European Strategy
Update

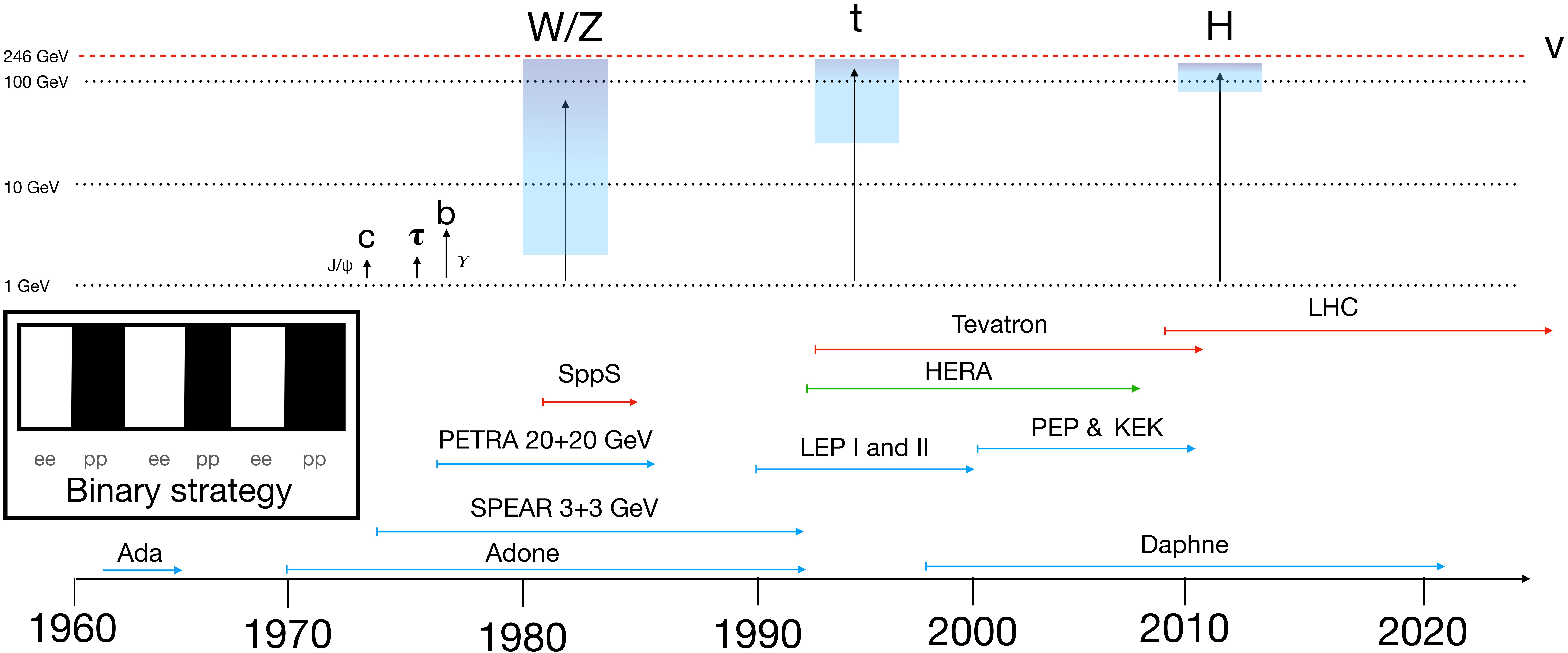
La Fisica nell'era post HL-LHC: Standard Model & beyond

Fabio Maltoni

INFN Sezione di Bologna
Università di Bologna

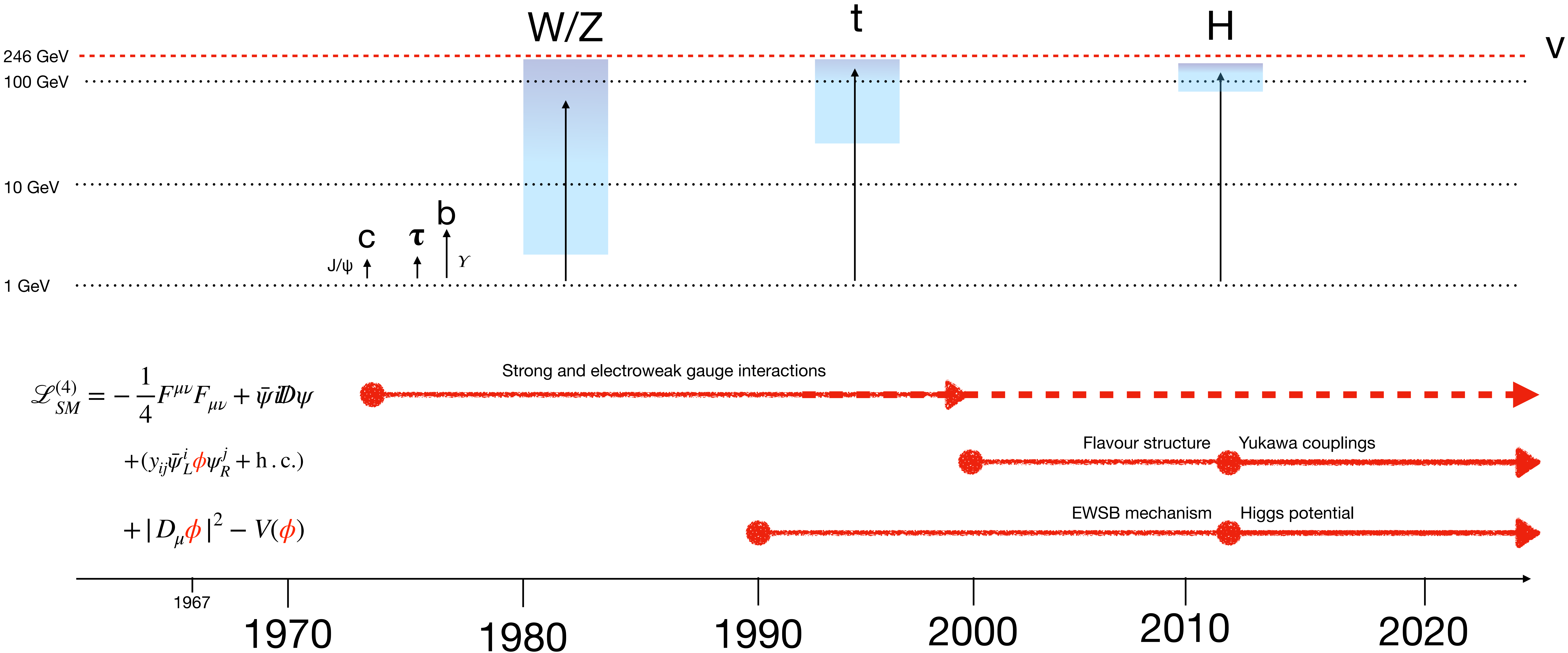
Experimental point of view

The story of collider physics in the last 60 years is marked by the accelerators eras and punctuated by key discoveries



(A) theorist's point of view

The story of collider physics in the last 60 years is the slow yet steady turning of the Standard Model into a Standard Theory for Strong and EW interactions.



$$\mathscr{L}^{(4)}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi$$

$$+(y_{ij}\bar{\psi}^{i}_{L}\phi\psi^{j}_{R} + \mathrm{h.c.})$$

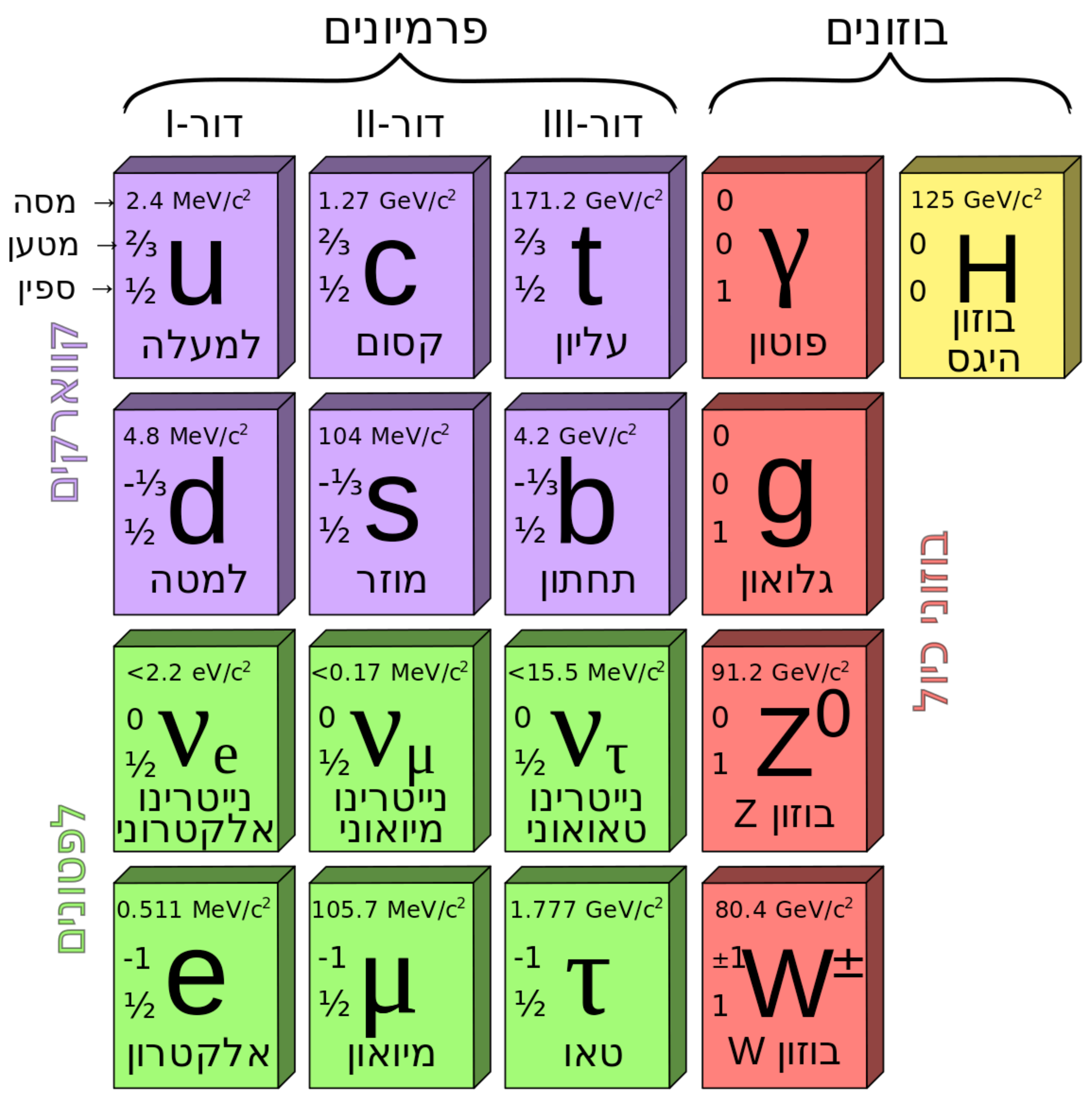
$$+|D_{\mu}\phi|^{2} - V(\phi)$$

Where do we stand?

$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D}\psi + (y_{ij}\bar{\psi}_L^i \phi \psi_R^j + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

3 gauge forces

1 scalar force



	פרמיונים			בוזונים		
	דור-I	דור-II	דור-III			
מסה → מטען → ספין → קווארקים	2.4 MeV/c^2 ⅔ ½ u למעלה	1.27 GeV/c^2 ⅔ ½ c קסום	171.2 GeV/c^2 ⅔ ½ t עליון	0 0 1 γ פוטון	בוזוני כוח	125 GeV/c^2 0 0 H בוזון היגס
קווארקים	4.8 MeV/c^2 -⅓ ½ d למטה	104 MeV/c^2 -⅓ ½ s מוזר	4.2 GeV/c^2 -⅓ ½ b תחתון	0 0 1 g גלואון		
לפטונים	<2.2 eV/c^2 0 ½ ν_e ניטרינו אלקטרוני	<0.17 MeV/c^2 0 ½ ν_μ ניטרינו מיואוני	<15.5 MeV/c^2 0 ½ ν_τ ניטרינו טאואוני	91.2 GeV/c^2 0 1 Z^0 בוזון Z		
לפטונים	0.511 MeV/c^2 -1 ½ e אלקטרון	105.7 MeV/c^2 -1 ½ μ מיואון	1.777 GeV/c^2 -1 ½ τ טאו	80.4 GeV/c^2 ±1 1 $W^\pm$ בוזון W		

- SU(3)$_c$ x SU(2)$_L$ x U(1)$_Y$ gauge symmetries
- Matter is organised in chiral multiplets of the fund. representation
- The SU(2) x U(1) symmetry is spontaneously broken to U(1)$_{EM}$
- Yukawa interactions lead to fermion masses, mixing and CP violation
- Matter+gauge group => Anomaly free
- Neutrino masses can be accommodated in a natural way

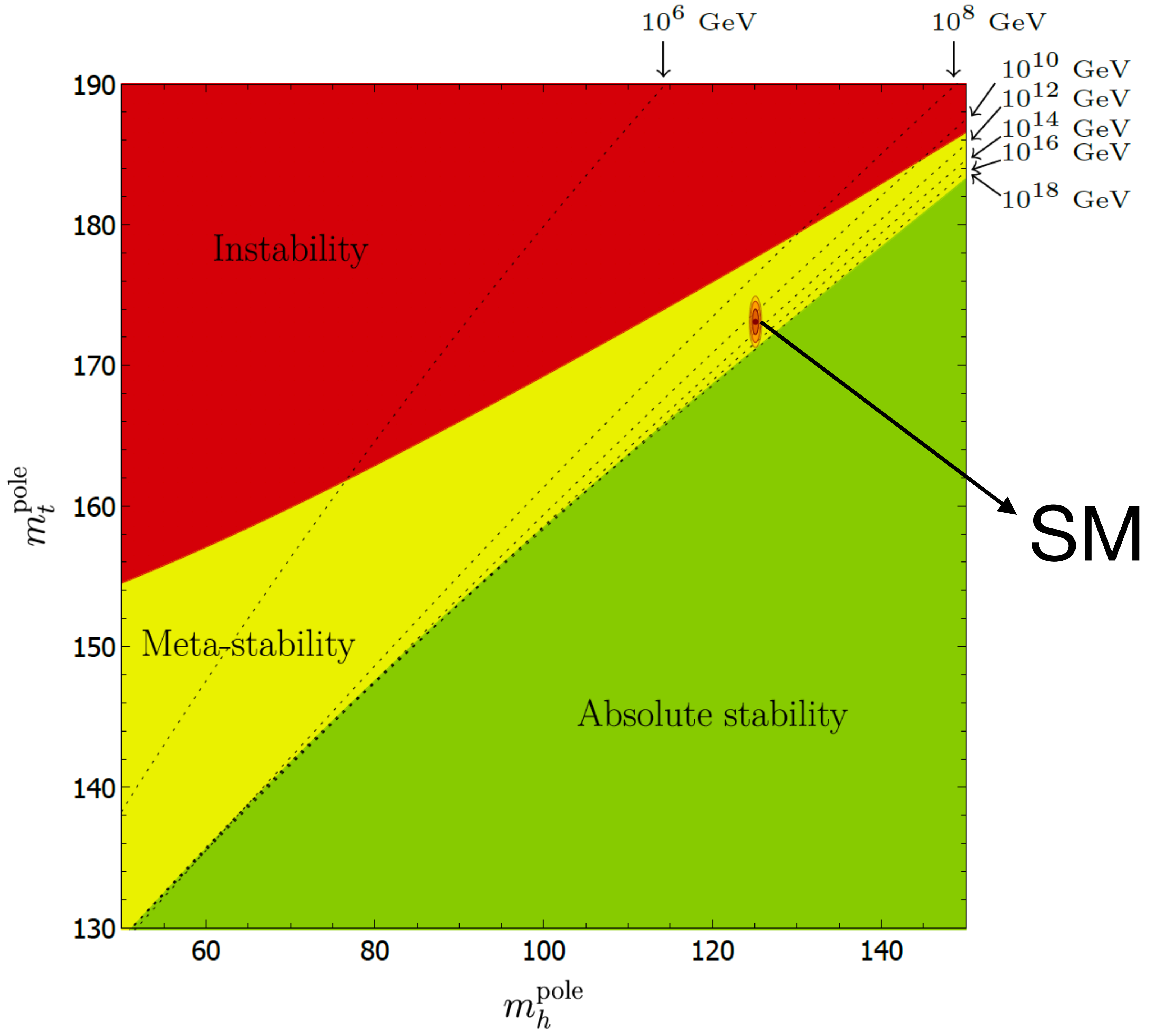
Where do we stand?

$$\mathcal{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}_L^i \phi \psi_R^j + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

MF, CPV, Flavour

Custiodial, MV

EWBG



[Andreassen et al. 1707.08124]

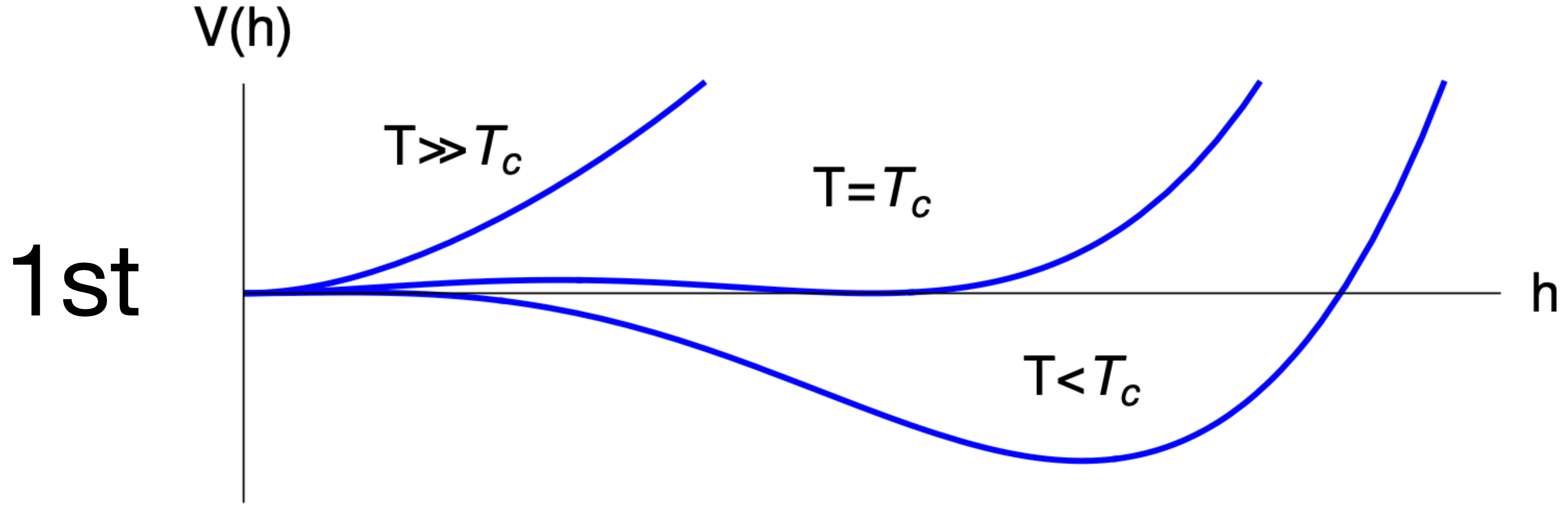
Apparently accidental, but key aspects for successful phenomenology:

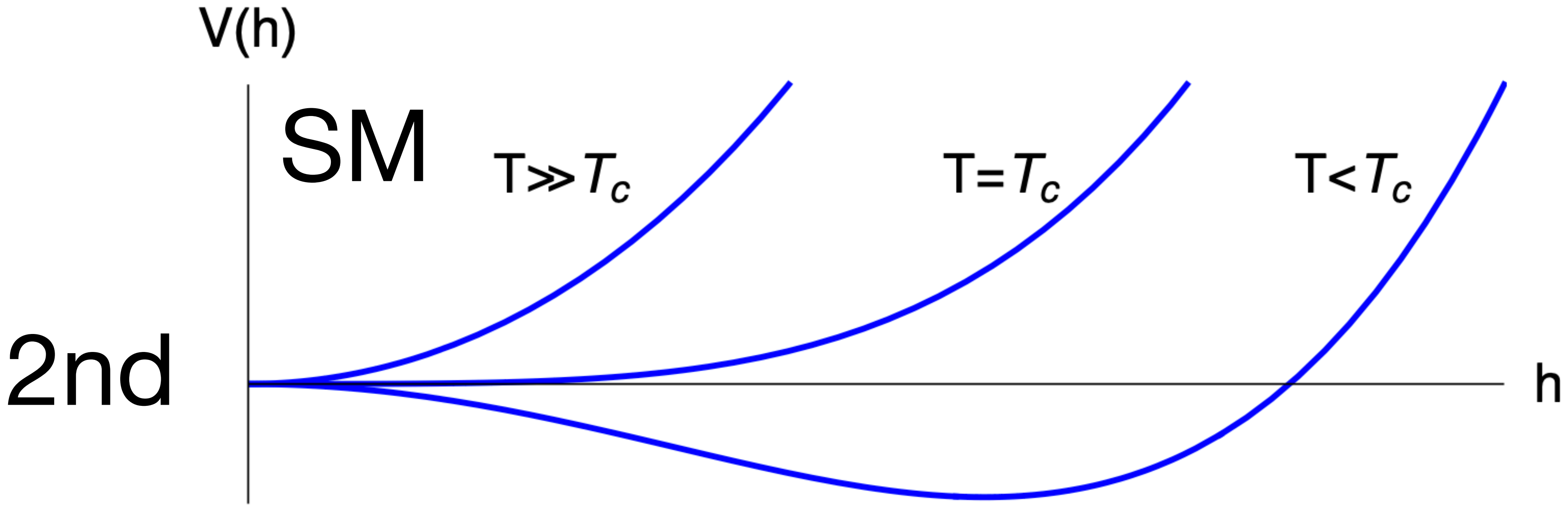
- Lepton and Baryon number conservation
- Custodial symmetry
- Absence of FCN interactions
- Small and hierarchical mixing among quarks
- Collective suppression of CP violation
- IR values of the parameters do not indicate any problem at high scales, including vacuum stability

All these aspects are not only difficult to explain in one go, but are also typically not respected by extensions of the SM.

Where do we stand?

$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}_L^i \phi \psi_R^j + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$





Yet many aspects of the SM are problematic vis-à-vis phenomenology:

- EWBG difficult because of smallness of CPV and no 1st order transition
- Nature of Dark Matter
- Unnaturally small Higgs mass and its origin
- Unnaturally small strong CP violation
- Fermion mass hierarchy and origin of CP violation

Beyond SM theories typically address one of the above problems at the time. We don't have a precise idea of where the scale of NP might reside.

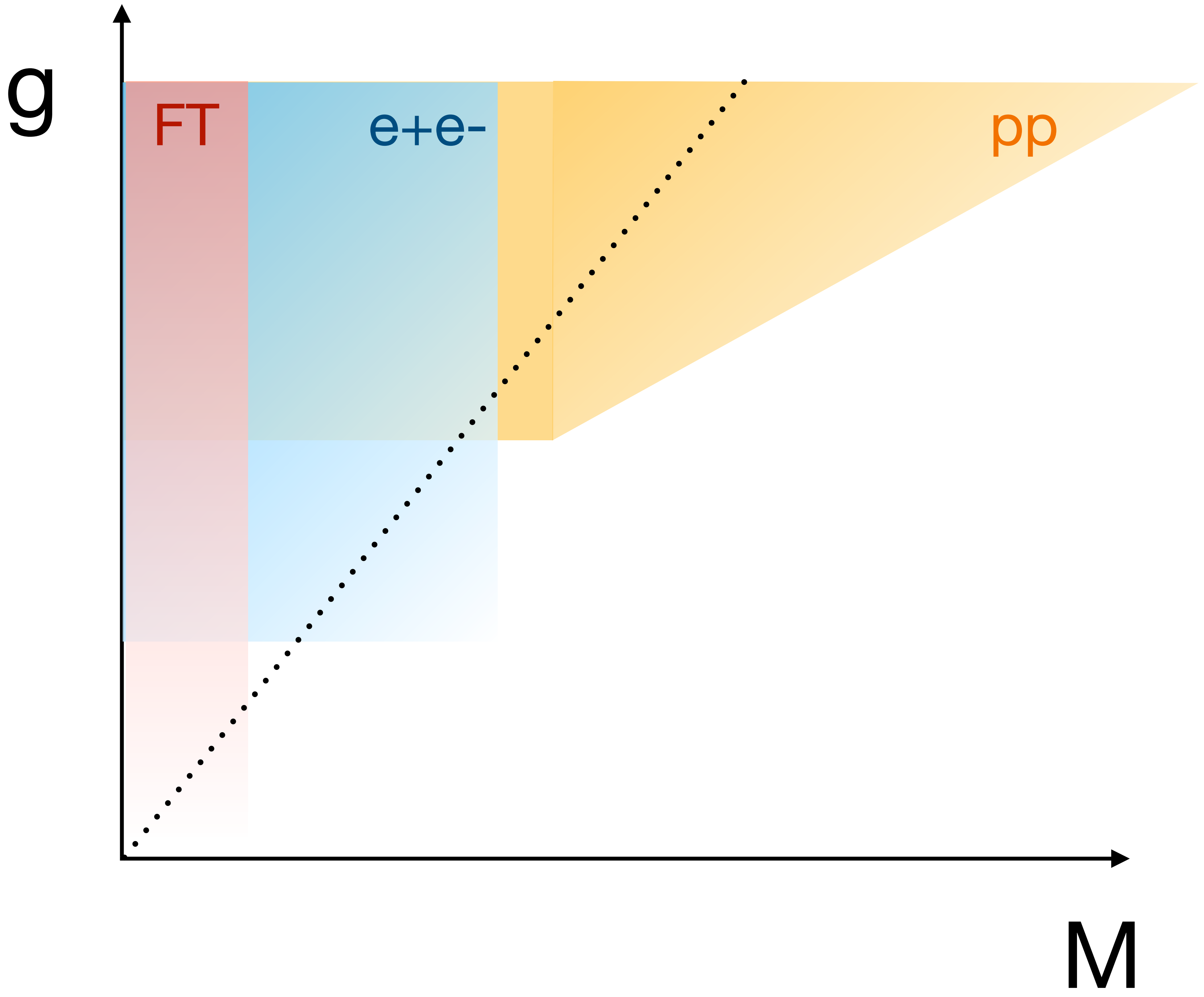
A quote

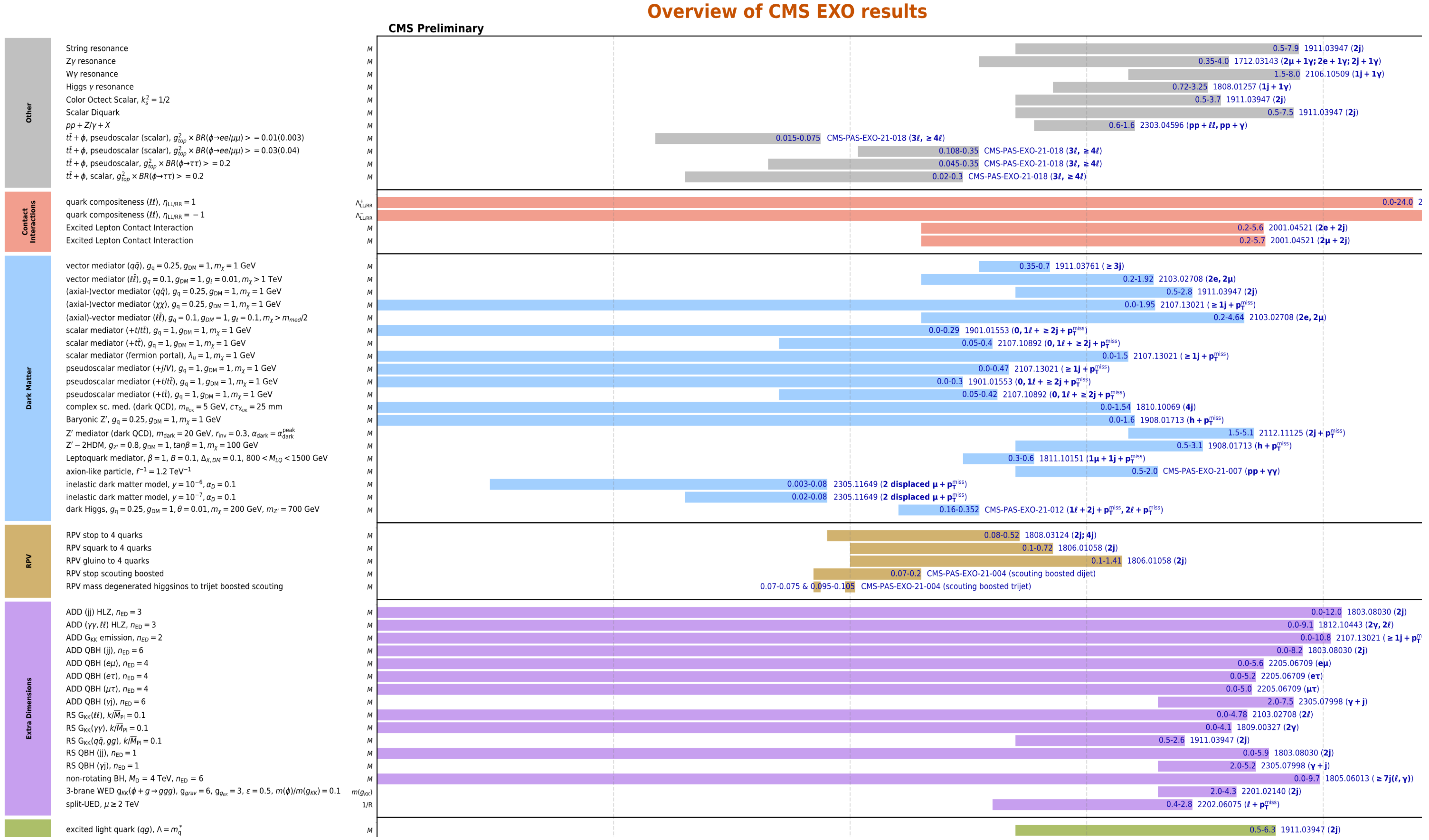
> [S]He who knows the art of
> the direct and the indirect approaches
> will be victorious.

