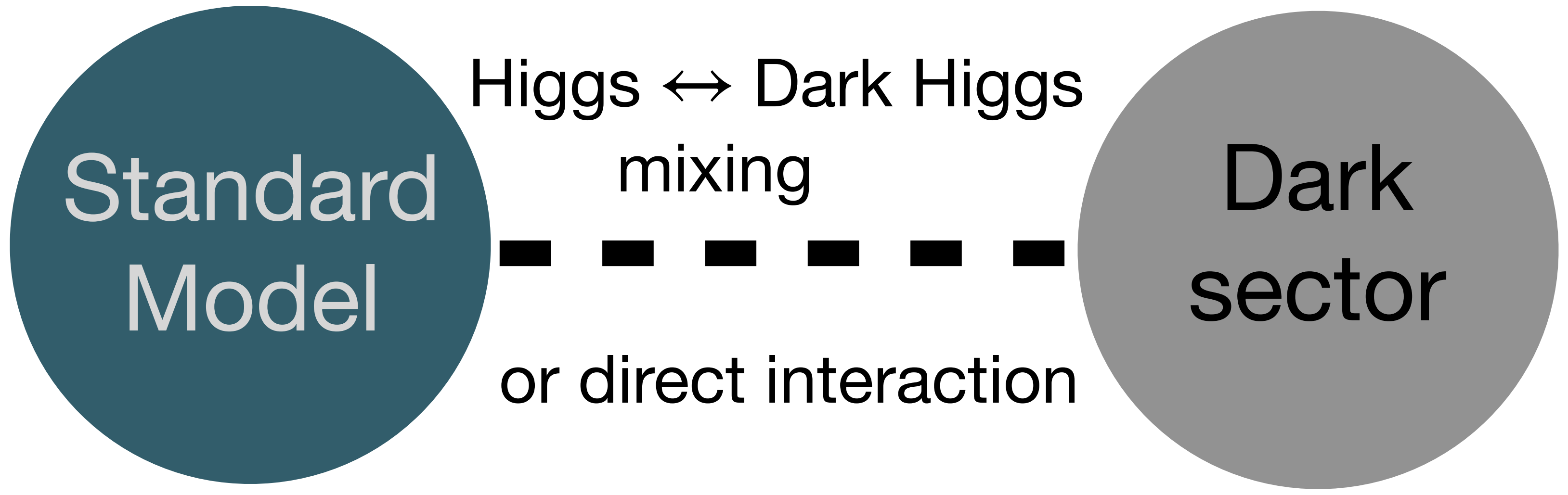
$$0.5 < \kappa_\lambda < 1.6$$

(68% Cl)

BSM: Higgs portal @HL-LHC

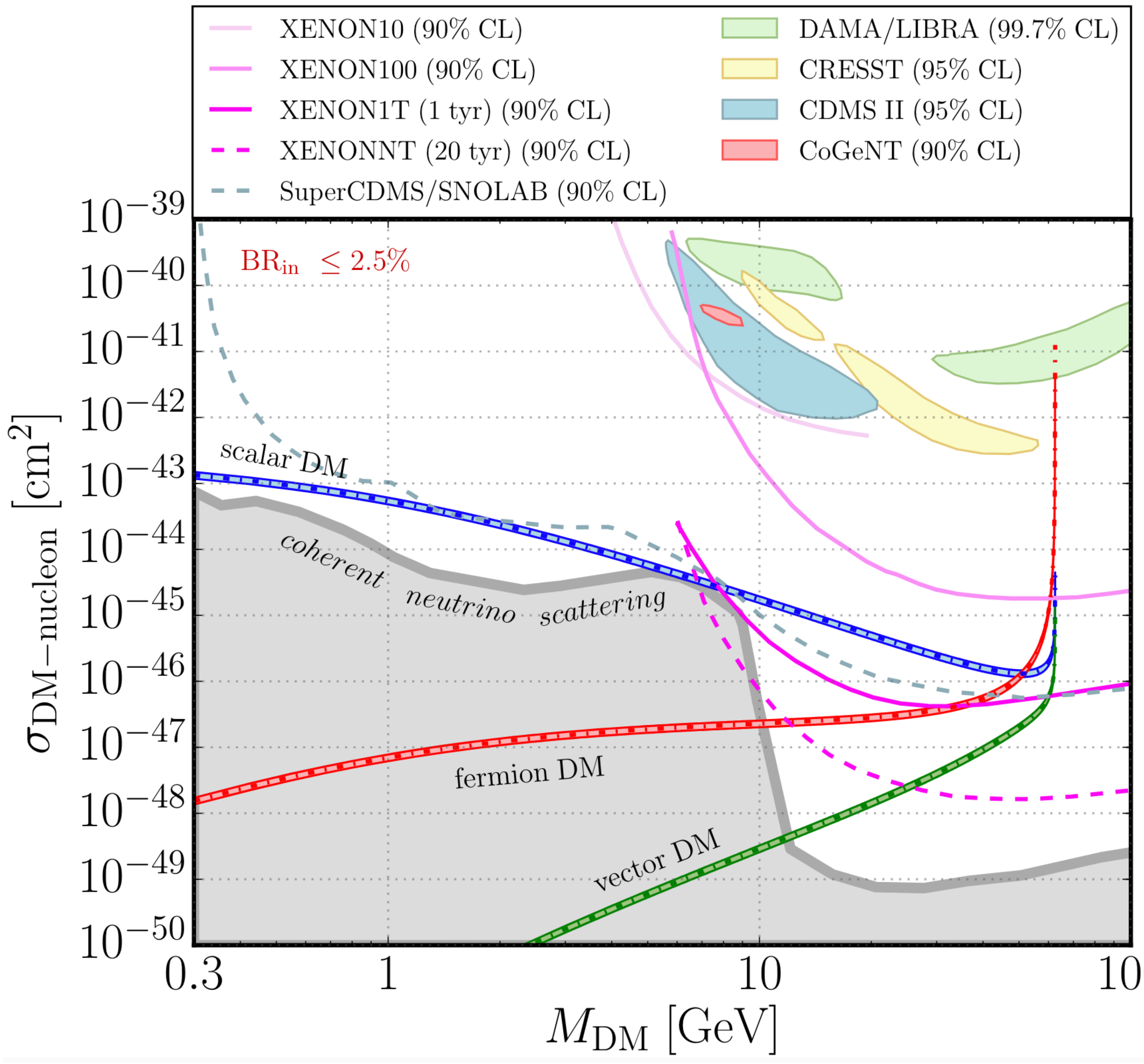
- Higgs **portal to dark sector** of new particles and interactions
  - Lowest-dimension operator $H^\dagger H\,\mathcal{O}_{\mathrm{DS}}$
  - Search for $H \to \mathrm{invisible}$ in VBF and ZH production
    SM rate: $B(H \to ZZ^* \to \nu\bar{\nu}\nu\bar{\nu}) \simeq 0.1\,\%$





  - Model-independent $B(H \to \mathrm{inv}) < 2.5\,\%$ (95% CL ATLAS+CMS)
  - HL-LHC sensitivity exceeds direct detection expts in minimal Higgs portal model for $m_{\mathrm{DM}} \lesssim$ 30 GeV
- Significant gains in BSM with low XS or BF from large luminosity
  - Electroweak SUSY, compressed spectra
  - Feeble interactions, dark sector portals, long-lived particles

CERN-2019-007 (YR18)



Search for Direct Evidence of New Particles

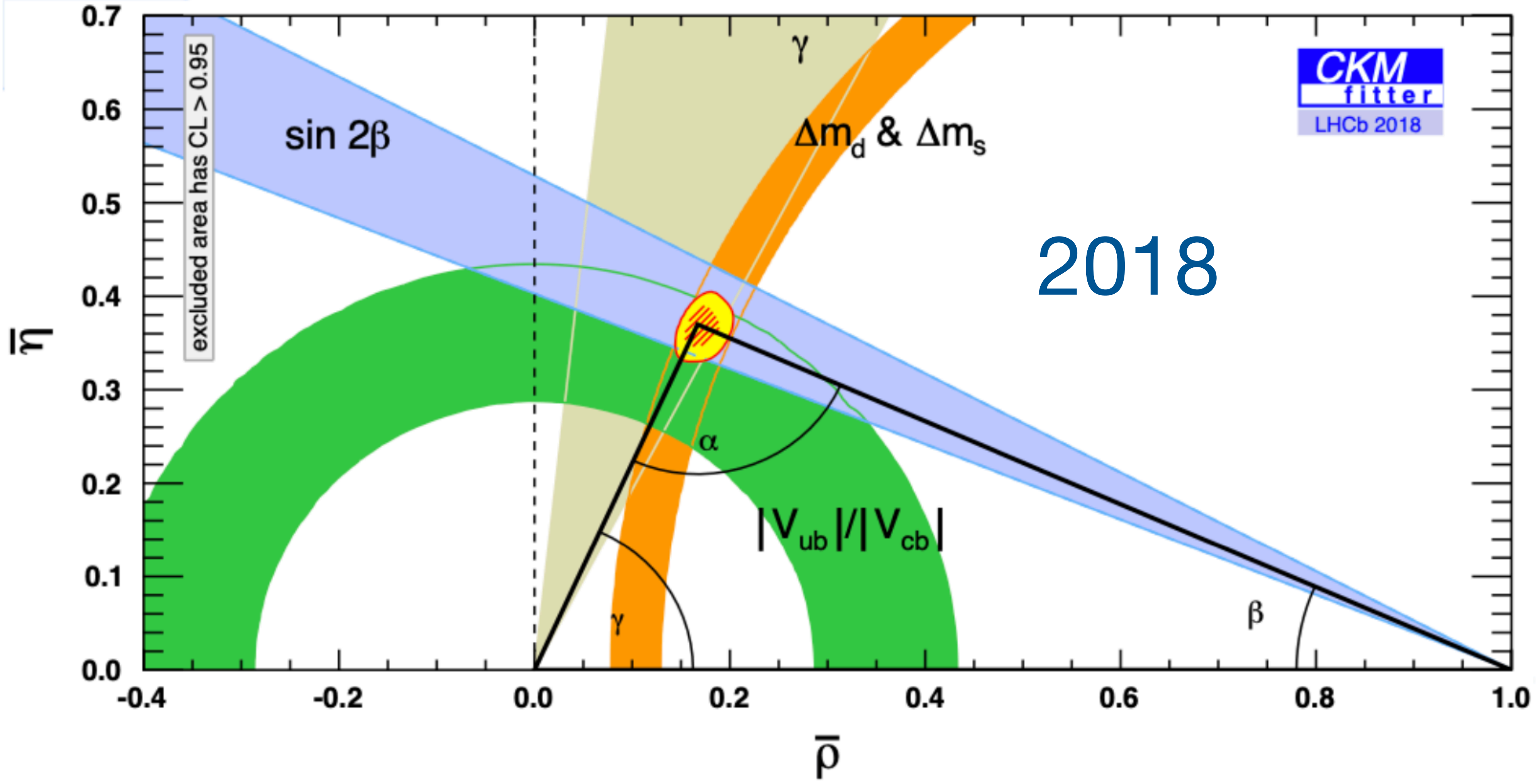
Determine the Nature of Dark Matter

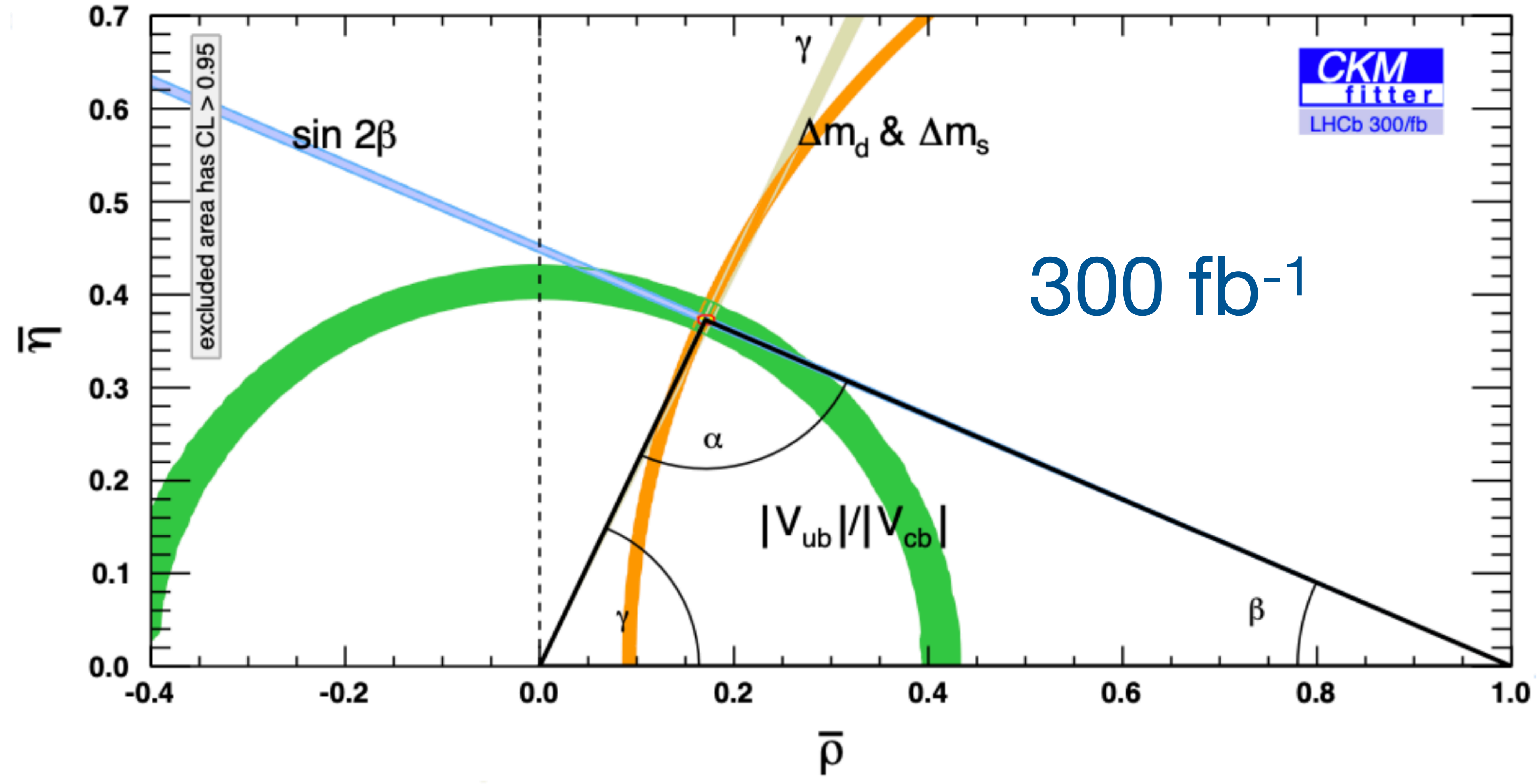
Flavor physics @HL-LHC

Pursue Quantum Imprints
of New Phenomena

New sources of CP violation?

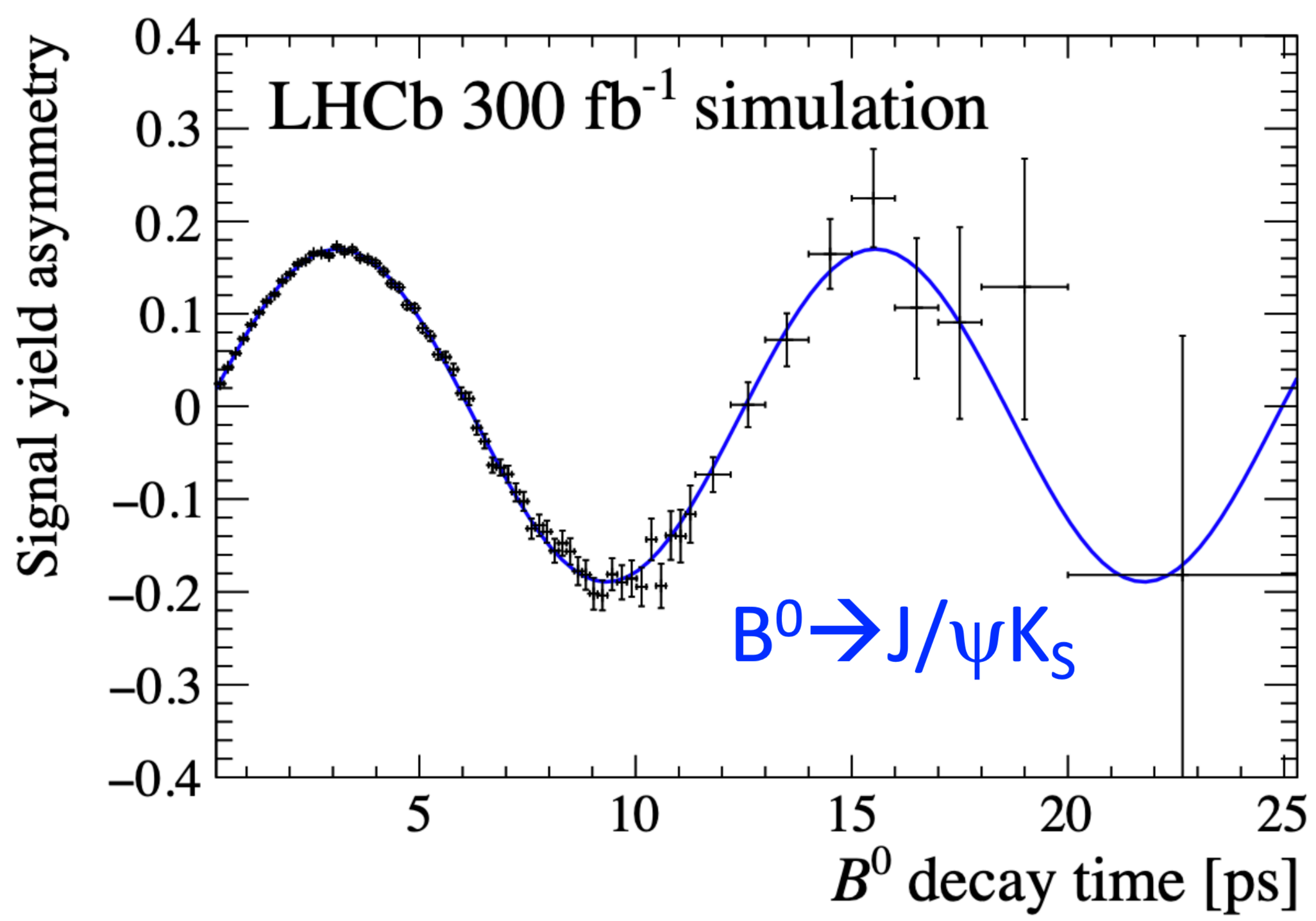
- **CP violation:** LHCb to put stringent test on CKM paradigm with 300 fb^{-1}



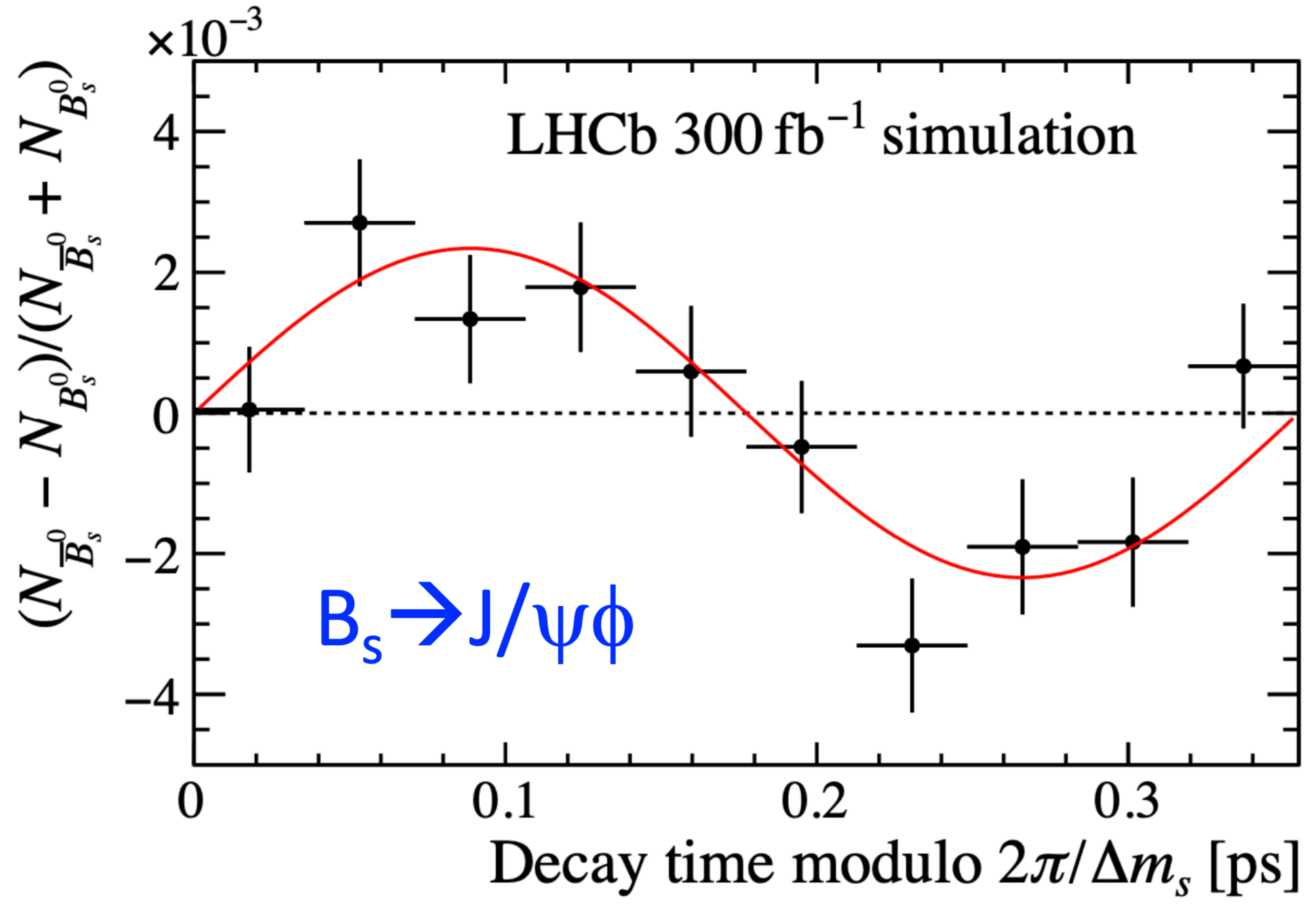


- High-precision CPV angles

arXiv:1808.08865



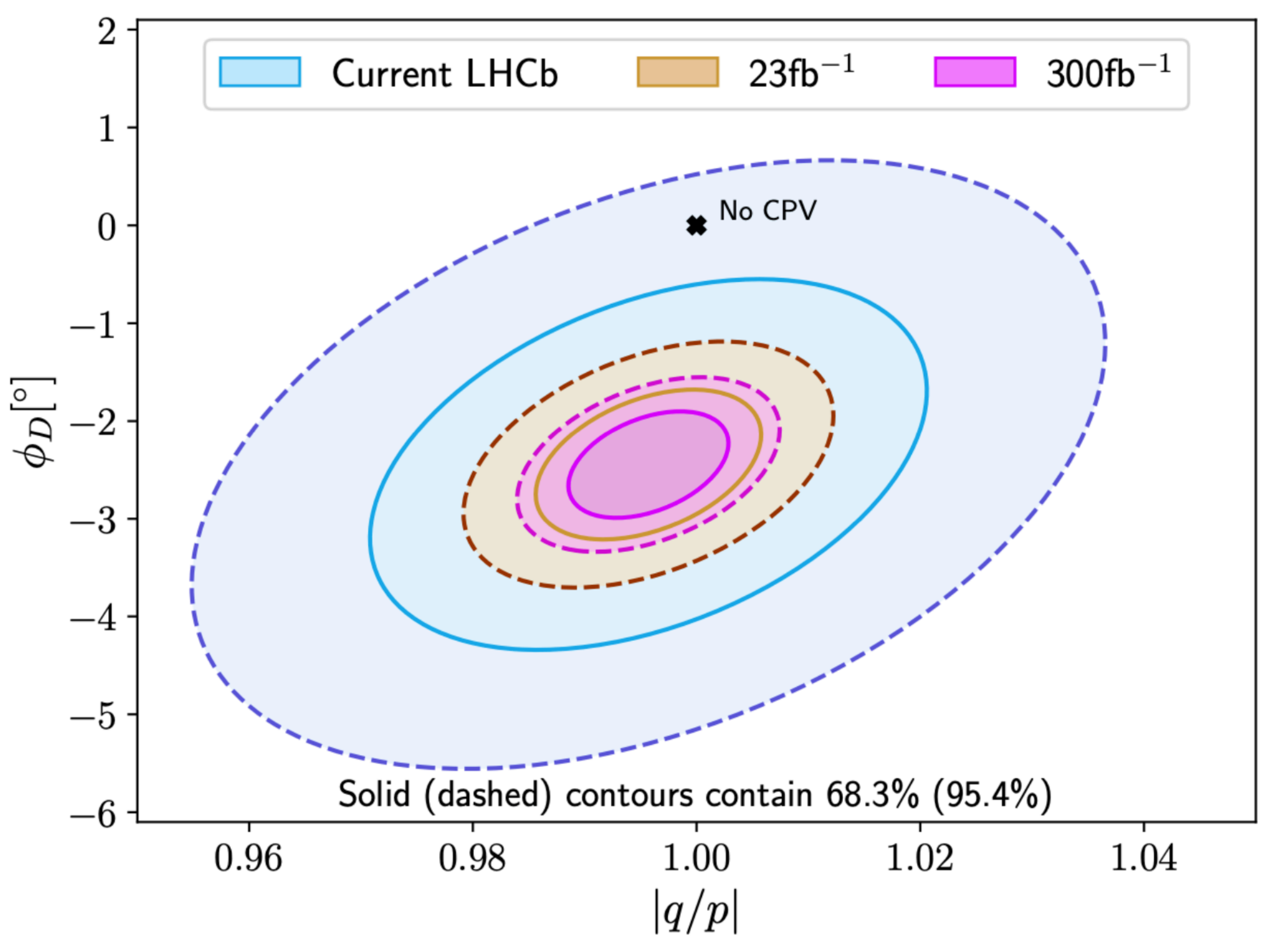
$$\sigma(\sin 2\beta) = 0.003$$



$$\sigma(\phi_s) = 0.004$$

- Highest sensitivity to find CP violation in charm mixing

LHCb-PUB-2022-012



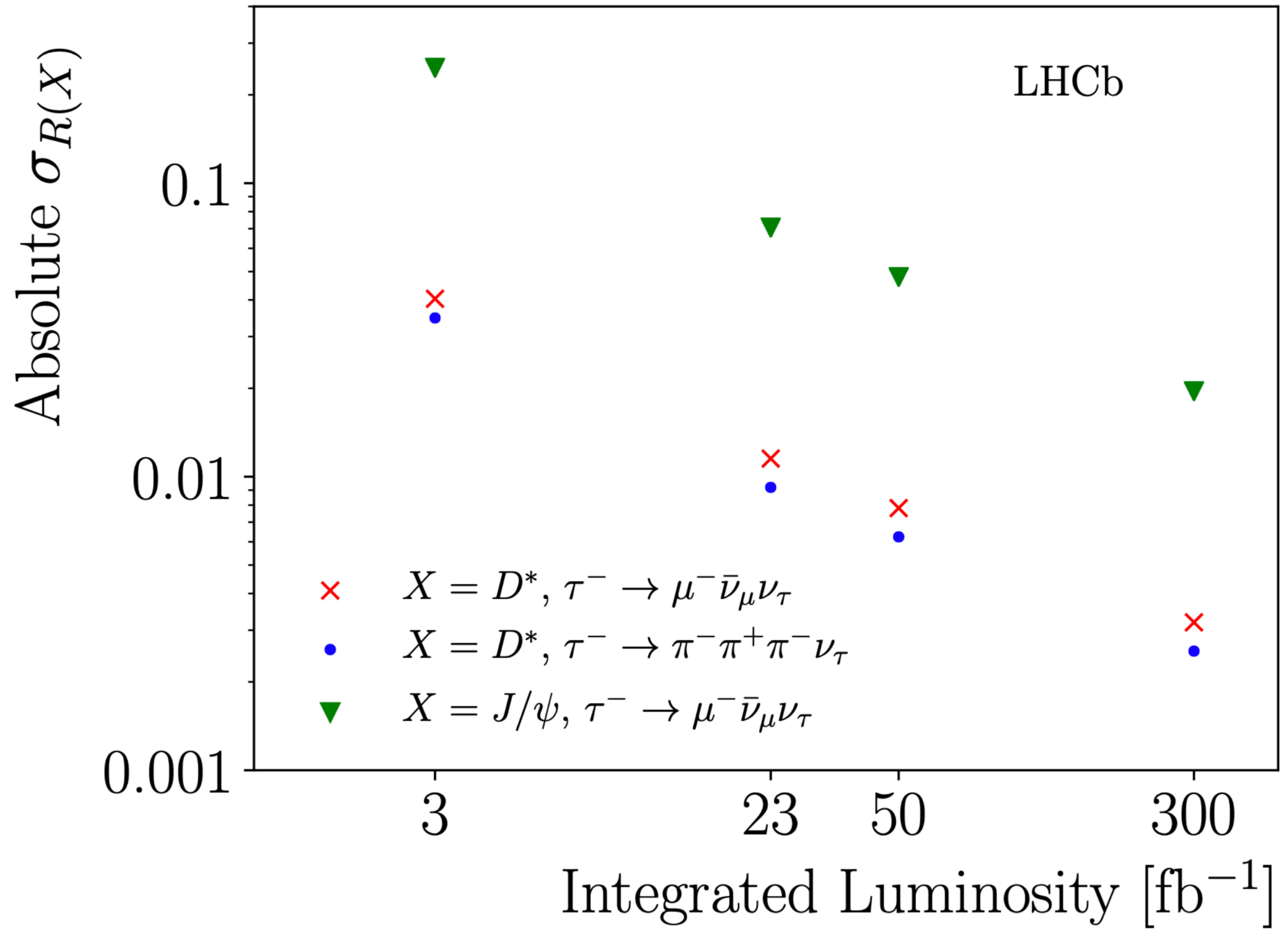
Independent determinations of UT apex $(\Delta m_d/\Delta m_s, \sin 2\beta)$ and (V_{ub}, γ)

Flavor physics @HL-LHC

Pursue Quantum Imprints
of New Phenomena

arXiv:1808.08865

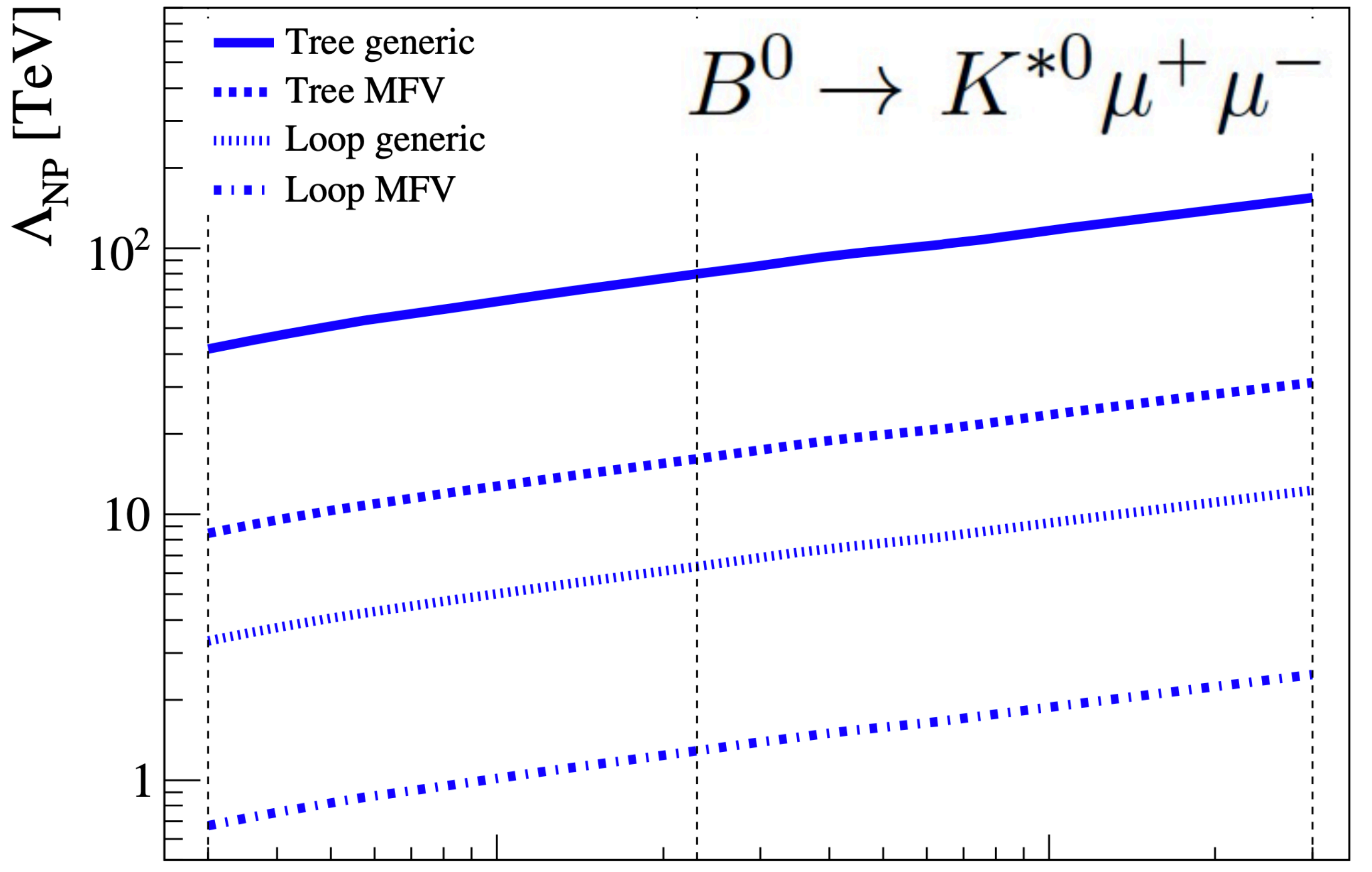
- Precise lepton-flavor universality tests



