National Seminar on Theoretical High-Energy Physics
NIKHEF Colloquium
15 March 2024

A Perspective on the Future of High-Energy Physics

Gavin Salam
University of Oxford & All Souls College

THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

Science and Technology Facilities Council

A preamble

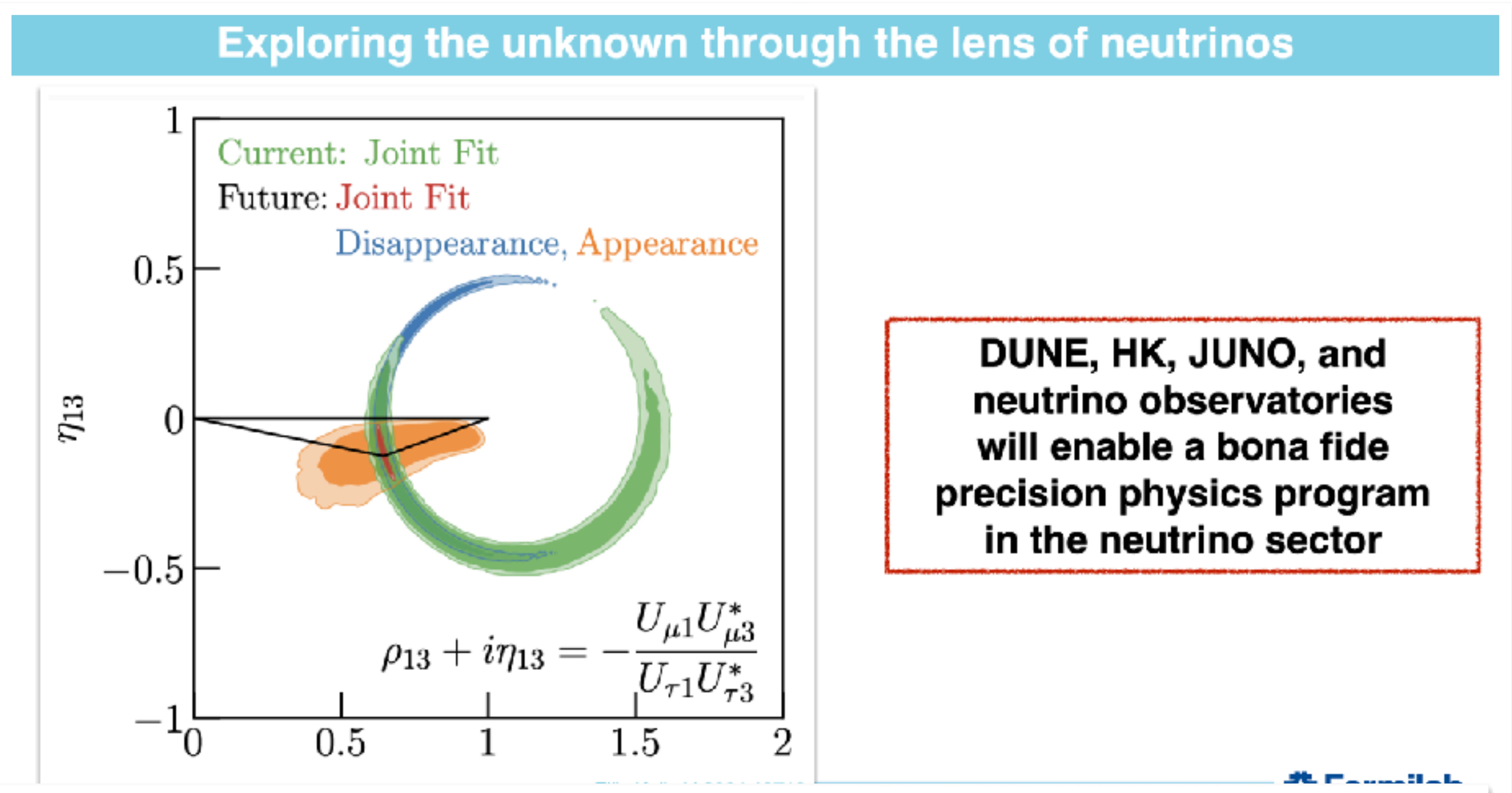
- this type of talk is often given by a theorist who builds models of new physics
- such a theorist can tell you with authority about the landscape of models that any given facility might probe

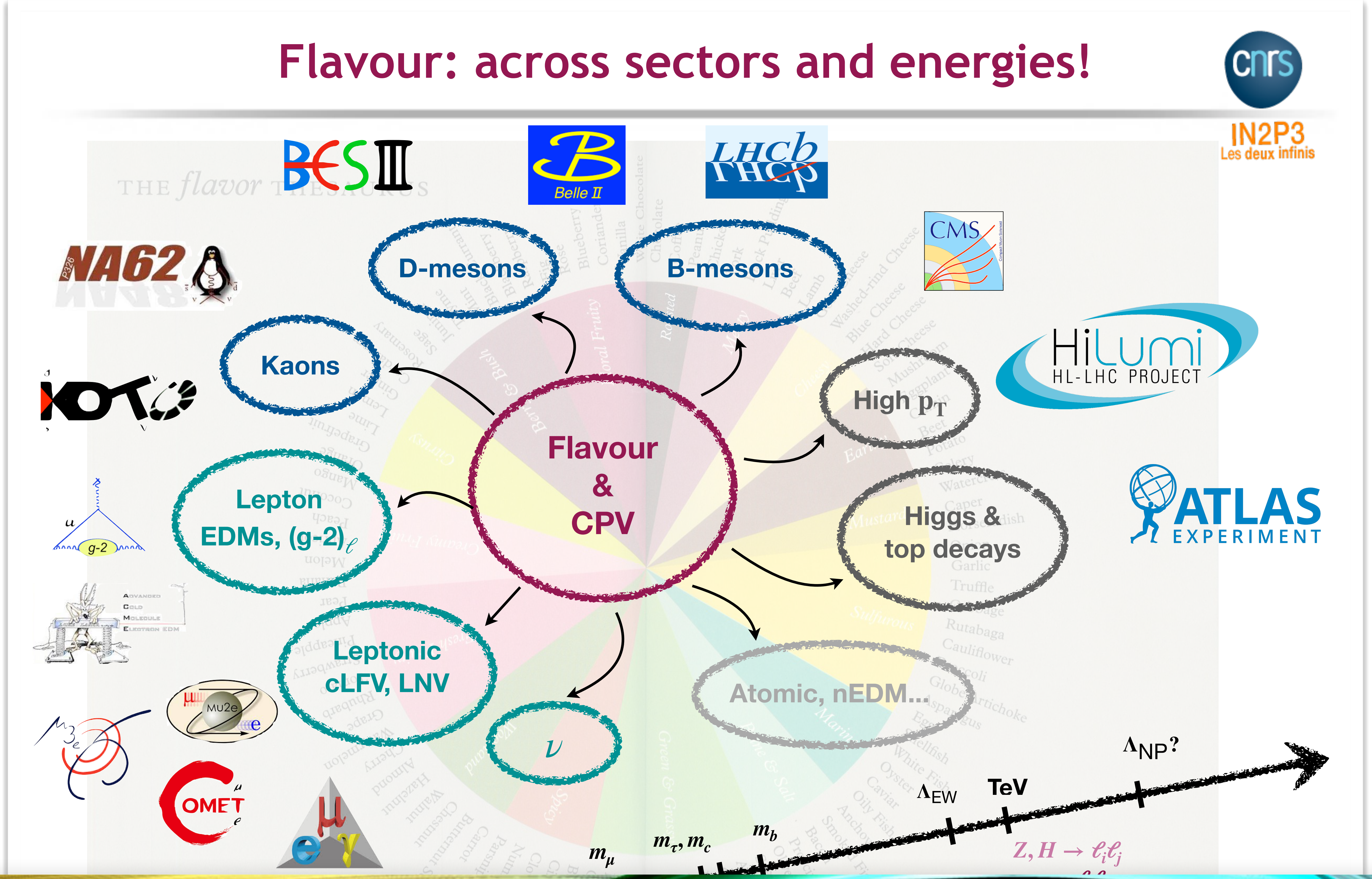
A preamble

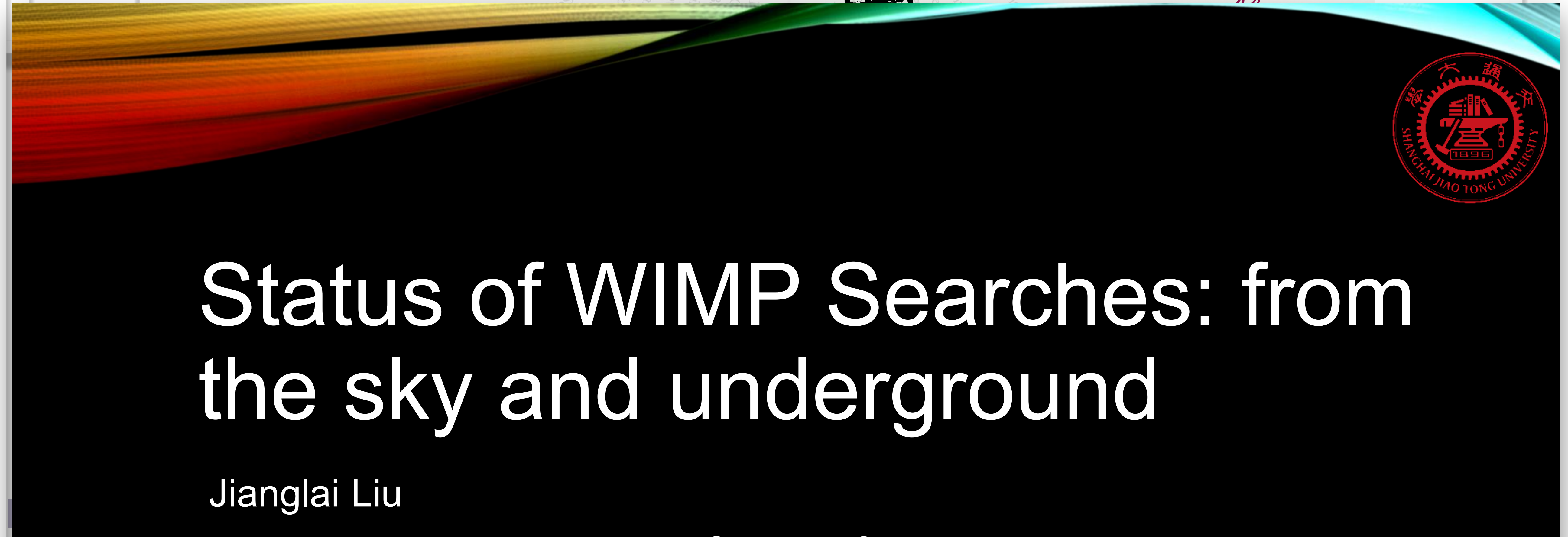
- this type of talk is often given by a theorist who builds models of new physics
- such a theorist can tell you with authority about the landscape of models that any given facility might probe

- 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 the future of large-scale HEP more generically

Medium-large projects: community knows how to motivate and get them funded







desirable features of the next major HEP project(s)?

an important target to be reached ~ guaranteed discovery

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (e.g. multiple experiments)

cost-effective construction & operation,
low carbon footprint, novel technologies

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

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*

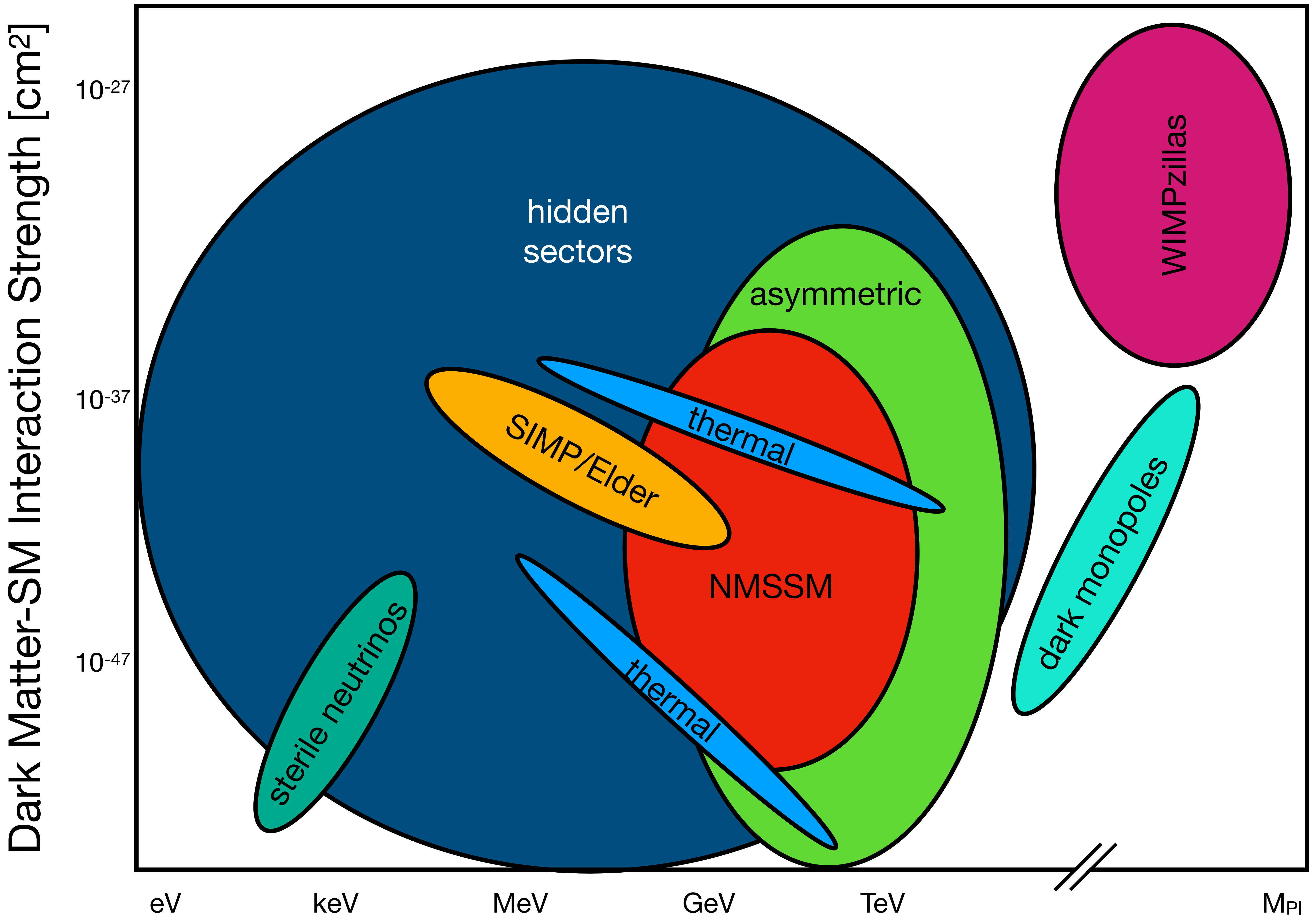
Thank you, Particle Physicists

ps: please, no anthropics

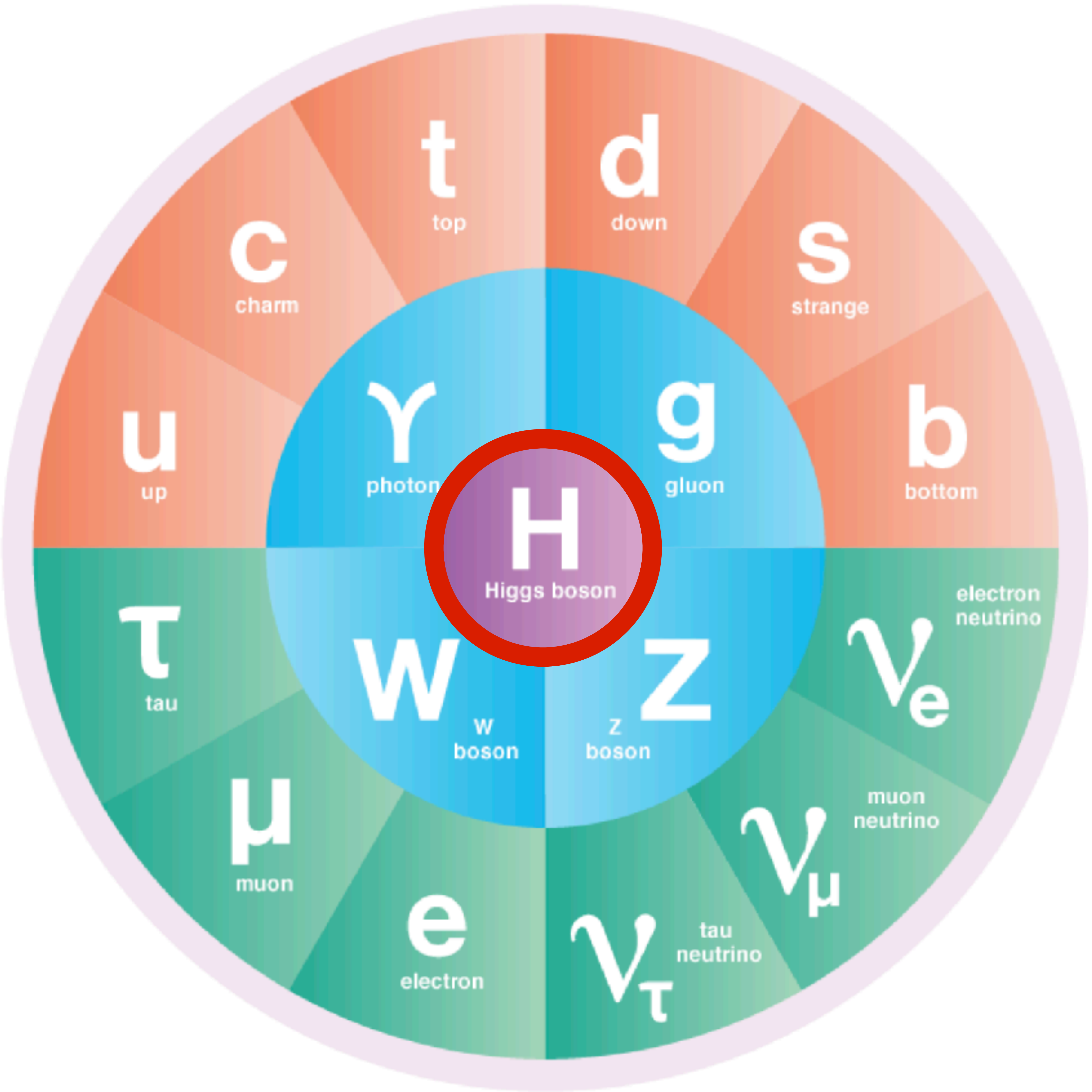
we have so far been unlucky in getting answers to these many questions

Snowmass Dark Matter report, 2209.07426

30 orders of magnitude in interaction strength



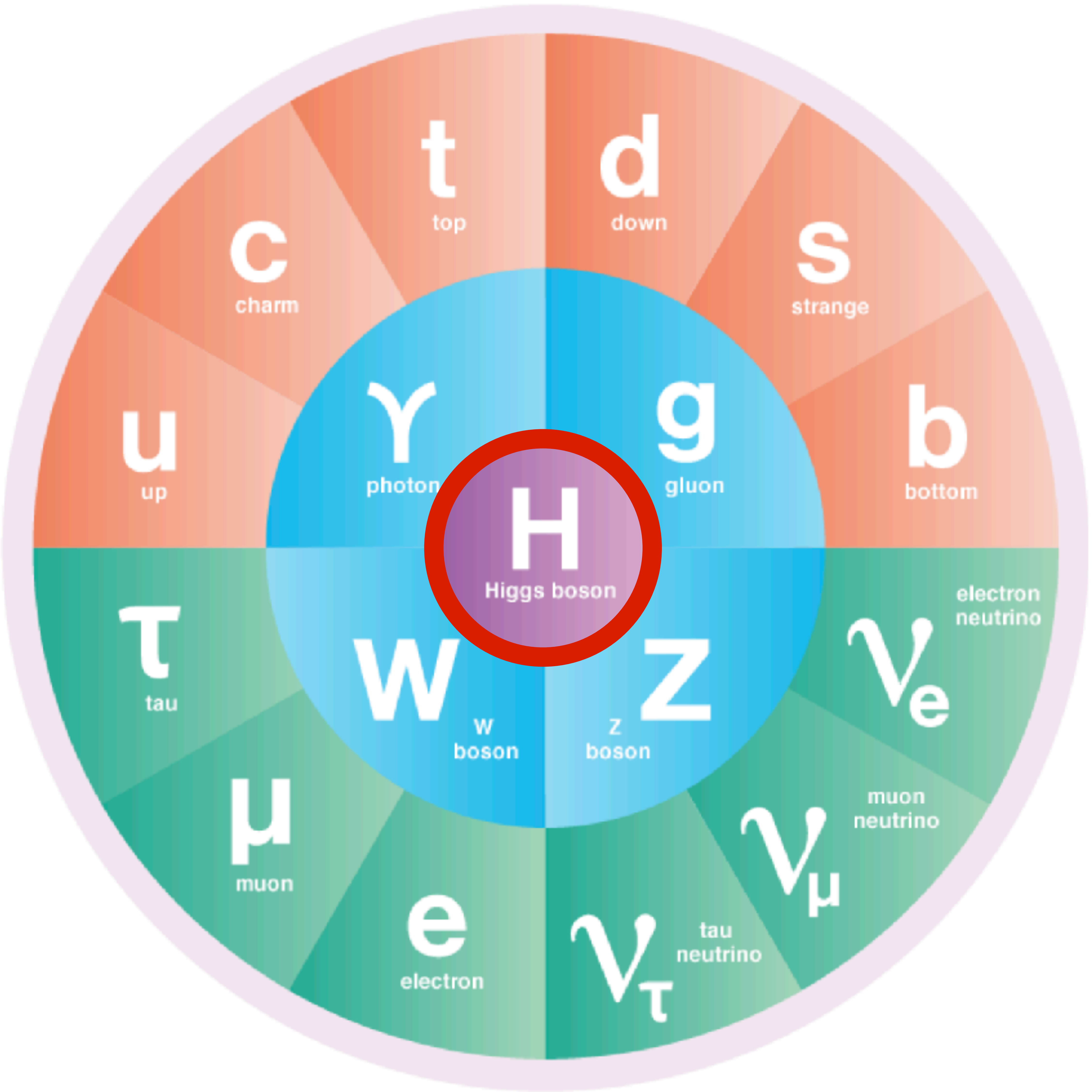
30 orders of magnitude in mass



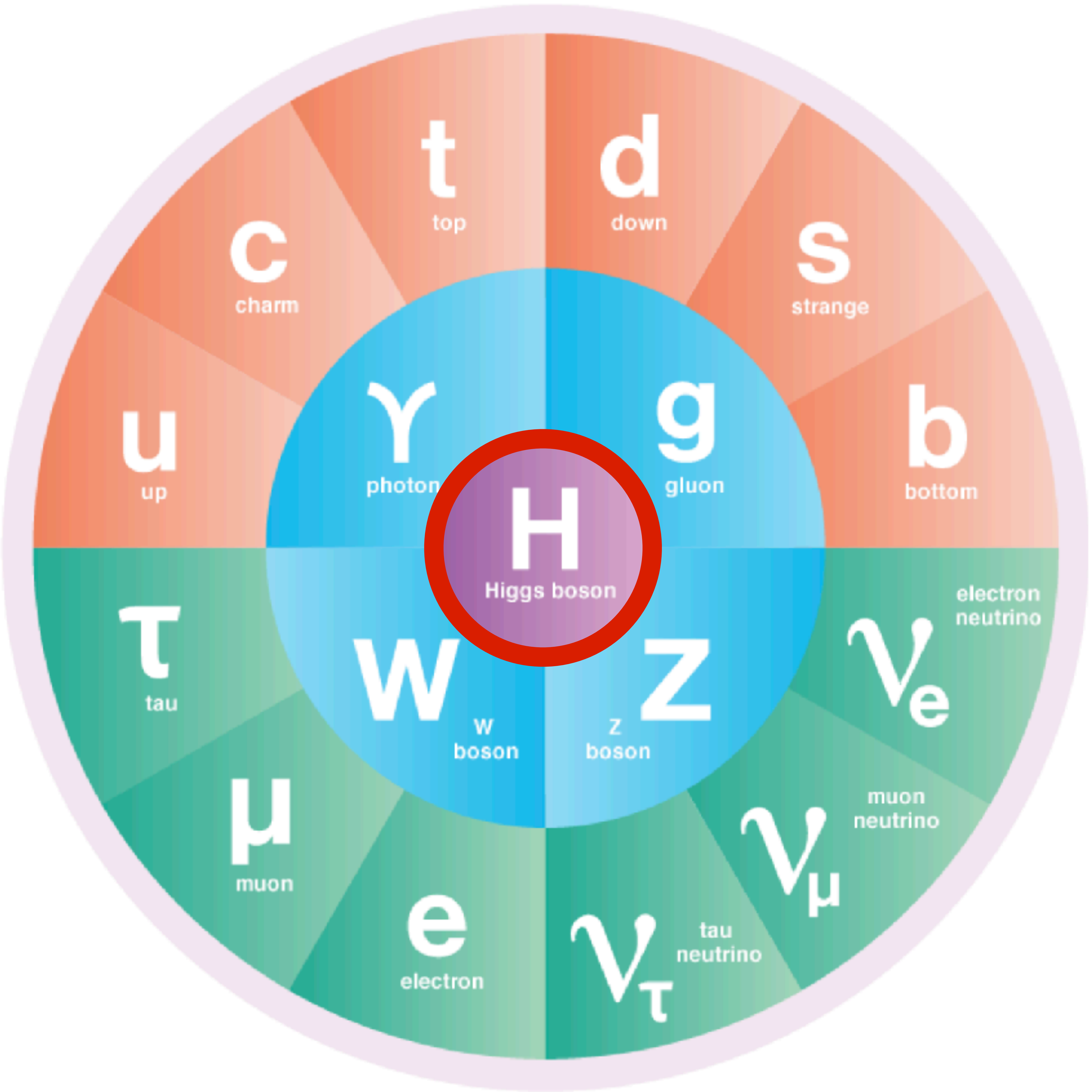
https://www.symmetrymagazine.org/standard-model/

"the standard-model is complete"

?



the standard-model particle set is complete



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

the standard-model particle set is complete

and we have been lucky with the Higgs boson's 125 GeV mass

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

desirable features of the next major HEP project(s)?

an important target to be reached ~ guaranteed discovery

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (e.g. multiple experiments)

cost-effective construction & operation,
low carbon footprint, novel technologies

Higgs physics

Higgs is the last particle of the SM.

with interactions unlike any we had studied before

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

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

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.

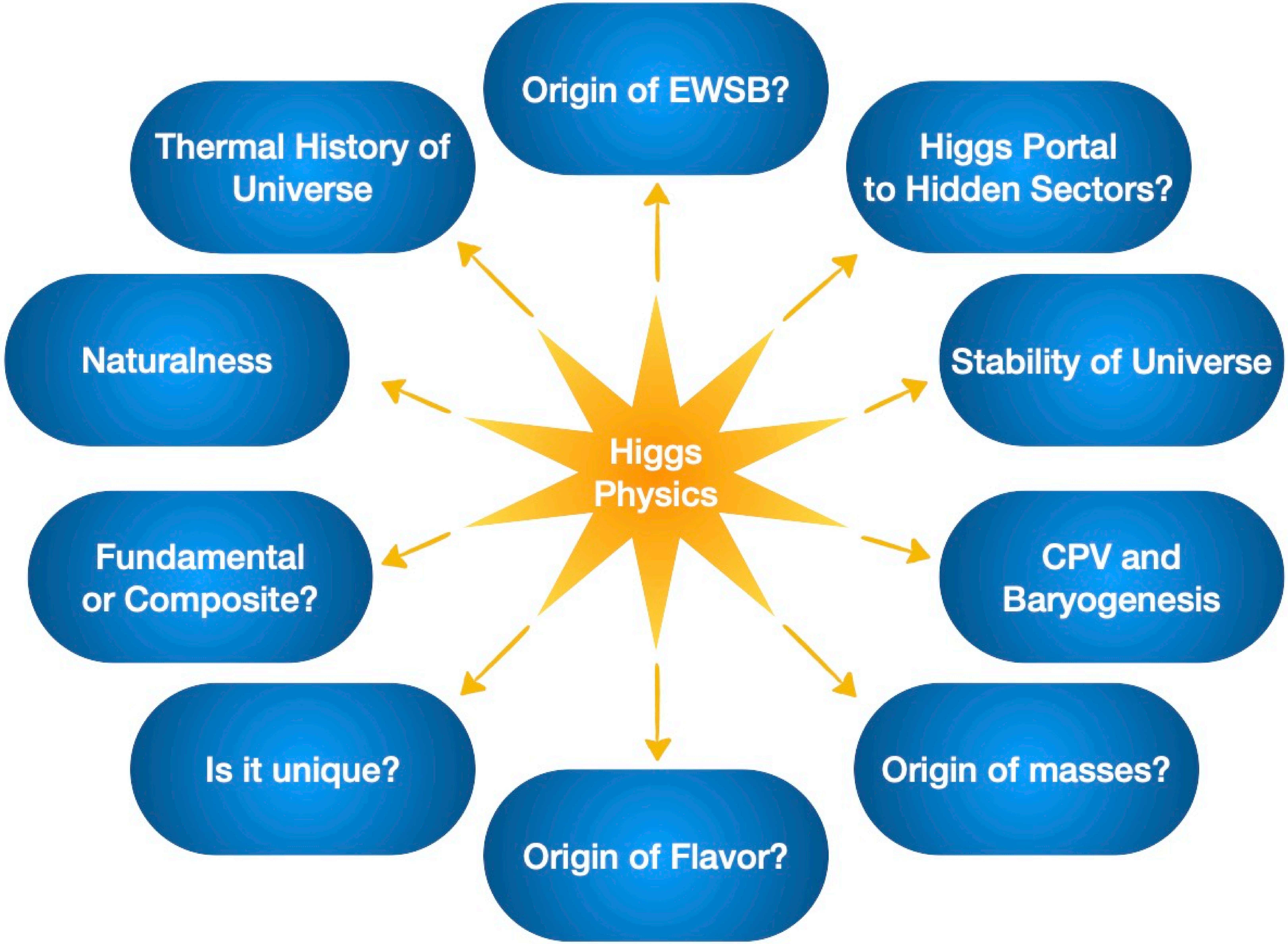
Unobserved

typeset from Gian Giudice original

Almost every problem of the Standard Model originates from Higgs interactions

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

- y → *flavour*
- μ^2 → *naturalness*
- λ → *stability*
- V_0 → *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

