LONDON
United Kingdom

05 – 09 June
FCC
WEEK
2023

https://cern.ch/fccweek2023

FUTURE
CIRCULAR
COLLIDER

Science and Technology Facilities Council

UNIVERSITY OF OXFORD · Imperial College London · UCL · KING'S College LONDON · Queen Mary University of London · ROYAL HOLLOWAY UNIVERSITY OF LONDON · MANCHESTER 1824 The University of Manchester · UNIVERSITY OF CAMBRIDGE

PHYSICS PERSPECTIVES

Gavin Salam

THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

A preamble

- this type of talk is often given by a theorist who builds models of new physics
- such a theorist can tell you with authority about the landscape of models that any given collider might probe

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- such a theorist can tell you with authority about the landscape of models that any given collider might probe

- there are many kinds of theorist
- while I'm a theorist, I am not a BSM model-builder
- my "day job" is to calculate phenomena in QCD (jets, parton showers, etc.), in order to help augment colliders' capabilities
- this talk will not involve specifics of models, but rather attempt to explore the case for new colliders more generically

desirable features of a worldwide HEP project?

an important target that is guaranteed to be reached
(no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (multiple experiments)

cost-effective construction & operation, low carbon footprint

top-down

figure out the best collider you can realistically build

establish what physics it will probe

bottom up

establish what you want to learn

figure out how to build a collider that will best achieve it

https://krea-prod-v1-generations.s3.us-east-1.amazonaws.com/images/665c051f-5540-4f33-b85e-da9ac2a81c36.webp

Dear Santa Claus,

We have been good these past decades. Please could you now bring us

- *a dark matter candidate*
- *an explanation for the fermion masses*
- *an explanation of matter-antimatter asymmetry*
- *an axion, to solve the strong CP problem*
- *a solution to fine tuning the EW scale*
- *a solution to fine tuning the cosmological constant*

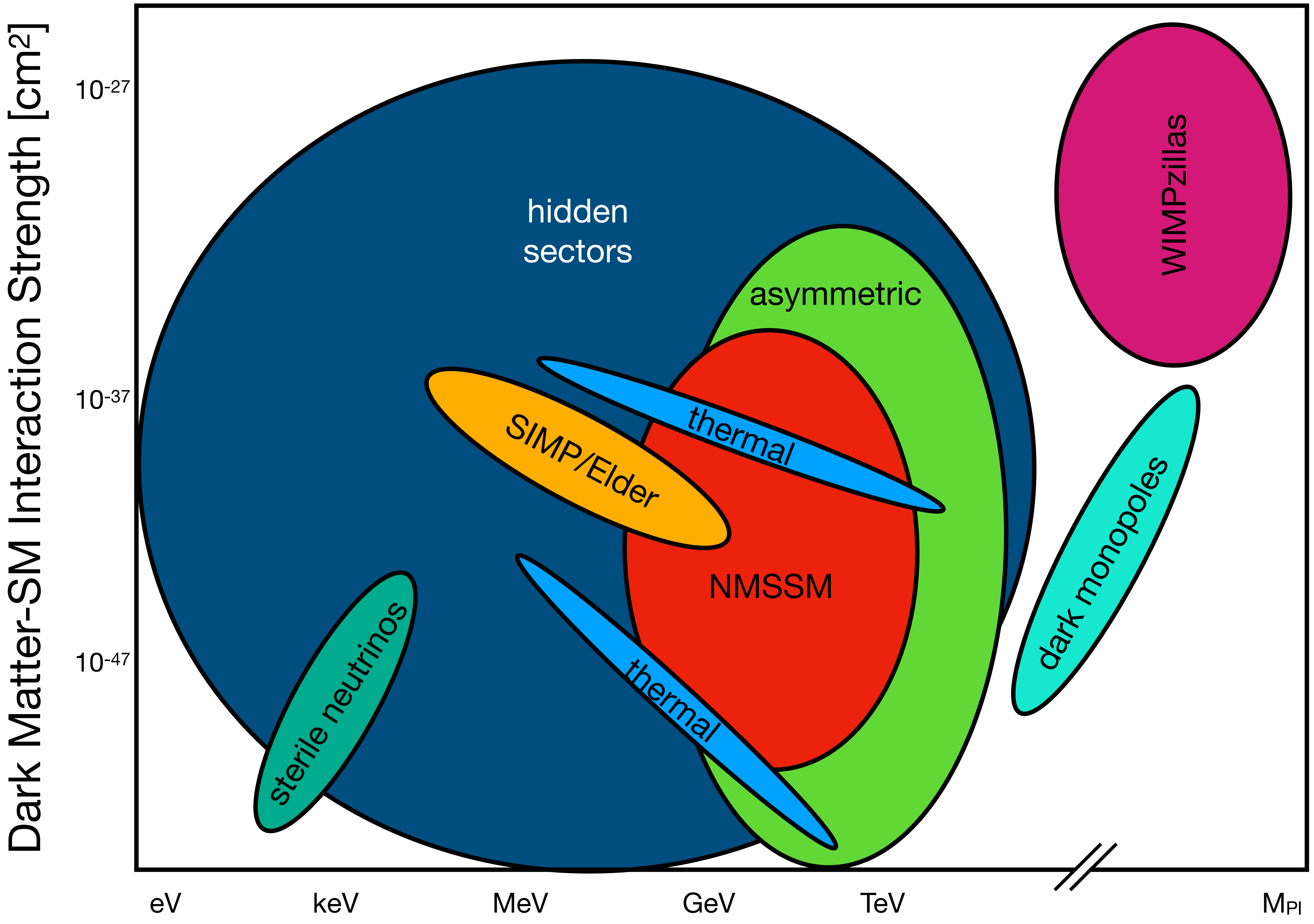
Thank you, Particle Physicists

ps: please, no anthropics

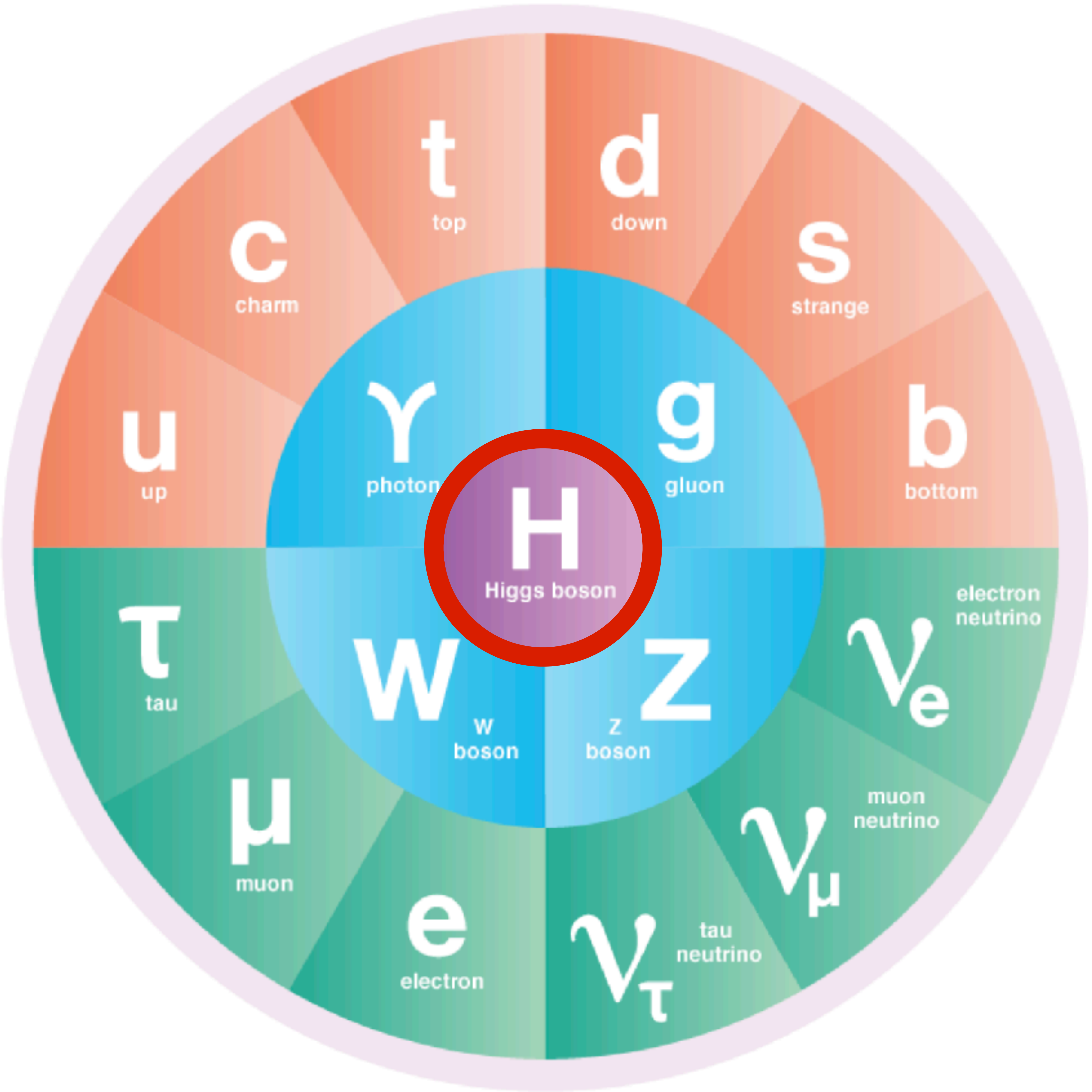
we have so far been unlucky in getting answers to these many questions

Snowmass Dark Matter report, 2209.07426

30 orders of magnitude in interaction strength



30 orders of magnitude in mass



https://www.symmetrymagazine.org/standard-model/

but we have been lucky in discovering a 125 GeV Higgs boson

it opens a door to the most mysterious part of the Standard Model

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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!

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

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!**

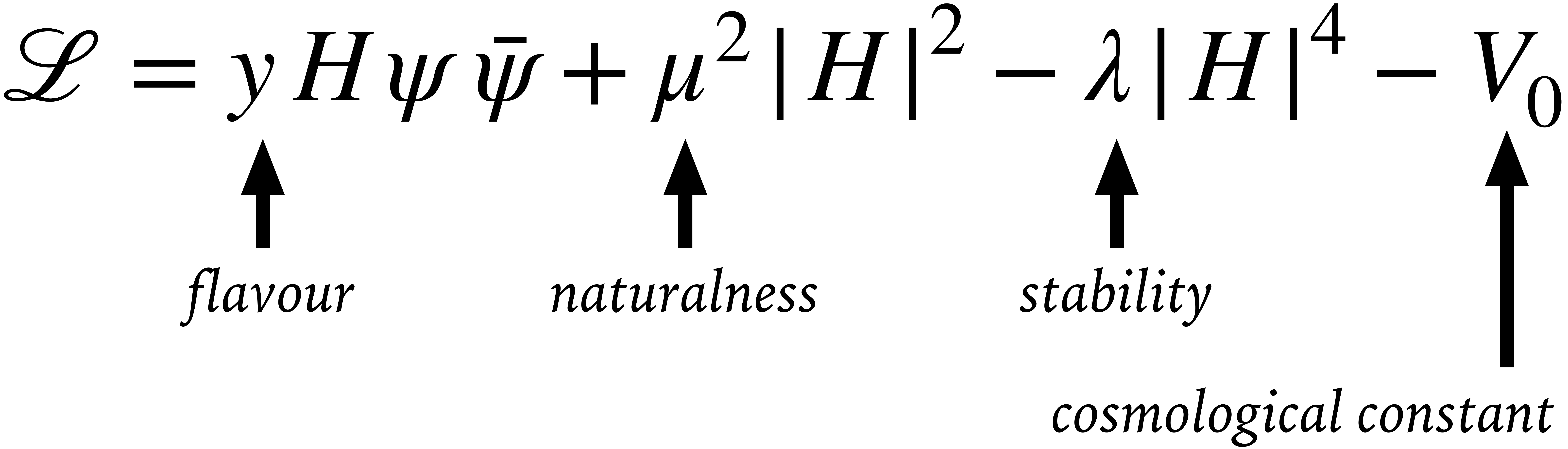
Higgs potential → self-interaction ("sixth?" force between scalars).

Holds the SM together.

Unobserved

typeset from Gian Giudice original

Almost every problem of the Standard Model originates from Higgs interactions



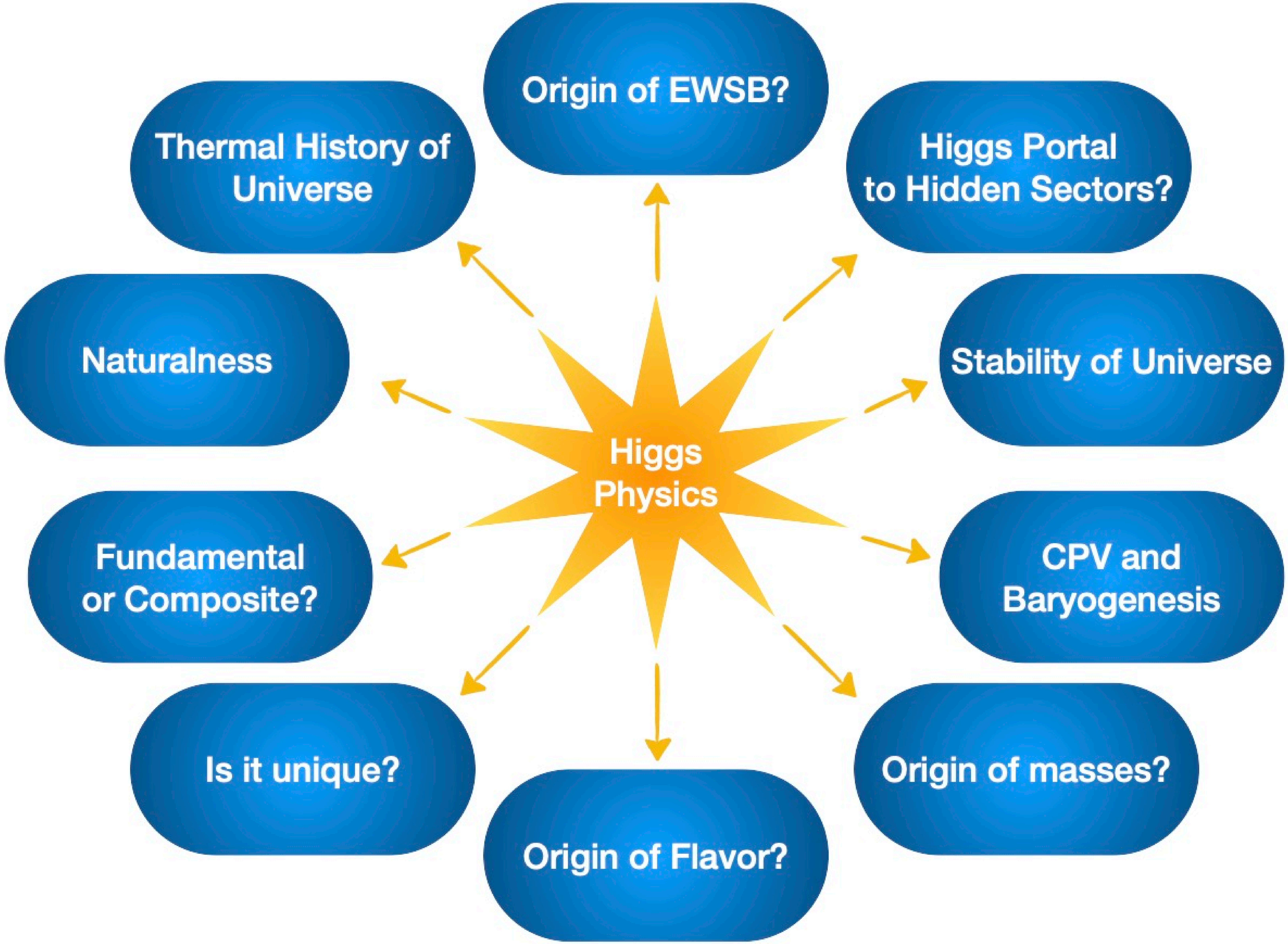
$$\mathscr{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

flavour

naturalness

stability

cosmological constant


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?

Yukawa interaction hypothesis

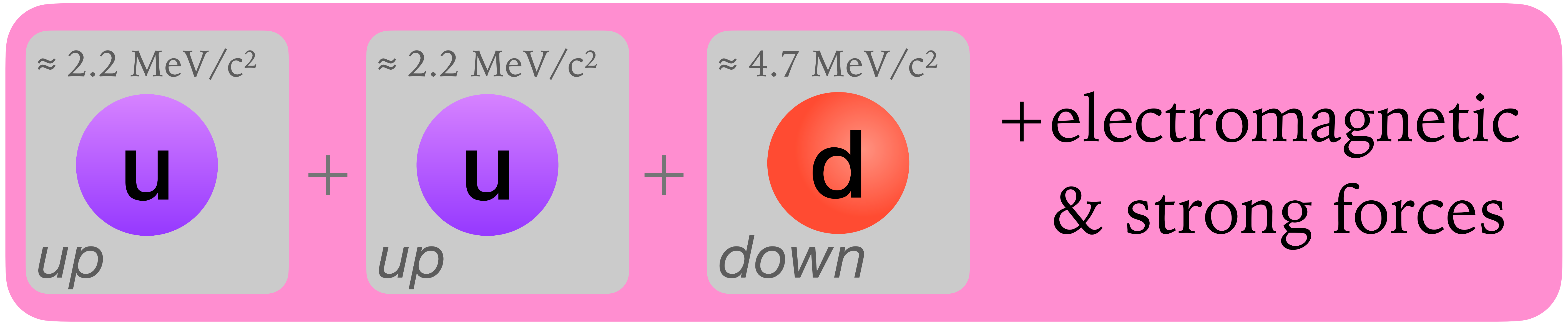
Yukawa couplings ~ fermion mass

first fundamental interaction that we probe at the quantum level where interaction strength (y_{ij}) not quantised

(i.e. no underlying unit of conserved charge across particles)

2.2 MeV **2.2 MeV** 4.7 MeV

proton:

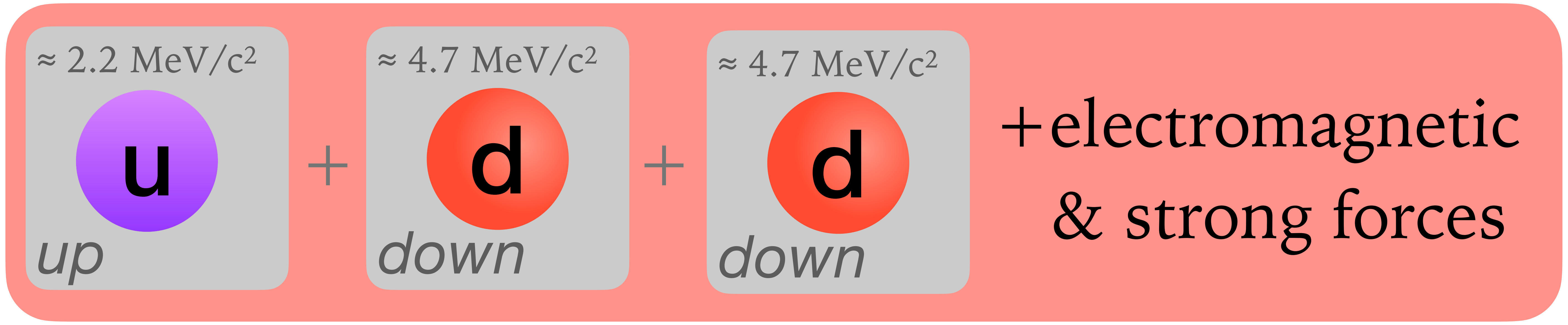


≈ 2.2 MeV/c² u up + ≈ 2.2 MeV/c² u up + ≈ 4.7 MeV/c² d down

+electromagnetic & strong forces

$\simeq$ **938.3 MeV**

neutron:



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$\simeq$ **939.6 MeV**

2.2 MeV **4.7 MeV** 4.7 MeV

Protons are **lighter** than neutrons→ protons are stable.
Giving us the hydrogen atom, & chemistry and biology as we know it

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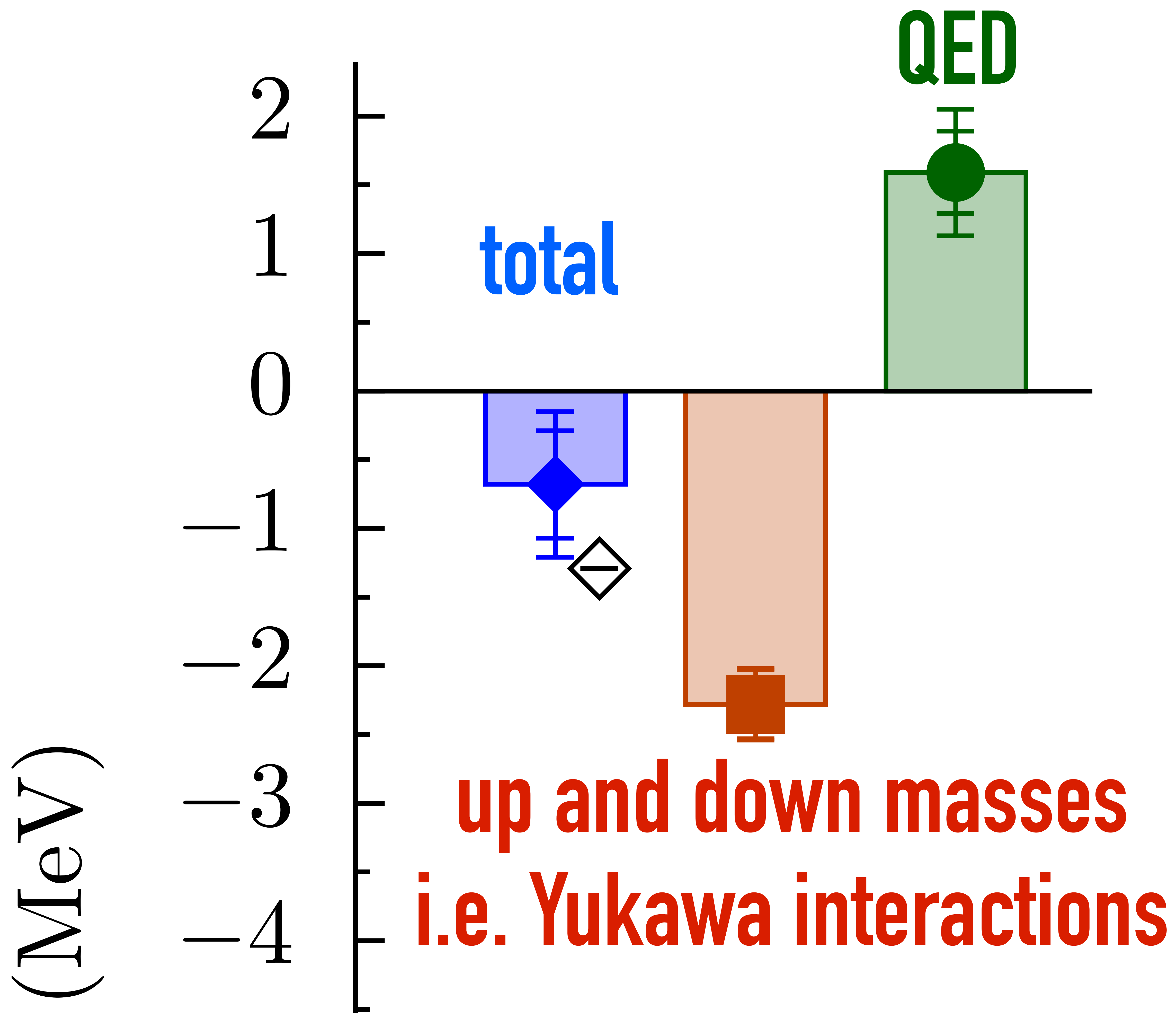
Supposedly because up quarks interact more weakly with the Higgs field than down quarks

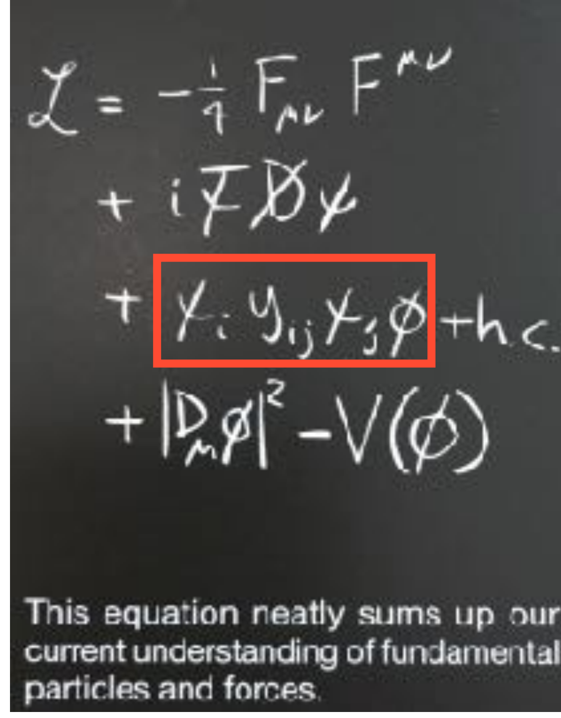
proton – neutron mass difference



Lattice calculation
(BMW collab.)
1306.2287
1406.4088

Why do Yukawa couplings matter?

(2) Because, within SM **conjecture**, they're what give masses to all **leptons**



This equation neatly sums up our current understanding of fundamental particles and forces.

Bohr radius

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c \alpha} \propto \frac{1}{y_e}$$

electron mass determines size of all atoms

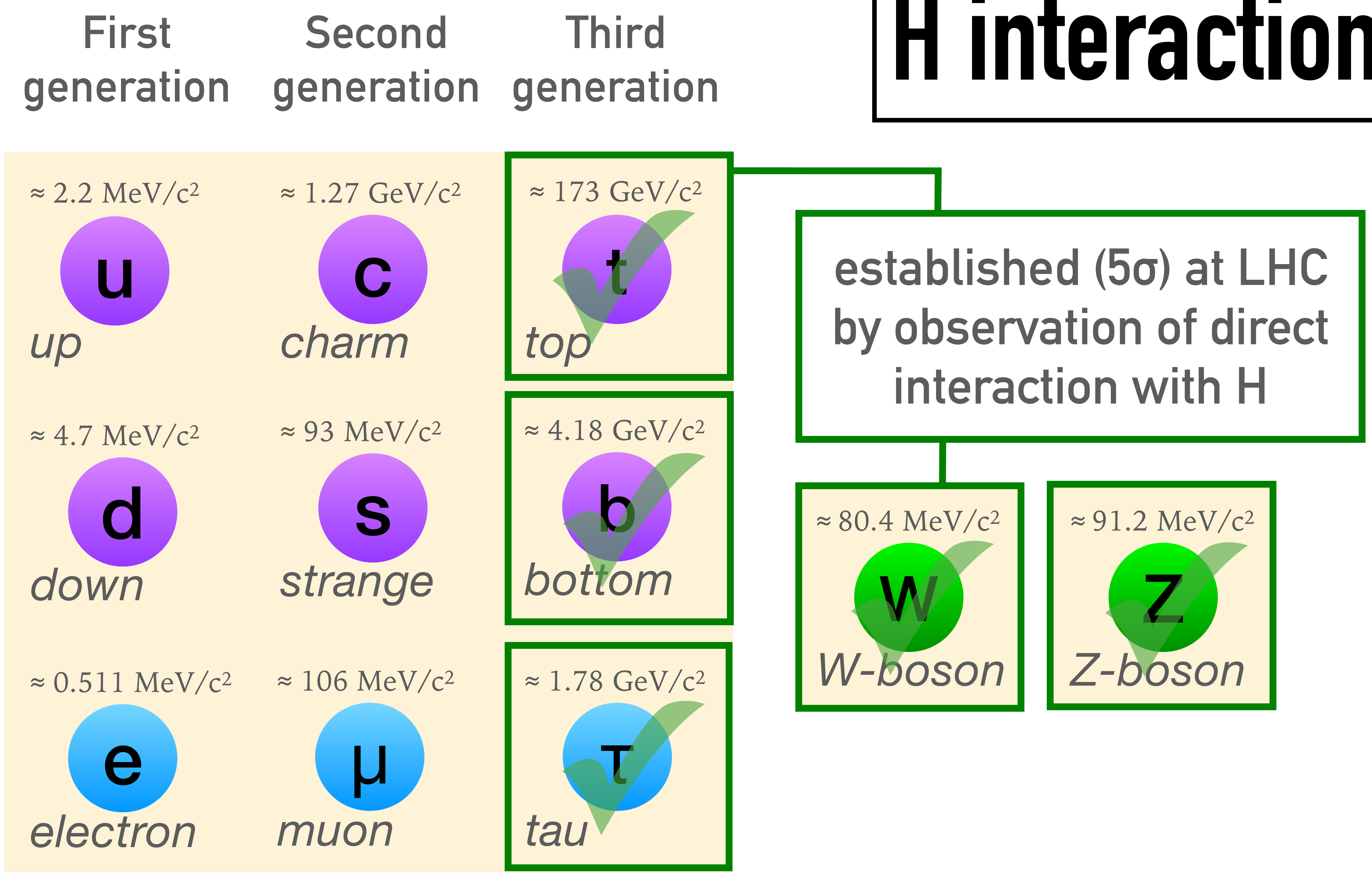
it sets energy levels of all chemical reactions currently we have no evidence that up and down quarks and electron get their masses from Yukawa interactions — it’s in textbooks, but is it nature?

H interactions

First generation	Second generation	Third generation
≈ 2.2 MeV/c^2 u *up*	≈ 1.27 GeV/c^2 c *charm*	≈ 173 GeV/c^2 t *top*
≈ 4.7 MeV/c^2 d *down*	≈ 93 MeV/c^2 s *strange*	≈ 4.18 GeV/c^2 b *bottom*
≈ 0.511 MeV/c^2 e *electron*	≈ 106 MeV/c^2 μ *muon*	≈ 1.78 GeV/c^2 τ *tau*

≈ 80.4 MeV/c^2 W *W-boson*	≈ 91.2 MeV/c^2 Z *Z-boson*

H interactions



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established (5σ) at LHC by observation of direct interaction with H

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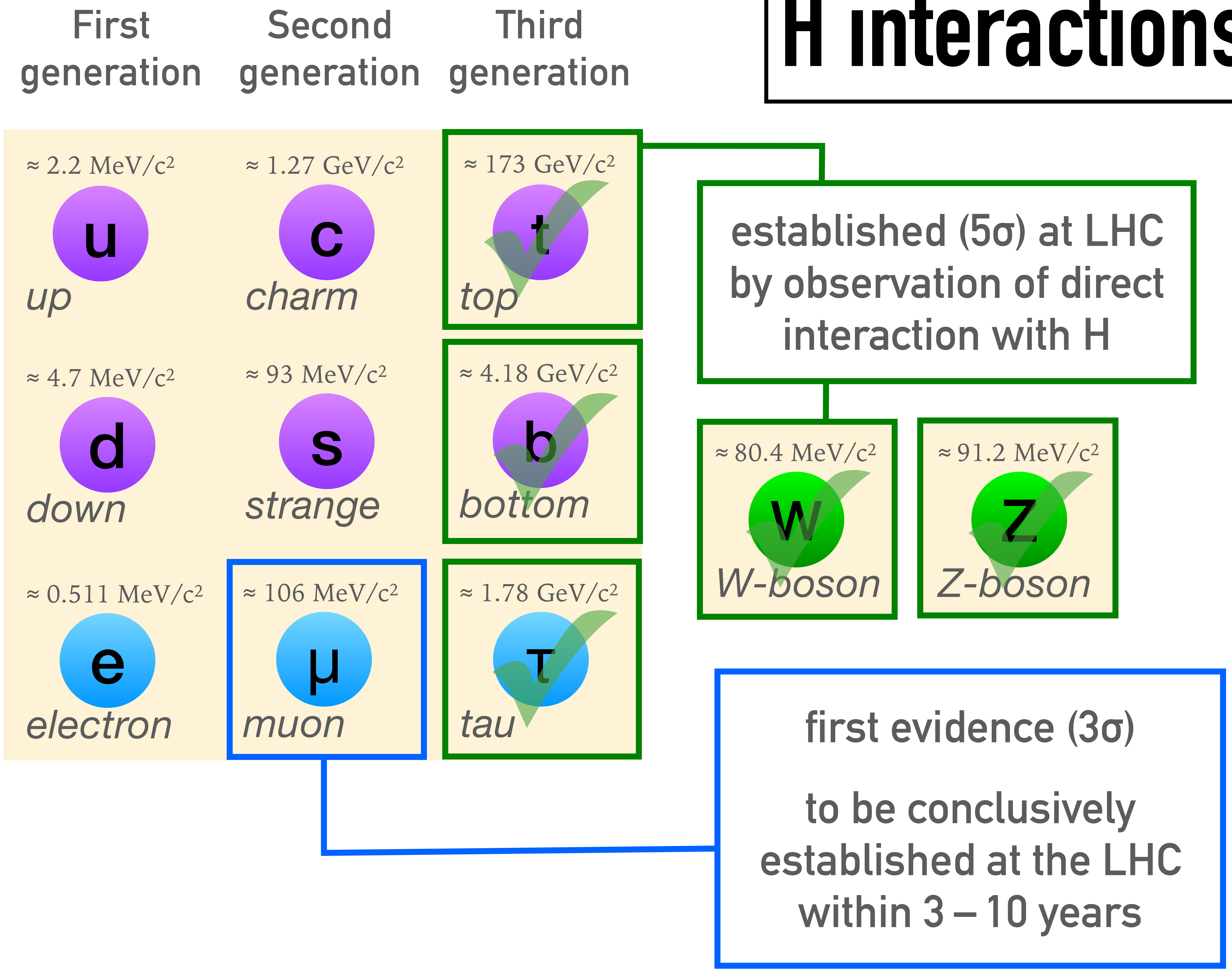

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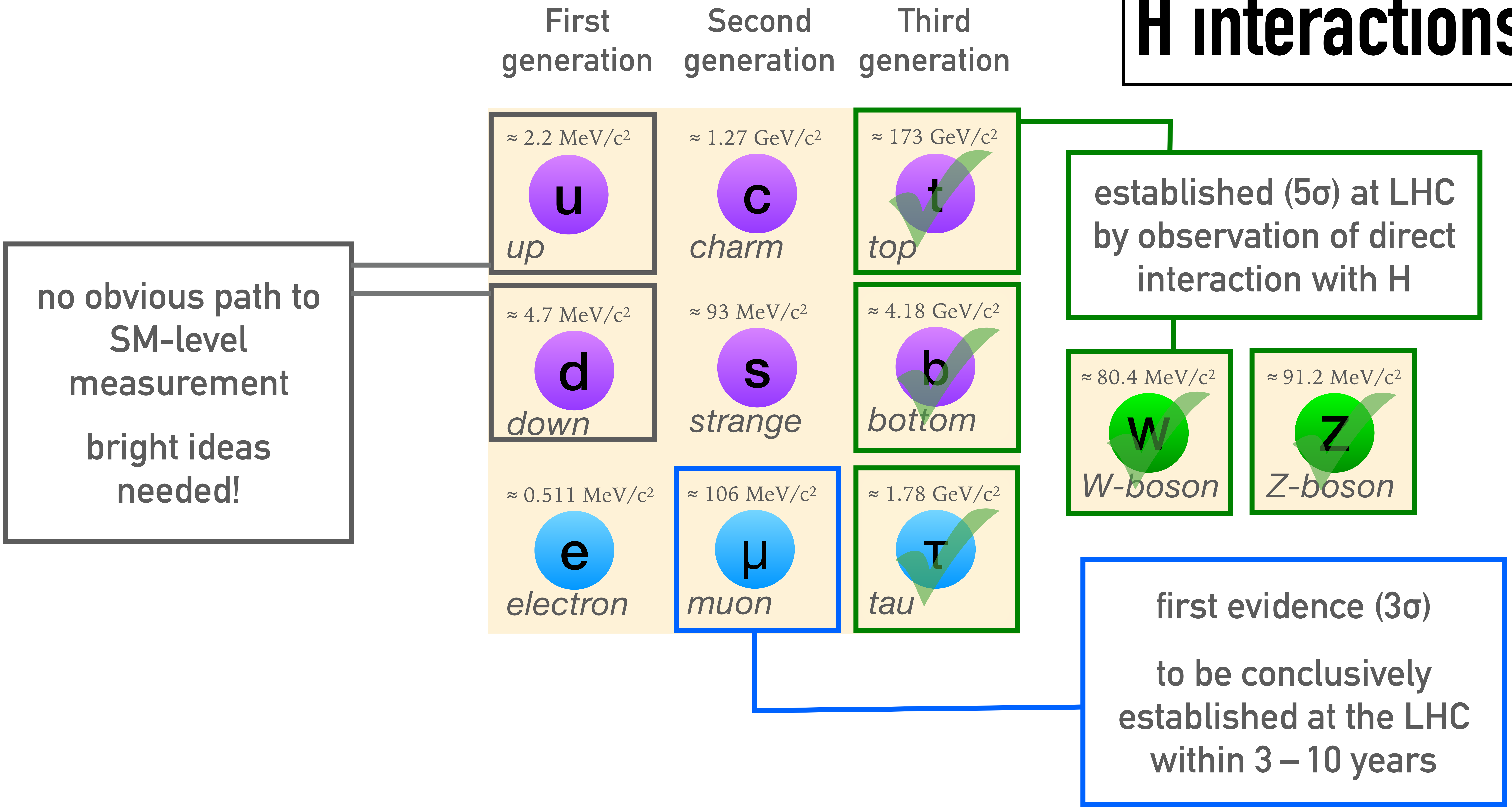
first evidence (3σ)

to be conclusively established at the LHC within 3 – 10 years

H interactions



no obvious path to SM-level measurement

bright ideas needed!

