FCC

FCC-UK: UK opportunities and the FCC feasibility study, November 2021

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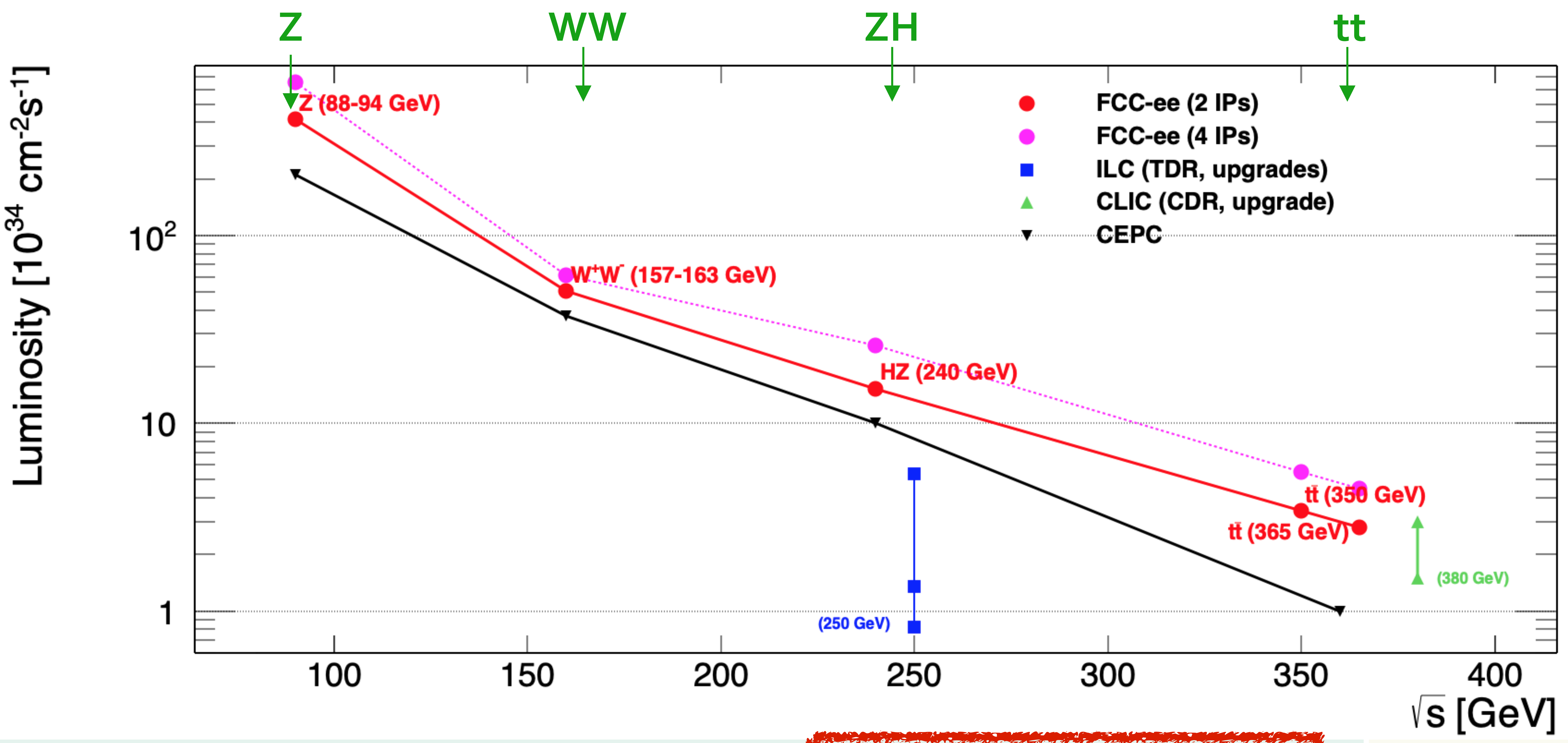
FCC PHYSICS OVERVIEW

Recalling the basic numbers

FCC-ee (numbers of events are for 2 detectors)



						$\sqrt{s}$ errors
ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s} \sim 350$ GeV	5 years	10^6	$e^+e^- \to t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	5×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 100 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$	LEP x 10^3	< 300 keV
s-channel H	$\sqrt{s} = 125$ GeV	? Years	~5000	$e^+e^- \to H$	Never done	< 200 keV

FCC-hh: what do 20/30ab^{-1} @ 100 TeV buy you?

- $\sim \times 5$ in mass reach of new-physics searches relative to HL-LHC
  (fairly independently of the new physics scenario)
- $100 \rightarrow 500\ \times$ higher numbers of Higgs bosons, $t\bar{t}$ pairs, etc. than HL-LHC
  (much more at high-p_T & for high-mass pairs)

Table 1.1. Higgs production event rates for selected processes at 100 TeV (N_{100}) and statistical increase with respect to the statistics of the HL-LHC ($N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\,\mathrm{ab}^{-1}$, $N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\,\mathrm{ab}^{-1}$).

	$gg \to H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

together with PbPb, ep and ePb options

	$\sqrt{s}$	L /IP ($cm^{-2}\,s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 $\times 10^{34}$ 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 $\times 10^{34}$ 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 $\times 10^{29}$	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

Higgs physics

Higgs is the last particle of the SM.

So the SM is complete, right?

The Lagrangian and Higgs interactions: two out of three qualitatively new!

$$\mathscr{L}_{\text{SM}} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

Gauge interactions, structurally like those in QED, QCD, EW, **studied for many decades** (but now with a scalar)

Yukawa interactions. Responsible for fermion masses, and induces “fifth force” between fermions. **Direct study started only in 2018!**

Higgs potential → self-interaction (“sixth?” force between scalars).

Holds the SM together.

Unobserved

Plenty of other important open questions on the Higgs sector

Mangano @ Higgs 2021

- Is the Higgs the only (fundamental?) scalar field, or **are there other Higgs-like states** (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do I_3=1/2 fermions (up-type quarks) get their mass from the **same** Higgs field as I_3=–1/2 fermions (down-type quarks and charged leptons)?
  - Do **Higgs couplings conserve flavour?** $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

➡ ***the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which require the LHC and a future generation of colliders*** 6

FCC as a Higgs factory

- **Higgs provides a very good reason why we need both e^+e^- AND pp colliders**
  - FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from σ_{ZH}
    - Γ_H, g_{Hbb}, g_{Hcc}, $g_{H\tau\tau}$, g_{HWW} follow
    - Standard candle fixes all HL-LHC / FCC-hh couplings
  - FCC-hh produces over 10^{10} Higgs bosons
    - (1^{st} standard candle →) $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}
  - FCC-ee measures top EW couplings ($e^+e^- \rightarrow t\bar{t}$)
    - Another standard candle
  - FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
    - (2^{nd} standard candle →) g_{Htt} and g_{HHH}

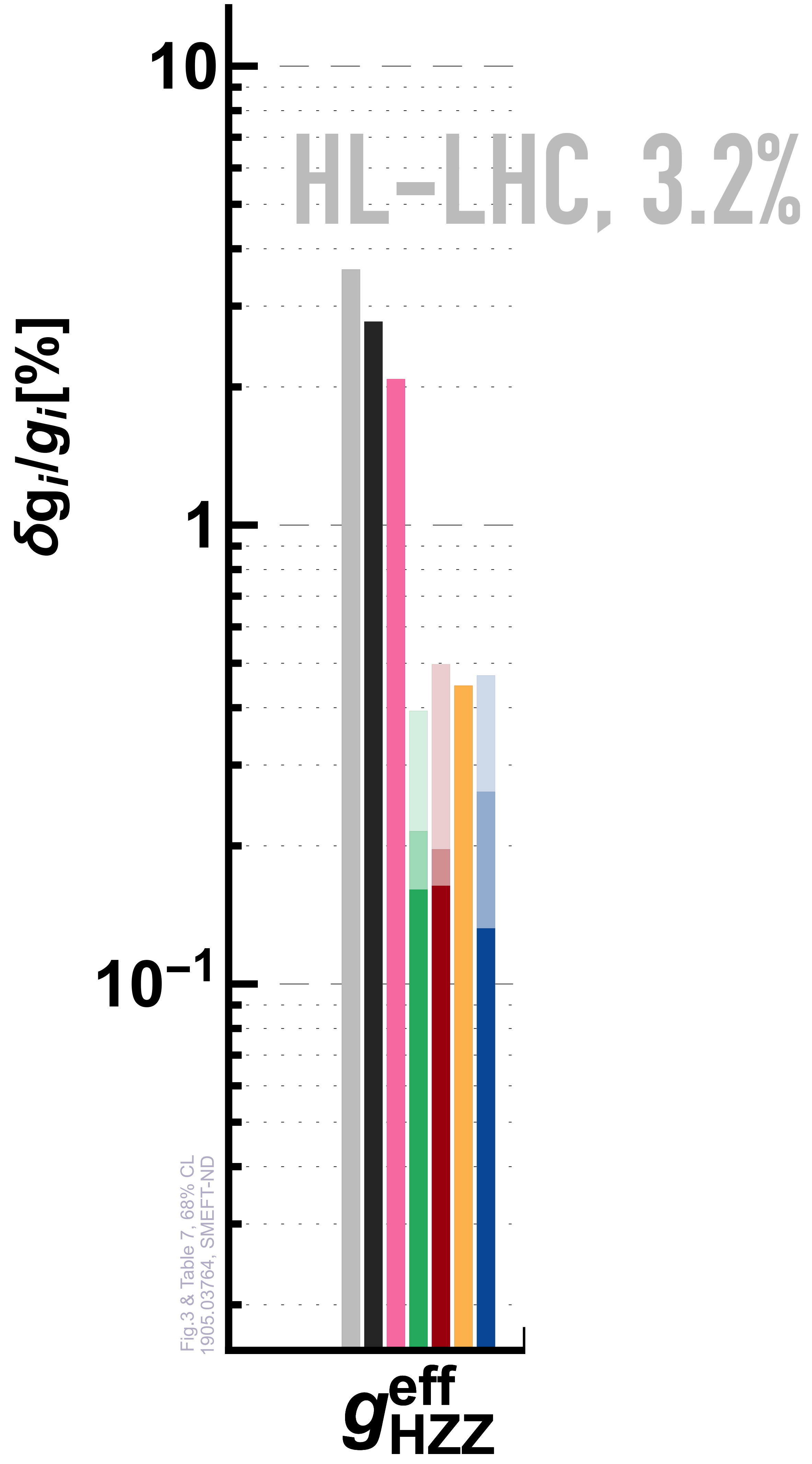
Collider	HL-LHC	FCC-ee$_{240\rightarrow365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	ee
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*	ee
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	ee
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	ee
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	ee
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	ee
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	pp
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	pp
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	pp
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	pp
g_{HHH} (%)	50.	44./33. 27./24.	3	pp
Γ_H (%)	SM	1.1	0.91	ee
BR_{inv} (%)	1.9	0.19	0.024	pp
BR_{EXO} (%)	SM (0.0)	1.1	1	ee

* g_{HWW} includes also ep

- **FCC-ee / FCC-hh complementarity is outstanding**
  - Unreachable by high-energy lepton colliders

- **FCC-ee is also the most pragmatic, safest, and most effective way toward FCC-hh**

meaning & value of EFT fit improvements



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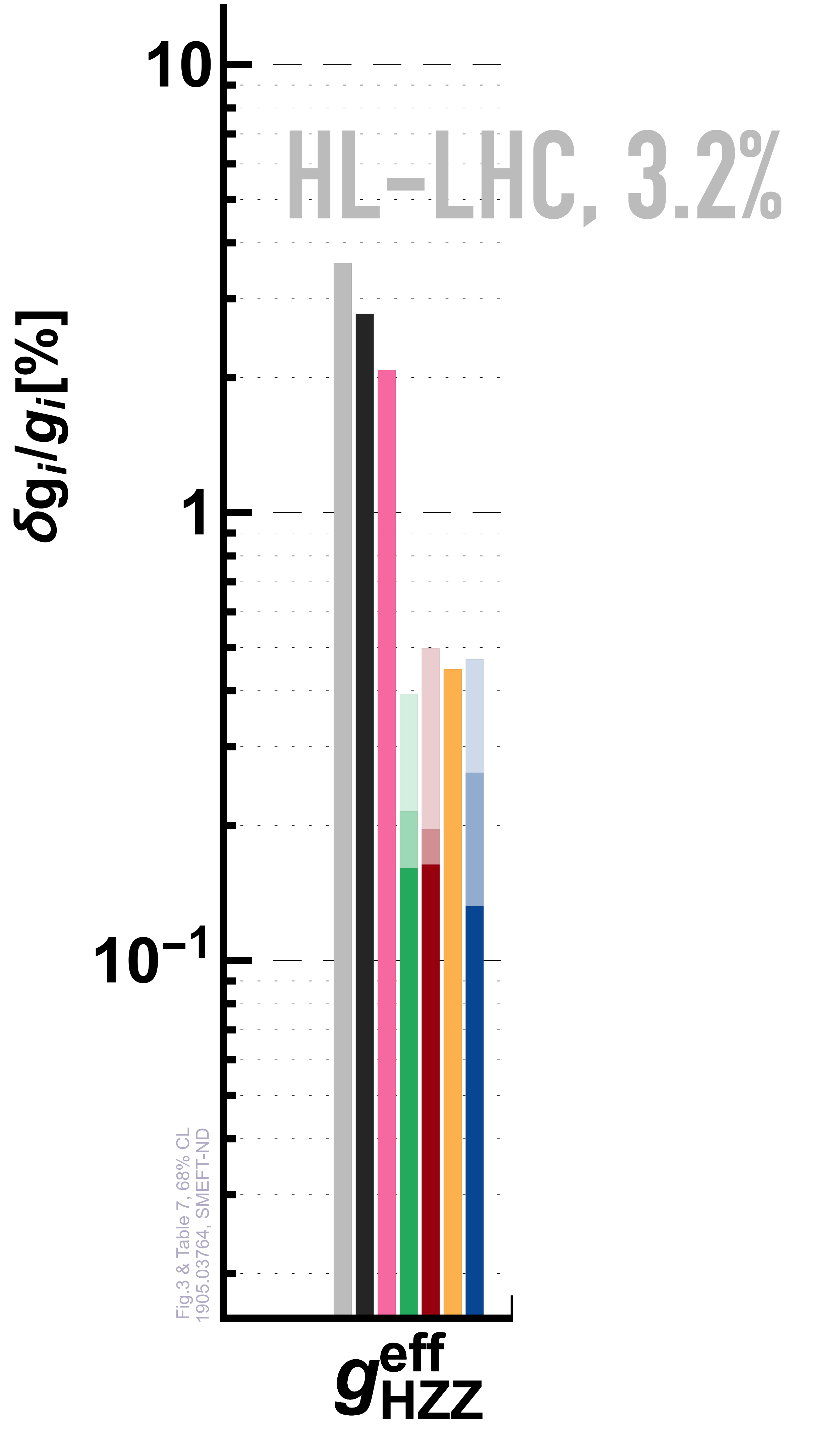
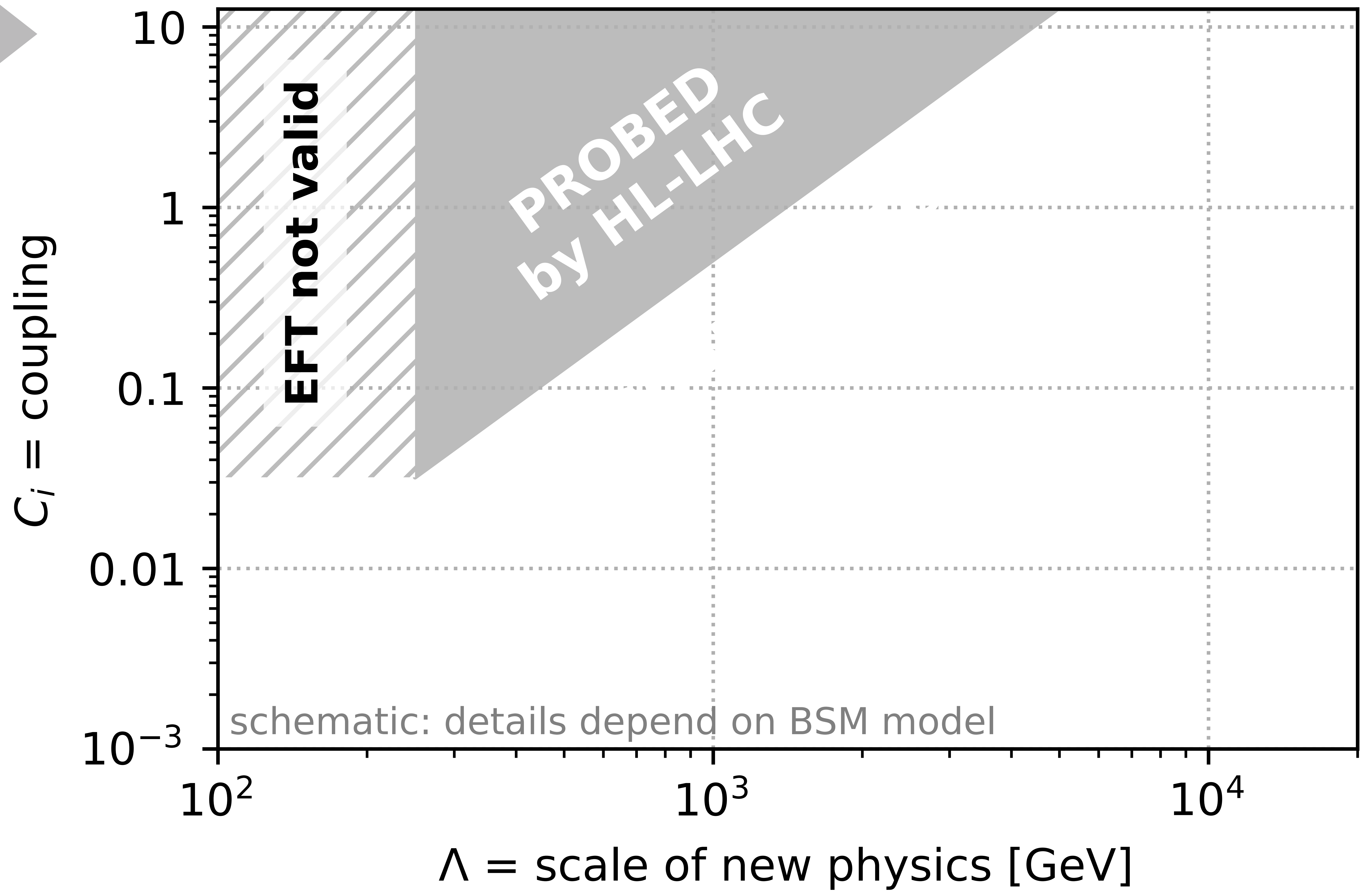


