Characterizing the Higgs boson

- present and future

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ICFA Meeting 2023

DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

The Higgs boson as a key particle

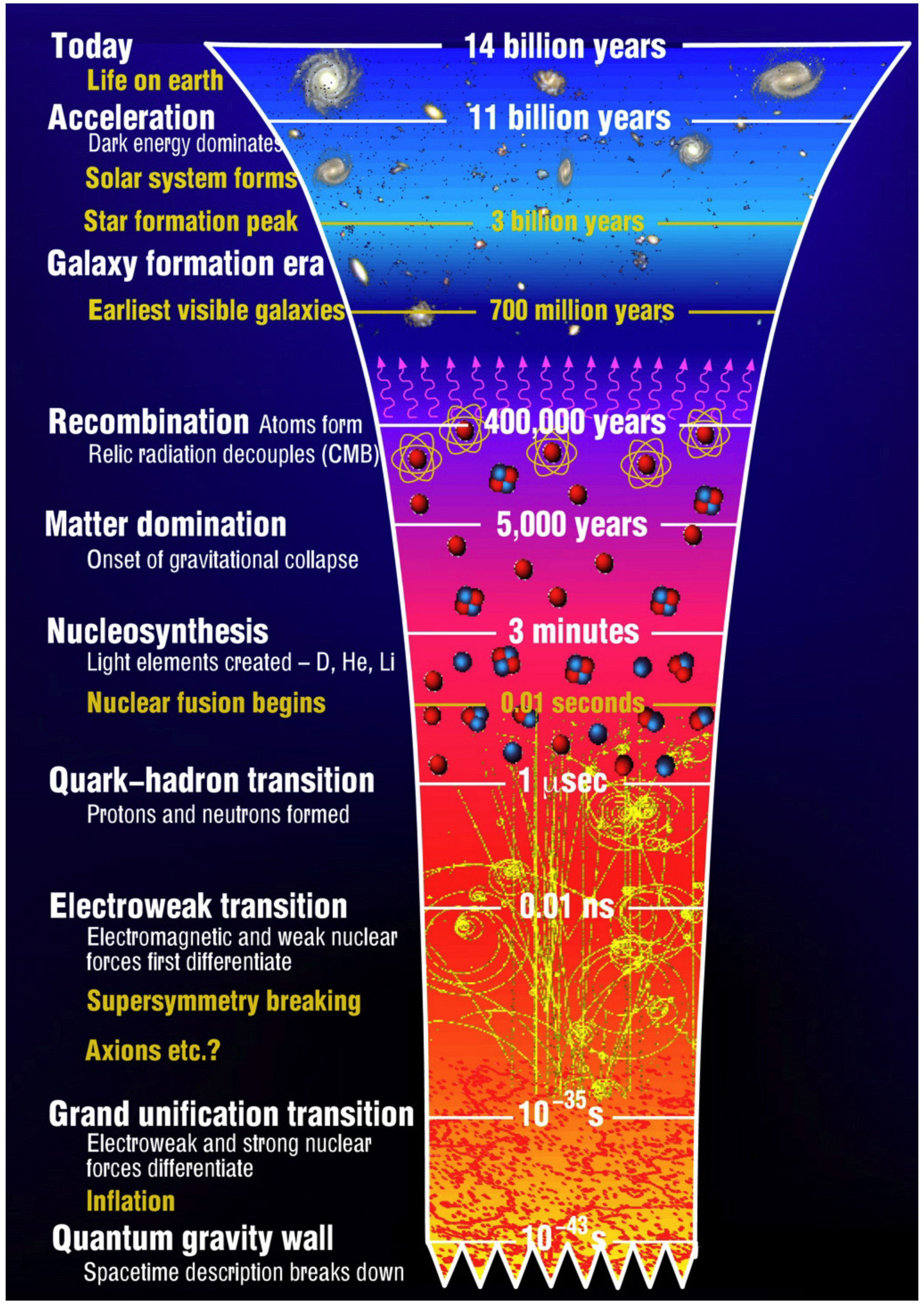
The Higgs boson/Higgs field

- only fundamental scalar we know
- non-zero vacuum expectation value
  - affects the structure of the vacuum
- plays an important role in the evolution of the universe
  - crucial role in electroweak symmetry breaking

Connected to our big questions

- matter-antimatter asymmetry
- dark matter density
- hierarchy problem

…and we only have started to explore its properties!



Possible future Higgs factories

Abbreviation	$\mathscr{L}$ [ab^{-1}]
HL-LHC	6.0
HE-LHC	15.0
FCC-hh	30.0
	150
	10
FCC-ee$_{240}$	5
FCC-ee$_{365}$	1.5
ILC$_{250}$	2.0
ILC$_{350}$	0.2
ILC$_{500}$	4.0
CEPC	16
	2.6
	5.6
CLIC$_{380}$	1.0
CLIC$_{1500}$	2.5
CLIC$_{3000}$	5.0

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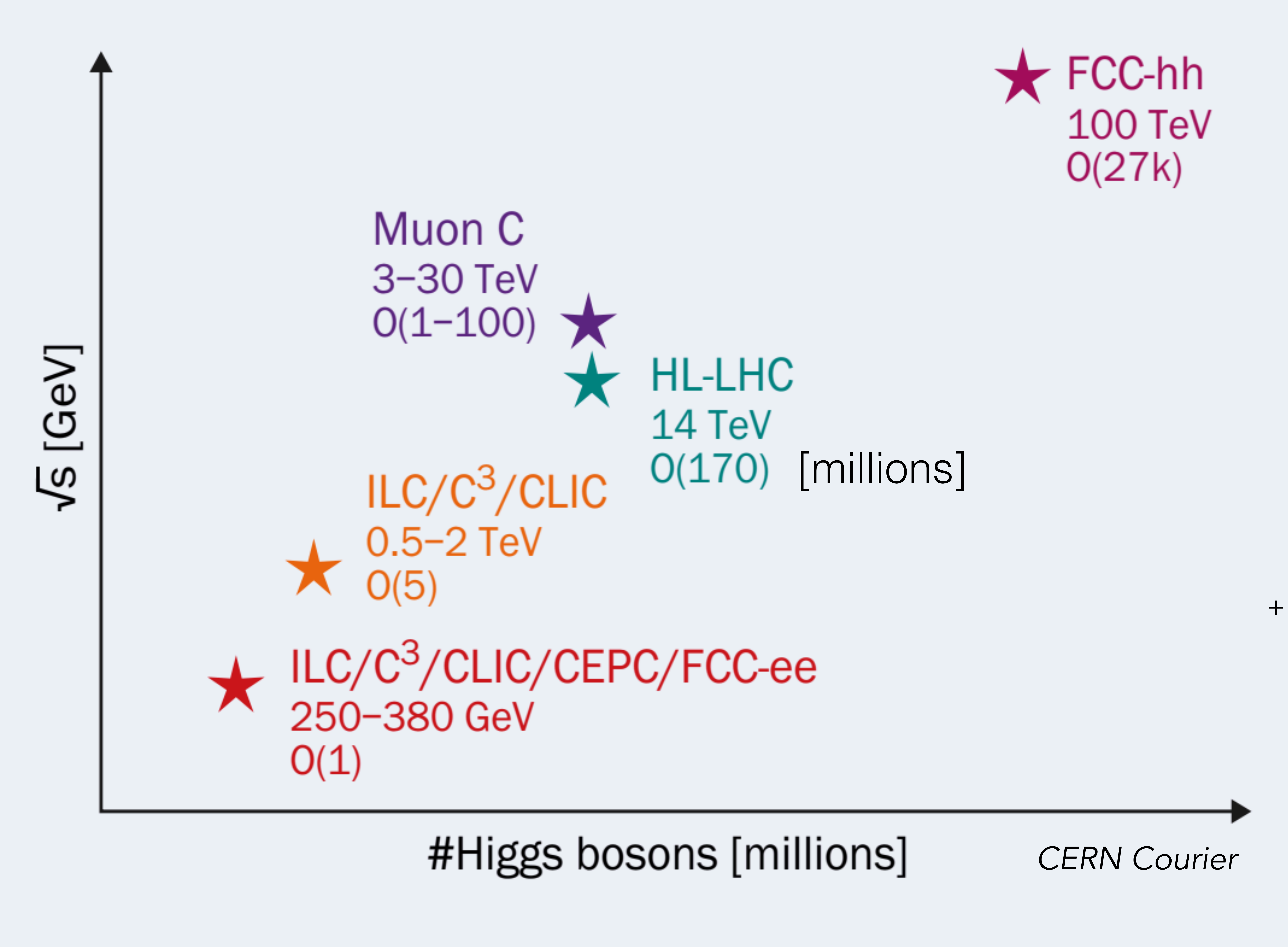
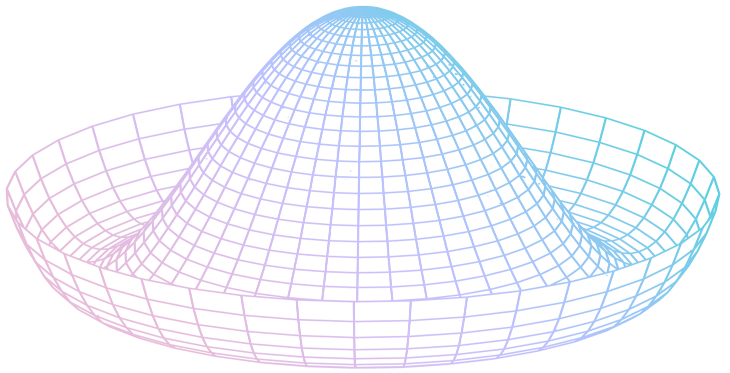


- improvements in analysis technologies
  - particle identification
  - event classification

Higgs boson properties

Mass and width

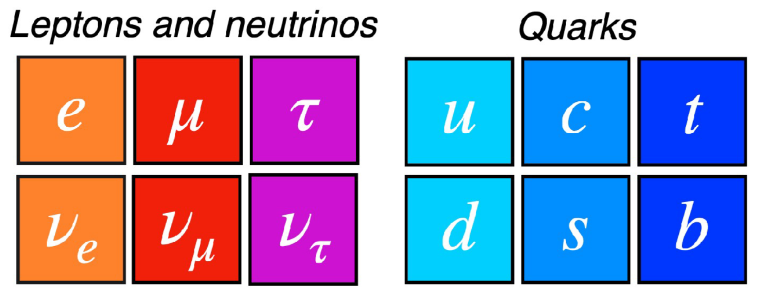
=> related to vacuum stability, exotic decays



Production and decays

=> couplings strengths

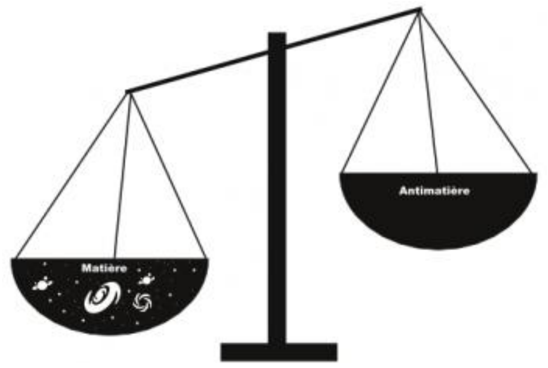
=> Higgs mechanism also for lighter fermions?



H

spin/CP properties of Higgs boson interactions

=> related to matter-antimatter asymmetry in the universe



See next talk!
Also for Higgs self-coupling

=> Is it really the Higgs boson of the Standard Model or something else?

Higgs boson properties in the Standard Model

Mass and width

=> related to vacuum stability, exotic decays

Production and decays

=> couplings strengths

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prop. to boson mass^2
prop. to fermion mass

H

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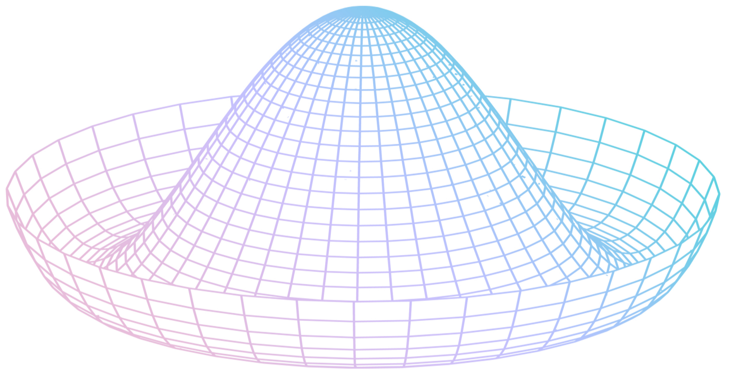