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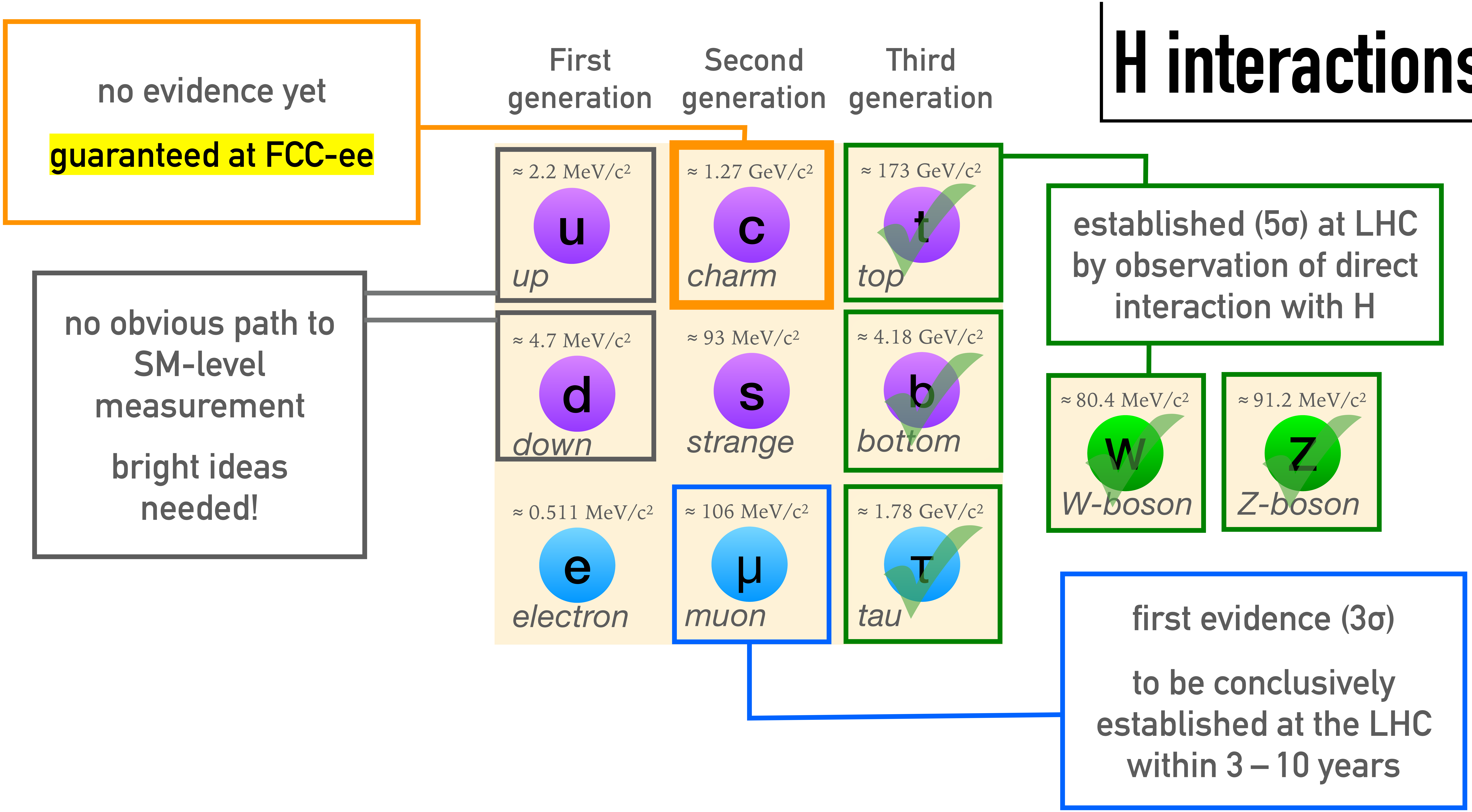

no evidence yet

guaranteed at FCC-ee

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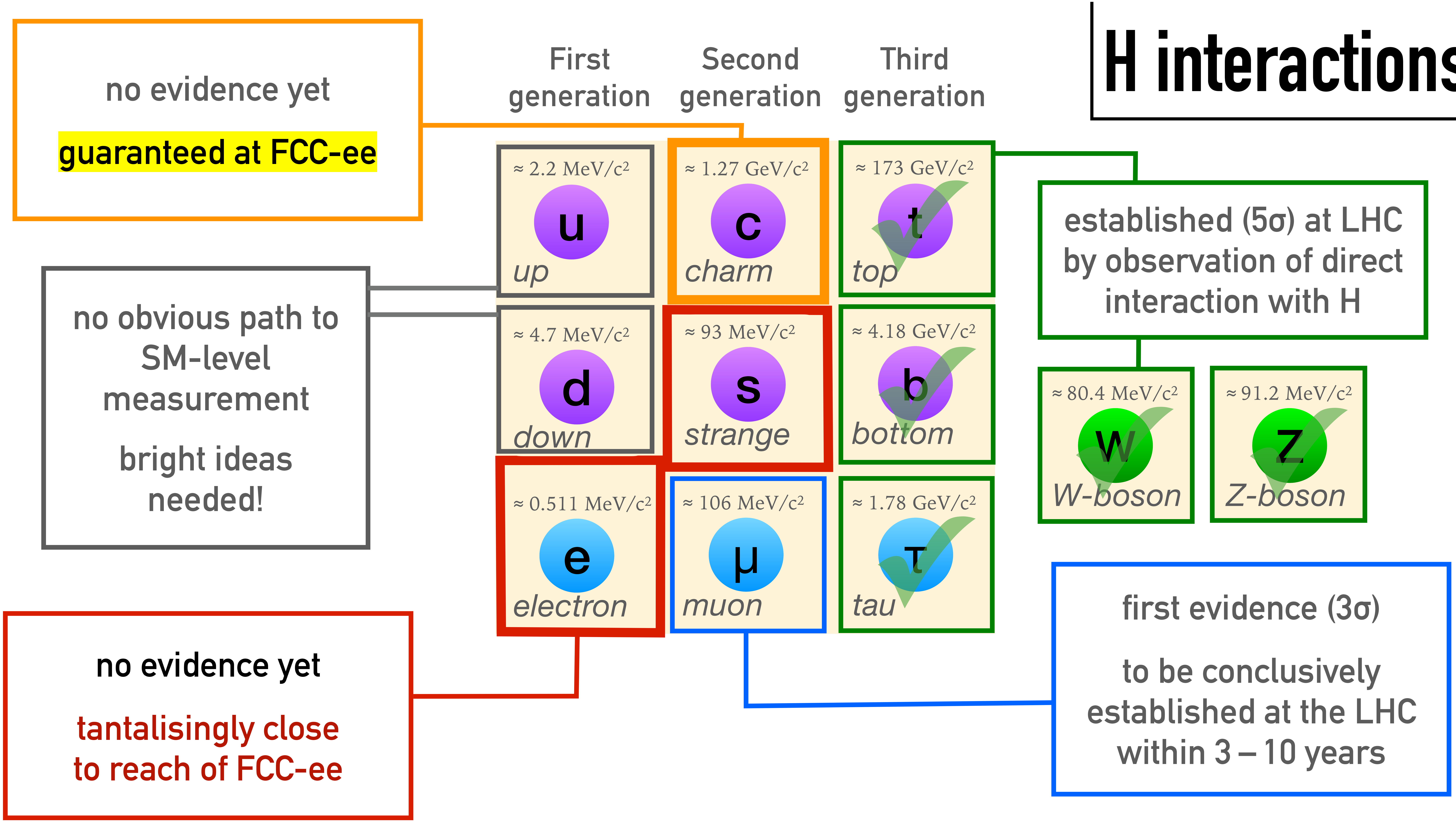

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bright ideas needed!

no evidence yet

tantalisingly close to reach of FCC-ee

established (5σ) at LHC by observation of direct interaction with H

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to be conclusively established at the LHC within 3 – 10 years

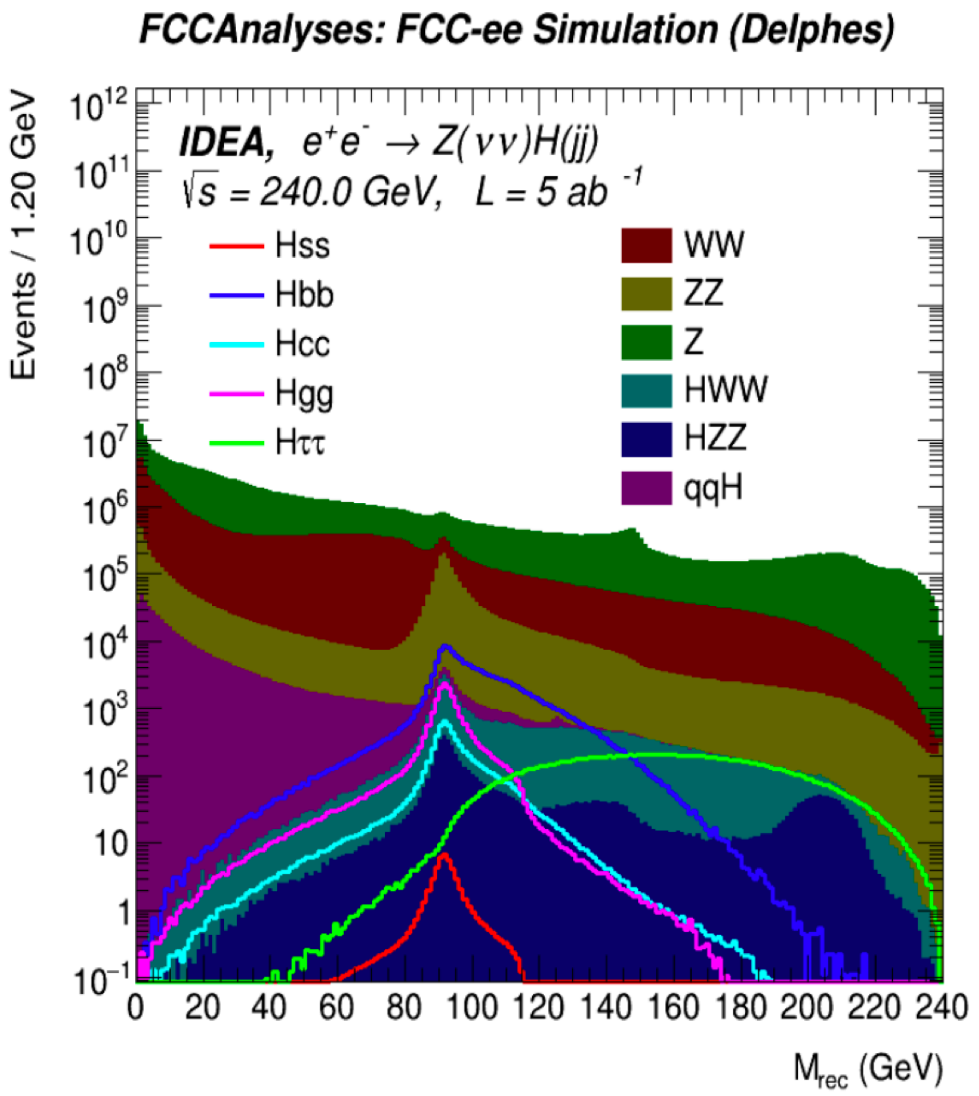
Teaser from the analysis front [FCC-ee, H → hadrons]

- Tools fully incorporated in FCCSW [details]
  - Example: Z(→vv)H(→qq)

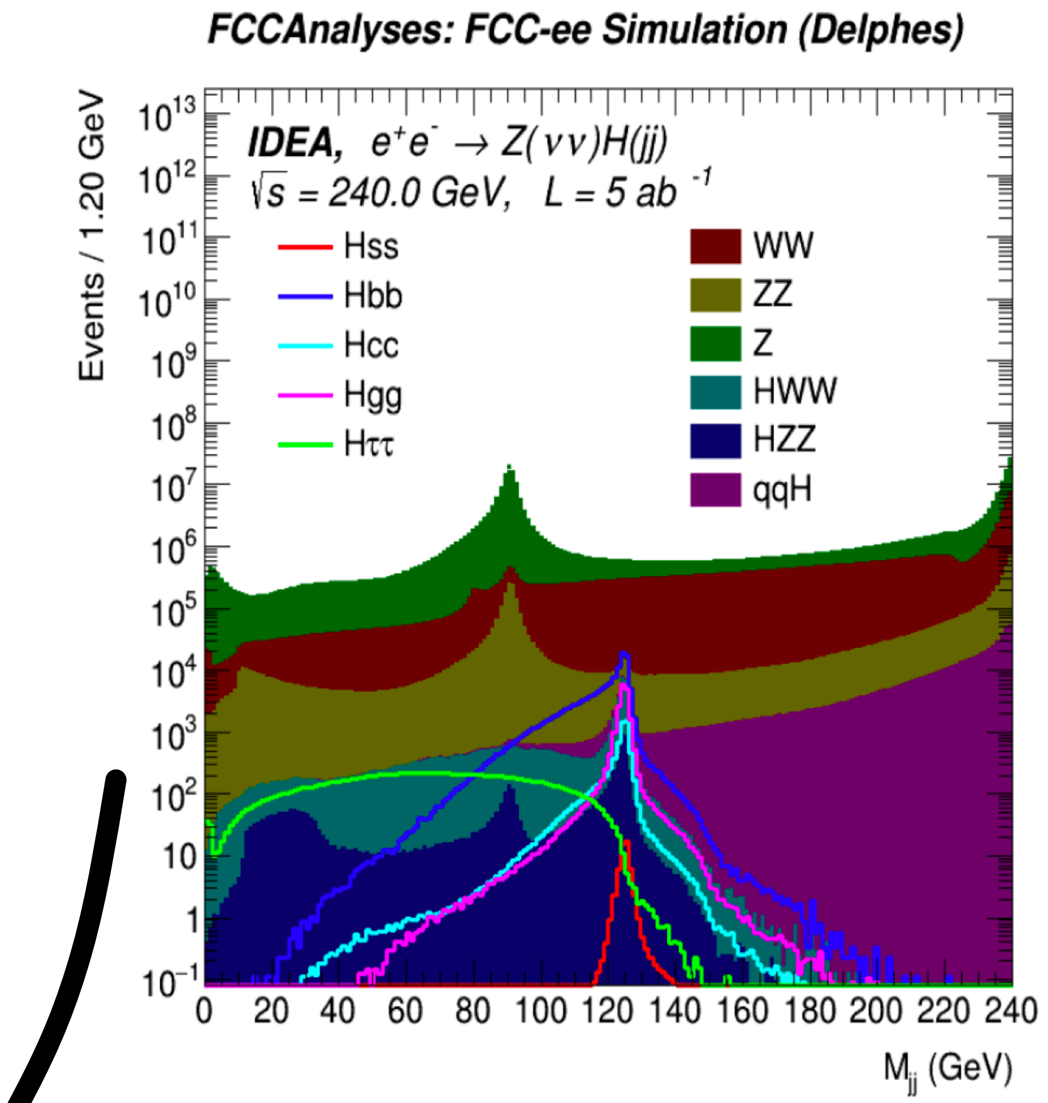
Categorize events: bb, cc, ss, gg
Sub-categories w/ different S/B

Signal extraction: 2D fit

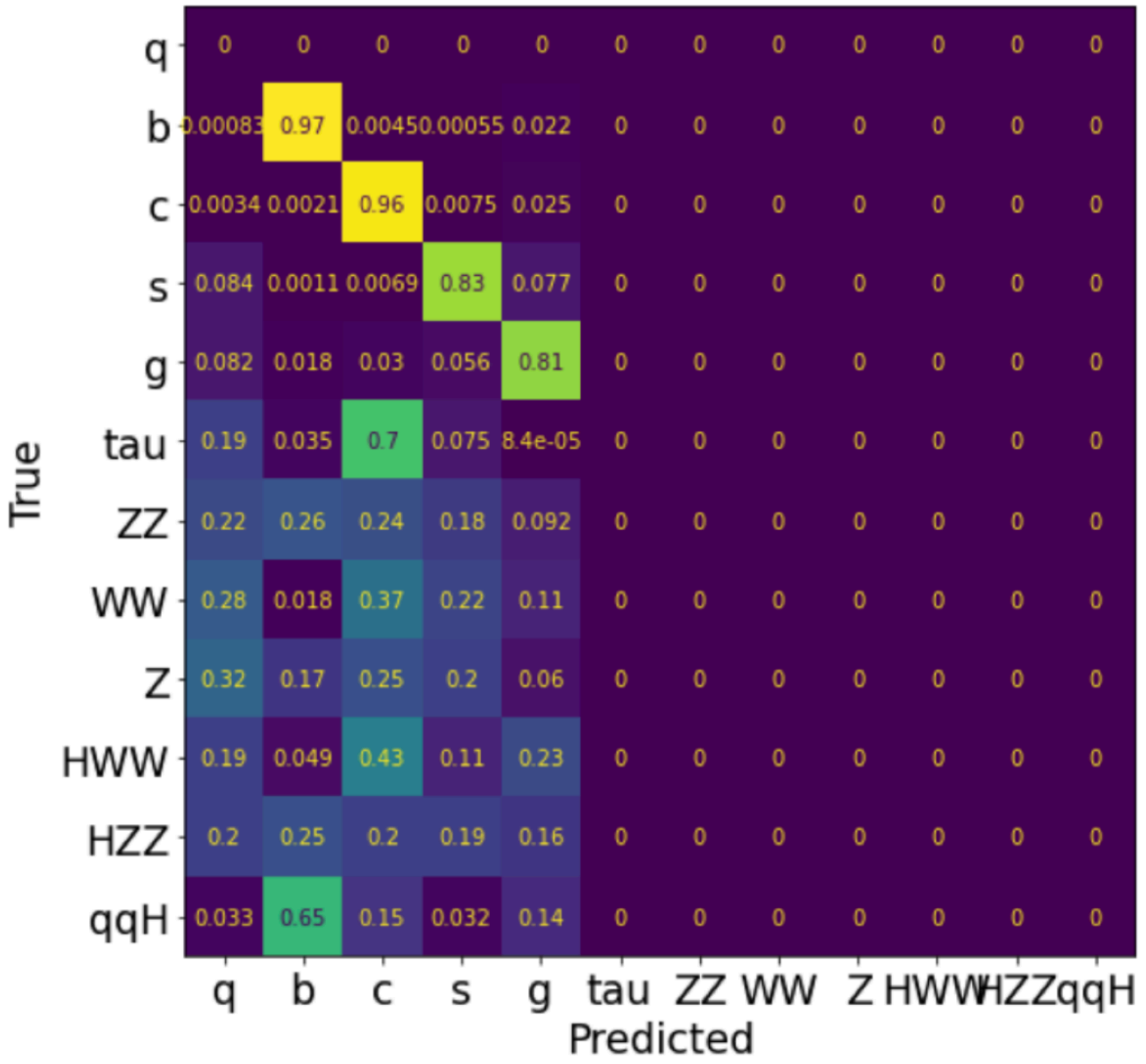
m(rec)



m(jj)



ParticleNet-ee



	q	b	c	s	g	tau	ZZ	WW	Z	HWW	HZZ	qqH
q	0	0	0	0	0	0	0	0	0	0	0	0
b	0.00083	0.97	0.0045	0.00055	0.022	0	0	0	0	0	0	0
c	0.0034	0.0021	0.96	0.0075	0.025	0	0	0	0	0	0	0
s	0.084	0.0011	0.0069	0.83	0.077	0	0	0	0	0	0	0
g	0.082	0.018	0.03	0.056	0.81	0	0	0	0	0	0	0
tau	0.19	0.035	0.7	0.075	8.4e-05	0	0	0	0	0	0	0
ZZ	0.22	0.26	0.24	0.18	0.092	0	0	0	0	0	0	0
WW	0.28	0.018	0.37	0.22	0.11	0	0	0	0	0	0	0
Z	0.32	0.17	0.25	0.2	0.06	0	0	0	0	0	0	0
HWW	0.19	0.049	0.43	0.11	0.23	0	0	0	0	0	0	0
HZZ	0.2	0.25	0.2	0.19	0.16	0	0	0	0	0	0	0
qqH	0.033	0.65	0.15	0.032	0.14	0	0	0	0	0	0	0

Results @ 5ab^{-1}
(syst: 5% BKG, 0.1% SIG)

Z(→vv) H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.4	2.9	160	1.2

***|κ_S|<1.9**

More on Friday:
G. Marchiori

Results @ 5ab^{-1}

(syst: 5% BKG, 0.1% SIG)

$Z(\rightarrow\nu\nu)$ $H(\rightarrow qq)$	bb	cc	ss	gg
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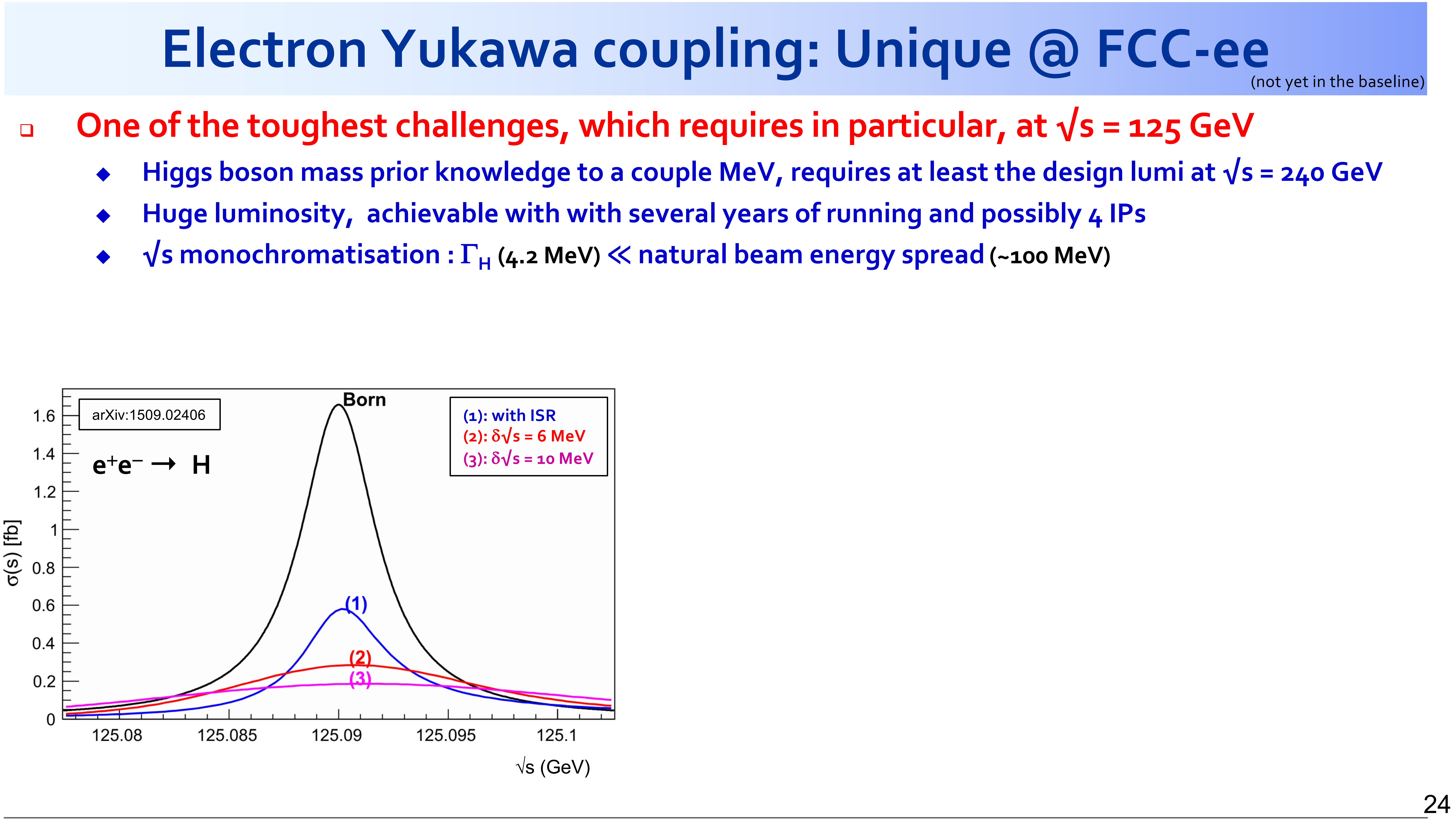
* $|\kappa_s|<1.9$

strange Yukawa tantalisingly close to being within reach

would complete 2nd generation Yukawas



Electron Yukawa coupling: Unique @ FCC-ee

(not yet in the baseline)

- **One of the toughest challenges, which requires in particular, at √s = 125 GeV**
  - ◆ **Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at √s = 240 GeV**
  - ◆ **Huge luminosity, achievable with with several years of running and possibly 4 IPs**
  - ◆ **√s monochromatisation : Γ_H (4.2 MeV) ≪ natural beam energy spread (~100 MeV)**

original slide from Patrick Janot

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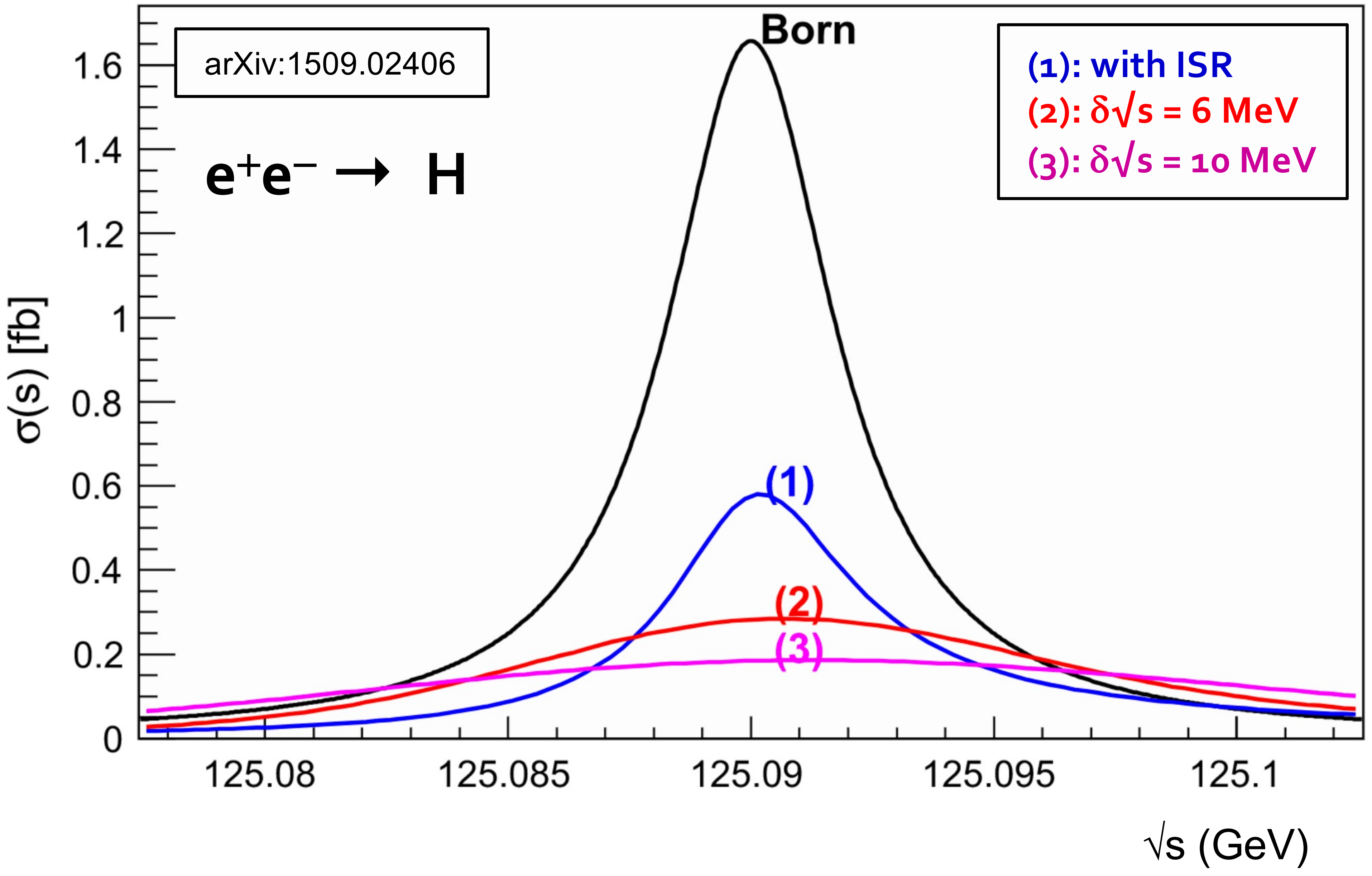
- First studies indicate a significance of 0.4σ with one detector in one year



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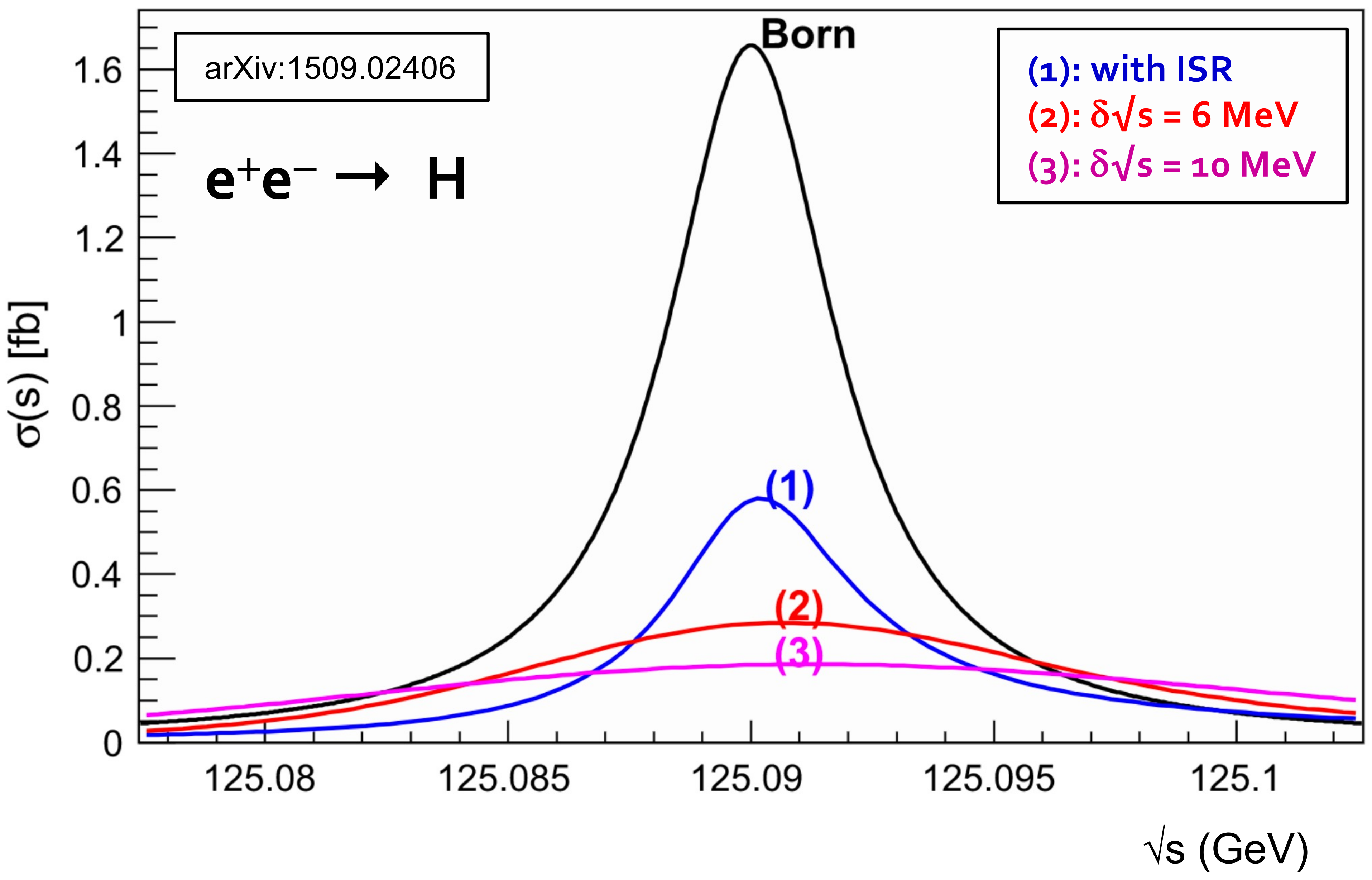

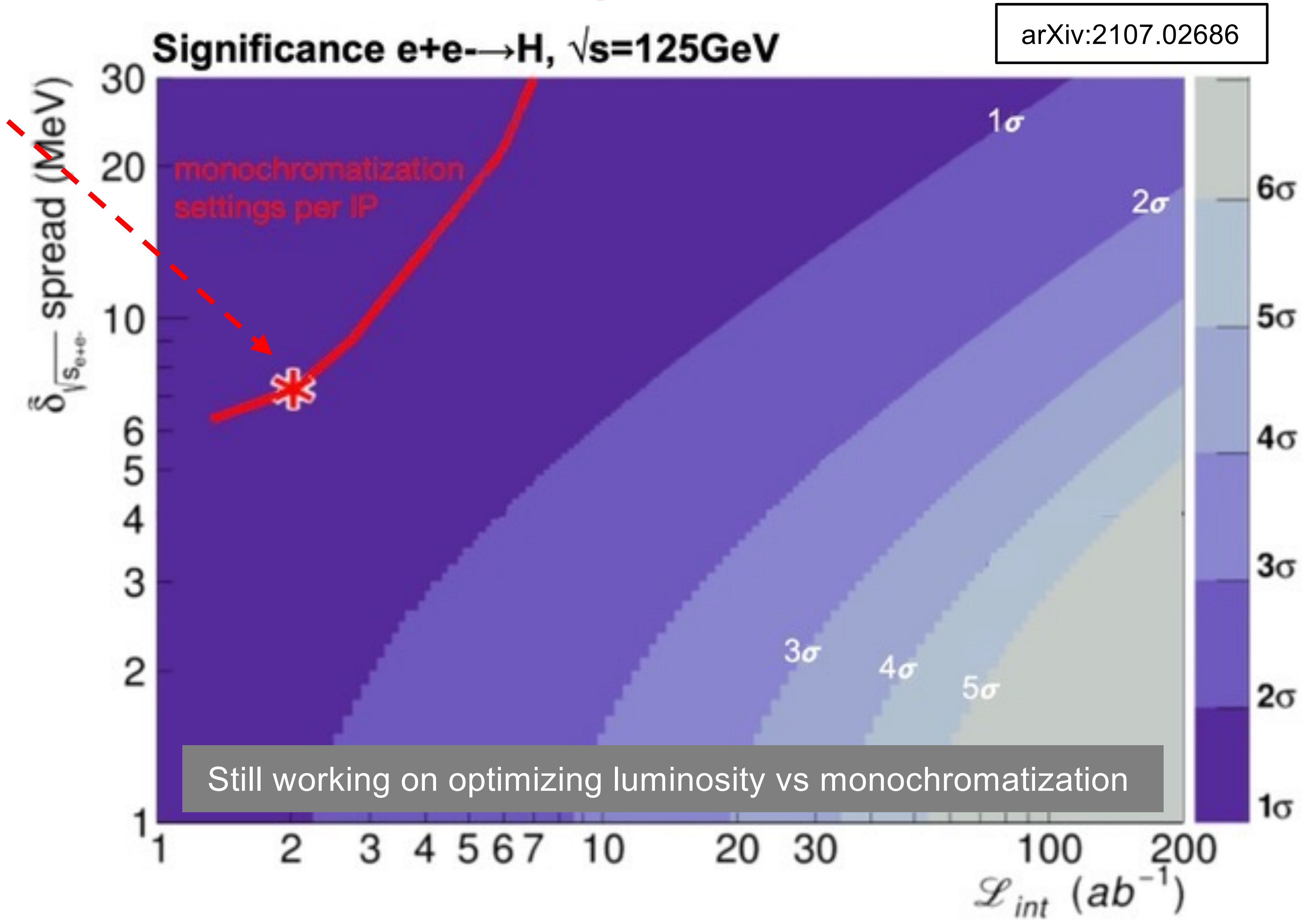

Still working on optimizing luminosity vs monochromatization

24

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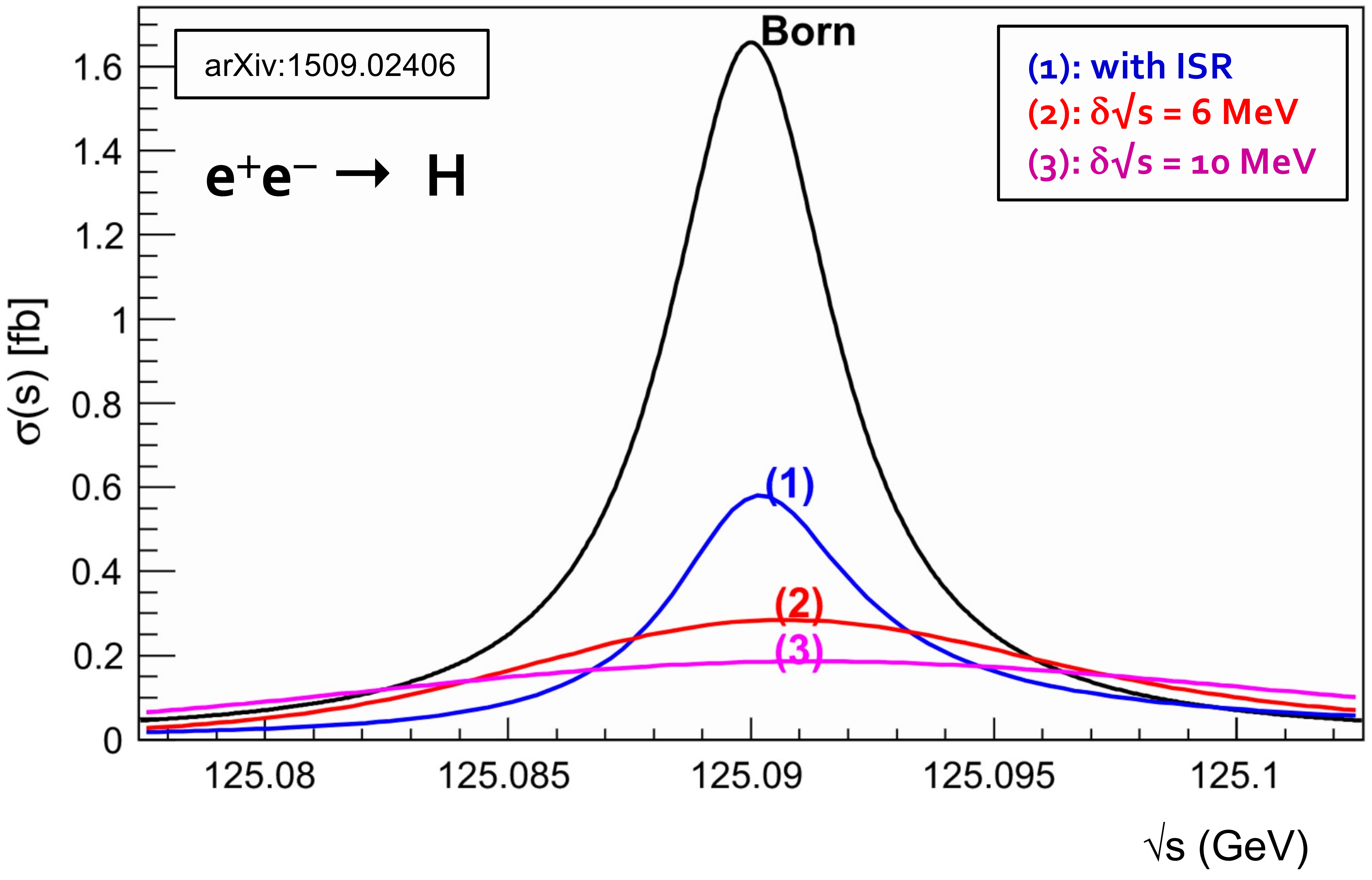
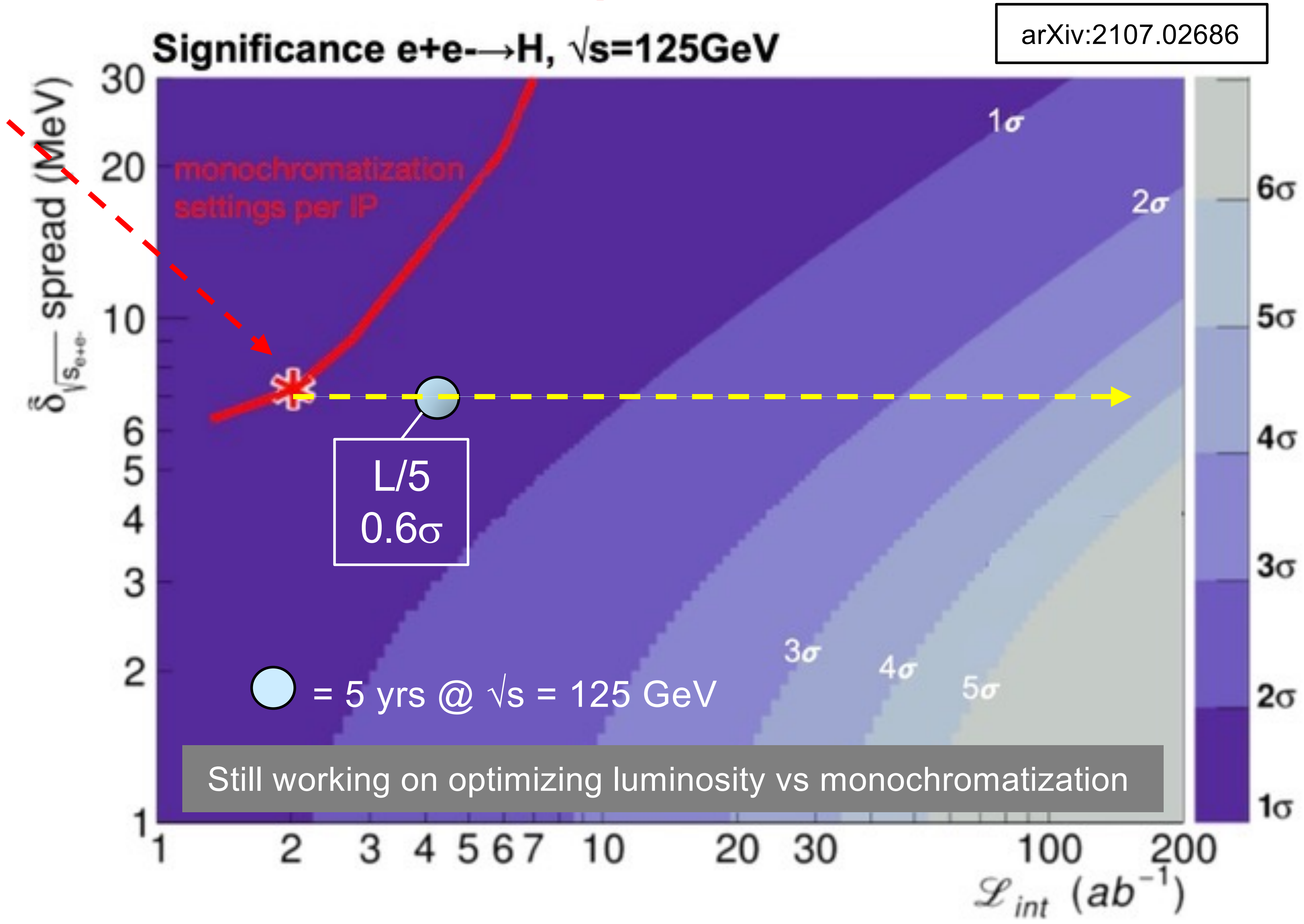

arXiv:1509.02406


arXiv:2107.02686

L/5
0.6σ

= 5 yrs @ √s = 125 GeV

Still working on optimizing luminosity vs monochromatization

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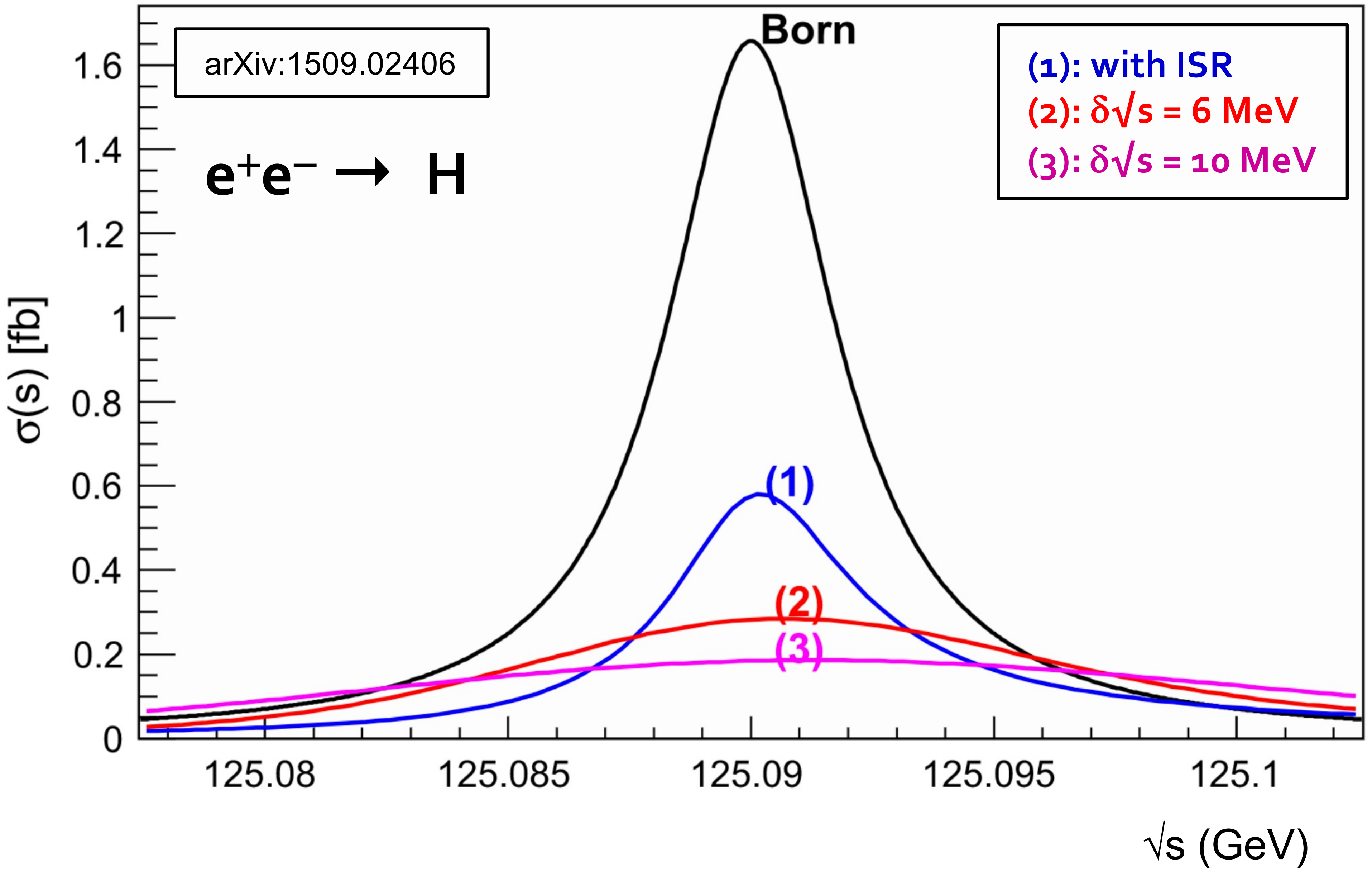

