SM and BSM Higgs conclusions from the Snowmass process

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Snowmass Report

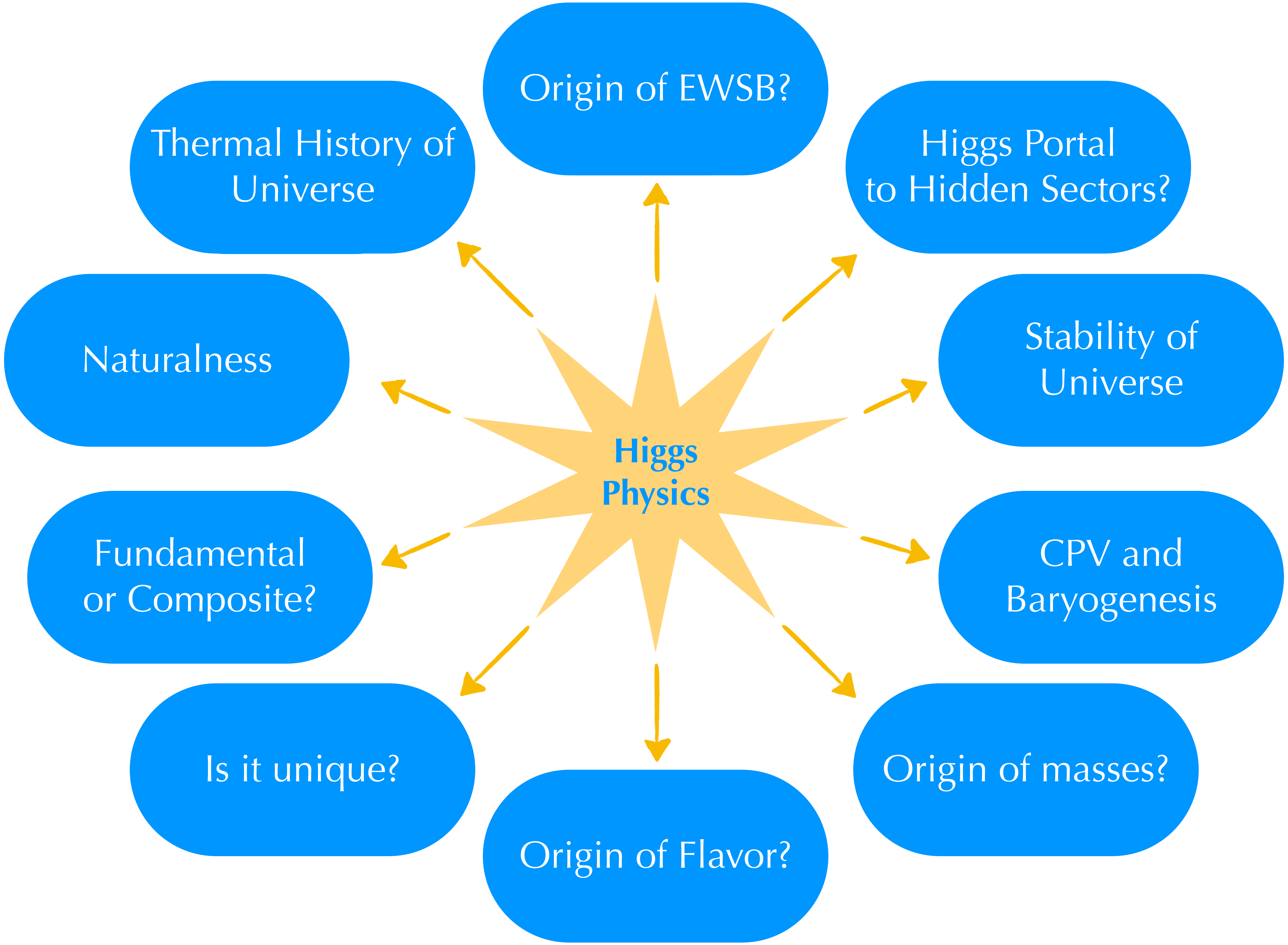
Snowmass Higgs TG

November 30, 2022

The 19th Workshop of the LHC Higgs Working Group

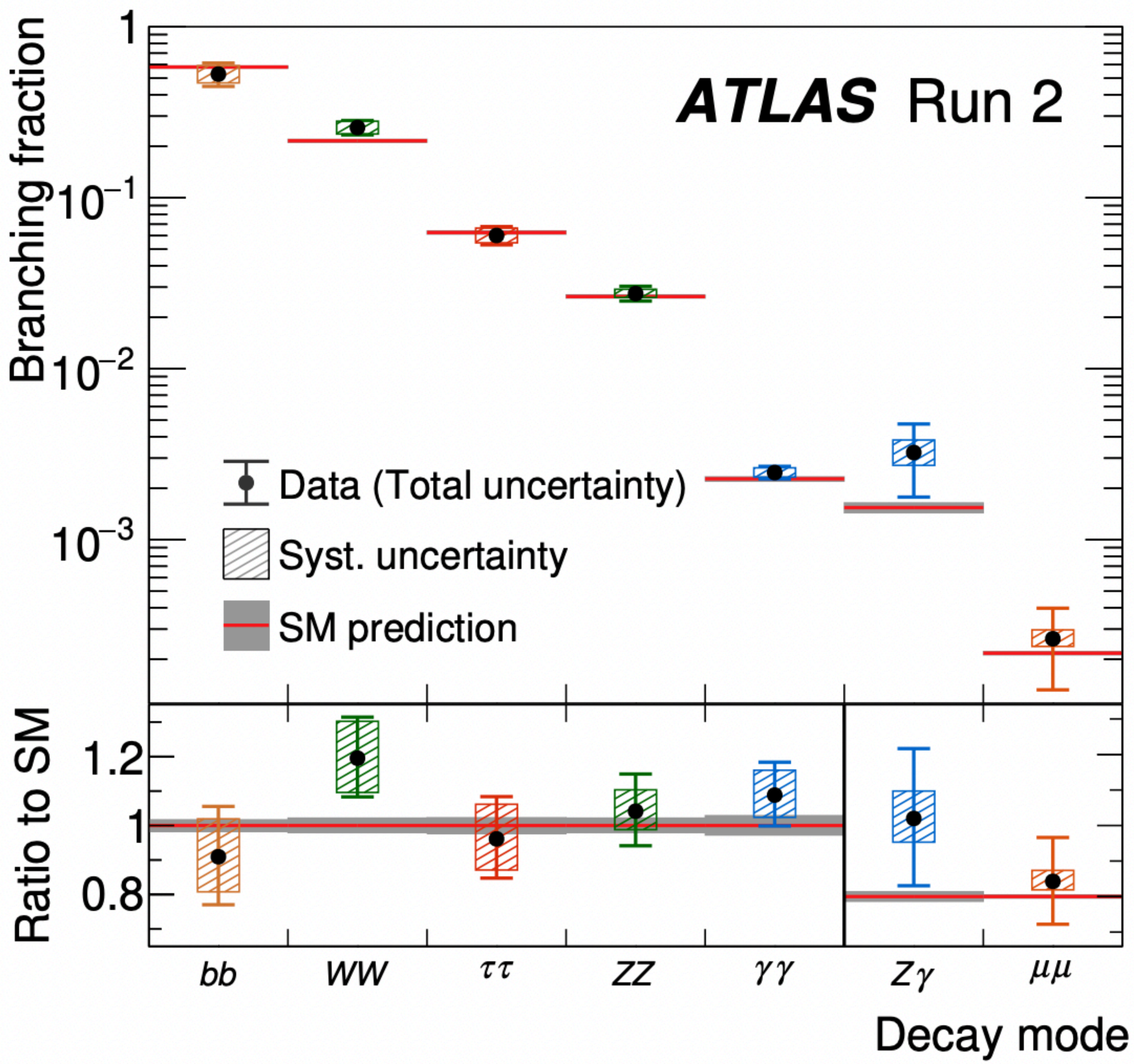
U.S. DEPARTMENT OF ENERGY
Office of Science

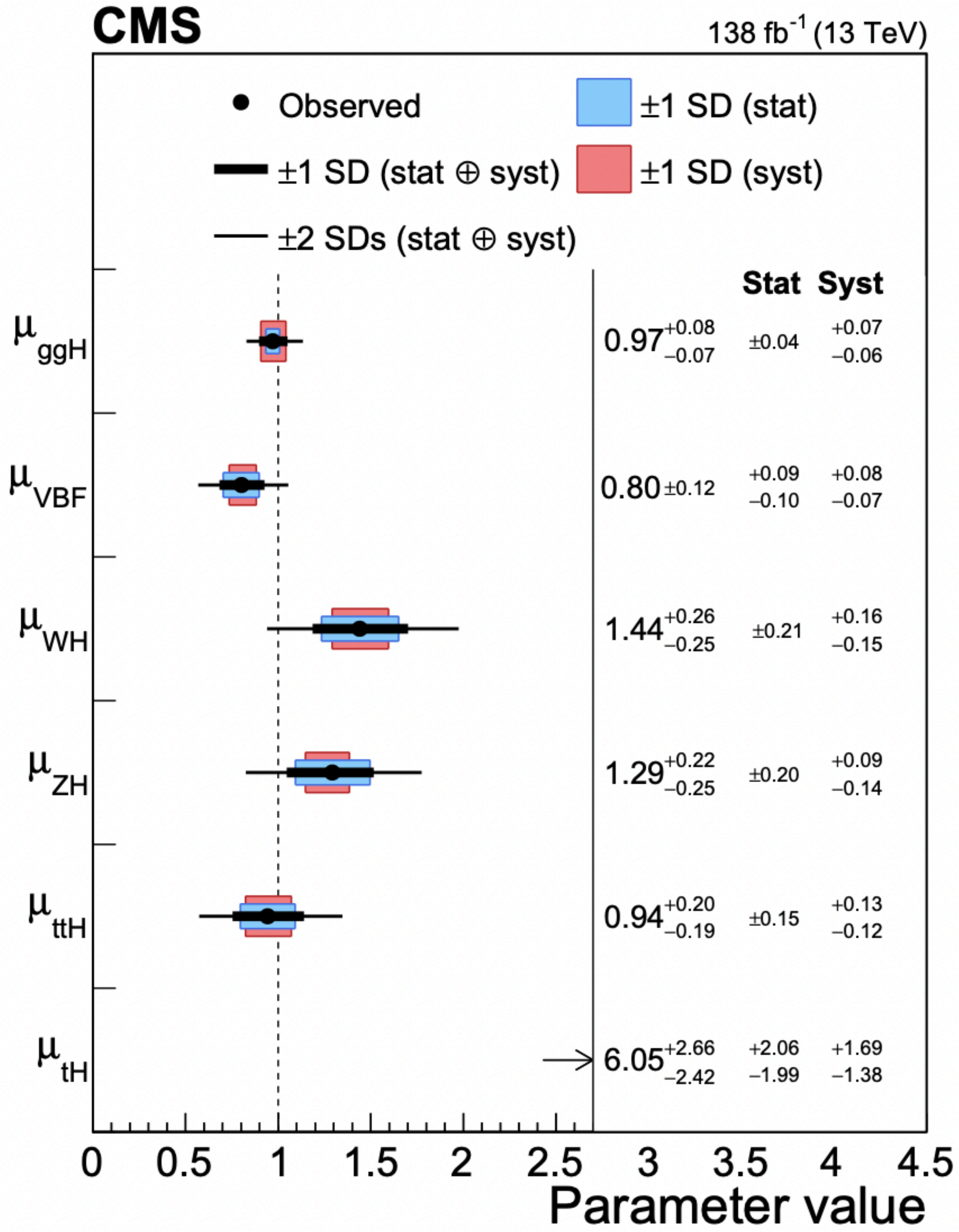
SLAC NATIONAL ACCELERATOR LABORATORY


Origin of EWSB?
Thermal History of Universe
Higgs Portal to Hidden Sectors?
Naturalness
Stability of Universe
Higgs Physics
Fundamental or Composite?
CPV and Baryogenesis
Is it unique?
Origin of masses?
Origin of Flavor?

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

Higgs in 2022





LHC → High Luminosity LHC

LHC | HL-LHC

Run 2
8M H

Upgrade of accelerator and experiments

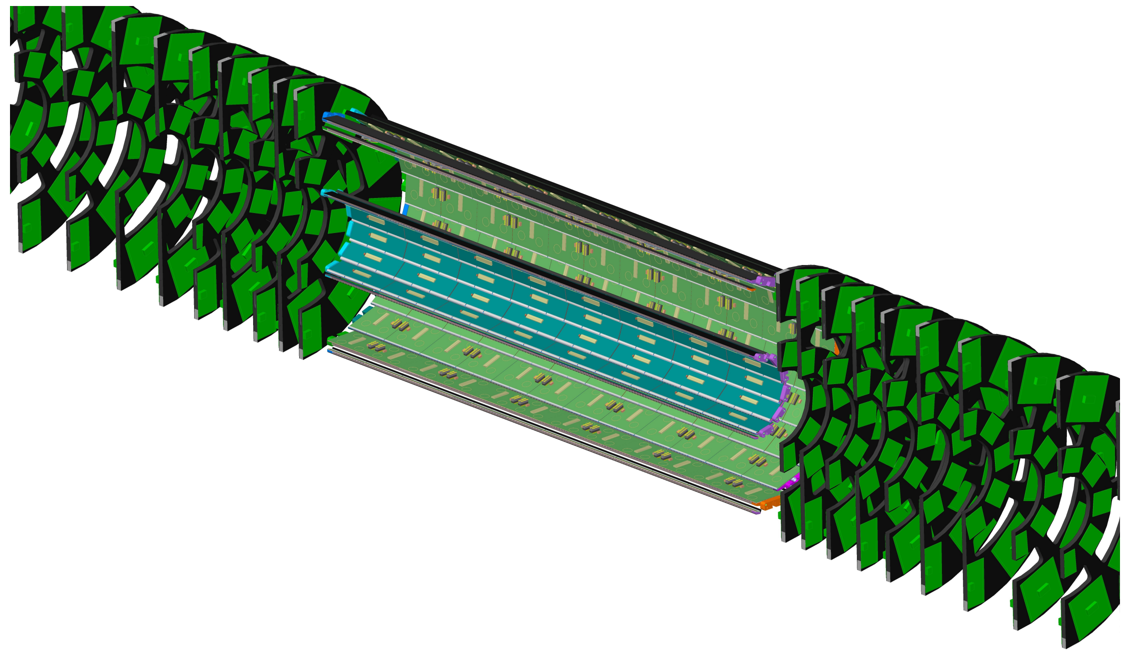
Run 3
16M H

HL-LHC installation
ATLAS/CMS Upgrades

Run 4/5
170M H
120k HH

2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | ... | 2039

link!