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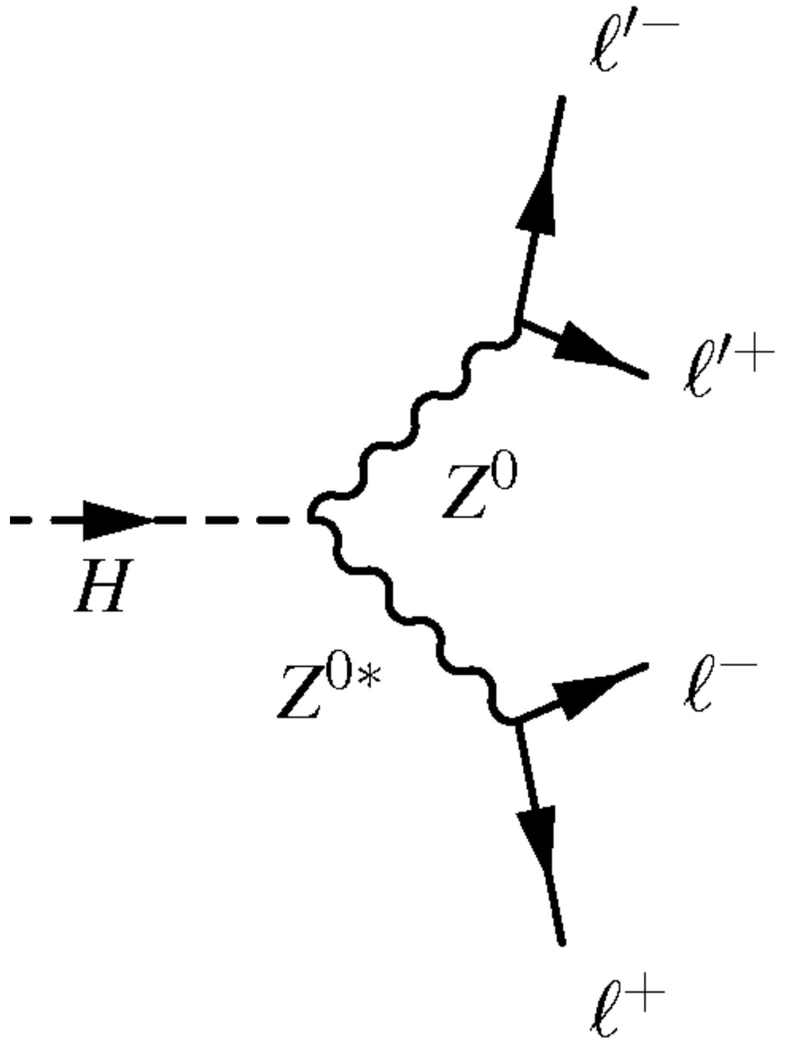
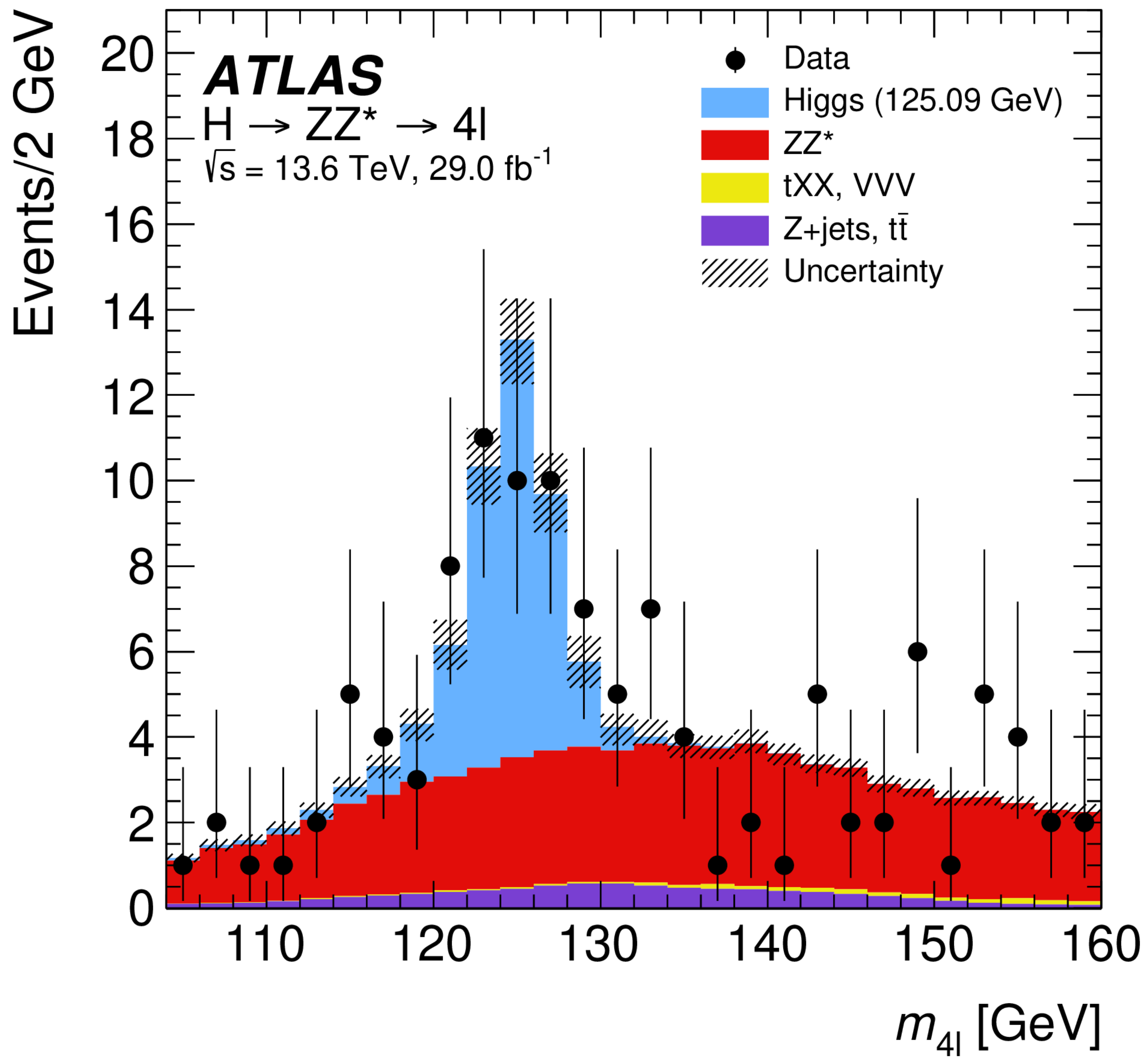
Higgs boson mass

- NOT predicted by the SM
- measured in the channels with the most precise peaks: $\gamma\gamma$ and 4l
  - biggest challenge: precise lepton and photon calibration
  - procedure: functional or MC template fit to peak





Current best result

ATLAS Run-2 combination: *2308.04775, acc. by PRL*

m_H = 125.11 ± 0.09 (stat.) ± 0.06 (syst.) GeV

= 125.11 ± 0.11 GeV

<1 permille accuracy!

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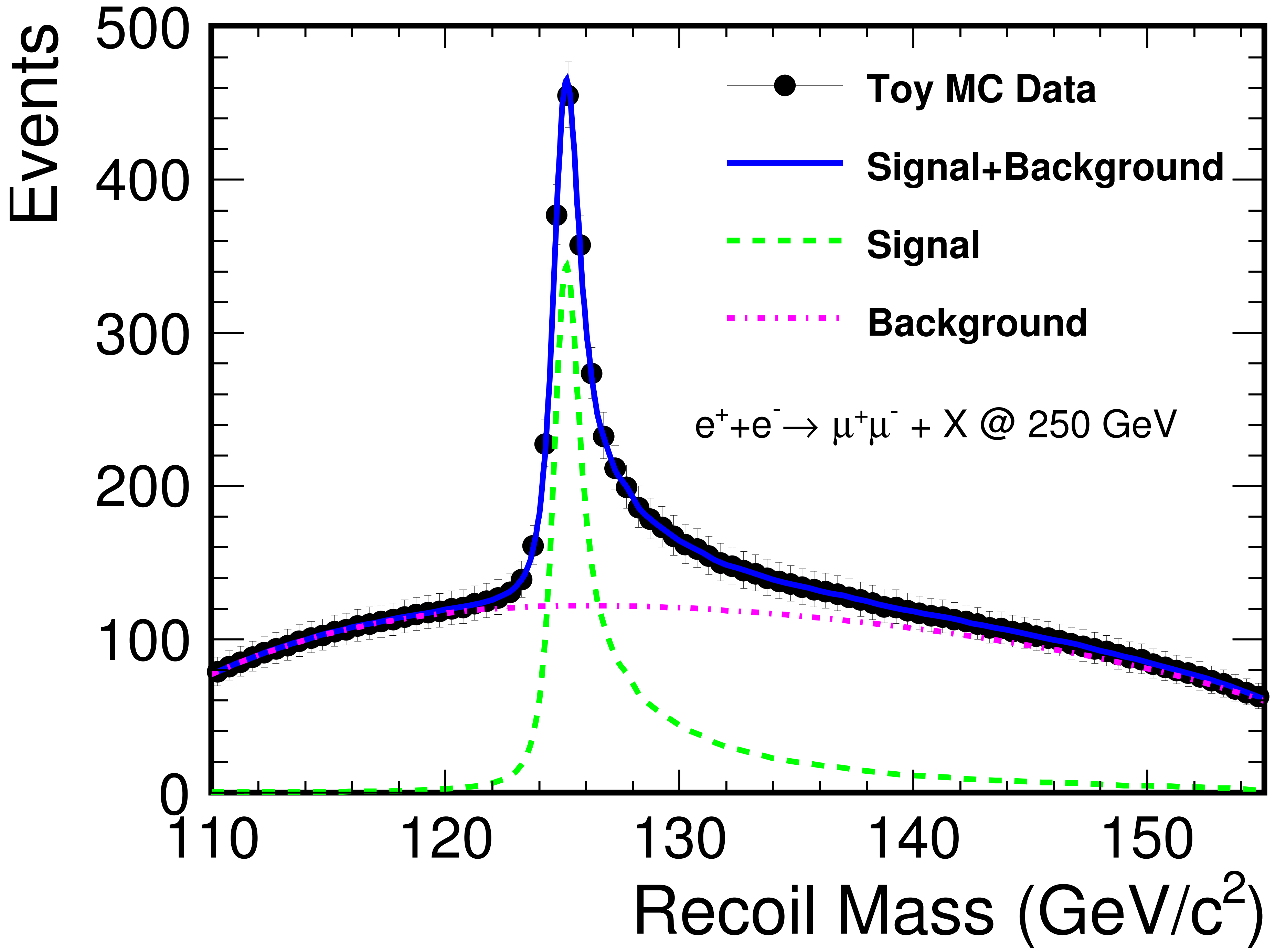

Phys. Rev. D 103, 099903 (2021)

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<1 permille accuracy!
HL-LHC: O(20) MeV
ILC: 14 MeV
FCC-ee: O(10) MeV

HL-LHC: arXiv:1902.00134
ILC: Phys. Rev. D 103, 099903 (2021)

- allows to calculate **cross sections, branching ratios, self-coupling** to adequate precision
- for s-channel Higgs production at e+e-: precision better than few MeV required (but: beam energy spread)
- if SM valid up to highest energies: vacuum **metastable**

Width

Width of SM Higgs boson is predicted to be 4.07 MeV

- much smaller than experimental resolution
- deviations could point to exotic decays, like Higgs boson decays to dark matter!

Hadron colliders

- comparisons of on- and offshell cross section measurements (indirect, model-dependent)
- CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV (HL-LHC 20%)
  Nat. Phys. 18 (2022) 1329

$$\frac{\frac{\sigma_{\rm off}}{\sigma_{\rm peak}}(\rm exp)}{\frac{\sigma_{\rm off}}{\sigma_{\rm peak}}(\rm SM)} = \frac{\Gamma}{\Gamma_{\rm SM}}$$

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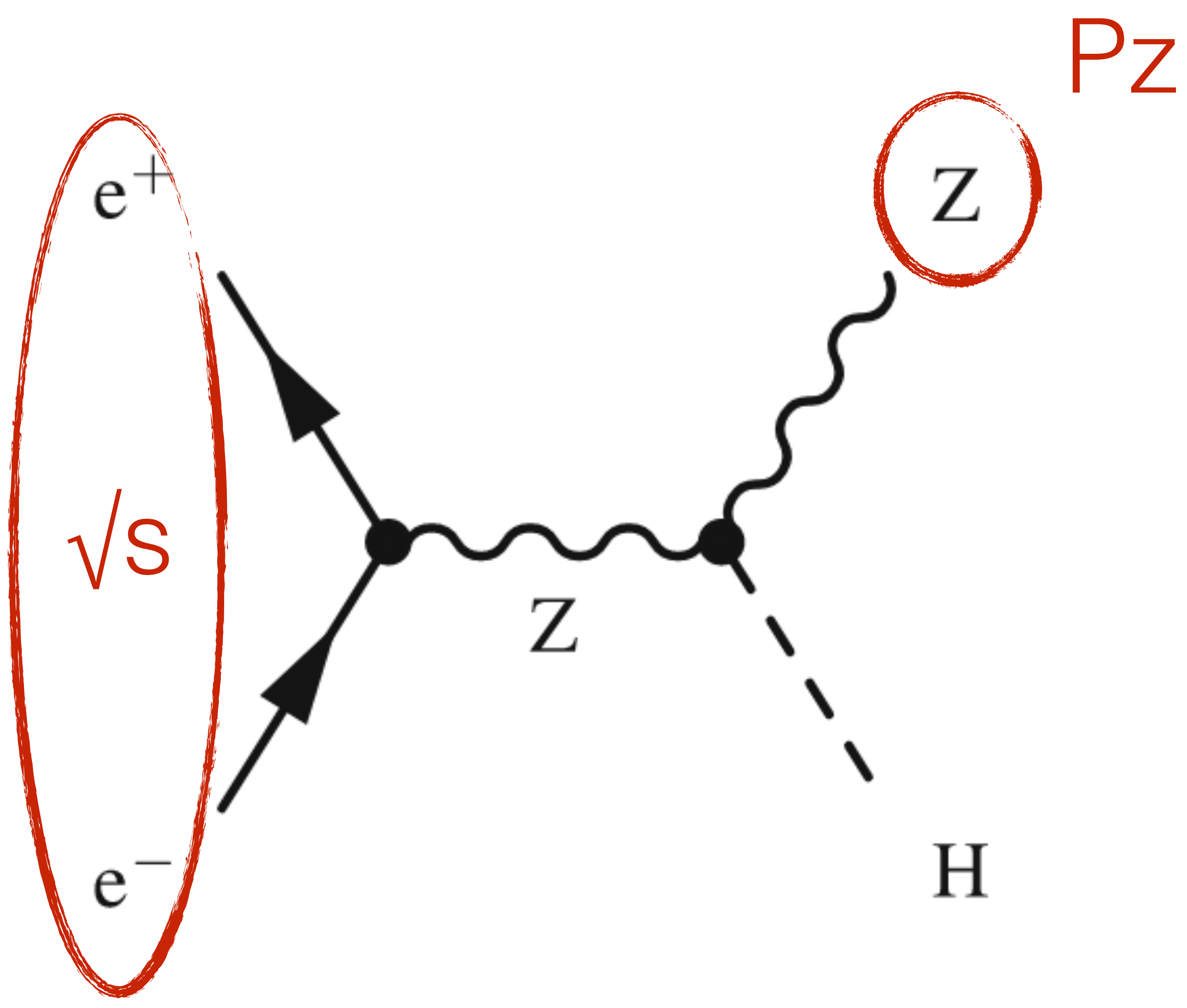

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(HL-LHC 20%)

$$\frac{\frac{\sigma_{\rm off}}{\sigma_{\rm peak}}({\rm exp})}{\frac{\sigma_{\rm off}}{\sigma_{\rm peak}}({\rm SM})} = \frac{\Gamma}{\Gamma_{\rm SM}}$$

At e+e- machines (initial state precisely knowm)

- mass recoil method, combine with exclusive decay measurements
- less model dependent

$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\rm SM} \times \Gamma_H$$

Predictions at different future machines: 1 - 5 %

JHEP 01 (2020) 139, arXiv:2209.07510 (Snowmass)

Higgs boson properties

Mass and width

=> related to vacuum stability, exotic decays

H

Production and decays

=> couplings strengths

=> Higgs mechanism also for lighter fermions?