Sun Tzu, The Art of War

Λ_{BSM} is low

BSM direct searches





$\Lambda_{\rm BSM}$ is high

Effective field theory

Λ_{UV}

TeV

Simplicity 🙂

Naturalness ☹️

TeV Λ_{UV}

Naturalness 🙂

Simplicity ☹️

$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \dots$$

$m_h^2 \simeq \Lambda^2$

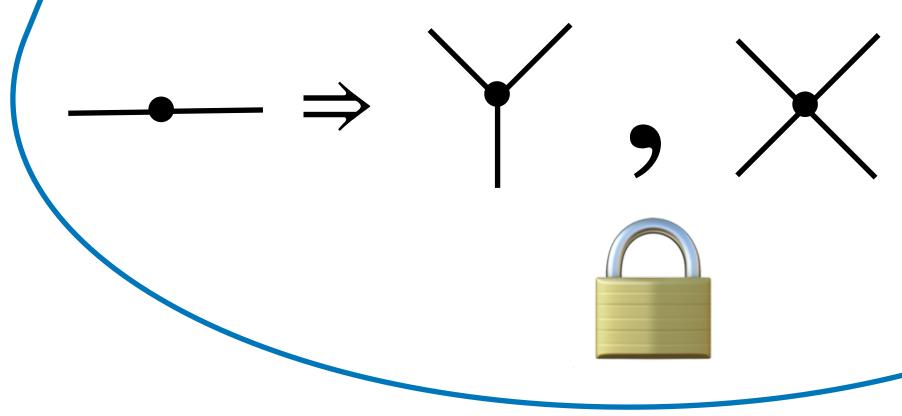
$\Rightarrow \Lambda \simeq 10^3$ GeV

$m_\nu = 0$

$U(1)_L^3 \times U(1)_B$

GIM

$Y_u, Y_d, Y_l \Rightarrow \cancel{\text{Flavor}}$ & $\cancel{CP}$



$\cancel{U(1)}_L \to m_\nu \neq 0$ $\Rightarrow \Lambda \geq 10^{14}$ GeV

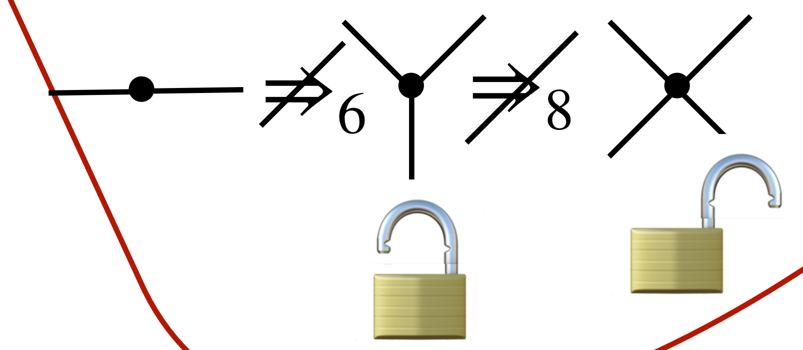
$\cancel{\text{Flavor}} \Rightarrow \mu \to e\gamma, \Delta m_K, \dots$

$\Rightarrow \Lambda \geq 10^{6}$ GeV

$\cancel{CP} \Rightarrow$ edm's

Dipoles $\Rightarrow (g-2)_\mu$

$U(1)_B \Rightarrow p \to \pi^0 e^+$ $\Rightarrow \Lambda \geq 10^{15}$ GeV

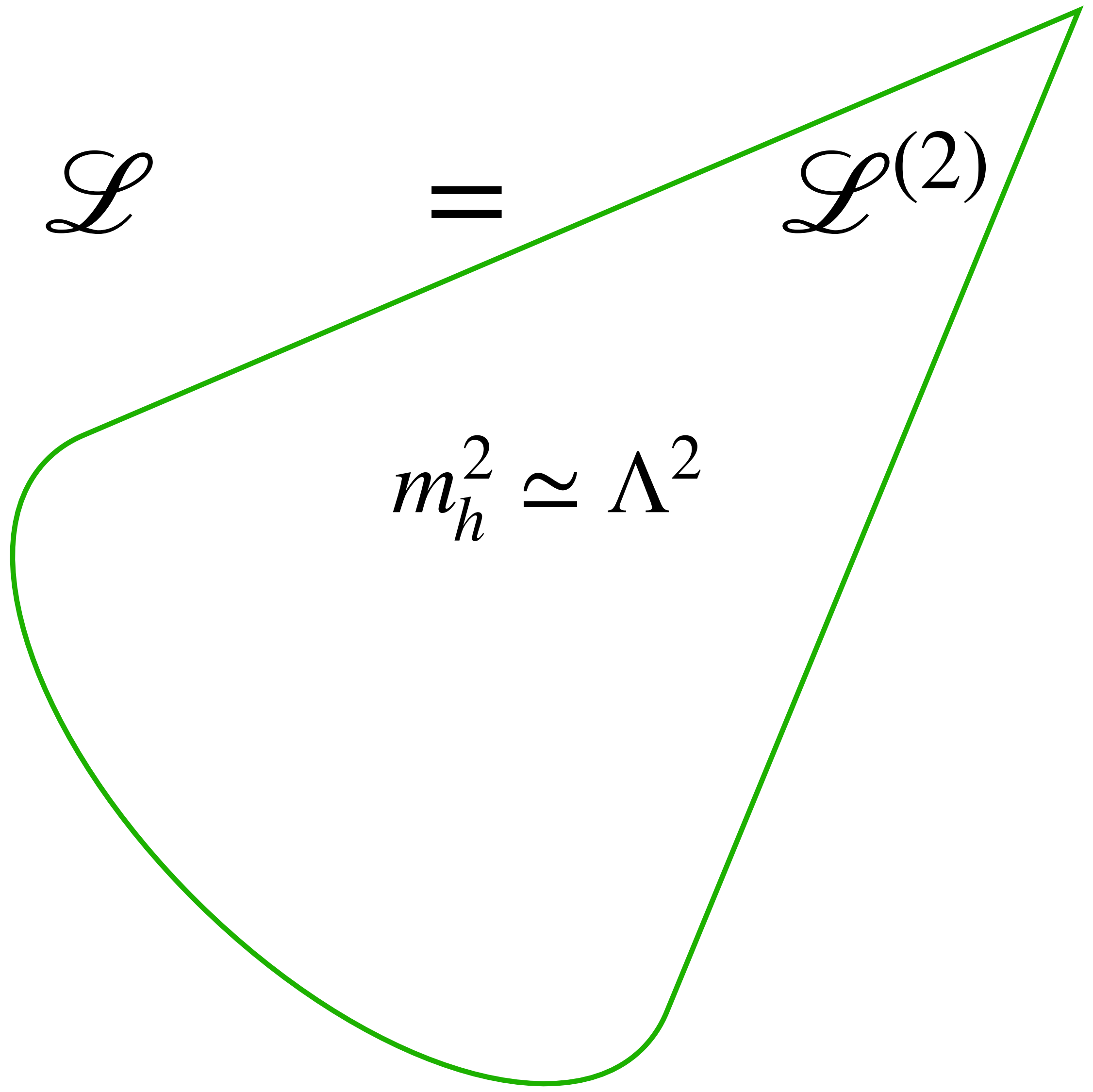


$\Rightarrow \Lambda \geq 10^{3}$ GeV

Rattazzi®

Λ_{BSM} is high

Effective field theory



Defining the amount of “tuning”

$$\varepsilon \equiv m_H^2/\Delta m_H^2$$

Consider the case of New Physics due to the presence of a top parter.
Different level of sensitivity can be realised:

- ***Soft:*** $\Delta m_H^2 \sim m_T^2$. This situation is realized in SUSY with soft terms generated at a high scale. In the absence of any tuning $m_T \sim m_H \sim 100\,\mathrm{GeV}$, within the energy range of LEP and Tevatron.
- ***SuperSoft:*** $\Delta m_H^2 \sim (3y_t^2)/(4\pi^2)\, m_T^2$. This situation is realized in SUSY with low scale mediation and in CH. Without any tuning one expects $m_T \sim m_H/\sqrt{3y_t^2/4\pi^2} \sim 450\,\mathrm{GeV}$, within the reach of the LHC.
- ***HyperSoft:*** $\Delta m_H^2 \sim (3\lambda_h)/(16\pi^2)\, m_T^2$. The mechanism of Neutral Naturalness is a prime example. The top partner mass is naturally pushed around 1.5 TeV.

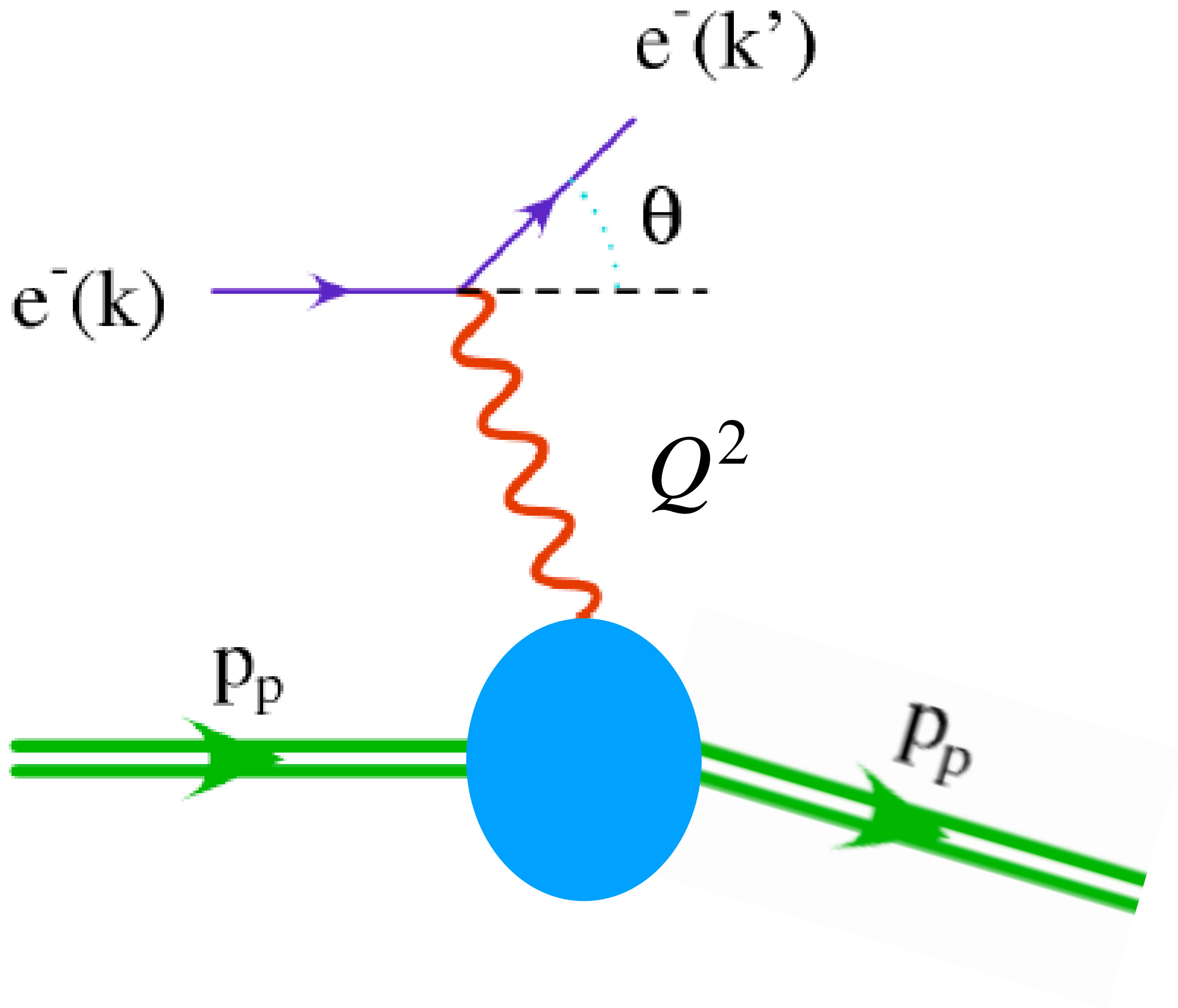
Rattazzi®GGI tea break

Λ_{BSM} is high

Effective field theory

Is the Higgs elementary?

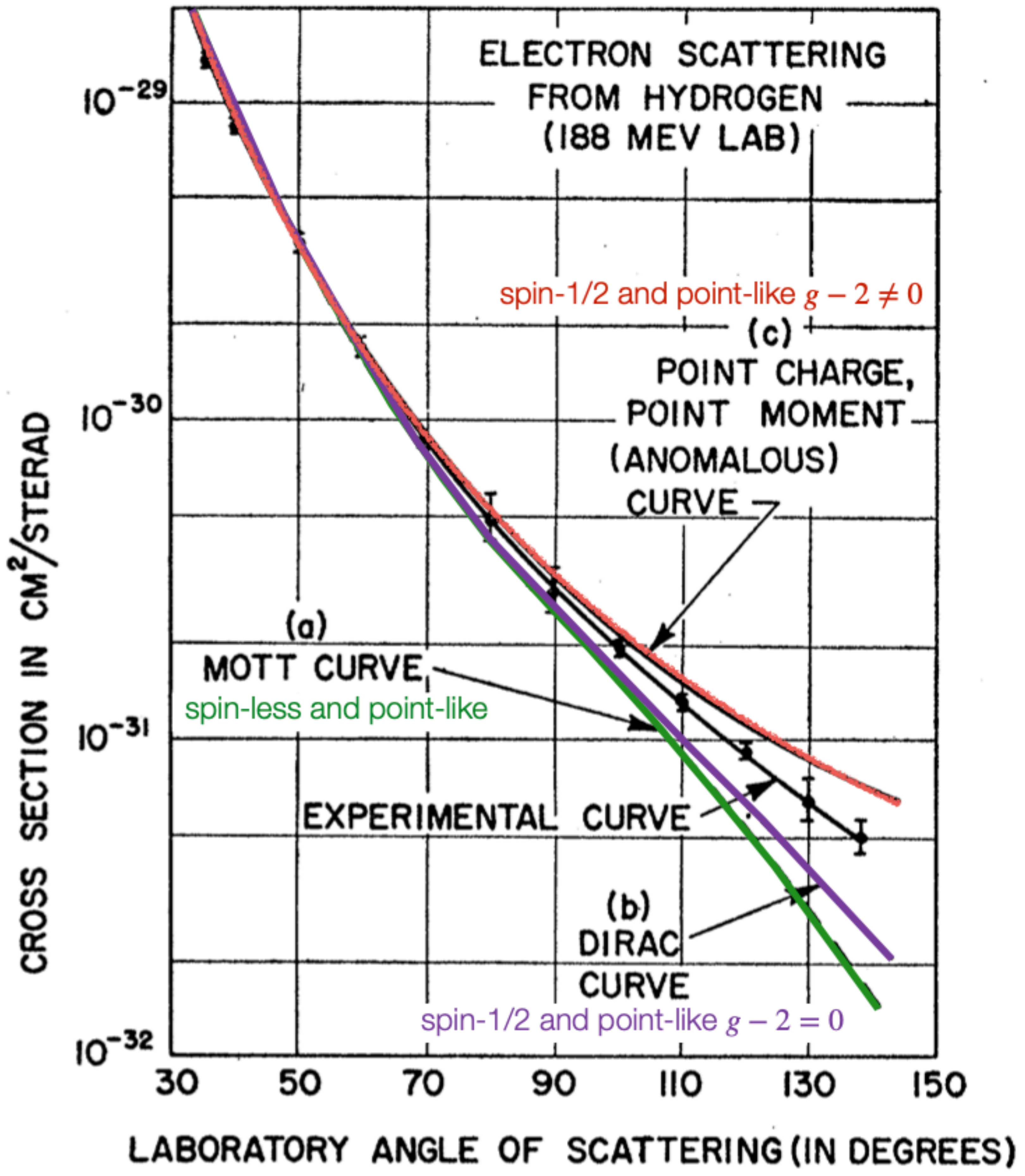
Remember the 1961 Nobel Prize:
internal structure of the proton



$$\frac{d\sigma_{\mathrm{elastic}}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\mathrm{point}} \cdot F^2_{\mathrm{elastic}}(q^2)$$

Higher-dimensional operator in the Lagrangian where the proton is elementary

R. Franceschini®

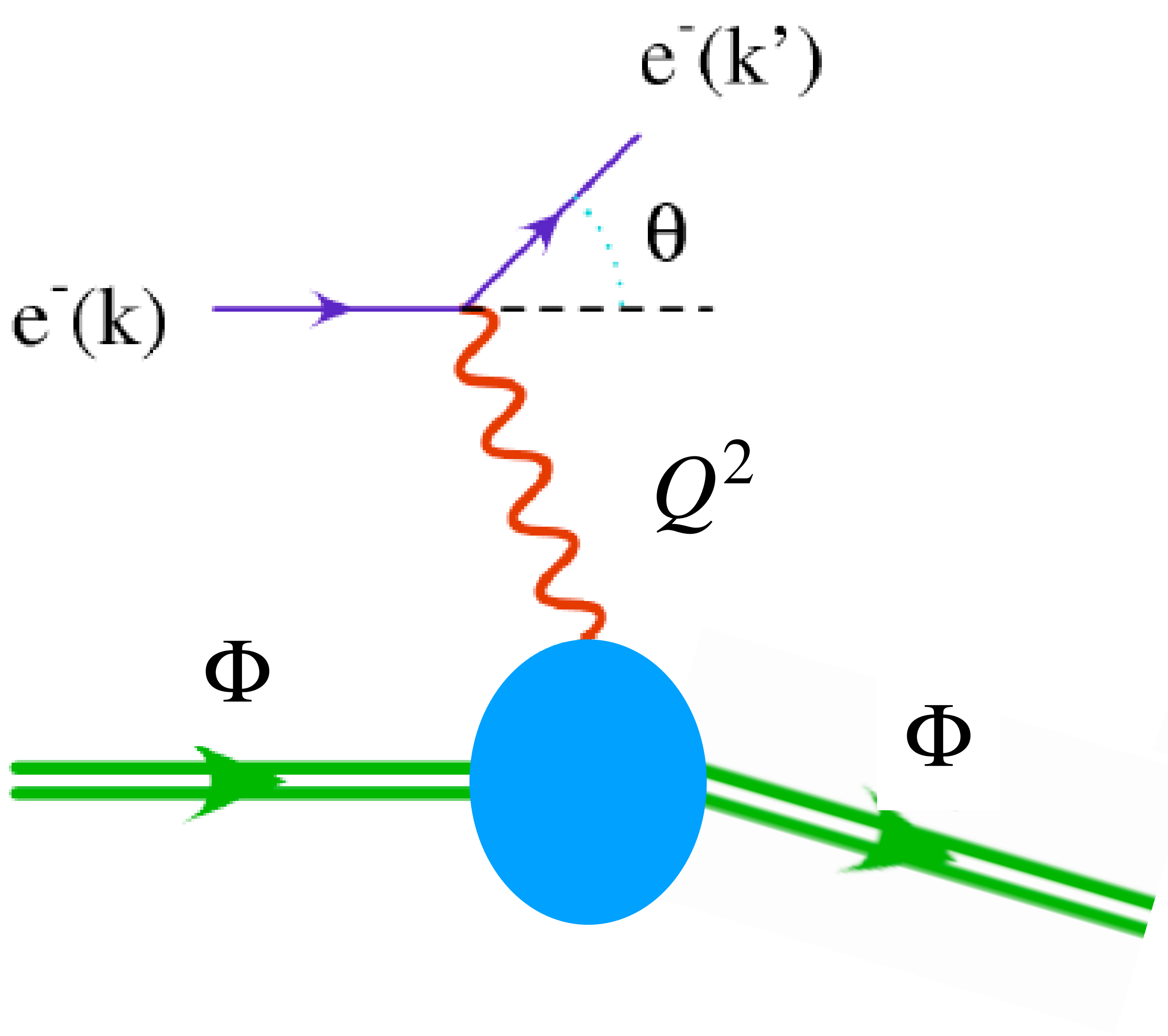


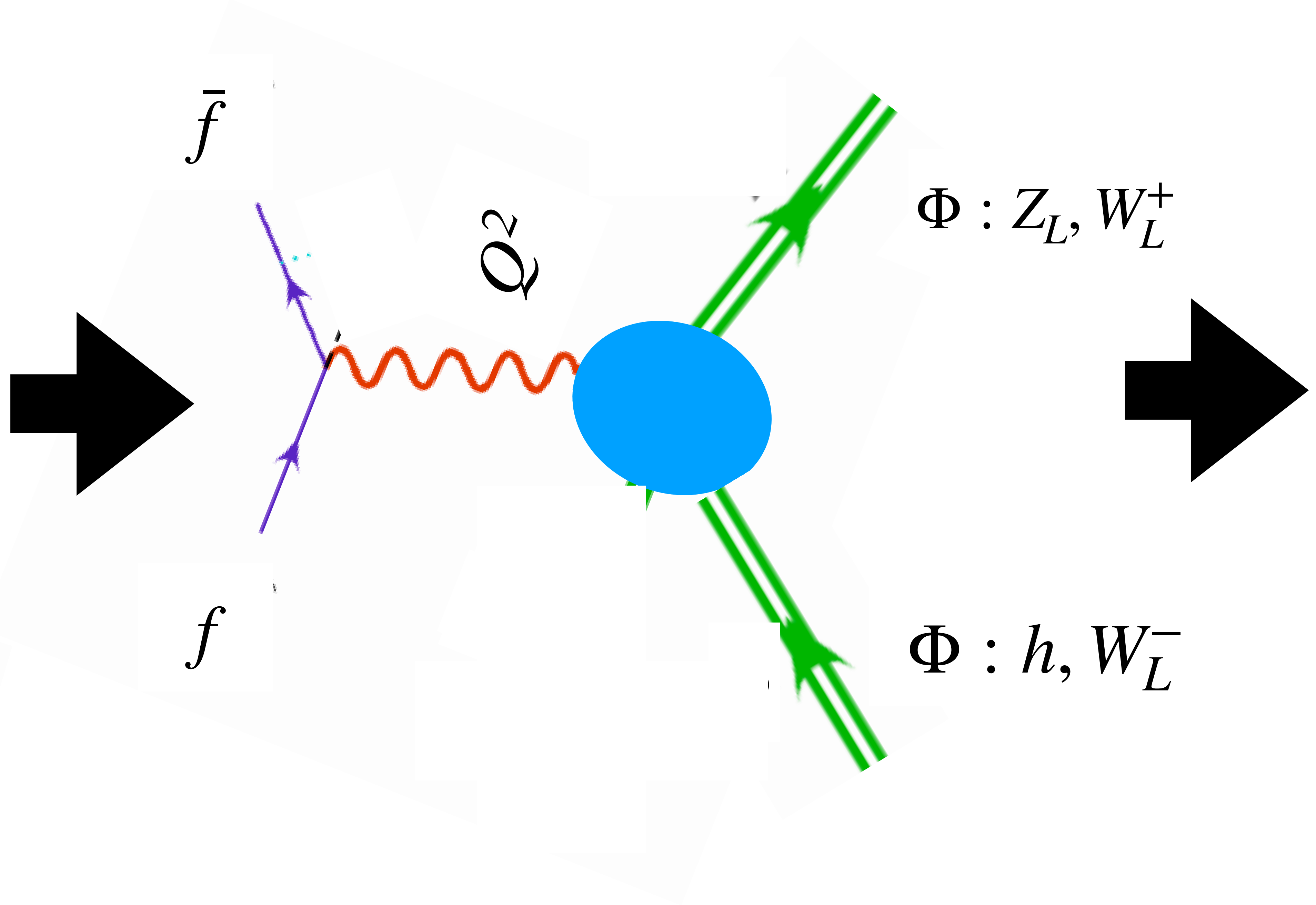
Λ_{BSM} is high

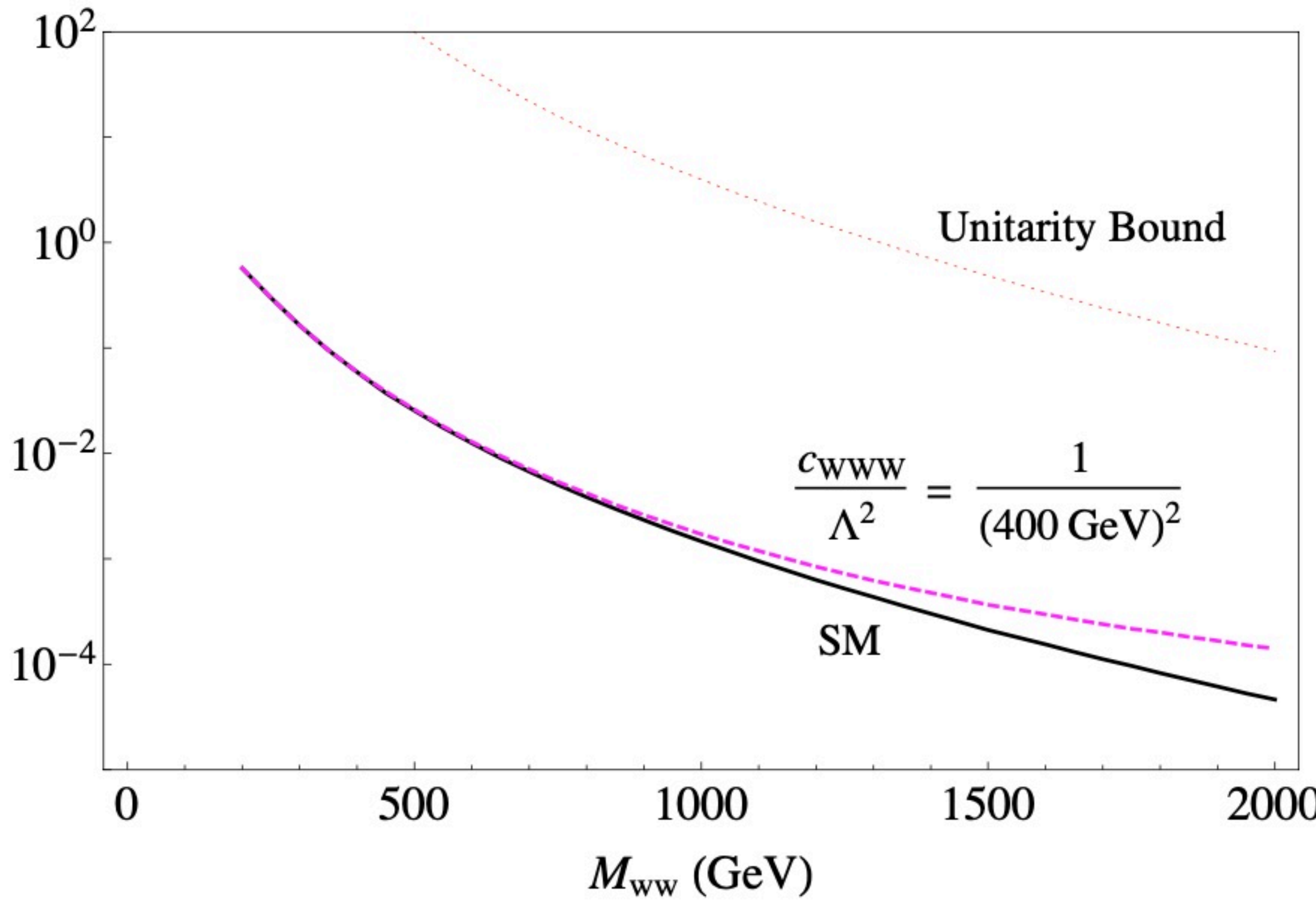
Effective field theory

Is the Higgs elementary?

What is the equivalent for the Higgs?



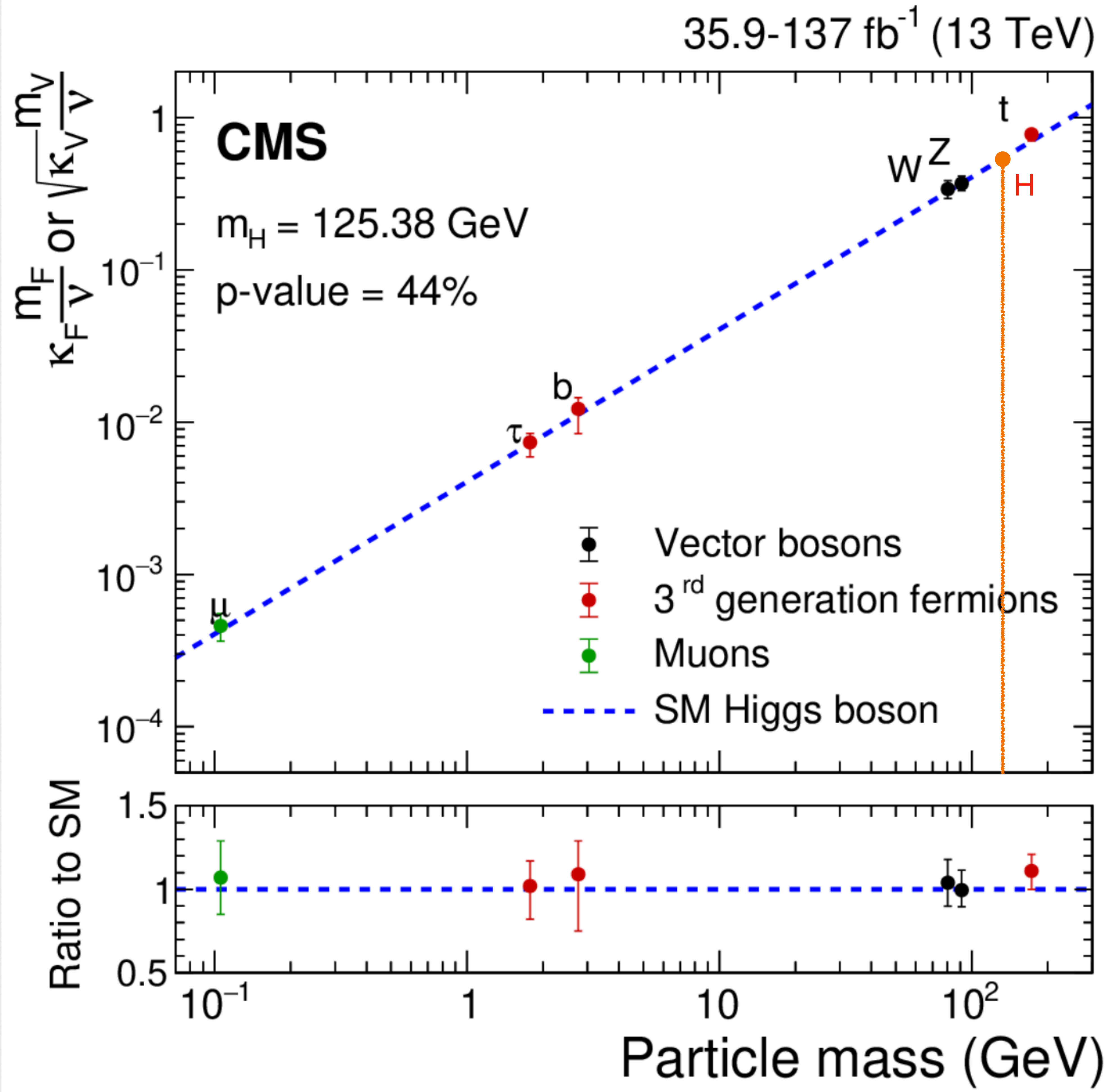




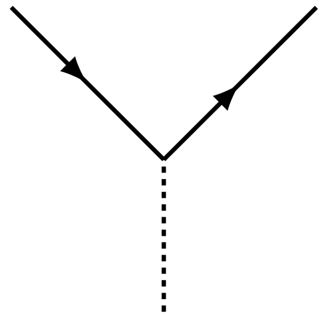
$$\frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

Present

Higgs couplings

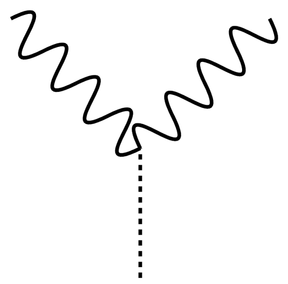


Unique mass generation mechanism for fermions/vectors and the scalar.

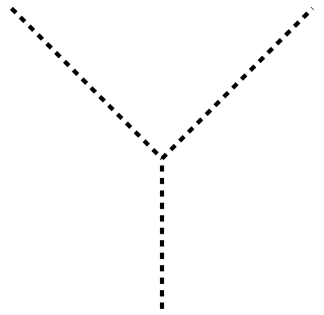


$$i\, m_f/v$$

$$ig m_W g_{\mu\nu} = 2i\, v g_{\mu\nu} \cdot m_W^2/v^2$$



$$ig\frac{m_Z}{\cos\theta_W} g_{\mu\nu} = 2iv g_{\mu\nu} \cdot m_Z^2/v^2$$



$$-3\, iv \cdot m_h^2/v^2$$

$\Bigg\}$ + 4 point interactions.

