Future colliders
Futuristic colliders

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New Frontiers in Theoretical Physics 2025
CONVEGNO NAZIONALE DI FISICA TEORICA

UCLouvain fnrs LA LIBERTÉ DE CHERCHER

INFN Istituto Nazionale di Fisica Nucleare

2025 Near future 2050 Future 2075

2050: Europe is the first climate neutral continent

2075: 0% growth rate of human population

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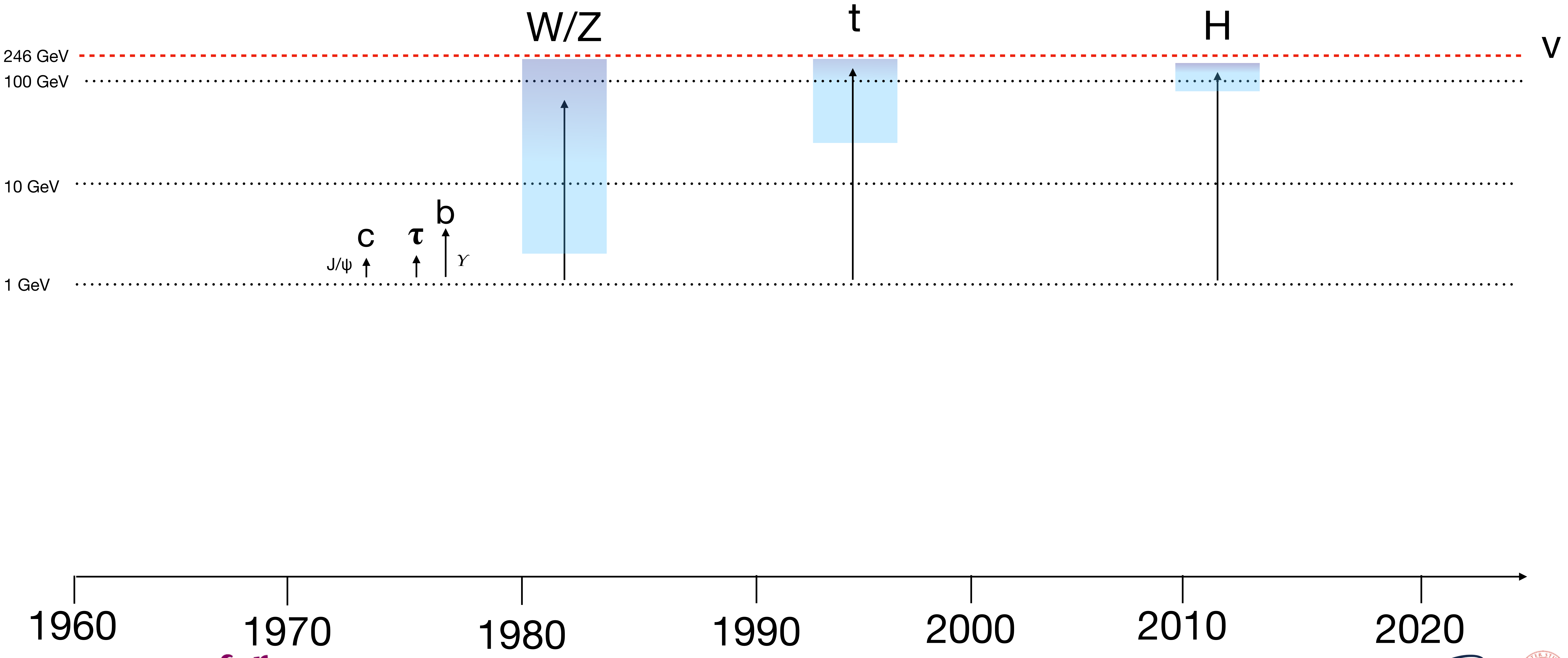
Experimental point of view

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



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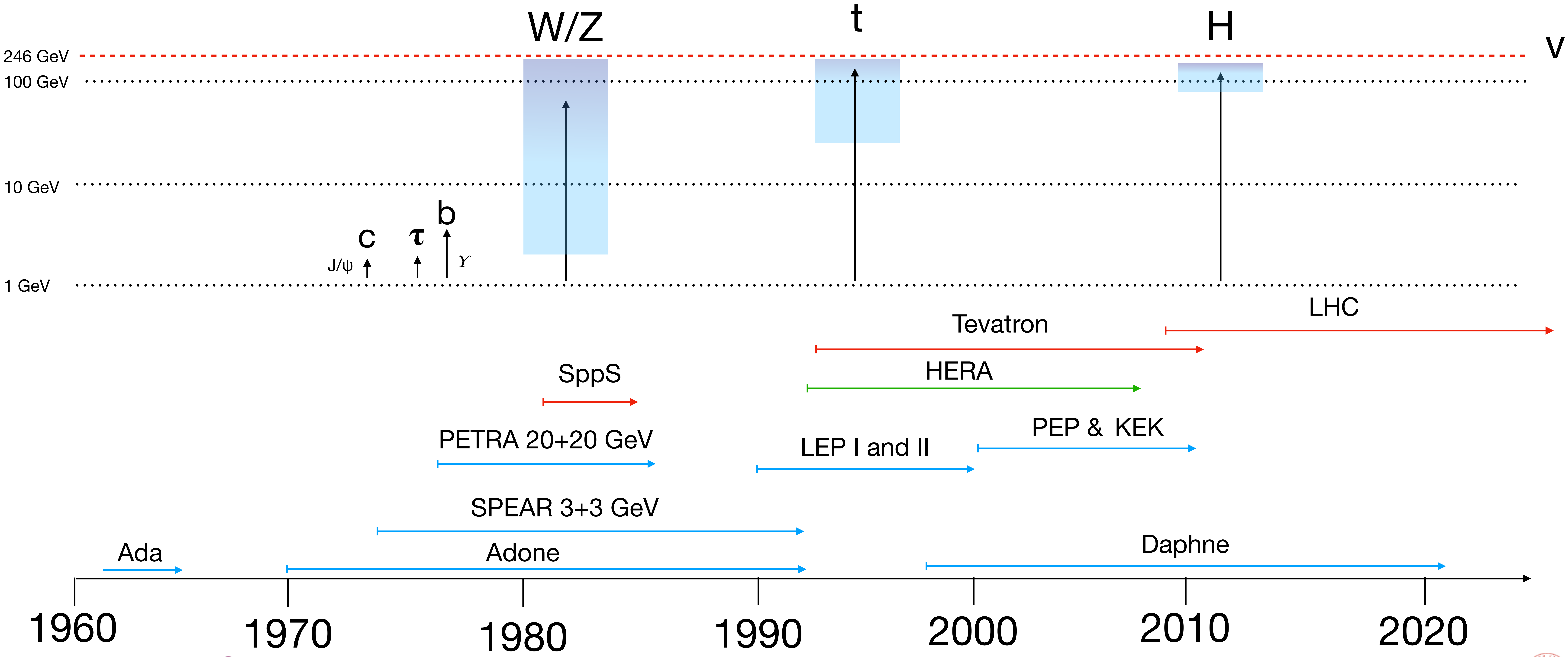

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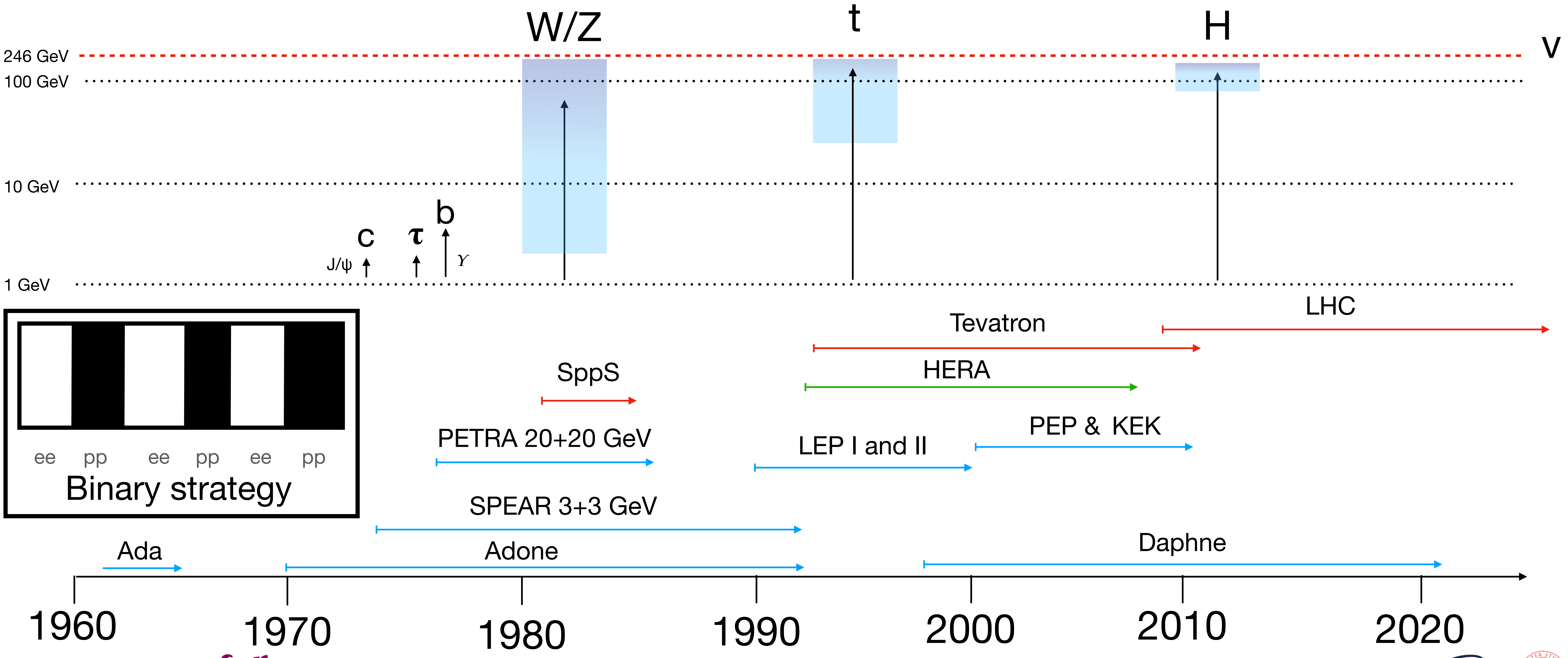
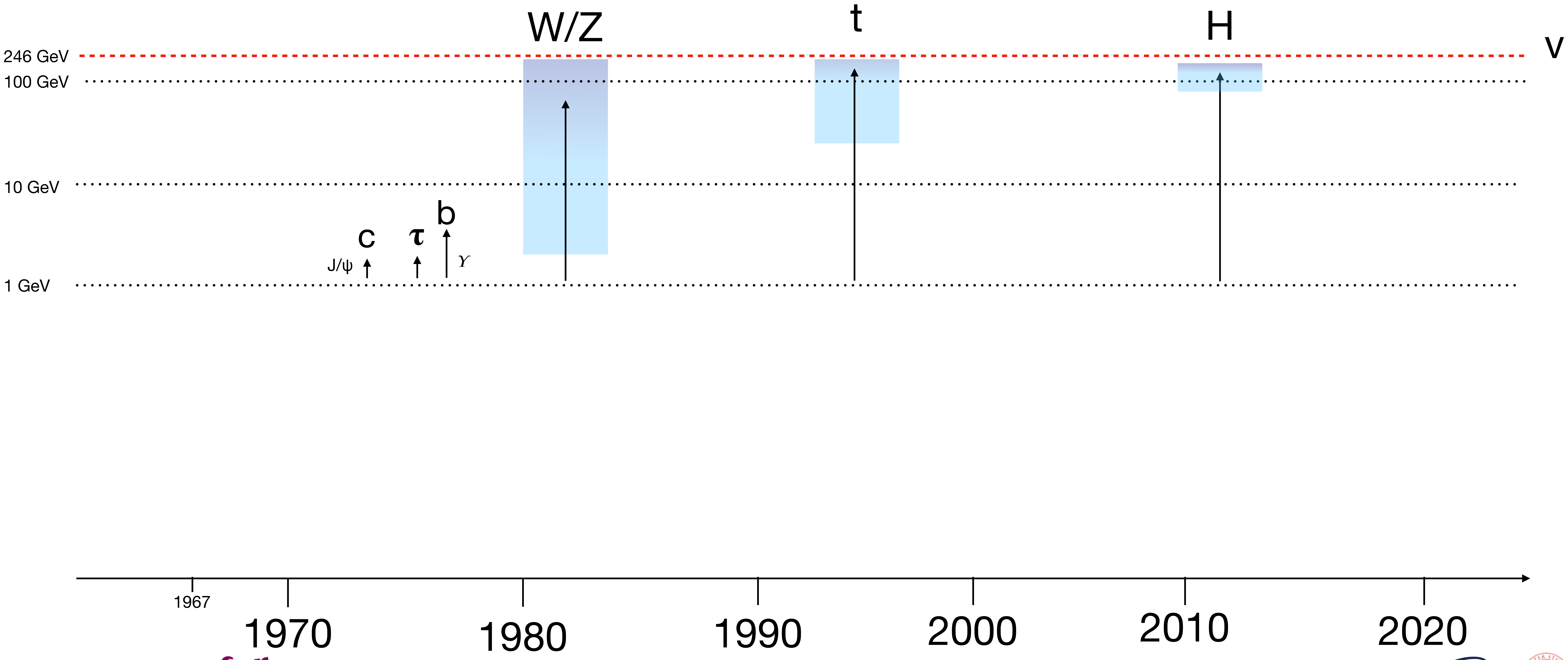


(A) theorist's point of view

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.



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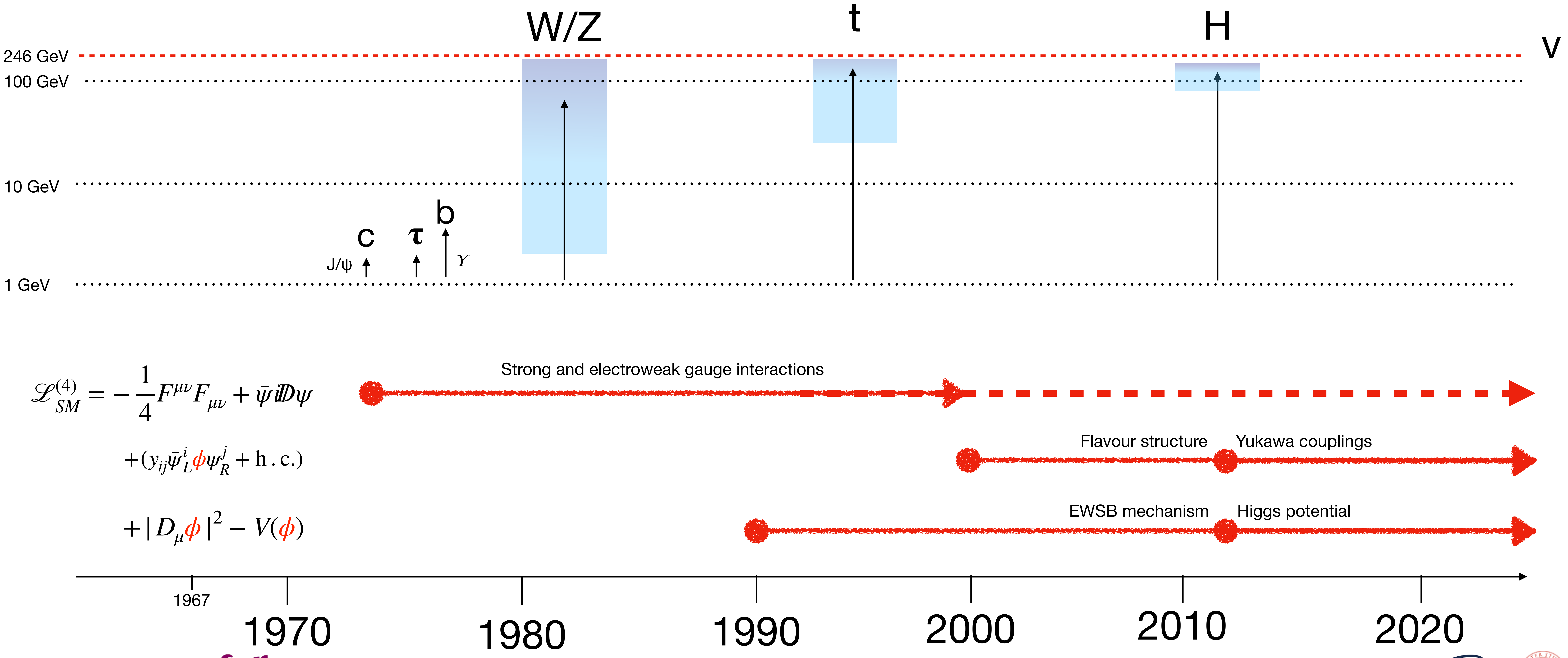
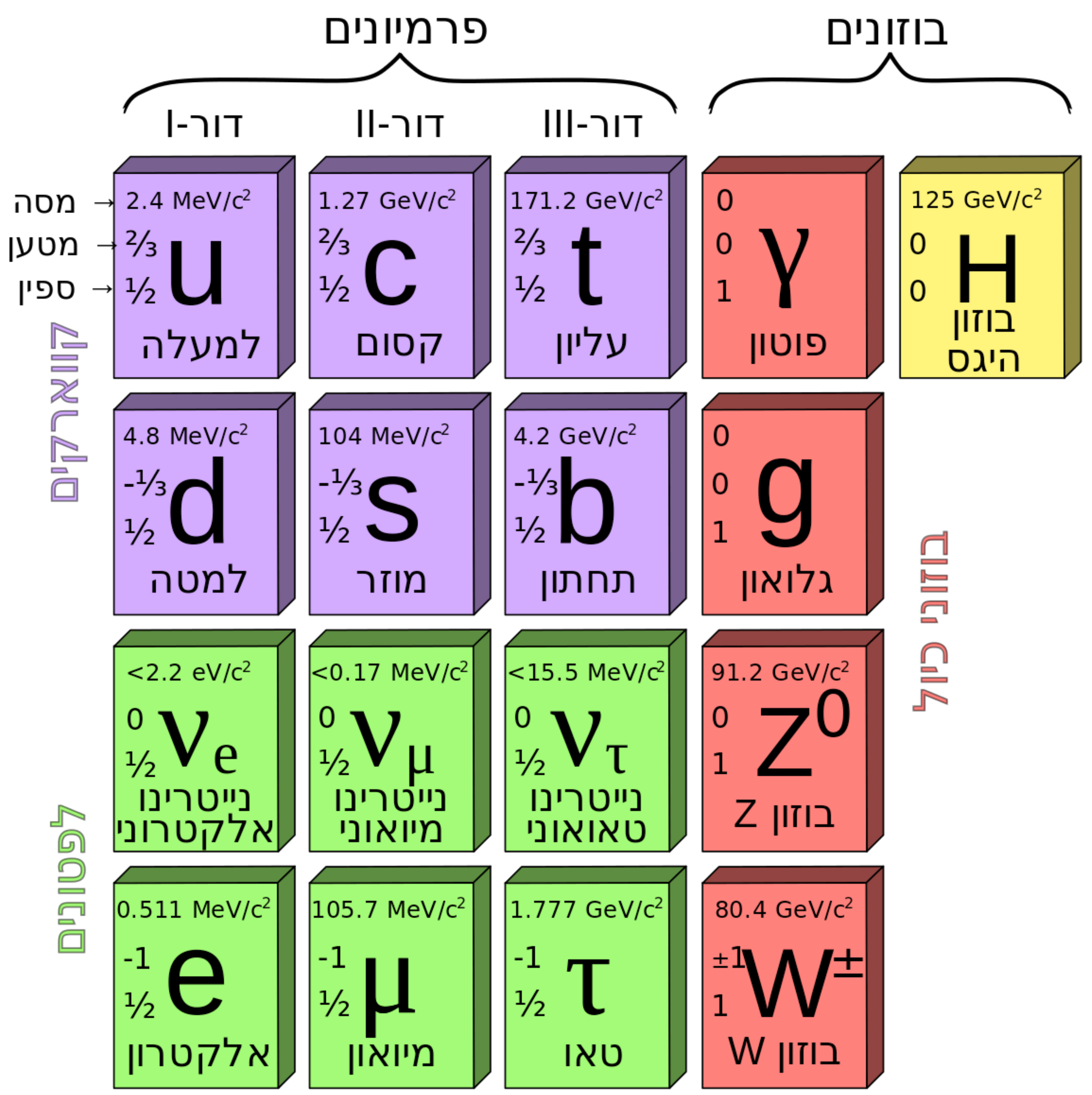


Where do we stand?

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

3 gauge forces

1 scalar force



- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetries
- Matter is organised in chiral multiplets of the fund. representation
- The $SU(2) \times U(1)$ 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

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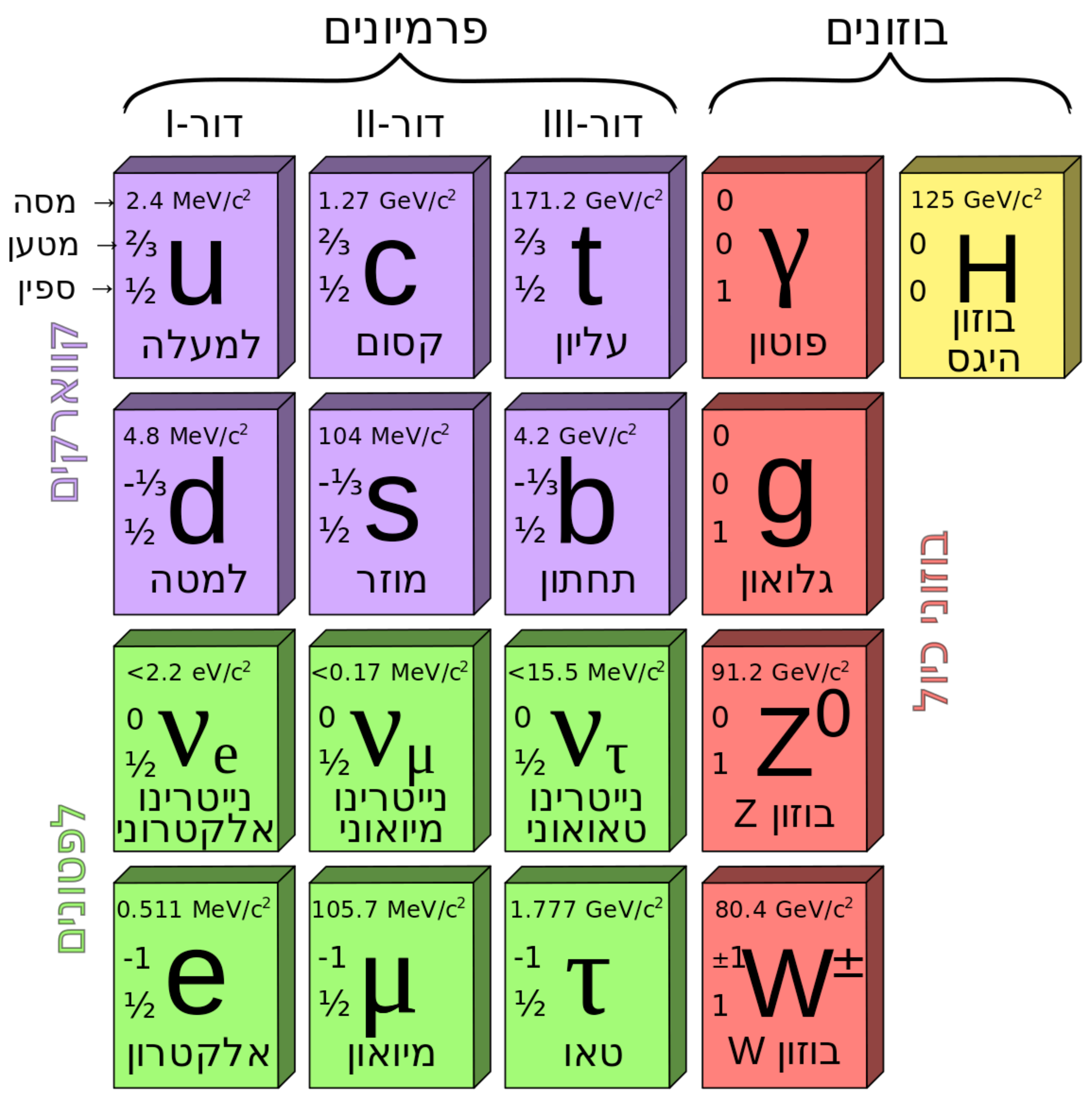

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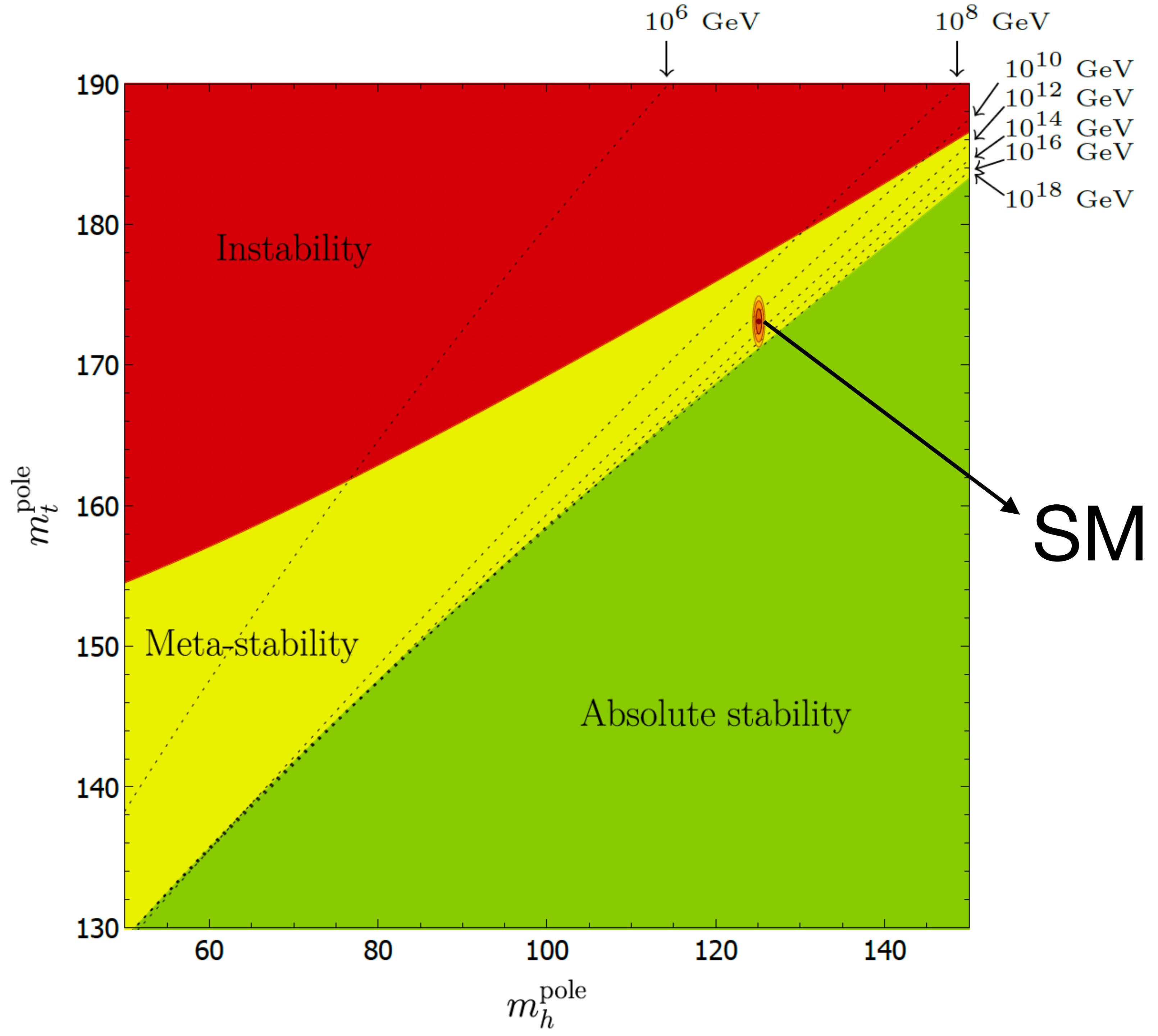
MF, CPV, Flavour   Custiodial, MV   EWBG



[Andreassen et al. 1707.08124]

Apparently accidental, but key aspects for successful phenomenology:

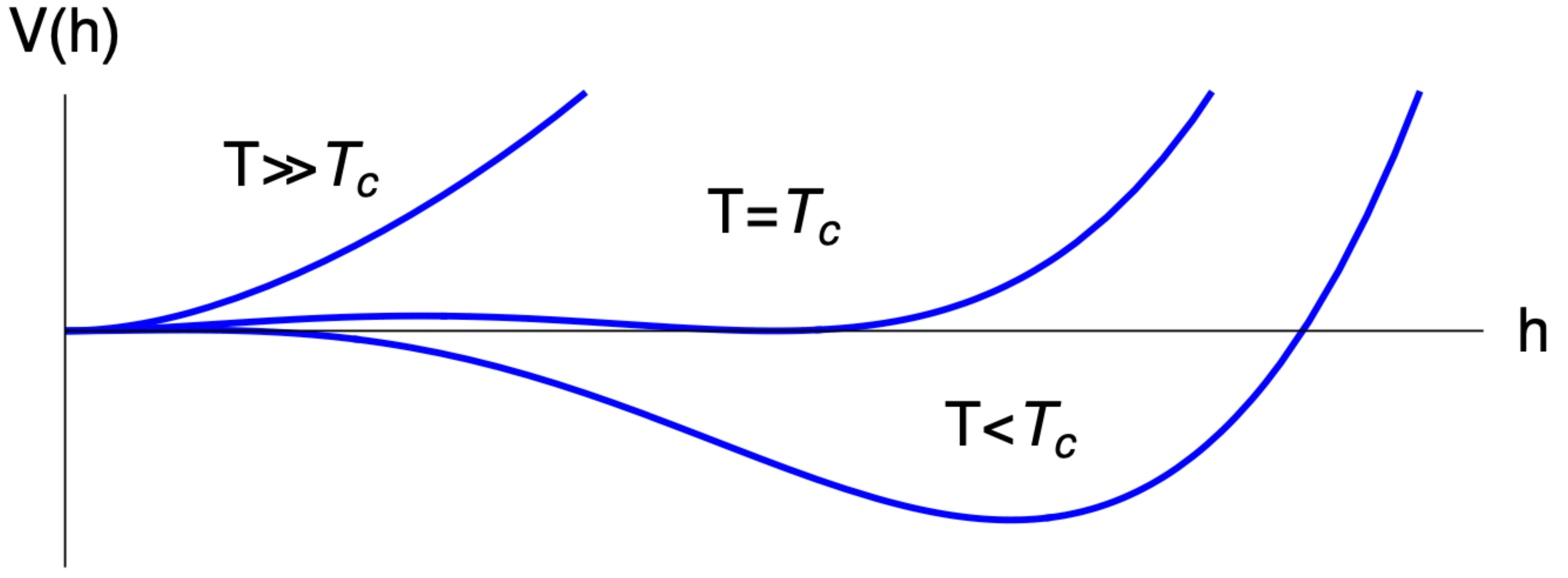
- Lepton and Baryon number conservation
- Custodial symmetry
- Absence of FCN interactions
- Small and hierarchical mixing among quarks
- Collective suppression of CP violation
- IR values of the parameters do not indicate any problem at high scales, including vacuum stability

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

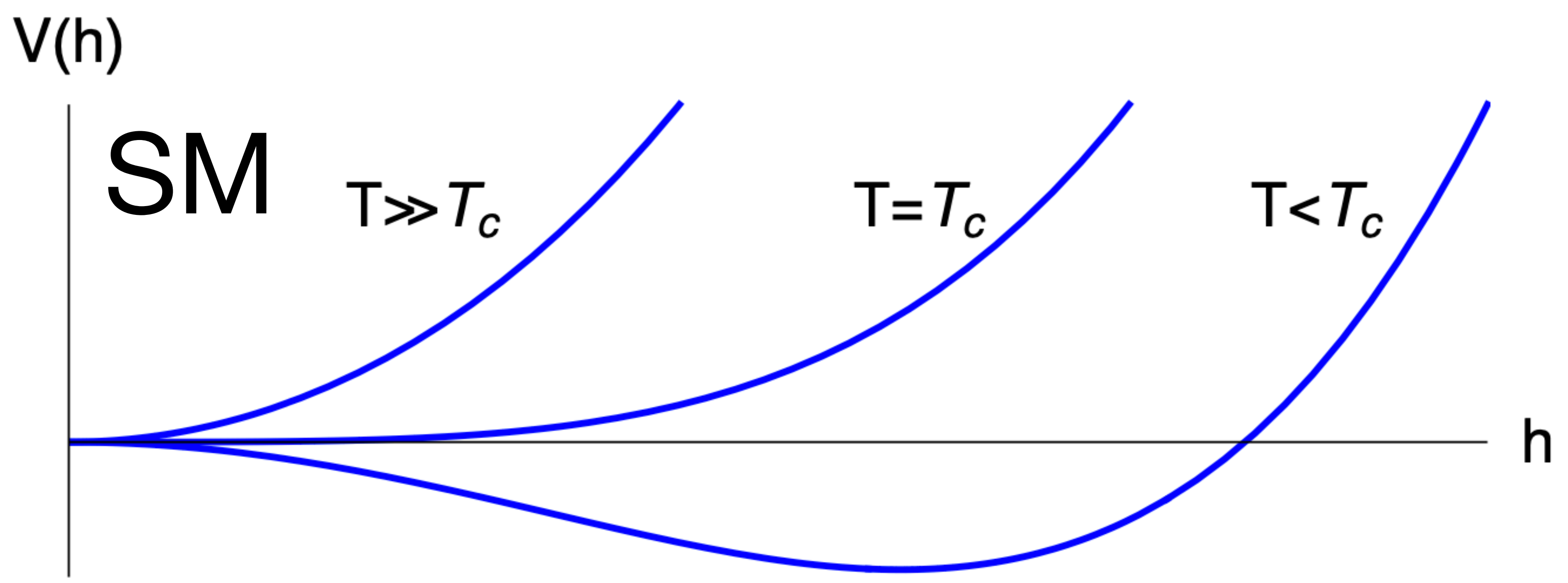
Where do we stand?