Leptons and neutrinos			Quarks		
e	μ	τ	u	c	t
ν_e	ν_μ	ν_τ	d	s	b

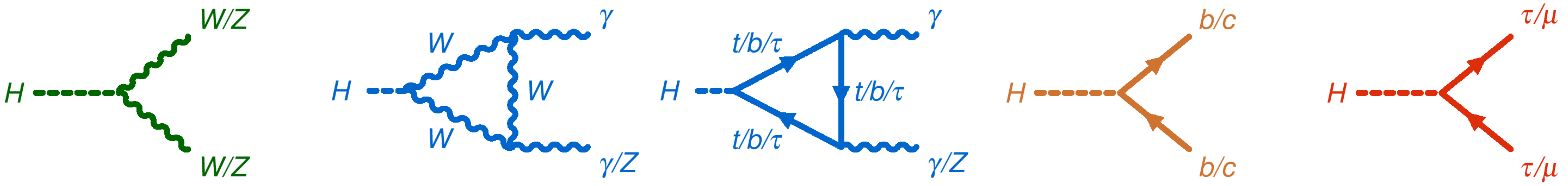
spin/CP properties of Higgs boson interactions

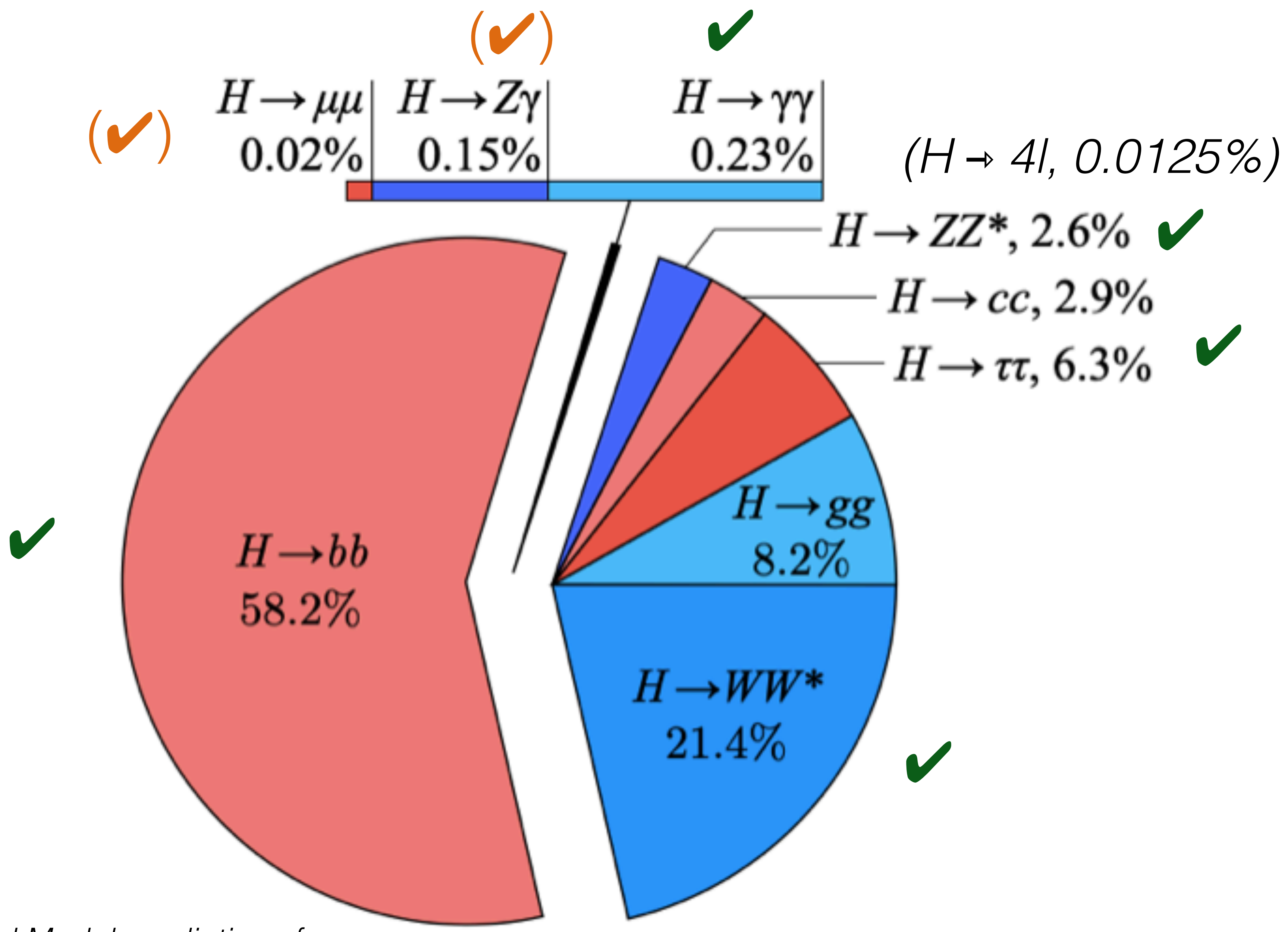
=> may be related to matter-antimatter asymmetry in the universe

See next talk!
Also for Higgs self-coupling

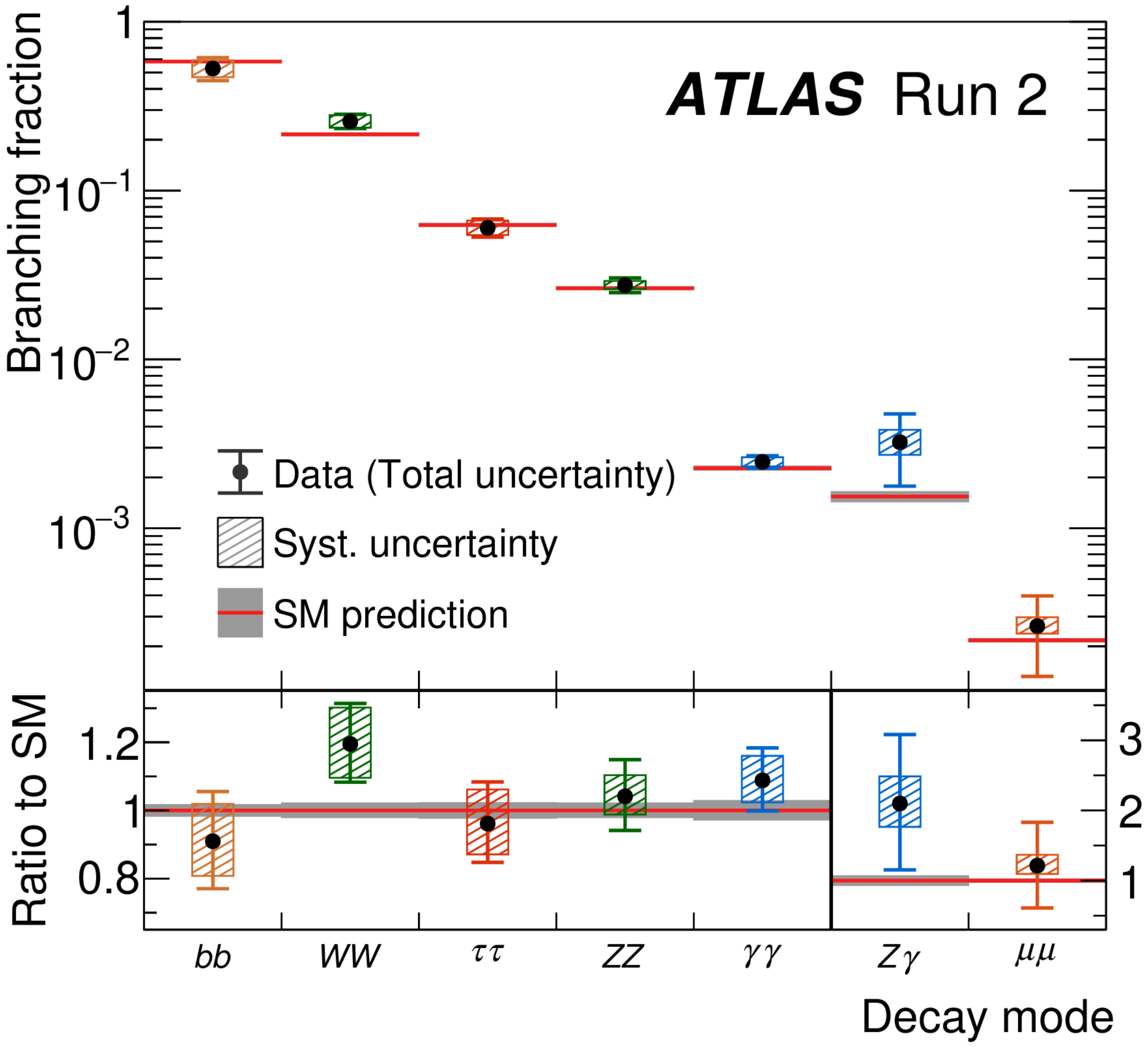
=> Is it really the Higgs boson of the Standard Model or something else?

Higgs boson decay measurements (thanks, nature!)





(Standard Model predictions for a Higgs boson with mass 125 GeV)

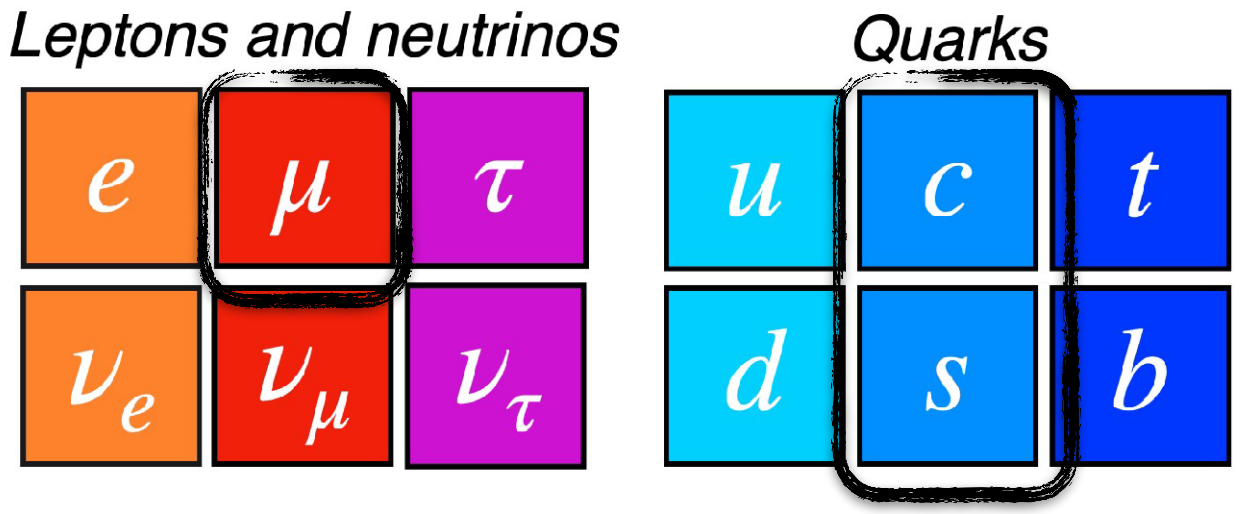


Nature 607, 52–59 (2022)

Decays to second generation fermions

H → μμ

- evidence by CMS in Run-2, observation at the end of Run-3?