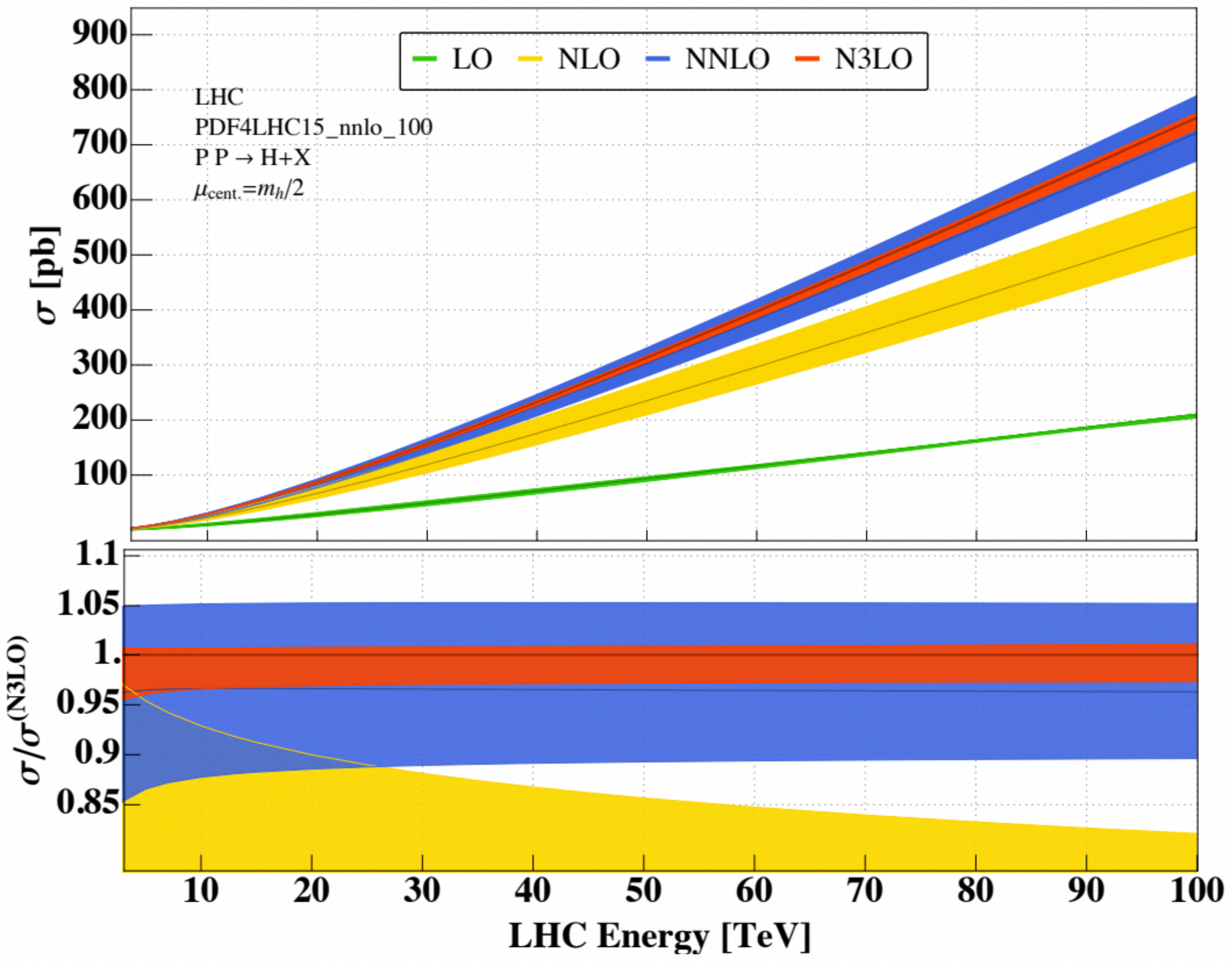


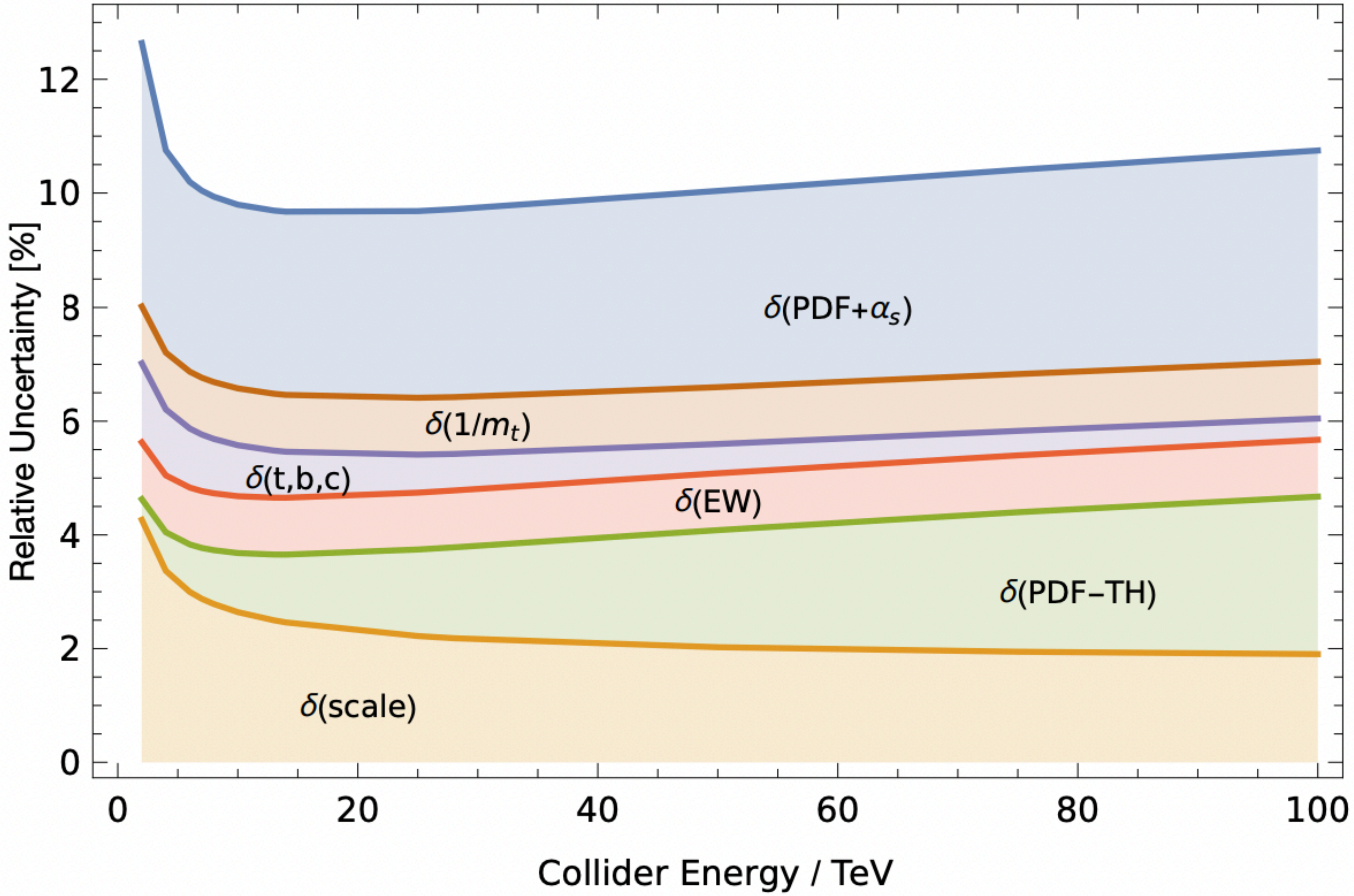
Today

Phase-2 HL-LHC detector upgrades are being built

Status Theory Predictions

arXiv:2203.06730
arXiv:1902.00134

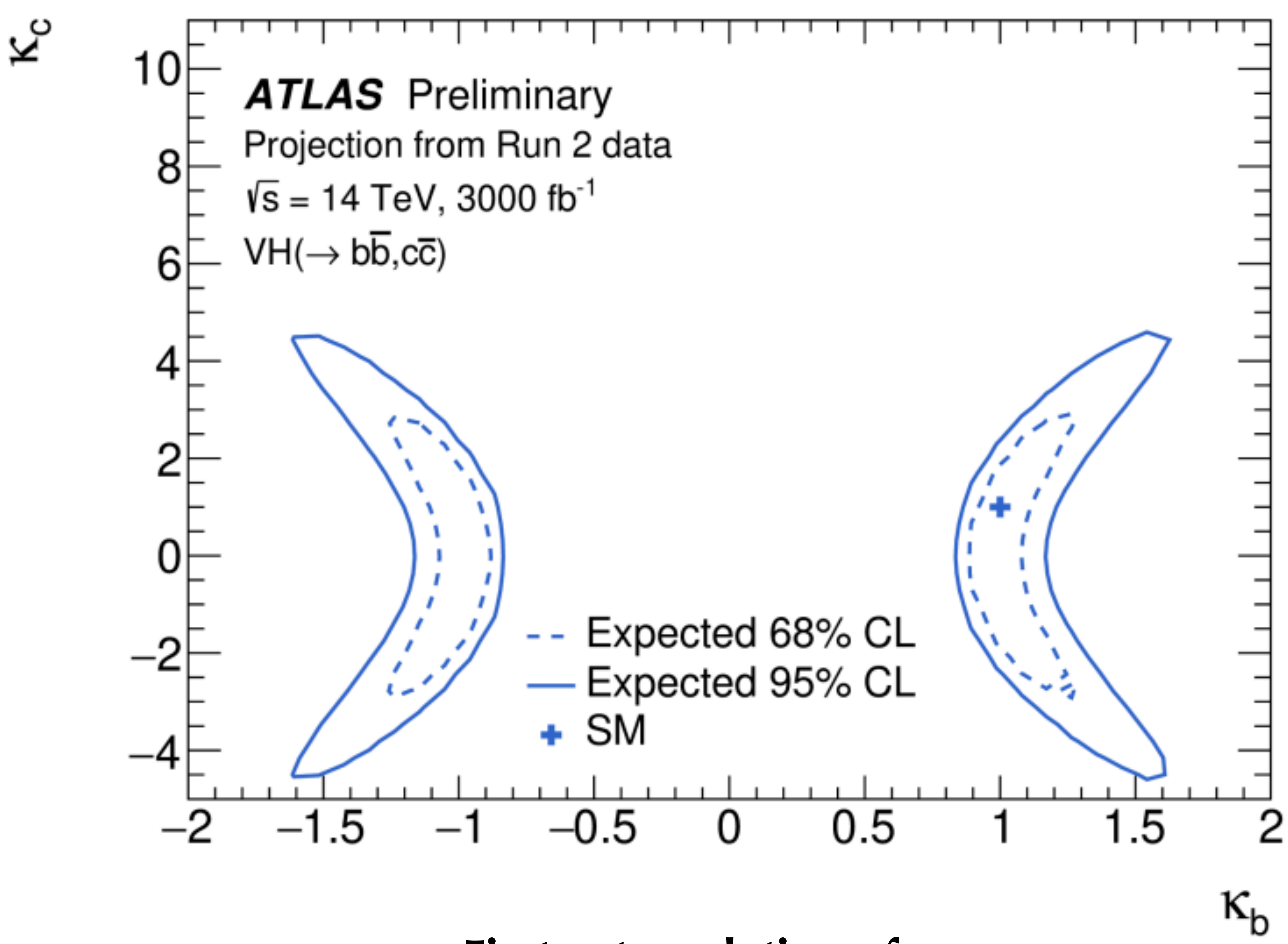




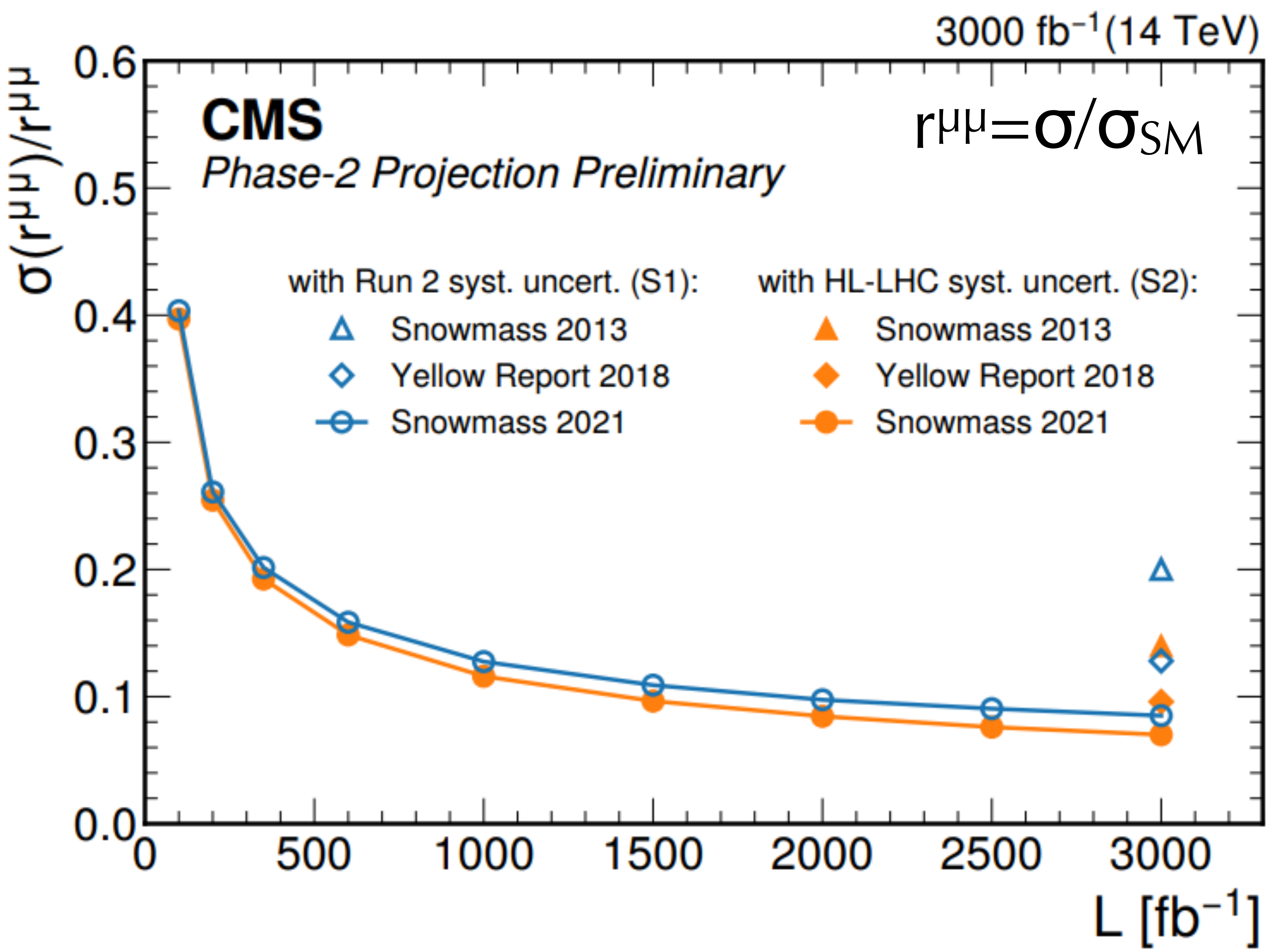
- The theory uncertainty expected to be comparable to the expected statistical and systematic uncertainties of the measurements.
  - Impressive progress so far, e.g. 1/mt is gone
    - theory uncertainties can be reduced by a factor of two in the future

Higgs physics at the HL-LHC

Extrapolations from Run 2 analyses

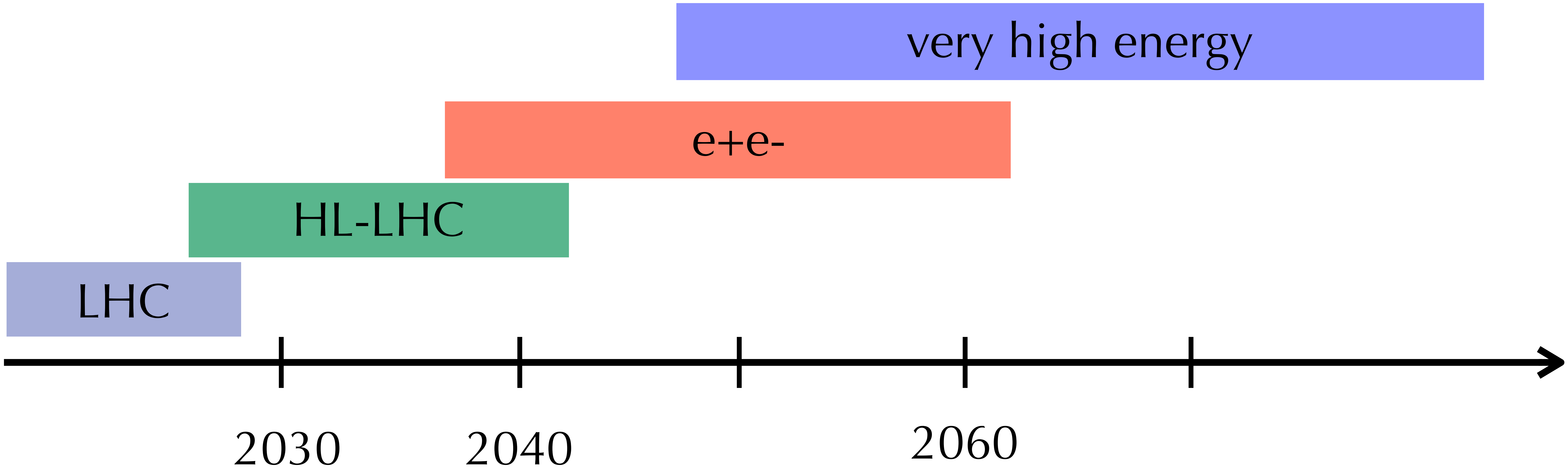


First extrapolation of κc



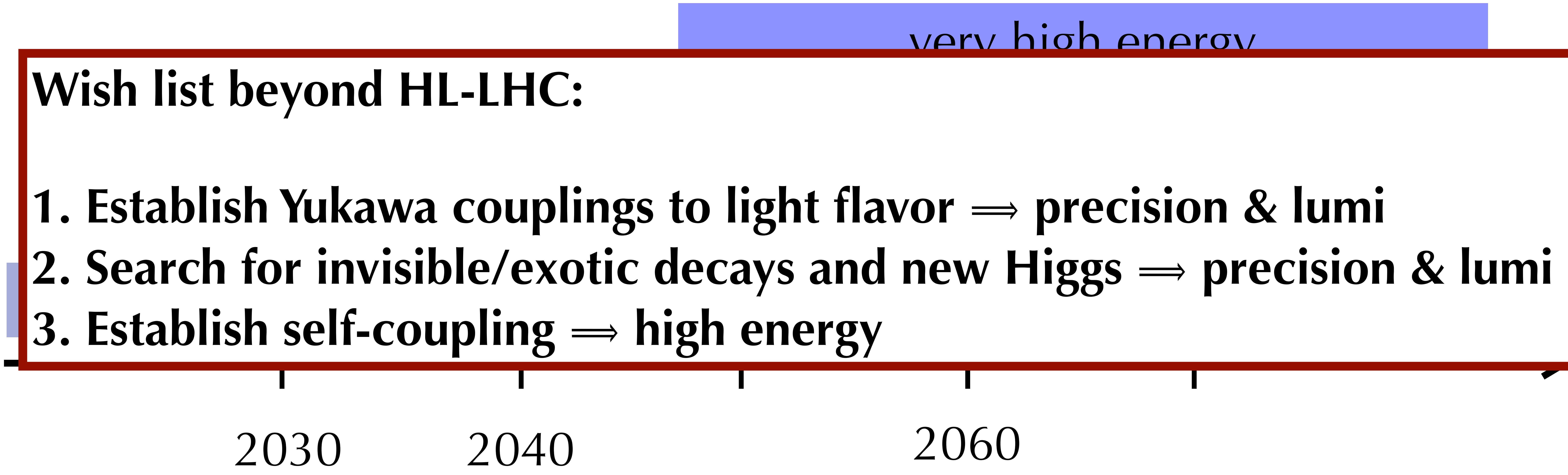
30% in the mass resolution with upgraded tracking system

Higgs as a guide



H couplings to:	**O(1-10)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

Higgs as a guide



Wish list beyond HL-LHC:

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

H couplings to:	O(1-10)%	O(0.1-1)%	O(1)‰
H self-coupling to	<O(50)%	O(20)%	O(1)%

Various machines to consider

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3	ee	250 GeV	$\pm80/\pm30$	2
c.o.m almost		350 GeV	$\pm80/\pm30$	0.2
similar		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

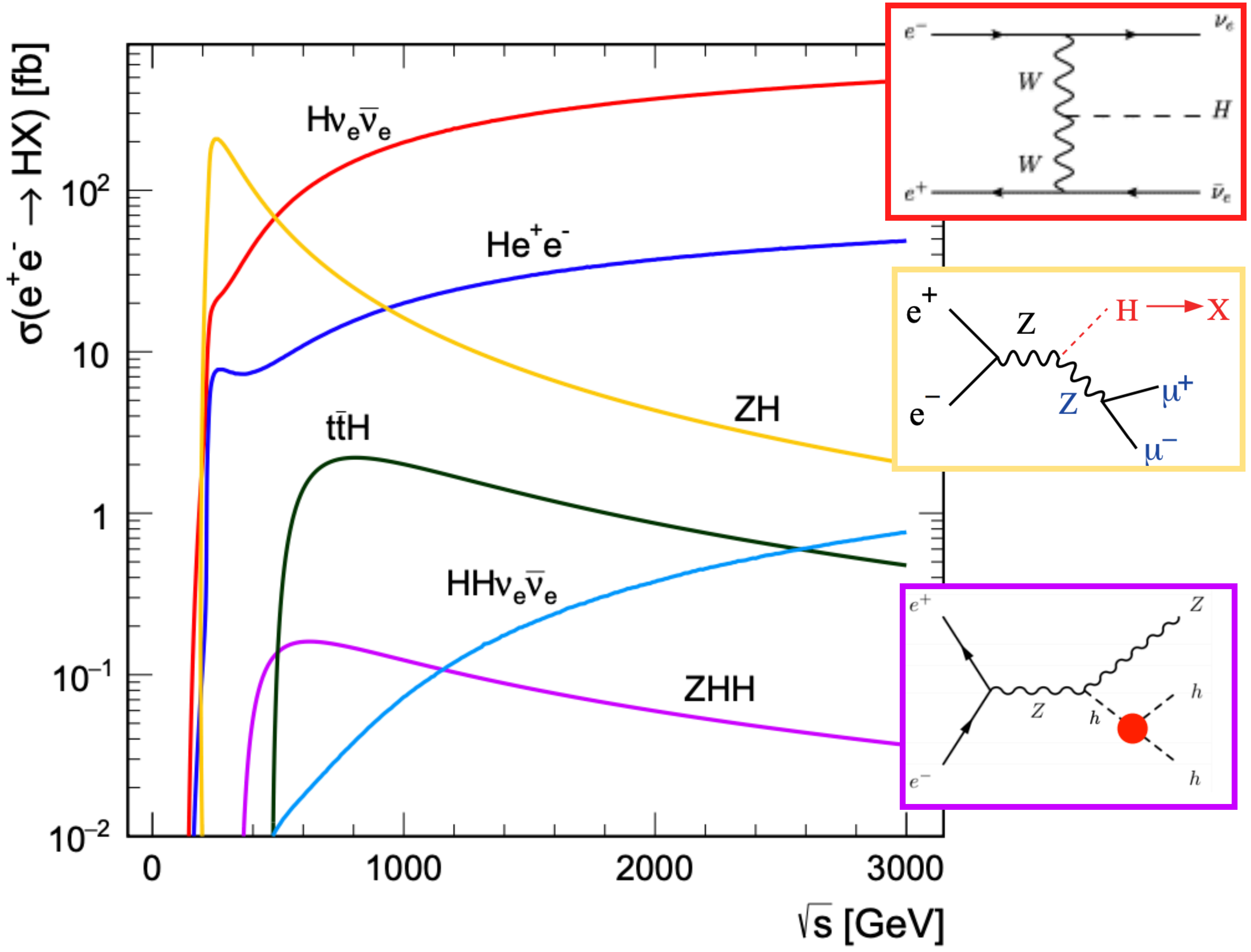
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV		15
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2
CLIC	ee	1.5 TeV	$\pm80/0$	2.5
		3.0 TeV	$\pm80/0$	5
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

Various machines to consider

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

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
Muon Collider	3 (1.5-14)	2.3 (4.6)	>10	19-24	7-12	~230