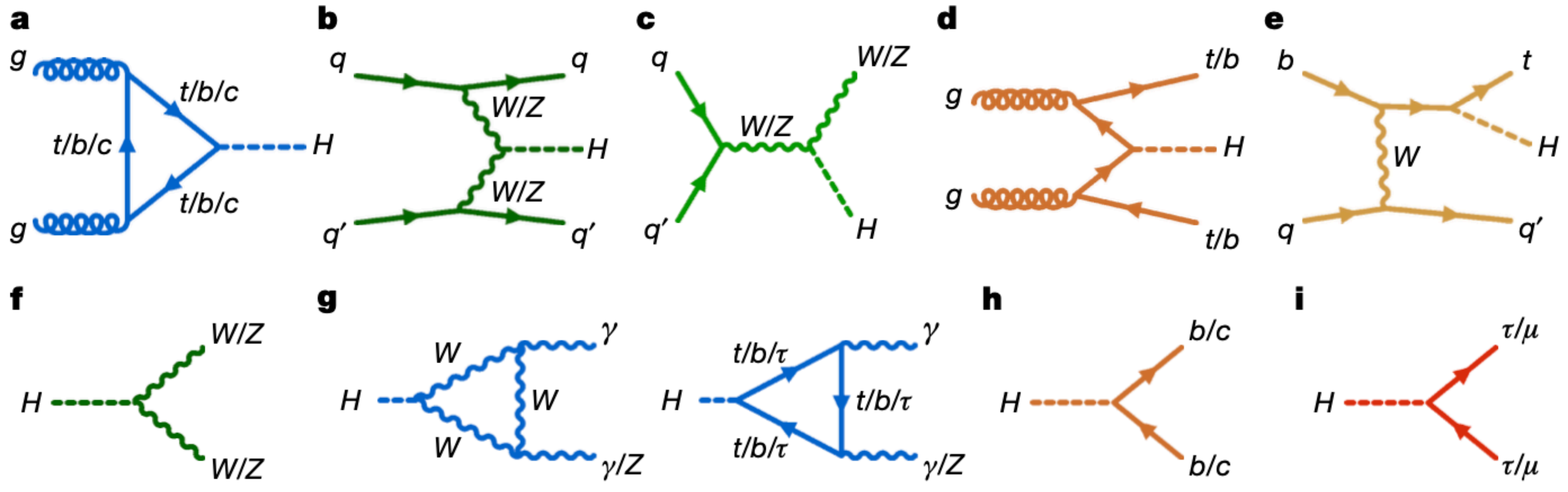
$$V(H) = \frac{m_H^2}{2}H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4}H^4 + \ldots$$

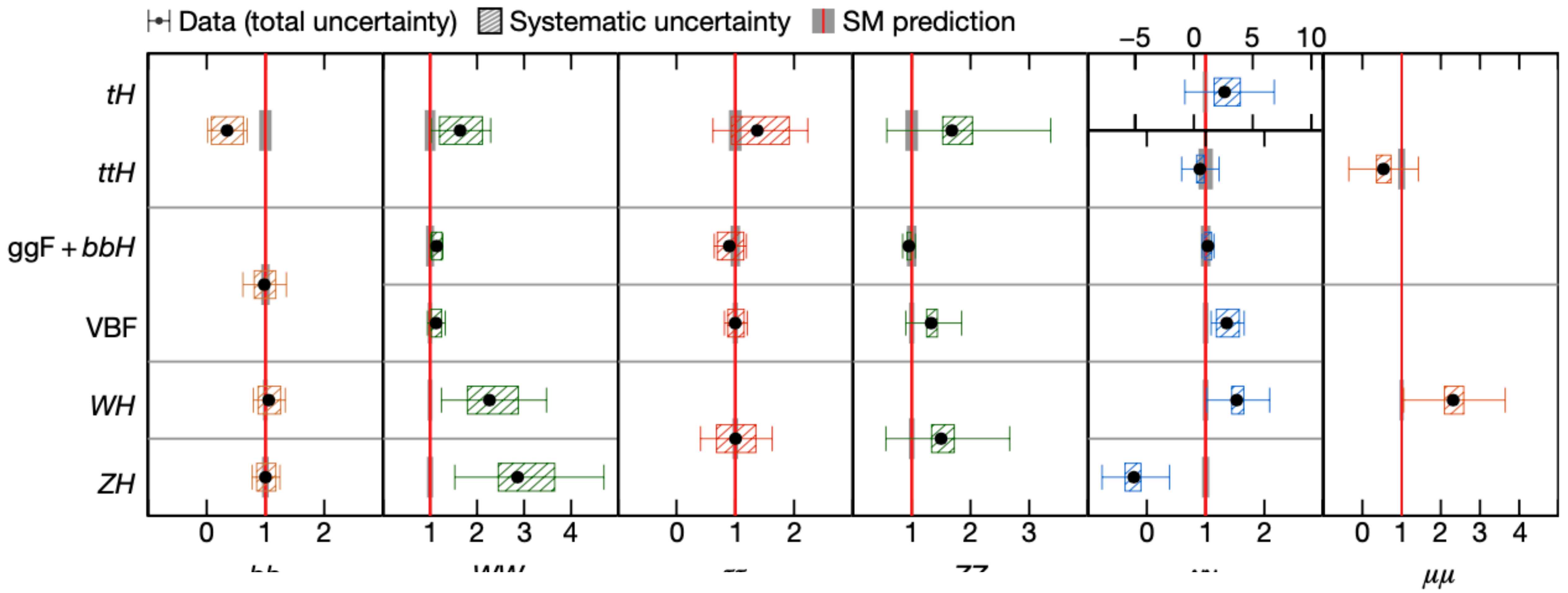
$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \quad \Rightarrow \left\{ \begin{array}{l} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{array} \right. \quad \left\{ \begin{array}{l} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{array} \right.$$

In the SM gauge invariance + SSB => constrained system. Two-point functions (propagators/masses) fix the 3-point and 4-point interactions!

Present

Higgs couplings





$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \;\pm 0.03\,(\text{exp.}) \;\pm 0.04\,(\text{sig. th.}) \;\pm 0.02\,(\text{bkg. th.}).$$

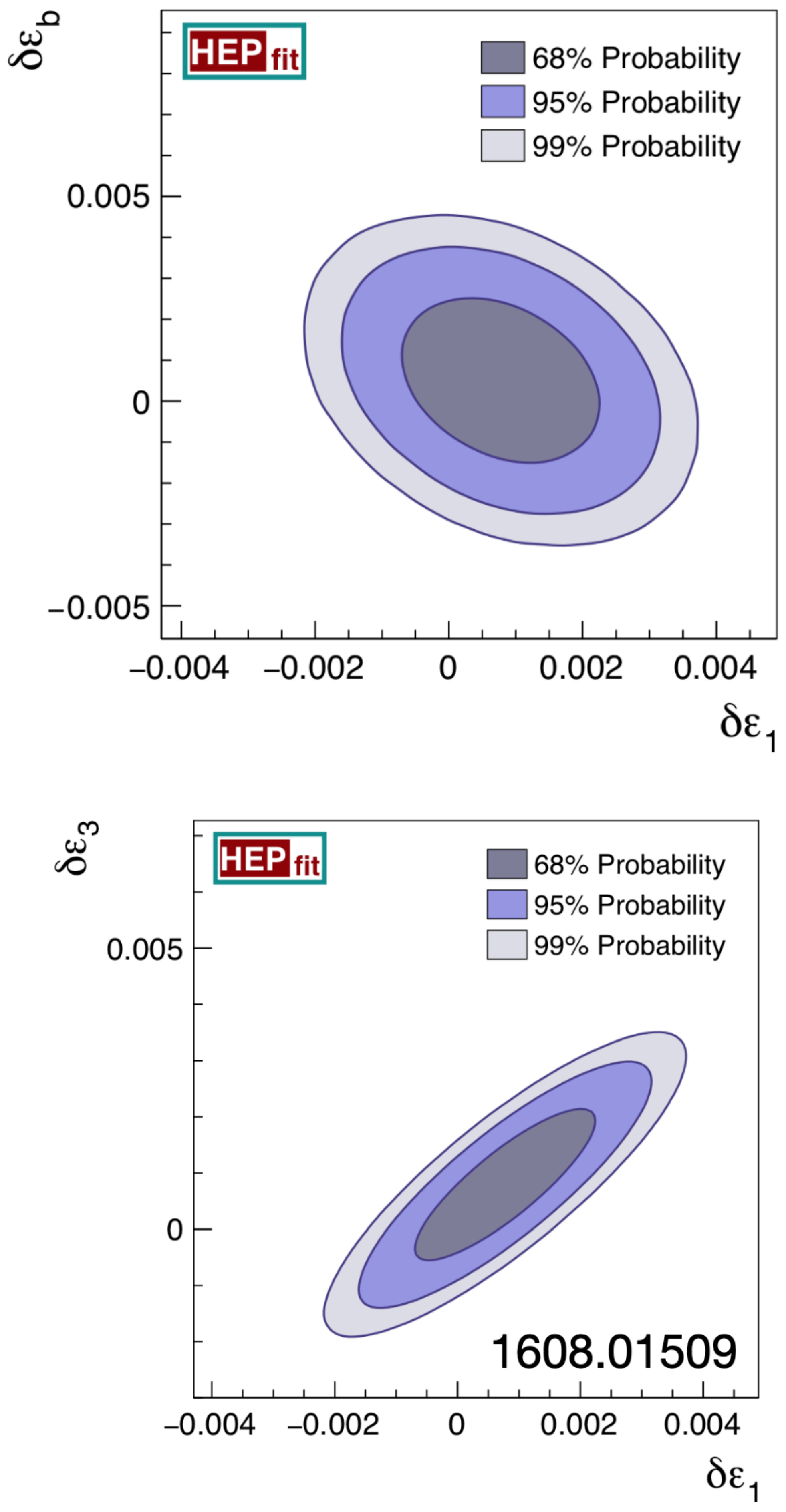
The deviations δg_H from the SM in single and multi-Higgs couplings satisfy

$$\delta g_H / {g_H}^{\text{SM}} \sim c\,\varepsilon$$

with *c* a coupling-dependent coefficient, and ε the Higgs mass correction. In basically all models, there always exists a set of couplings where *c* ~ *O*(1). The only exception is strictly supersoft SUSY, where one can cleverly go down to *c* ~ 0.1. Not surprisingly full Naturalness basically mandates *O*(1) deviations in Higgs couplings.

Present

EW precision



1608.01509

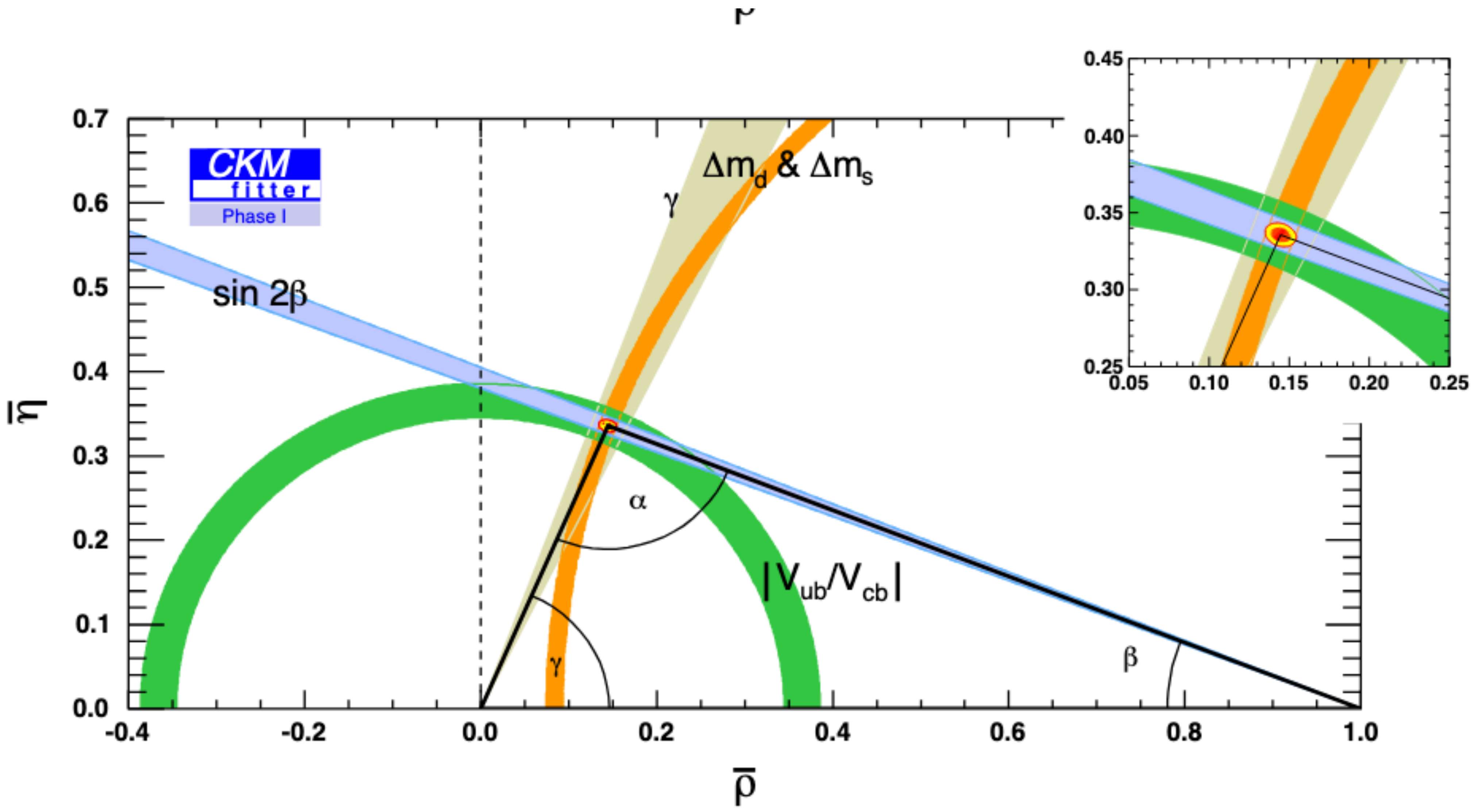
While Higgs couplings probe naturalness, EWPO sense the dynamics off EWSB indirectly via loops. Consider the S parameter,

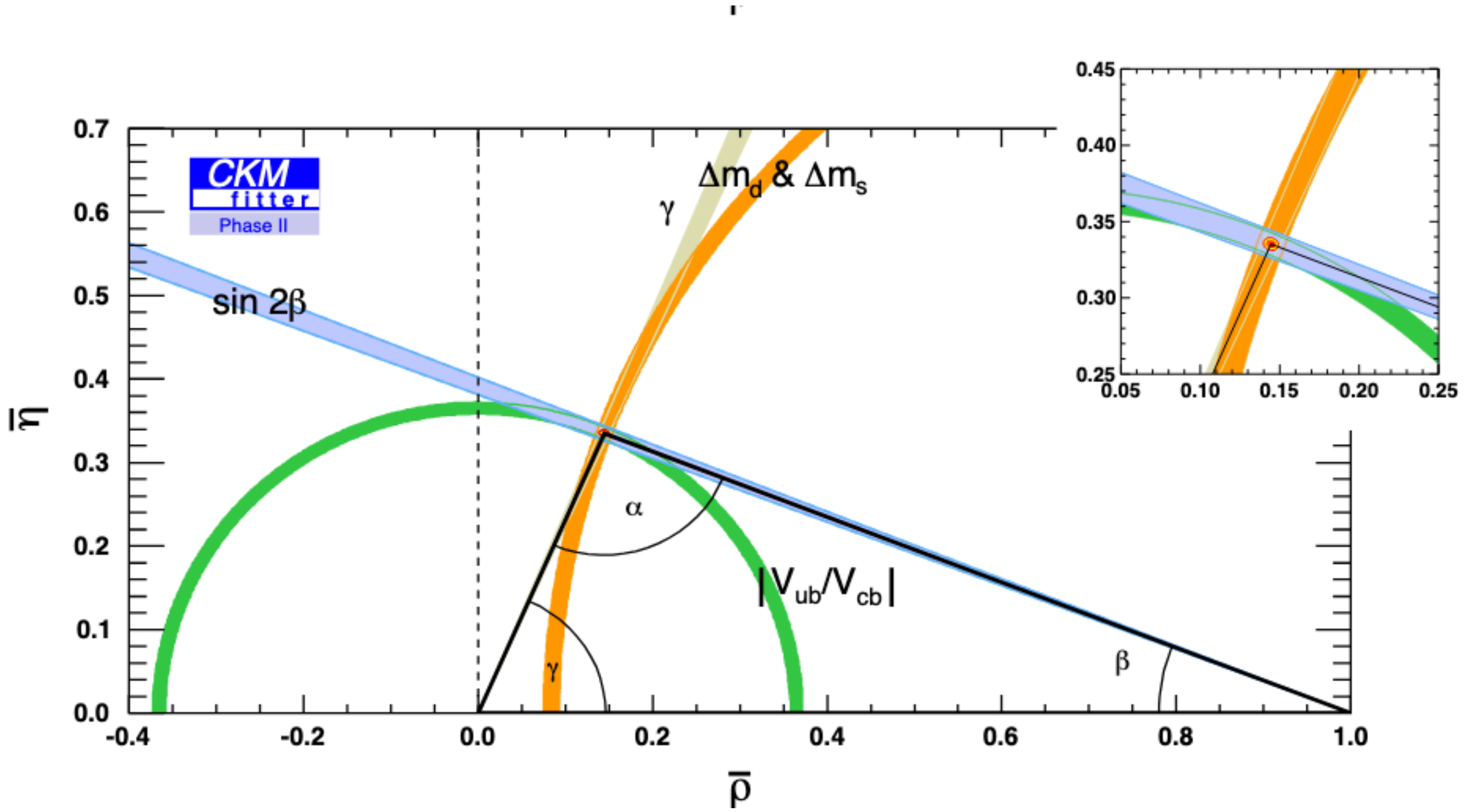
$$\widehat{S} \sim \frac{\alpha_W}{4\pi}\frac{g_*^2 v^2}{m_*^2} N \lesssim \frac{m_W^2}{m_*^2}$$

For CH one obtains $3 \cdot 10^{-2}\,\epsilon$,indicating a sensitivity of order 10^{-5} corresponds to 10^{-3} in the Higgs couplings. SUSY does not saturate the bound.

Present and near future

Flavor





(upgrade 2)

- O(10^{14}) b and c hadrons
- O(10^{11}) τ leptons

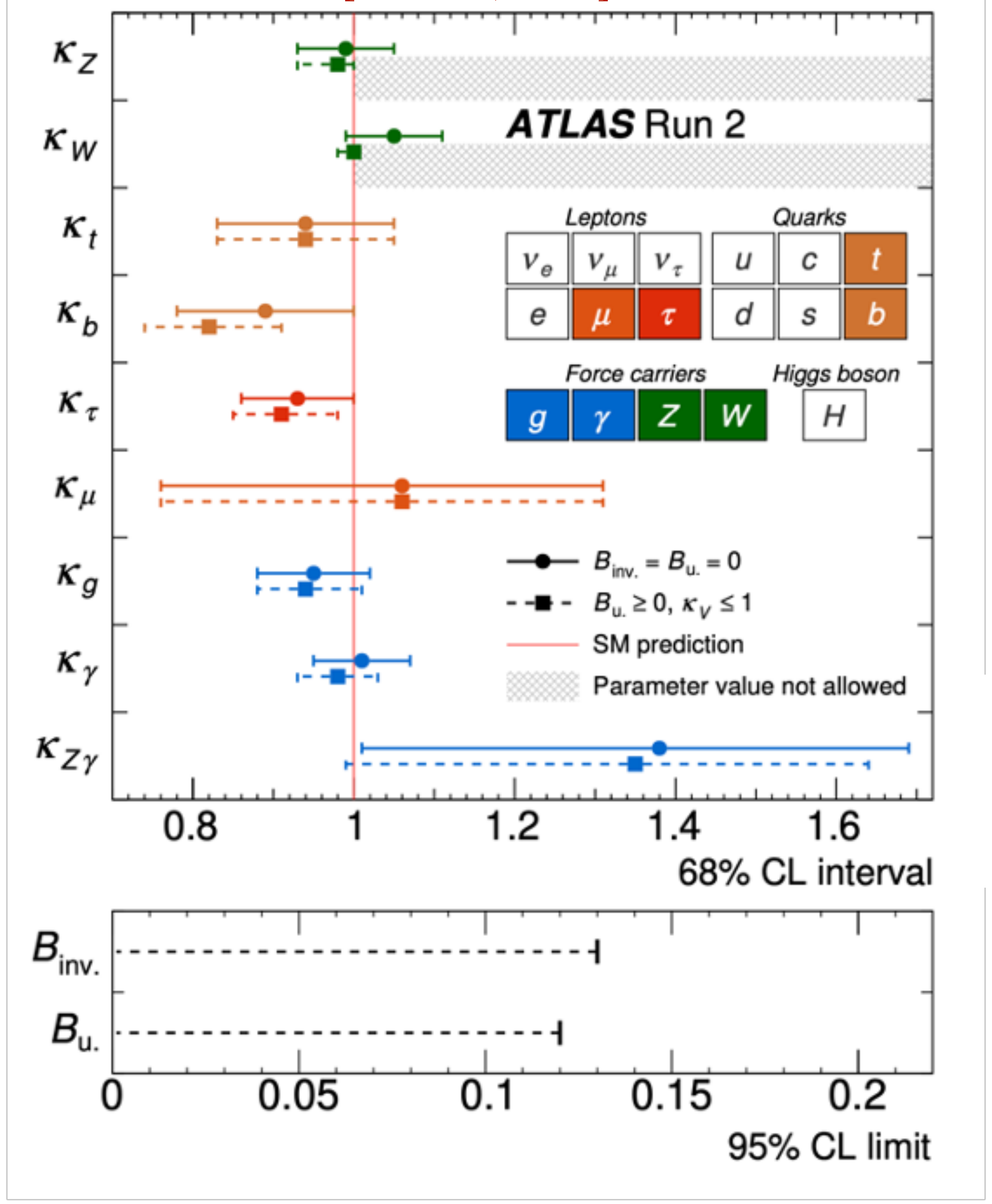
- O(10^{10}) B mesons
- O(10^{10}) τ's

in clean environment

The Higgs near future

Couplings at HL-LHC

[ATLAS, 2024]

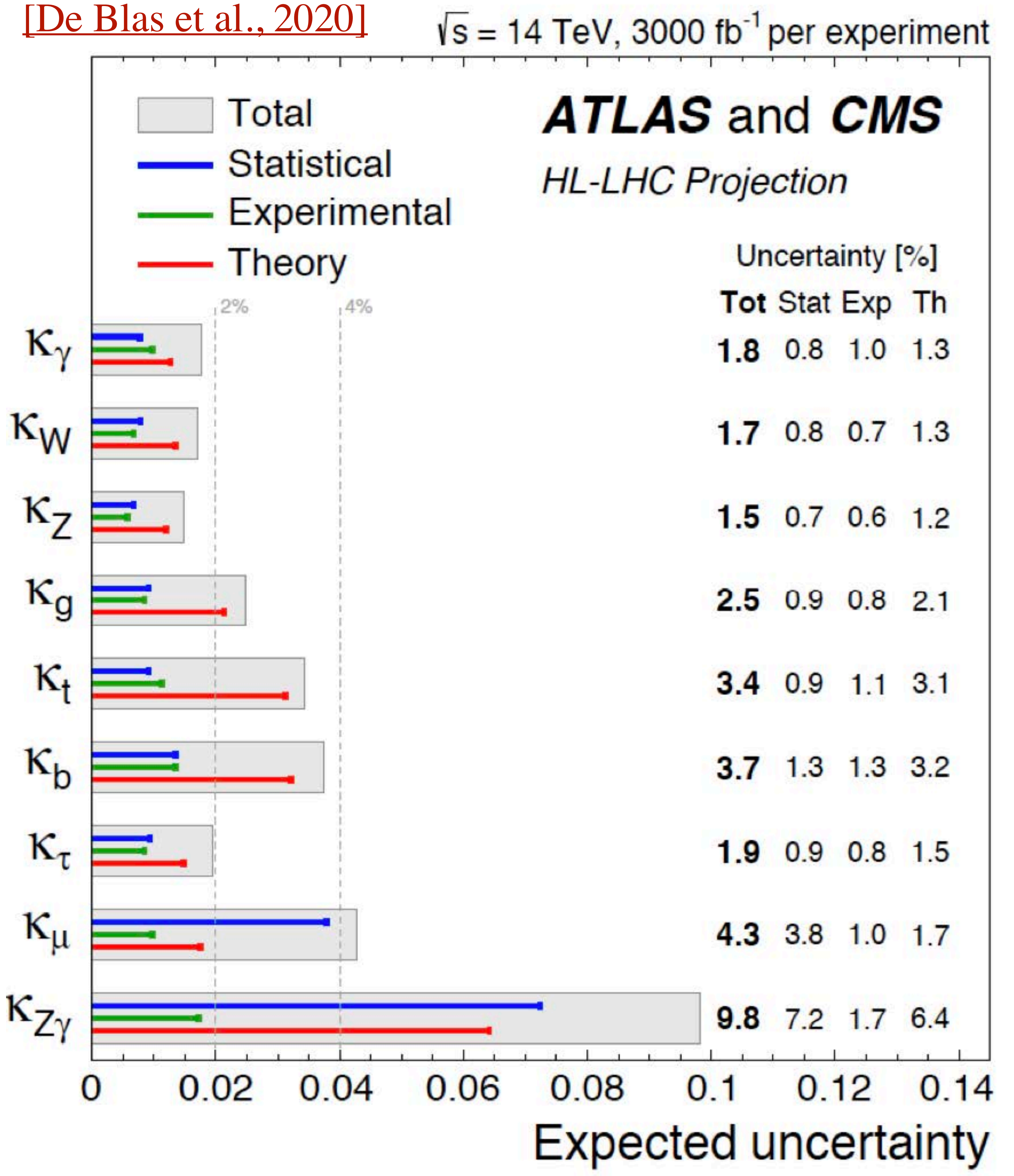


10-20% → 2-4%

$$\delta g_H / g_H{}^{SM} \sim c\,\varepsilon$$

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM}\kappa_i^2 \cdot \Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

[De Blas et al., 2020]



Uncertainty [%]

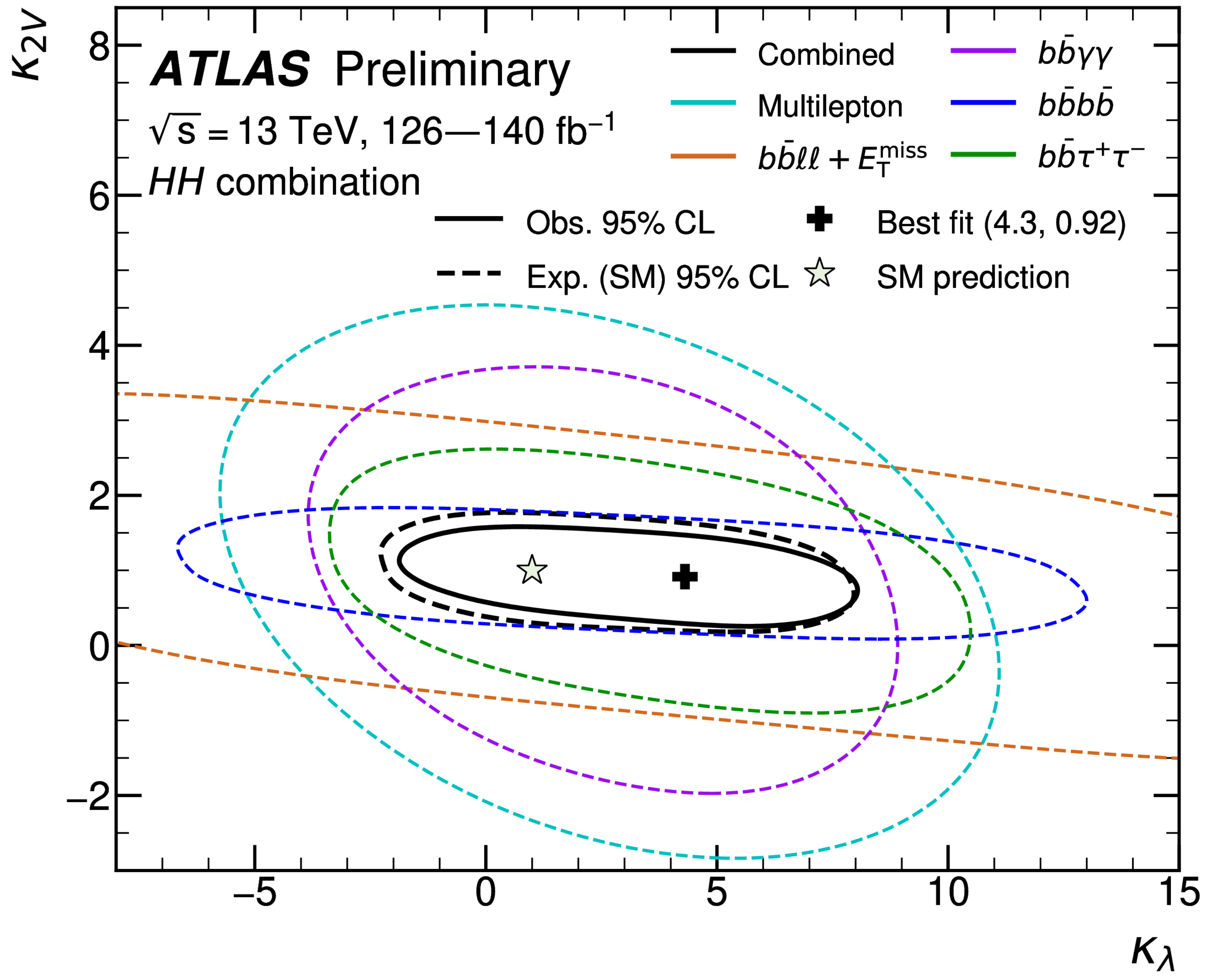
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