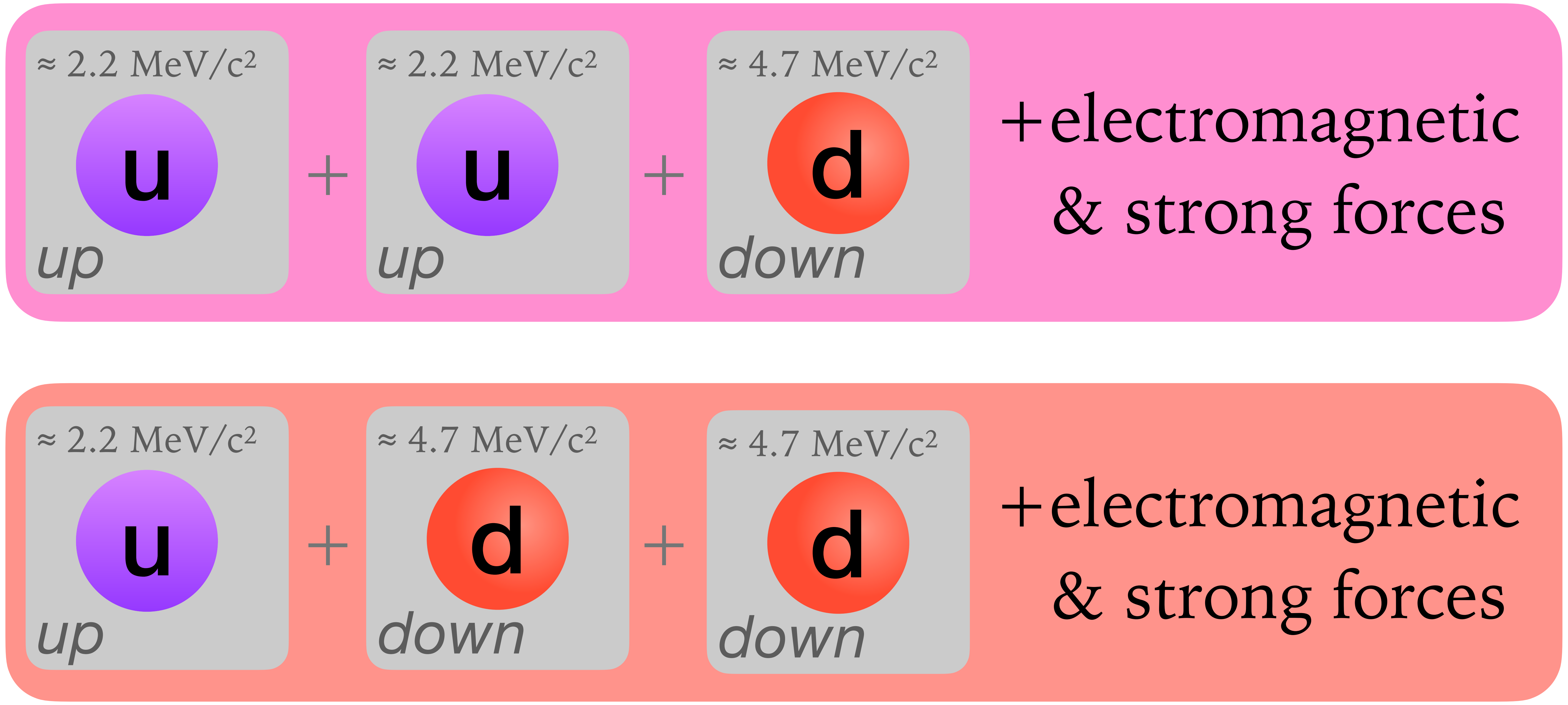
Yukawa couplings ~ fermion mass

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: ≃ 938.3 MeV



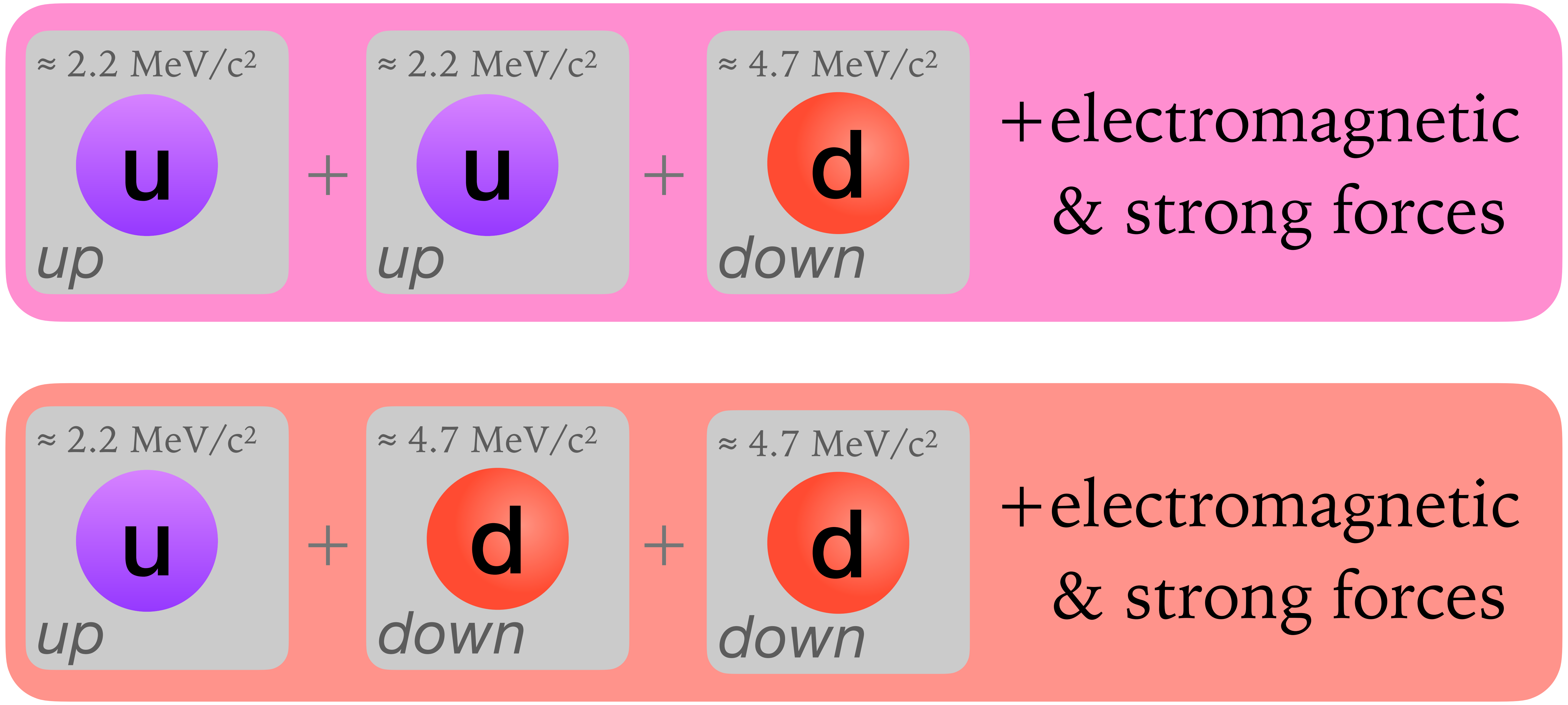
neutron: ≃ 939.6 MeV

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

2.2 MeV **2.2 MeV** 4.7 MeV

proton: ≃ 938.3 MeV



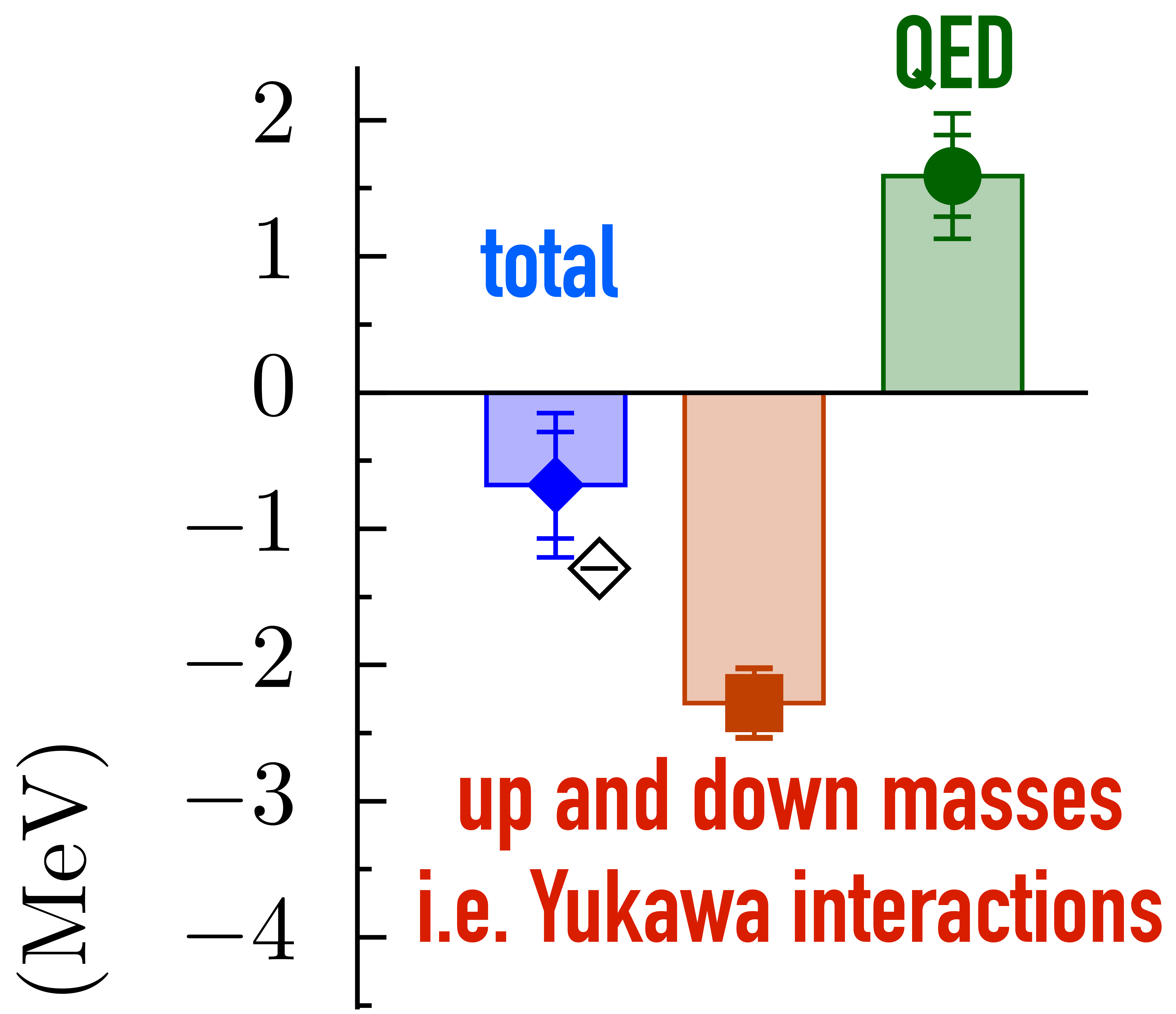
neutron: ≃ 939.6 MeV

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

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

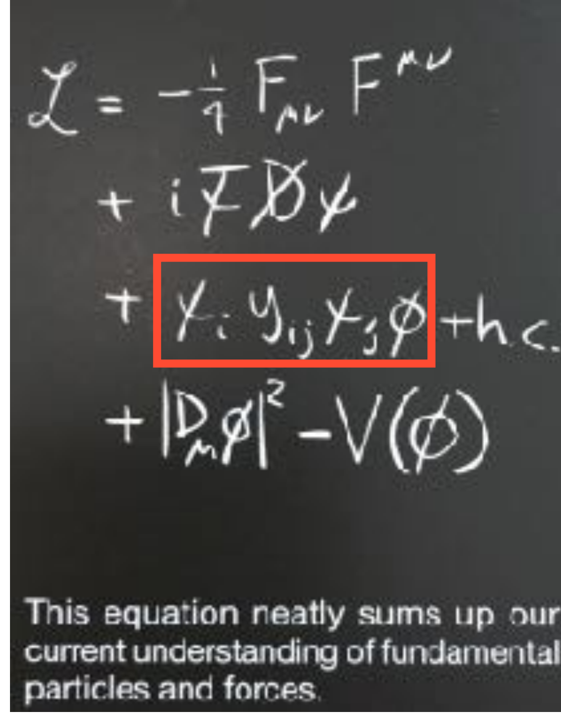
proton – neutron mass difference



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**



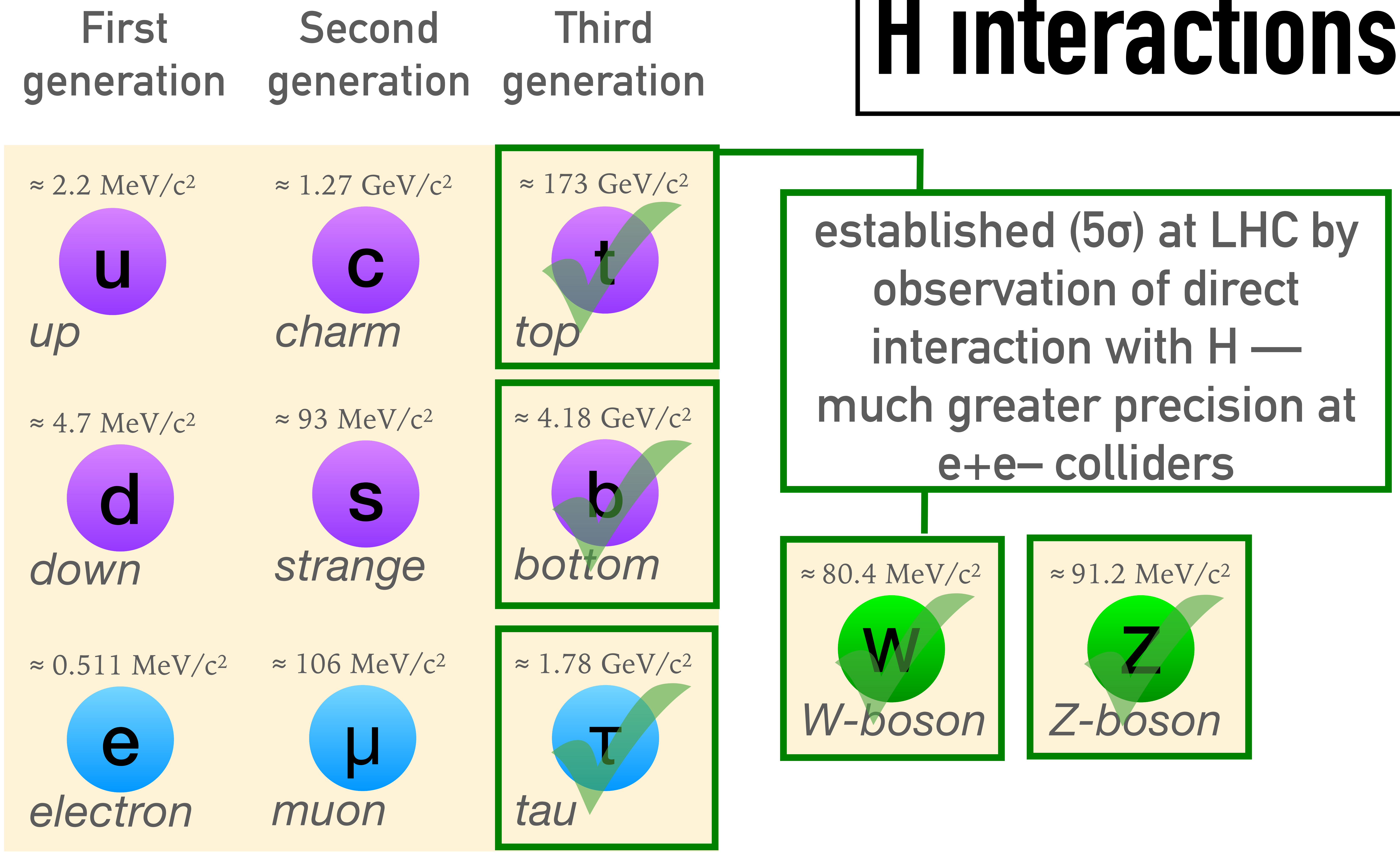
Bohr radius

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

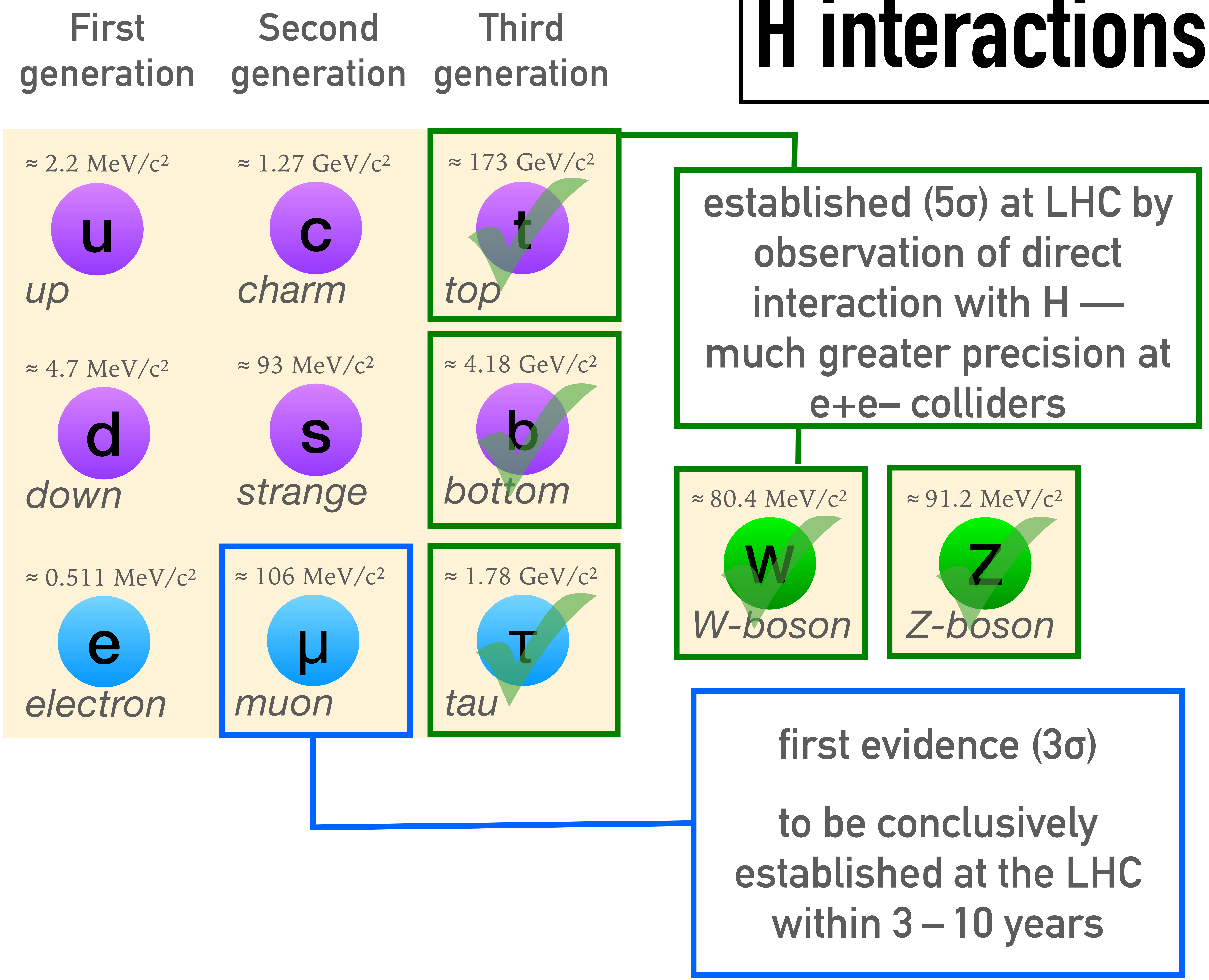
electron mass determines size of all atoms

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?

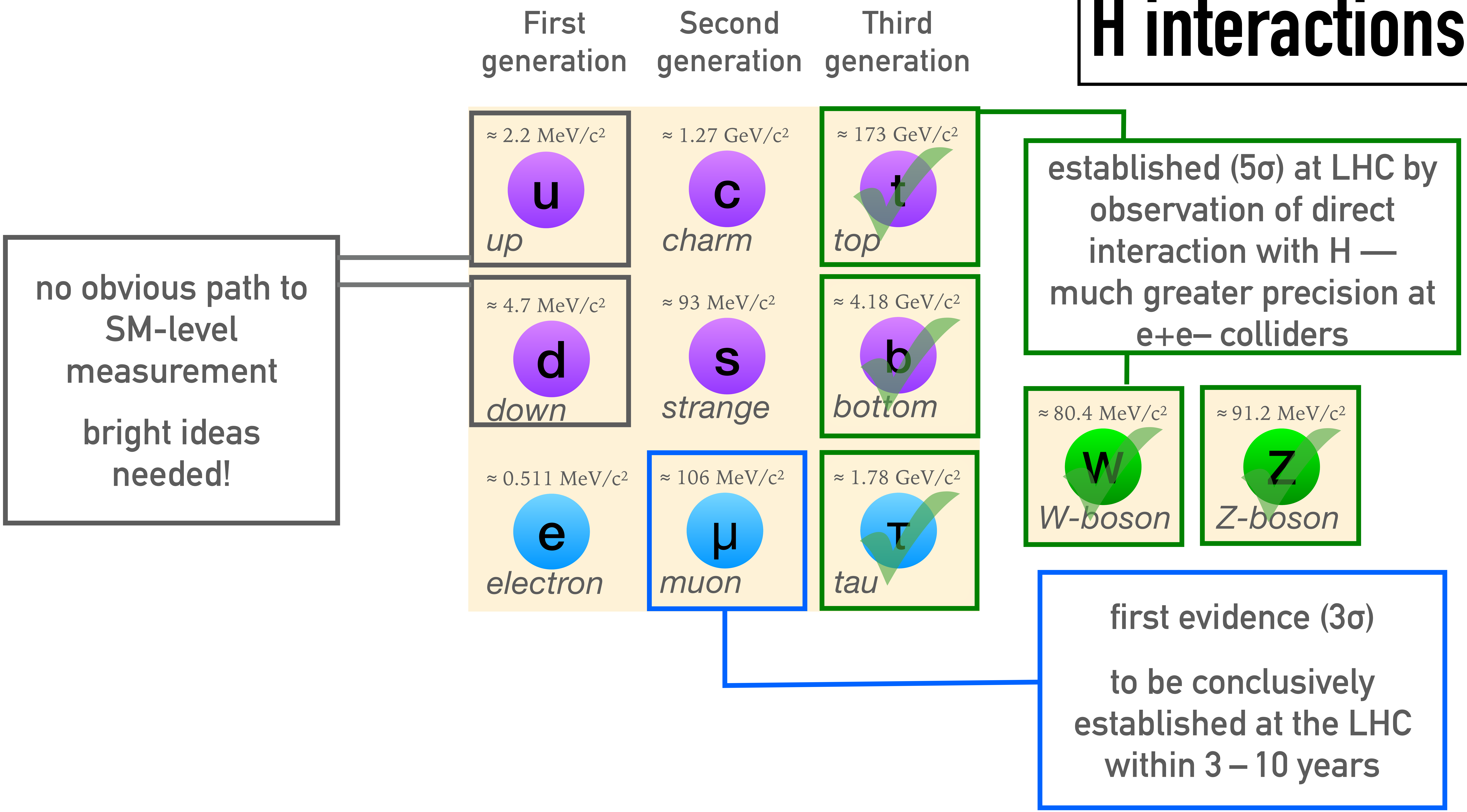
H interactions



H interactions



H interactions




H interactions
no evidence yet
guaranteed at future e+e− colliders
no obvious path to SM-level measurement
bright ideas needed!
First generation
Second generation
Third generation
≈ 2.2 MeV/c²
u
up
≈ 1.27 GeV/c²
c
charm
≈ 173 GeV/c²
t
top
≈ 4.7 MeV/c²
d
down
≈ 93 MeV/c²
s
strange
≈ 4.18 GeV/c²
b
bottom
≈ 0.511 MeV/c²
e
electron
≈ 106 MeV/c²
μ
muon
≈ 1.78 GeV/c²
τ
tau
established (5σ) at LHC by observation of direct interaction with H — much greater precision at e+e– colliders
≈ 80.4 MeV/c²
W
W-boson
≈ 91.2 MeV/c²
Z
Z-boson
first evidence (3σ)
to be conclusively established at the LHC within 3 – 10 years

H interactions

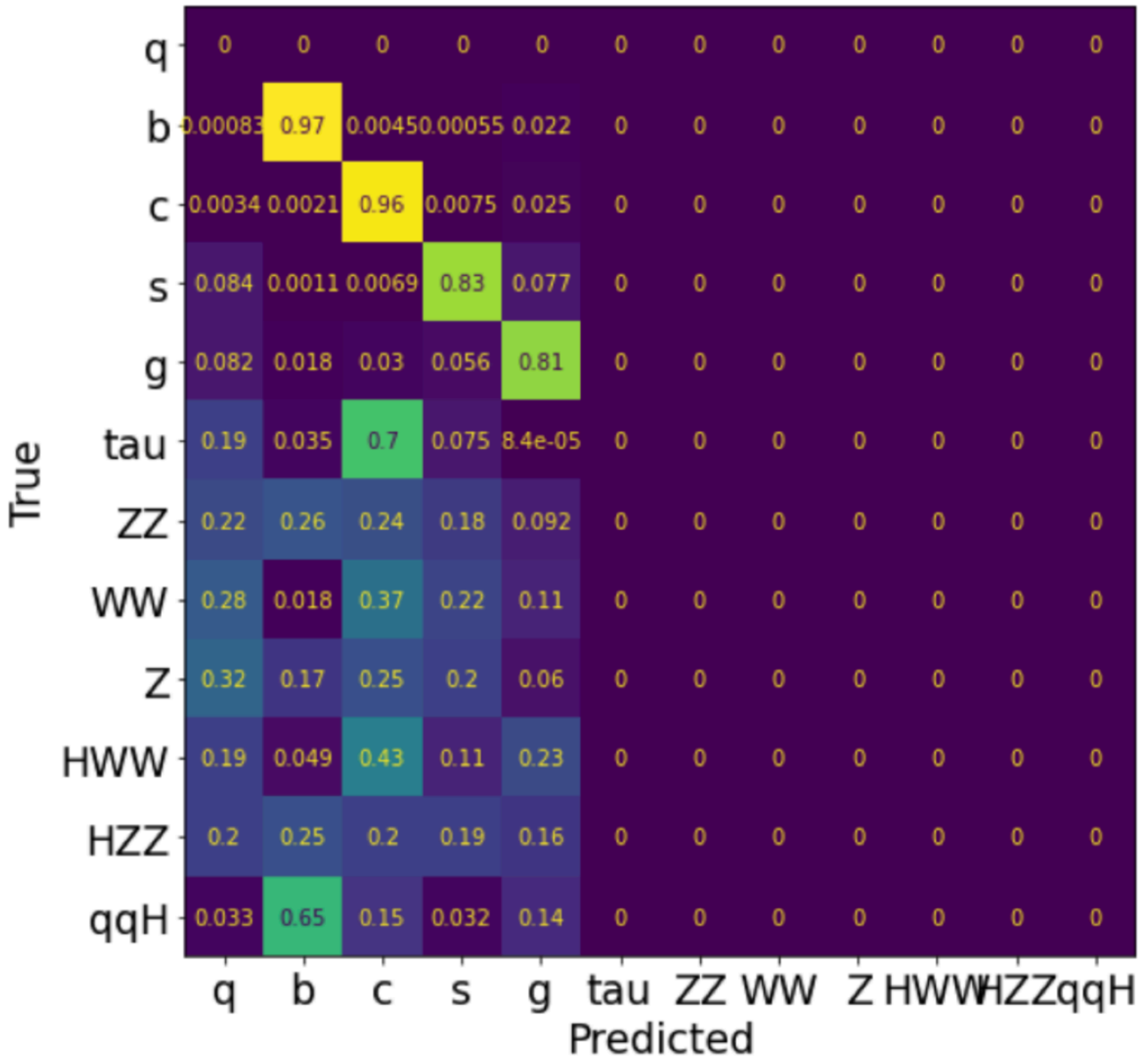
Teaser from the analysis front [FCC-ee, H → hadrons]

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

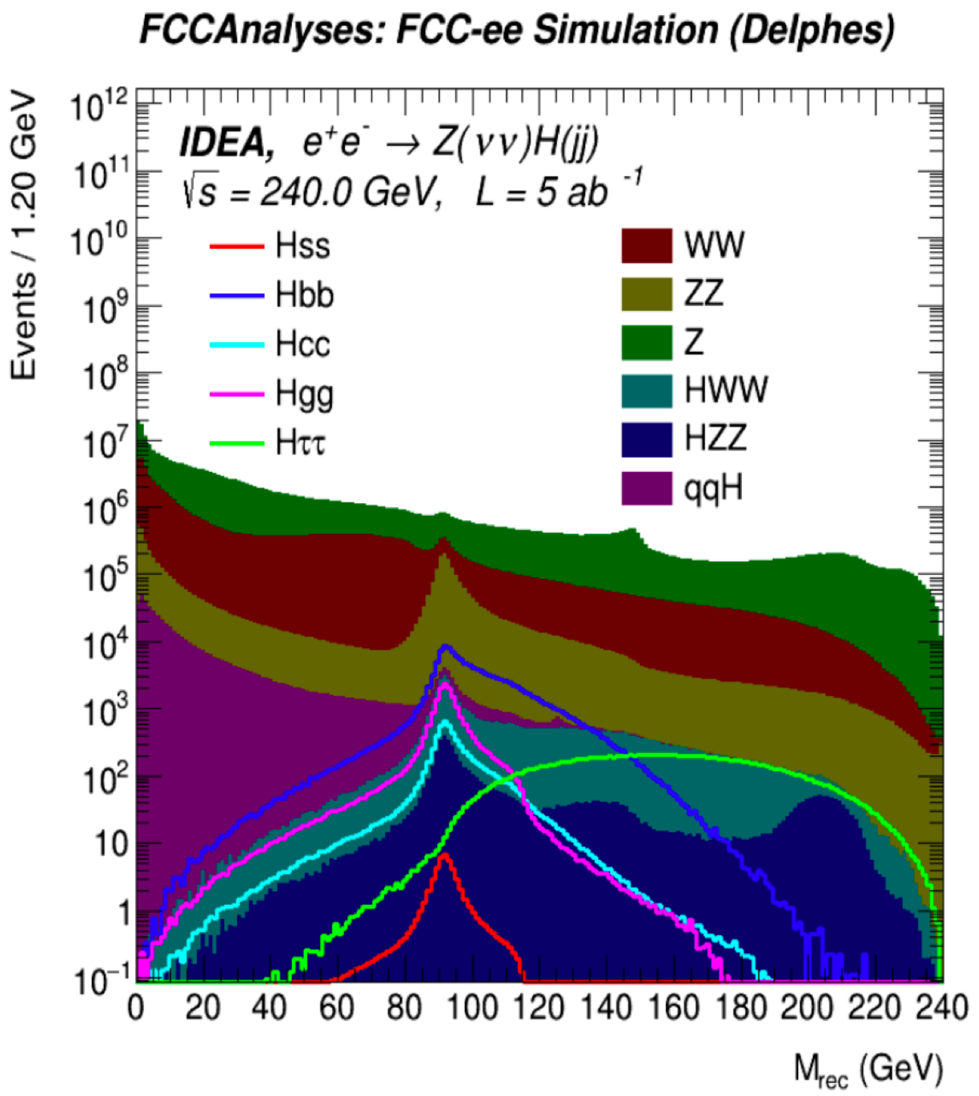
Categorize events: bb, cc, ss, gg
Sub-categories w/ different S/B

Signal extraction: 2D fit

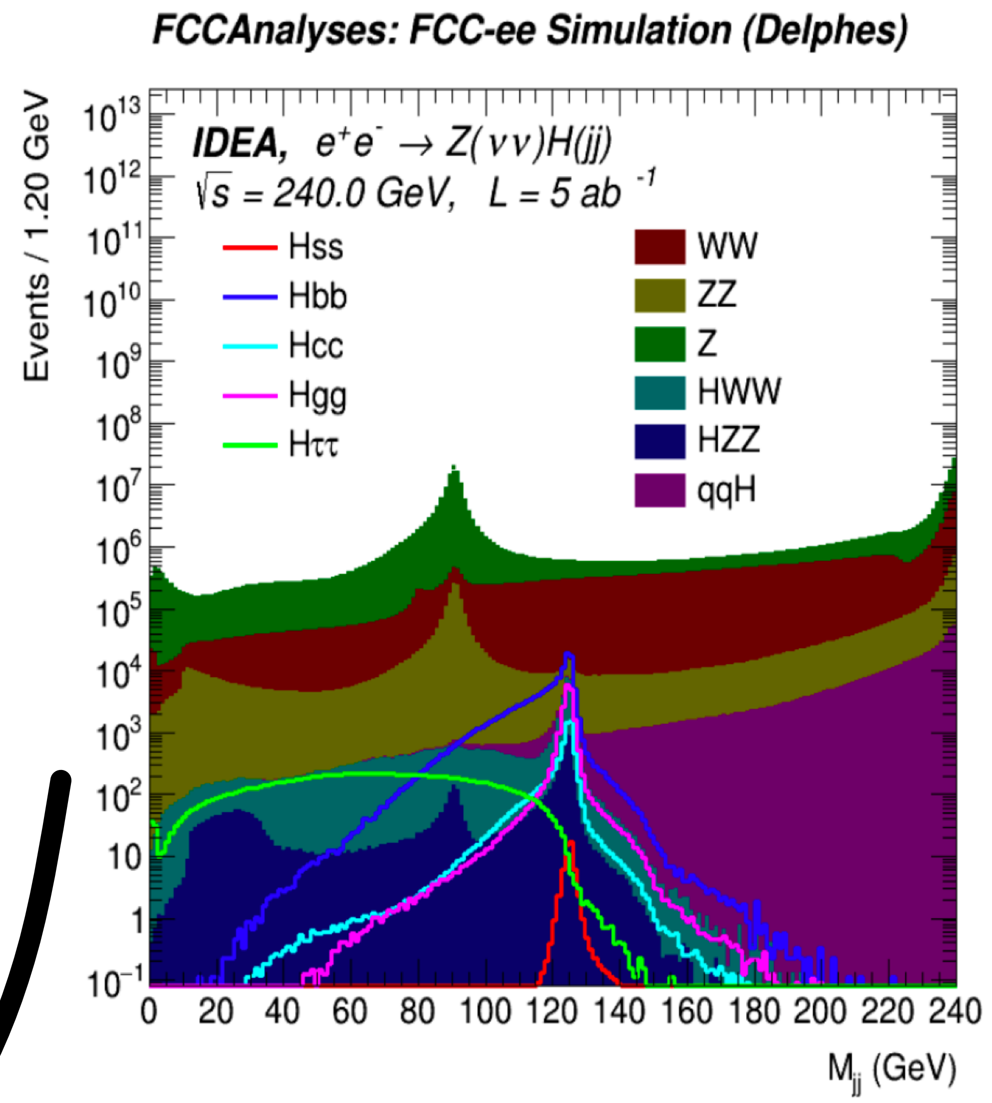
ParticleNet-ee



m(rec)



m(jj)



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

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

$*|\kappa_S|<1.9$

More on Friday: G. Marchiori

Results @ 5ab^{-1}

(syst: 5% BKG, 0.1% SIG)

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

* $|\kappa_s|<1.9$

strange Yukawa tantalisingly close to being within reach

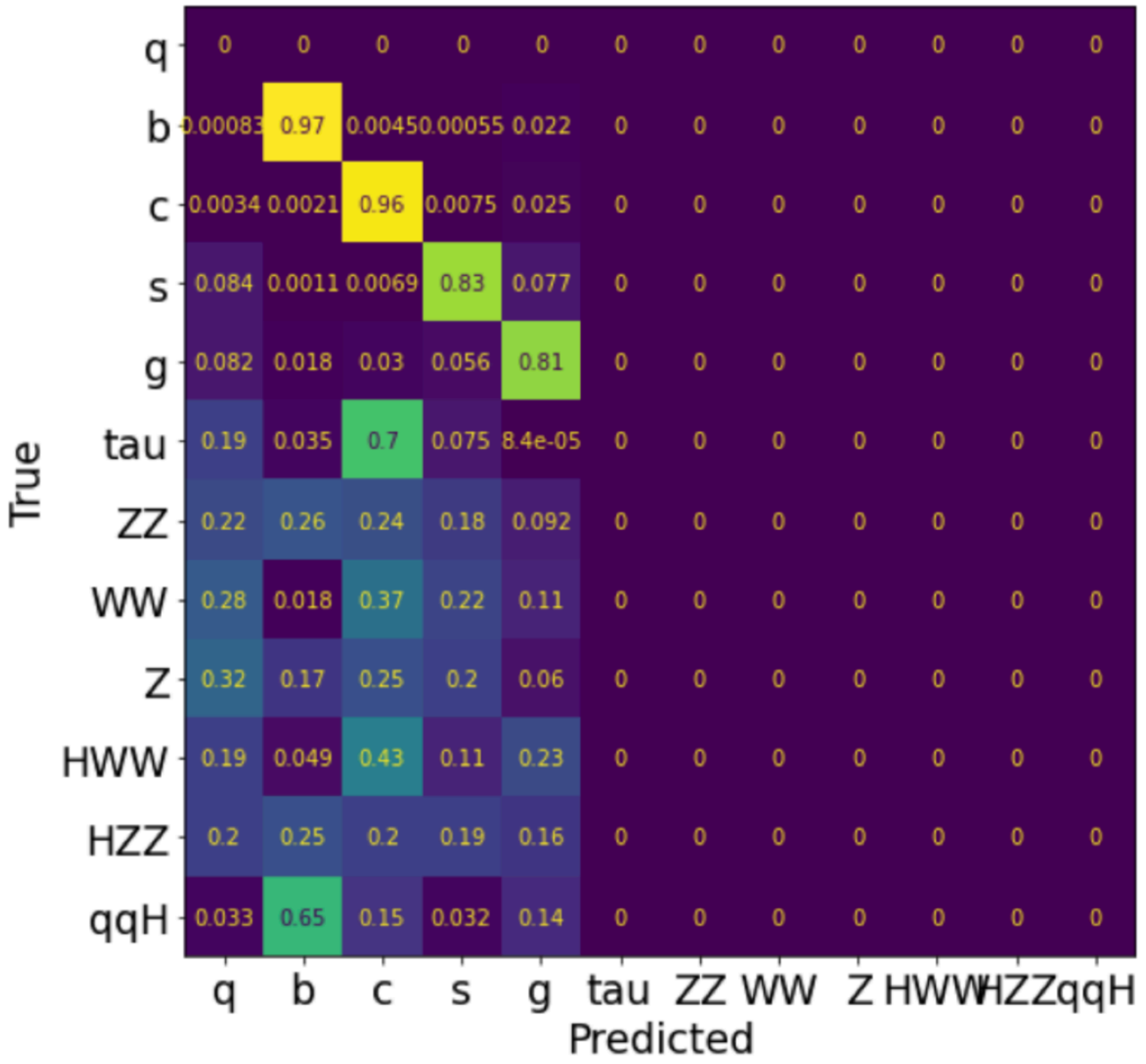
would complete 2nd generation Yukawas

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

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

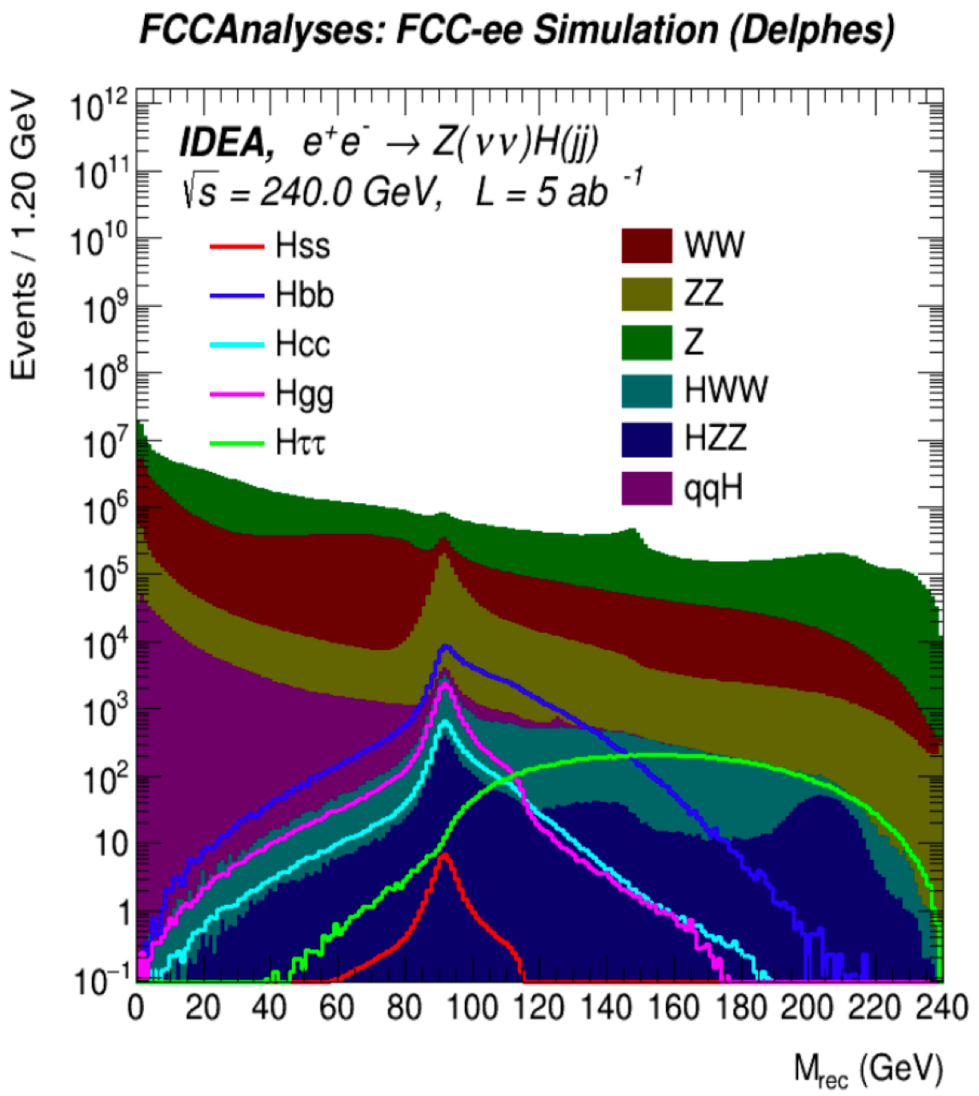
Categorize events: bb, cc, ss, gg
Sub-categories w/ different S/B