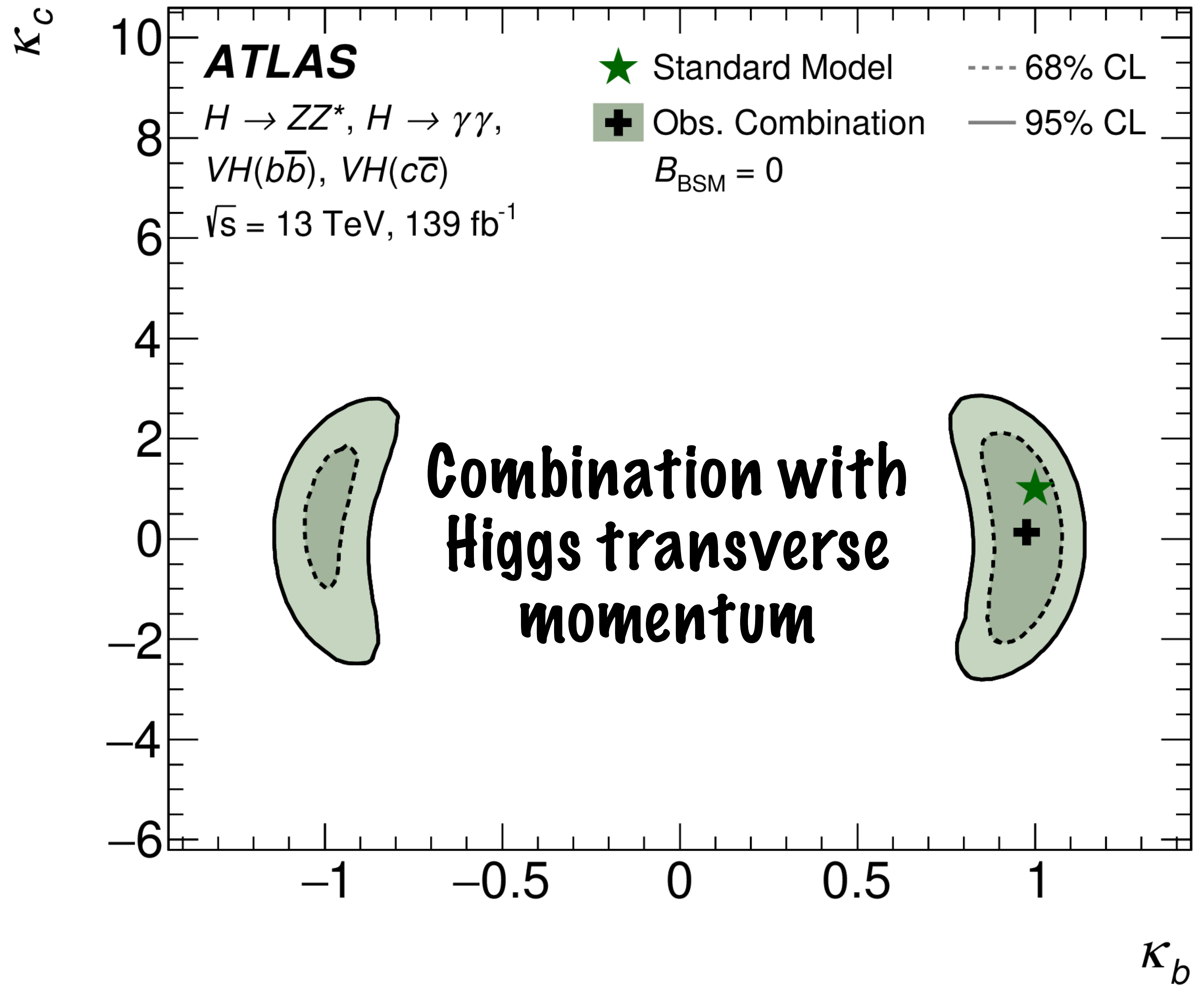
H → cc

Phys. Rev. Lett. 131 (2023) 061801

- CMS: upper limit on VH, H->cc of 14.4* SM (exp. 7.8 * SM)
- ILC all stages/FCC all stages: coupling ~ 1%

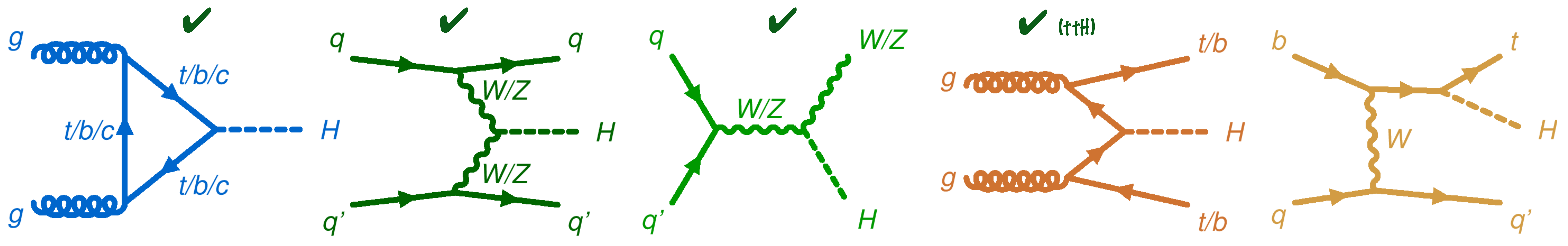
H → ss (BR < 10^{-3})

- out of reach at (HL-)LHC, possibly within reach at e+e- collider:
- advances in strange-tagging needed
- current best estimates, p.ex. CEPC: Z(vv/ll)H limit with 20 ab^{-1}: BR(H → ss) < 3×SM at 95% CL (*2310.03440*)

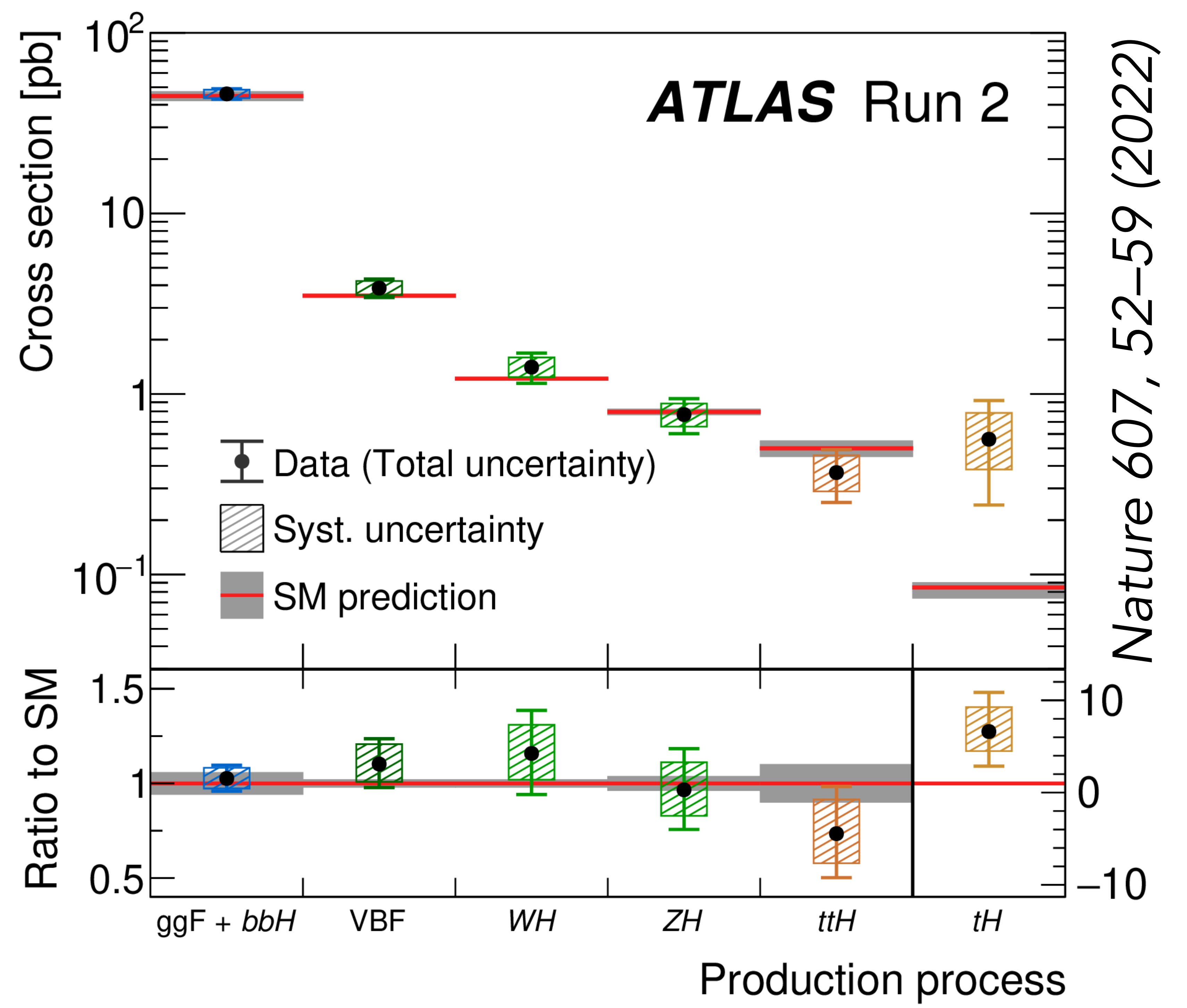


JHEP 05 (2023) 028

Higgs boson production measurements



- each has a particular final state in addition to Higgs
  - VBF: 2 forward jets
  - VH: 2 leptons from vector boson
  - ttH: two top quarks
- can be measured in different decay channels



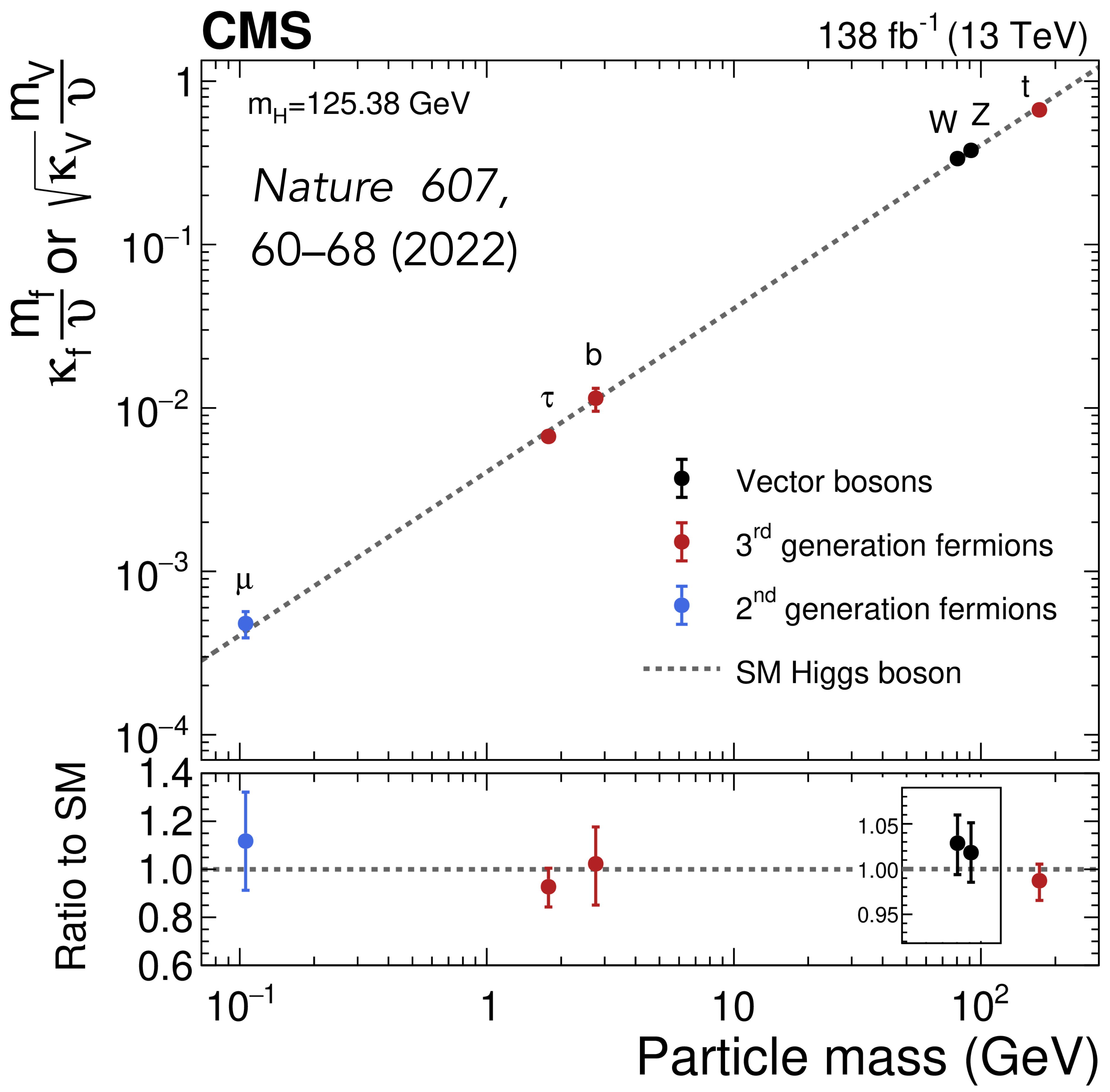
Couplings to other particles

- from all available production and decay measurements in different channels can extract couplings
- deviations expected in many **BSM models**, p.ex.
  - Composite Higgs
  - SUSY Higgs sectors
- Kappa-framework:
  - assume SM coupling structure
  - define scaling factors

$$\sigma(i \to H \to f) = \kappa_i^2 \sigma_i^{\mathrm{SM}} \frac{\kappa_f^2 \Gamma_f^{\mathrm{SM}}}{\kappa_H^2 \Gamma_H^{\mathrm{SM}}}$$

- Higgs couplings: the higher the mass, the stronger the coupling
  - to bosons: ~ (boson mass)²
  - to fermions: ~ (fermion mass)