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

1st



2nd



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.

A quote

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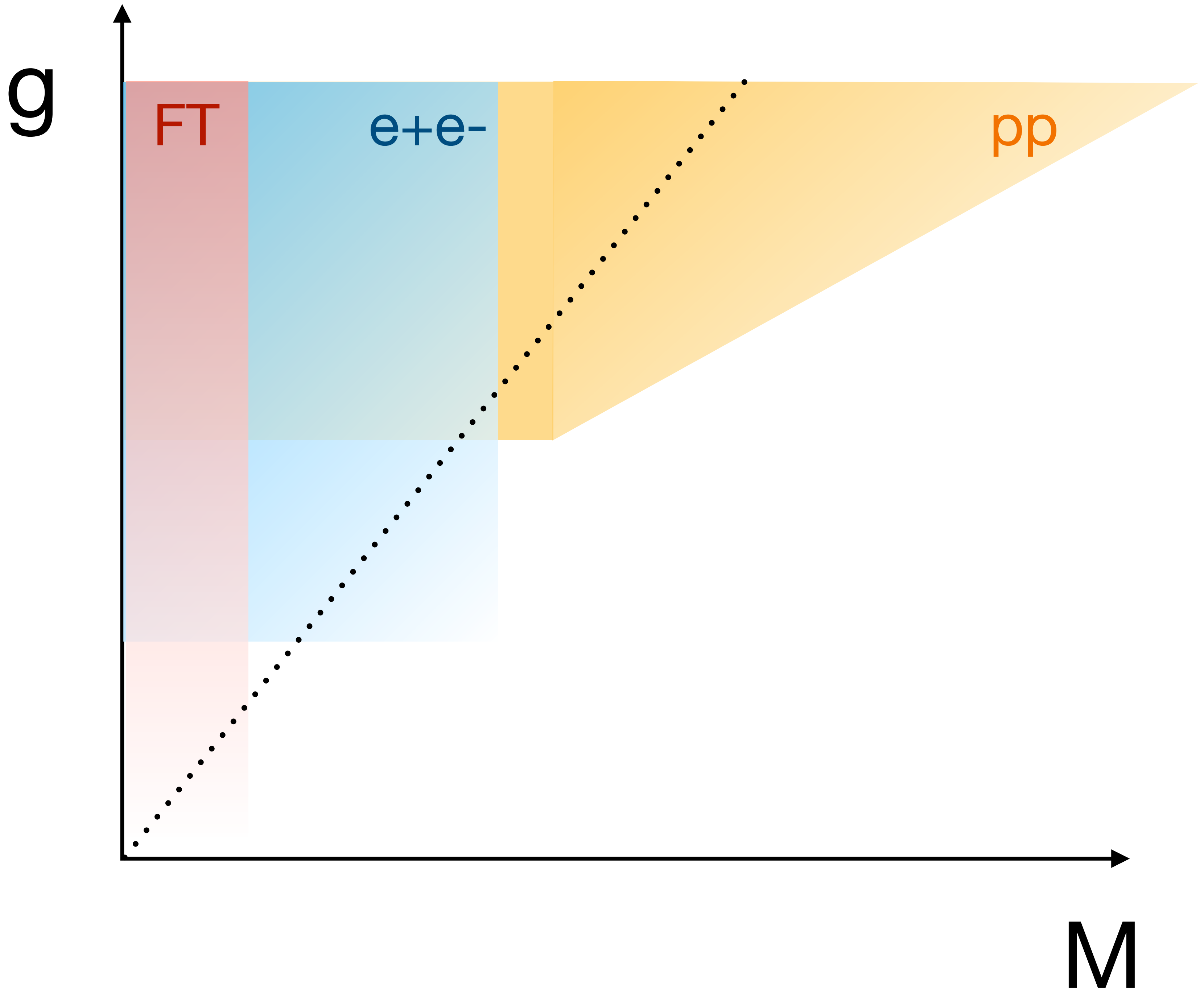
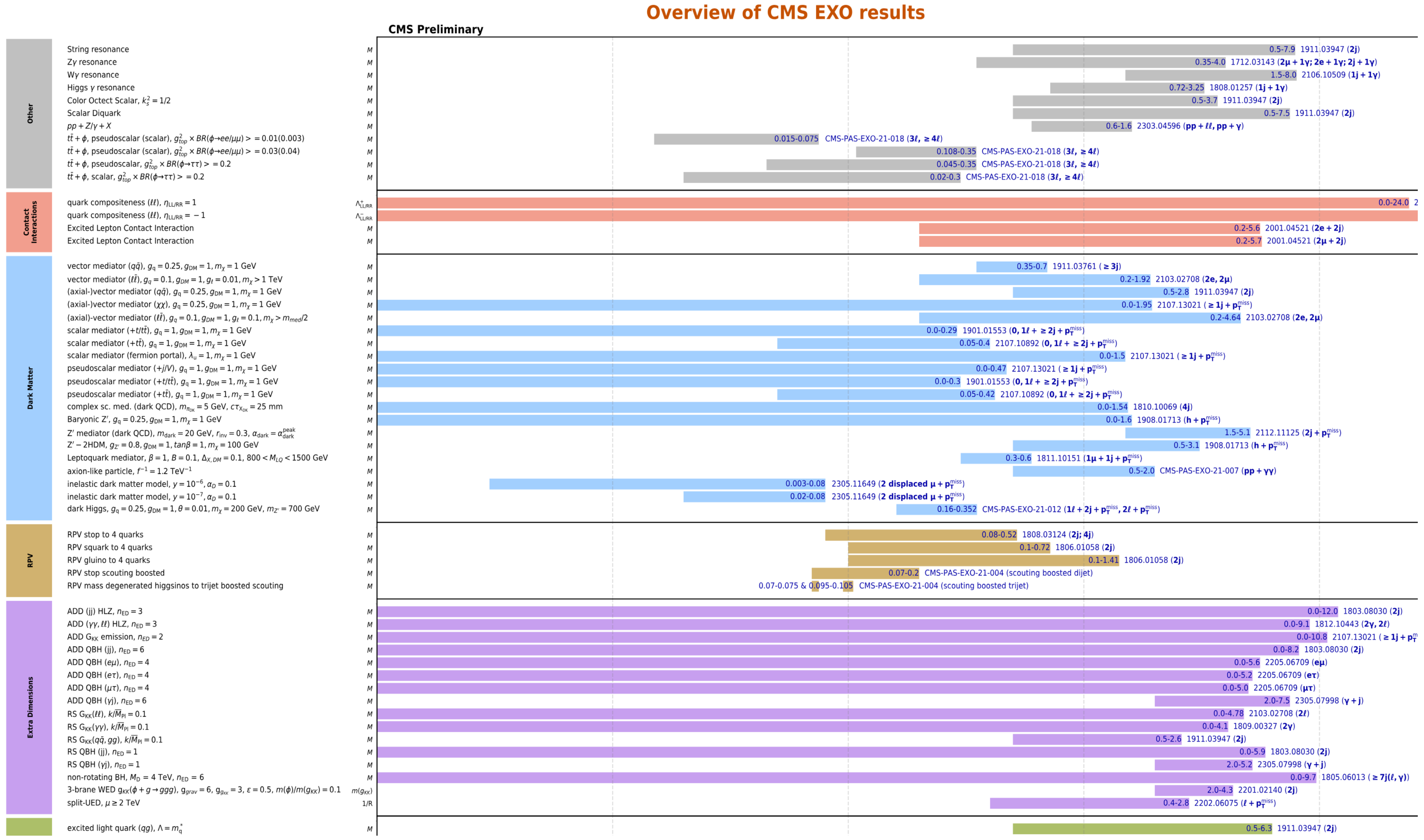
Sun Tzu, The Art of War

Λ_{BSM} is low
BSM direct searches





Λ_{BSM} is high
Indirect searches

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

Rattazzi®

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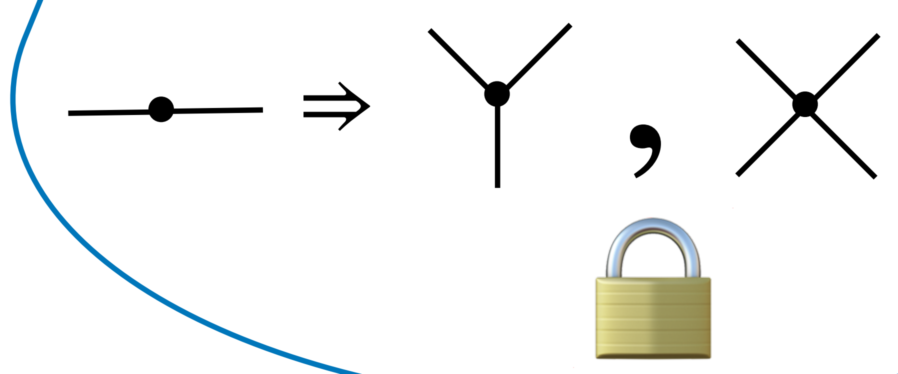
$m_\nu = 0$

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

GIM

$Y_u, Y_d, Y_l \Rightarrow \not{\text{Flavor}}\ \&\ \not{CP}$



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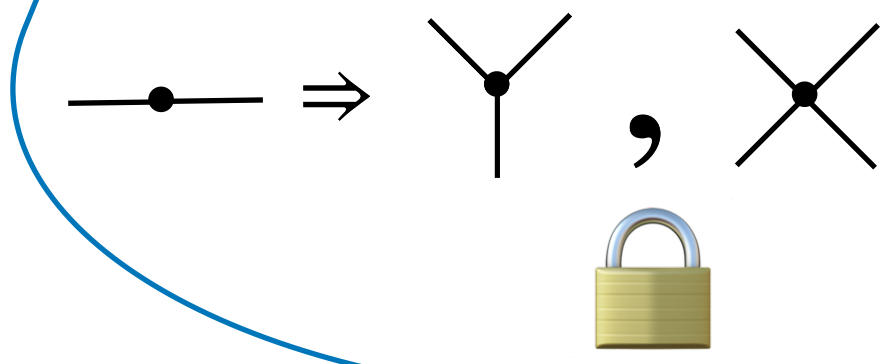


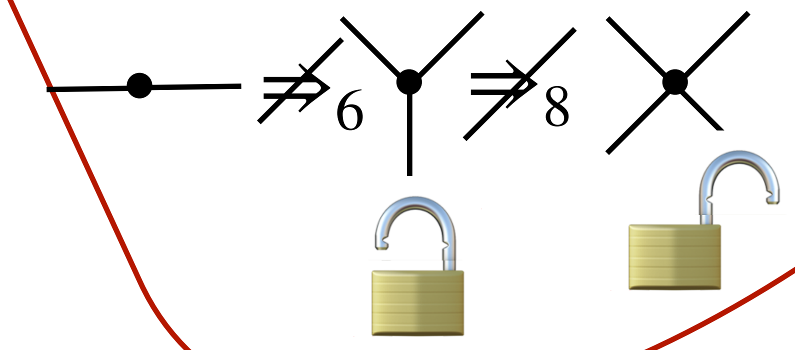
$\cancel{U(1)}_L \to m_\nu \neq 0$

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

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

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

$U(1)_B \Rightarrow p \to \pi^0 e^+$



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$m_h^2 \simeq \Lambda^2$

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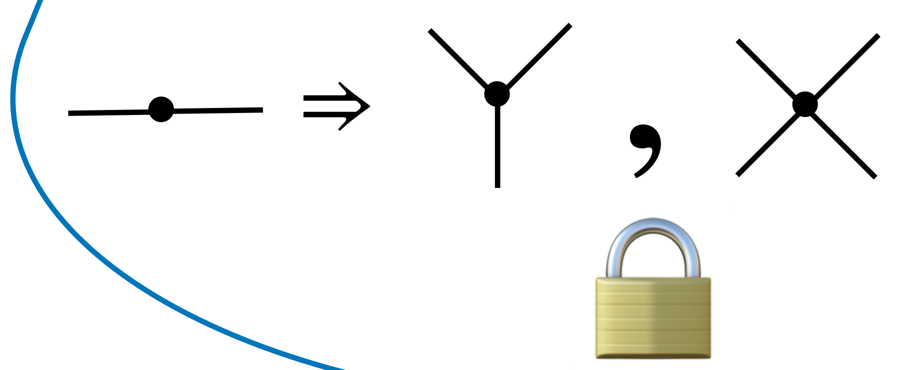

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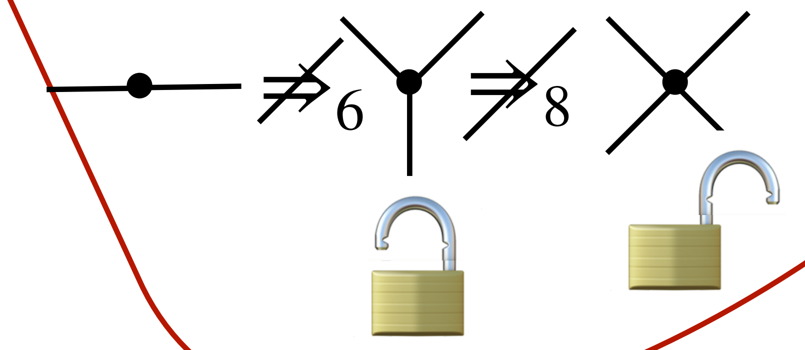

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$m_h^2 \simeq \Lambda^2$

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

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GIM

$Y_u, Y_d, Y_l \Rightarrow$ F̸lavor & C̸P̸

$\not{U}(1)_L \to m_\nu \neq 0$ $\Rightarrow \Lambda \geq 10^{14}$ GeV

F̸lavor $\Rightarrow \mu \to e\gamma, \Delta m_K, \dots$ $\Rightarrow \Lambda \geq 10^{6}$ GeV

C̸P̸ $\Rightarrow$ 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

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$\Lambda_{\rm BSM}$ is high

Indirect searches

Λ_{UV}

TeV

Simplicity 🙂

Naturalness ☹️

TeV Λ_{UV}

Naturalness 🙂

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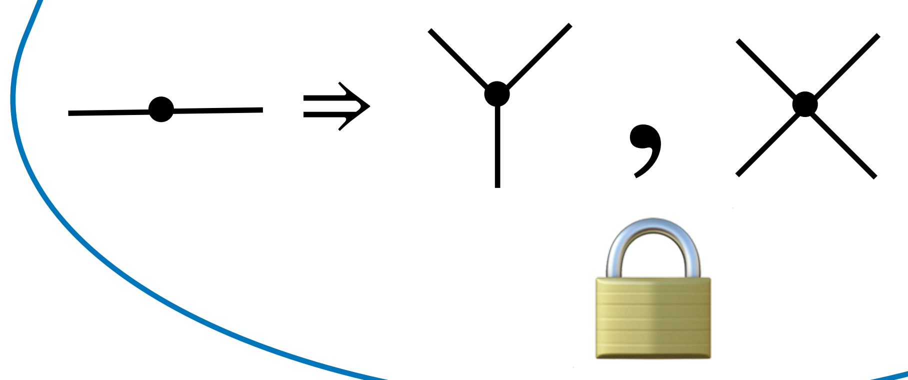

~~$U(1)_L$~~ $\rightarrow m_\nu \neq 0$ $\Rightarrow \Lambda \geq 10^{14}$ GeV

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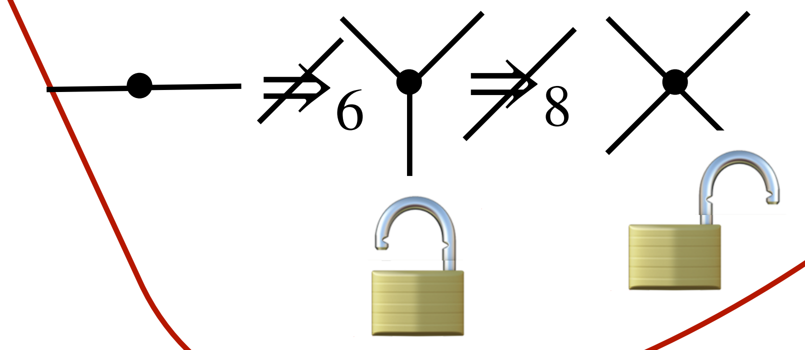

$\Rightarrow \Lambda \geq 10^{3}$ GeV

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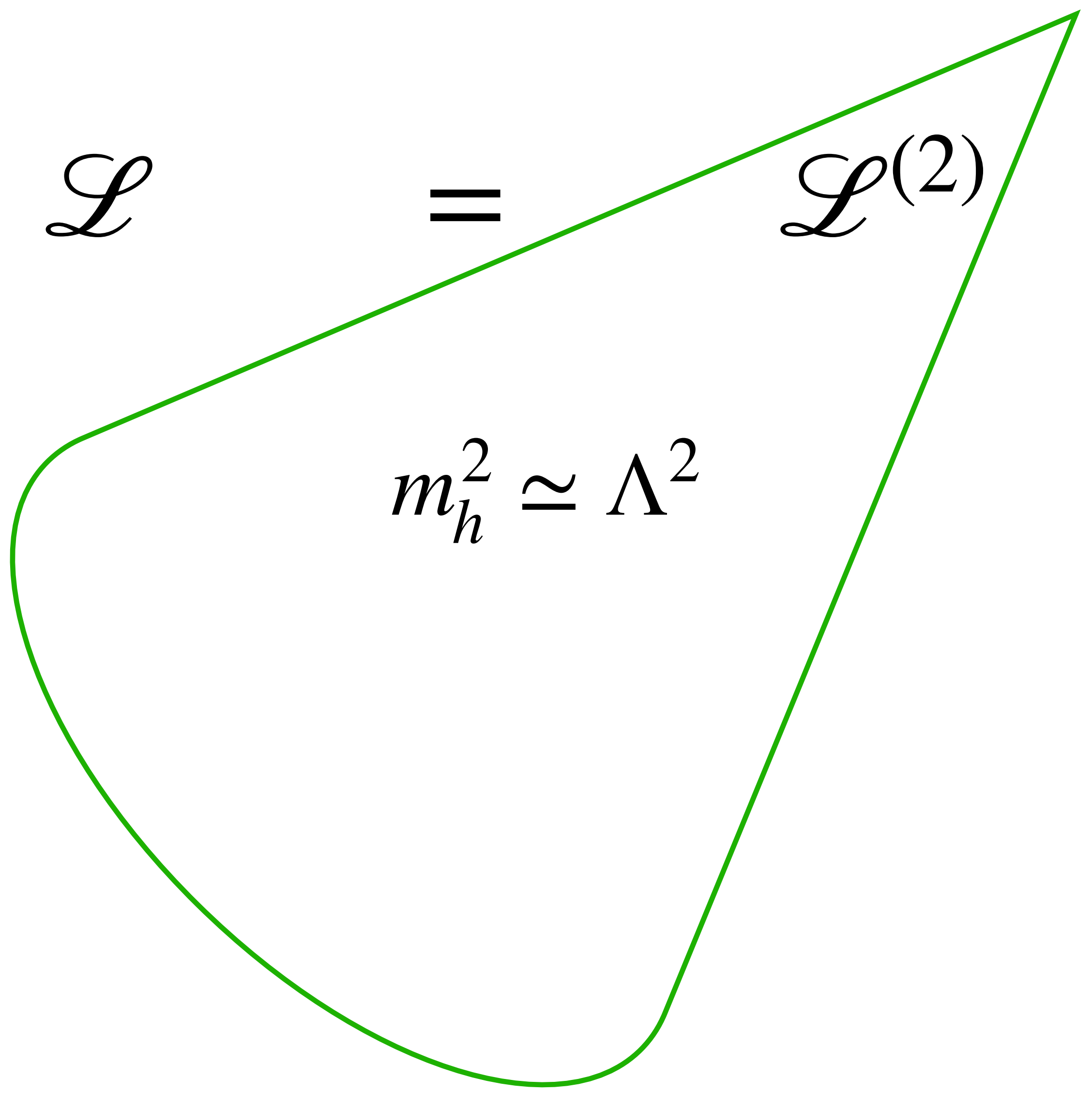
Λ_{BSM} is high
Tuning



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 partner. 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 $m_T \sim m_H \sim 100\,\text{GeV}$, 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 $m_T \sim m_H / \sqrt{3y_t^2/4\pi^2} \sim 450\,\text{GeV}$, 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.

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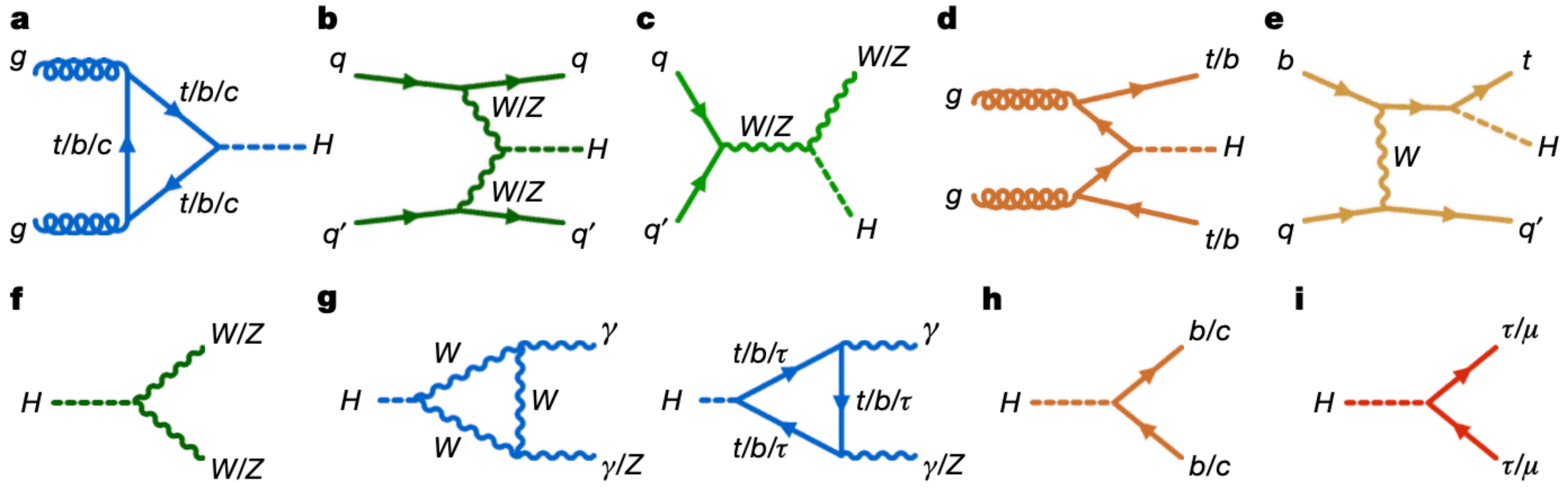
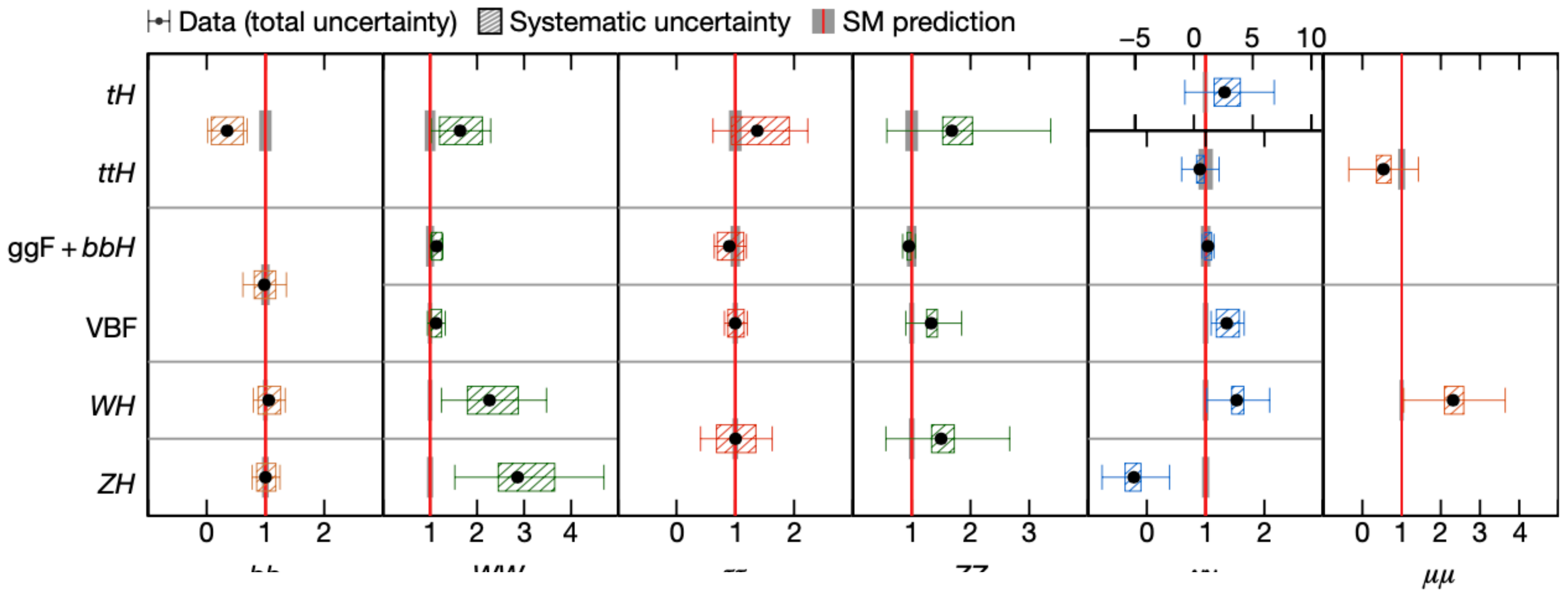
Present

Higgs couplings





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

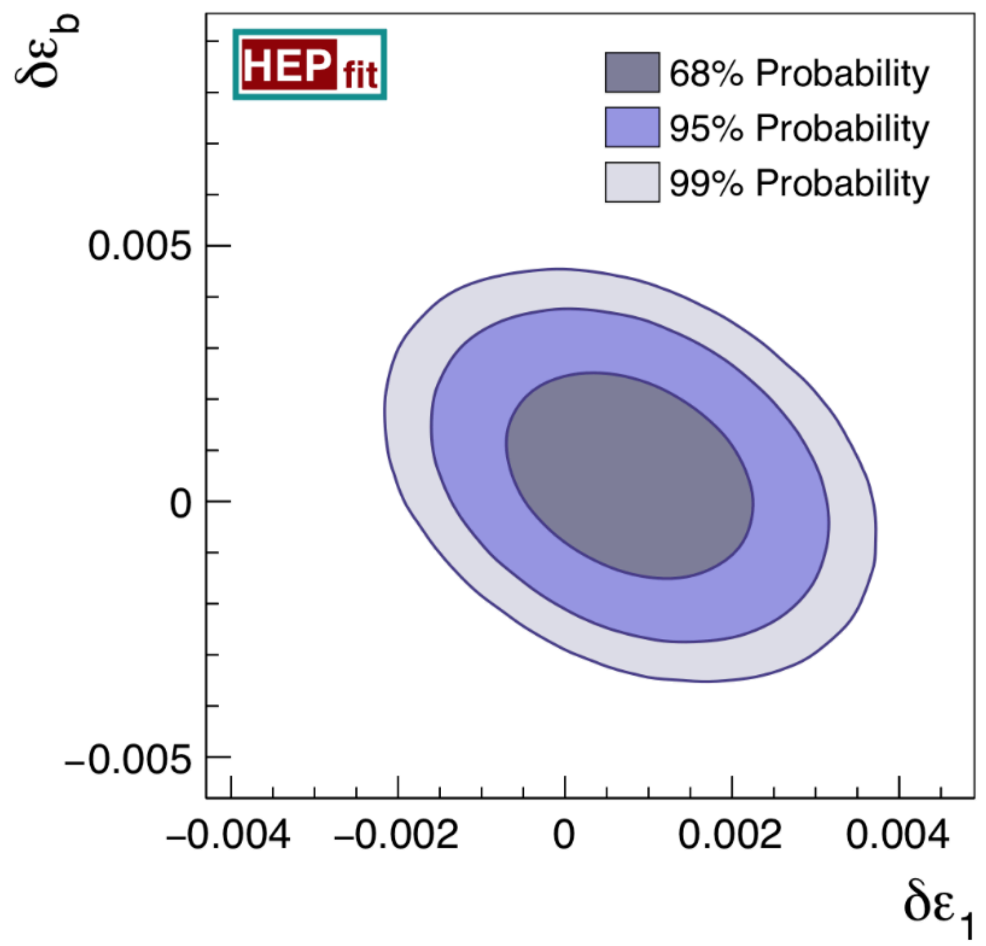
The deviations δg_H from the SM in single and multi-Higgs couplings satisfy

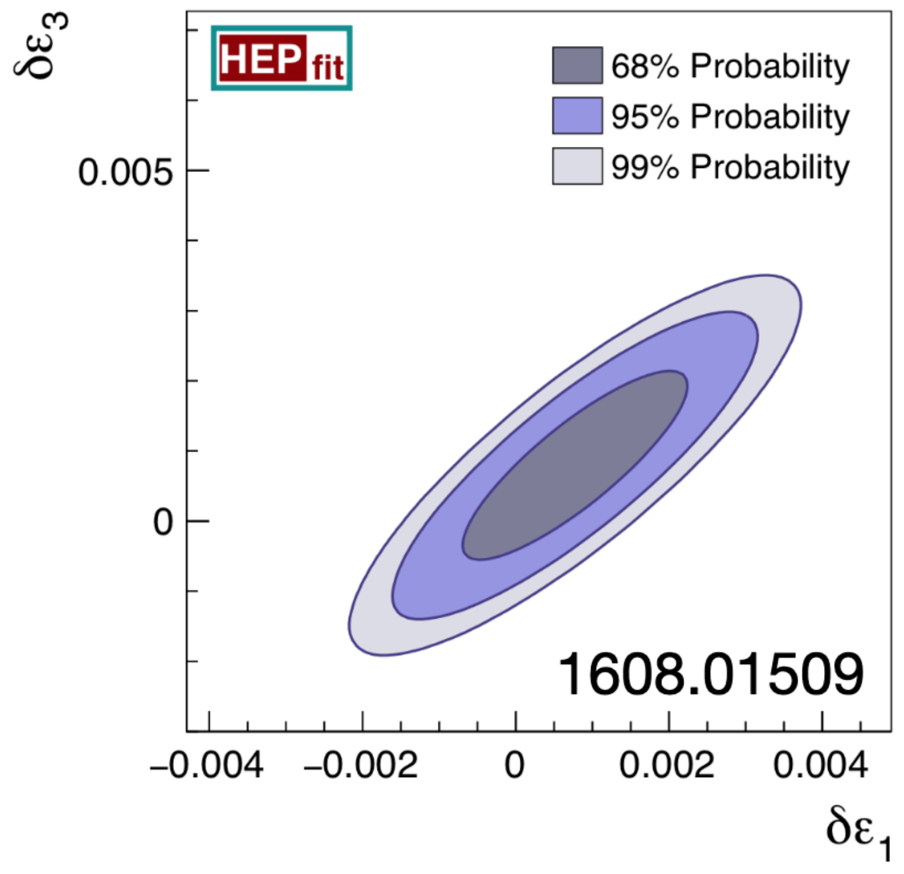
$$\delta g_H / g_H{}^{\text{SM}} \sim c\,\varepsilon$$