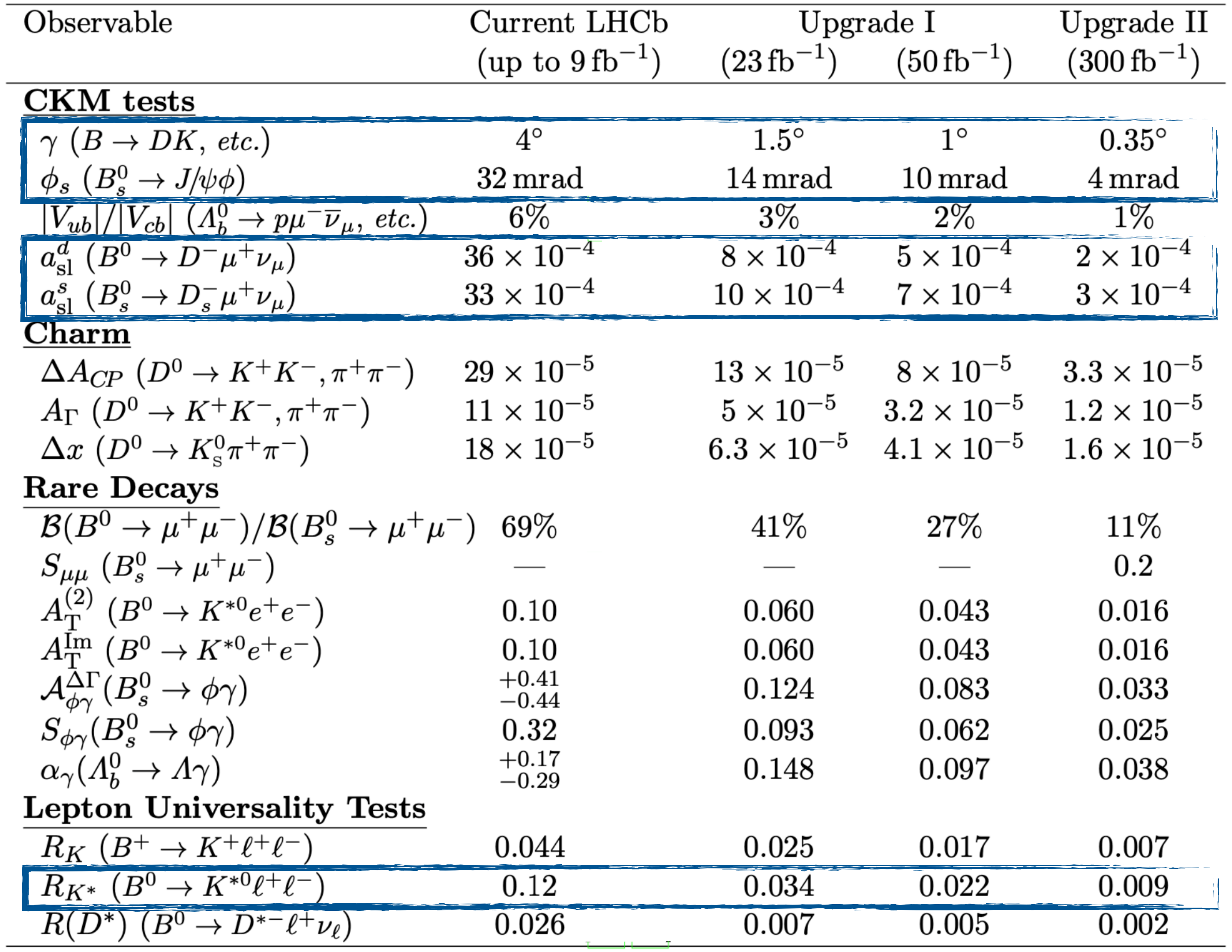
$$R = \frac{B \to X\tau\nu}{B \to X\mu\nu}$$

uncertainty as low as 0.2% for $X = D^*$

- Sensitivity to non-flavor diagonal BSM up to ~100 TeV
  HL-LHC increases reach by factor of 2



LHCb



Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (23 fb^{-1})	(50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests				
γ ($B \to DK$, *etc.*)	4°	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$, *etc.*)	6%	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm				
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_{\rm S}^0\pi^+\pi^-$)	18×10^{-5}	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—	—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	0.148	0.097	0.038
Lepton Universality Tests				
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	0.007	0.005	0.002

- ATLAS and CMS also will perform key flavor meas$^{\rm ts}$ incl. $B^0_{(s)} \to \mu\mu$, ϕ_s, $R_{K^{(*)}}$
- Theoretically clean, not syst. limited

Future colliders

Recommendation 2c

- Next priority: **e^+e^- Higgs factory**

	Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1} /IP
	HL-LHC	pp	14 TeV		3
linear ee	ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2
			350 GeV	$\pm80/\pm30$	0.2
			500 GeV	$\pm80/\pm30$	4
			1 TeV	$\pm80/\pm20$	8
	CLIC	ee	380 GeV	$\pm80/0$	1
circular ee	CEPC	ee	M_Z		50
			$2M_W$		3
			240 GeV		10
			360 GeV		0.5
	FCC-ee	ee	M_Z		75
			$2M_W$		5
			240 GeV		2.5
			$2\ M_{top}$		0.8
$\mu\mu$	μ-collider	$\mu\mu$	125 GeV		0.02

Reveal the Secrets of the Higgs Boson

Pursue Quantum Imprints of New Phenomena

Future colliders

Search for Direct Evidence of New Particles

Recommendation 2c

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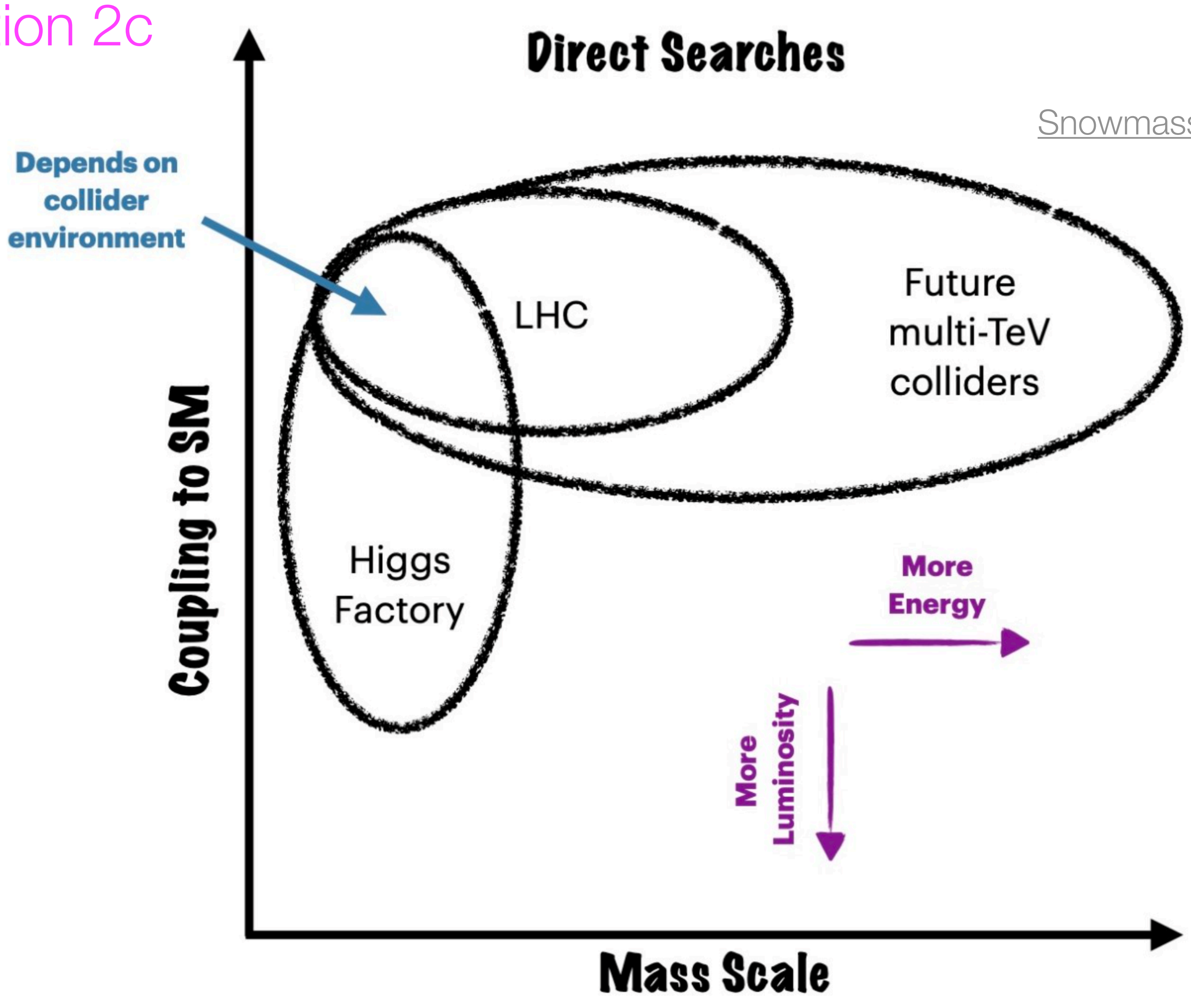
			360 GeV		0.5
	FCC-ee	ee	M_Z		75
			$2M_W$		5
			240 GeV		2.5
			$2\ M_{top}$		0.8
μμ	μ-collider	$\mu\mu$	125 GeV		0.02



Snowmass EF report

Recommendation 4

- Longer term: **10-TeV pCM collider**

Collider	Type	$\sqrt{s}$ (TeV)	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP
HE-LHC	pp	27		15
FCC-hh	pp	100		30
SPPC	pp	75-125		10-20
LHeC	ep	1.3		1
FCC-eh		3.5		2
CLIC	ee	1.5	$\pm80/0$	2.5
		3.0	$\pm80/0$	5
μ-collider	$\mu\mu$	3		1
		10		10

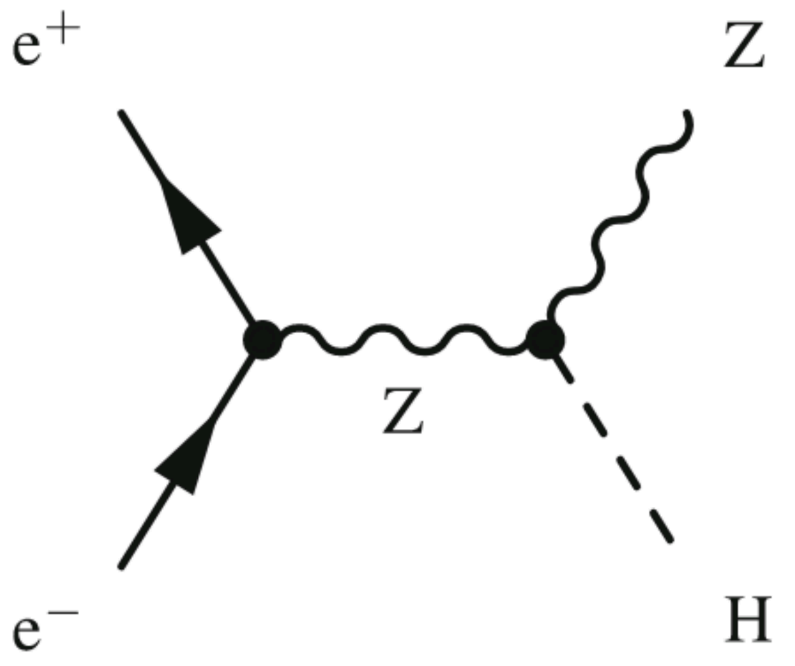
- **Much interest for muon collider in US**

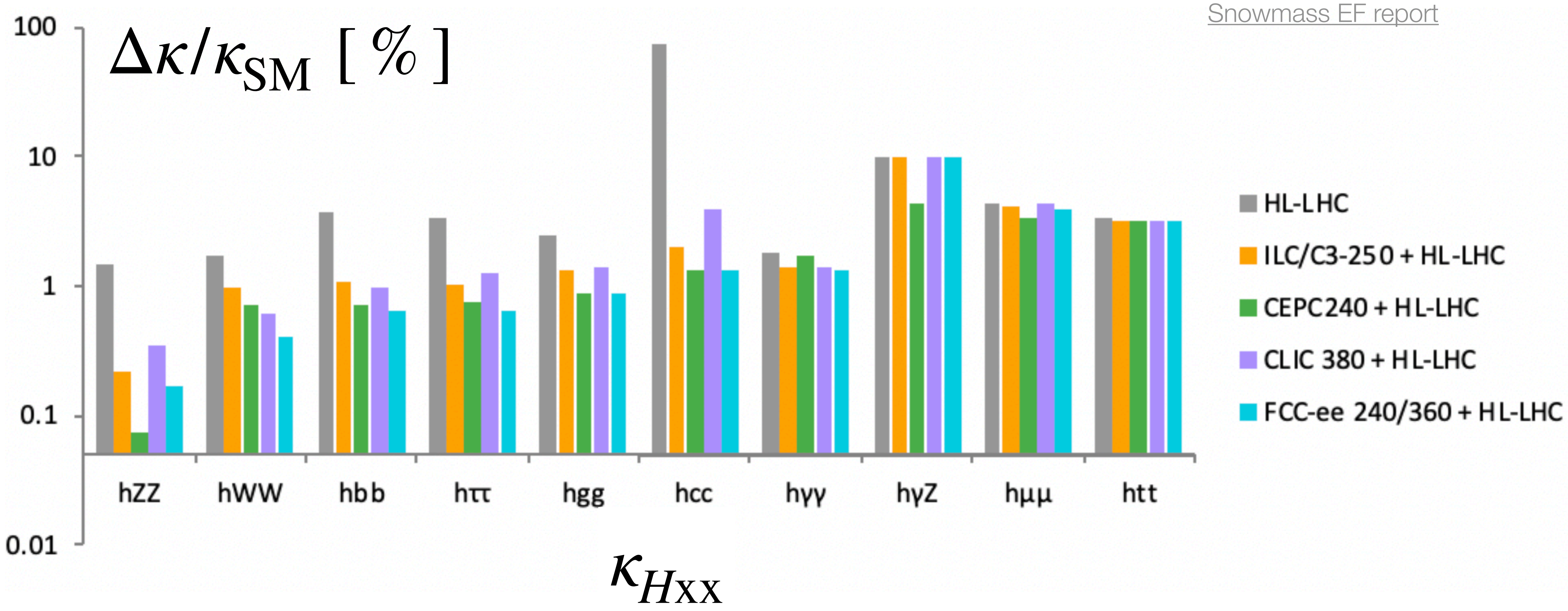
Reveal the Secrets of the Higgs Boson

Pursue Quantum Imprints of New Phenomena

e^+e^- : Higgs boson

- *Fully inclusive* Higgs sample via recoil mass in ZH production (~1 M events)





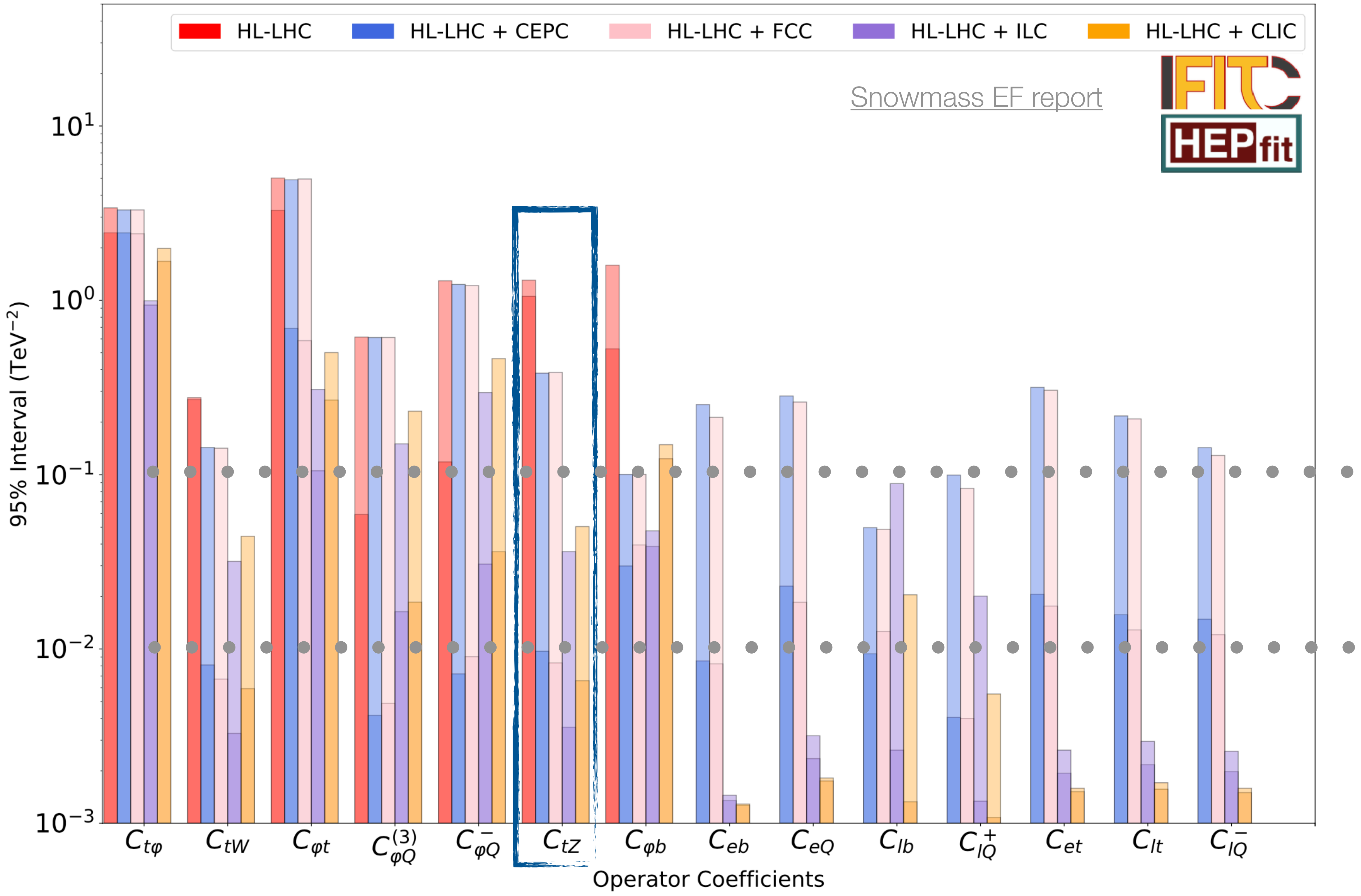
Snowmass EF report

- **Absolute** measurement of g_{HZZ} with 0.05% statistical precision reachable
  - Allows to translate cross-section ratios from HL-LHC into model-independent coupling measurements

- Sharp improvement wrt HL-LHC for Higgs coupling to Z, W, b, ***c***, τ (factor 10 for Z or H_{inv})
- **Higgs width precision**
  - 1% combining e^+e^- with HL-LHC
  - 1.7% direct measurement via line-shape at μC
- FCC-ee exploring running at $\sqrt{s} = 125$ GeV to measure coupling to electrons

e^+e^- : Top quark

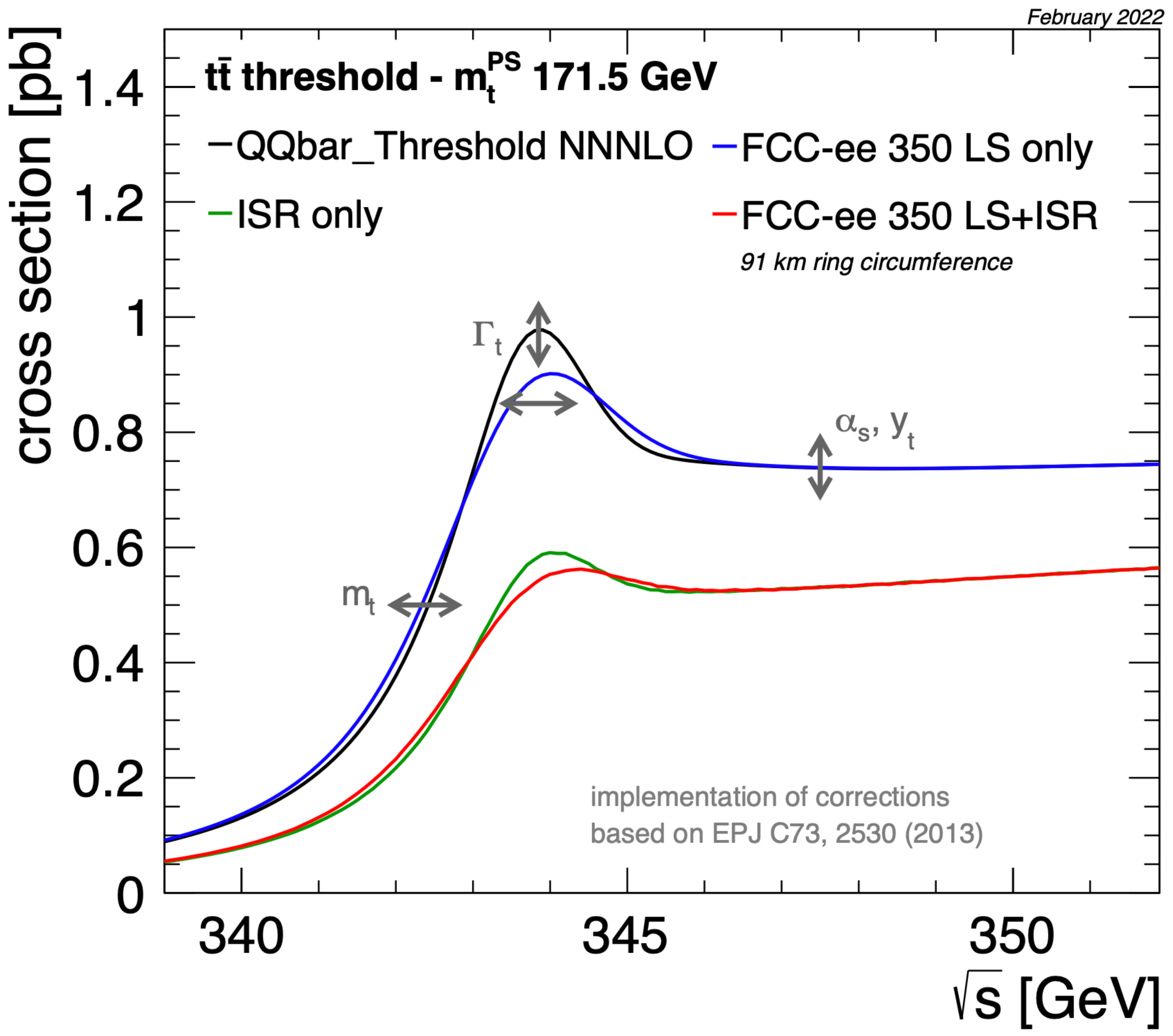
- **Top quark:** key role in SM
    - Yukawa coupling $y_t \simeq 1$, quadratic corr^s to m_H, vacuum stability
    - Only quark that does not hadronize before decay
- Expect ~2M $t\,\bar{t}$ events w/ clean environment + ability to scan $\sqrt{s}$
- Top-mass precision: 40-75 MeV from scan
- Sharply improved ttZ coupling + EFT constraints on top couplings



3 TeV (c = 1)

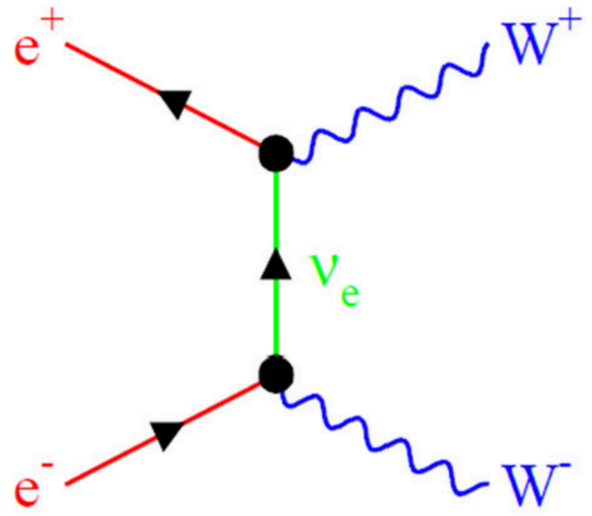
10 TeV (c = 1)

arXiv:2203.06520

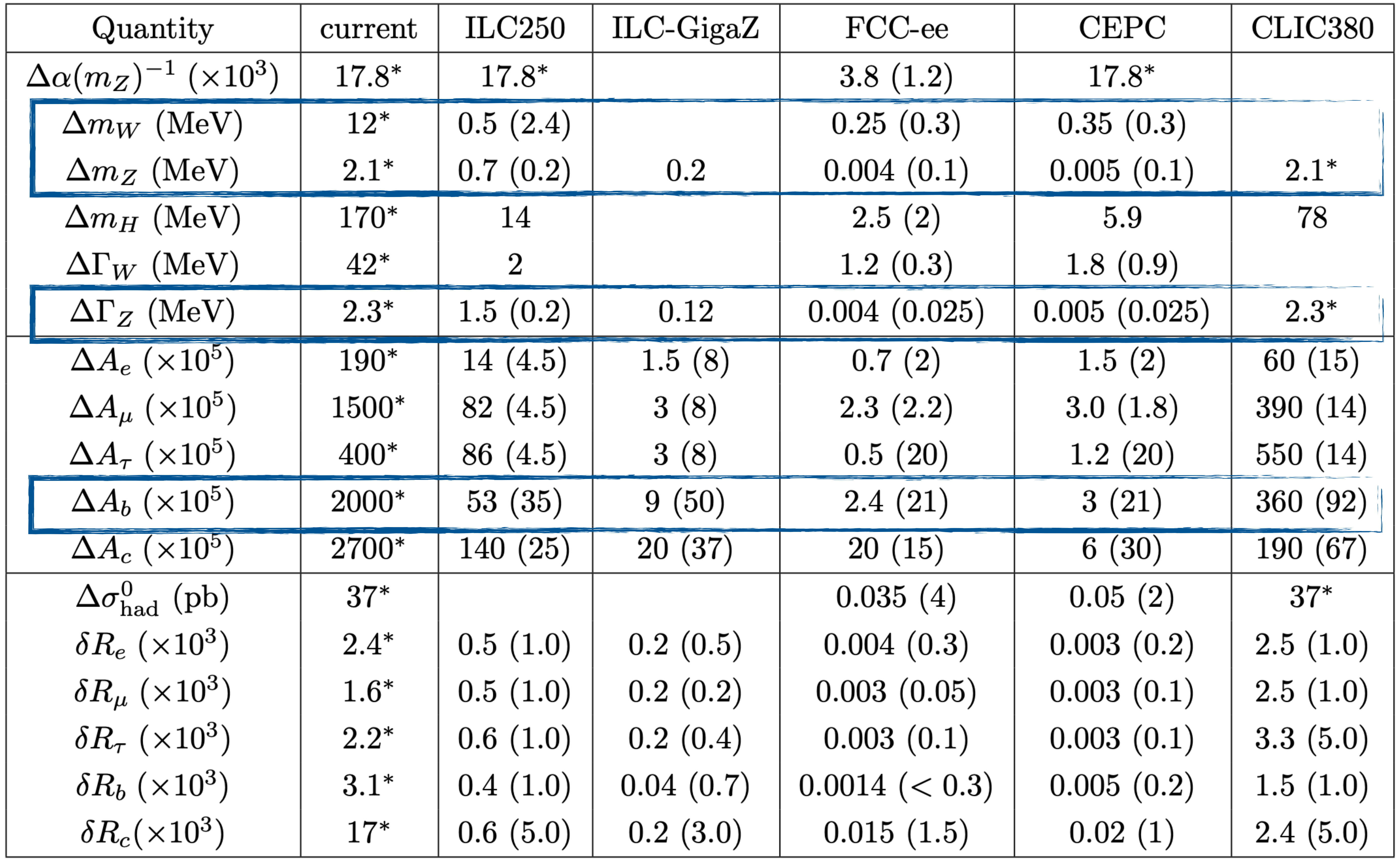


e^+e^- : Precision Electroweak

- **Giga-Z (ILC) & Tera-Z (FCC-ee, CEPC) runs**: up to 6 x 10^{12} Z bosons
  —> 5+ orders of magn. more than LEP
  - **Reduced statistical uncertainties by factor up to ~500**
  - Requires theory calculations at next order or higher + improved $\alpha_s, \alpha_{EM}, m_t$
- **WW threshold**: 2 x 10^8 WW boson pairs
  —> 3 orders of magn. more than LEP



Snowmass EF report



Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e $(\times 10^5)$	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ $(\times 10^5)$	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ $(\times 10^5)$	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b $(\times 10^5)$	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c $(\times 10^5)$	2700*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_{\text{had}}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e $(\times 10^3)$	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ $(\times 10^3)$	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ $(\times 10^3)$	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b $(\times 10^3)$	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
$\delta R_c (\times 10^3)$	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

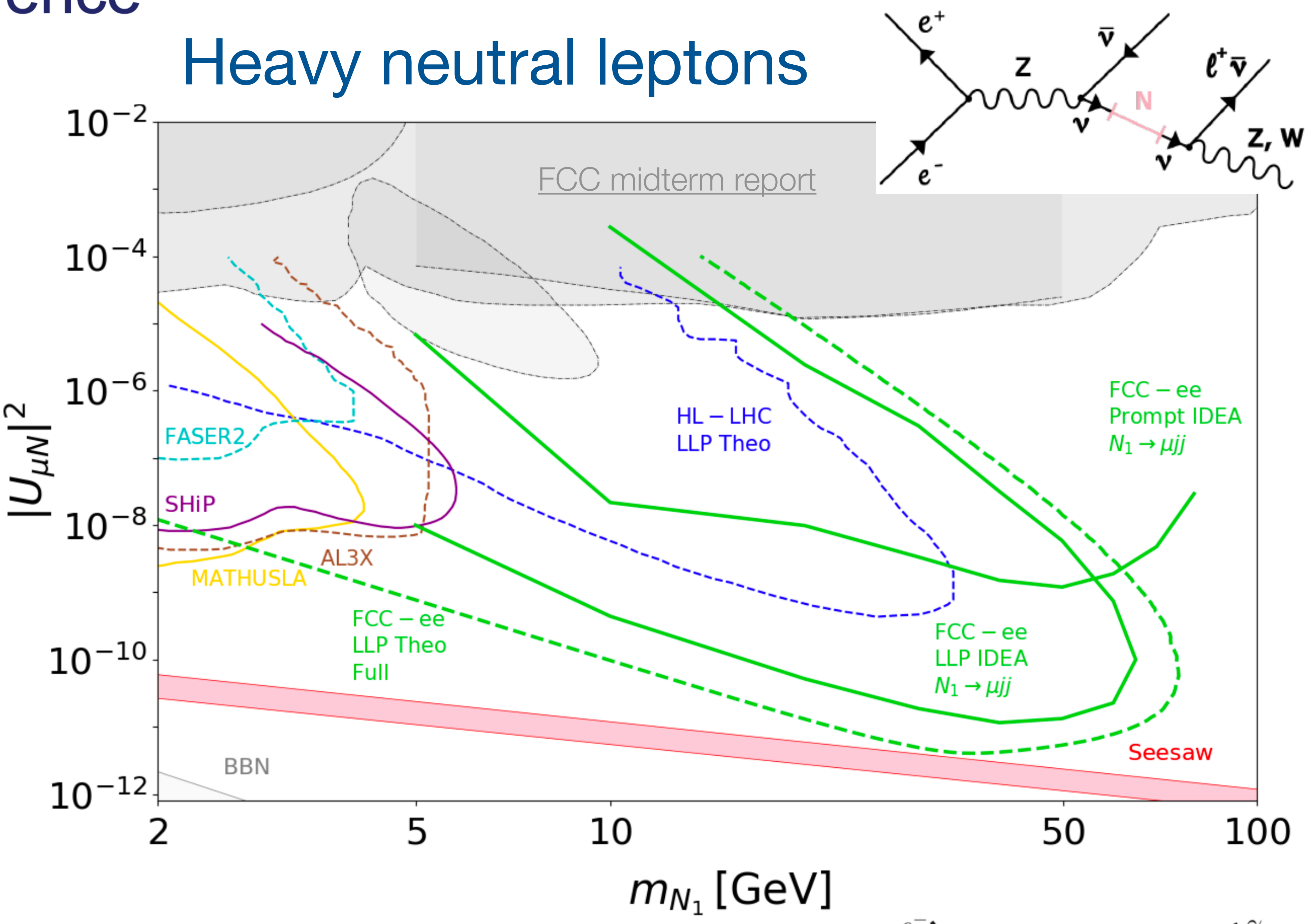
Stat. (exp. syst.) uncertainties improve by up to factors of 20-50