SM prediction



Assumptions: No new particles in the loops

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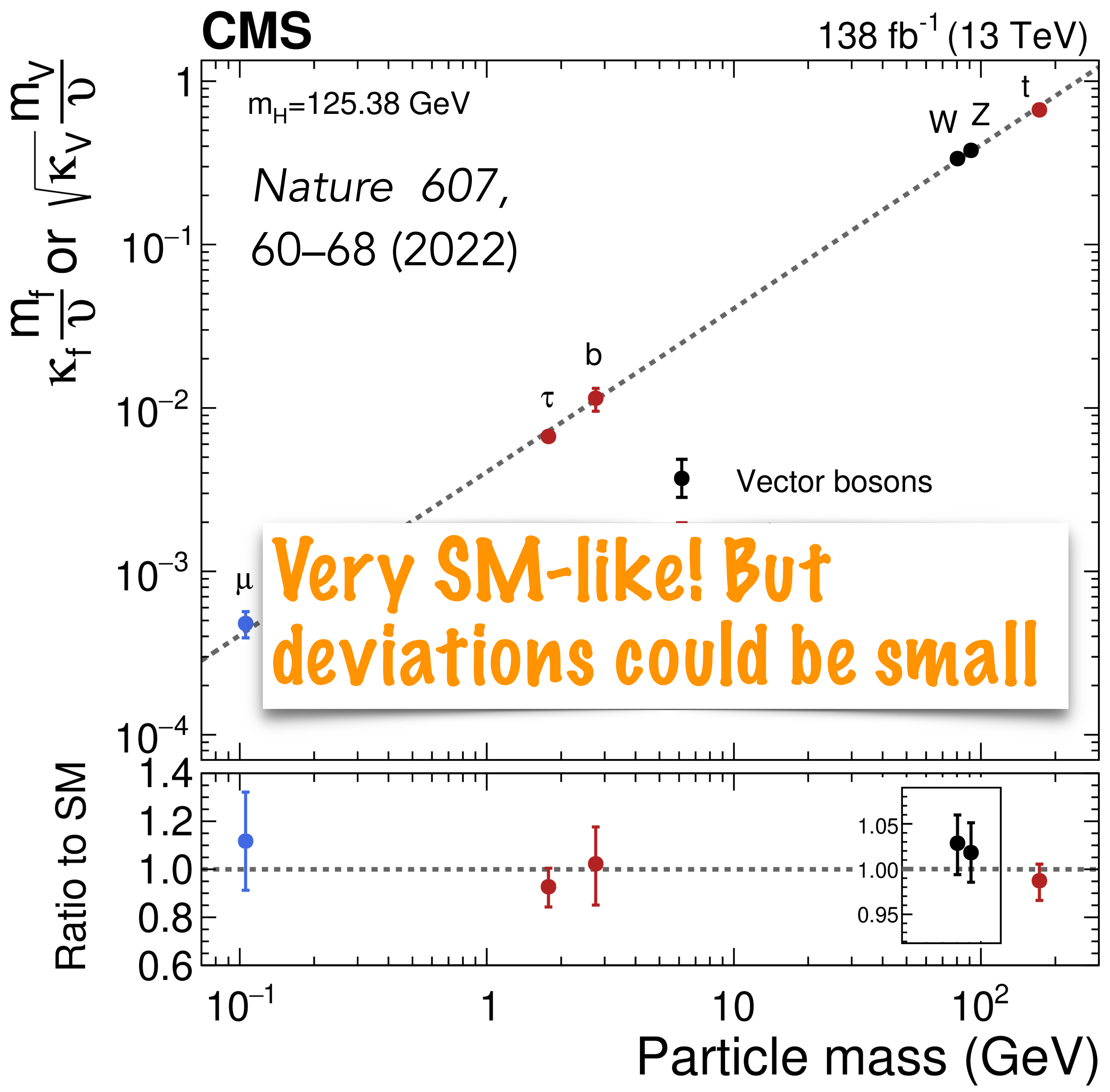

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Couplings uncertainties at future colliders

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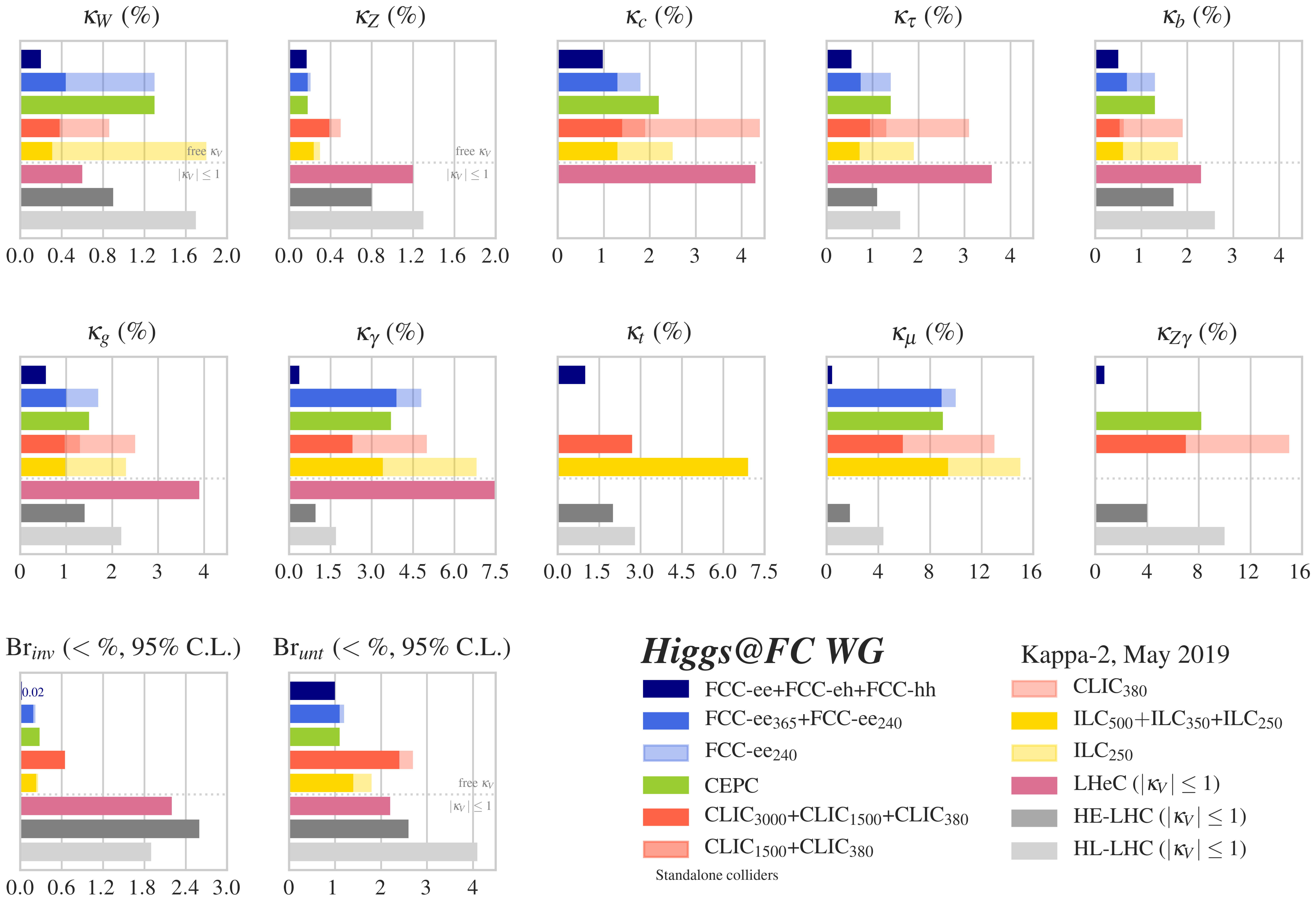
One of the main goals of HL-LHC and beyond



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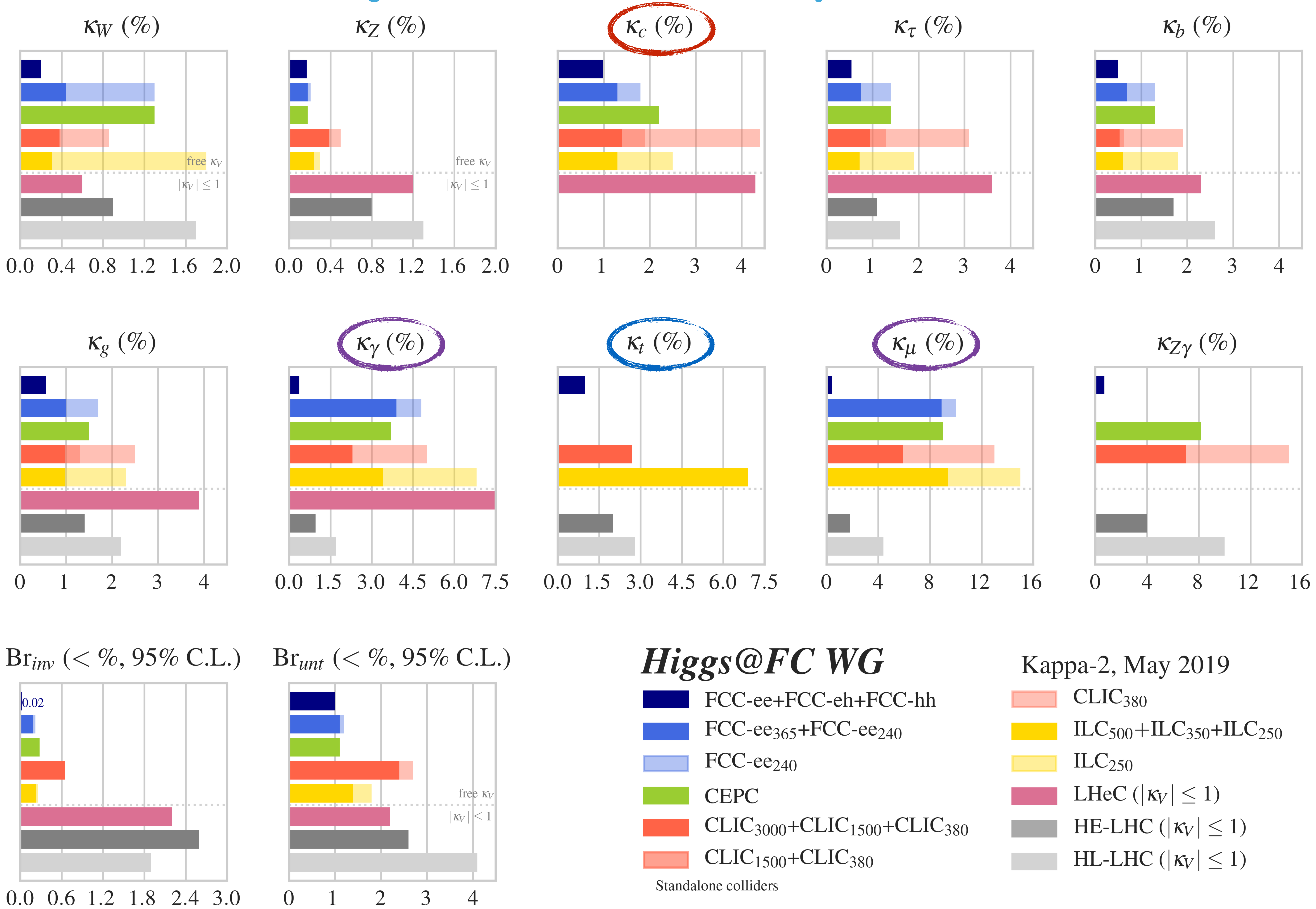

- Complementarity between HL-LHC and lepton colliders:
  - HL-LHC: k_t, rare decays
  - e+e-: k_c
- Lepton colliders benefit from increase in CM energies

Couplings uncertainties at future colliders

Combination between future colliders and HL-LHC

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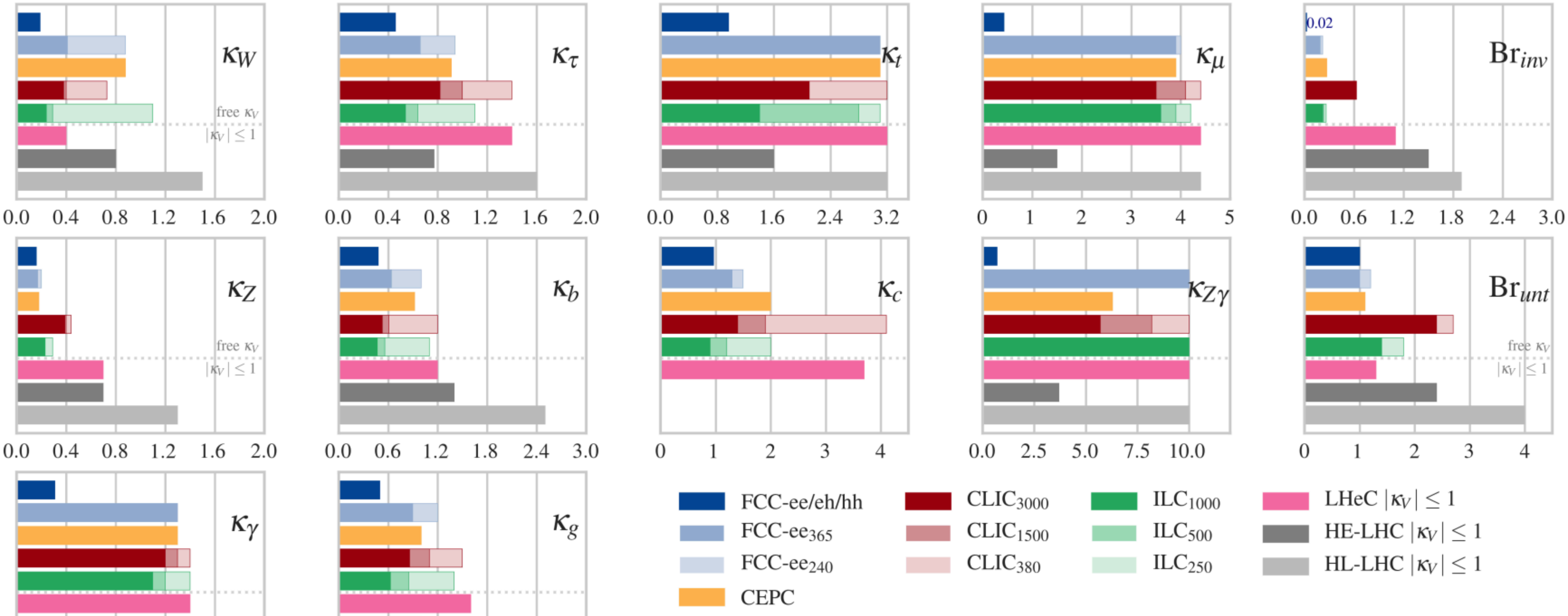


Higgs@FC WG
Kappa-3, 2019

Future colliders combined with HL-LHC
Uncertainty values on $\Delta\kappa$ in %.
Limits on Br (%) at 95% CL.