ParticleNet-ee

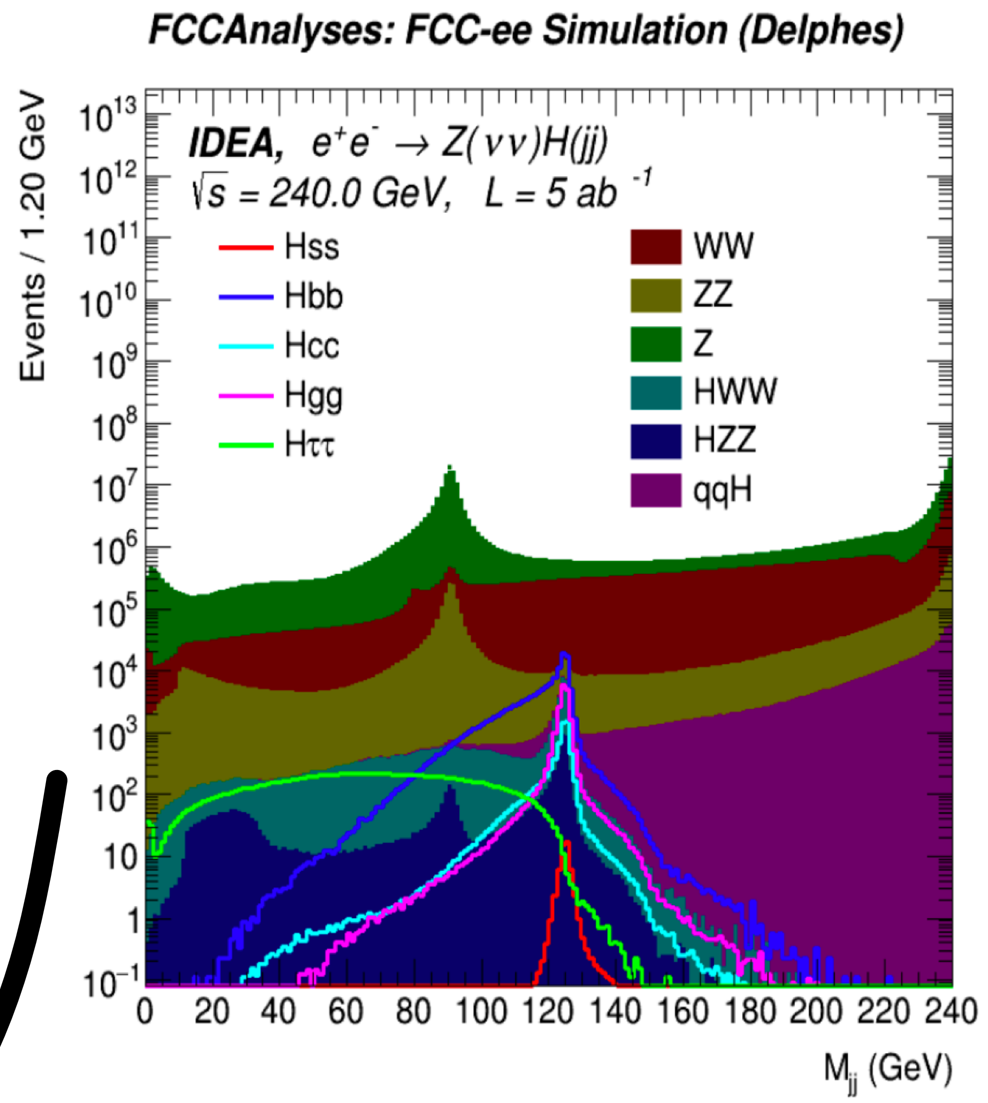


Signal extraction: 2D fit

m(rec)



m(jj)



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

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

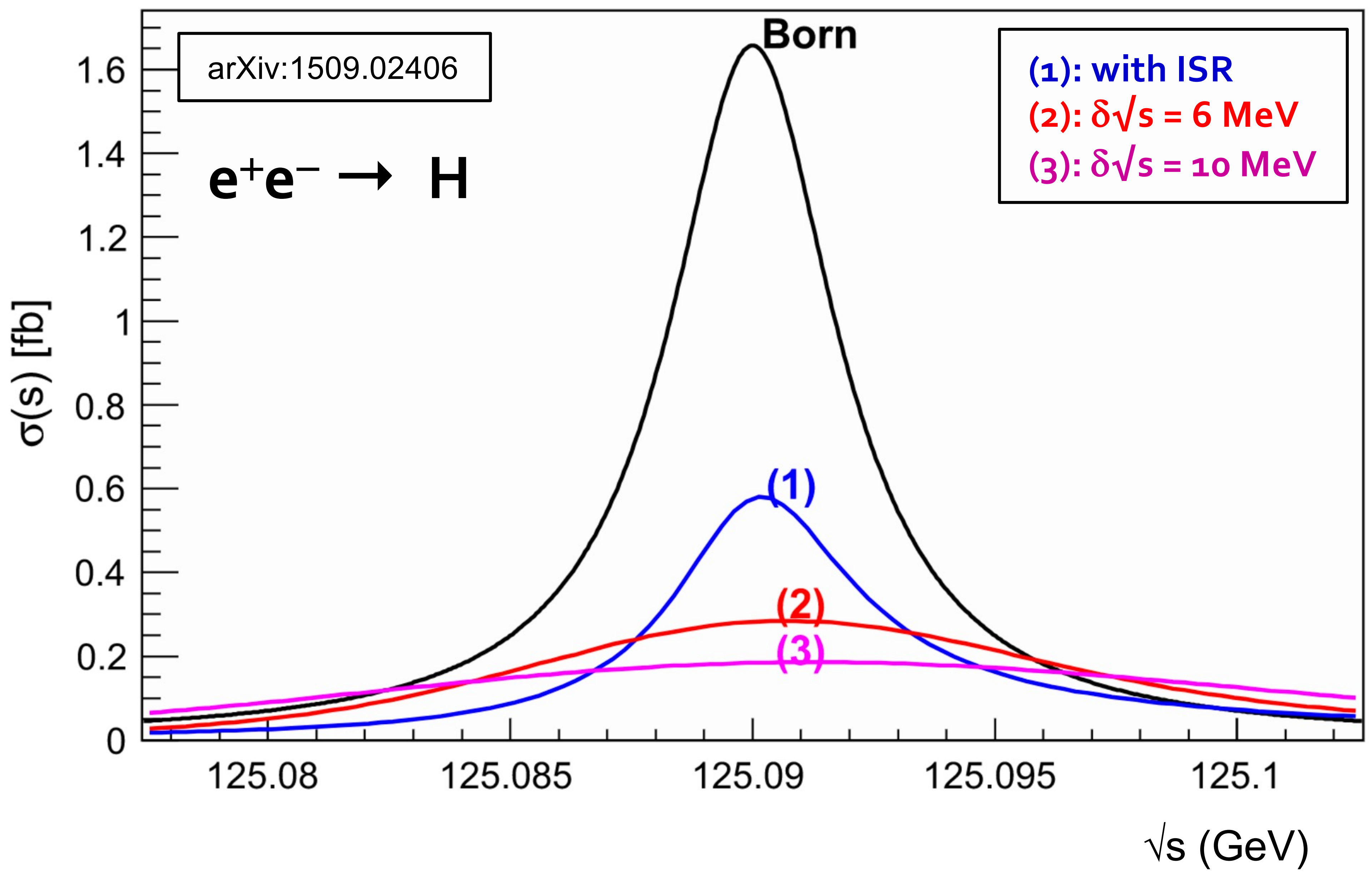
*** $|\kappa_S|<1.9$**

More on Friday: G. Marchiori

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)



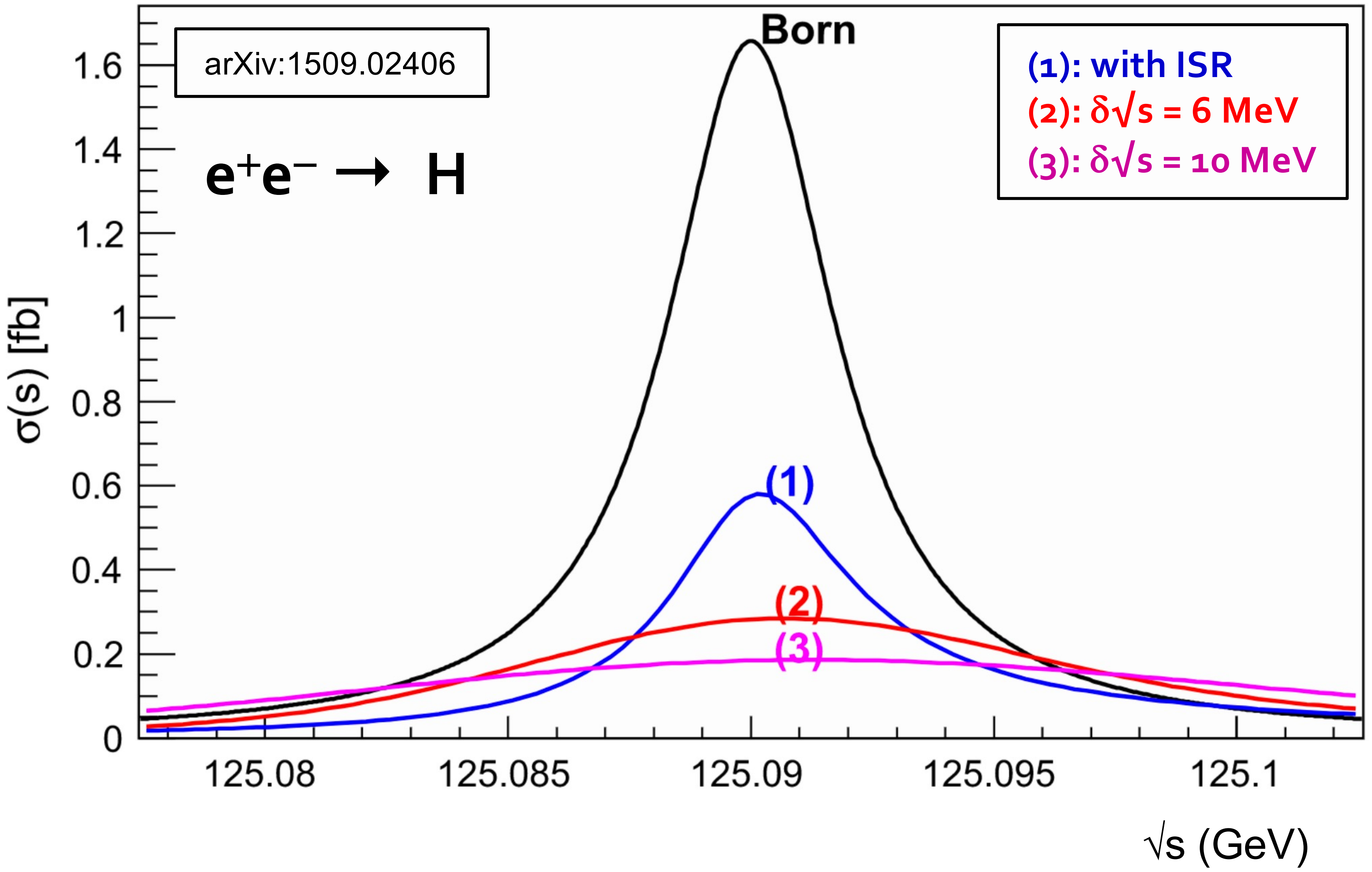
original slide from Patrick Janot

24

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



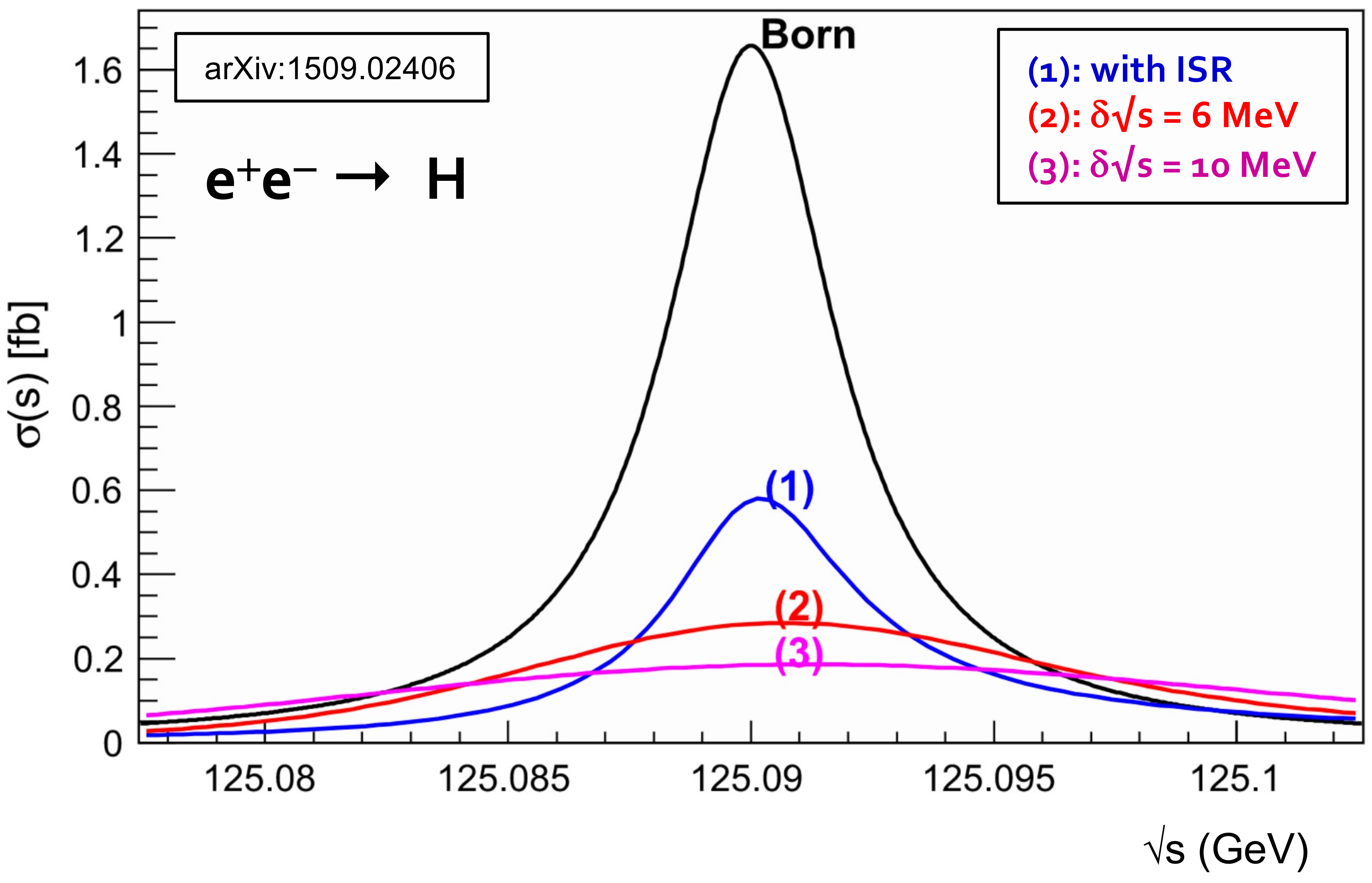
24

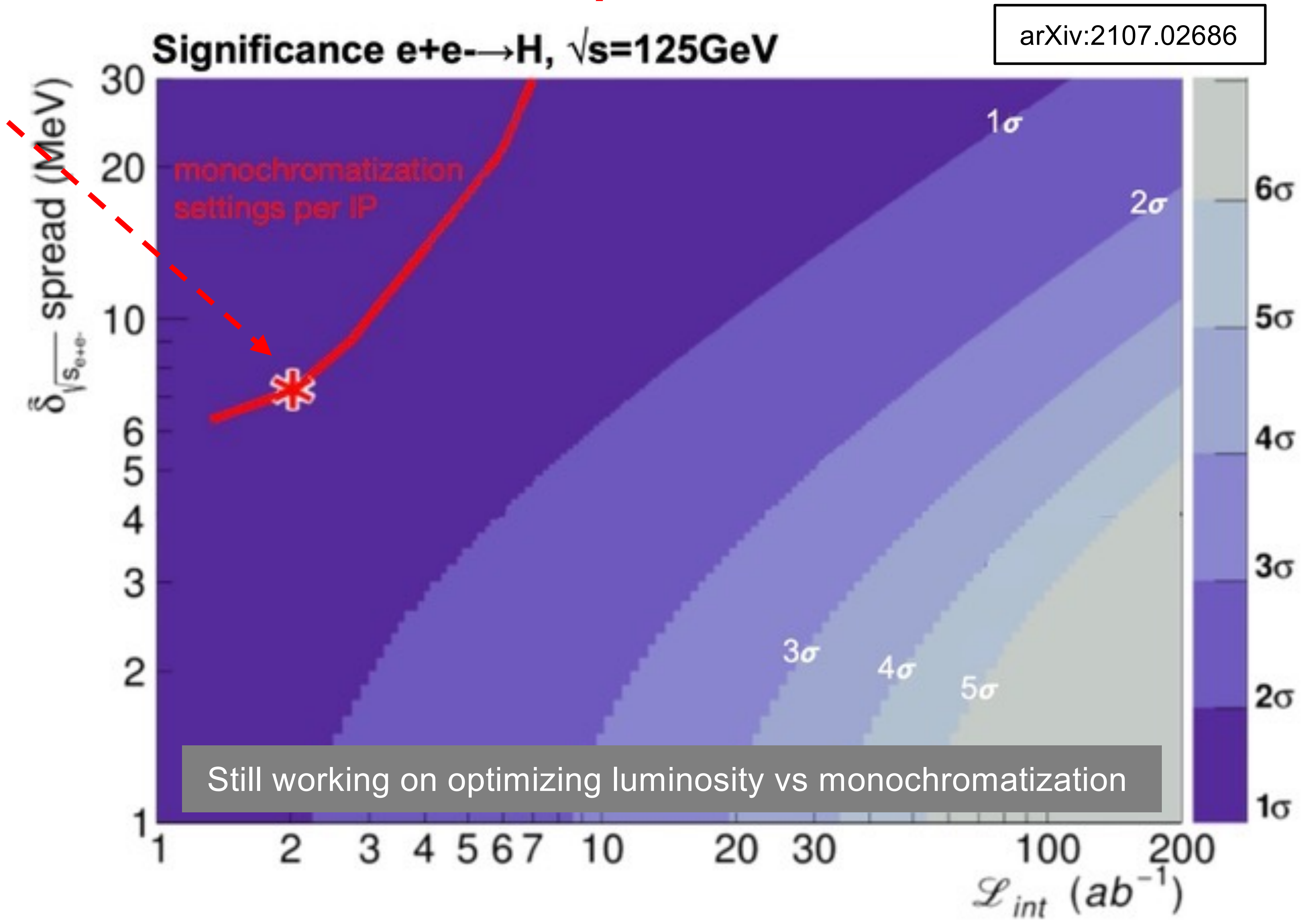
original slide from Patrick Janot

Electron Yukawa coupling: Unique @ FCC-ee

(not yet in the baseline)

- **One of the toughest challenges, which requires in particular, at $\sqrt{s}$ = 125 GeV**
  - Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s}$ = 240 GeV
  - Huge luminosity, achievable with with several years of running and possibly 4 IPs
  - $\sqrt{s}$ monochromatisation : Γ_H (4.2 MeV) ≪ natural beam energy spread (~100 MeV)
- **First studies indicate a significance of 0.4σ with one detector in one year**





24

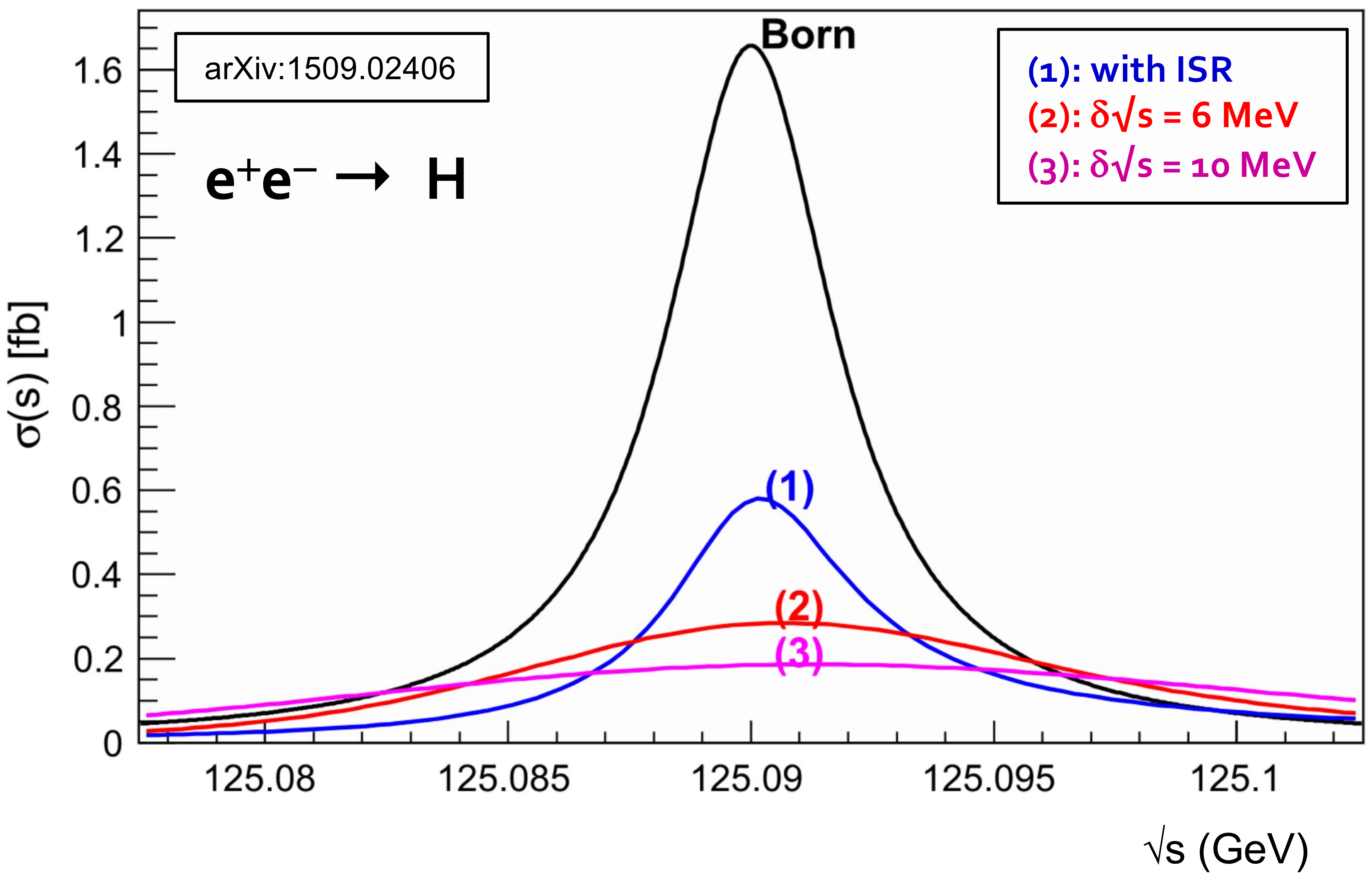
original slide from Patrick Janot

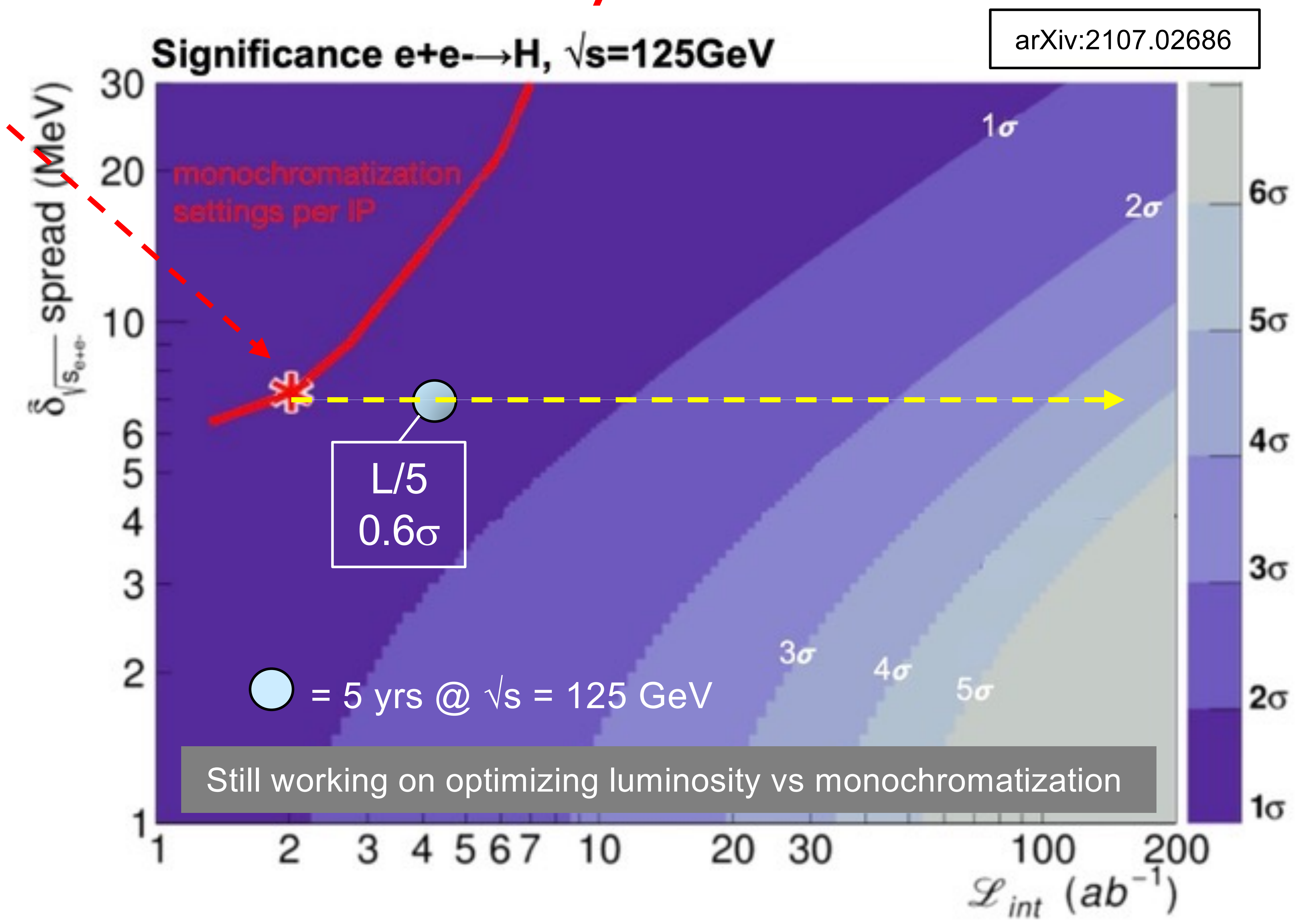
Electron Yukawa coupling: Unique @ FCC-ee

(not yet in the baseline)

original slide from Patrick Janot

- **One of the toughest challenges, which requires in particular, at $\sqrt{s}$ = 125 GeV**
  - Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s}$ = 240 GeV
  - Huge luminosity, achievable with with several years of running and possibly 4 IPs
  - $\sqrt{s}$ monochromatisation : Γ_H (4.2 MeV) ≪ natural beam energy spread (~100 MeV)
- **First studies indicate a significance of 0.4σ with one detector in one year**



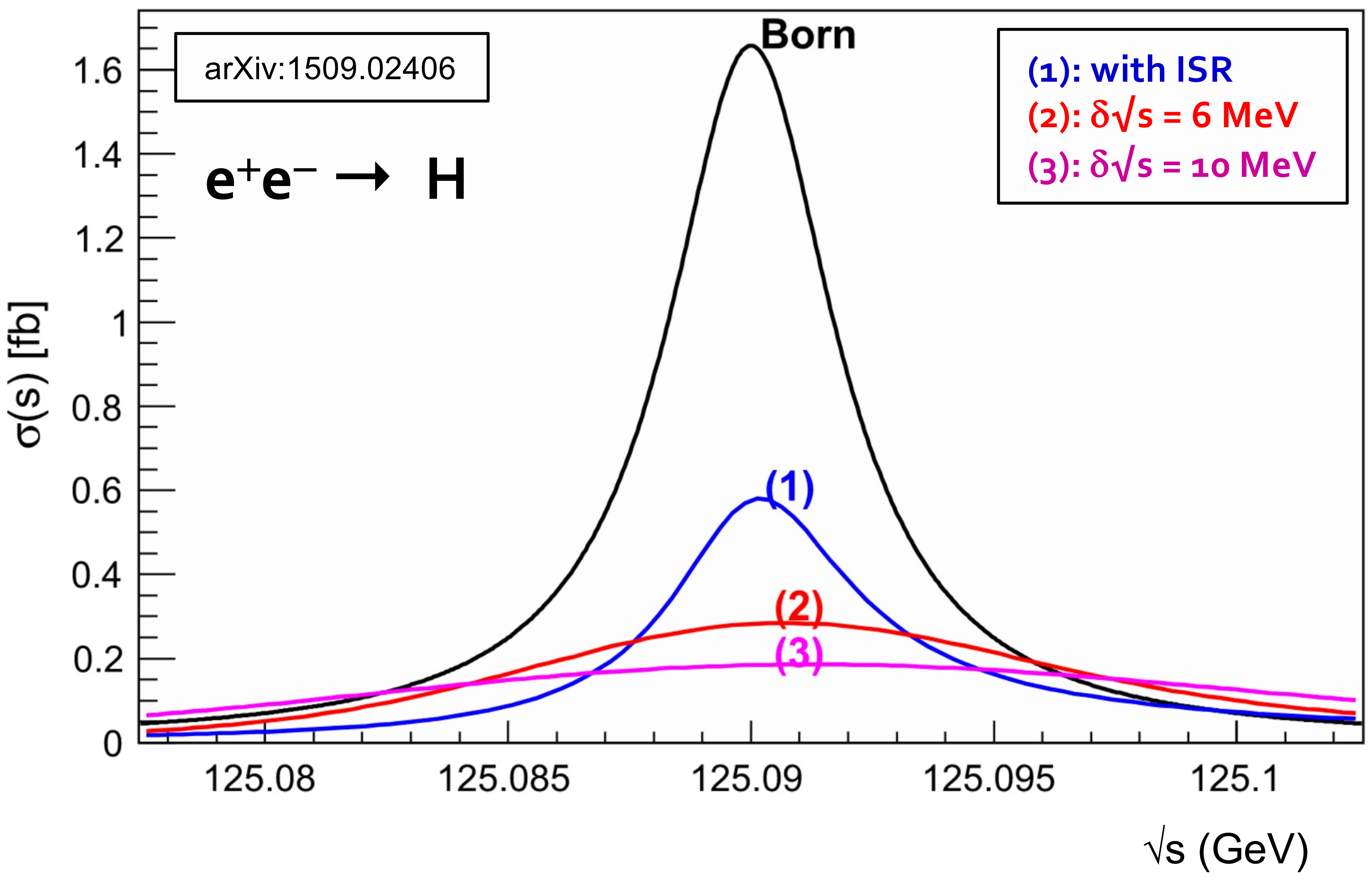


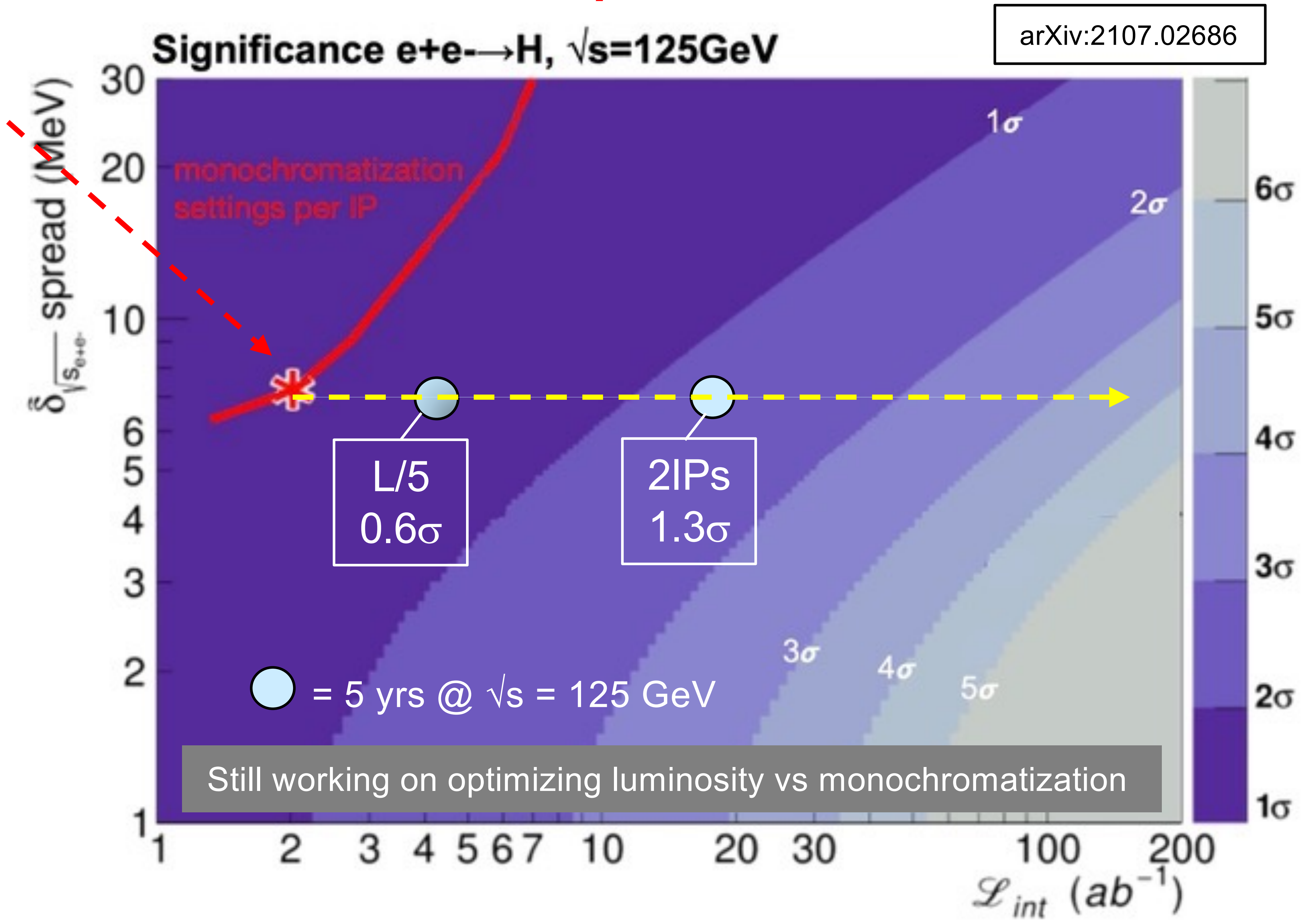
Electron Yukawa coupling: Unique @ FCC-ee