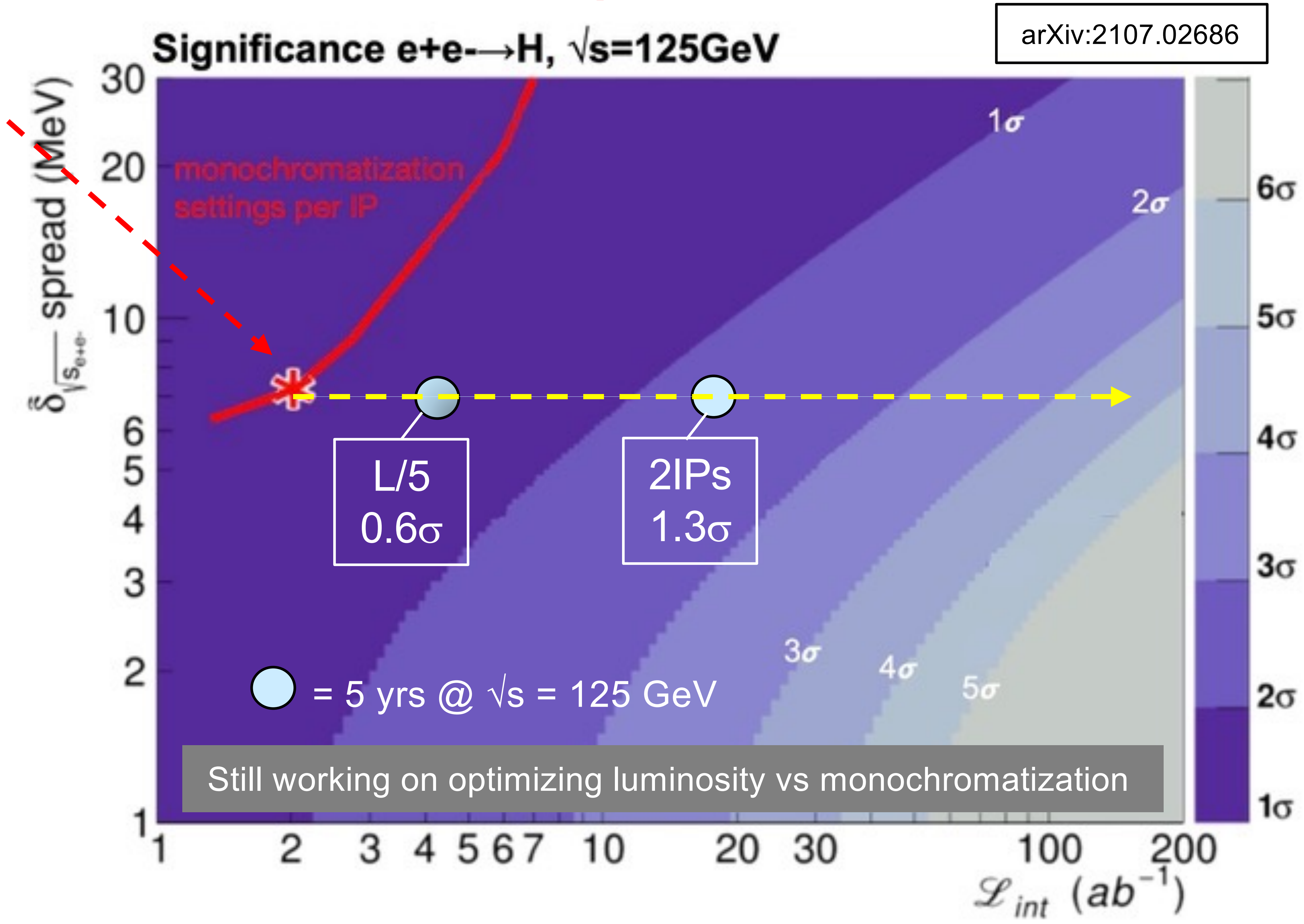

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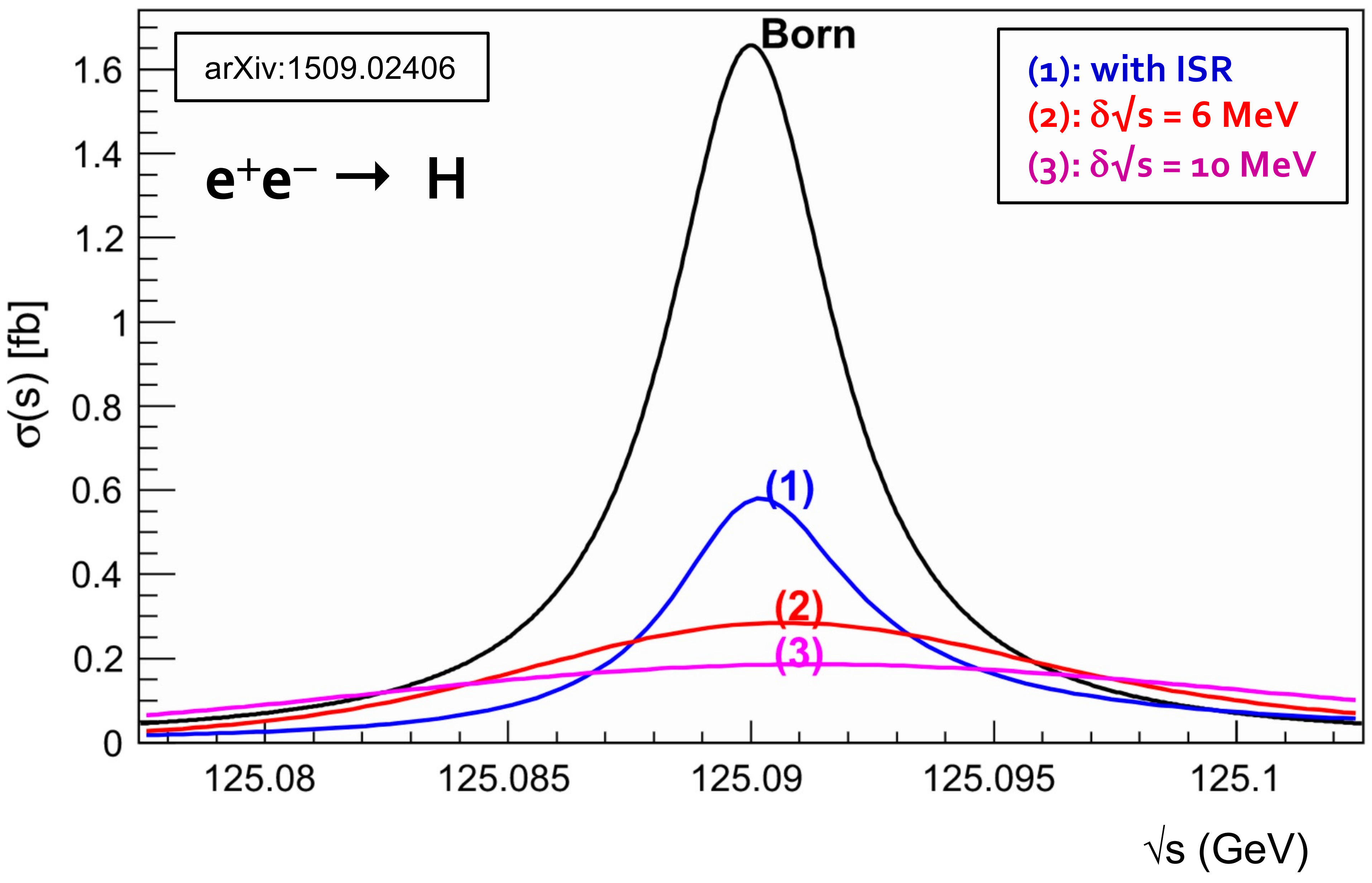

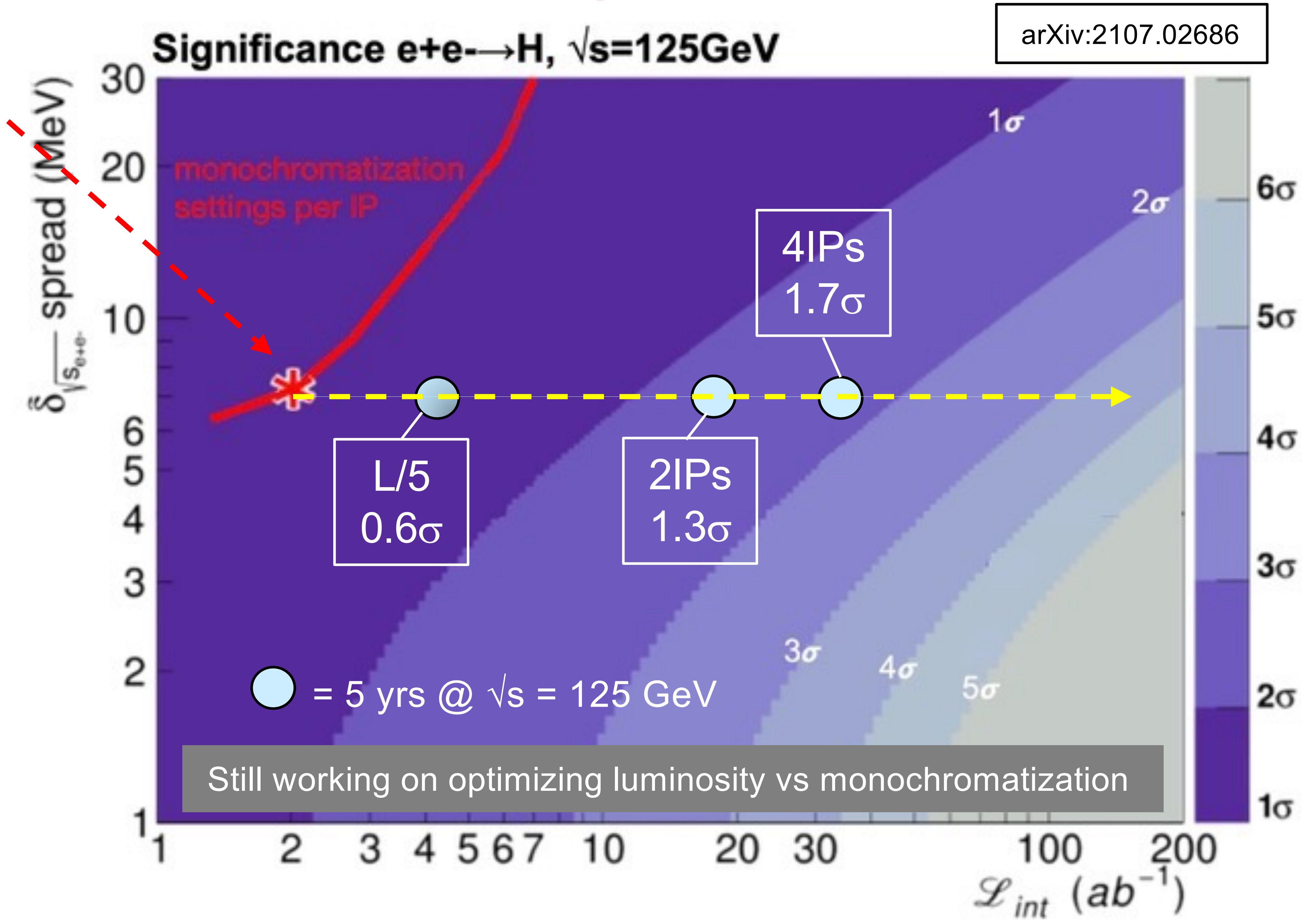

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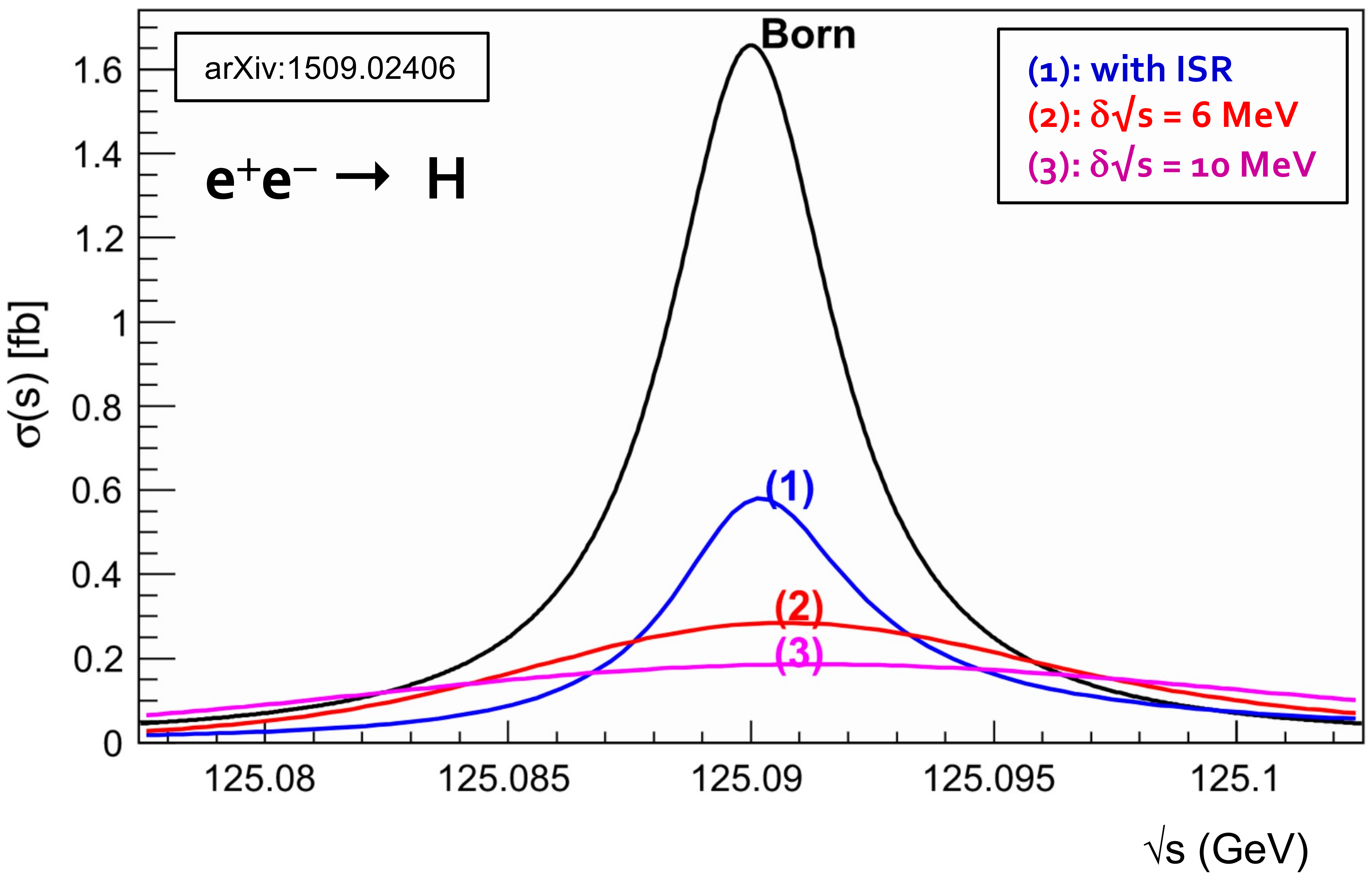

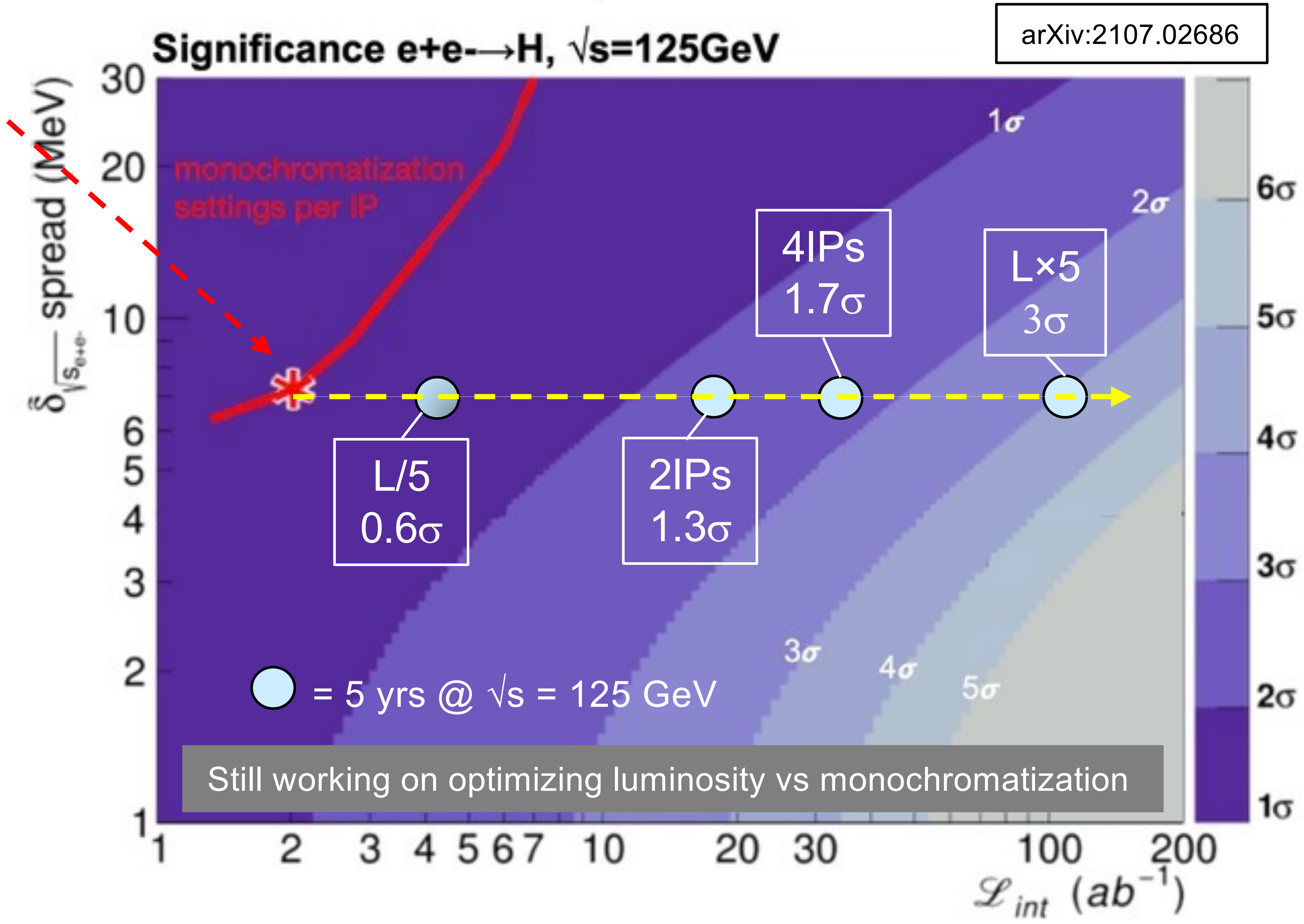

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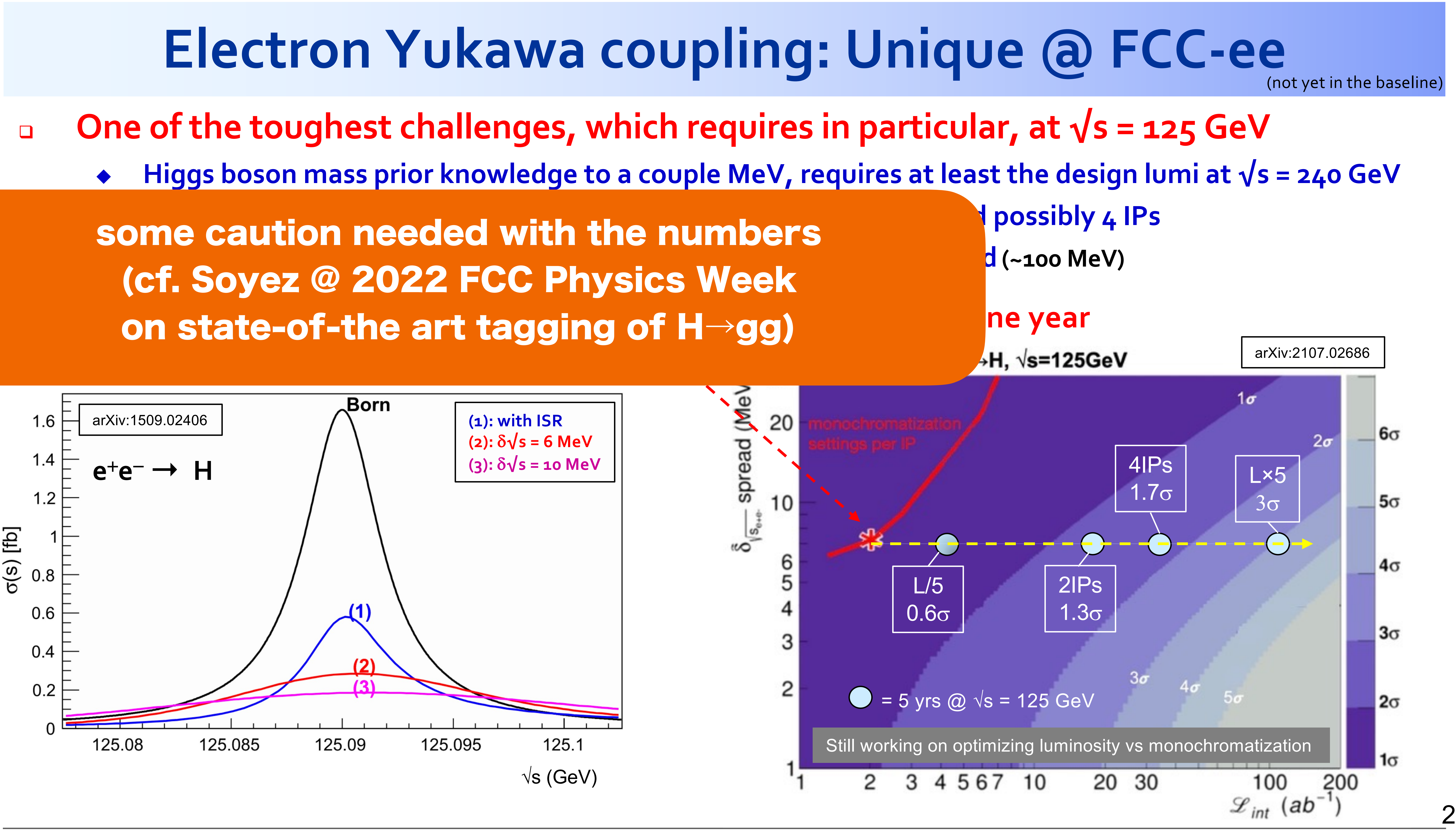

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ne year

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some caution needed with the numbers
(cf. Soyez @ 2022 FCC Physics Week
on state-of-the art tagging of H→gg)

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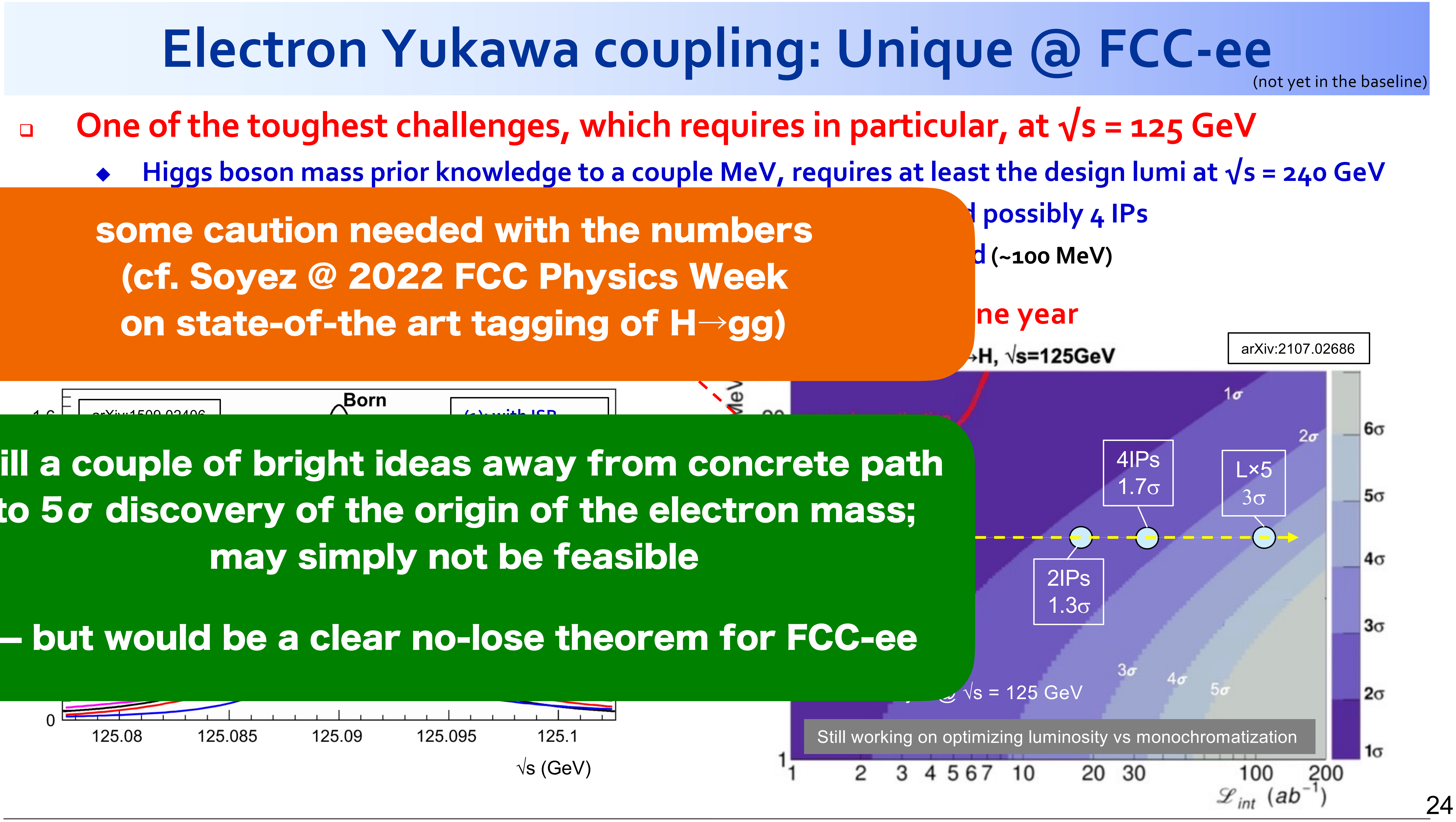

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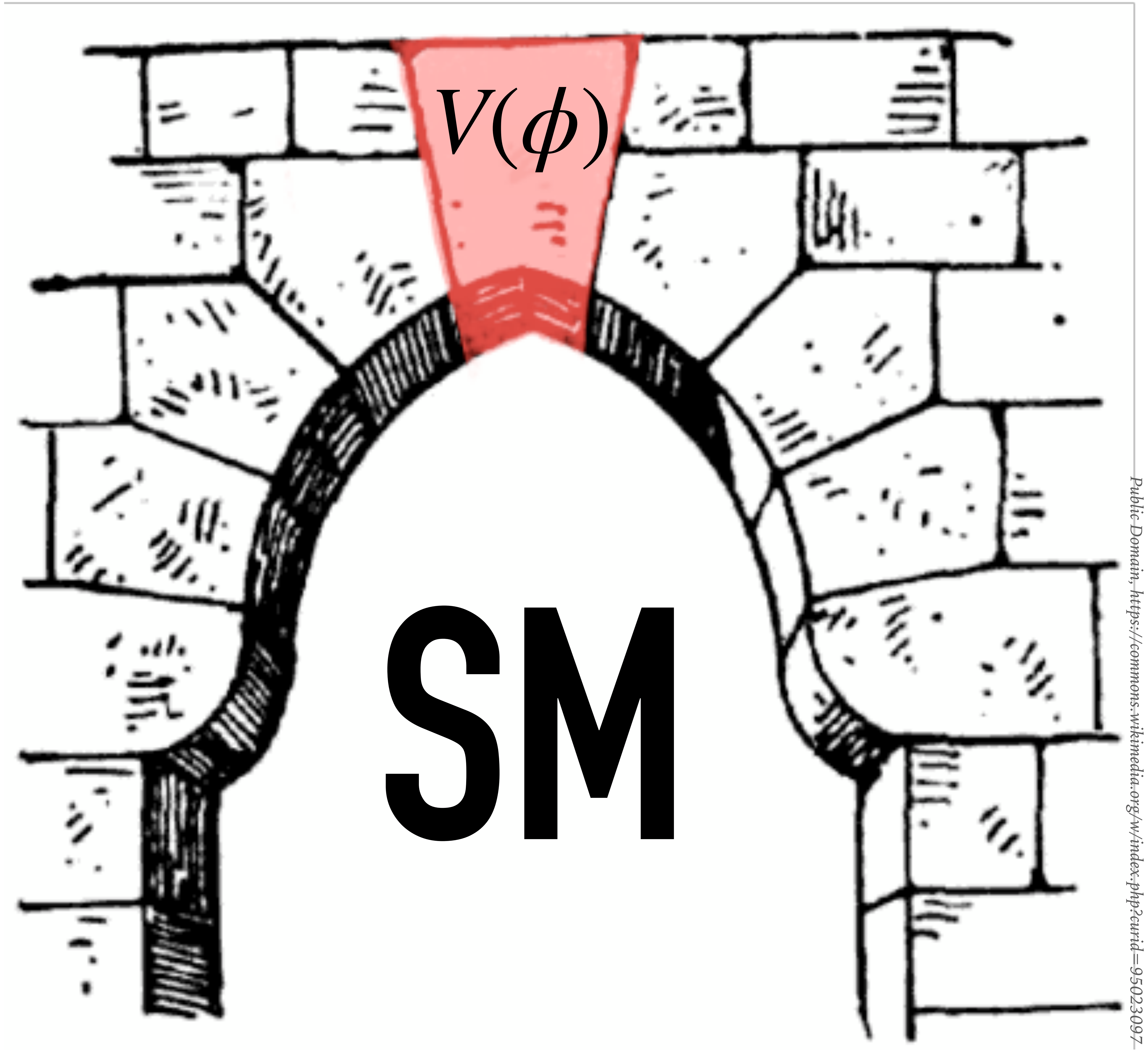
still a couple of bright ideas away from concrete path to 5σ discovery of the origin of the electron mass; may simply not be feasible

— but would be a clear no-lose theorem for FCC-ee

original slide from Patrick Janot

A side comment on the near future at LHC

- particle physics normally deals with esoteric particles that have [almost] no relation with the world as we experience it
- LHC will reach 5σ sensitivity for $H \to \mu\mu$ in the coming years (if it is SM-like), offering first proof that particles other than 3rd generation also get their mass from Yukawa mechanism
- that will be a crucial step on the way from 3rd generation Yukawas to 1st
- it deserves a big event with the world's press to announce it
- an opportunity to explain the quest for understanding the origin of the mass of the fundamental particles that **we are made of**



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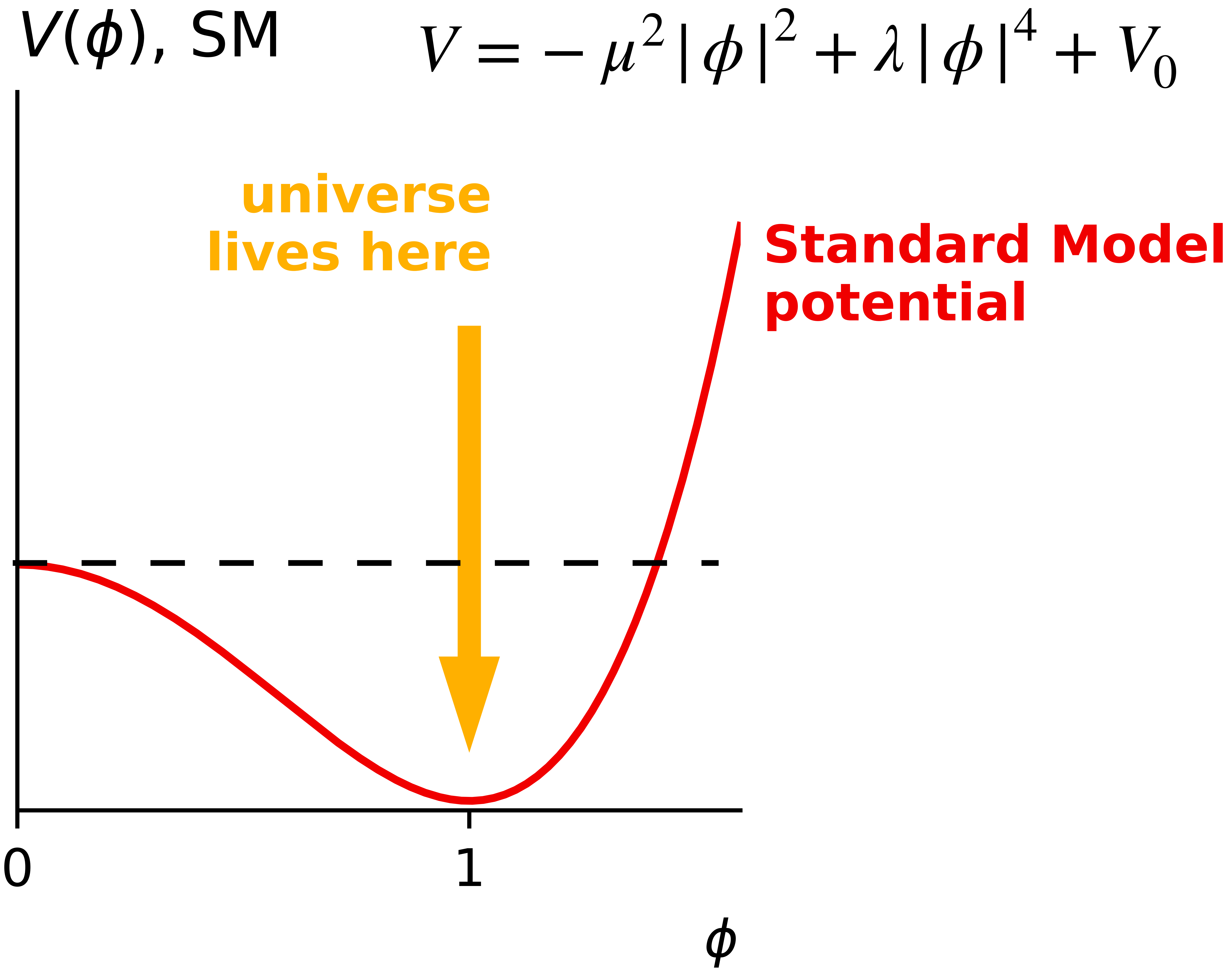
the Higgs potential

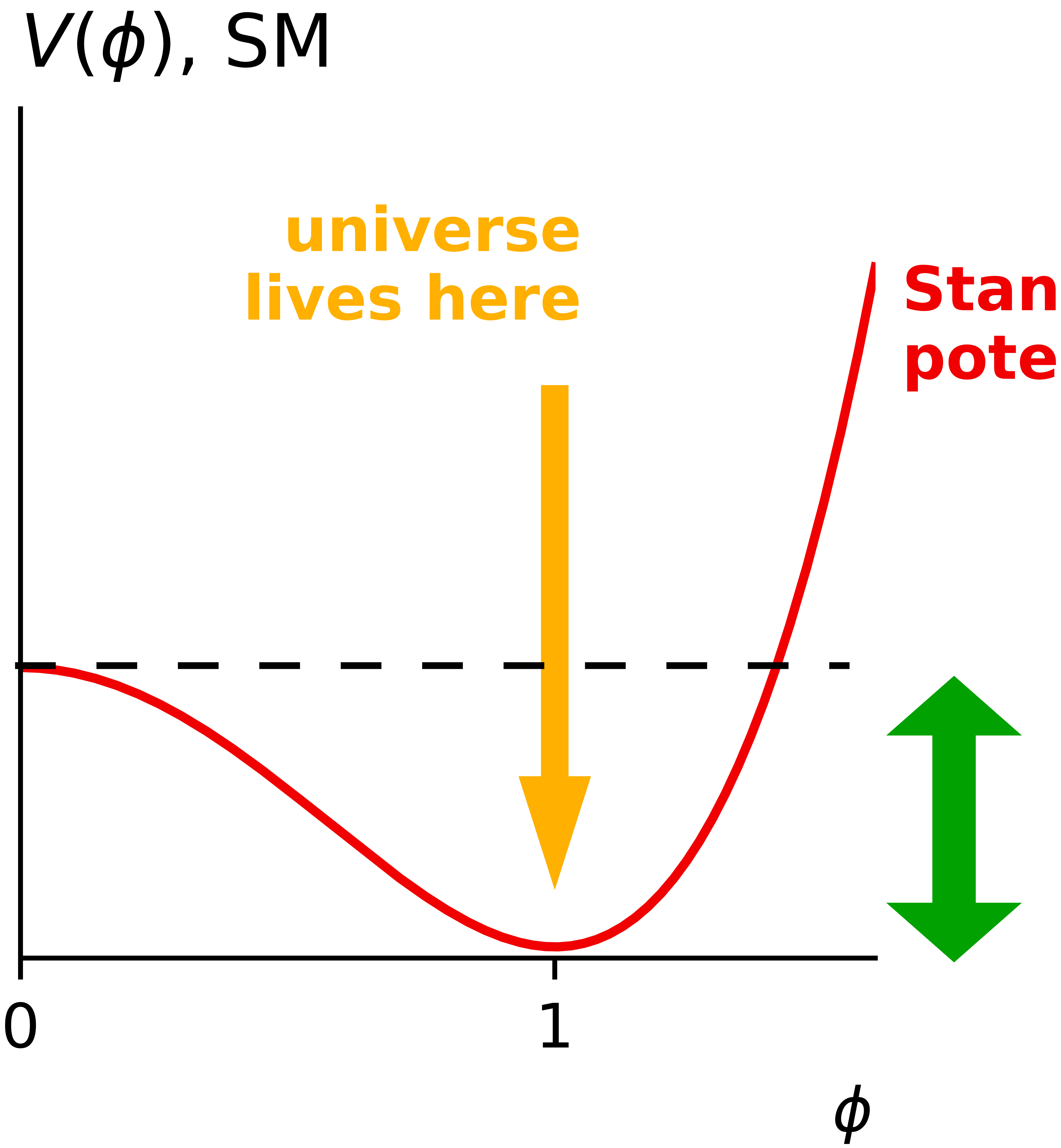
Higgs potential



the Higgs mechanism gives mass to particles because the Higgs field φ is non-zero

That happens because the minimum of the SM potential is at non-zero φ

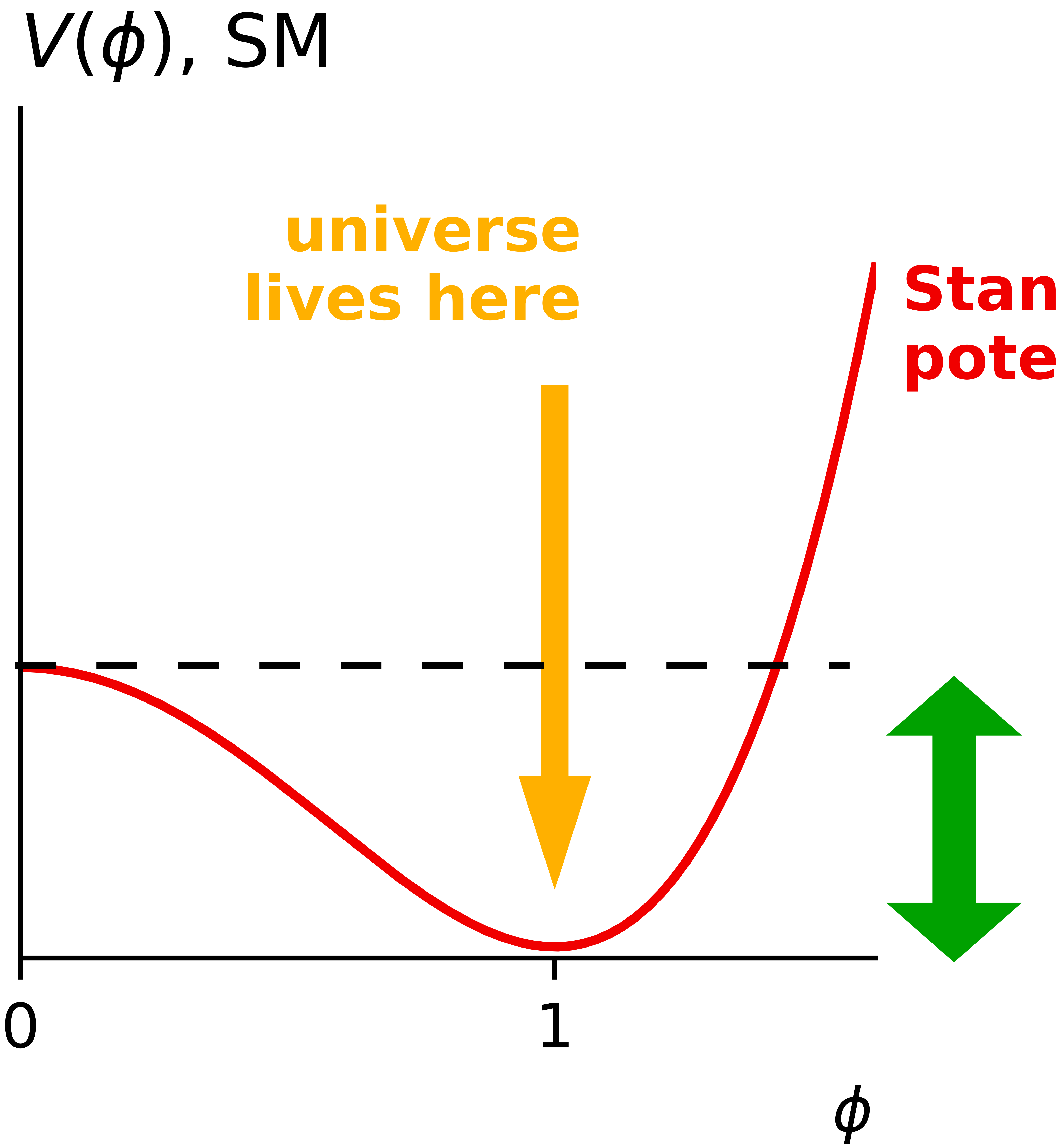
Higgs potential



depth is $\frac{m_H^2 v^2}{8}$ $(m_H \simeq 125\,\text{GeV},\ v \simeq 246\,\text{GeV})$

a fairly innocuous sounding $(104\,\text{GeV})^4$

Higgs potential – remember: it's an energy density



Corresponds to an energy density of $1.5 \times 10^{10}\,\mathrm{GeV/fm}^3$
i.e. **10 billion times nuclear density**

Mass density of $2.6 \times 10^{28}\,\mathrm{kg/m}^3$

What does 2.6×10^{28} kg/m^3 mean?

By KMJ, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1443327

What does 2.6×10^{28} kg/m^3 mean?

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https://solarsystem.nasa.gov/resources/768/nasas-sdo-sees-sun-emit-mid-level-flare-oct-1/

By Danny Cornelissen - http://www.portpictures.nl, Attribution, https://commons.wikimedia.org/w/index.php?curid=435125

What does 2.6×10^{28} kg/m^3 mean?