Effective field theories

Next step: Drop assumption of SM coupling structure

=> Effective field theories

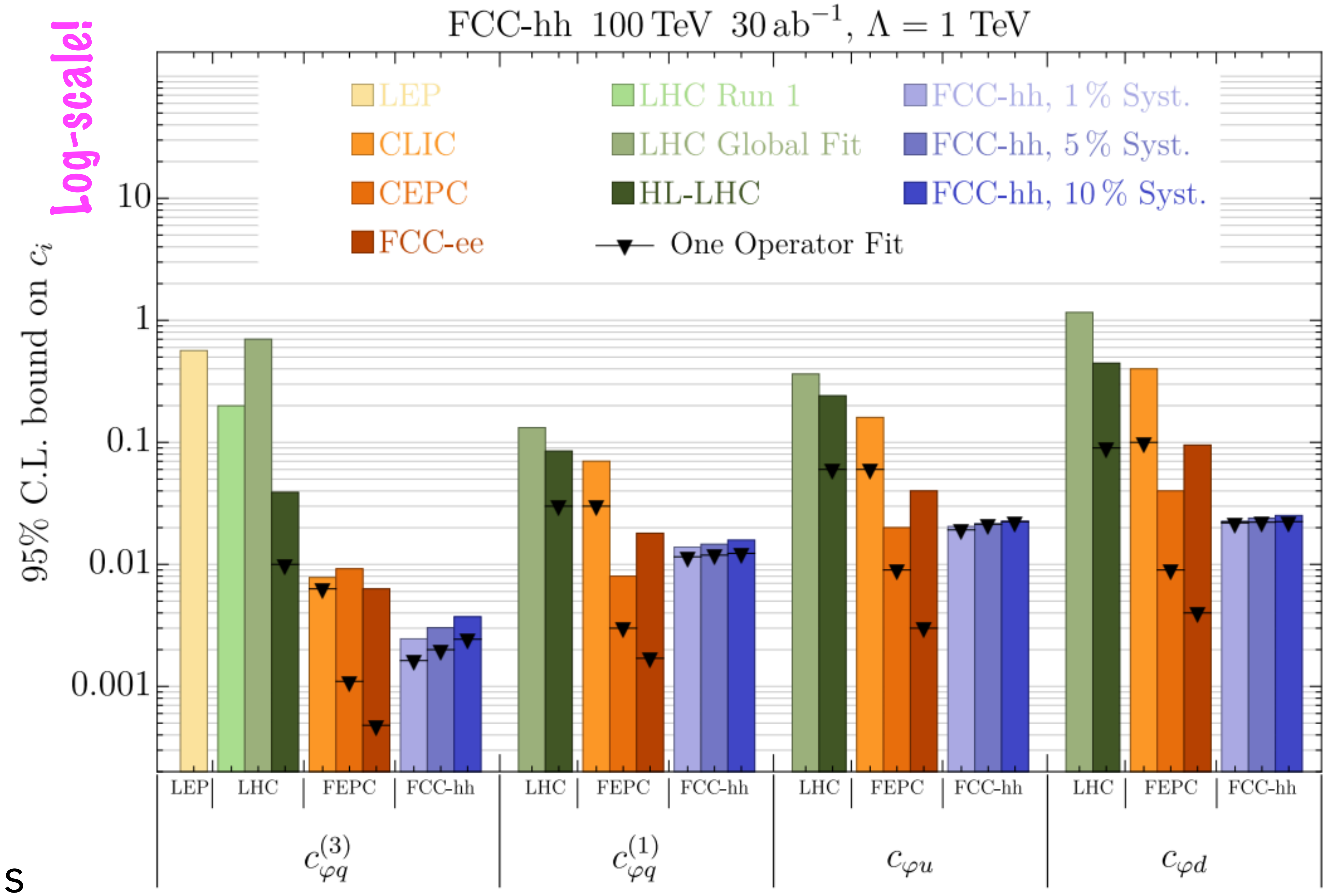
- constrain contributions of BSM physics at high energy scale Λ_{EFT} in a more general way
- introduce additional operators, fit for Wilson coefficients (0 in SM)

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$$

Example dimension 6: first lepton number conserving order

- Much development is happening
  - Higgs measurements as inputs to global fits
  - constrain as many coefficients at the same time as possible
  - EFT-model matching

Log-scale!



J. High Energ. Phys. 2021, 154 (2021)

Rare, precise channel: V(ll, lν, νν)H(γγ)

Higgs boson properties

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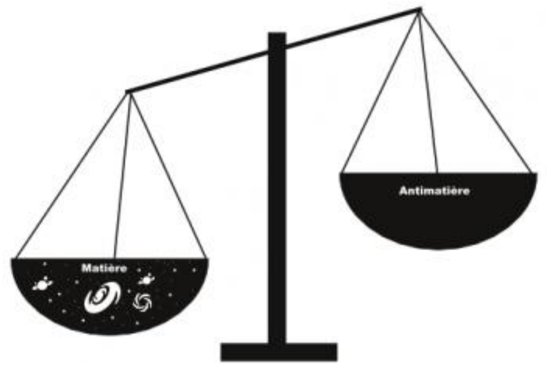

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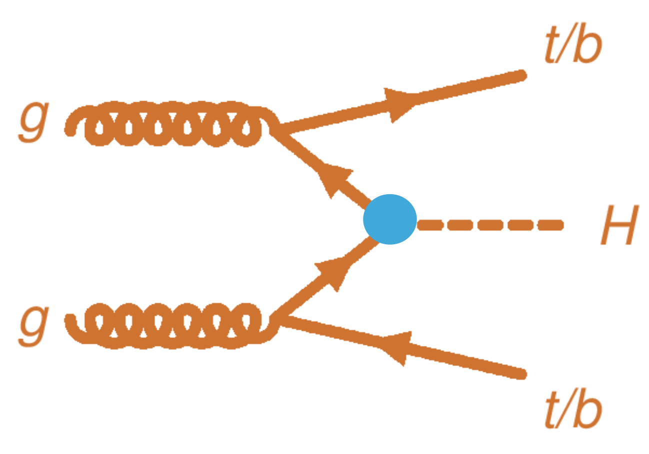
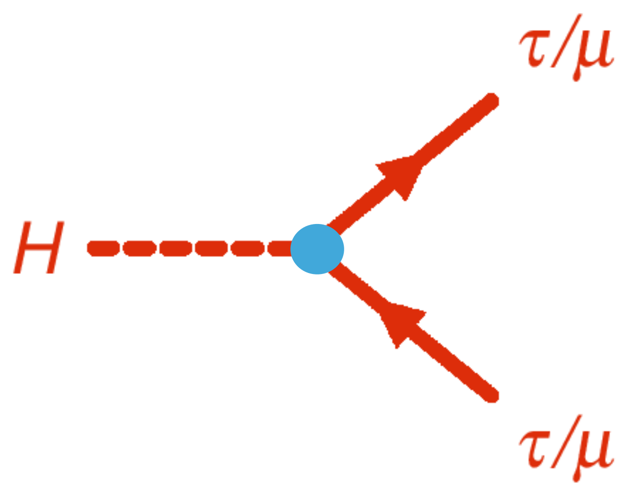
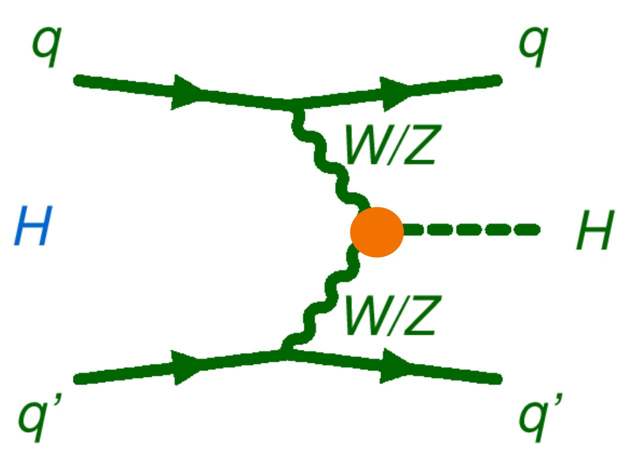
The Matter-Antimatter Issue

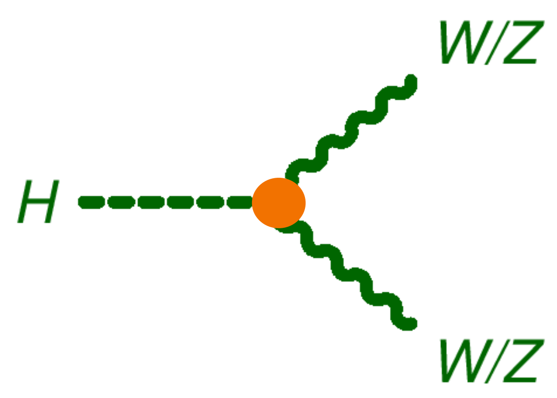
- One of the Sakharov conditions for explaining matter-antimatter asymmetry: CP violation
- SM does not have enough CP-violation to explain the effect
- Additional source of CP violation in Higgs sector?
- In SM: Higgs is CP even. Many BSM models: CP-odd Higgs or mixed state

- Important: CP of Higgs couplings is checked separately for
  - fermions (CP odd terms possible at tree level)
  - bosons (CP-odd terms suppressed by energy scale of new physics)









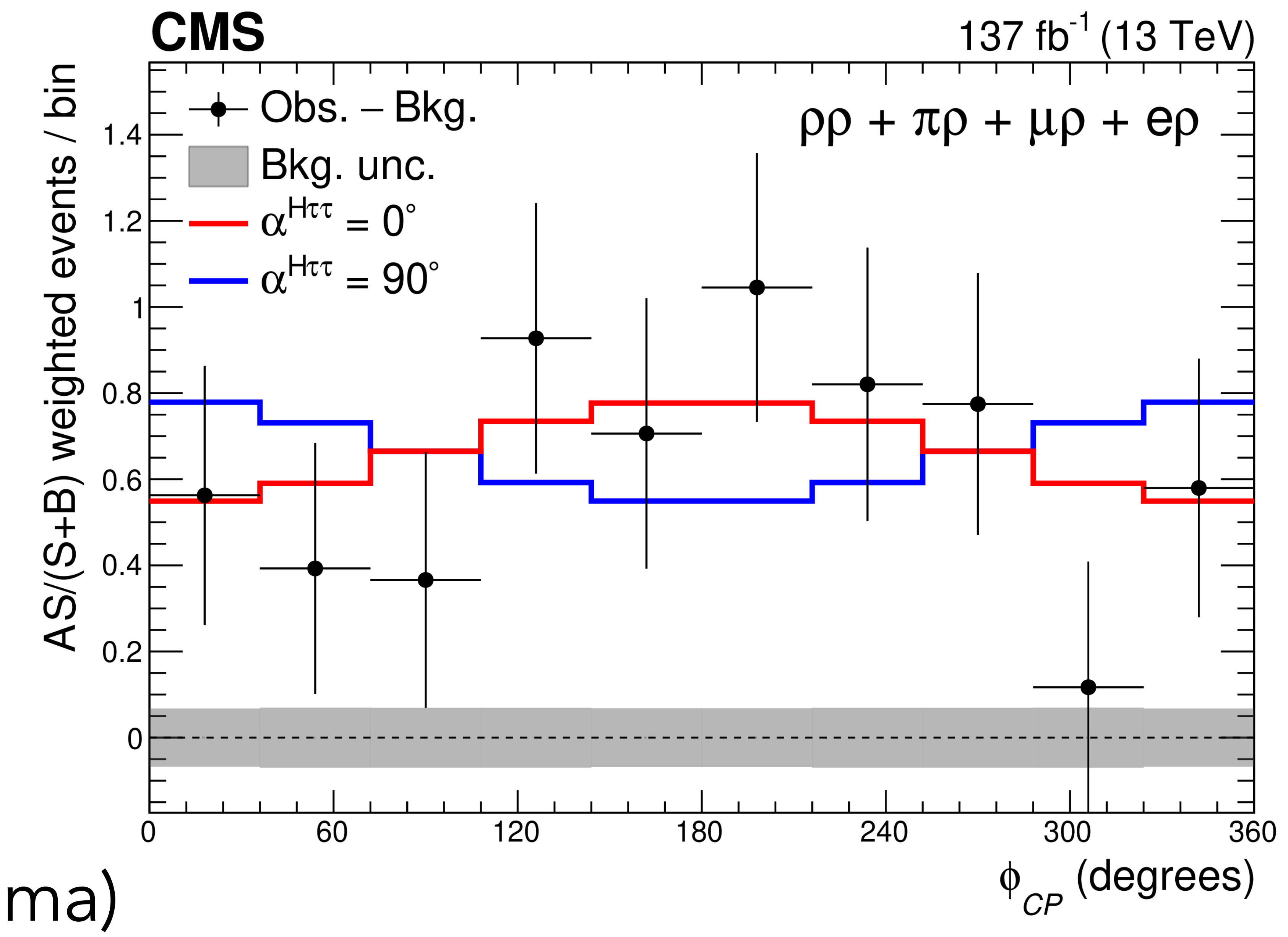
CP studies

Use CP sensitive observables, often angles or matrix element ratios

- potential for optimization

Results

- pure parity odd Higgs coupling to W, Z bosons excluded at > 99.9% (ATLAS, CMS)
    - effective gluon and photon coupling at HL-LHC
- pure parity odd Higgs coupling to taus, tops excluded with 99.7% (3 sigma)
- **admixtures (CP even and CP odd couplings) still possible**
    - constraints set on mixing angles and EFT coefficients