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



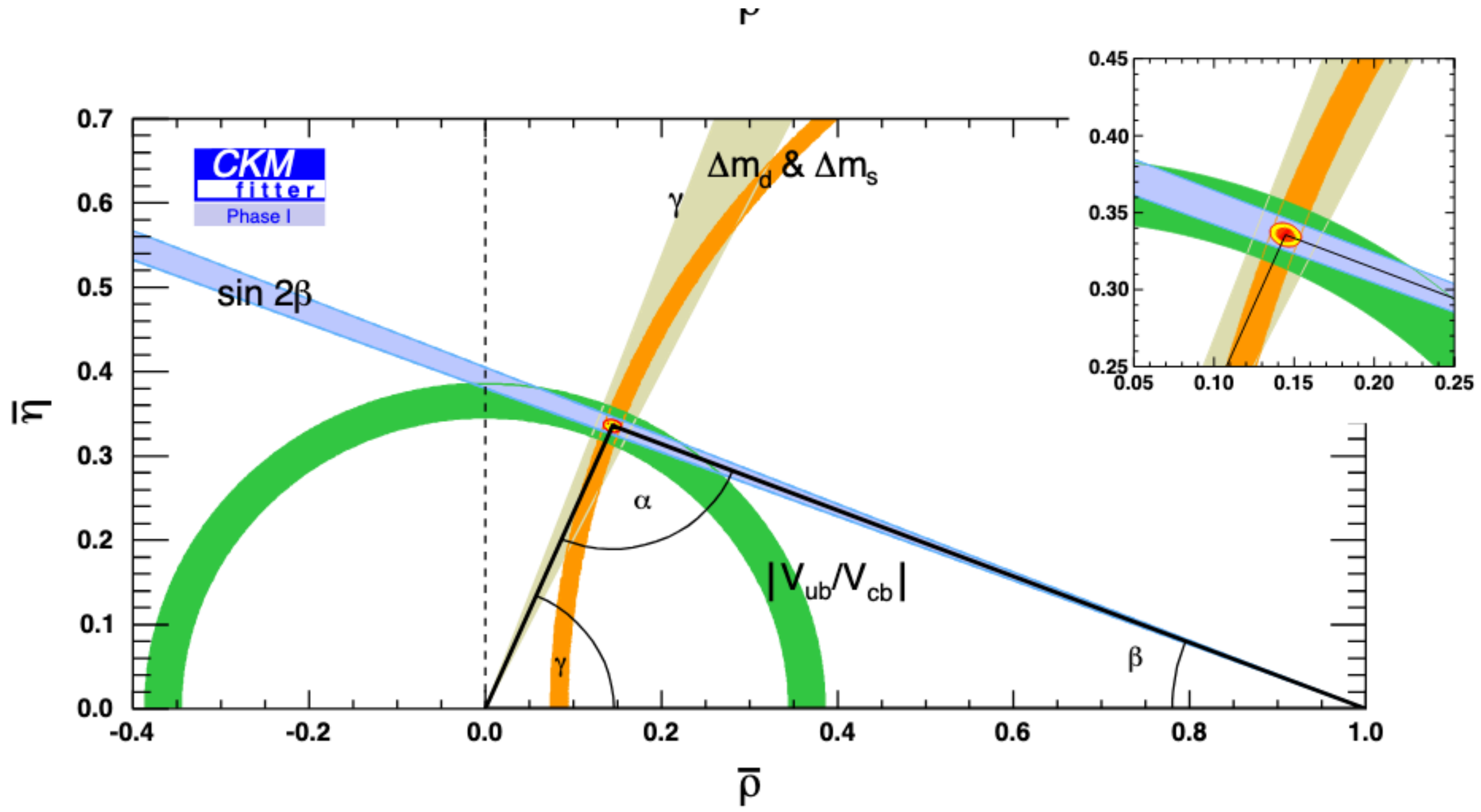


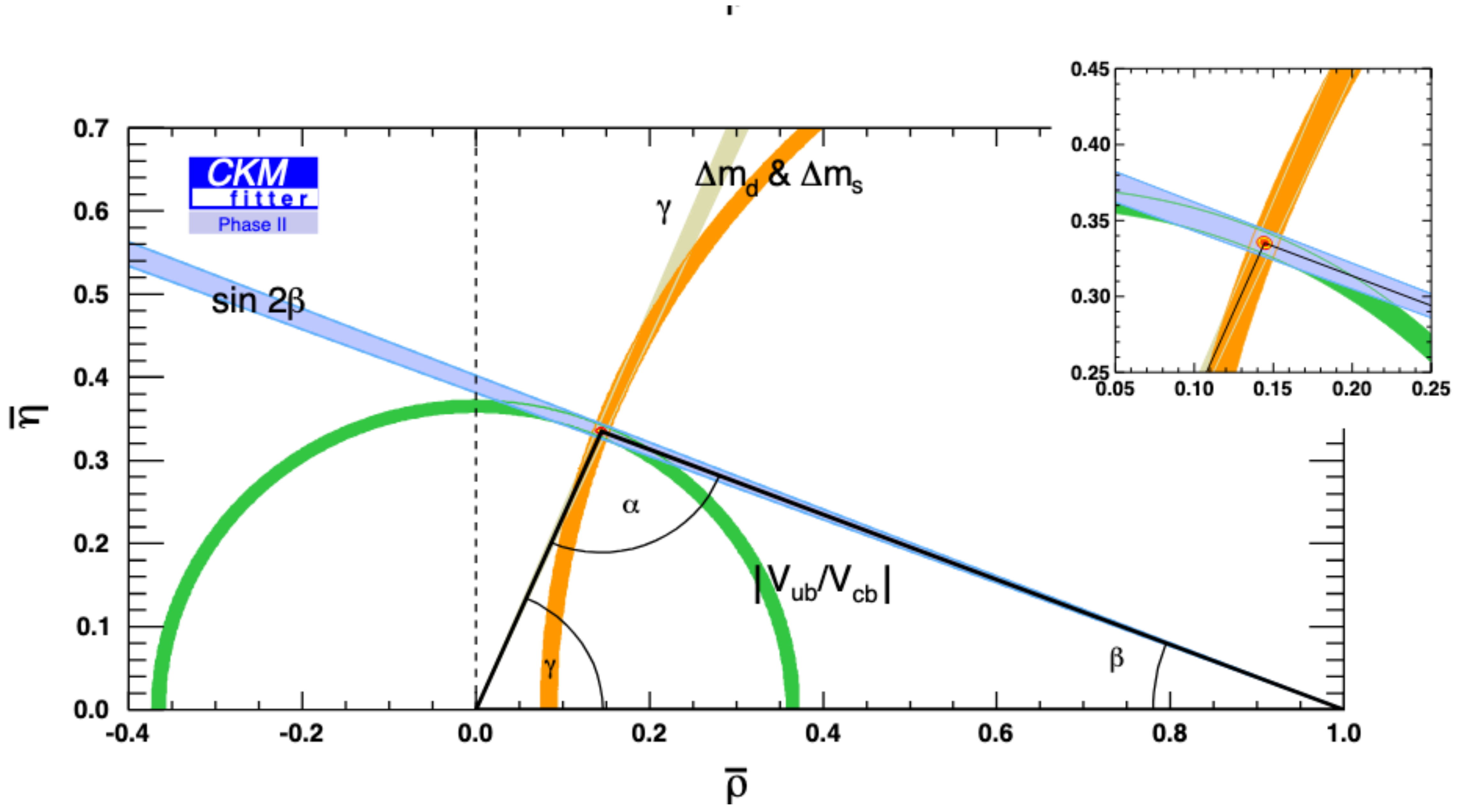
While Higgs couplings probe naturalness, EWPO sense the dynamics off EWSB indirectly via loops. Consider the S parameter,

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

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





LHCb (upgrade 2)

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

Belle II

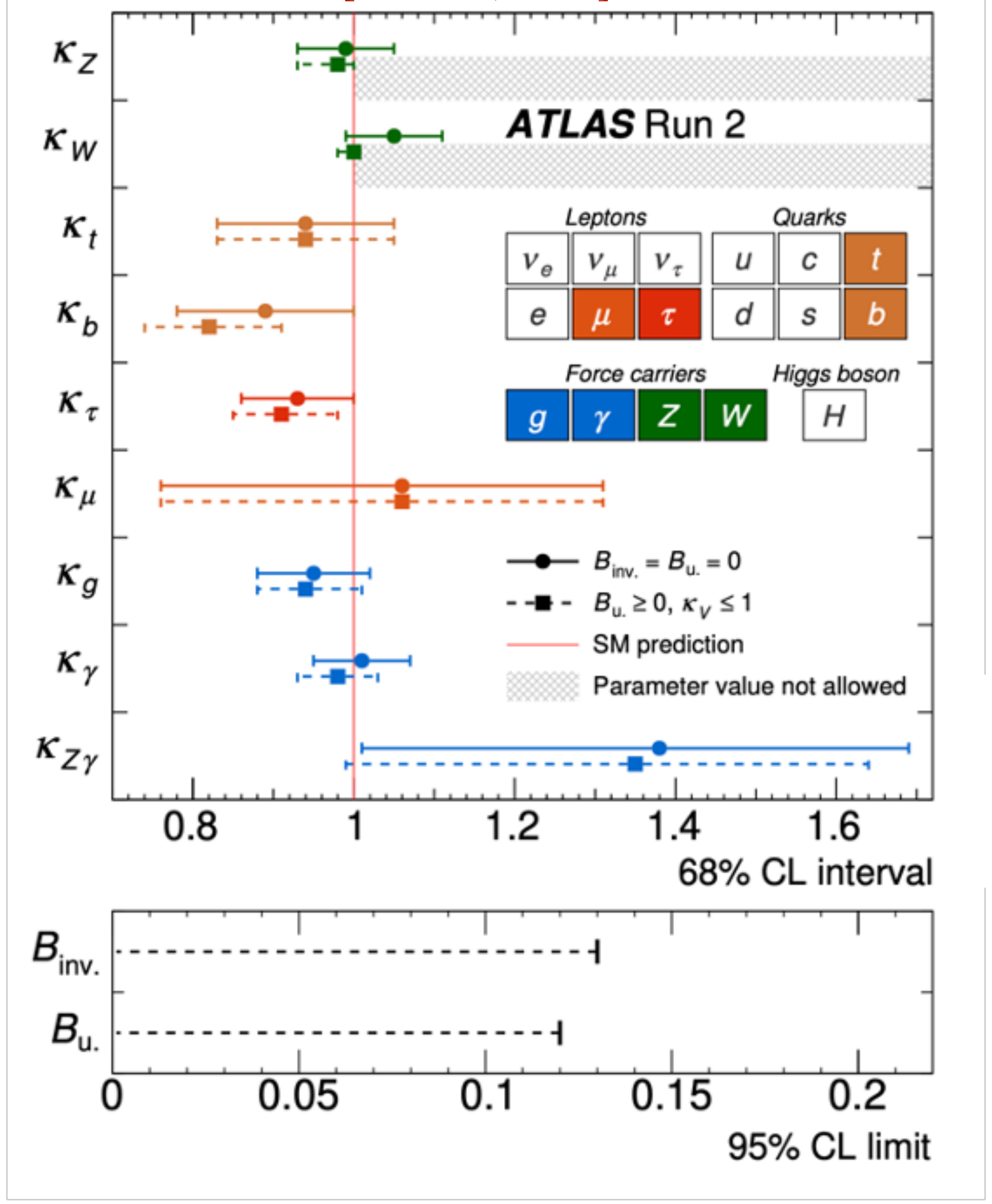
- $O(10^{10})$ B mesons
- $O(10^{10})$ τ's

in clean environment

The Higgs near future

Couplings at HL-LHC

[ATLAS, 2024]

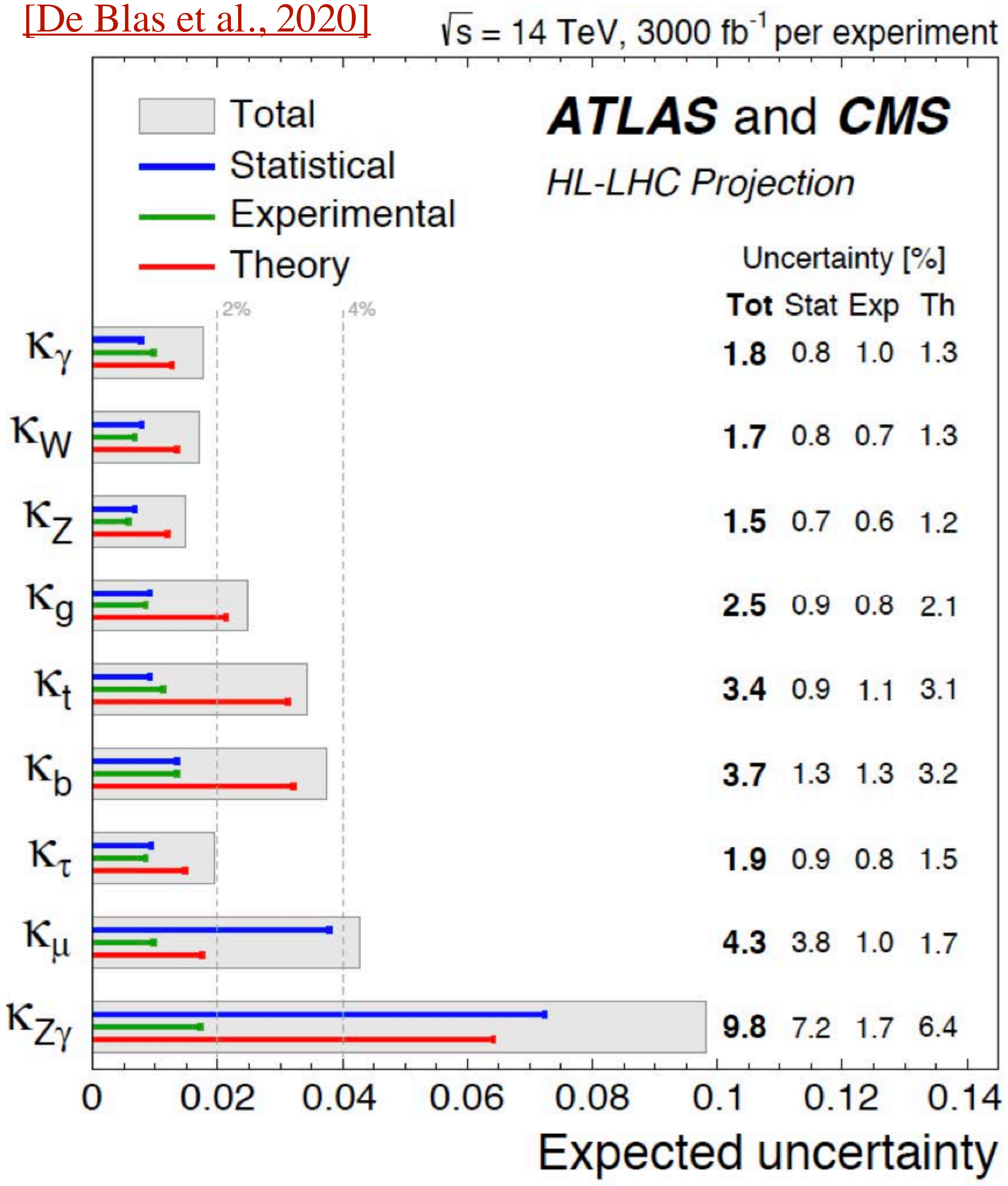


10-20% → 2-4%

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

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

[De Blas et al., 2020]

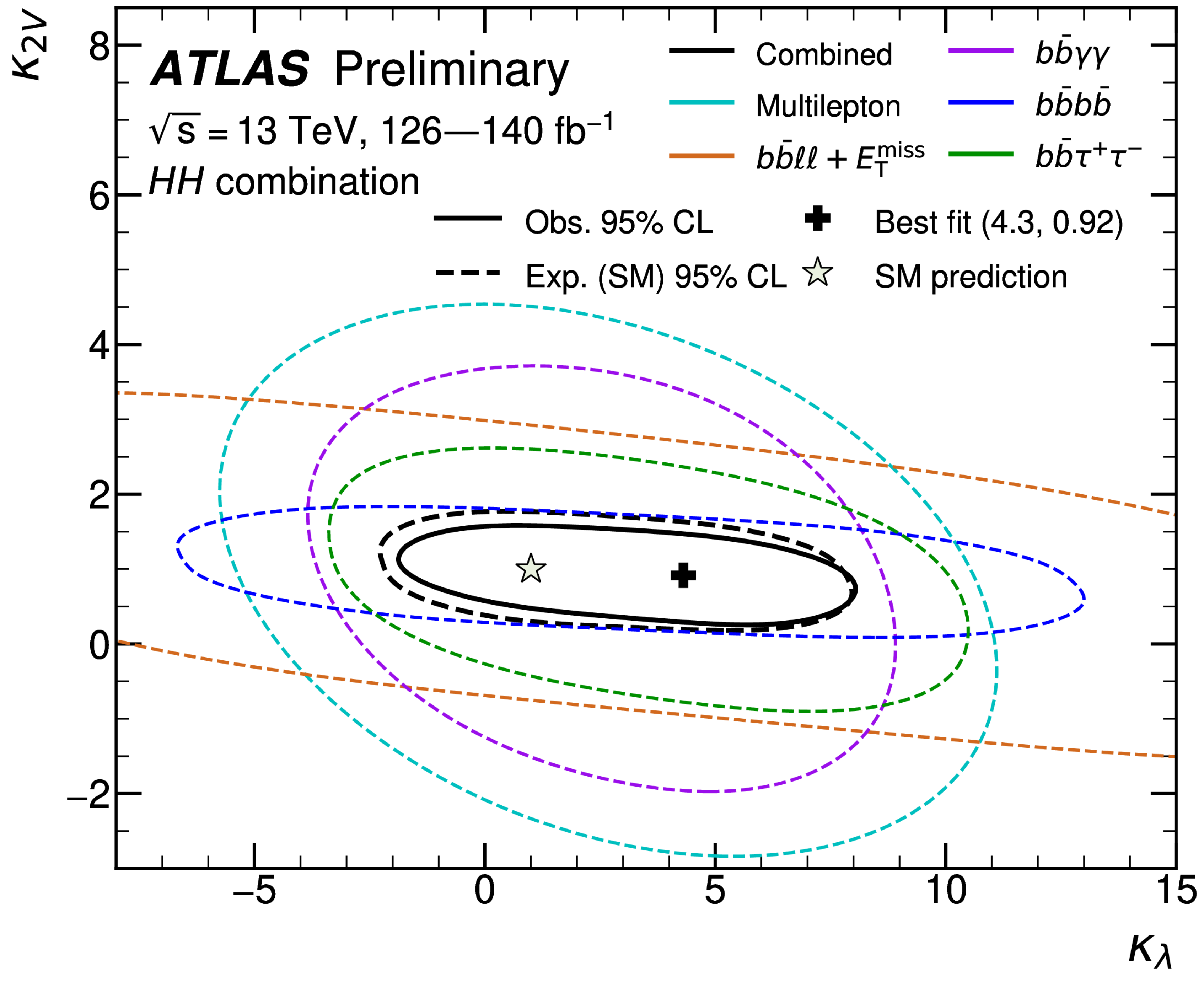


The Higgs near future

Higgs potential

Now

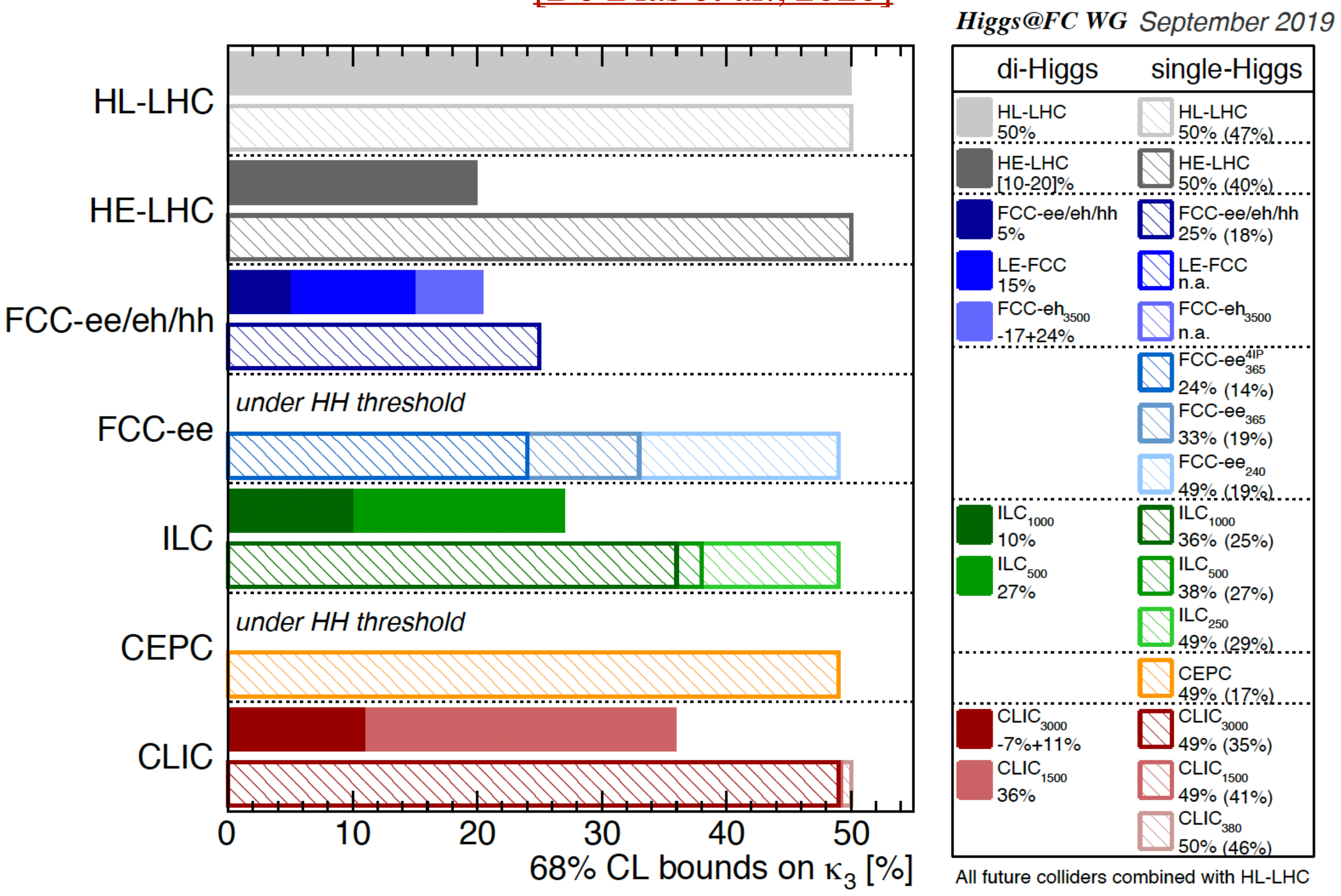
[ATLAS, 2024]



Current limits on k_λ and k_{2V}

Future

[De Blas et al., 2020]

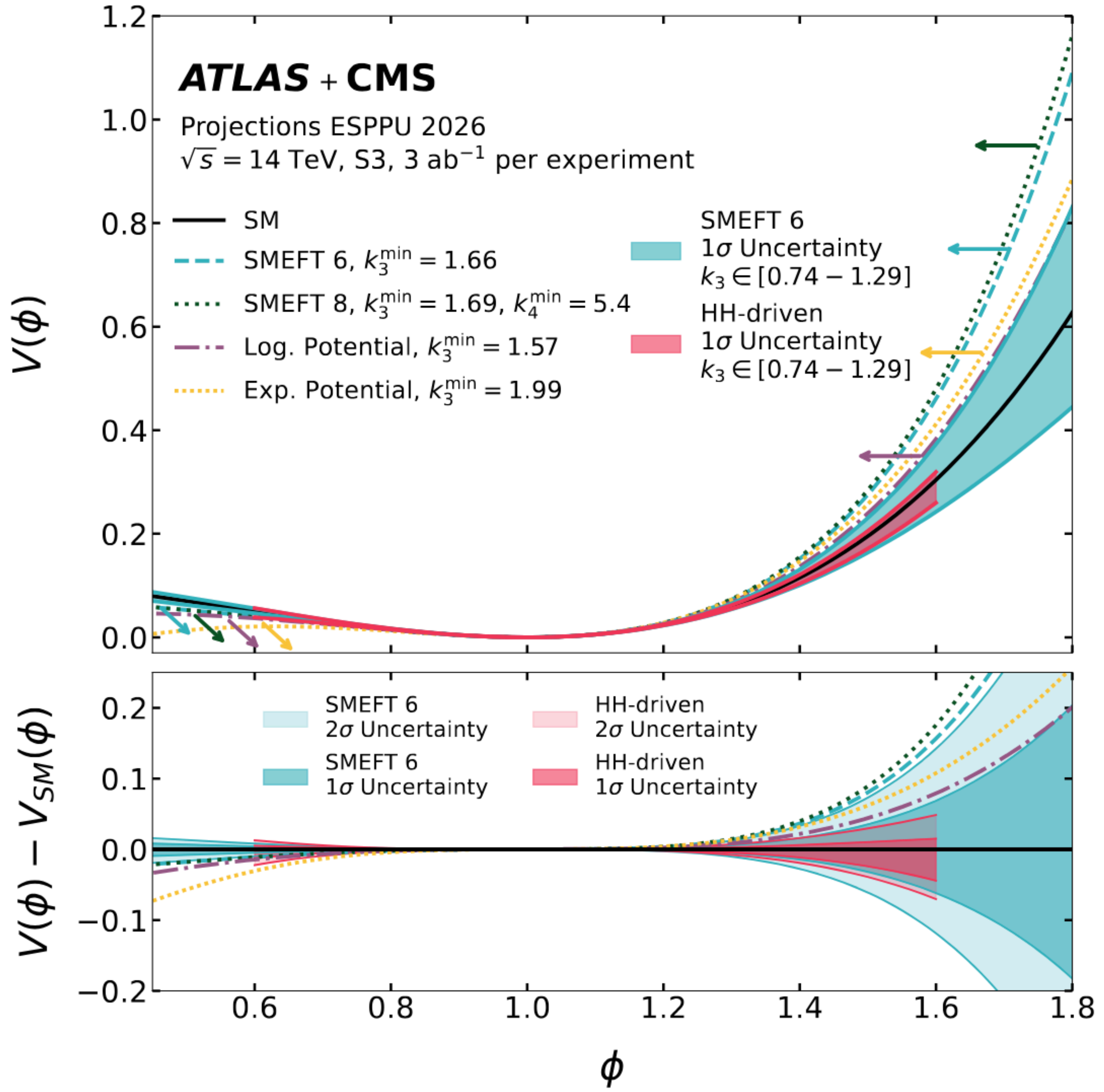


Future limits on k_λ

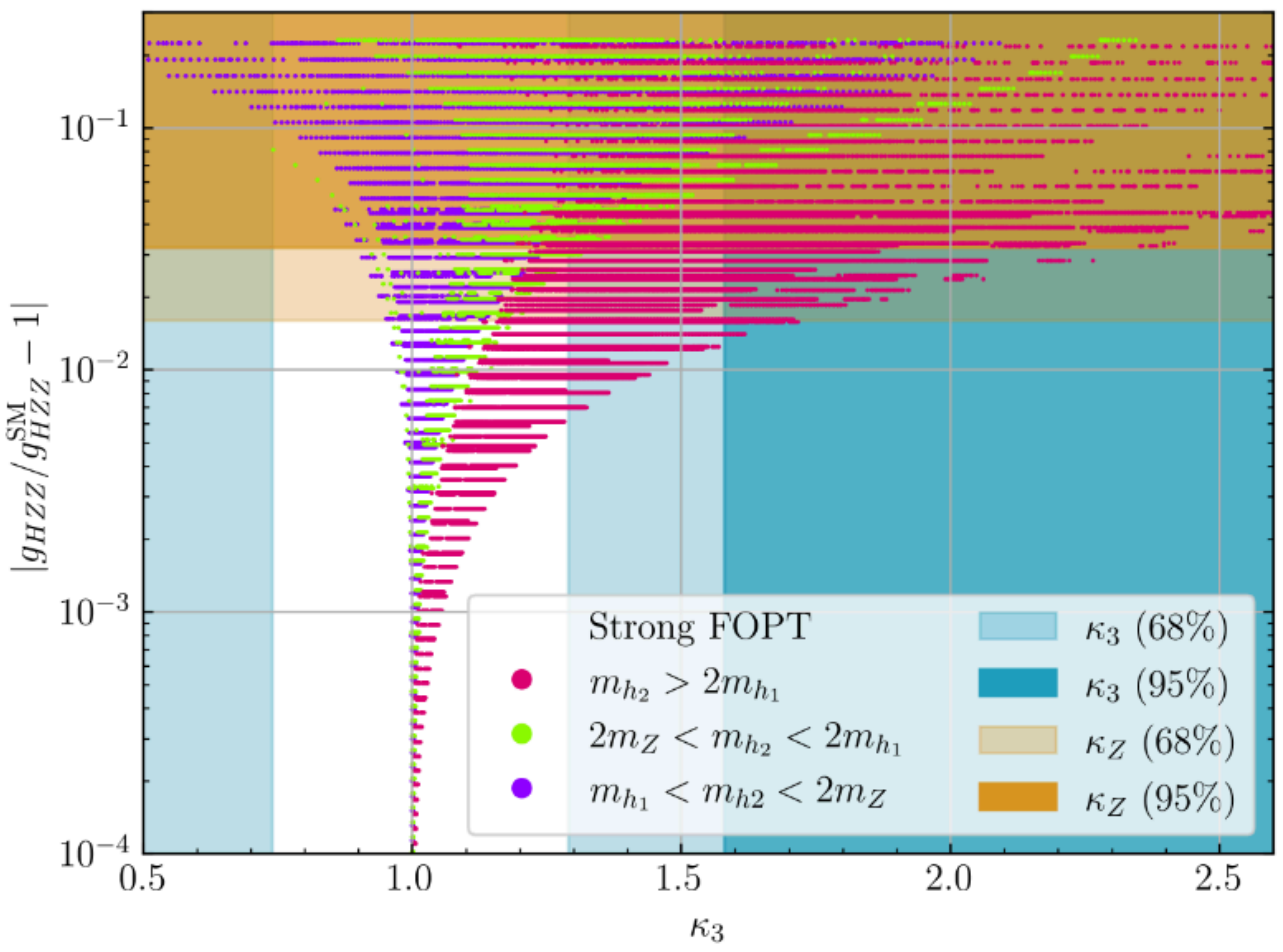
The Higgs near future

Higgs potential

[CMS/ATLAS ESPPU 2026]



[CMS/ATLAS ESPPU 2026]



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.