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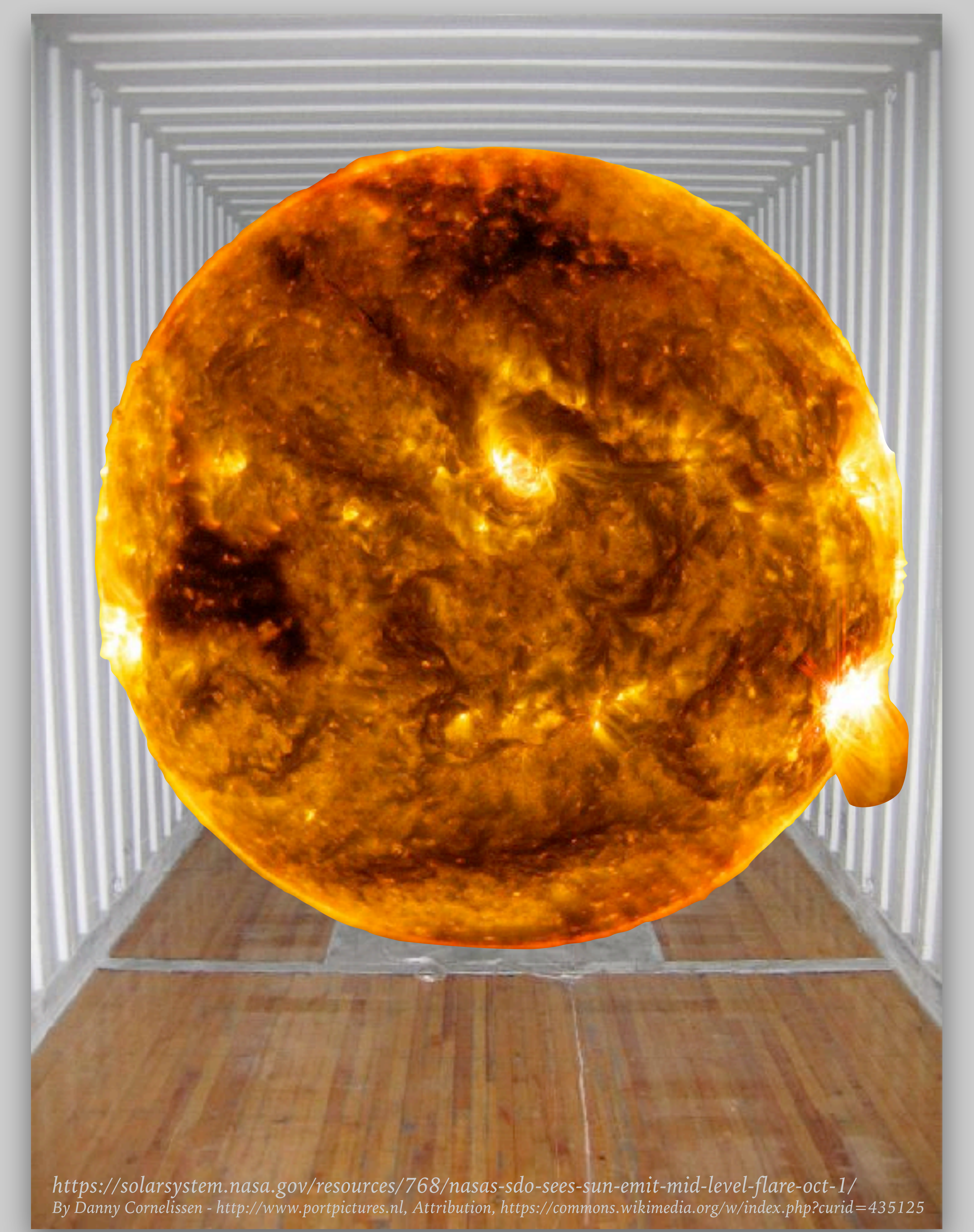


https://solarsystem.nasa.gov/resources/768/nasas-sdo-sees-sun-emit-mid-level-flare-oct-1/
By Danny Cornelissen - http://www.portpictures.nl, Attribution, https://commons.wikimedia.org/w/index.php?curid=435125

fit the mass of the sun into a standard 40ft shipping container

cosmological constant & fine-tuning [classically]

$$V_{min} = \left[-\mu^2|\phi|^2 + \lambda|\phi|^4\right]_{\phi_0} + V_0$$

cosmological constant

$$= -2.6 \times 10^{28}\, kg/m^3 \quad + \; V_0 = \boxed{5.96 \times 10^{-27}\, kg/m^3}$$

- V_0 needs to be fine tuned for cosmological constant to have today's size (also with respect to various sources of quantum correction)
- not the only fine-tuning problem in fundamental physics, — arguably special in that it appears already classically
- collider physics cannot tell us anything about V_0 — but it would seem negligent not to try and establish the rest of the potential

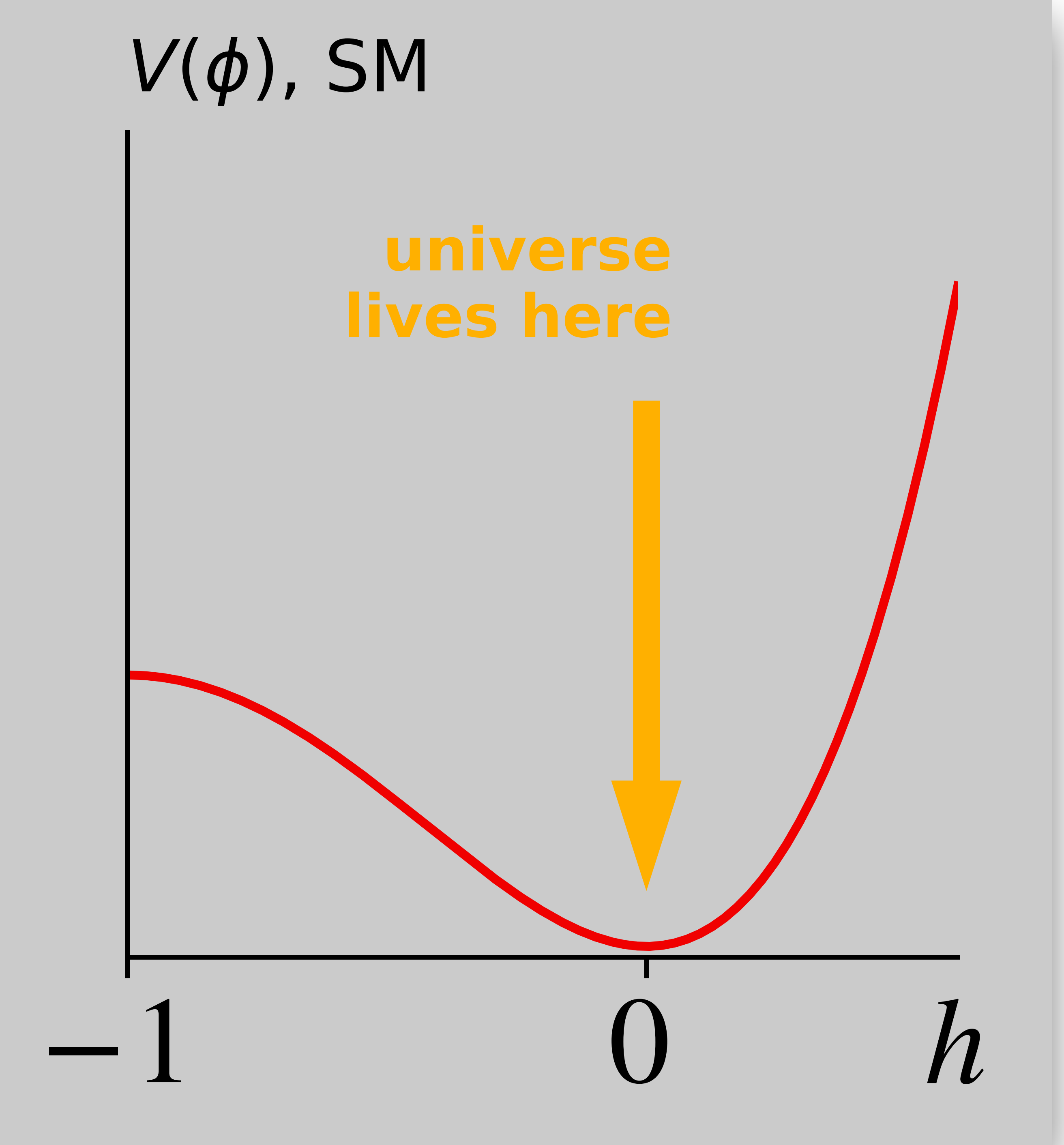
The potential expanded around the minimum

- take h as the Higgs field excitation in units of the field at minimum

$$V = \frac{m_H^2 v^2}{8}\left(-1 + 4h^2 + 4h^3 + h^4\right)$$

the Higgs boson mass term

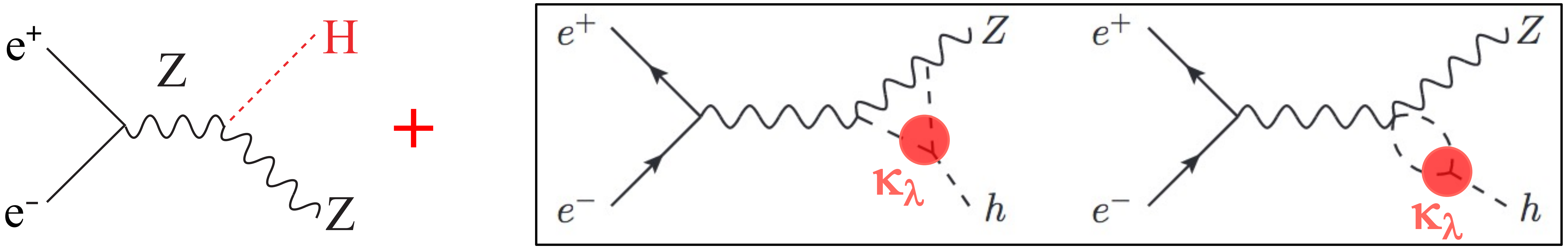
prediction of the strength of HHH interaction
[modifier may be called κ_λ or κ_3]

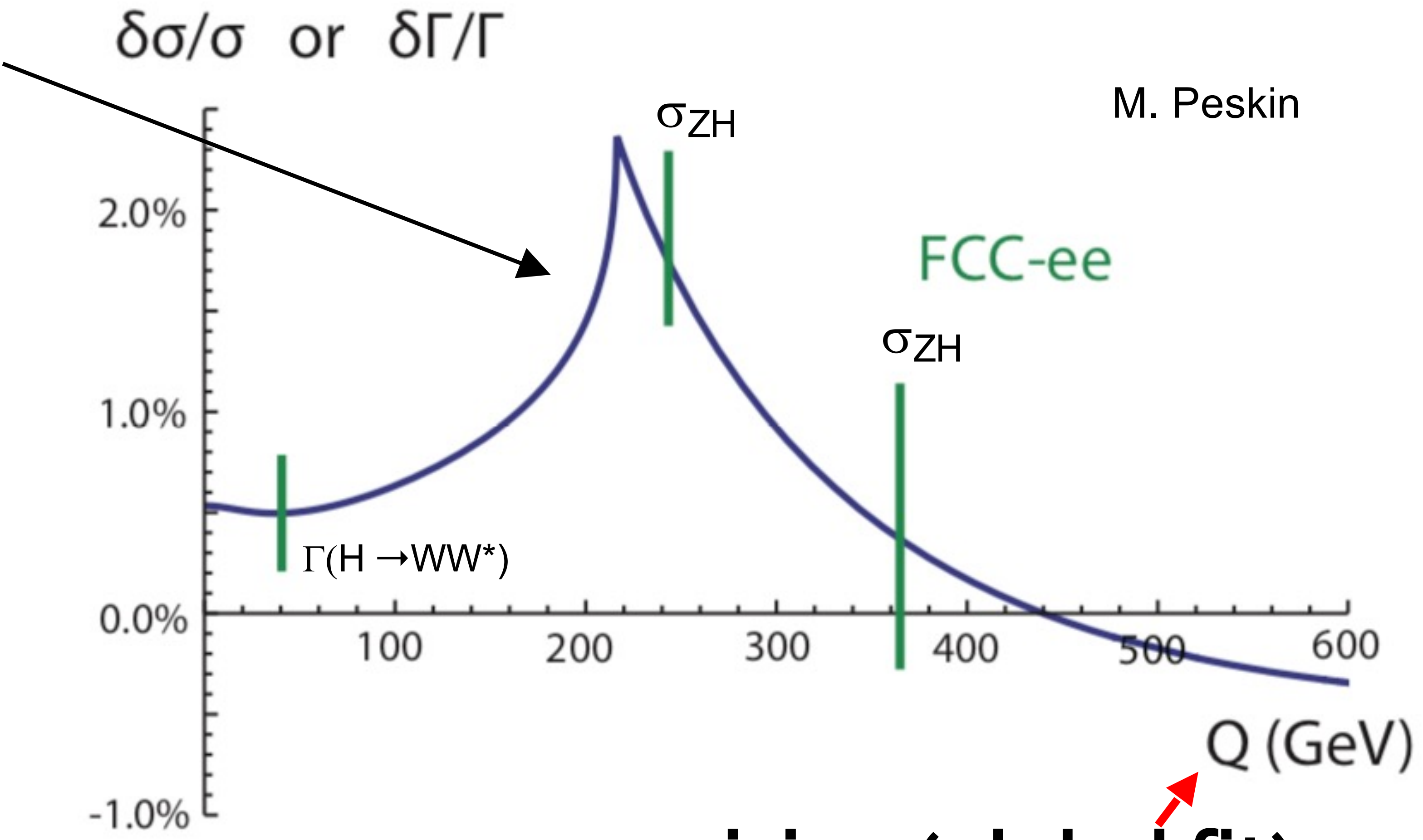


[slide from P. Janot]

Higgs self-coupling at FCC-ee

- Statistics-limited sensitivity comes from $\sigma_{ee\to ZH}$ measurements at 240 and 365 GeV
  - Thanks to the relative change with centre-of-mass energy

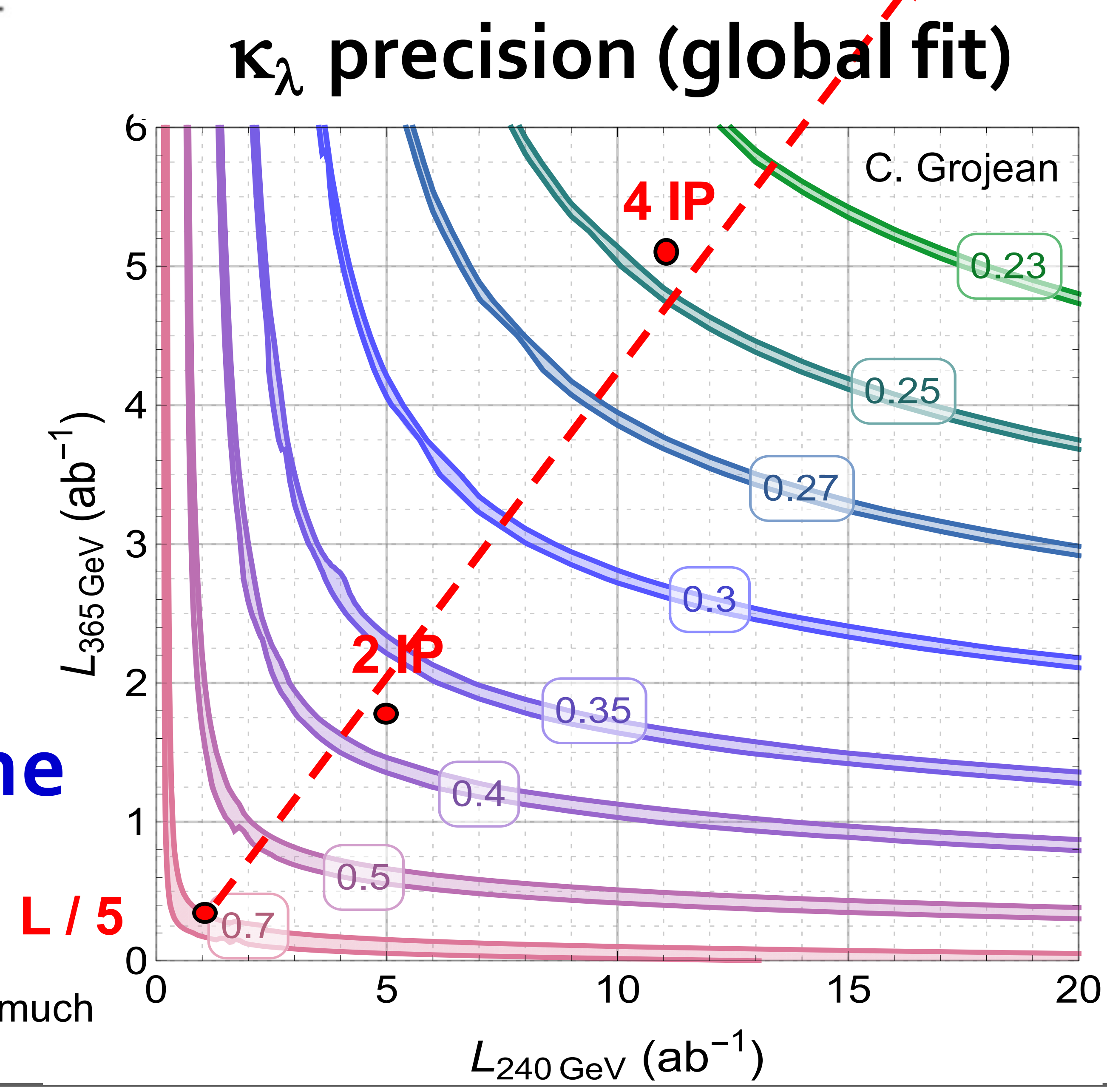




- Estimate with present run plan and 2 IPs: ≥ 2σ from $\kappa_\lambda = 0$
  - Analyses will improve, but no hope with 5 times less luminosity

(Discovery)

- With 4 IPs and optimization of run plan: target ≥ 5σ, $\delta\kappa_\lambda$~20%
  - Increase duration at 240 and 365 GeV (to 4 and 7 years)
    - Reduce Z and WW run duration @ constant statistics
  - Or better: increase specific luminosity and/or overall running time
    - If it is worth doing, it is worth doing well



HL-LHC alone cannot do much
in a global EFT fit …

Testing SM $V(\varphi)$ by measuring HH production at FCC: ~3–5% accuracy

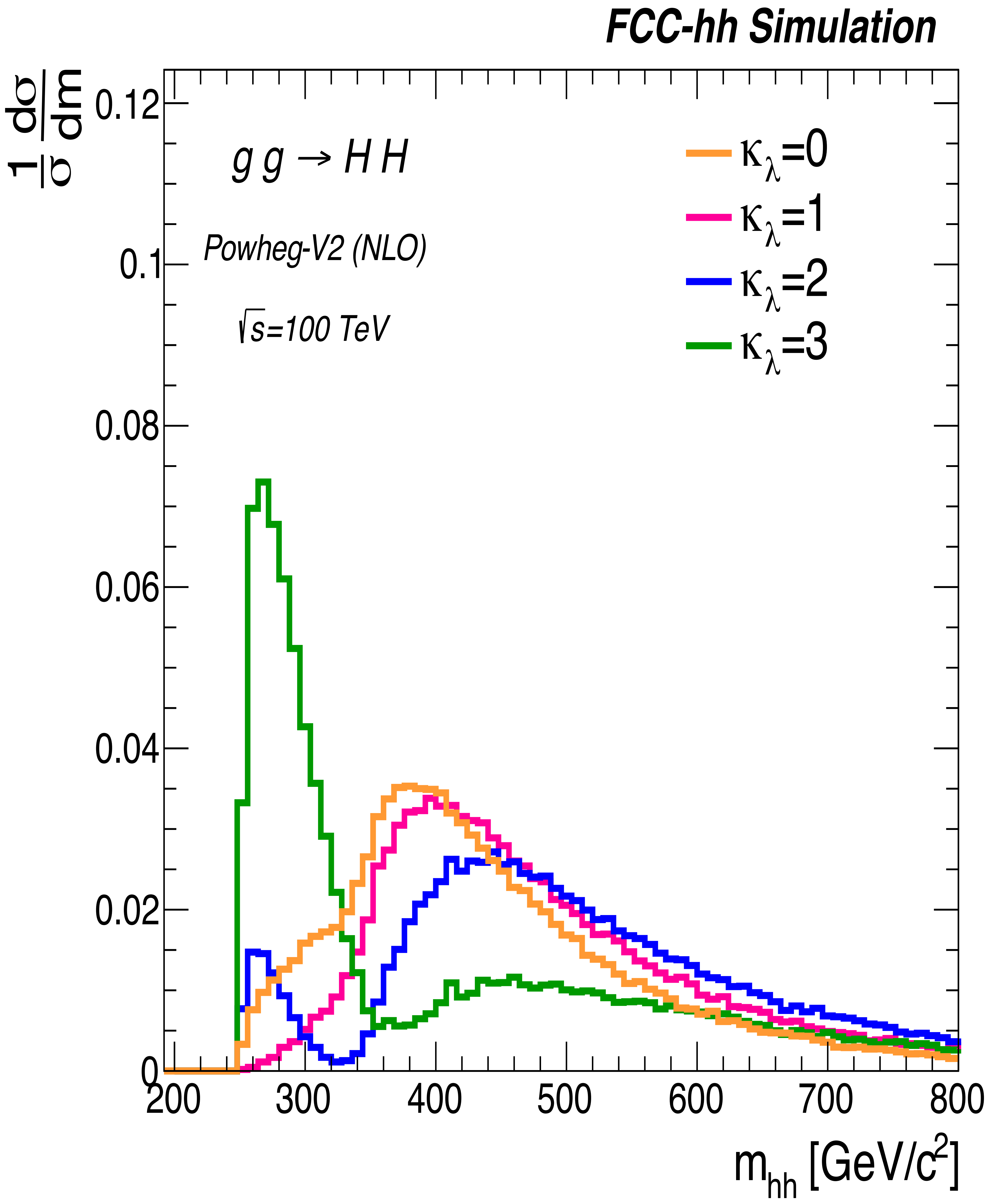
- kinematic shape of HH pair clearly distinguishes independent HH production from correlated HH
- FCC-hh → few % determination
  (needs accurate $t\bar{t}Z$ and Higgs couplings from FCC-ee)

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)



when would we claim discovery? [5σ in each of two independent experiments is our gold standard]

- equivalent for an interaction is a bit ambiguous — but better than ±20% determination is probably a reasonable target
- for something of this importance, I am wary of relying on 20% only from a combination of N experiments — a result's robustness comes from confirmation by independent experiments
- indirect v. direct:
  - all measurements are indirect (we measure hadrons and leptons…)
  - single H is good to have
  - but HH & kinematic structure brings assurance that what we are seeing is indeed HHH coupling
- NB there exist different points of view on this

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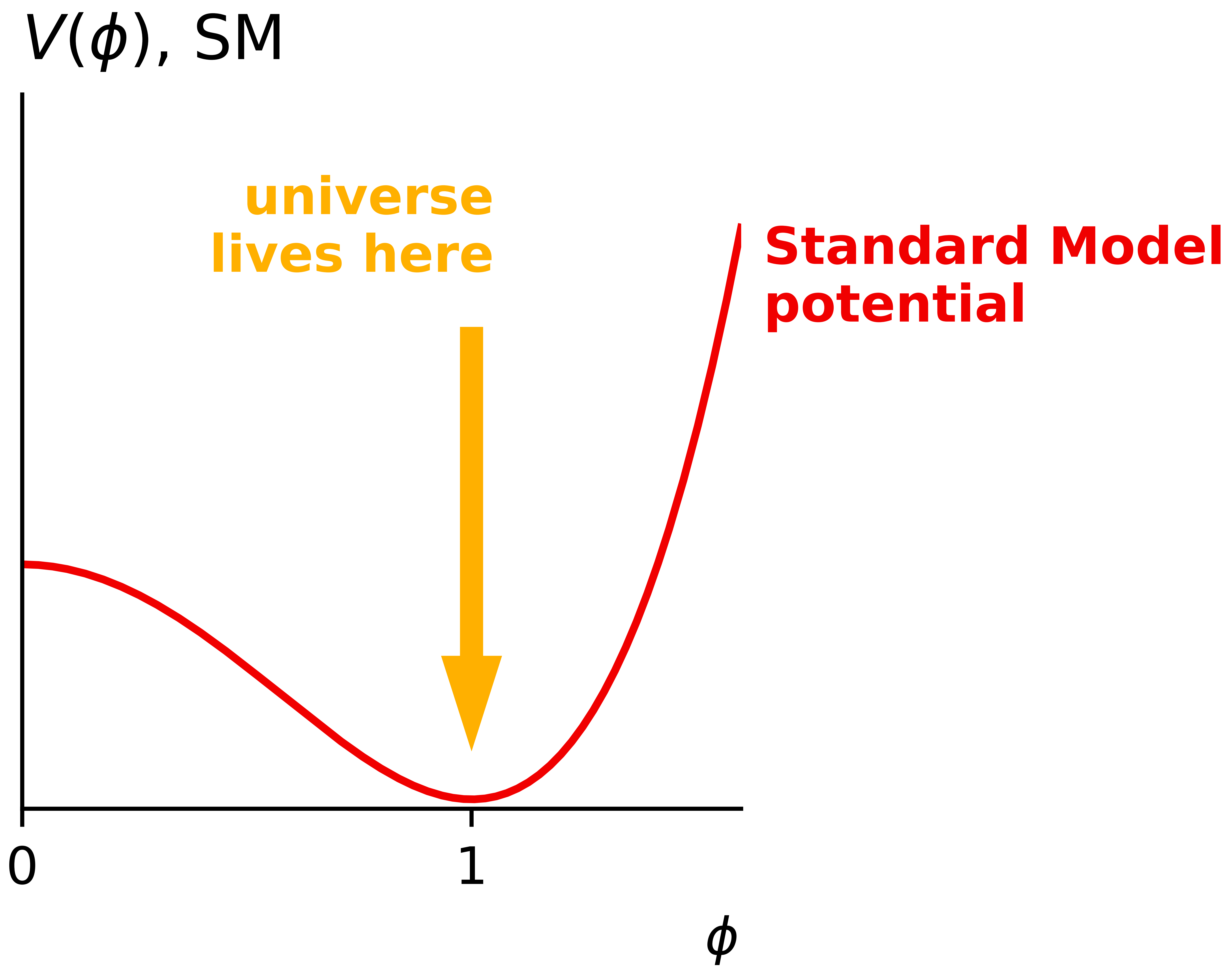
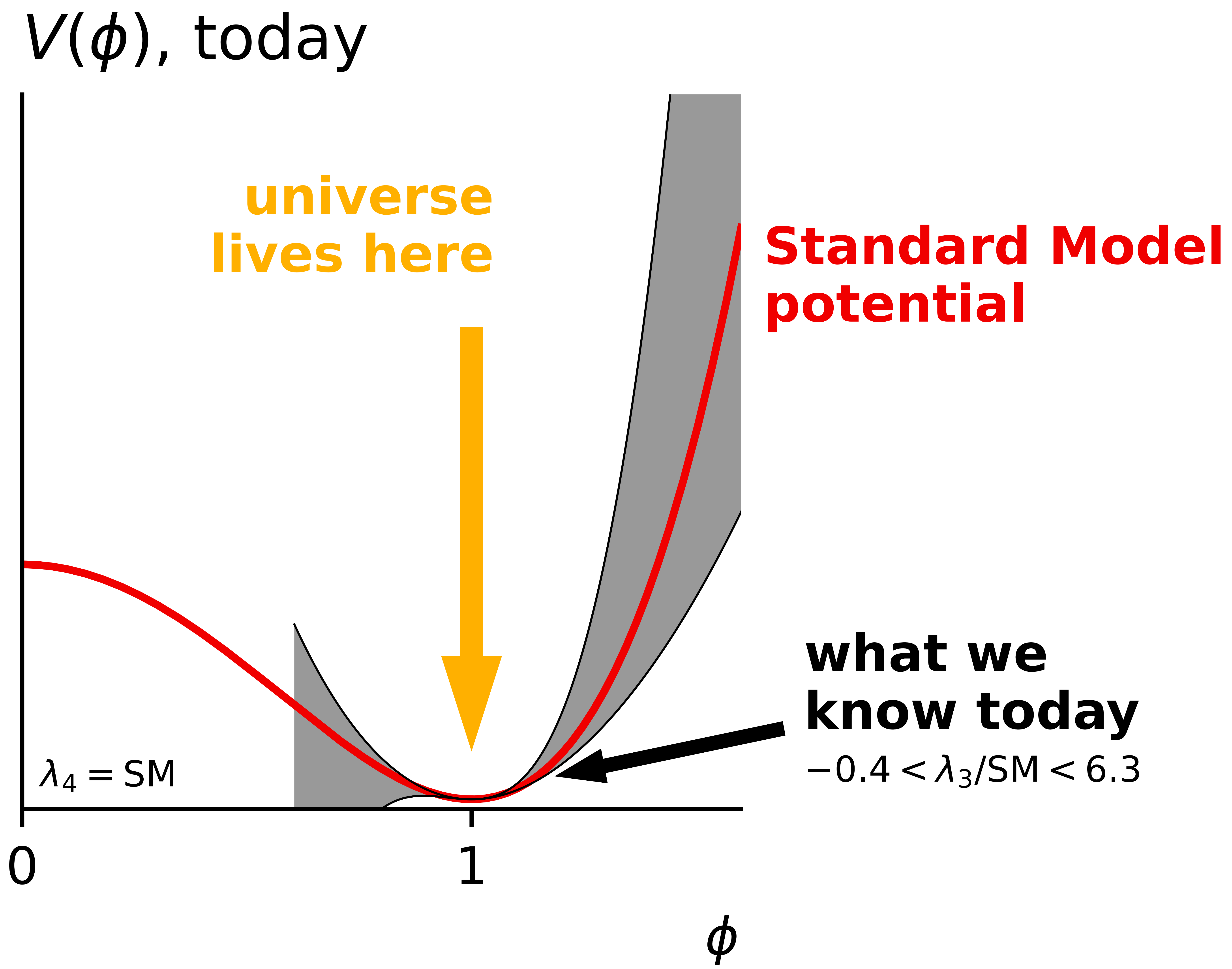
my view: observation of HHH interaction is the “no-lose theorem” of combined FCC programme

Higgs potential – impact of measurements



- this is a cartoon
- caution needed: e.g. realistic BSM models do not just modify the potential, but may bring extra scalars
  (often modify other couplings, but not always, e.g. 2209.00666)
- even if we take the picture seriously we may want to consider impact of limited constraints on λ_4
  (how many coincidences are needed for a BSM model to leave λ_3 untouched while modifying λ_4?)

Higgs potential – impact of measurements



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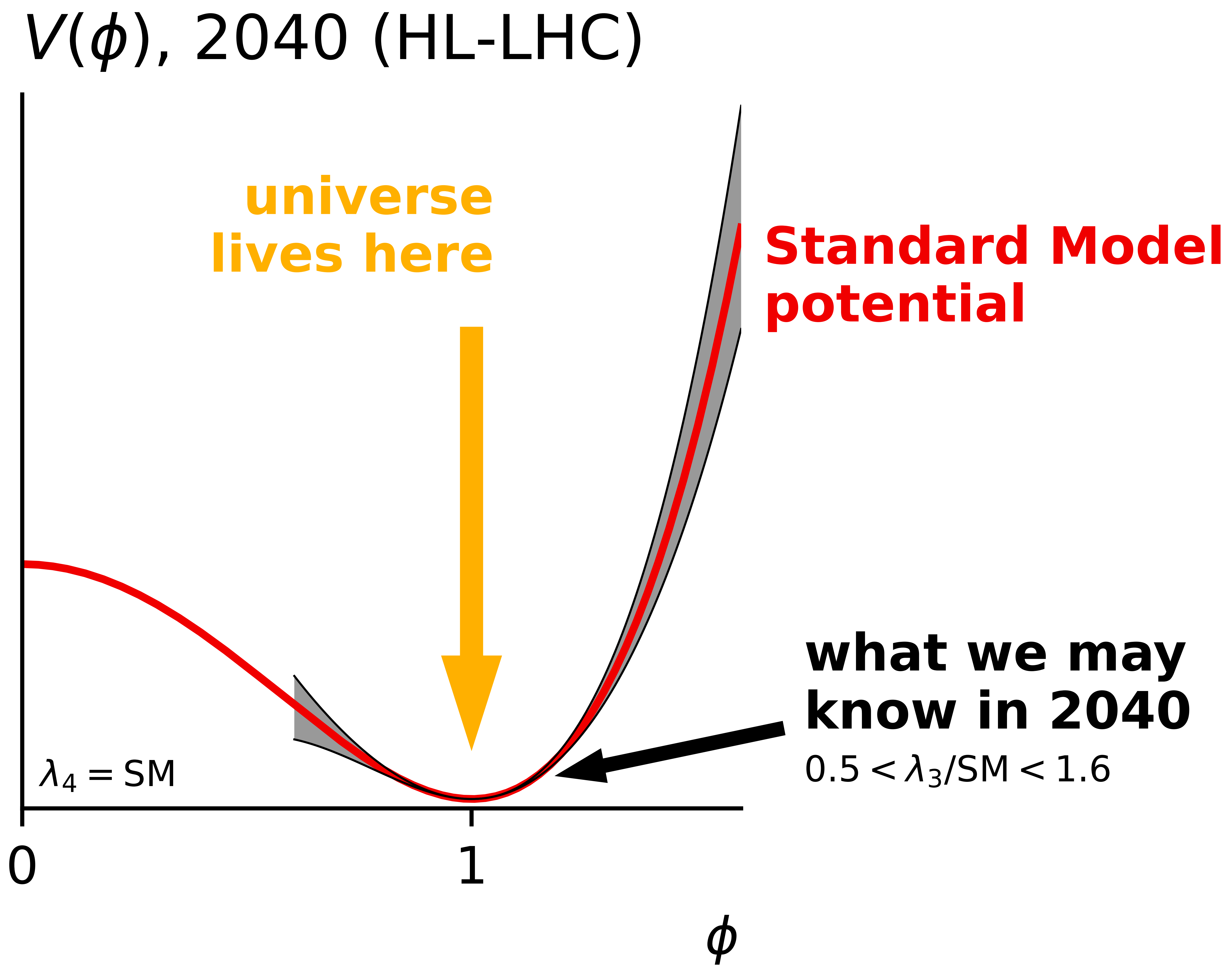

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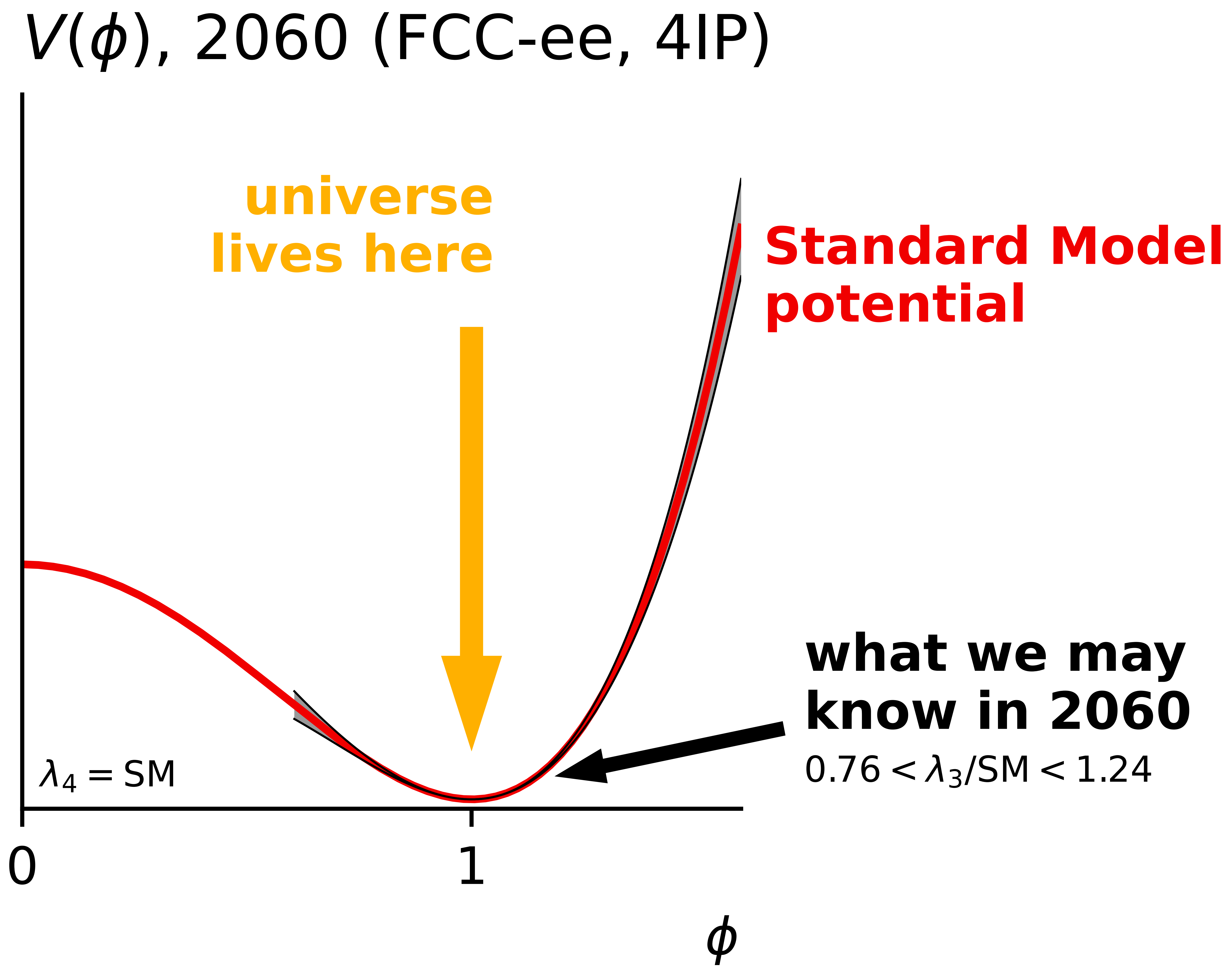

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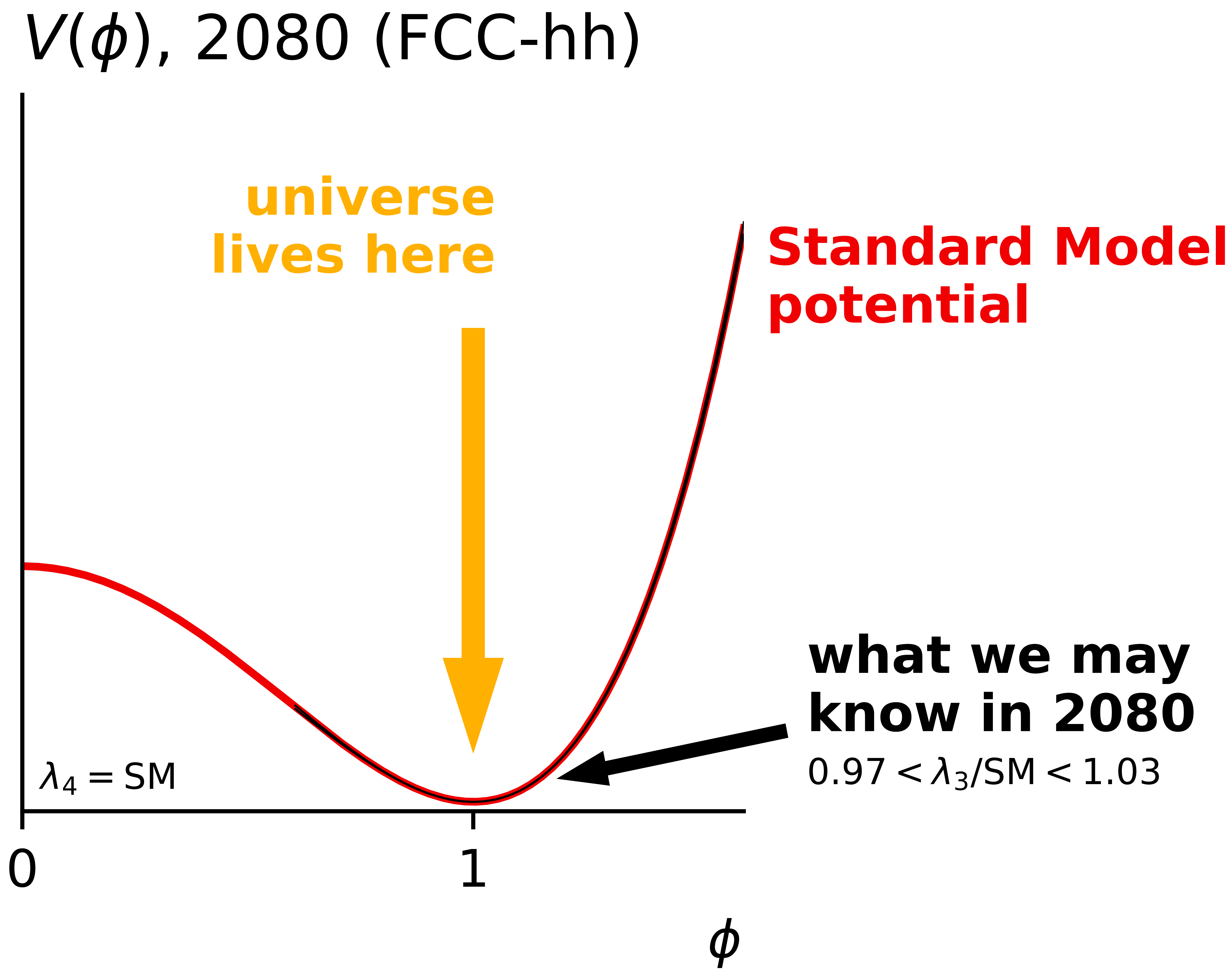

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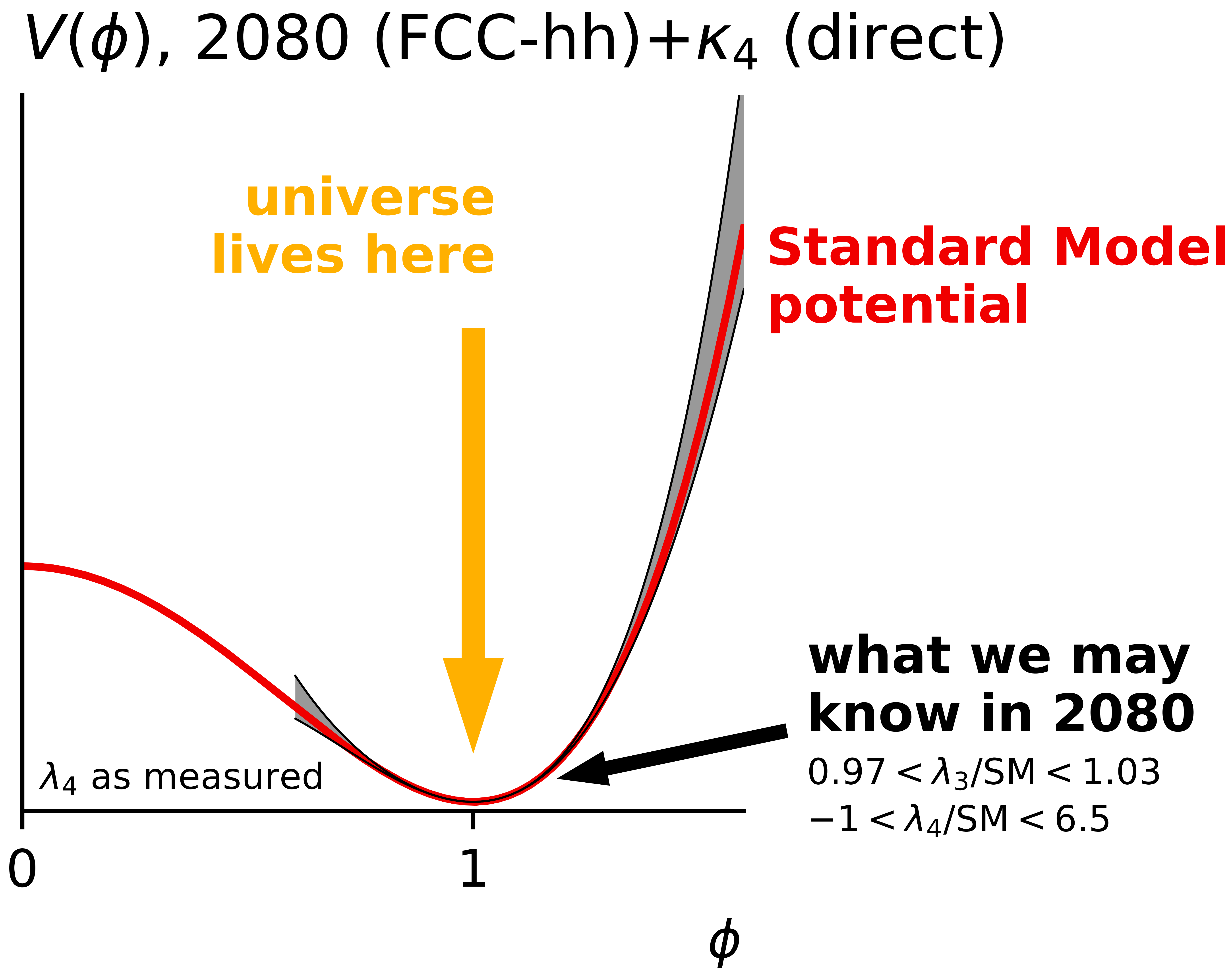

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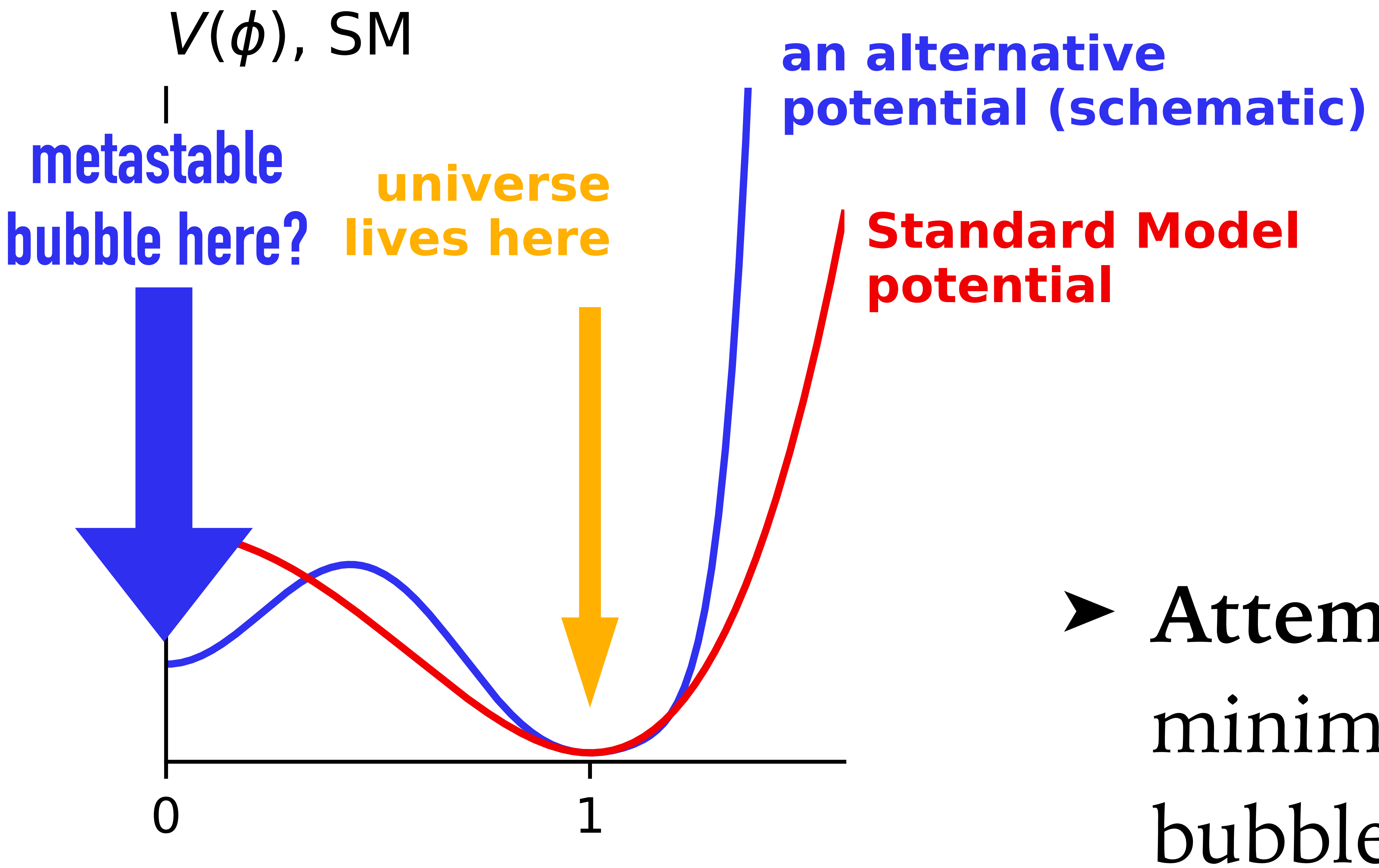
A wildly speculative aside [science fiction!]