(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)

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





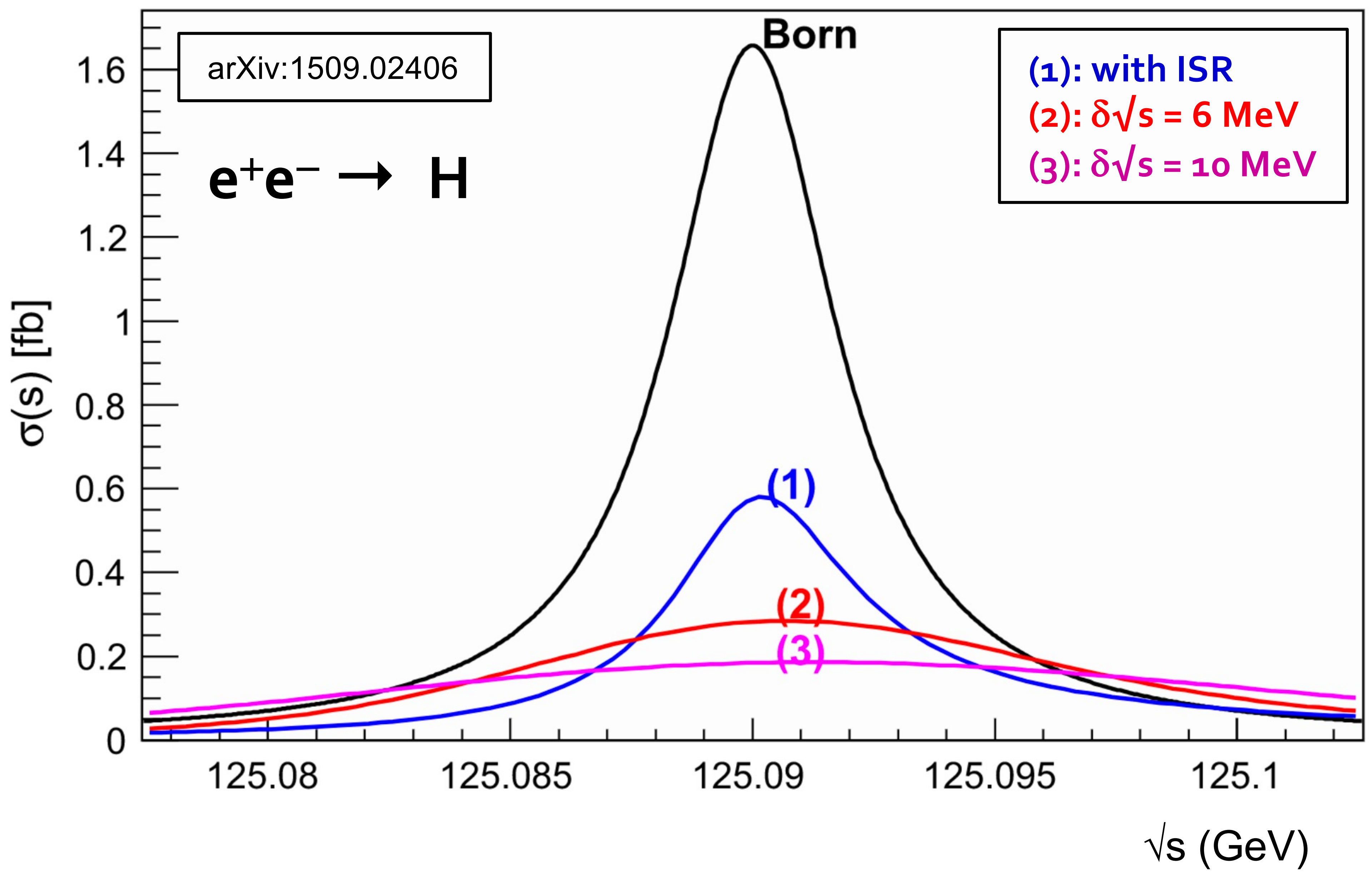
original slide from Patrick Janot

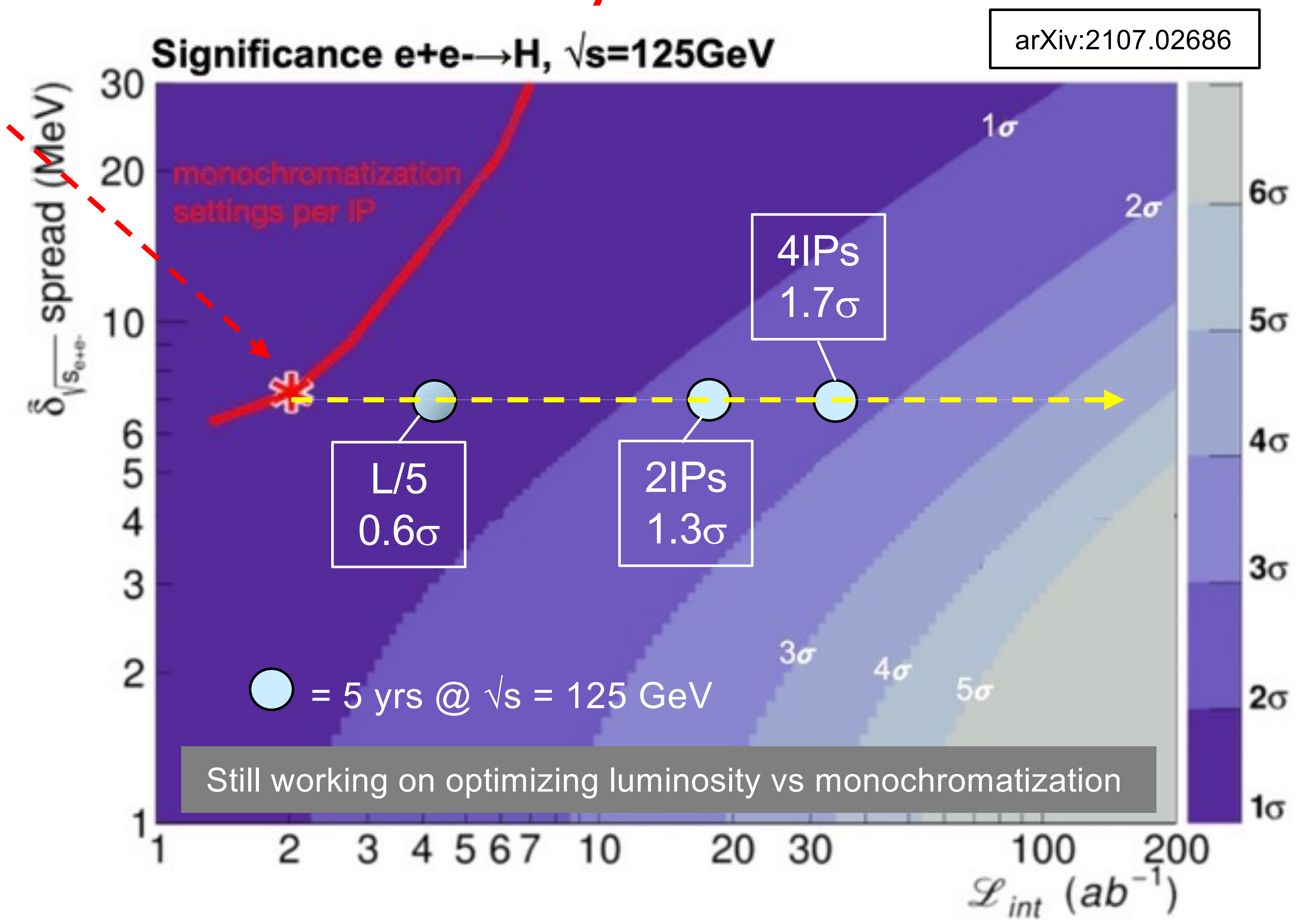
24

Electron Yukawa coupling: Unique @ FCC-ee

(not yet in the baseline)

- **One of the toughest challenges, which requires in particular, at $\sqrt{s}$ = 125 GeV**
  - Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s}$ = 240 GeV
  - Huge luminosity, achievable with with several years of running and possibly 4 IPs
  - $\sqrt{s}$ monochromatisation : Γ_H (4.2 MeV) ≪ natural beam energy spread (~100 MeV)
- **First studies indicate a significance of 0.4σ with one detector in one year**





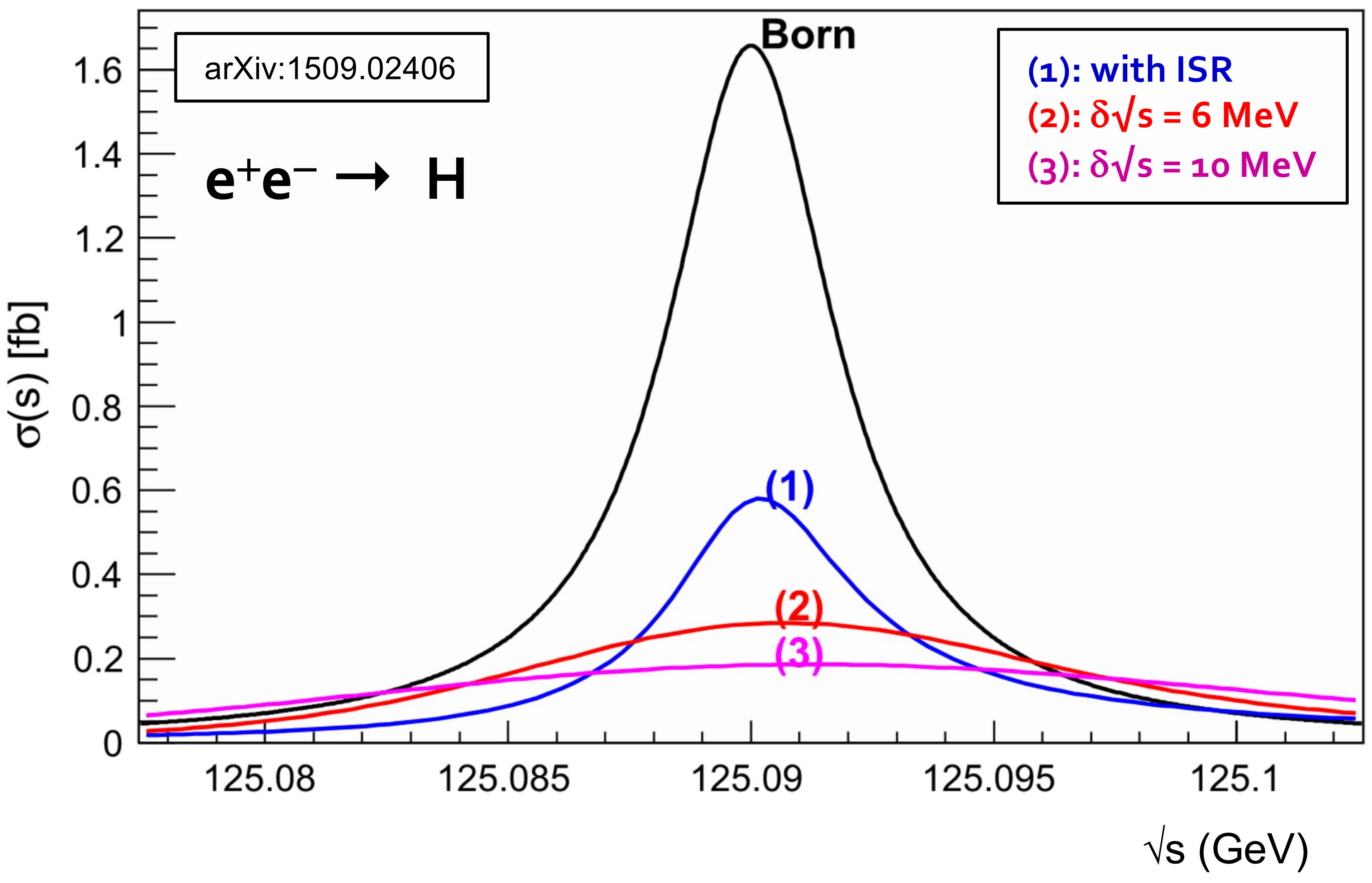
24

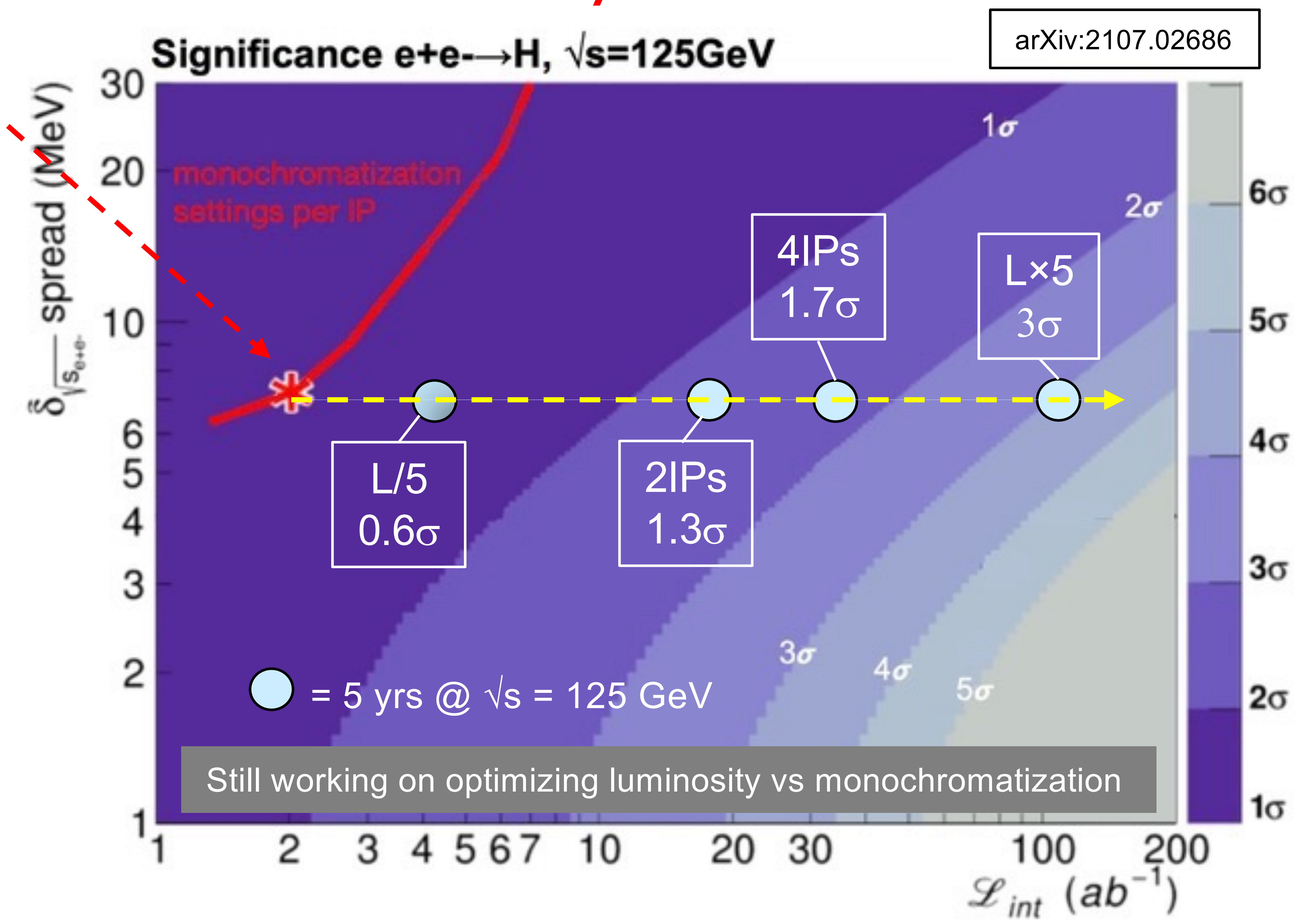
original slide from Patrick Janot

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





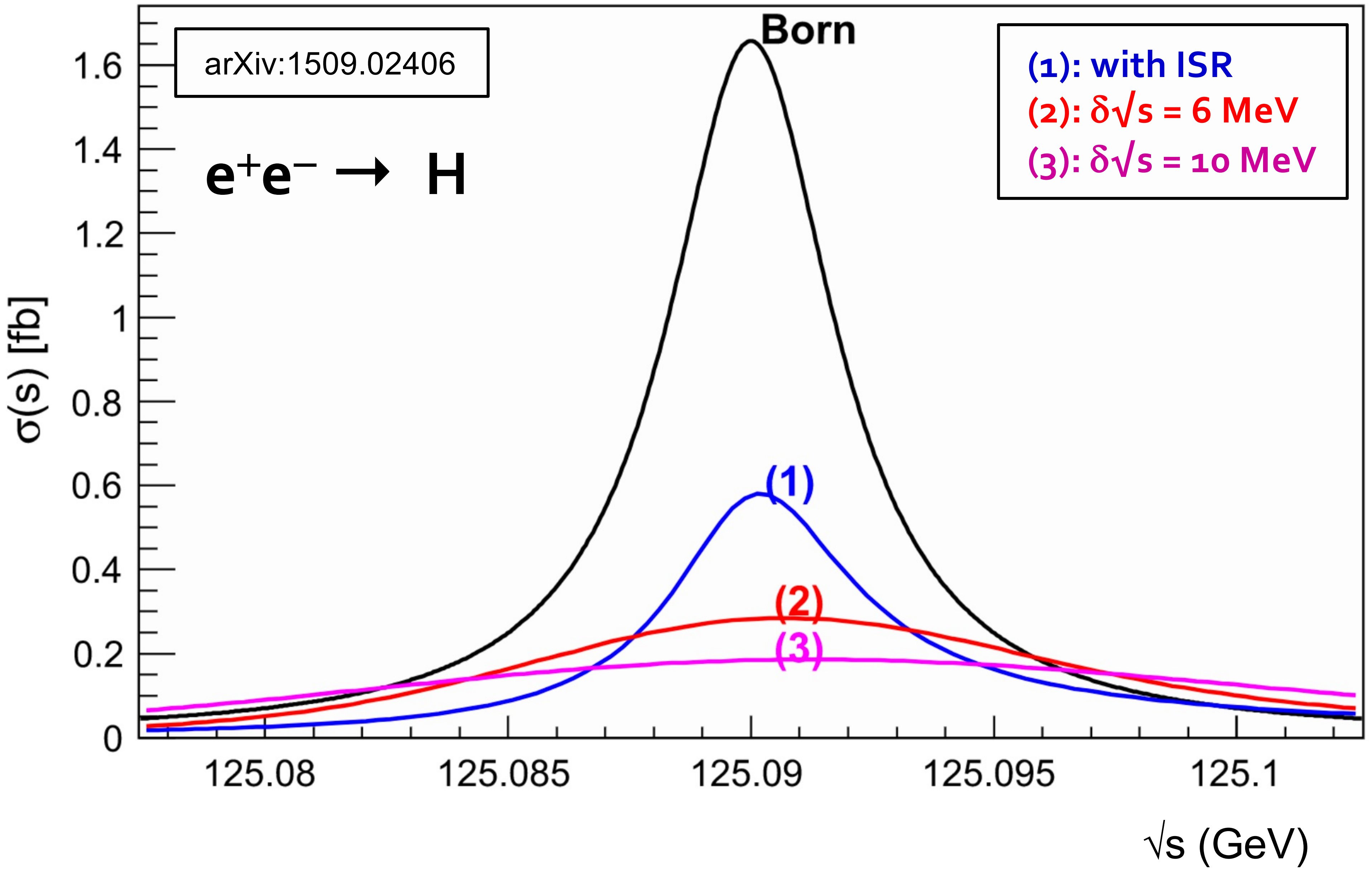
24

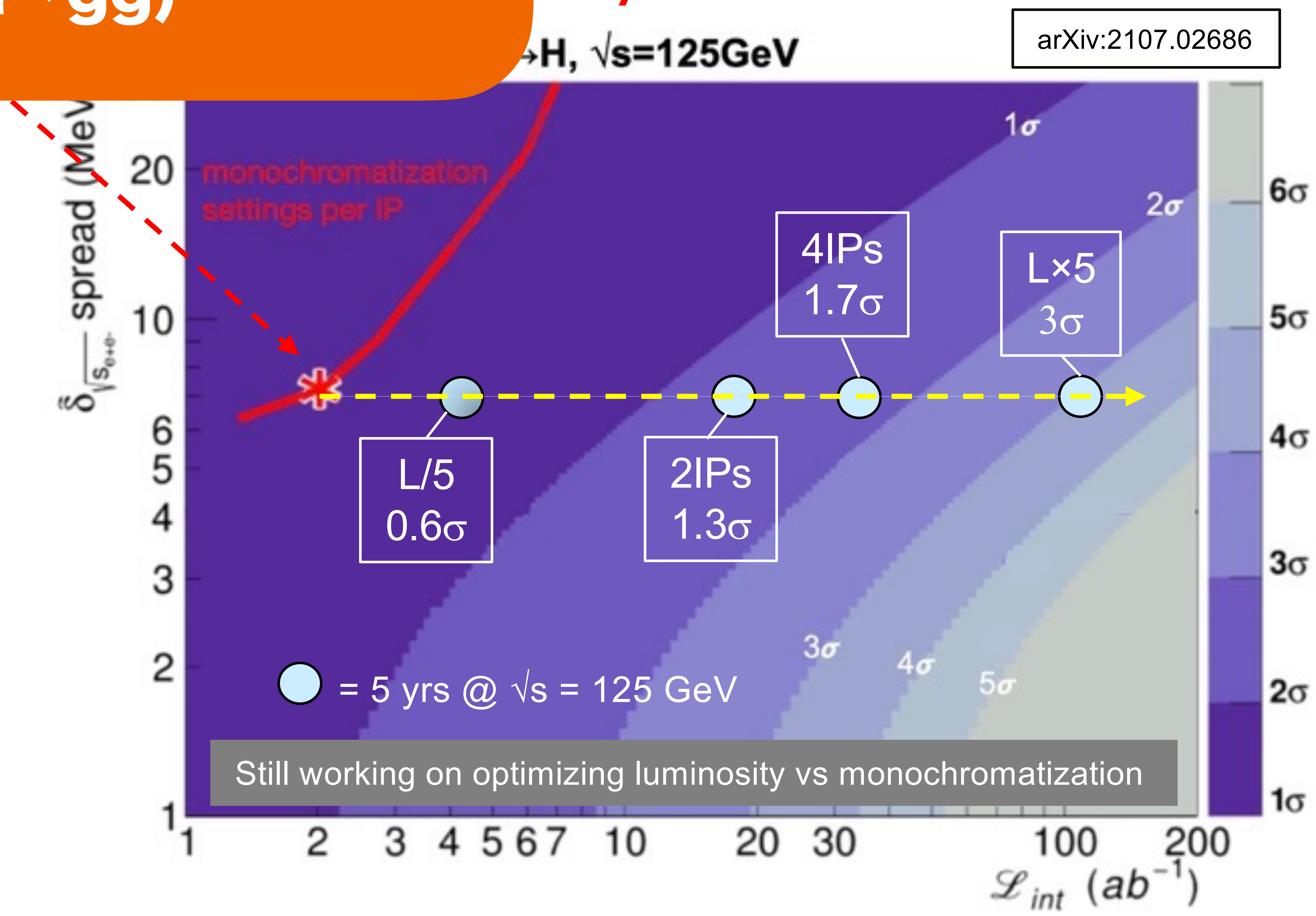
original slide from Patrick Janot

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
  - … possibly 4 IPs
  - … d (~100 MeV)
- … ne year

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





24

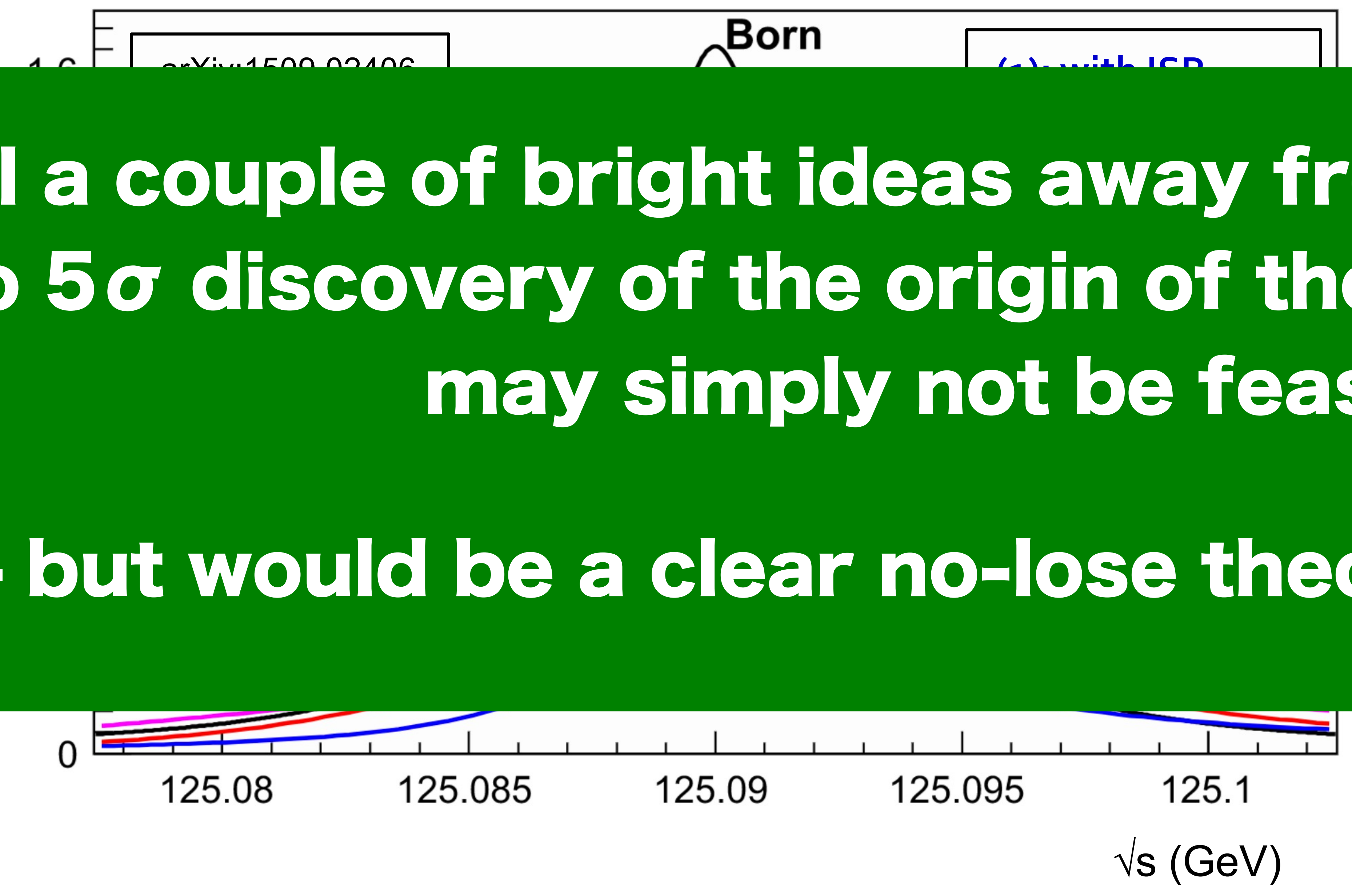
original slide from Patrick Janot

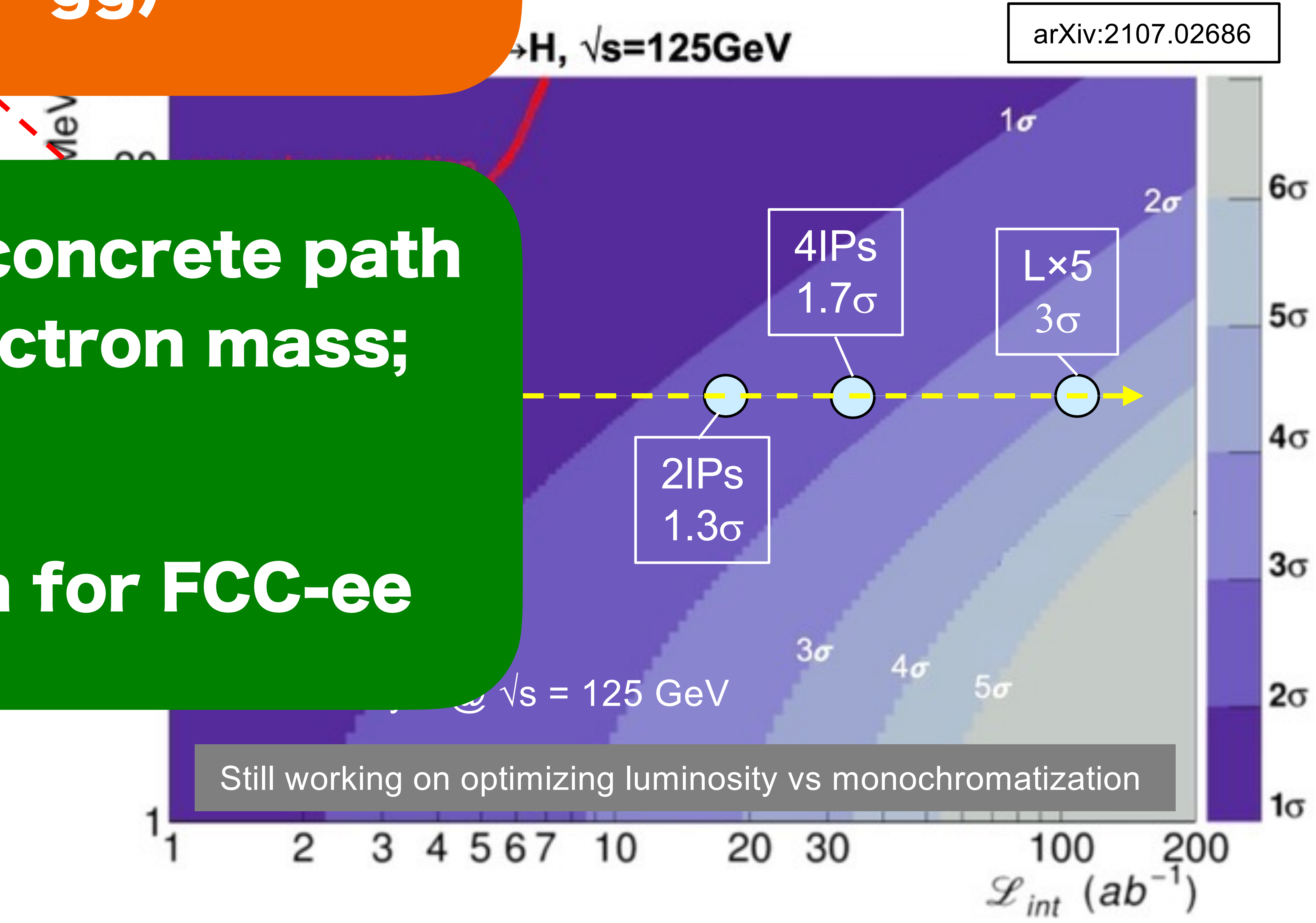
Electron Yukawa coupling: Unique @ FCC-ee

(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
  - …d possibly 4 IPs
  - …d (~100 MeV)
- …ne year

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





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

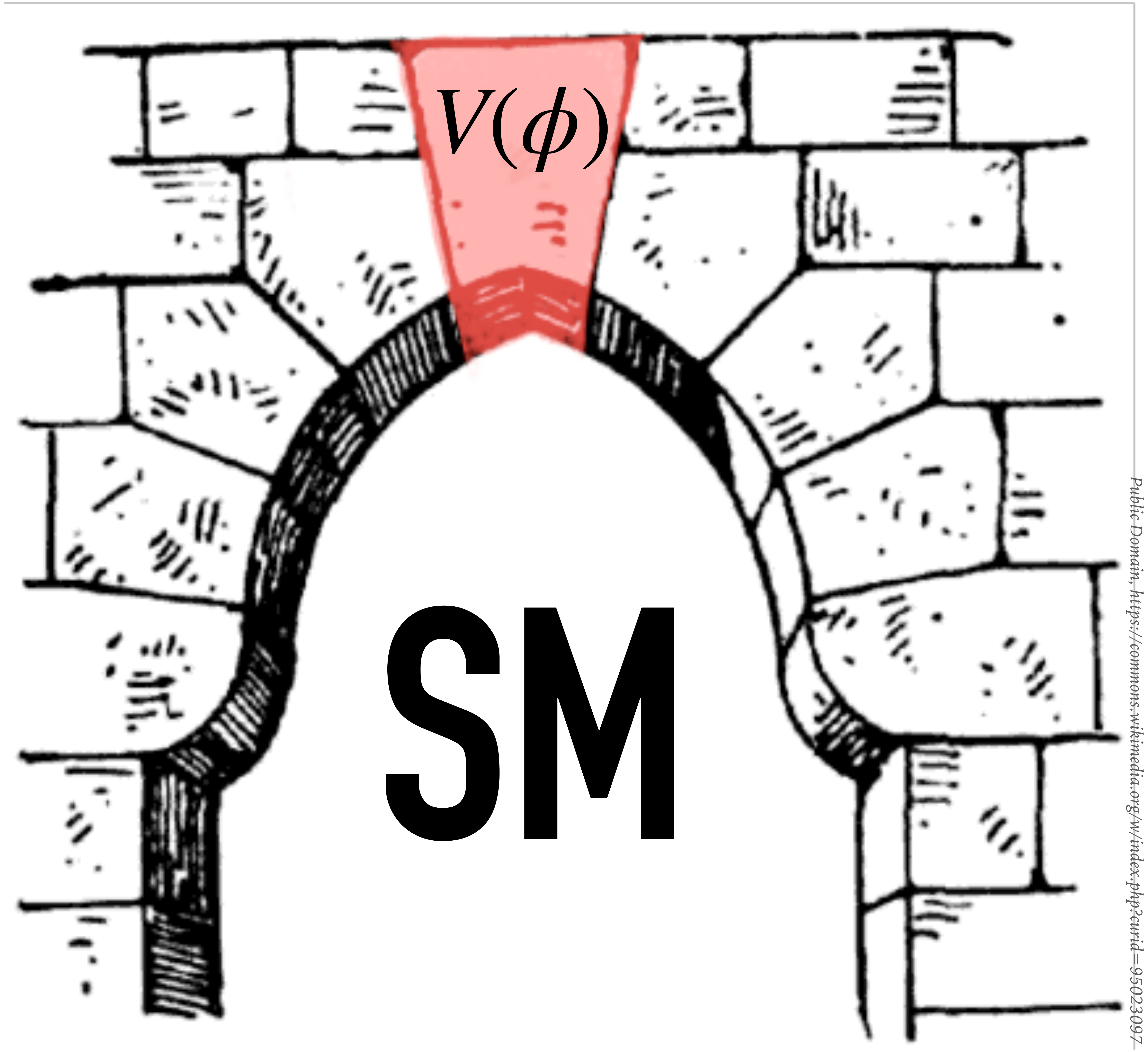
— but would be a clear no-lose theorem for FCC-ee