  - W mass and width from line shape —> $\delta m_W = 0.4$ MeV, $\delta\Gamma_W = 1.2$ MeV
- **EFT study w/ dim-6 operators for Higgs + EW:** indirect BSM sensitivity up to 70 TeV (Tera-Z)

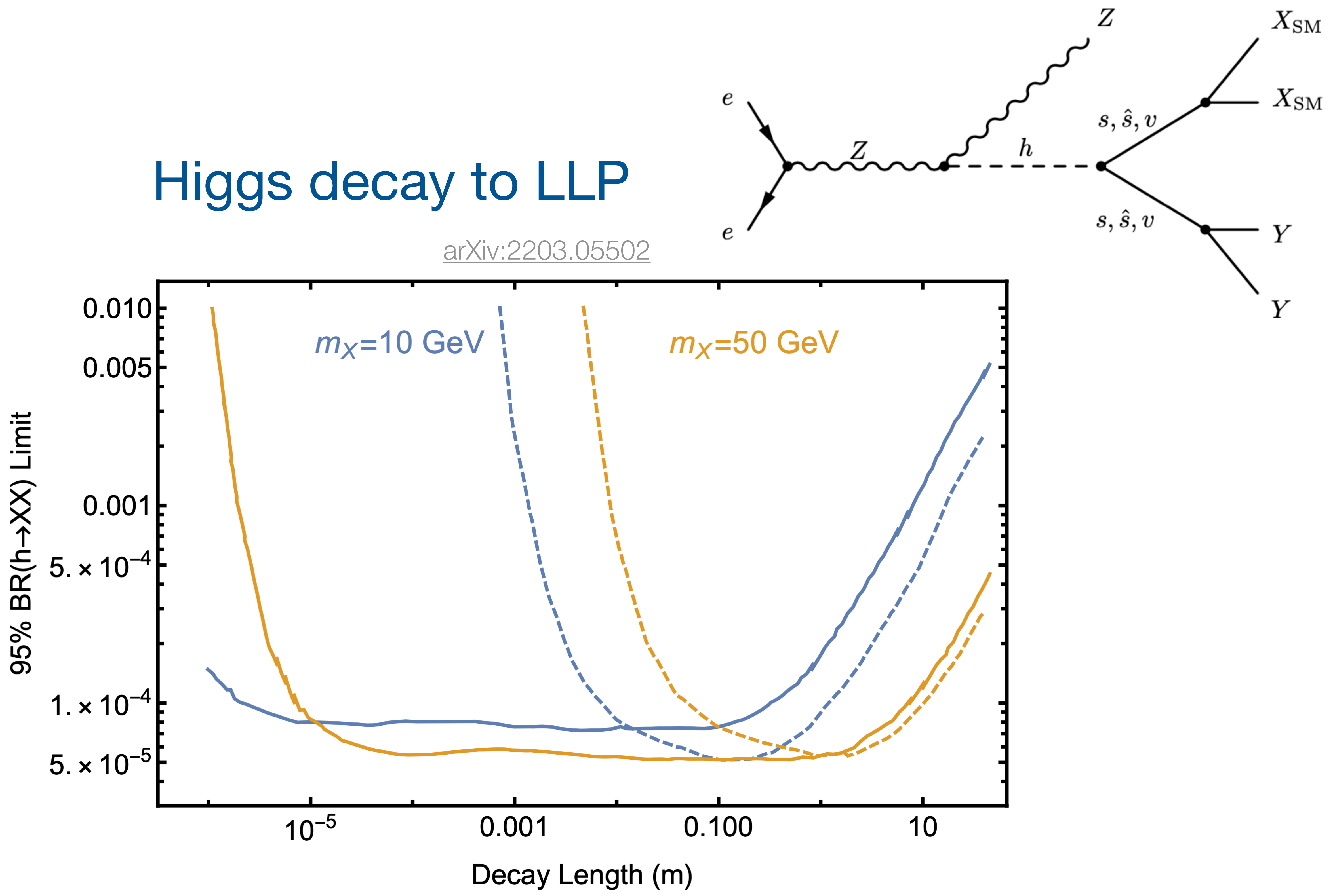
e⁺e⁻ : Beyond the SM

Search for Direct Evidence of New Particles

- Direct searches exploiting vast samples of Z and H bosons
  - **Origin of neutrino mass**: HNL reach down to $U^2 \simeq 10^{-11}$
  - **Dark sector**: ALP mediators reach to $g_{a\gamma} \simeq 10^{-4}\ \mathrm{TeV}^{-1}$
  - **Higgs portal**: BF reach down to 5×10^{-5}

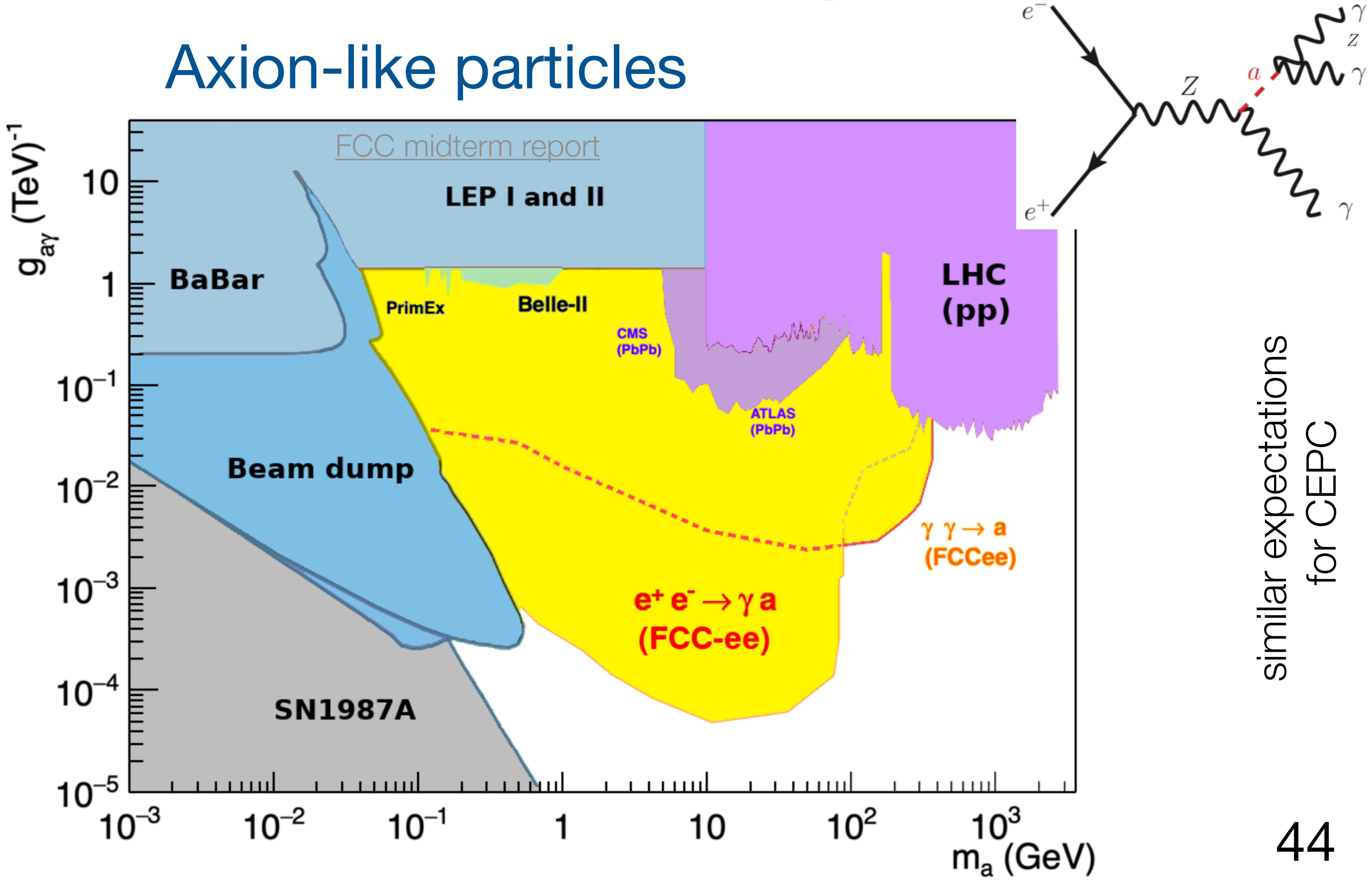

Heavy neutral leptons

FCC midterm report


Higgs decay to LLP

arXiv:2203.05502

All above search channels involve displaced vertices


Axion-like particles

FCC midterm report

similar expectations for CEPC

FCC-ee: US - CERN statement of intent

★ ★ ★

Joint Statement of Intent between The United States of America and The European Organization for Nuclear Research concerning Future Planning for Large Research Infrastructure Facilities, Advanced Scientific Computing, and Open Science

OTHER RELEASE

BUREAU OF OCEANS AND INTERNATIONAL ENVIRONMENTAL AND SCIENTIFIC AFFAIRS

APRIL 26, 2024

Deirdre Mulligan (Deputy US Chief Technology Officer)
Fabiola Gianotti (CERN Director General)

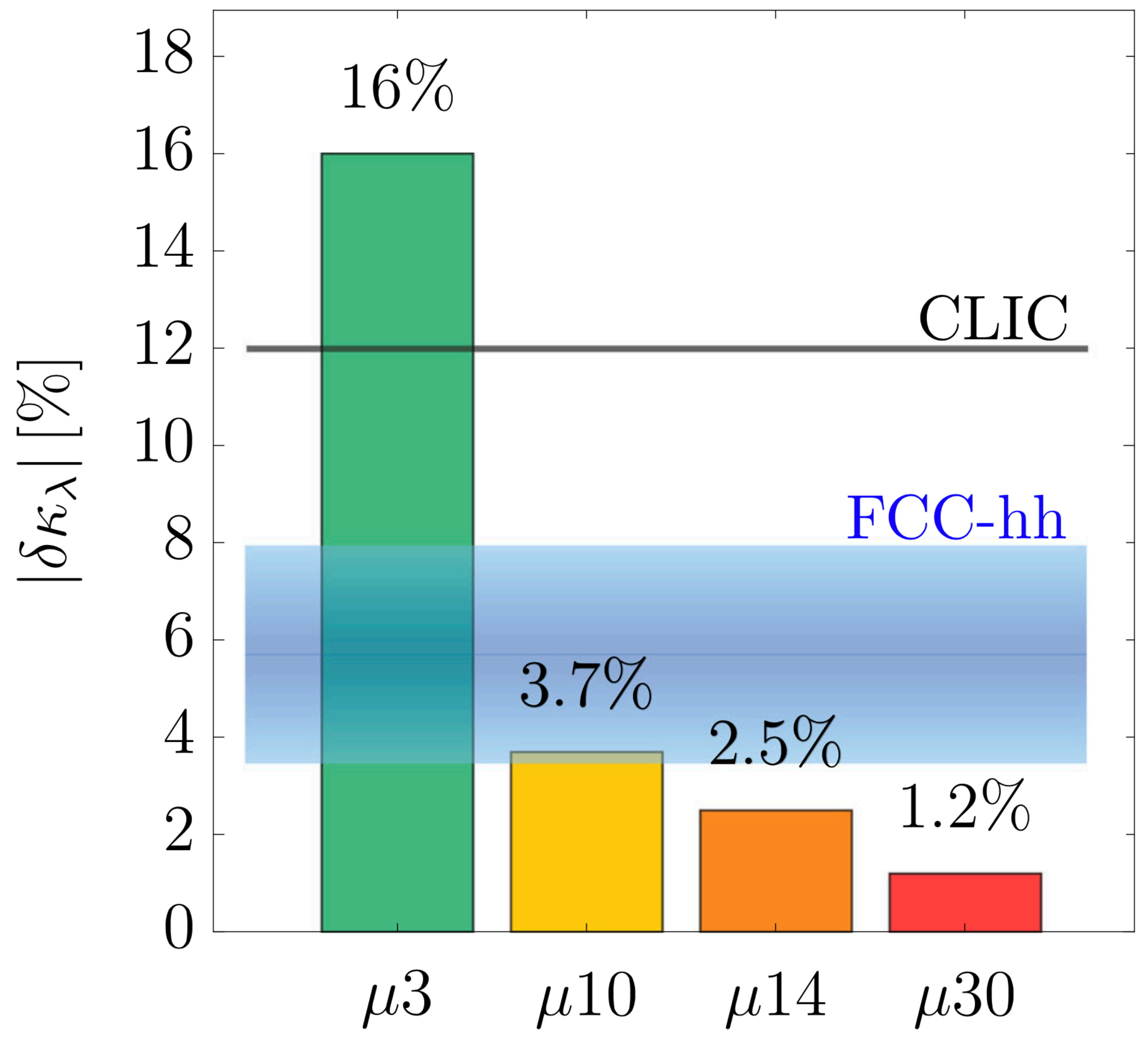
- Statement (26 Apr 2024)
  - U.S. and CERN to continue collaborating in the FCC Higgs Factory feasibility study
  - Subject to appropriate processes, the intention for the U.S. to collaborate on the FCC-ee, should the CERN Member States determine the FCC-ee is likely to be CERN's next research facility following the HL-LHC
  - Statement aligned with P5: should FCC-ee receive a "green-light" following the next update of the European Strategy, U.S. intends to collaborate; and nature of the contributions to be discussed by the panel prescribed in recommendation 6.1

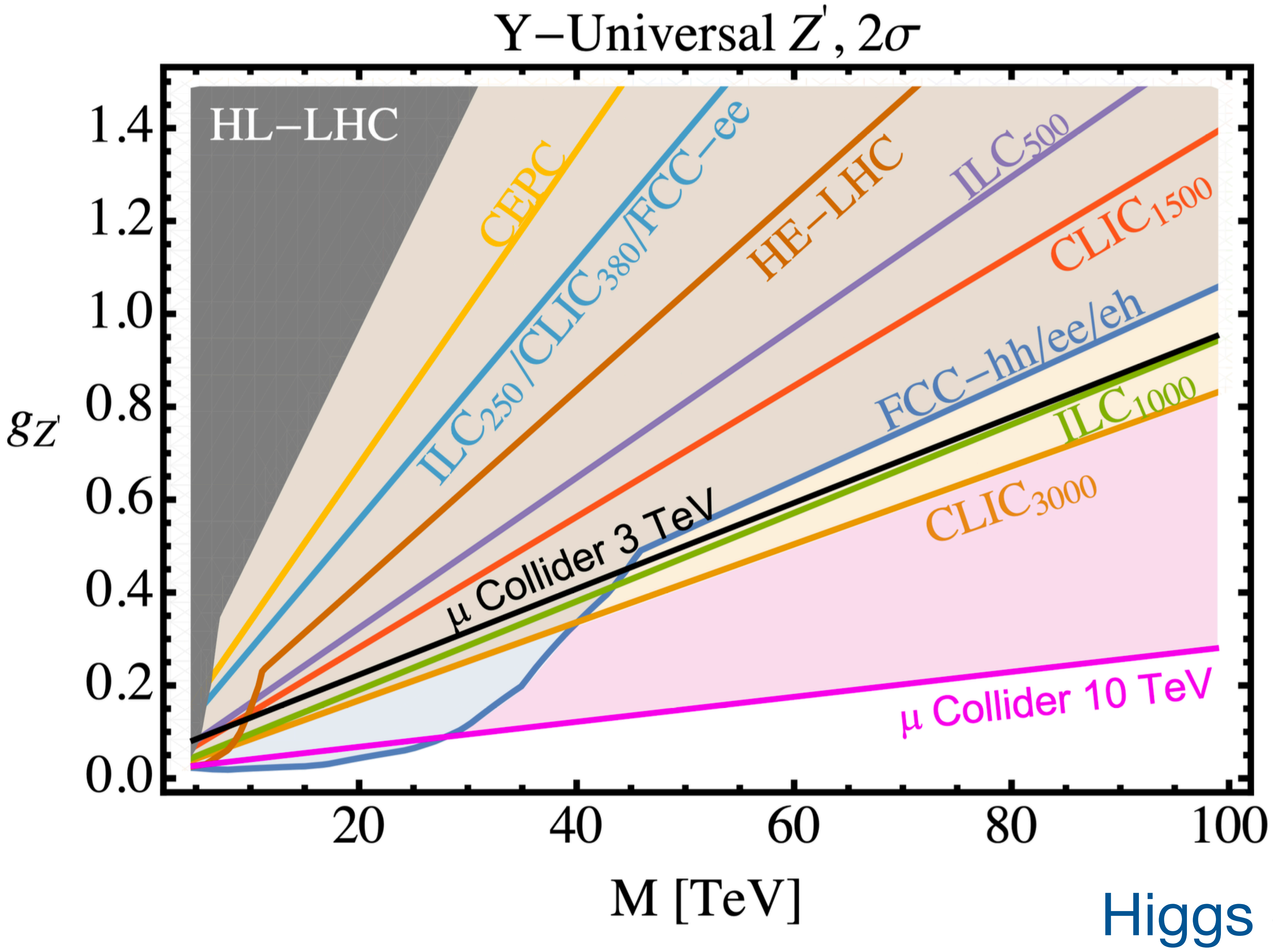
Multi-TeV colliders

Recommendation 4

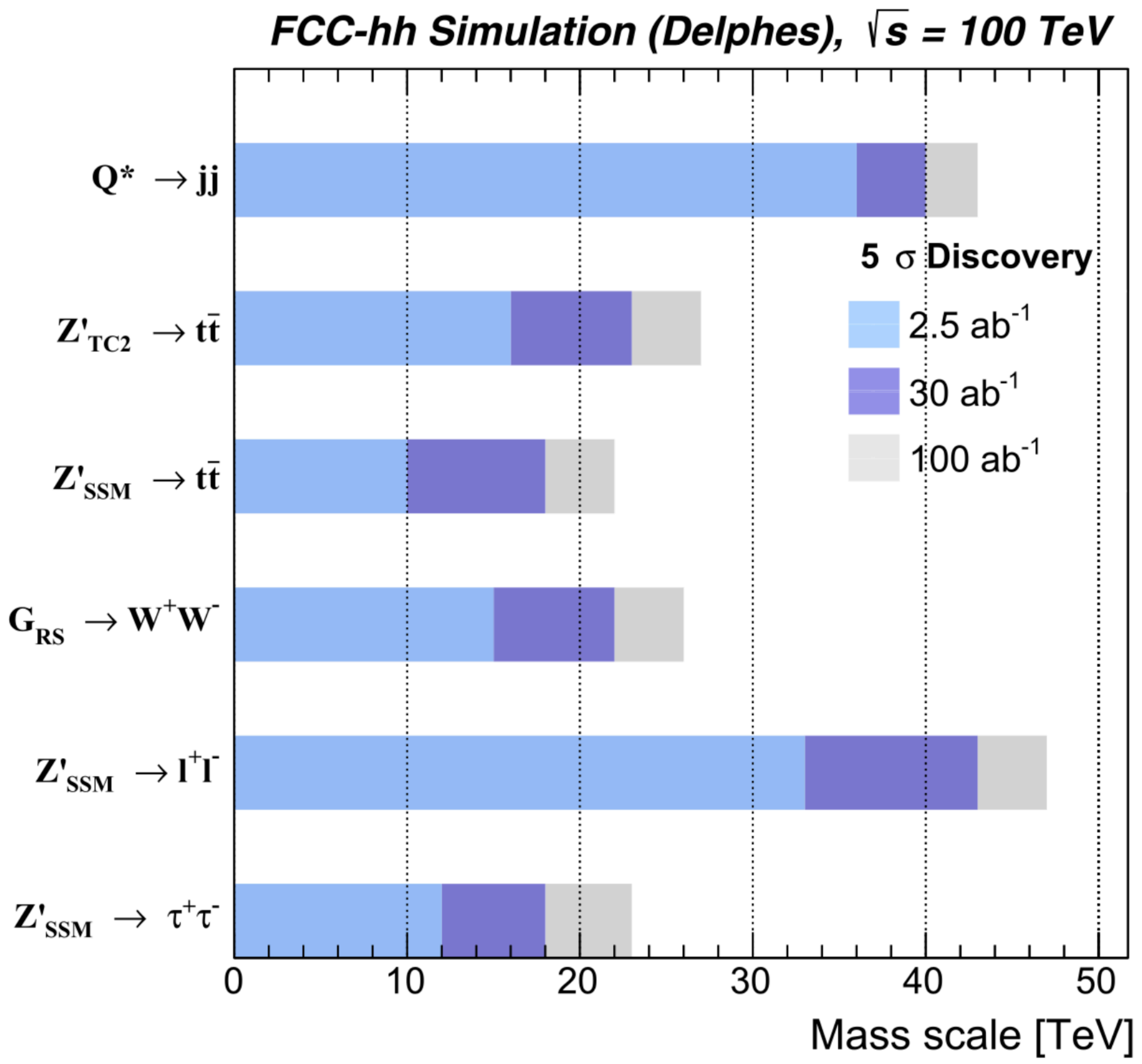
- **Higgs potential via self-coupling**
  precision of
  ~5% (100 TeV *hh*)
  ~4% (10 TeV μC)

arXiv:2303.08533





Heavy resonances up to 40 TeV



Search for Direct Evidence of New Particles

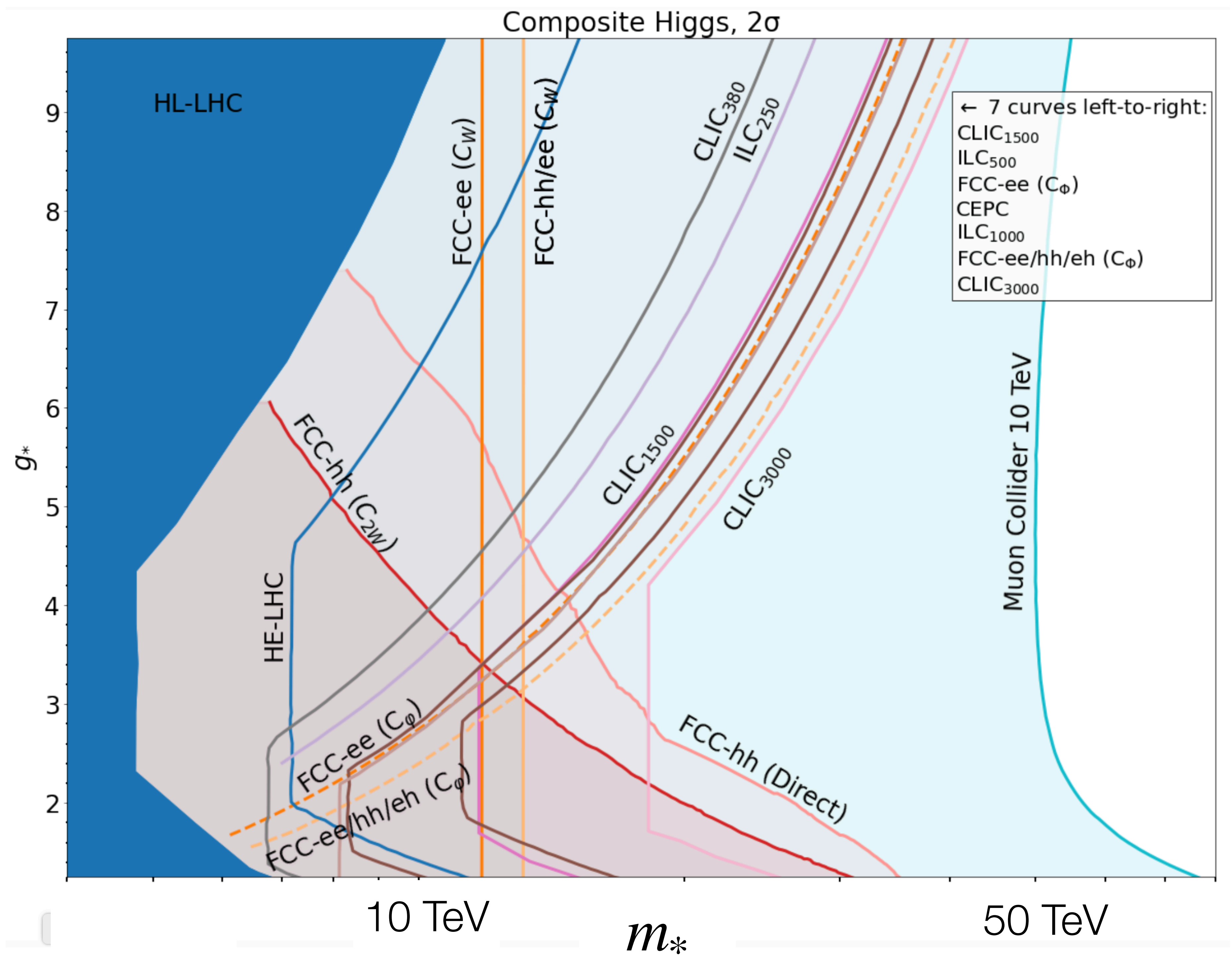
Snowmass EF report

Vector resonances reach to ~100 TeV

Complementarity of direct and indirect searches

arXiv:2209.13128

Higgs compositeness scale up to 50 TeV (μ-coll.)



Neutrino physics

Elucidate the Mysteries of Neutrinos

- **Previous breakthroughs**
  - Non-zero neutrino mass discovered via observation of neutrino oscillations
  - Oscillations observed (or inferred) between all flavors
  - Mixing angles and mass splittings measured
- **Compelling future program**
  - Mass ordering
  - Origin of neutrino mass
  - Dirac or Majorana?
  - CP violation?
  - Non-standard interactions

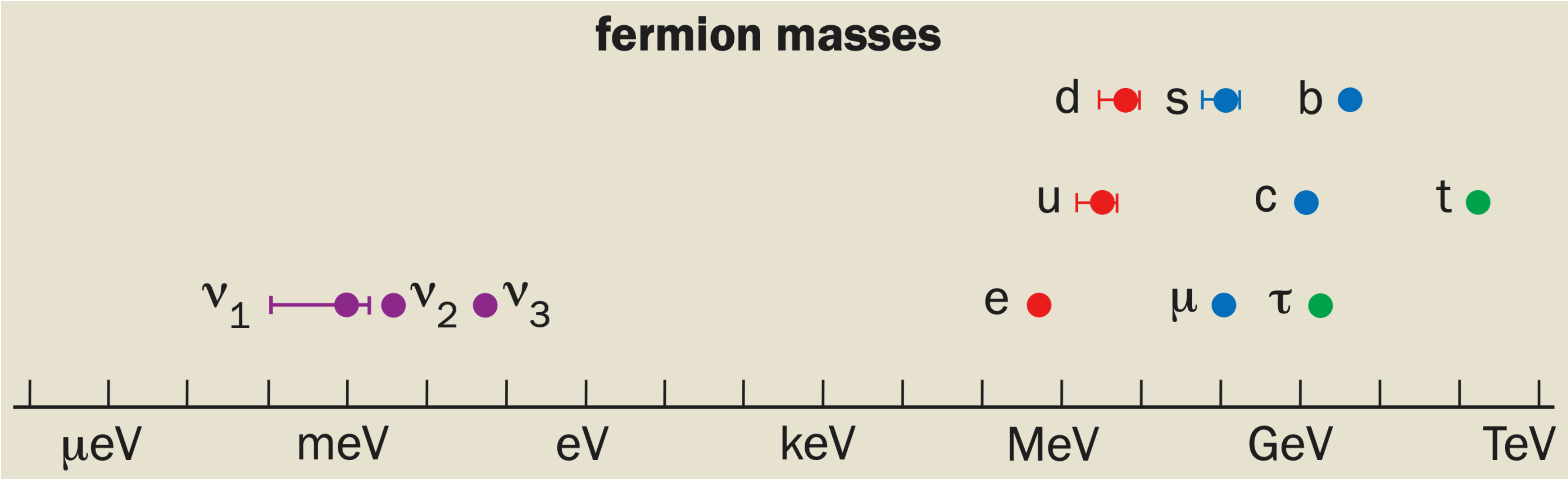
$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\mathrm{CP}}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{13}\,c_{23} \end{pmatrix}$$

J. Pedro Ochoa-Ricoux (ICHEP 2024)

From PDG 2024

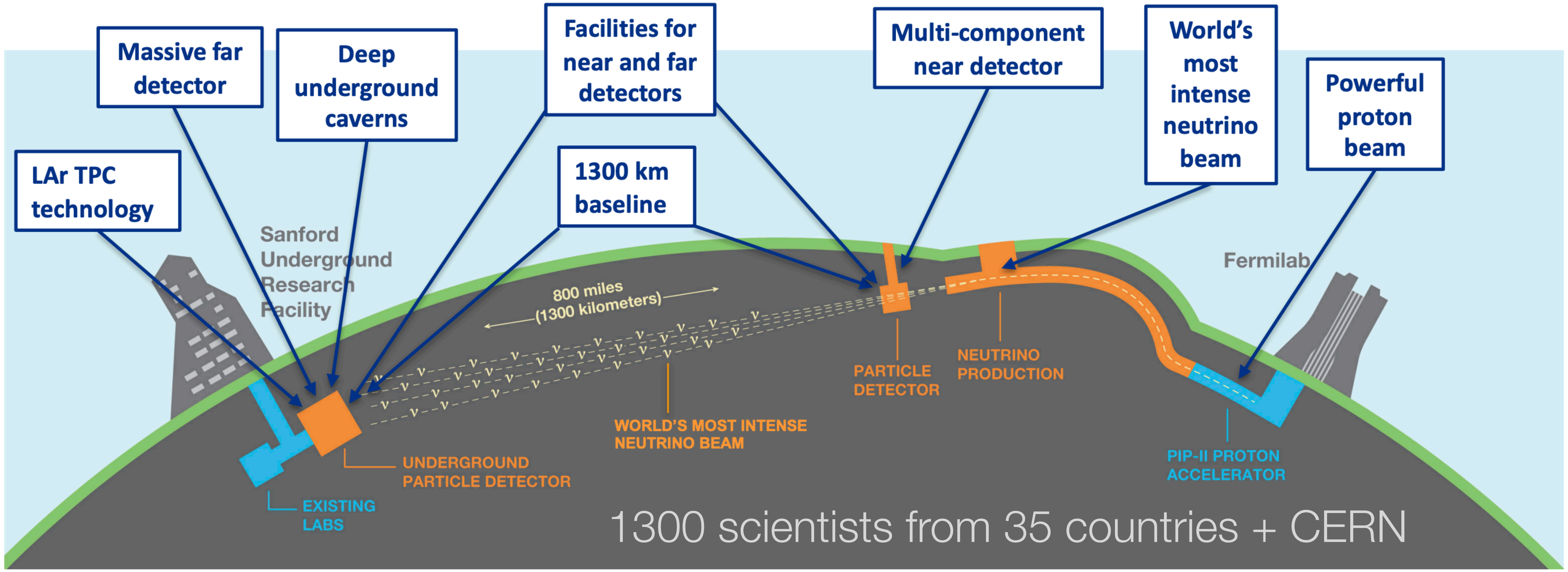
		Precision
$\sin^2(\theta_{12})$	0.307 ± 0.013	4.2 %
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2	2.4 %
$\sin^2(\theta_{23})$	$0.558^{+0.015}_{-0.021}$	3.2 %
Δm^2_{32}	$(2.455 \pm 0.028) \times 10^{-3}$ eV^2	1.1 %
$\sin^2(\theta_{13})$	0.0219 ± 0.0007	3.2 %

UC Berkeley



Neutrino oscillations

- **Deep Underground Neutrino Experiment** (DUNE) at Long Baseline Neutrino Facility (LBNF)



1300 scientists from 35 countries + CERN

Largest US project in Office of Science $3.2B

- **Goals**
  - Determine mass ordering
  - Test 3-flavor mixing model
  - Supernova ν_e detection
  - CP violating phase

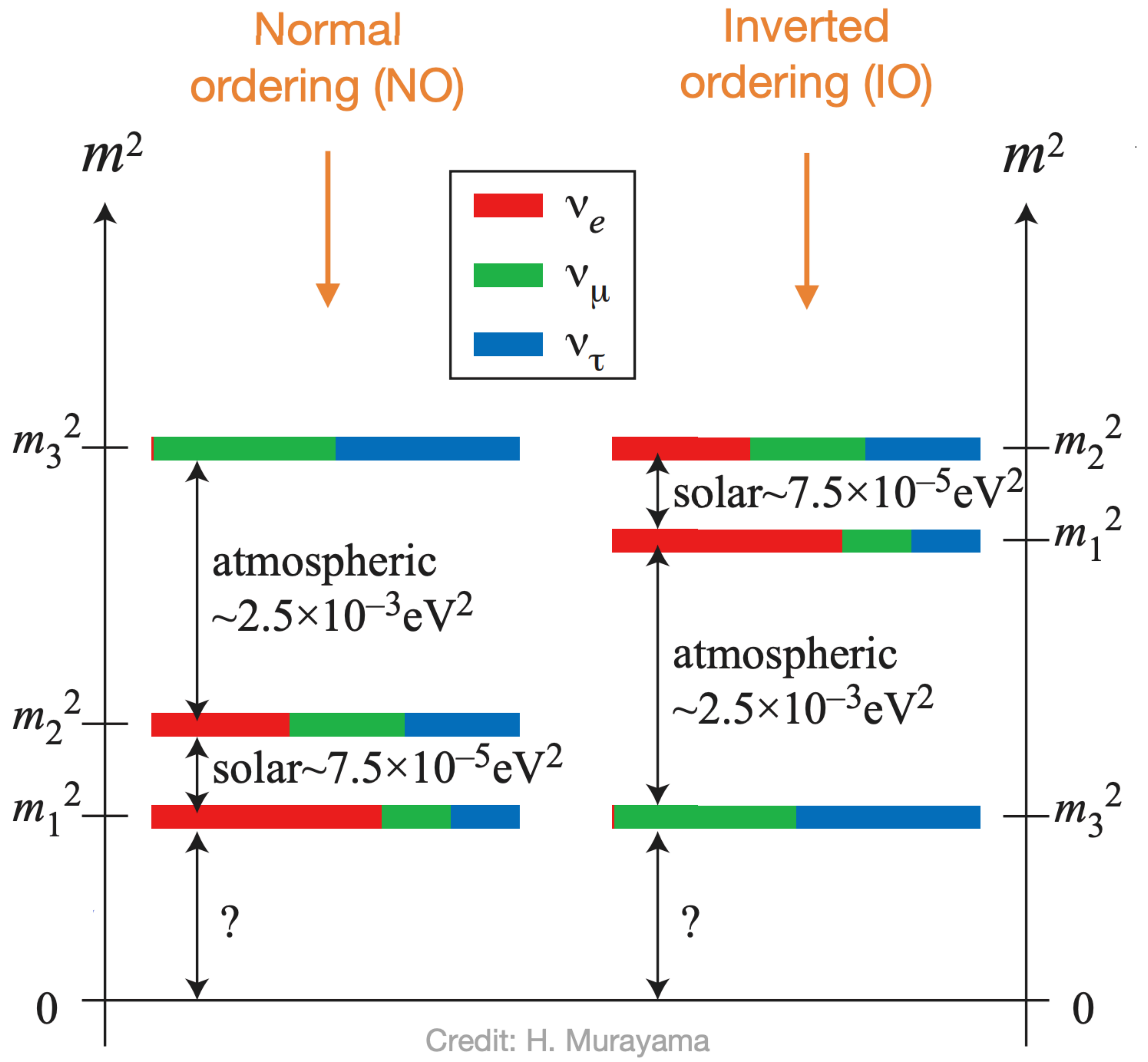
DUNE complementary to other planned ν experiments (esp. T2HK)