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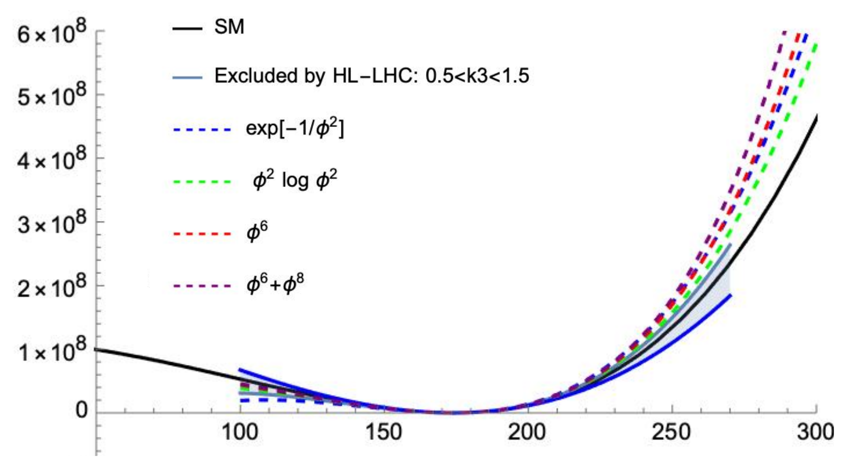

1st or 2nd order

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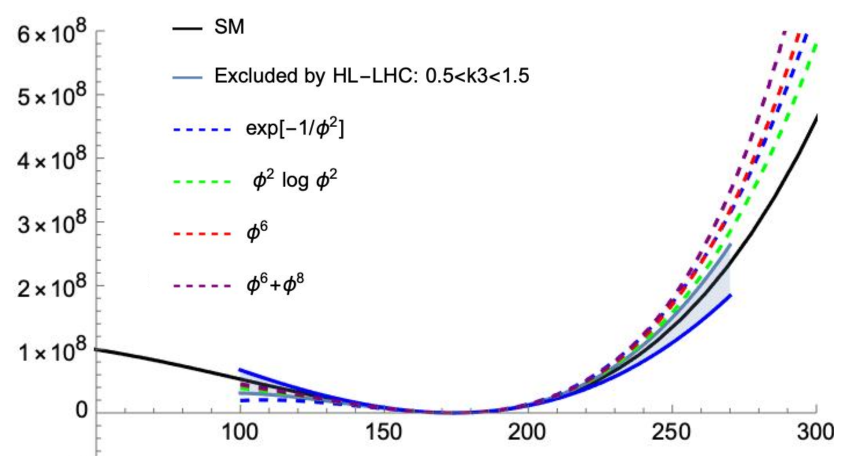
E

v — $4\pi v$



1st or 2nd order

$$\phi^{\pm} = W_L^{\pm}$$

$$\phi^{0} = Z_L^{0}$$

EW restoration

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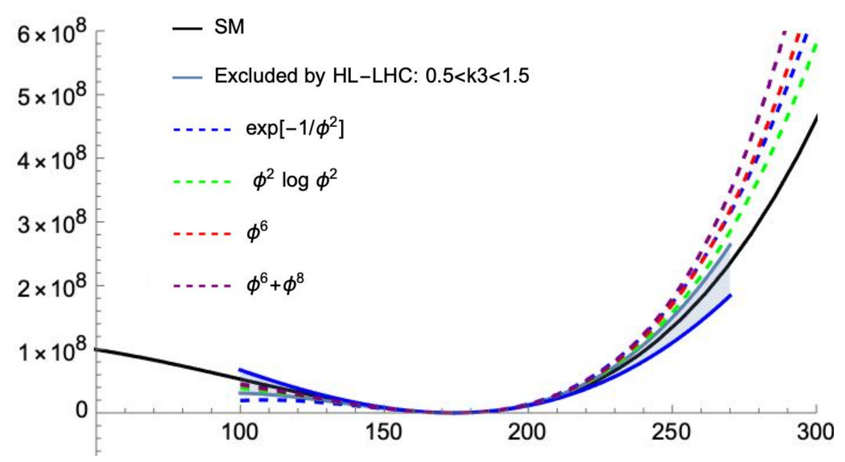

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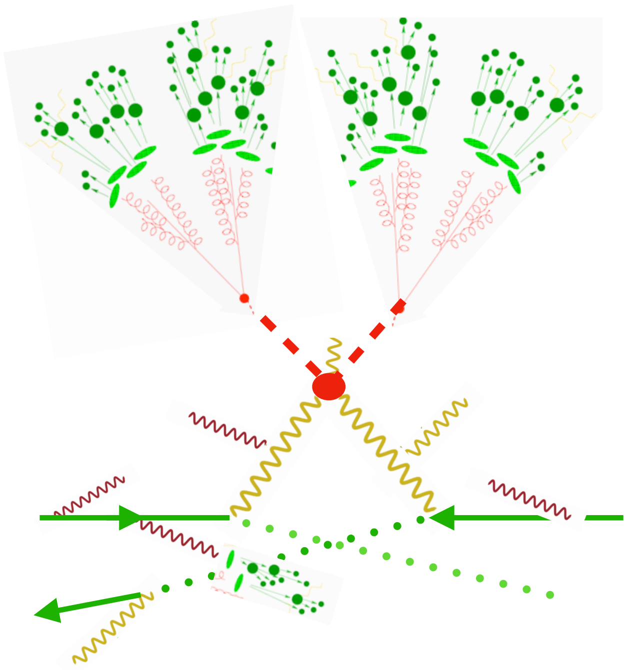

EW showers

EW interactions are the new QCD

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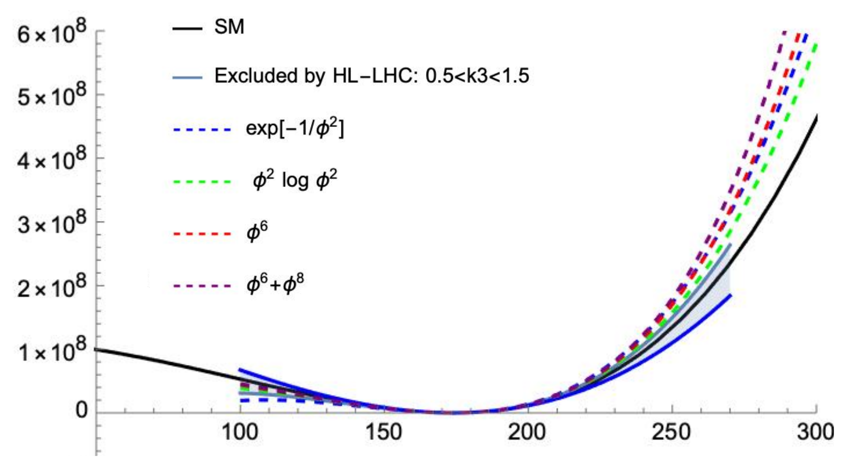
E

v — $4\pi v$ — a few $4\pi v$ — $\Lambda_{\rm UV}$



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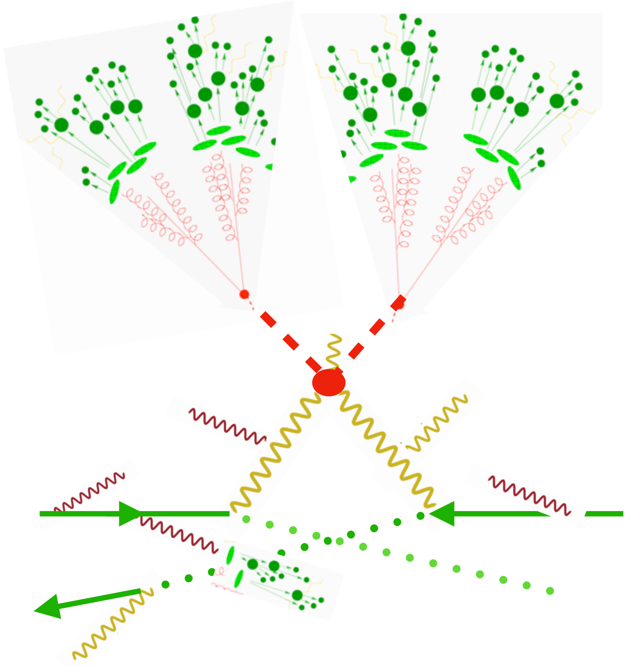

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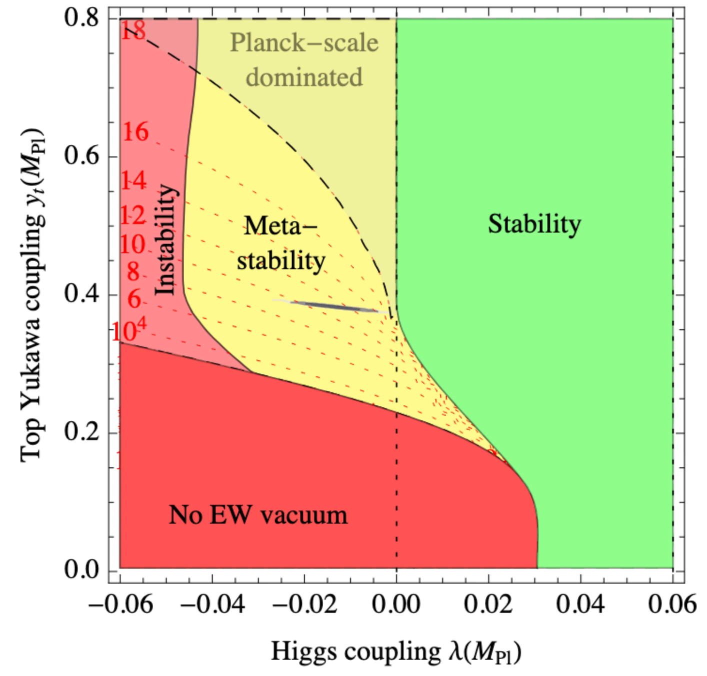
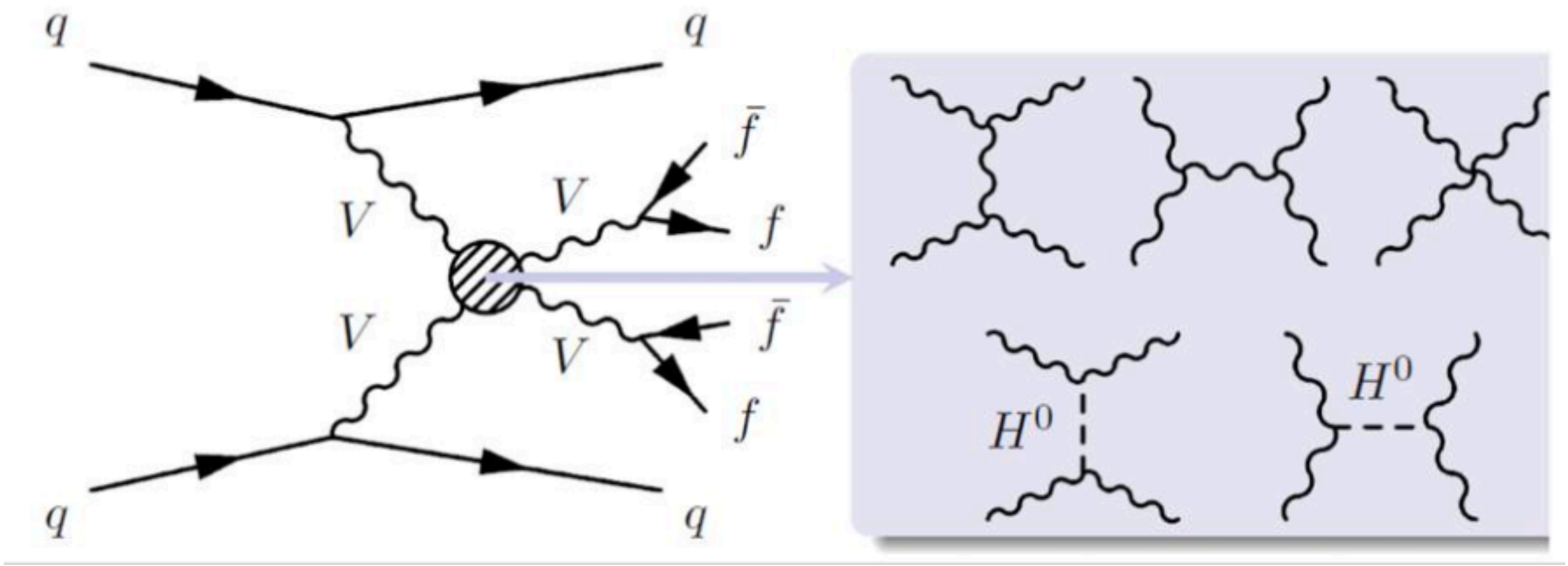


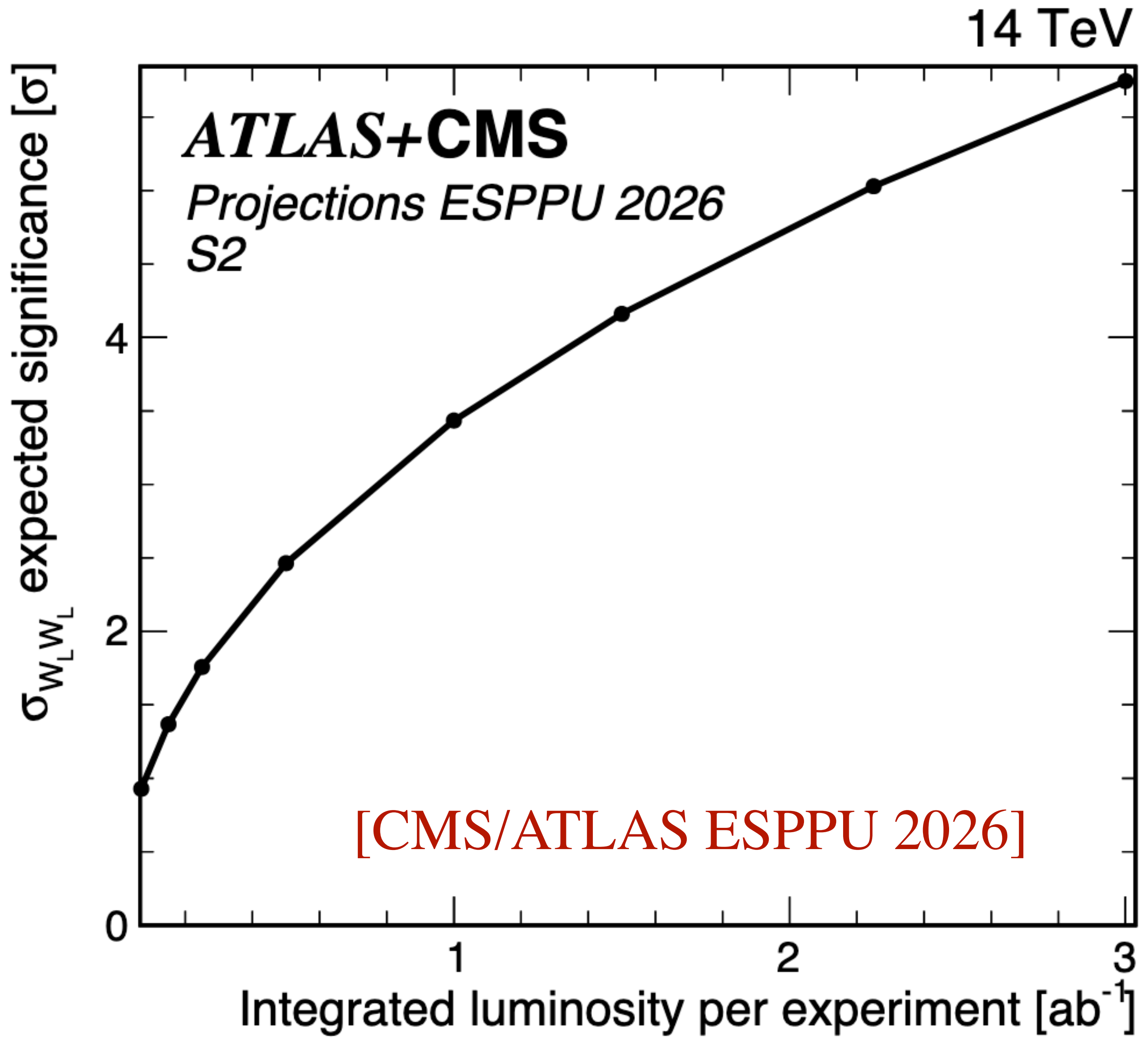
Vacuum Stability

The full exploration of EW interactions

EW restoration

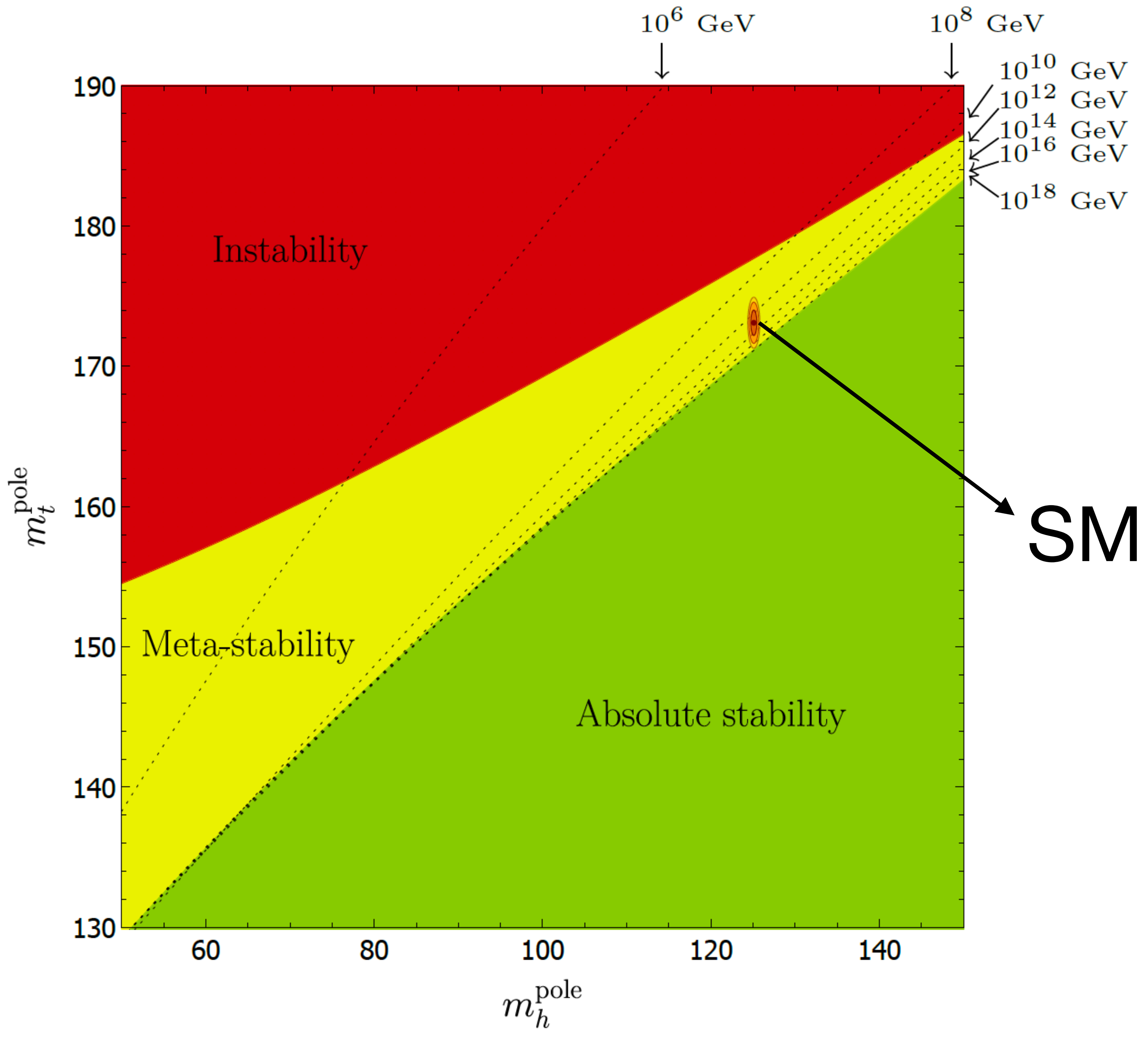
VBS, such as W+W+jj, gives access to longitudinally polarised vector bosons. However cross sections are very small (about 10% of the total) and significant only in the tails





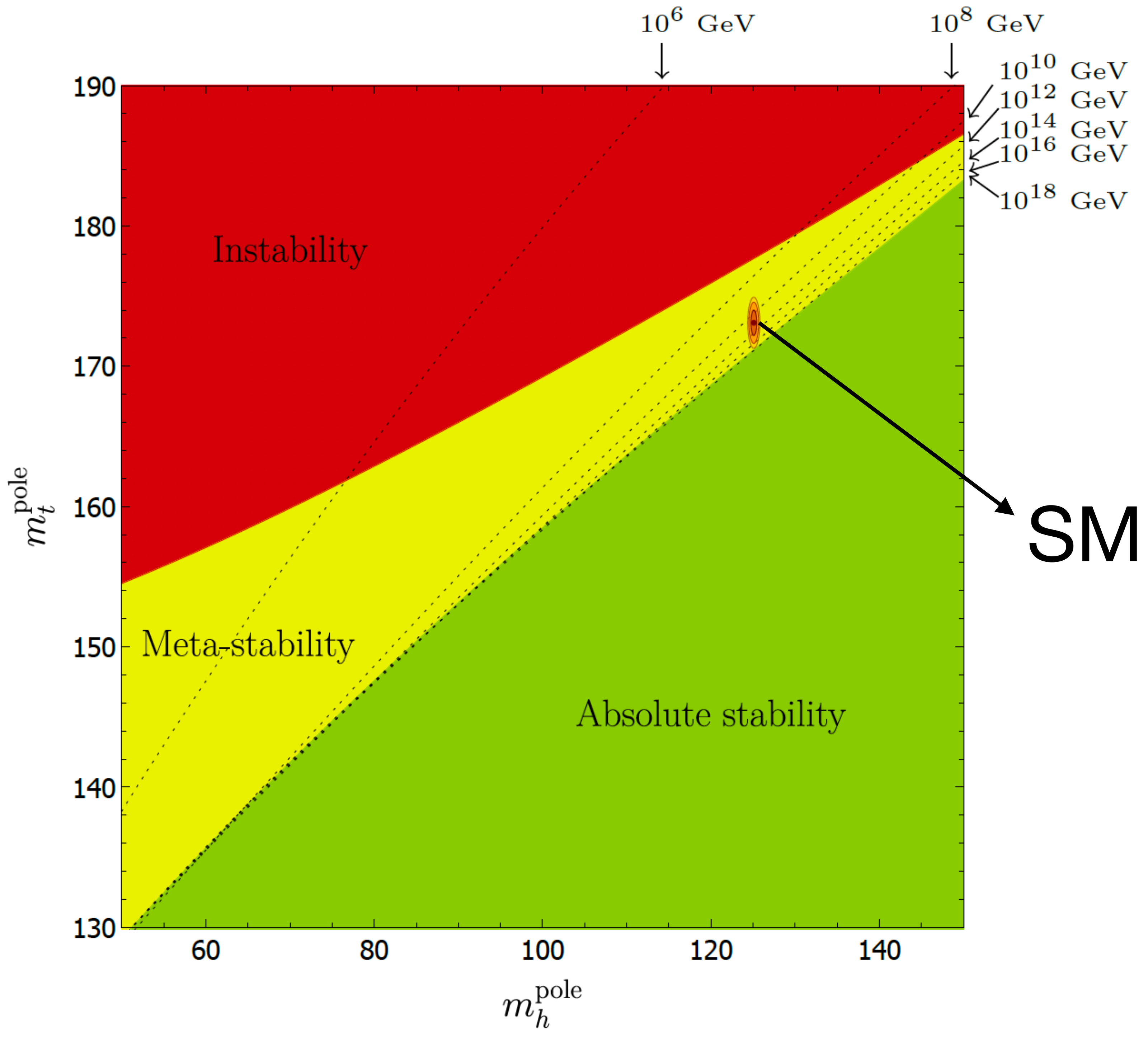
Considering all channels, and both experiments we could get at 5 sigma level for LL at 3 iab.

The vacuum stability near future

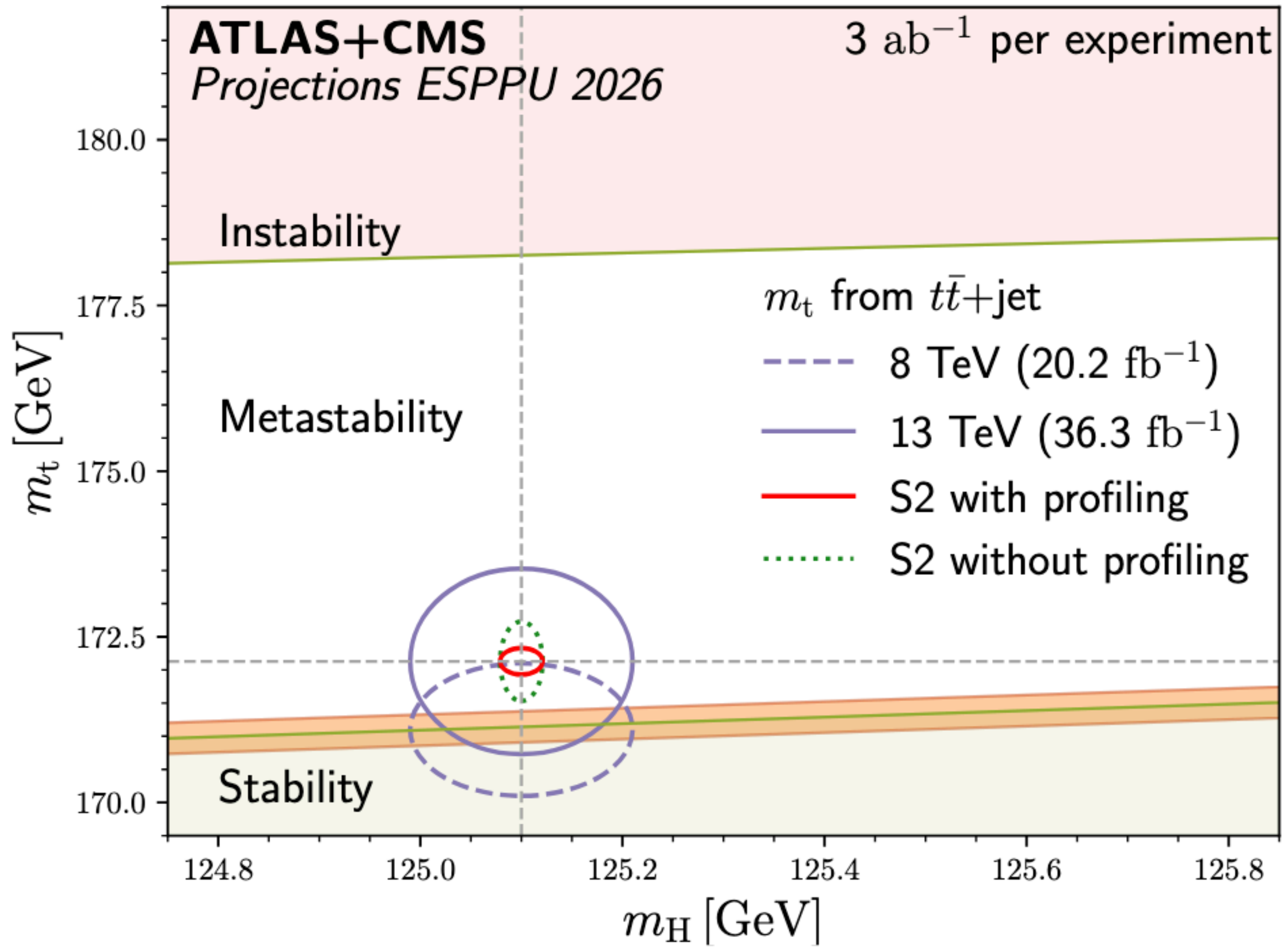


[Andreassen et al. 1707.08124]

The vacuum stability near future



[Andreassen et al. 1707.08124]



Timeline(s)

Schematic

Timeline(s)

Schematic

Timeline(s)

Schematic

Timeline(s)
Schematic

Timeline(s)

Schematic

Timeline(s)

Schematic

Timeline(s)
Schematic

Timeline(s)

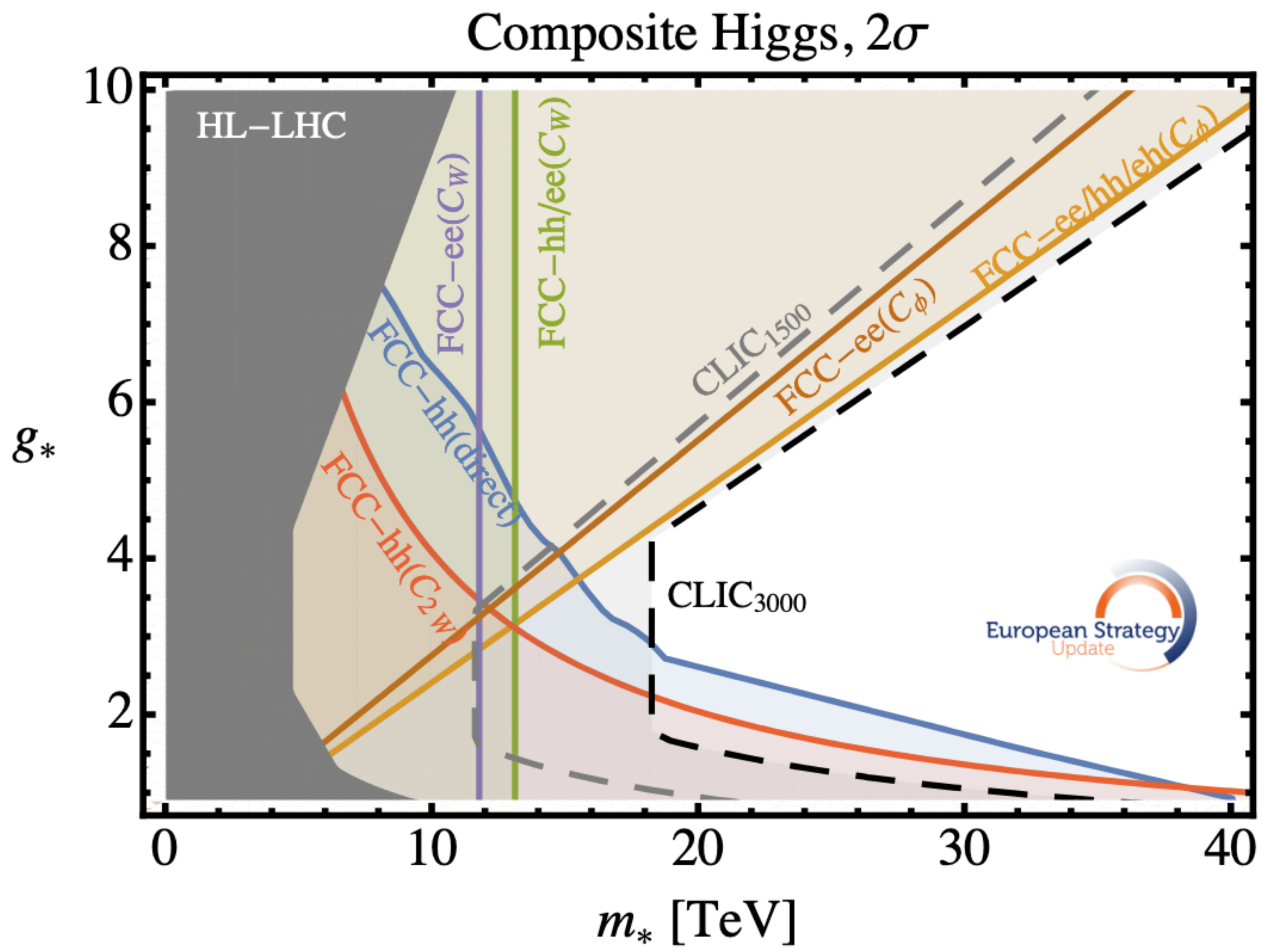
Schematic

Future colliders

Reach in Higgs couplings

[De Blas et al., 2020]

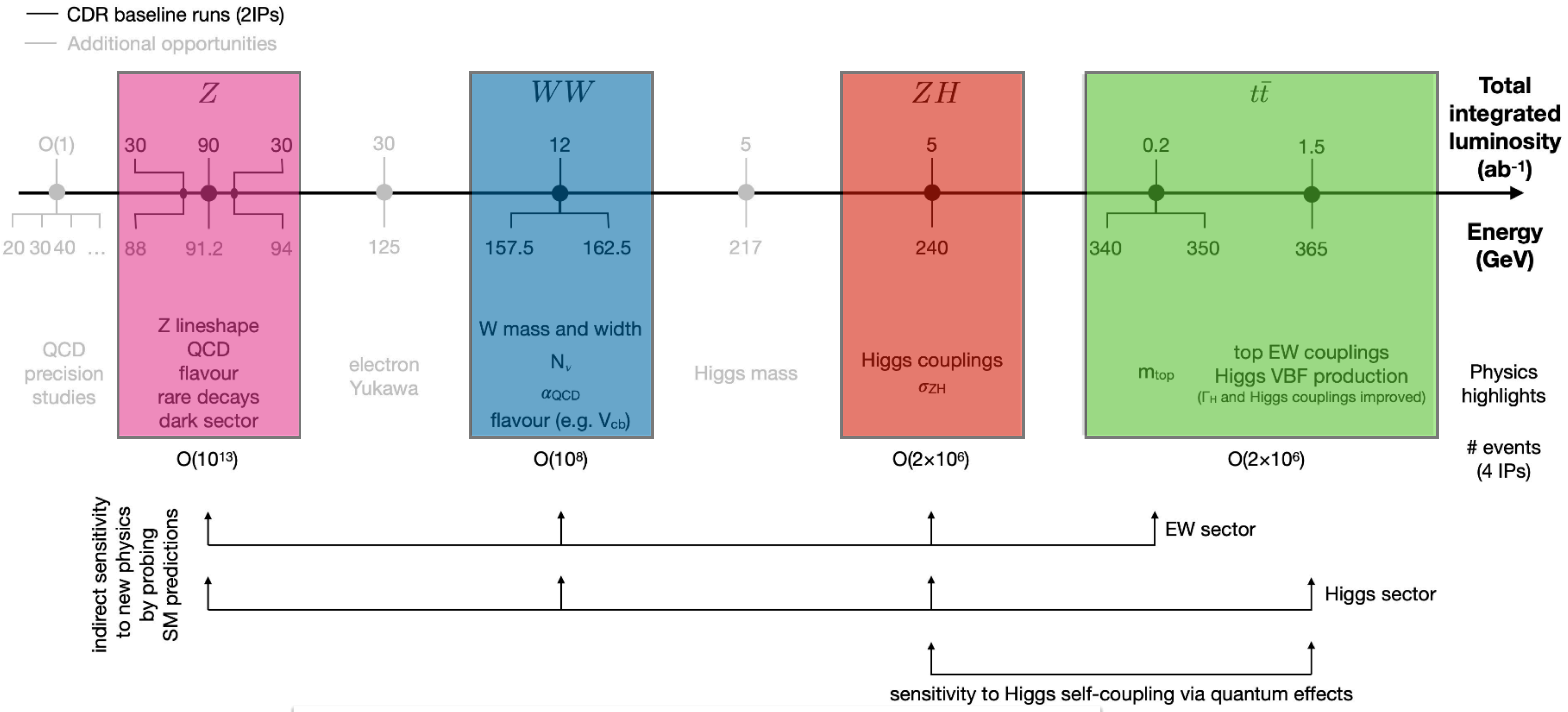
kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	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⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	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⋆	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