interpret as mass-coupling sensitivity



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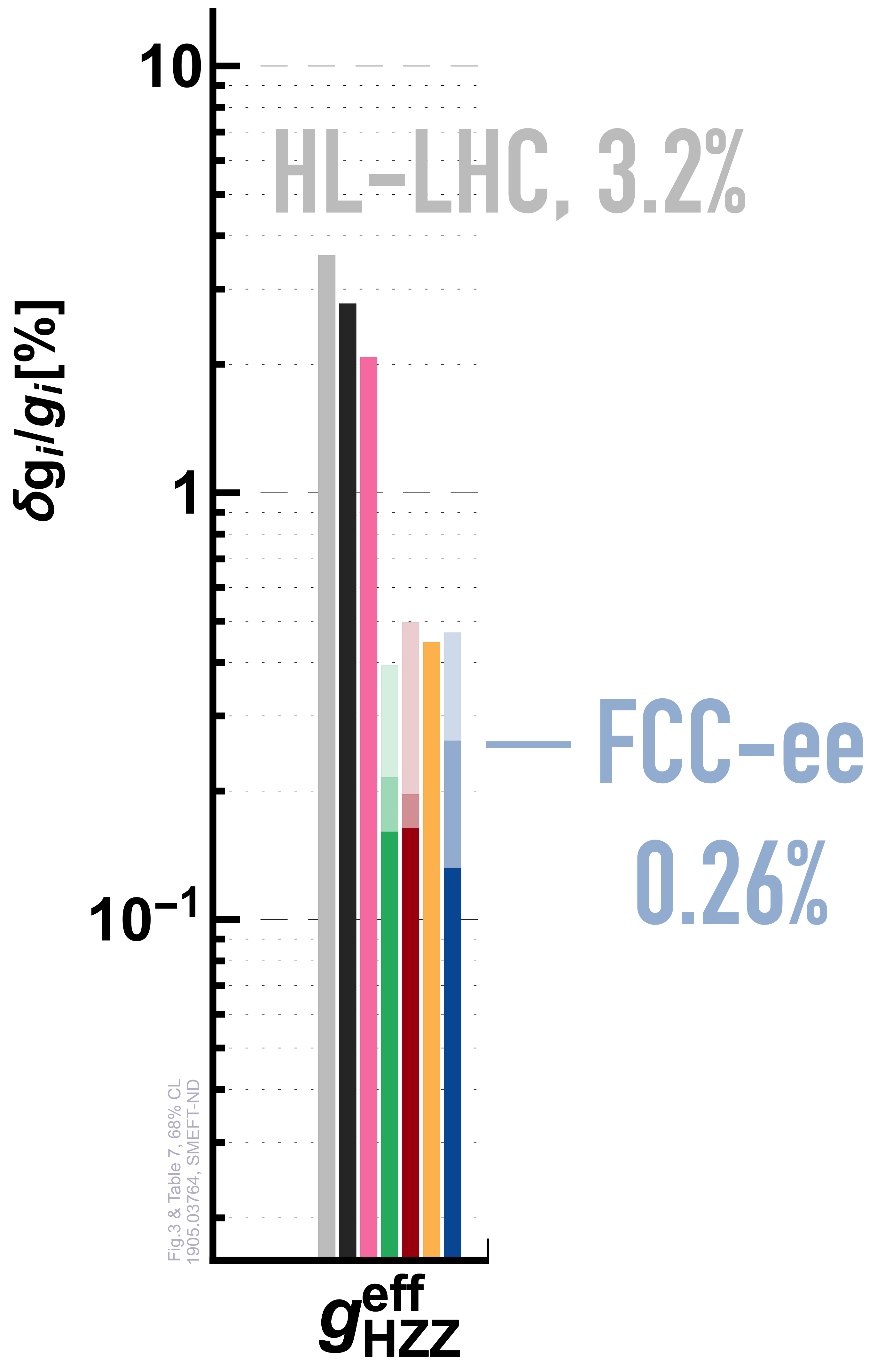

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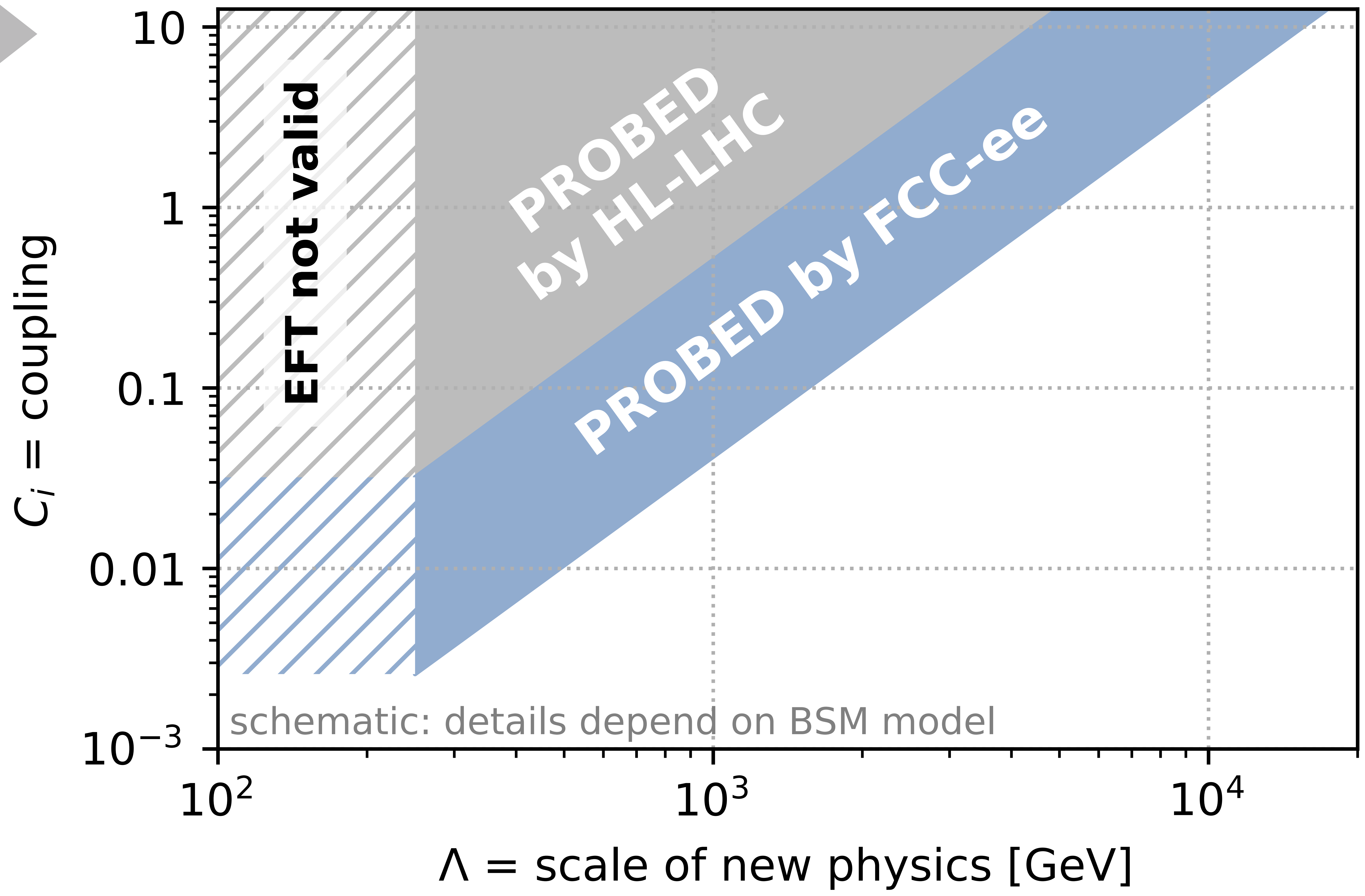

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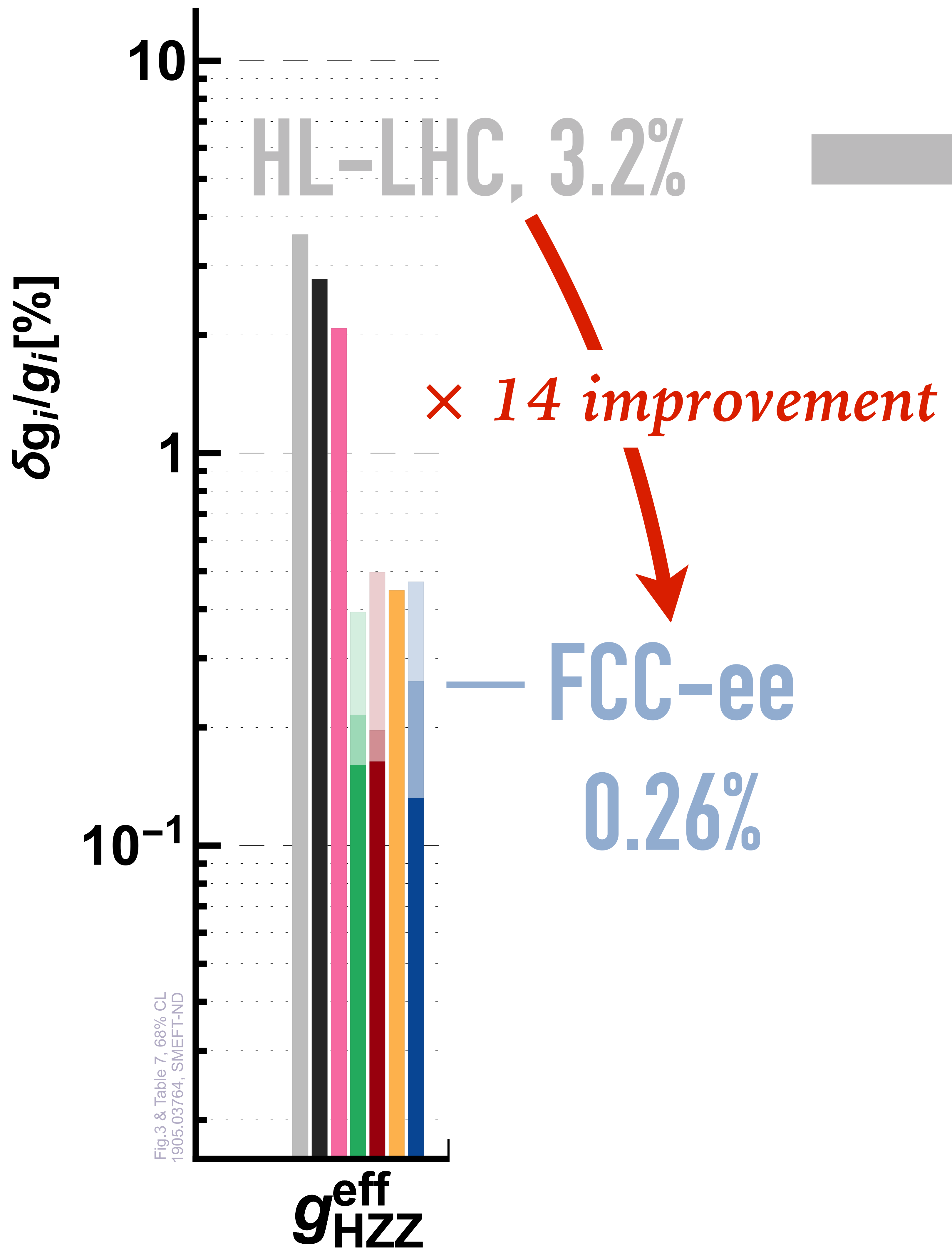
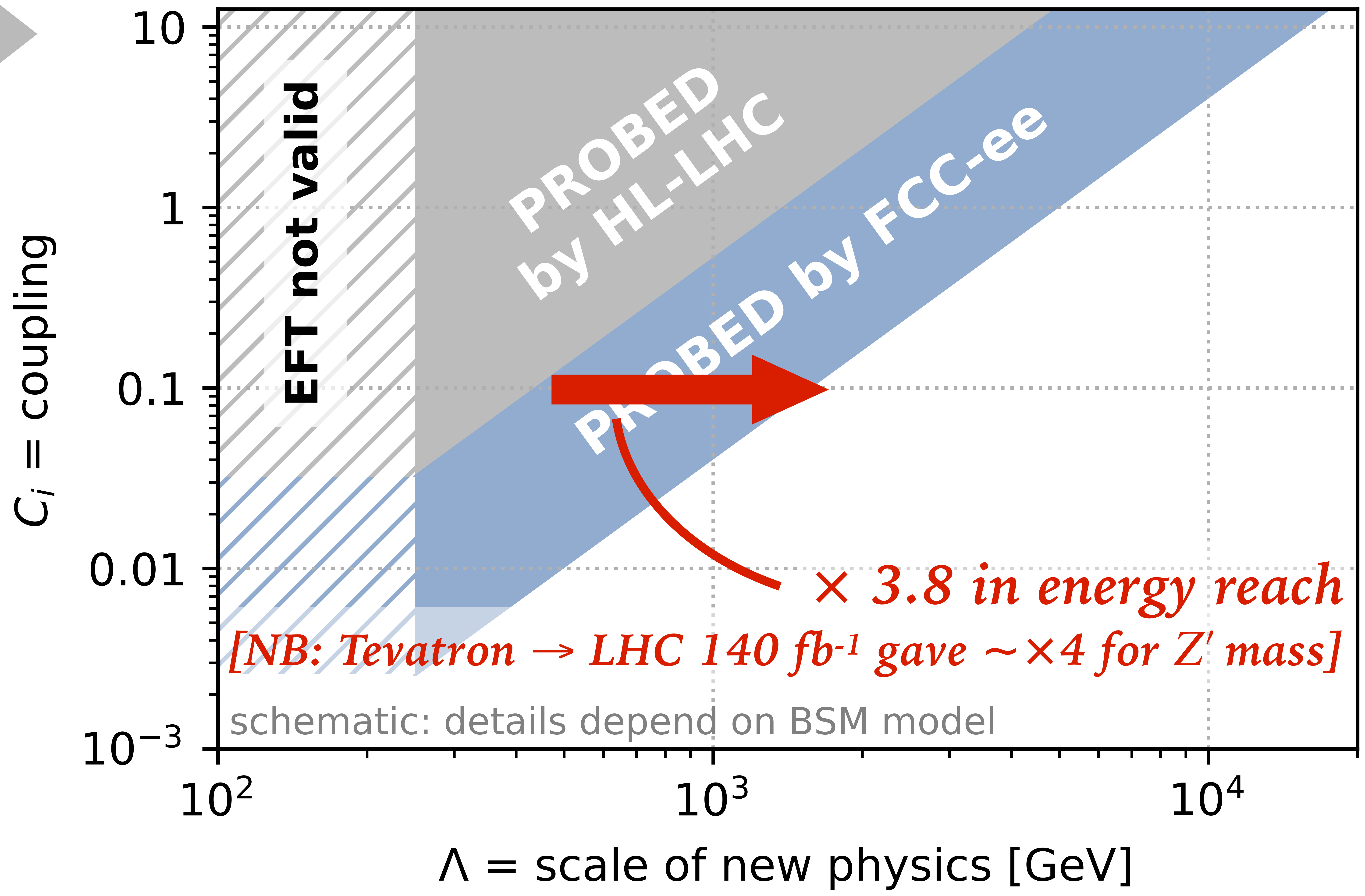