- Wide-band energy spectrum (on axis)
- Relatively high ν beam energy
- Long baseline
- Different detector systematic uncertainties

Neutrino oscillations

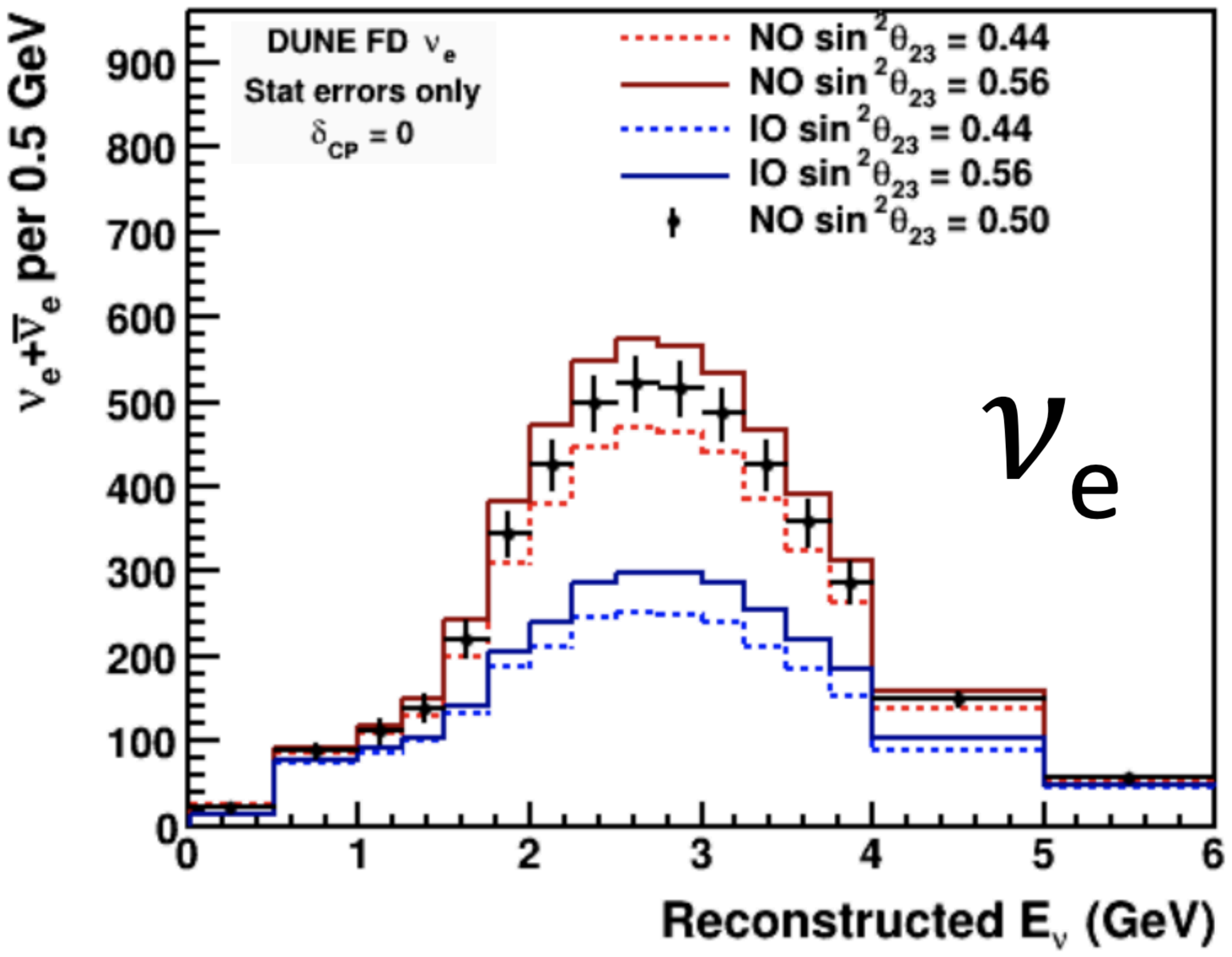
Elucidate the Mysteries of Neutrinos

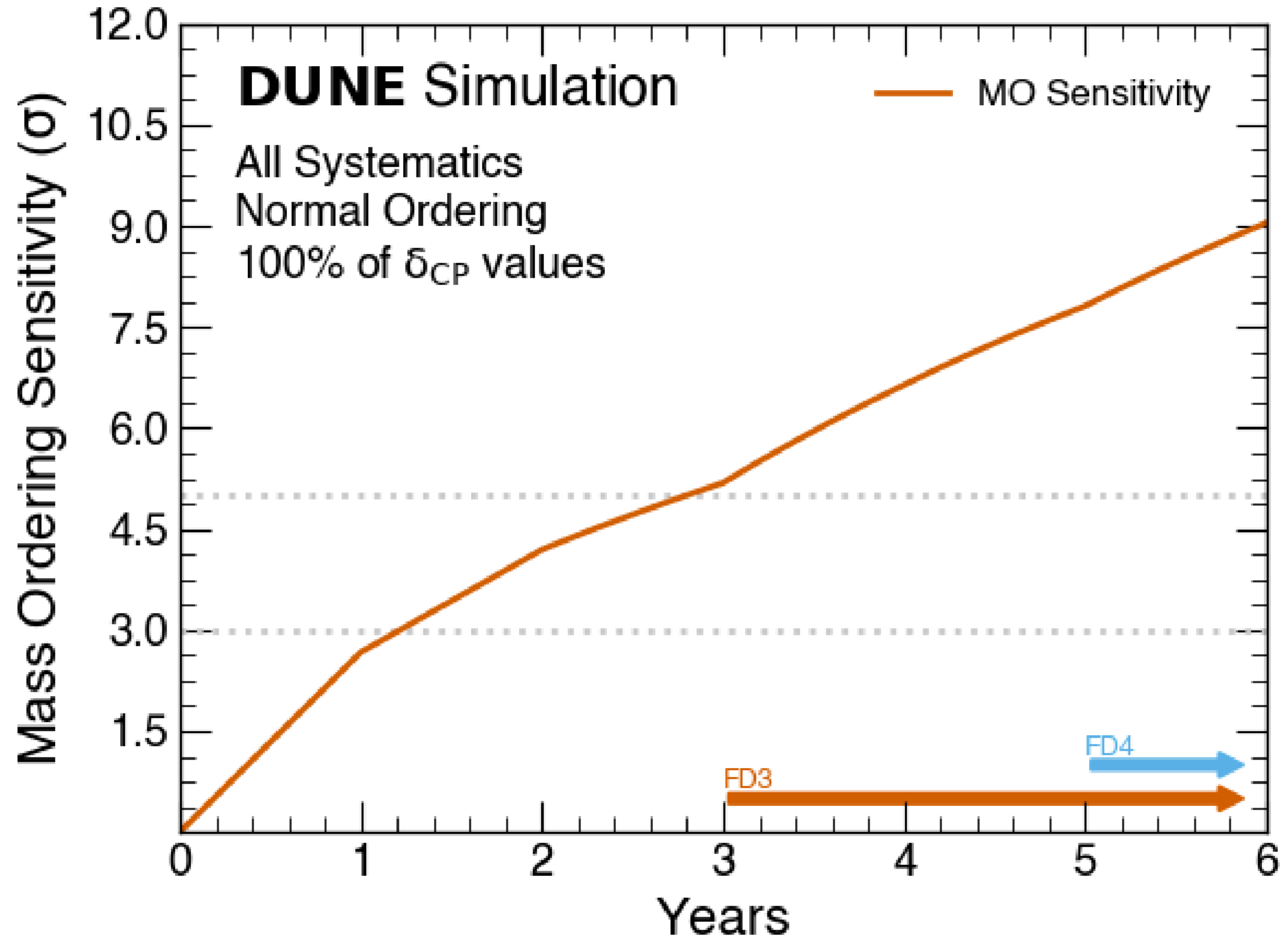
- **DUNE Phase I** Recommendation 1b
  - 1.2 MW proton beam —> wide-band neutrino beam
  - Two 10 kt (fid.vol.) LAr TPCs @SURF
  - Establish mass ordering at $> 5\,\sigma$ for any δ_{CP}
  - Evidence ($> 3\,\sigma$) for CP violation if large CPV



Credit: H. Murayama

I. Gil Botella (ICHEP 2024)





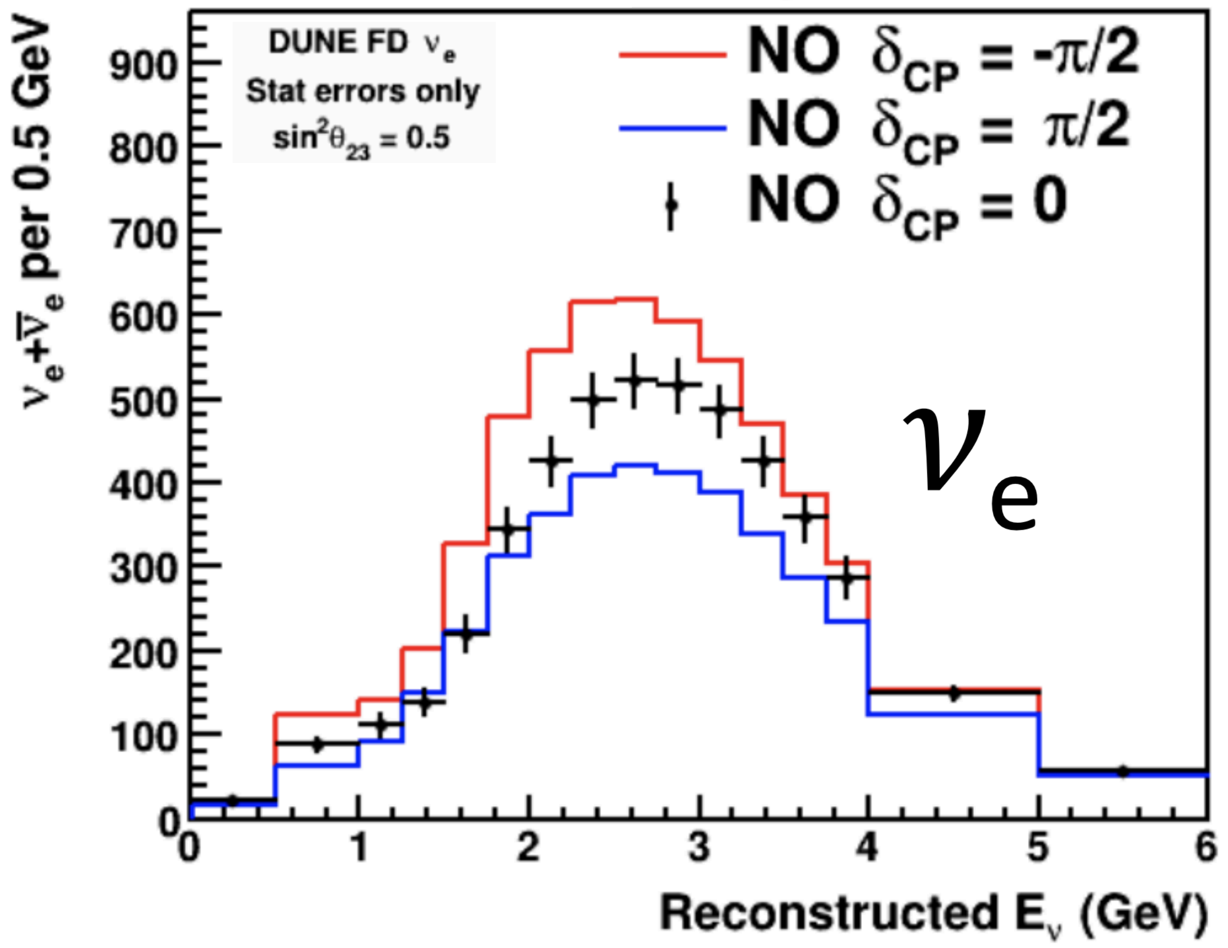
Neutrino oscillations

Elucidate the Mysteries of Neutrinos

- **DUNE Phase II** Recommendation 2b
  - 2.1 MW proton beam
  - Third far detector
  - Discover CP violation for 50% of δ_{CP} values

} to reach target 600 MWktyr

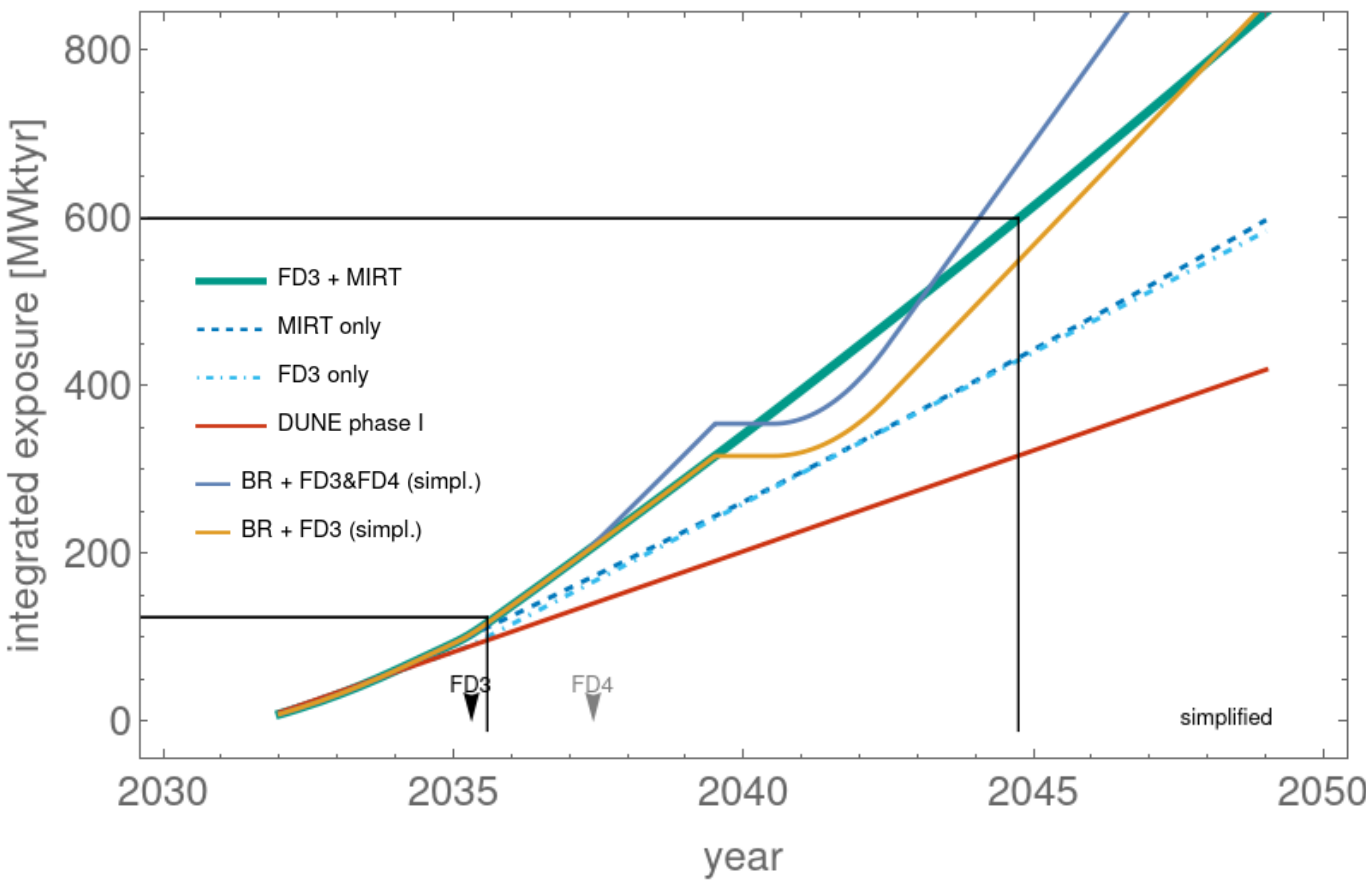
I. Gil Botella (ICHEP 2024)



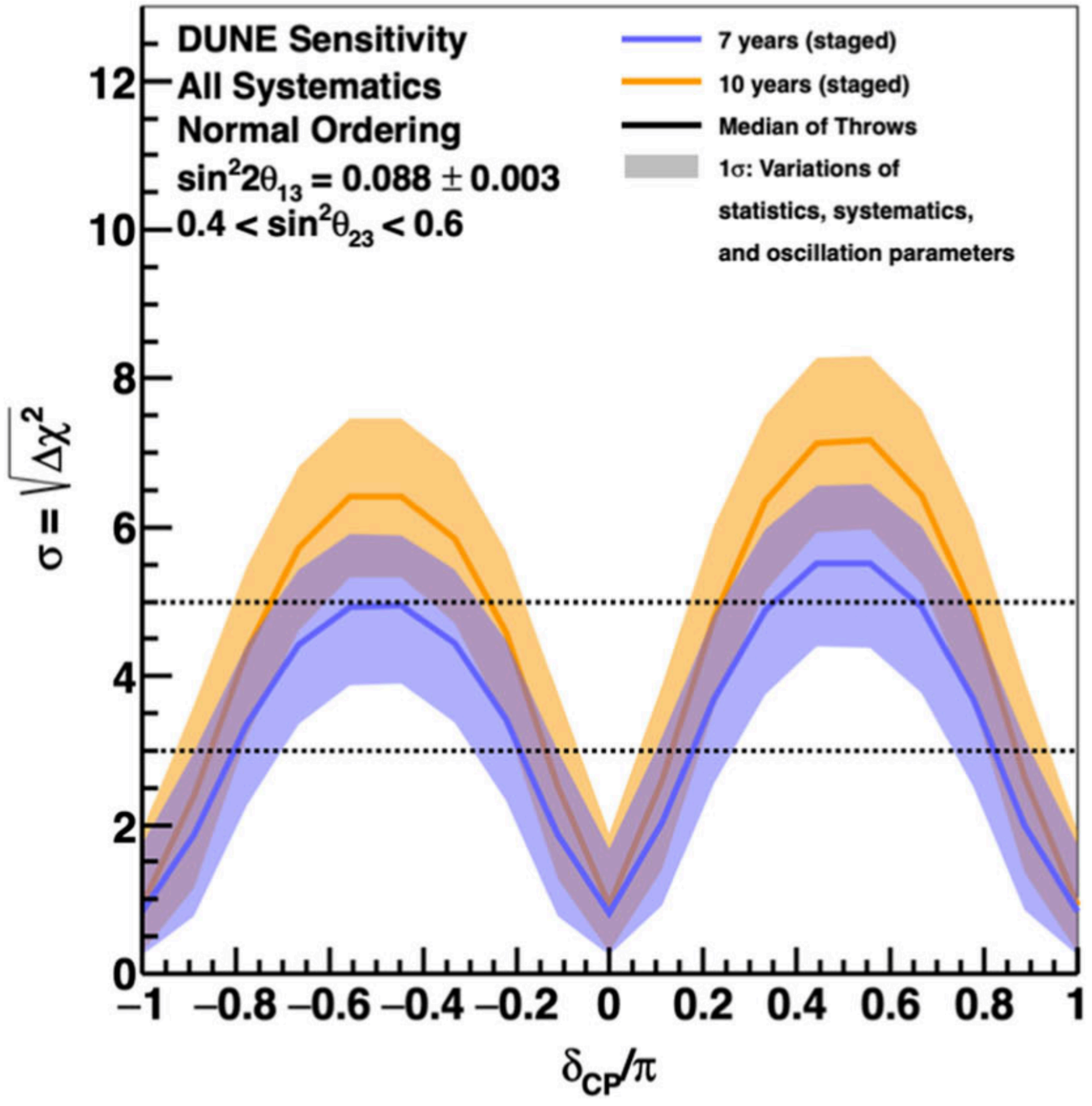
If $\delta_{\text{CP}} = -\pi/2$:

- increased ν_e appearance in ν_μ beam
- decreased $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam

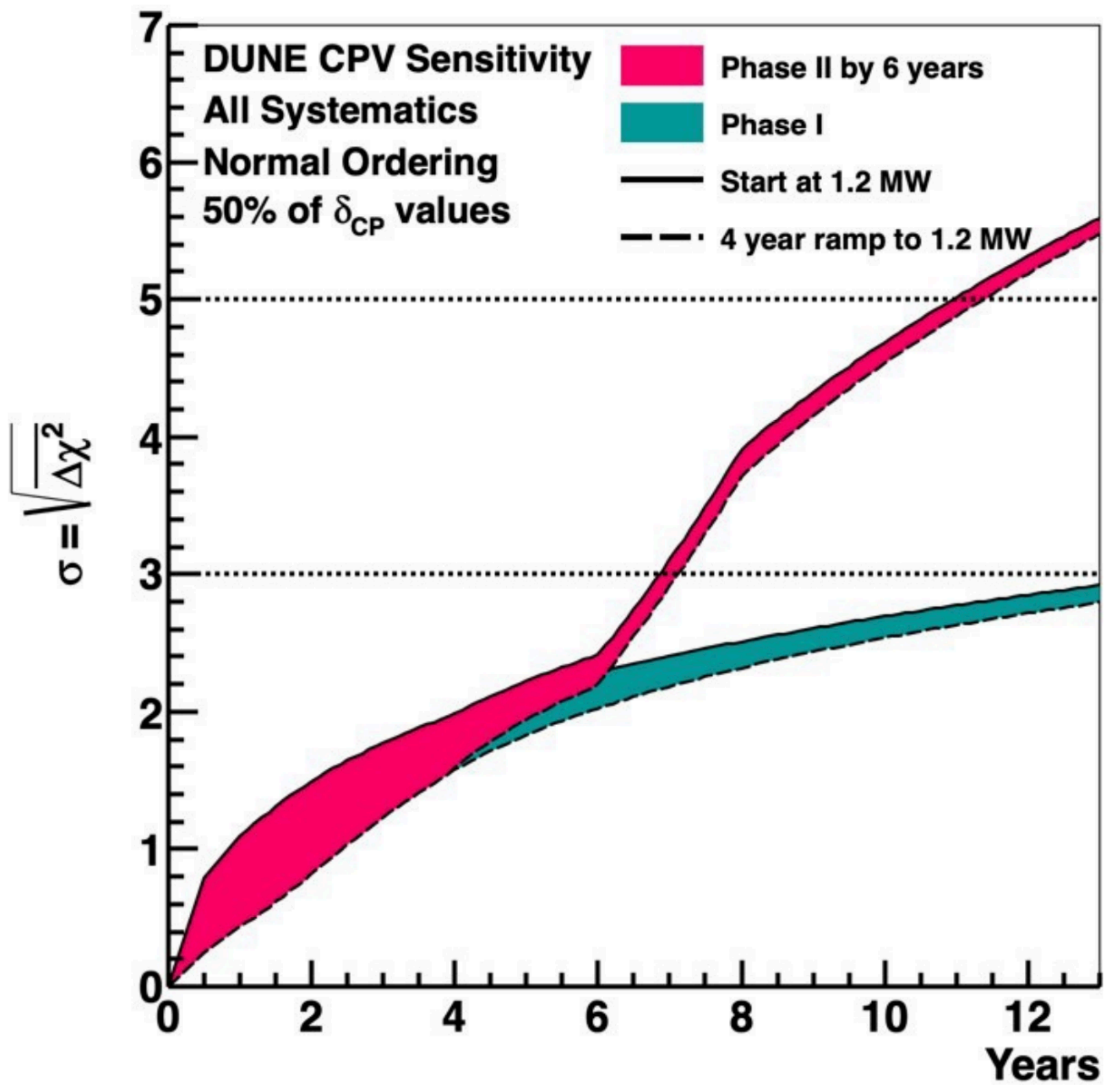
DUNE exposure (revised for P5)



EPJC 80 (2020) 978



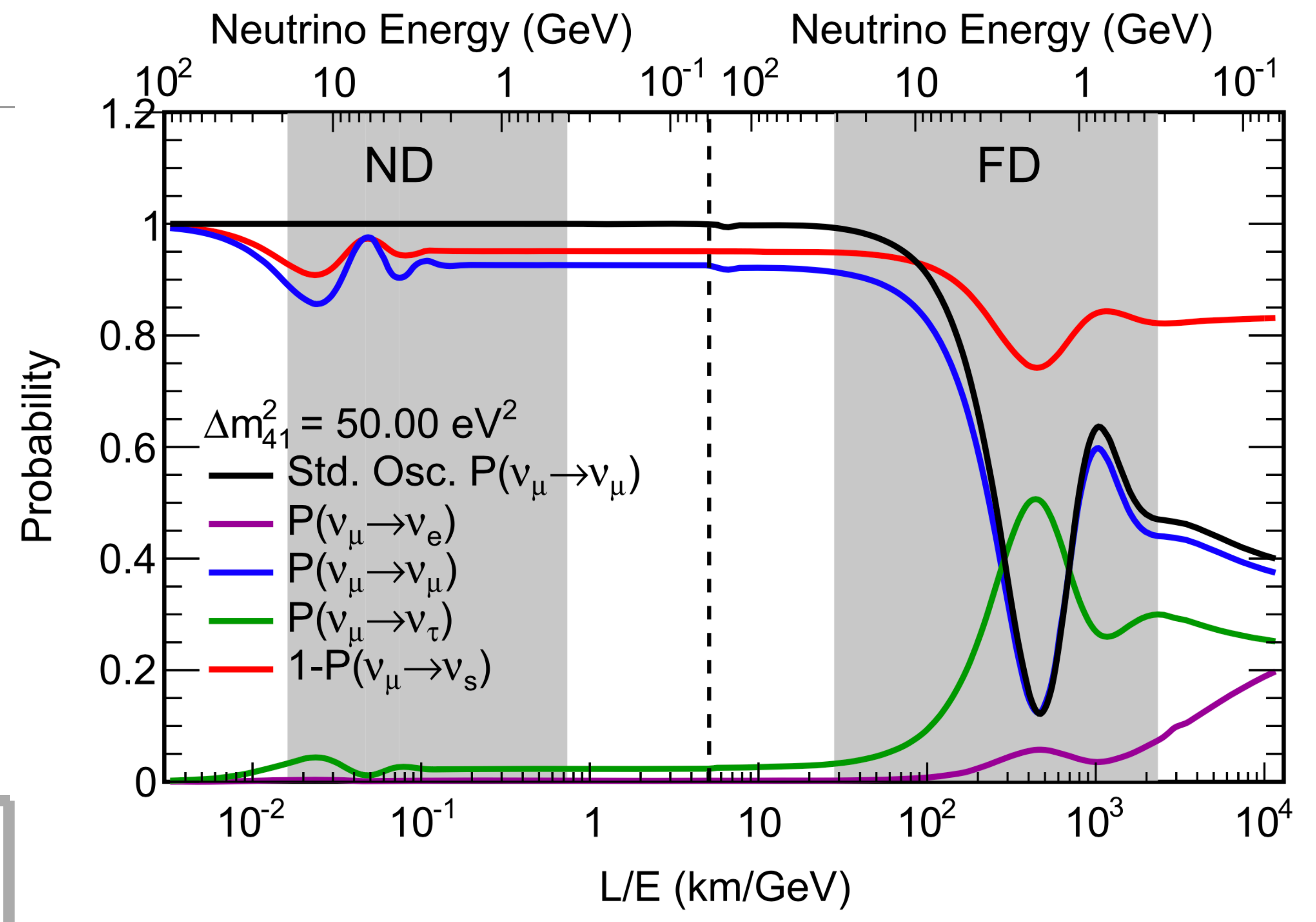
S. Brice (Snowmass 2021)



Neutrino BSM physics

Pursue Quantum Imprints of New Phenomena

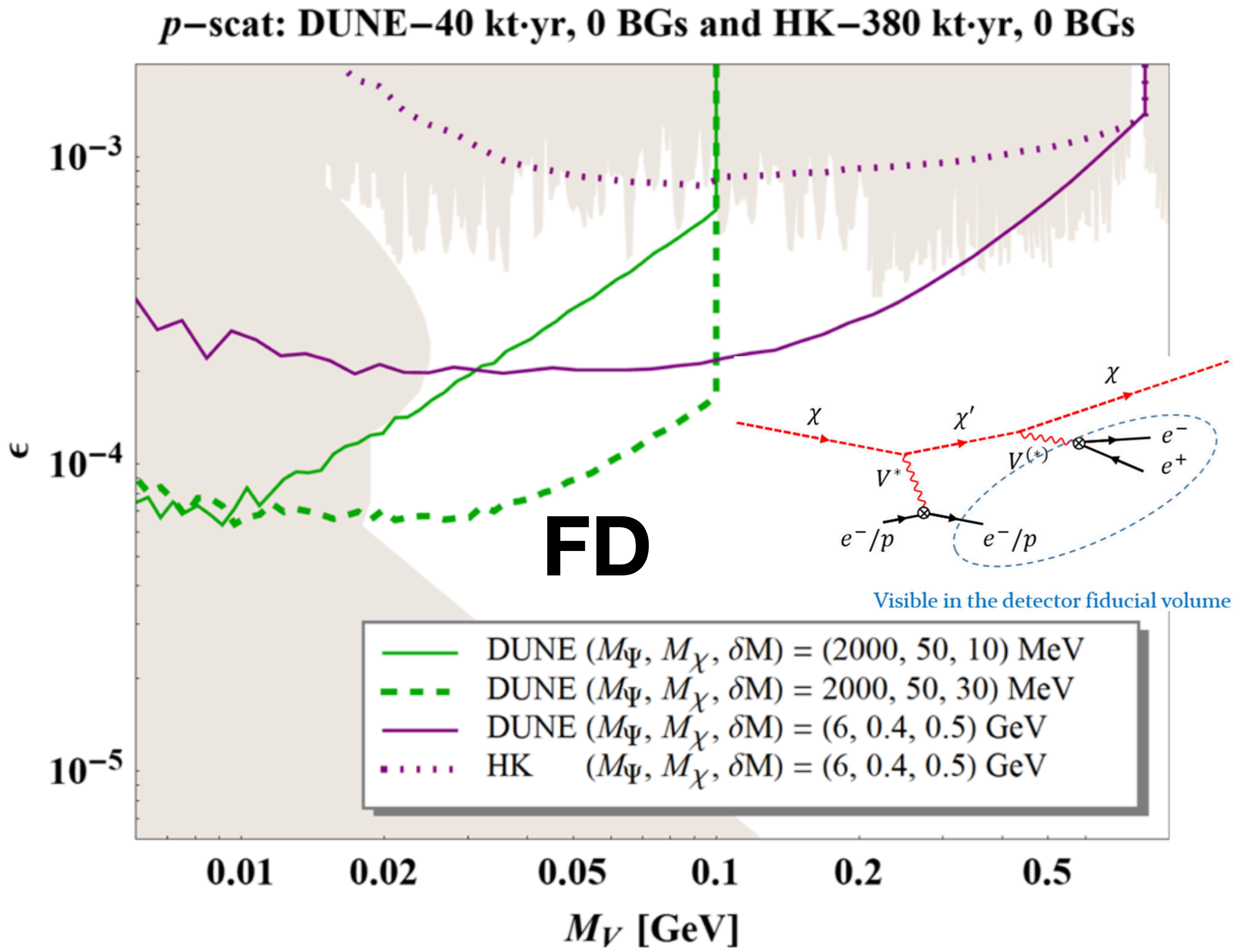
- **DUNE BSM** EPJC 81 (2021) 322
  - **Tests of 3-flavor mixing model** via high-precision oscillation measurements
    —> sterile neutrino mixing,
    CPT violation, non-standard interactions, etc.