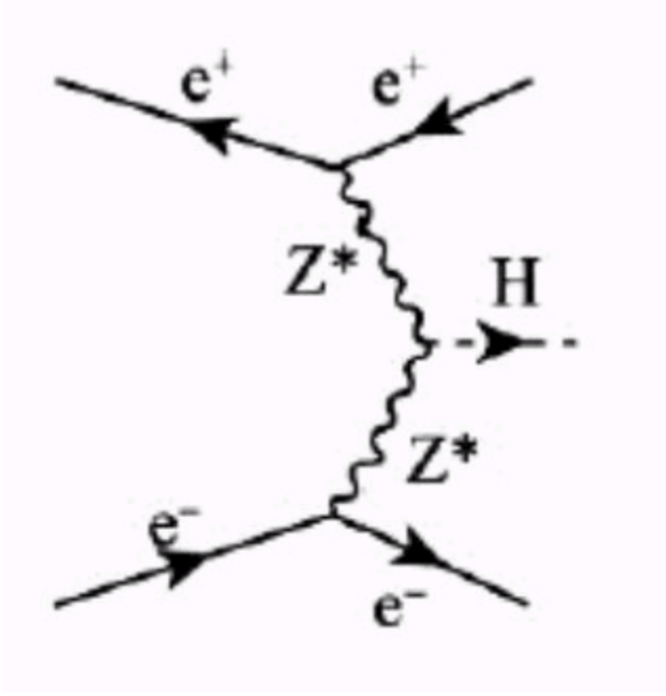


CMS *(JHEP 06 (2022) 012)*

ϕ_τ = -1 ± 19° (0 ± 21°)

Future:

- more global studies (EFT)
- new opportunities at e+e- colliders: ZH, ZZ fusion production with polarized/unpolarized beams



Conclusion

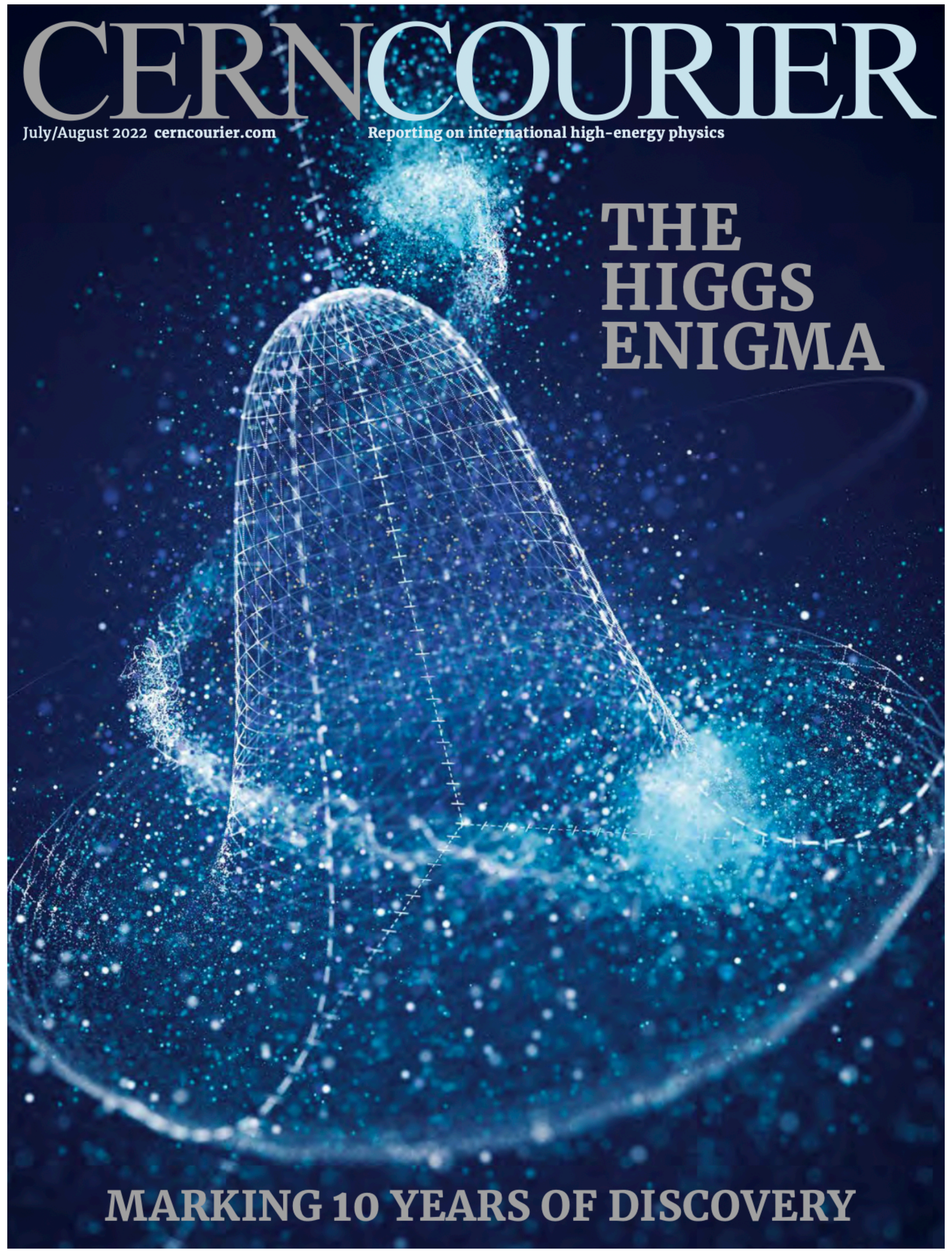
Since the discovery 11 years ago, we learned a lot about the Higgs sector

However, we are still trying to answer the question: Is it really the Higgs boson of the Standard Model or something else?

=> Higgs boson could be a first clue to the big questions in particle physics

- mass generation
- structure of the vacuum
- matter/anti-matter asymmetry
- dark matter
- history of the universe

=> expect growing connection to cosmology and flavor physics



BACKUP

Collider scenarios

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Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Dummy slide

Result of the coupling (a.k.a. κ) fit

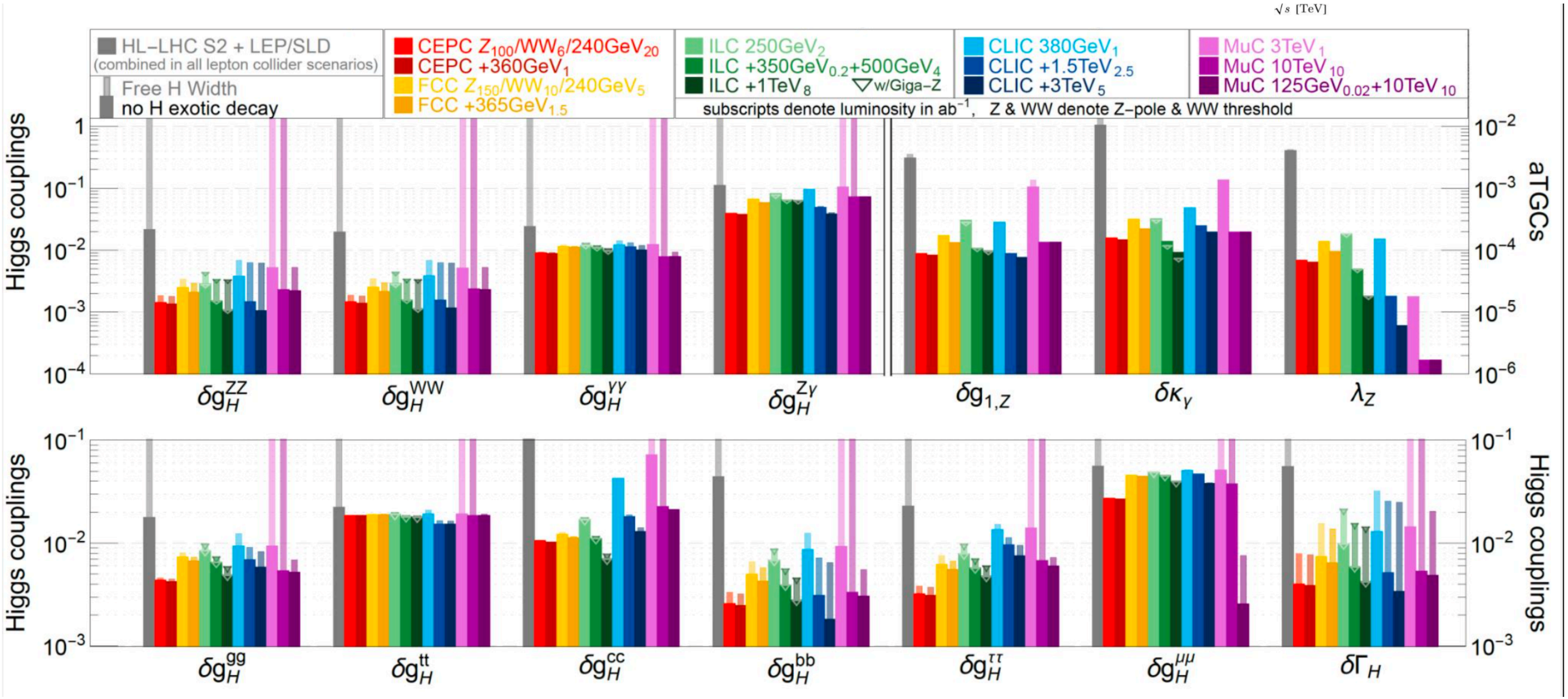
- Comparison(*) with other lepton colliders at the EW scale (up to 380 GeV)

Collider	μ Coll$_{125}$	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240}$	FCC-ee$_{365}$	HL-LHC
Years	6	15	7	6	7	3	+4	25
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	+1.5	3
δm_H (MeV)	0.1	14	110	10	5	7	6	100
$\delta\Gamma_H / \Gamma_H$(%)	6.1	3.8	6.3	3.7	2.6	2.8	1.6	50
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	1.8	1.3	1.4	0.68	8.2
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.3	1.7	1.2	1.3	0.47	3.5
$\delta g_{H\tau} / g_{H\tau}$(%)	6.2	1.9	4.2	1.9	1.4	1.4	0.80	6.5
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	3.8	3.6
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6	5.0
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22	3.5
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2	SM
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0	3.9
Br$_{invis}$ (%)$_{95\%CL}$	SM	< 0.3	< 0.6	< 0.5	< 0.15	< 0.3	< 0.25	< 3
BR$_{EXO}$ (%)$_{95\%CL}$	SM	< 1.8	< 3.0	< 1.6	< 1.2	< 1.2	< 1.1	SM

(*) Green = best
Red = worst

Coupling constraints

Snowmass



Mass table

Collider Scenario	Strategy	δm_H (MeV)	Ref.	$\delta(\Gamma_{ZZ^*})$ (%)
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160	[83]	1.9
HL-LHC	$m(ZZ)$	10-20	[10]	0.12-0.24
ILC_{250}	ZH recoil	14	[3]	0.17
CLIC_{380}	ZH recoil	78	[85]	1.3
CLIC_{1500}	$m(bb)$ in $H\nu\nu$	30[15]	[85]	0.56
CLIC_{3000}	$m(bb)$ in $H\nu\nu$	23	[85]	0.53
FCC-ee	ZH recoil	11	[86]	0.13
CEPC	ZH recoil	5.9	[2]	0.07

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Muon collider @125 GeV: 0.1 MeV

Width table

Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [85]	2.6
CLIC_{1500}	2.6	κ-framework [85]	1.7
CLIC_{3000}	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, $\mathrm{BR}(H \to Z, b\bar{b}, WW)$ [90]	1.8
$\mathrm{FCC\text{-}ee}_{240}$	2.7	κ-framework [1]	1.9
$\mathrm{FCC\text{-}ee}_{365}$	1.3	κ-framework [1]	1.2

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How to add a CP-odd term to the SM Lagrangian

For fermions

$$\mathcal{L}_{Hff} = -\frac{m_f}{\nu}\kappa_f(\cos\alpha\bar{\psi}\psi + \sin\alpha\bar{\psi}i\gamma_5\psi)H.$$

SM: a= 0

- at "tree" level

For bosons

Wilson coefficients

Operators (CP even or CP odd)

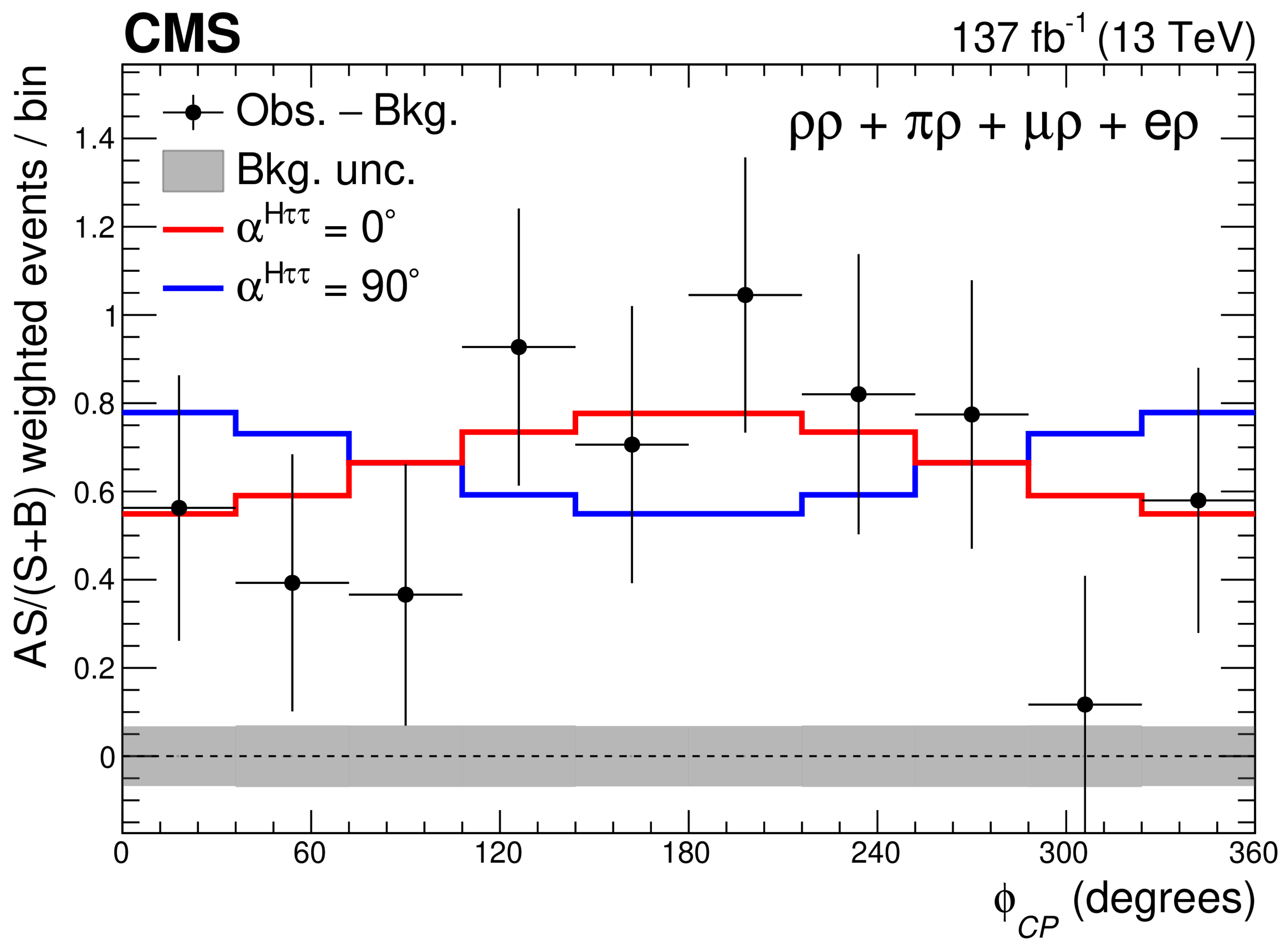
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)} \quad \text{for } d > 4.$$