interpret as mass-coupling sensitivity



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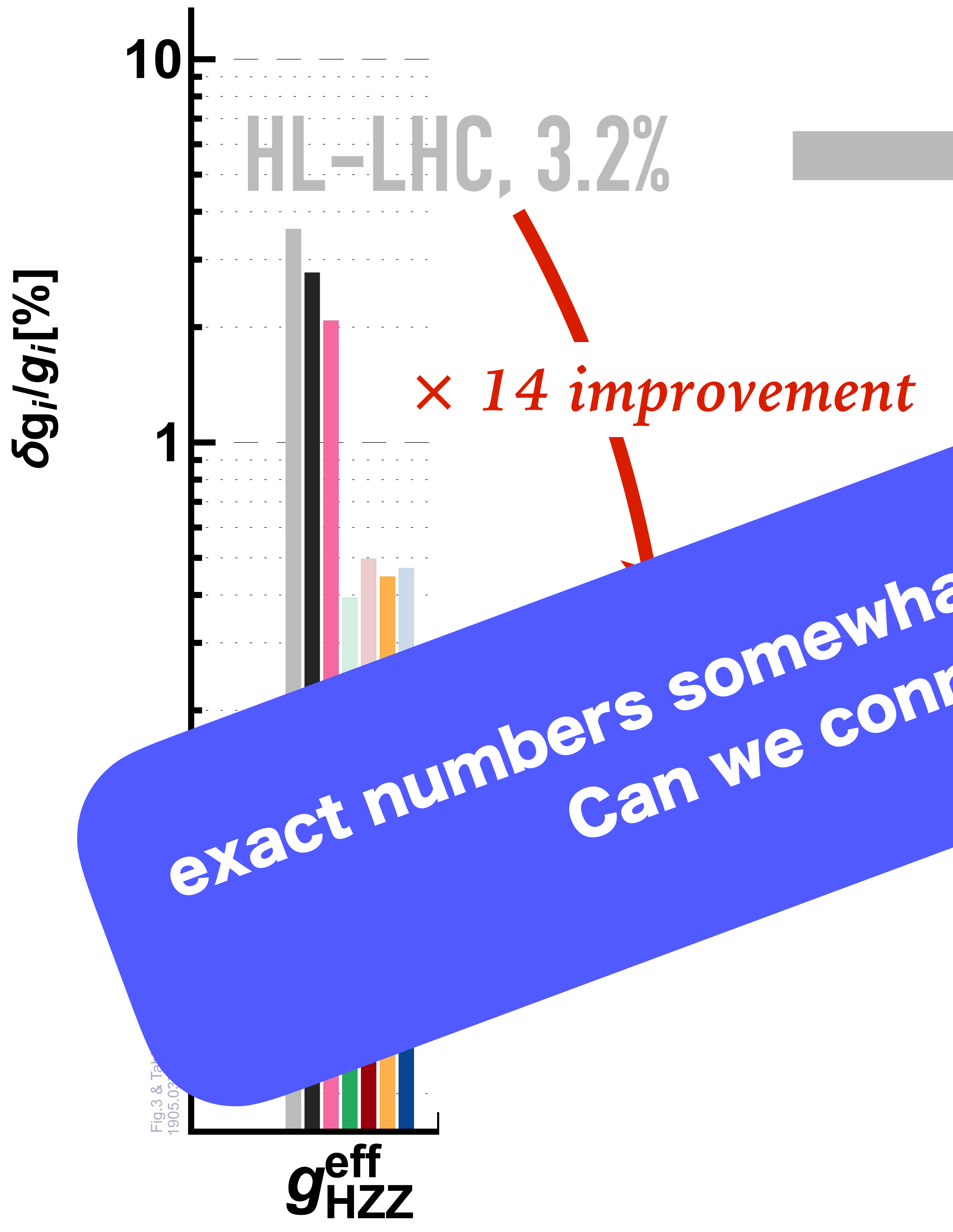
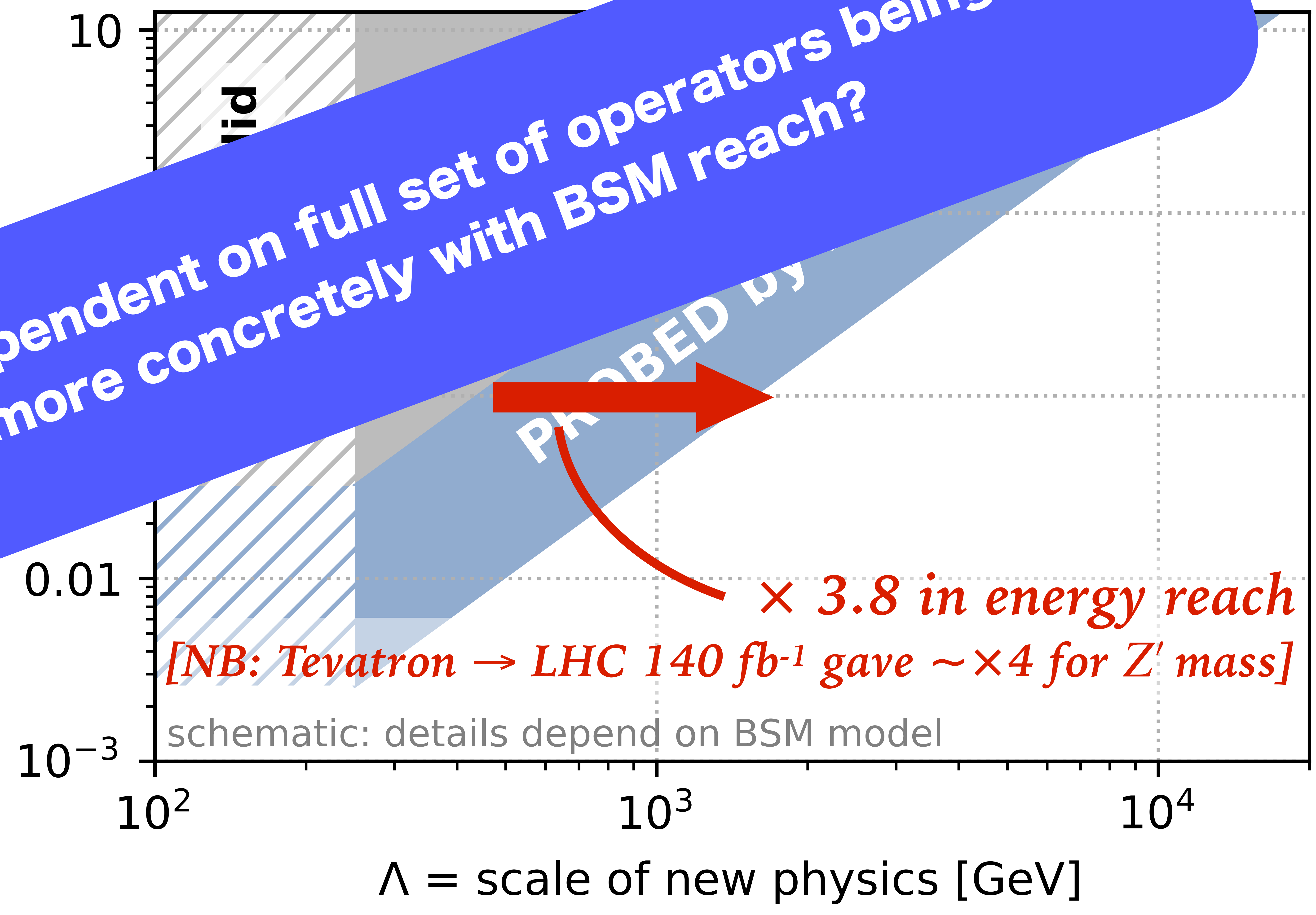
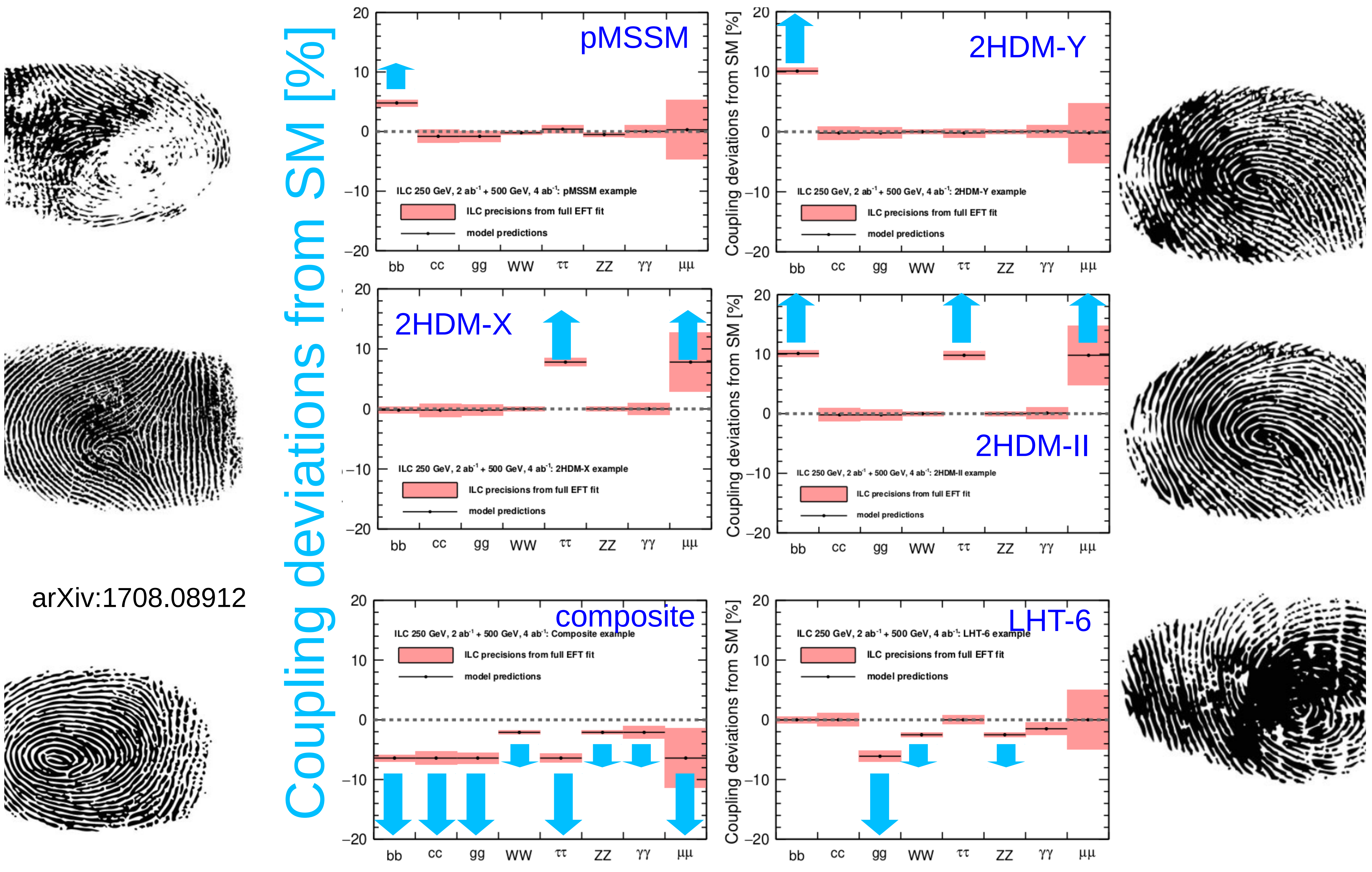


interpret as mass-co[...]ity



exact numbers somewhat dependent on full set of operators being fitted
Can we connect more concretely with BSM reach?

FCC will explore many operators ≡ many observables (incl. high-p_T @ FCC-hh)



arXiv:1708.08912

Pattern of deviations is “fingerprint” of new physics

Illustration from ILC studies (slide taken from D. Jeans @ ICHEP 2020)

Testing SM V(φ) by measuring HH production

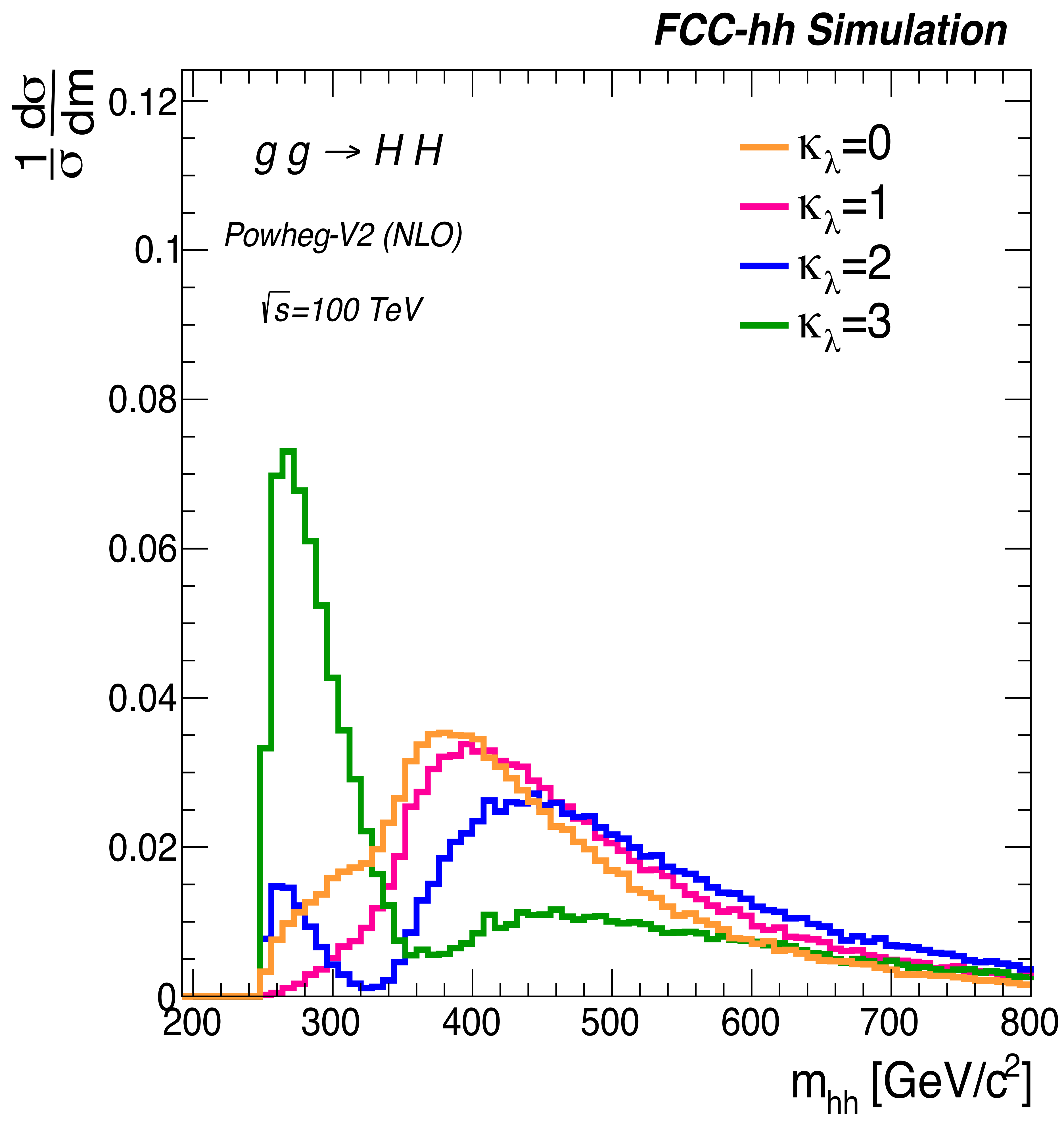
- Higgs self-interaction holds the SM together
- FCC-ee will also provide indirect constraints at @ ~20% level
- FCC-hh → few % determination
  (needs accurate $t\bar{t}Z$ and Higgs couplings from FCC-ee)

FCC-hh 68%cl precision (%) on double-Higgs production

	@68% CL	scenario I	scenario II	scenario III
δ_μ	stat only	2.2	2.8	3.7
	stat + syst	2.4	3.5	5.1
δ_{κ_λ}	stat only	3.0	4.1	5.6
	stat + syst	3.4	5.1	7.8

(optimistic ~ LHC Run 2 perf)

(30fb-1 @ 100 TeV, Mangano, Ortona & Selvaggi, 2004.03505)



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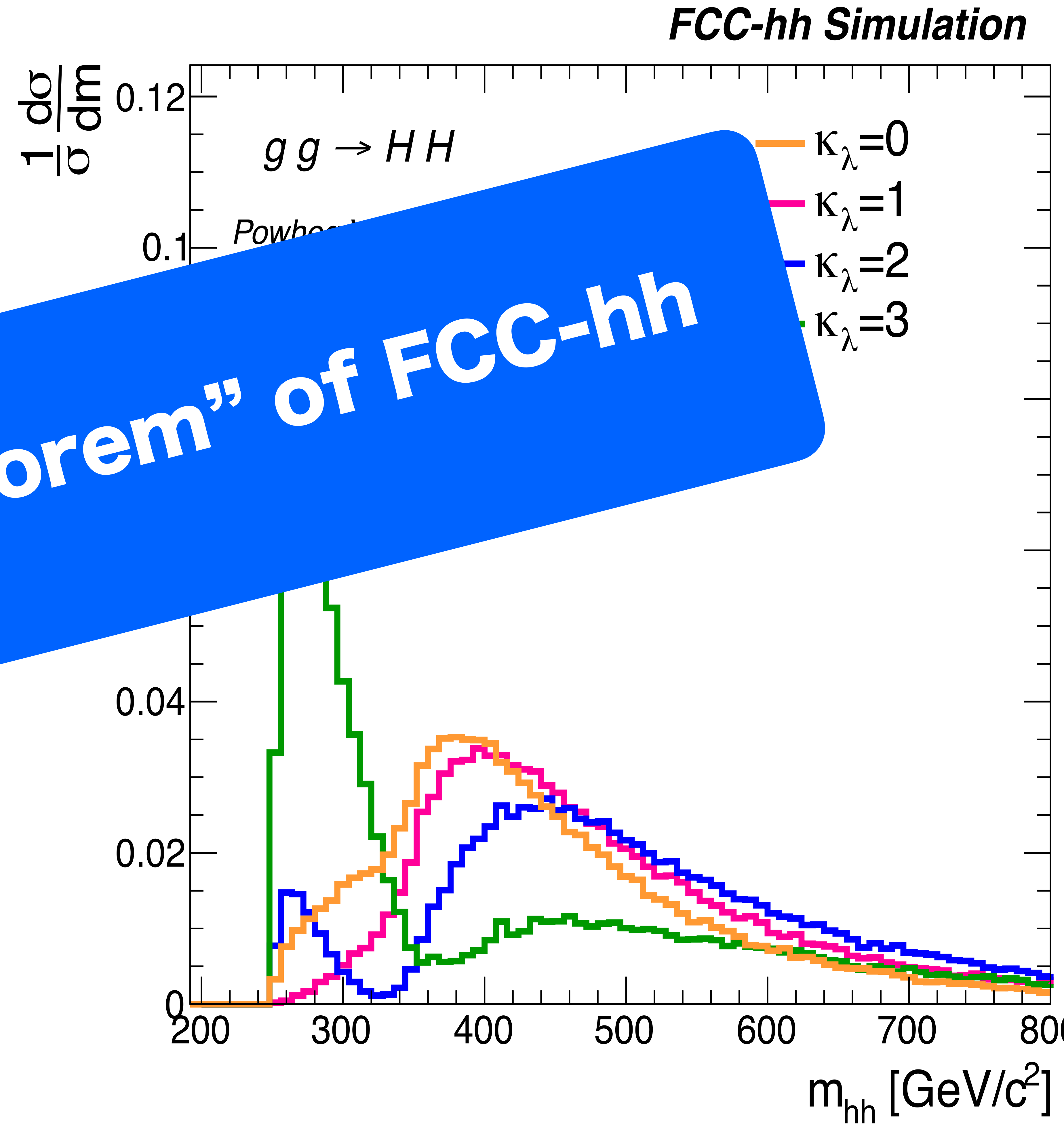
FCC-hh 68%cl precisi...