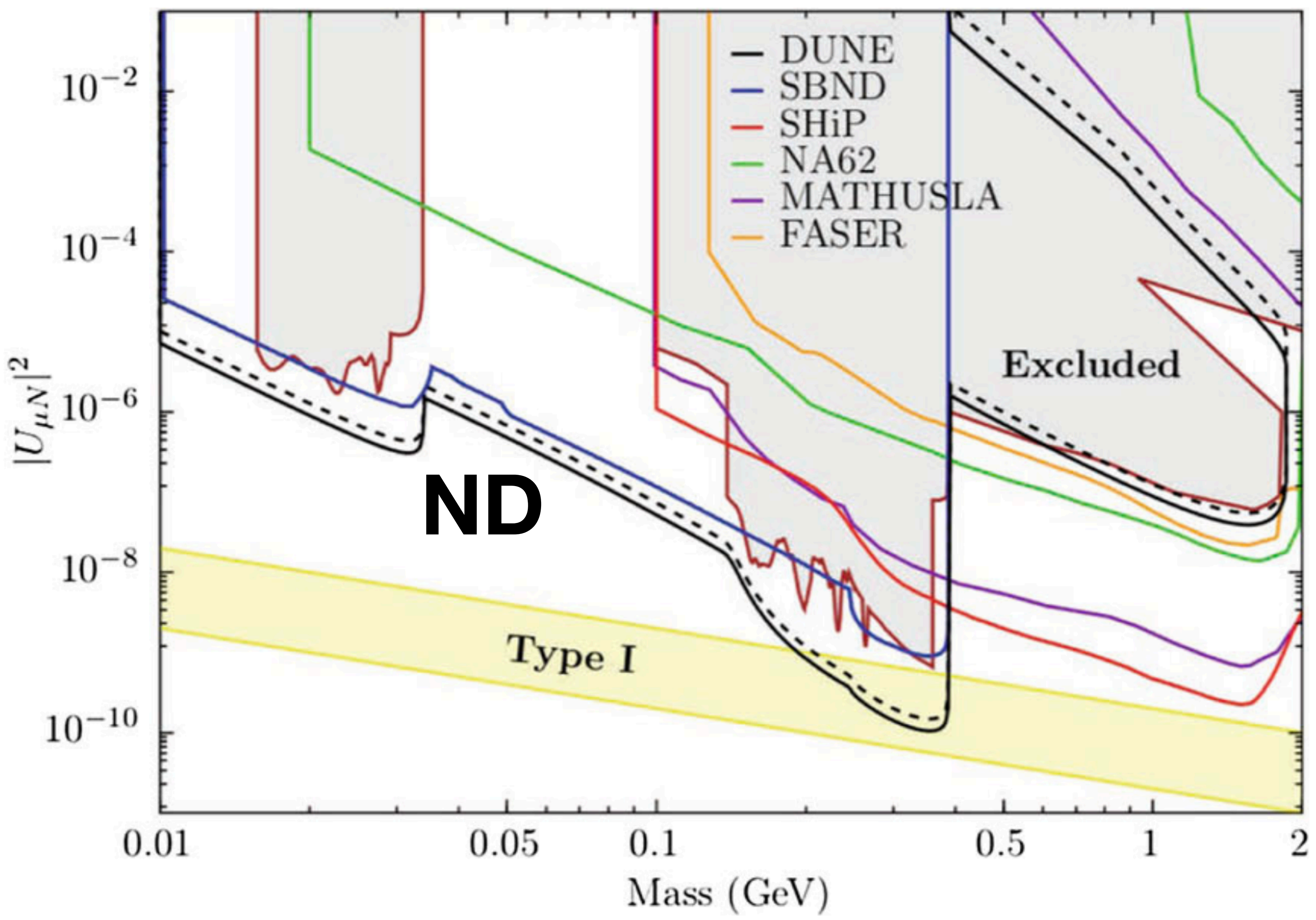


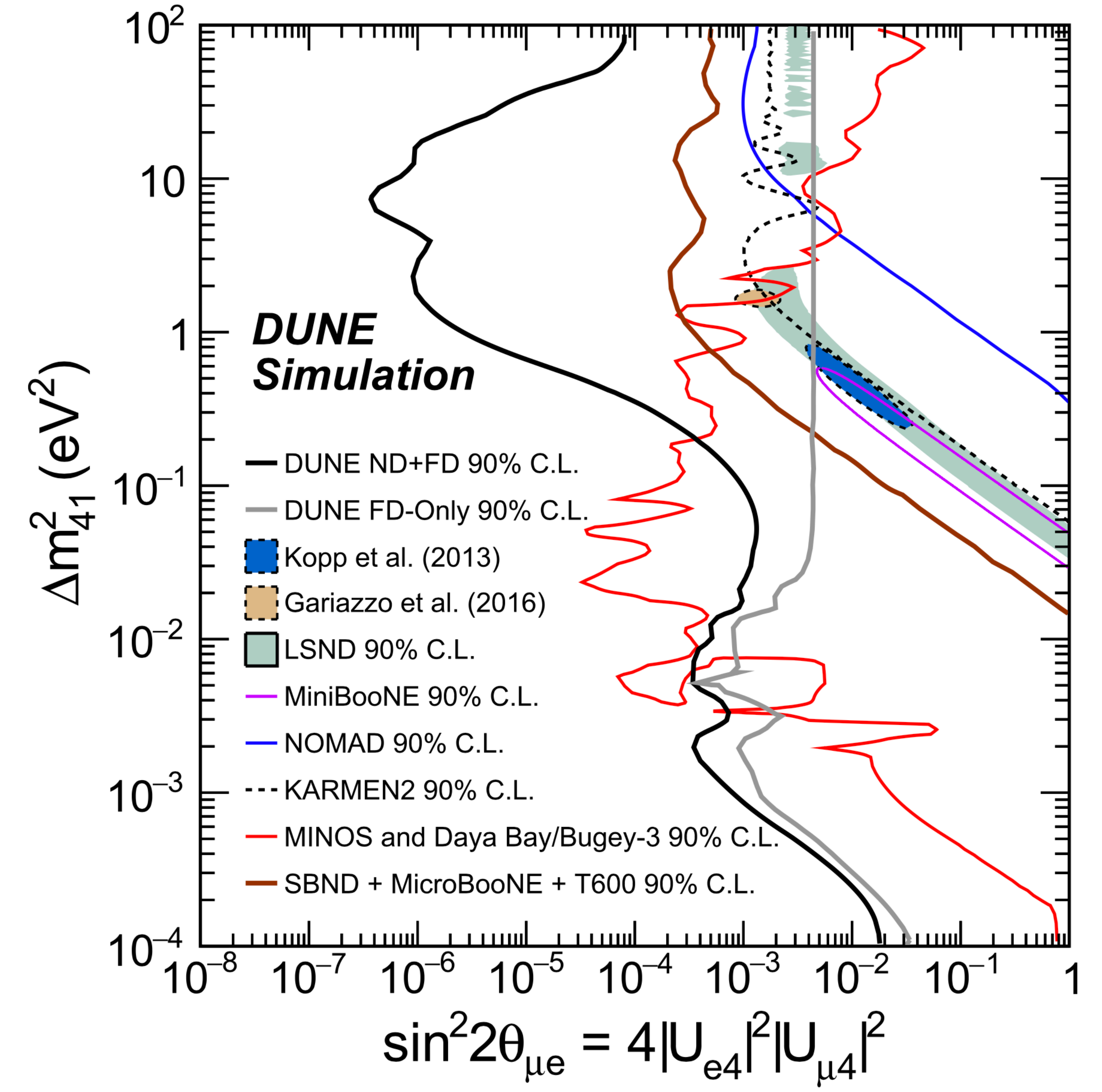
  - **Direct searches**

Search for Direct Evidence of New Particles

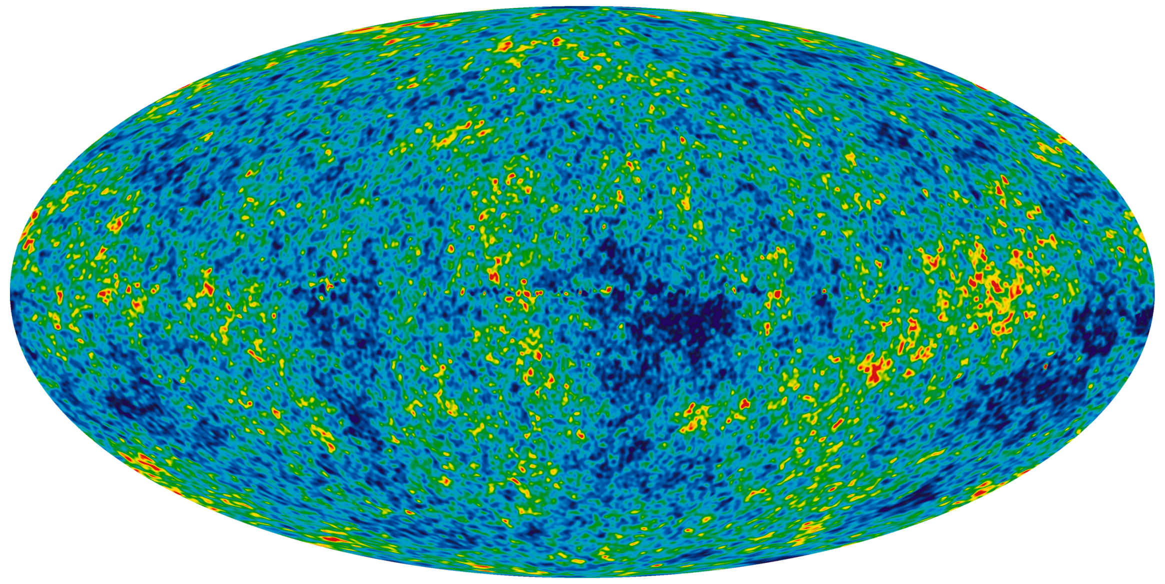
    - Searches for dark matter, heavy neutral leptons, etc. with both near-detector (ND) and far-detector (FD)

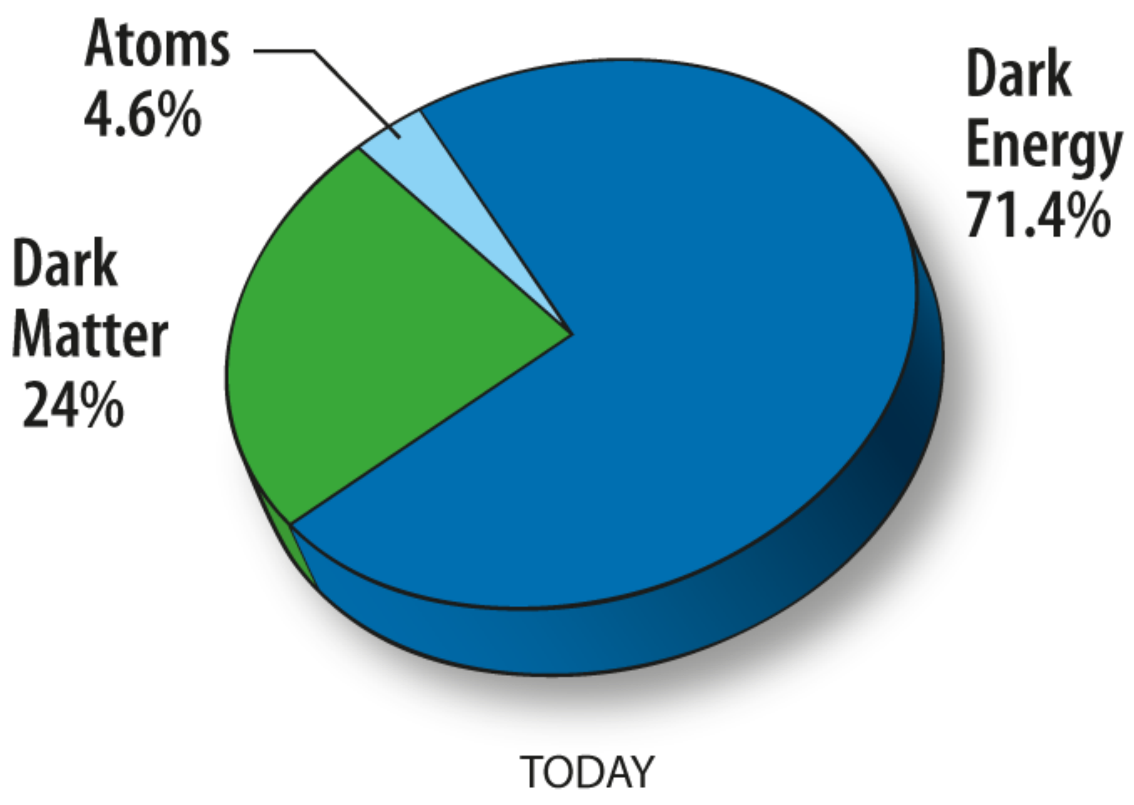






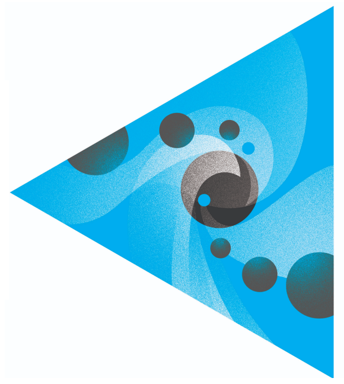
Cosmic frontier



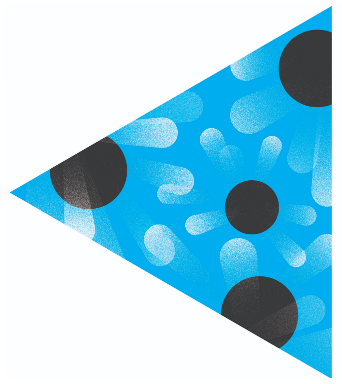


- **Previous breakthroughs**
  - Inflation: Quantum fluctuations seeded large-scale structures —> discovered in CMB
  - Discovery of dark matter and dark energy —> guiding cosmic evolution
  - Established theoretical framework: ΛCDM
- **Compelling future program**
  - Extend hunt for dark matter, increase sensitivity over wide mass range
  - Understand cause of cosmic acceleration for inflationary era and modern era (dark energy)
  - Challenge ΛCDM model with high-precision imaging and spectroscopic surveys (LSST, DESI)

Determine the Nature of Dark Matter



Understand What Drives Cosmic Evolution

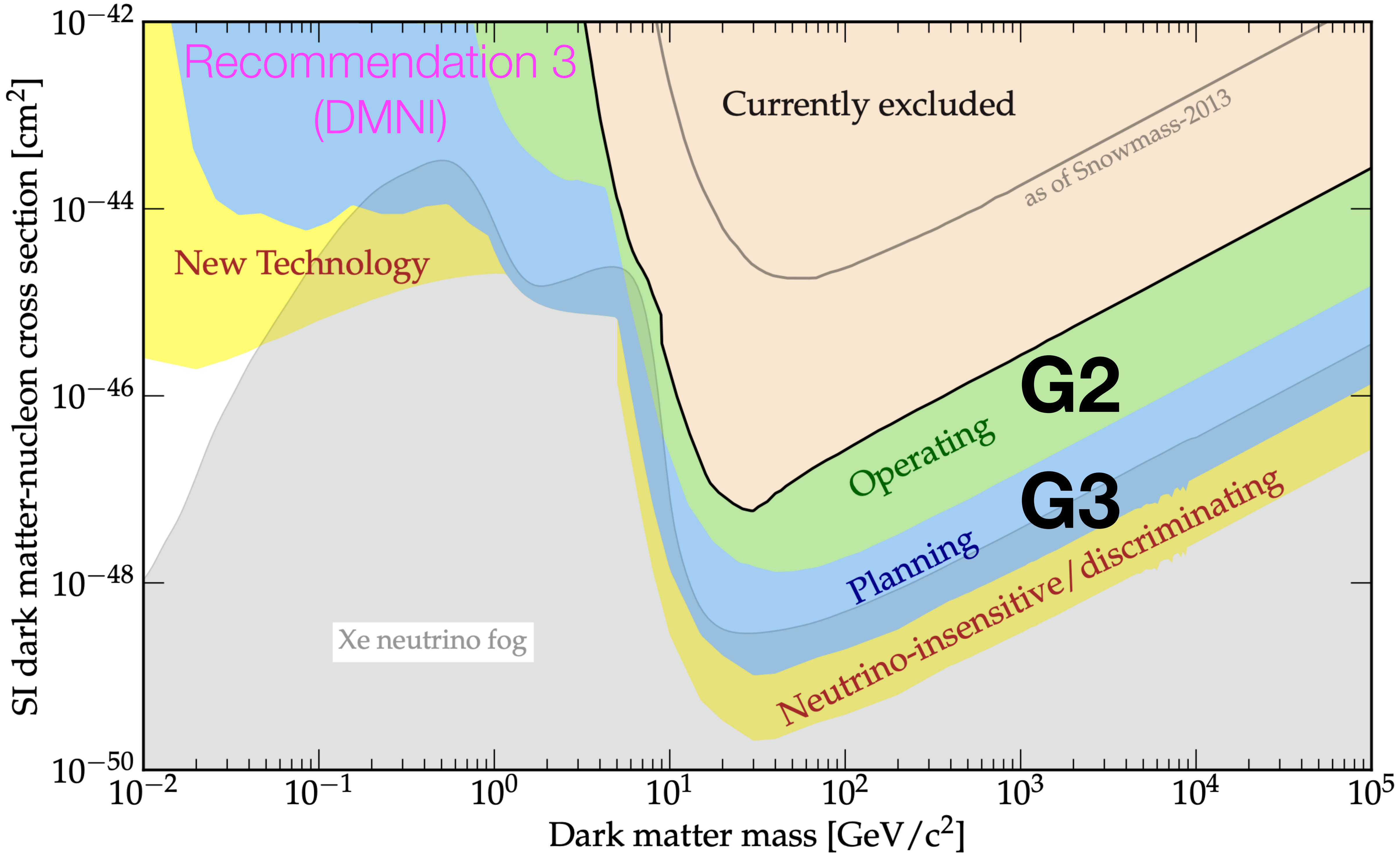


Dark matter: Direct detection

Determine the Nature of Dark Matter

- Third generation (G3) **DM direct detection expt** reaching "neutrino fog" Recommendation 2d
- **Liquid xenon** detector combining best of LZ, XENONnT, Darwin —> 60 T LXe **XLZD** (~10x mass of LZ or XENONnT)
- **Liquid argon** detector combining best of ArDM, DarkSide, DEAP, MiniCLEAN —> 300 T LAr
  Global Argon Dark Matter Collab. (**GADMC**)
- P5 propose one G3 experiment could be funded and hosted at SURF

Snowmass cosmic frontier report (2022)

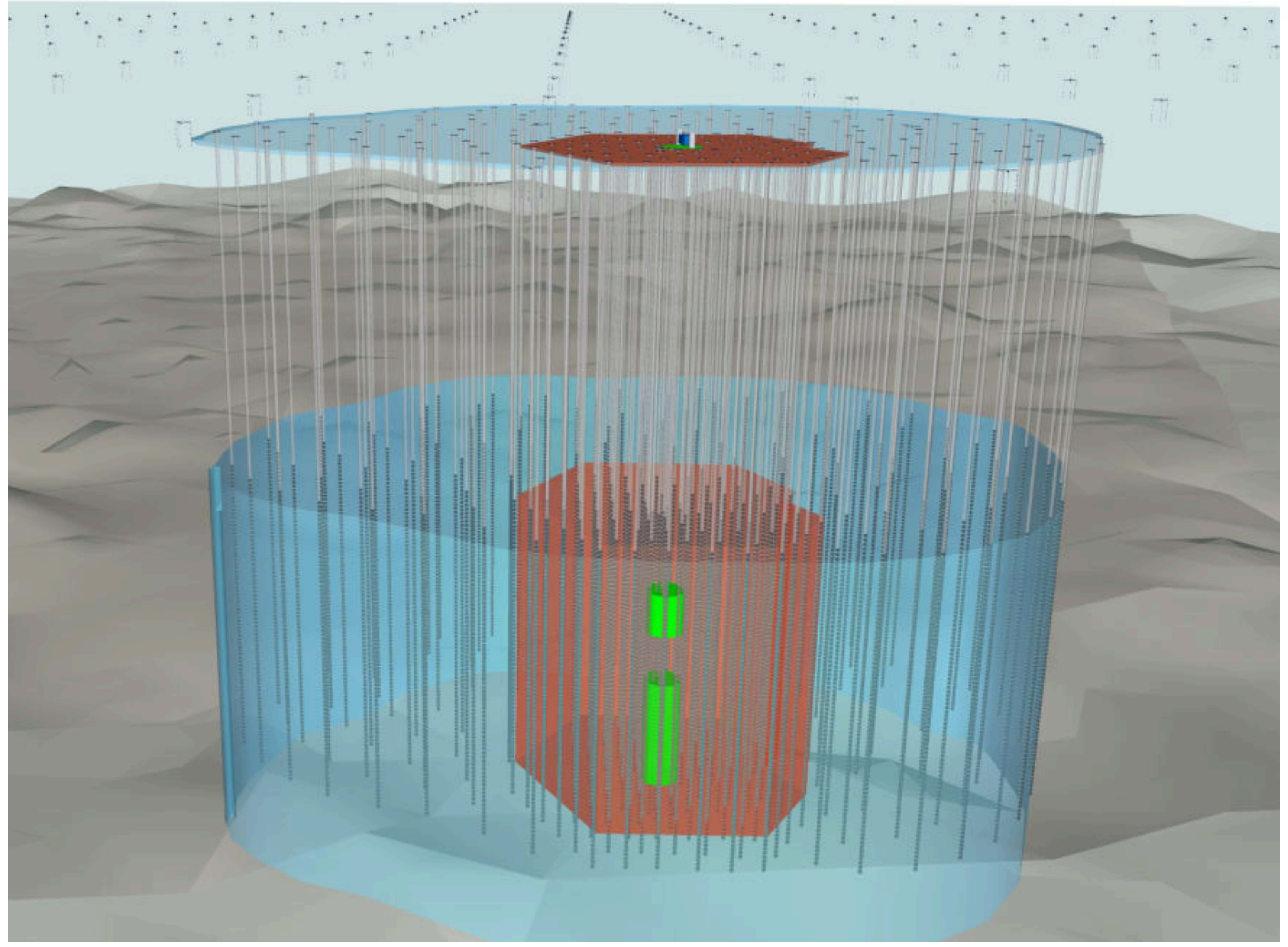


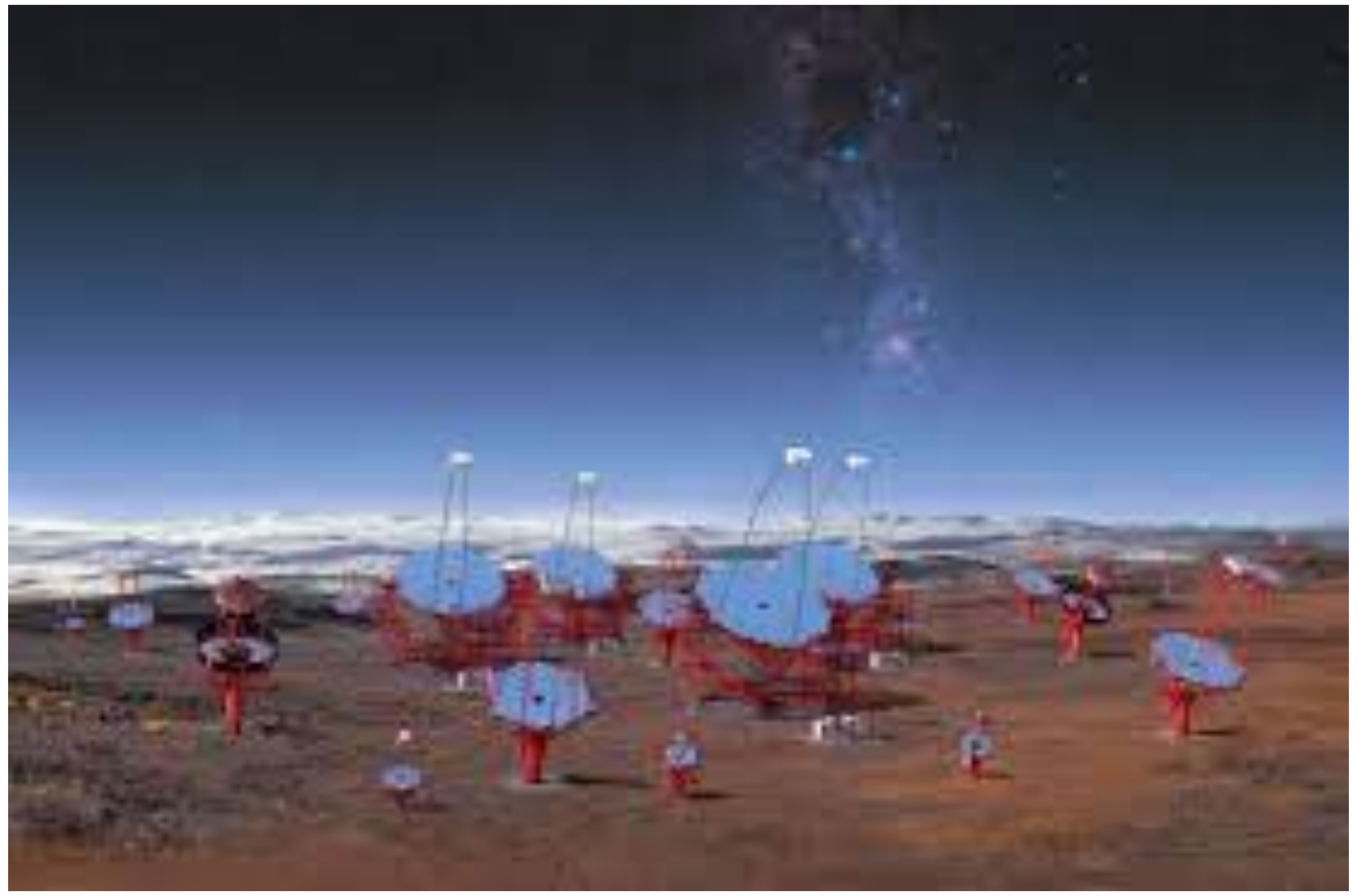
- Large portfolio of smaller experiments Recommendation 3 exploring **new technologies reaching lower DM mass**, incl. wave-like DM

Dark matter: Indirect detection

- **New initiatives proposed for NSF**
  - **IceCube-Gen2**

    Recommendation 2d
    - 10x sensitivity to astrophysical ν —> study ν properties
    - Indirect dark matter detection (e.g. annihilation in Sun) most sensitive to heavy dark matter
  - **Cherenkov Telescope Array (CTA)** in La Palma and Chile
    - Indirect dark matter detection via high-energy γ rays
    - Sensitivity to WIMP thermal targets (e.g. annihilation in Milky Way galaxy center) beyond G3 reach, up to 100 TeV

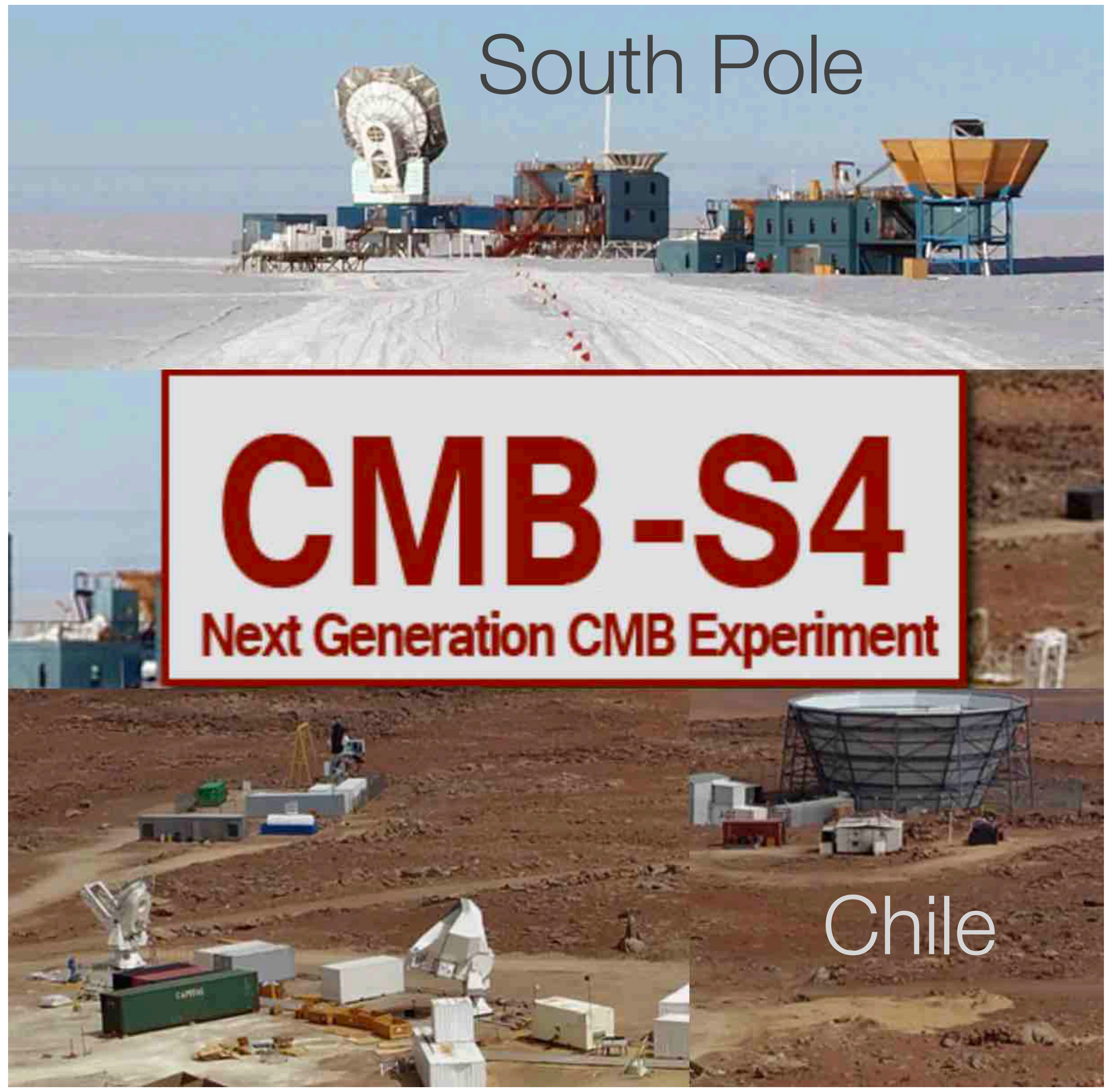


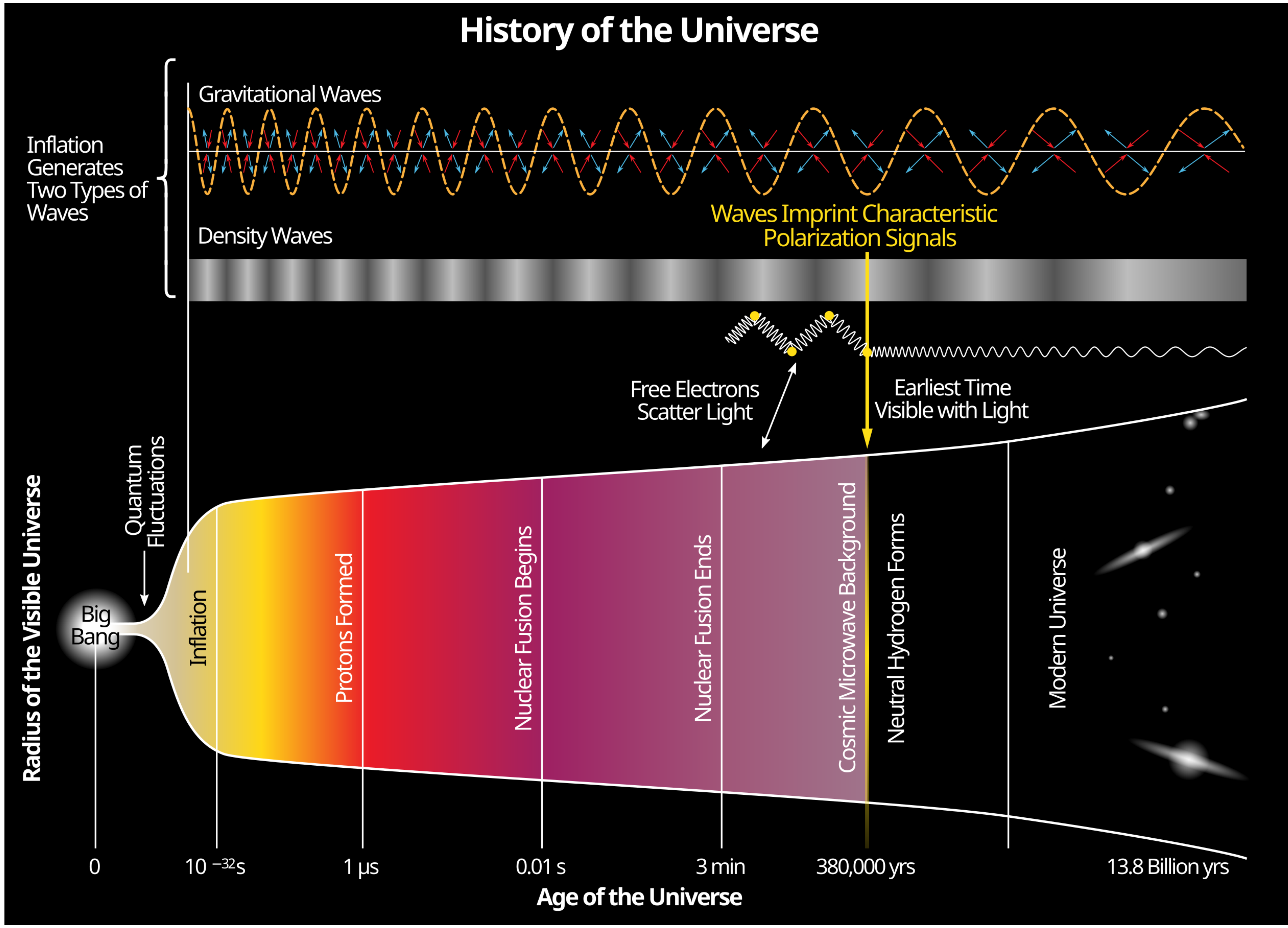


Cosmic evolution

Understand What Drives Cosmic Evolution

- **CMB-S4** Recommendation 2a
  - Precise CMB measurements
  - **Probe inflation era** via imprint of primordial gravitational waves on CMB —> **probe ultra-high-energy scales**
  - Dark matter and dark energy via gravitational lensing of CMB