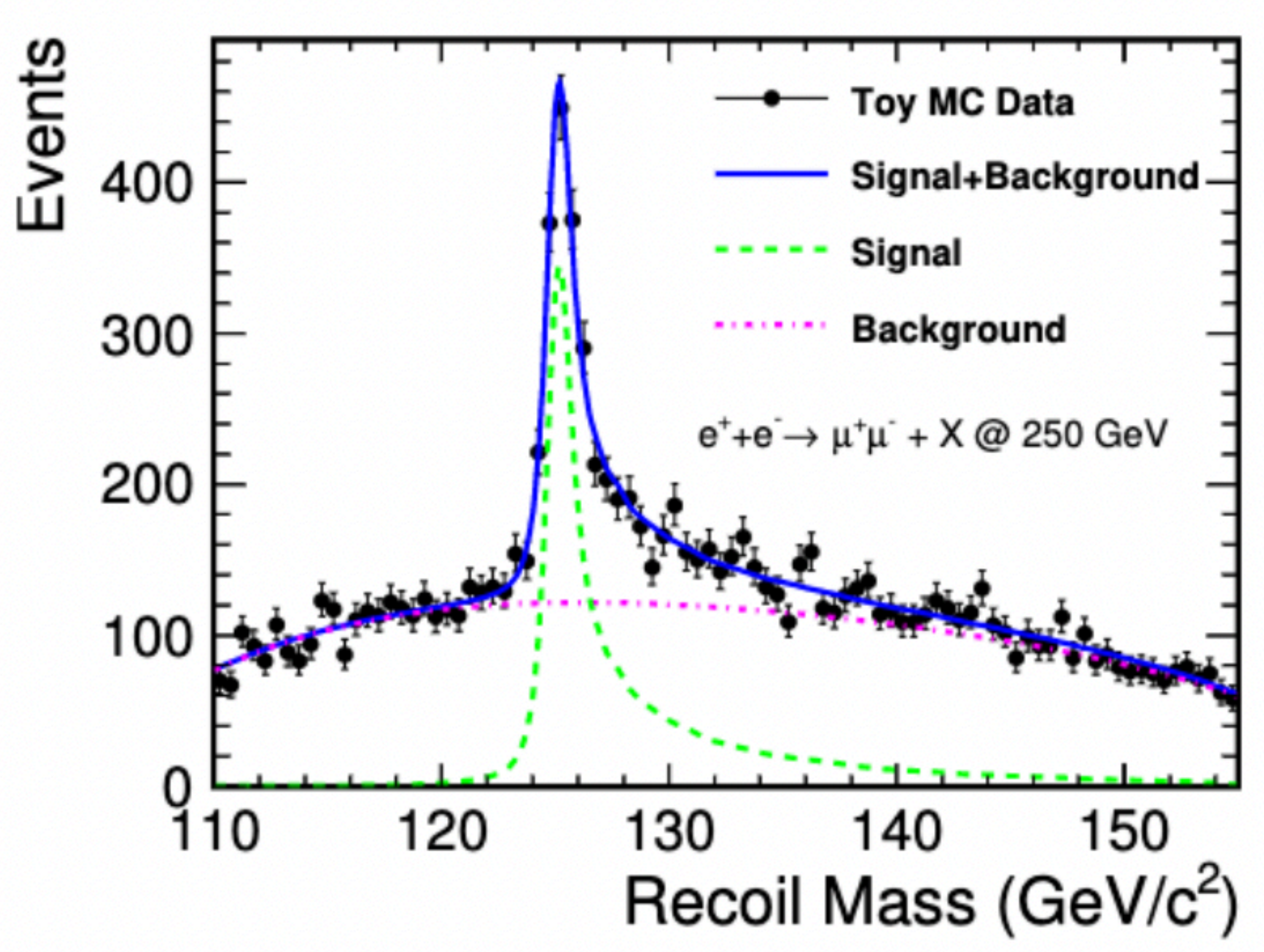
Higgs at e+e-



- ZH is dominant at **250 GeV**
- Above **500 GeV**
  - hVV dominates
  - tth opens up
  - hh production accessible with Zhh

Higgs at e^+e^-

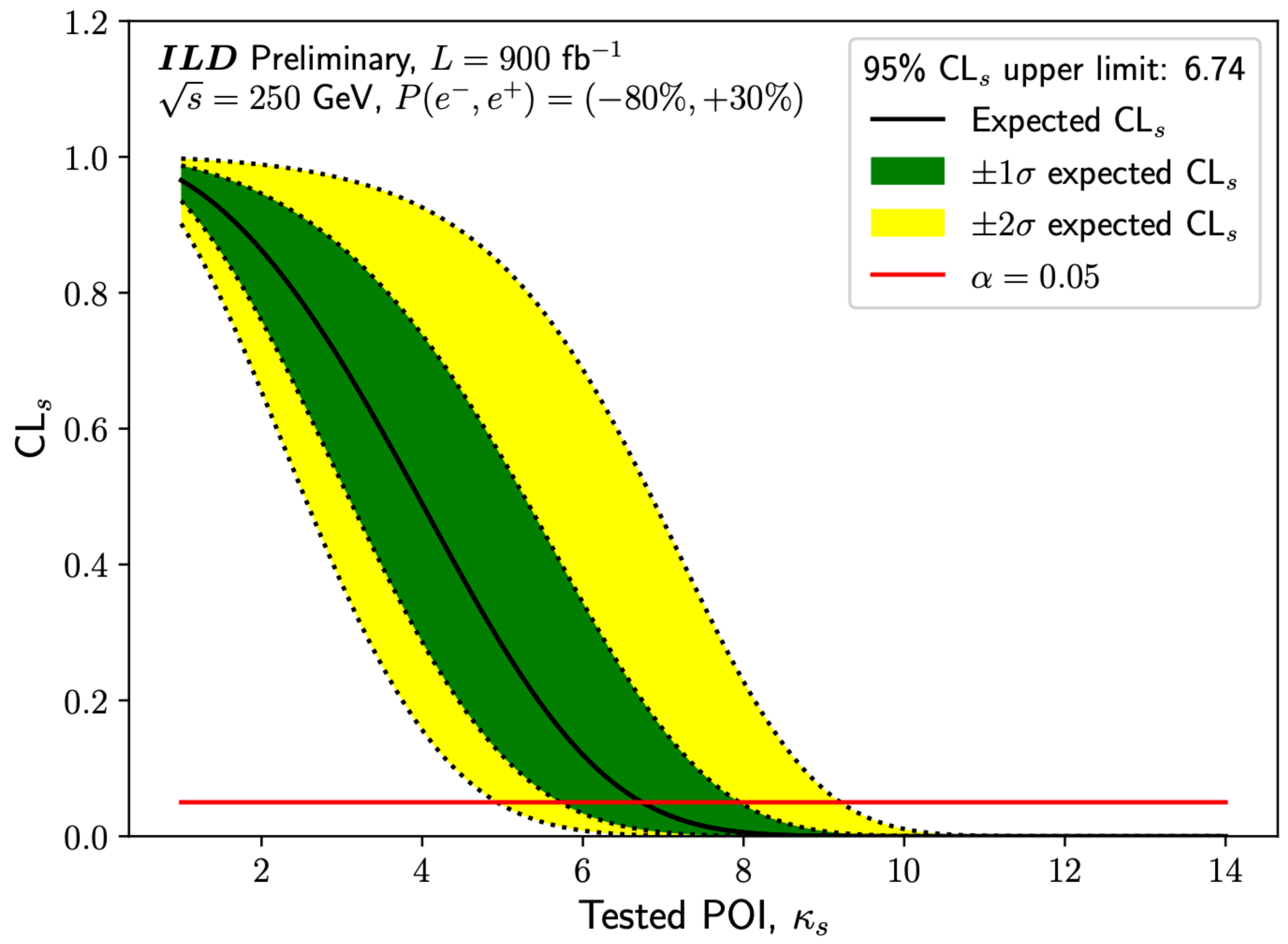
- At 250 GeV the total Zh cross section can be extracted independently of the Higgs boson's detailed properties by counting events with an identified Z boson
- The **Zh total cross section** can be measured from the area of the signal peak to ~ **O(1%) precision**
  - This **model-independent** measurement of the **hZZ** coupling is unique to e+e- colliders
- In combination with the measurement of the rate of Zh events with a h→ZZ decay, a model-independent determination of the Higgs total width can be obtained

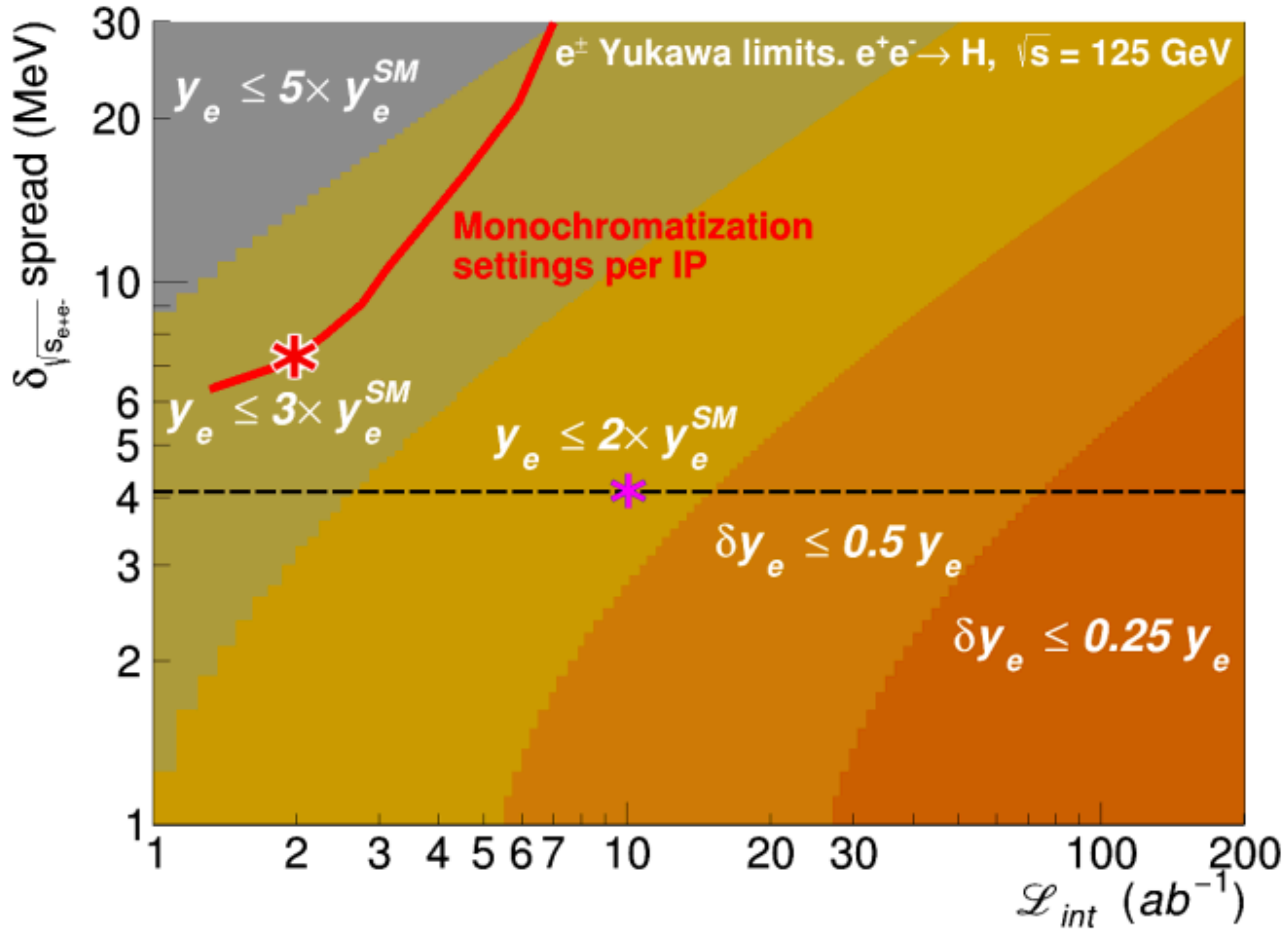


strange and electron Yukawa

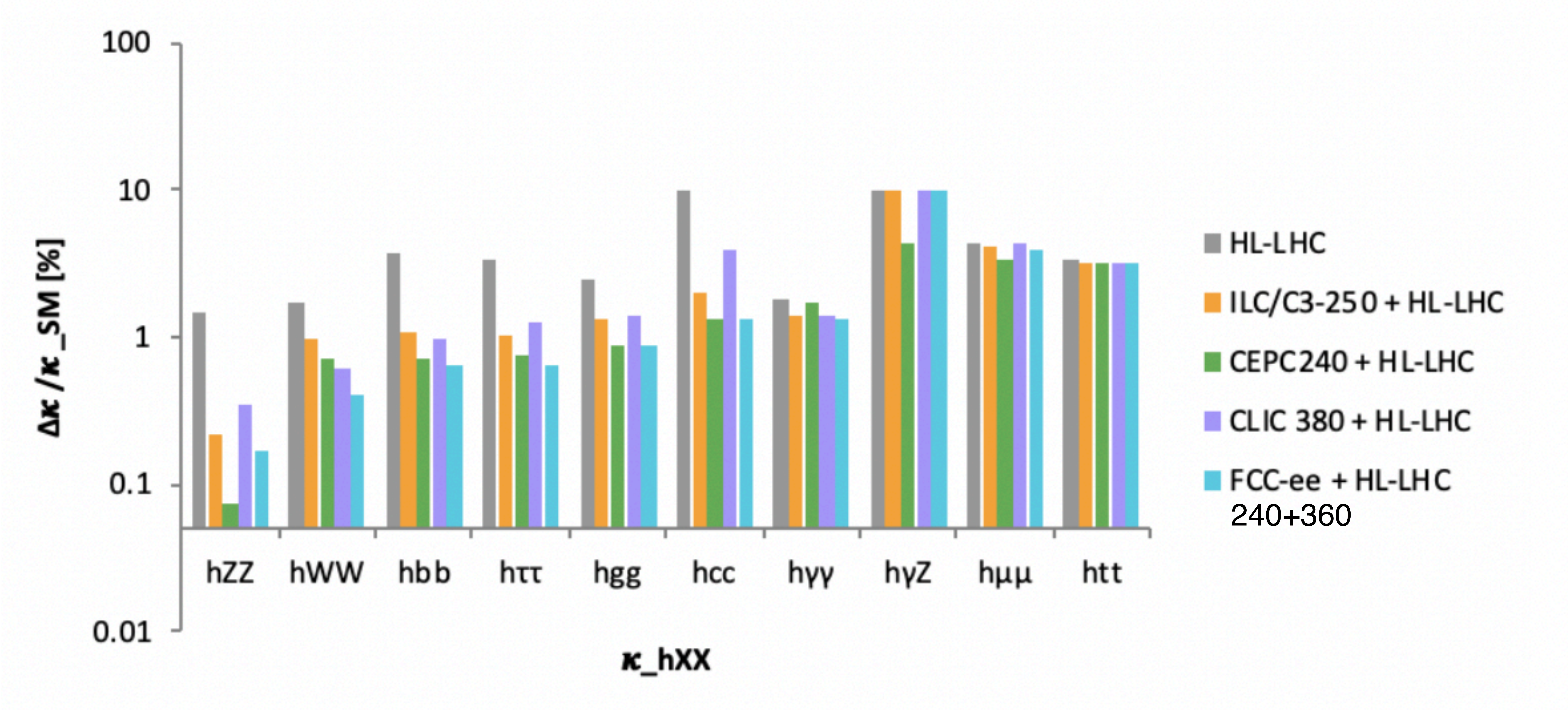
arxiv:2107.02686
arXiv:2203.07535

- ILD combined limit for κs < 6.74 at 95% CL with 900/fb at 250 GeV (i.e. half dataset)
- **Electron** Yukawa at FCC-ee with a dedicated 4 years run at the Higgs mass
    - $\kappa_e < 1.6$ at 95% CL





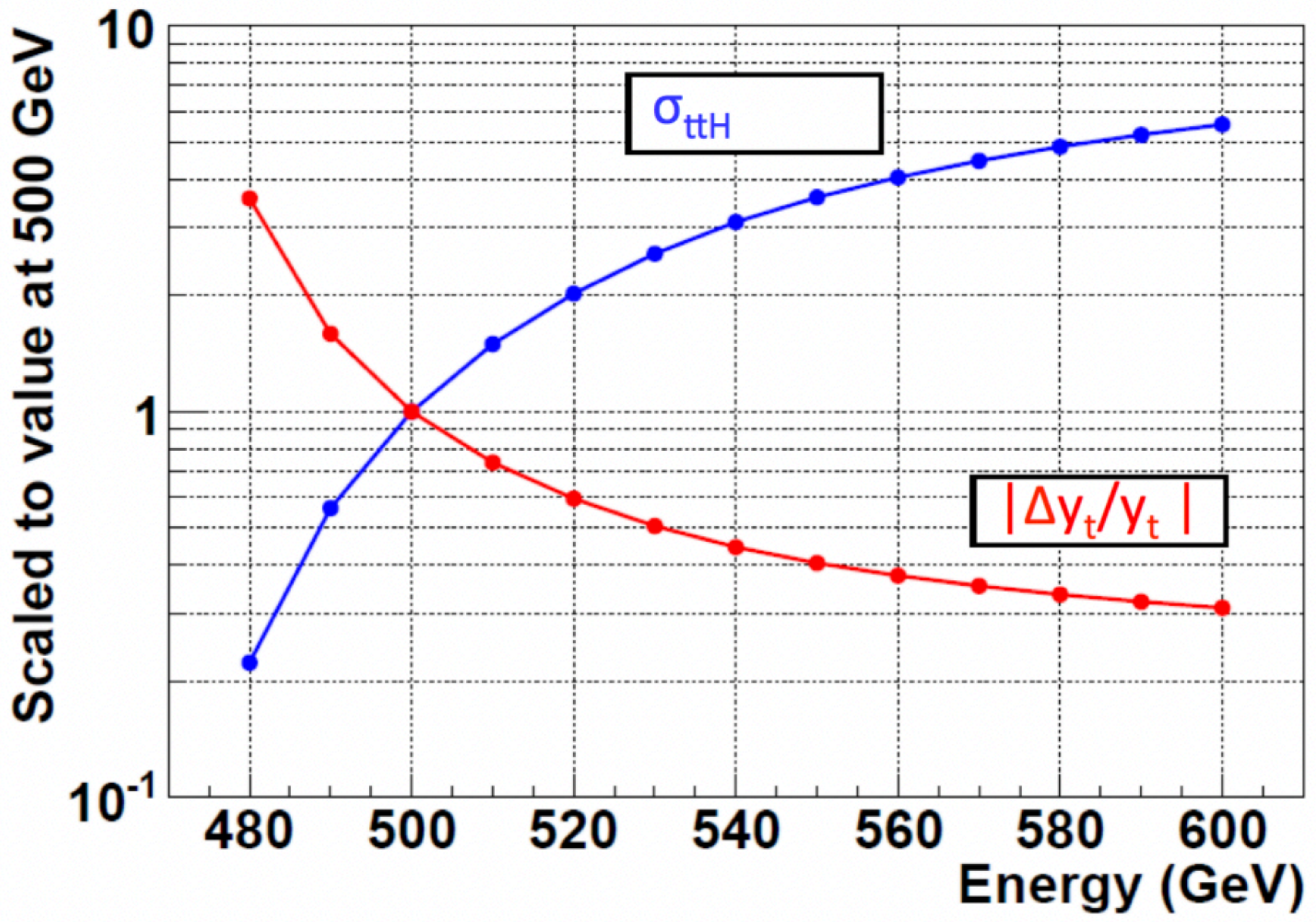
Higgs Boson couplings at (first stage) e+e-