The Higgs near future

Higgs self-coupling

Now

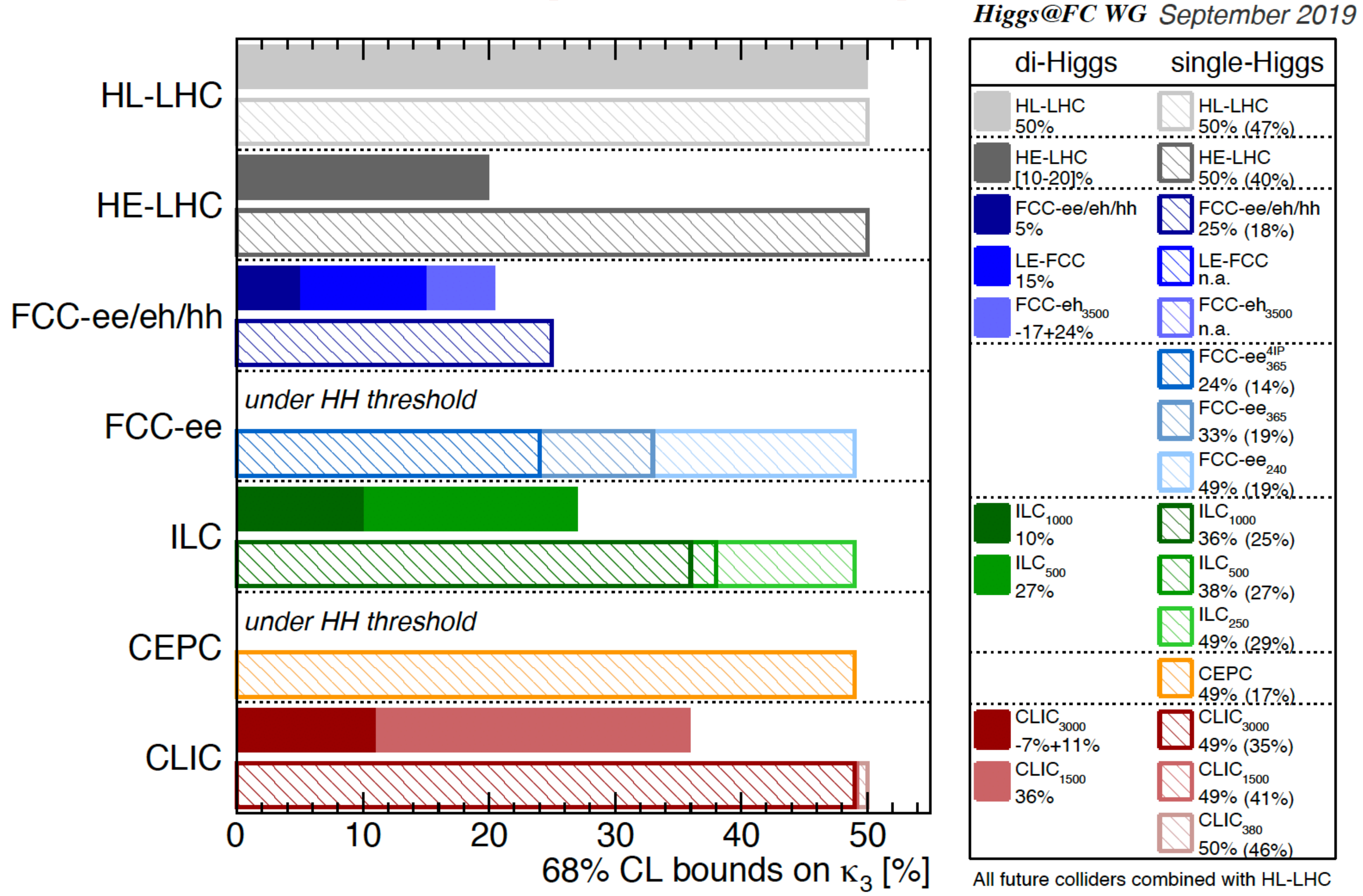
[ATLAS, 2024]



Current limits on k_λ and k_{2V}

Future

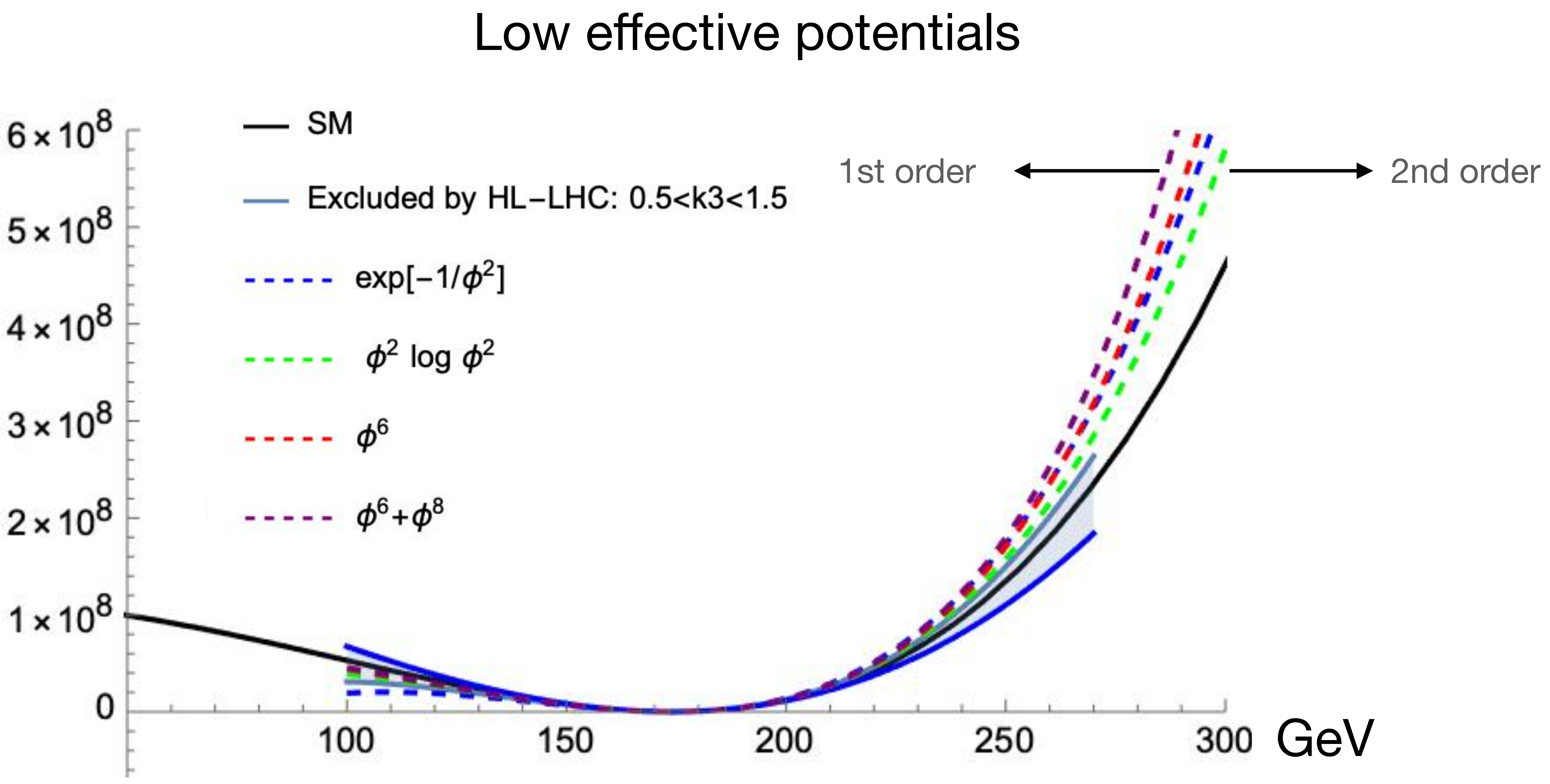
[De Blas et al., 2020]



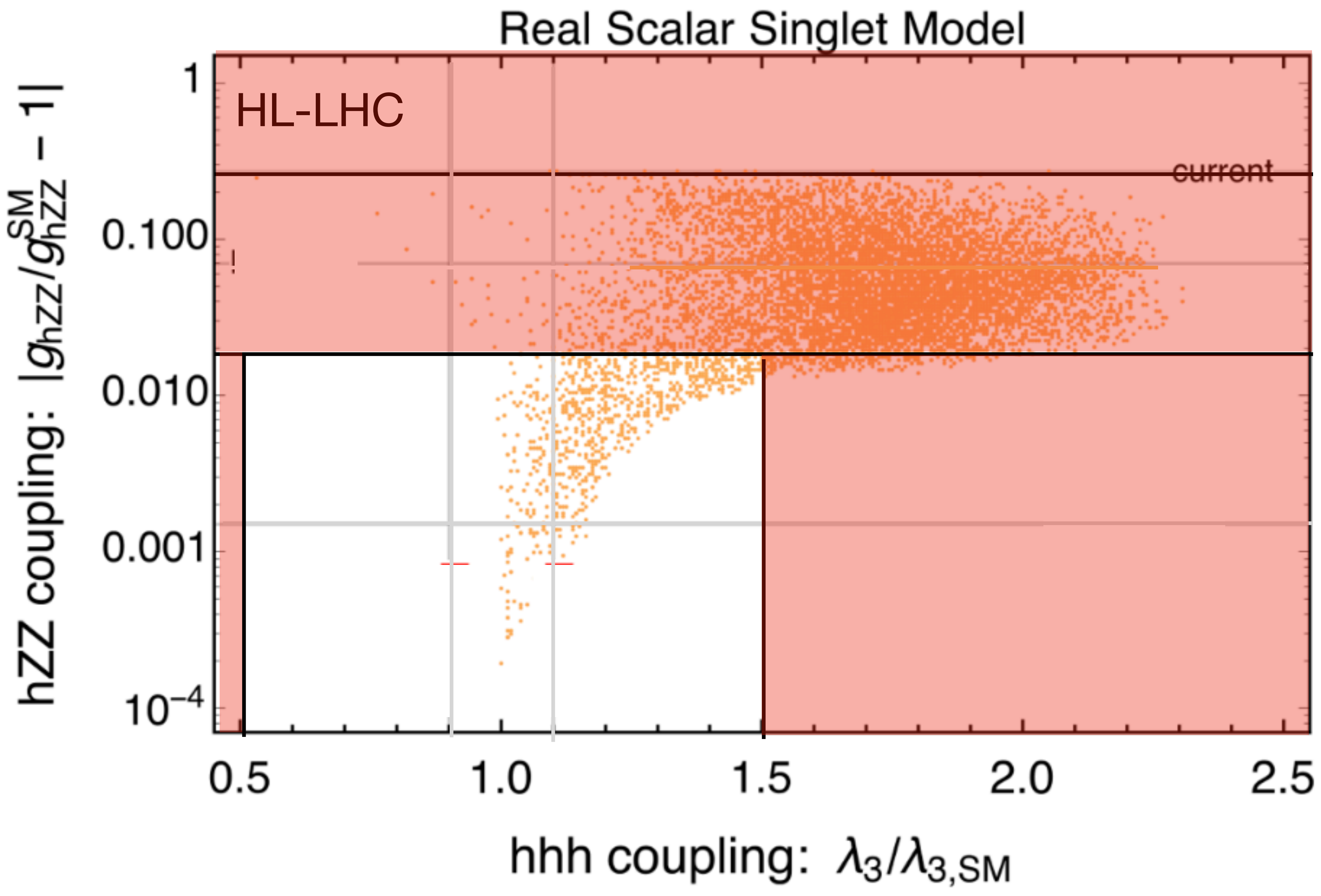
Future limits on k_λ

The Higgs near future

Higgs potential



Plot based on the results of 1711.00019 [hep-ph]



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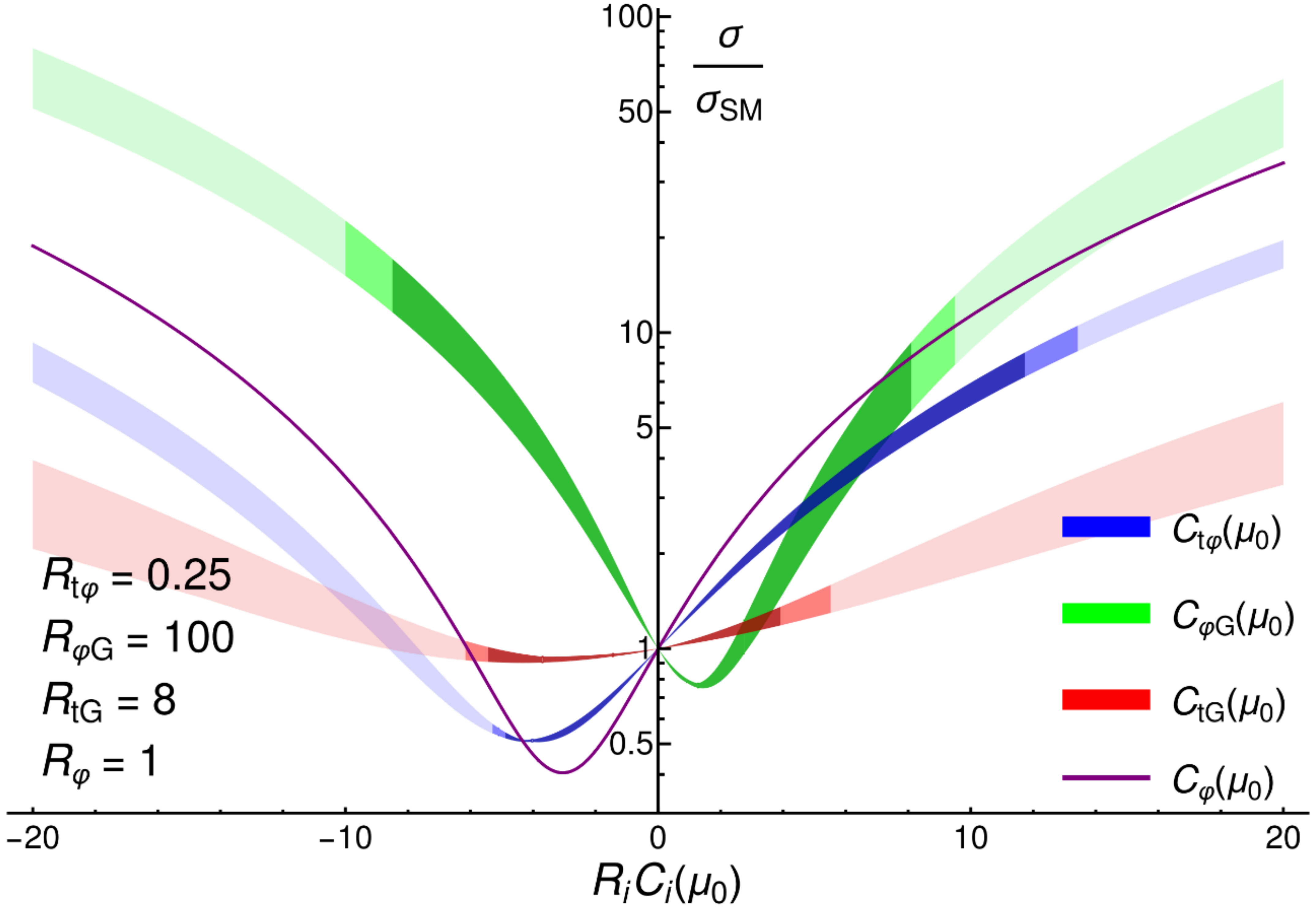
All plotted potentials are at the border of the first-second order transition. **HL-LHC will be able to probe (excluding) a 1st order phase transition in a generic EFT.**

HL-LHC will be able to exclude a large number of simple alternative BSM scenarios for 1st phase order transition.

The Higgs near future

Higgs potential

FM, Ventura, Vryonidou, 2406.06670 [hep-ph]



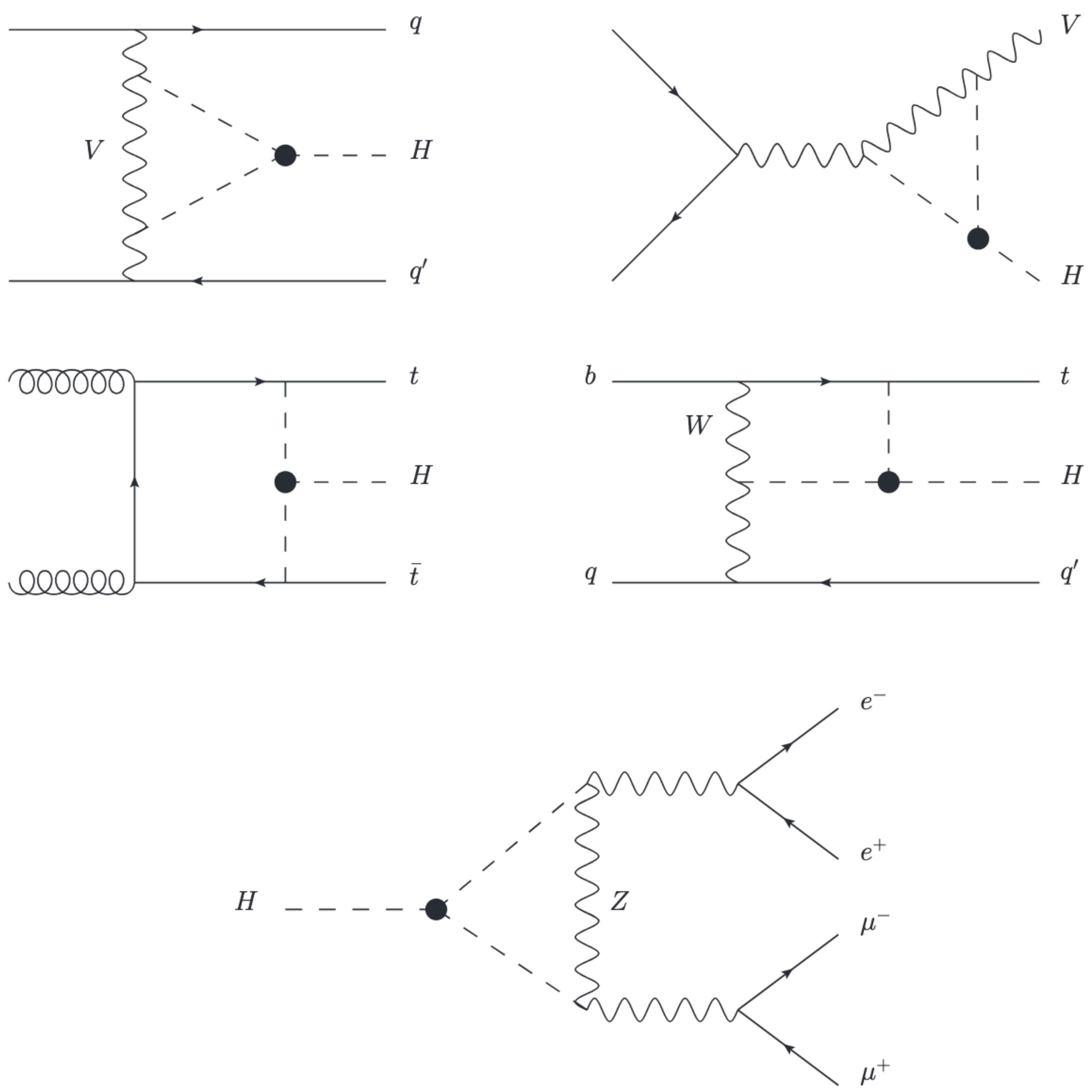
To learn about the Higgs self-coupling one needs to control several other couplings.

The Higgs near future

Indirect determinations

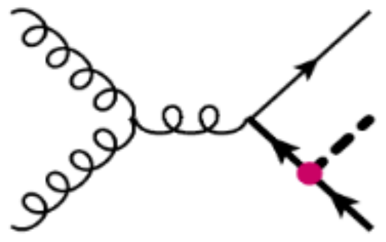
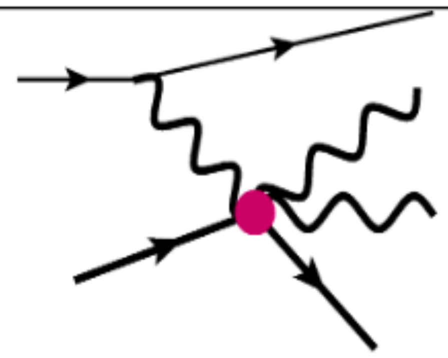
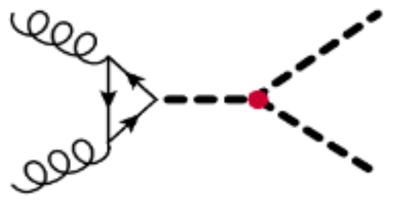
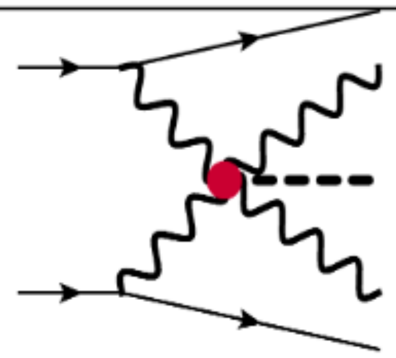
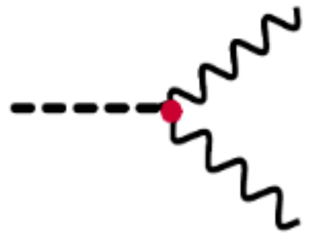
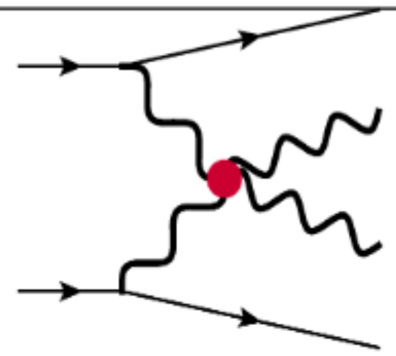
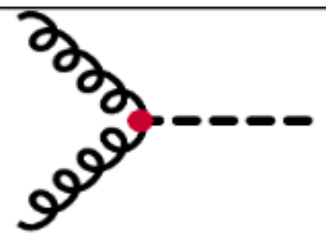
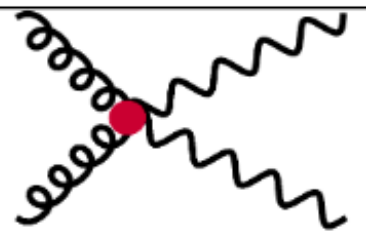
Precision (loops)

[Degrassi et al, 1607.04251 , 1709.08649]



Possibility to learn about Higgs couplings from processes with just one Higgs from loops.

[Henning et al. 2018]

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

Energy (More states)

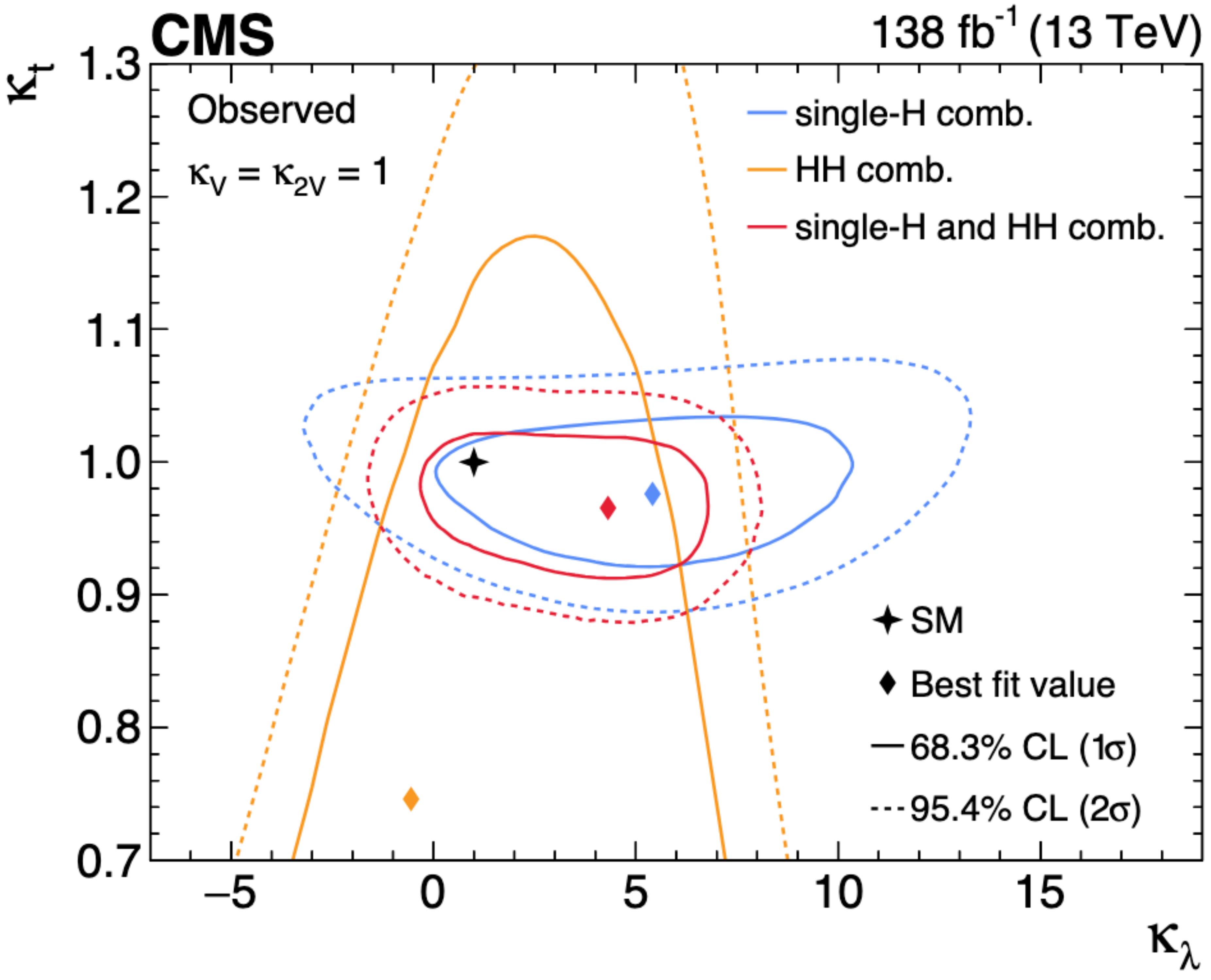
Possibility to learn about (trilinear) Higgs couplings from processes with no (one) Higgs.

The Higgs near future

Indirect determinations

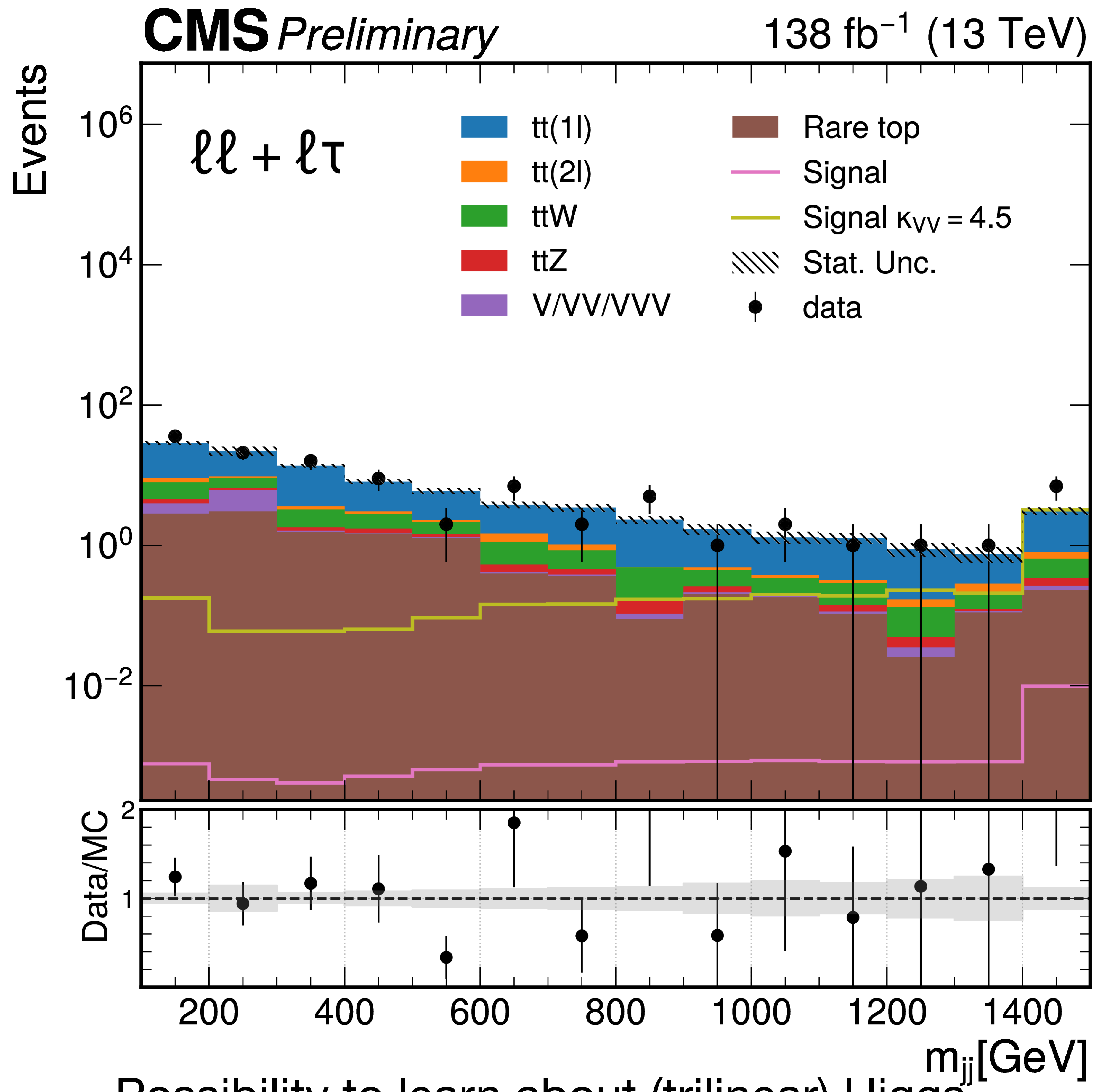
Precision (loops)

[Degrassi et al, 1607.04251 , 1709.08649]



Possibility to learn about Higgs couplings from processes with just one Higgs from loops.

[Henning et al. 2018]



Possibility to learn about (trilinear) Higgs couplings from processes with no (one) Higgs.

Energy (More states)

EW interactions are the new QCD

We start only now to test EW interactions but only in a very low energy regime, i.e., in their broken phase.