		@...			
δ_μ	s...				3.7
	st...			3.5	5.1
δ_{κ_λ}	st...		3.0	4.1	5.6
	stat + syst		3.4	5.1	7.8

(optimistic ~ LHC Run 2 perf)

(30fb-1 @ 100 TeV, | Mangano, Ortona & Selvaggi, 2004.03505)

my view: this is the “no-lose theorem” of FCC-hh



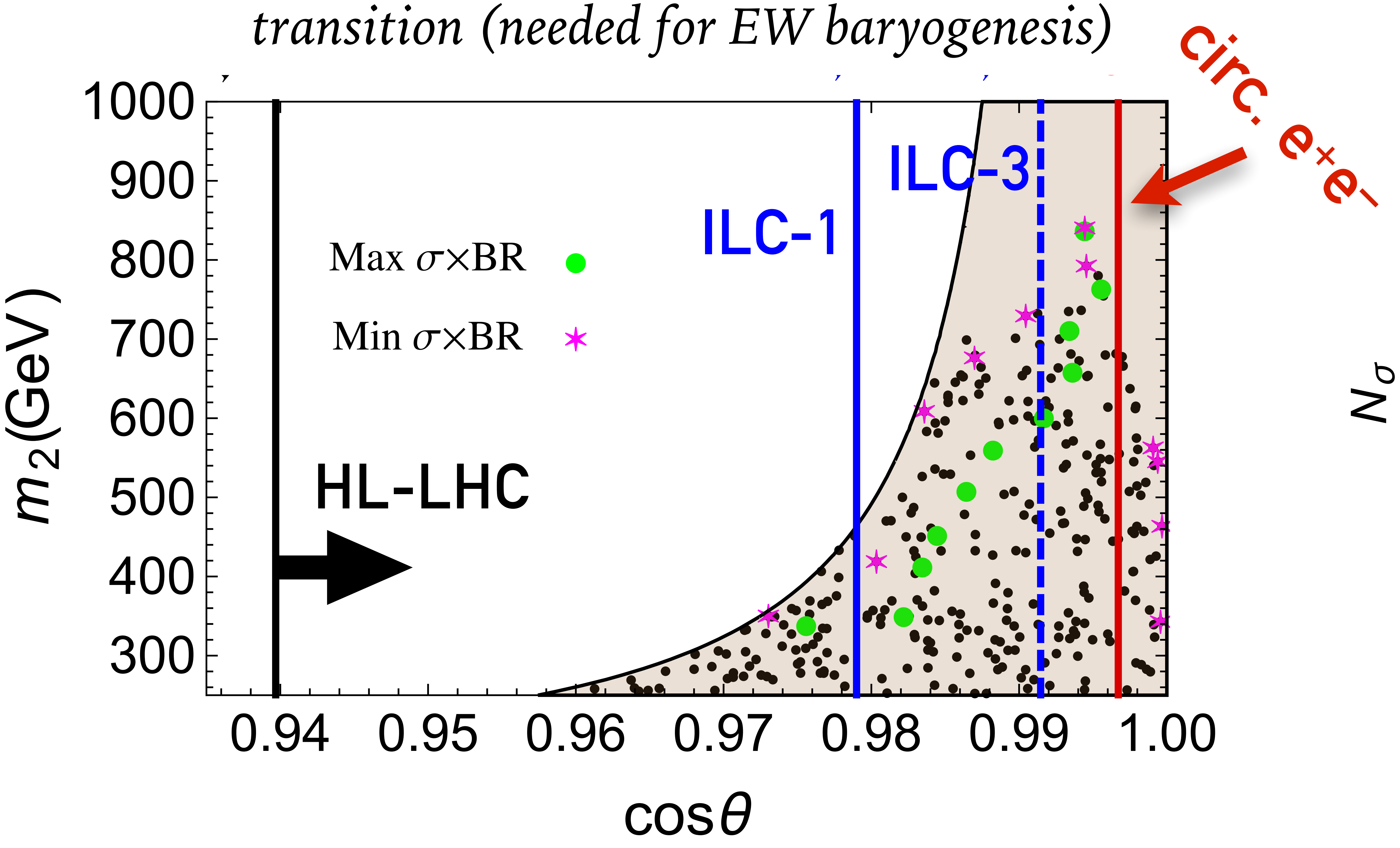
Direct BSM searches

*FCC-hh: ~****×5 in reach wrt HL-LHC across many hundred search channels*** *+ some interesting specific targets*

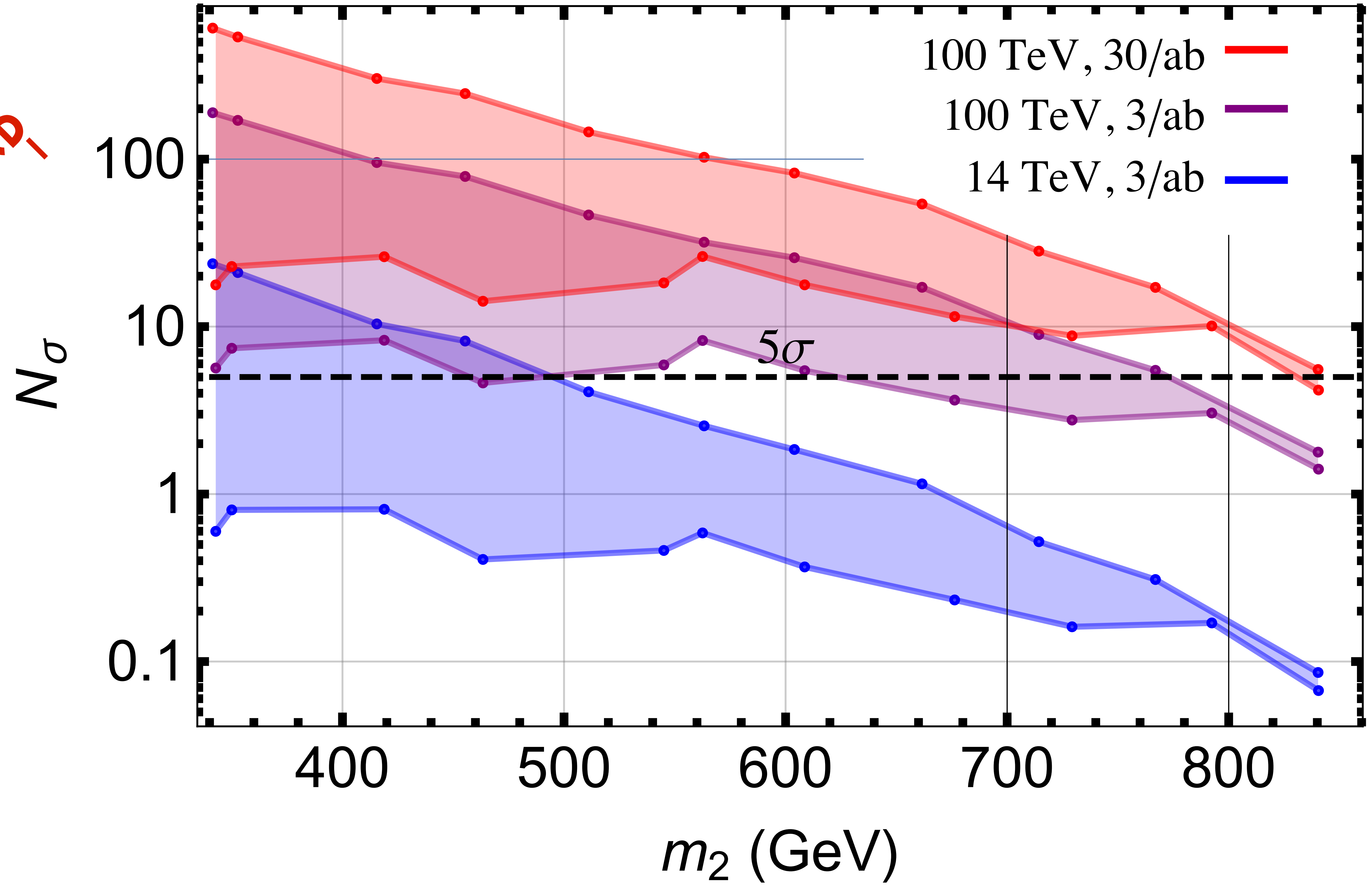
FCC-ee & FCC-eh: sensitivity to specific classes of models

Extension of SM with one extra scalar (“h_2”, gauge singlet)

precision constraints on all models (with $m_2 > 2m_1$) that give strong 1st-order EW phase transition (needed for EW baryogenesis)



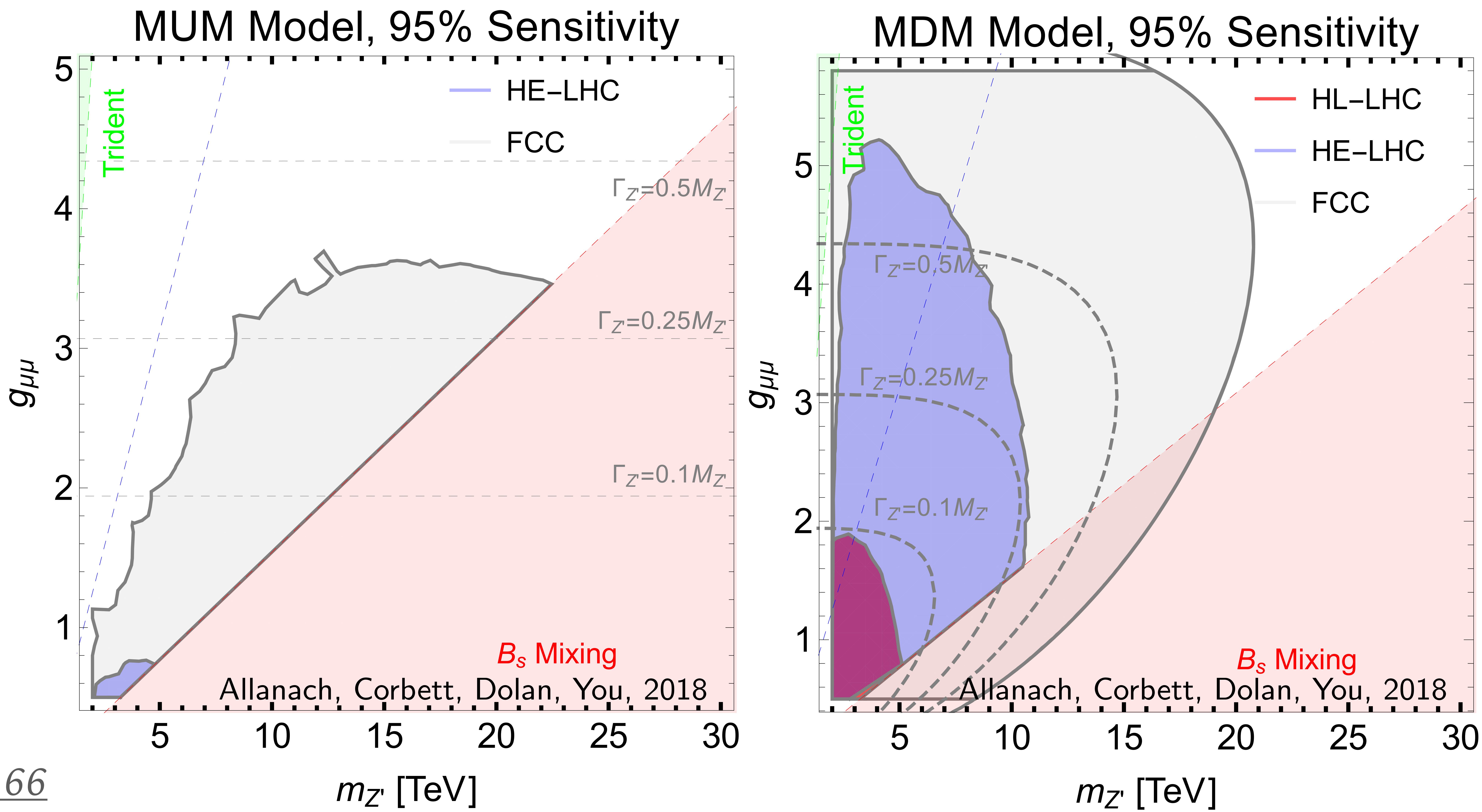
>5σ significance for discovery of (almost) all such models at FCC-hh



1605.06123

It is **important to take these conclusions somewhat impressionistically,** as we have made a number of simplifying assumptions in order to paint the broad picture.

FCC-hh: strong reach for some models to explain $B \to K\ell\ell$ anomalies



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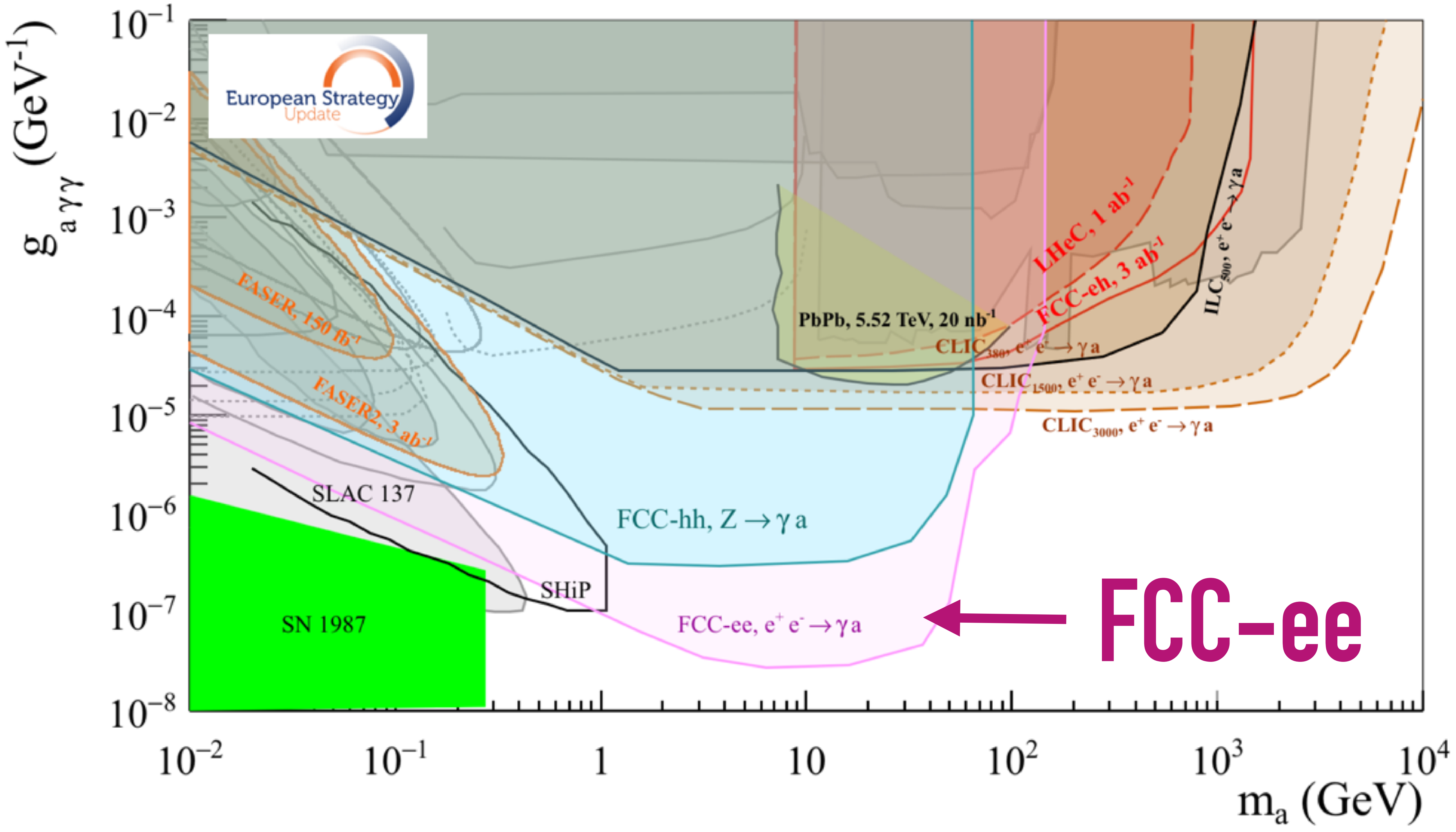
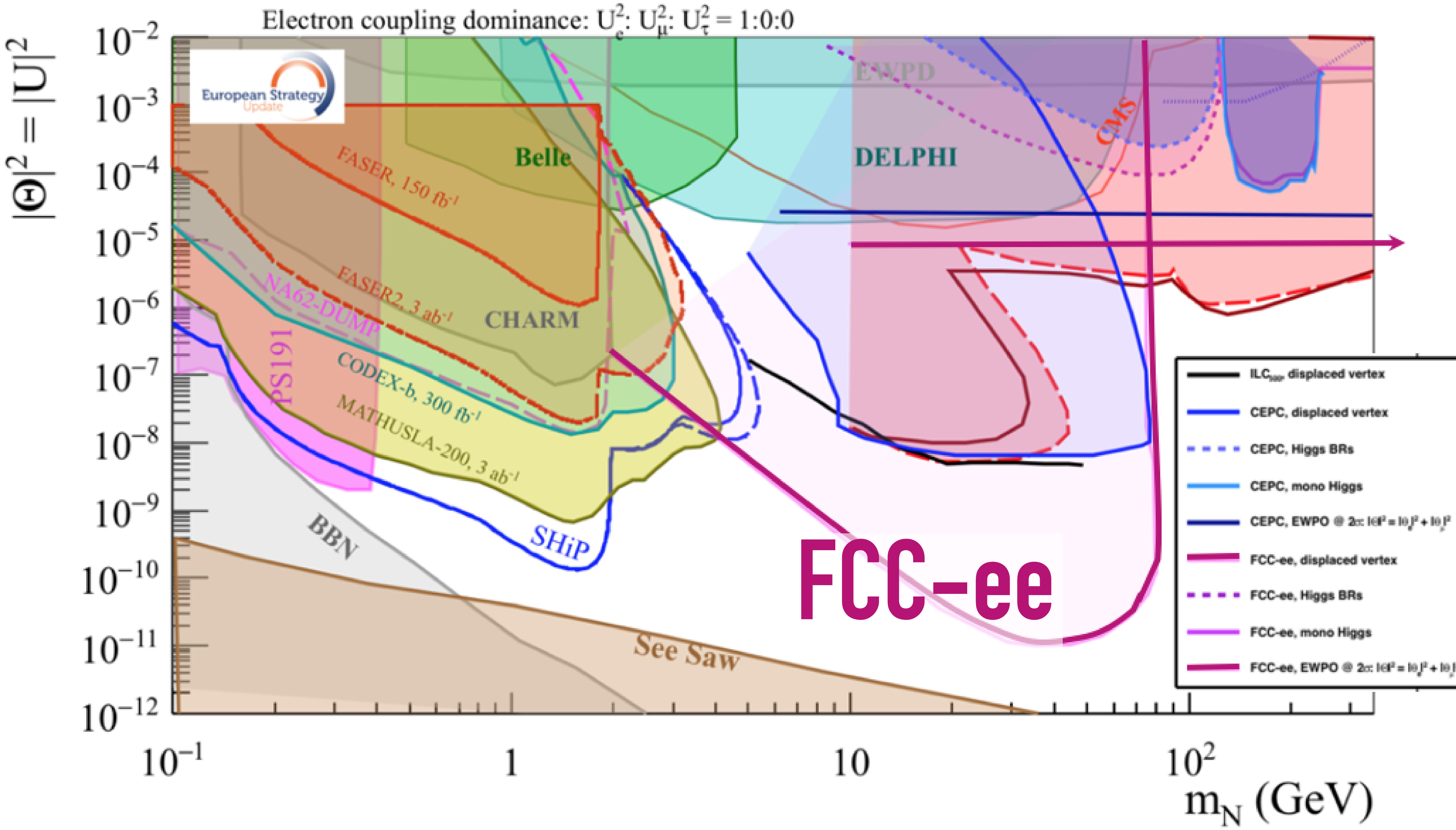
FCC-ee, e.g. axion and heavy-neutral lepton searches





benefits from huge Z-pole luminosity
(some models in these regions have potential to connect with dark matter, baryond asymmetry, neutrino masses, etc.)