- common argument for fundamental research: it may pay off in terms of technological advances in a century or two
- in particular physics, it's hard to conceive of a way in which this could be true
- **Attempt at counterexample:** if there were 2nd minimum in Higgs potential, could we create metastable bubbles of alternative vacuum? (cf. EW phase transition)
- likely very short lifetime, unless some kind of protection
- what might we do with it? E.g. very different nuclear physics, if light quarks get all mass from Yukawa interactions, long-range strong force (pion ~ massless), etc.
- **this scenario is very far fetched: do not take it seriously! (But we can't even tell how far fetched it is if we haven't measured the potential)**

desirable features of a worldwide HEP project?

an important target that is guaranteed to be reached
(no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (incl. multiple experiments)

cost-effective construction & operation, low carbon footprint

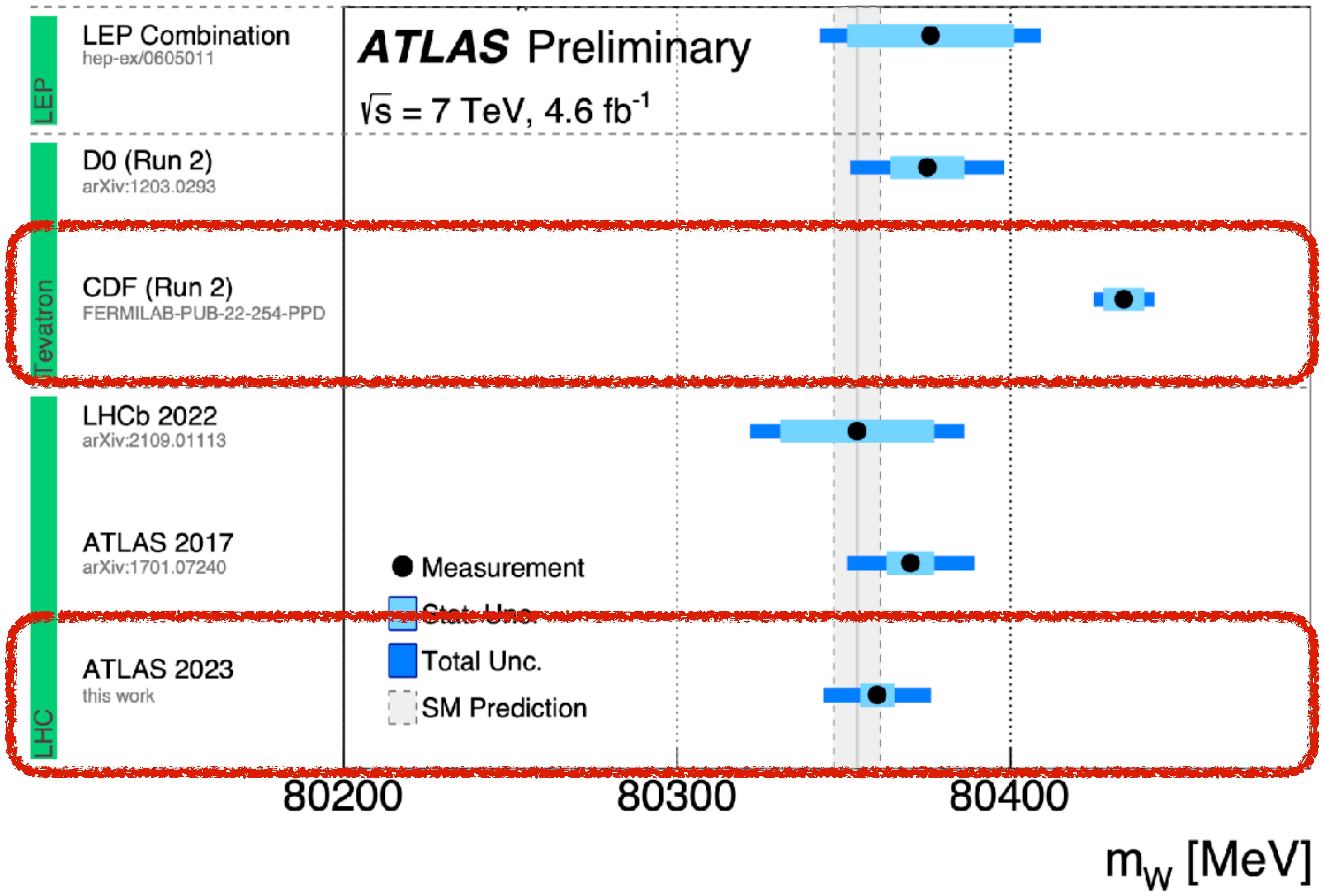
various arguments favour a circular e^+e^- collider [you all know them well]

- historical track record of delivering luminosity [LEP]
- unlike linear colliders, they naturally accommodate multiple experiments
- energy efficiency/unit luminosity from Z-pole to ZH
- electrons are a lot easier than muons

But some people ask if we need a lepton collider at all; should we not just go for the next hadron collider?

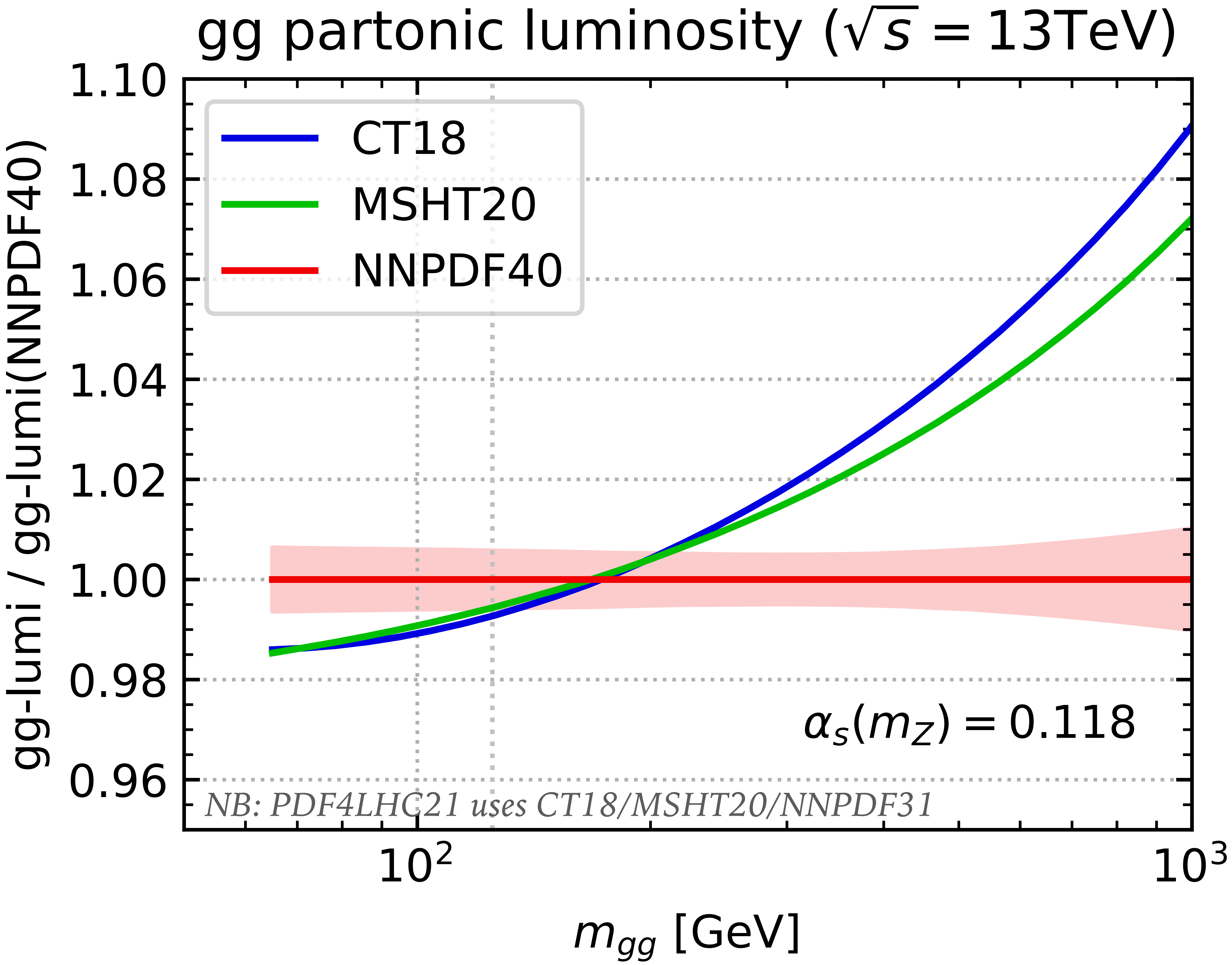
[practical arguments against: we don't really know how to build the magnets for a 100 TeV collider; cost of 91km collider is high even with LHC-type magnets]

m_W measurements



do you believe the measurement when it **disagrees** with your expectations?

we don't know the precision limit of hadron colliders — but we may be close to reaching it



NB: PDF4LHC21 uses CT18/MSHT20/NNPDF31

gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	1.0000	±	0.0184
PDF4LHC21	0.9930	±	0.0155
CT18	0.9914	±	0.0180
MSHT20	0.9930	±	0.0108
NNPDF40	0.9986	±	0.0058

× 3

Parton Distribution Functions are one of several elements that may limit LHC/FCC-hh precision:

- essential for hadron-collider interpretation
- PDF fits are complex, e.g. involve (sometimes inconsistent) data, some of it close to non-perturbative scale
- only partial understanding of their limits

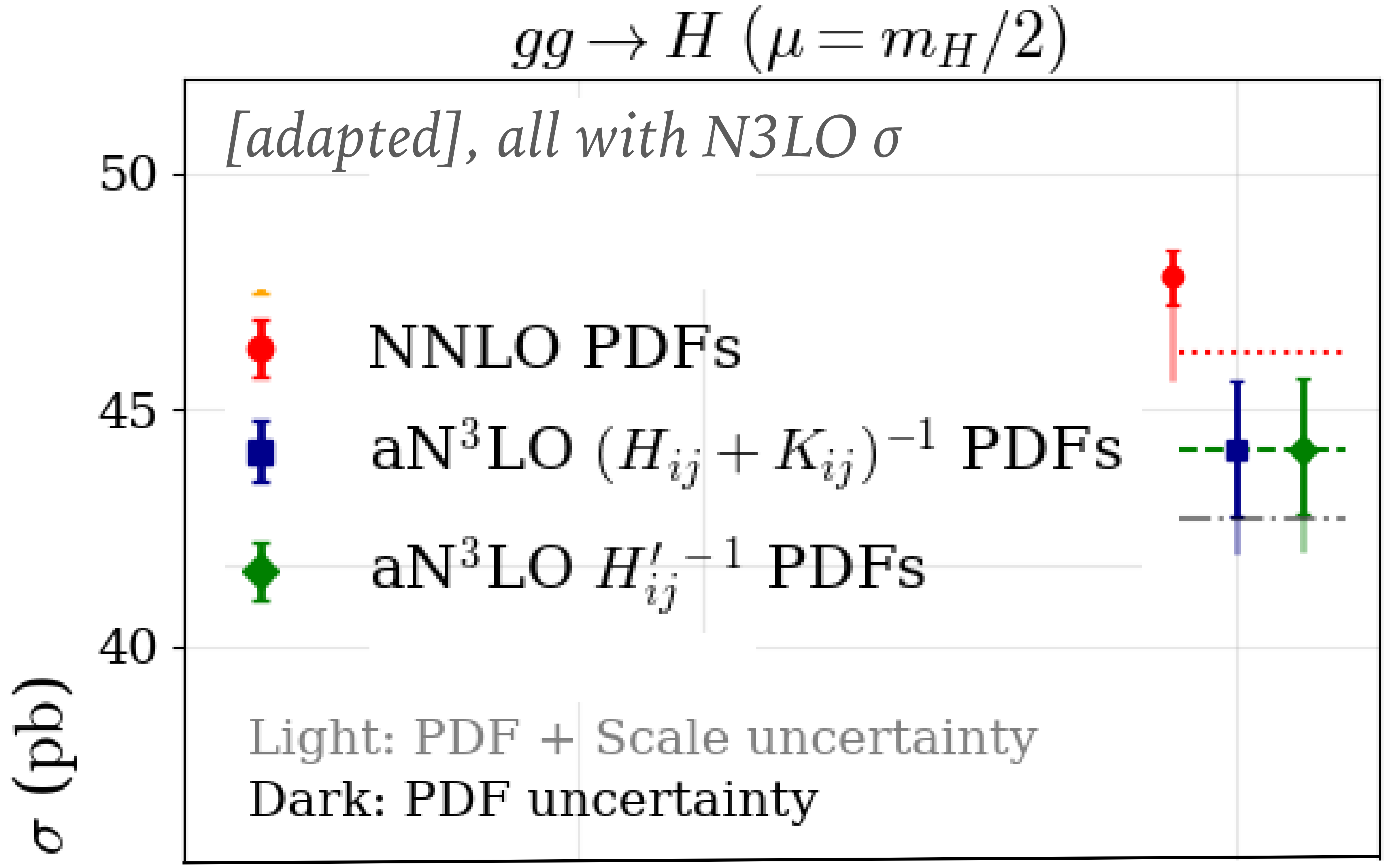
first approx N3LO PDFs

Approximate N^{3}LO Parton Distribution Functions with Theoretical Uncertainties:

MSHT20aN^{3}LO PDFs

arXiv:2207.04739v1

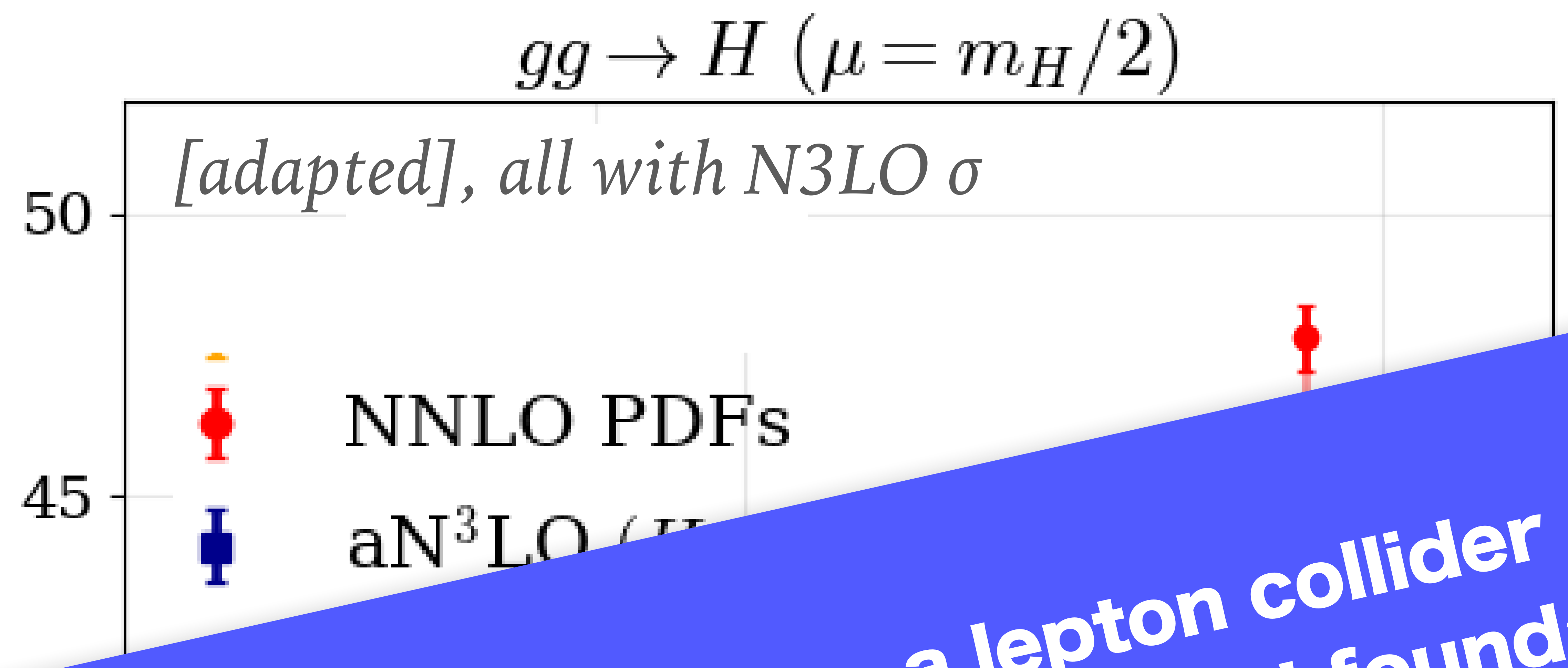
J. McGowan[a], T. Cridge[a], L. A. Harland-Lang[b], and R.S. Thorne[a]



σ order	PDF order	σ (pb) + $\Delta\sigma_+$ − $\Delta\sigma_-$ (%)
		PDF uncertainties
N^{3}LO	aN^{3}LO (no theory unc.)	44.164 + 3.03% - 3.13%
	aN^{3}LO $(H_{ij} + K_{ij})$	44.164 + 3.34% - 3.15%
	aN^{3}LO (H'_{ij})	44.164 + 3.43% - 3.07%
	NNLO	47.817 + 1.17% - 1.22%

- includes approximations & data-driven fits to parts of N3LO currently unknown
- **7.6% decrease in Higgs cross section** (w. N3LO σ)
- PDF part of **uncertainty goes up by ×2.5–3**
- fairly surprising; starting point for many future investigations

first approx N3LO PDFs



		$_+ - \Delta\sigma_-$ (%)
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Approximate N^{3}LO Parton Distribution Functions
with Theoretical Uncertainties:

MSHT20aN^{3}LO PDFs

arXiv:2207.04739v1

J. McGowan[a], T. Cridge[a], L. A.

oss

LO σ)

- PDF part of uncertainty goes up by ×2.5–3
- fairly surprising; starting point for many future investigations

a lepton collider as a next step
ensures solid foundations for the field

e.g. measurement of H→gg at 1% at FCC-ee underpins precision of FCC-hh
(and similarly ttZ coupling for ttH normalisation, etc.)

desirable features of a worldwide HEP project?

an important target that is guaranteed to be reached
(no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (incl. multiple experiments)

cost-effective construction & operation, low carbon footprint

what should we expect as a step up in energy?

I like the Z'_{SSM} as a simple measure of progress
(perhaps not very “exciting”, but simple and most experiments look for it)

Tevatron
$p\bar{p}$, 1.96 TeV, 10 fb^{-1}

Exclusion limit ~ 1.2 TeV

(if they had analysed all their data in electron and muon channels; actual CDF limit 1.071 TeV, 4.7fb^{-1}, μμ only)

× 4

LHC
pp, 13.6 TeV, 139 fb^{-1}

Exclusion limit ~ 5.1 TeV

(electron and muon channels, single experiment)

what should we expect as a step up in energy?

I like the Z'_{SSM} as a simple measure of progress
(perhaps not very "exciting", but simple and most experiments look for it)

LHC
pp, 13 TeV, 139 fb^{-1}

Exclusion limit ~ 5.1 TeV

(electron and muon channels, single experiment)

× 7.8 →

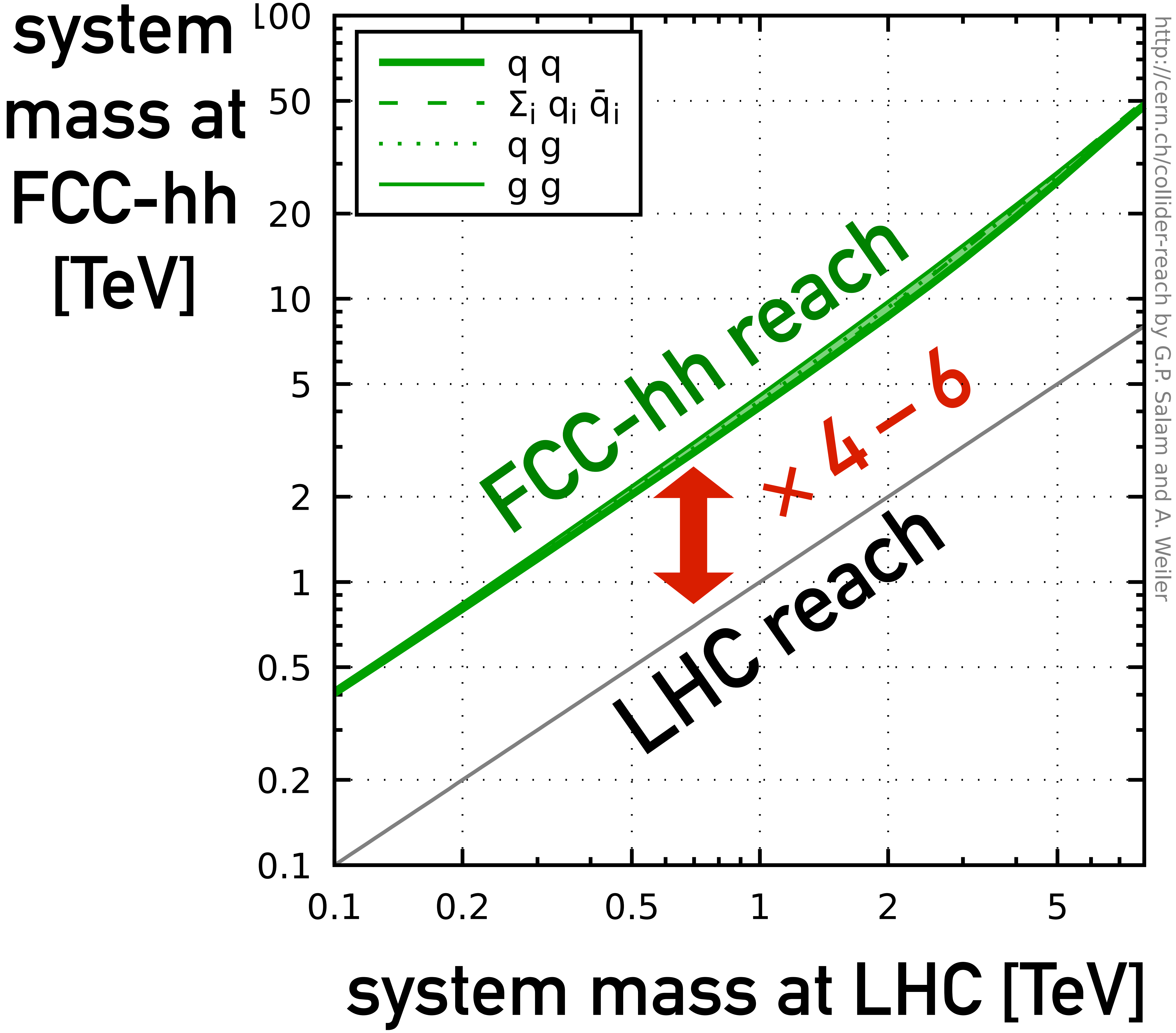
FCC-hh
pp, 100 TeV, 20 ab^{-1}

Exclusion limit ~ 41 TeV

(based on PDF luminosity scaling, assuming detectors can handle muons and electrons at these energies)

LHC 3 ab^{-1} → FCC–hh 20 ab^{-1}

Collider 1: CoM energy 14 TeV, integrated luminosity 3000 fb^{-1}
Collider 2: CoM energy 100 TeV, integrated luminosity 20000 fb^{-1}

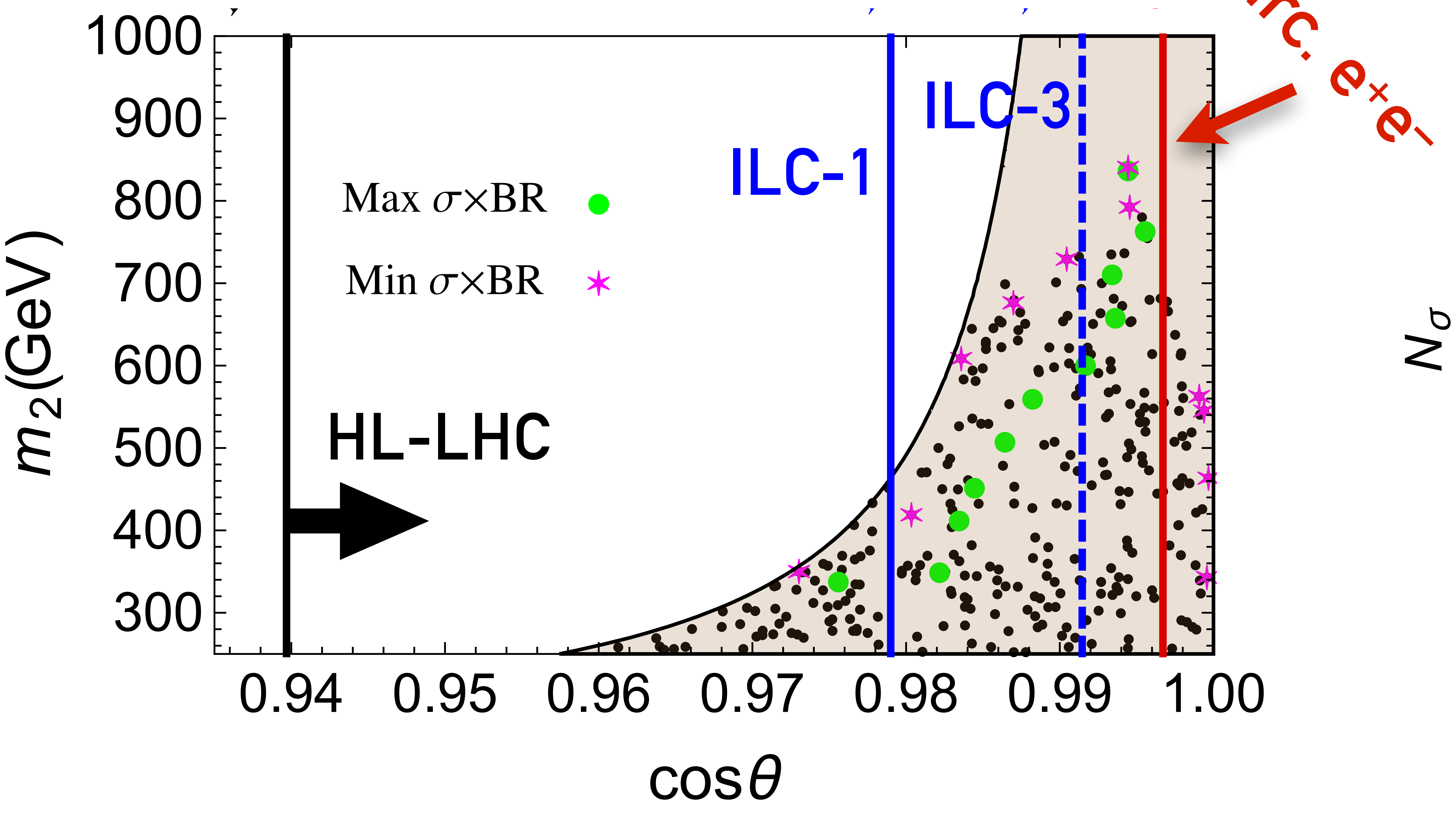


http://cern.ch/collider-reach by G.P. Salam and A. Weiler

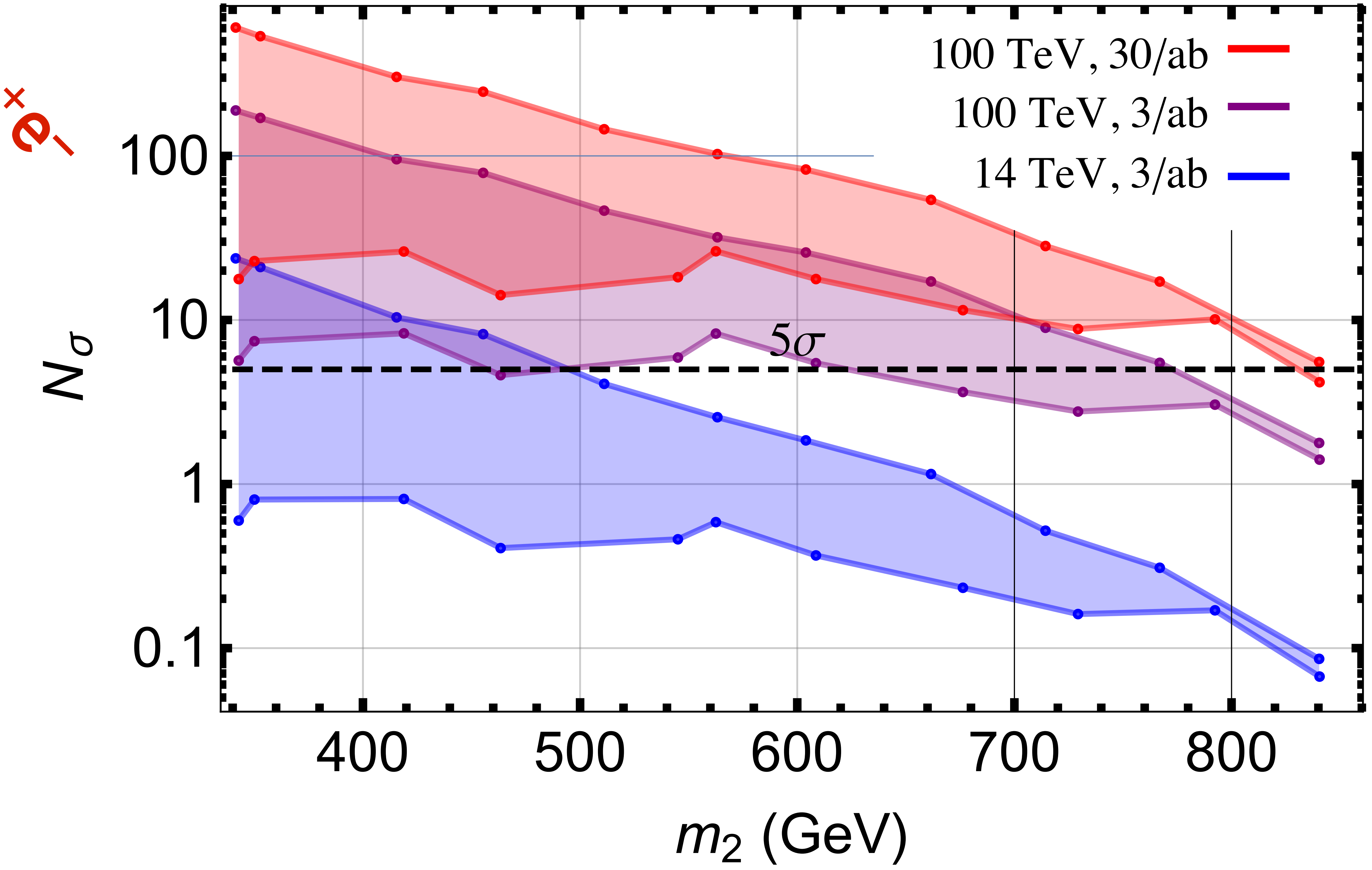
FCC-hh delivers the kind of step up in direct-search sensitivity (× 4 – 6) that we would hope for

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)



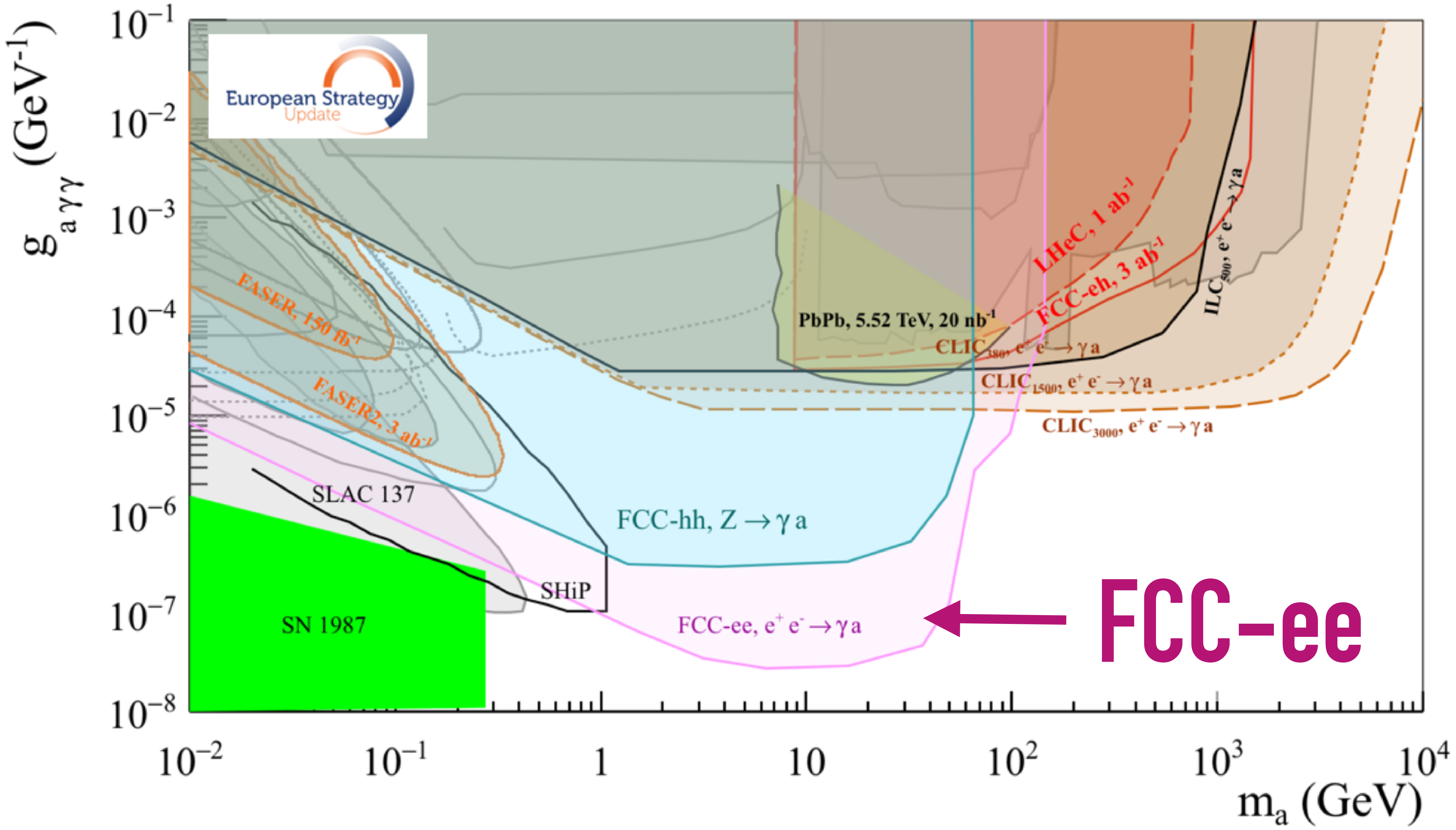
>5σ significance for discovery of (almost) all such models at FCC-hh

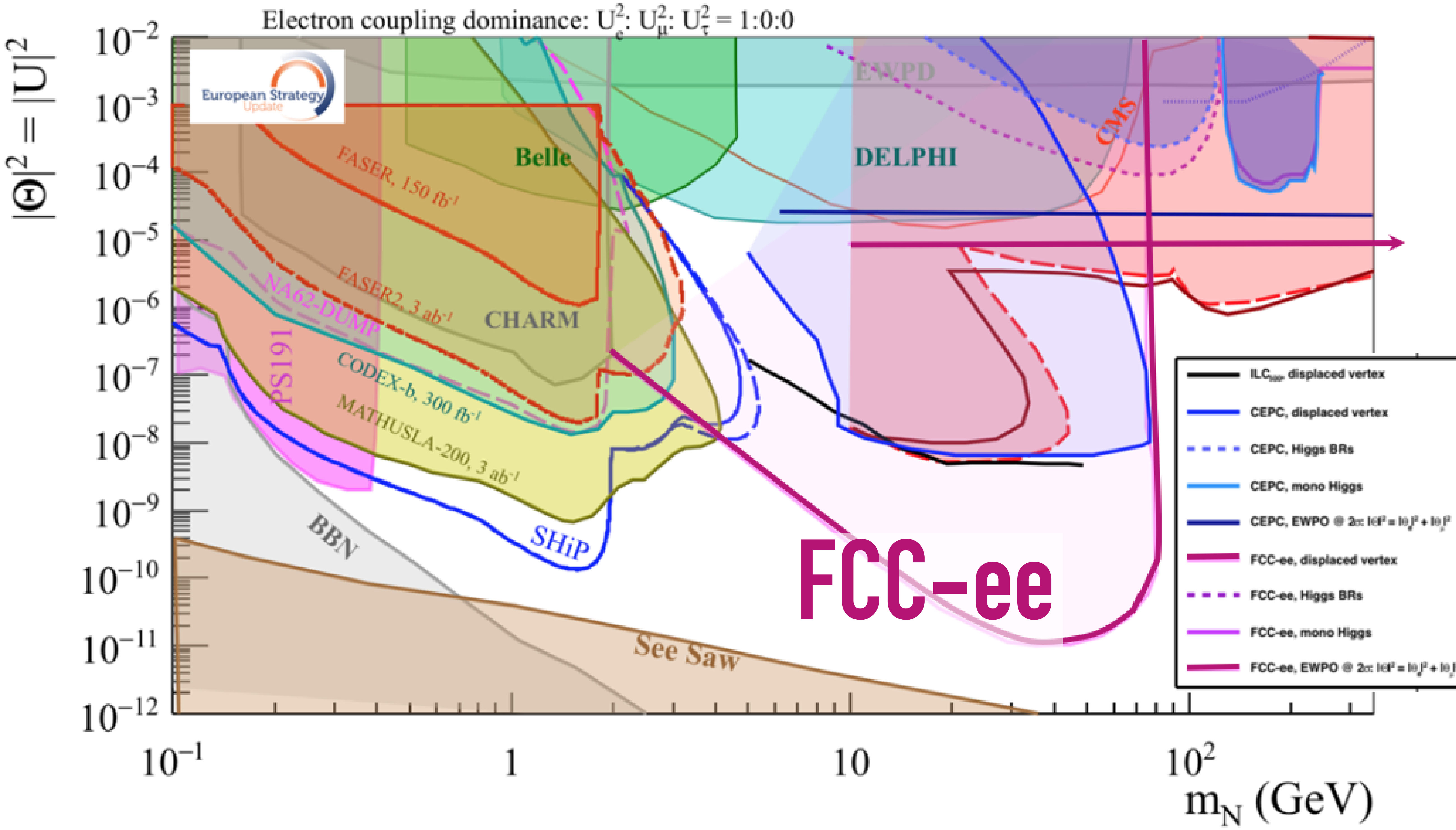


1605.06123

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

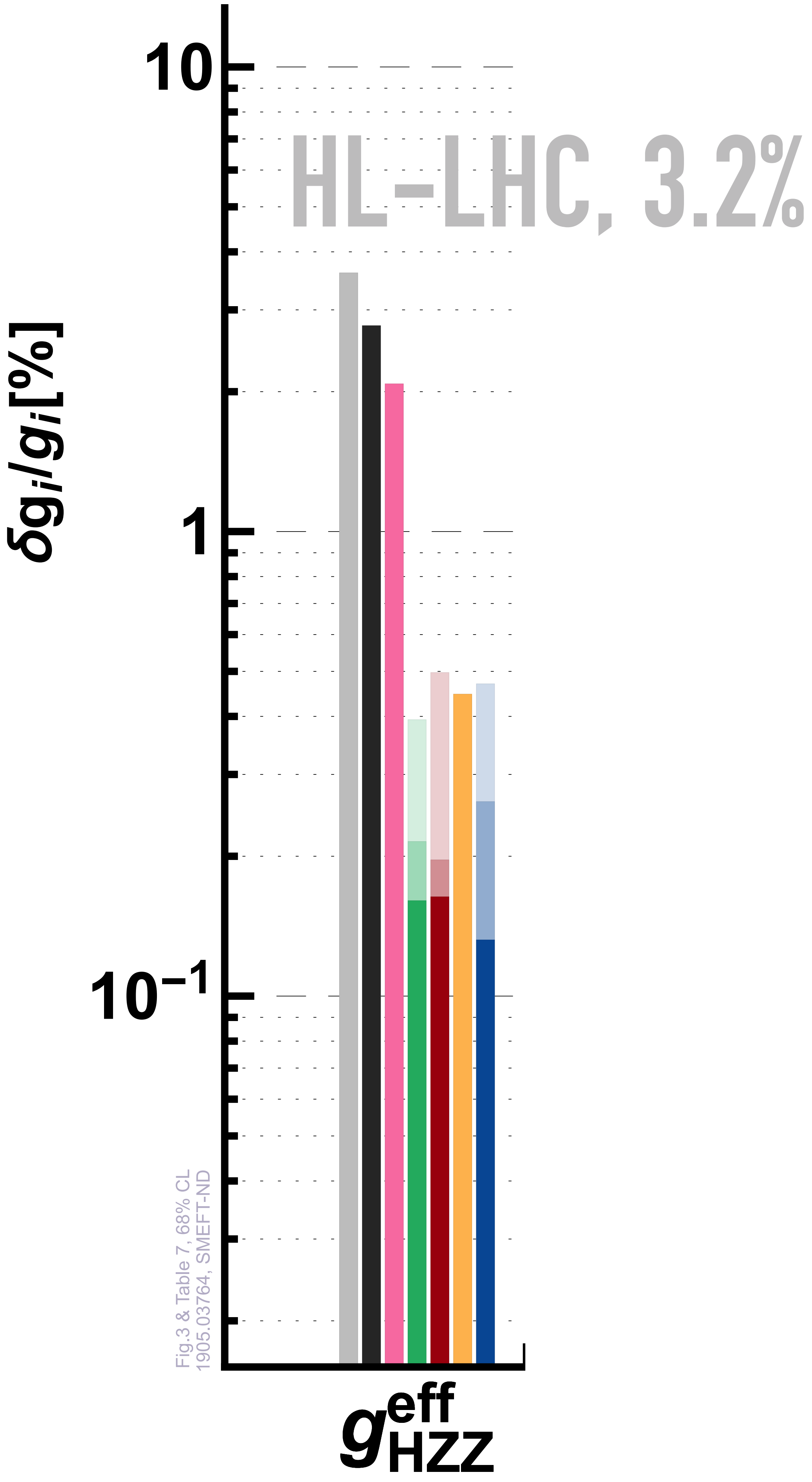




benefits from huge Z-pole luminosity

(some models in these regions have potential to connect with dark matter, baryon asymmetry, neutrino masses, etc.)