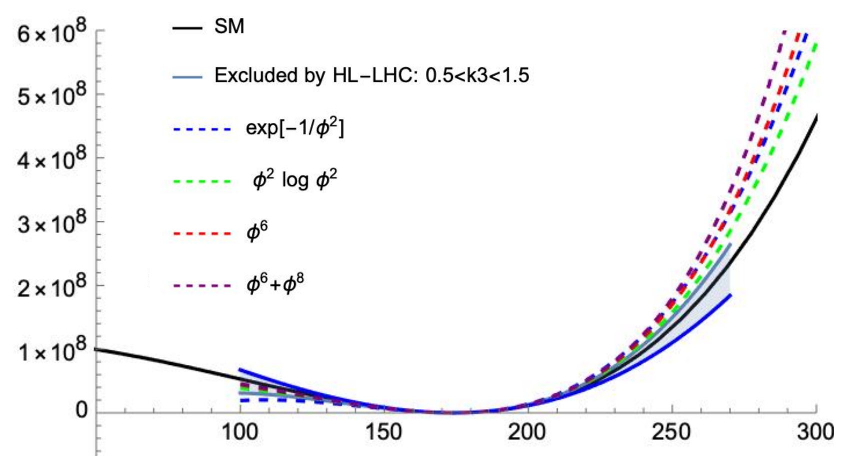
E

v

$4\pi v$

a few $4\pi v$

Λ_{UV}

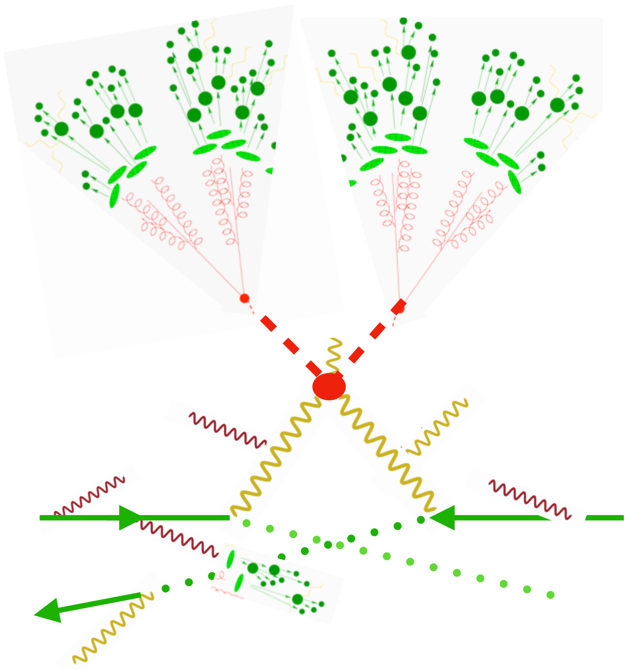


1st or 2nd order

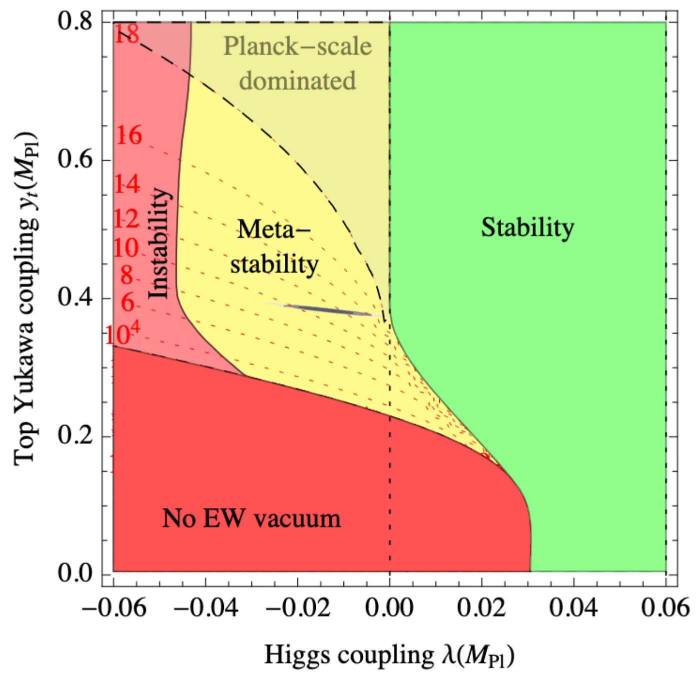
$$\phi^\pm = W_L^\pm$$

$$\phi^0 = Z_L^0$$

EW restoration



EW showers



Vacuum Stability

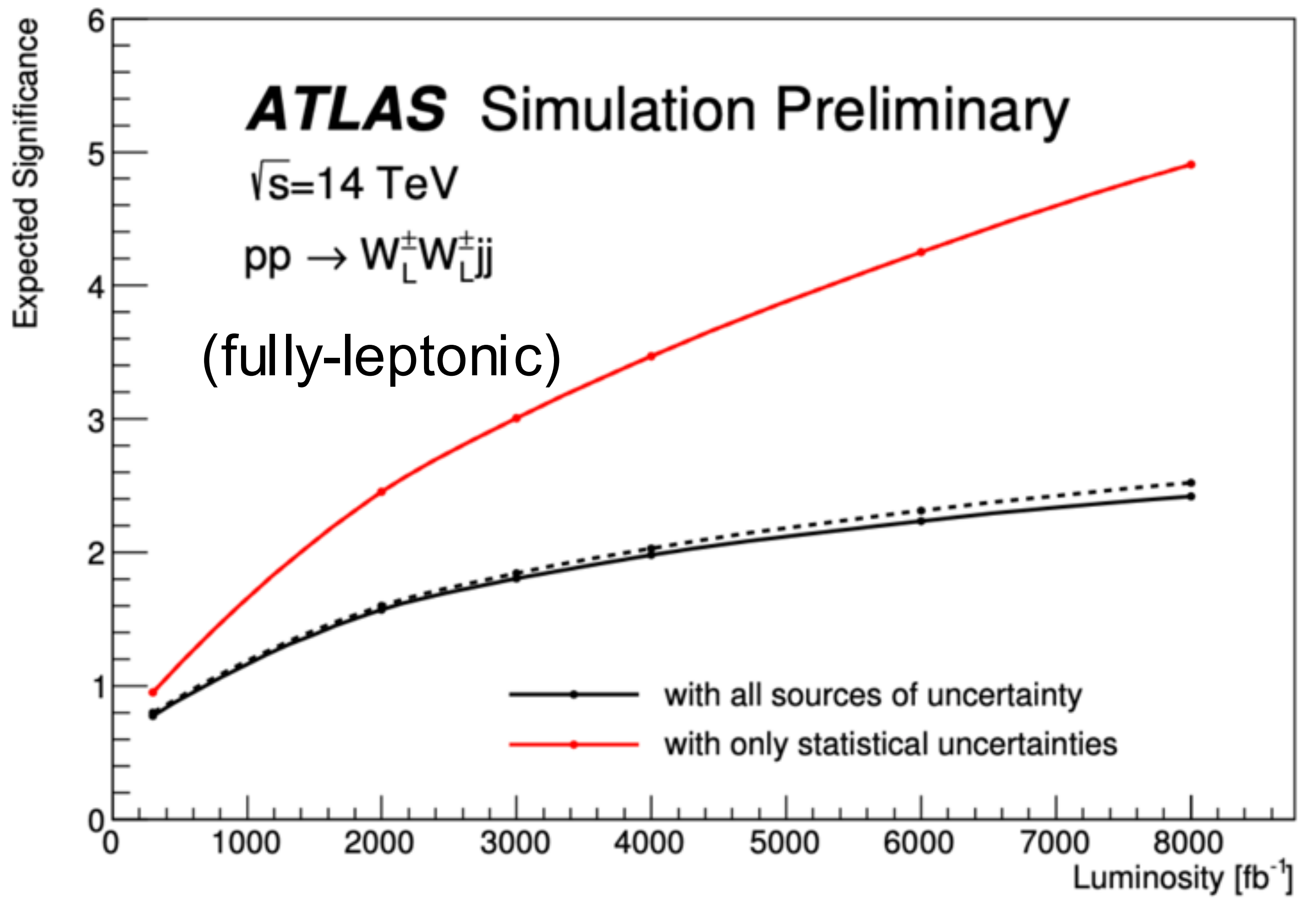
EW interactions are the new QCD

EW restoration

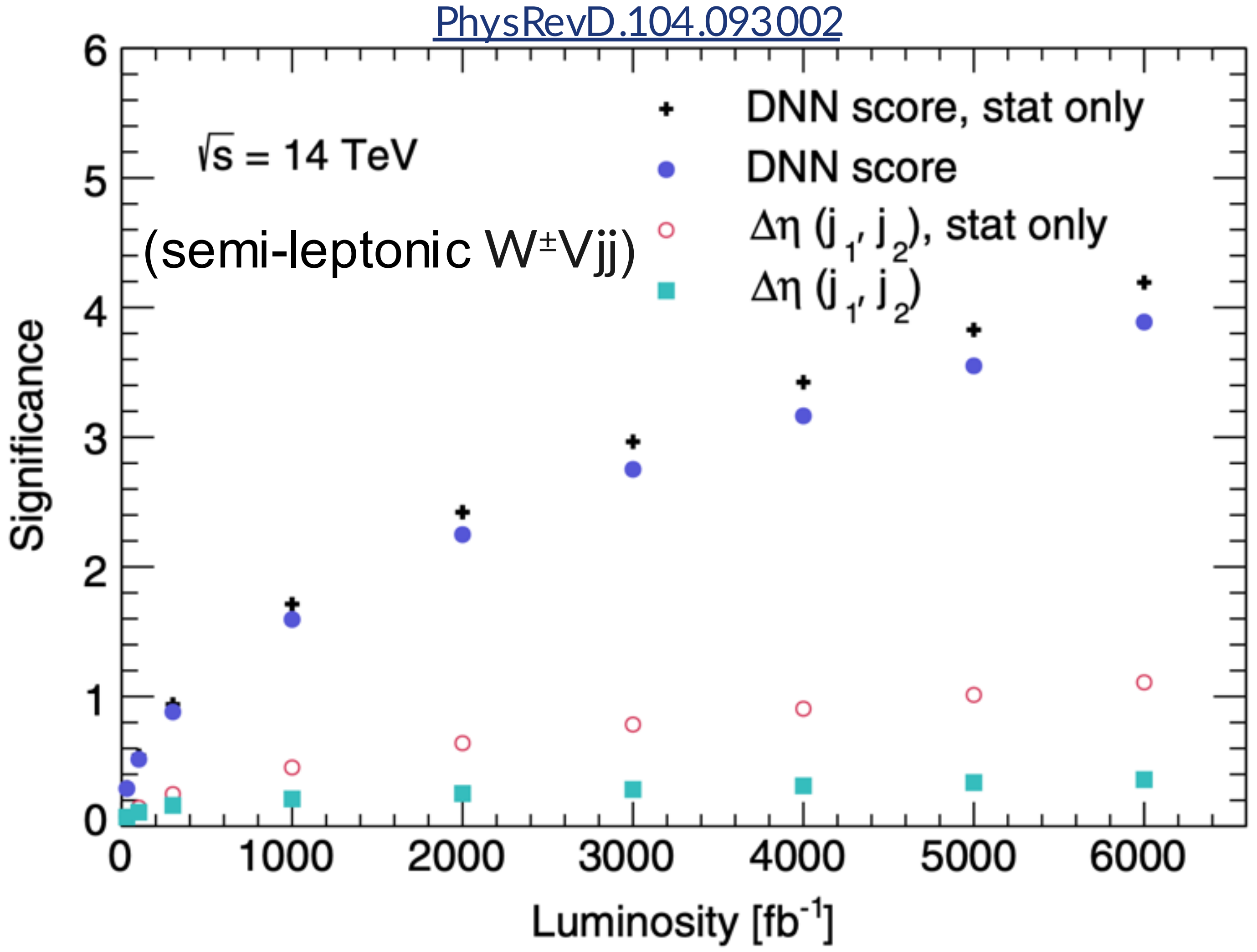
[Mwewa, FCC-hh kick-off meeting]

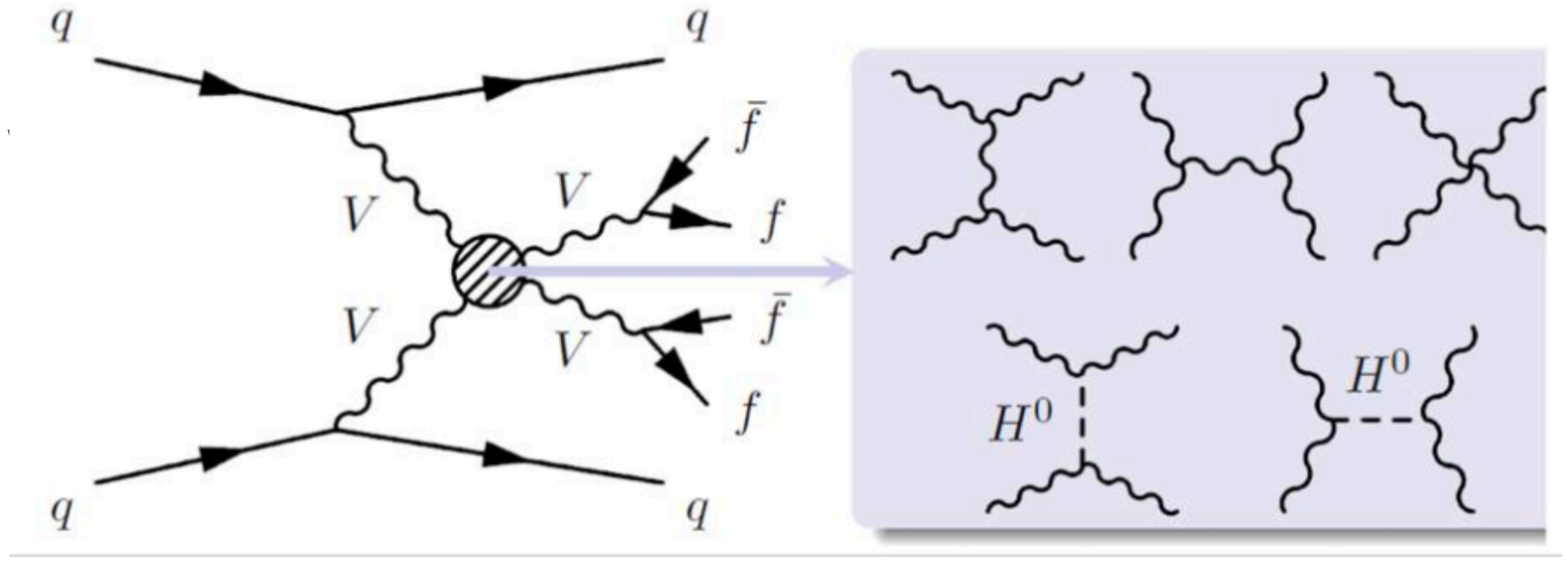
VBS, such as W+W+jj, gives access to longitudinally polarised vector bosons. However cross sections are very small (about 10% of the total) and significant only in the tails

ATL-PHYS-PUB-2018-052



PhysRevD.104.093002



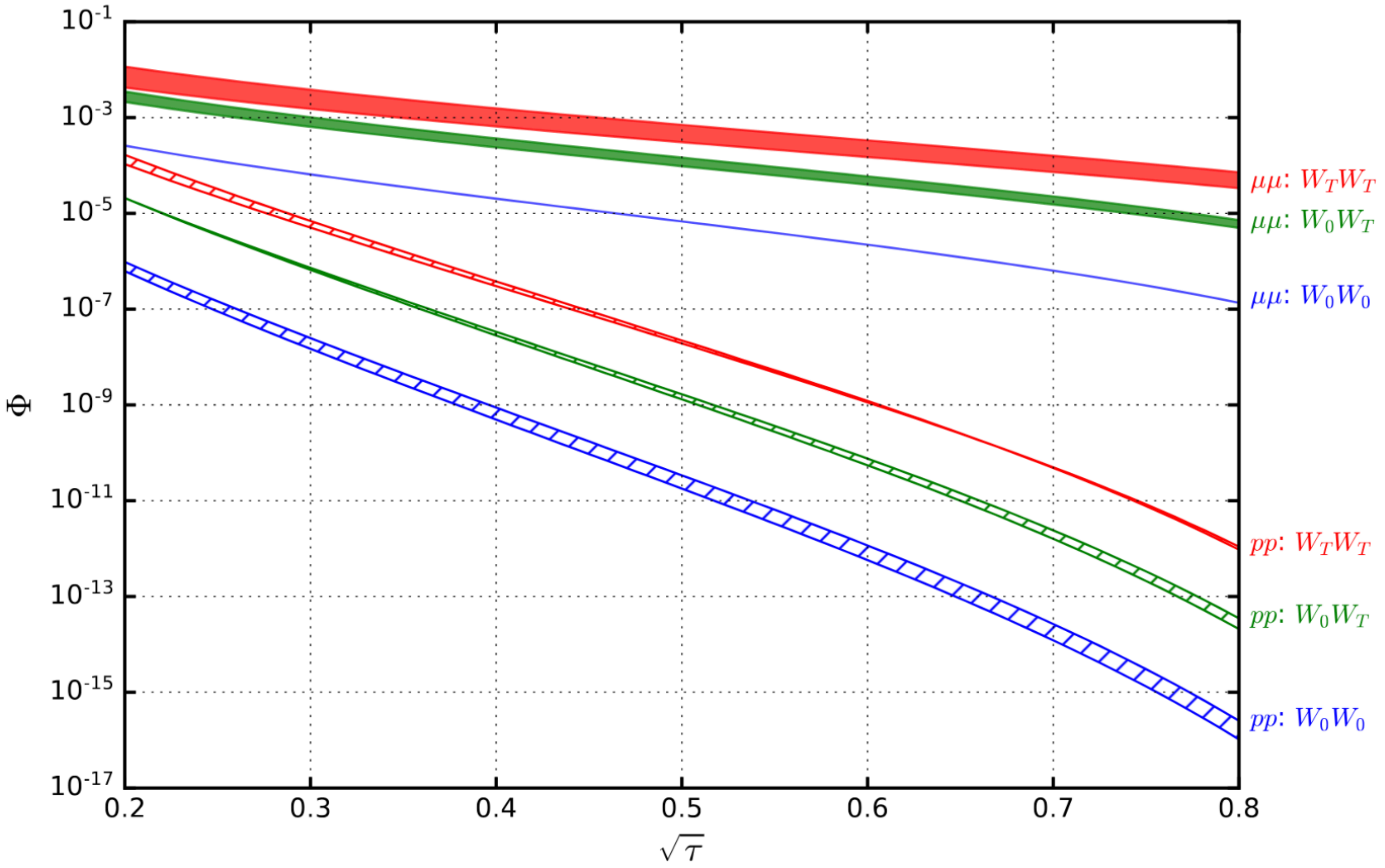


3

Considering all channels, and both experiments we could get at 5 sigma level for LL at 3 iab.

EW interactions are the new QCD

EW restoration



High-energy lepton colliders would be perfect for such studies.

Assuming the same collider energy:

$\sqrt{s_\mu} = \sqrt{s_p}$ (for illustration!)

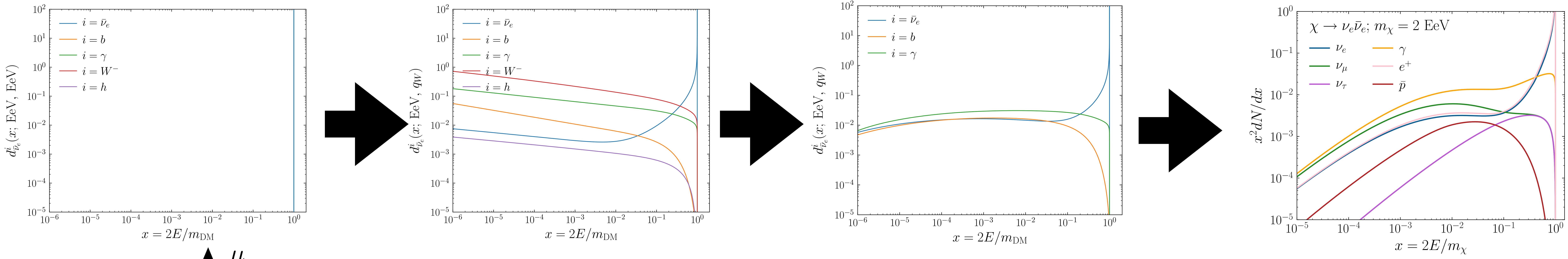
Luminosities for VV are significantly higher in a lepton collider.

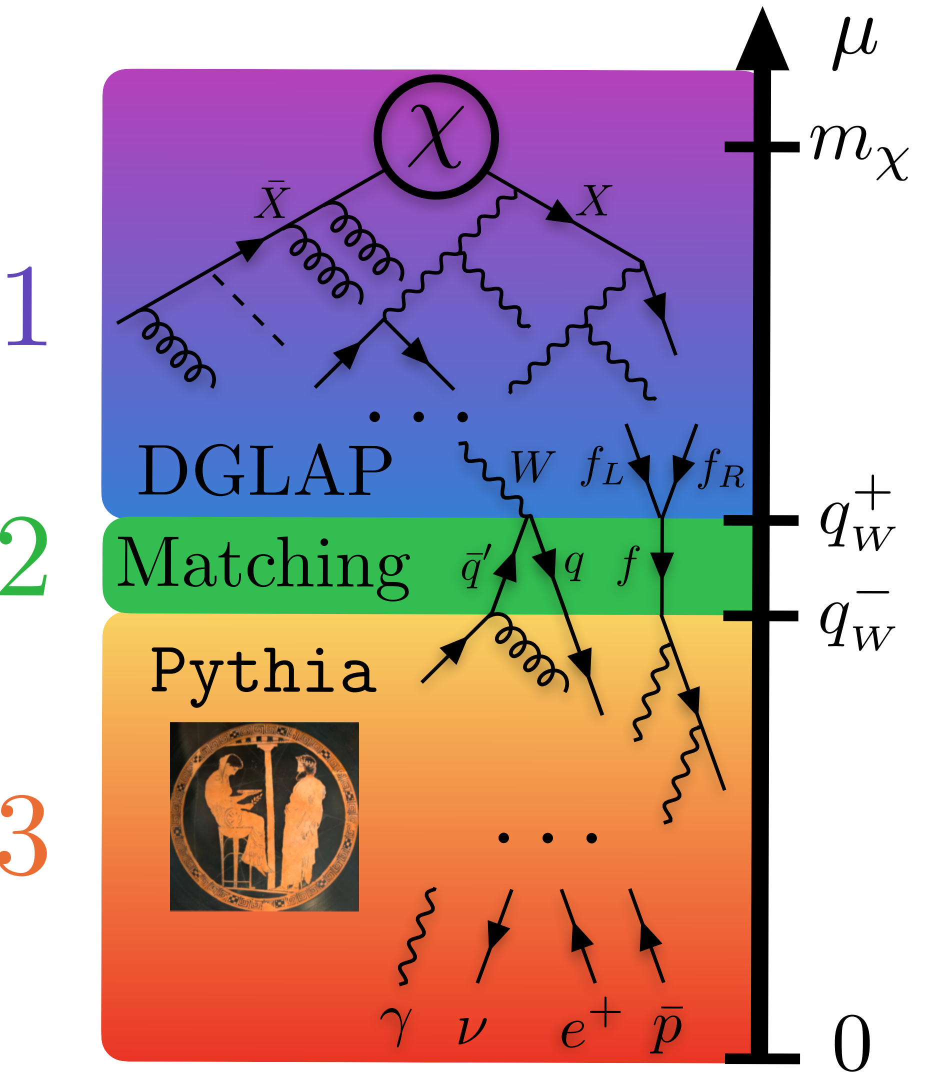
And QCD backgrounds much lower.

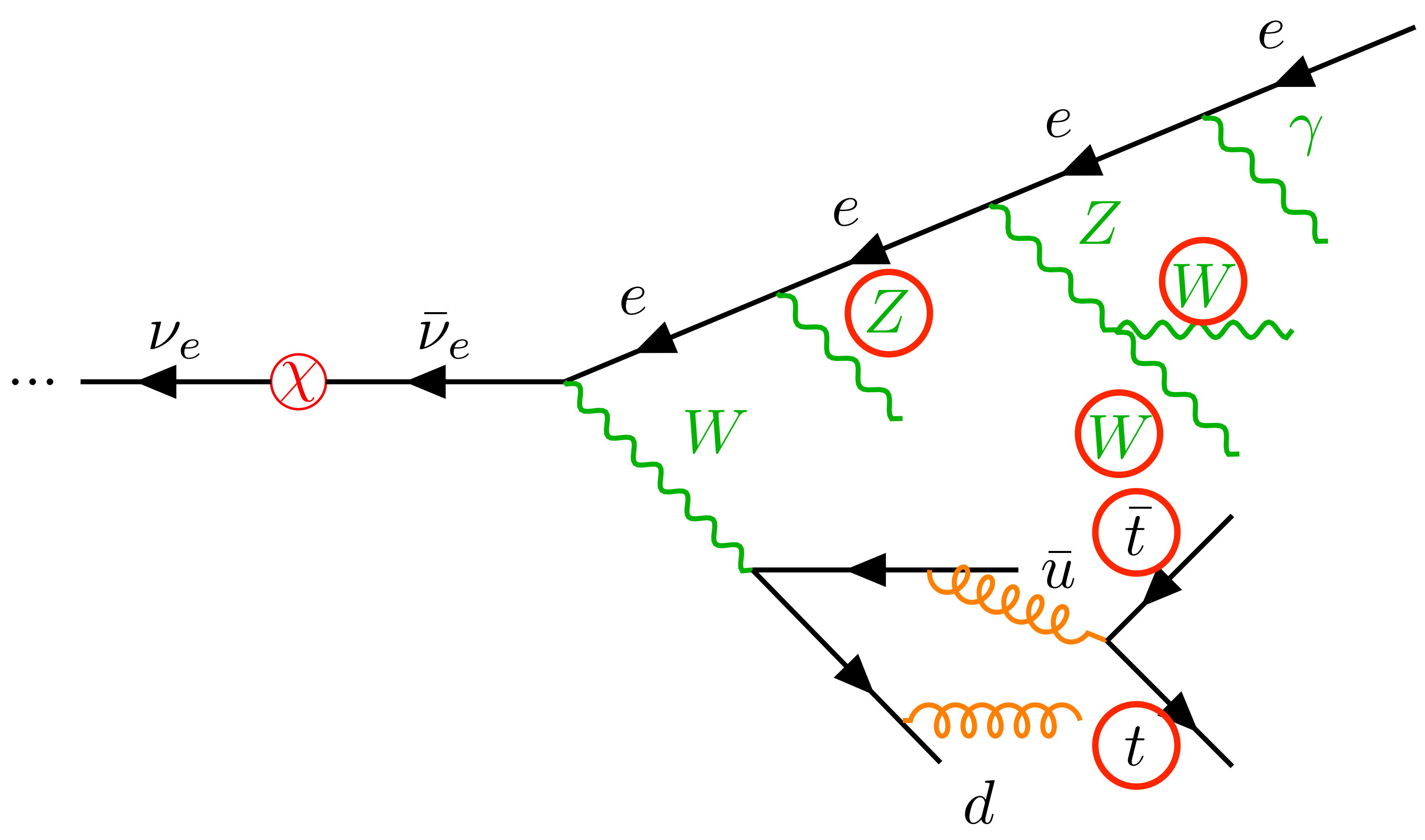
EW interactions are the new QCD

EW showers

At very high energies, E>>v, SU(2) x U(1) is restored and evolution through EW radiation will take place. The non-abelian nature of SU(2) will make a shower look more like QCD. One the scales are down to ~v EWSB effects will start to become important again.







Evolution (EW double logs and polarisation):

- [Christiansen, Sjostrand 1401.5238]
- [Christiansen, Prestel 1510.01517]
- [Chen, Han, Tweedie 1611.00788]
- [Manohar, Waalewijn 1802.08687]
- [Bauer, Provasoli, Webber 1806.10157]
- [Bauer, Webber 1808.08831]
- [Kleiss, Verheyen, 2002.09248]
- [Bauer, Rodd, Webber 2007.15001]
- [Masouminia, Richardson, 2108.10817]
- [Brooks, Skands, Verheyen 2108.10786v2]

NicolasRodd®

Timeline(s)

To be taken cum grano salis

SuperKEKB

e+e- CEPC

ppPC

e+e- ILC 250

e+e- ILC 500

e+e- ILC 1000

A

e+e- FCC-ee : 91,240,365 GeV

FCC-hh

FCC-eh with ERL

LHC

HL-LHC

FCC-hh at 80 TeV with 14T magnets

B’s

LEP3 with Lumi=1/5 Lumi FCC-ee

LHeC with ERL

2025

Near future

2050

Future

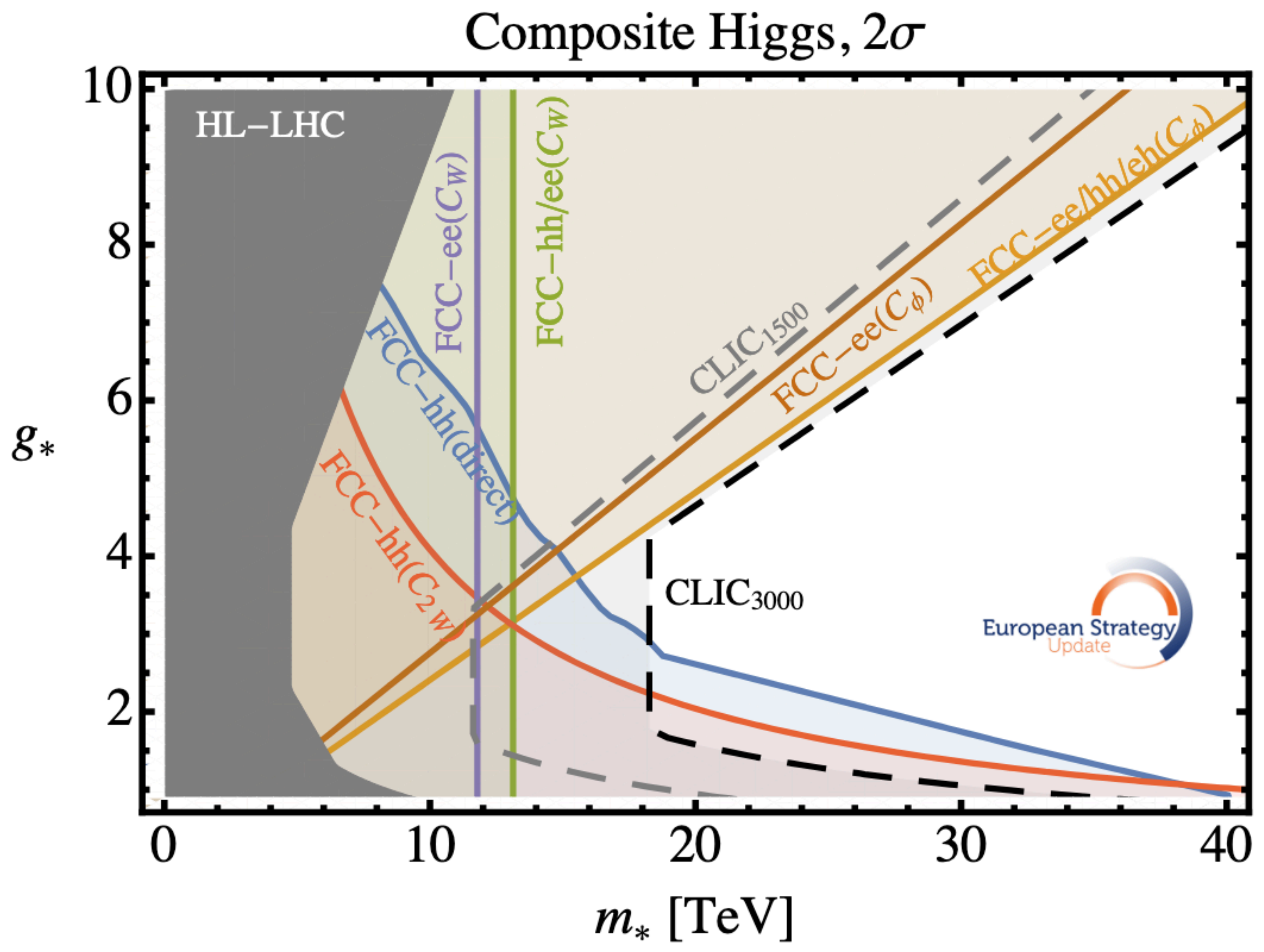
2075

Future colliders

Reach in Higgs couplings

[De Blas et al., 2020]

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	$98\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	$99\star$	$86\star$	$85\star$	$120\star$	15	6.9	8.2	$81\star$	$75\star$	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	$320\star$	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

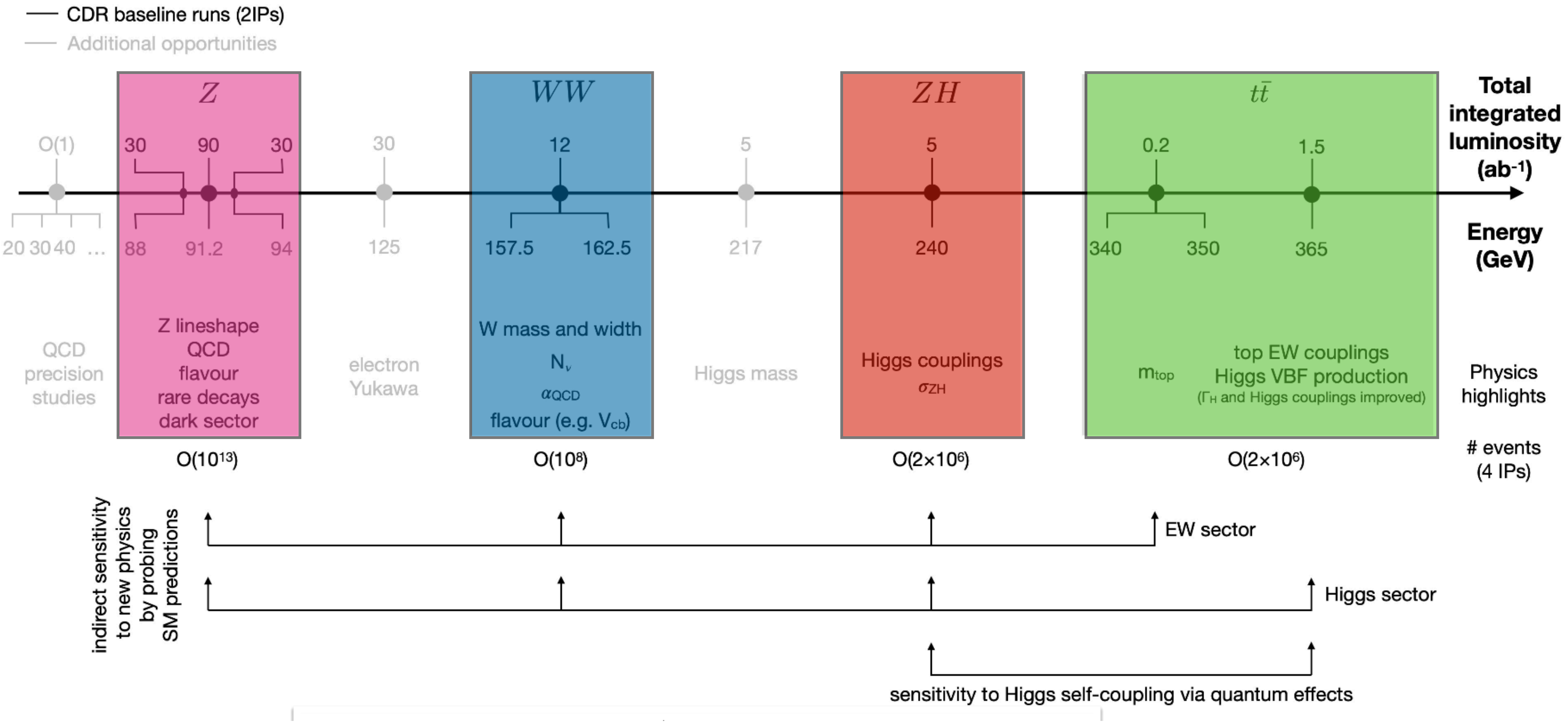


Improvements by factors of 5-10 ⇒ same on the scale

$$\delta g_H / g_H^{SM} \sim c\,\varepsilon$$

FCC-ee runs

Schematic!