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

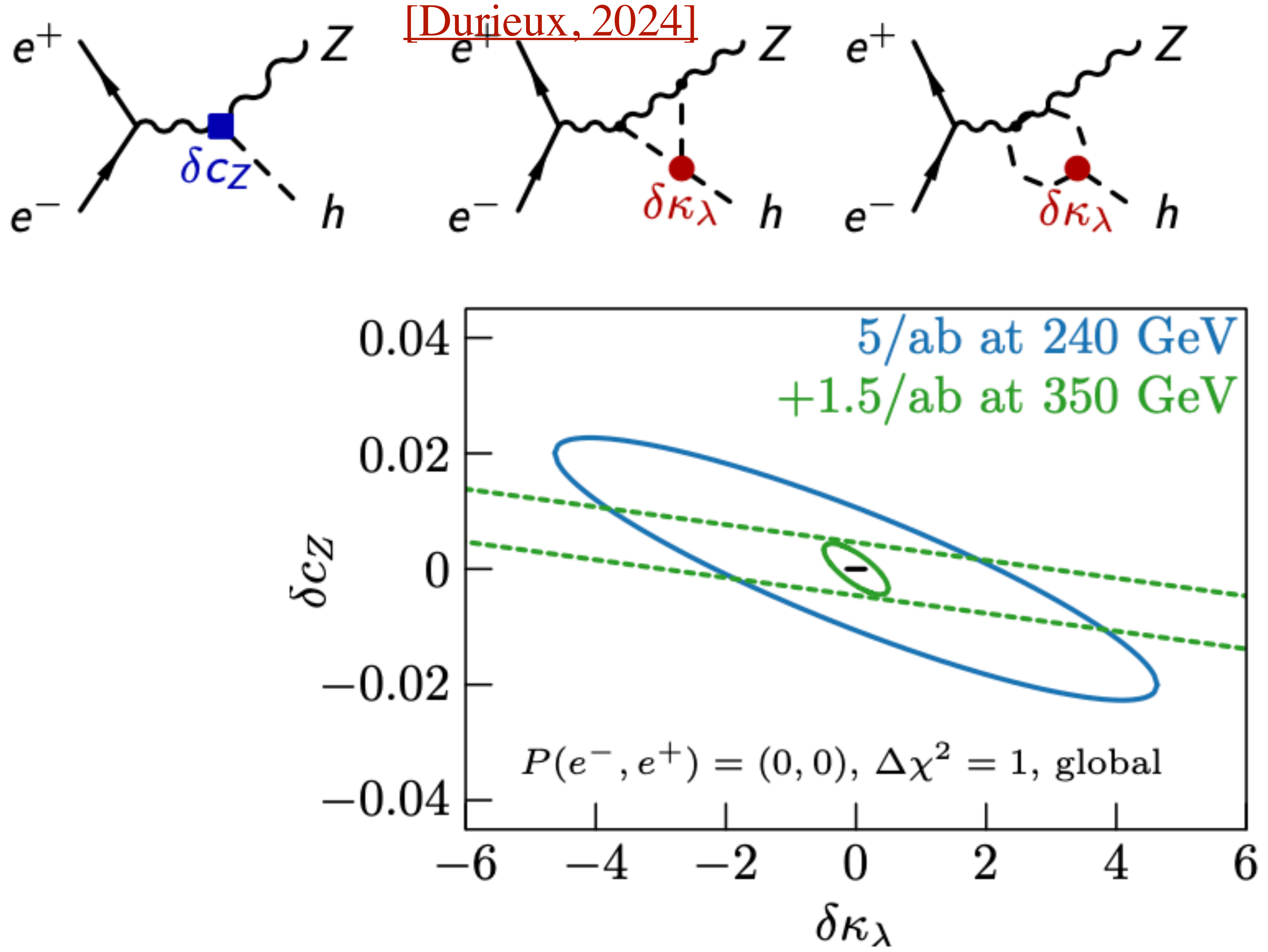
FCC-ee runs


CDR baseline runs (2IPs)
Additional opportunities
Z
WW
ZH
$t\bar{t}$
Total integrated luminosity (ab^{-1})
O(1)
30 90 30
30
12
5
5
0.2
1.5
Energy (GeV)
20 30 40 …
88 91.2 94
125
157.5 162.5
217
240
340 350 365
QCD precision studies
Z lineshape
QCD
flavour
rare decays
dark sector
electron Yukawa
W mass and width
N_ν
α_{QCD}
flavour (e.g. V_{cb})
Higgs mass
Higgs couplings
σ_{ZH}
m_{top}
top EW couplings
Higgs VBF production
(Γ_H and Higgs couplings improved)
Physics highlights
O(10^{13})
O(10^8)
O(2×10^6)
O(2×10^6)
# events (4 IPs)
indirect sensitivity to new physics by probing SM predictions
EW sector
Higgs sector
sensitivity to Higgs self-coupling via quantum effects

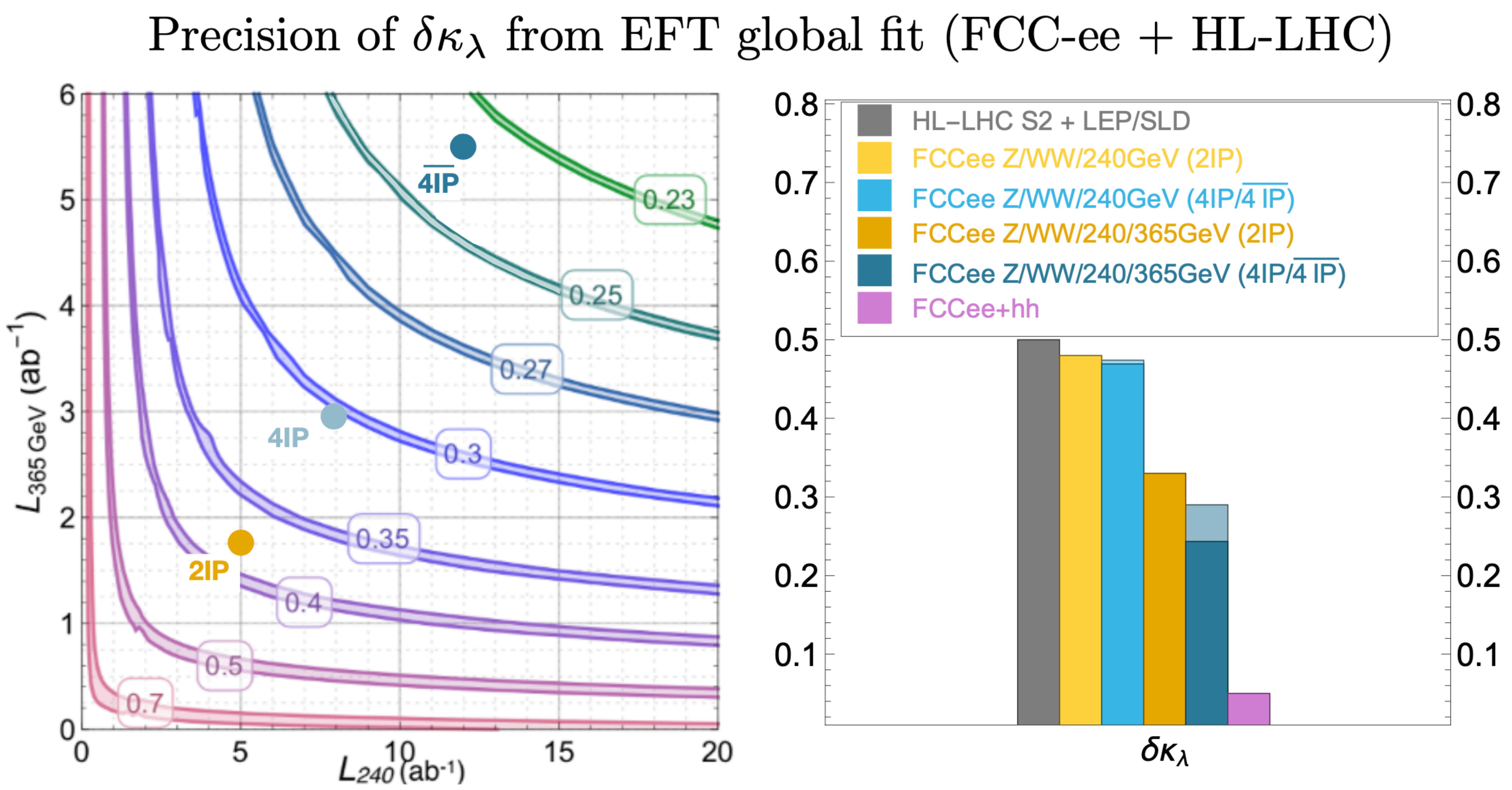
Higgs self-coupling

FCC-ee (and FCC-hh)

[Durieux, 2024]



[Interim FCC feasibility report, 2024]



k_λ can be constrained by two measurements and provide competitive info.

Flavour at the Z-pole

Physics potential

Particle species	B^0	B^+	B_s^0	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 are enough to meet the needs for the HZ run.

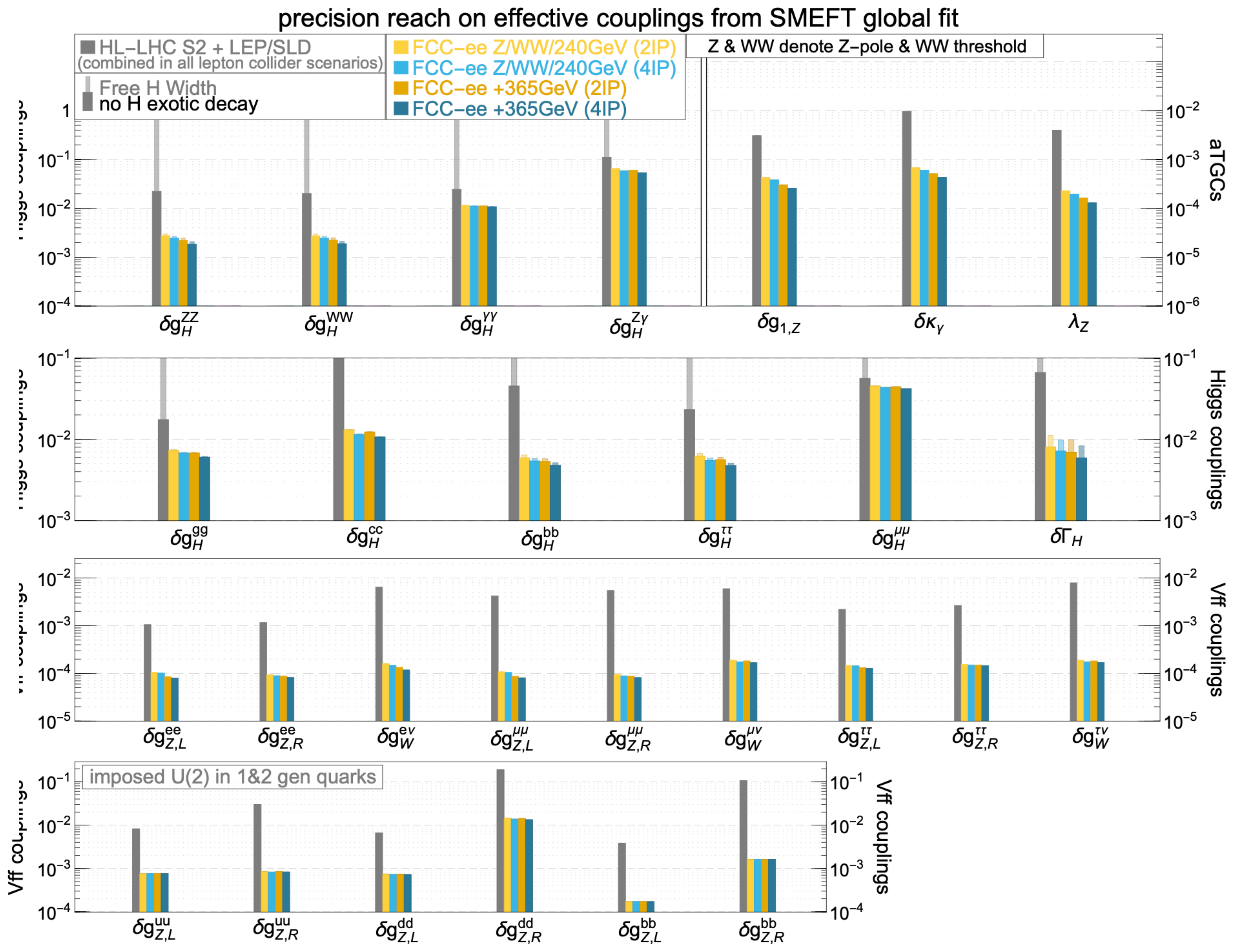
[Interim FCC feasibility report, 2024]

Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and 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
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	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
σ_{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
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	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_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	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

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



A Plan B

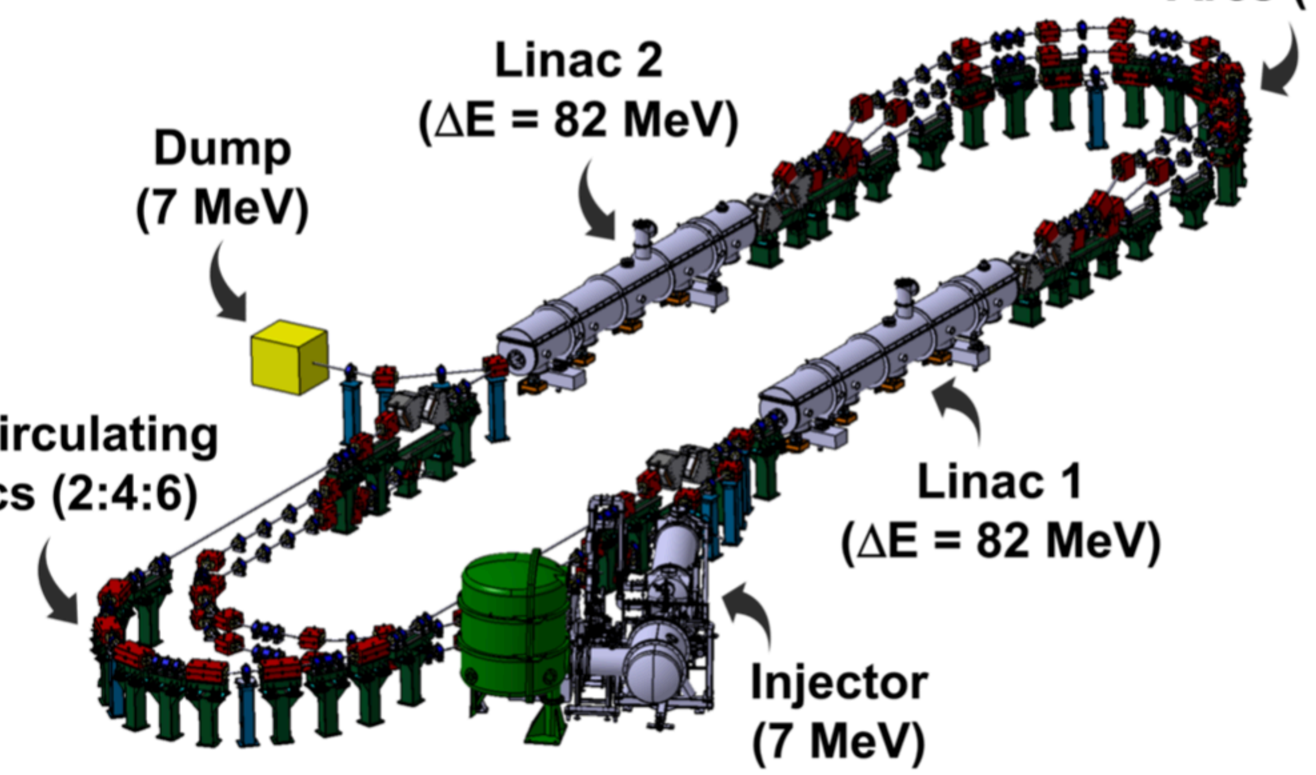
LEP3

- 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.

Another Plan B
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**



Alternative scenario

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

Alternative scenario

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)
Schematic

Timeline(s)

Schematic

Timeline(s)

Schematic

Timeline(s)

Schematic

The muon shot

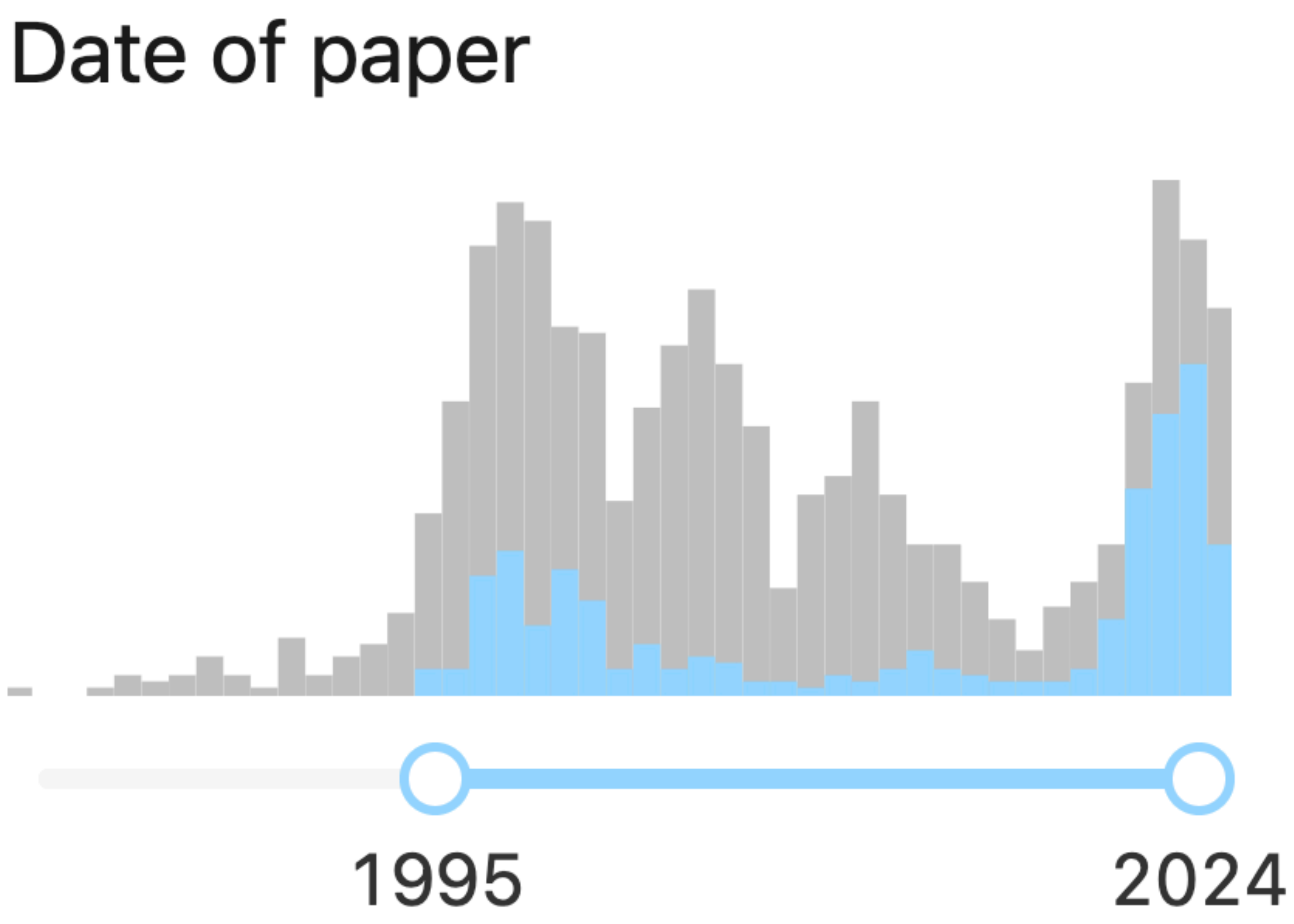
P5:

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.

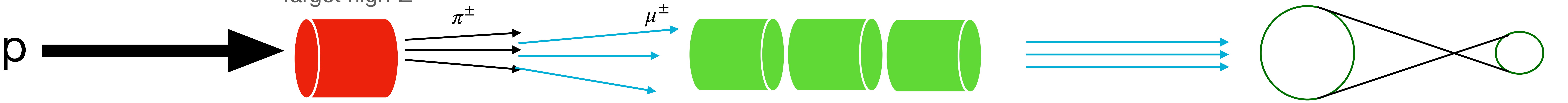
Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D toward a muon collider. At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

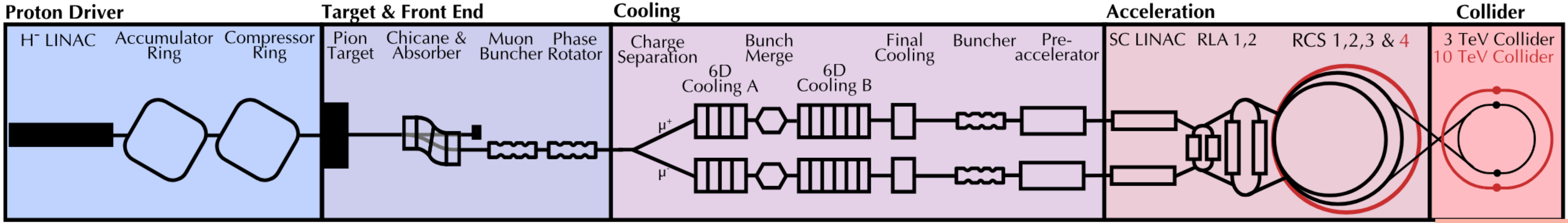


122 pheno papers in the last 5 years

Basic elements

The proposed scheme





The proton driver produces a short, high-intensity proton pulse.

The pulse hits the target and produces pions. The decay channel guides the pions and forms a beam with the resulting muons via a buncher and phase rotator system.

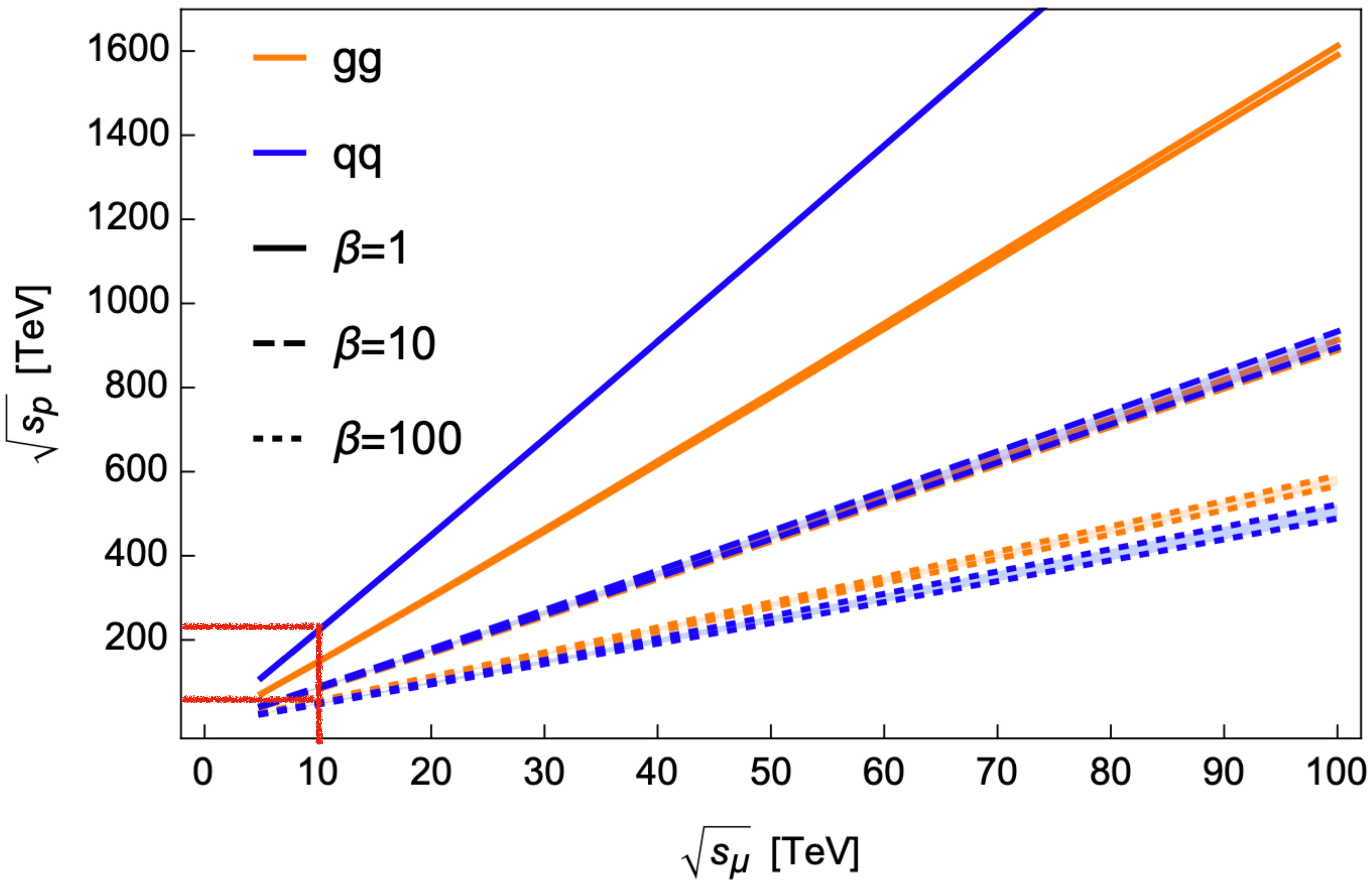
Several cooling stages (purple) reduce the longitudinal and transverse emittance of the beam using a sequence of absorbers and RF cavities in a high magnetic field.

A system of a linac and two recirculating linacs accelerate the beams to 63 GeV followed by a sequence of accelerator rings which reach 1.5 or 5 TeV

Finally the beams are injected at full energy into the collider ring (red). Here, they will circulate and collide within the detectors until they decay.

Muon collider physics

The essentials #0 : Energy availability



muC@10 TeV ~ pp@70 TeV

Simple/Naive/Rough estimate based on parton-parton luminosity for a generic $2 \to 2$ scattering.

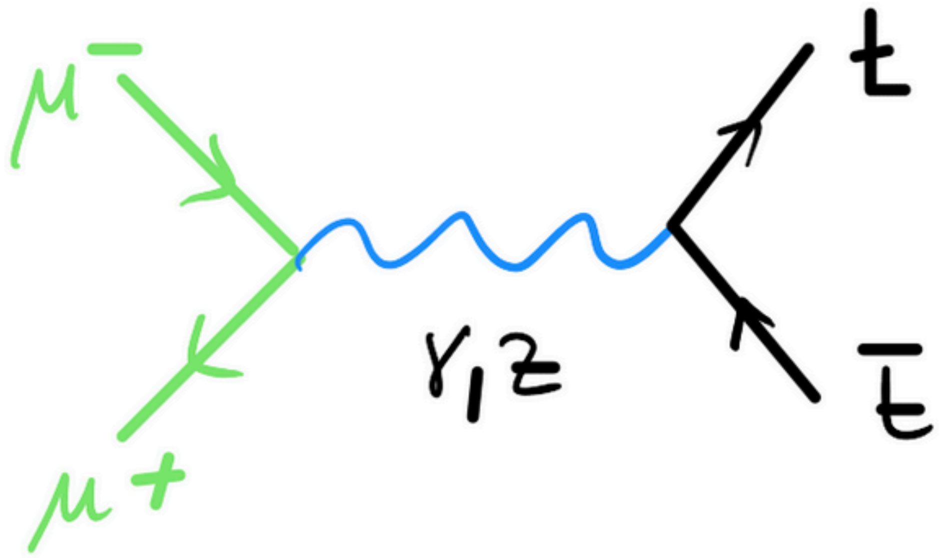
$$EW : \beta \sim 1$$

$$QCD : \beta \sim (\alpha_S/\alpha)^2 \sim 100$$

Muon collider physics

The essentials #1 : Two colliders in one

O(10) TeV muon collider energy allows to have two colliders in one:

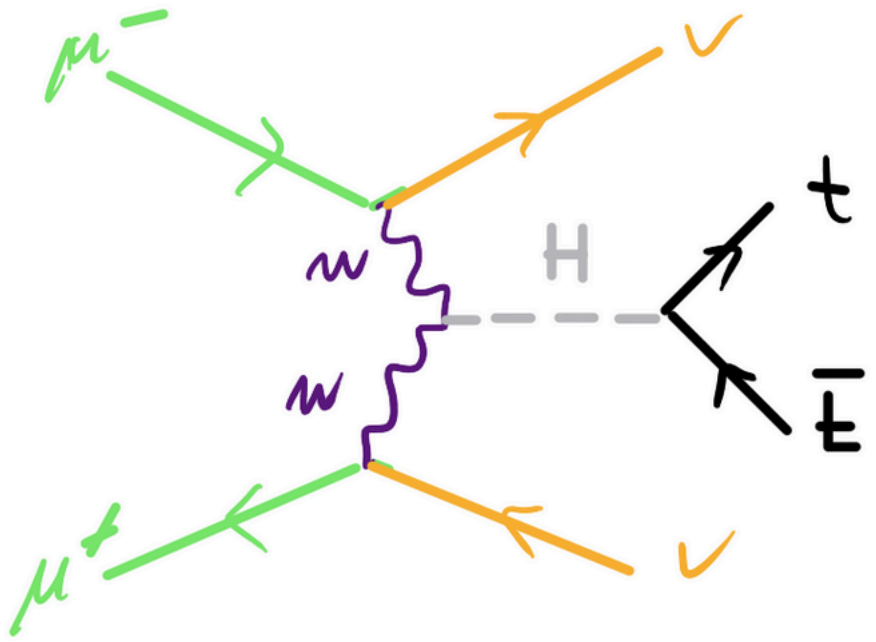


Energetic final states
(either heavy or very boosted)

$$\sigma_s \sim \frac{1}{s}$$

$$\Longleftrightarrow$$

$$\sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$



Large production rates,
SM coupling measurements
Discovery light and weakly interacting

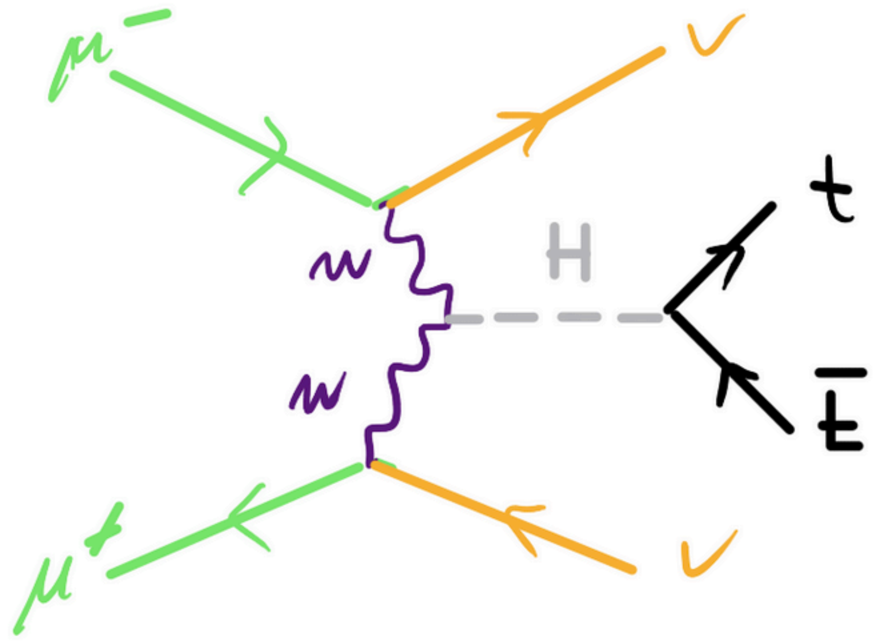
A completely new regime opening for a multi-TeV muon collider

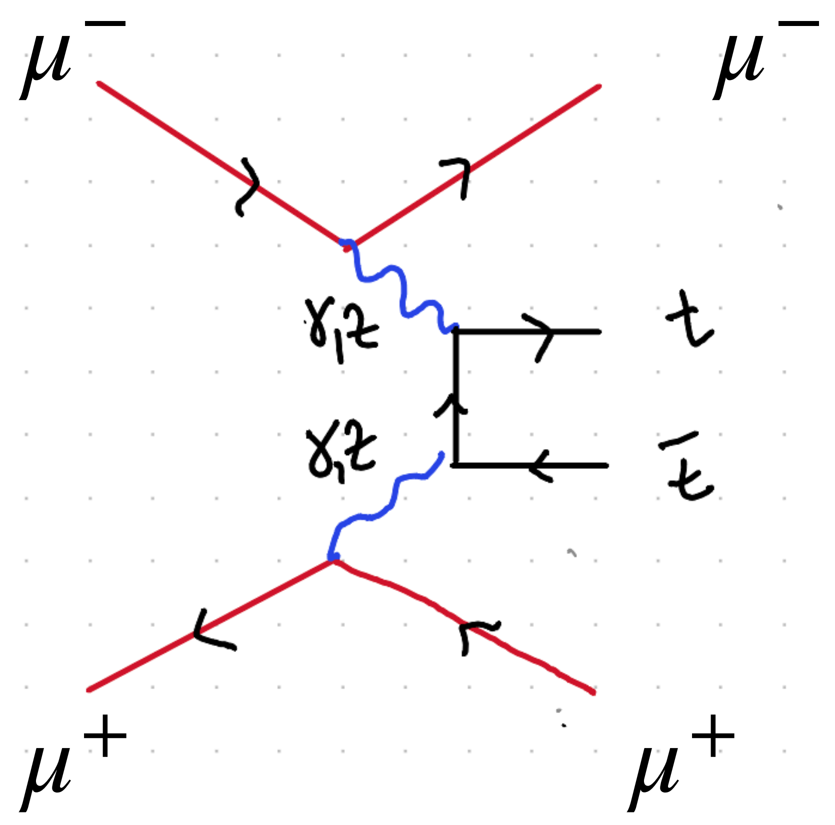
Different physics being probed in the two channels