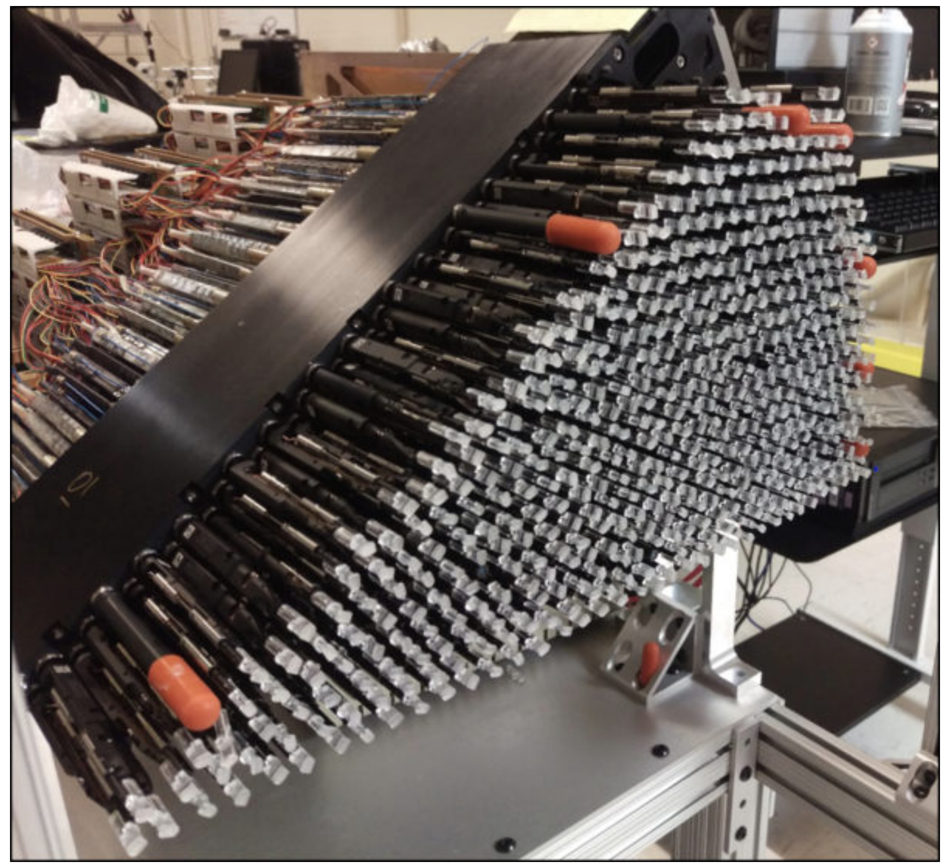
Cosmic evolution

Understand What Drives
Cosmic Evolution

- **Cosmic surveys**
  - Primary tools to study origin, structure, composition, and evolution of universe

    Recommendation 1c
  - **Imaging survey:** Legacy Survey of Space and Time (LSST) at Vera Rubin Observatory in Chile
    - 3200-megapixel camera to image entire sky every 3-4 nights
    - Dark matter/energy: gravitational lensing, galaxy clustering, Type 1a supernovae to map cosmic acceleration
      —> dark energy density unc. ~1%

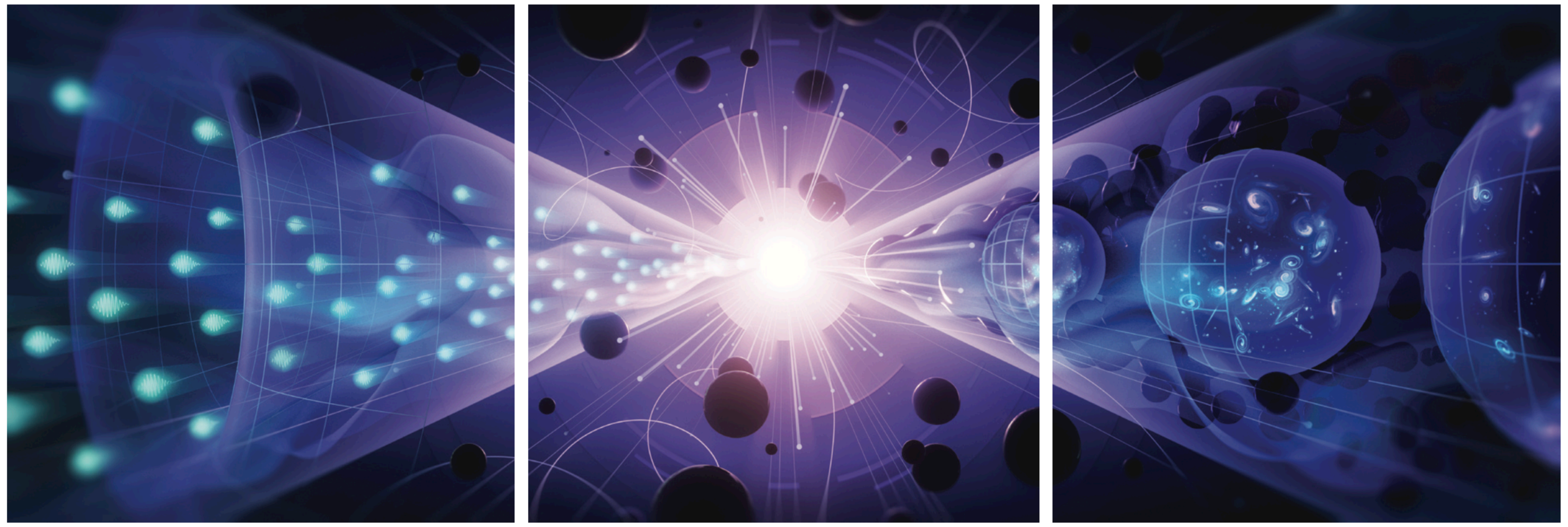
    Recommendation 1f
  - **Spectroscopic survey:** Dark Energy Spectroscopic Instrument (DESI) at Kitt Peak (Arizona)
    - 3D maps of matter distribution to probe evolution of dark energy since CMB era
    - DESI-II to focus on higher redshift (z > 2)



DESI focal plane

Summary

- P5 recommended a **broad and ambitious 10-year program** for particle physics, in 20-year vision
- **Building on community input** from Snowmass process, town halls, individual communications
- **Balanced program** of projects at different frontiers, with large-, mid-, small-scale experiments
- Advocated for **greater support of enablers**:
  accelerators, instrumentation, theory, software and computing —> **robust R&D for 20-year vision**



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

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Summary

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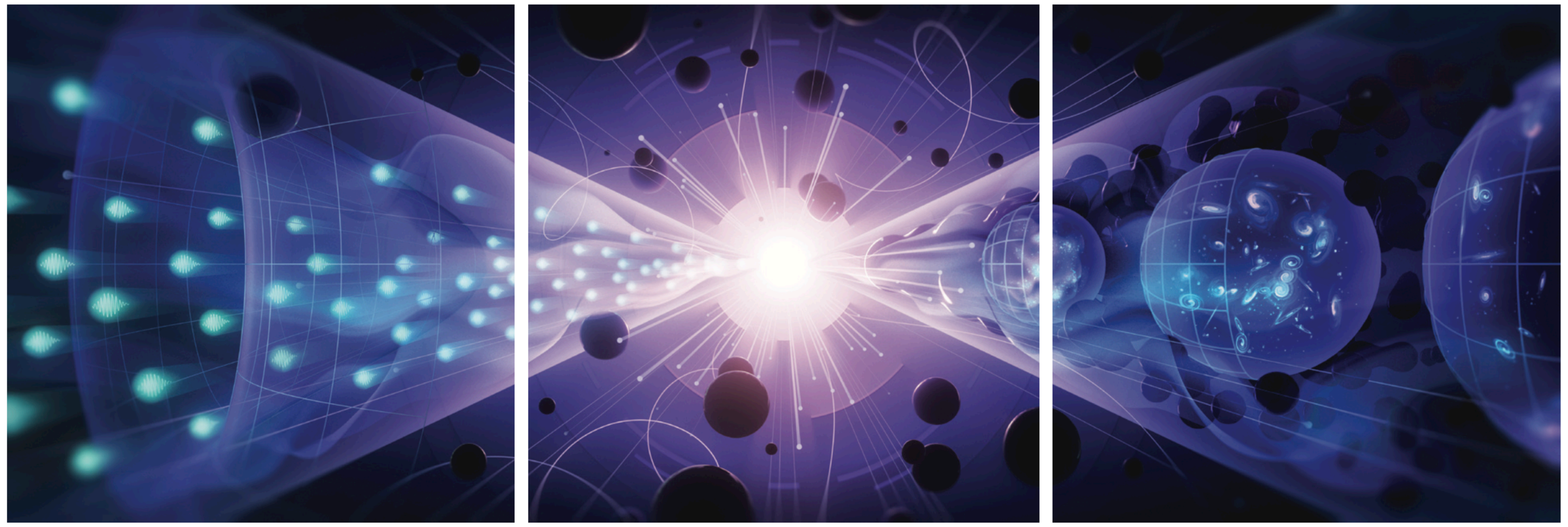

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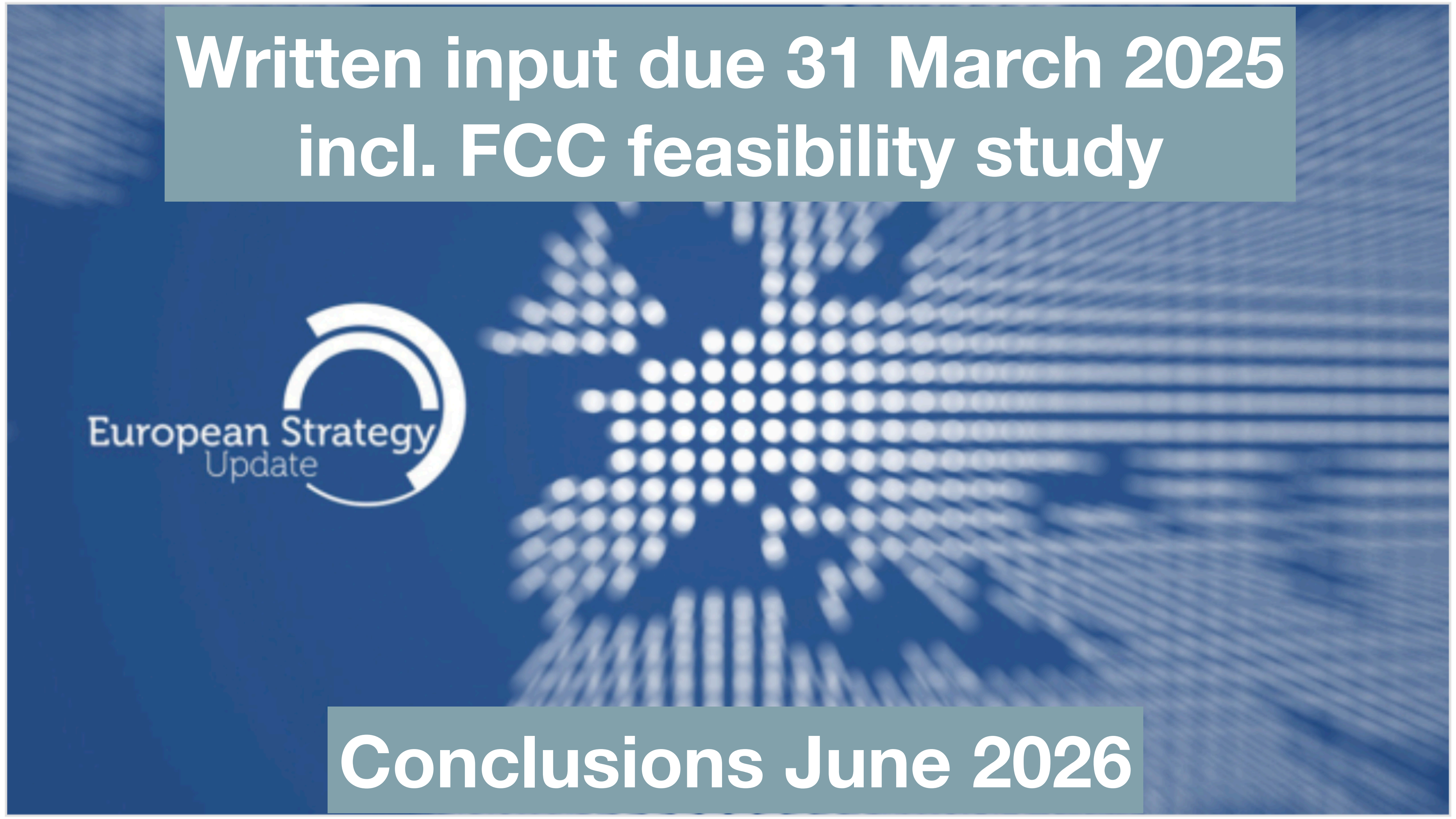
European strategy update

3 May 2024

CERN courier 3 May 2024



Written input due 31 March 2025 incl. FCC feasibility study

Conclusions June 2026

Setting priorities The third update of the European strategy for particle physics gets under way.

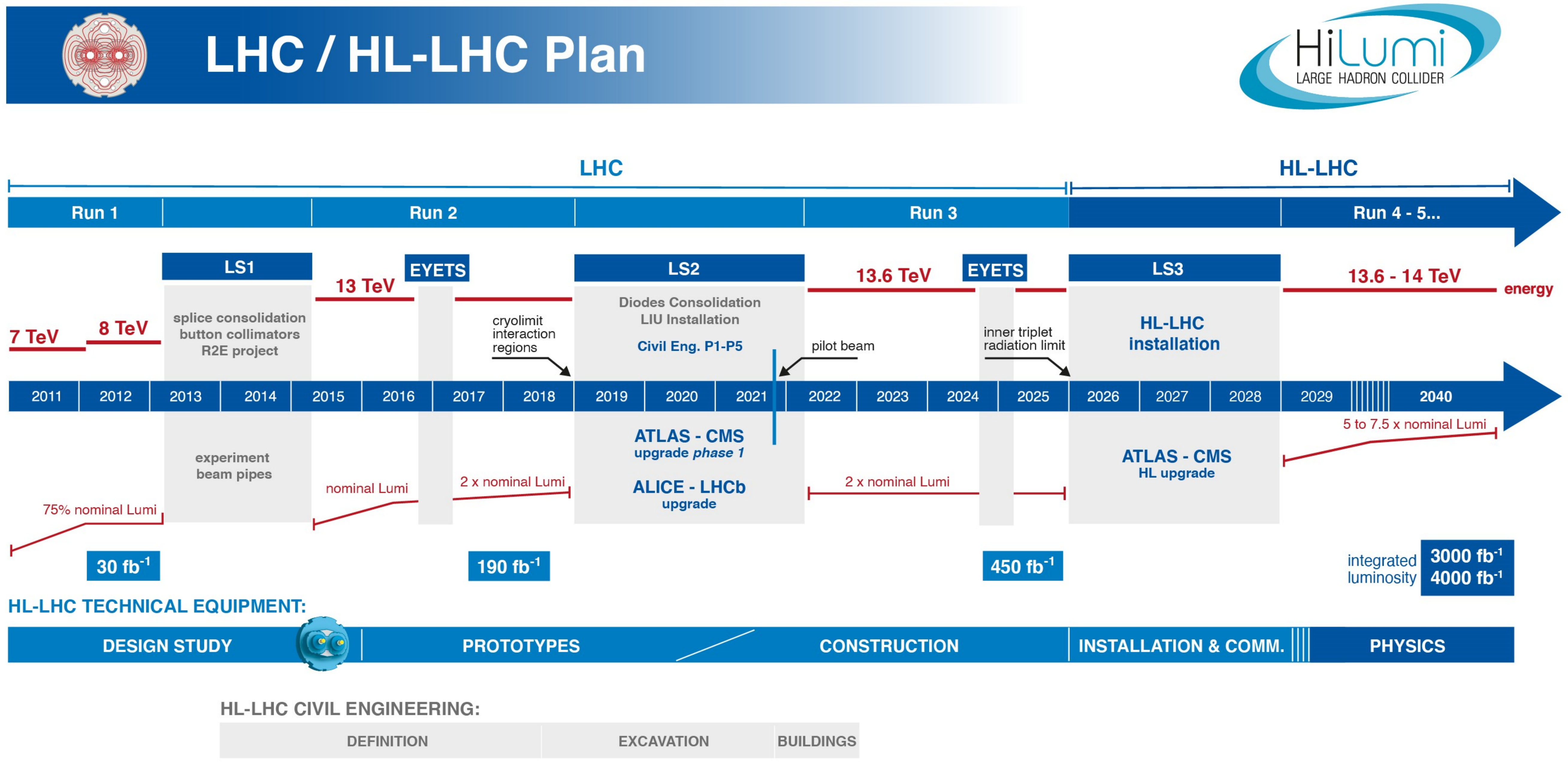
BONUS SLIDES

HL-LHC plans

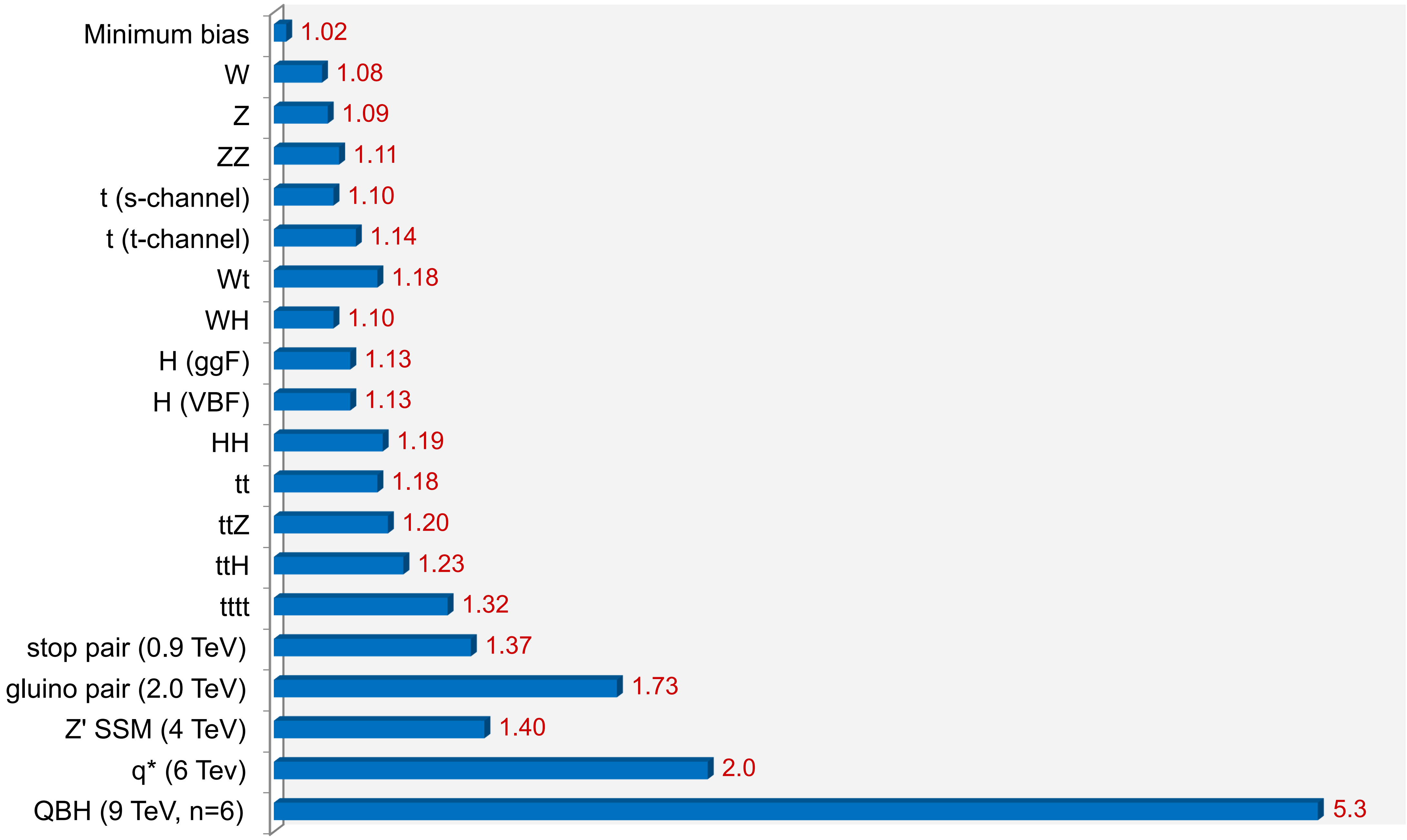
- **Plan for 3,000 fb^{-1} of pp collisions delivered to ATLAS & CMS each**

(HL-)LHC project schedule

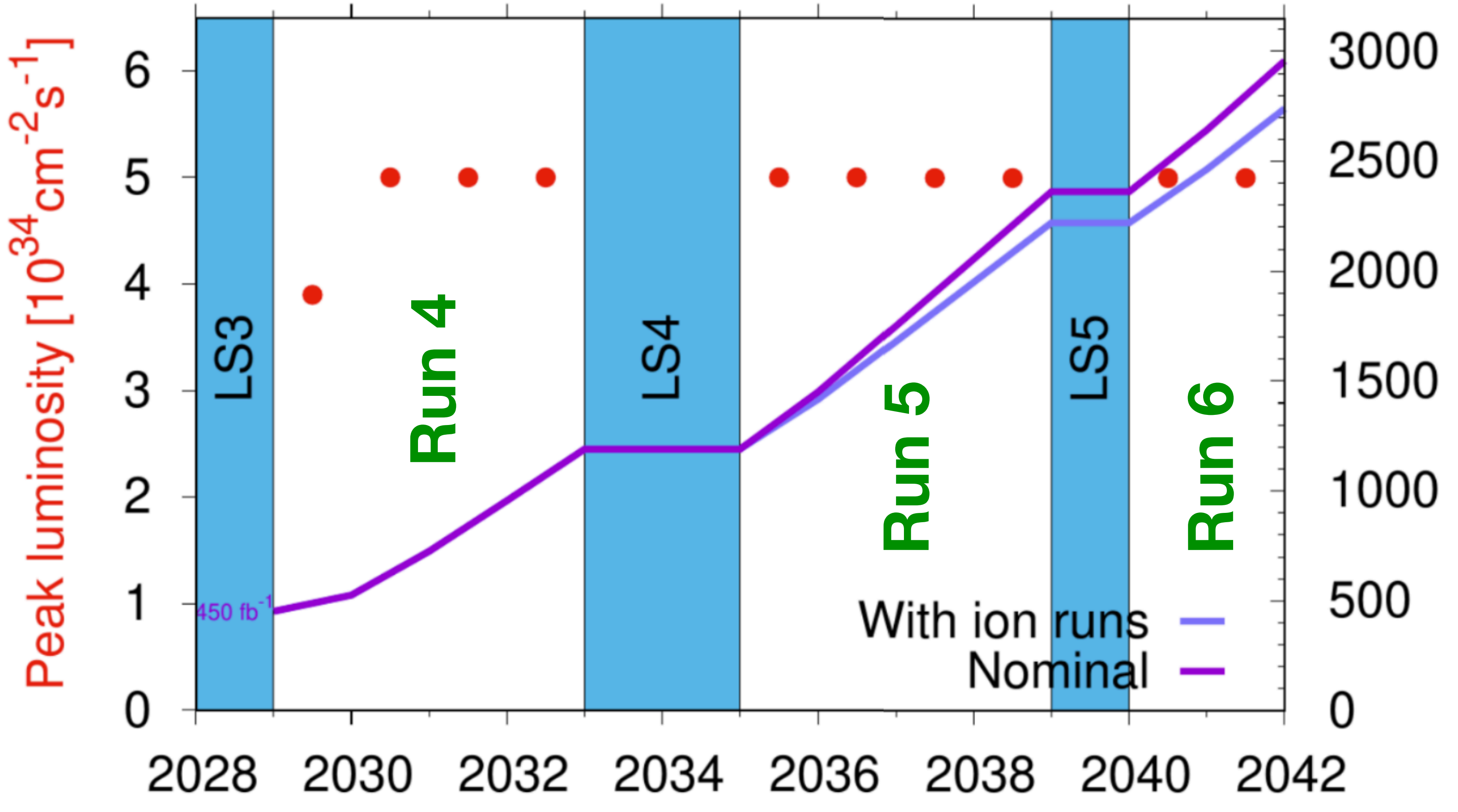
  - 20 times more int. luminosity than current physics results are based on
  - HL-LHC to run at $\sqrt{s} = 14$ TeV
—> significant cross-section increase
for massive final states



14 TeV / 13 TeV inclusive pp cross section ratio A. Hoecker

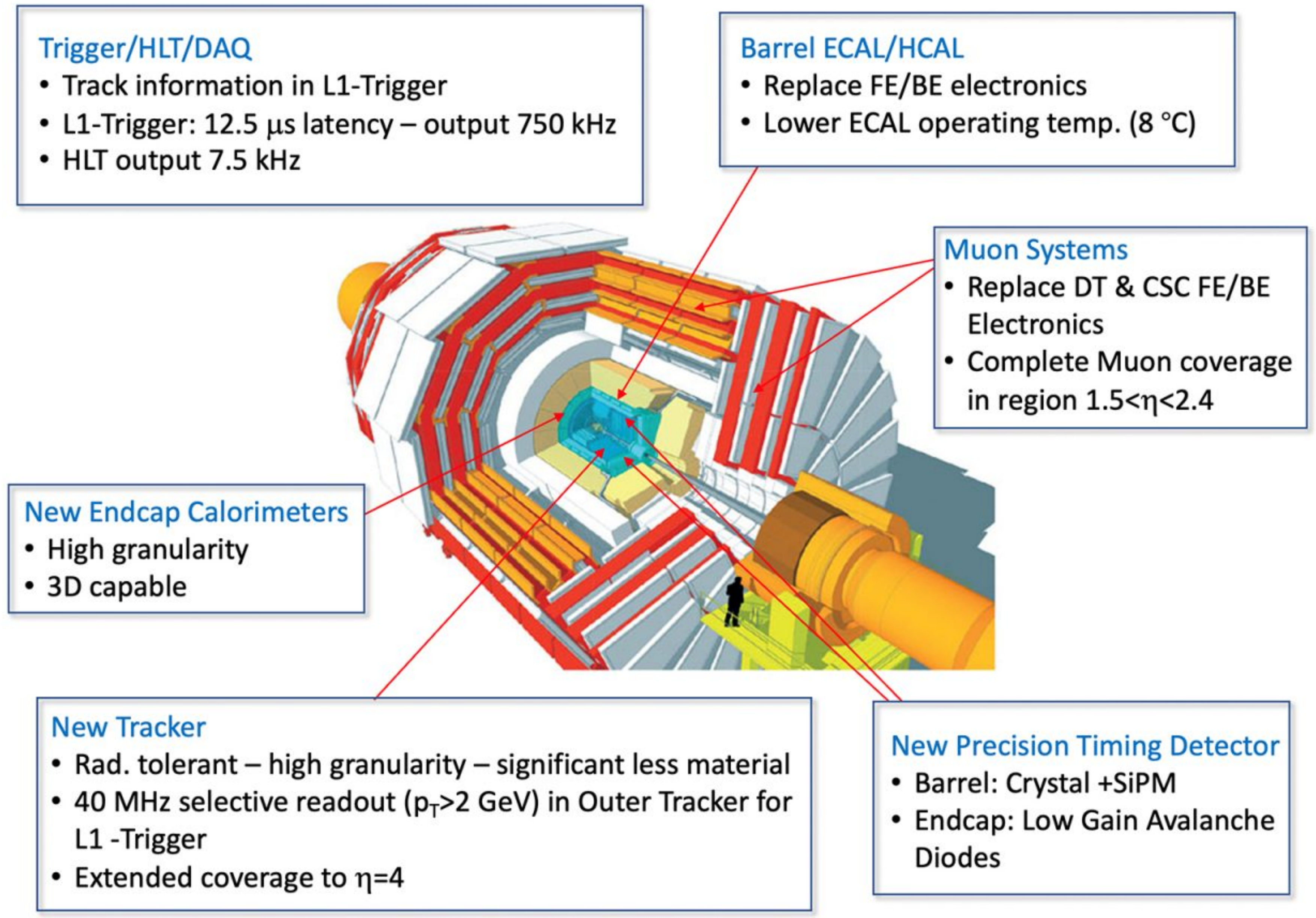


R. De Maria (Chamonix 2024)



ATLAS and CMS detector upgrades for HL-LHC

- **ATLAS and CMS Phase-II upgrades for Runs 4, 5 & 6**
  - Challenge: pileup μ = 200
    data acquisition rates 10x higher than LHC
    maintain or lower trigger thresholds
  - Significant enhancement to sensitivity with
    - higher-resolution tracking systems (extending to $|\eta| = 4$)
    - improved calorimetry
    - increased muon coverage
    - enhanced trigger capability
    - novel timing systems
  - Aggressive R&D in trigger, software and computing
    - exploit AI/ML techniques online and offline
    - develop software for heterogeneous computing technologies



Trigger/HLT/DAQ
- Track information in L1-Trigger
- L1-Trigger: 12.5 μs latency – output 750 kHz
- HLT output 7.5 kHz

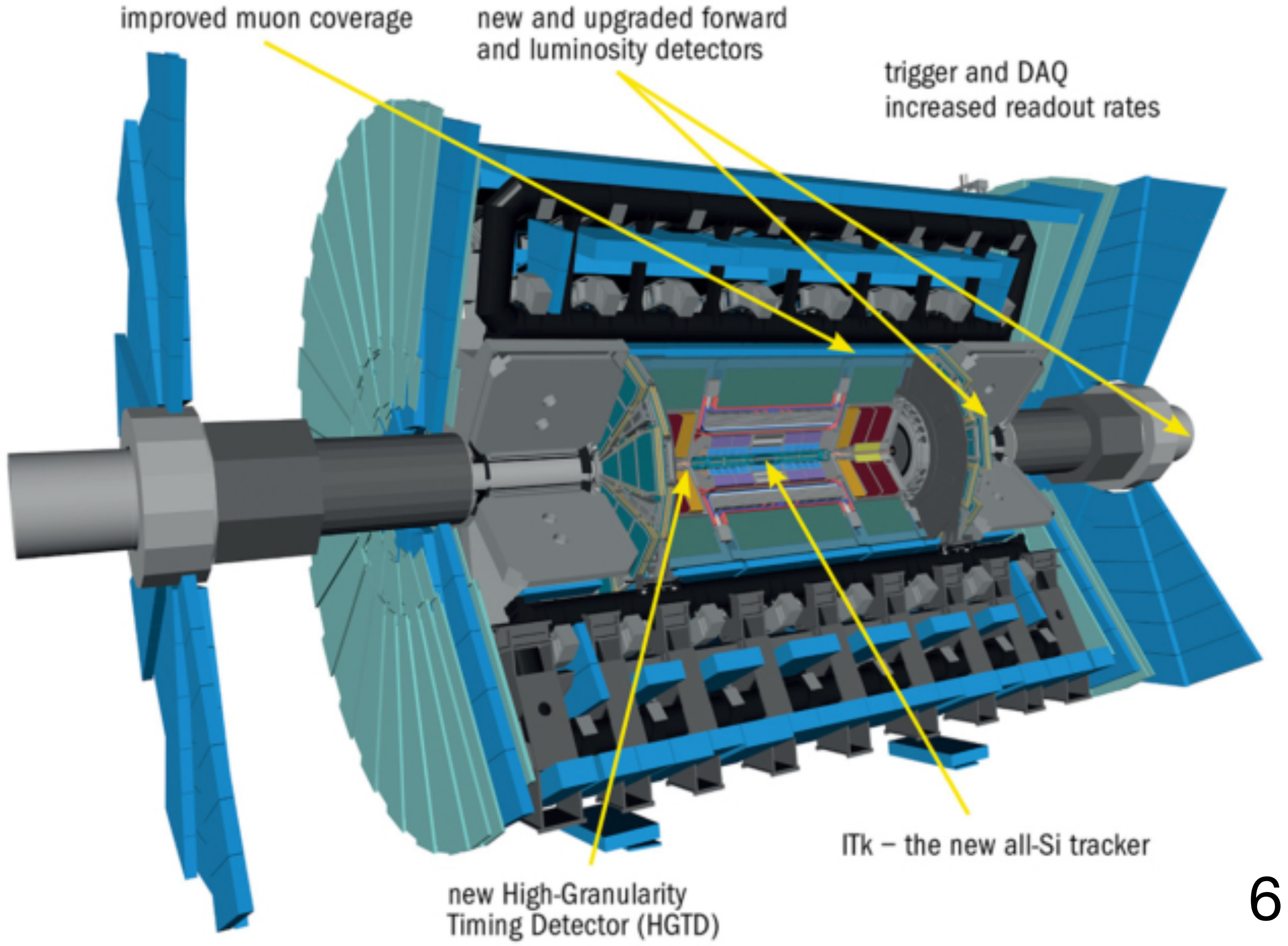
Barrel ECAL/HCAL
- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems
- Replace DT & CSC FE/BE Electronics
- Complete Muon coverage in region $1.5<\eta<2.4$