CDR baseline runs (2IPs)

Additional opportunities

Total integrated luminosity (ab^{-1})

Energy (GeV)

Physics highlights

events (4 IPs)

O(1)
20 30 40 …
QCD precision studies

Z
30 90 30
88 91.2 94
Z lineshape
QCD
flavour
rare decays
dark sector
O(10^{13})

30
125
electron Yukawa

WW
12
157.5 162.5
W mass and width
N_ν
α_{QCD}
flavour (e.g. V_{cb})
O(10^8)

5
217
Higgs mass

ZH
5
240
Higgs couplings
σ_{ZH}
O(2×10^6)

$t\bar{t}$
0.2 1.5
340 350 365
m_{top}
top EW couplings
Higgs VBF production
(Γ_H and Higgs couplings improved)
O(2×10^6)

indirect sensitivity to new physics by probing SM predictions

EW sector

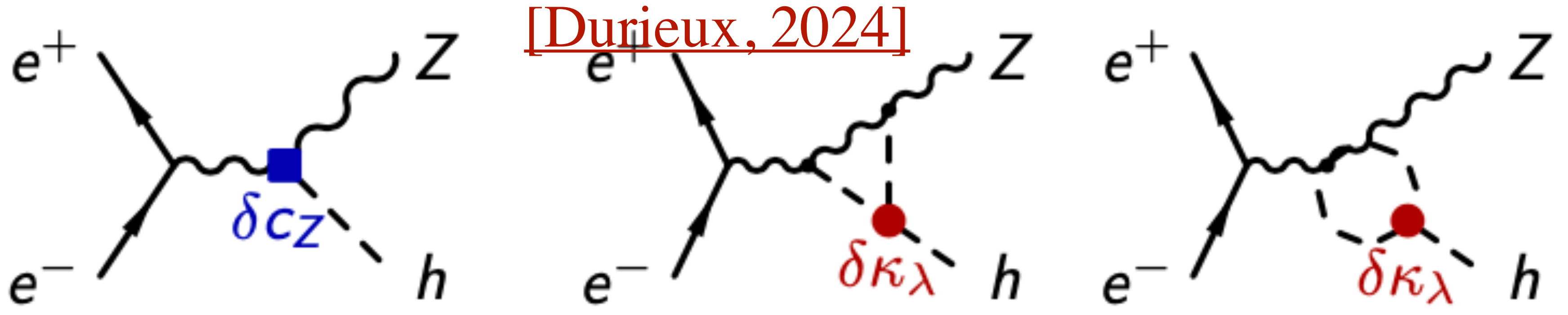
Higgs sector

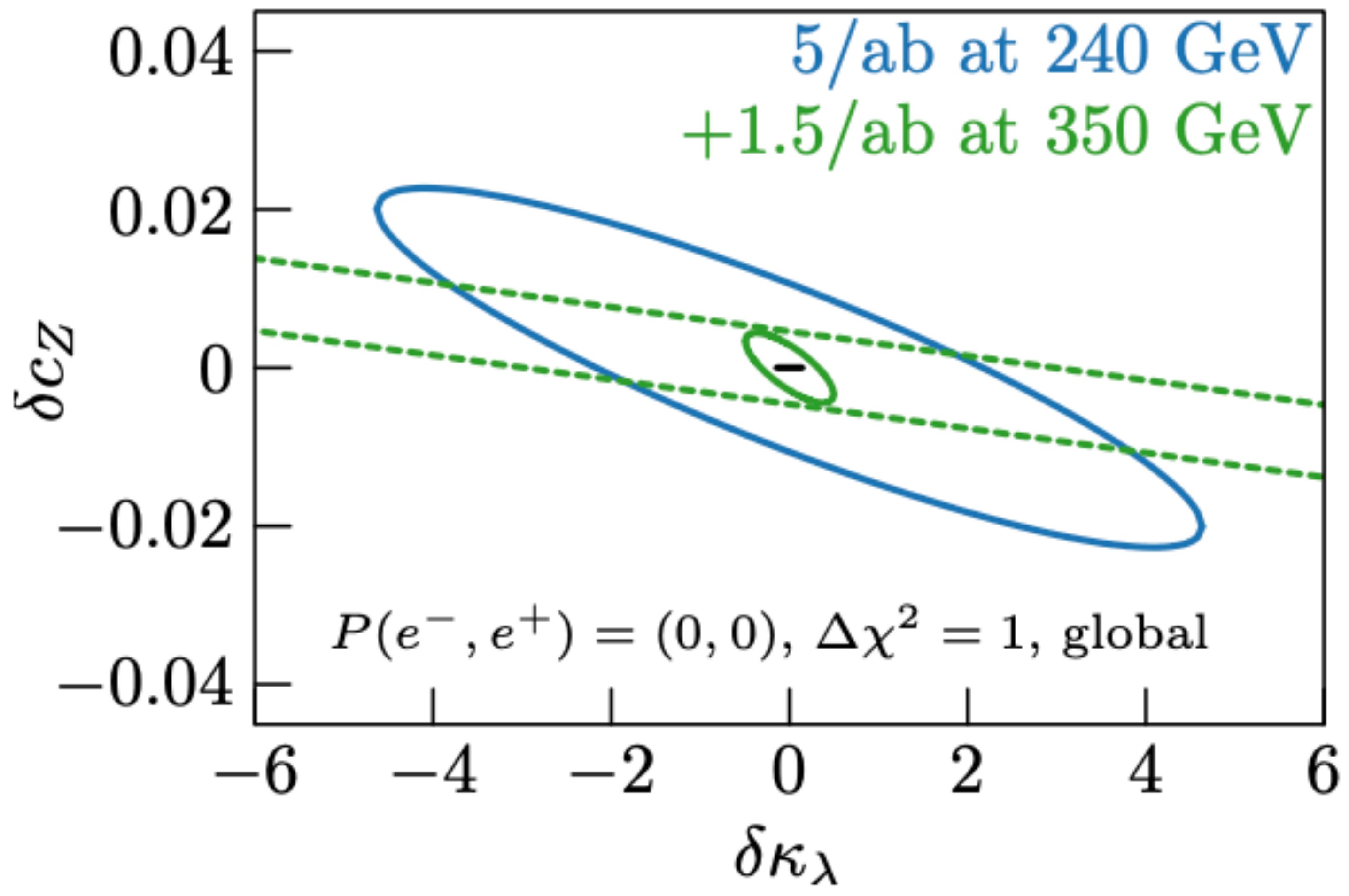
sensitivity to Higgs self-coupling via quantum effects

Higgs self-coupling

FCC-ee (and FCC-hh)

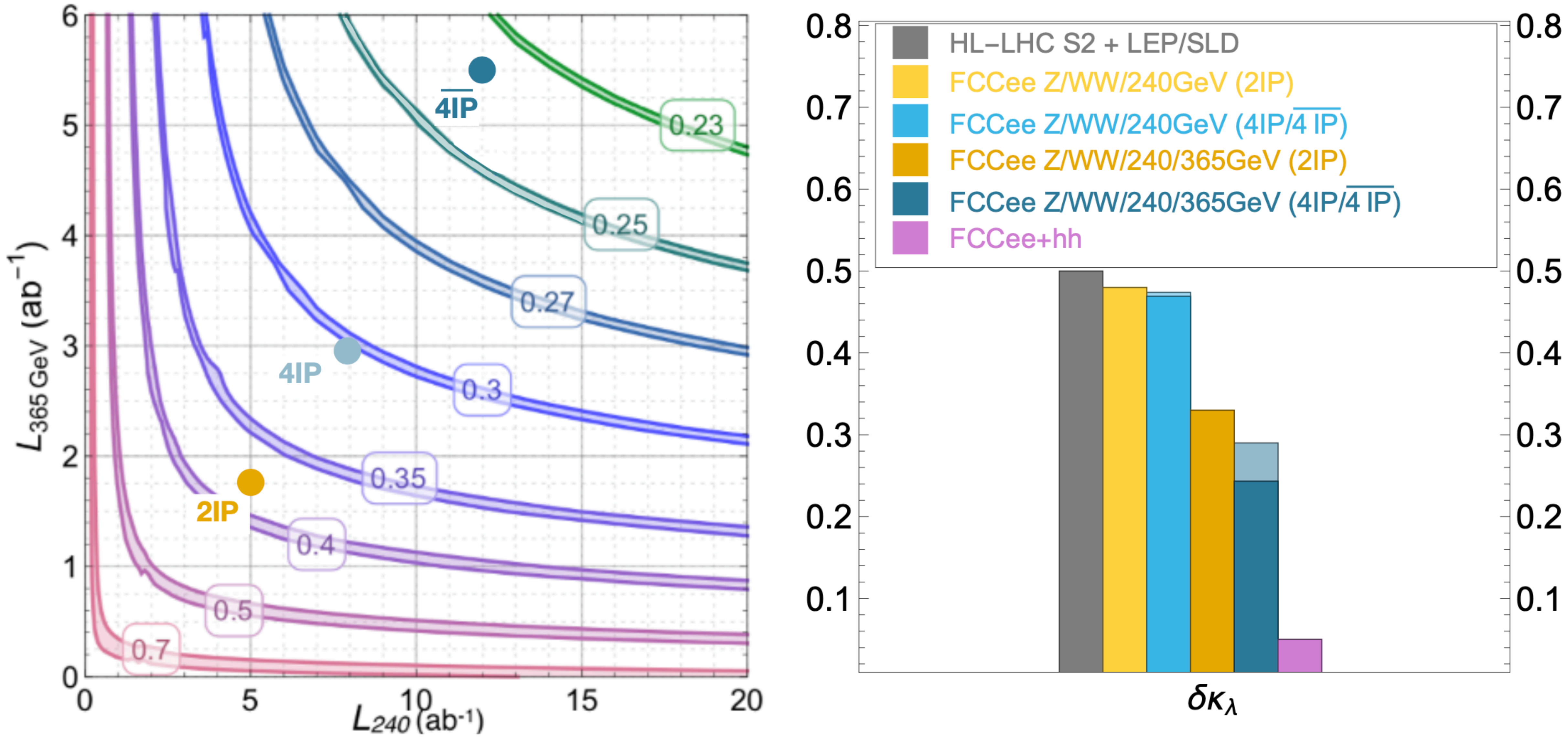
[Durieux, 2024]





[Interim FCC feasibility report, 2024]

Precision of $\delta\kappa_\lambda$ from EFT global fit (FCC-ee + HL-LHC)



k_λ can be constrained by two measurements. Is this competitive with HL-LHC?

Flavour at the Z-pole

Physics potential

Particle species	B^0	B^+	B^0_s	Λ_b	B^+_c	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

Clean environment, with precise momentum of the pair-produced b's, c's and τ from Z decays (as in B-factories), with ~ 10 times more $b\bar{b}$ and $c\bar{c}$ pairs compared to the final Belle-II statistics.

Boosted b's and τ's, leading to significantly higher efficiency (compared to B fac- tories) for modes with missing energy (especially multiple-ν modes) and inclusive modes, and smaller error in lepton ID efficiencies.

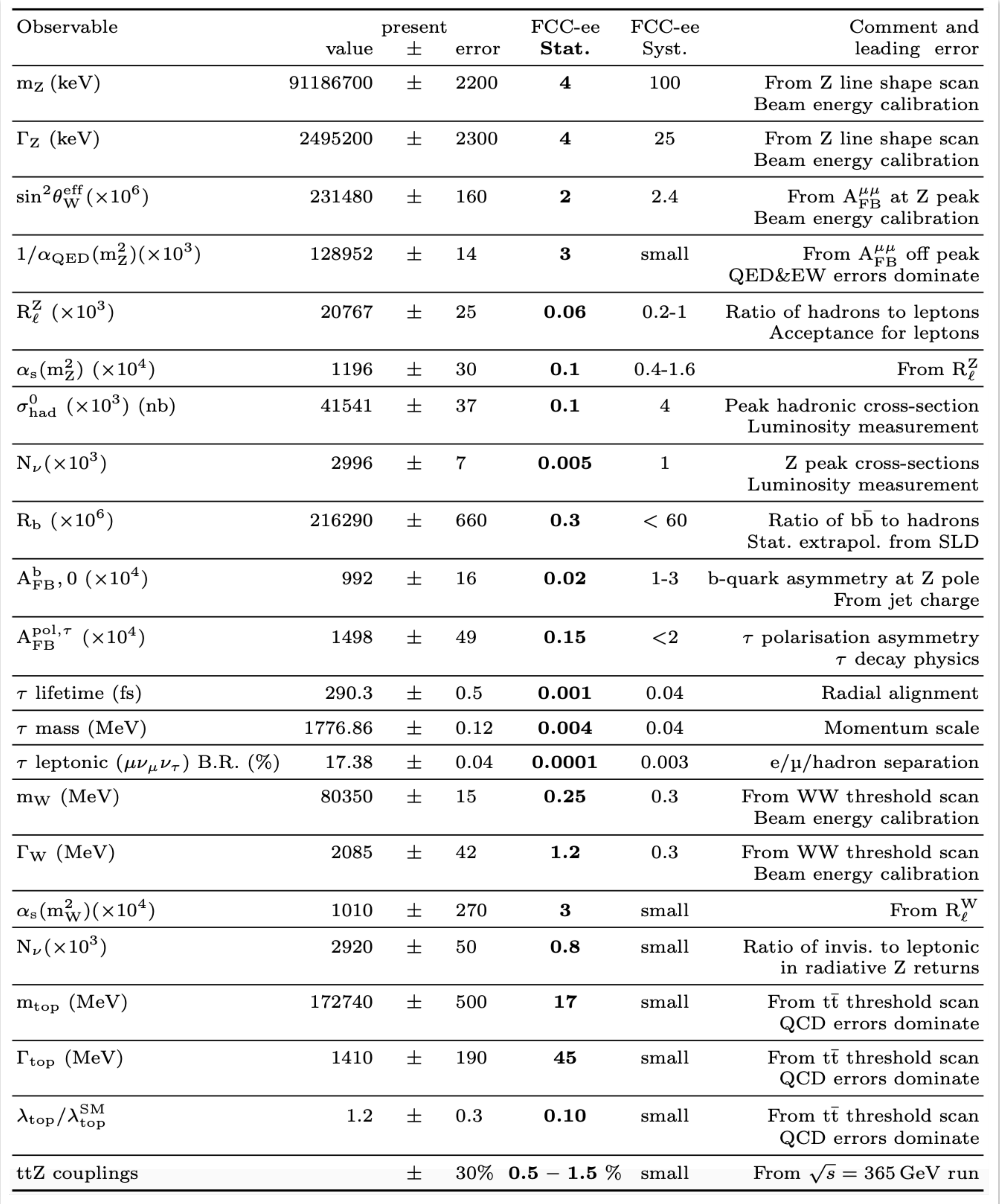
1. Rare b-hadron decays with $\tau\bar{\tau}$ pairs in the final state (about 3 orders of magnitude between SM predictions and data).
2. Charged-current b-hadrons decays with a τν pair in the final state.
3. Lepton flavour violating τ decays.
4. Lepton-universality tests in τ decays.

EWPO

FCC-ee

- Experimental precision of the typical EWPO attainable at FCC-ee runs.
- Improvements in precision typically at level of 2-3 orders of magnitude.
- Sensitivity to NP goes up to10-100 TeV scale
- $5 \cdot 10^{12}$ Z bosons would allow the electroweak precision tests, the KM consistency checks and flavour physics in general, including the study of rare decays, and the search for feebly-interacting particles.
- $5 \cdot 10^{9}$ Z bosons would enough to meet the needs for the HZ run.

[Interim FCC feasibility report, 2024]

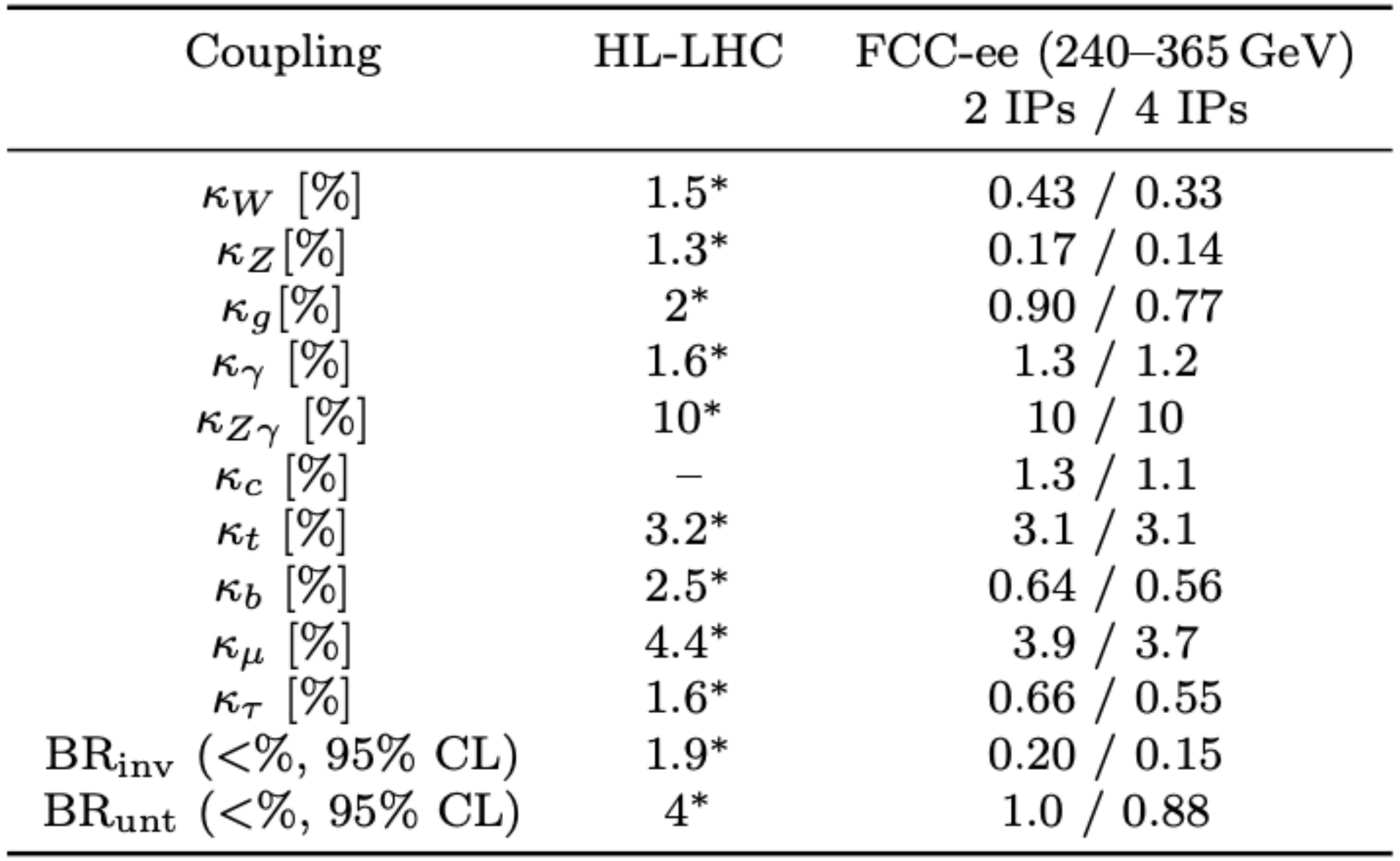


Observable	present			FCC-ee	FCC-ee	Comment and
	value	±	error	**Stat.**	Syst.	leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^{b}, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 − 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

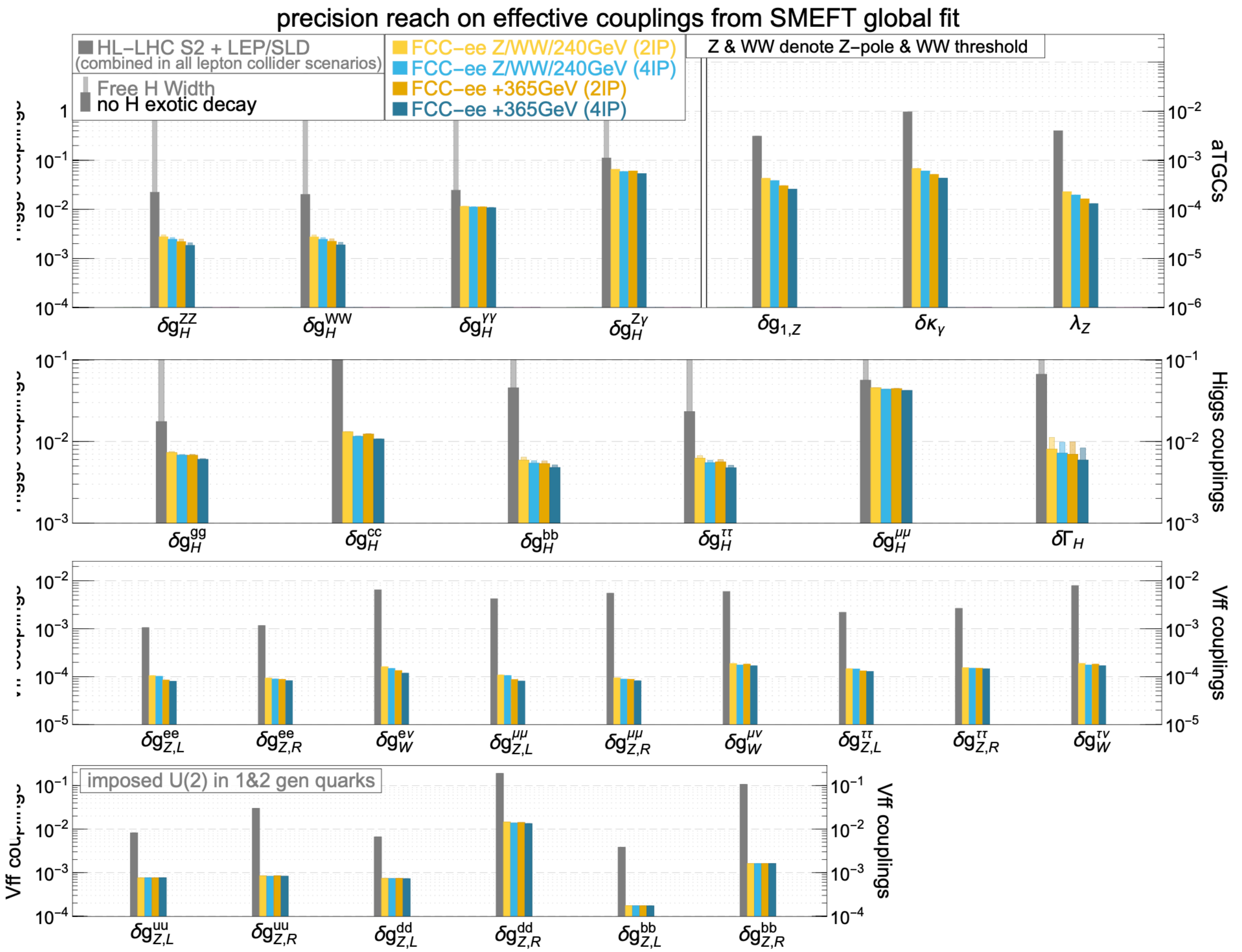
[Interim FCC feasibility report, 2024]

Global fits

FCC-ee



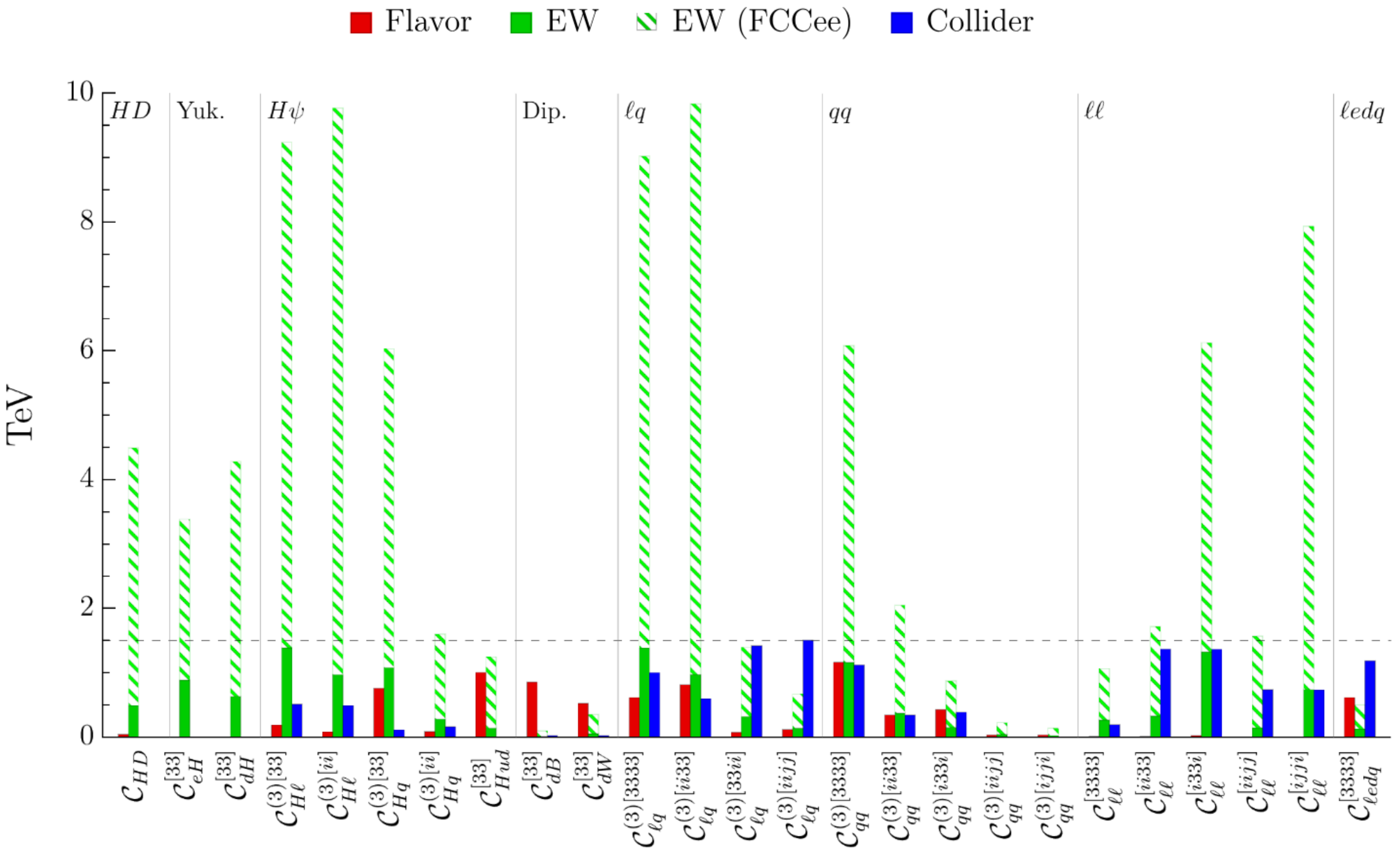
Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88



[Allwicher et al. 2311.00020]

Global fit w/ flavour

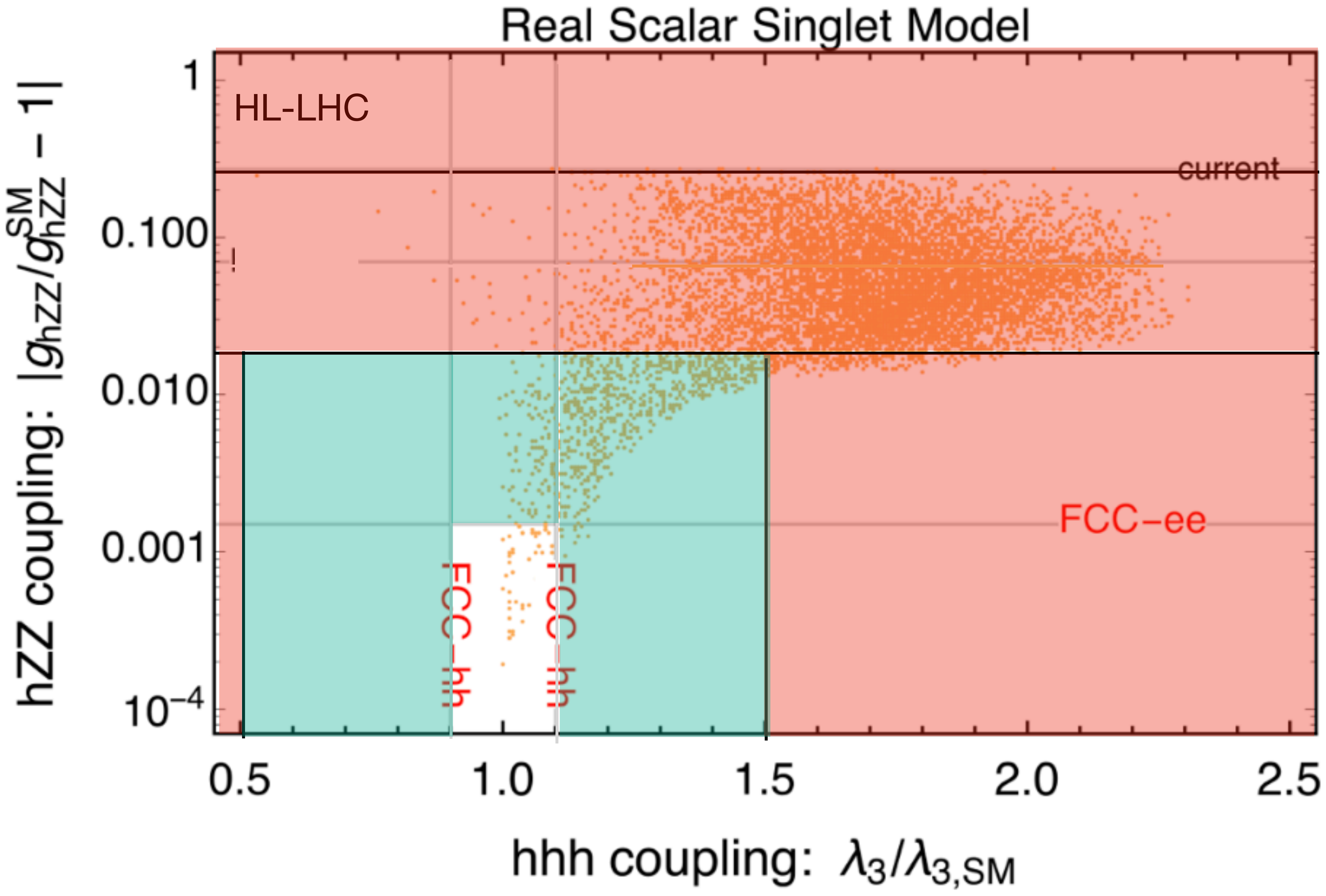
FCC-ee



[Interim FCC feasibility report, 2024]