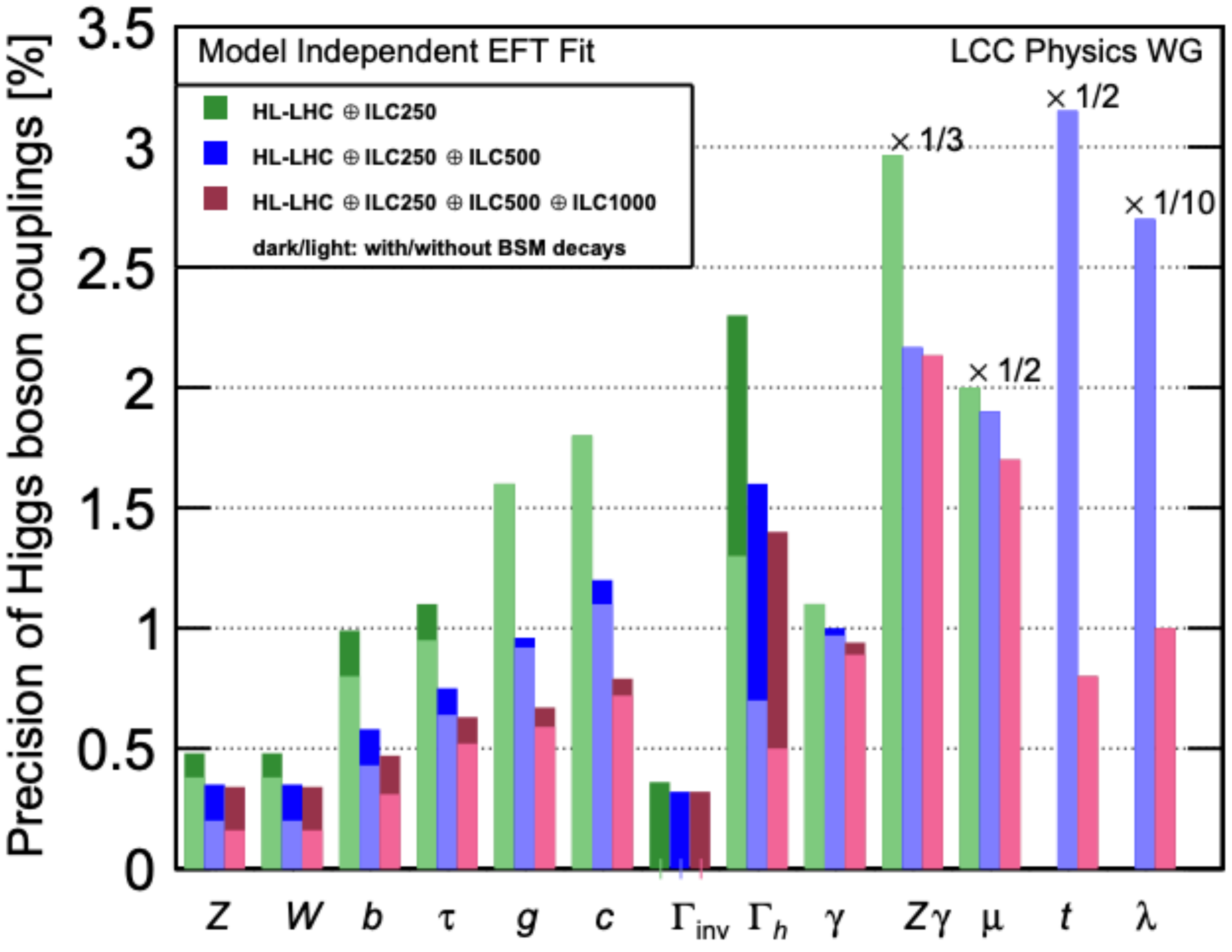


- All the e+e- machines being considered at ~ 250 GeV energy collisions will improve with respect to the HL-LHC the understanding of the Higgs boson couplings - 1-5%
  - **Coupling to charm** quark could be measured with an accuracy of ~1% in future e+e- machines
  - **Couplings to μ/γ/Zγ** benefit the most from the large dataset available at HL-LHC
  - At low energy top-Higgs and self-coupling coupling is not accessible, > 500 GeV is required

Higgs couplings for ILC

arXiv:2203.07622
arXiv:1506.07830

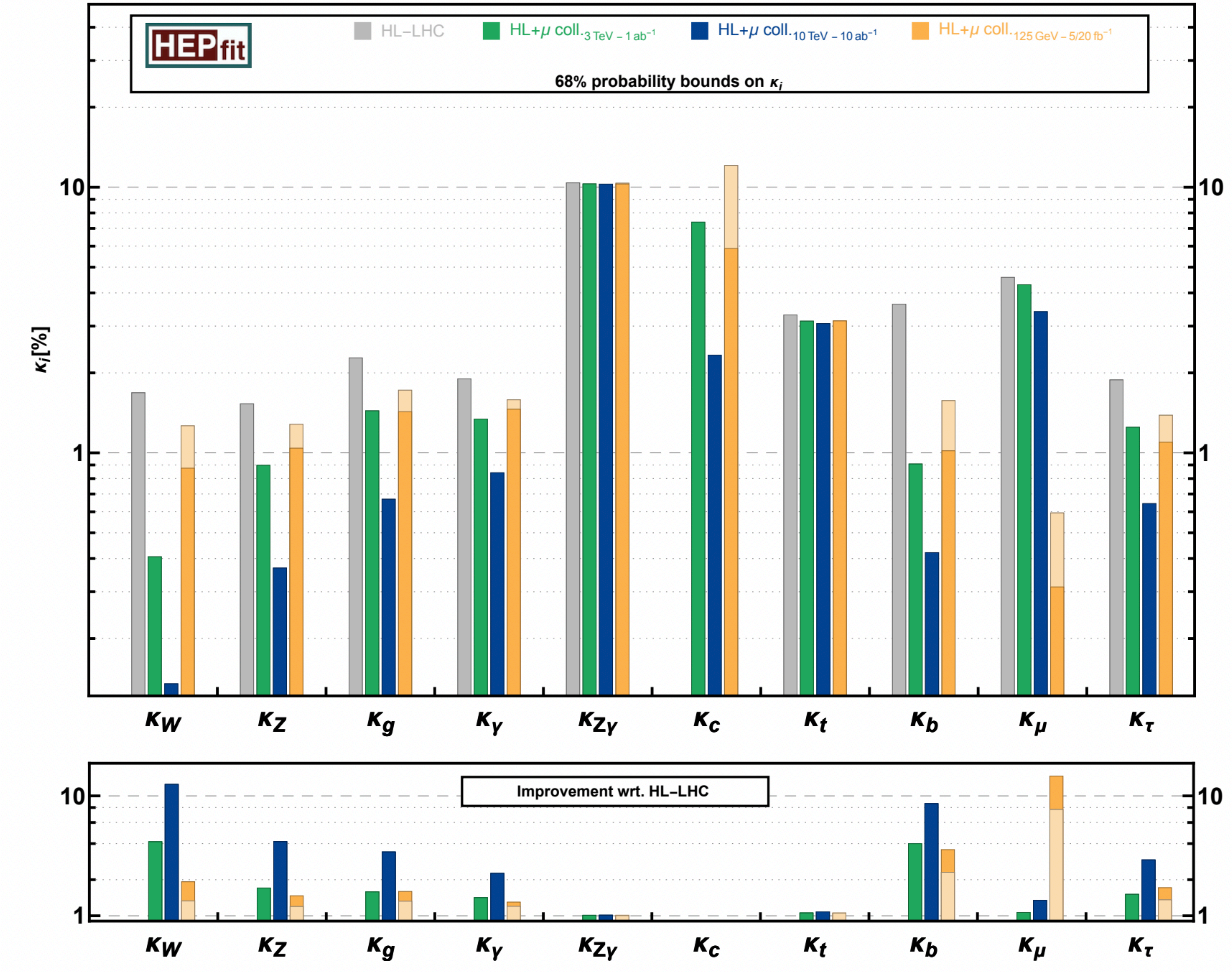


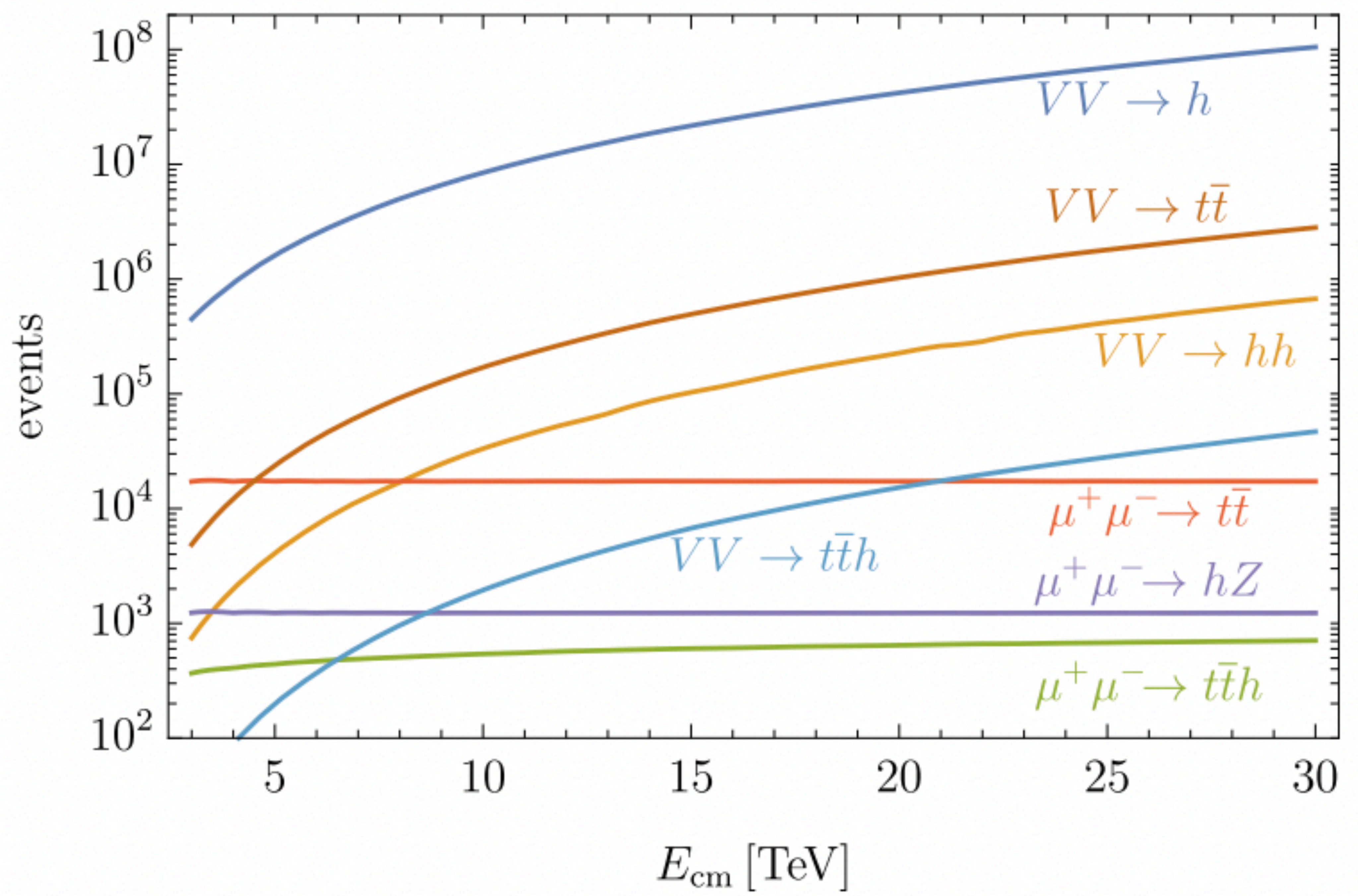


From 500 to 550 GeV a factor two gain
in precision on the Higgs-top coupling

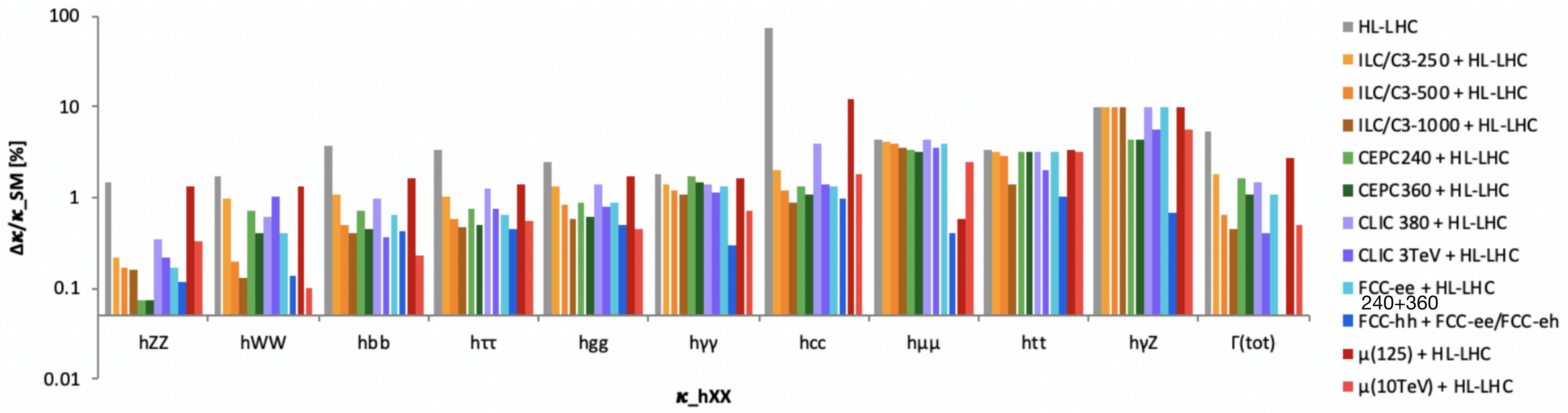
Higgs couplings at the muon collider

arXiv:2203.07261





Higgs couplings at future machines



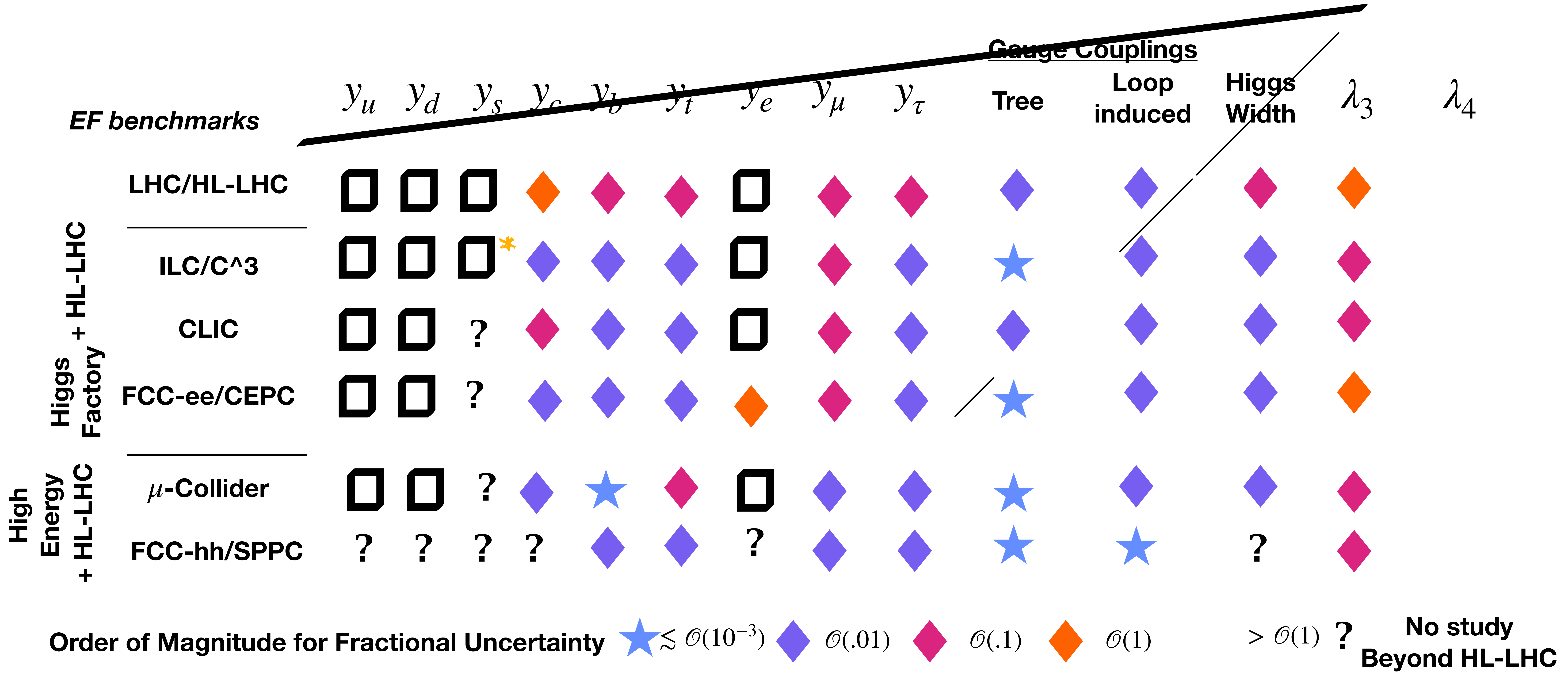
- These results are based on the κ_0 scenario of the ESG (combined with projections for HL-LHC results) and do not allow for BSM decays
- The Zγ interaction remains difficult to measure at all future machines
- Higher energy collision is required (factor 2 from 500 to 550 GeV e+e-) to test the Higgs-top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

The Higgs self-coupling at future colliders

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

Not updated (yet) since the YR, although new projections available based on full Run 2 dataset

Summary plot



How we get to new physics from here?

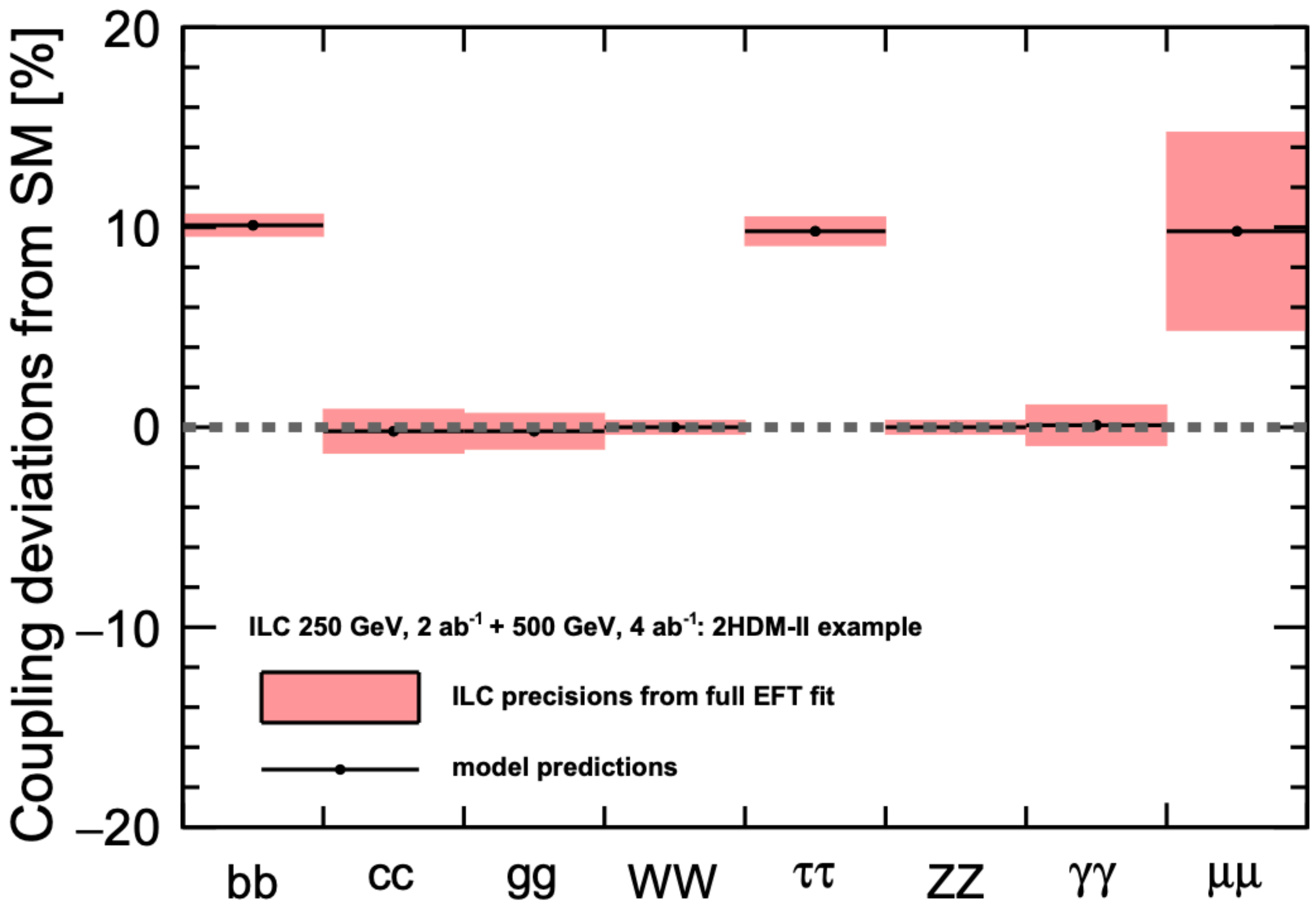
Higgs Inverse problem of how to map from observables to new physics