Flavour physics

besides quark-flavour physics illstrated in next slides

there's also a strong τ-physics programme

(cf. arXiv:2107.12832)

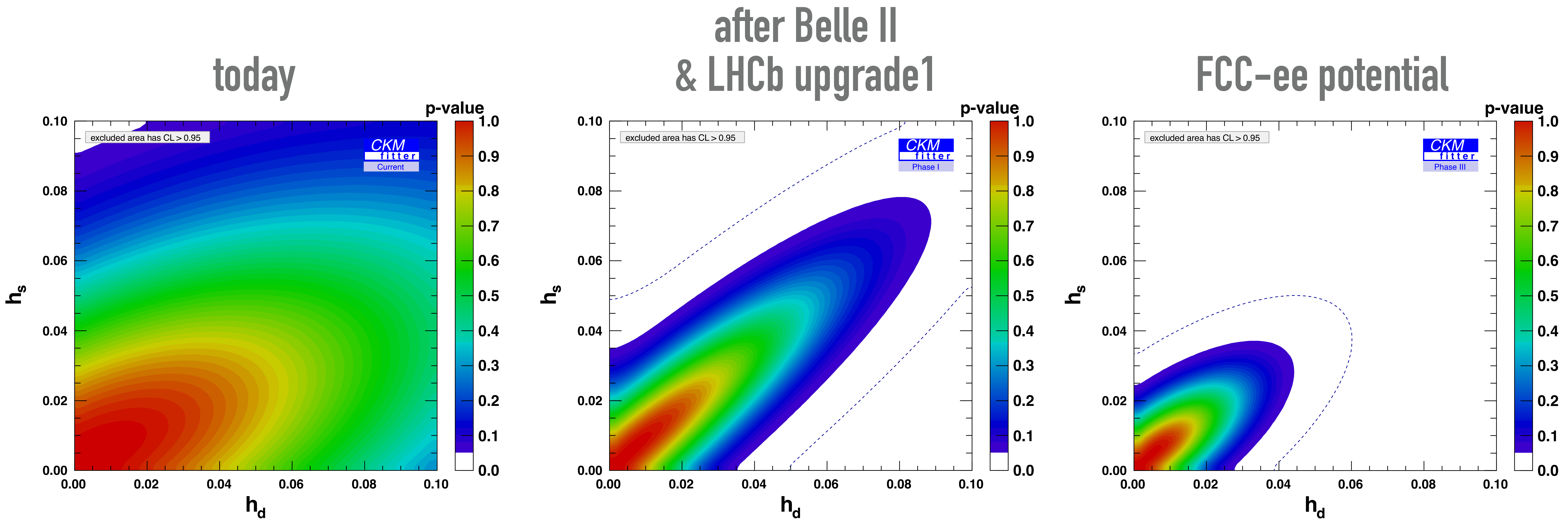
15× more b-pairs at FCC-ee than at Belle II

2106.01259

FCC-ee

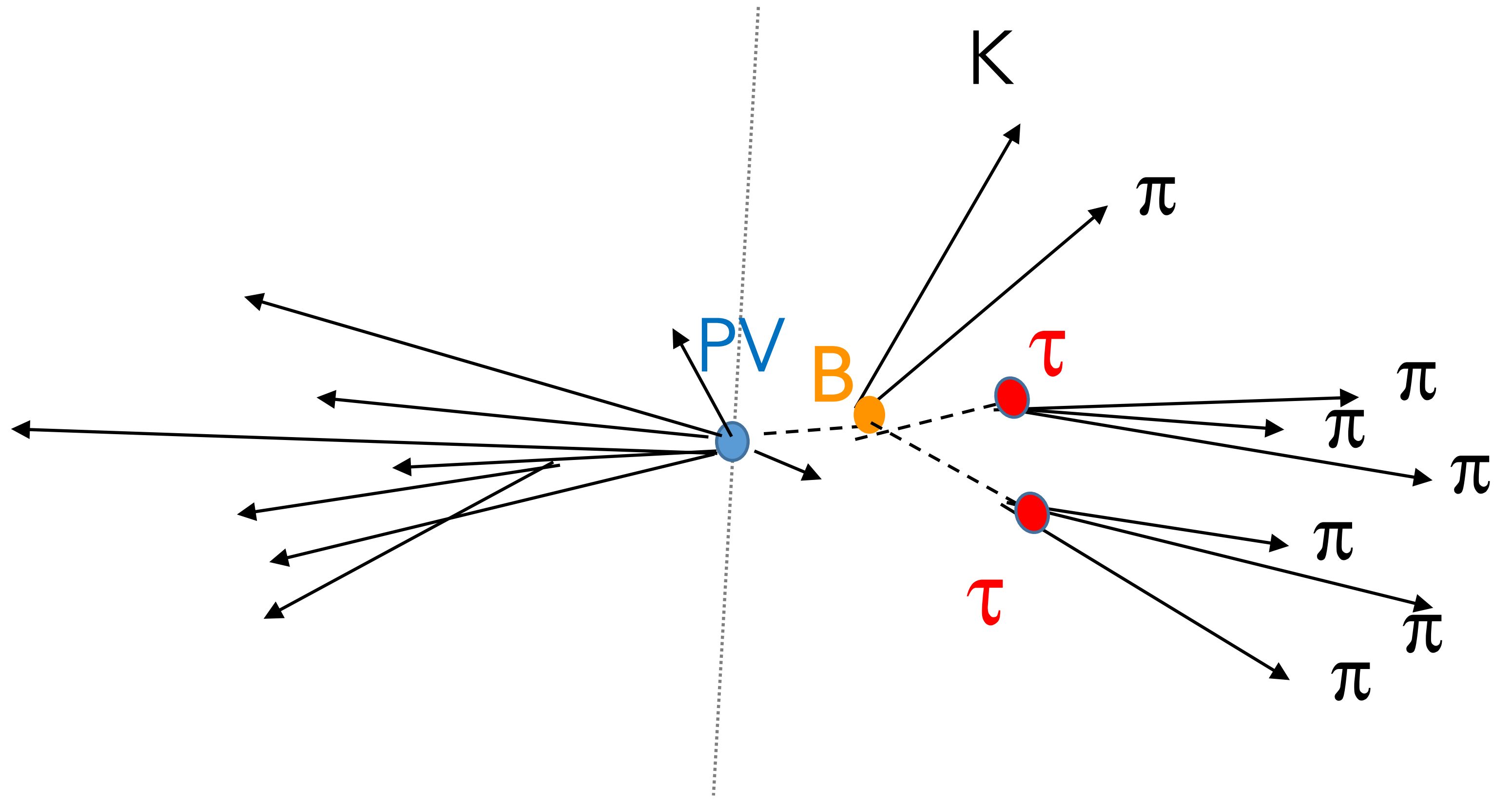
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

h_d and h_s (BSM contributions to $B^0 - \bar{B}^0$ and $B_s^0 - \bar{B}_s^0$ mixing)

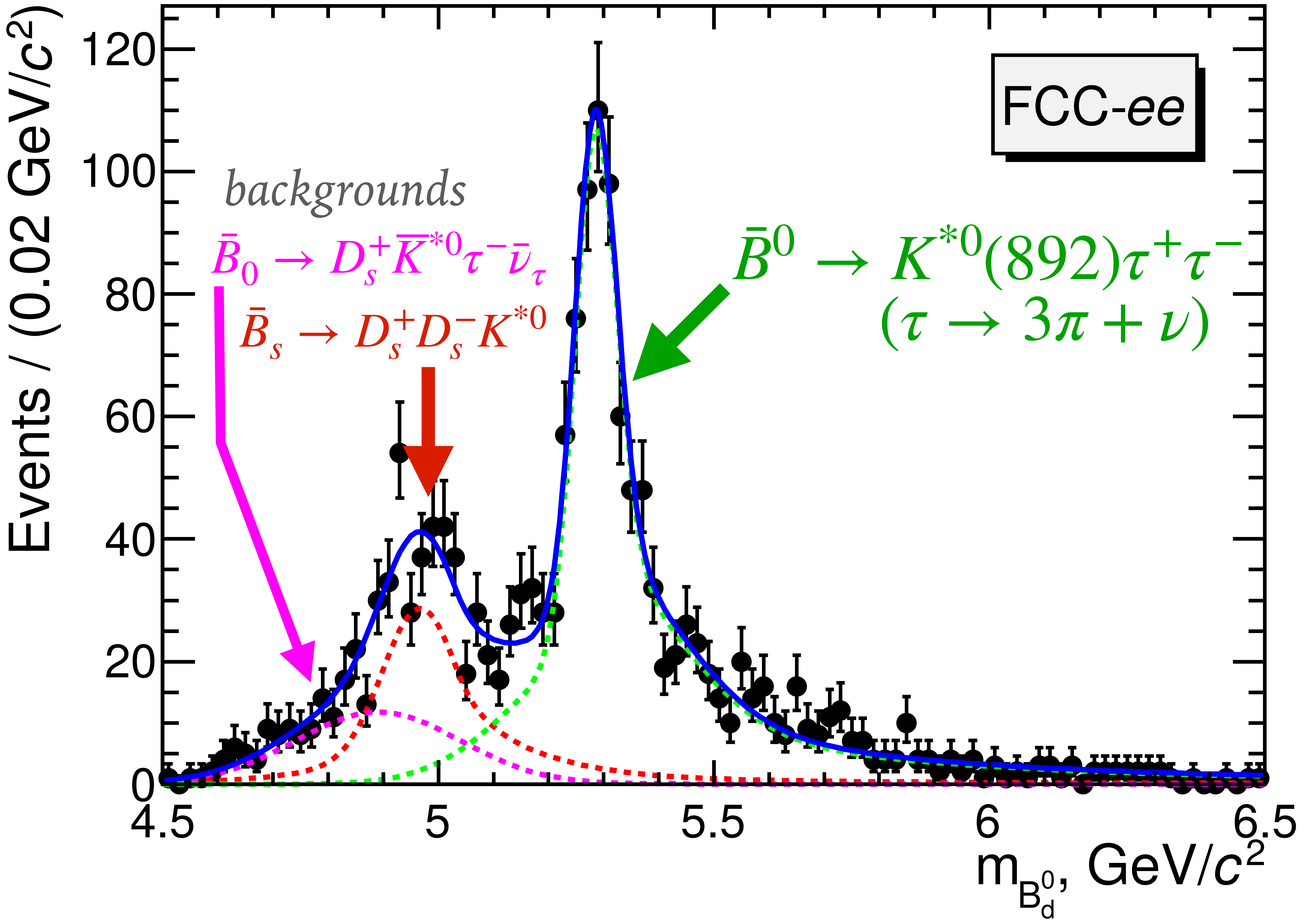


in light of flavour anomalies: FCC-ee is unique place to study $B^0 \to K^* \tau\tau$

Search for $B^0 \to K^* \tau\tau$ arXiv:1705.11106



(NB:plot is for 10^{13} Z's)



Z-pole, WW and ttbar FCC-ee

EW & top precision

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
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
$\sin^2\theta_W^{\rm eff} (\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu (\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^{b}, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
$A_{FB}^{\rm pol,\tau}$ $(\times 10^4)$	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
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
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