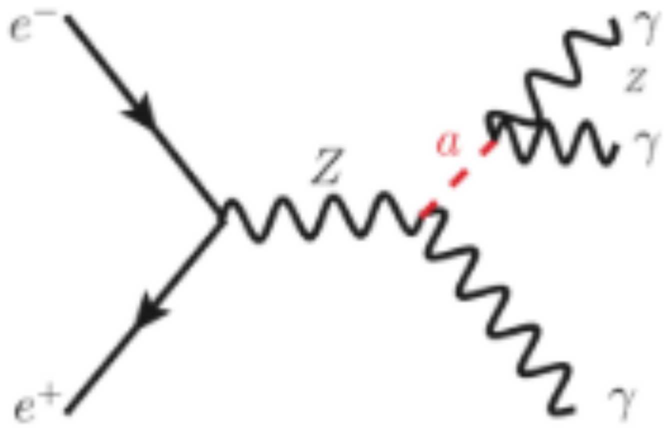
Scalar singlet

FCC-ee (and FCC-hh)

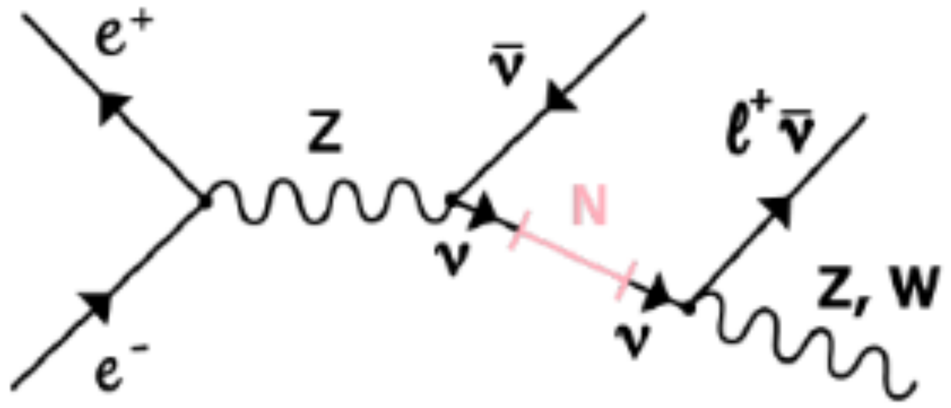


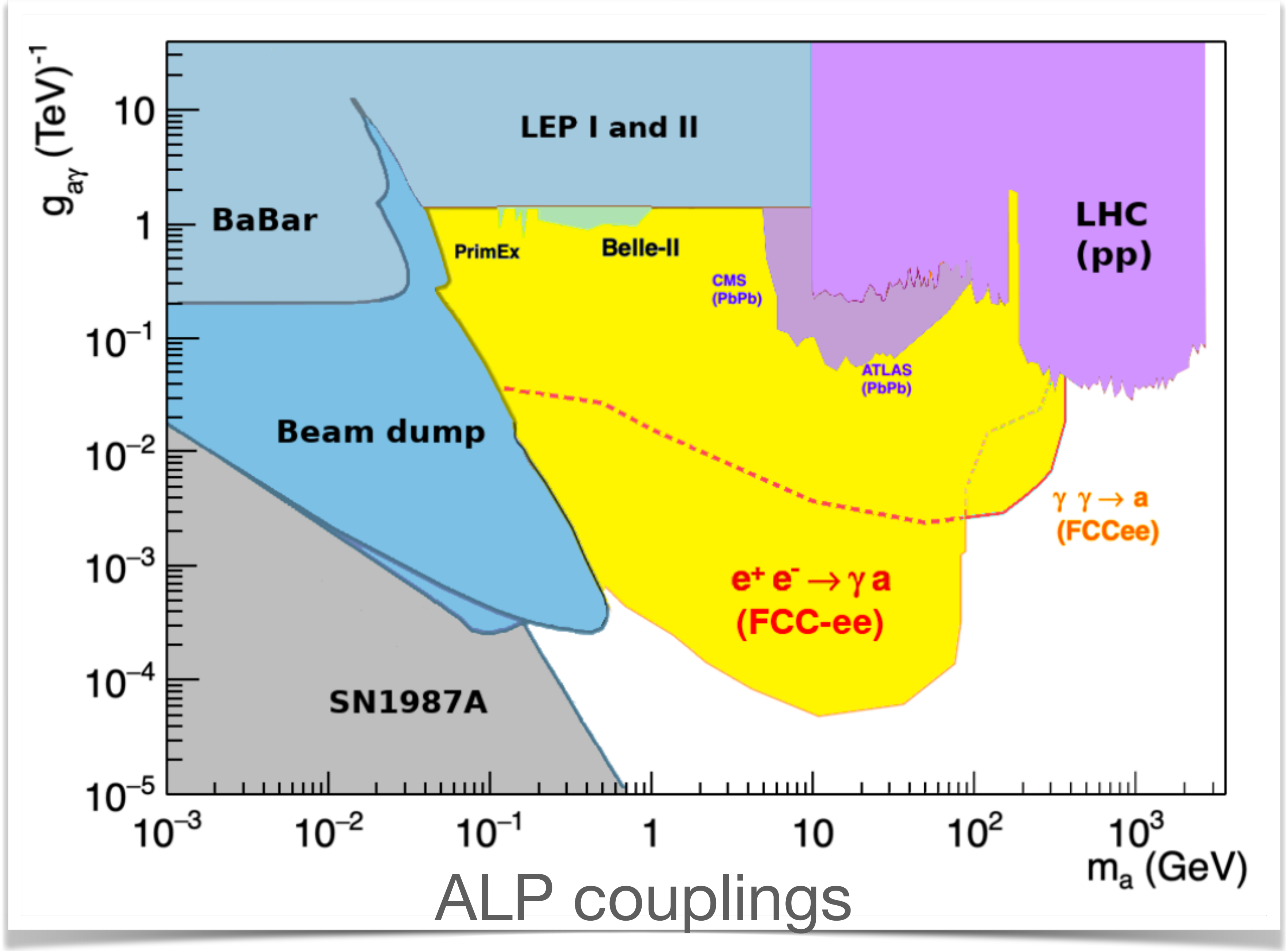
Alps and ν_R's

FCC-ee

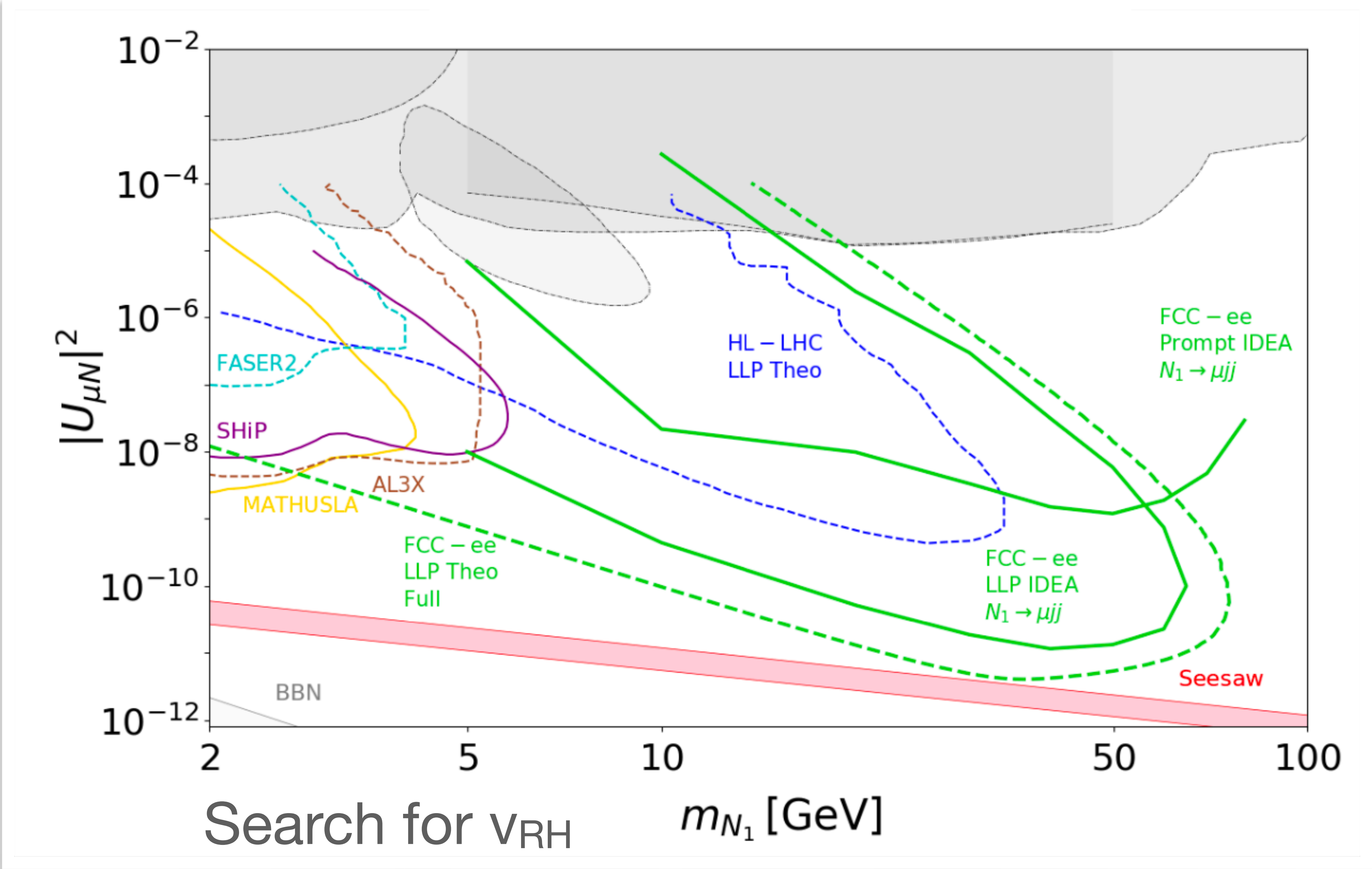


[Interim FCC feasibility report, 2024]





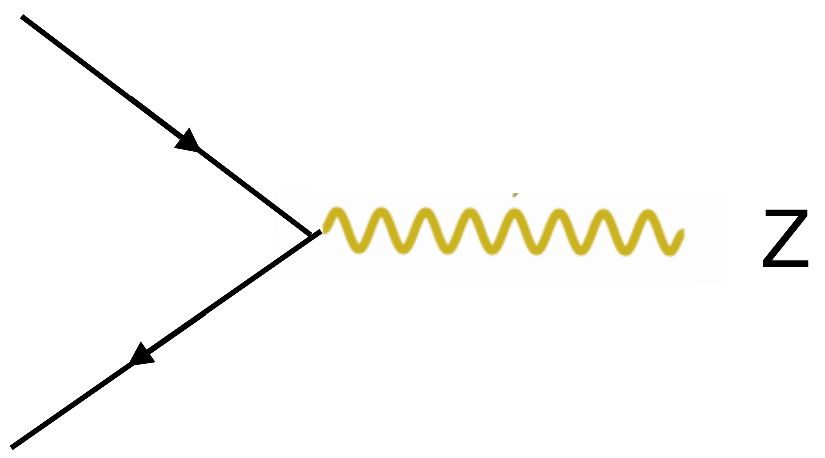
ALP couplings

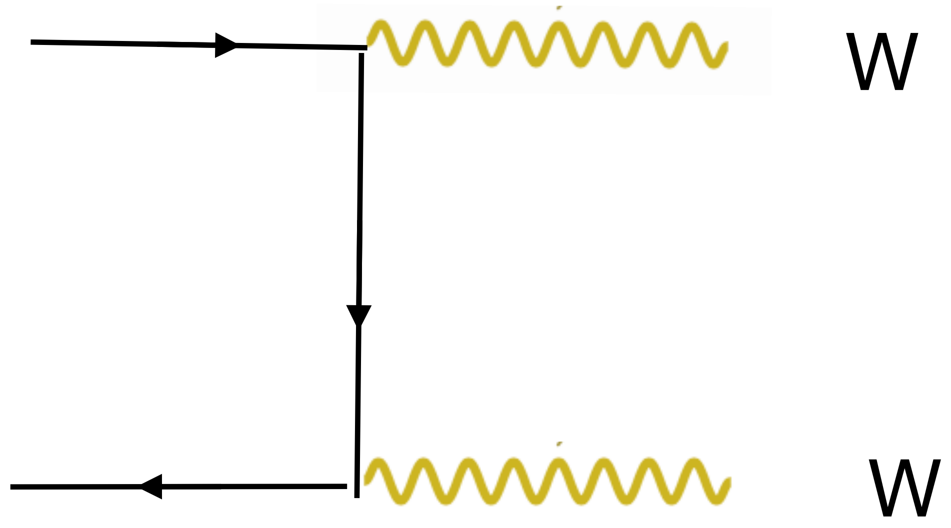


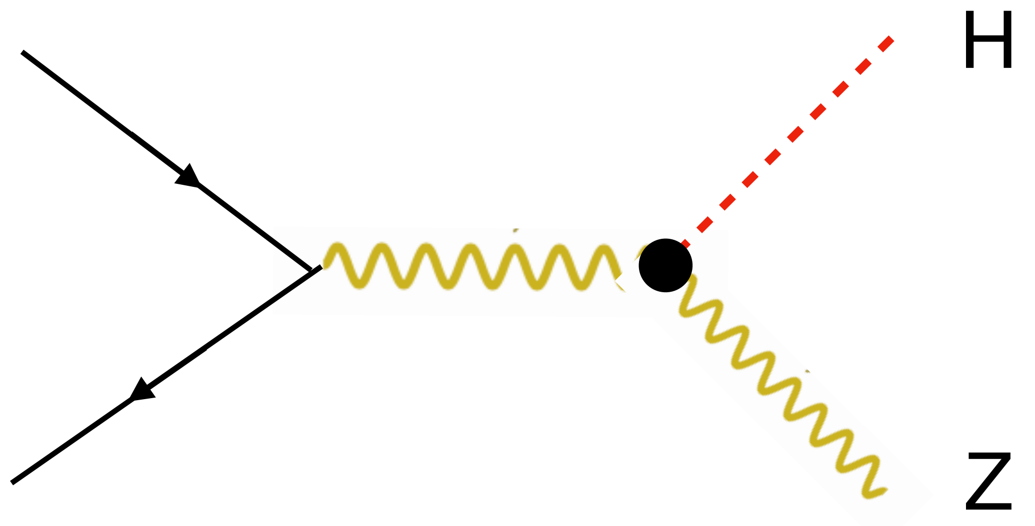
Search for ν_{RH}

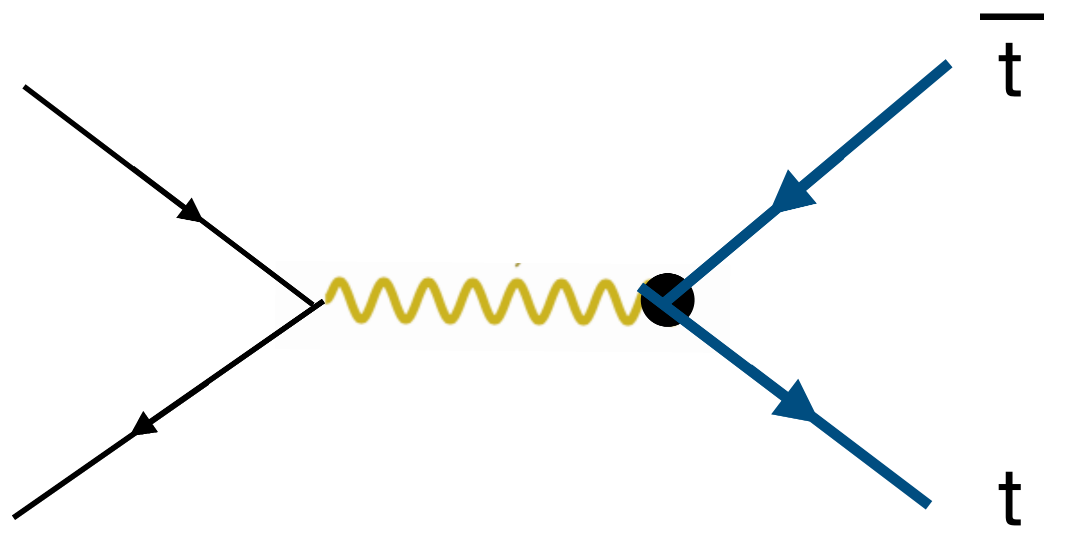
Precision calculations for weak scale factories

The workhorses









Z-pole observables. Need for NNLO EW in $2 \to 2$ scatterings and N3LO for $2 \to 1$. The current use and definition of PO's will need to be reconsidered.

Known at NLO in EW with W decays. In order to determine mW at 1 MeV needs to be known at the subpermill level. NNLO EW computation involves many scales. In addition an EFT treatment of the W threshold is necessary.

Workhorse for H studies. Known at NLO in EW with Z decays. NNLO correct. Gives access to trilinear and top-Yukawa at one loop and quadrilinear Higgs self-couplings and others at two loops.

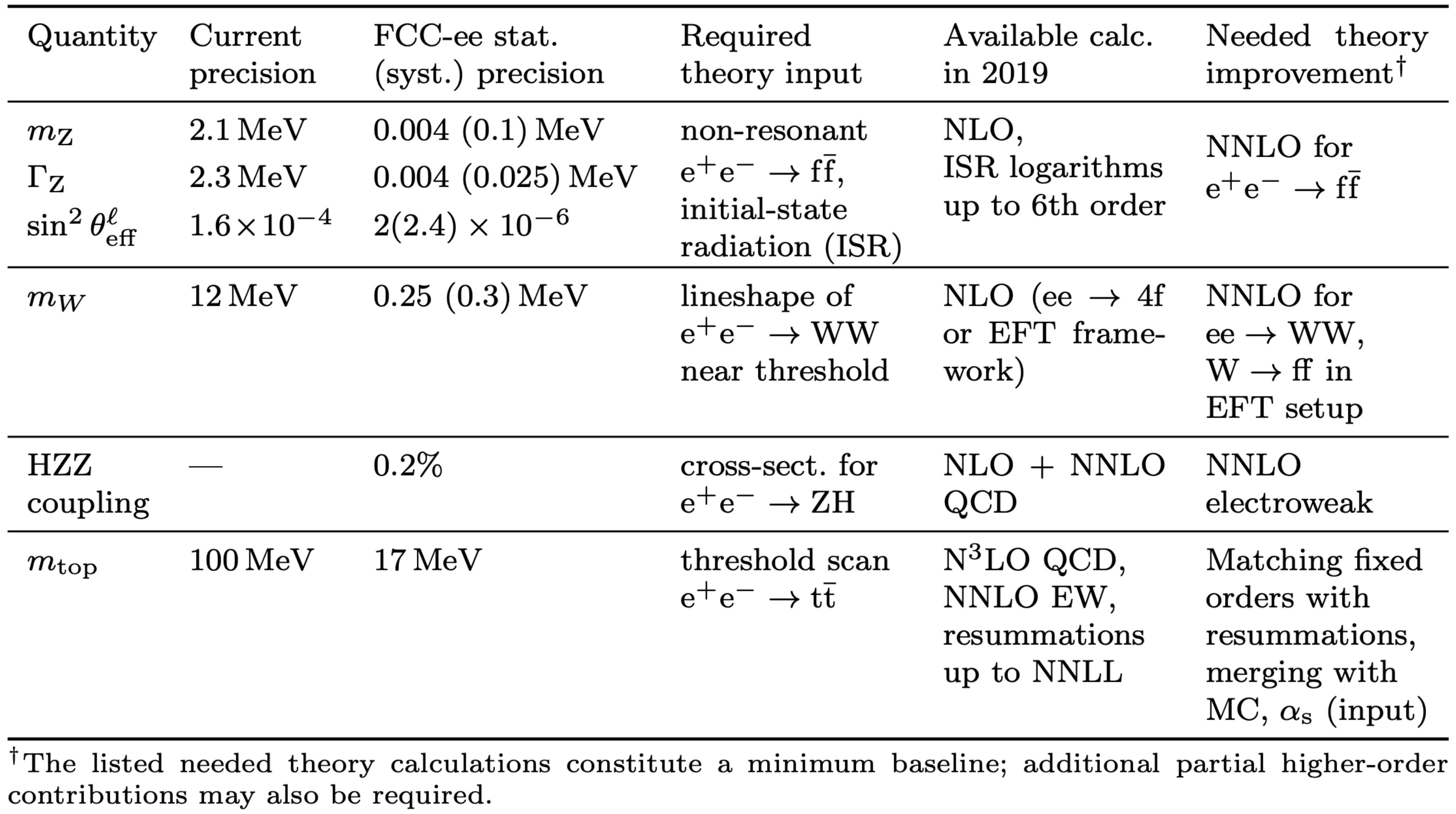
Known at N3LO in the NRQCD EFT approach at threshold for top mass and width determination. NLO QCD corrections for the 2->6 known. NNLO EW corrections are not known.

In addition ISR effects, collinear and soft need to be included.

[Interim FCC feasibility report, 2024]

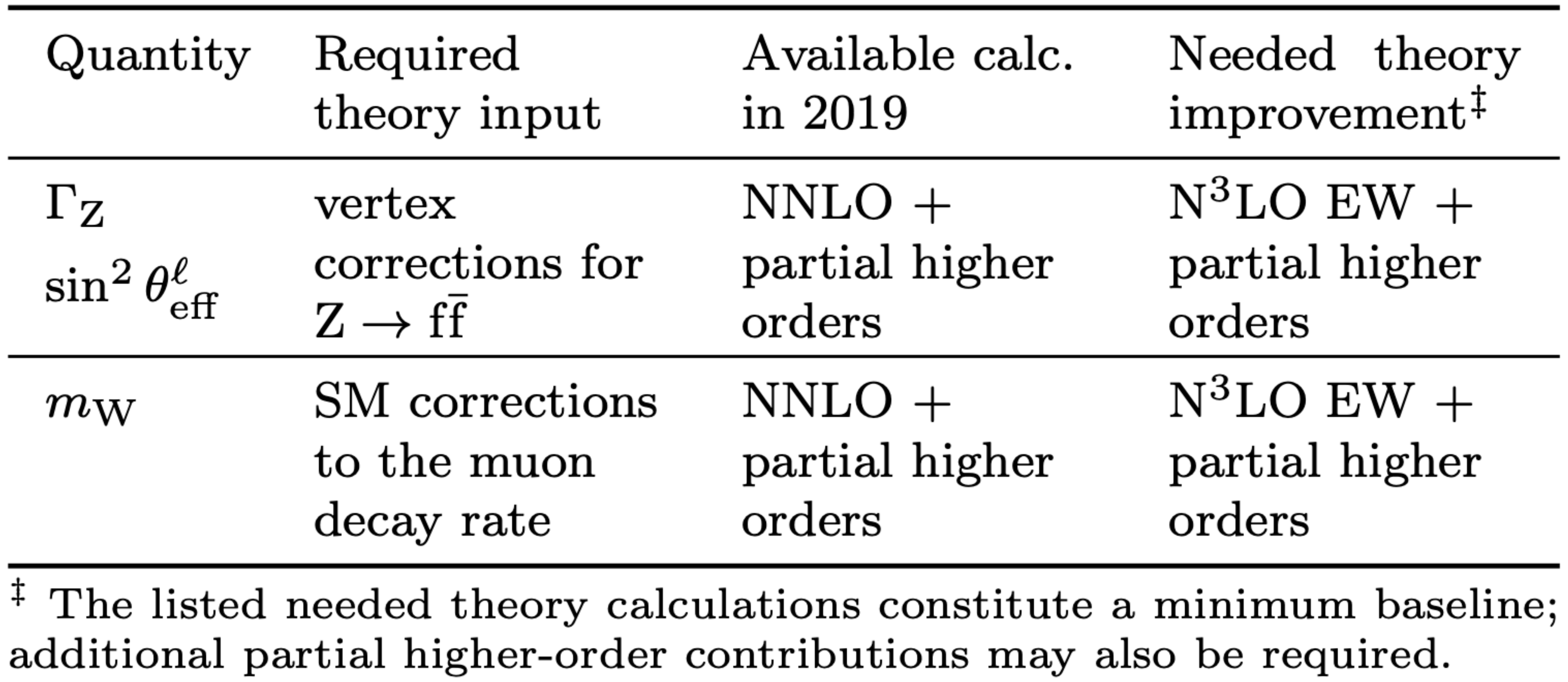
Precision calculations for weak scale factories

Summary of the needs



Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Available calc. in 2019	Needed theory improvement[†]
m_Z Γ_Z $\sin^2\theta^\ell_{\rm eff}$	2.1 MeV 2.3 MeV 1.6×10^{-4}	0.004 (0.1) MeV 0.004 (0.025) MeV $2(2.4)\times10^{-6}$	non-resonant $e^+e^-\to f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6th order	NNLO for $e^+e^-\to f\bar{f}$
m_W	12 MeV	0.25 (0.3) MeV	lineshape of $e^+e^-\to WW$ near threshold	NLO ($ee\to 4f$ or EFT framework)	NNLO for $ee\to WW$, $W\to f\bar{f}$ in EFT setup
HZZ coupling	—	0.2%	cross-sect. for $e^+e^-\to ZH$	NLO + NNLO QCD	NNLO electroweak
$m_{\rm top}$	100 MeV	17 MeV	threshold scan $e^+e^-\to t\bar{t}$	N^{3}LO QCD, NNLO EW, resummations up to NNLL	Matching fixed orders with resummations, merging with MC, α_s (input)

[†] The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.



Quantity	Required theory input	Available calc. in 2019	Needed theory improvement[‡]
Γ_Z $\sin^2\theta^\ell_{\rm eff}$	vertex corrections for $Z\to f\bar{f}$	NNLO + partial higher orders	N^{3}LO EW + partial higher orders
m_W	SM corrections to the muon decay rate	NNLO + partial higher orders	N^{3}LO EW + partial higher orders

[‡] The listed needed theory calculations constitute a minimum baseline; additional partial higher-order contributions may also be required.

FCC your questions answered, 1906.02693 [hep-ph]

Alternative scenarios

LEP3

- A similar accelerator technology as that foreseen for FCC-ee could be installed in the LEP tunnel after HL-LHC.

- Engineering works would be needed to accomodate for the cavities and cryogenics.

- Estimates for time for installation indicate at least 5 years.

- Energy from 91 to 240, no ttbar threshold, with about 1/5 of instant luminosity (~R).

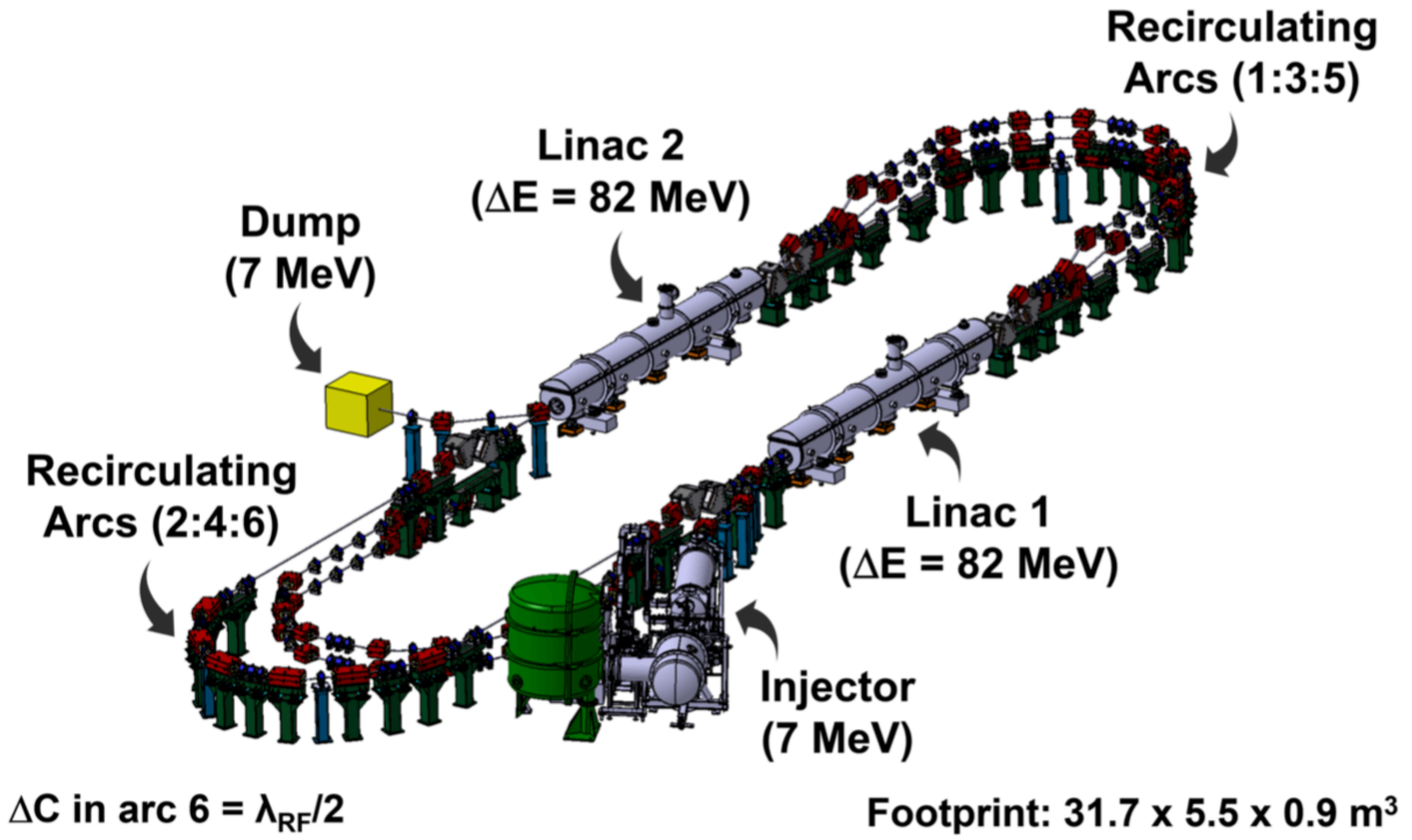
- Possible limitations: polarisation (~1/Sqrt[R]), energy resolution, energy consumption,…need to be studied.