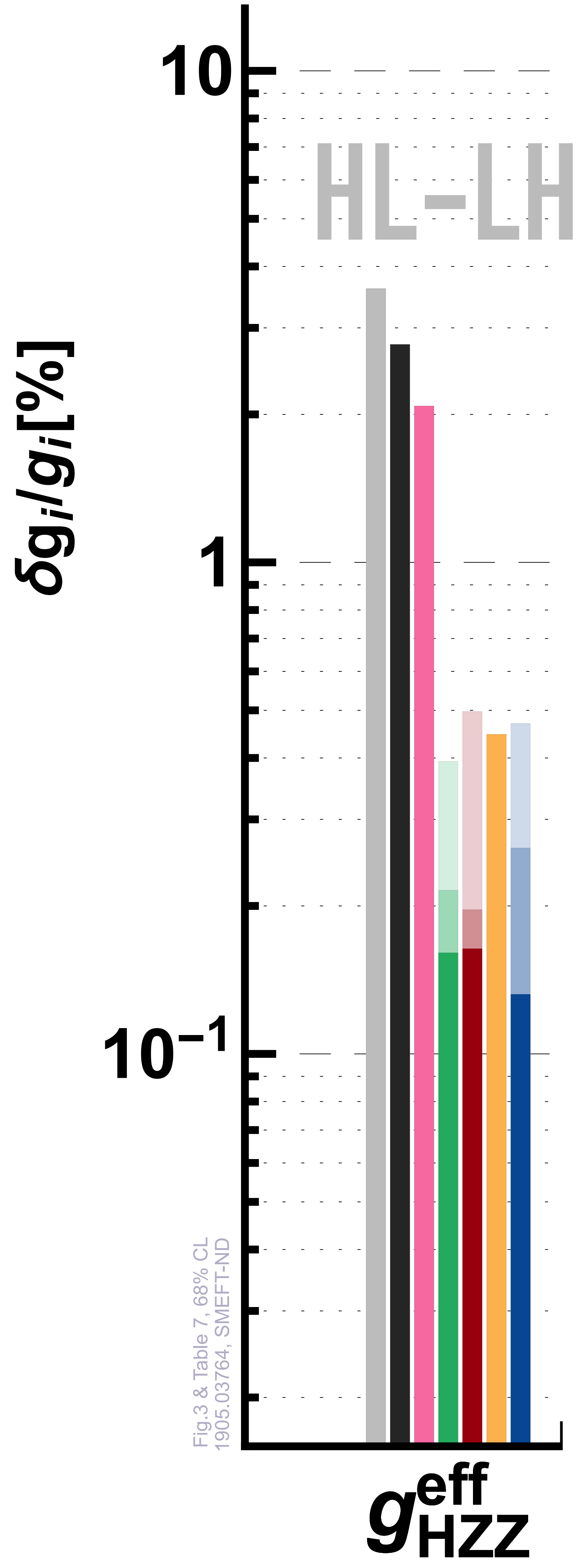
Interpret higher precision as increase in indirect reach



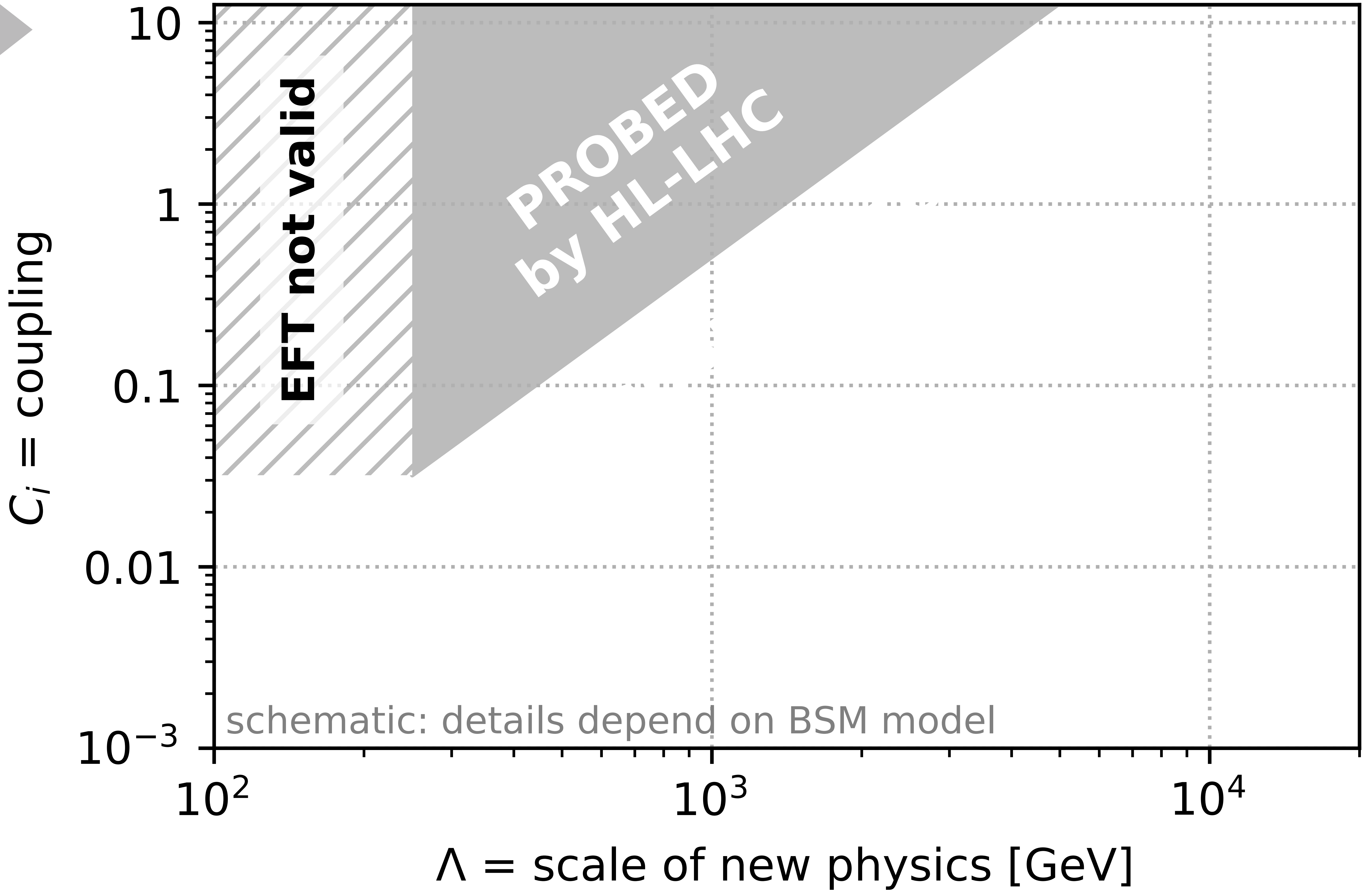
HL-LHC, 3.2%

Fig.3 & Table 7, 68% CL
1905.03764, SMEFT-ND

Interpret higher precision as increase in indirect reach



interpret as mass-coupling sensitivity



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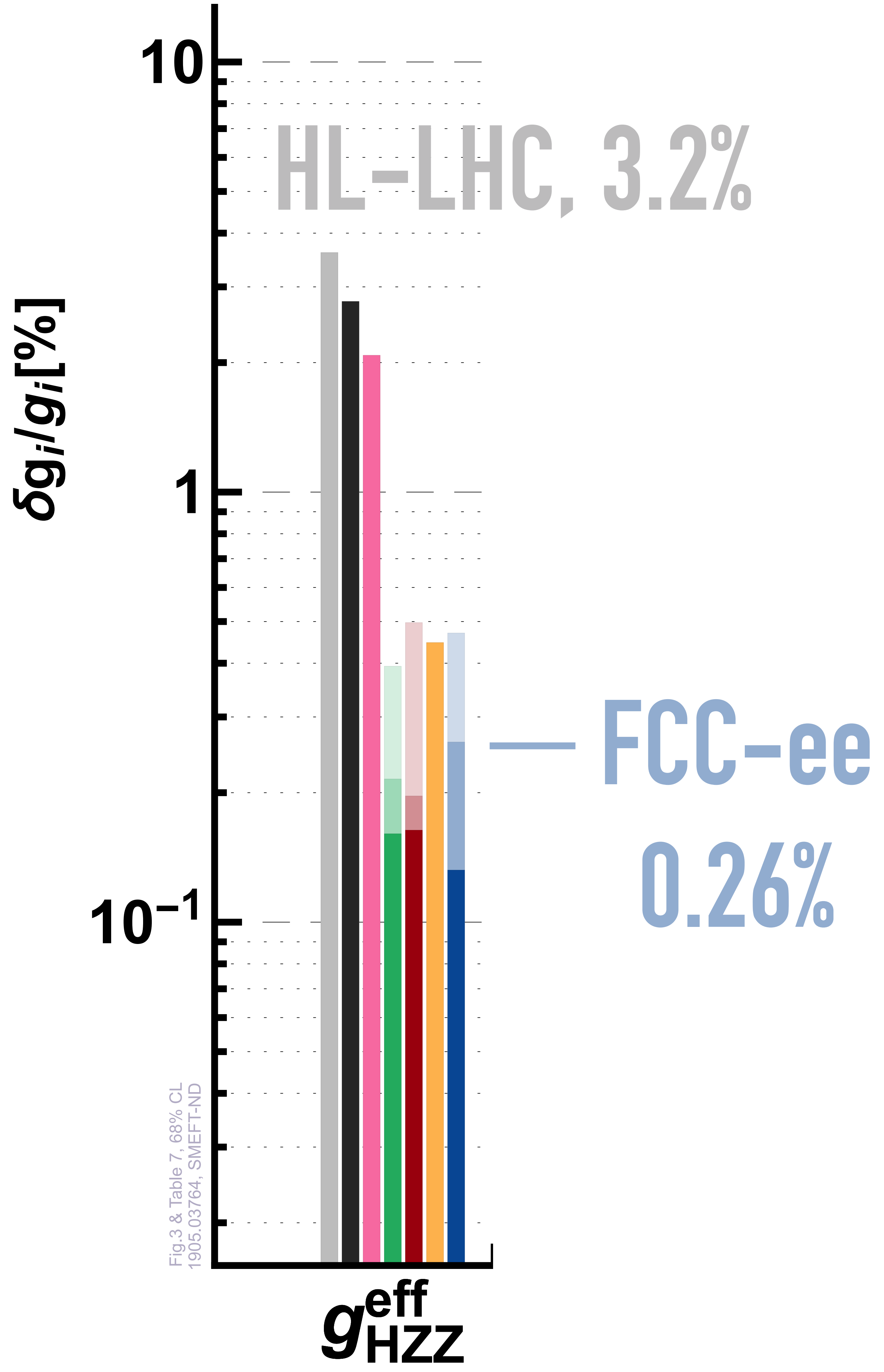

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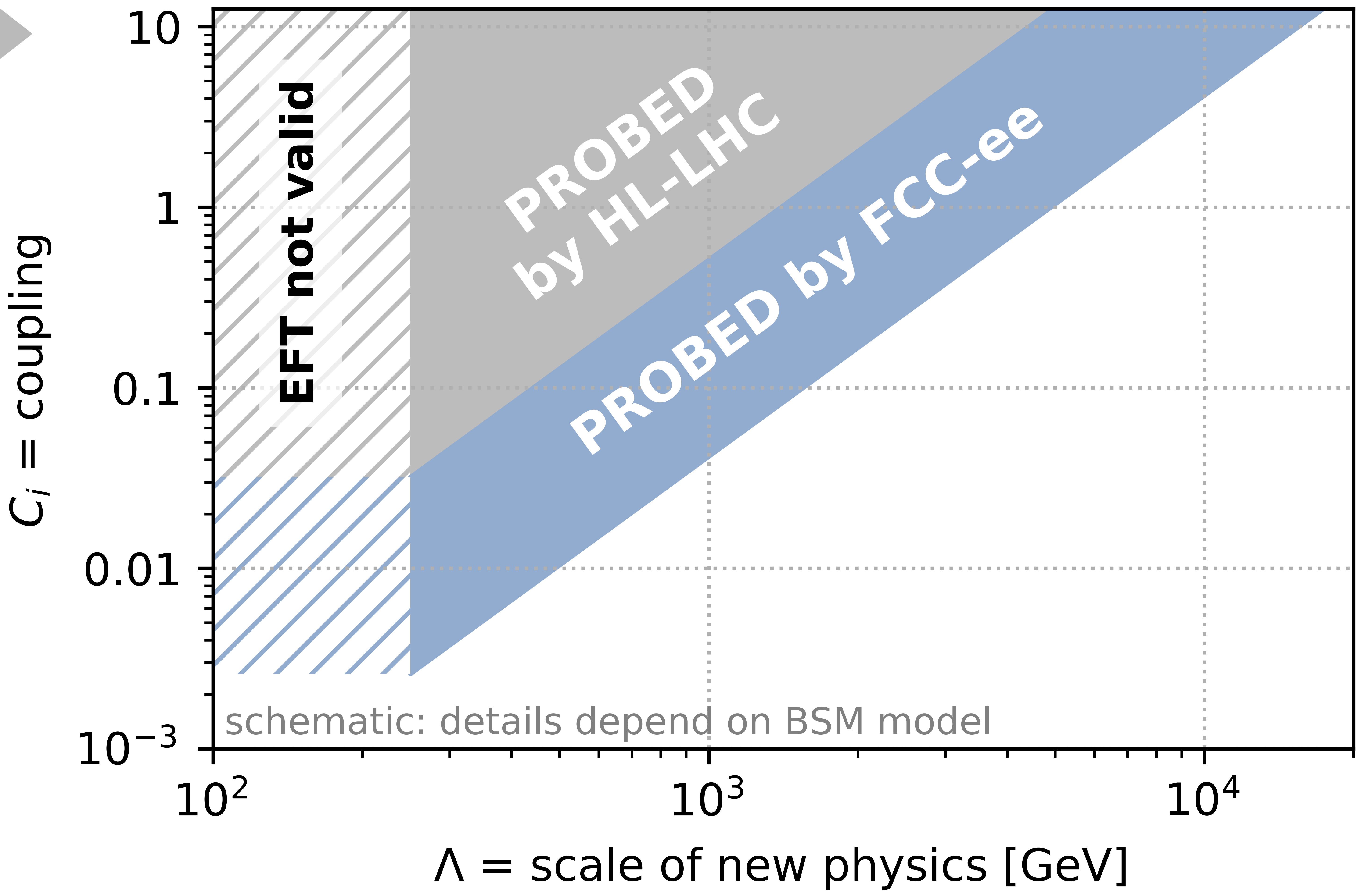

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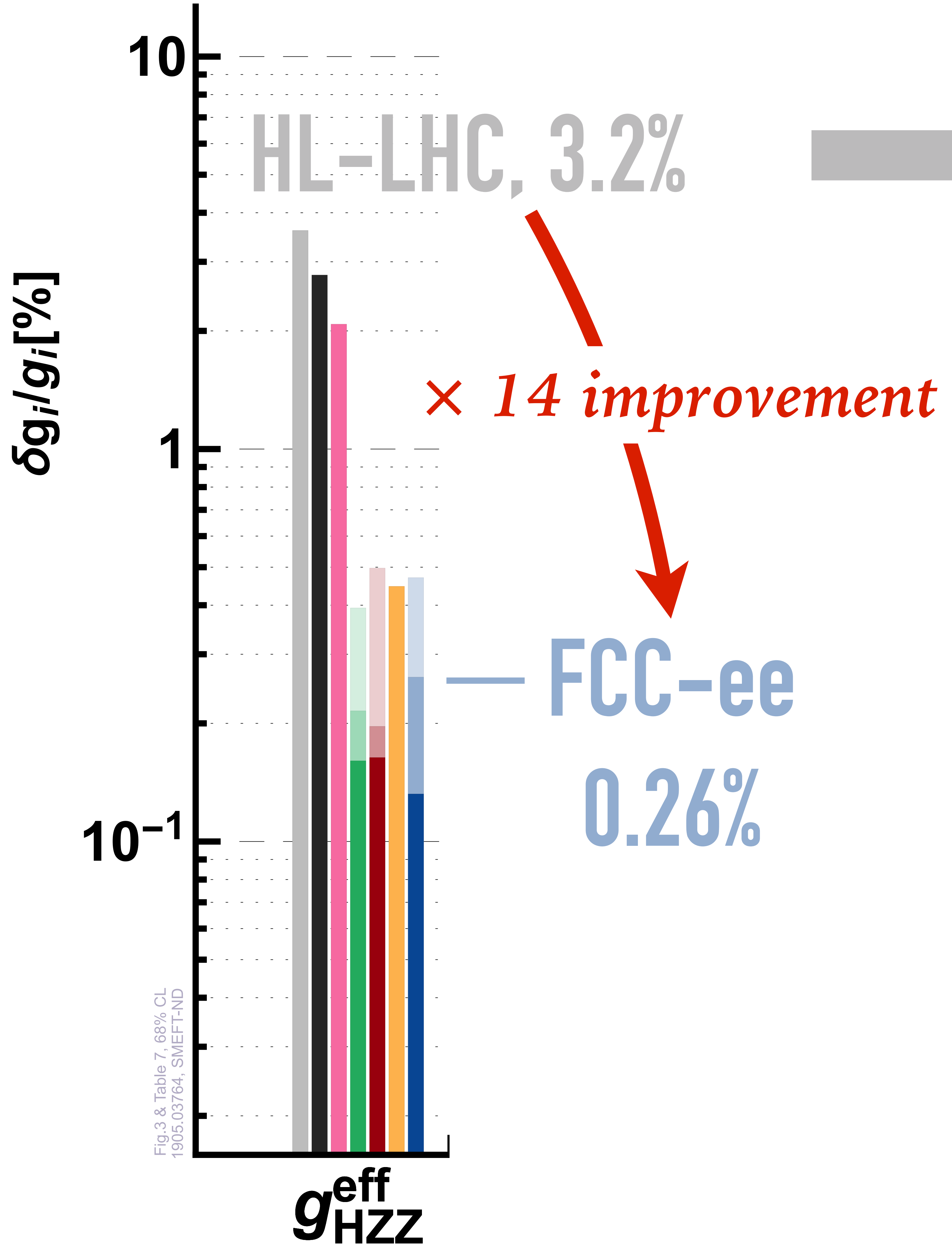

Fig.3 & Table 7, 68% CL
1905.03764, SMEFT-ND

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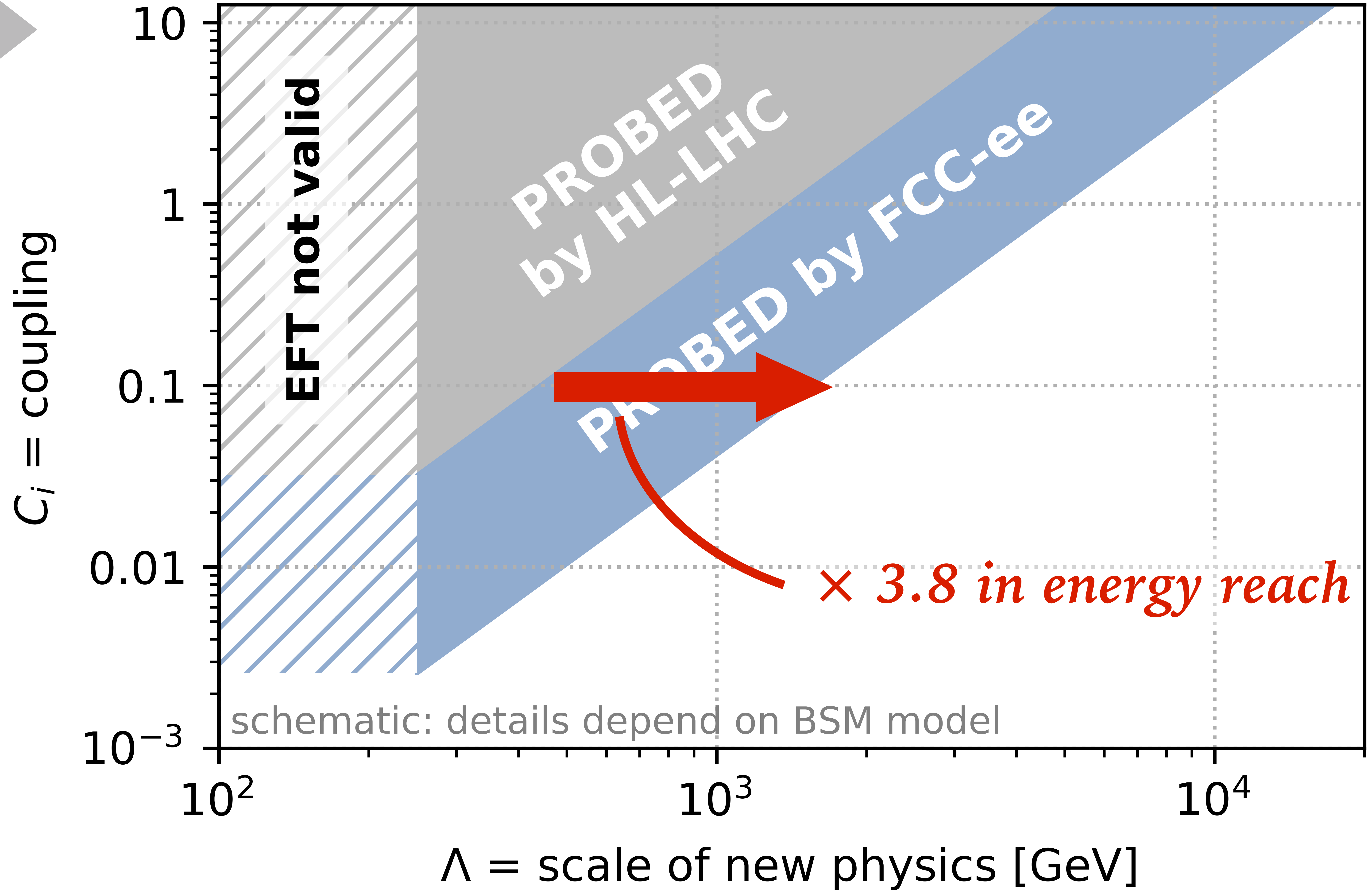
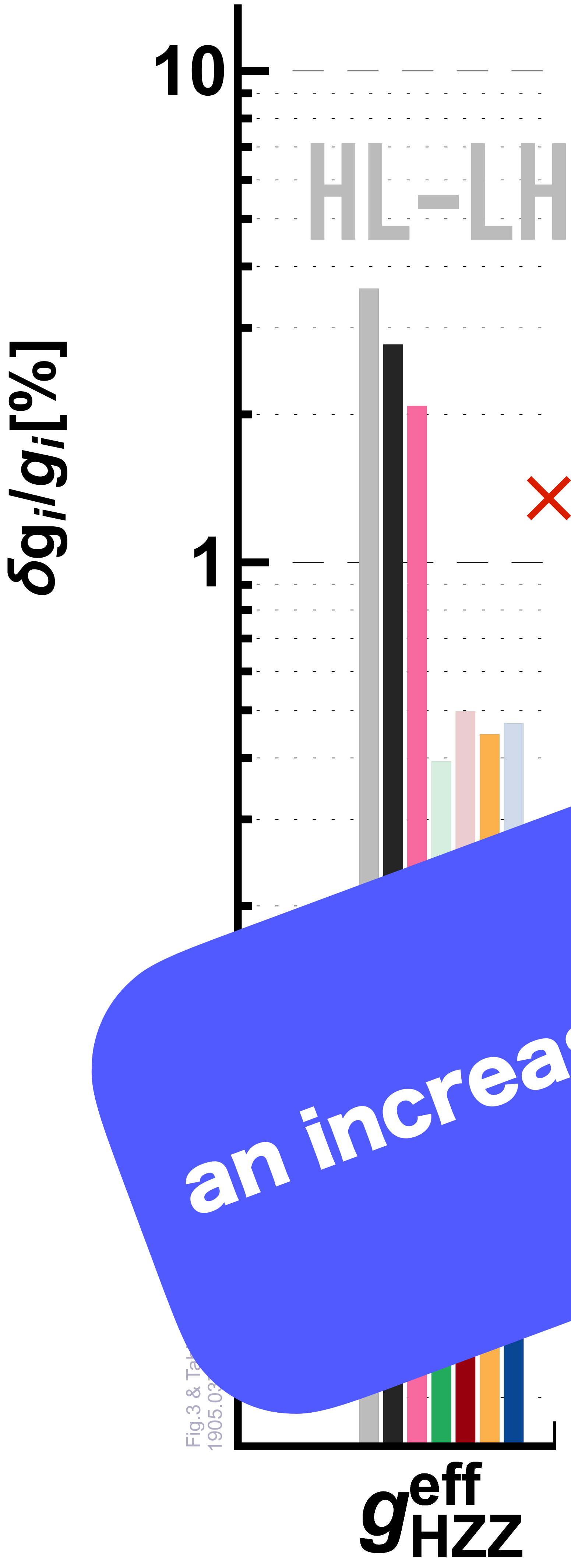


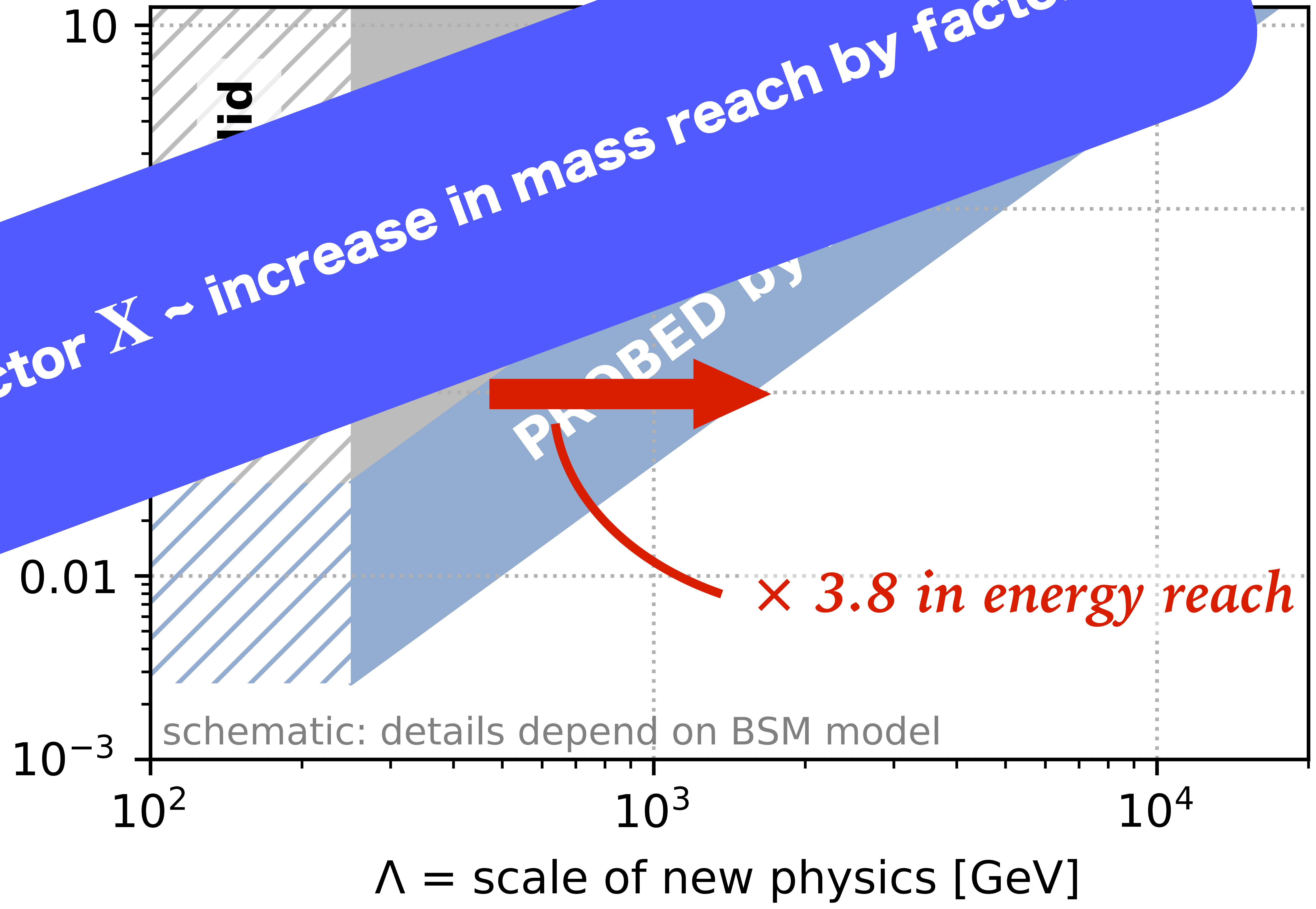
schematic: details depend on BSM model

Interpret higher precision as increase in indirect reach



× 14 improvement

interpret as mass-co ity

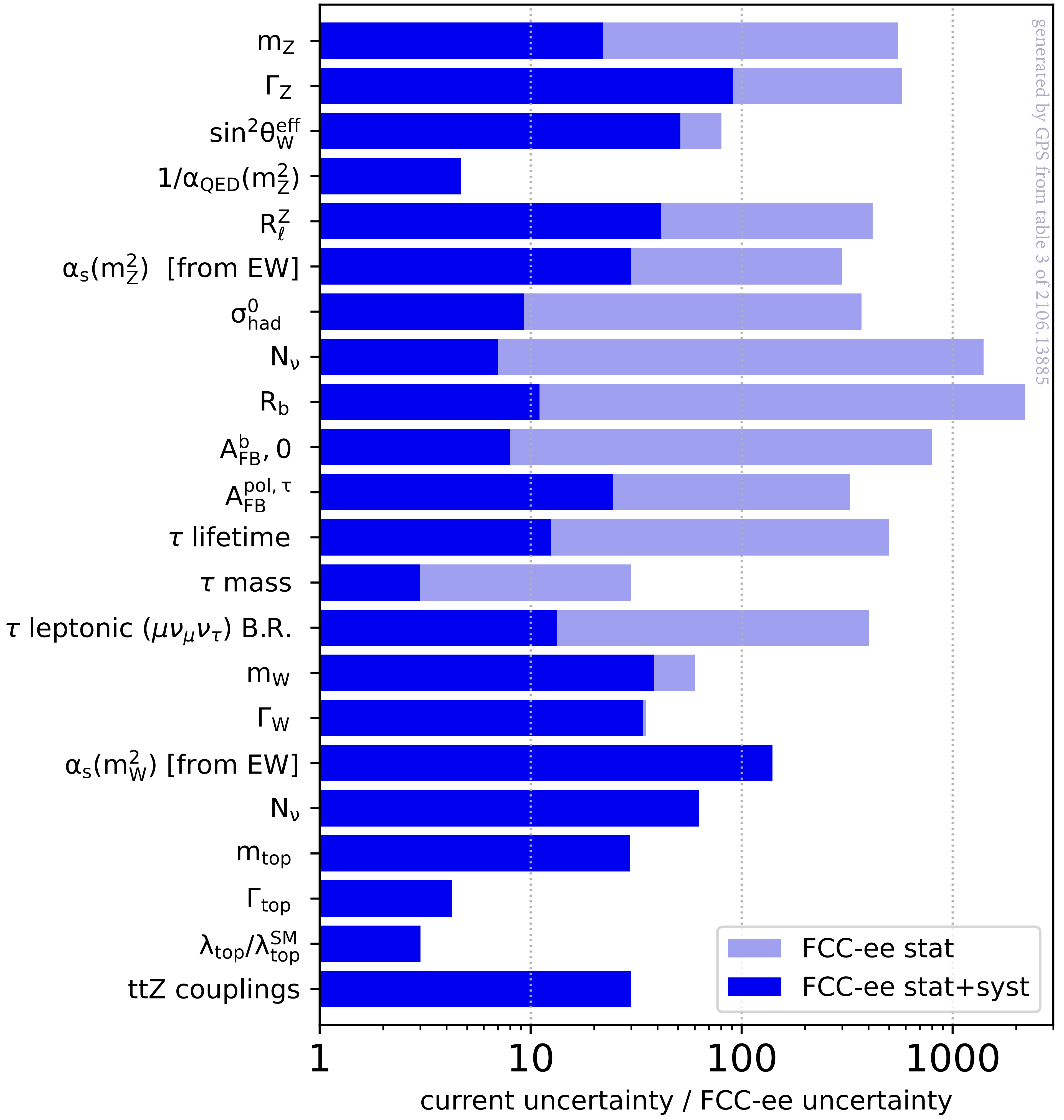


× 3.8 in energy reach

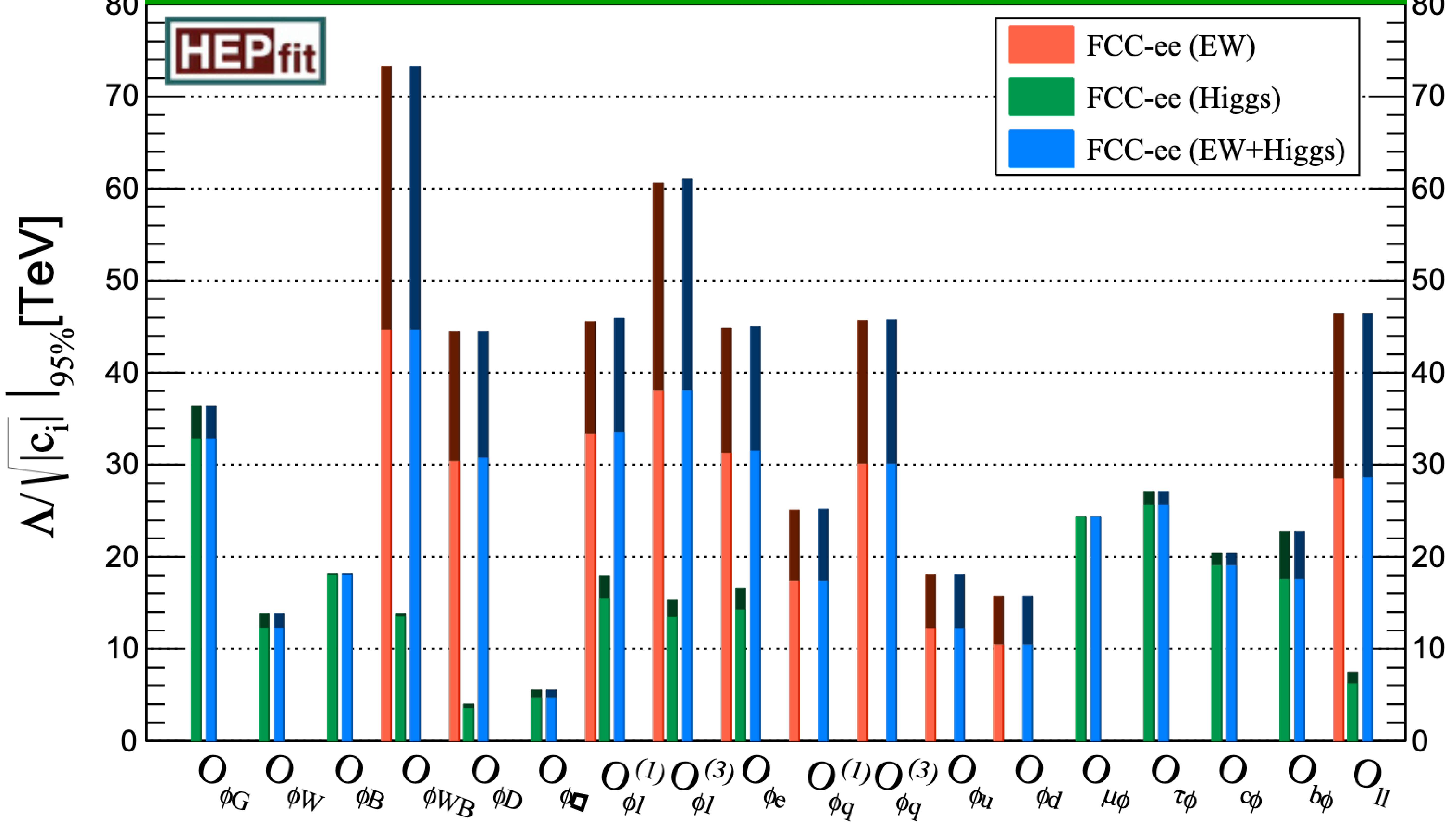
an increase in precision by factor X ~ increase in mass reach by factor $\sqrt{X}$

increase in precision at FCC-ee is equivalent to × 4 – 5 increase in energy reach

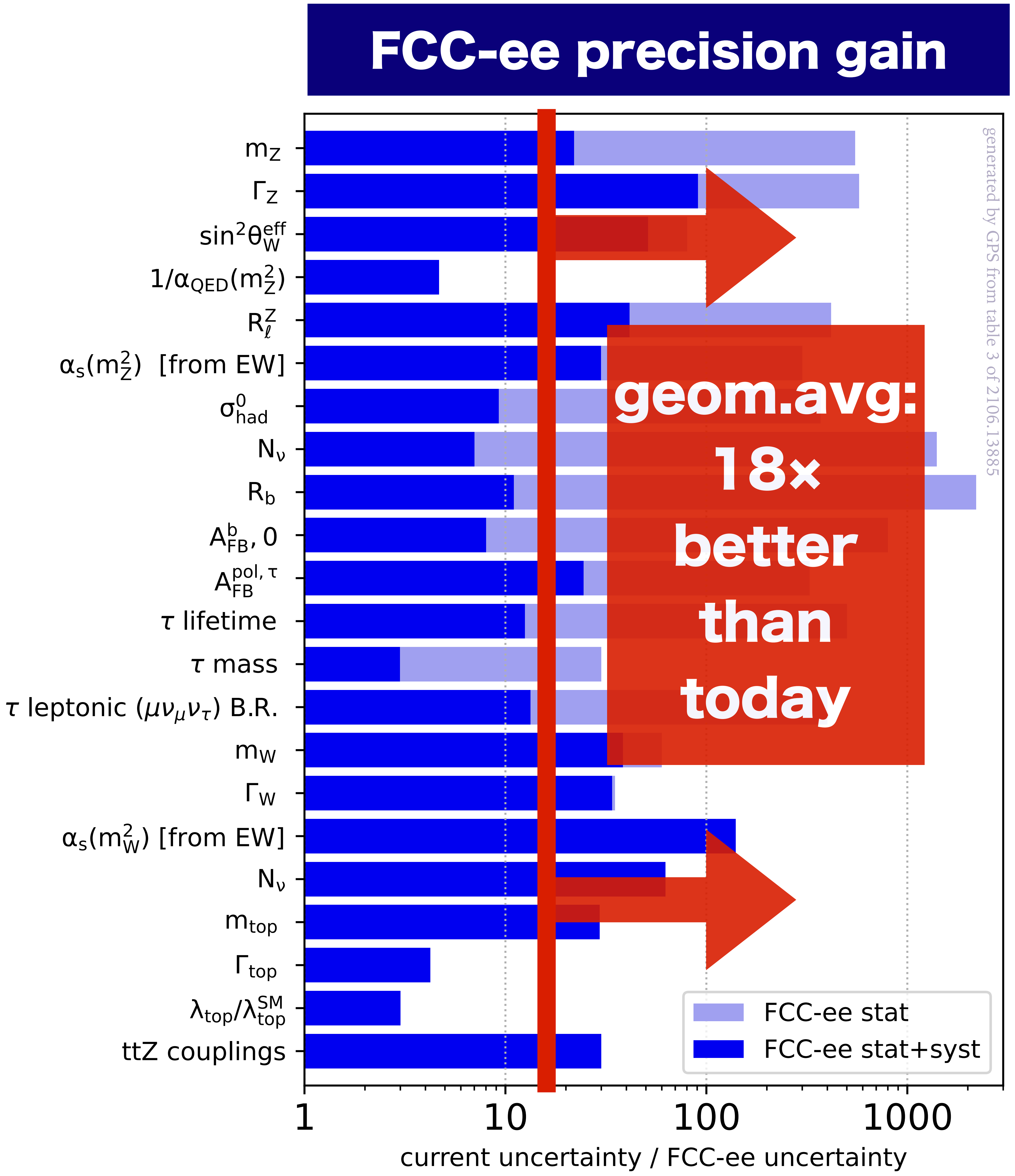
FCC precision gain



maximum scale probed indirectly — up to 70 TeV



increase in precision at FCC-ee is equivalent to × 4 – 5 increase in energy reach



geom.avg: 18× better than today

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

desirable features of a worldwide HEP project?