24

original slide from Patrick Janot

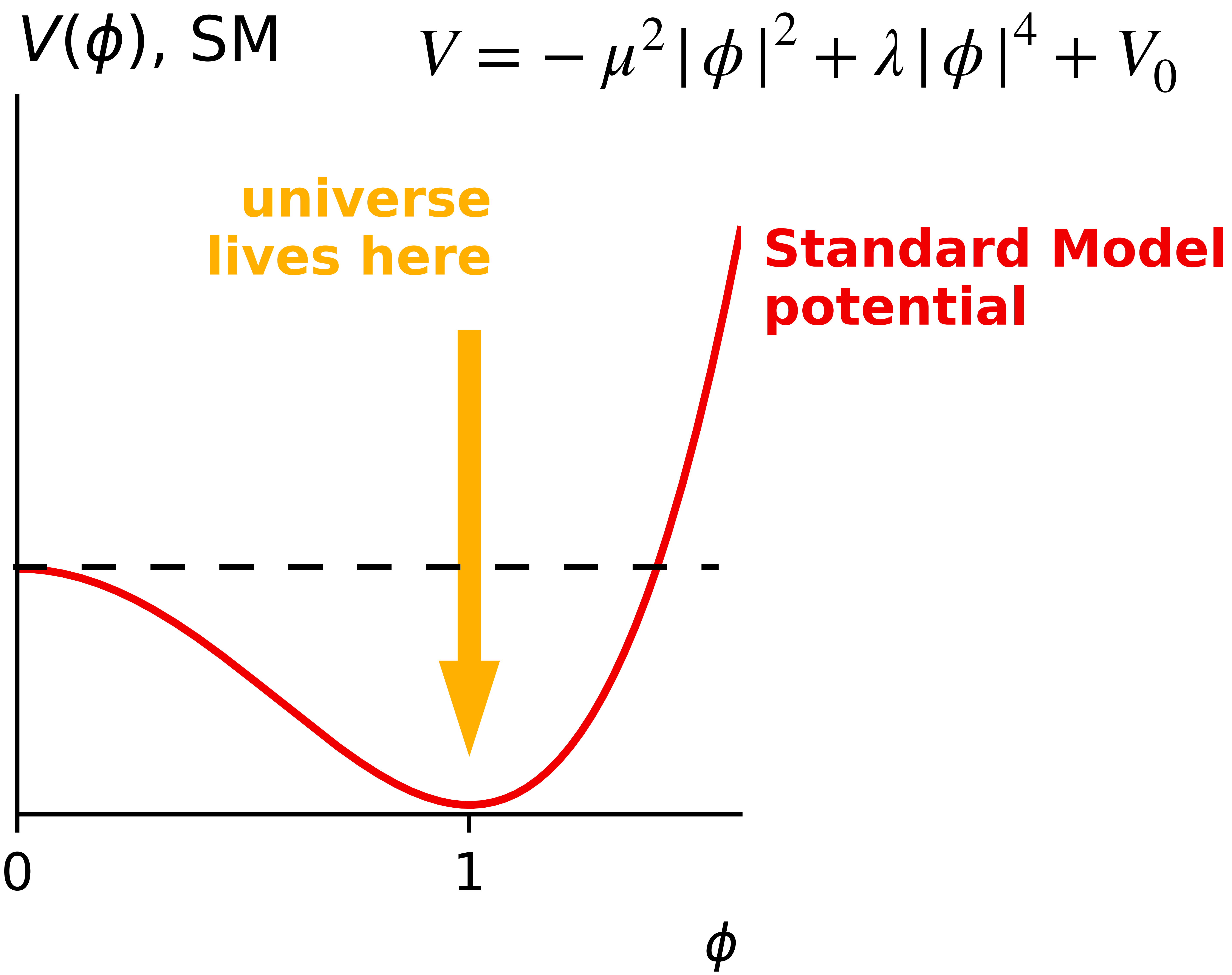
A side comment on the near future at LHC

- 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**



the Higgs potential

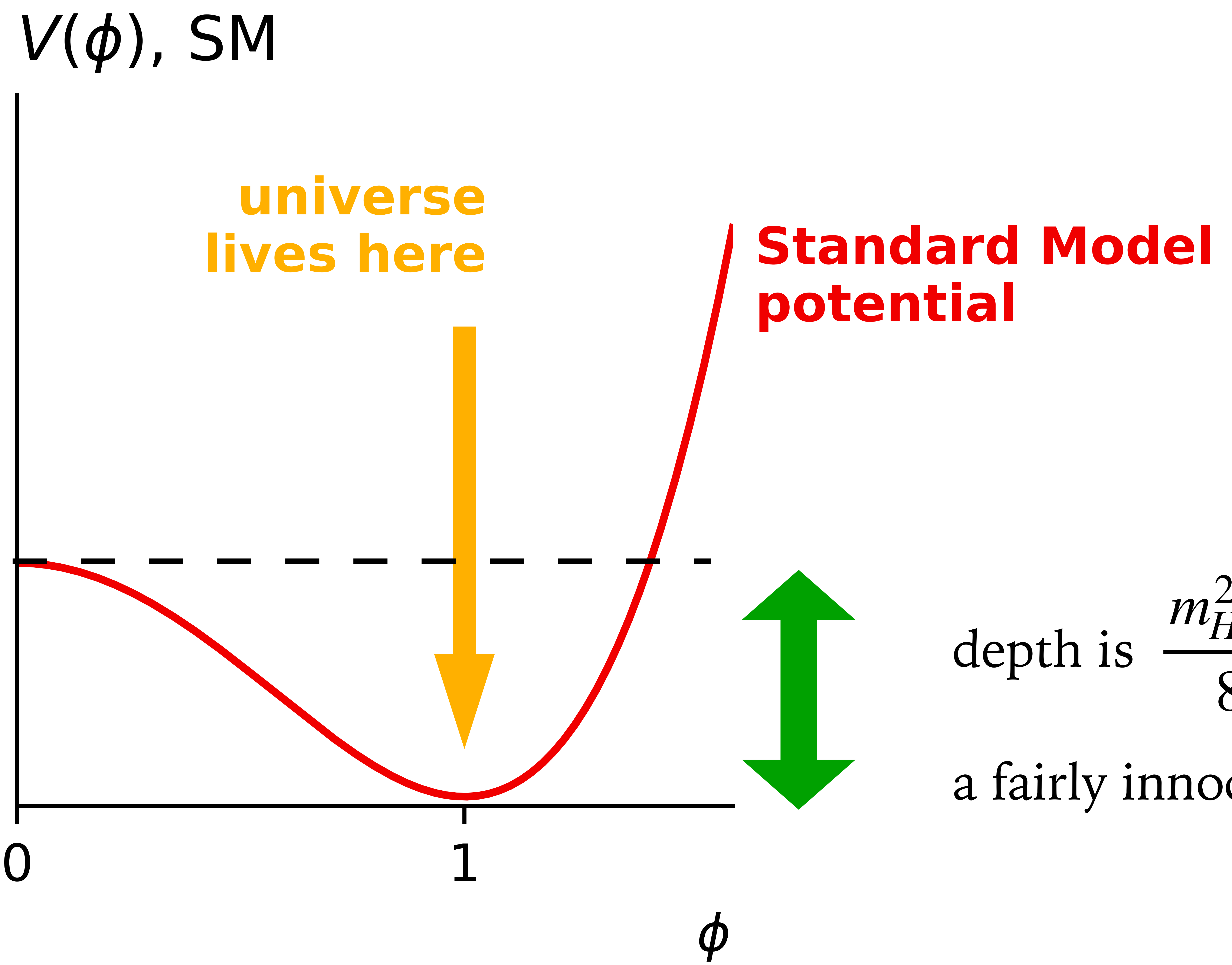
Higgs potential



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

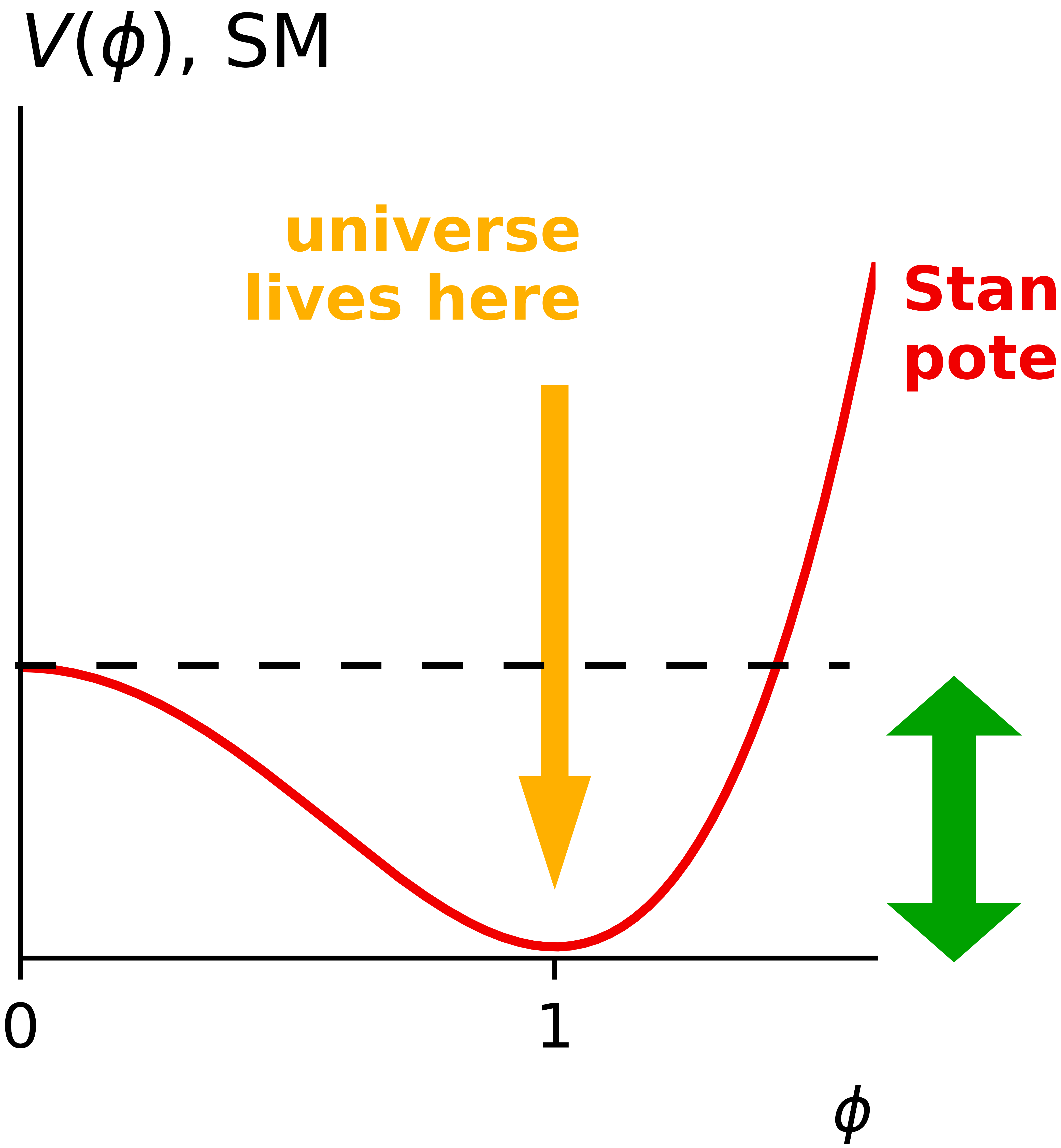
Higgs potential



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
1.5×10^{10} GeV/fm^3
i.e. >**40 billion times nuclear density**

Mass density of 2.6×10^{28} kg/m^3

https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg
https://en.wikipedia.org/wiki/File:Arena,_Ajax_stadion,_Amsterdam.JPG

Earth at neutron star density

https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg
https://en.wikipedia.org/wiki/File:Arena,_Ajax_stadion,_Amsterdam.JPG

Earth at neutron star density

Earth at Higgs potential density

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

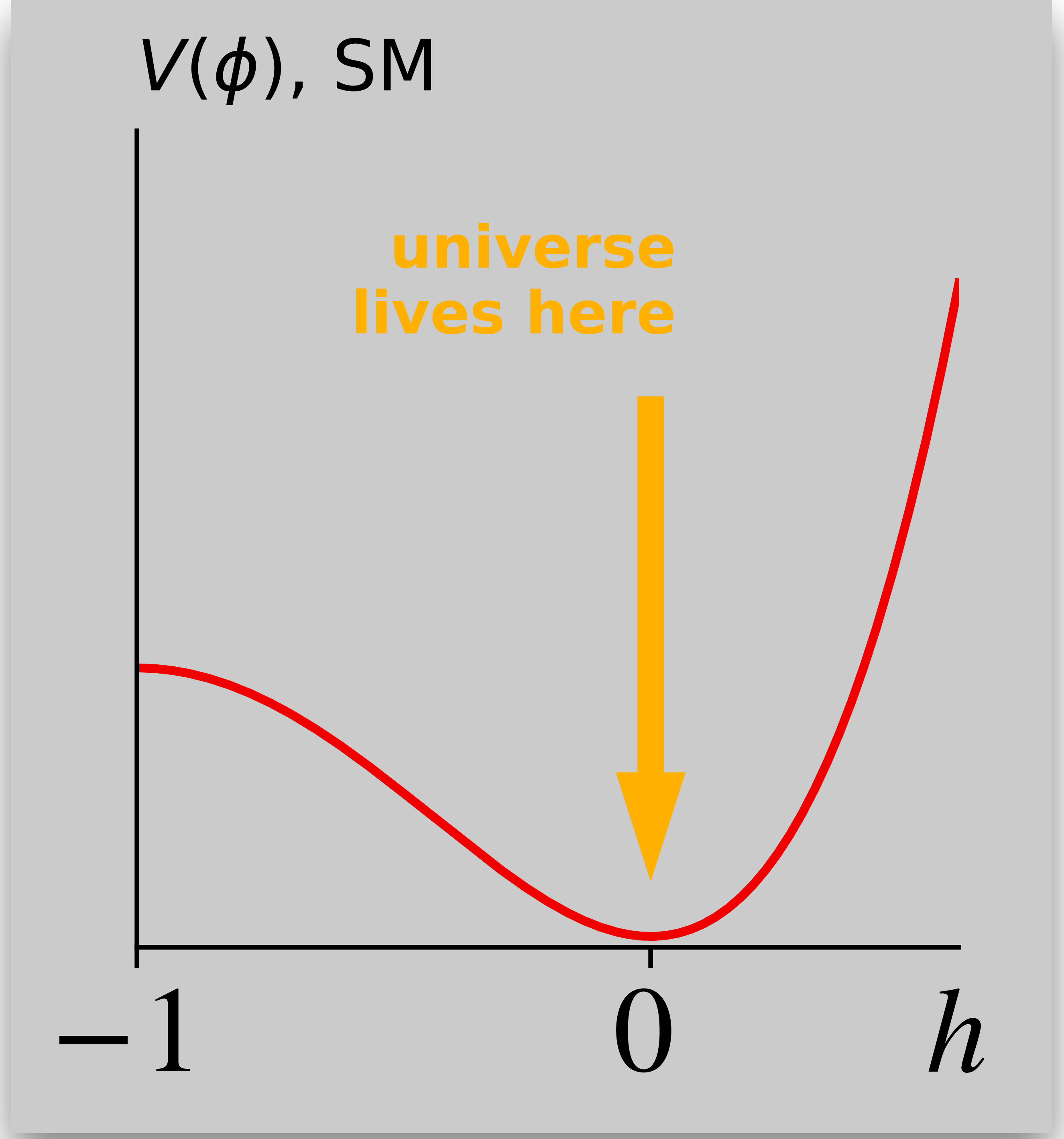
The potential expanded around the minimum

- 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

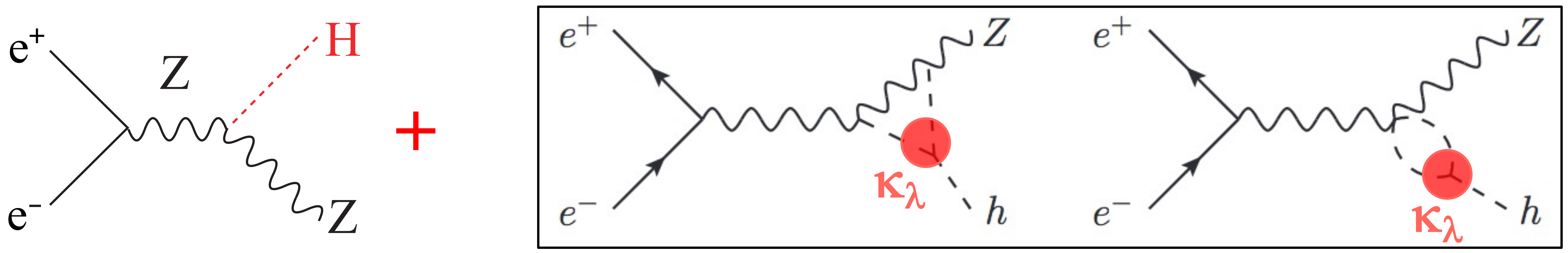
prediction of the strength of HHH interaction
[modifier may be called κ_λ or κ_3]

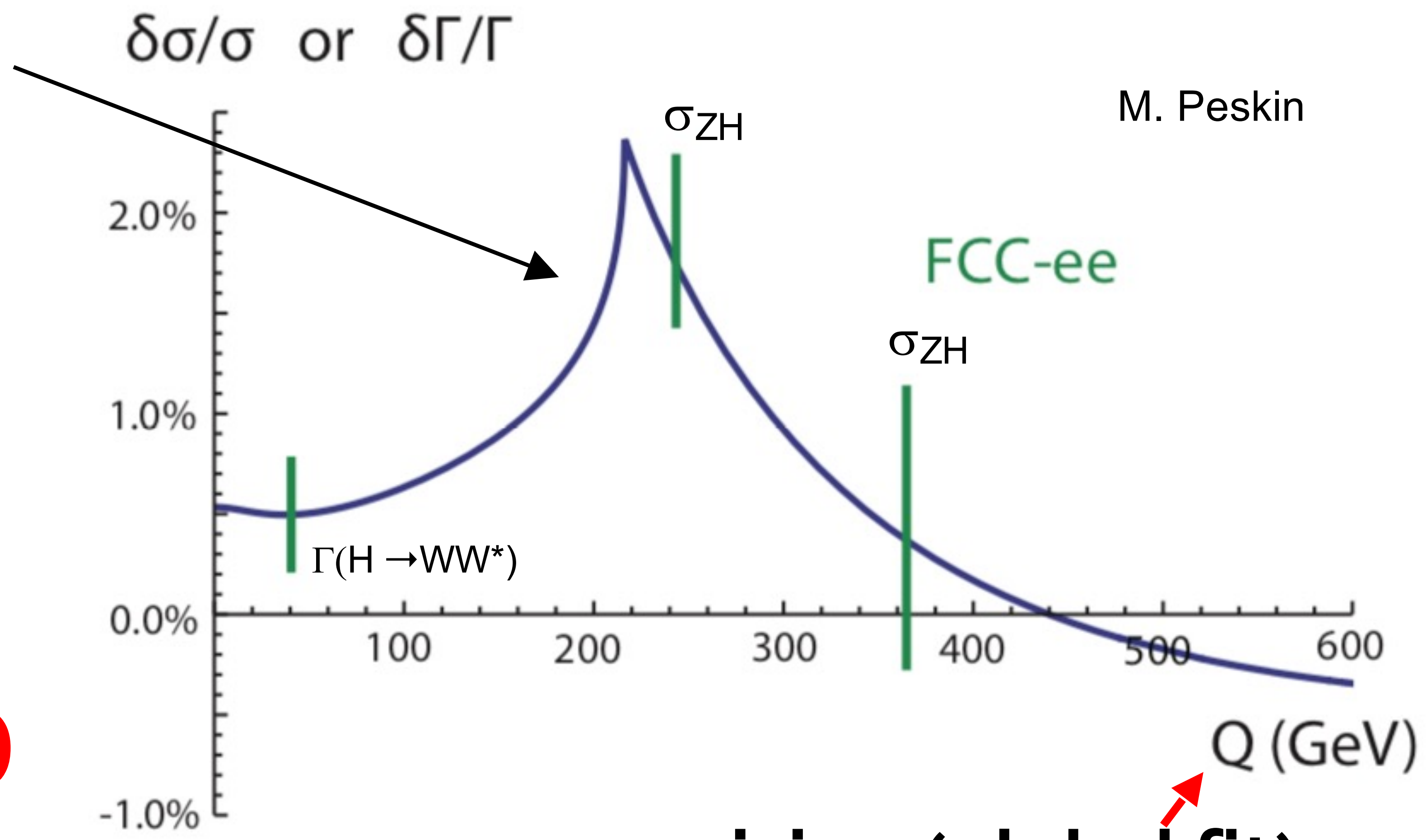


[slide from P. Janot]

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

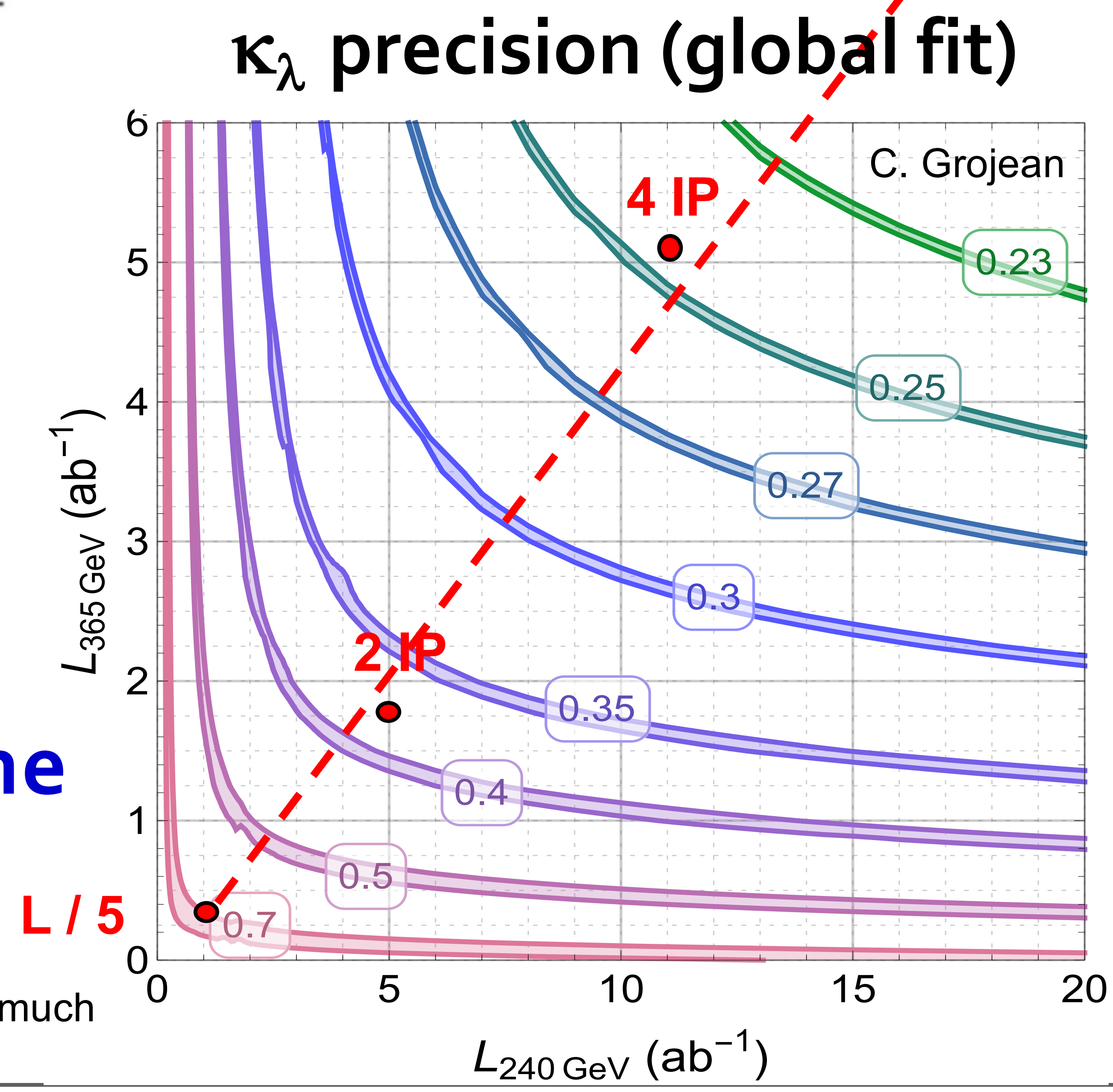




- **Estimate with present run plan and 2 IPs: ≥ 2σ from $\kappa_\lambda = 0$**
  - Analyses will improve, but no hope with 5 times less luminosity

(Discovery)

- **With 4 IPs and optimization of run plan: target ≥ 5σ, $\delta\kappa_\lambda \sim 20\%$**
  - 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 …

22


g
g
H
c_3
H
H
luon
gluo
φ
y
x
Higgs field in space


g
g
H
c3
H
H
luon
gluo
Φ
y
x
Higgs field in space


g
g
H
c_3
H
H
luon
gluo
Φ
y
x
Higgs field in space

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

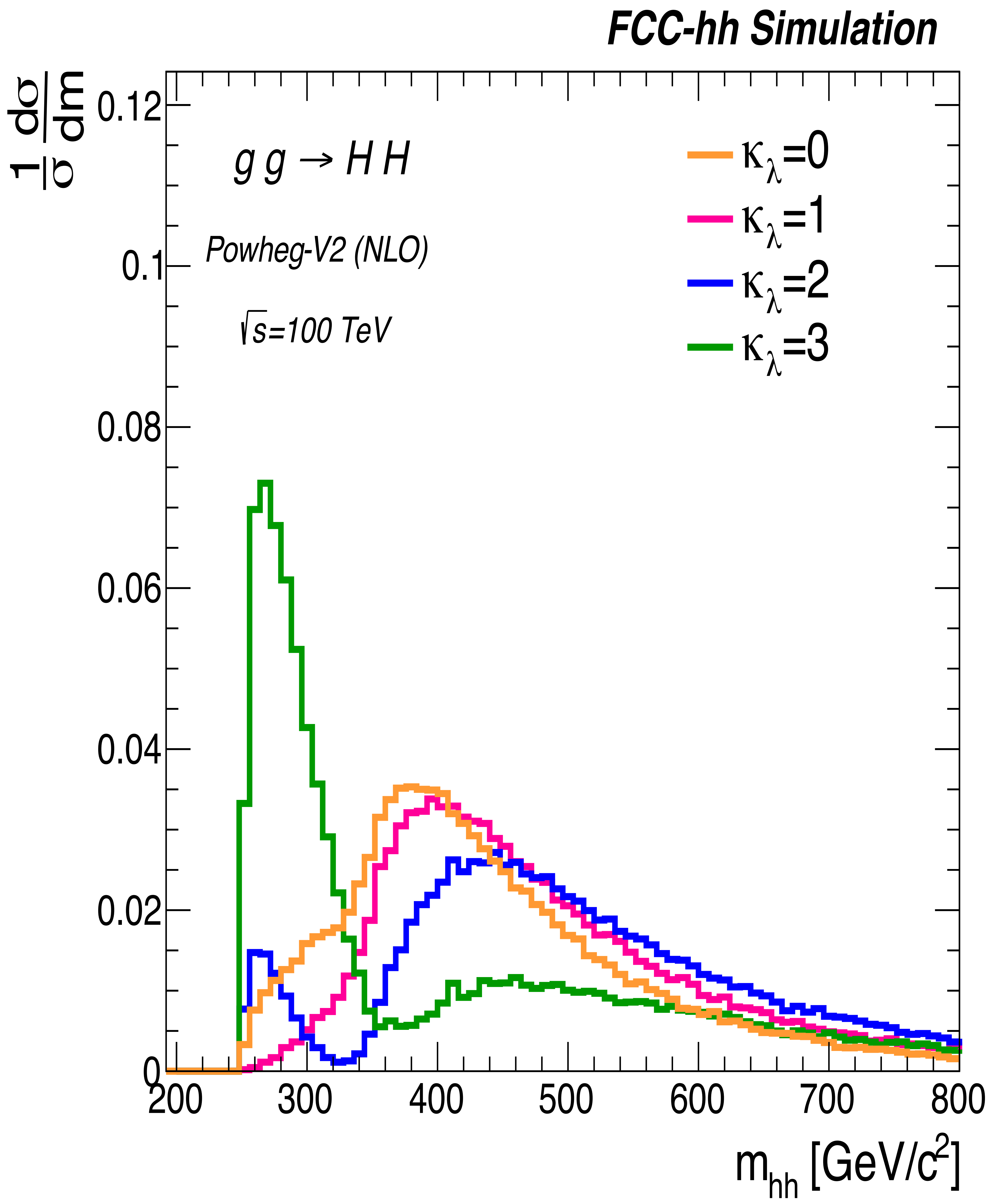
- kinematic shape of HH pair clearly distinguishes independent HH production from correlated HH
- FCC-hh → few % determination
  (needs accurate $t\bar{t}Z$ and Higgs couplings from FCC-ee)

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]

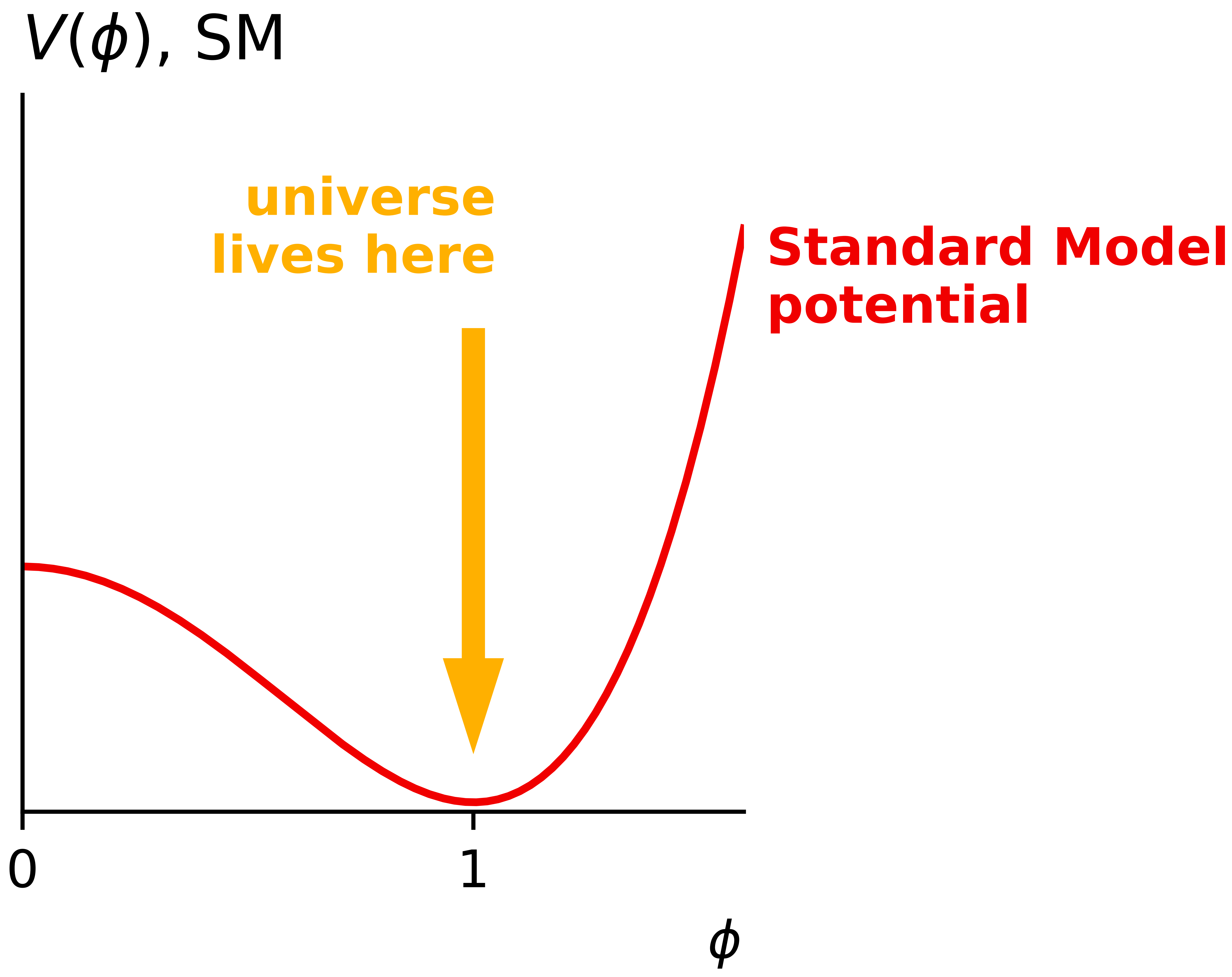
- equivalent for an interaction is a bit ambiguous — but better than ±20% determination is probably a reasonable target
- for something of this importance, we may be wary of relying on 20% only from a combination of N experiments — a result's robustness comes from confirmation by independent experiments
- 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

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, we may be … from a combination of N experiments – … ation by independent experim…
- ➤ indirec…
  - ➤ all me… …ure hadrons and leptons…)
  - ➤ single … …ve
  - ➤ but HH & kinematic structure brings assurance that what we are seeing is indeed HHH coupling
- ➤ NB there exist different points of view on this

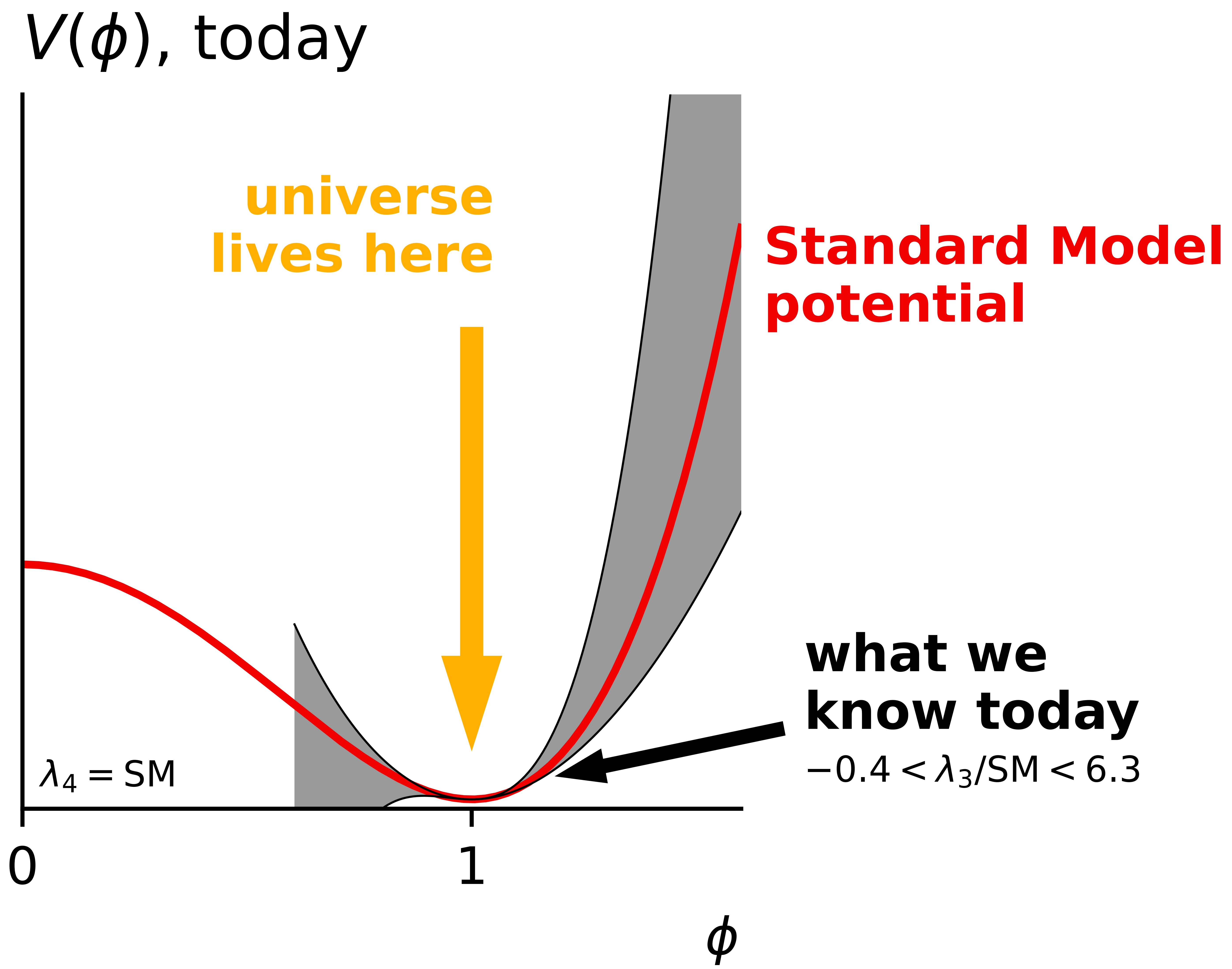
observation of HHH interaction is a "guaranteed discovery" that HEP should be aiming for