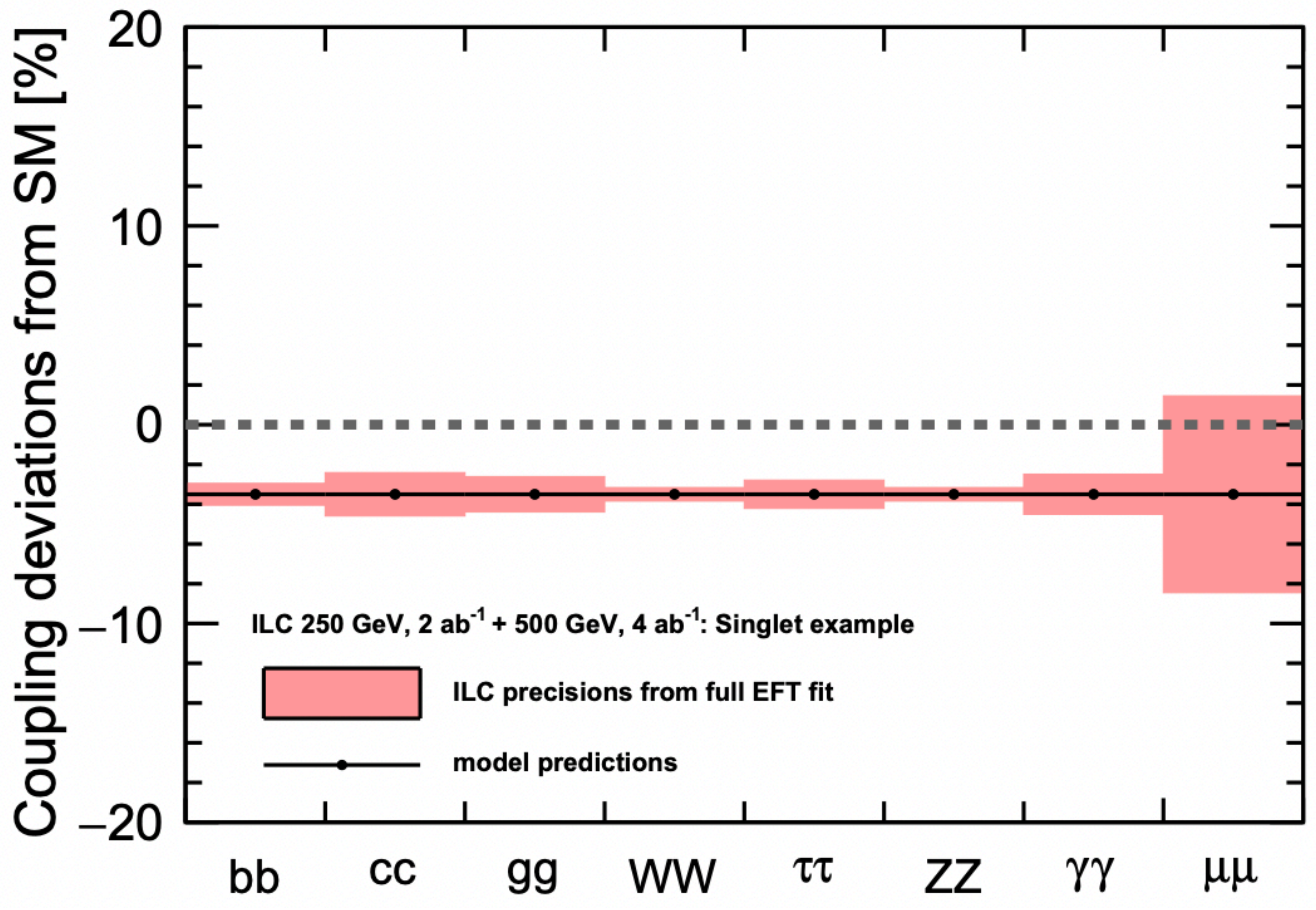
New since the ESG update

- Phenomenology of a **strong electroweak phase transition**
  - It can manifest through shifts in the Higgs cubic coupling, but could still occur without any deviation in this coupling
  - Deviations in all types of observables are also possibly correlated with the phase transition, including exotic Higgs decays
- **Flavored phenomenology**
  - Flavor violating decays
  - Flavor preserving deviations in light quarks Yukawas : studies for direct probes of this at e+e- colliders and related resonance probes from the LHC and other colliders
- **Singlet phenomenology**
  - introduction of scalar resonance decaying to particles with different masses
- Viable models of **triple-Higgs production** at the HL-LHC and beyond
  - Triple Higgs and quad Higgs measurements should be pursued at future colliders.

An example of complementarity

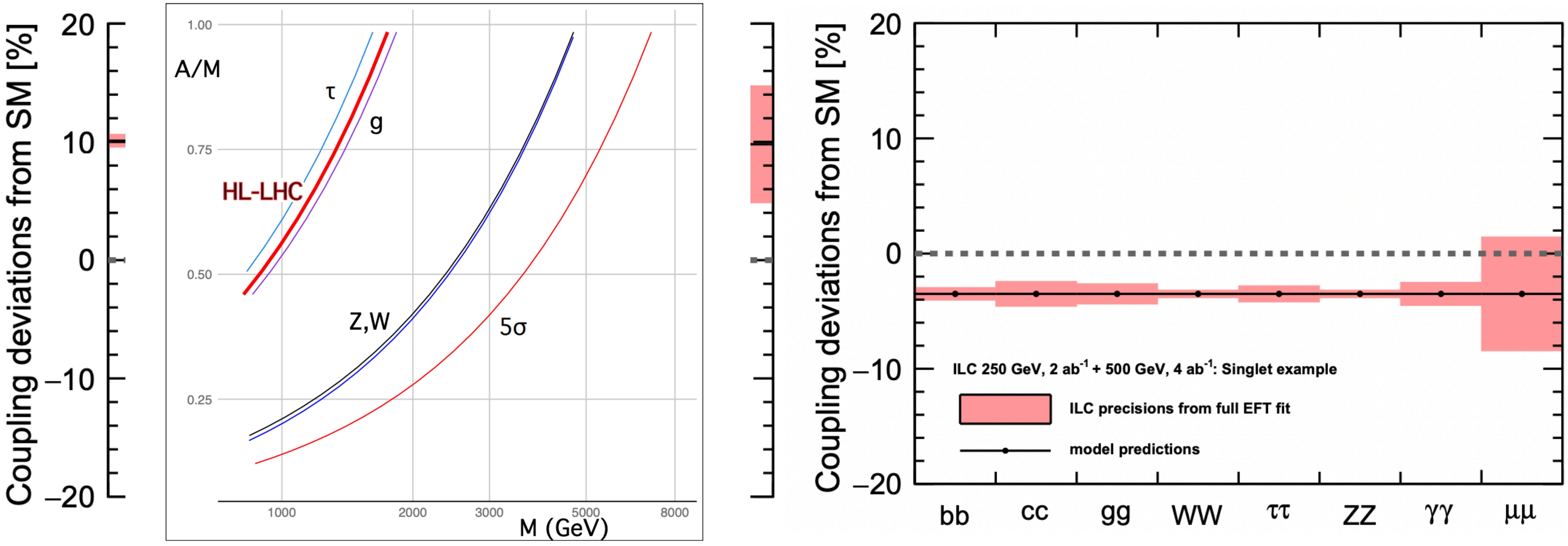
arXiv:2203.07622
arXiv:2209.03303





- Pattern of deviations associated with a particular parameter point in a 2HDM model is quite different from a singlet model
  - 2HDM with a 600 GeV mass scale and asinglet with a 2.8 TeV scalar. Both of these are clearly out of the direct search reach of circular e+e– Higgs factories despite having the precision to test them via Higgs couplings
  - High energy collisions would be then required to study such new particles

An example of complementarity



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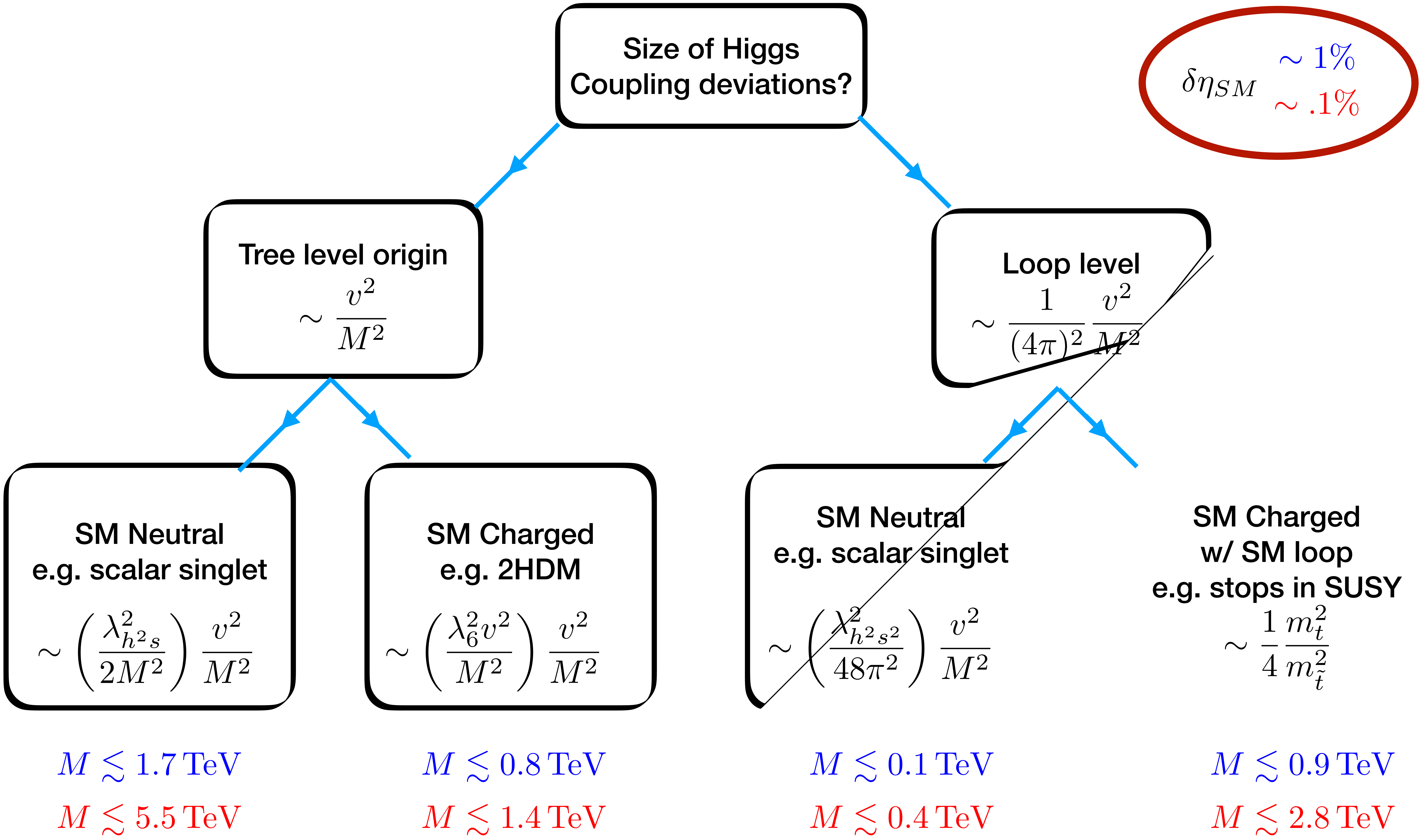
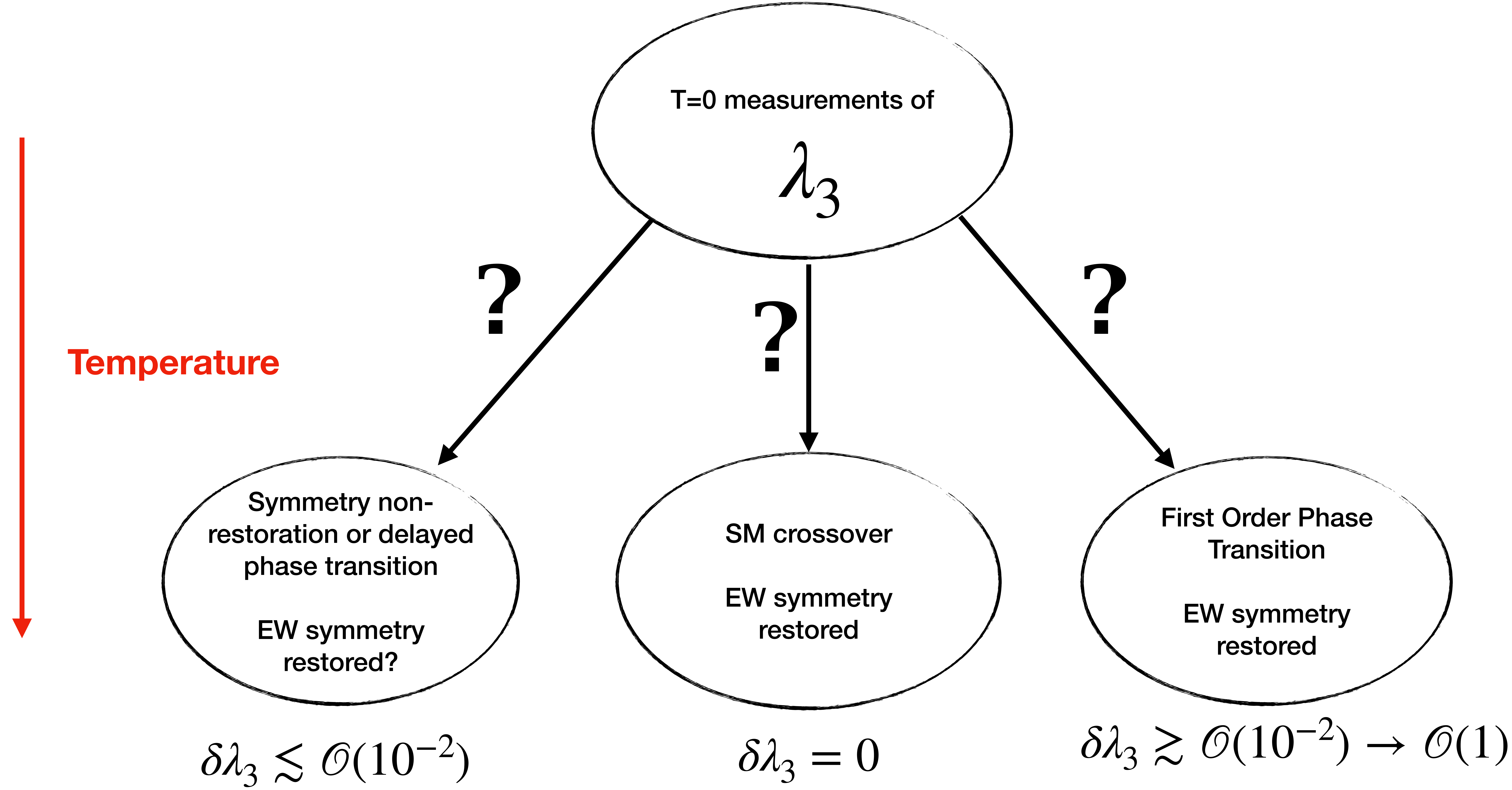


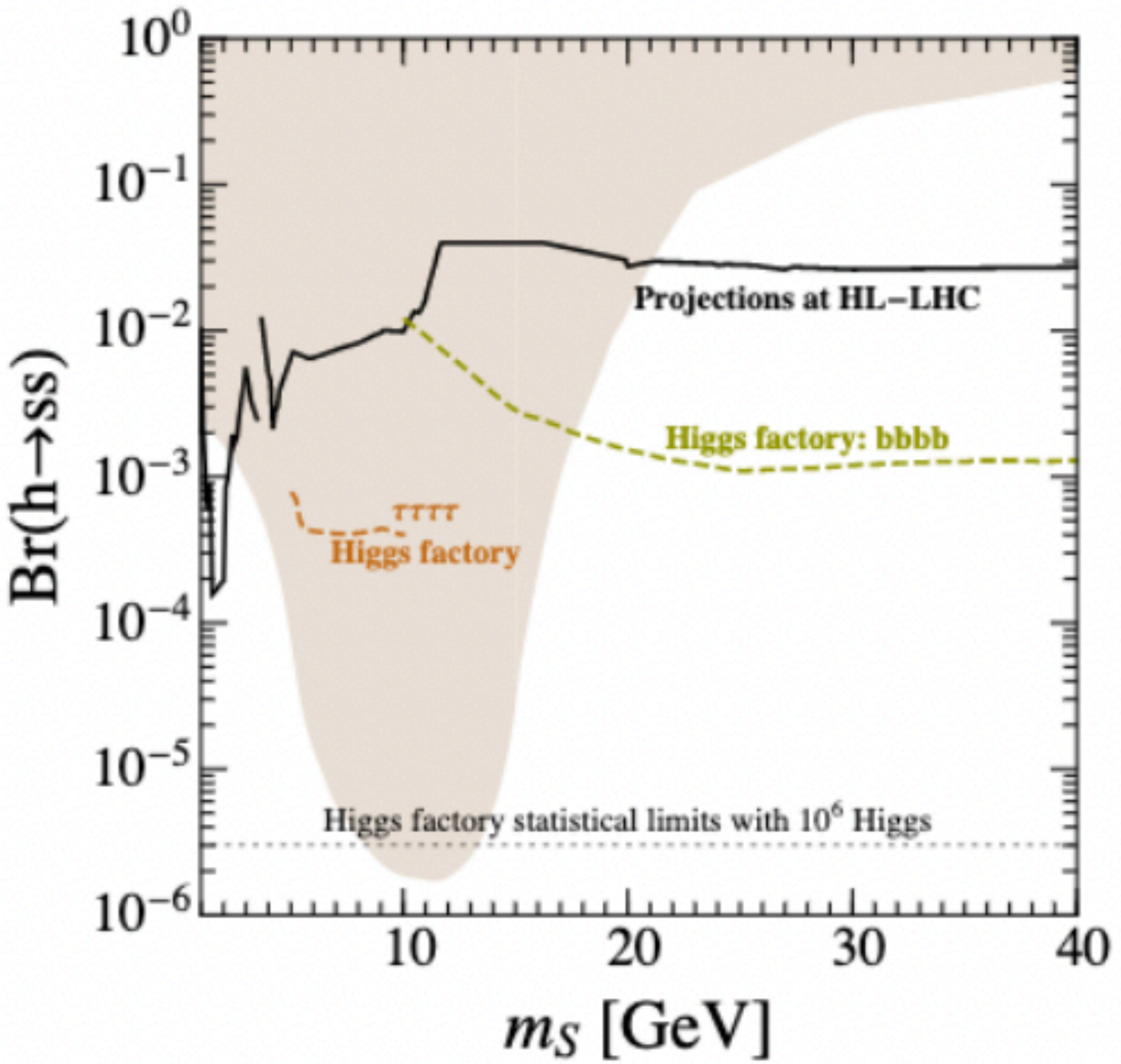
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision


T=0 measurements of
λ_3
?
?
?
Temperature
Symmetry non-restoration or delayed phase transition
EW symmetry restored?
SM crossover
EW symmetry restored
First Order Phase Transition
EW symmetry restored
$\delta\lambda_3 \lesssim \mathcal{O}(10^{-2})$
$\delta\lambda_3 = 0$
$\delta\lambda_3 \gtrsim \mathcal{O}(10^{-2}) \to \mathcal{O}(1)$