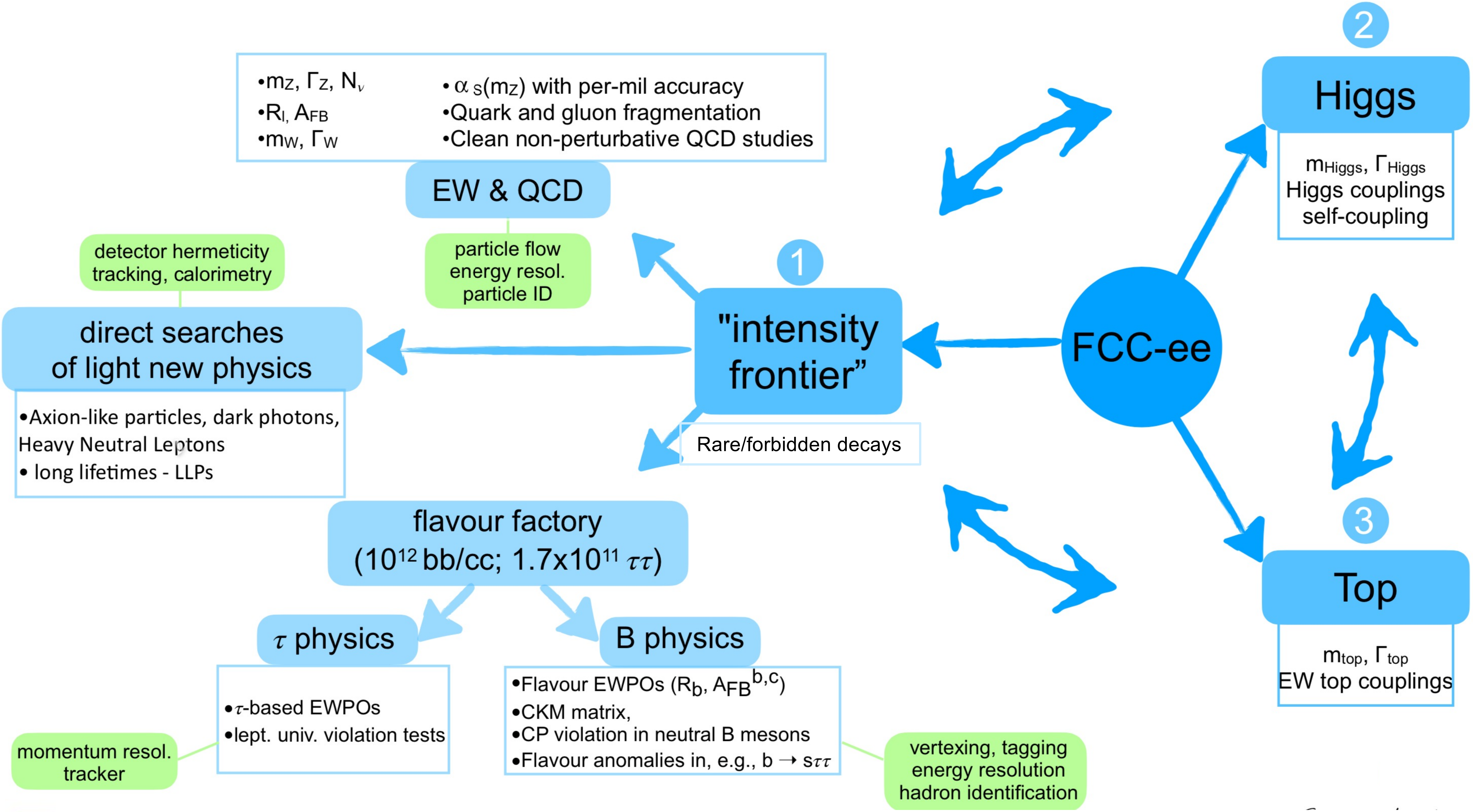
an important target that is guaranteed to be reached
(no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (incl. multiple experiments)

cost-effective construction & operation, low carbon footprint



FCC-ee

① "intensity frontier"

Rare/forbidden decays

EW & QCD

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

particle flow
energy resol.
particle ID

direct searches of light new physics

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

detector hermeticity
tracking, calorimetry

flavour factory (10^{12} bb/cc; 1.7×10^{11} $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

momentum resol.
tracker

B physics

- Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \to s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

② **Higgs**

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

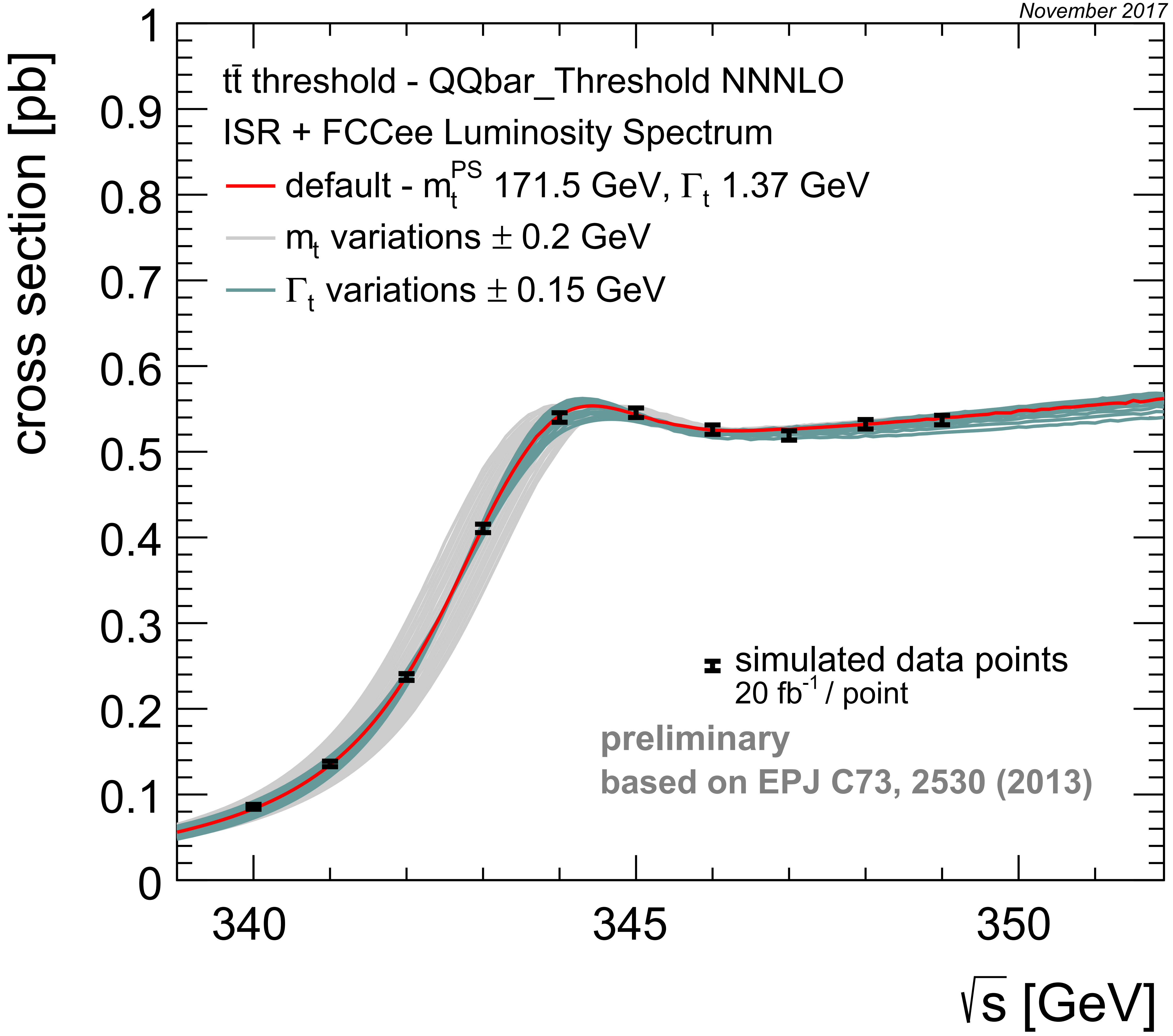
③ **Top**

m_{top}, Γ_{top}
EW top couplings

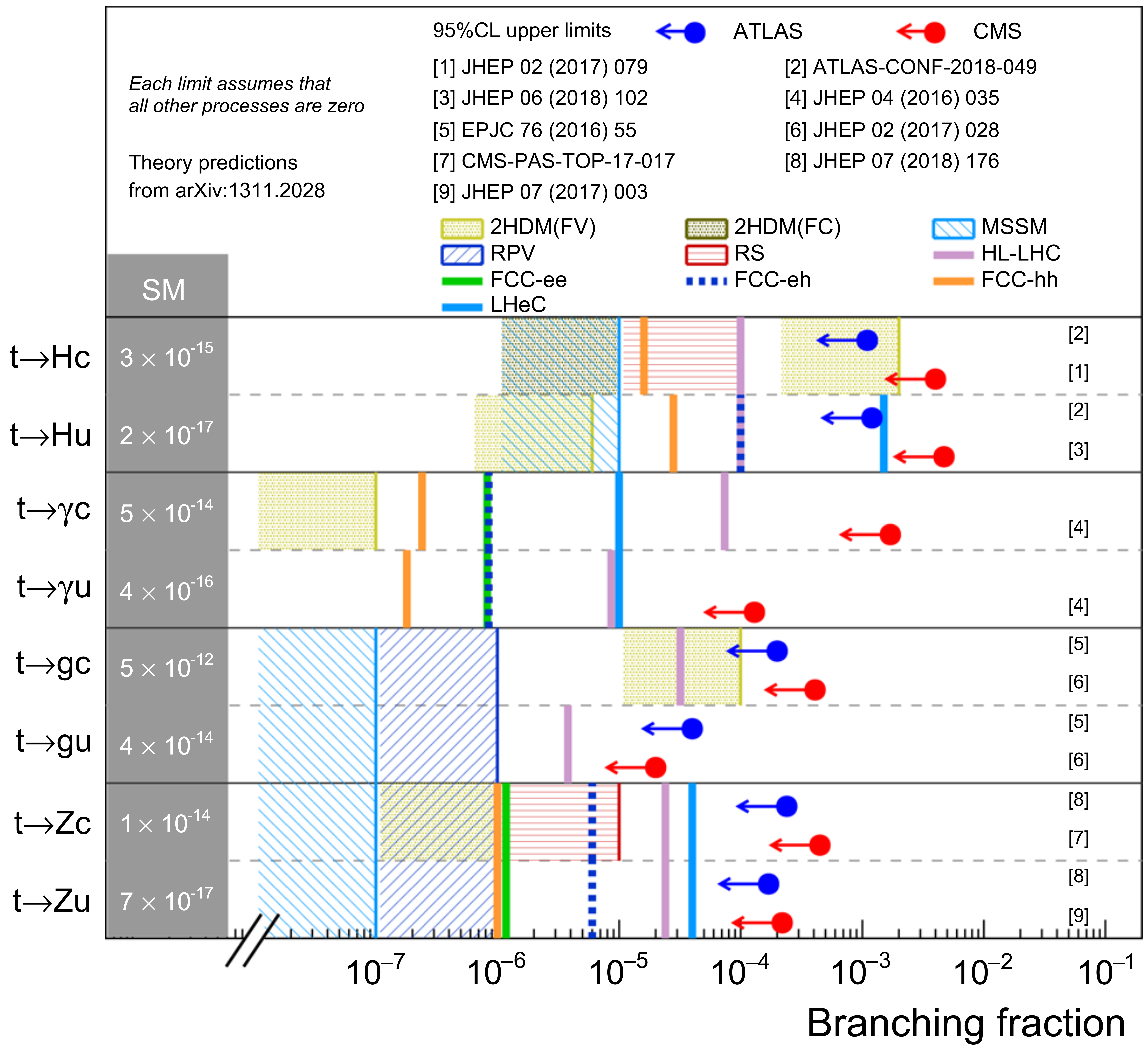
🟩 detector req.

Slide from C. Grojean @ FCC Week'22

threshold scan for top mass



limits on top FCNF



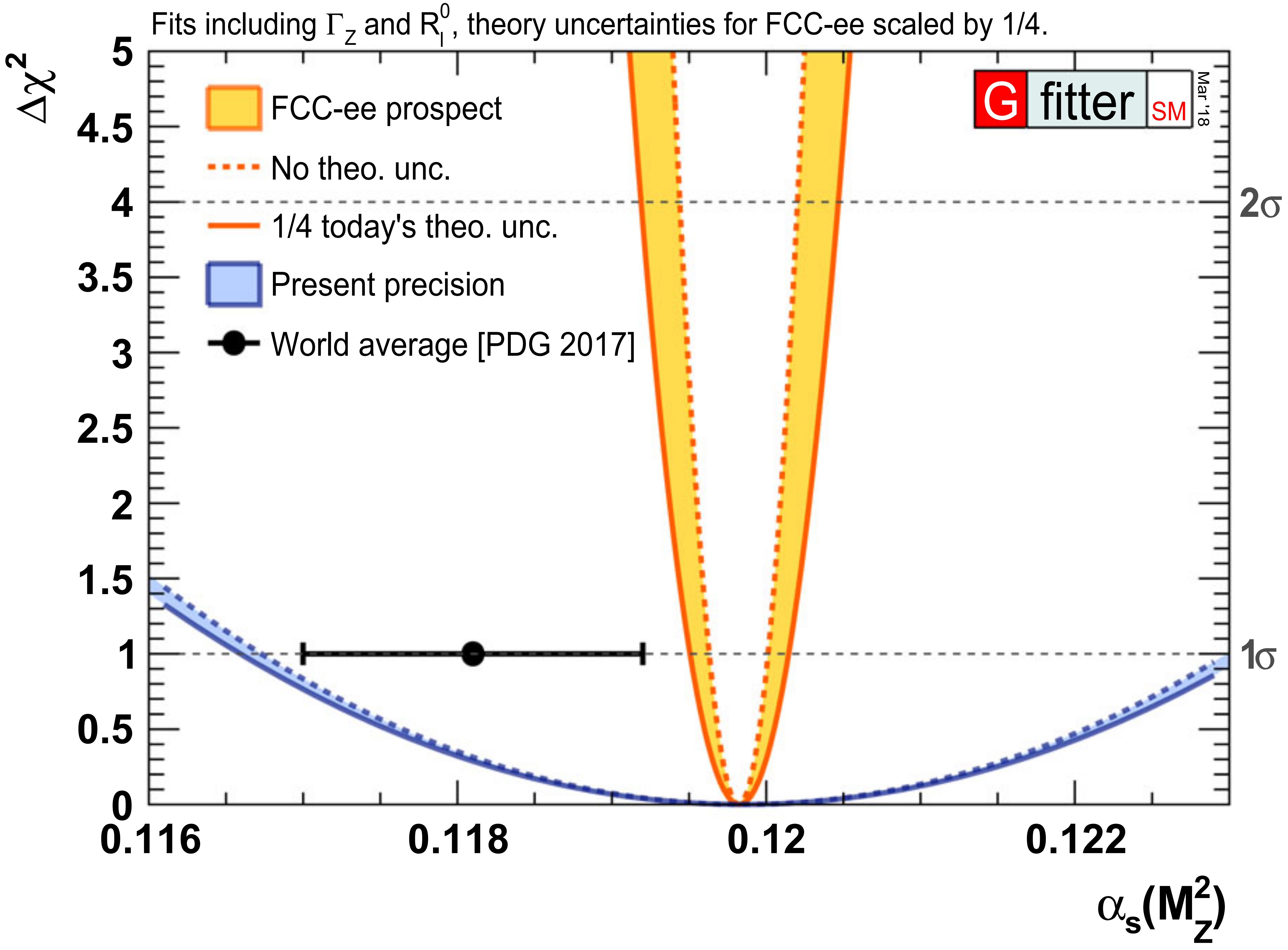
Flavour physics: 15× more b-pairs at FCC-ee than at Belle II

2106.01259

FCC-ee

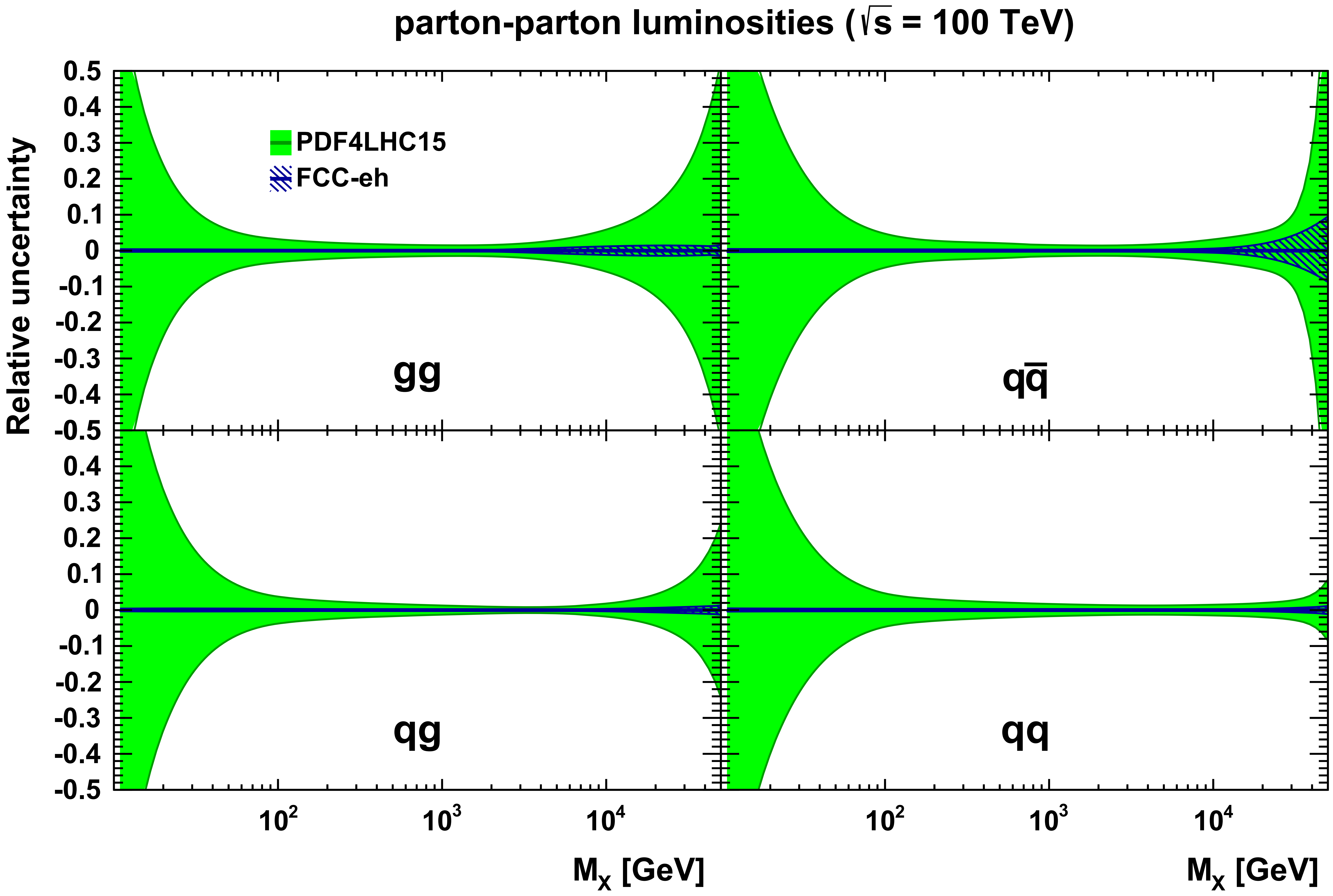
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

FCC-ee & QCD: 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: potential worries about non-perturbative contributions in PDF fits to moderate-Q^2 DIS data

& reliance on data from single experiment

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

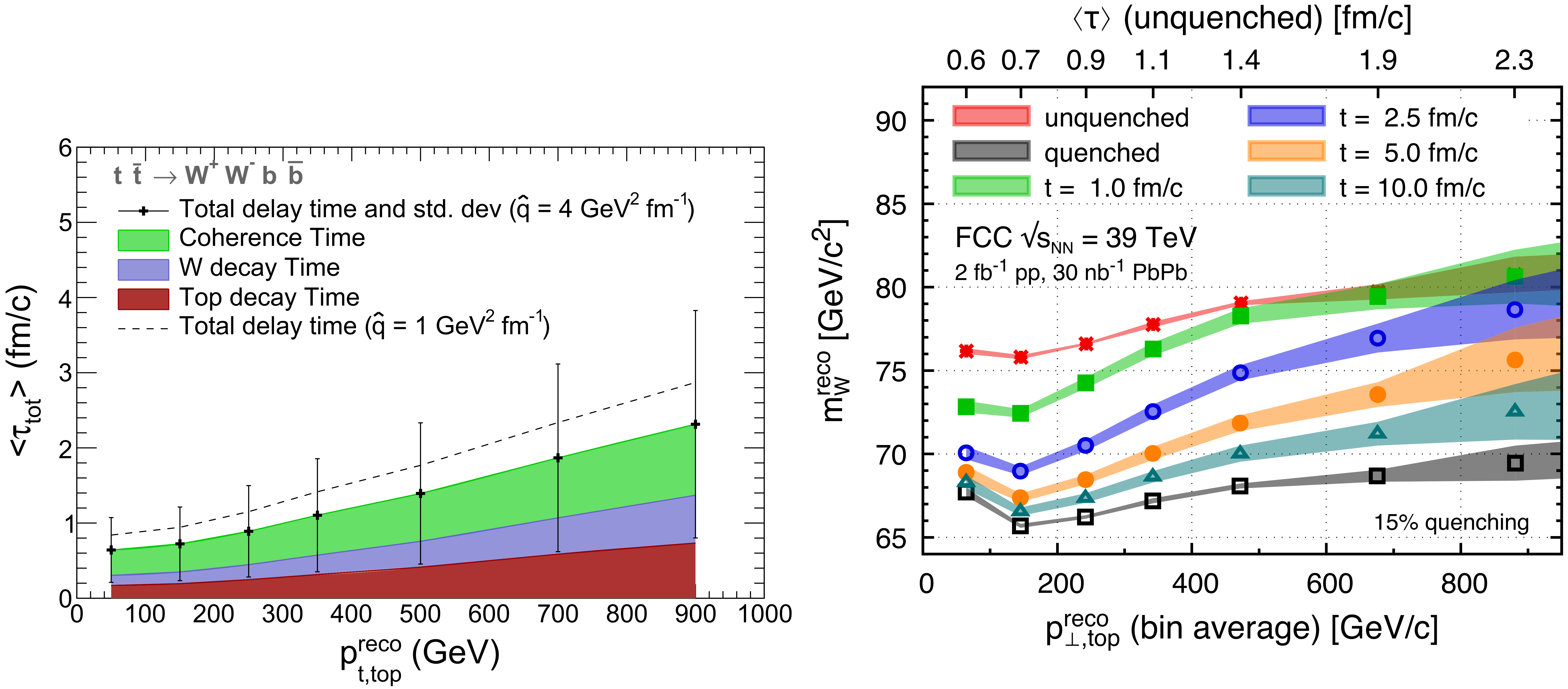


Fig. S.6 Left: total delay time for the QGP energy-loss parameter $\hat{q} = 4\ \mathrm{GeV}^2/\mathrm{fm}$ as a function of the top transverse momentum (black dots) and its standard deviation (error bars). The average contribution of each component is shown as a coloured stack band. The dashed line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

desirable features of a worldwide HEP project?

an important target that is guaranteed to be reached
(no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (incl. multiple experiments)

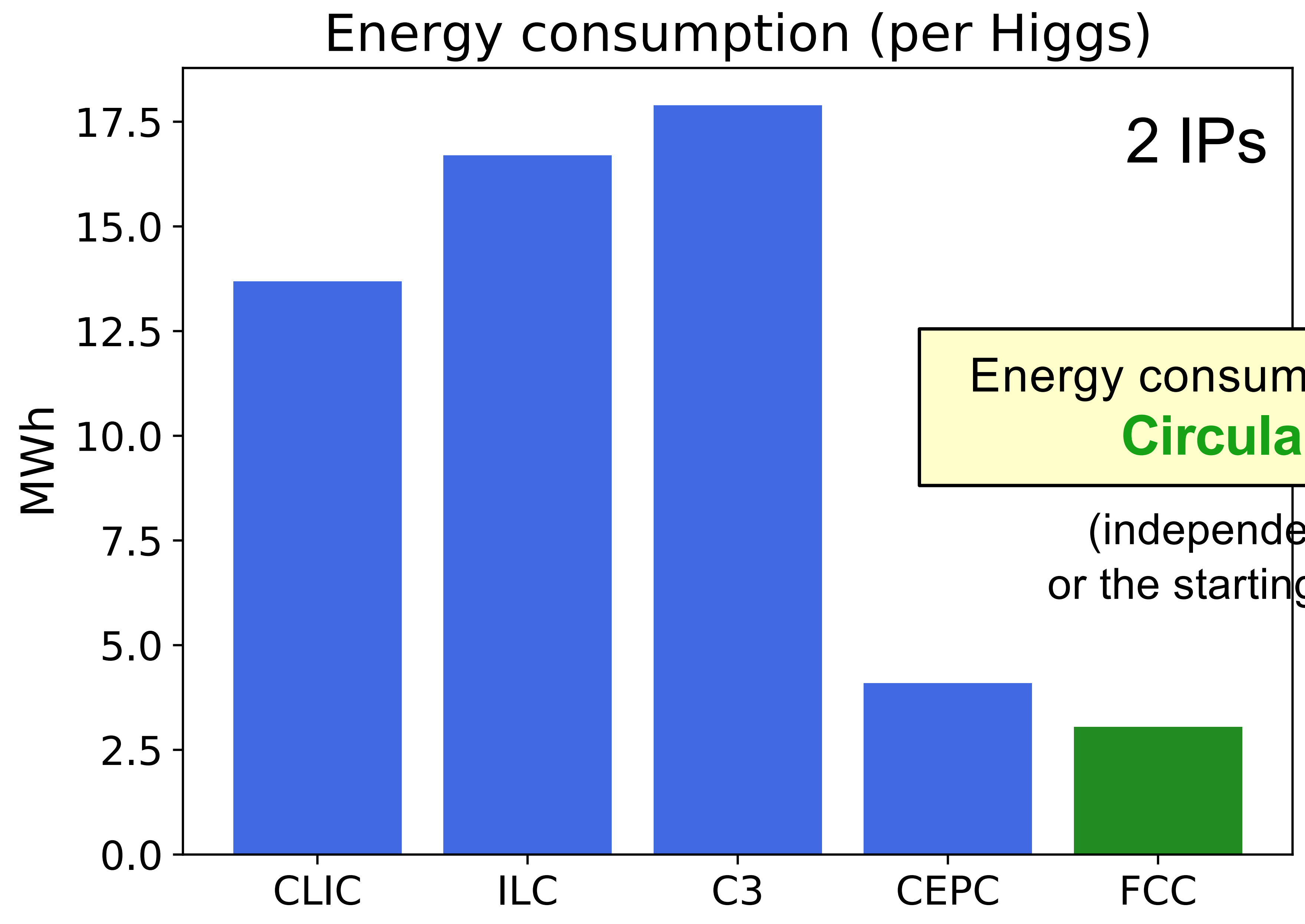
cost-effective construction & operation, low carbon footprint

Energy consumption and carbon footprint @ 240 GeV

- **Our first responsibility (as particle physicists) is to do the maximum of science**
  - **With the minimum energy consumption and the minimum environmental impact for our planet**
    - Should become one of our top-level decision criteria for design, choice and optimization of a collider

- **All Higgs factories have a "similar" physics outcome (ESU'20 and Snowmass'21)**
  - **Natural question: what is their energy consumption or carbon footprint for the same physics outcome?**
    - Circular colliders have a much larger instantaneous luminosity and operate several detectors
    - FCC-ee is at CERN, where electricity is already almost carbon-free (and will be even more so in 2048)

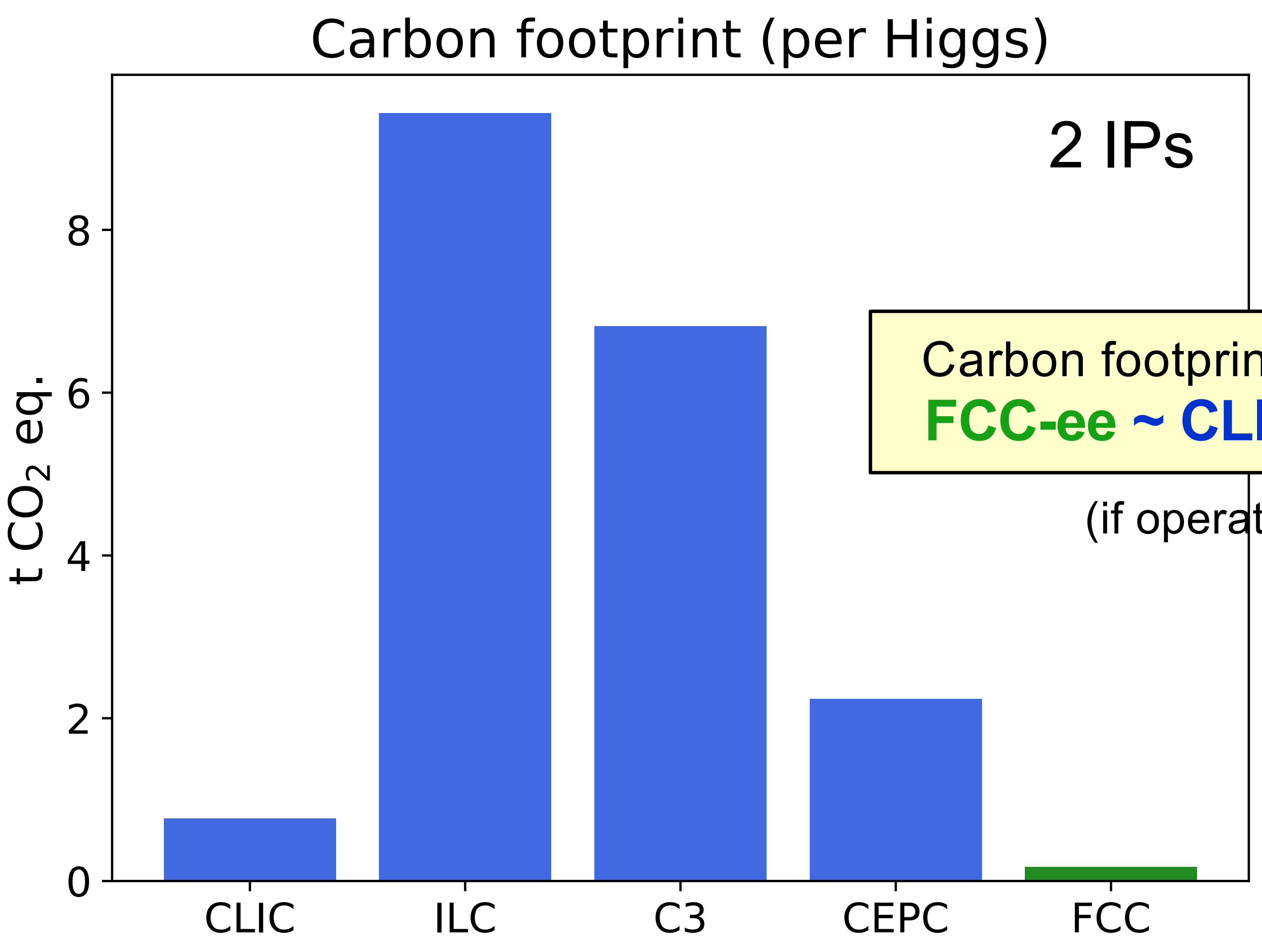
slide from Patrick Janot



arXiv:2208.10466

Energy consumption / Higgs with 2IP
Circular ~ Linear / 5

(independently of the location
or the starting time of the collider)



Carbon footprint / Higgs with 2IP
FCC-ee ~ CLIC / 5 ~ ILC / 50

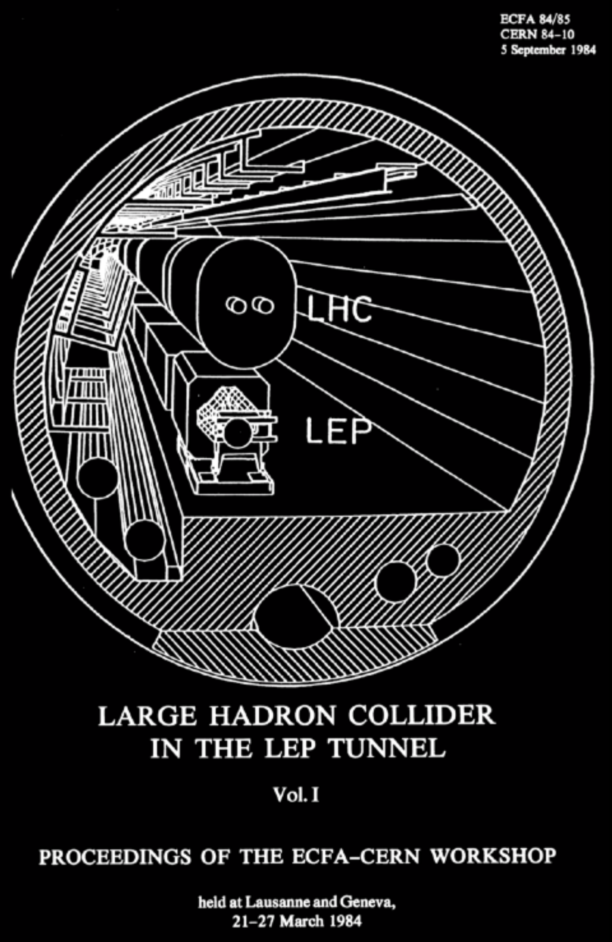
(if operating today)

conclusions

Conclusions

- There is a **no-lose theorem:** directly establishing Higgs self-interaction (it holds the SM together), which is made solid by precision of FCC-ee and direct measurement at FCC-hh
  - is there a chance of a second no-lose theorem in establishing (or disproving) SM origin of electron mass?
- The **step up in energy reach** that we expect is $\sim$ **× 4 – 5**
  - FCC-ee delivers that in "indirect" sensitivity, through precision increase $\sim \times 18$
  - FCC-hh delivers that in direct search sensitivity
- The programme is **diverse and robust**
- One issue: **timeline**.
  - Probably no realistic faster route to a new collider of any kind, but the field as a whole is at risk if we don't soon consolidate the path to a new collider that starts in next c. 20 years.

from Nathaniel Craig @ CERN-TH naturalness workshop



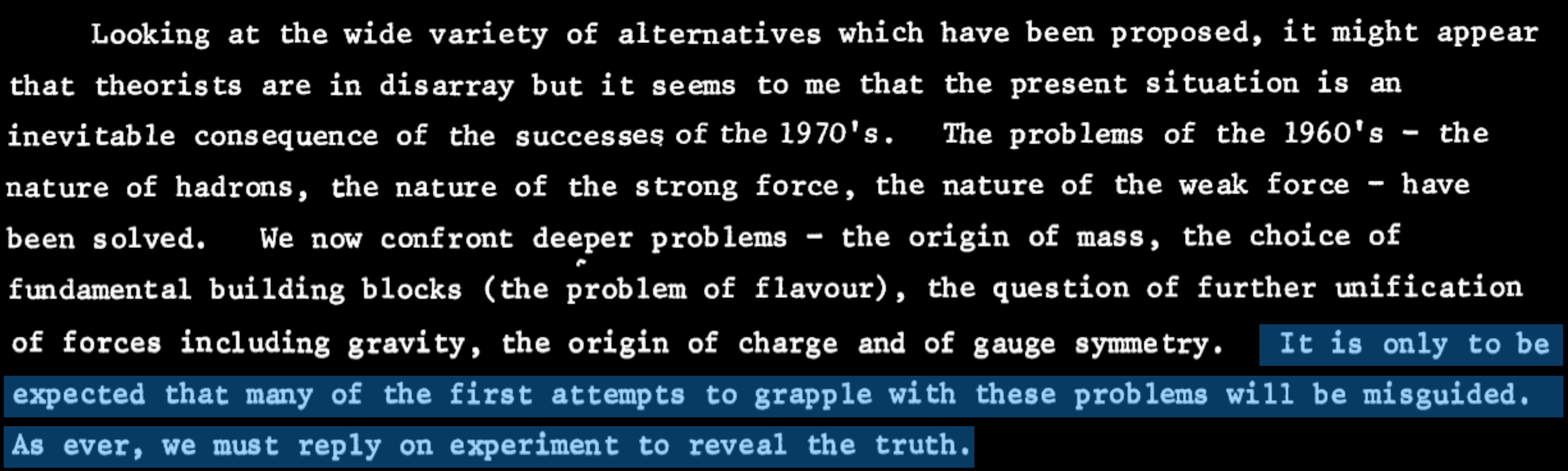
ECFA 84/85
CERN 84-10
5 September 1984

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984



PHYSICS WITH A MULTI-TeV HADRON COLLIDER

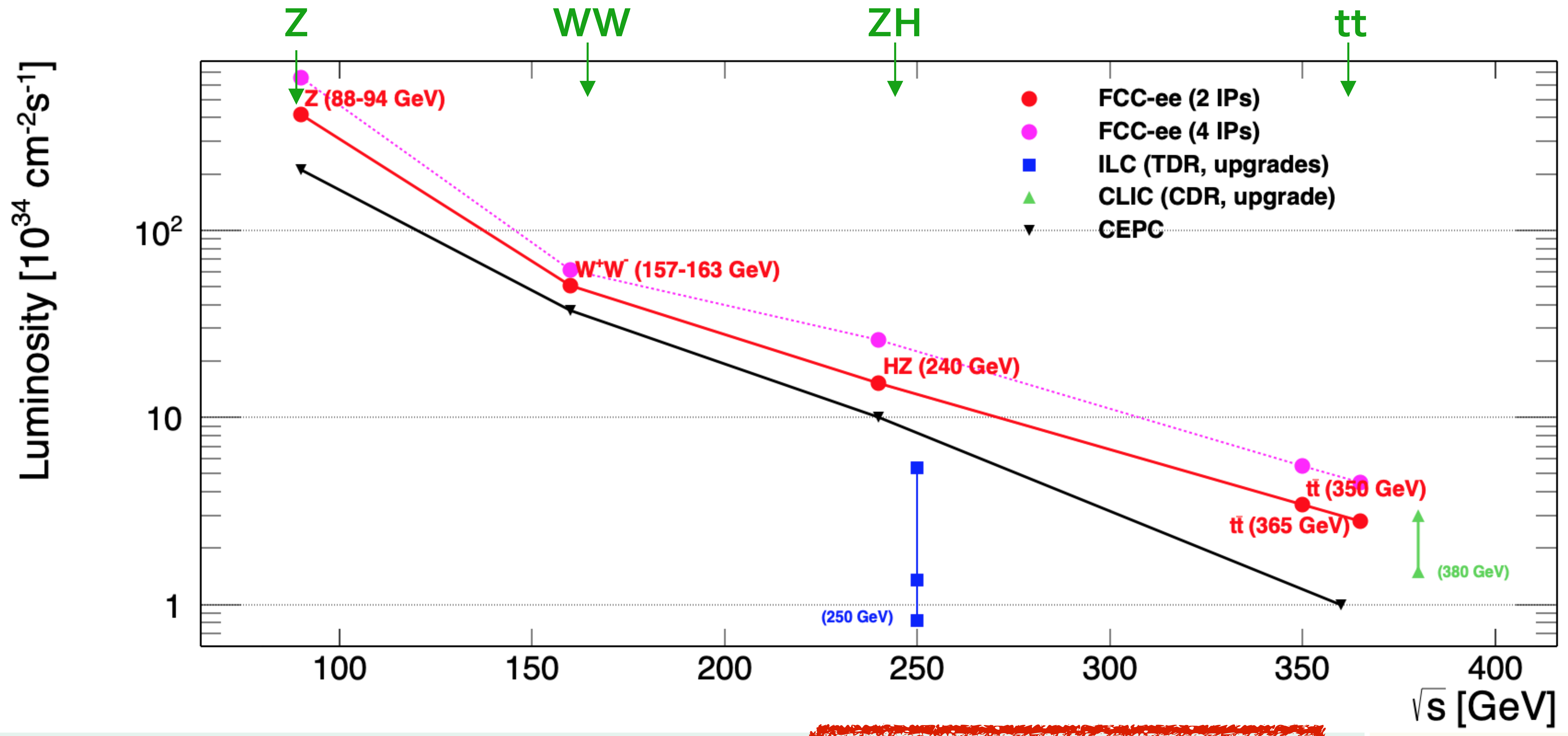
C.H. Llewellyn Smith,

Looking at the wide variety of alternatives which have been proposed, it might appear that theorists are in disarray but it seems to me that the present situation is an inevitable consequence of the successes of the 1970's. The problems of the 1960's - the nature of hadrons, the nature of the strong force, the nature of the weak force - have been solved. We now confront deeper problems - the origin of mass, the choice of fundamental building blocks (the problem of flavour), the question of further unification of forces including gravity, the origin of charge and of gauge symmetry. It is only to be expected that many of the first attempts to grapple with these problems will be misguided. As ever, we must reply on experiment to reveal the truth.