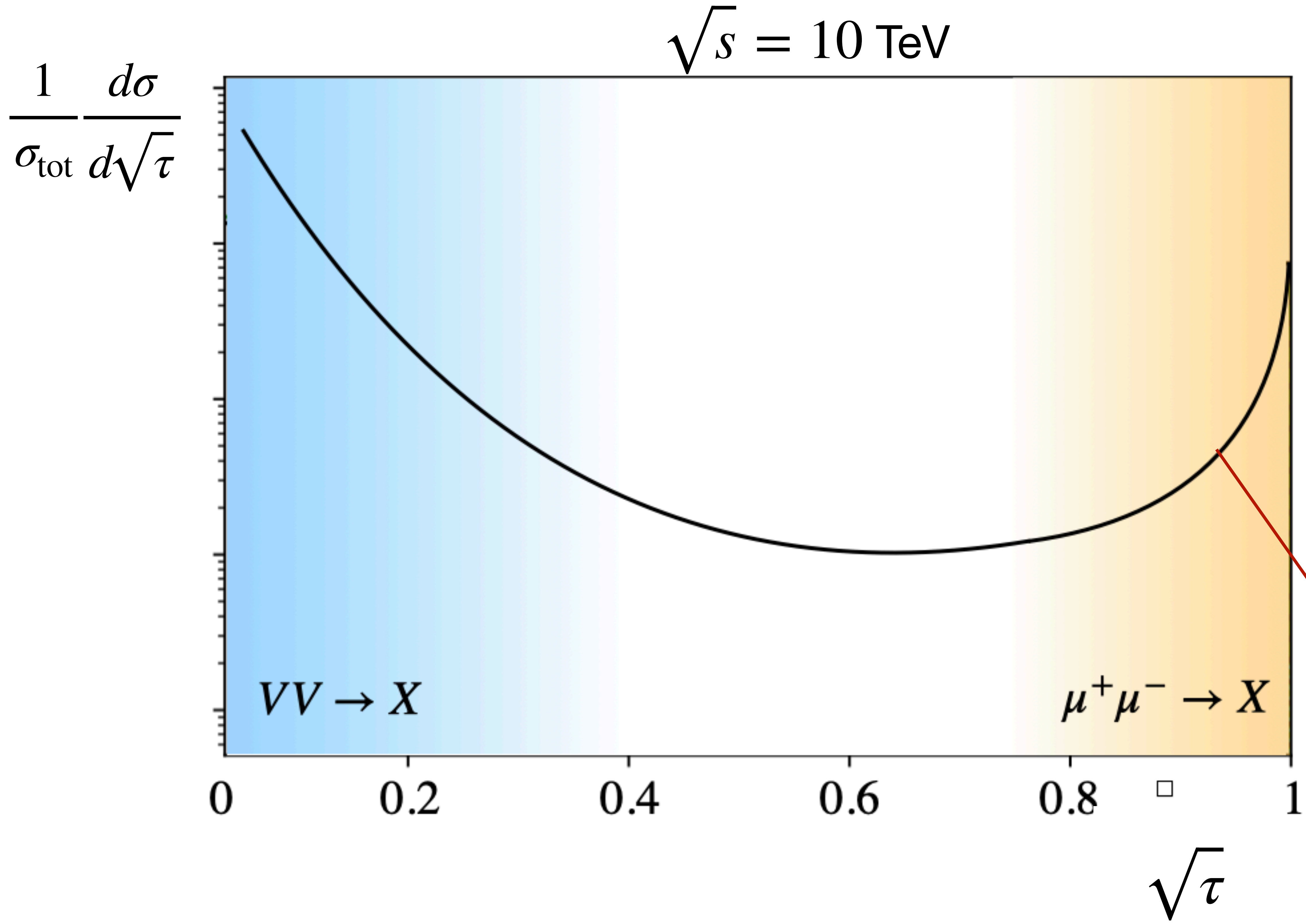
Muon collider physics

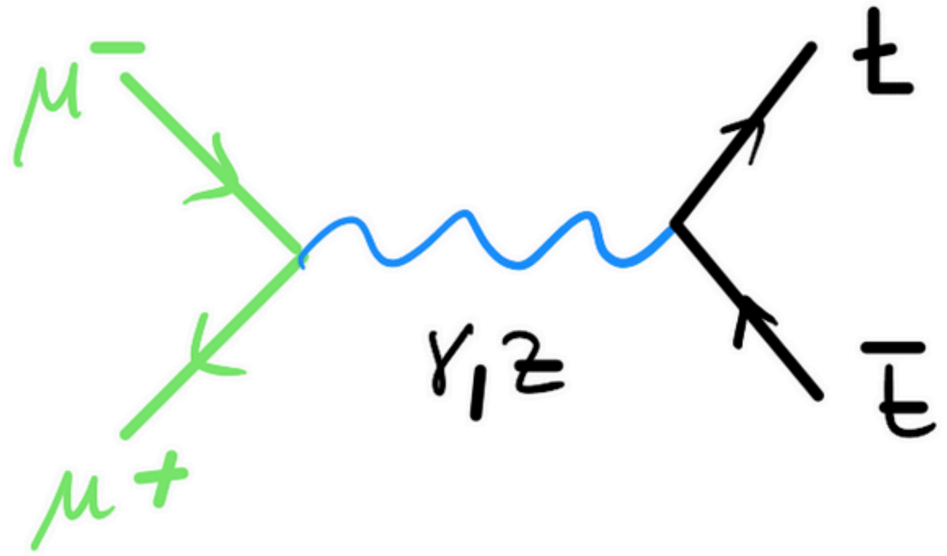
The essentials #1 : Two colliders in one

O(10) TeV muon collider energy allows to have two colliders in one:









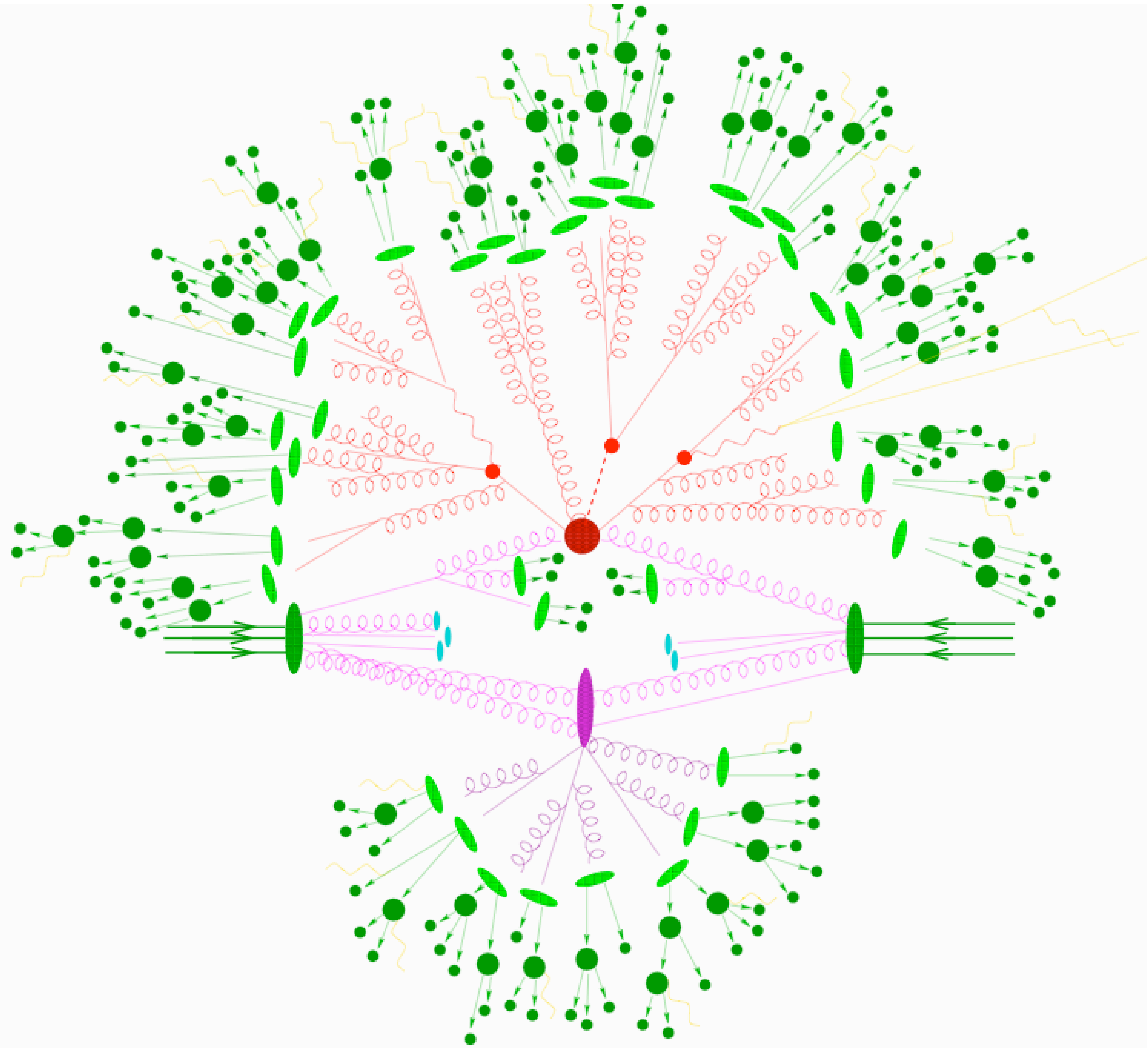
Accurate and precise theory predictions available to reach percent level accuracy [Frixione, FM, Pagani, Zaro, to appear]

Contribution to: 2022 Snowmass Summer Study e-Print: 2203.07256 [hep-ph]

Muon collider physics

The essentials #1 : Two colliders in one

tth production at the LHC (Fully hadronic)



Muon collider physics

The essentials #1 : Two colliders in one

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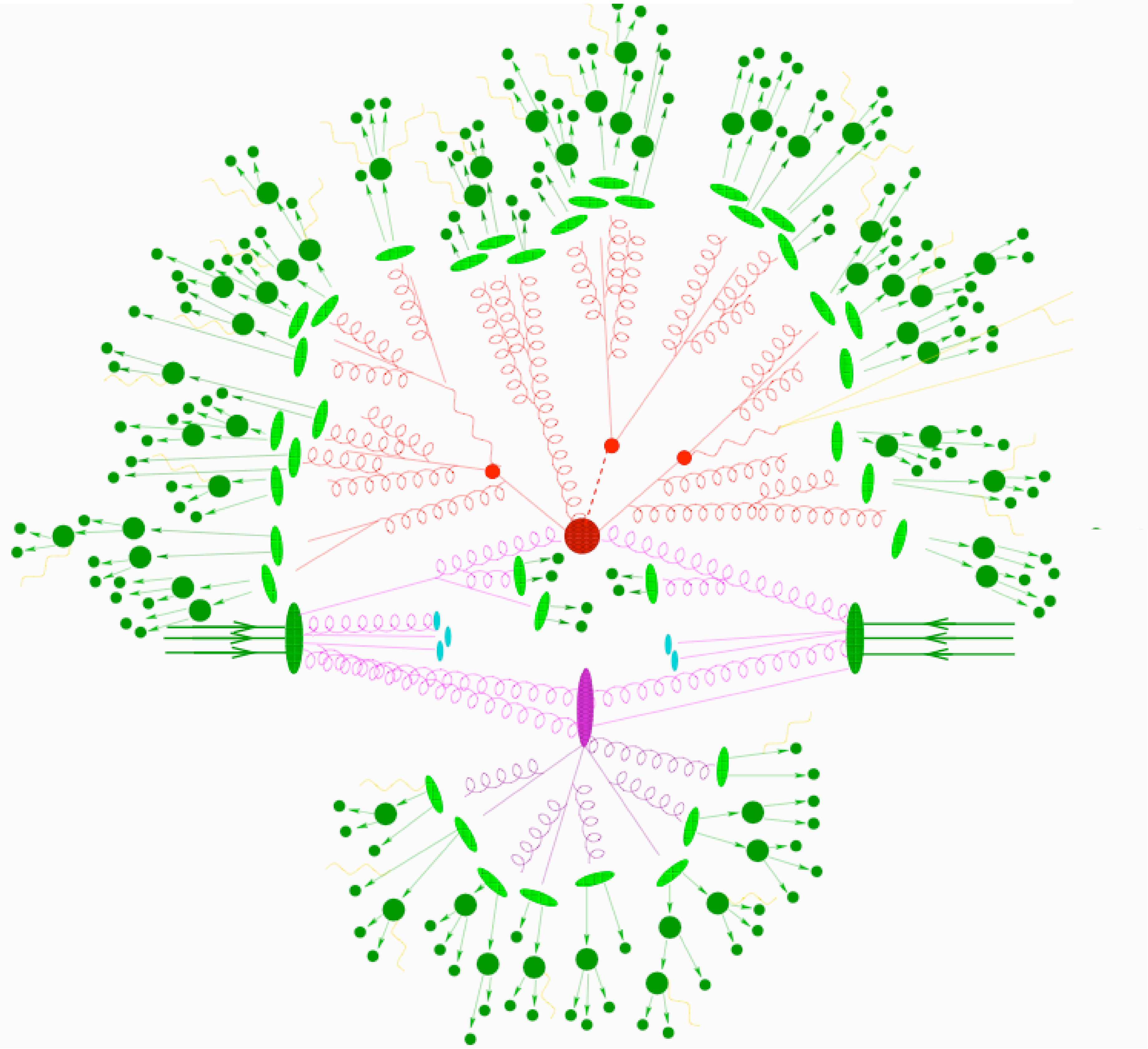
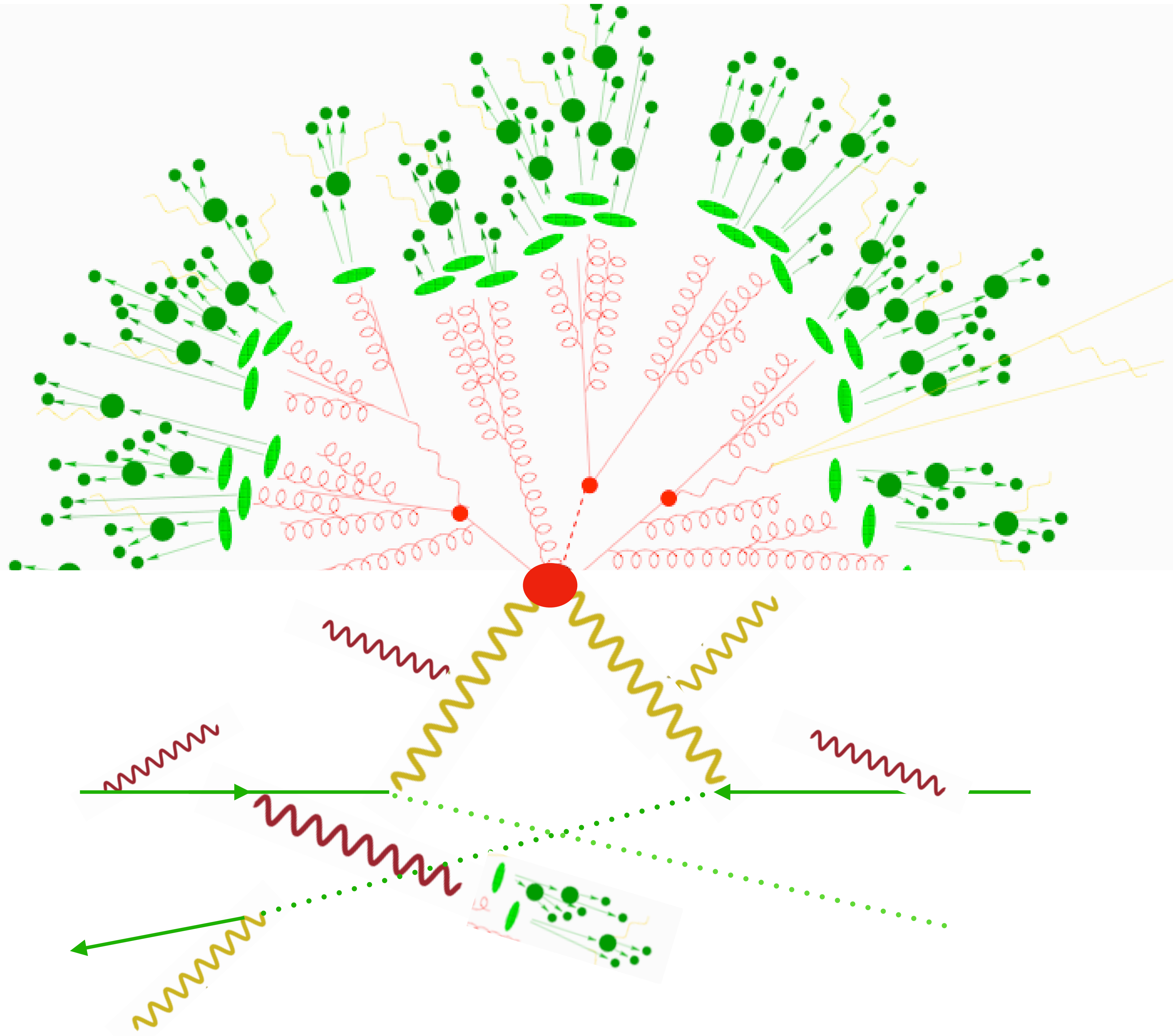


tth production at the muC 100 TeV

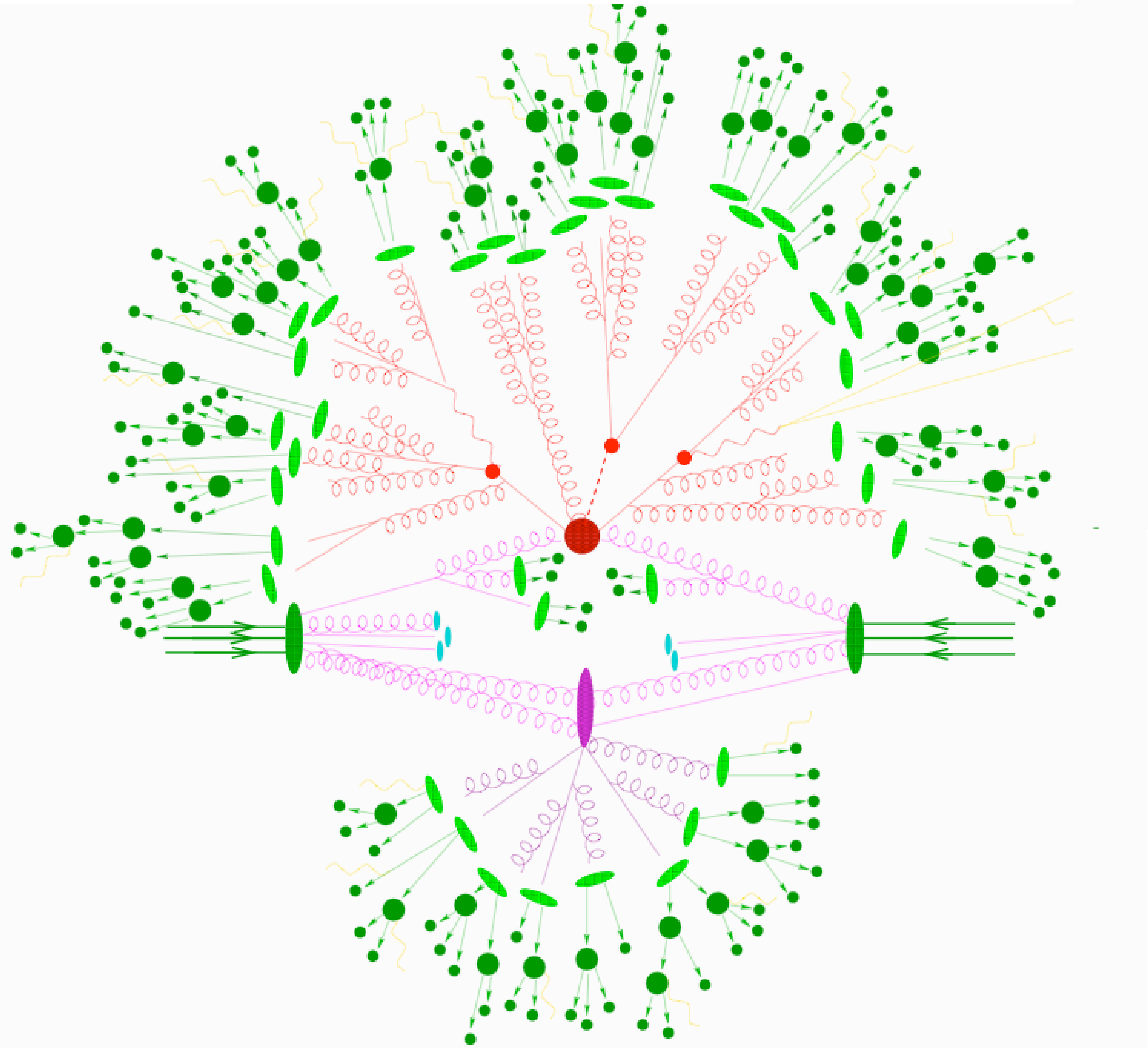


Contribution to: 2022 Snowmass Summer Study e-Print: 2203.07256 [hep-ph]

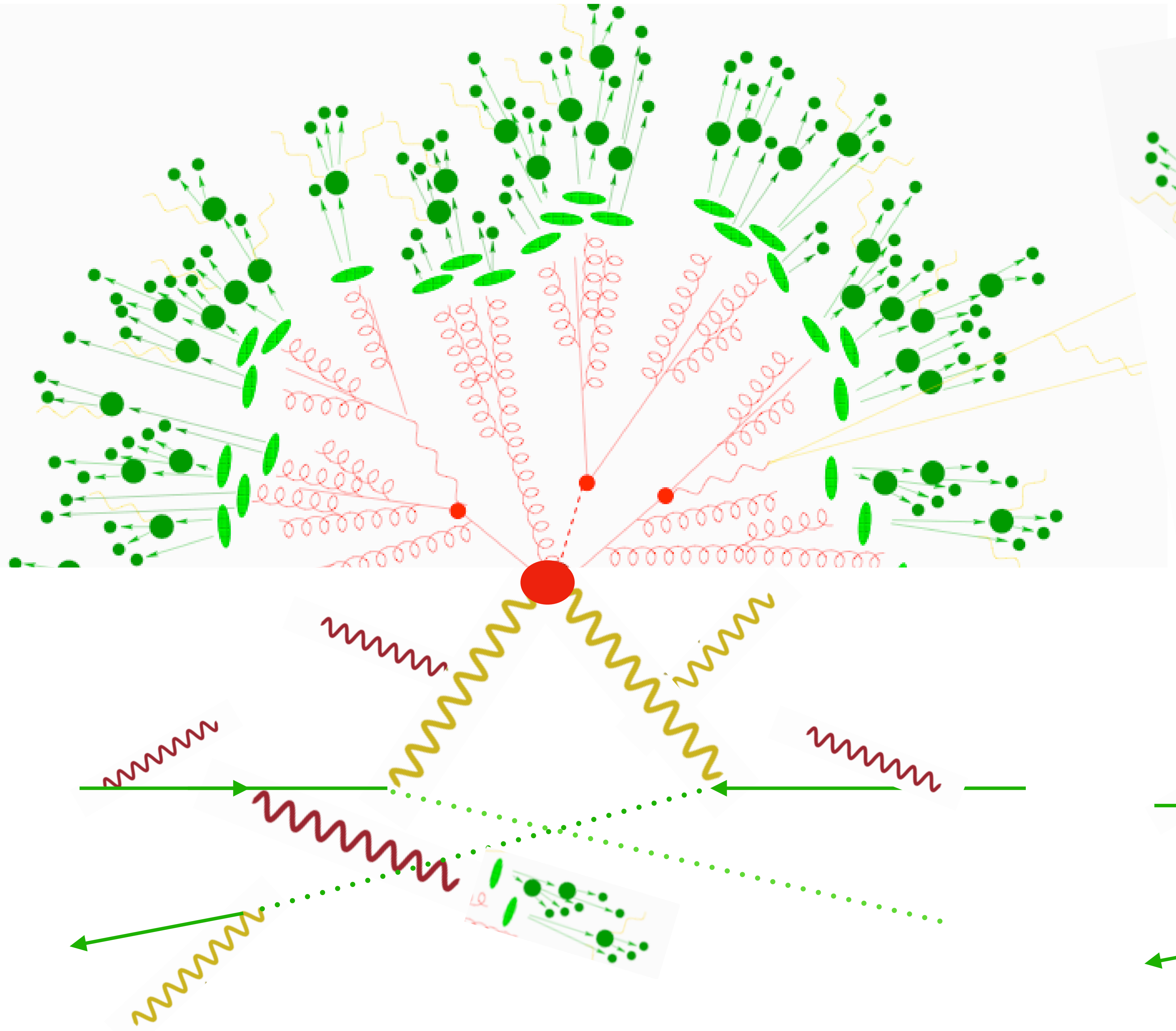
Muon collider physics

The essentials #1 : Two colliders in one

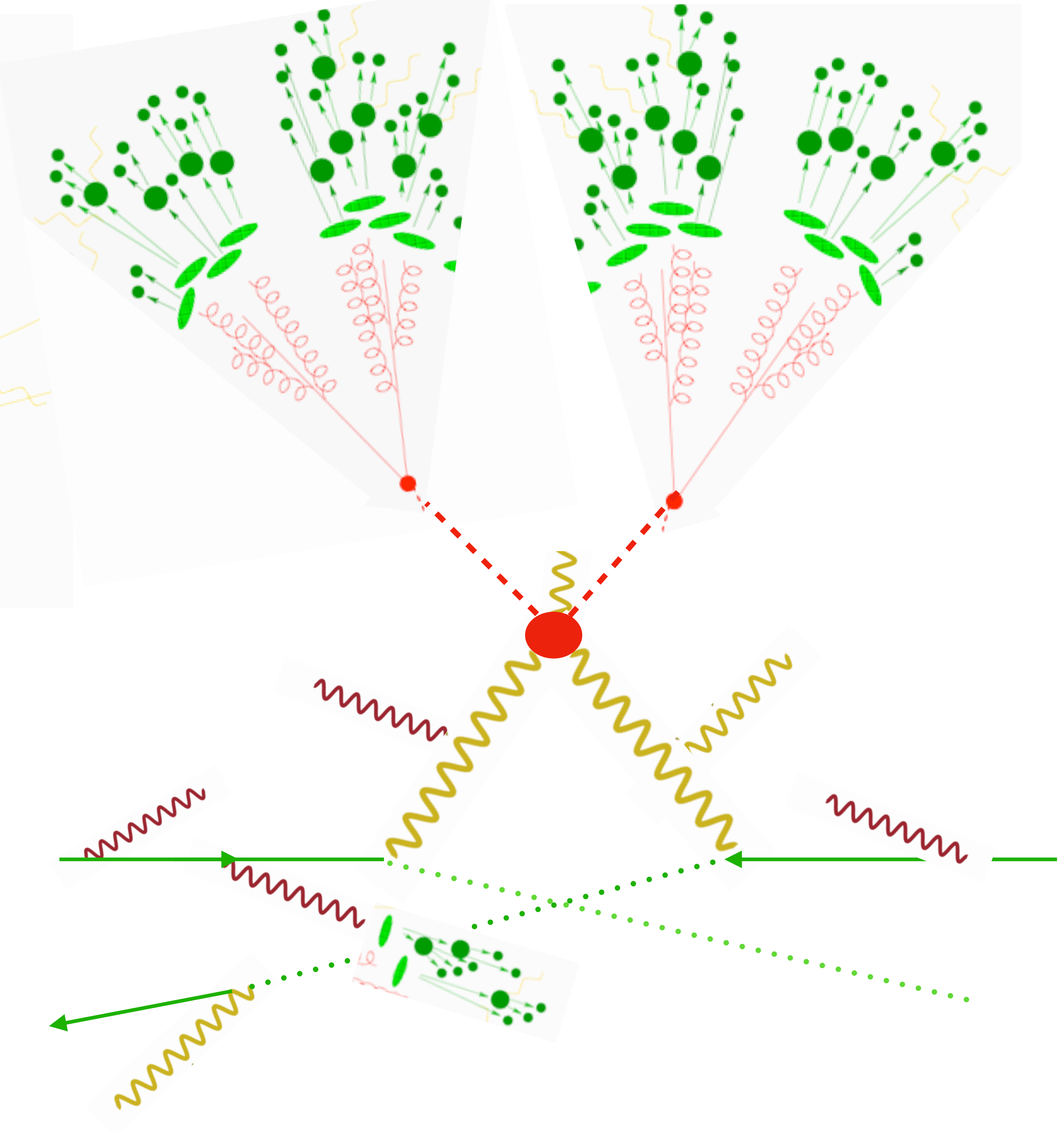
tth production at the LHC (Fully hadronic)



tth production at the muC 100 TeV



HH→4b production at a multi-TeV muC

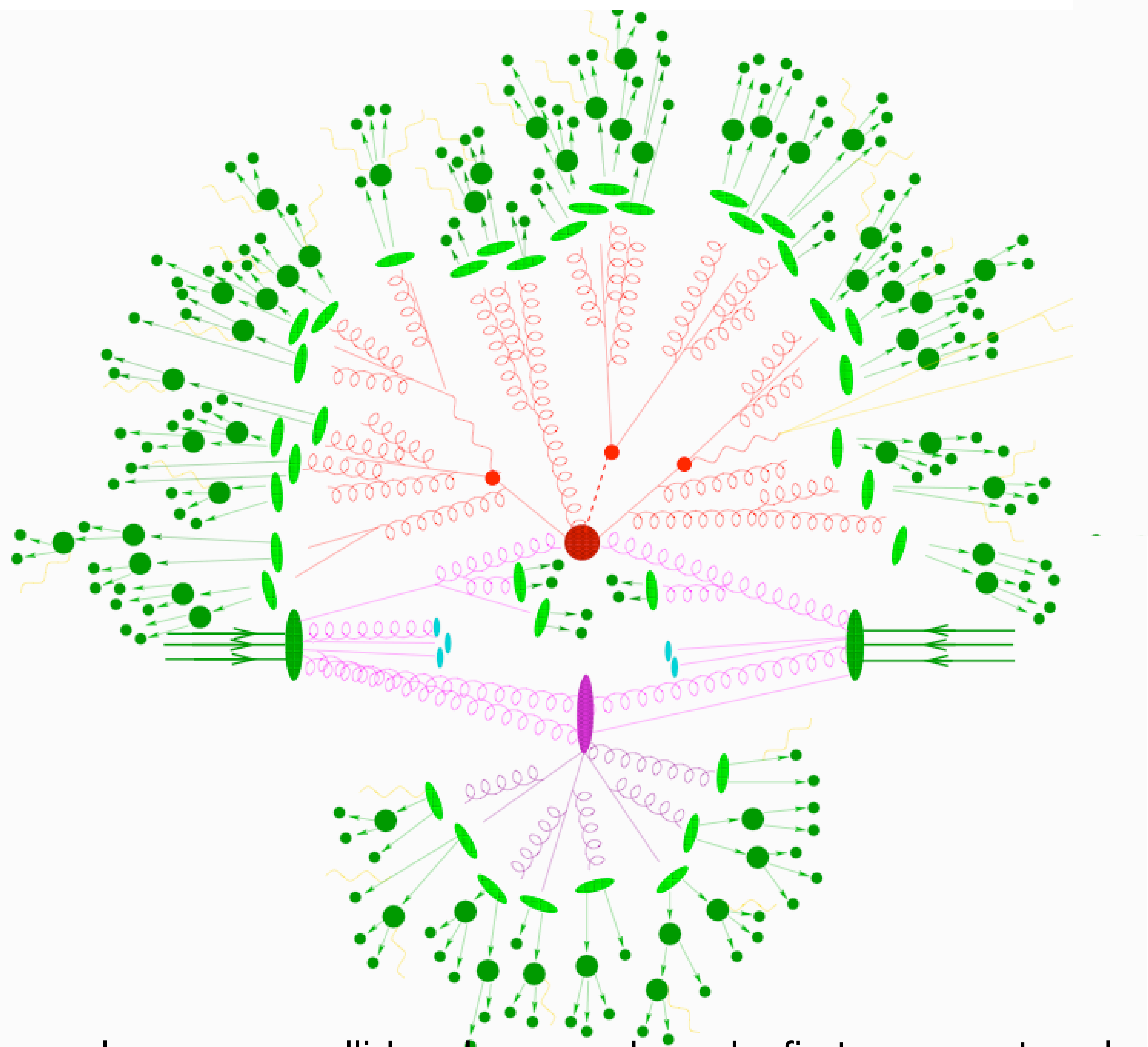


Contribution to: 2022 Snowmass Summer Study e-Print: 2203.07256 [hep-ph]