Higgs potential



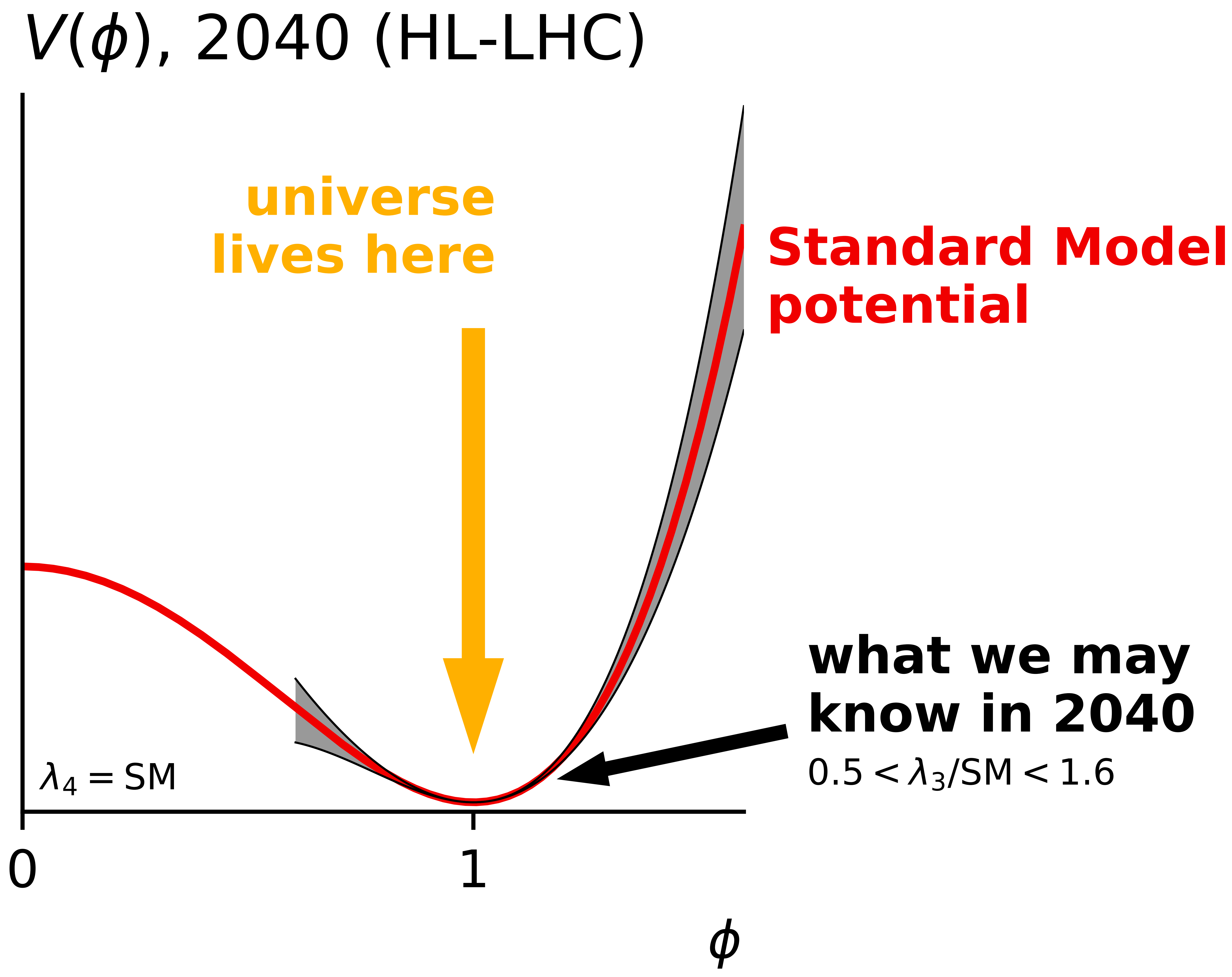
- this is a cartoon
- caution needed: e.g. realistic BSM models do not just modify the potential, but may bring extra scalars
  (often modify other couplings, but not always, e.g. 2209.00666)
- even if we take the picture seriously we may want to consider impact of limited constraints on λ_4
  (figures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

Higgs potential



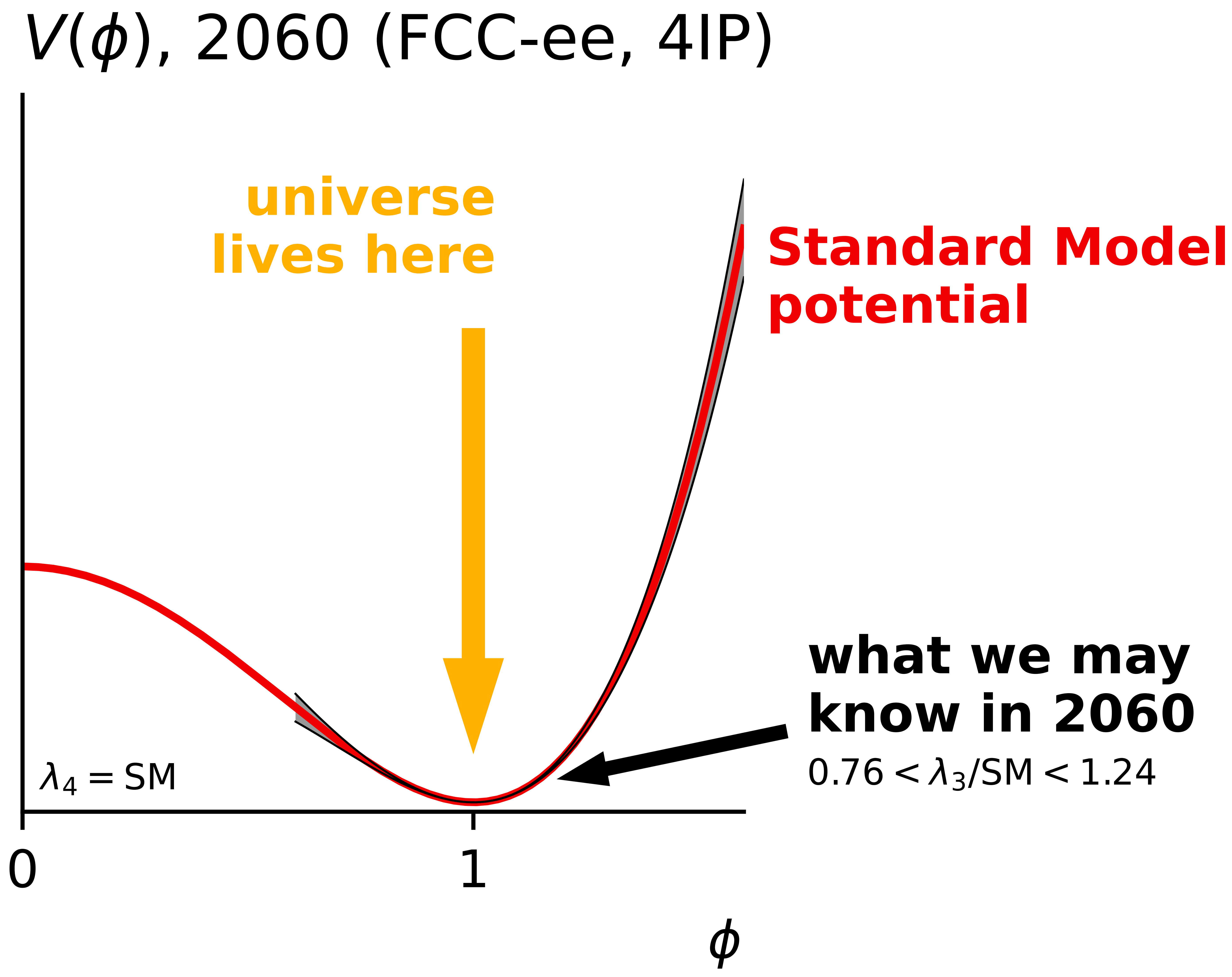
- this is a cartoon
- caution needed: e.g. realistic BSM models do not just modify the potential, but may bring extra scalars
  (often modify other couplings, but not always, e.g. 2209.00666)
- even if we take the picture seriously we may want to consider impact of limited constraints on λ_4
  (figures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

Higgs potential



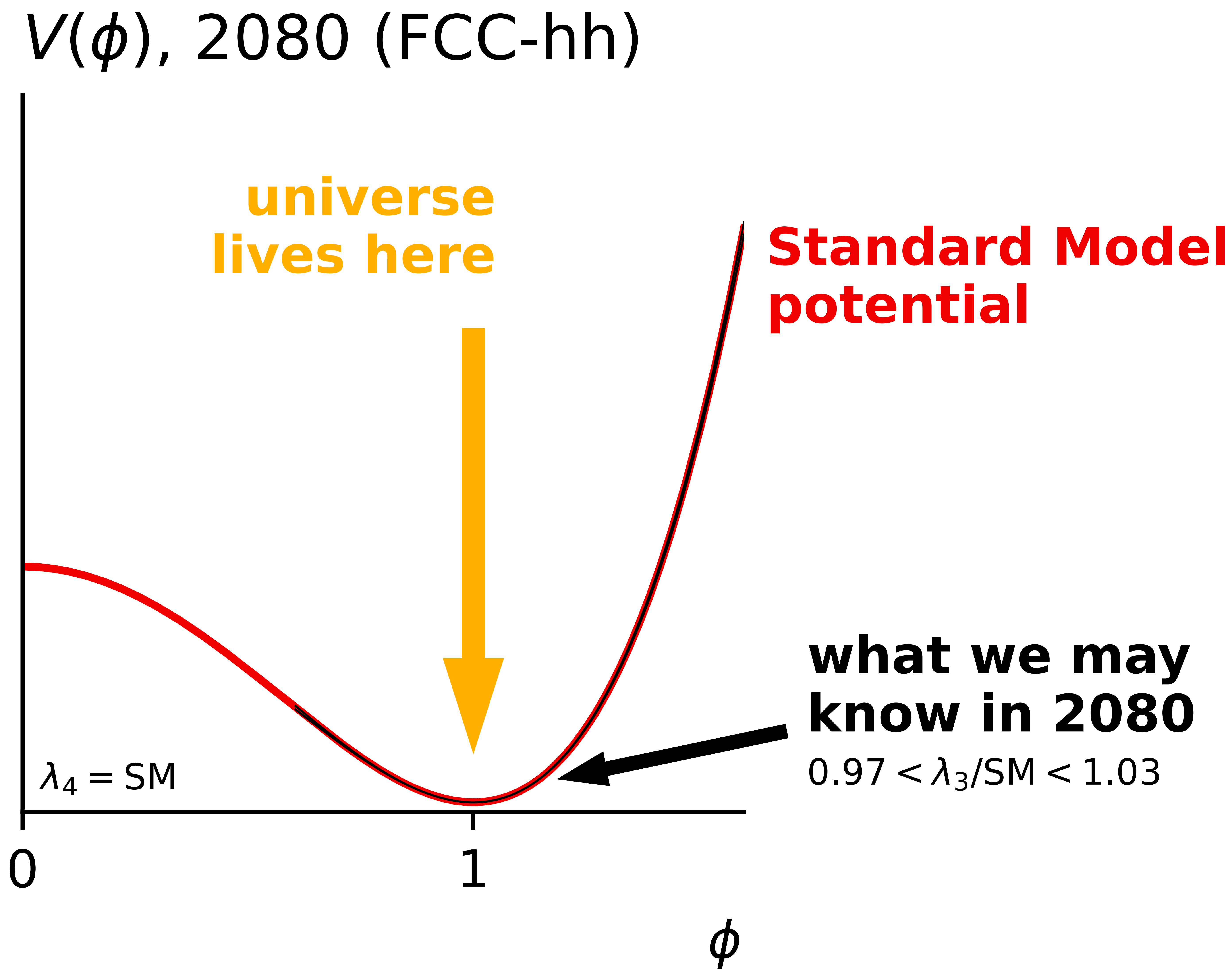
- this is a cartoon
- caution needed: e.g. realistic BSM models do not just modify the potential, but may bring extra scalars
  (often modify other couplings, but not always, e.g. 2209.00666)
- even if we take the picture seriously we may want to consider impact of limited constraints on λ_4
  (figures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

Higgs potential



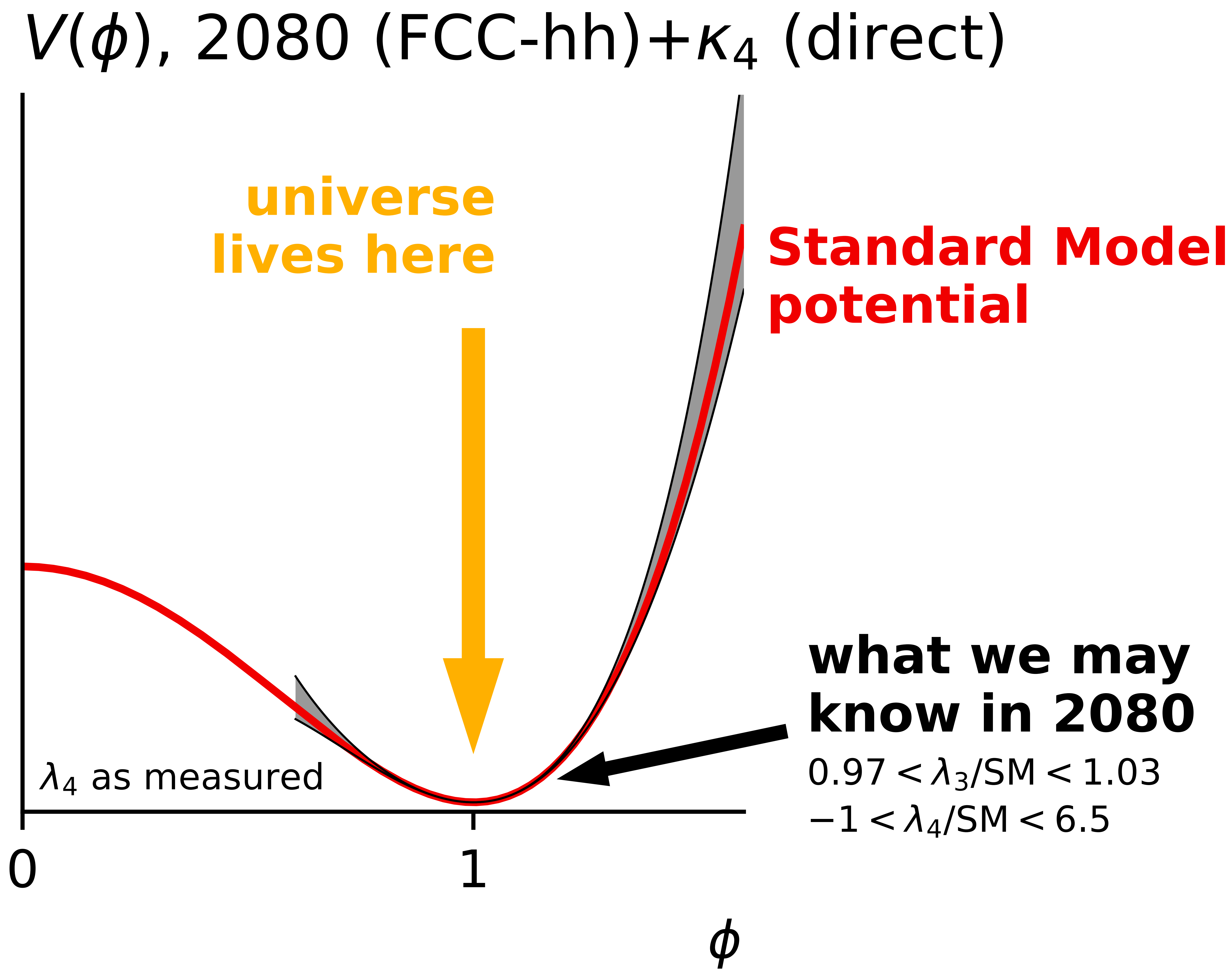
- this is a cartoon
- caution needed: e.g. realistic BSM models do not just modify the potential, but may bring extra scalars
  (often modify other couplings, but not always, e.g. 2209.00666)
- even if we take the picture seriously we may want to consider impact of limited constraints on λ_4
  (figures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

Higgs potential



- 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 (figures show either SM or FCC-hh constraint; how many coincidences are needed for a BSM model to leave λ_3 untouched while modifying λ_4?)

Higgs potential



- 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
  (figures show either SM or FCC-hh constraint; how many coincidences are needed for a BSM model to leave λ_3 untouched while modifying λ_4?)

desirable features of the next major HEP project(s)?

an important target to be reached ~ guaranteed discovery

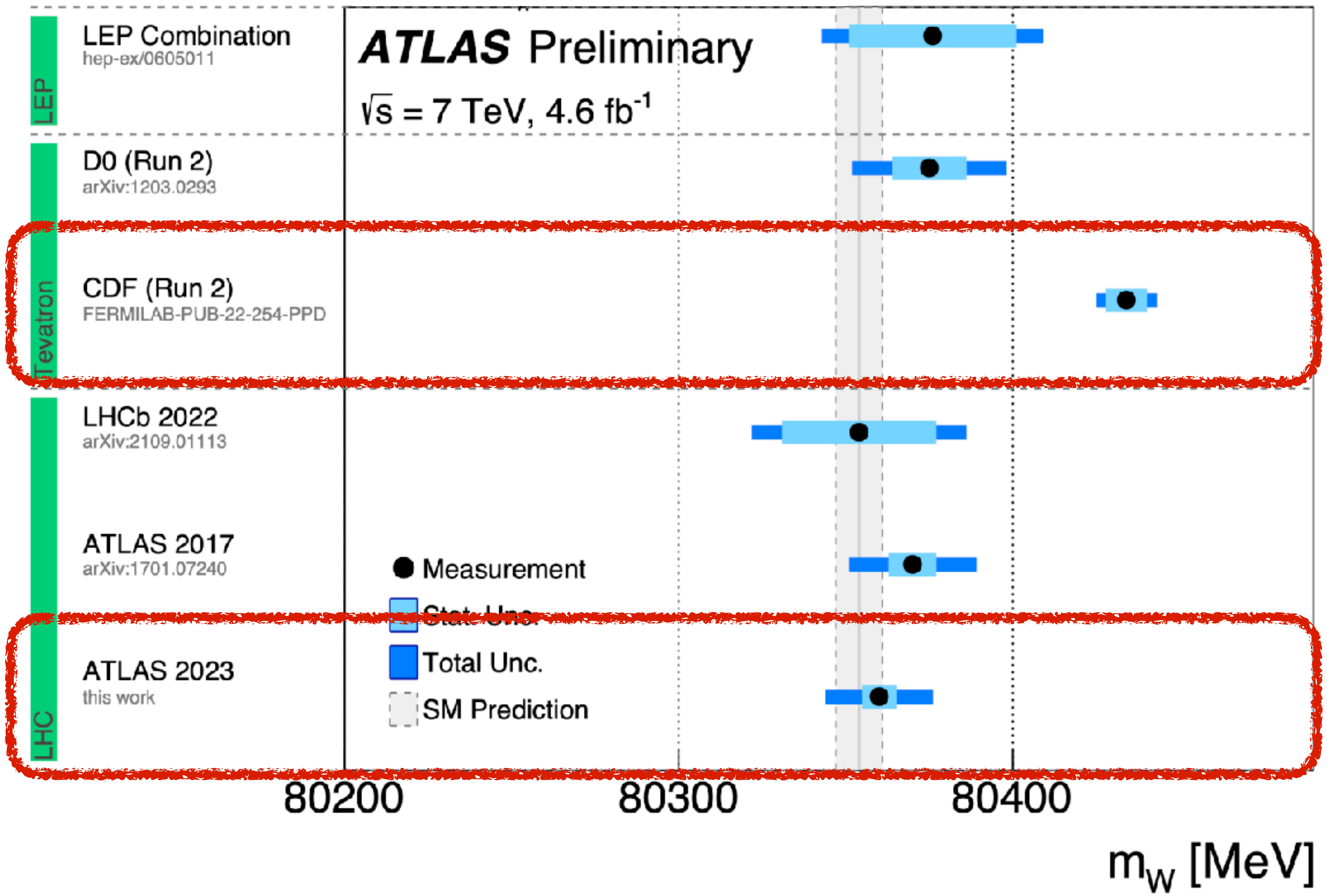
exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (e.g. multiple experiments)

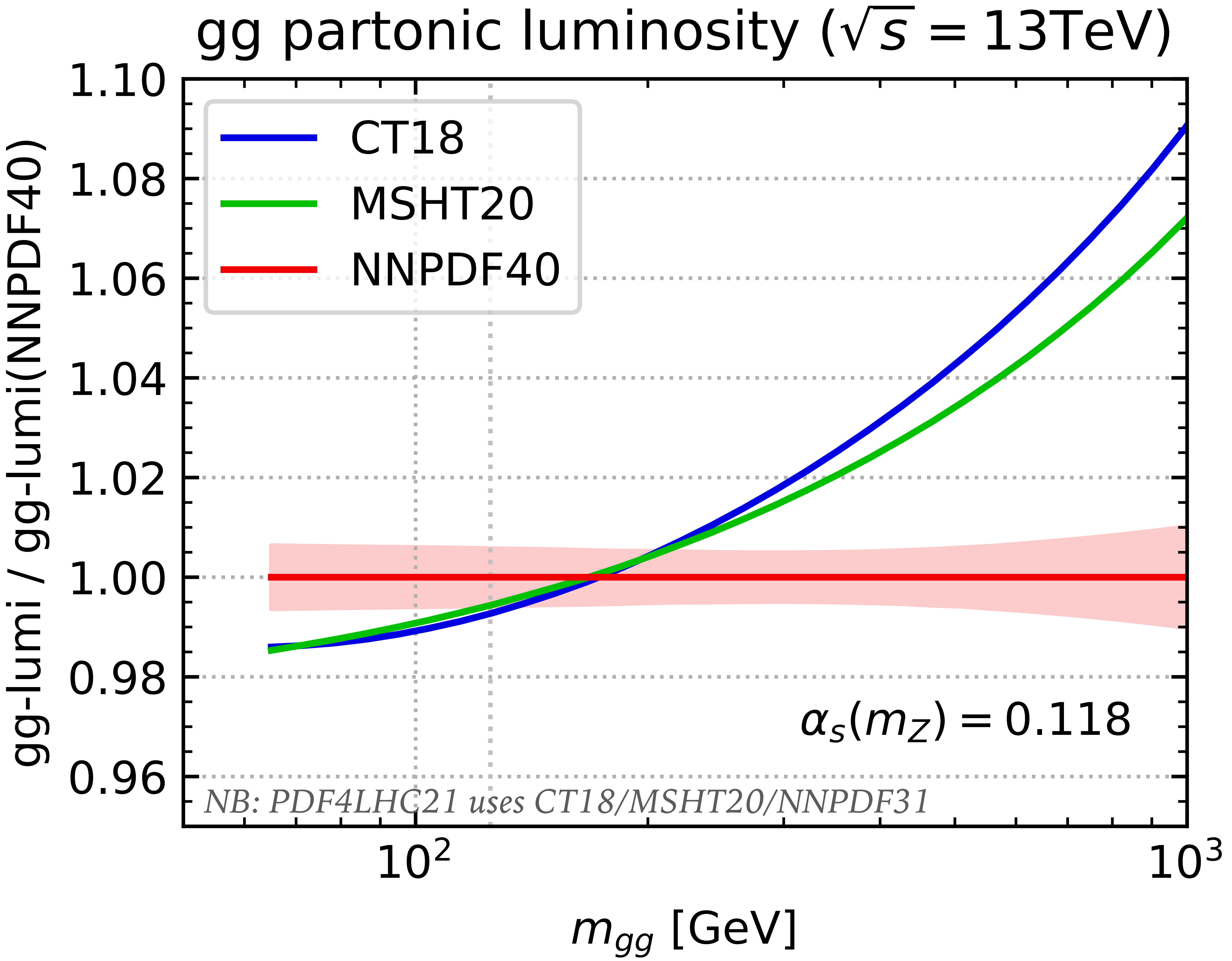
cost-effective construction & operation,
low carbon footprint, novel technologies

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



gg-lumi, ratio to PDF4LHC15 @ m_H

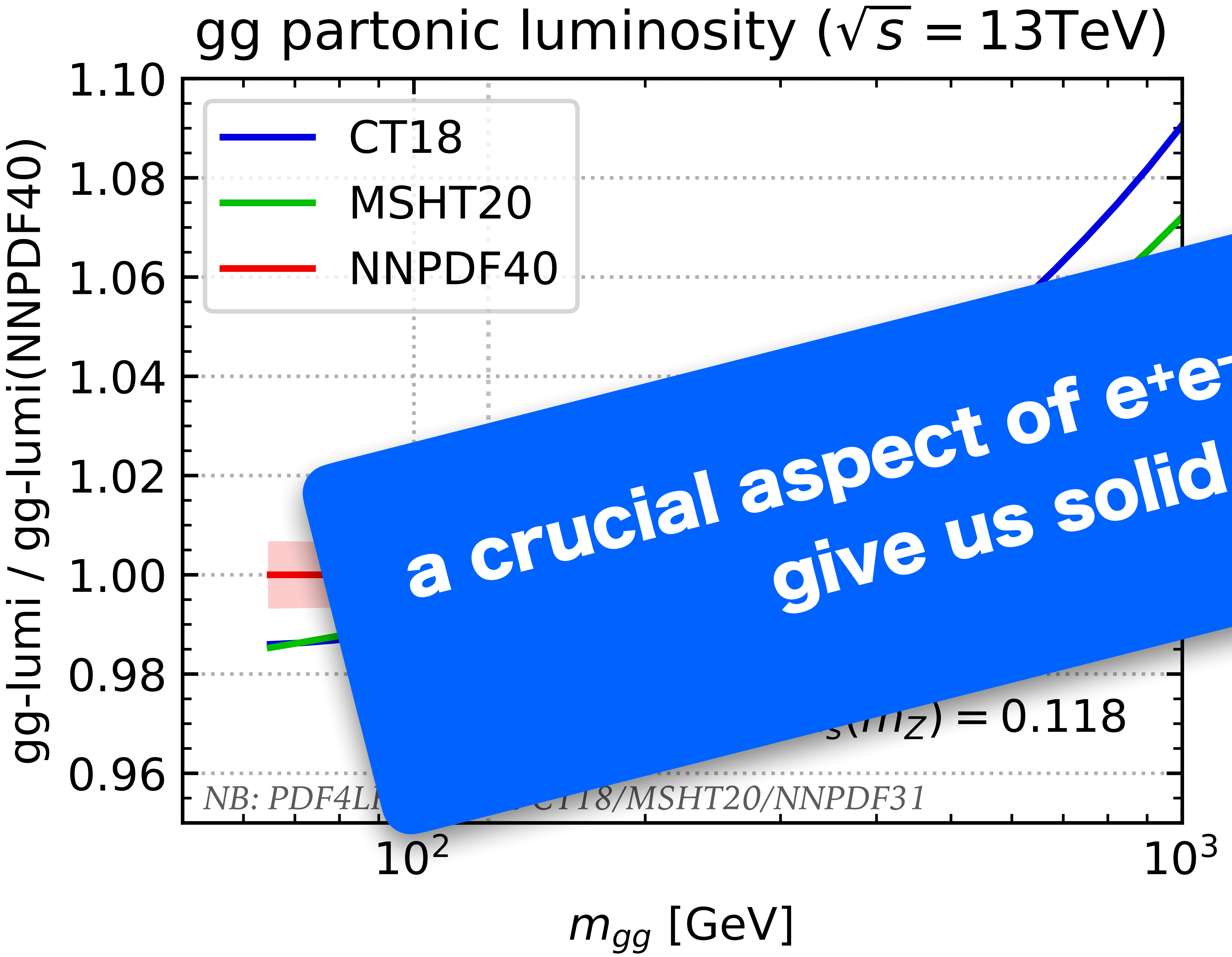
PDF4LHC15	1.0000	±	0.0184
PDF4LHC21	0.9930	±	0.0155
CT18	0.9914	±	0.0180
MSHT20	0.9930	±	0.0108
NNPDF40	0.9986	±	0.0058

× 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

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



gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	.0184
	0155
	0180
	108
	0.0058

$\times 3$

a crucial aspect of e+e- colliders is that they give us solid foundations

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

various arguments favour a circular e^+e^- collider

- 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]

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 $Z'_{\rm SSM}$ as a simple measure of progress
(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)

× 5.6 →

replicated across myriad search channels

LHC
pp, 14 TeV, 3000 fb^{-1}

Exclusion limit ~ 6.7 TeV

(electron and muon channels, single experiment)

step up in energy for direct searches?

I like the Z'_{SSM} as a simple measure of progress
(simple and most experiments look for it)

LHC
pp, 13 TeV, 3000 fb^{-1}

Exclusion limit ~ 6.7 TeV

(electron and muon channels, single experiment)

× 6.1 →

replicated across myriad search channels

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)

step up in energy for direct searches?

I like the Z'_{SSM} as a simple measure of progress
(simple and most experiments look for it)

LHC
pp, 13 TeV, 3000 fb^{-1}

Exclusion limit ~ 6.7 TeV

(electron and muon channels, single experiment)

× 6.4 →

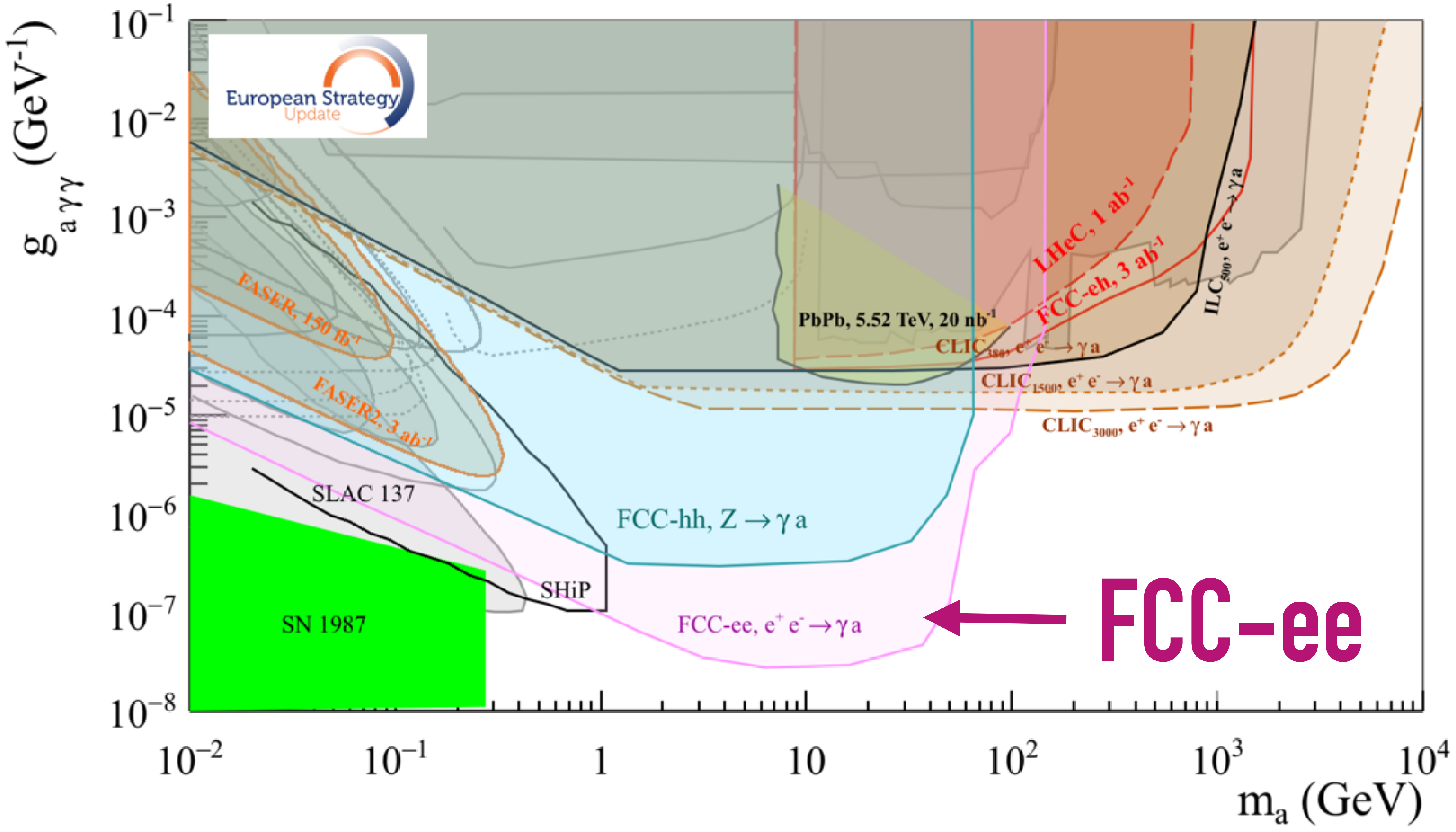
replicated across myriad search channels