Exotic Higgs Decays

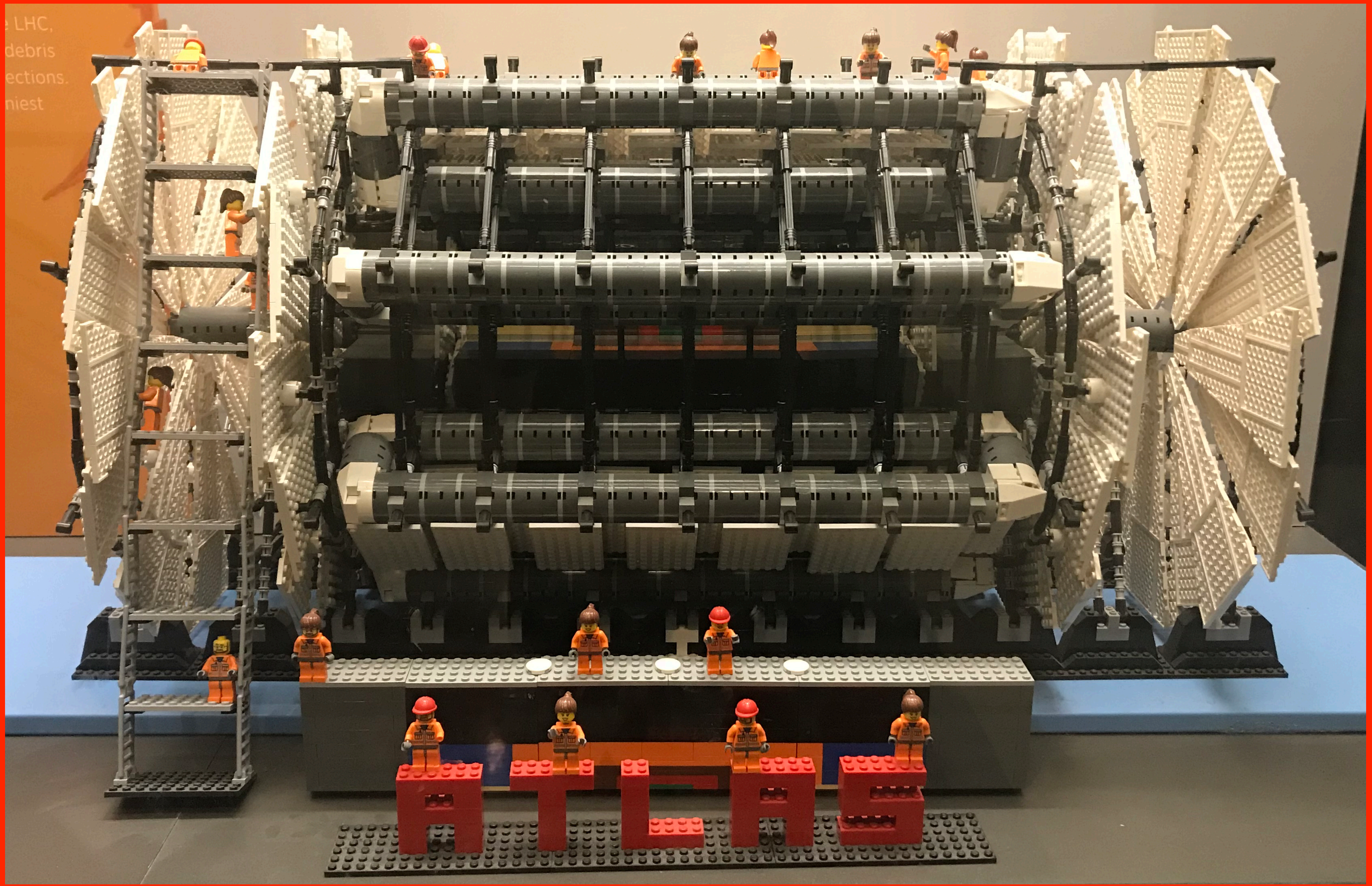
- At low energy, e+e- running near the Zh maximum cross section extra bounds on h→ anything can be derived
  - One order of magnitude improvement over HL-LHC
- Connection to allowed phase transitions as a function of the light scalar mass and the branching ratio h→SS
  - Both the HL-LHC and future Higgs factories can probe the region with an allowed electroweak phase transition.

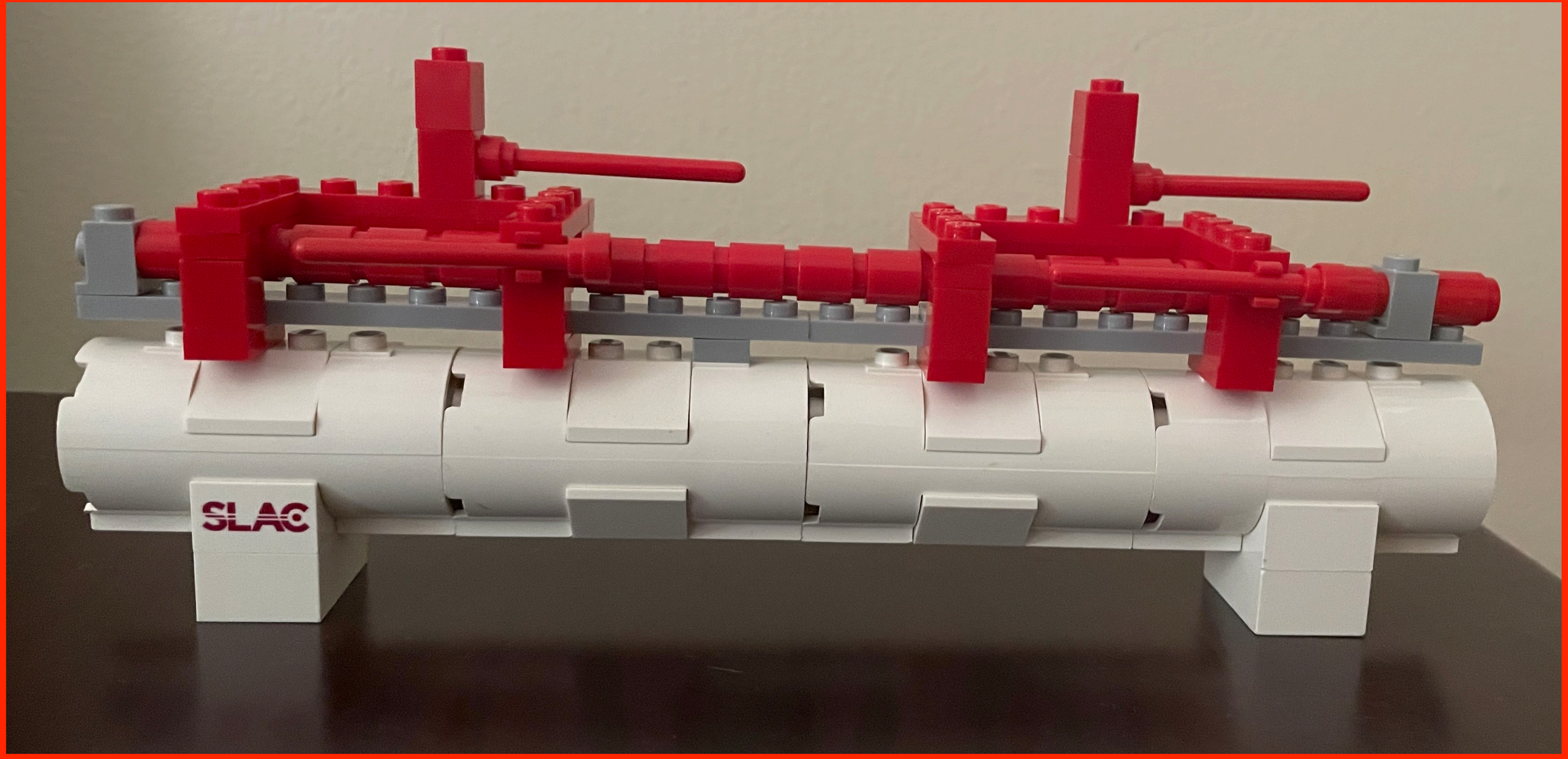
Channel	HL-LHC	ILC	FCC-ee
E_T^{miss}	0.056	.0025	.005
$b\bar{b}b\bar{b}$	0.2	9×10^{-4}	3×10^{-4}
$b\bar{b}E_T^{miss}$	0.2	2×10^{-4}	5×10^{-5}
$jj\gamma\gamma$	0.01	2×10^{-4}	3×10^{-5}



Conclusions

- New reports available Snowmass Report and Snowmass Higgs TG
  - Comments/typos/errors to be addressed with a new version on the arXiv soon
- Updated global fits
  - Included new HL-LHC projections and updated analyses at future colliders
  - Updated list of machines and their parameters (including timelines)
    - New: muon collider, C^3 are recent developments
- They include discussions on how new physics phase maps to (precision) constraints on EFT operators

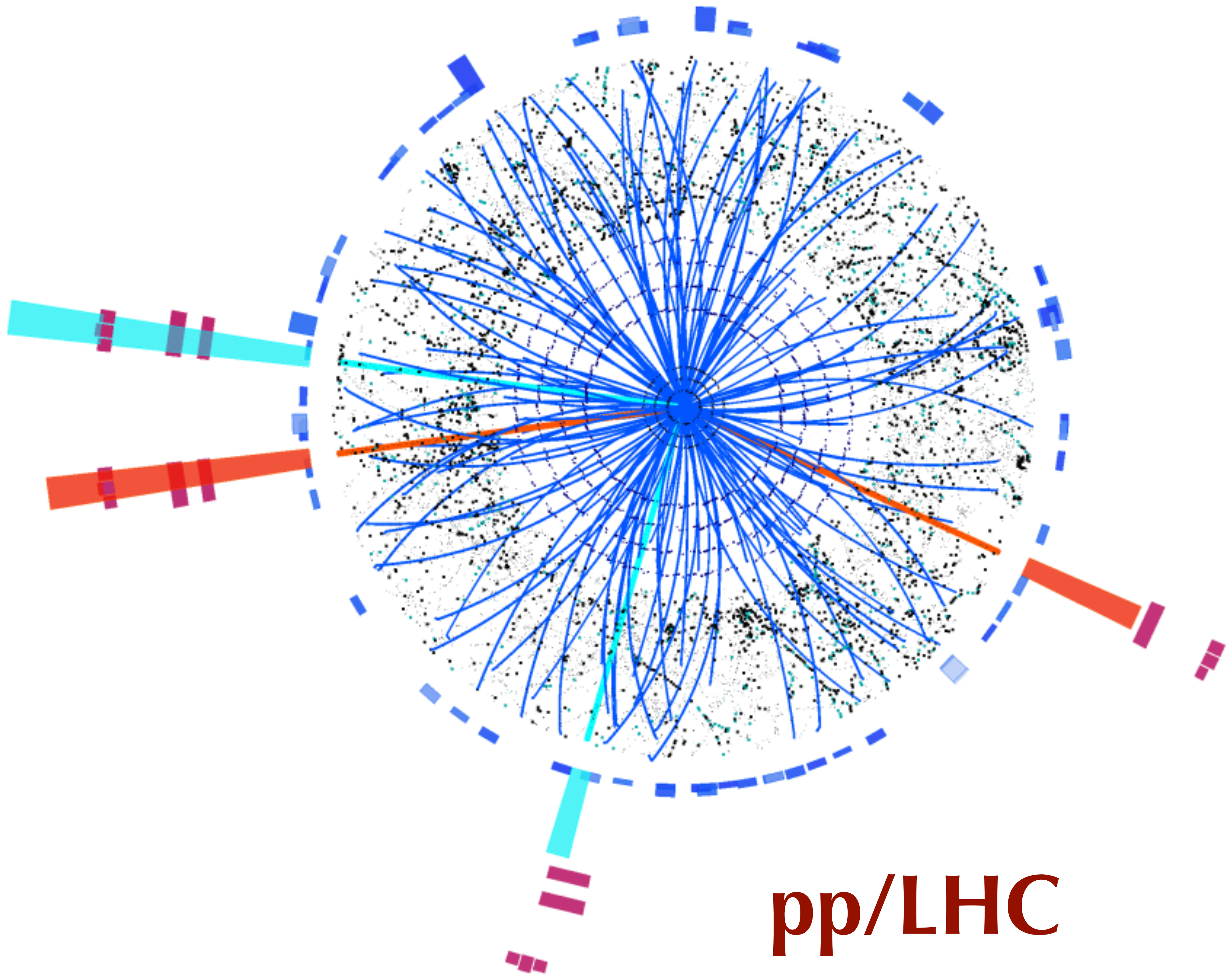




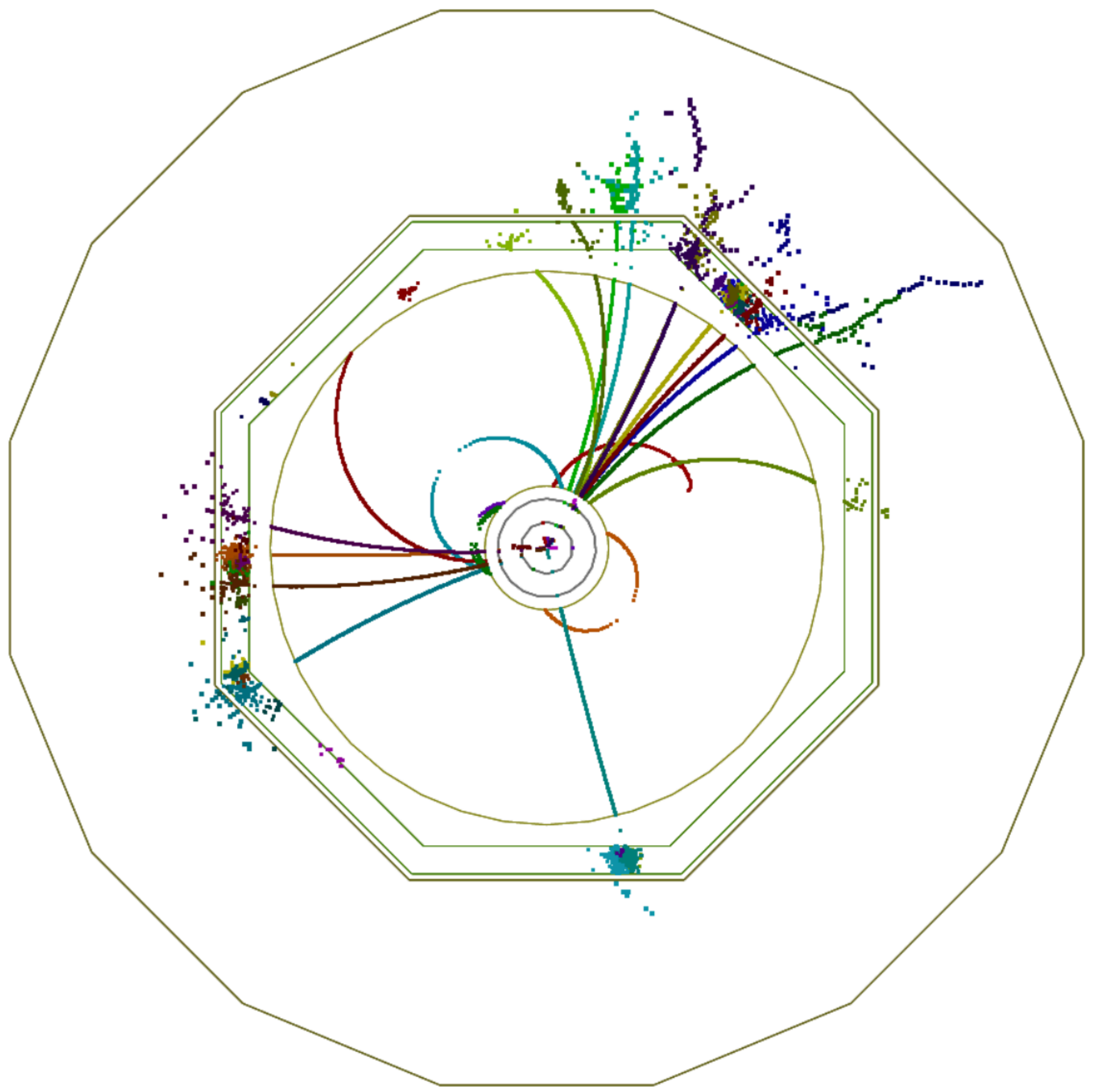
Extra

Why leptons?