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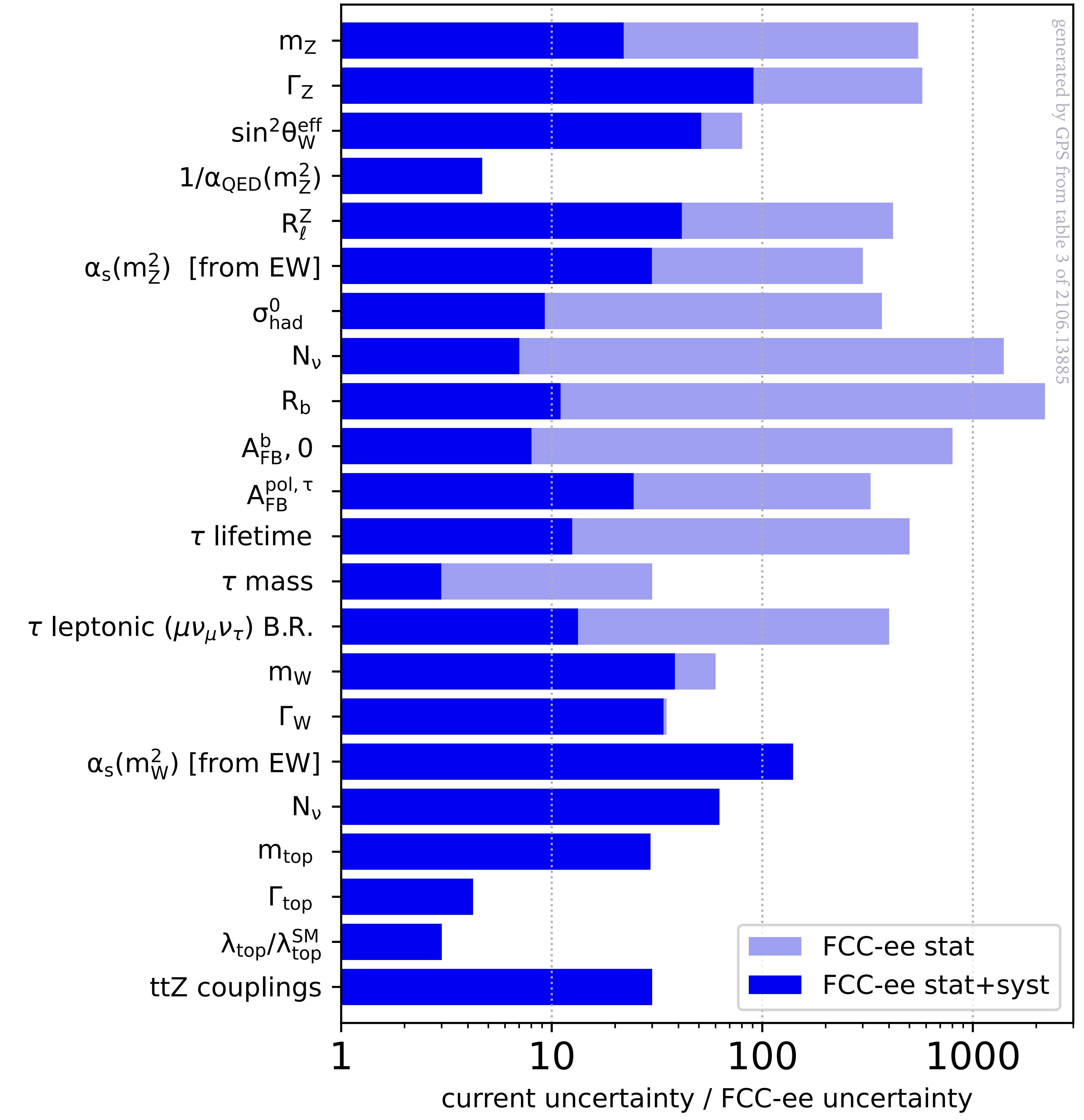
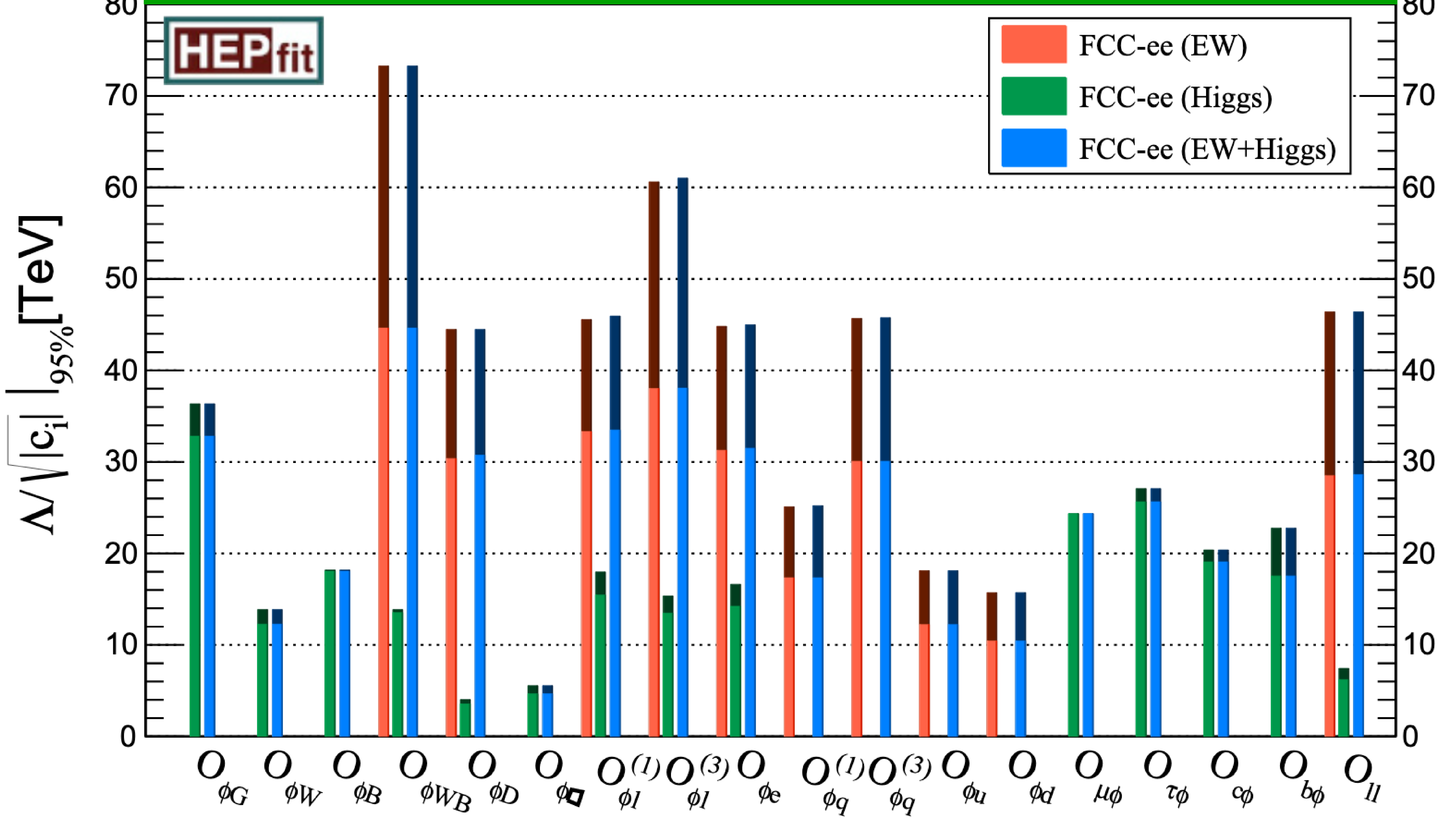
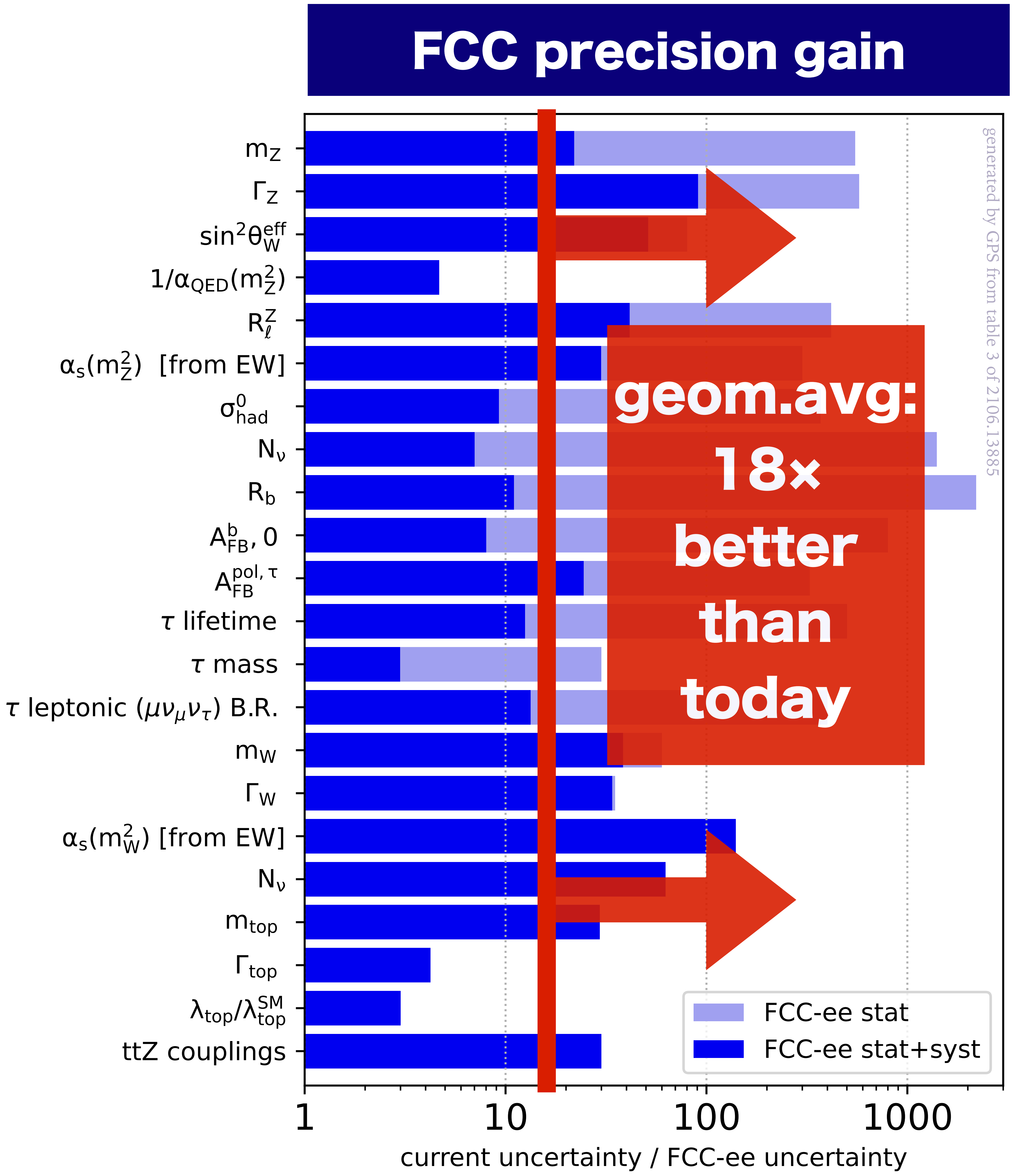
FCC precision gain



maximum scale probed indirectly — up to 70 TeV





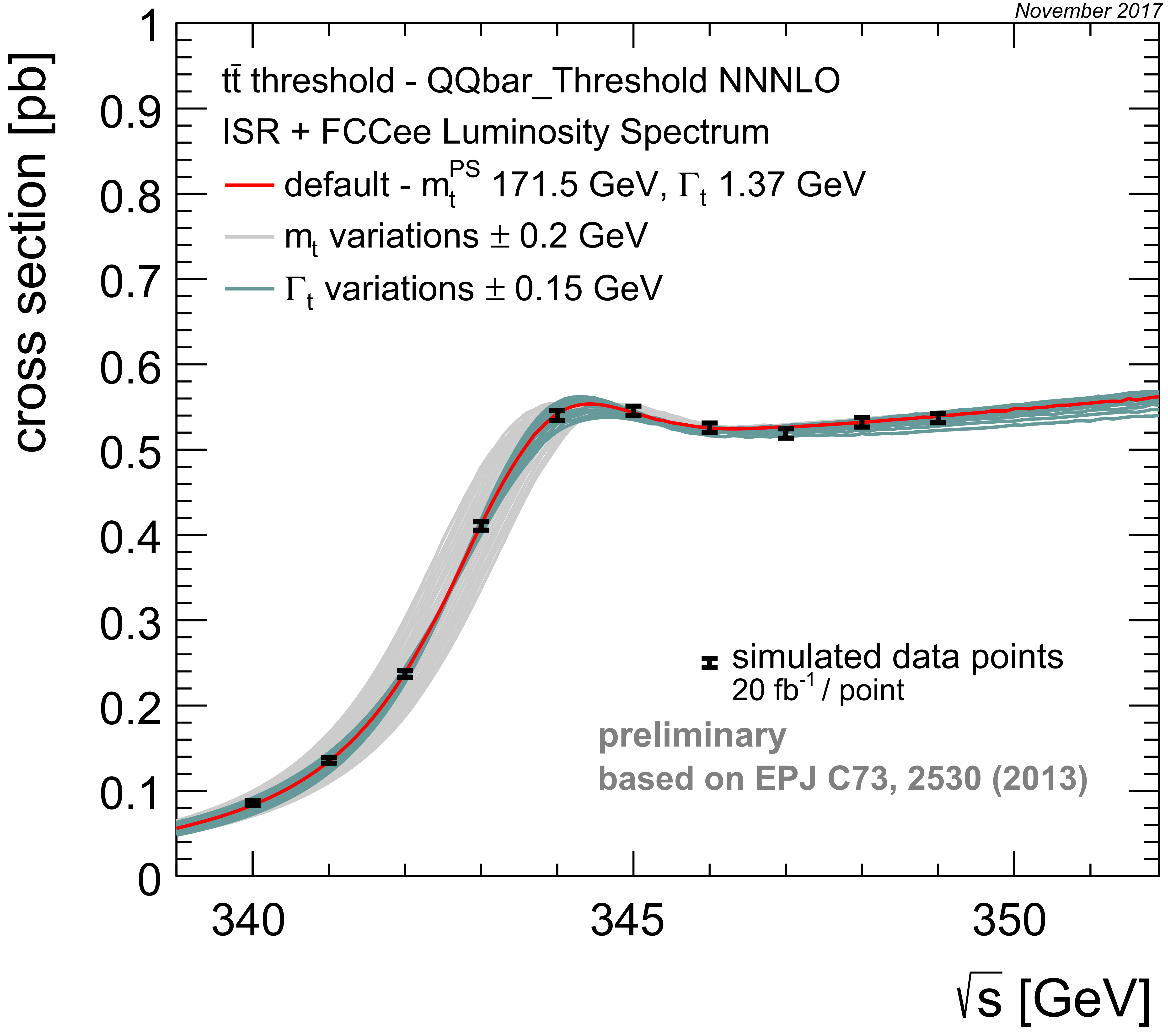
Two messages

- with a rough estimate for systematics, FCC brings a big step forward (geom.avg. = × 18, across ≳ 20 observables)
- still huge scope for thinking about how to improve systematics (gain of up to further × 100 in some cases)

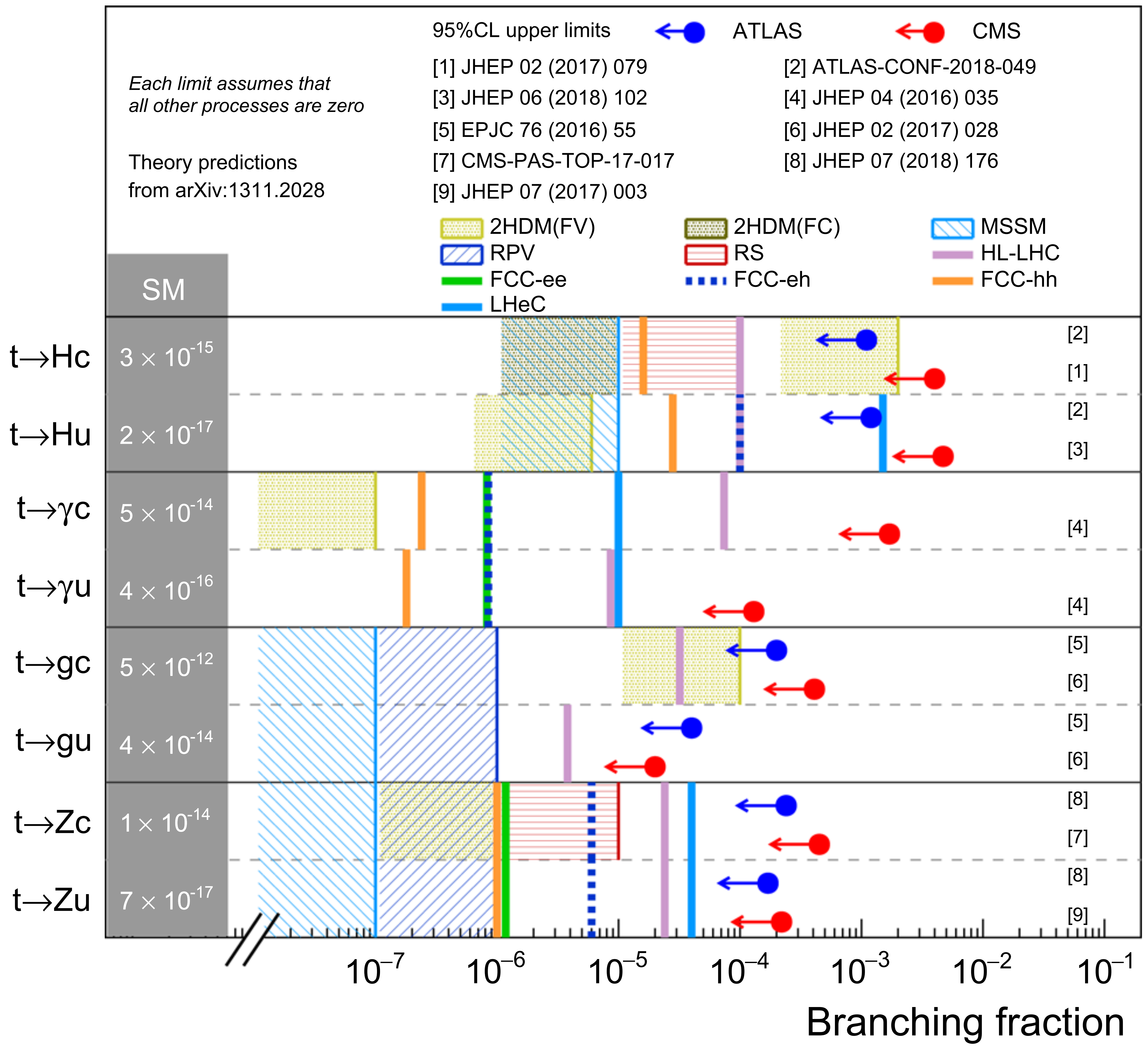
This is the fun part for us as physicists!