Alternative scenarios

LHeC

- A proposed colliding beam facility at **HL-LHC**
- Collide an **electron beam** (50-60 GeV) with protons or heavy ions
- Deep inelastic **lepton-nucleon** scattering
  - Nuclear parton density functions at unprecedented precision
  - Higgs boson production via VBF
  - Top quark properties •…
- Center-of-mass energy of **1.3 TeV** (x4 HERA)
- At least one detector to study **asymmetric** collisions

- LHeC/FCC-eh would need a **new electron accelerator**
- Use a combination of **10 GeV racetrack Energy Recovery Linacs (ERLs)**
- Keep low beam emittance through **recycling** of particles' kinetic energy - transfer energy from decelerating to accelerating beam via RF
- **Sustainable particle acceleration** of 1 GW electron beams at 100 MW used power
- Additionally use ERL as a source of **high-energy photons**



Zimmerman at the ES FCC-hh kick-off meeting

Alternative scenarios

FCC-hh at 70-80 TeV

- Proven magnet technology could allow to go straight to pp collisions in the 91 Km tunnel and have a pp@70 TeV by 2050.
- Possible option also in case China goes for the CEPC.
- Studies are on-going to assess the reach of such a machine.
- Very expensive

Dipole field [T]	c.m. energy	Comment
12	72	not far above peak field of HL-LHC Nb_3Sn quadrupoles
14	84	Nb_3Sn or HTS
17	102	HTS
20	120	HTS

Mangano at the ES FCC-hh kick-off meeting

Alternative scenarios

FCC-hh at 70-80 TeV

ttH coupling from ttH/ttZ

$p_{T,min}$ (GeV)	0	100
σ(80)/σ(100)	0.68	0.67

At 80 TeV expect stat degradation of precision from 1% to 1.2%

$H\gamma\gamma, H\mu\mu, HZ\gamma$ couplings

Coupling precision	100 TeV CDR baseline	80 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	0.65	0.7
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	0.9	1.0

Higgs self-coupling

100 TeV	s I	s II	s III
stat	3.0	4.1	5.6
syst	1.6	3.0	5.4
tot	**3.4**	**5.1**	**7.8**

80 TeV	s I	s II	s III
stat	3.5	4.7	6.4
syst	1.6	3.0	5.4
tot	**3.8**	**5.6**	**8.4**

$$\frac{\sigma_{HH}(80\text{TeV})}{\sigma_{HH}(100\text{TeV})} \sim 0.72$$ => increase δ_{stat} by 15%

Collider discovery reach

	100 TeV	80 TeV
Q*	40	33
$Z'_{TC2}\to tt$	23	20
$Z'_{SSM}\to tt$	18	15
$G_{RS}\to WW$	22	19
$Z'_{SSM}\to ll$	43	36
$Z'_{SSM}\to \tau\tau$	18	15

- **15-20% reach loss at 80 TeV**

The loss in rate for key observables of the guaranteed deliverables is around 20-30% with marginal impact on measurements. Discovery reach in mass goes down of 15-20%.

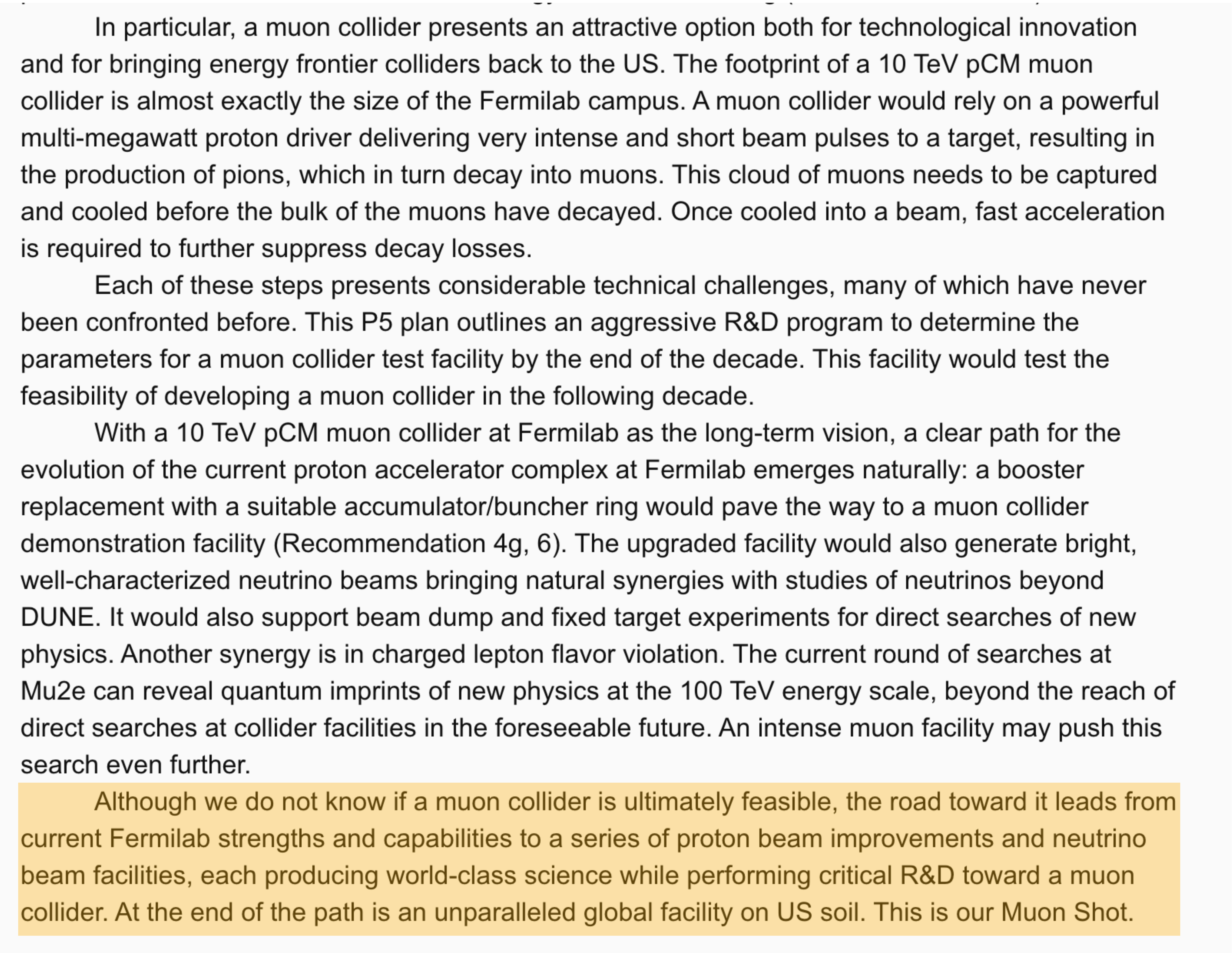
Timeline(s)

To be taken cum grano salis

The non-binary strategy

The muon shot

P5:

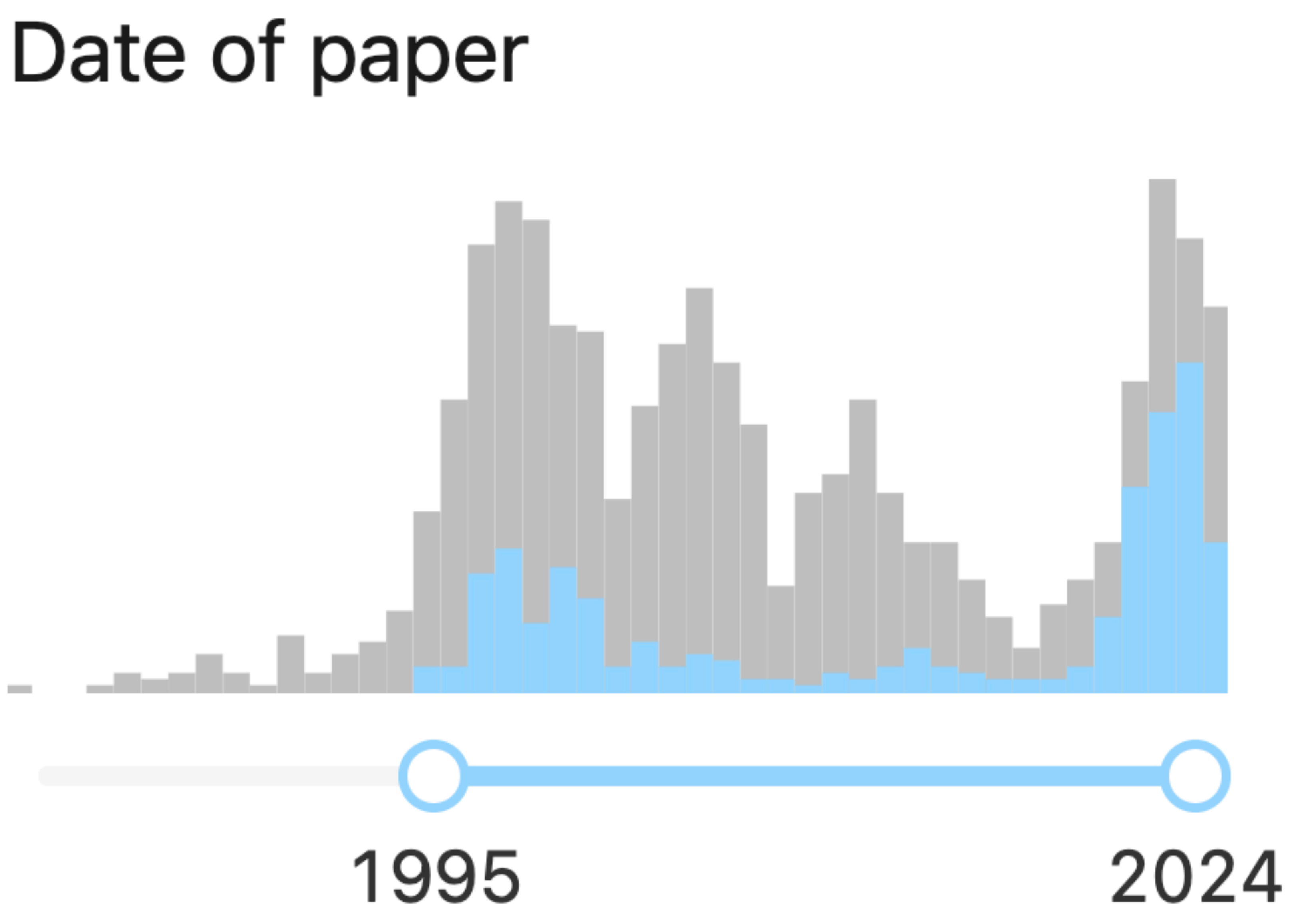


In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

Each of these steps presents considerable technical challenges, many of which have never been confronted before. This P5 plan outlines an aggressive R&D program to determine the parameters for a muon collider test facility by the end of the decade. This facility would test the feasibility of developing a muon collider in the following decade.

With a 10 TeV pCM muon collider at Fermilab as the long-term vision, a clear path for the evolution of the current proton accelerator complex at Fermilab emerges naturally: a booster replacement with a suitable accumulator/buncher ring would pave the way to a muon collider demonstration facility (Recommendation 4g, 6). The upgraded facility would also generate bright, well-characterized neutrino beams bringing natural synergies with studies of neutrinos beyond DUNE. It would also support beam dump and fixed target experiments for direct searches of new physics. Another synergy is in charged lepton flavor violation. The current round of searches at Mu2e can reveal quantum imprints of new physics at the 100 TeV energy scale, beyond the reach of direct searches at collider facilities in the foreseeable future. An intense muon facility may push this search even further.

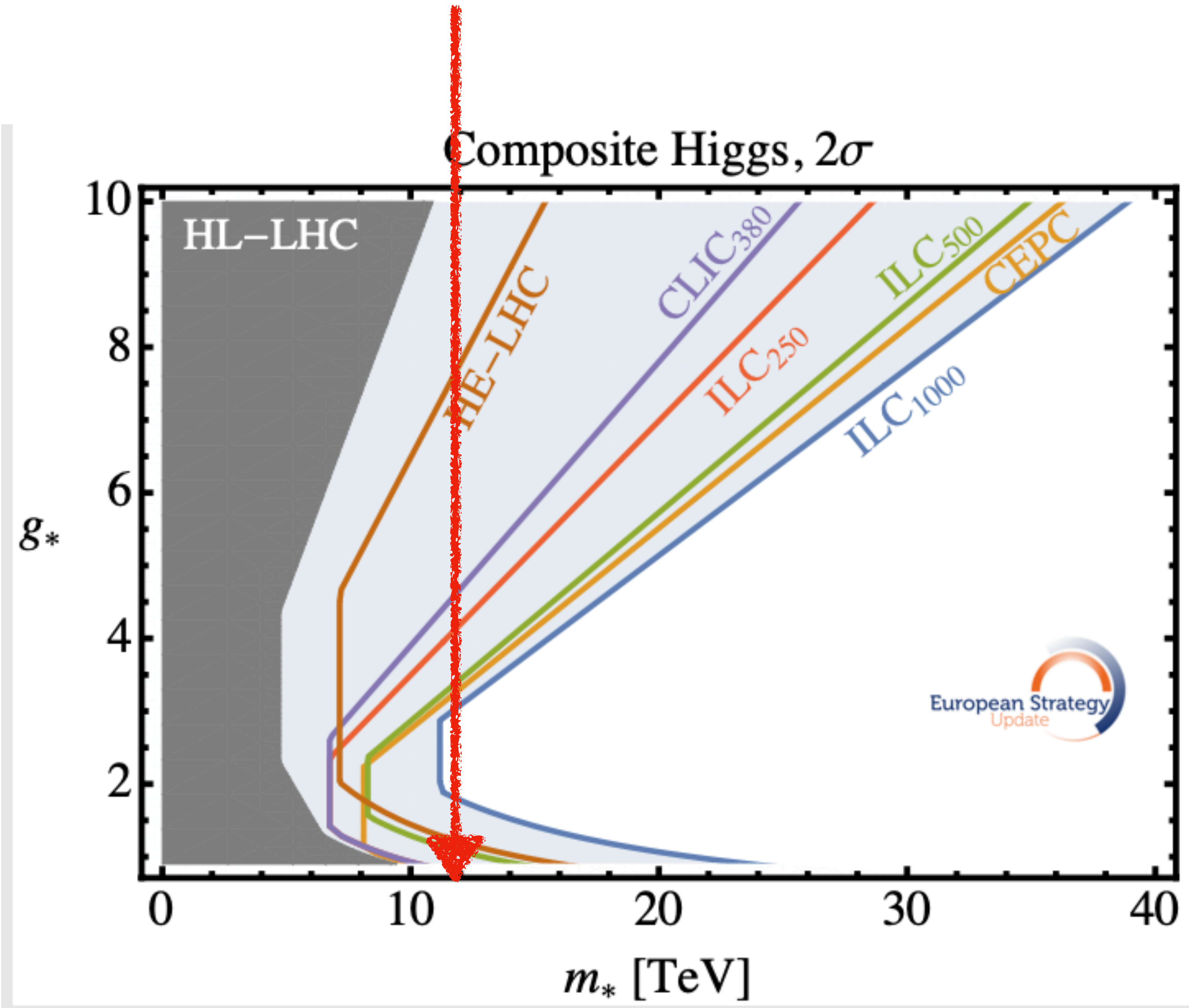
Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D toward a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.



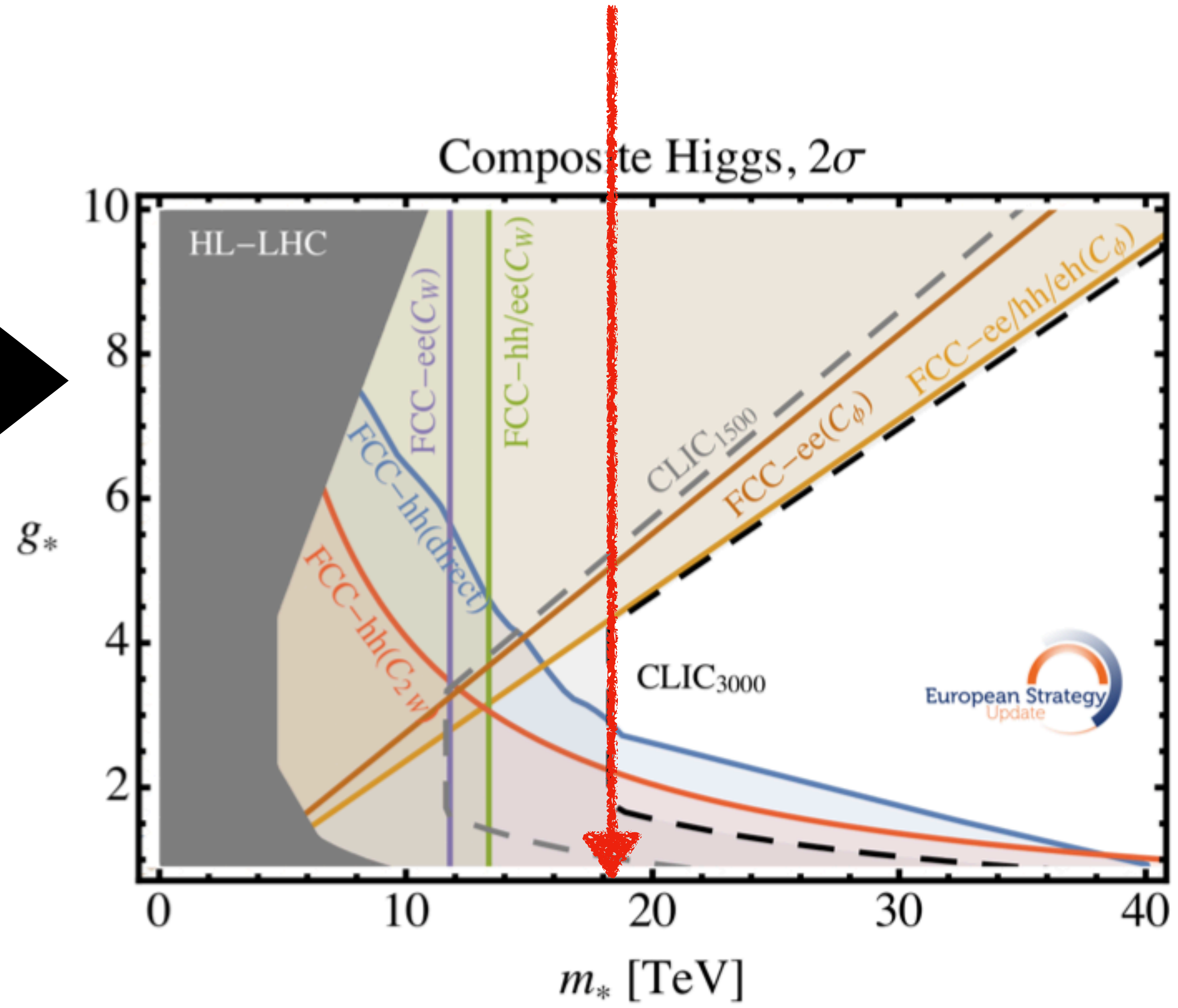
122 pheno papers in the last 5 years

The muon shot

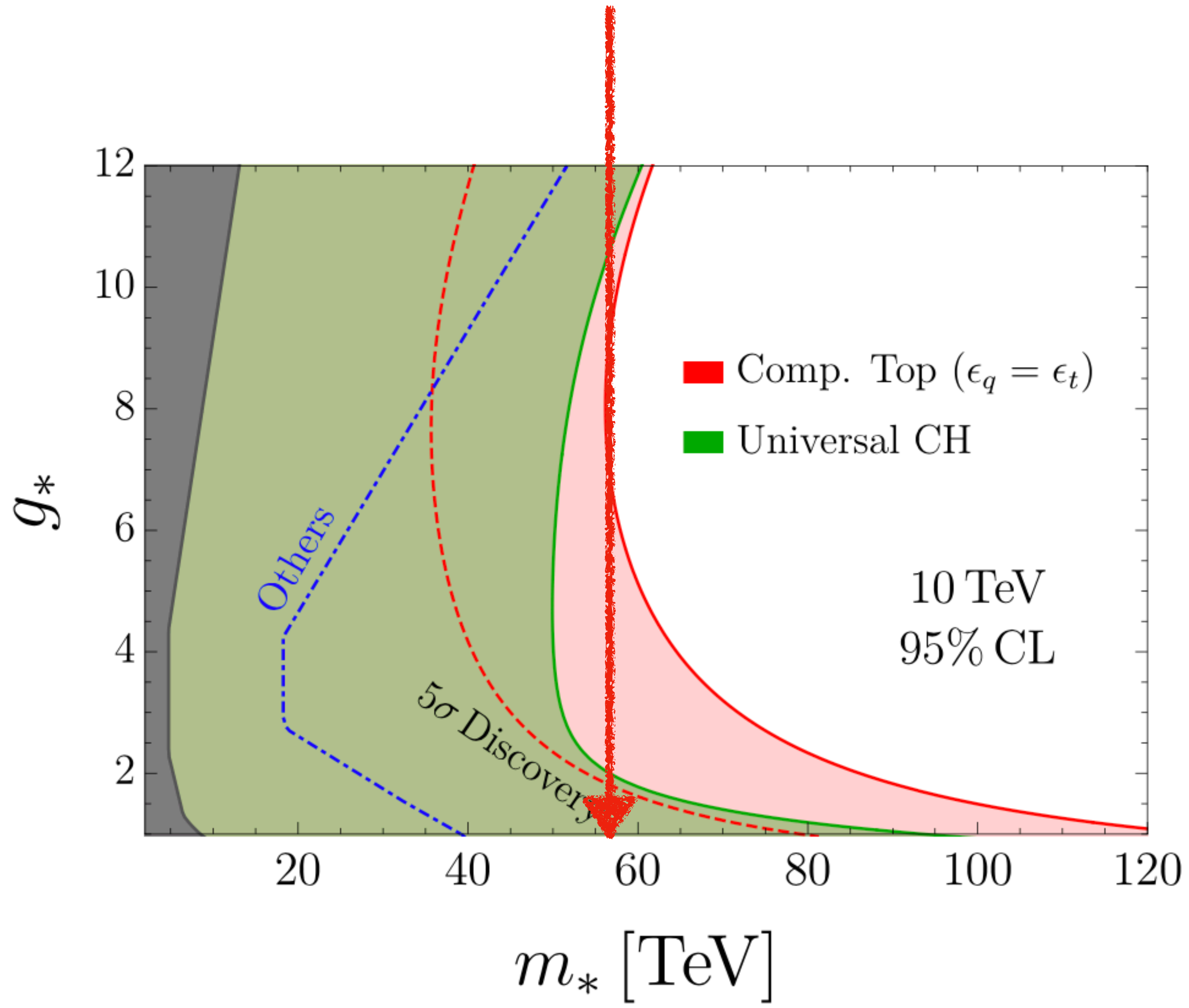
Higgs compositeness



LHC+FCCee



CLIC+others



Muon Collider

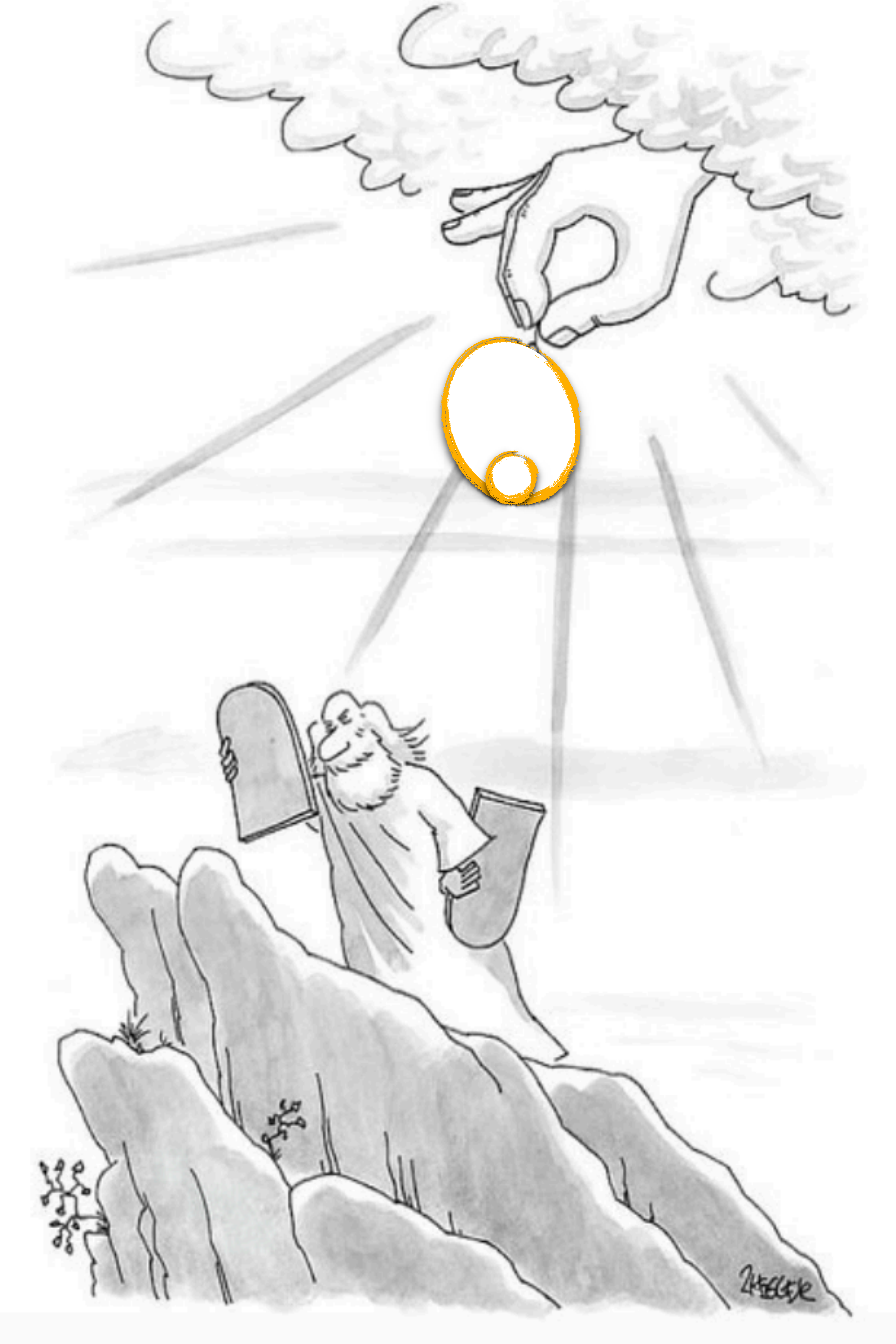
95% reach on the Composite Higgs scenario from high-energy measurements in di- boson and di-fermion final states.

Summary

- In the **near future**, i.e. for the next 25 years the LHC will be THE machine to continue to map Higgs physics and the TeV scale through a compelling programme of challenging measurements.

- For the **future**, i.e. after 2050, the most mature option for CERN is an e+e- “weak-scale factory” in a new 91 Km circular tunnel with a possible pp option after. FCC-ee would allow mapping properties of the Higgs up to scales of order 10+ TeV.

- In the meantime, R&D on new accelerator technologies, e.g. accelerating muons, should be strongly pursued as this could open a new era in HEP experiments, with very exciting physics cases.

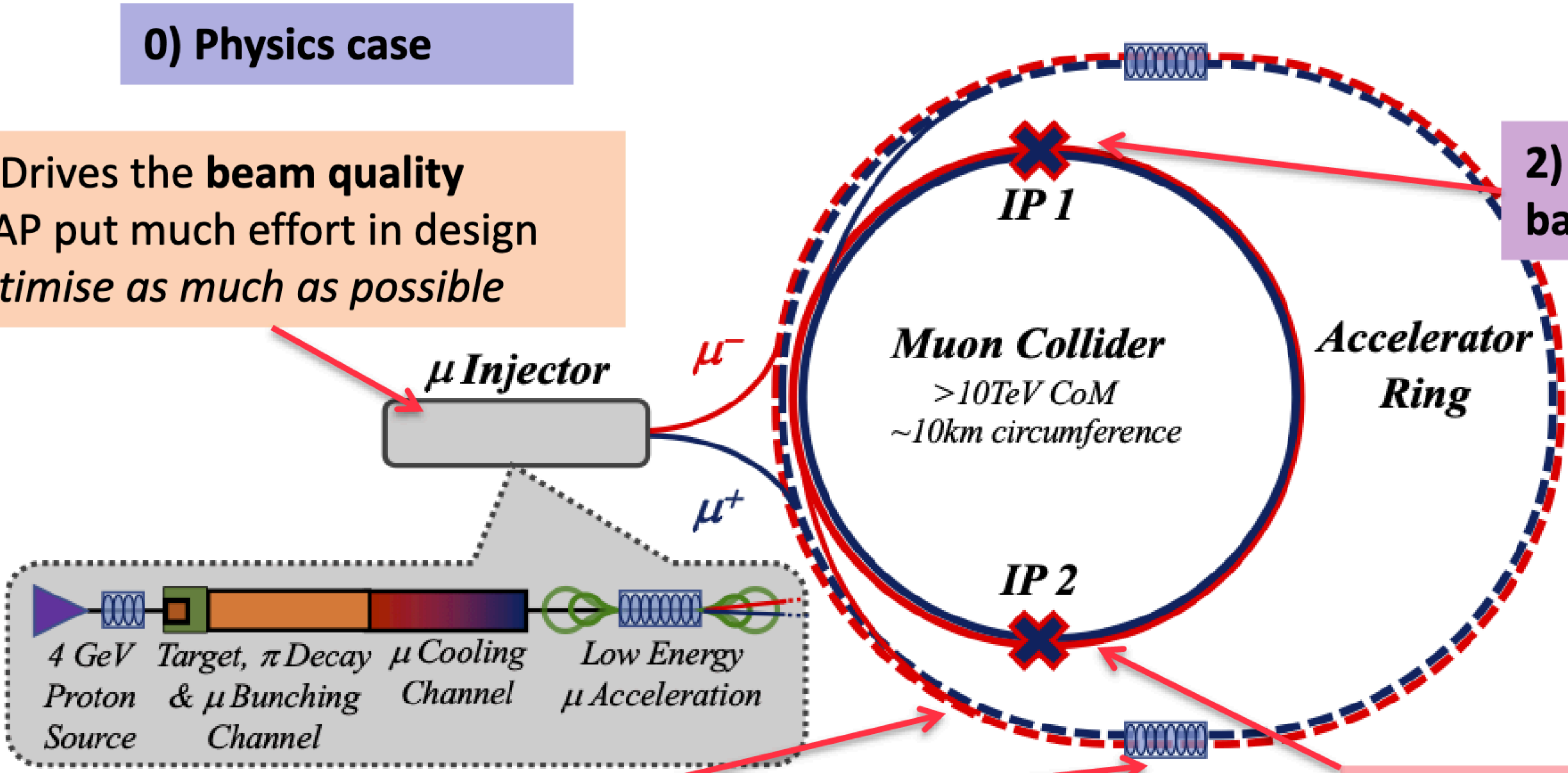


2407.12450 Muon Collider Interim Report

Muon collider

0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible



2) Beam-induced background

1) Dense neutrino flux
mitigated by mover system
and site selection

3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

arXiv:2203.07256v1 Muon Collider Physics Summary

Higgs precision physics

Higgs coupling sensitivities

%	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa_{Z\gamma}^*$	10	10	10
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

arXiv:2308.02633