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



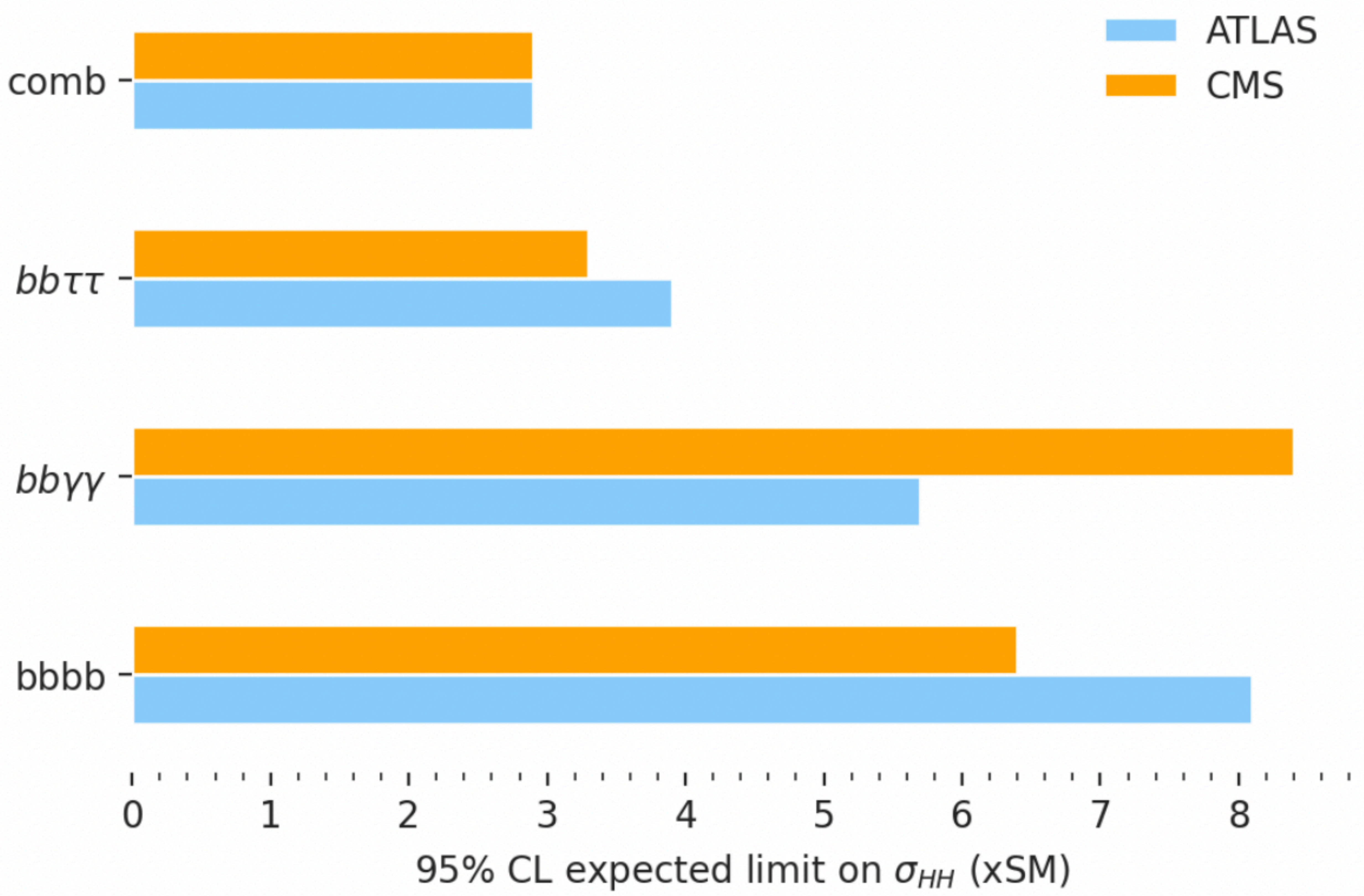
pp/LHC

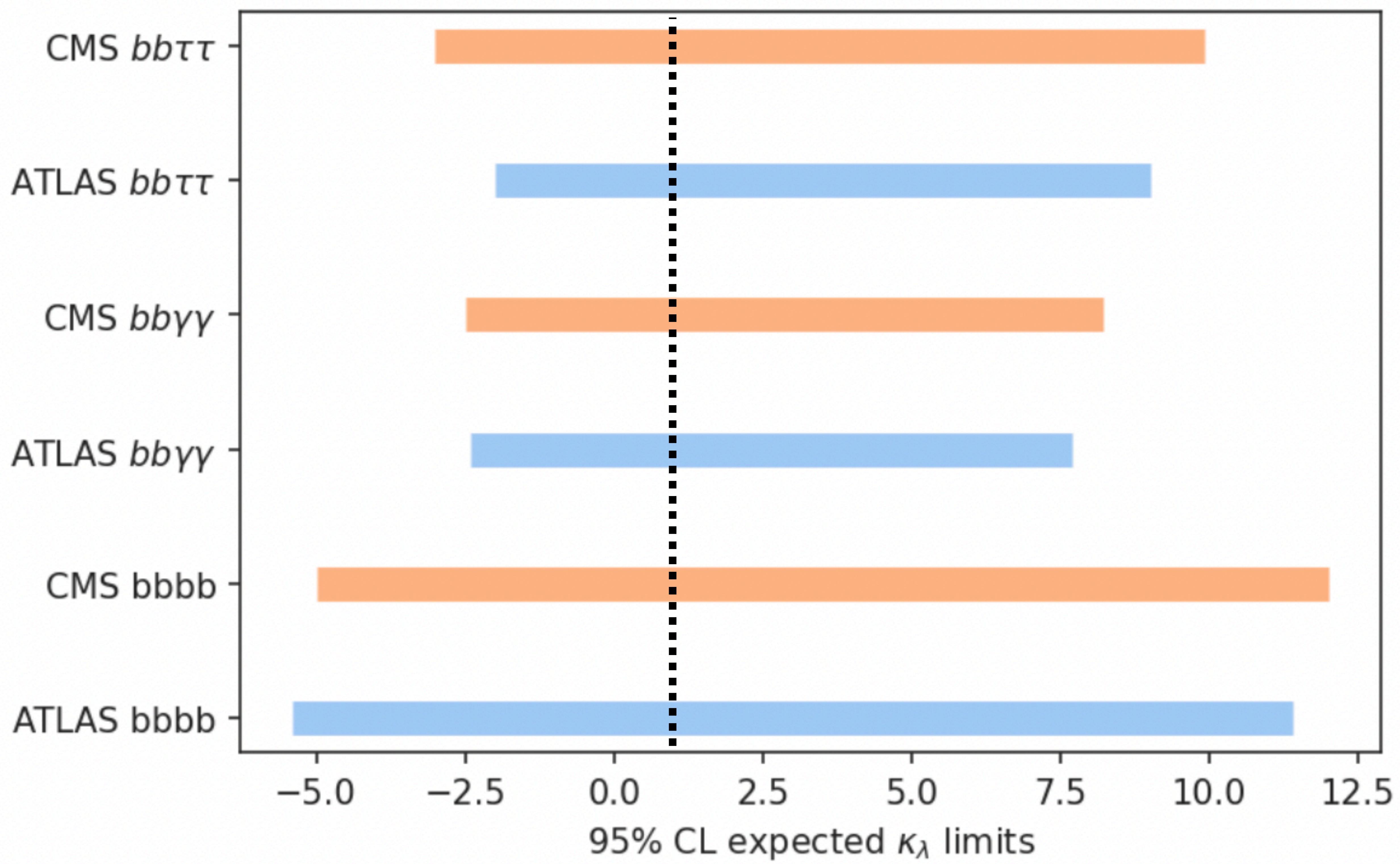


e^+e^-

Self-coupling : HH searches at the LHC

Snowmass Higgs report

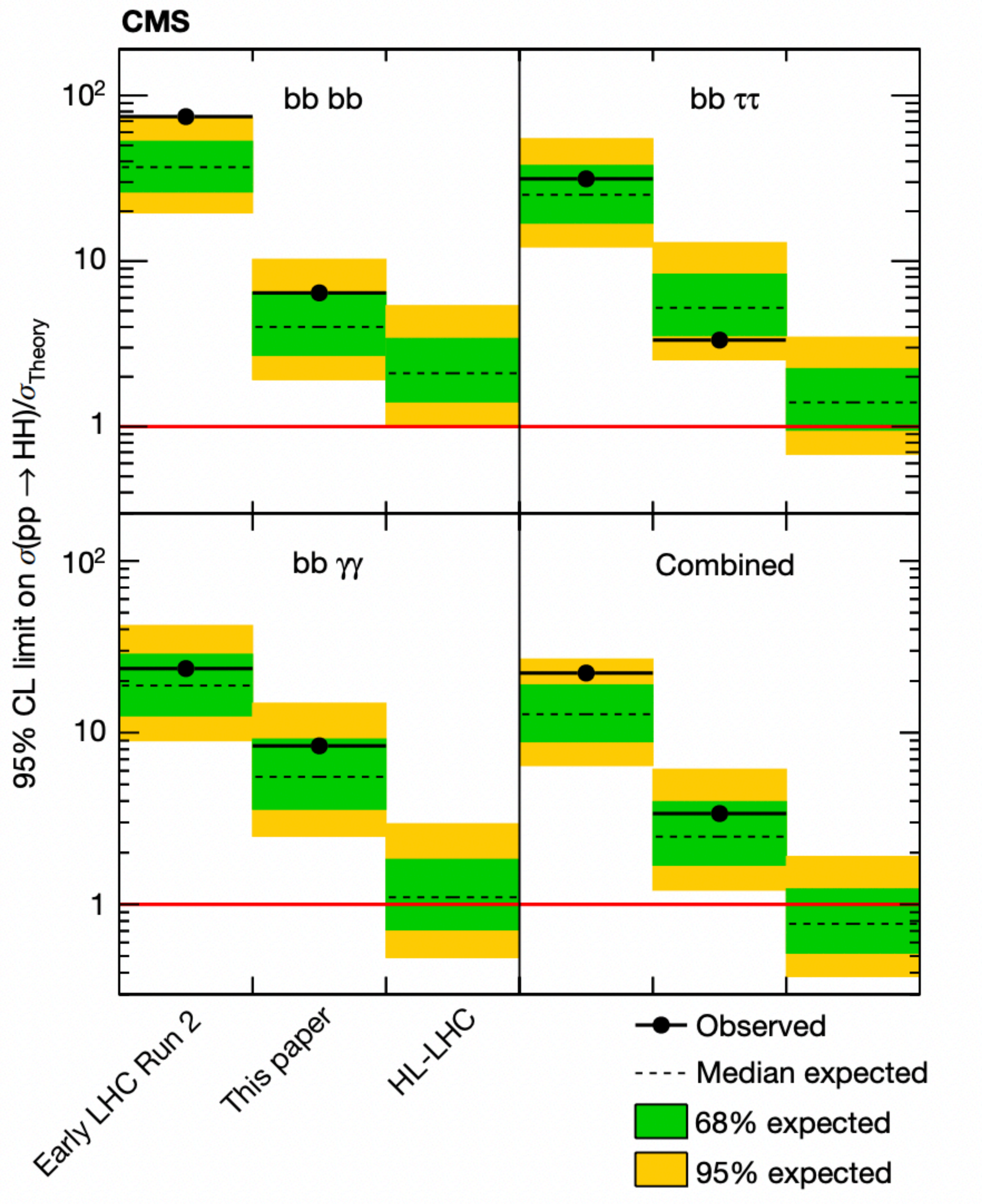


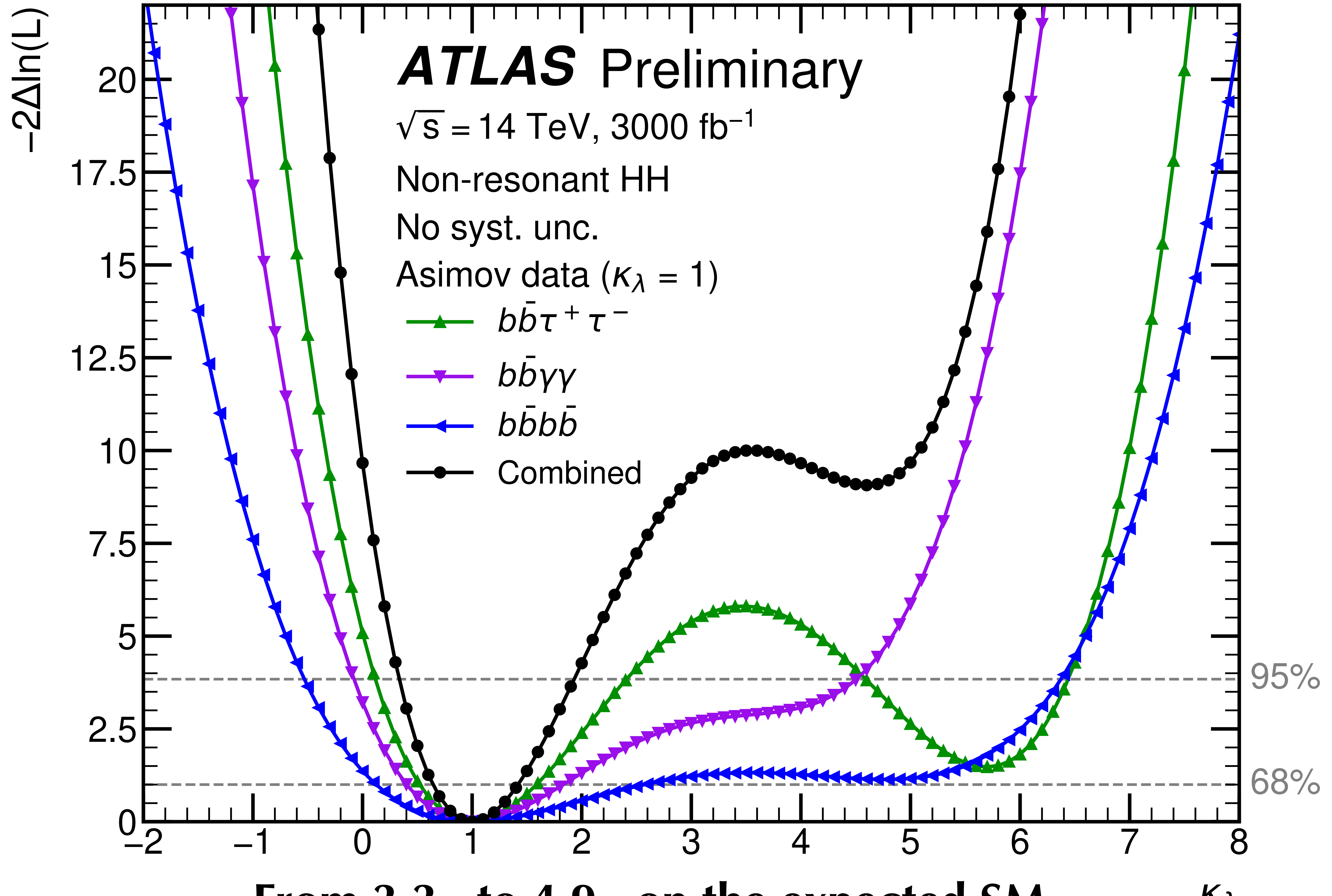


Main channels only based on full Run 2 (126-139/fb) analyses

Higgs physics at the HL-LHC

Extrapolations from Run 2 analyses





From 3.3σ to 4.9σ on the expected SM σ_{HH}

Light Yukawa ?

CP properties

arXiv:2205.07715

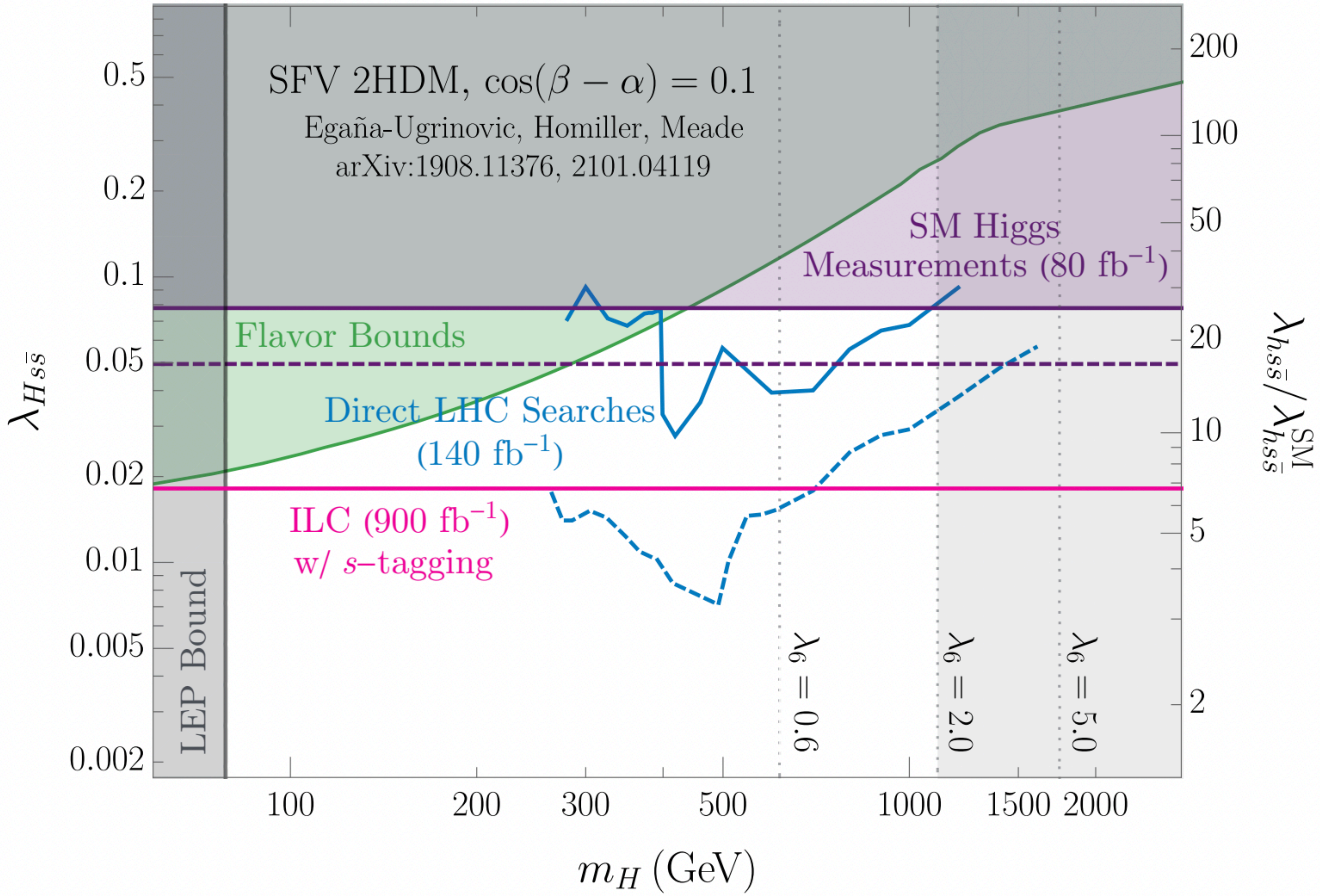
- Most processes could be studied at an e+e- collider with the beam energy above the tth threshold.
- Future e+e- colliders are expected to provide comparable sensitivity to HL-LHC in hff couplings, and potentially higher sensitivity in hZZ couplings.
- The muon collider operating at the Higgs boson pole allows to measure the CP structure of the hμμ vertex with the beam polarization

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	125	125	≥ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000	250	350	500	1,000	250			
HZZ/HWW	$4{\cdot}10^{-5}$	$2.5{\cdot}10^{-6}$	✓	$3.4{\cdot}10^{-4}$	$1.1{\cdot}10^{-4}$	$4{\cdot}10^{-5}$	$8{\cdot}10^{-6}$	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~ 1	✓	–	–	–	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Higgs width

- The measurement of the width is also extremely sensitive to high scale new physics.
- **HL-LHC** can constrain the Higgs boson width indirectly from the $ZZ \rightarrow 4l$ channel $4.1^{+.7}_{-.8}$ MeV ~17% accuracy
  - The indirect measurement is more akin to an absolute coupling normalization and can be viewed as part of the larger ``Higgs without Higgs" framework.
- The full **FCC-ee** program (combined with HL-LHC) allows for a 1% measurement of the Higgs width.
- Using a SMEFT fit, the **ILC** finds similar results for the full program, but with just the initial 250 GeV run, a 2% measurement on the total width can be obtained.
- A muon collider running at 125 GeV can obtain a model independent measurement of the Higgs total width 2.7% with 5/fb by using a line-shape measurement
  - A high energy muon collider should obtain a similar order of magnitude precision using the indirect methods employed at the LHC with the same theoretical assumptions, and the FCC-hh could in principle also use these methods with further study.

Flavor violating 2HDM



A spontaneous flavour violating (SFV) 2HDM allows for large couplings of additional Higgs to strange/light quarks while suppressing flavor-changing neutral currents


Exotic Decays
Self coupling measurements
Multi-Higgs resonances
Higgs signal strengths
Higgs Mass
Higgs Width
BSM particle searches
Electric Dipole Moments
Differential Cross Sections
Origin of Flavor?
Higgs Portal to Hidden Sectors?
Thermal History of Universe
Naturalness
Stability of Universe
Origin of EWSB?
CPV and Baryogenesis

One note on polarization

arXiv:1708.08912
arXiv:1801.02840

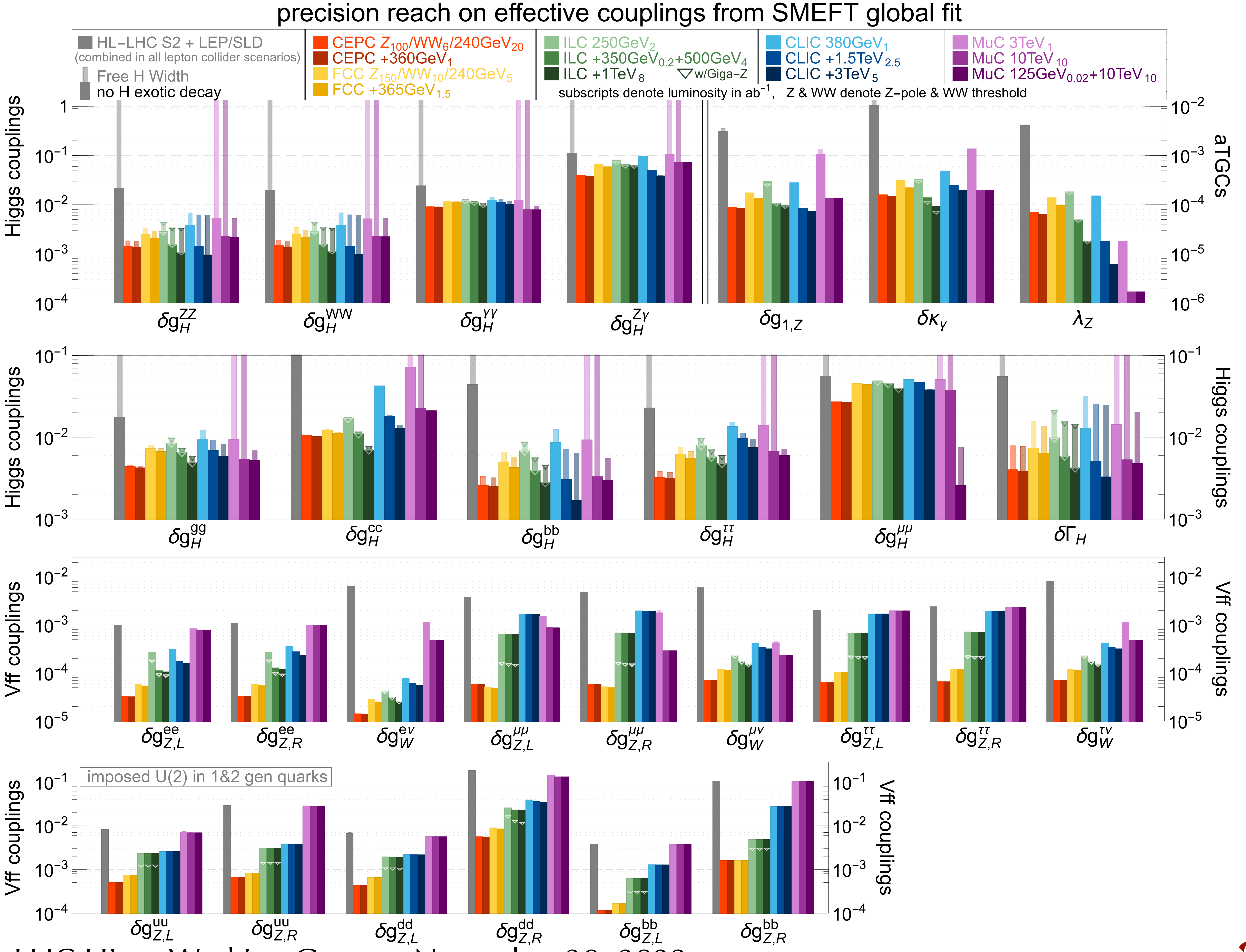
SLAC

- There are extensive comparisons between the FCC-ee plan and the C3/ILC runs that show they are rather **compatible to study the Higgs Boson**
- When analyzing Higgs couplings with SMEFT, 2 ab^{-1} of polarized running is essentially equivalent to 5 ab^{-1} of unpolarized running.
    - **Electron polarization is essential** for this
    - There is almost no difference in the expectation with and without **positron polarization**.
        - more cross-checks of systematic errors.
        - relevant at high energy (> TeV) where the most important cross sections are initiated from $e^-_L e^+_R$