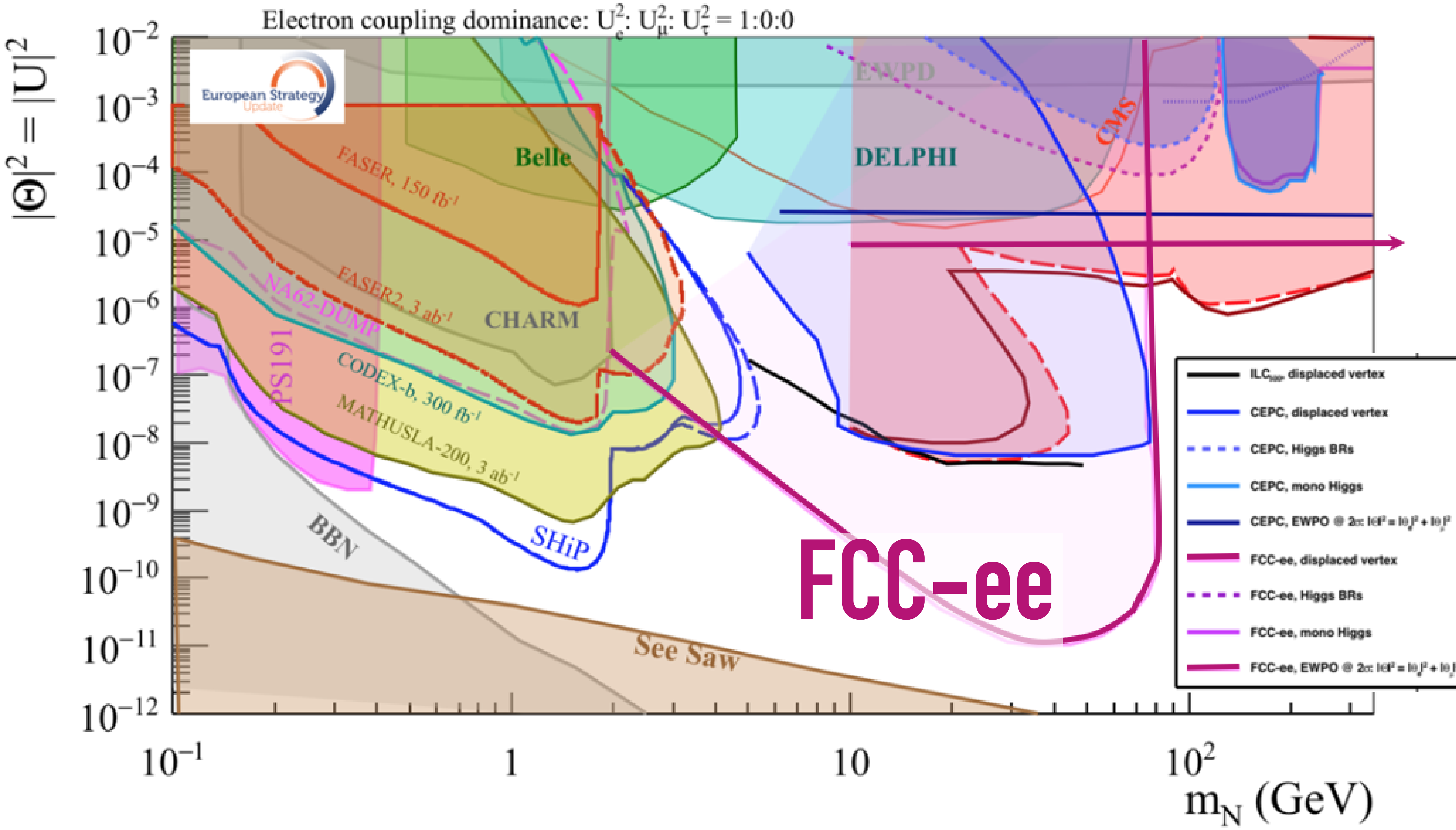
SppC
125 TeV, 5 ab^{-1}

Exclusion limit ~ 43 TeV

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

Direct search at lepton colliders: e.g. axion and heavy-neutral lepton searches

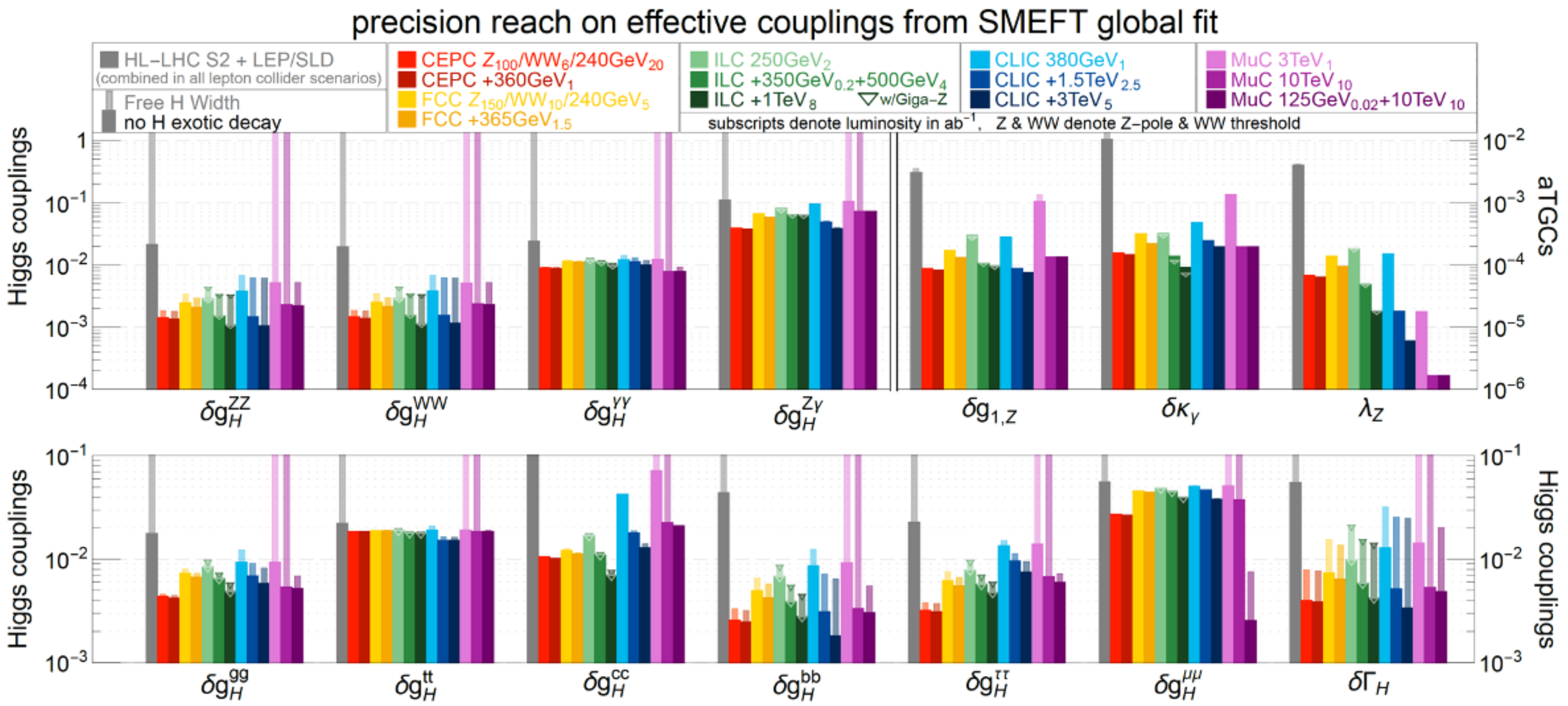




benefits from huge Z-pole luminosity

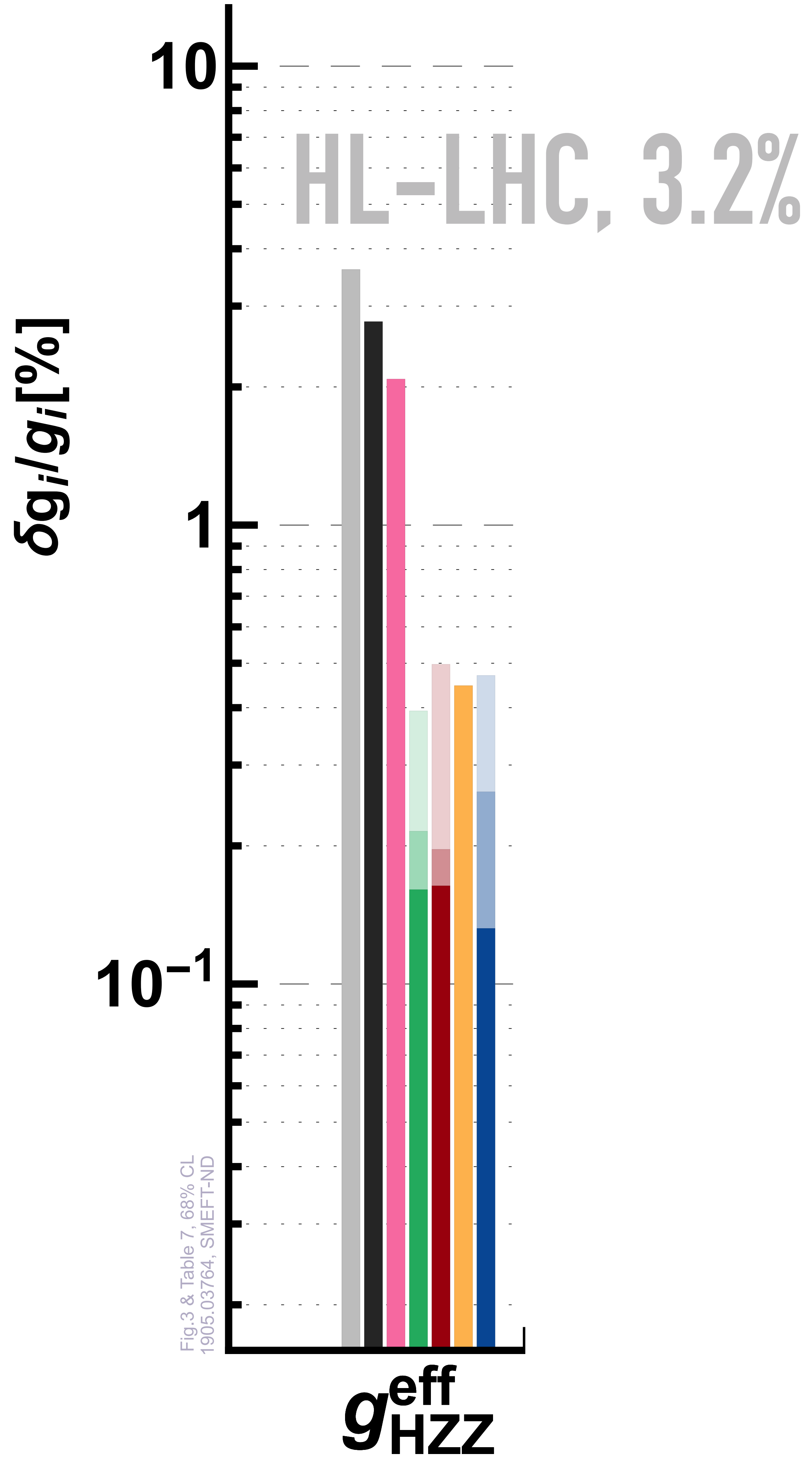
(some models in these regions have potential to connect with dark matter, baryon asymmetry, neutrino masses, etc.)

increase in precision at lepton colliders [here: Higgs couplings]

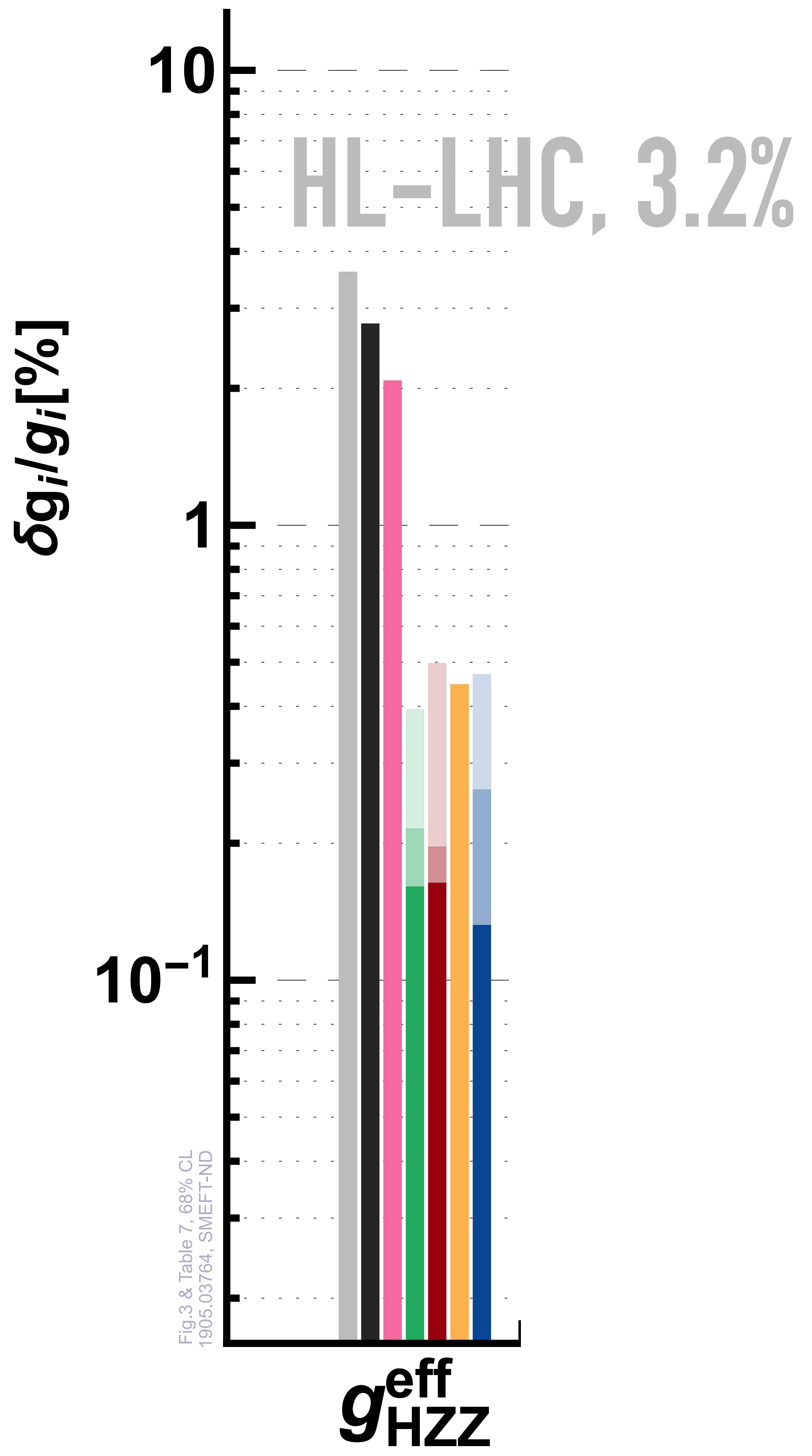


https://arxiv.org/abs/2206.08326

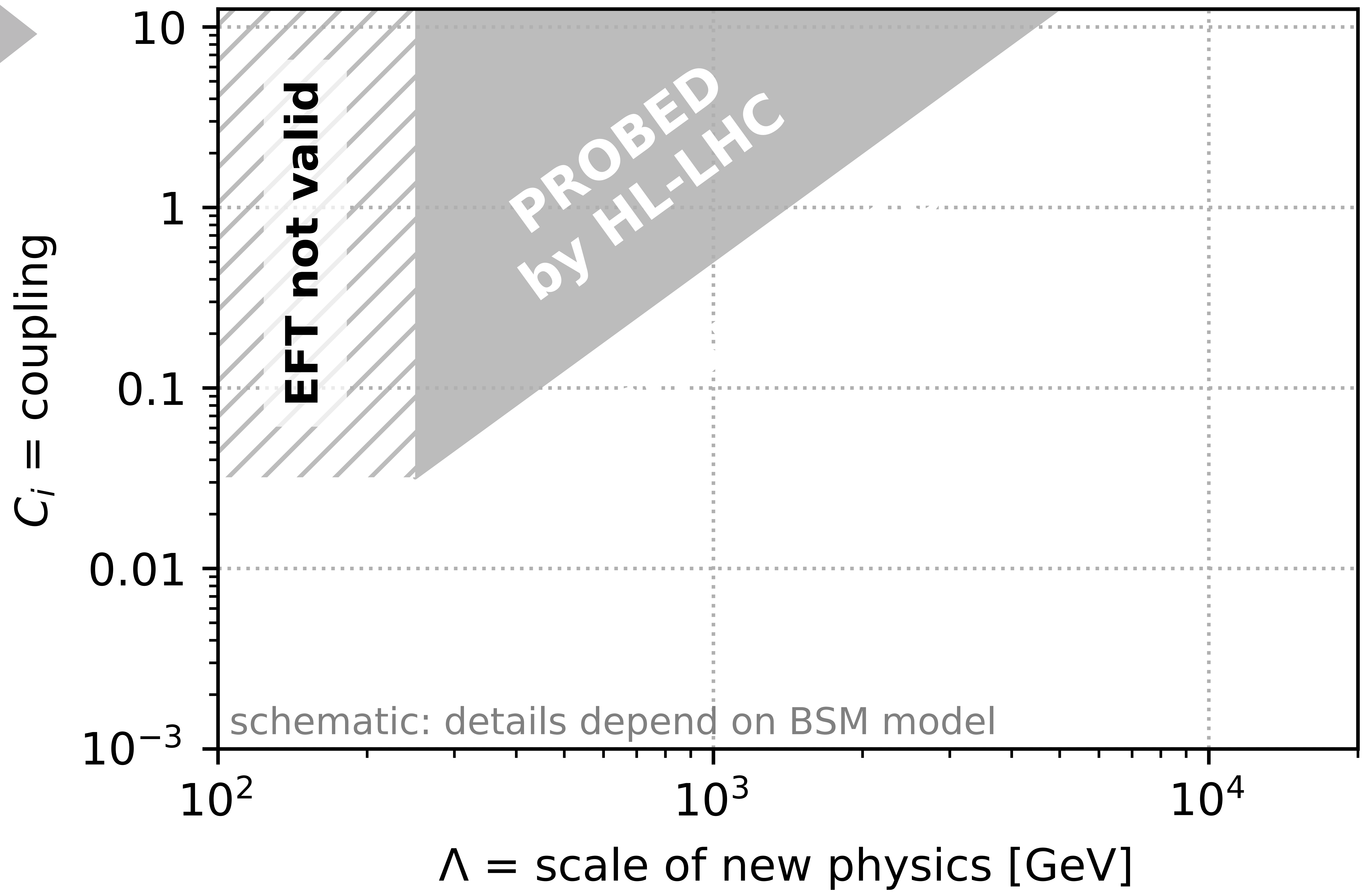
Interpret higher precision as increase in indirect reach



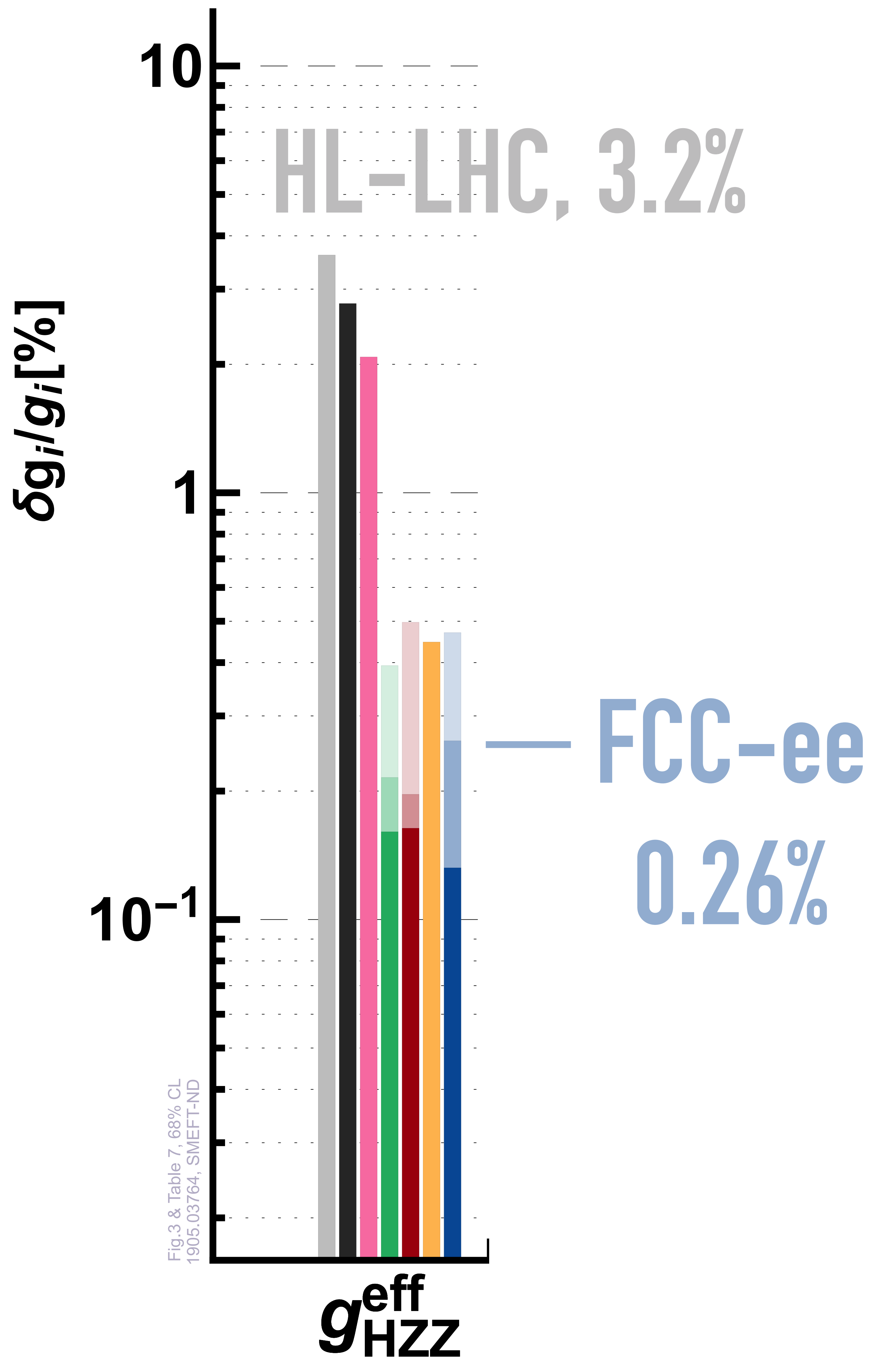
Interpret higher precision as increase in indirect reach

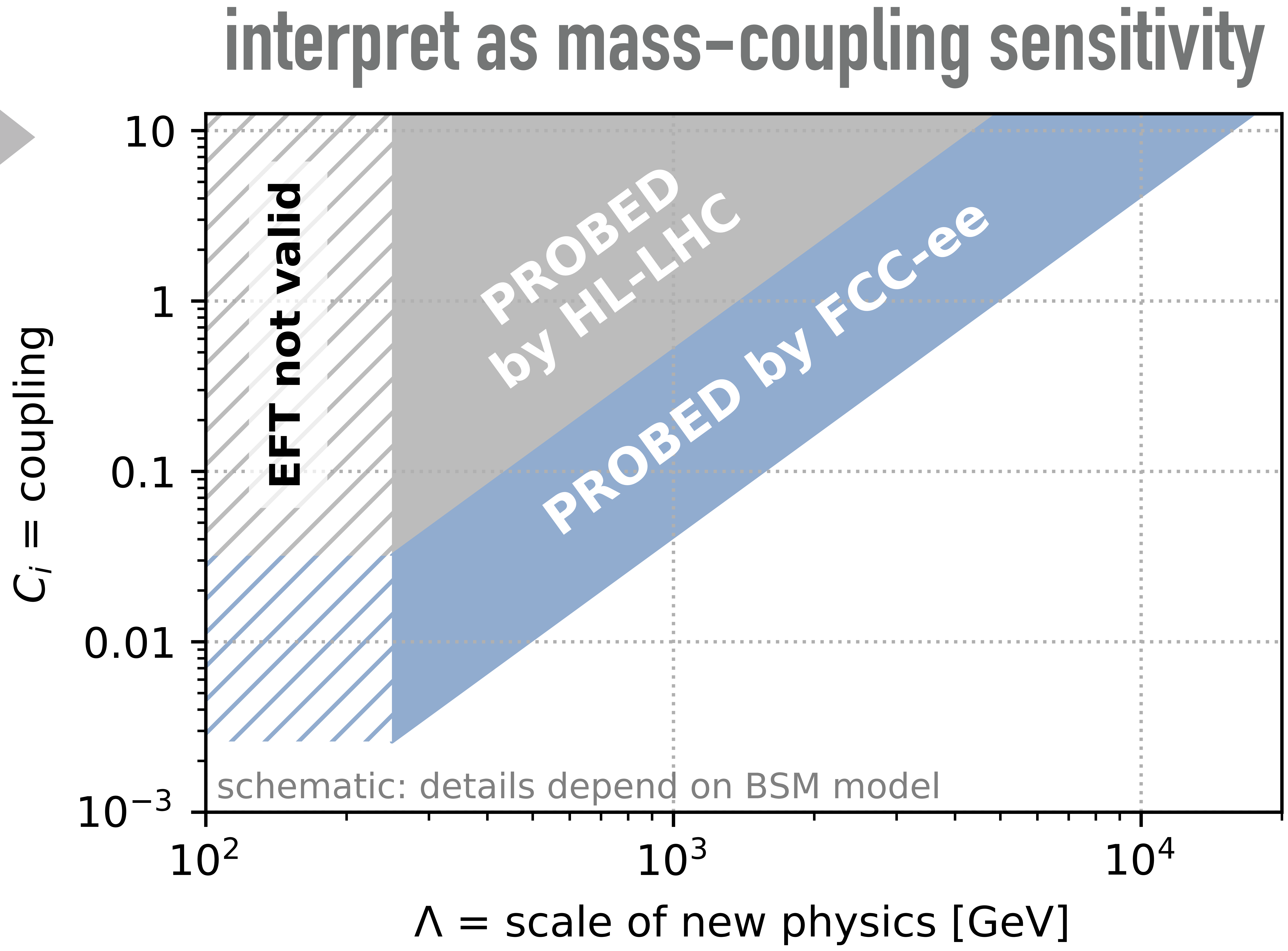


interpret as mass-coupling sensitivity

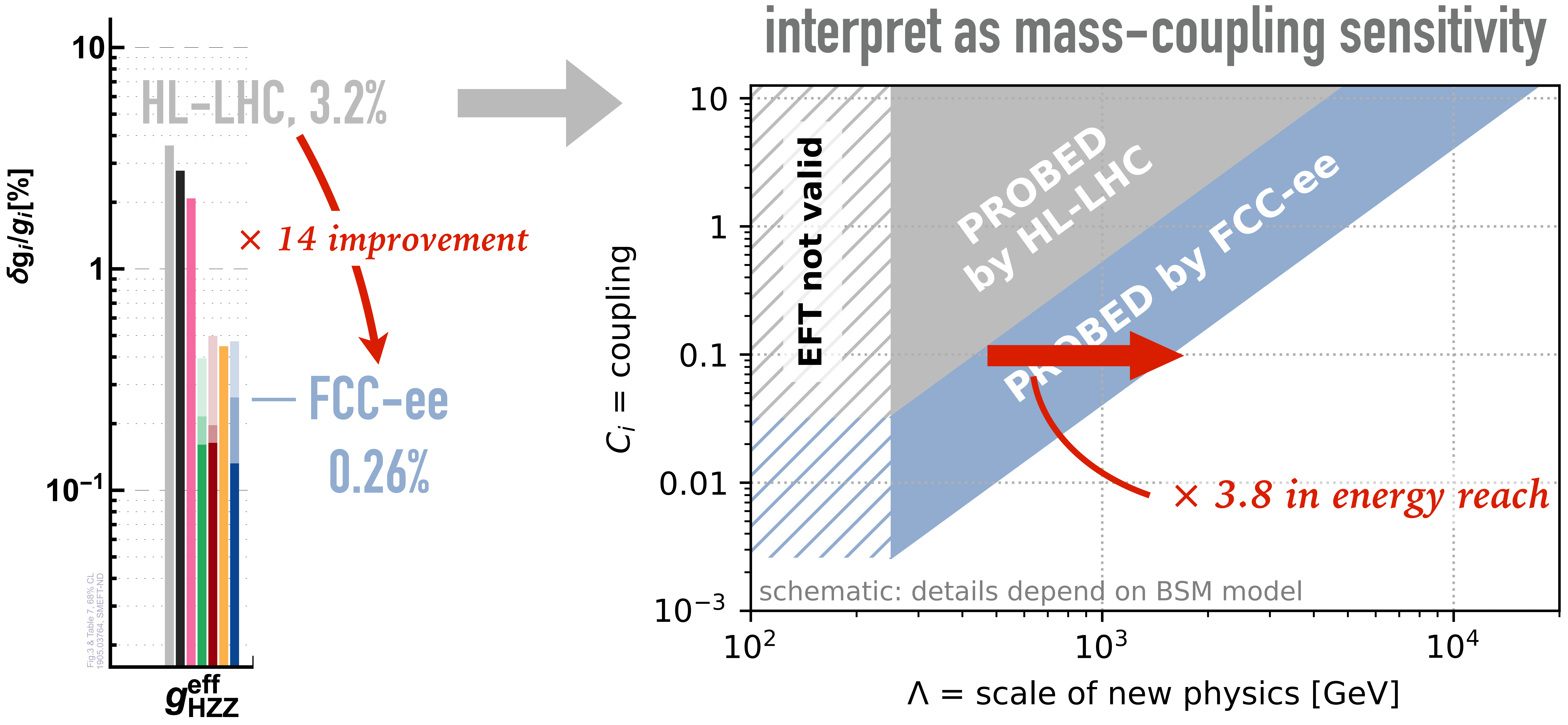


Interpret higher precision as increase in indirect reach

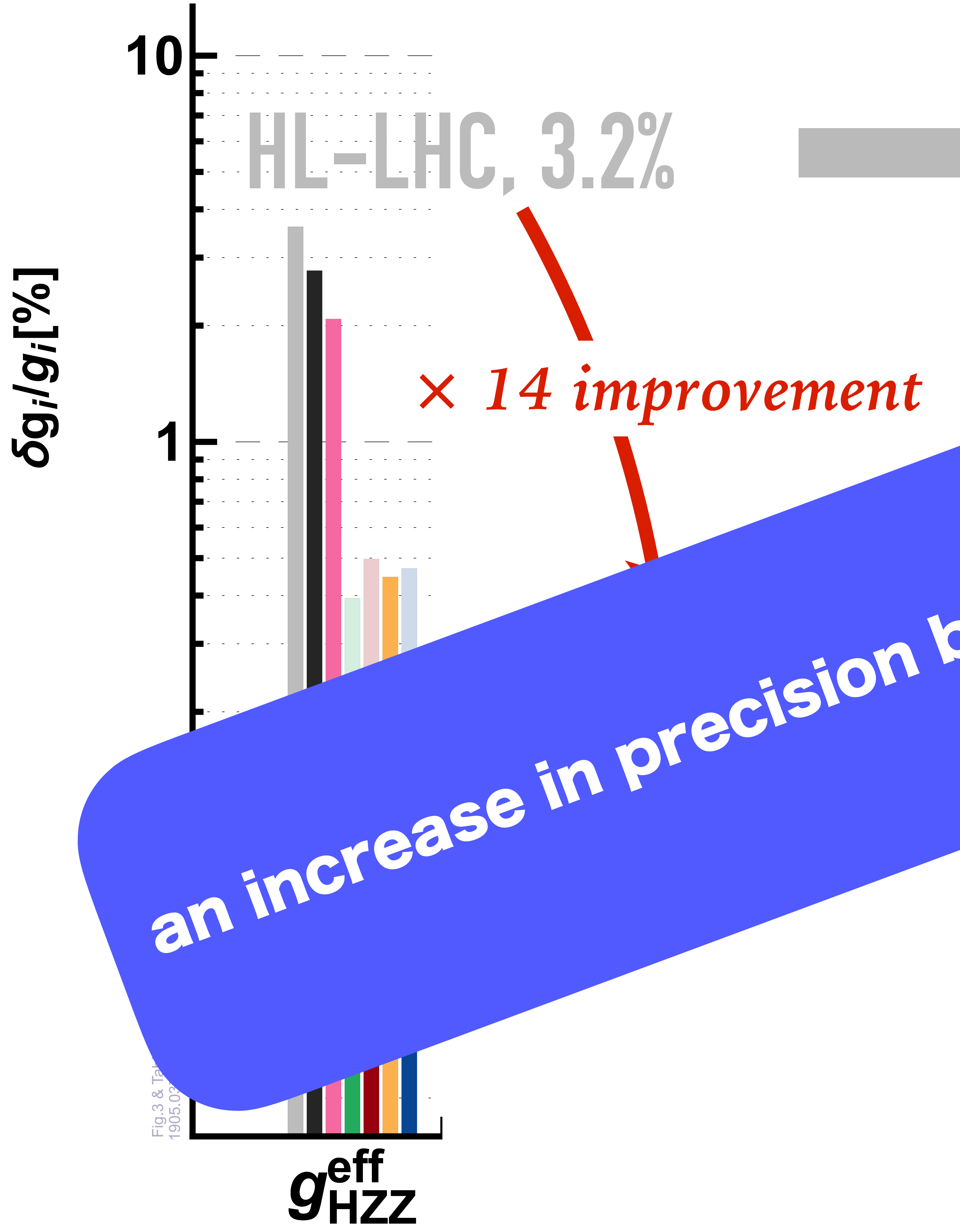


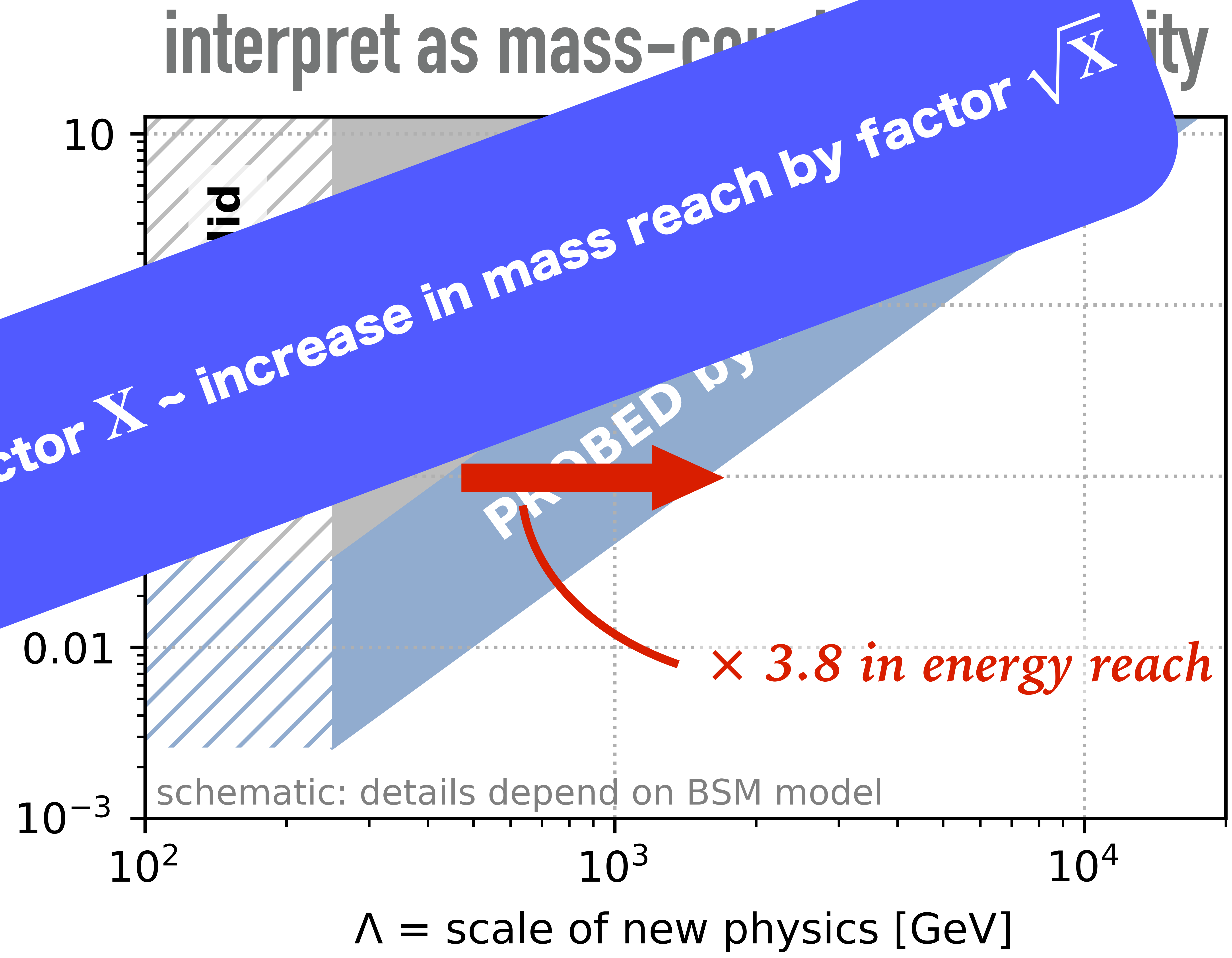


Interpret higher precision as increase in indirect reach



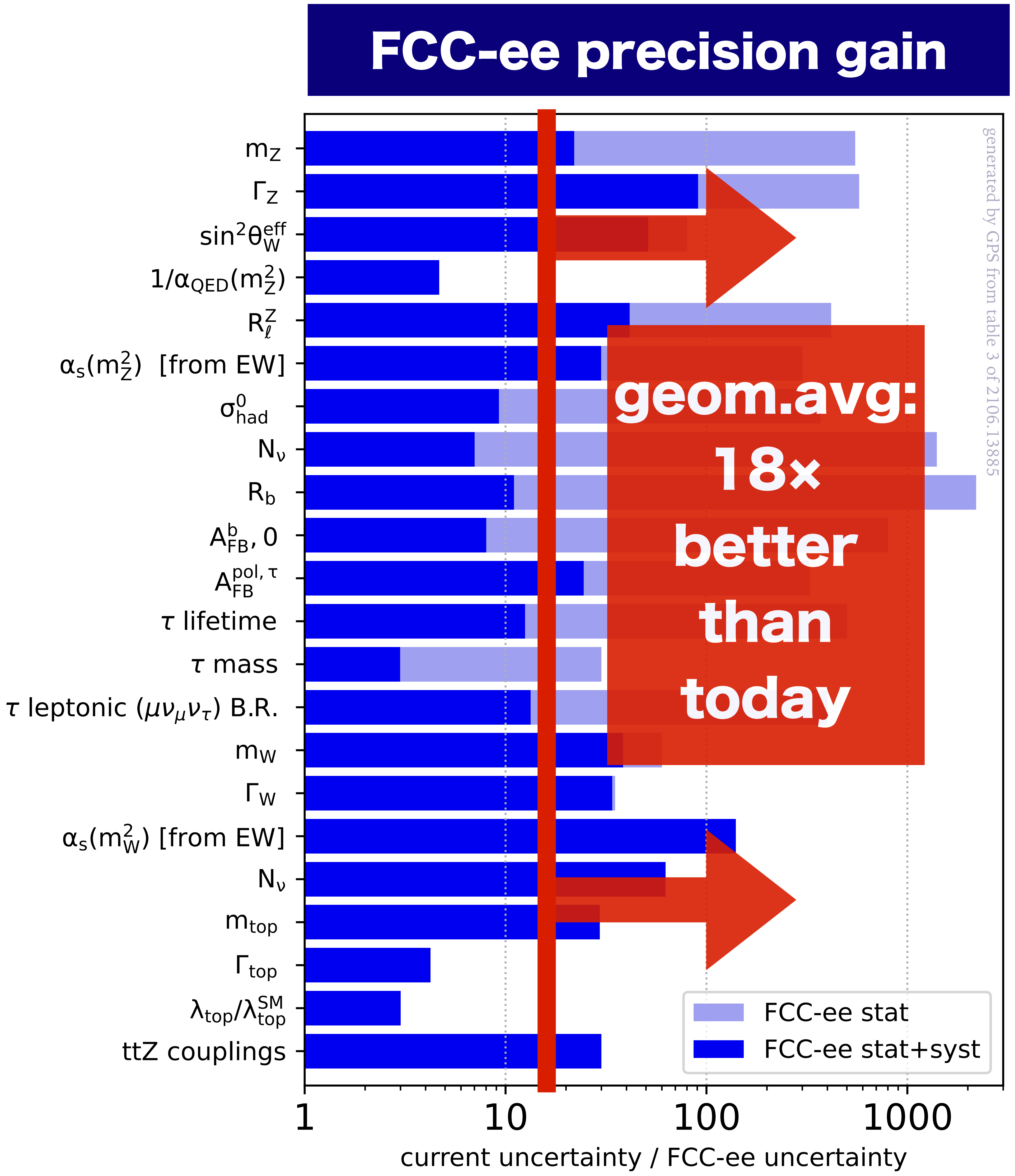
Interpret higher precision as increase in indirect reach





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

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



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!