and will call for joint efforts by experiment/theory/accelerator physicists

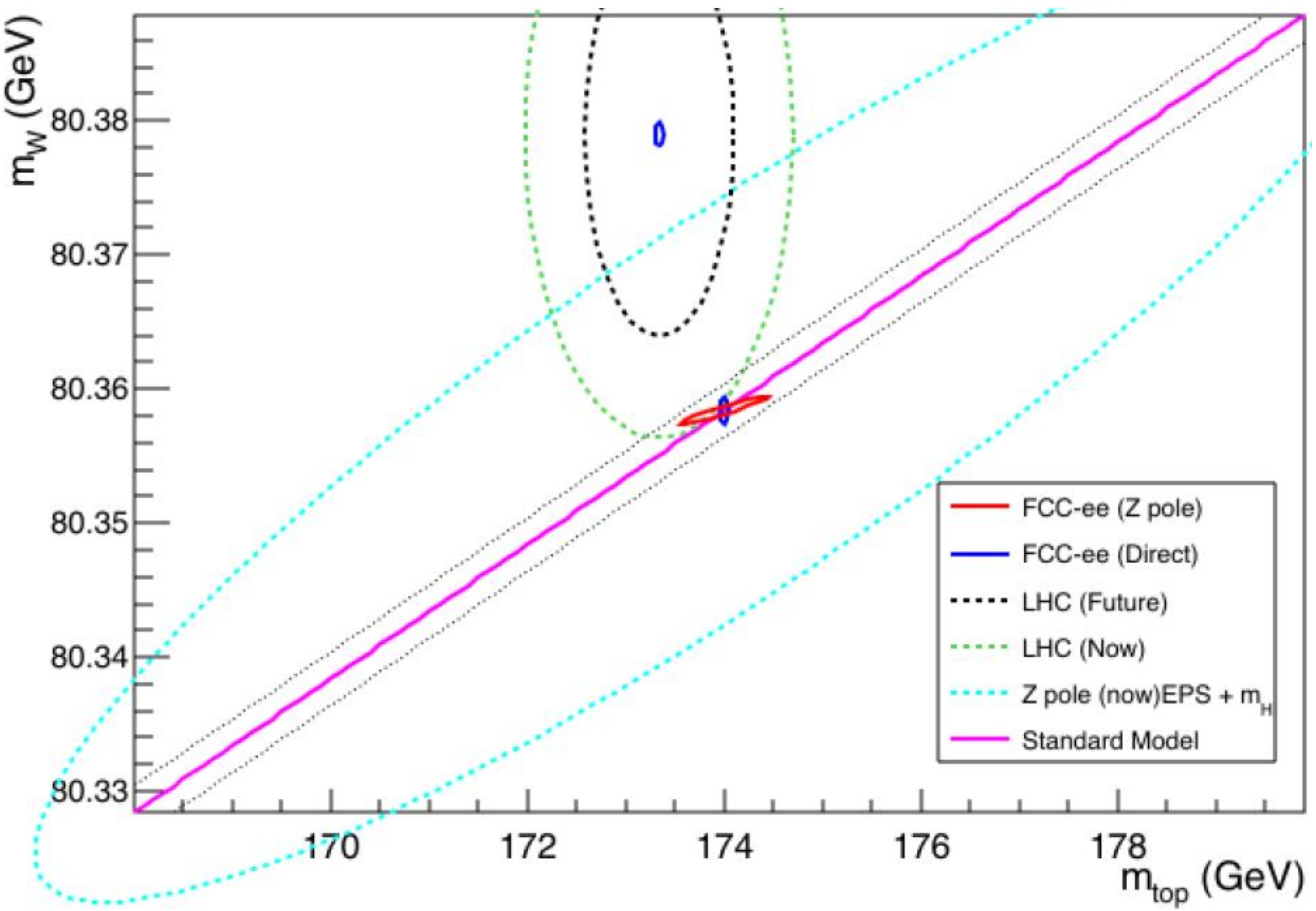
threshold scan for top mass



limits on top FCNF

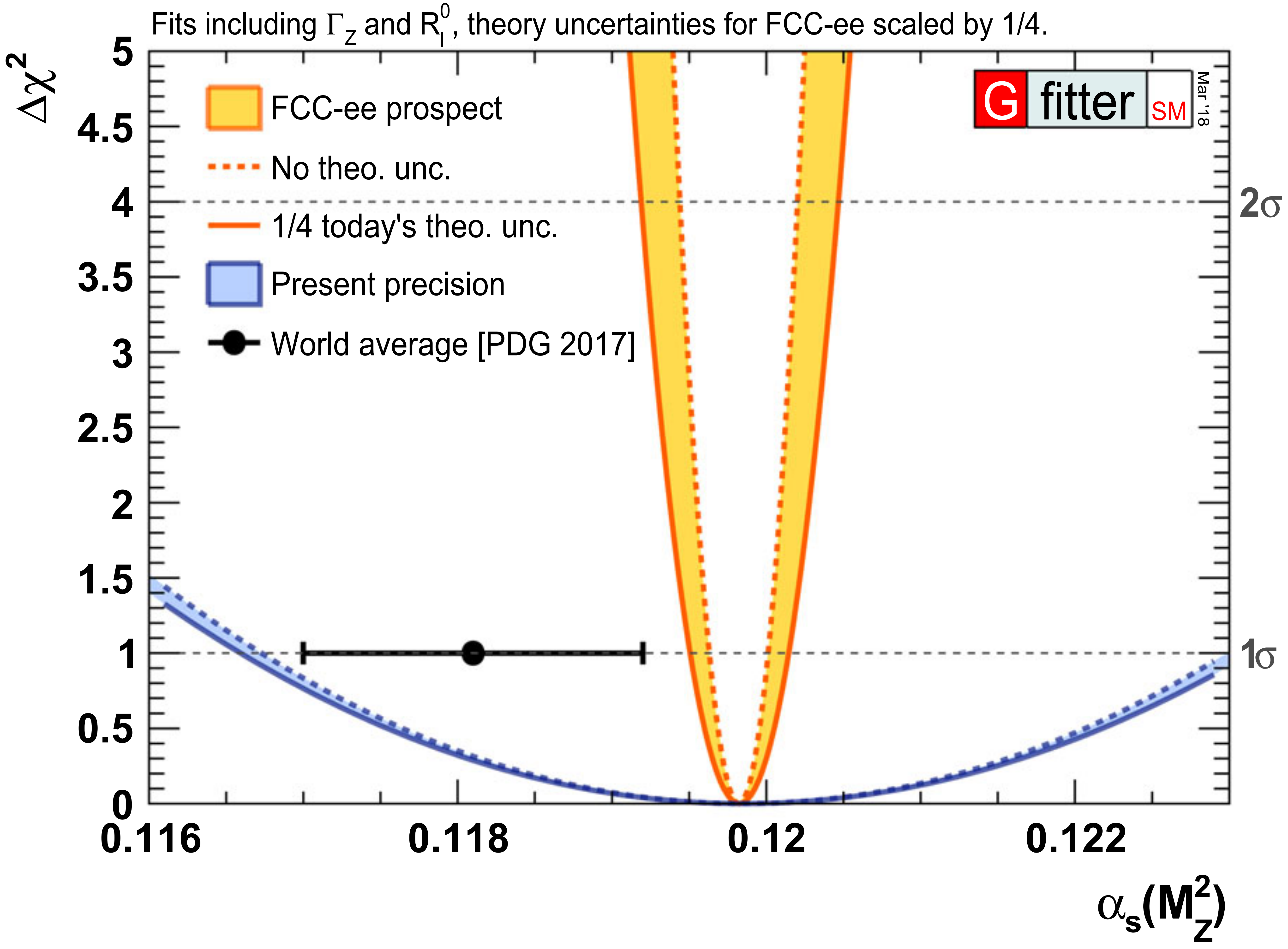


Status of closure test after Z, W^+W^- and $t\bar{t}$ runs



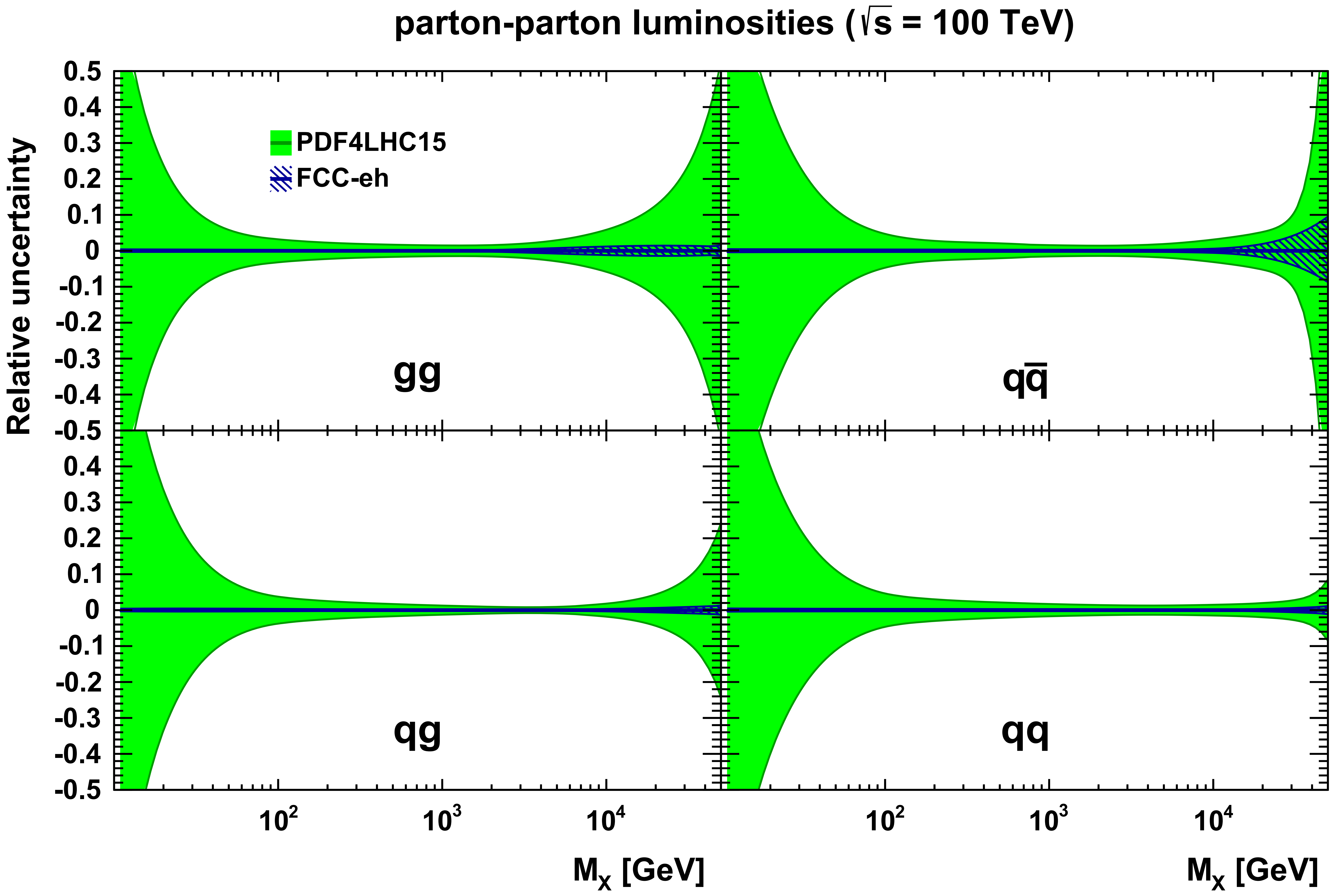
strong interactions

FCC-ee: strong coupling, etc.



- strong coupling from EW precision to per-mil accuracy
- studies of colour reconnection in W-pair events
- jet rates, substructure, flavour, fragmentation
- etc.

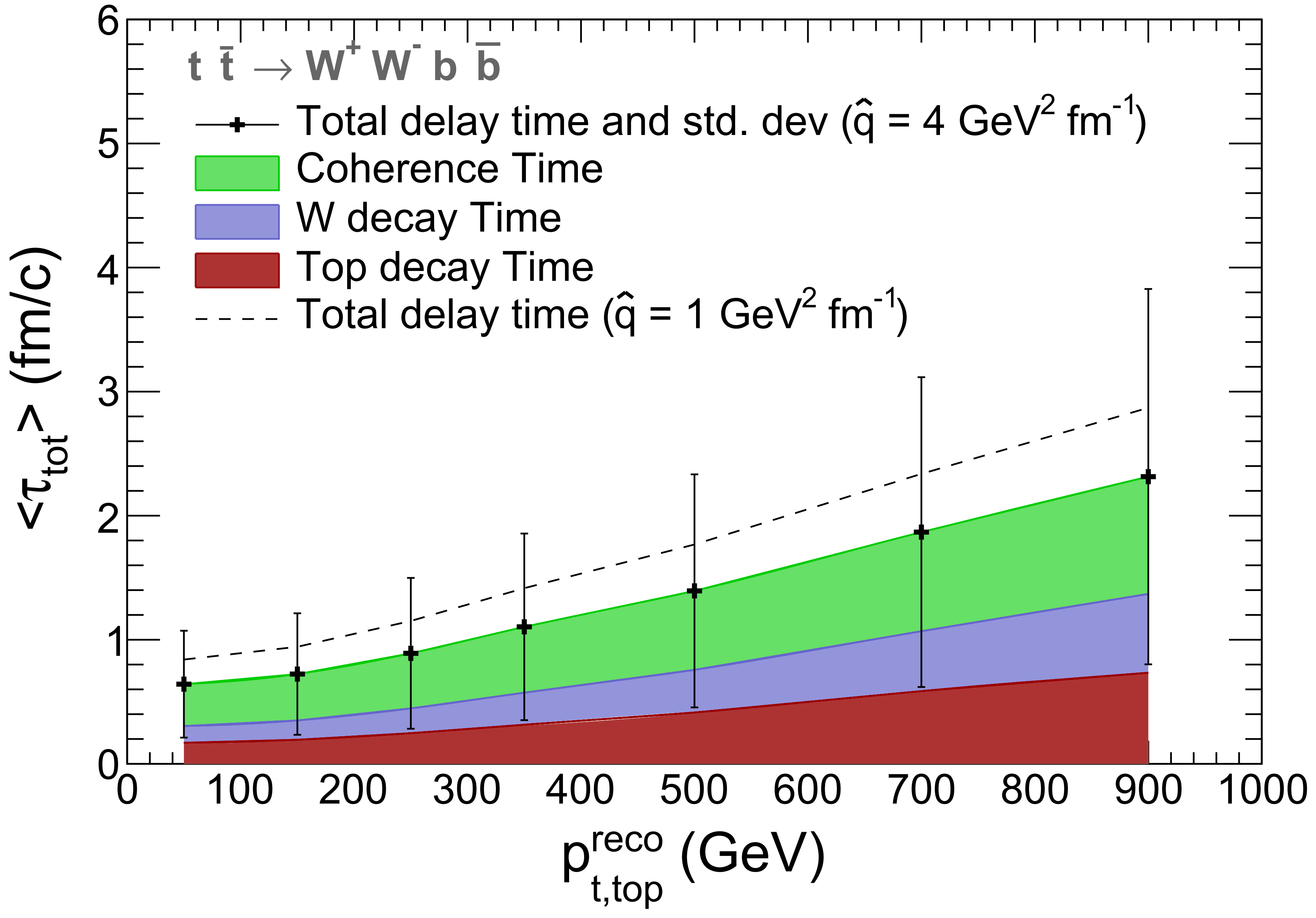
FCC-eh: huge improvement partonic luminosities



PDFs from FCC-eh are potentially crucial for full exploitation of FCC-hh physics programme.

NB: at this level of precision, one may start worrying about non-perturbative contributions in PDF fits to moderate-Q^2 DIS data

FCC-hh PbPb collisions: top & W decays probe q/g-plasma across yoctosecond time-scales



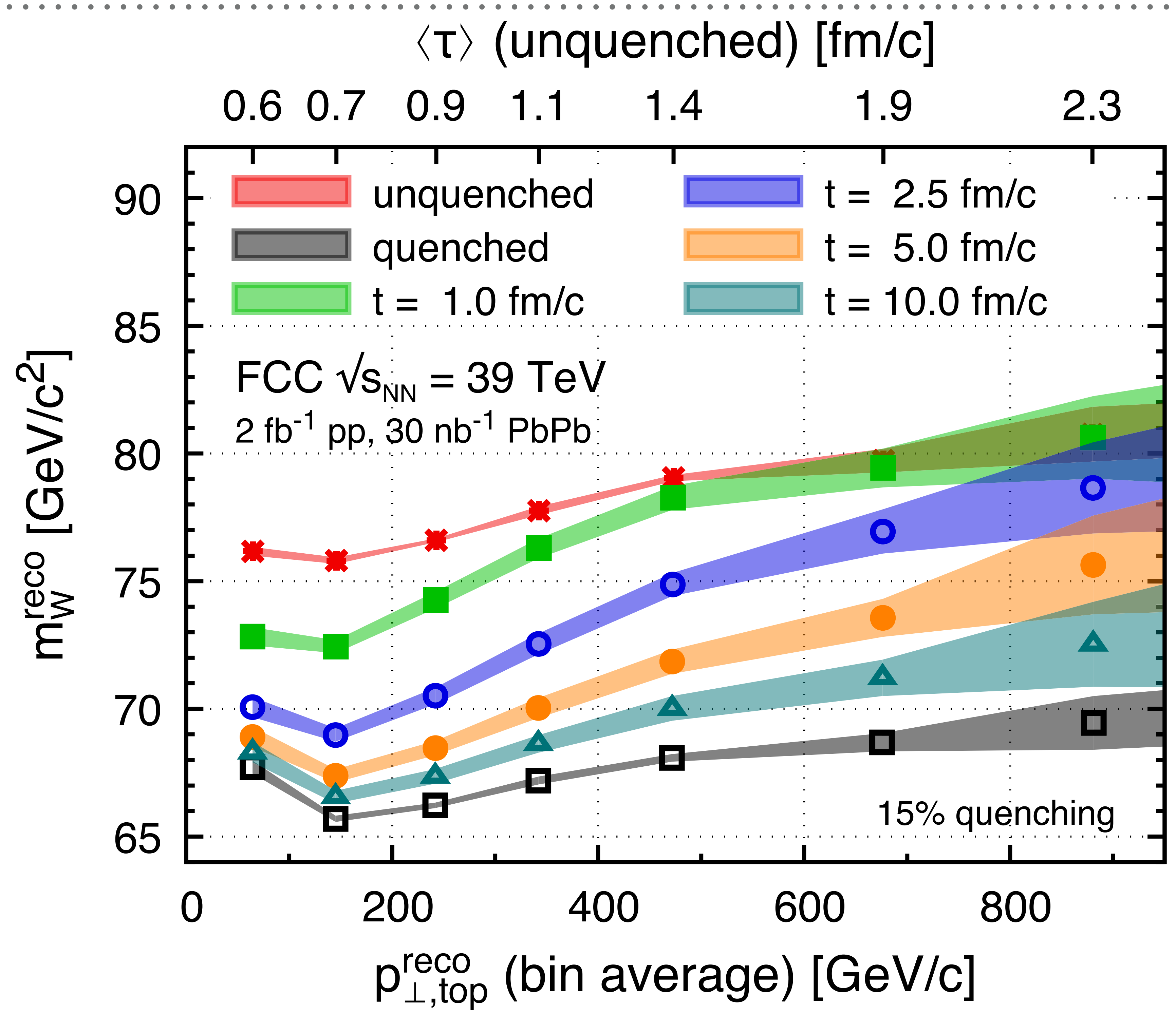


Fig. S.6 Left: total delay time for the QGP energy-loss parameter $\hat{q} = 4\ \text{GeV}^2/\text{fm}$ as a function of the top transverse momentum (black dots) and its standard deviation (error bars). The average contribution of each component is shown as a coloured stack band. The dashed line corresponds to a $\hat{q} = 1\ \text{GeV}^2/\text{fm}$. Right: reconstructed W boson mass, as a function of the top p_T. The upper axis refers to the average total time delay of the corresponding top p_T bin

Interplay of EW & Higgs with strong interaction

$e^+e^- \to H(gg) \to jj$

2 gluon-tagged jet, 70% eff/jet
light-quark mistag: 1%

BDT MVA result (removing some jet vars already used in g-uds discrimination)

2107.02686

For $\mathscr{L}_{int}$=10 ab^{-1}
$S/\sqrt{B} = 55/\sqrt{2500} \approx 1.1$
Significance ≈ 1.1

$e^+e^- \to ZH(\to WW)$

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to W^+W^-$	± 1.2		± 2.6	± 3.0

With $> 200{,}000$ $H \to WW$ events, can one do better than 1% on the measurement?