New Endcap Calorimeters
- High granularity
- 3D capable

New Tracker
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (p_T>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to η=4

New Precision Timing Detector
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes



improved muon coverage

new and upgraded forward and luminosity detectors

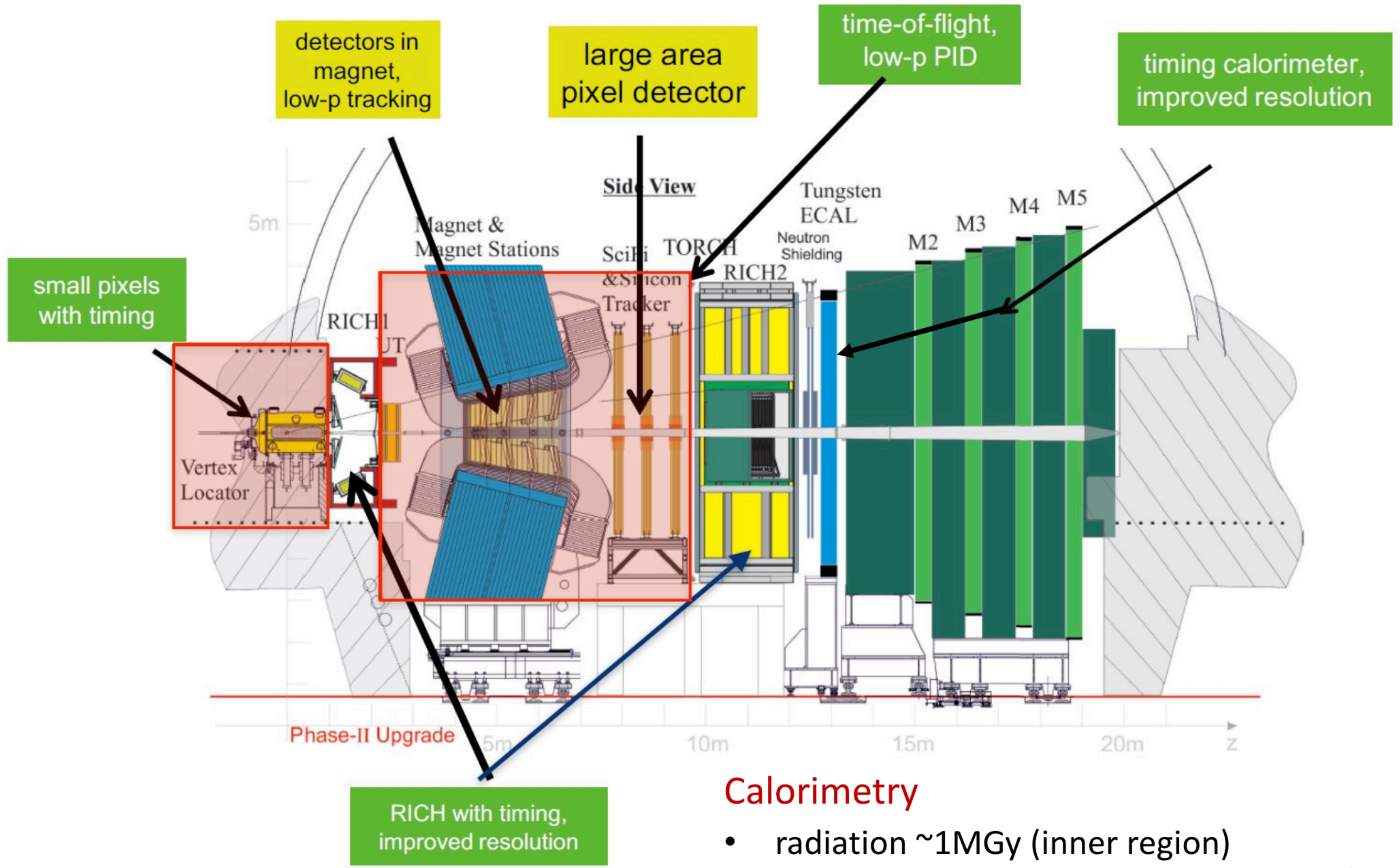
trigger and DAQ increased readout rates

ITk – the new all-Si tracker

new High-Granularity Timing Detector (HGTD)

LHCb and ALICE upgrades for HL-LHC

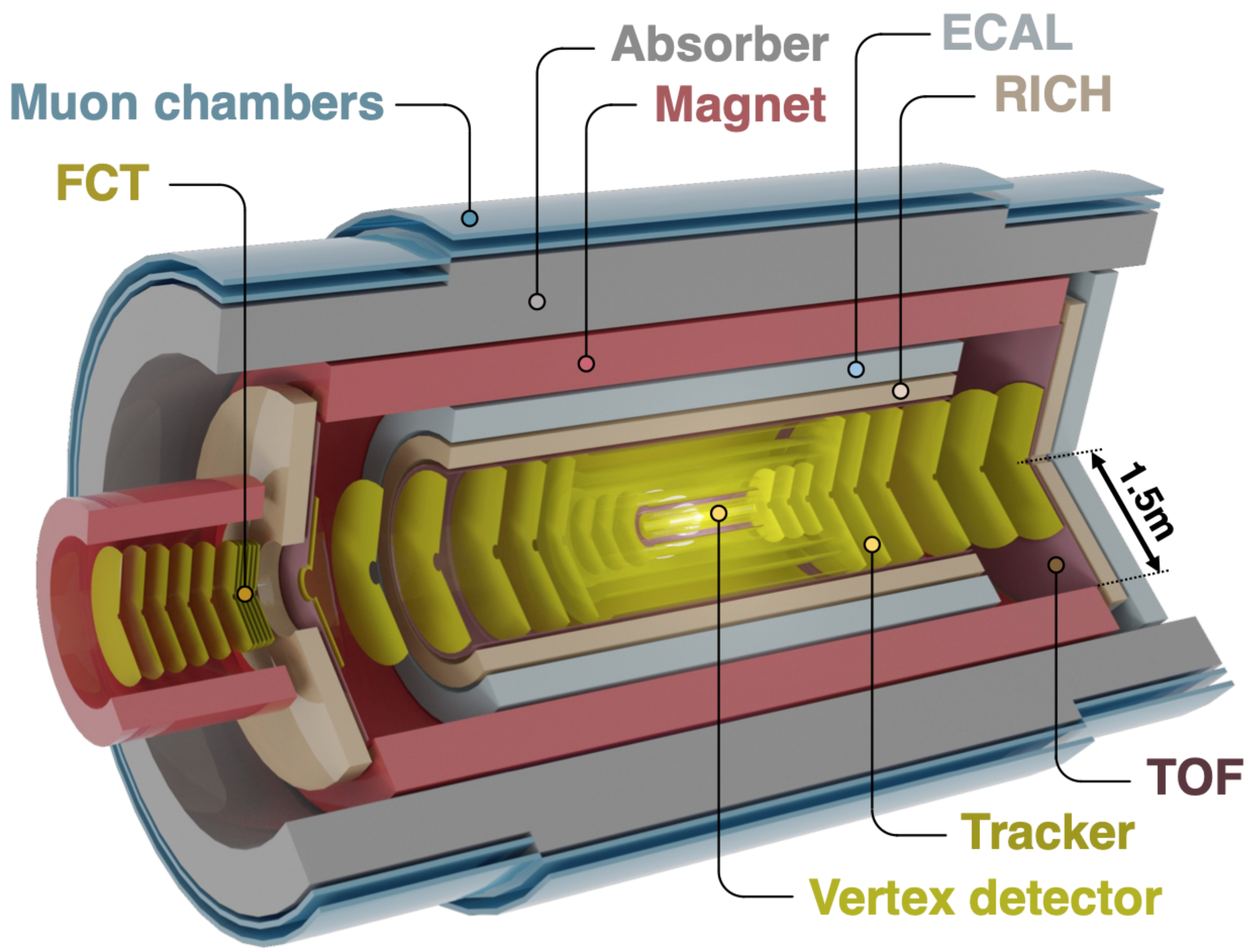
- Proposed **LHCb Upgrade 2** arXiv:1808.08865
  - Runs 5 & 6 —> goal to collect 300 fb^{-1} of pp collisions
  - Same or better performance than current detector but with 7 x more pileup
  - New tracker, PID, and EM calo systems with higher resolution and added timing



Calorimetry

- radiation ~1MGy (inner region)
- large combinatoric background from π^0

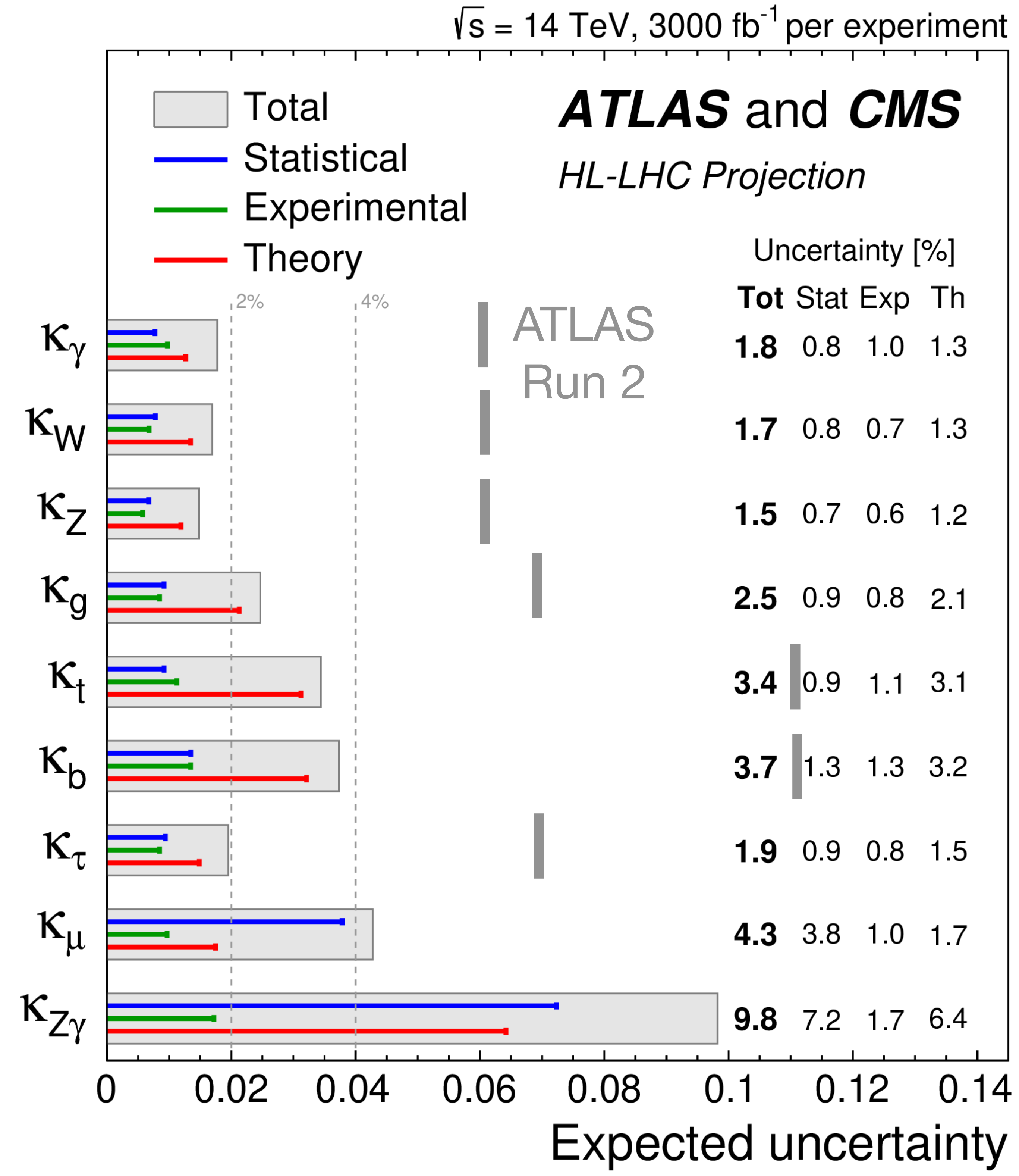
- Proposed **ALICE 3 Upgrade** arXiv:2211.02491 (LoI)
  - Runs 5 & 6 —> goal to collect 35 nb^{-1} of Pb+Pb collisions
  - New detector, with excellent pointing resolution, tracking and PID
  - η coverage 4 x larger than ALICE
  - ALICE upgrades for Run 4: ITS3 and FoCal



Higgs couplings @HL-LHC

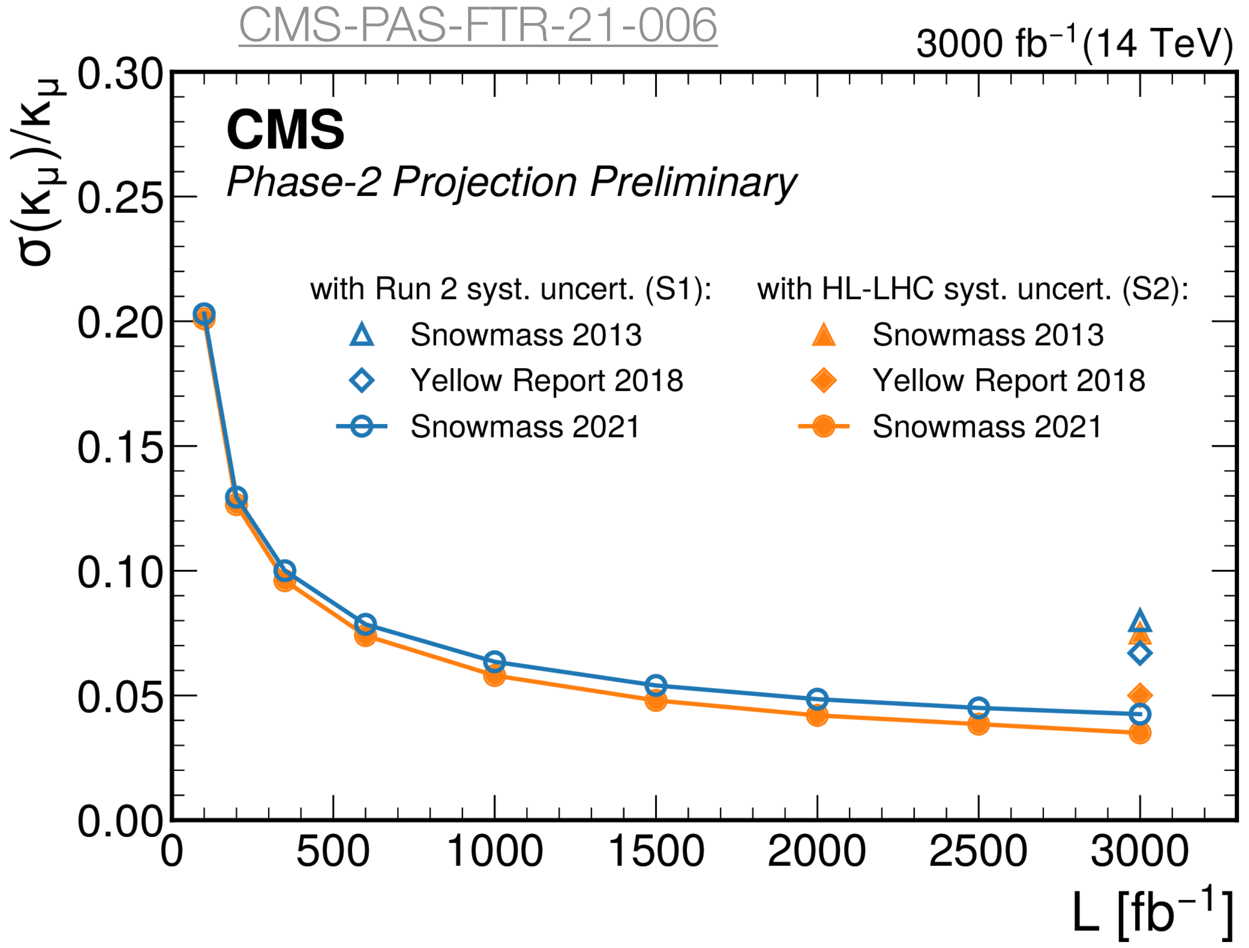
- Combination of ATLAS and CMS measurements extrapolated from (early) Run 2 analyses for YR18
- Precision on tree-level coupling modifiers (κ_i)
  - 1.5 - 1.8% for couplings to bosons (γ, W, Z)
  - 1.9 - 4.3% for couplings to fermions (μ, τ, b, t)

CERN-2019-007 (YR18)

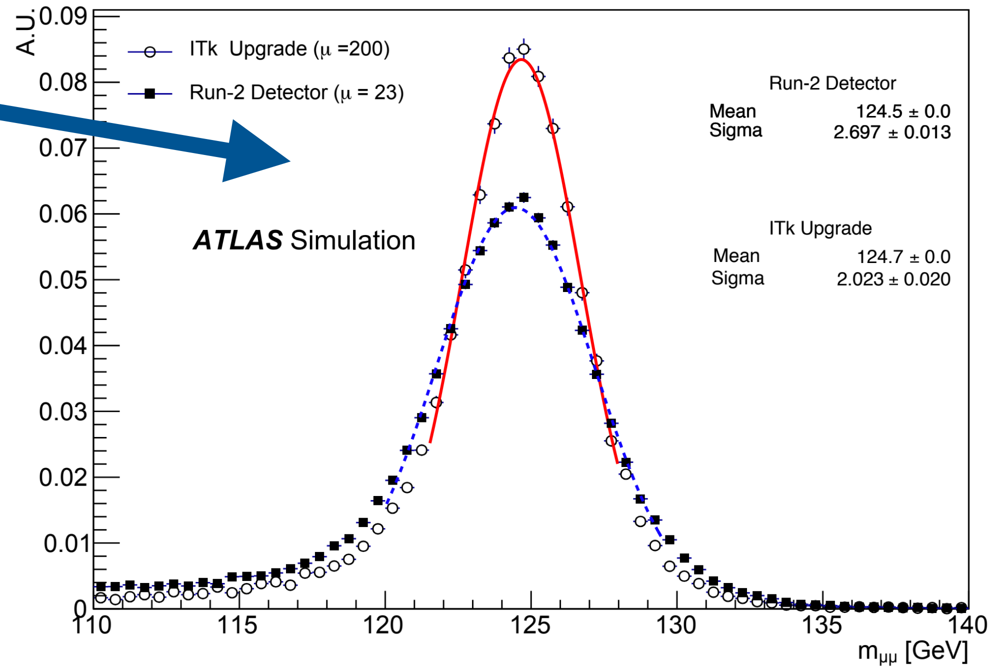


- Access to couplings to 2nd generation fermions via $H \to \mu^+\mu^-$
  Given $B(H \to \mu\mu) = 2 \times 10^{-4}$, statistics dominate even with 3,000 fb^{-1}

CMS-PAS-FTR-21-006



- New tracking system: 30% improvement in $m(\mu\mu)$ resolution
- Uncertainty reduced from 5.0% (YR18) to 3.5% by extrapolating full Run 2 analysis



- Coupling to charm difficult due to $B(H \to c\bar{c}) = 2.9\,\%$, large background and c-tagging performance

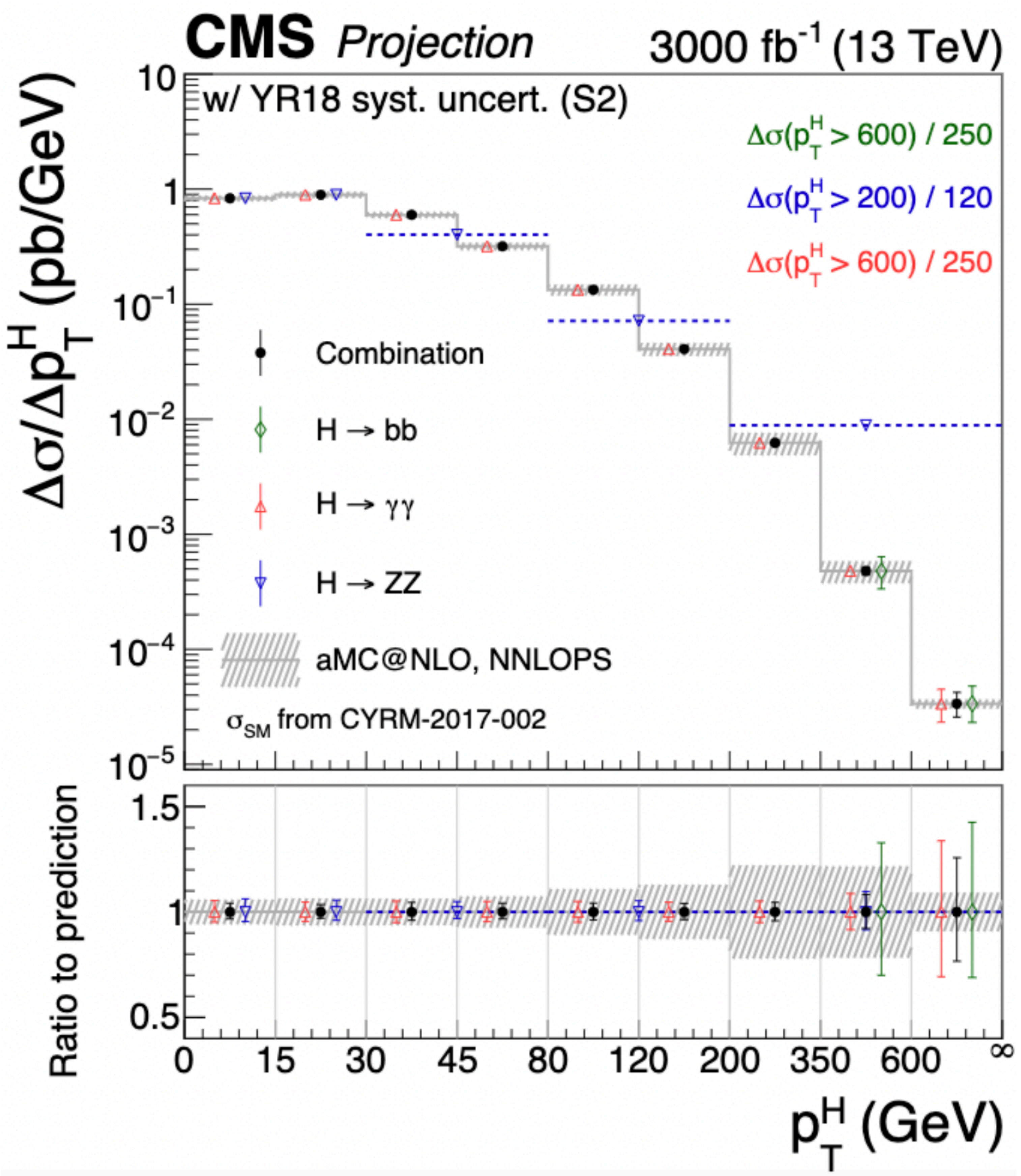
Snowmass 2021

$\kappa_c < 1.75$ (95% CL)

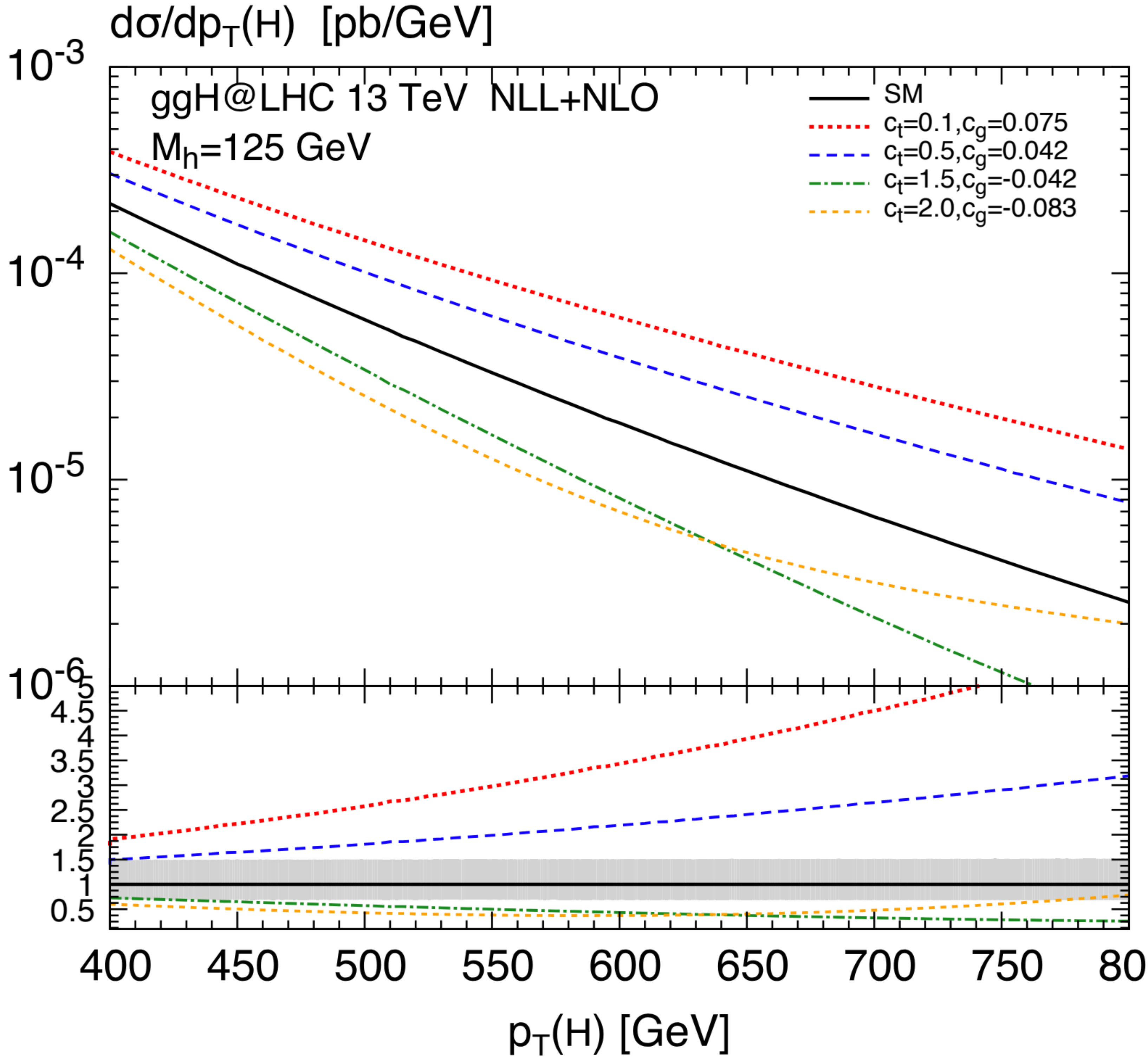
Impact of precision on BSM @HL-LHC

- **Higgs differential cross sections**
  - High p_T region sensitive to BSM effects
  - Directly benefits from statistical power of HL-LHC

CERN-2019-007 (YR18)



arXiv:1612.00283



Deviations from ggH and ttH effective operators

Higgs self-coupling @HL-LHC

- Expected HH signal significance ATLAS-PHYS-PUB-2022-053

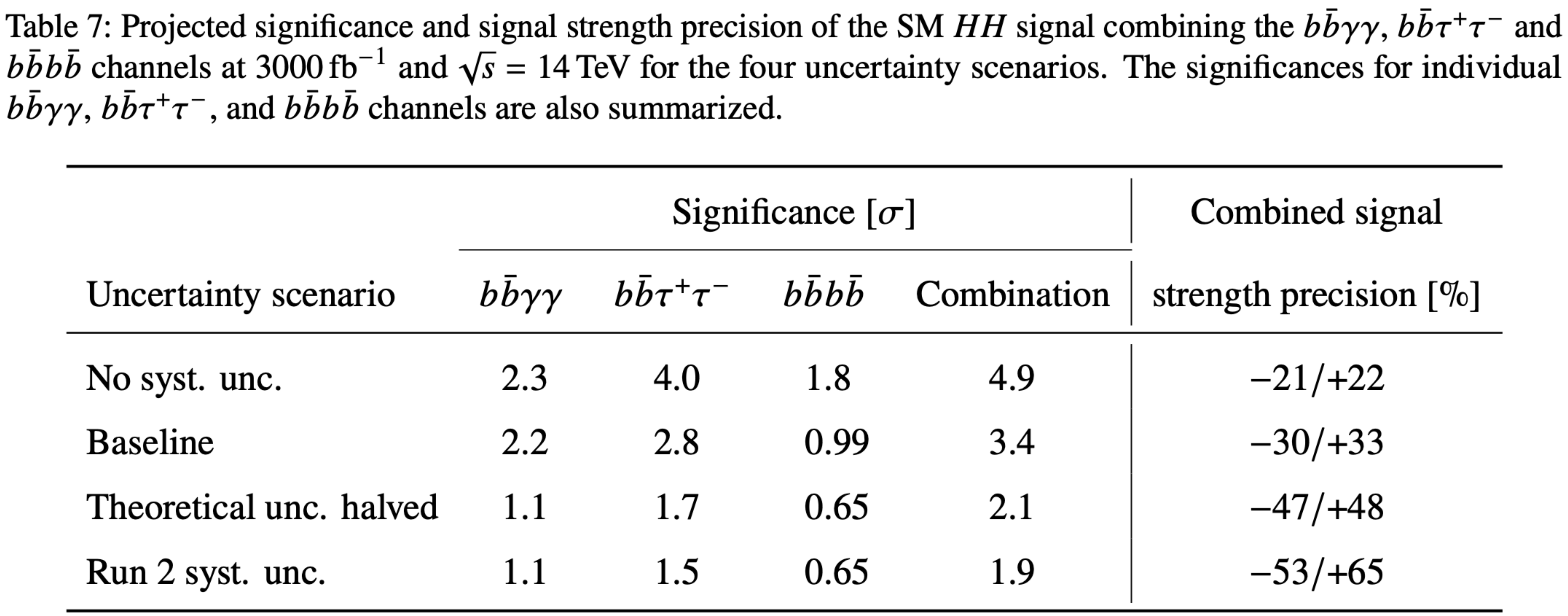


Table 7: Projected significance and signal strength precision of the SM HH signal combining the $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}b\bar{b}$ channels at 3000 fb^{-1} and $\sqrt{s}$ = 14 TeV for the four uncertainty scenarios. The significances for individual $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}b\bar{b}$ channels are also summarized.

	Significance [σ]				Combined signal
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	−21/+22
Baseline	2.2	2.8	0.99	3.4	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

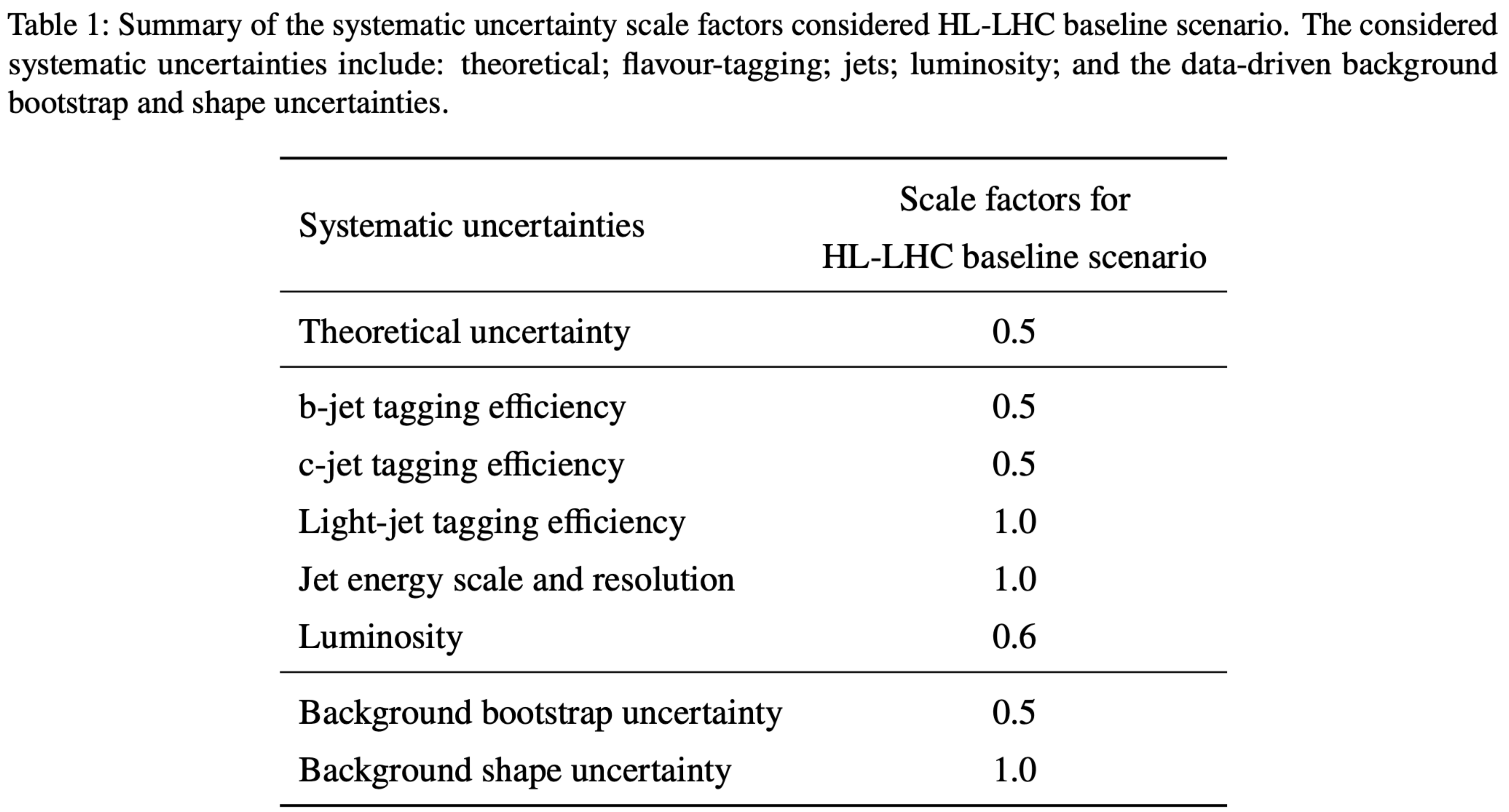


Table 1: Summary of the systematic uncertainty scale factors considered HL-LHC baseline scenario. The considered systematic uncertainties include: theoretical; flavour-tagging; jets; luminosity; and the data-driven background bootstrap and shape uncertainties.