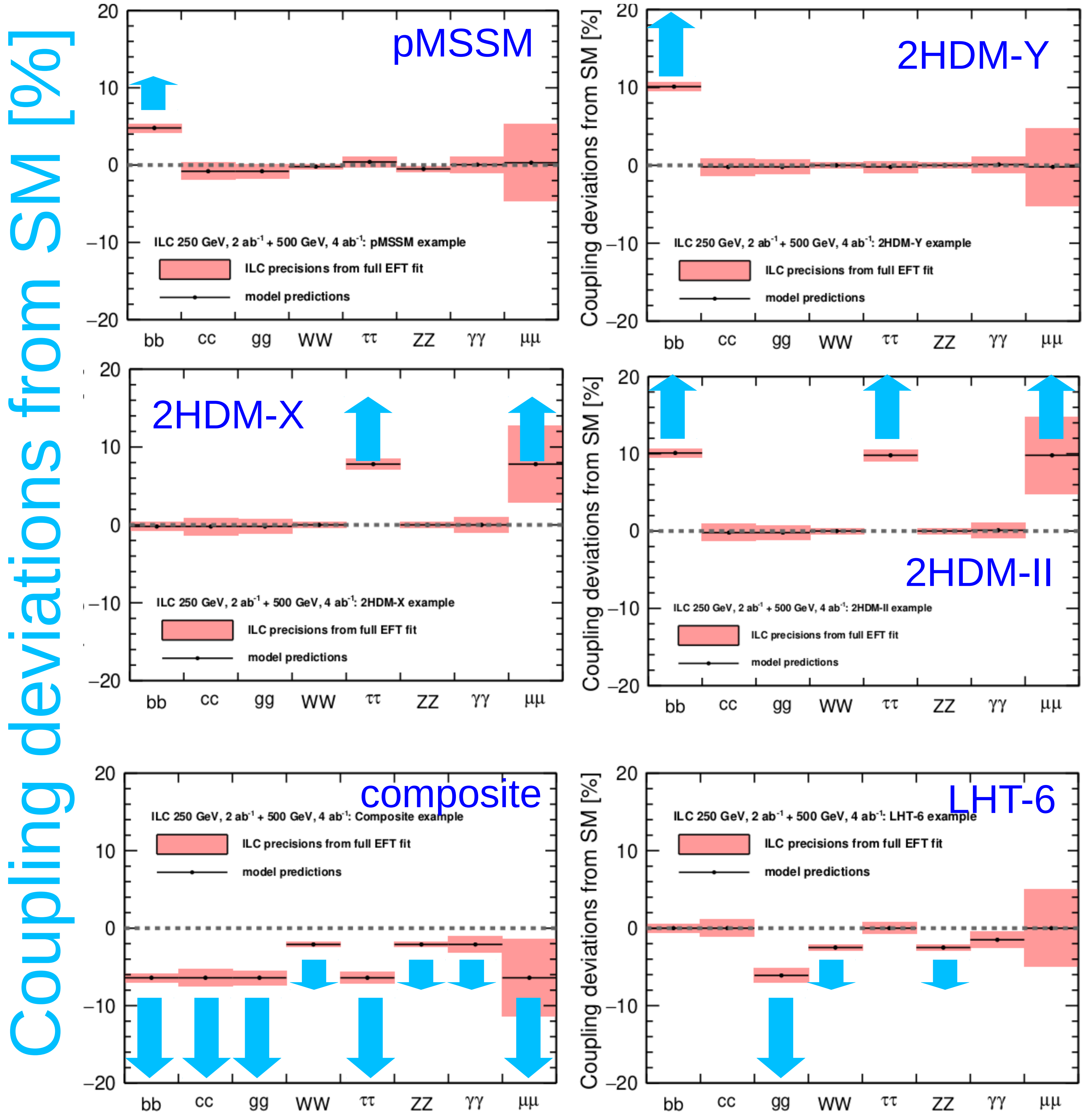
and will call for joint efforts by experiment/theory/accelerator physicists

similarly for other colliders (here: 4–fermion contact operators)

https://arxiv.org/abs/2206.08326

exploring many operators ≡ many observables (incl. high-p_T @ FCC-hh/SppC)

arXiv:1708.08912



Pattern of deviations is "fingerprint" of new physics

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

desirable features of the next major HEP project(s)?

an important target to be reached ~ guaranteed discovery

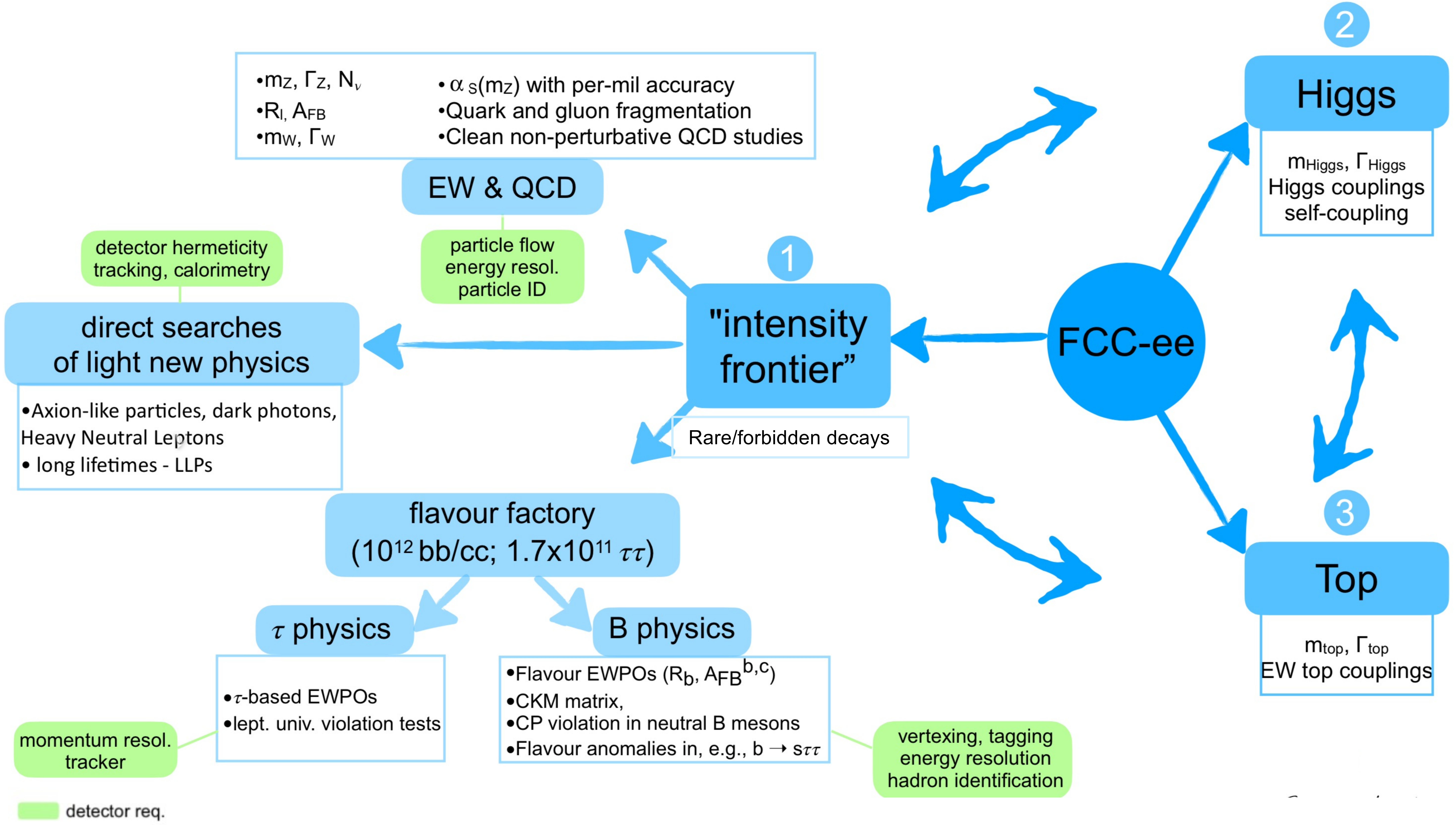
exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

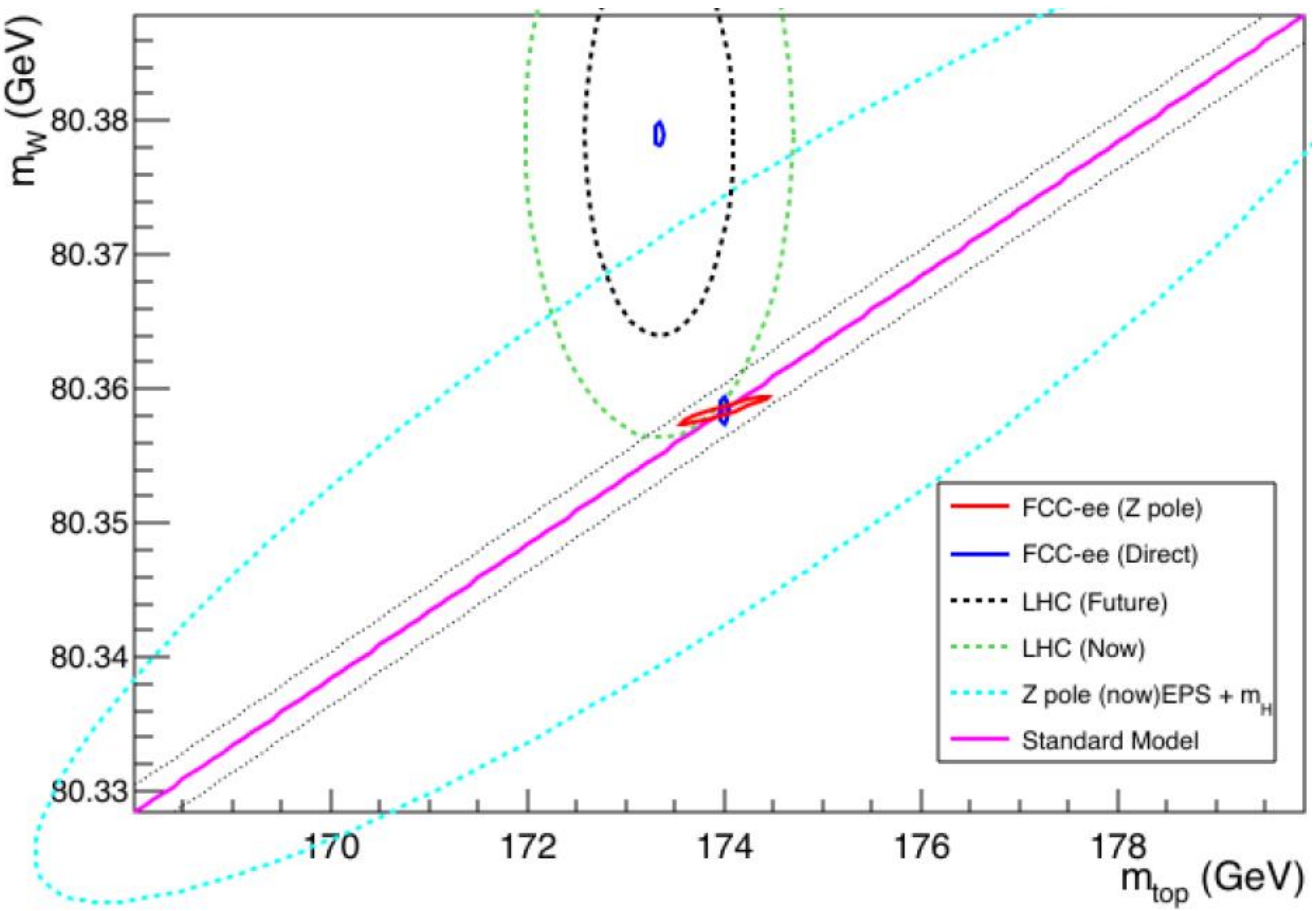
likelihood of success, robustness (e.g. multiple experiments)

cost-effective construction & operation,
low carbon footprint, novel technologies

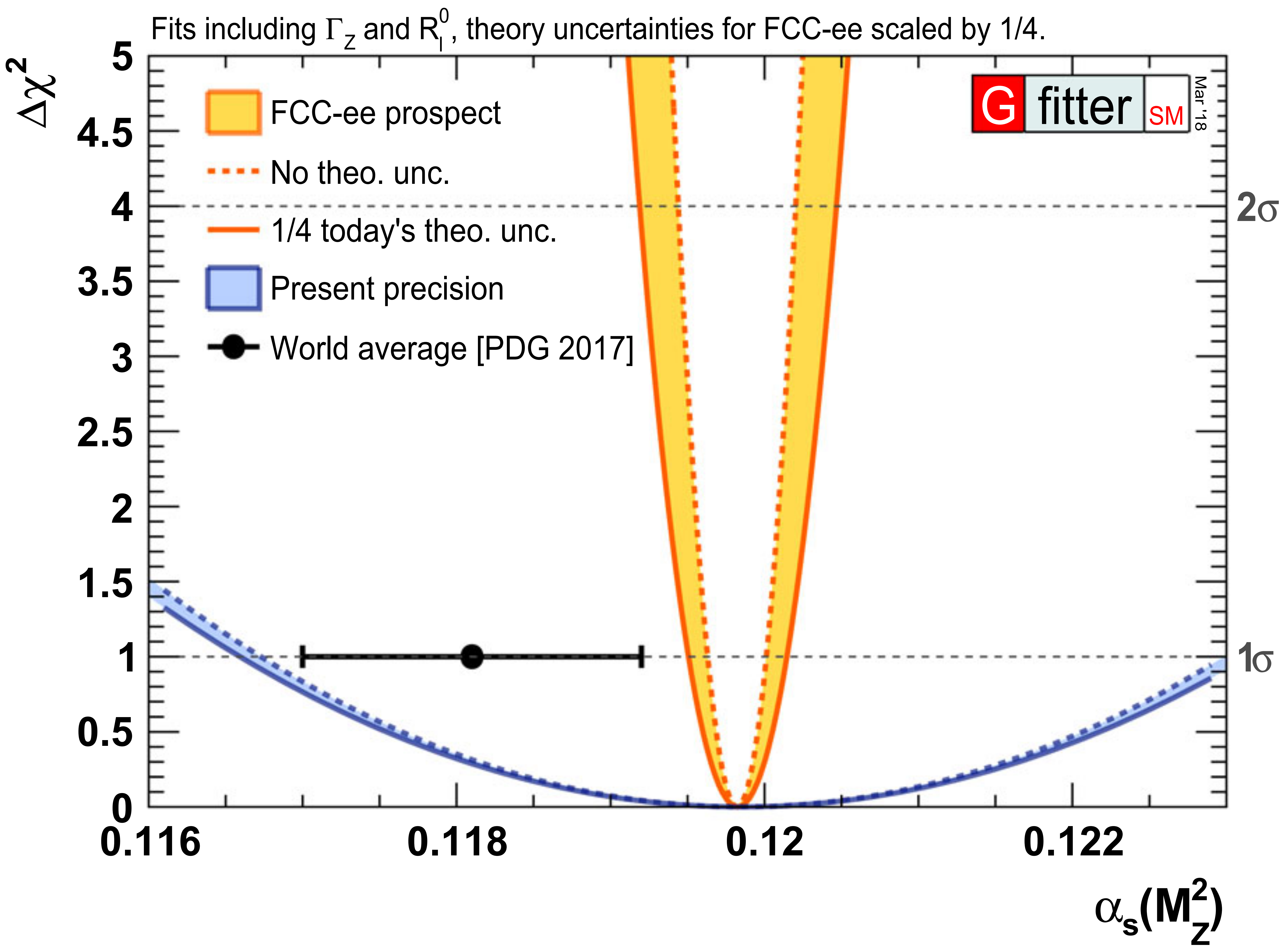
illustration is for FCC — but message is comparable for other colliders



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



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.

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

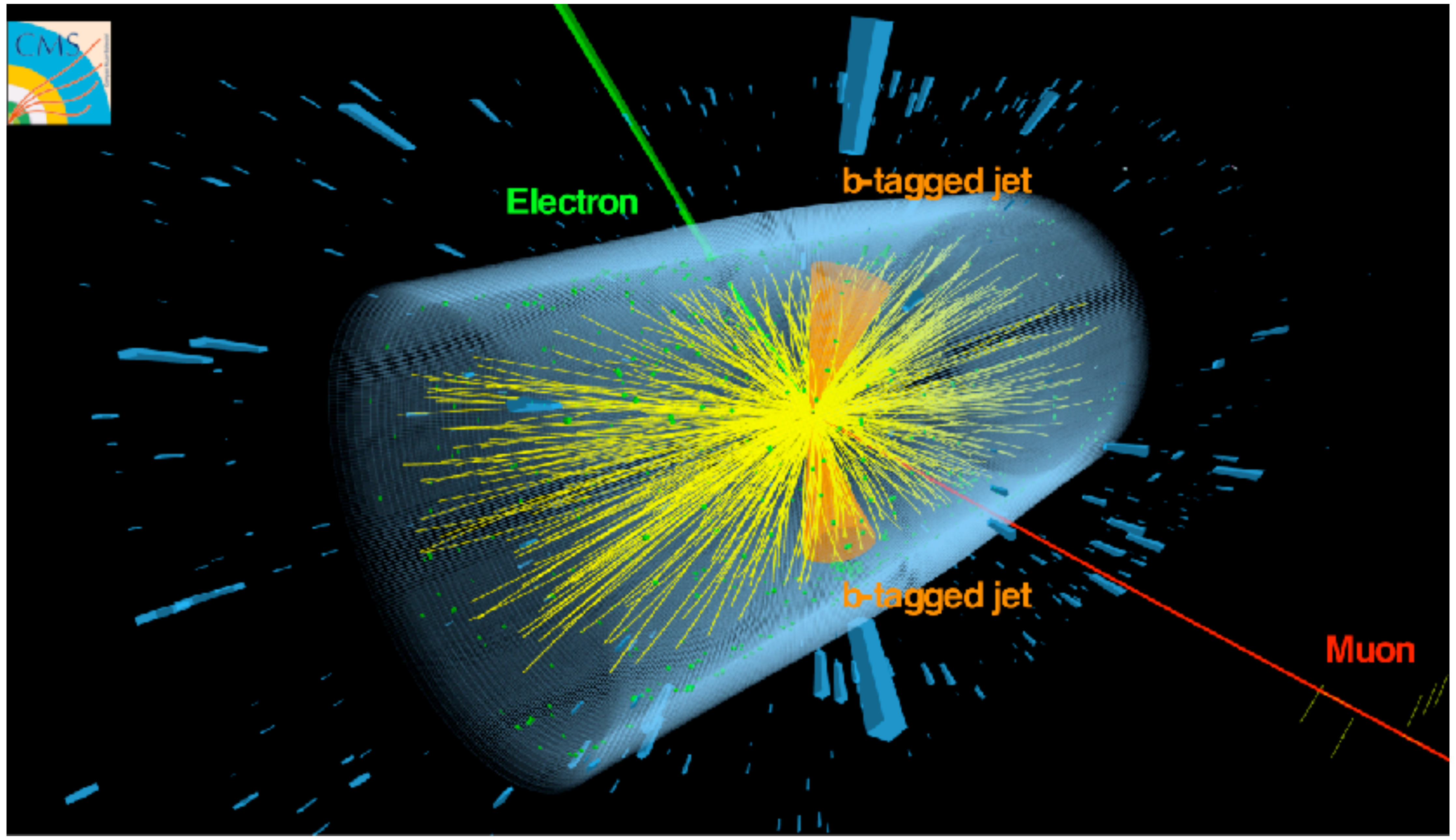
2106.01259

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	✓		(✓)

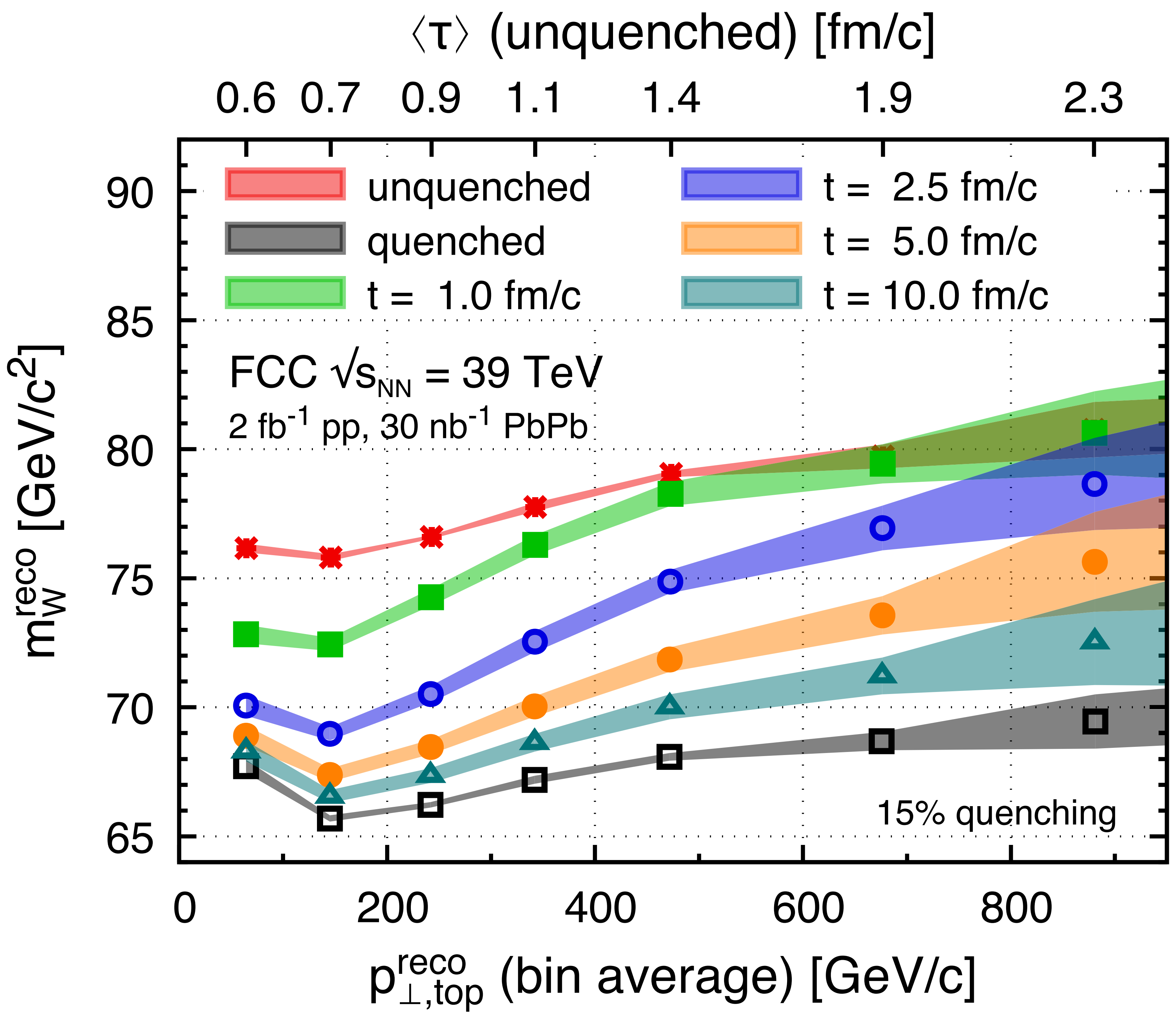
FCC-hh PbPb collisions: top & W decays probe q/g-plasma across yoctosecond time-scales

Top quarks in heavy-ion collisions (CMS)



arXiv:2006.11110

Reconstructed W-mass v. top-quark p_T at FCC-PbPb, showing sensitivity to medium lifetime *t*



Apolinário, Milhano, Salgado, GPS, 1711.03105

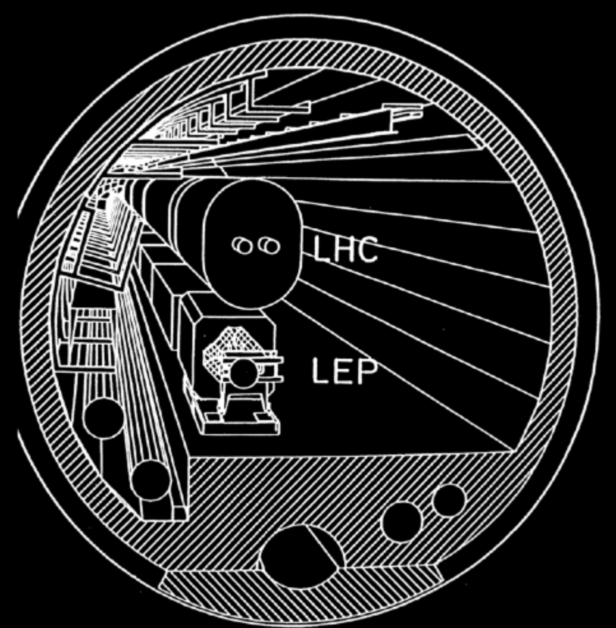
conclusions

Conclusions

- There is a **guaranteed discovery:** directly establishing Higgs self-interaction, which holds the SM together, via robust precision of Higgs factory and direct measurement at higher-energy colliders
  - is there a chance of a second no-lose theorem in establishing (or disproving) SM origin of electron mass at circular e^+e^- colliders?
- The **step up in energy reach** that we expect is $\sim$ **$\times$ 4 – 5**
  - e^+e^- colliders deliver that mostly in “indirect” sensitivity, through precision increase $\sim \times 18$
  - FCC-hh/SppS deliver that in direct search sensitivity (muon collider does for some scenarios)
- **Diversity and robustness of the programme** = essential part of their strength

via 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

How to progress?

Explore the regions of the unknown,
the unanswered questions

Try to divine where the secrets are hidden

Seek out soft spots in our current understanding,
especially where the stories we tell are
unprincipled $\equiv$ not founded on sound principles

Supersymmetry: + R-parity + μ problem + tame FCNC + ...

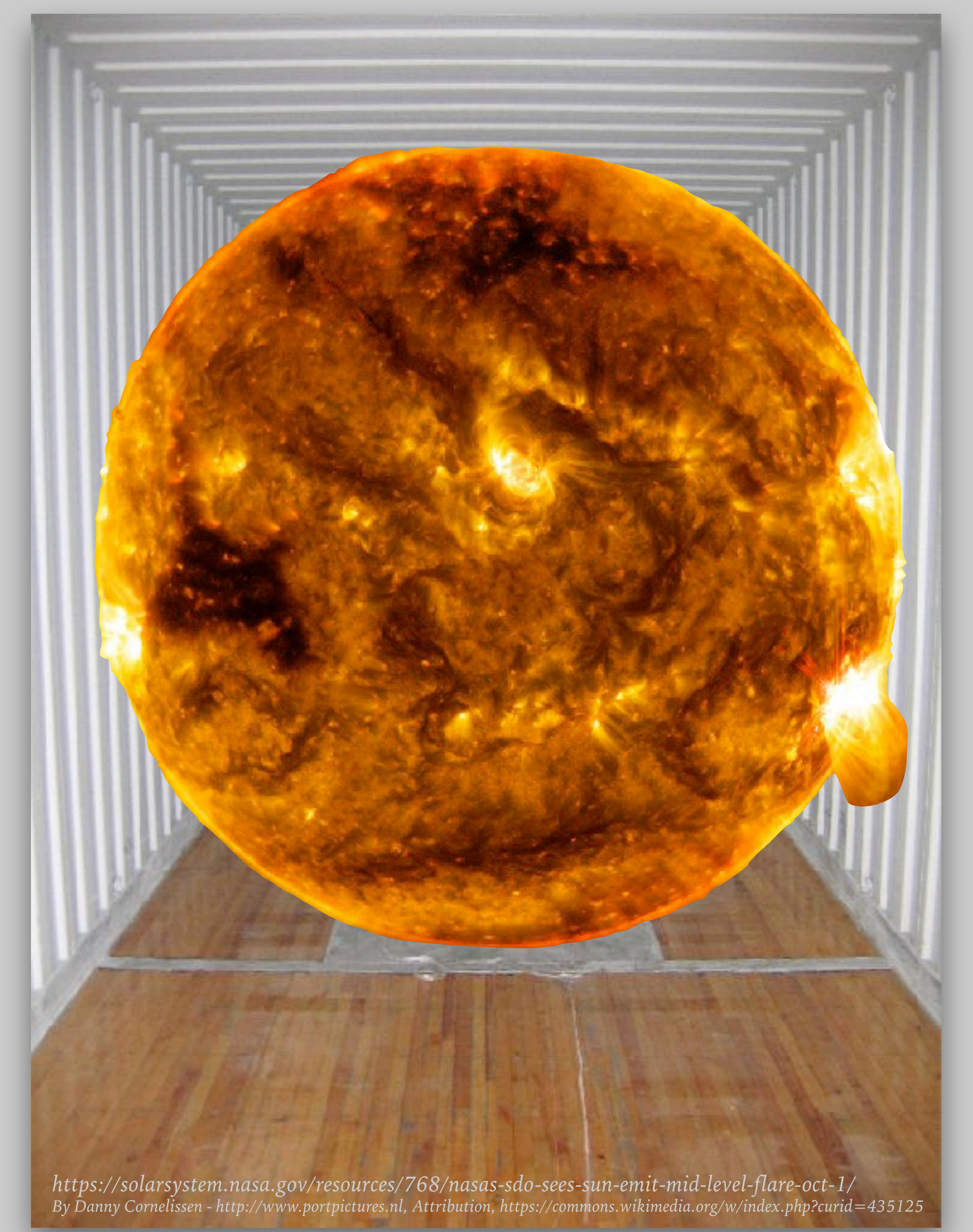
Big-Bang Cosmology: + inflation + dark matter + dark energy + ...

Particle content, even gauge groups, of the Standard Model

What does 2.6×10^{28} kg/m^3 mean?

What does 2.6×10^{28} kg/m^3 mean?

What does 2.6×10^{28} kg/m^3 mean?



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

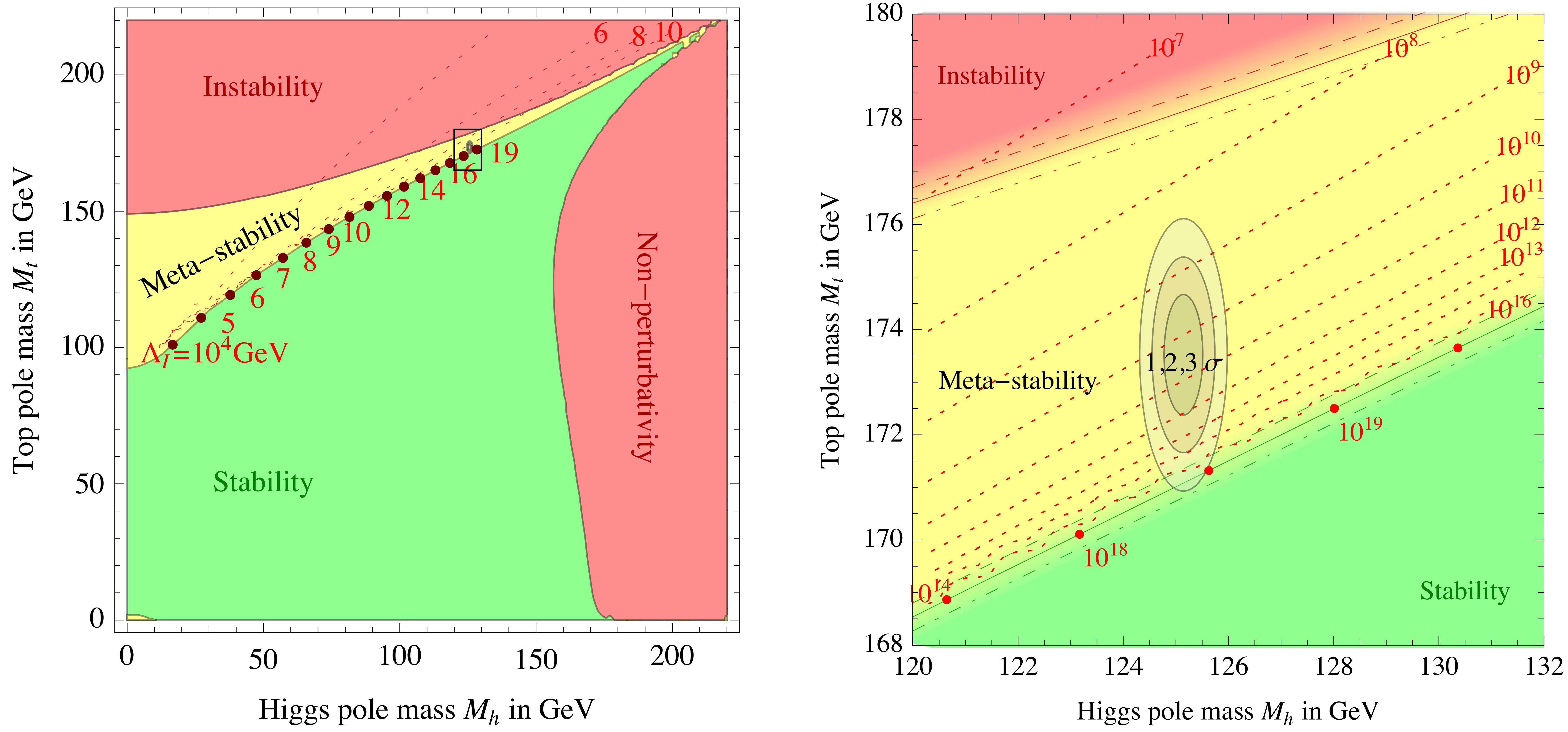
https://upload.wikimedia.org/wikipedia/commons/4/44/Mecanismo_de_Higgs_PH.png
https://en.wikipedia.org/wiki/Neutron_star#/media/File:Neutron_Star_X-ray_beaming_with_accretion_disk.jpg

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

improvements of up to
$\times$ *14–18*



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

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