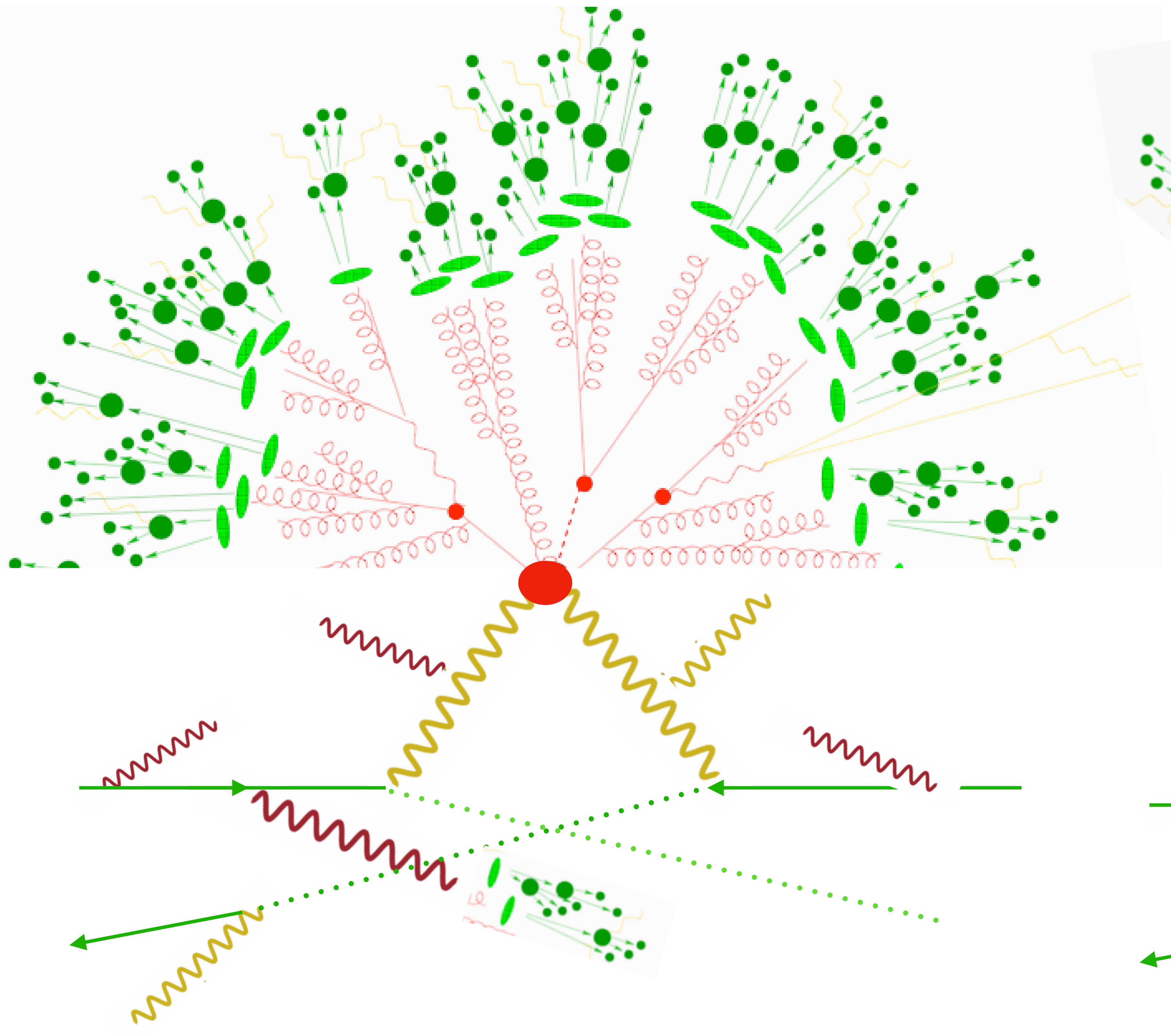
Muon collider physics

The essentials #1 : Two colliders in one

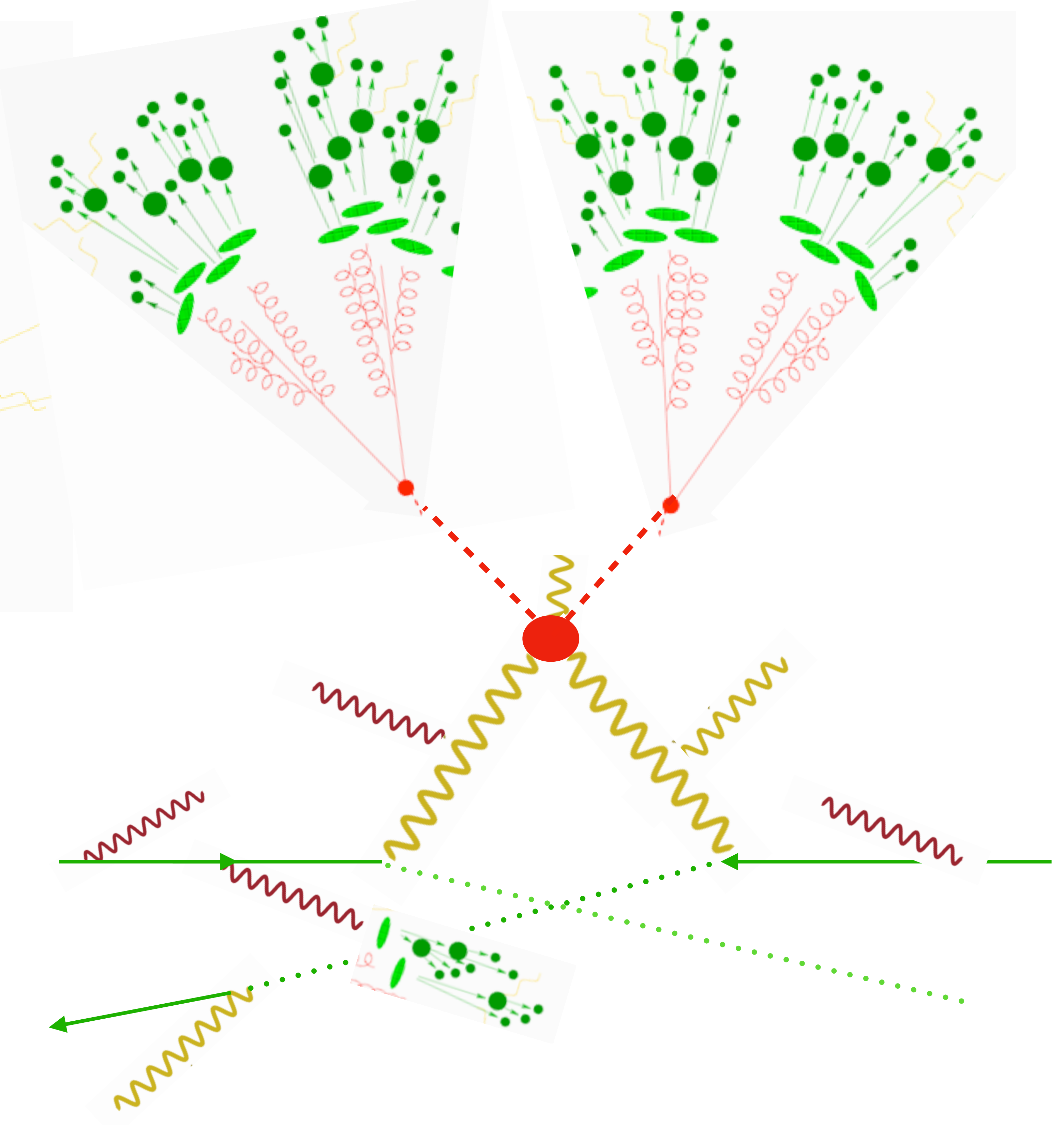
tth production at the LHC (Fully hadronic)



tth production at the muC 100 TeV



HH→4b production at a multi-TeV muC



In a muon collider gluons and quarks first appear at scales of order 100 GeV in the decays of W,Z,H (from either initial state or final state radiation) or from photon splitting.

Multijet final states are of EW origin.

[2504.21417 The Muon Collider]

Muon collider physics

The essentials #2 : Energy helps precision

Another crucial aspect is that at a muon collider one can fully exploit the typical precision of a lepton collider as NP effects can be enhanced by energy.

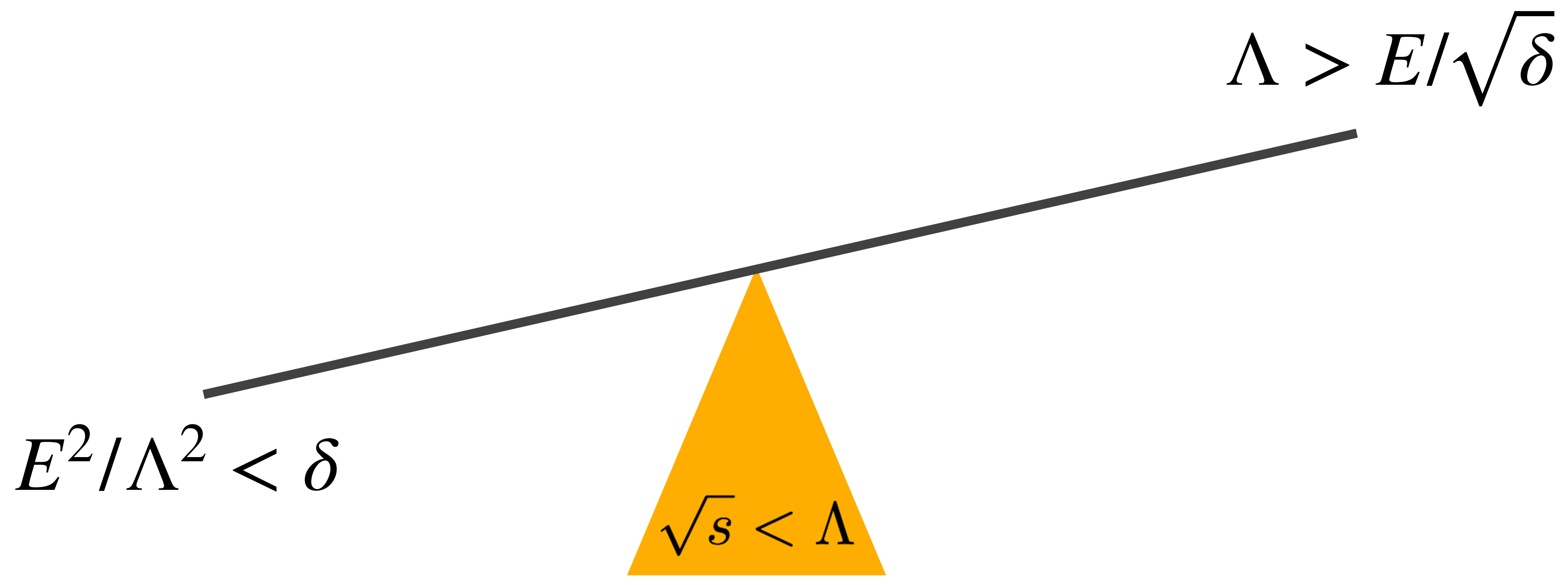
The importance of this fact can be seen within an EFT

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

Which induces corrections on observables

$$\text{Obs} = \text{Obs}^{\text{SM}} \cdot \left(1 + \sum_i \frac{E^2}{\Lambda^2} c_i \Delta_i\right)$$

For $\Lambda = 100$ TeV, one needs $\delta = 10^{-6}$ precision for E=100 GeV, while δ=1% is enough at 10 TeV (for $c_i\Delta_i \sim 1$).



Energy helps precision

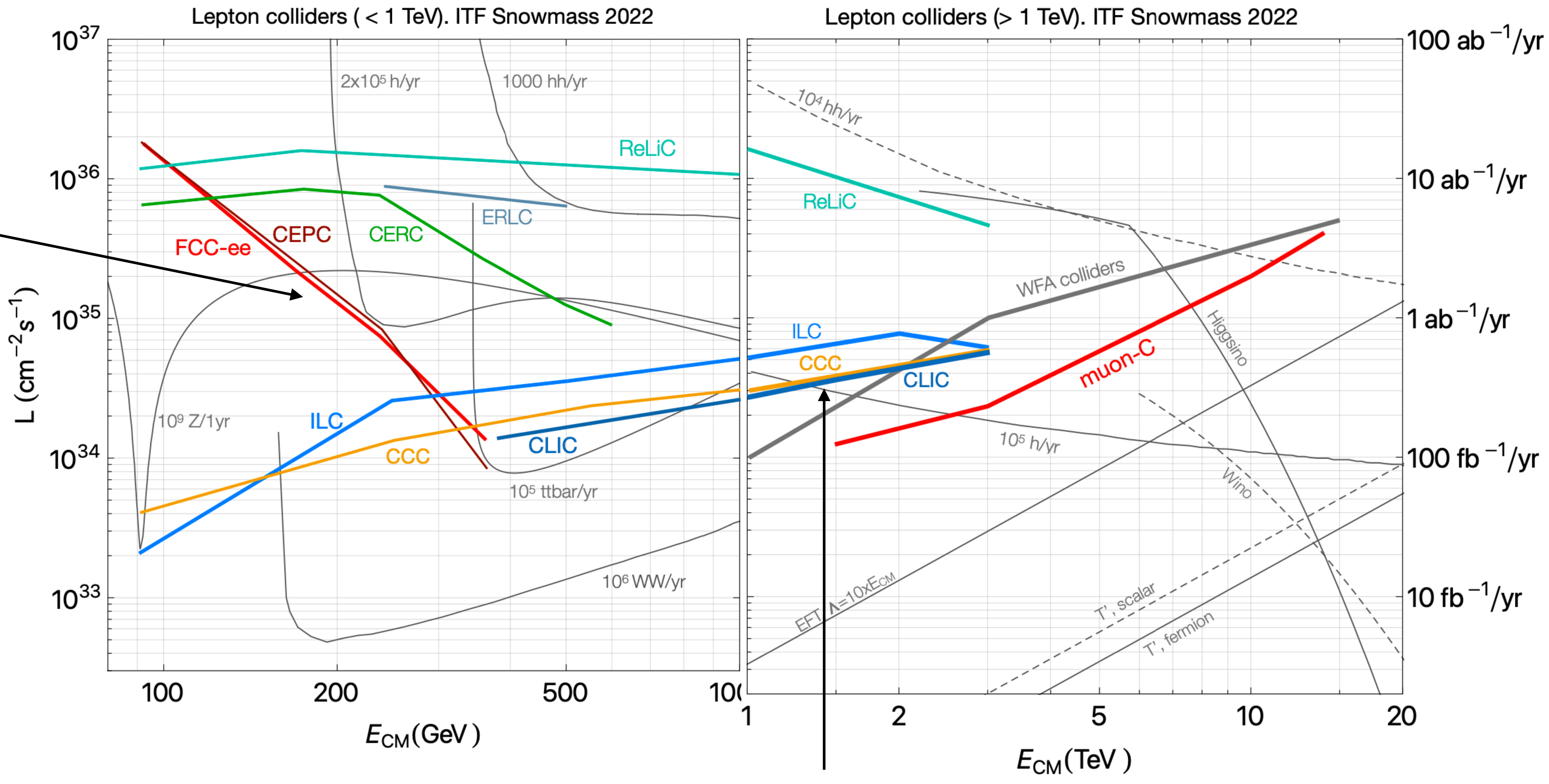
* Sufficiently weakly interacting states may also exist without spoiling the EFT.

arXiv:2208.06030 Collider Implementation Task Force

Muon collider physics

The essentials #3 : Energy helps Luminosity

$L = P_{\text{synrad}} E_{\text{cm}}^{-3.5}$

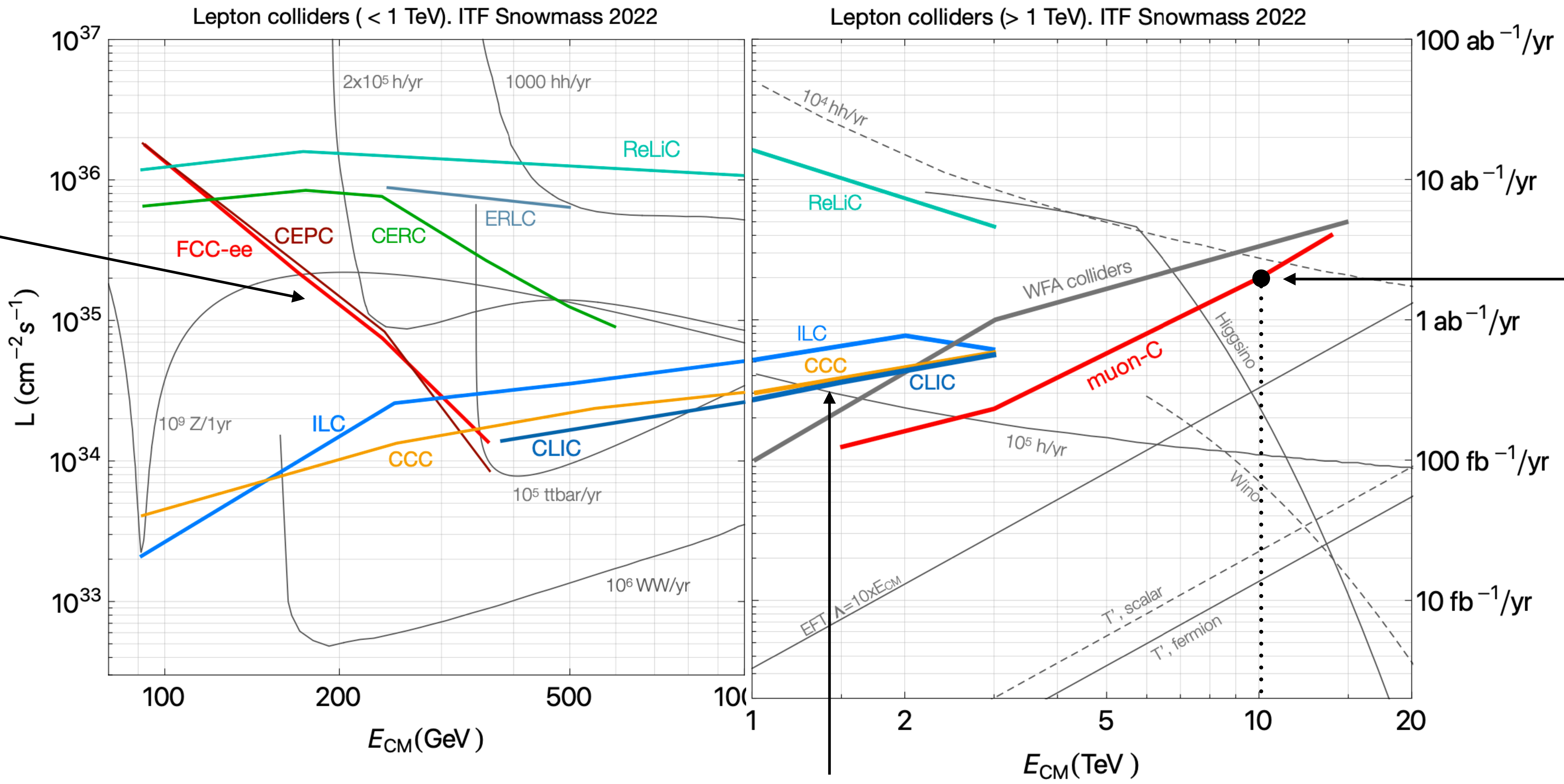


$L = P_{\text{RF}}$

Muon collider physics

The essentials #3 : Energy helps Luminosity

$L = P_{\text{synrad}} E_{\text{cm}}^{-3.5}$



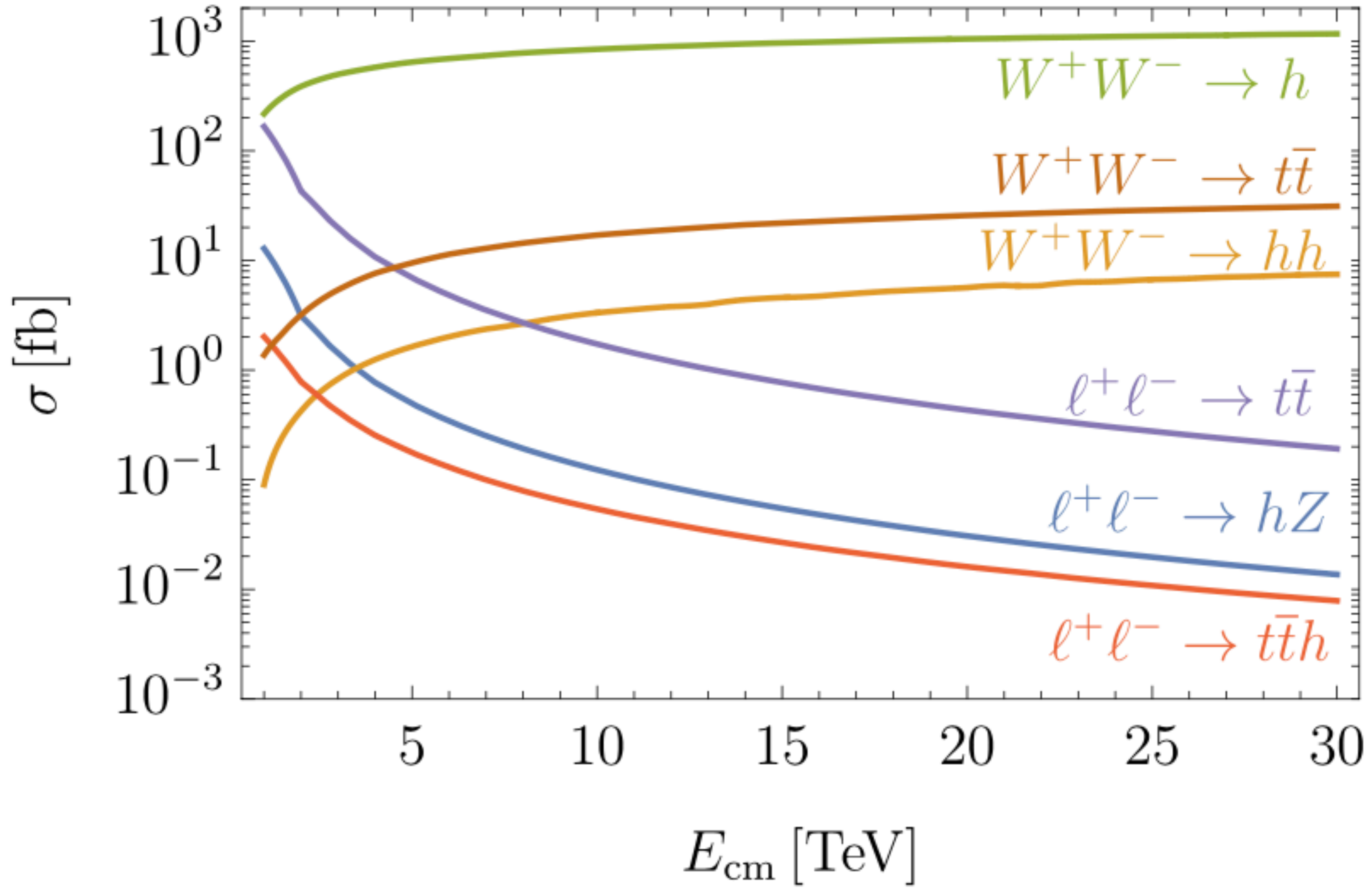
10 ab^{-1} in 5 years

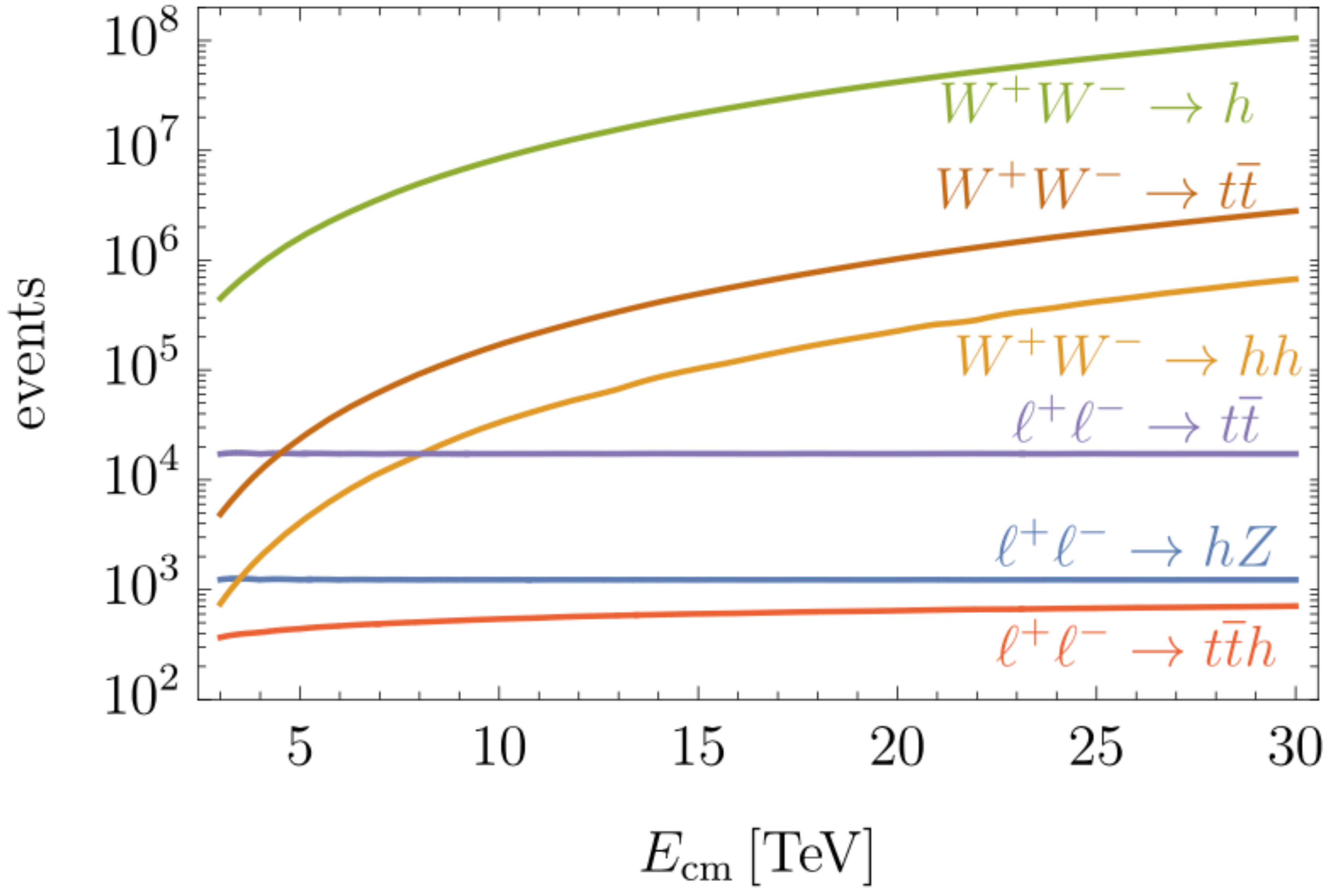
$L = P_{\text{RF}}$

Muon collider physics

The essentials #3 : Energy helps Luminosity

$$L \gtrsim \frac{5\,\text{years}}{\text{time}}\left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}}\right)^2 2\cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$$





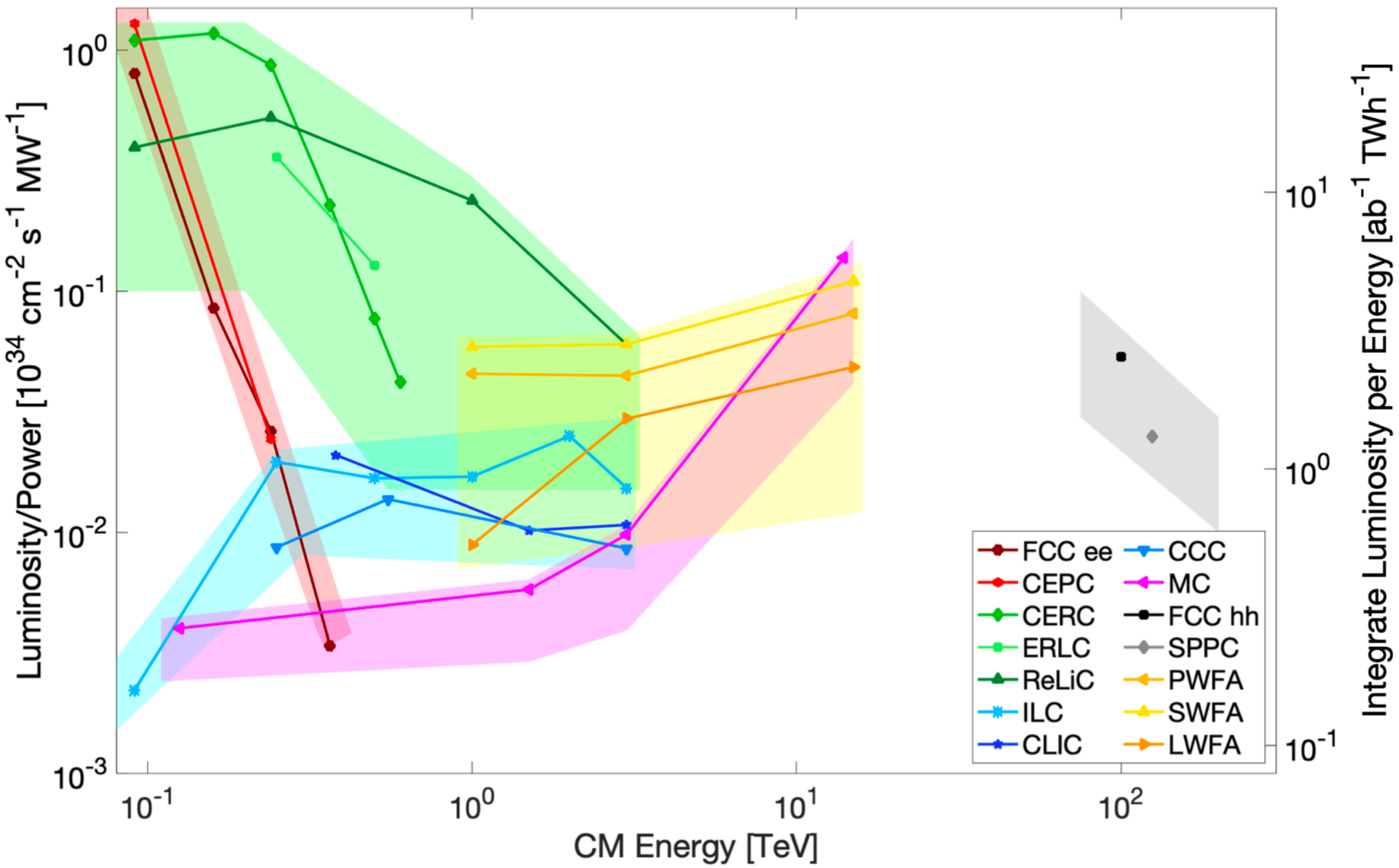
$$\widehat{\mathcal{L}} = 10\,\text{ab}^{-1}\left(\frac{E_{\text{cm}}}{10\,\text{TeV}}\right)^2$$