Systematic uncertainties	Scale factors for HL-LHC baseline scenario
Theoretical uncertainty	0.5
b-jet tagging efficiency	0.5
c-jet tagging efficiency	0.5
Light-jet tagging efficiency	1.0
Jet energy scale and resolution	1.0
Luminosity	0.6
Background bootstrap uncertainty	0.5
Background shape uncertainty	1.0

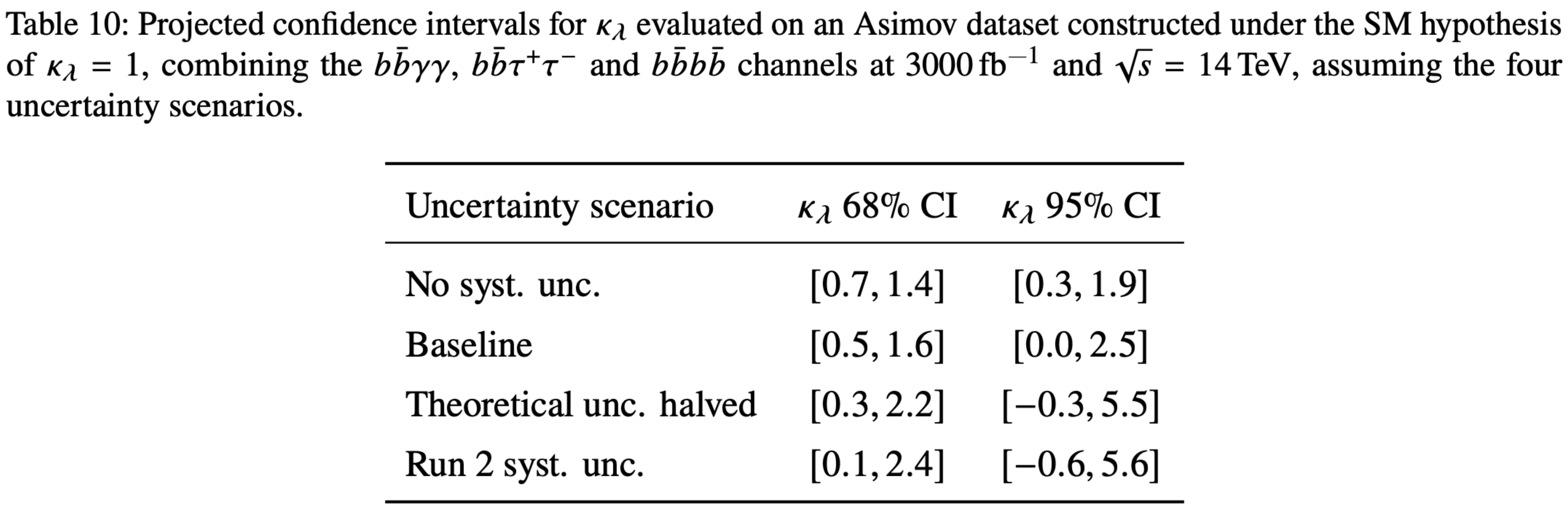


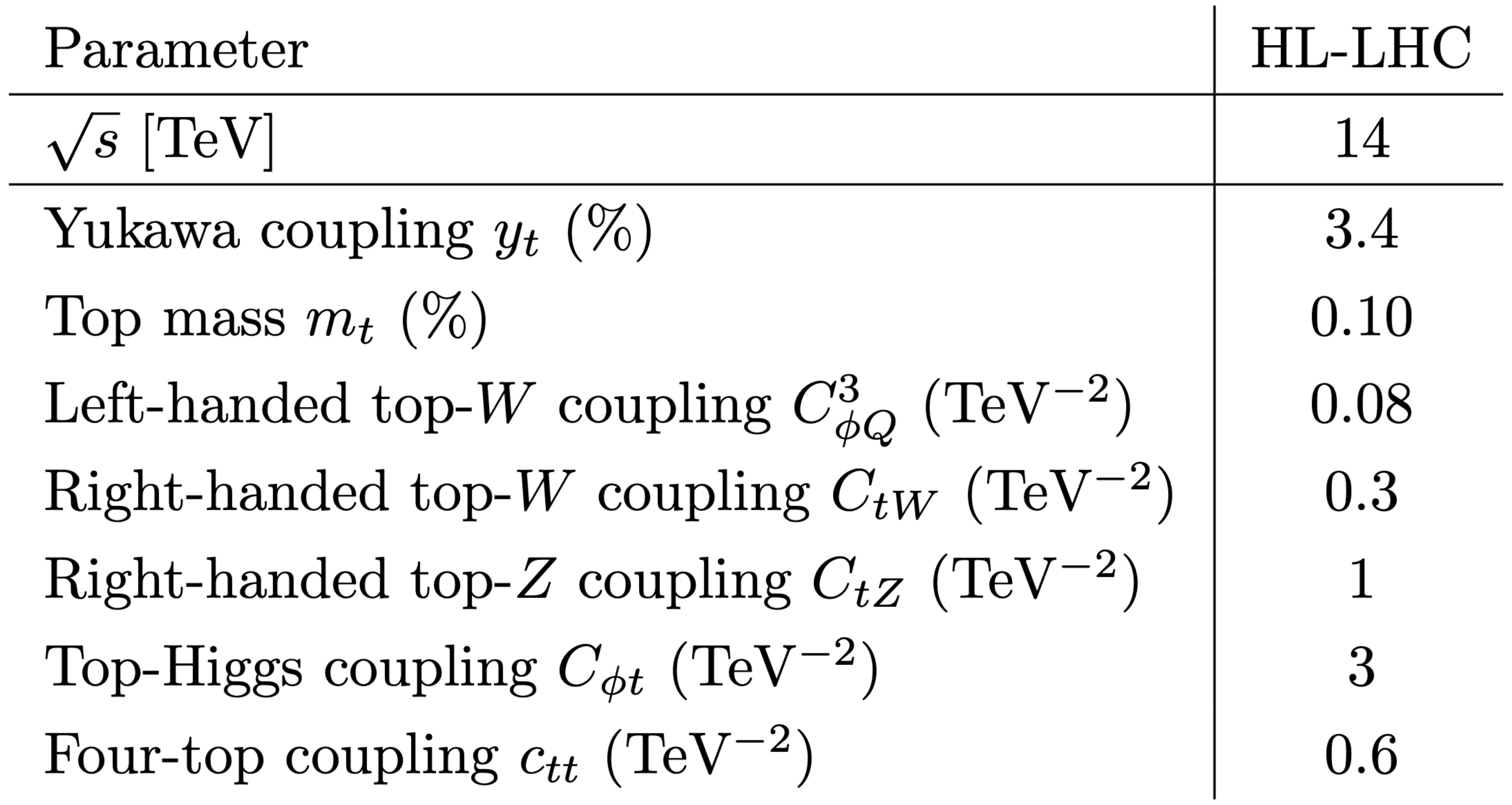
Table 10: Projected confidence intervals for κ_λ evaluated on an Asimov dataset constructed under the SM hypothesis of $\kappa_\lambda = 1$, combining the $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}b\bar{b}$ channels at 3000 fb^{-1} and $\sqrt{s}$ = 14 TeV, assuming the four uncertainty scenarios.

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

Other highlights @HL-LHC

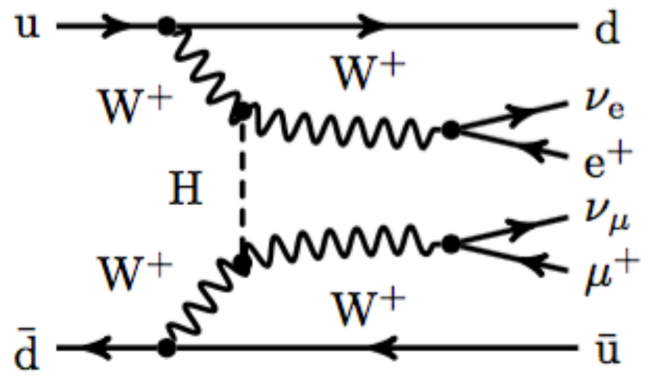
- **EWPO & Top quark**
  - $\sigma(m_W) \simeq$ 5 MeV (CDF: 9.4 MeV)
  - $\sigma(m_t) \simeq$ 0.2 GeV (LHC: 0.6 GeV)
  - $\sigma(\sin^2\theta^\ell_{\text{eff}}) \simeq 10 \times 10^{-5}$ (LEP+SLD: 16×10^{-5})
  - $\Lambda \gtrsim 3.5$ TeV ($c = 1$) for LH tW

Snowmass EF report



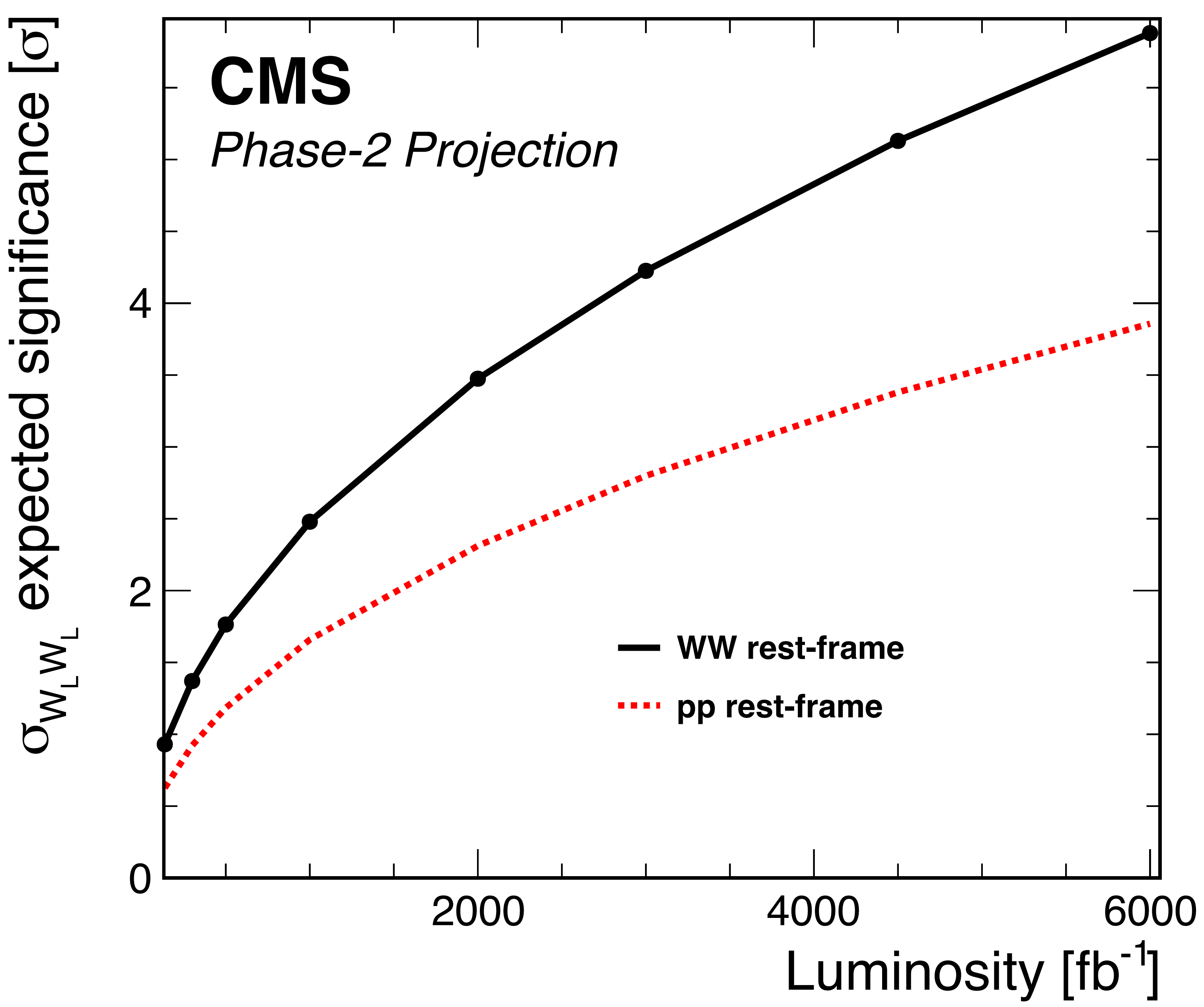
Parameter	HL-LHC
$\sqrt{s}$ [TeV]	14
Yukawa coupling y_t (%)	3.4
Top mass m_t (%)	0.10
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3
Right-handed top-Z coupling C_{tZ} (TeV^{-2})	1
Top-Higgs coupling $C_{\phi t}$ (TeV^{-2})	3
Four-top coupling c_{tt} (TeV^{-2})	0.6

- **Vector-boson scattering**
  - Higgs vs. unitarity violation
- $W^\pm_L W^\pm_L$ only 6-7% of total VBS xs



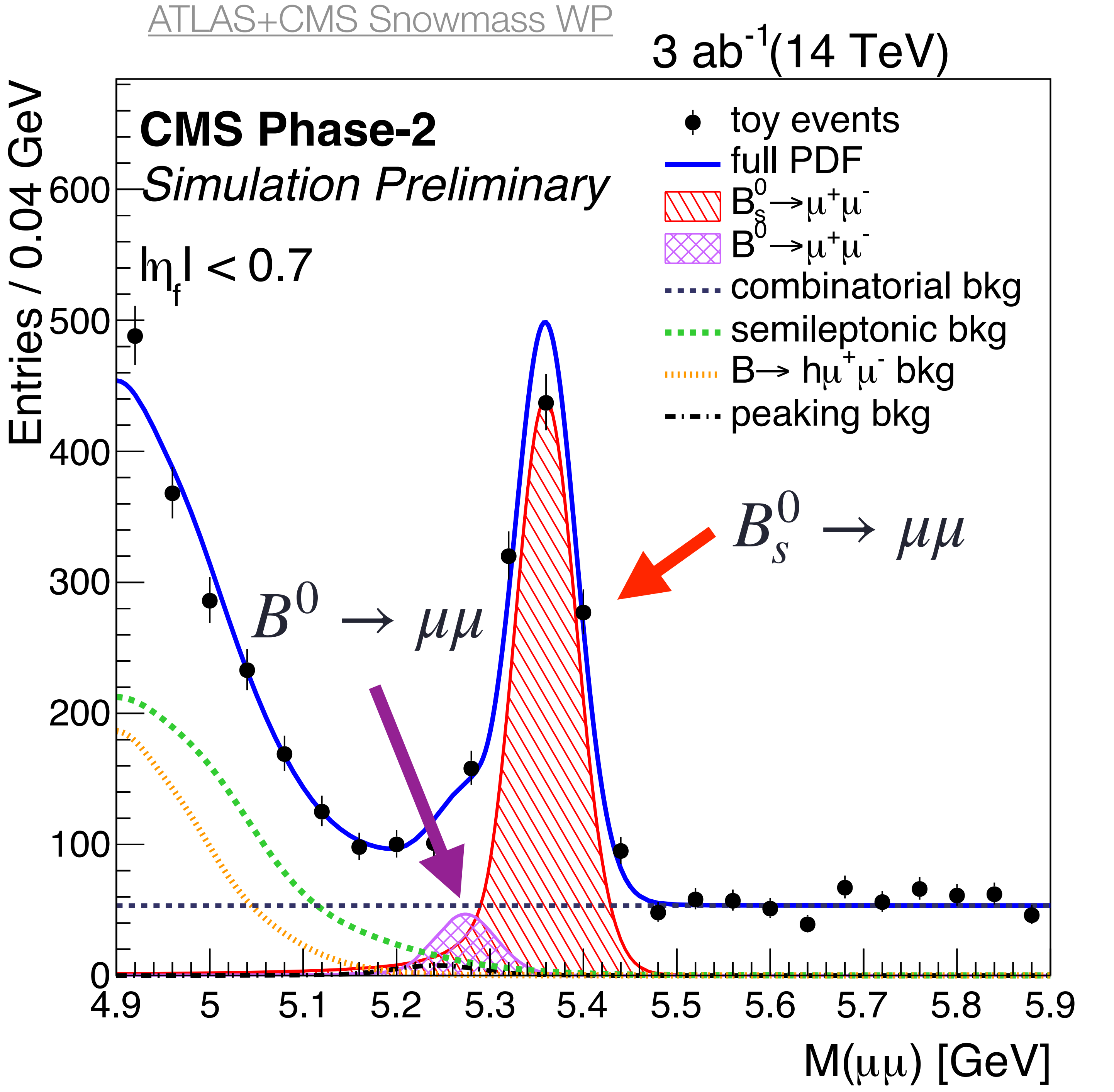
- Significance ~5 σ expected ATLAS + CMS

ATLAS+CMS Snowmass WP



- **Rare decays**
  - Observation ($> 5\,\sigma$) of FCNC $B^0 \to \mu\mu$ with SM BF $\sim 10^{-10}$
  - Requires upgraded trigger + new tracker improves $m(\mu\mu)$ resolution by 40-50%

ATLAS+CMS Snowmass WP



e^+e^- : Higgs couplings

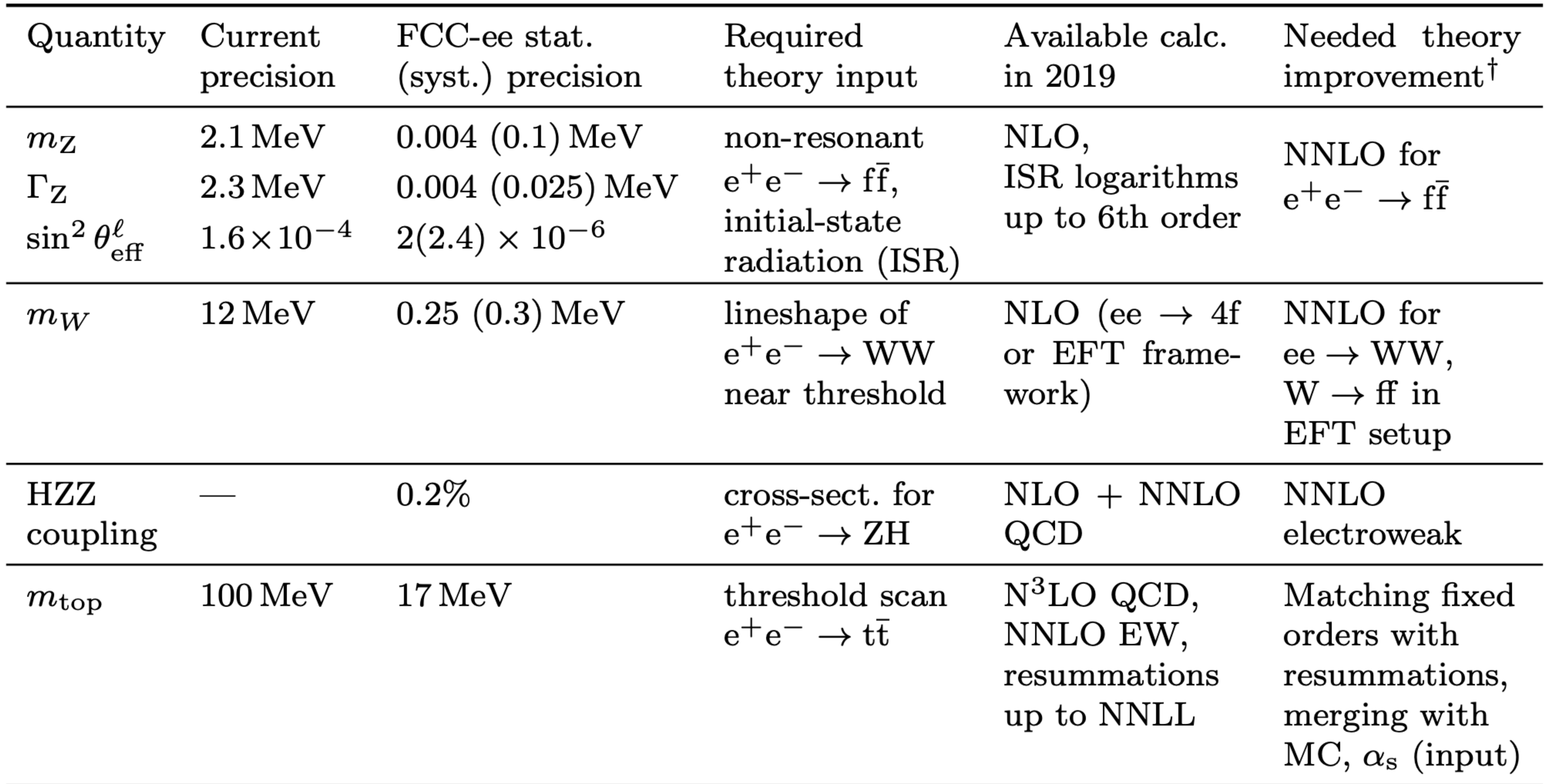
- Higgs coupling measurements
  —> indirect sensitivity to BSM scale
  up to ~70 TeV
  (strongly-coupled models)

FCC midterm report

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

e^+e^- : Electroweak

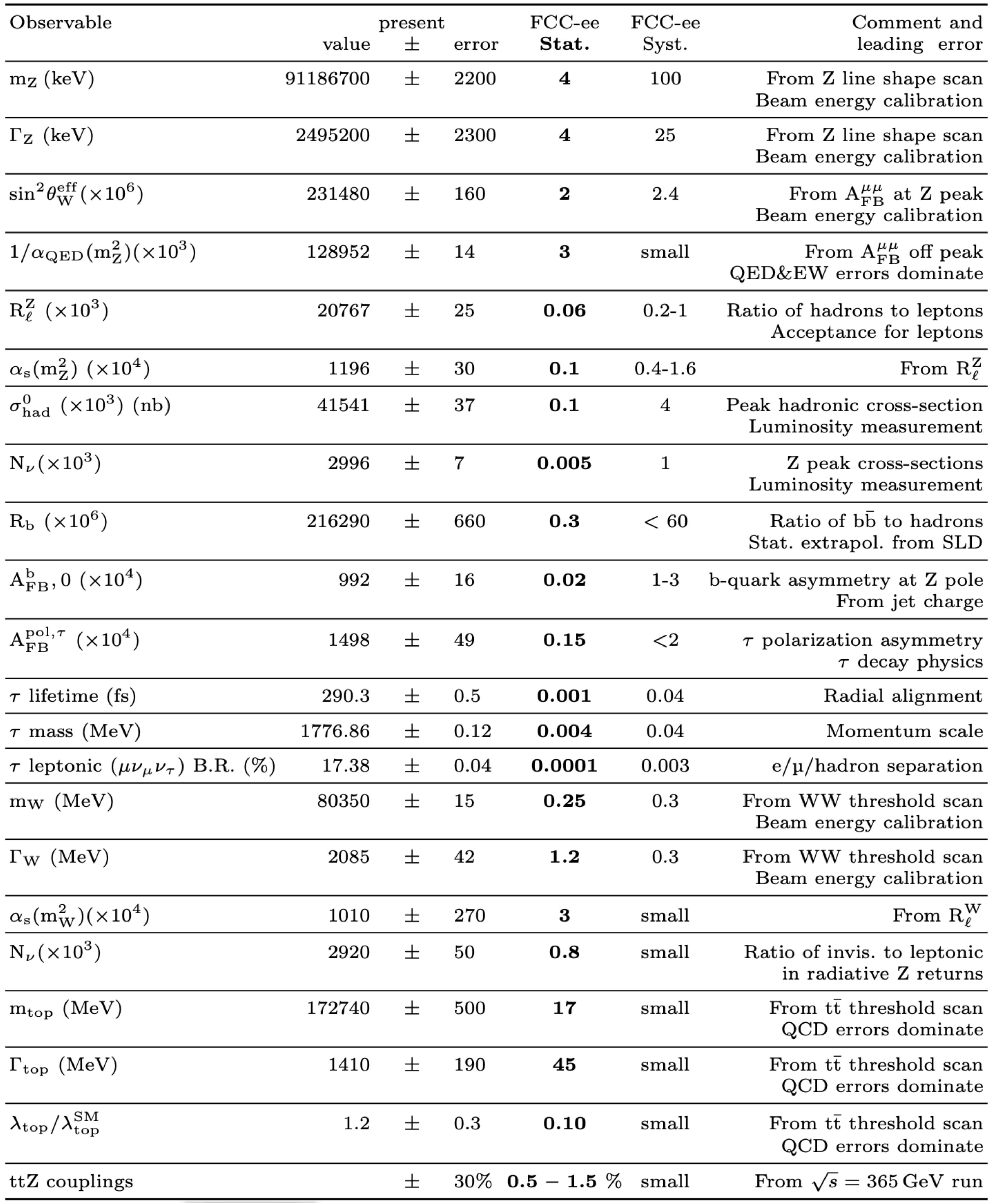
- Z pole measurements



Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement[†]
m_Z Γ_Z $\sin^2\theta^{\ell}_{\rm eff}$	2.1 MeV 2.3 MeV 1.6×10^{-4}	0.004 (0.1) MeV 0.004 (0.025) MeV $2(2.4)\times10^{-6}$	non-resonant $\mathrm{e^+e^-\to f\bar{f}}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $\mathrm{e^+e^-\to f\bar{f}}$
m_W	12 MeV	0.25 (0.3) MeV	lineshape of $\mathrm{e^+e^-\to WW}$ near threshold	NLO ($\mathrm{ee\to 4f}$ or EFT framework)	NNLO for $\mathrm{ee\to WW}$, $\mathrm{W\to f\bar{f}}$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $\mathrm{e^+e^-\to ZH}$	NLO + NNLO QCD	NNLO electroweak
$m_{\rm top}$	100 MeV	17 MeV	threshold scan $\mathrm{e^+e^-\to t\bar{t}}$	$\mathrm{N^3LO}$ QCD, NNLO EW, resummations up to NNLL	Matching fixed orders with resummations, merging with MC, α_s (input)

[†] The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.

FCC midterm report

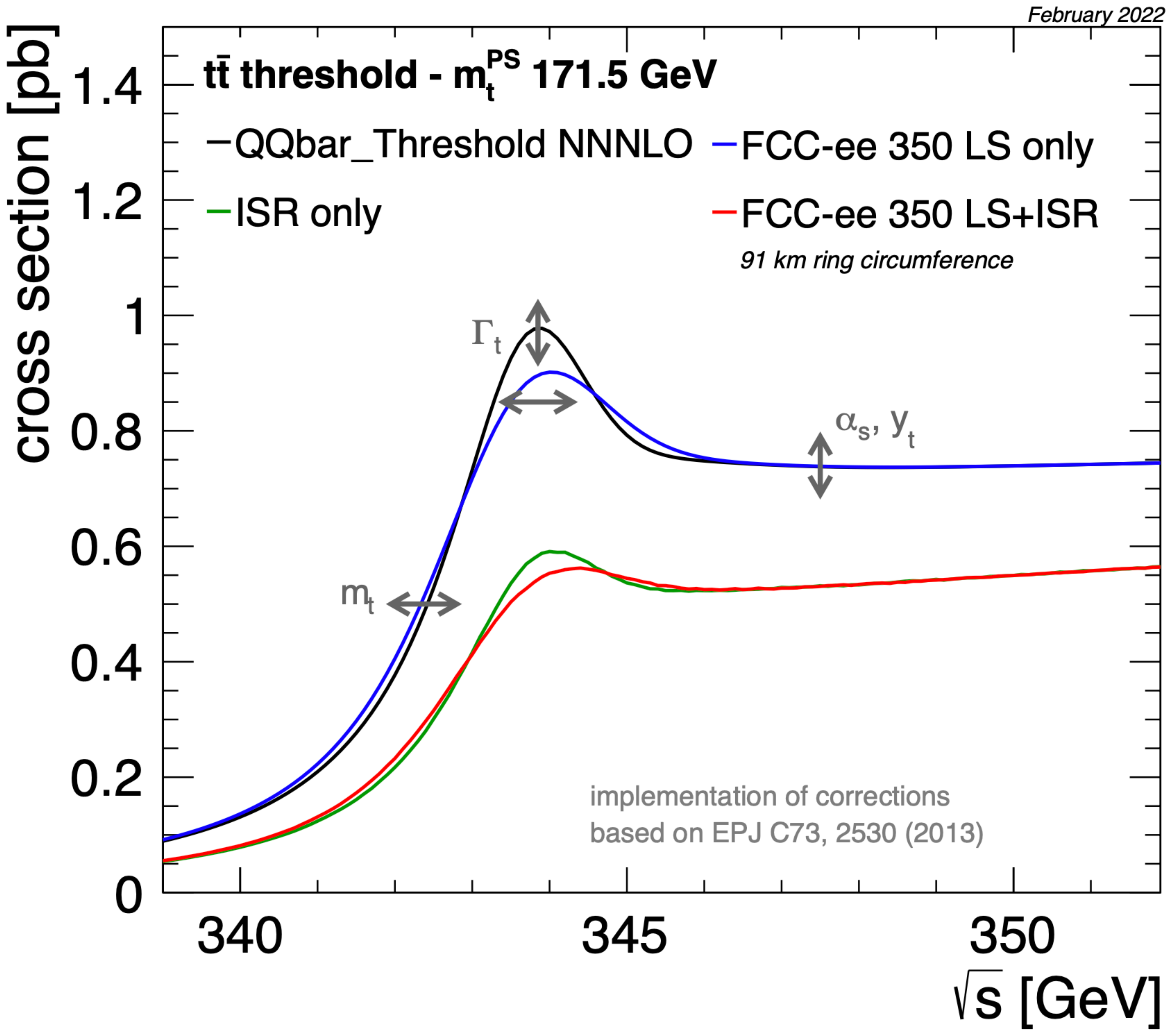


Observable		present		FCC-ee	FCC-ee	Comment and
	value	±	error	**Stat.**	Syst.	leading error
$\mathrm{m_Z}$ (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_\mathrm{W}^\mathrm{eff}(\times10^6)$	231480	±	160	**2**	2.4	From $\mathrm{A_{FB}^{\mu\mu}}$ at Z peak Beam energy calibration
$1/\alpha_\mathrm{QED}(\mathrm{m_Z^2})(\times10^3)$	128952	±	14	**3**	small	From $\mathrm{A_{FB}^{\mu\mu}}$ off peak QED&EW errors dominate
$\mathrm{R_\ell^Z}$ $(\times10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_\mathrm{s}(\mathrm{m_Z^2})$ $(\times10^4)$	1196	±	30	**0.1**	0.4-1.6	From $\mathrm{R_\ell^Z}$
σ^0_had $(\times10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$\mathrm{N}_\nu(\times10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
$\mathrm{R_b}$ $(\times10^6)$	216290	±	660	**0.3**	< 60	Ratio of $\mathrm{b\bar{b}}$ to hadrons Stat. extrapol. from SLD
$\mathrm{A_{FB}^b}, 0$ $(\times10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$\mathrm{A_{FB}^{pol,\tau}}$ $(\times10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
$\mathrm{m_W}$ (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_\mathrm{s}(\mathrm{m_W^2})(\times10^4)$	1010	±	270	**3**	small	From $\mathrm{R_\ell^W}$
$\mathrm{N}_\nu(\times10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
$\mathrm{m_{top}}$ (MeV)	172740	±	500	**17**	small	From $\mathrm{t\bar{t}}$ threshold scan QCD errors dominate
Γ_top (MeV)	1410	±	190	**45**	small	From $\mathrm{t\bar{t}}$ threshold scan QCD errors dominate
$\lambda_\mathrm{top}/\lambda_\mathrm{top}^\mathrm{SM}$	1.2	±	0.3	**0.10**	small	From $\mathrm{t\bar{t}}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365\,\mathrm{GeV}$ run

e^+e^- : Top quark

- Expect ~2M $t\,\bar{t}$ events
  w/ clean environment and ability to scan $\sqrt{s}$
- **Test of Higgs mechanism** via measurement of top mass and top Yukawa coupling
  - m_t measurement at ee collider with clear interpretation from cross-section measurement near threshold

δm_t^{PS} [MeV]	ILC	CLIC	FCC-ee
$\mathcal{L}[\mathrm{fb}^{-1}]$	200	100 [200]	200
Statistical uncertainty	10	20 [13]	9
Theoretical uncertainty (QCD)	40 – 45		
Parametric uncertainty α_s	26	26	3.2
Parametric uncertainty y_t HL-LHC	5		
Non-resonant contributions	< 40		
Experimental systematic uncertainty	20 – 30		11 – 20
Total uncertainty	40 – 75		



e^+e^- : Rare Z decays

- **Rare/exotic Z or H decays:**
  - Extended scalar sector, SUSY, Higgs portal, vector portal
  - BF sensitivity improved by 1-4 orders of magn. for H decays, 2-9 orders of magn. for Z decays relative to HL-LHC
    - strongest gains in hadronic final states with or w/o missing momentum

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