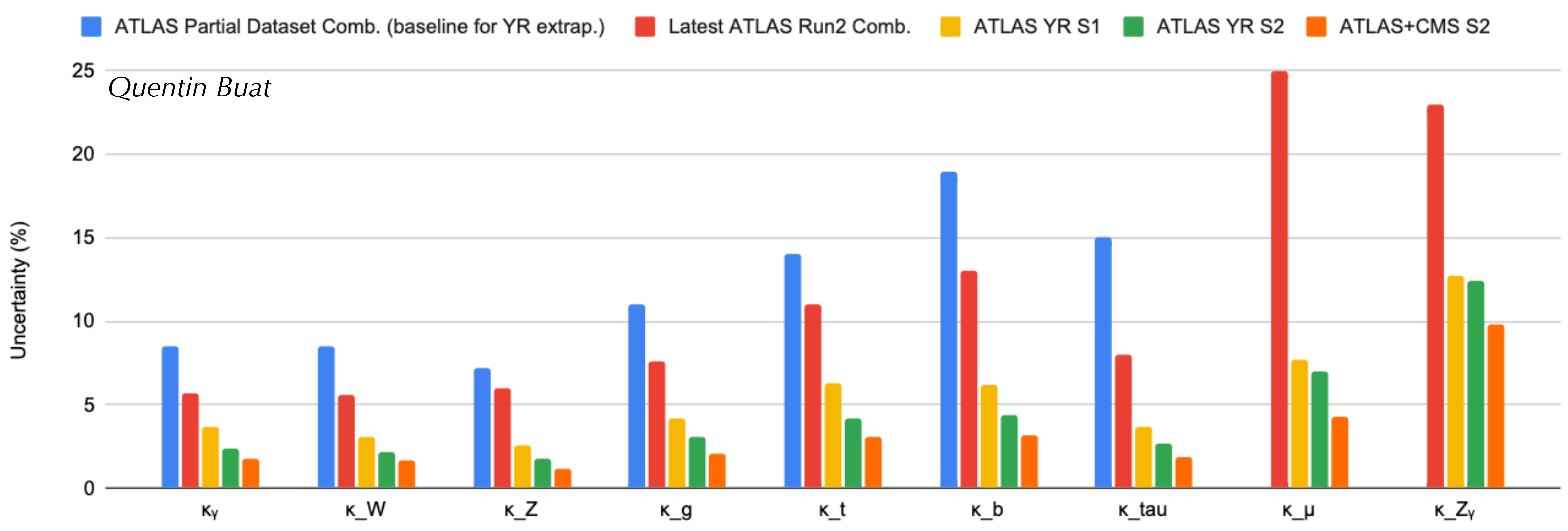
coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7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

Global fit results - from EF04

- Solid has no exotic Higgs decays, the light fits the width



New from HL-LHC



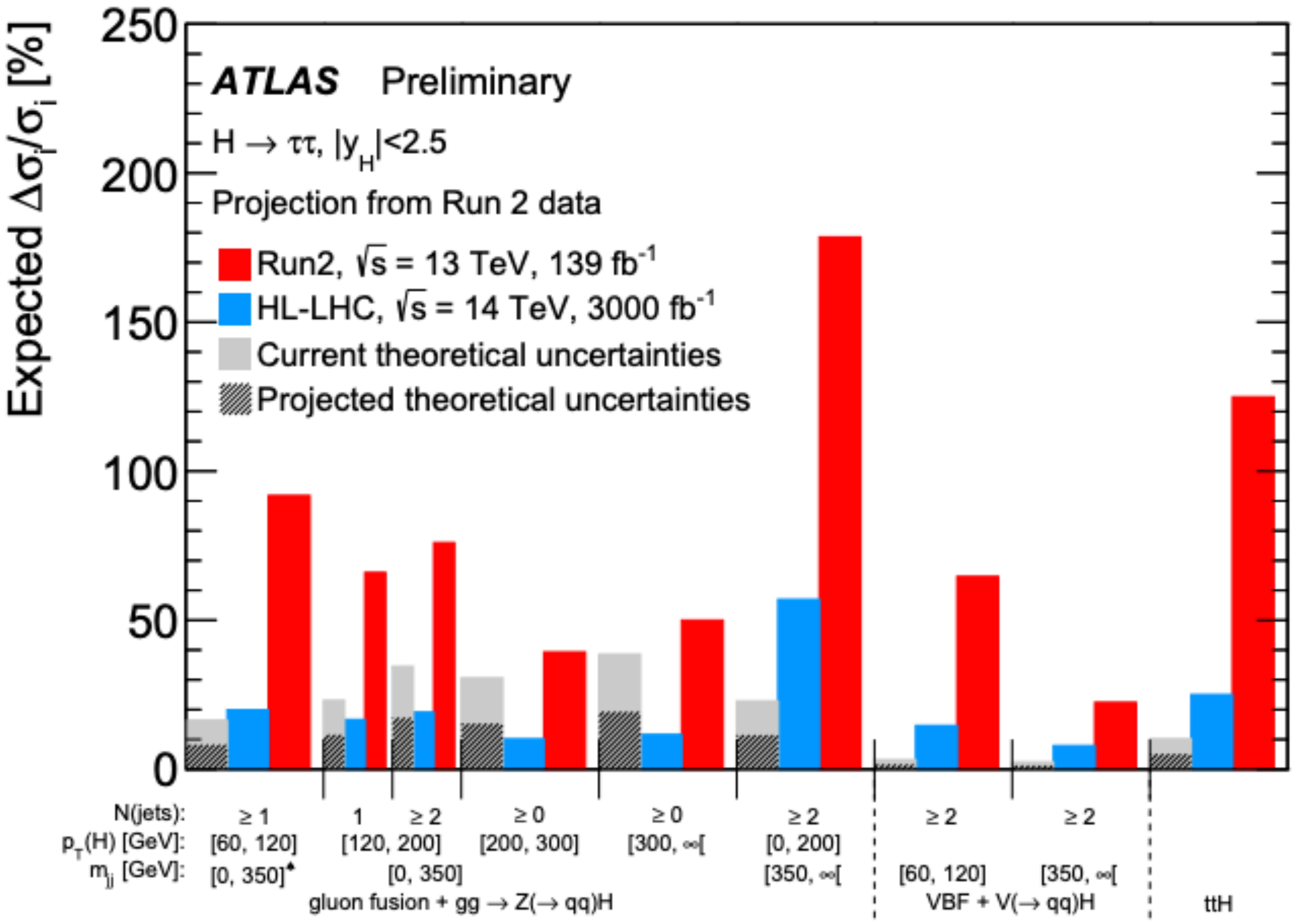
YR projections based on analyses of partial Run 2 dataset

Full Run 2 measurements have drastically improved previous results

We need to update our HL-LHC projections

Higgs production at large p_T

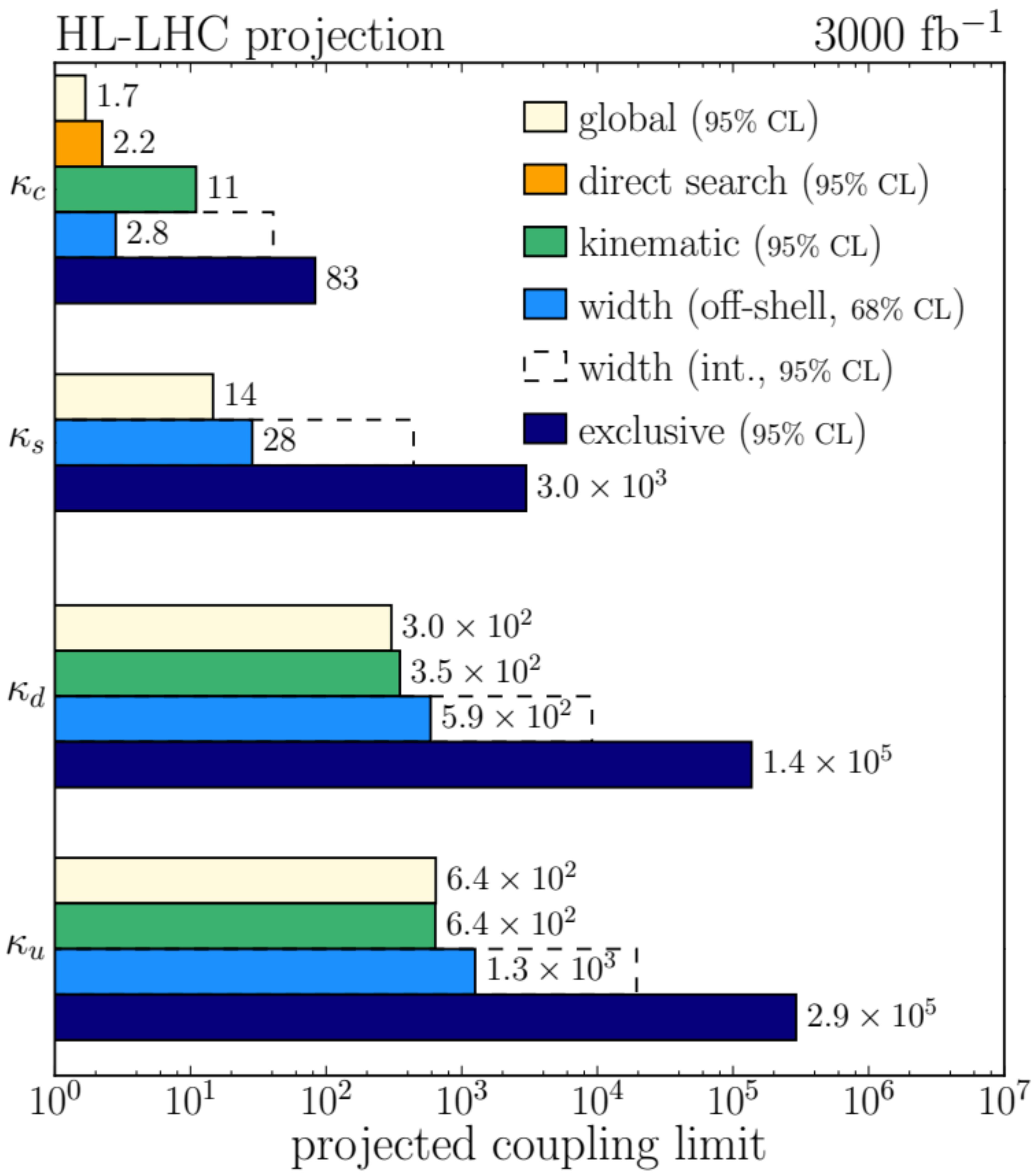
ATLAS+CMS HL-LHC 2022 study



Prospects for light quark couplings at HL-LHC

CERN-LPCC-2018-04

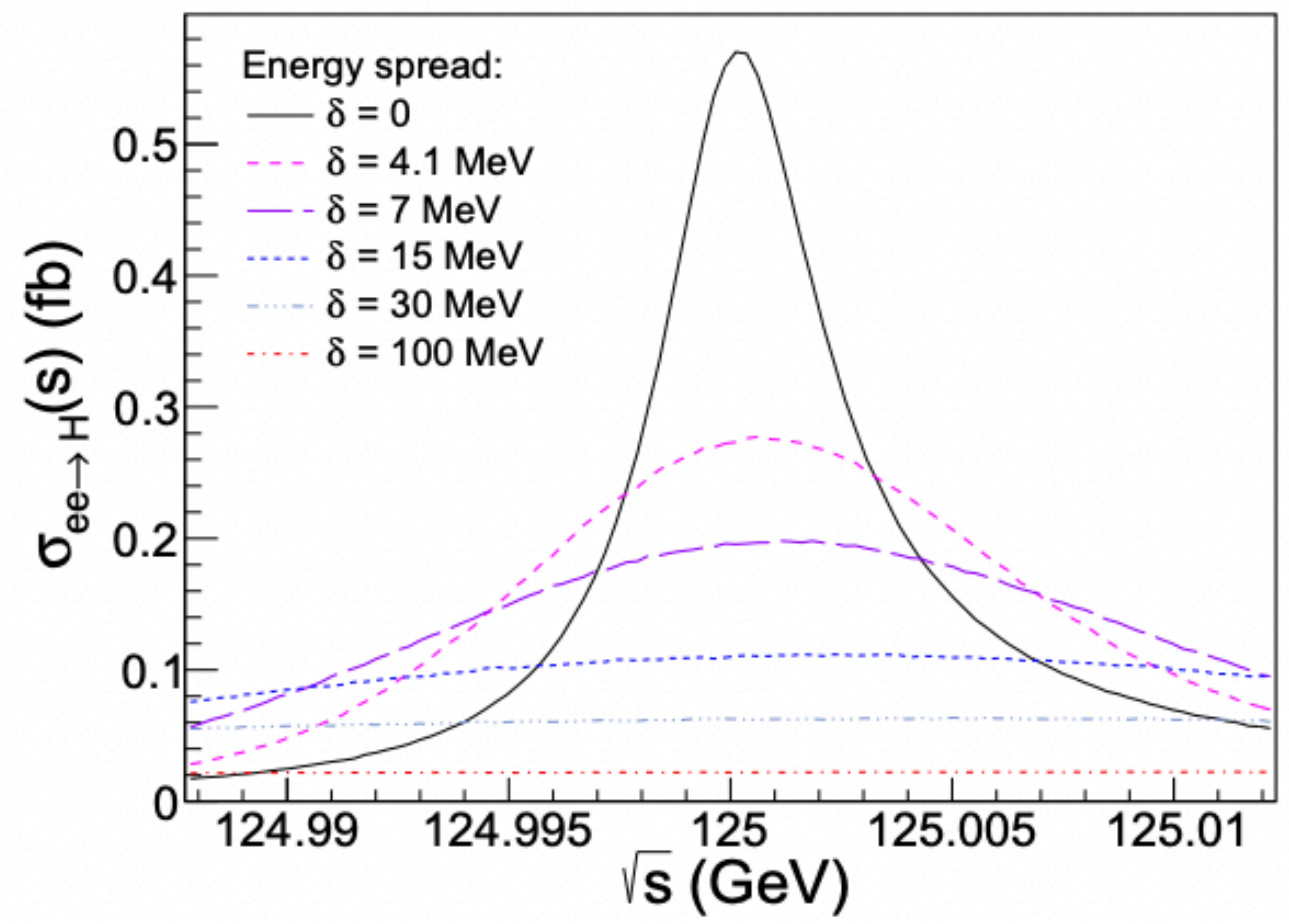
- Exclusive decays to γ+meson include contributions from light quark Yukawa couplings
- Interpretation of Higgs width constraint: direct measurement and via off-shell
- Interpretation of kinematic distributions
- Direct search for H→cc
- Global fit of all Higgs couplings (assuming no other BSM decays)

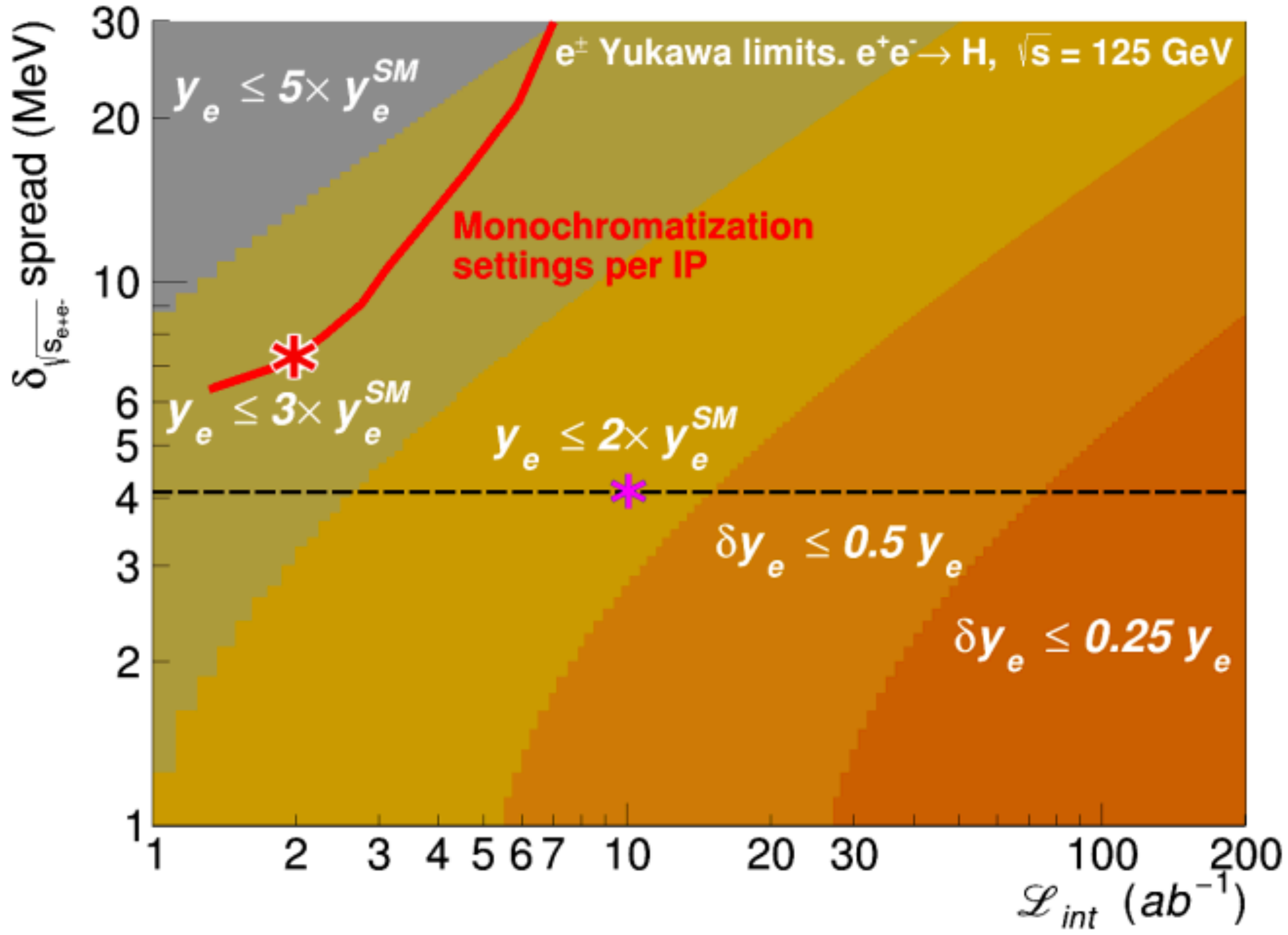


Higgs-electron Yukawa

arxiv:2107.02686

- **Electron** Yukawa at FCC-ee with a dedicated 4 years run at the Higgs mass
  - $\kappa_e < 1.6$ at 95% CL





Extended Higgs sector

arXiv:2203.07261