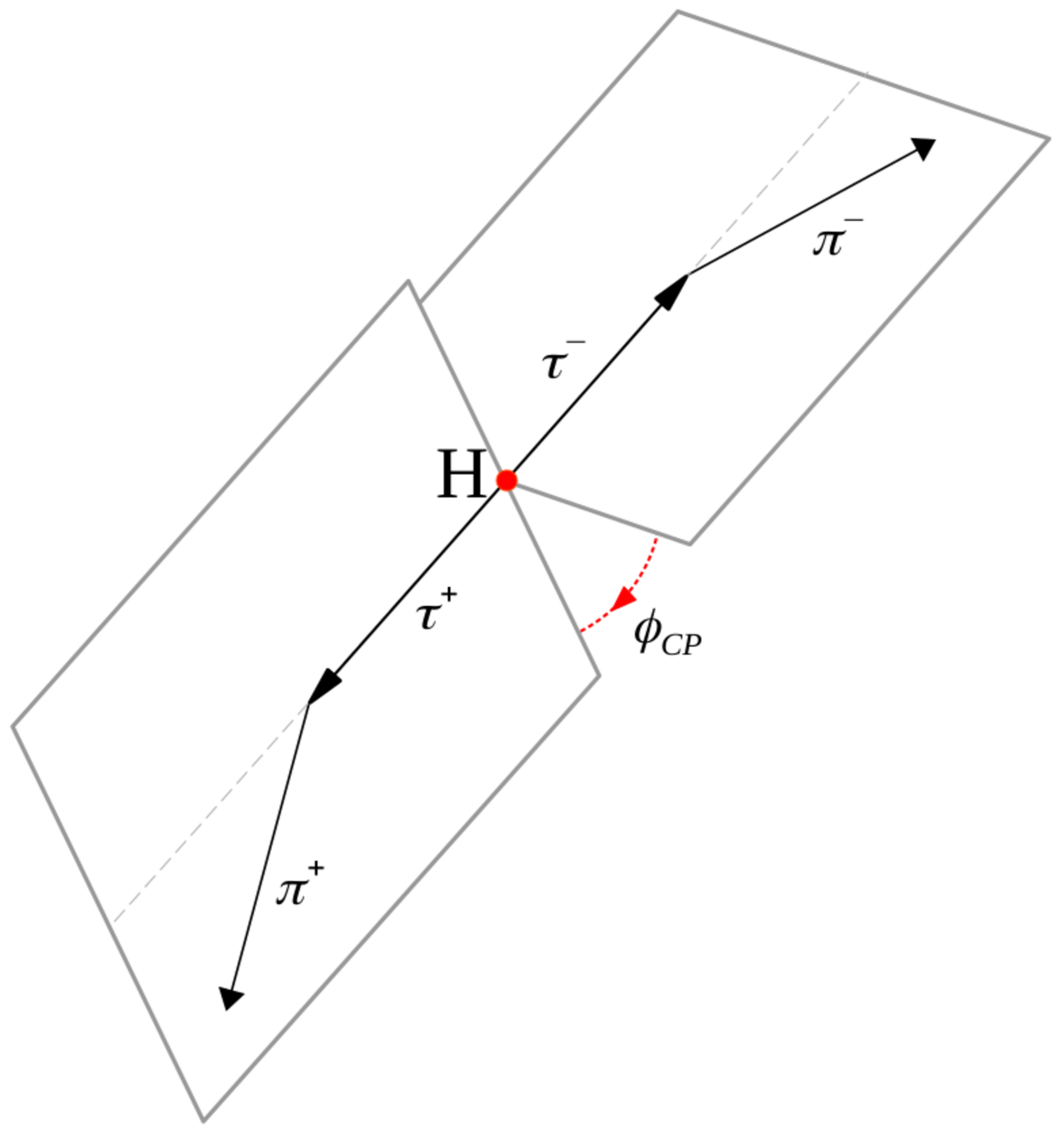
- Without knowing the exact mechanism:
  - Assume new phenomena appear at very high energies
  - Construct an effective field theory starting from the known SM fields and symmetries
    - Terms are suppressed by energy scale of the new theories

How to check the CP of Higgs couplings?

Use CP sensitive observables, often angles or matrix element ratios

$$\mathcal{O}_{\text{opt}} = \frac{2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$





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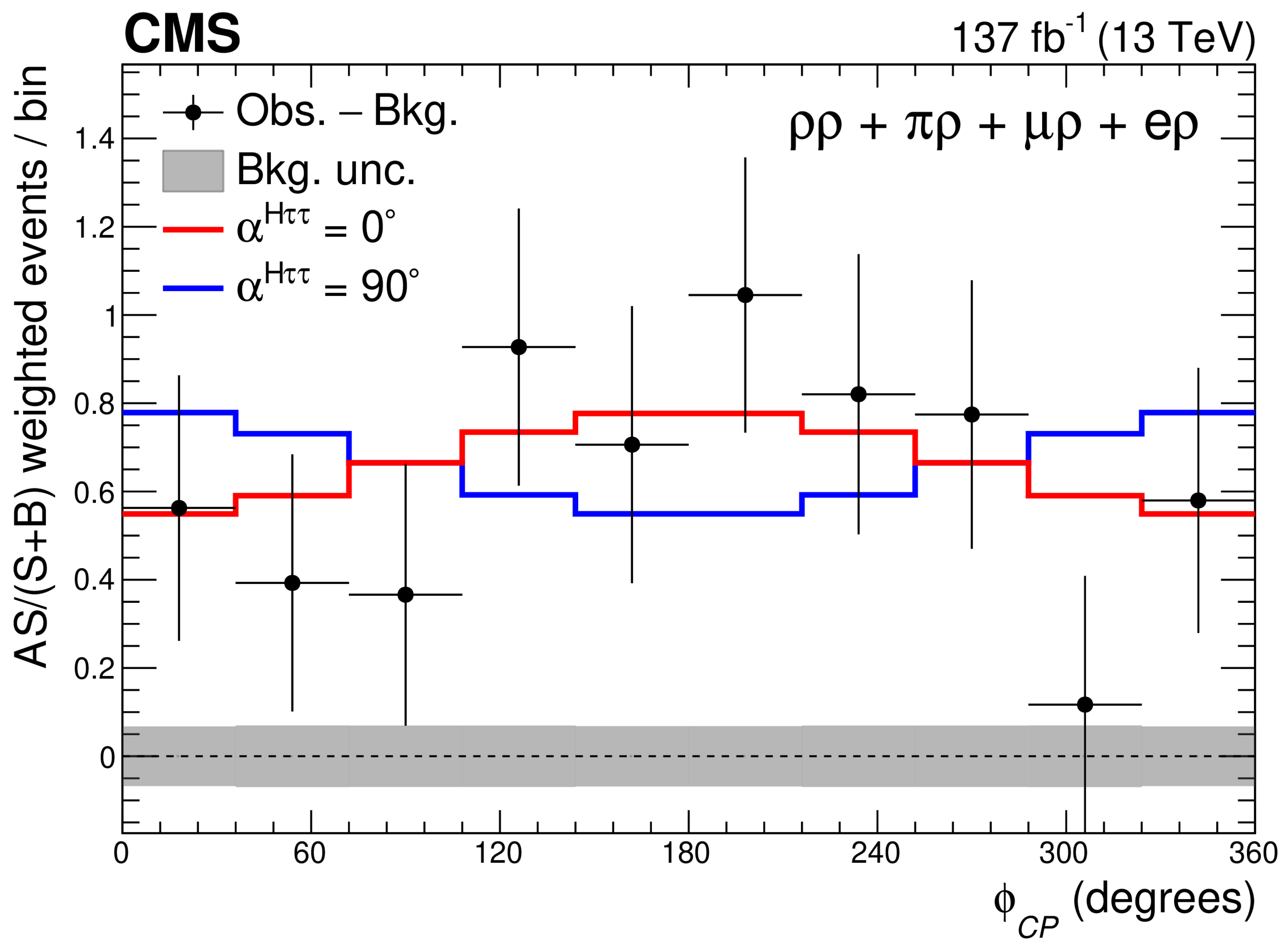

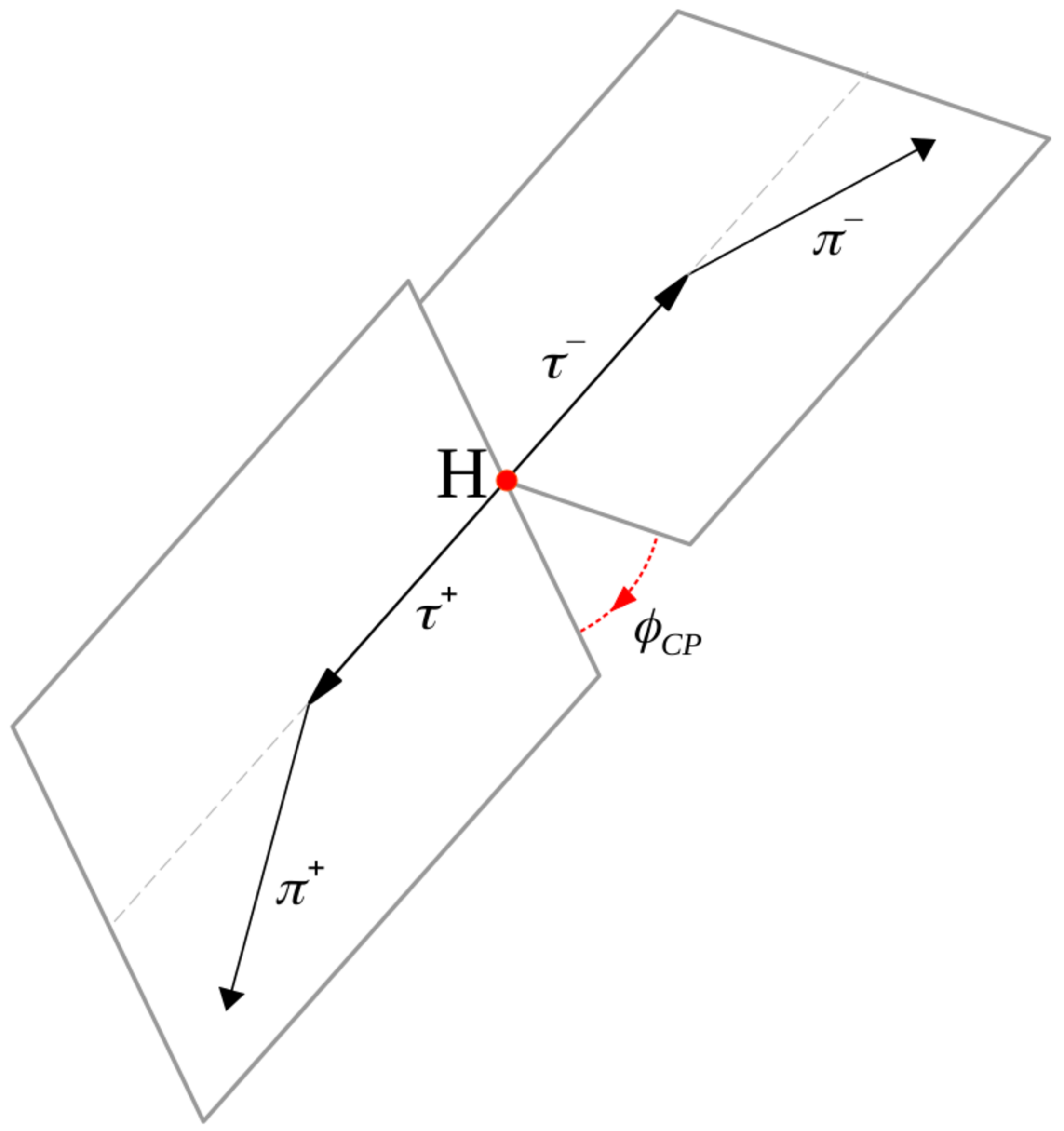

Results

- pure parity odd Higgs coupling to **bosons** excluded at > 99.9% (ATLAS, CMS)
- pure parity odd Higgs coupling to **fermions** with 3 sigma (translate to %)
- admixtures (CP even and CP odd couplings) still possible

CP table

Reference?

Current status and future outlook

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~1	✓	–	–	–	~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	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Limits set on: $f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{CP\,\mathrm{odd}}}{\Gamma_{H\to X}^{CP\,\mathrm{odd}} + \Gamma_{H\to X}^{CP\,\mathrm{even}}}$

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tH

(important - sign of coupling)

Currently: tH<12*SM

tH <2*SM at HL-LHC