backup

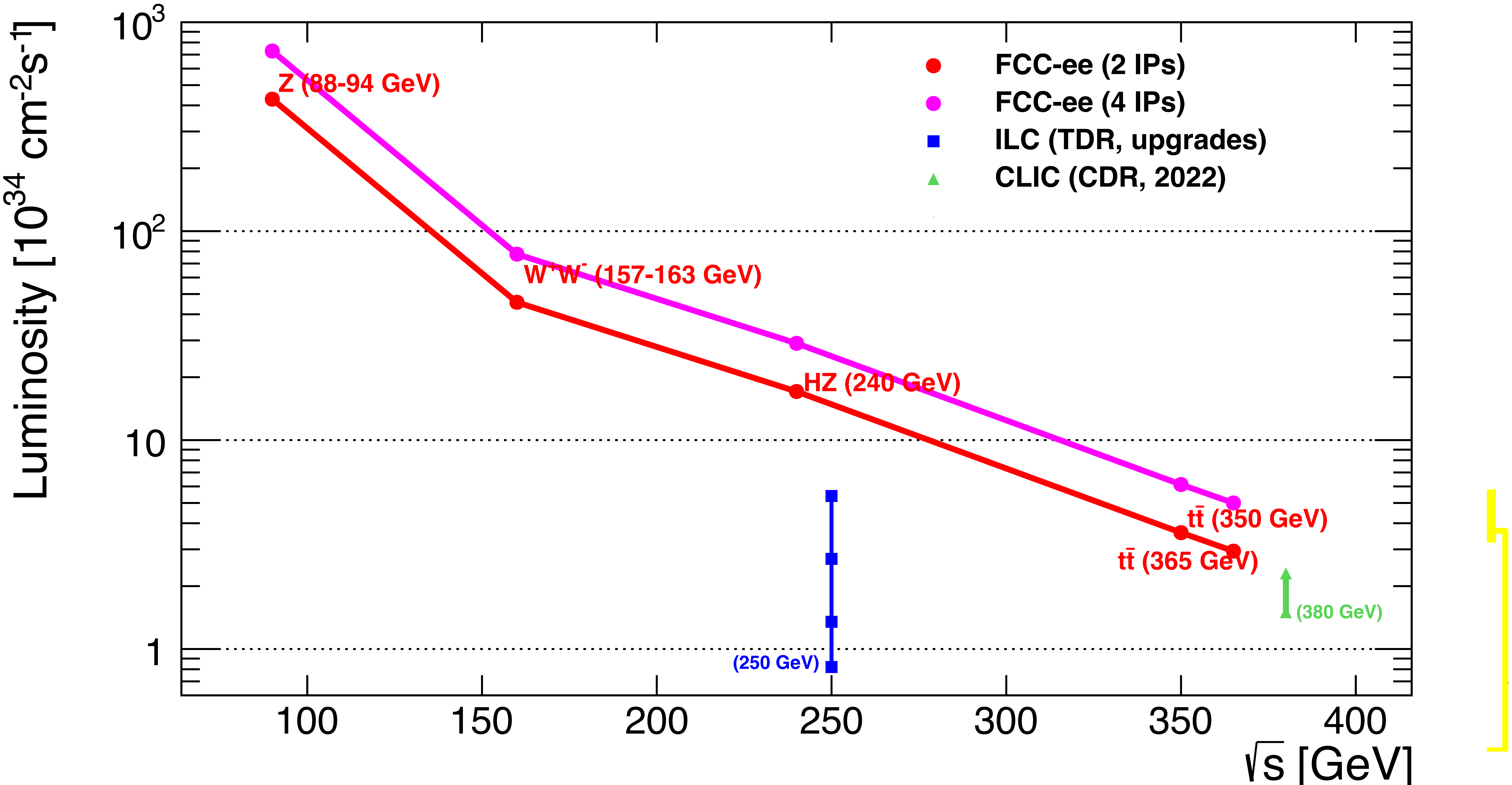
Recalling the basic numbers

FCC-ee (numbers of events are for 2 detectors — baseline is now 4)



						$\sqrt{s}$ 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-ee (updated plot for 4 detectors)



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

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

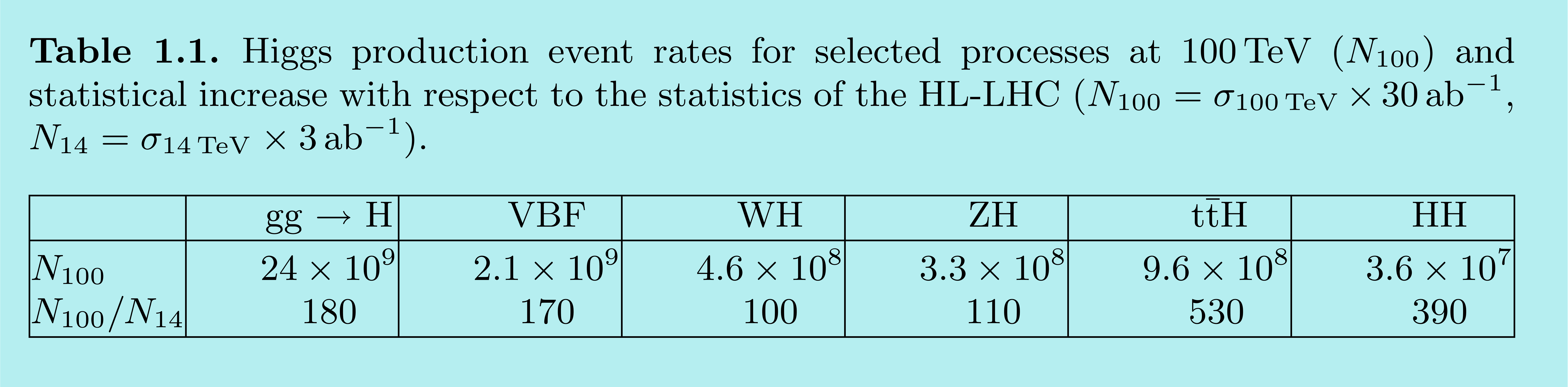
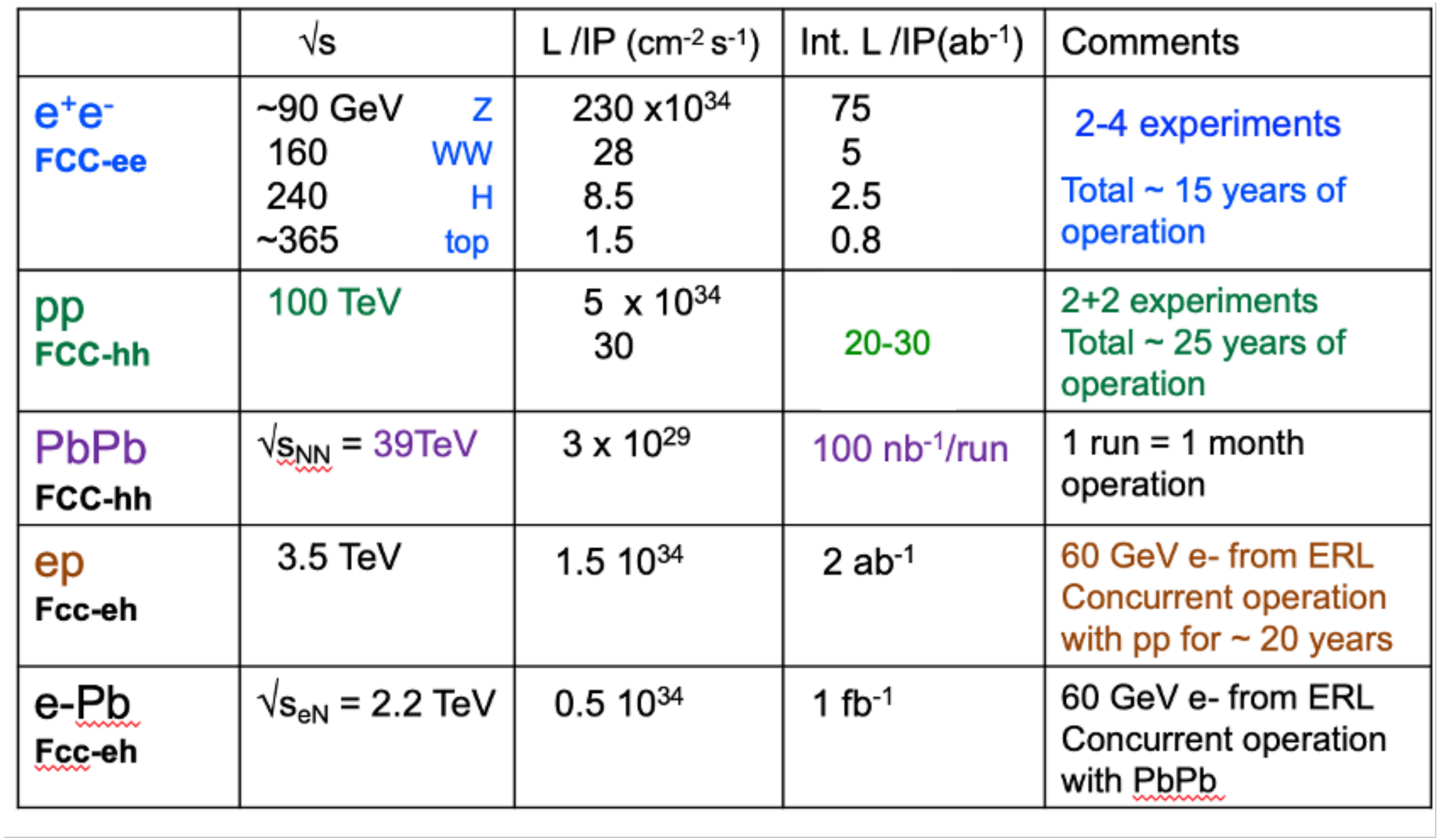


Table 1.1. Higgs production event rates for selected processes at 100 TeV (N_{100}) and statistical increase with respect to the statistics of the HL-LHC ($N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\,\mathrm{ab}^{-1}$, $N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\,\mathrm{ab}^{-1}$).

	gg → 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 [and maybe ep and ePb options]

NB ee numbers are outdated (2IP, should be 4)



	$\sqrt{s}$	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 x10^{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 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 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

FCC as a Higgs factory [NB numbers are for 2 IP — new baseline is 4 IP]

- **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 ($e^+e^- \to t\bar{t}$)
    - Another standard candle
  - FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
    - (2^{nd} standard candle →) g_{Htt} and g_{HHH}

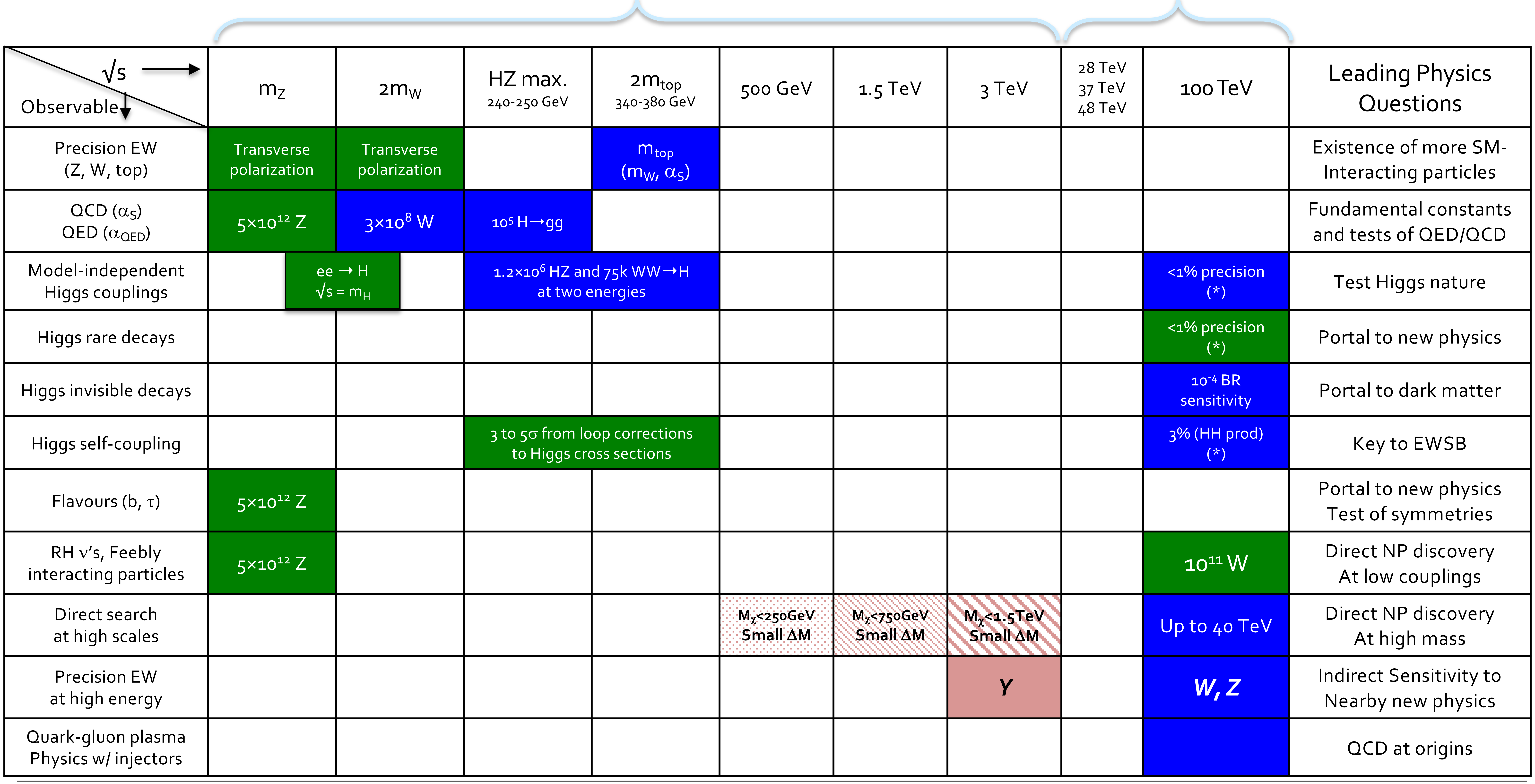
Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	ee
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*	
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	
$g_{H\mu\mu}$ (%)	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	
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	
g_{HHH} (%)	50.	44./33. 27./24.	3	
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**

Refs for the table: arXiv:1905.03764, arXiv:2004.03505 arXiv:1906.02693, FCC-ee: Your questions answered



√s → Observable ↓	e⁺e⁻ collisions							pp collisions		
	m_Z	$2m_W$	HZ max. 240-250 GeV	$2m_{top}$ 340-380 GeV	500 GeV	1.5 TeV	3 TeV	28 TeV 37 TeV 48 TeV	100 TeV	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)

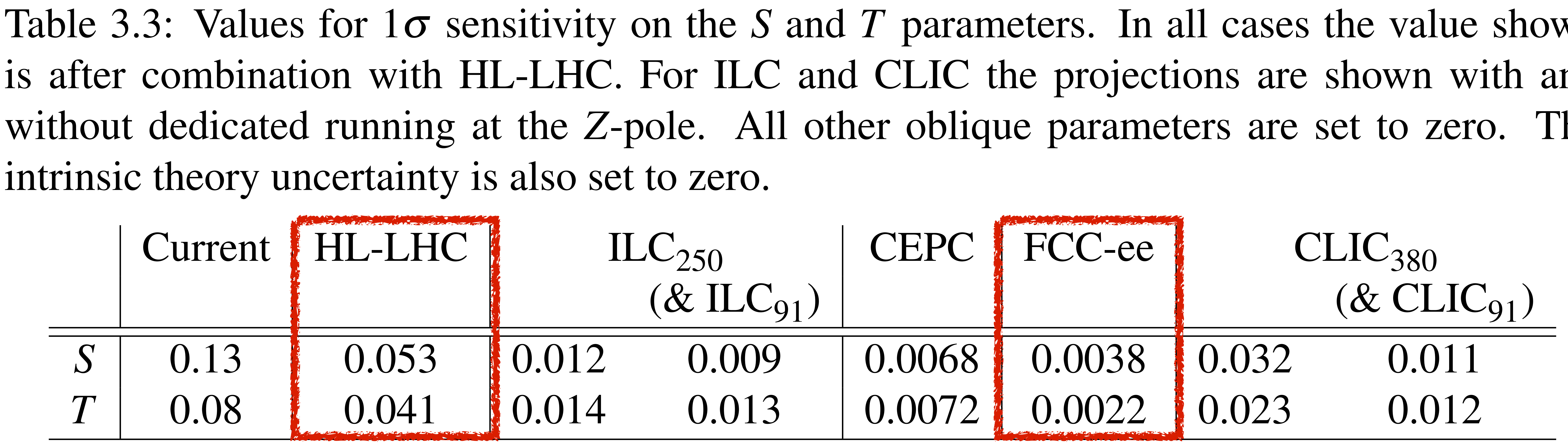
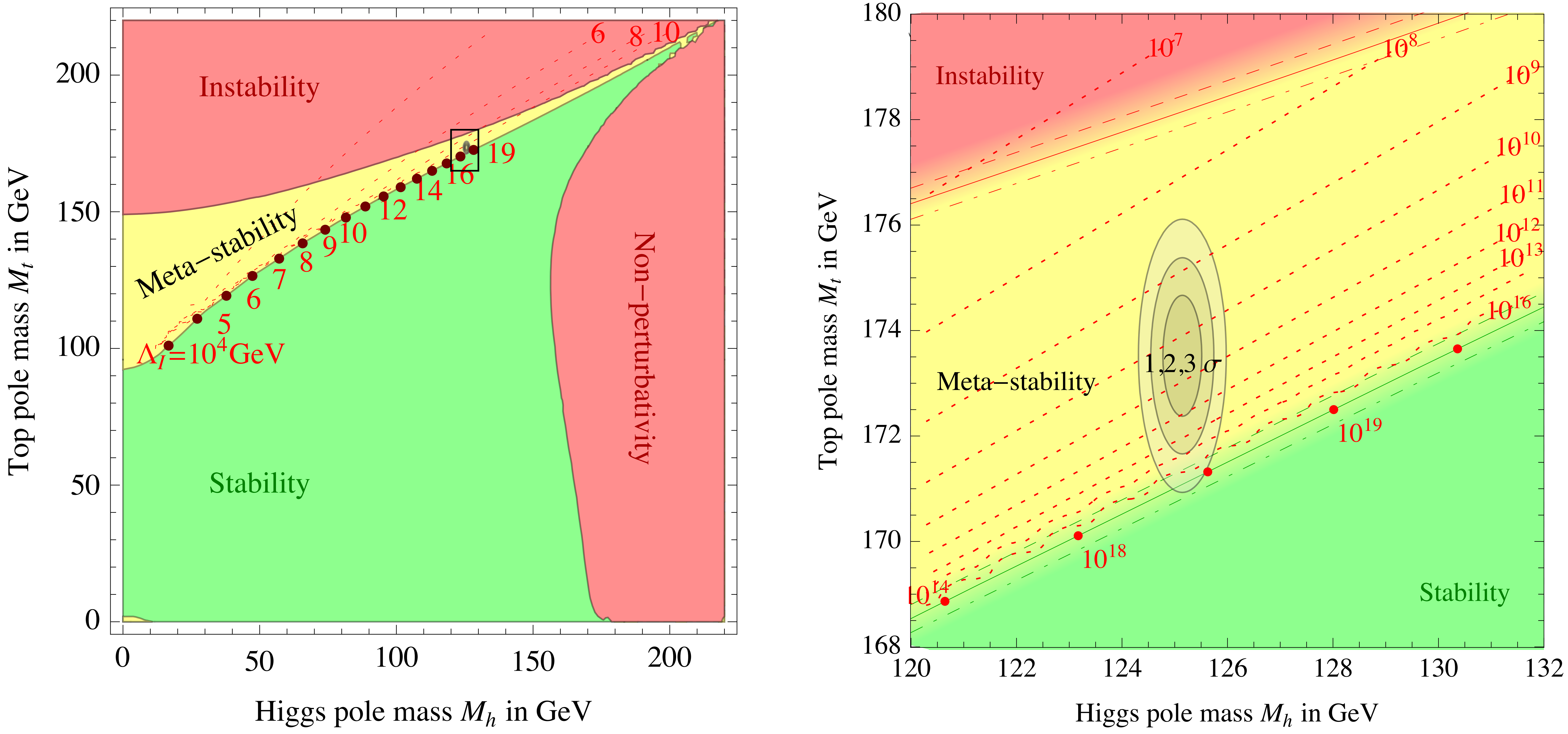


Table 3.3: Values for 1σ sensitivity on the S and T parameters. In all cases the value shown is after combination with HL-LHC. For ILC and CLIC the projections are shown with and without dedicated running at the Z-pole. All other oblique parameters are set to zero. The intrinsic theory uncertainty is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

	Current	HL-LHC	ILC$_{250}$		CEPC	FCC-ee	CLIC$_{380}$	
				(& ILC$_{91}$)				(& 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

muon colliders

Higgs at muon collider

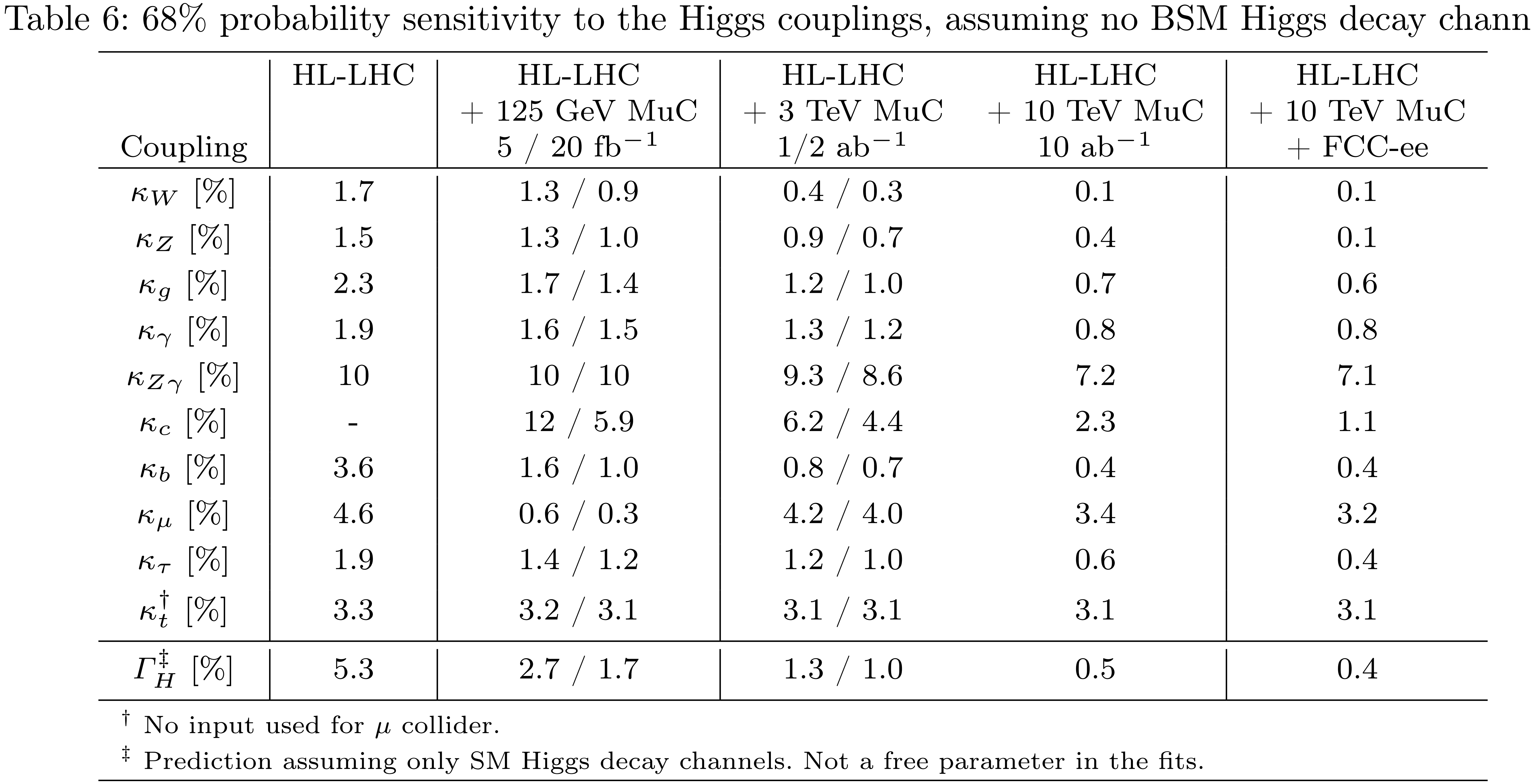


Table 6: 68% probability sensitivity to the Higgs couplings, assuming no BSM Higgs decay chann

Coupling	HL-LHC	HL-LHC + 125 GeV MuC 5 / 20 fb^{-1}	HL-LHC + 3 TeV MuC 1/2 ab^{-1}	HL-LHC + 10 TeV MuC 10 ab^{-1}	HL-LHC + 10 TeV MuC + FCC-ee
κ_W [%]	1.7	1.3 / 0.9	0.4 / 0.3	0.1	0.1
κ_Z [%]	1.5	1.3 / 1.0	0.9 / 0.7	0.4	0.1
κ_g [%]	2.3	1.7 / 1.4	1.2 / 1.0	0.7	0.6
κ_γ [%]	1.9	1.6 / 1.5	1.3 / 1.2	0.8	0.8
$\kappa_{Z\gamma}$ [%]	10	10 / 10	9.3 / 8.6	7.2	7.1
κ_c [%]	-	12 / 5.9	6.2 / 4.4	2.3	1.1
κ_b [%]	3.6	1.6 / 1.0	0.8 / 0.7	0.4	0.4
κ_μ [%]	4.6	0.6 / 0.3	4.2 / 4.0	3.4	3.2
κ_τ [%]	1.9	1.4 / 1.2	1.2 / 1.0	0.6	0.4
$\kappa_t^\dagger$ [%]	3.3	3.2 / 3.1	3.1 / 3.1	3.1	3.1
$\Gamma_H^\ddagger$ [%]	5.3	2.7 / 1.7	1.3 / 1.0	0.5	0.4

† No input used for μ collider.

‡ Prediction assuming only SM Higgs decay channels. Not a free parameter in the fits.

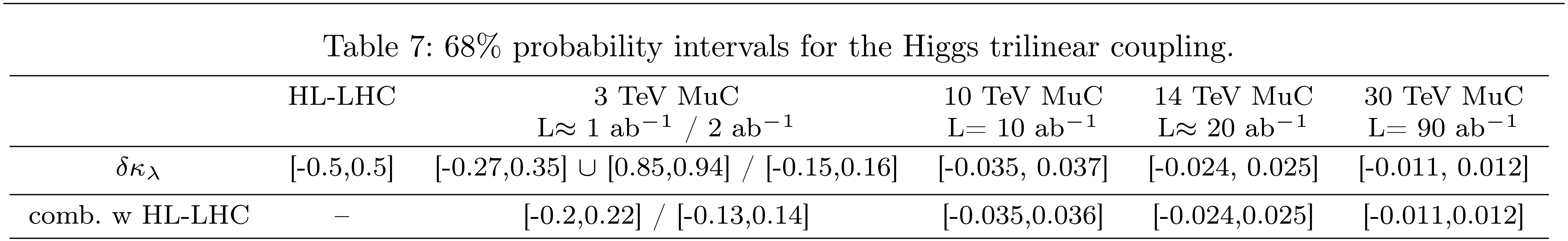


Table 7: 68% probability intervals for the Higgs trilinear coupling.

	HL-LHC	3 TeV MuC L$\approx$ 1 ab^{-1} / 2 ab^{-1}	10 TeV MuC L= 10 ab^{-1}	14 TeV MuC L$\approx$ 20 ab^{-1}	30 TeV MuC L= 90 ab^{-1}
$\delta\kappa_\lambda$	[-0.5,0.5]	[-0.27,0.35] $\cup$ [0.85,0.94] / [-0.15,0.16]	[-0.035, 0.037]	[-0.024, 0.025]	[-0.011, 0.012]
comb. w HL-LHC	–	[-0.2,0.22] / [-0.13,0.14]	[-0.035,0.036]	[-0.024,0.025]	[-0.011,0.012]

triple Higgs at muon collider from 2003.13628

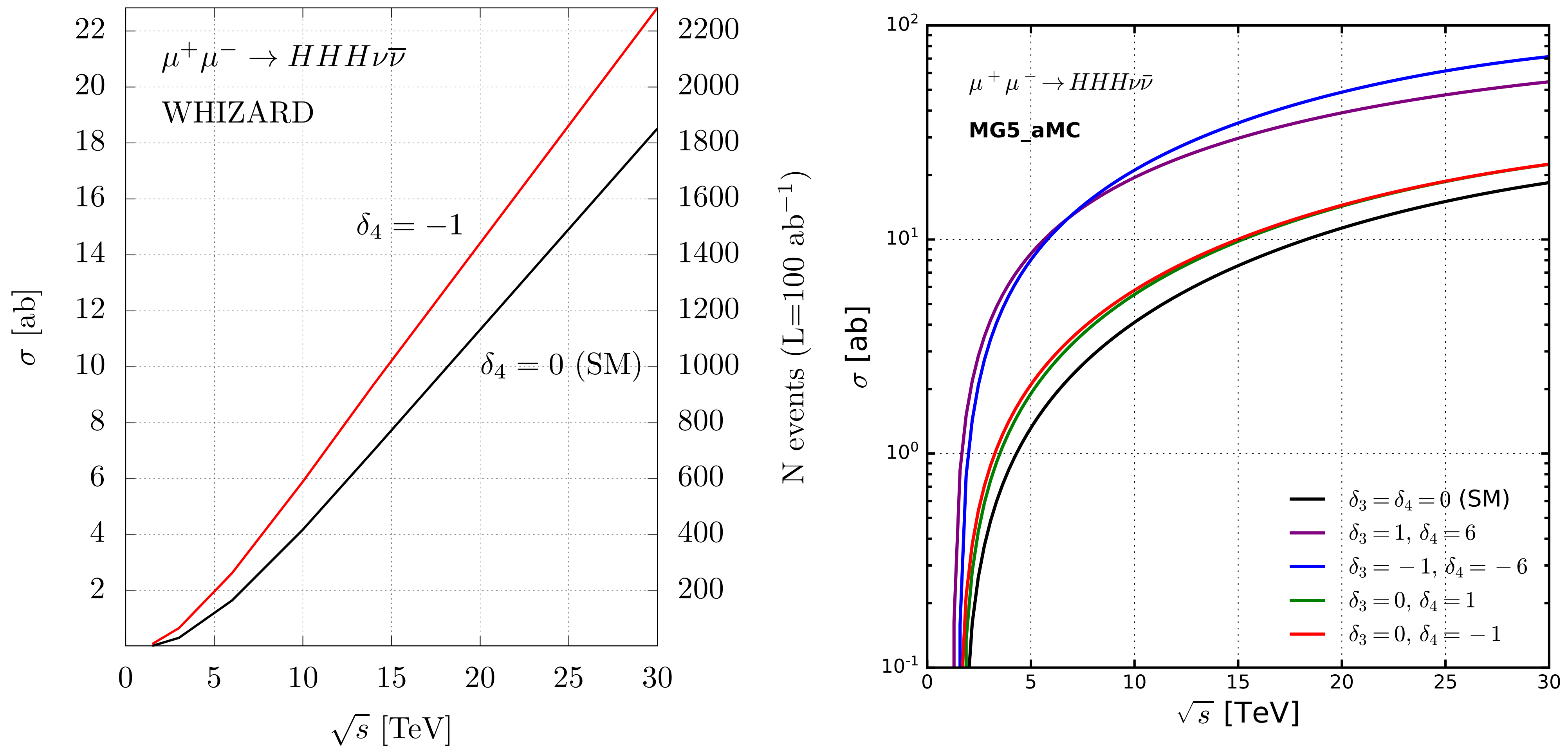


Figure 2: Expected cross sections (left) and signal event numbers for a reference integrated luminosity of 100 ab^{-1} (right) for $\mu^+\mu^- \to HHH\nu\bar{\nu}$ versus the c.m. collision energy, for $M_{\bar{\nu}\nu} \gtrsim 150$GeV. Cross sections for different assumptions of the trilinear and quartic couplings are presented, as well as for the SM case, obtained by WHIZARD (left-hand side) and MADGRAPH5_AMC@NLO (right-hand side). Details on the scenarios are given in the text.

$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	Constraints on δ_4 (with $\delta_3 = 0$) x-sec only $1\ \sigma$	x-sec only $2\ \sigma$	threshold + $M_{HHH} > 1$ TeV $1\ \sigma$
6	12	$[-0.60, 0.75]$	$[-0.90, 1.00]$	$[-0.55, 0.85]$
10	20	$[-0.50, 0.55]$	$[-0.70, 0.80]$	$[-0.45, 0.70]$
14	33	$[-0.45, 0.50]$	$[-0.60, 0.65]$	$[-0.35, 0.55]$
30	100	$[-0.30, 0.35]$	$[-0.45, 0.45]$	$[-0.20, 0.40]$
3	100	$[-0.35, 0.60]$	$[-0.50, 0.80]$	$[-0.45, 0.65]$

Table 5: Summary of the constraints on the quartic deviations δ_4, assuming $\delta_3 = 0$, for various muon collider energy/luminosity options, as obtained from the total expected cross sections (1σ and 2σ CL). The third column shows the bounds obtained from the combination of the constraints corresponding to the setups $M_{HHH} < 1$ TeV and $M_{HHH} > 1$ TeV.

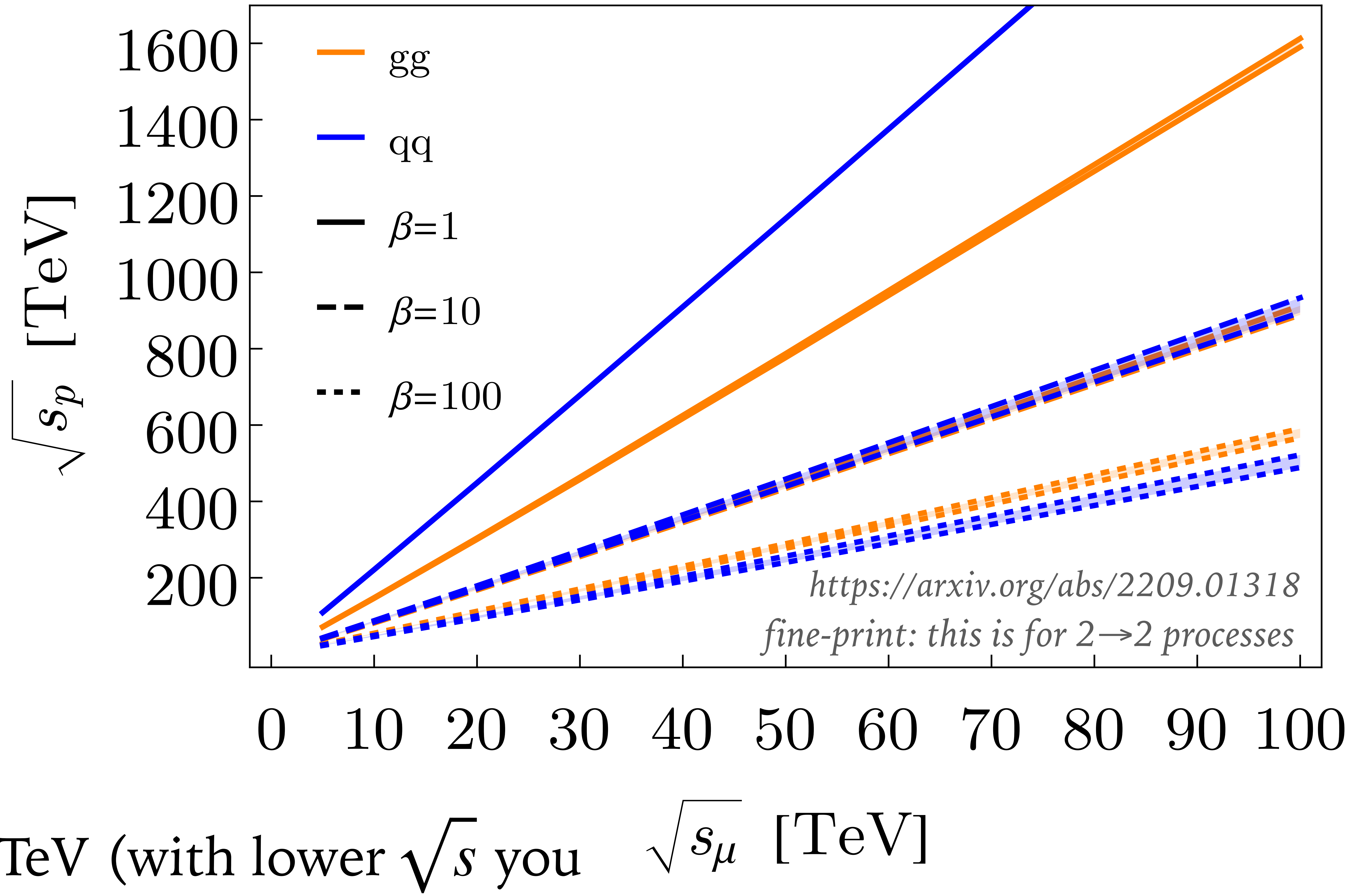
Searches at muon collider

Plots being shown suggest:
4 TeV muon collider beats a
100 TeV pp collider
in searches for new physics.

Useful to nuance the statement:

- 100 TeV pp, 20 ab^{-1} can discover Z' up to $m_{Z'} \sim 38$ TeV
- For $\mu\mu$ collider to discover Z' at $m_{Z'} \sim 38$ TeV, it needs $\sqrt{s} \sim 38$ TeV (with lower $\sqrt{s}$ you would see deviation from SM, but not know what it is)
- However a 38 TeV muon collider would be much better at studying the Z' than the 100 TeV pp machine

Fig. 3 of Snowmass Muon Collider Forum Report

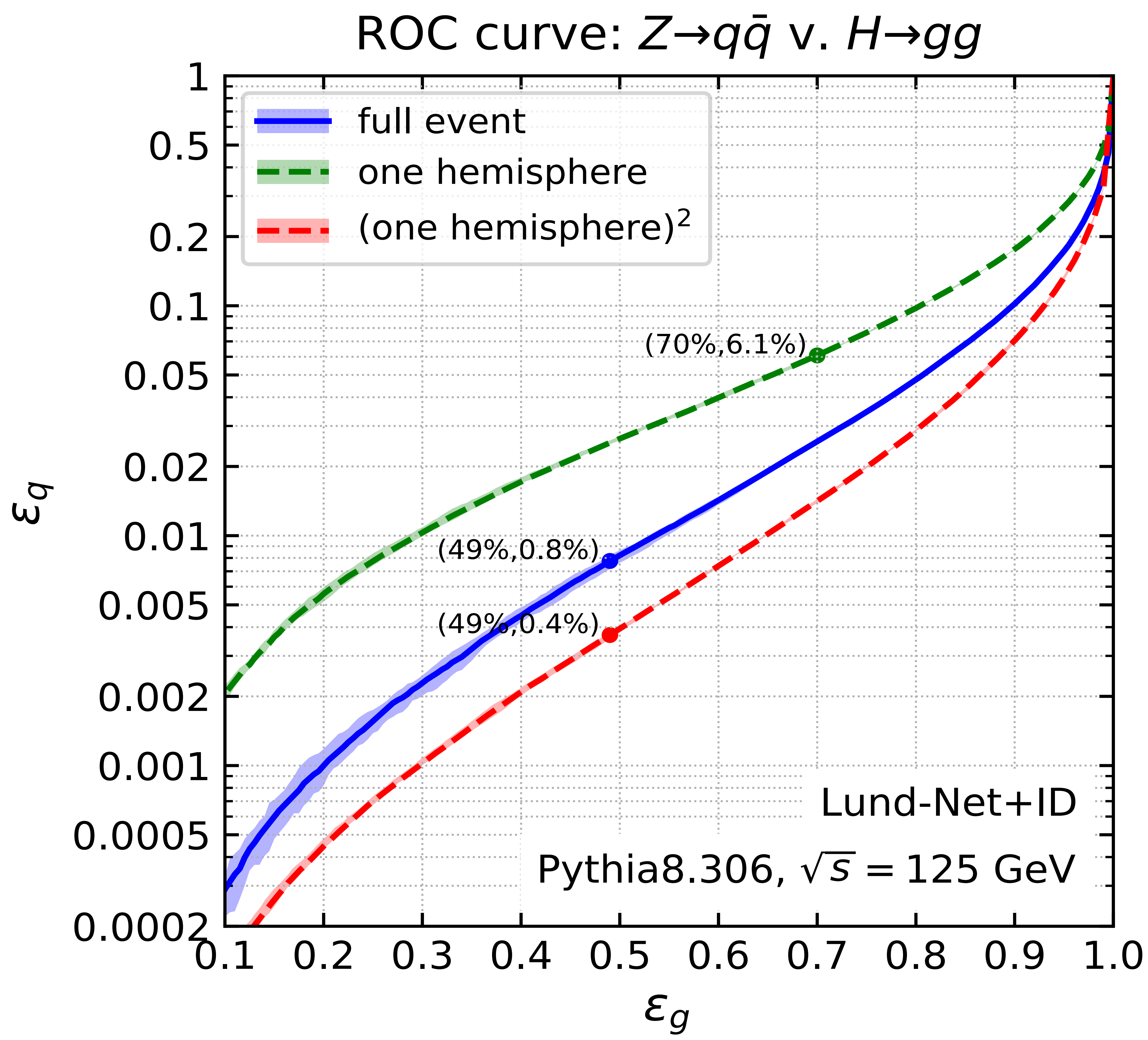


https://arxiv.org/abs/2209.01318

fine-print: this is for 2→2 processes

$H \to gg$ at FCC-ee

$$e^+e^- \to Z \to q\bar{q} \text{ v. } e^+e^- \to H \to gg \qquad (\sqrt{s} = 125 \text{ GeV, no ISR})$$



Observed performance:

- per jet: 6% quark mistag
  for 70% gluon efficiency
  Not quite the 1% quark mistag in 2107.02686
- full event: 0.8% quark mistag
  for 49% gluon efficiency
  full event worse that (jet)^2