Many decay channels, each with specific features / difficulties

W boson decay \ Z boson decay	ee	$\mu\mu$	$\tau\tau$	$\nu\nu$	qq
$WW^* \to e\nu e\nu$	88	88	88	525	1836
$WW^* \to \mu\nu\mu\nu$	87	87	87	517	1808
$WW^* \to e\nu\mu\nu$	175	175	175	1052	3644
$WW^* \to e\nu\tau\nu$	187	187	188	1116	3901
$WW^* \to \mu\nu\tau\nu$	186	186	186	1107	3872
$WW^* \to \tau\nu\tau\nu$	99	99	99	593	2072
$WW^* \to e\nu qq$	1111	1112	1114	6612	23112
$WW^* \to \mu\nu qq$	1103	1104	1105	6562	22939
$WW^* \to \tau\nu qq$	1181	1182	1183	7025	24558
$WW^* \to qqqq$	3498	3502	3506	20808	72735

Liao Libo 2017 @ CEPC

Progress needed:

Today's best machine-learning, at particle level, gives $\sim 1/4$ the corresponding $S/\sqrt{B}$ for (gluon/quark)^2 part of H discrimination (Dreyer, Soyez & Takacs prelim)

resources

Resources: FCC CDR (https://fcc-cdr.web.cern.ch/) & EPJ+ special issue

- **EPJ+ special issue "A future Higgs and EW Factory: Challenges towards discovery"**

All 34 references in this Overleaf document: https://www.overleaf.com/read/xcssxqyhtrgt

MDI, √s

Challenges to match statistical precision

Detector requirements & possible solutions

Theory challenges

Software and computing challenges

Patrick Janot   Engagement meeting   4

Benchmark studies (https://www.overleaf.com/read/dyjpdszrqxhz)

1. Towards an ultimate measurement of $R_\ell = \frac{\sigma(Z\to\text{hadrons})}{\sigma(Z\to\text{leptons})}$
2. Towards an ultimate measurement of the Z total width Γ_Z
3. Towards an ultimate measurement of the Z peak cross section
4. Direct determination of $\sin^2\theta^\ell_{\text{eff}}$ and of $\alpha_{\text{QED}}(m^2_Z)$ from muon pair asymmetries
5. Determination of the QCD coupling constant $\alpha_S(m^2_Z)$
6. Tau Physics, Lepton Universality, and Lepton Flavour Violation
7. Tau exclusive branching ratios and polarization observables
8. Z-pole Electroweak observables with heavy quarks
9. Long lived particle searches
10. Measurement of the W mass
11. Measurement of the Higgs boson coupling to the c quark
12. Measurement of the ZH production cross section
13. Measurement of the Higgs boson mass - Part I
14. Measurement of the Higgs boson mass - Part II
15. Inferring the total Higgs boson decay width - Part I
16. Inferring the total Higgs boson decay width - Part II
17. Determination of the HZγ effective coupling
18. Electron Yukawa via s-channel $e^+e^- \to H$ production at the Higgs pole
19. Measurement of top properties at threshold and above
20. Search for FCNC in the top sector
21. Theory Needs for FCC-ee
22. Beyond MFV: constraints on RH charged currents and on dipole operators
23. Construction of CP-odd observables to probe CP-violating Higgs couplings
24. Combined fit of Higgs and top data

More detailed letters of interest and contacts specific to each case study (if not already indicated below) will be available shortly. Meanwhile, Alain Blondel, Patrick Janot, and Markus Klute are the main entry points to these case studies. The complete document is available at https://www.overleaf.com/read/dyjpdszrqxhz and will be regularly updated with more case studies and contacts.

FCC feasibility study: Physics-Experiments-Detector (PED), many places to get involved!

Abstract submission deadline:
8 December

Registration deadline for in-person participation:
16 January

https://cern.ch/FCCPhysics2022

conclusions

Conclusions

- no single talk can do justice to the wealth of physics possible across the FCC programme
- **FCC programme combines strong ambition with likely feasibility**
  - an effective $\times 3-5$ in direct energy reach (like Tevatron → LHC)
  - at least an order of magnitude in precision (potentially much more) and associated indirect energy reach
- **no-lose theorem:** directly establishing Higgs self-interaction (it holds the SM together)
- beyond that we don't know what will come out, but it is **win/win:**
  - establish SM simplicity up to unprecedented scales (a win for Occam's razor and firm foundations for future theories and experiments)
  - or gain clues to problems such as scale-hierarchy/DM/flavour/etc

Tasks ahead

- **Consolidate & communicate the physics case**
  - as part of building a broad FCC community
  - & explaining why it is exciting to those outside the FCC
- **Design experimental setup & develop theoretical foundations**
  - ensure accelerator design / interface is optimal for physics case
  - develop tools for detailed, robust studies (detector simulations, software, theory)
  - carry out representative physics analyses (make firmer/better statements about performance, establish detector requirements)
  - use them to benchmark detector concepts (up to 4 for FCC-ee), evaluate computing requirements, etc.

backup

arXiv:1906.02693, FCC-ee: Your questions answered

Observable ↓ / $\sqrt{s}$ →	m_Z (e⁺e⁻ collisions)	$2m_W$ (e⁺e⁻ collisions)	HZ max. 240-250 GeV (e⁺e⁻ collisions)	$2m_{top}$ 340-380 GeV (e⁺e⁻ collisions)	500 GeV (e⁺e⁻ collisions)	1.5 TeV (e⁺e⁻ collisions)	3 TeV (e⁺e⁻ collisions)	28 TeV 37 TeV 48 TeV (pp collisions)	100 TeV (pp collisions)	Leading Physics Questions
Precision EW (Z, W, top)	Transverse polarization	Transverse polarization		m_{top} (m_W, α_S)						Existence of more SM-Interacting particles
QCD (α_S) QED (α_{QED})	5×10^{12} Z	3×10^8 W	10^5 H→gg							Fundamental constants and tests of QED/QCD
Model-independent Higgs couplings	ee → H $\sqrt{s} = m_H$		1.2×10^6 HZ and 75k WW→H at two energies						<1% precision (*)	Test Higgs nature
Higgs rare decays									<1% precision (*)	Portal to new physics
Higgs invisible decays									10^{-4} BR sensitivity	Portal to dark matter
Higgs self-coupling			3 to 5σ from loop corrections to Higgs cross sections						3% (HH prod) (*)	Key to EWSB
Flavours (b, τ)	5×10^{12} Z									Portal to new physics Test of symmetries
RH ν's, Feebly interacting particles	5×10^{12} Z								10^{11} W	Direct NP discovery At low couplings
Direct search at high scales					M_χ<250GeV Small ΔM	M_χ<750GeV Small ΔM	M_χ<1.5TeV Small ΔM		Up to 40 TeV	Direct NP discovery At high mass
Precision EW at high energy							*Y*		***W, Z***	Indirect Sensitivity to Nearby new physics
Quark-gluon plasma Physics w/ injectors										QCD at origins

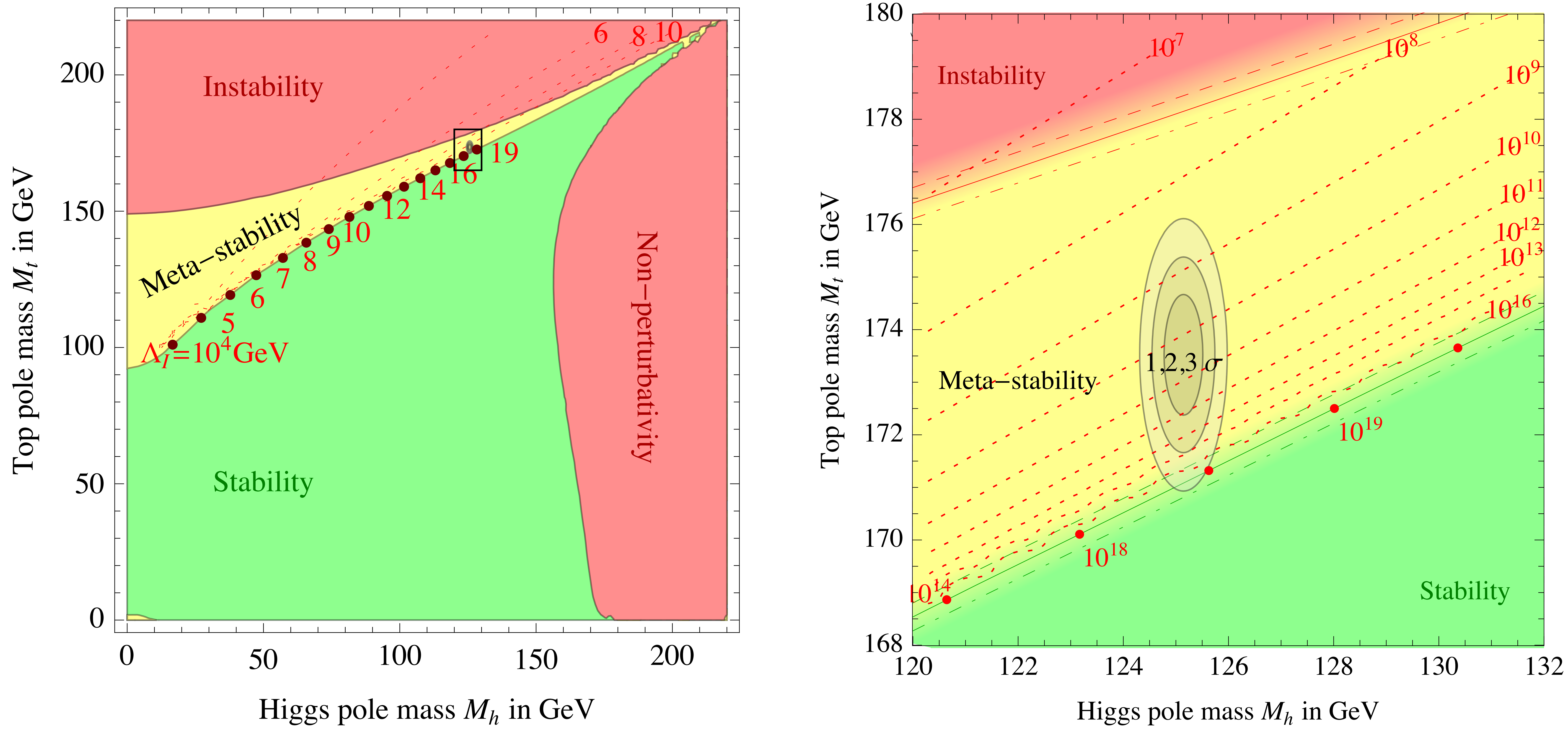
Green = Unique to FCC; **Blue = Best with FCC**; **(*) = if FCC-hh is combined with FCC-ee**; **Pink = Best with other colliders**

Electroweak fits (1910.11775), e.g. S & T parameters (i.e. specific EFT operator combinations)

Table 3.3: Values for 1σ sensitivity on the S and T parameters. In all cases the value shown is after combination with HL-LHC. For ILC and CLIC the projections are shown with and without dedicated running at the Z-pole. All other oblique parameters are set to zero. The intrinsic theory uncertainty is also set to zero.

	Current	HL-LHC	ILC_{250}	(& ILC_{91})	CEPC	FCC-ee	CLIC_{380}	(& CLIC_{91})
S	0.13	0.053	0.012	0.009	0.0068	0.0038	0.032	0.011
T	0.08	0.041	0.014	0.013	0.0072	0.0022	0.023	0.012

FCC-ee brings × 14-18 increase in precision



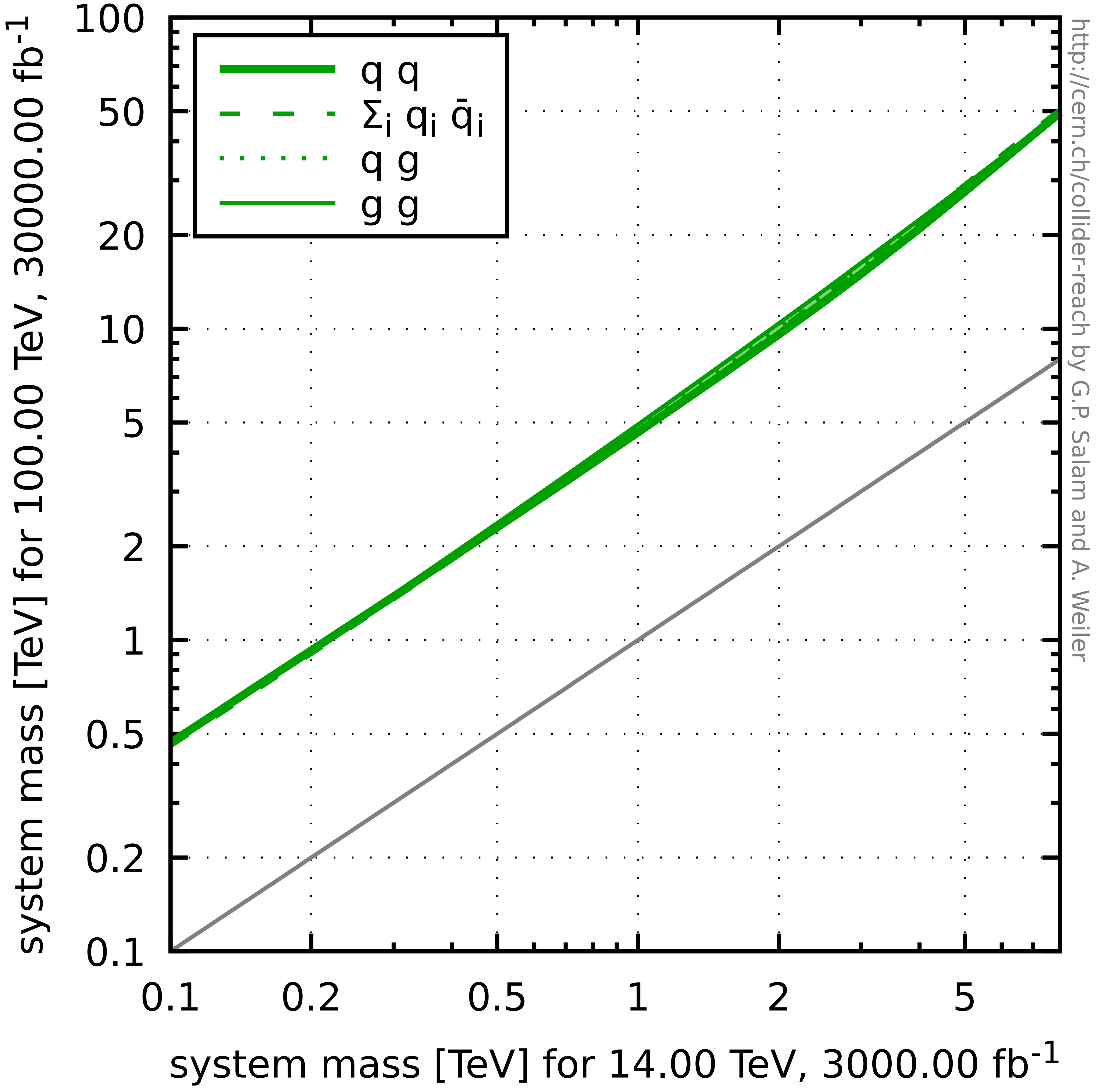
It's not inconceivable that the top mass could be sufficiently mis-measured at hadron colliders that the SM-universe is stable all the way to the Planck scale

condition in terms of the pole top mass. We can express the stability condition of eq. (64) as

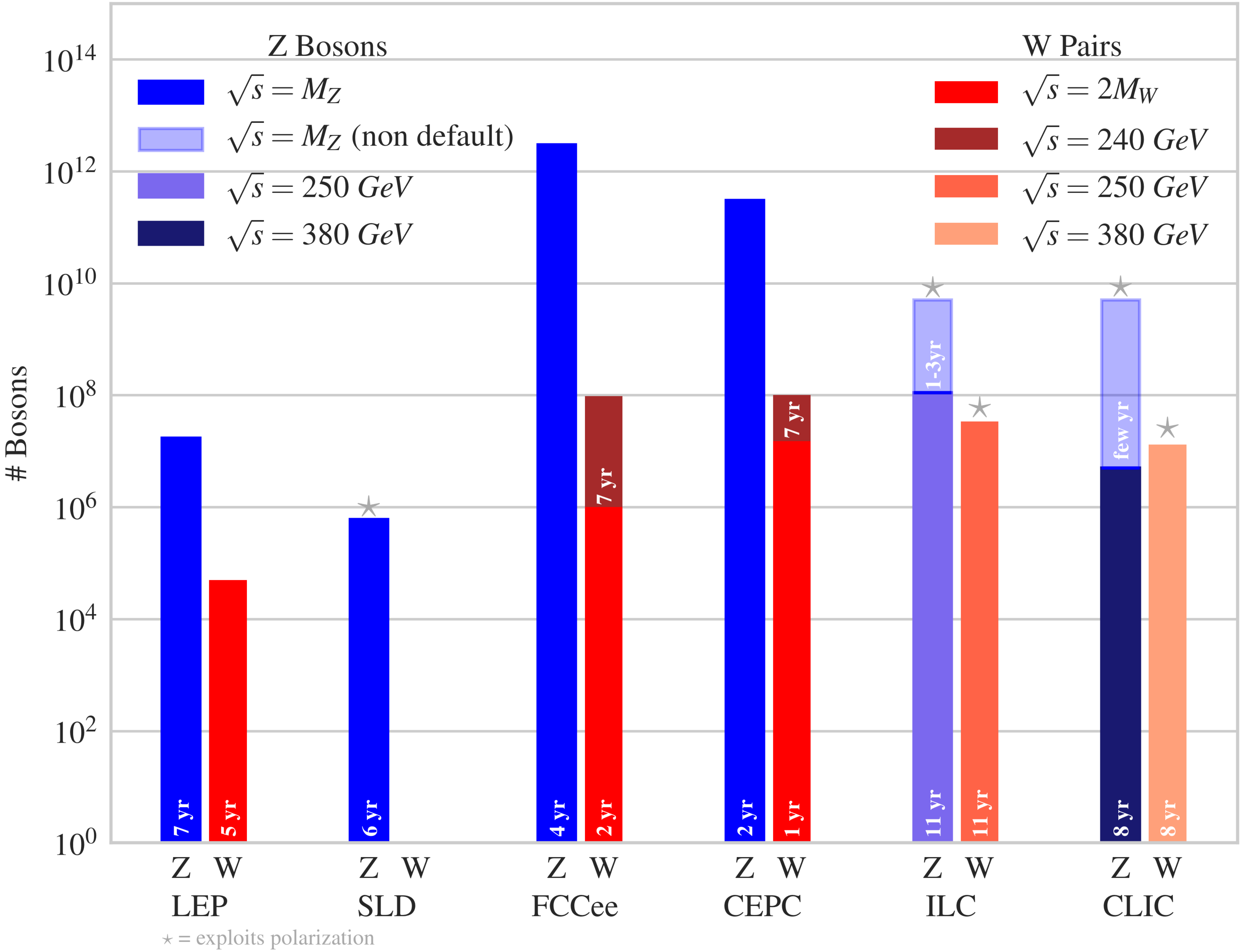
$$M_t < (171.53 \pm 0.15 \pm 0.23_{\alpha_3} \pm 0.15_{M_h})\,\text{GeV} = (171.53 \pm 0.42)\,\text{GeV}. \qquad (66)$$

arXiv:1307.3536

mass reach at FCC-hh v. LHC (http://collider-reach.web.cern.ch/)



1910.11775 Fig 3.5: numbers of bosons (FCC-ee W breakdown looks wrong)



current gluon/quark discrimination (Dreyer, Soyez, Takacs prelim, particle-level)