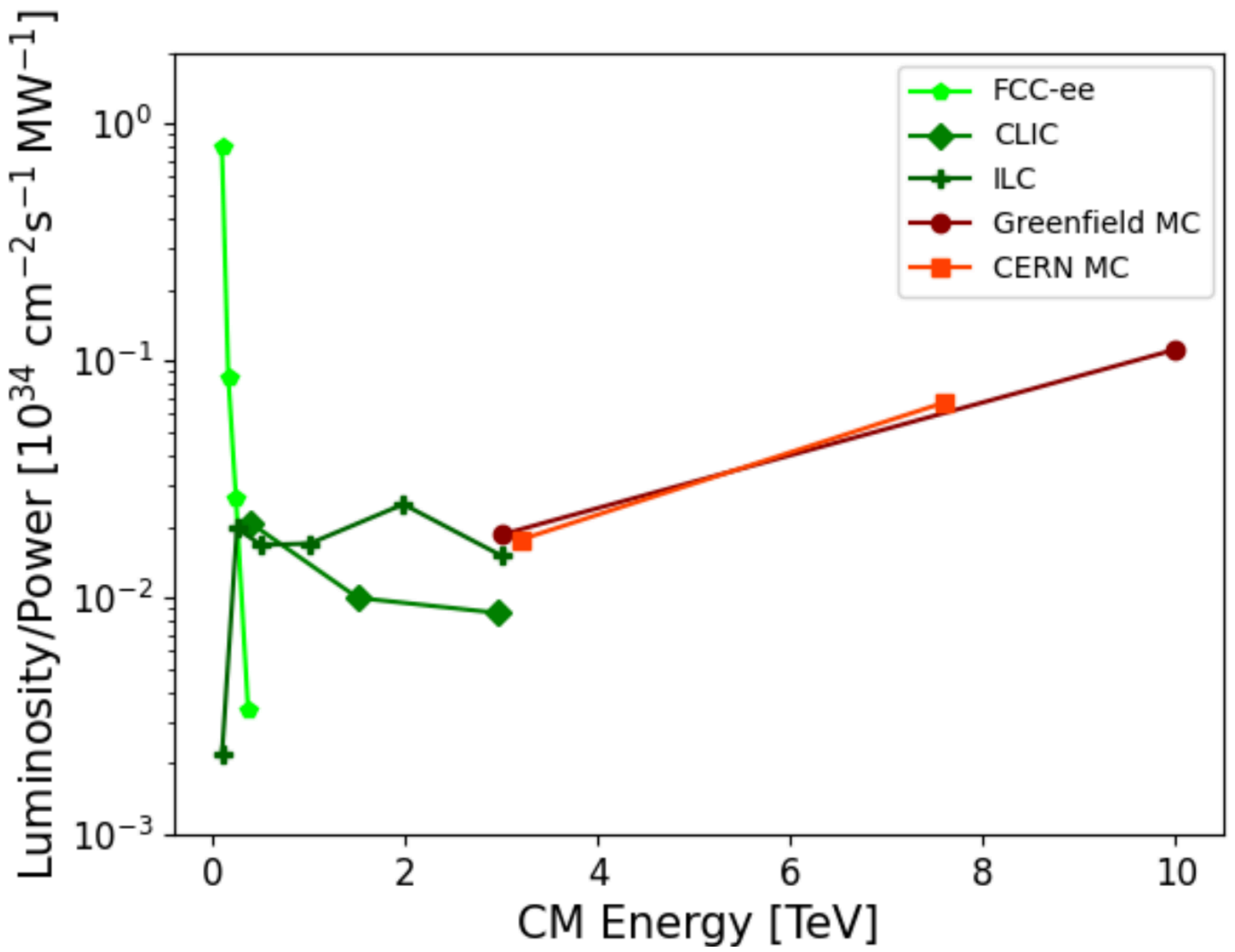
[arXiv:2208.06030 Collider Implementation Task Force]

[2504.21417 The Muon Collider]

Muon collider physics

The essentials #4 : The green side





Muon collider physics

The essentials #5: Compactness

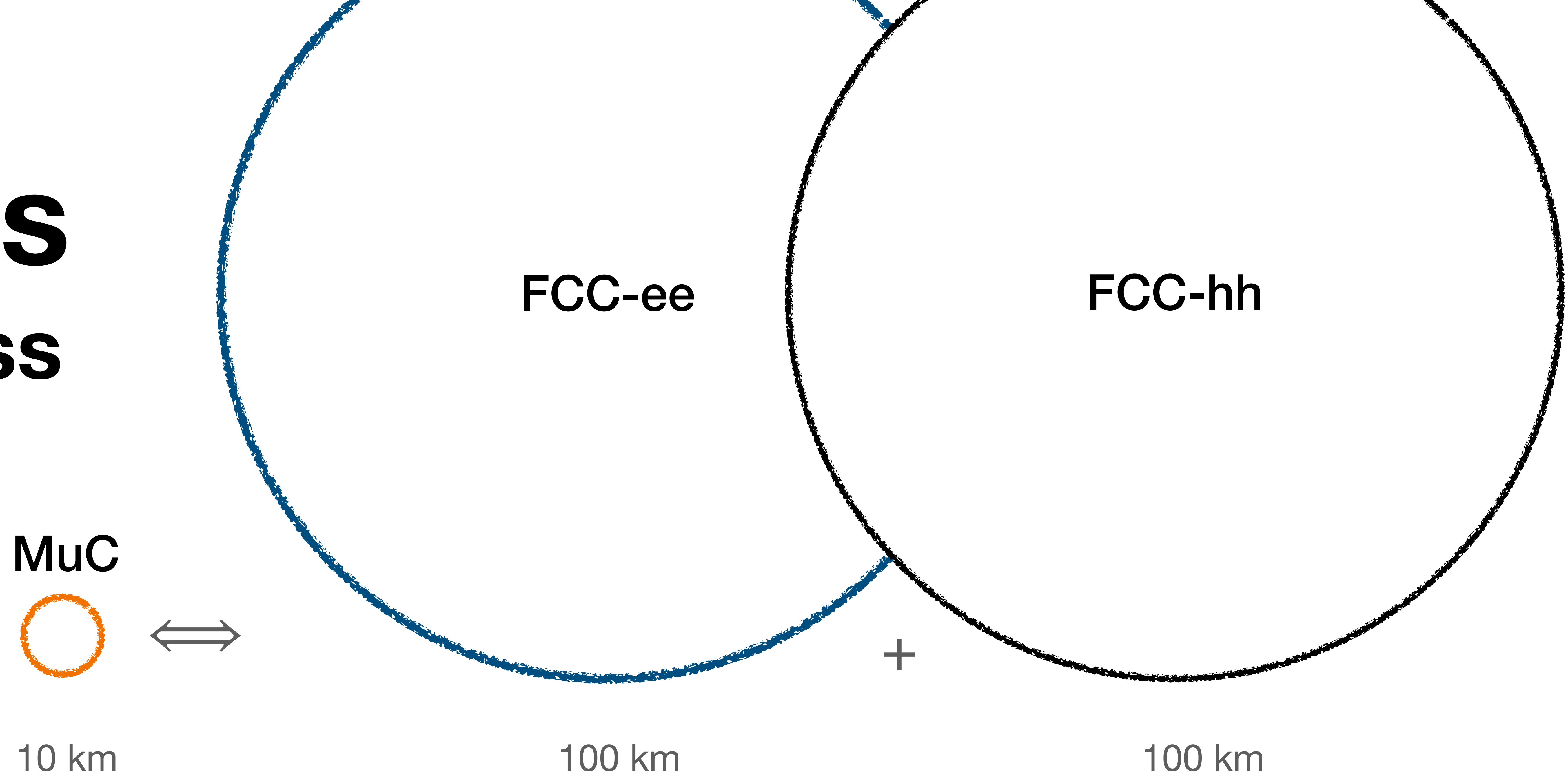
x

t

Muon collider physics

The essentials #5: Compactness

1] O(10) TeV Energy small hybrid collider:



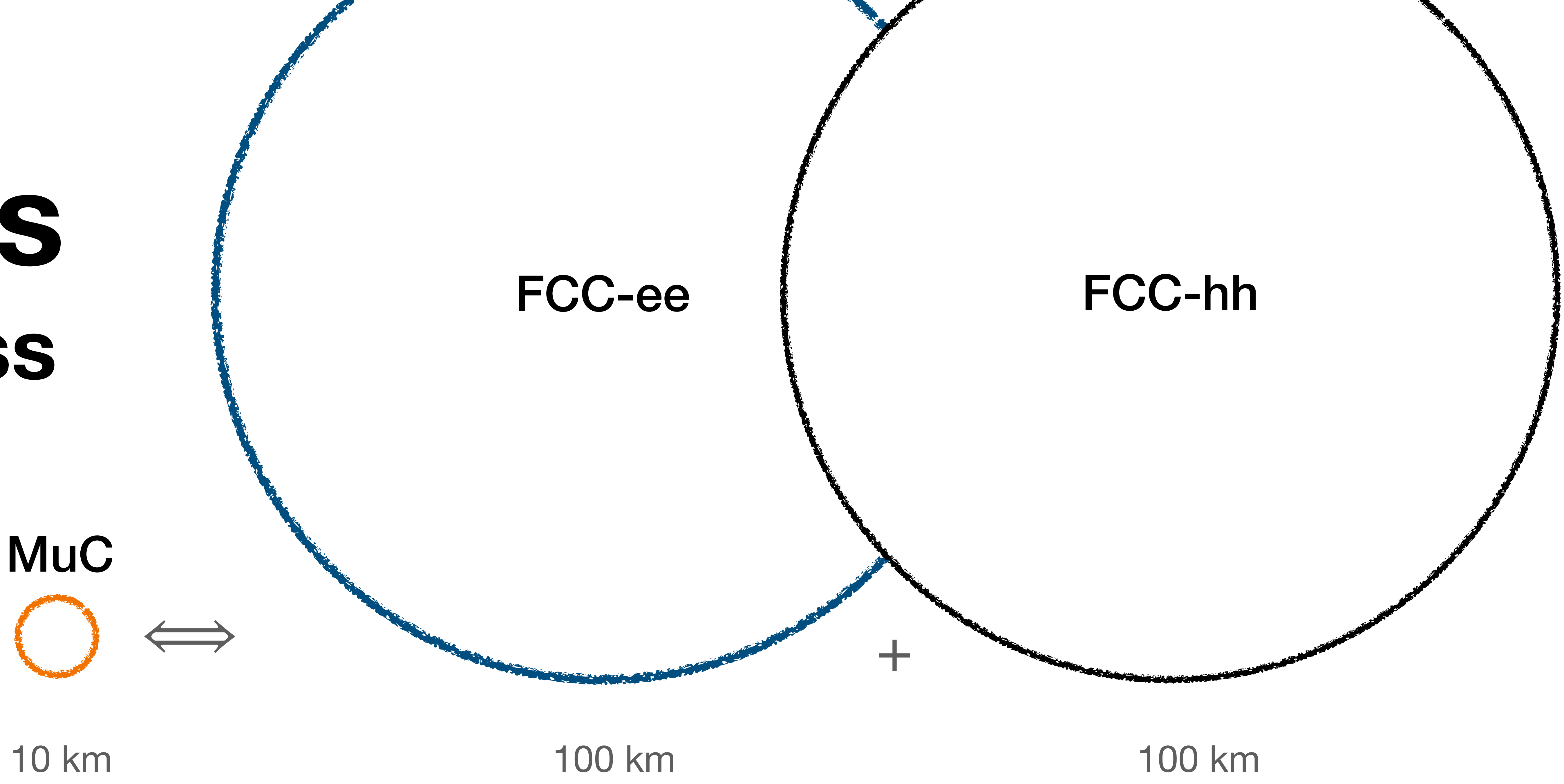
x

t

Muon collider physics

The essentials #5: Compactness

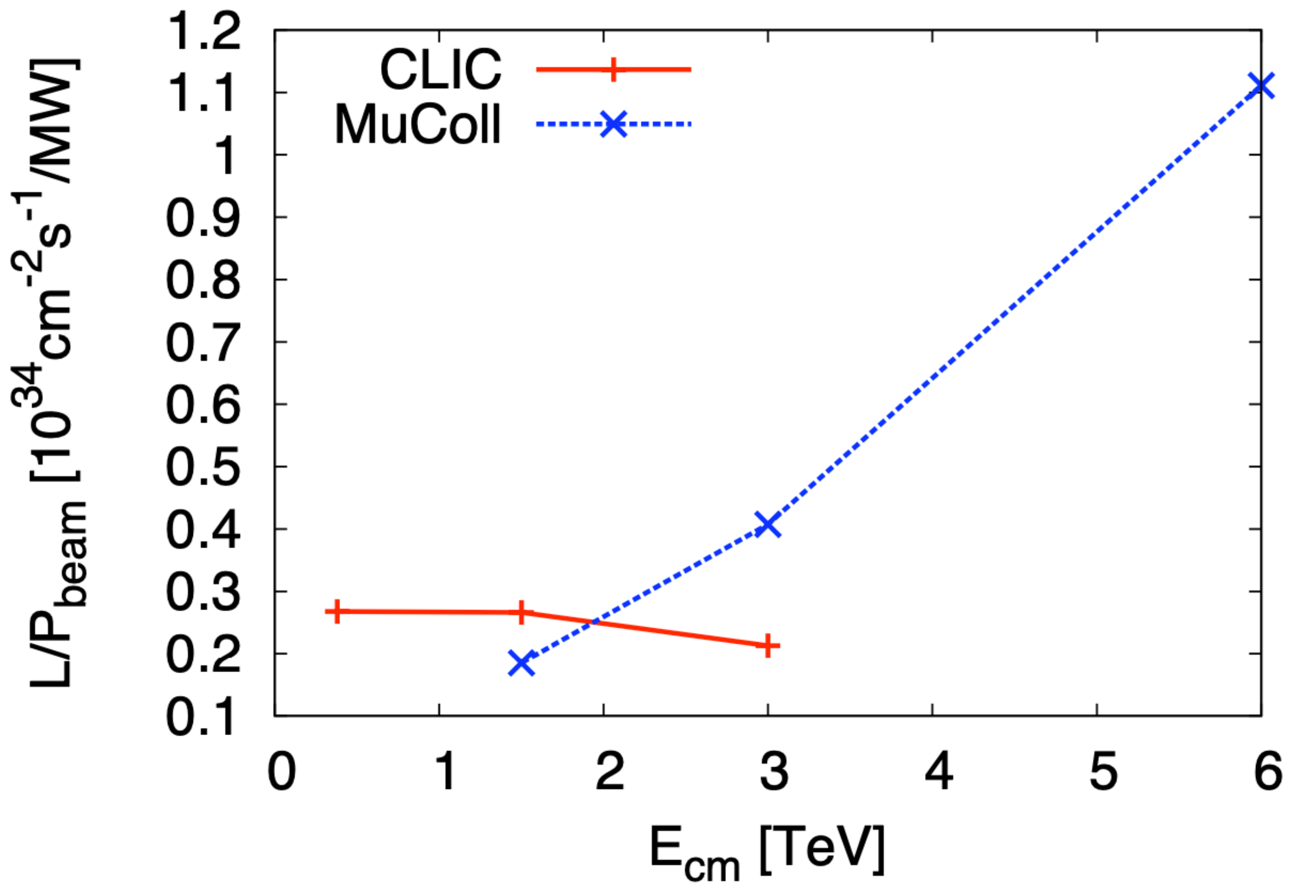
1] O(10) TeV Energy small hybrid collider:



x

t

2] Luminosity growing with energy:

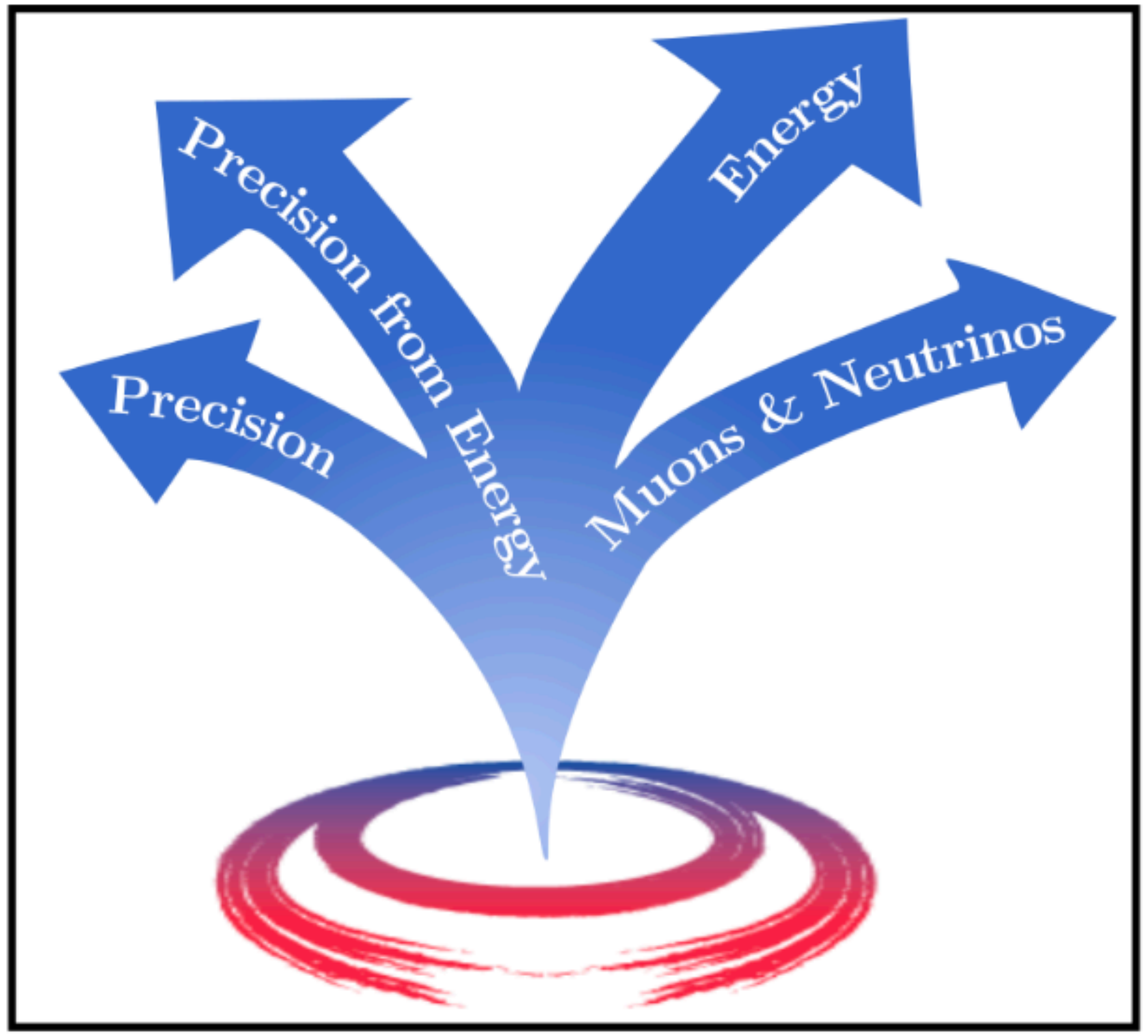


⇒**MuC is an STCC =** Space-Time-Compact Collider

⇒ **Goal of the tens:**

10 TeV , 10 iab, 10 x smaller and O(10) x faster than the FCC

Muon collider physics



[arXiv:2203.07256v1 Muon Collider Physics Summary]

[2504.21417 The Muon Collider]

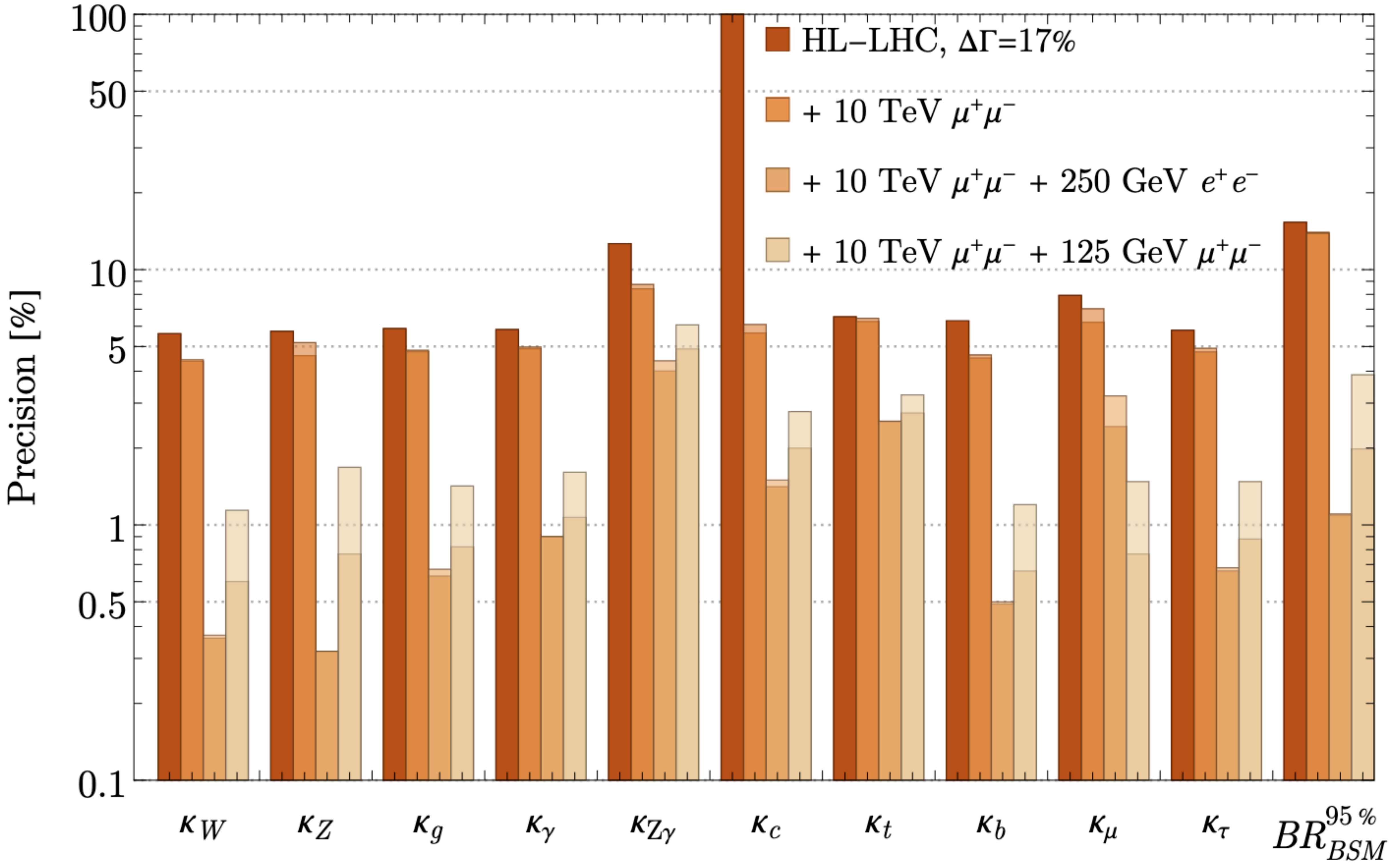
Precision

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	0.2	0.1
κ_g	2.3	0.5	0.5
κ_γ	1.9	0.7	0.7
$\kappa_{Z\gamma}$	10	5.2	3.9
κ_c	-	1.9	0.9
κ_b	3.6	0.4	0.4
κ_μ	4.6	2.4	2.2
κ_τ	1.9	0.5	0.3
κ_t^*	3.3	3.0	3.0

* No input used for the MuC

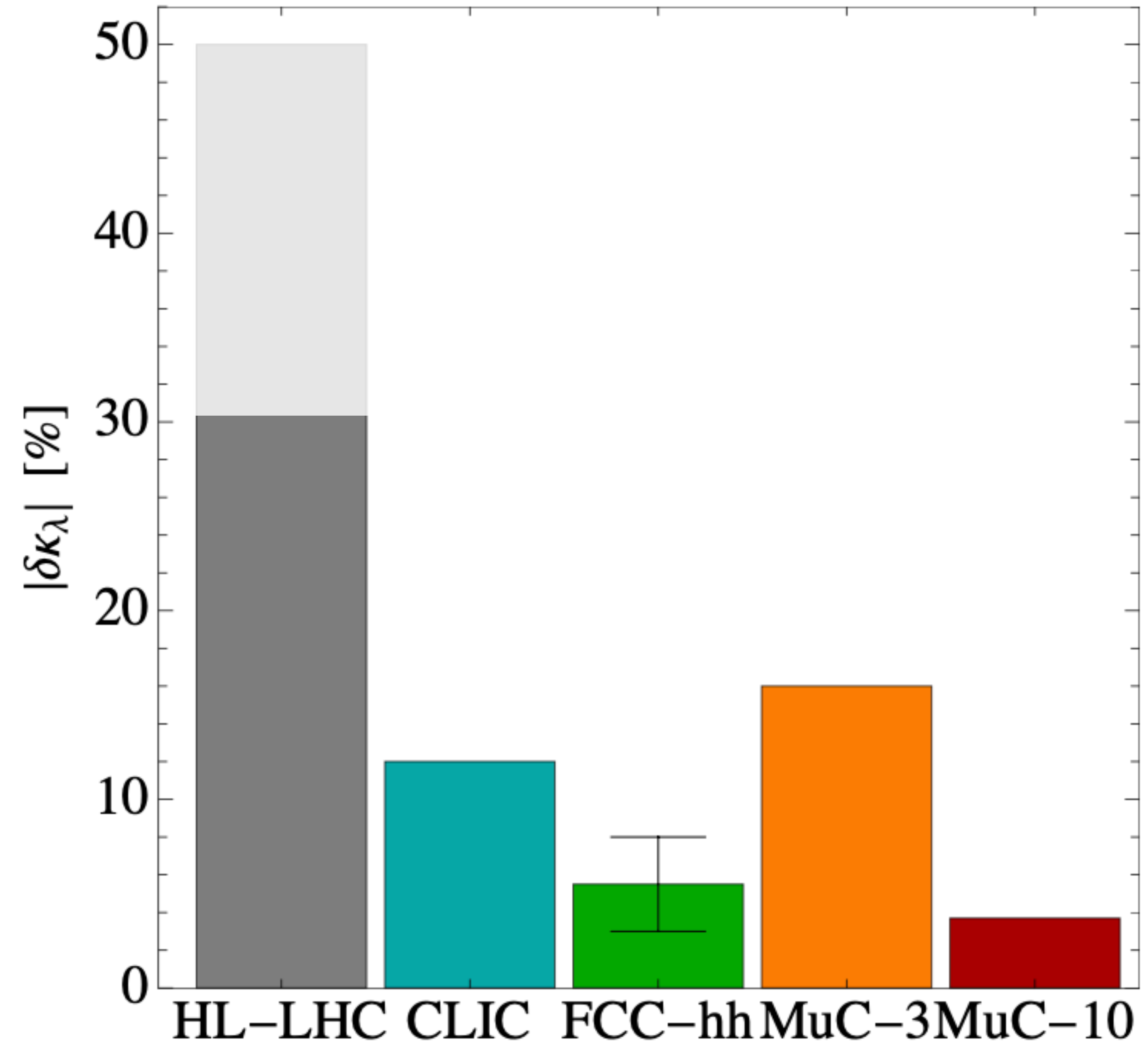
arXiv:2308.02633

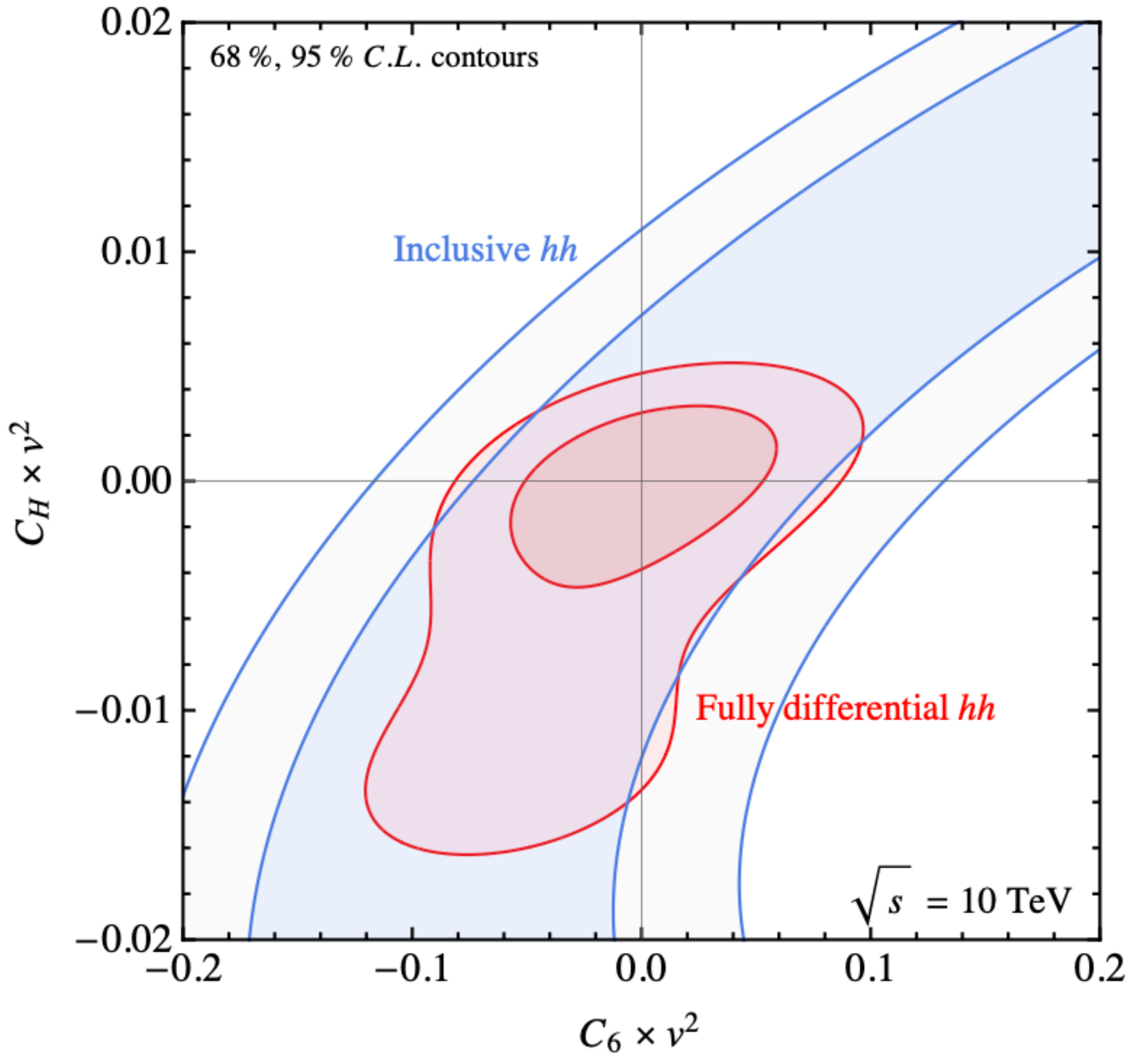


[2504.21417 The Muon Collider]

Precision

The shape of the H potential: HH production

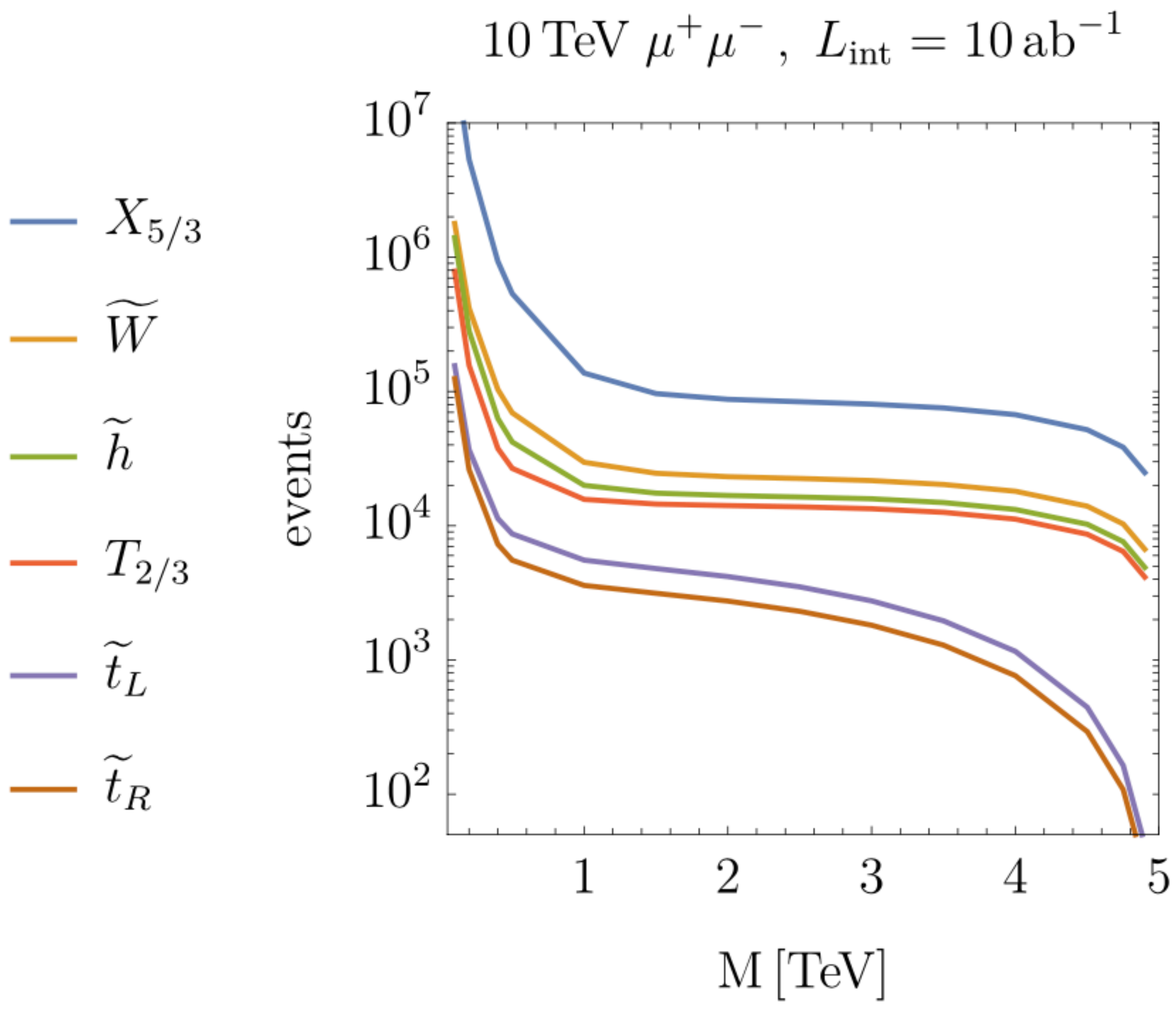




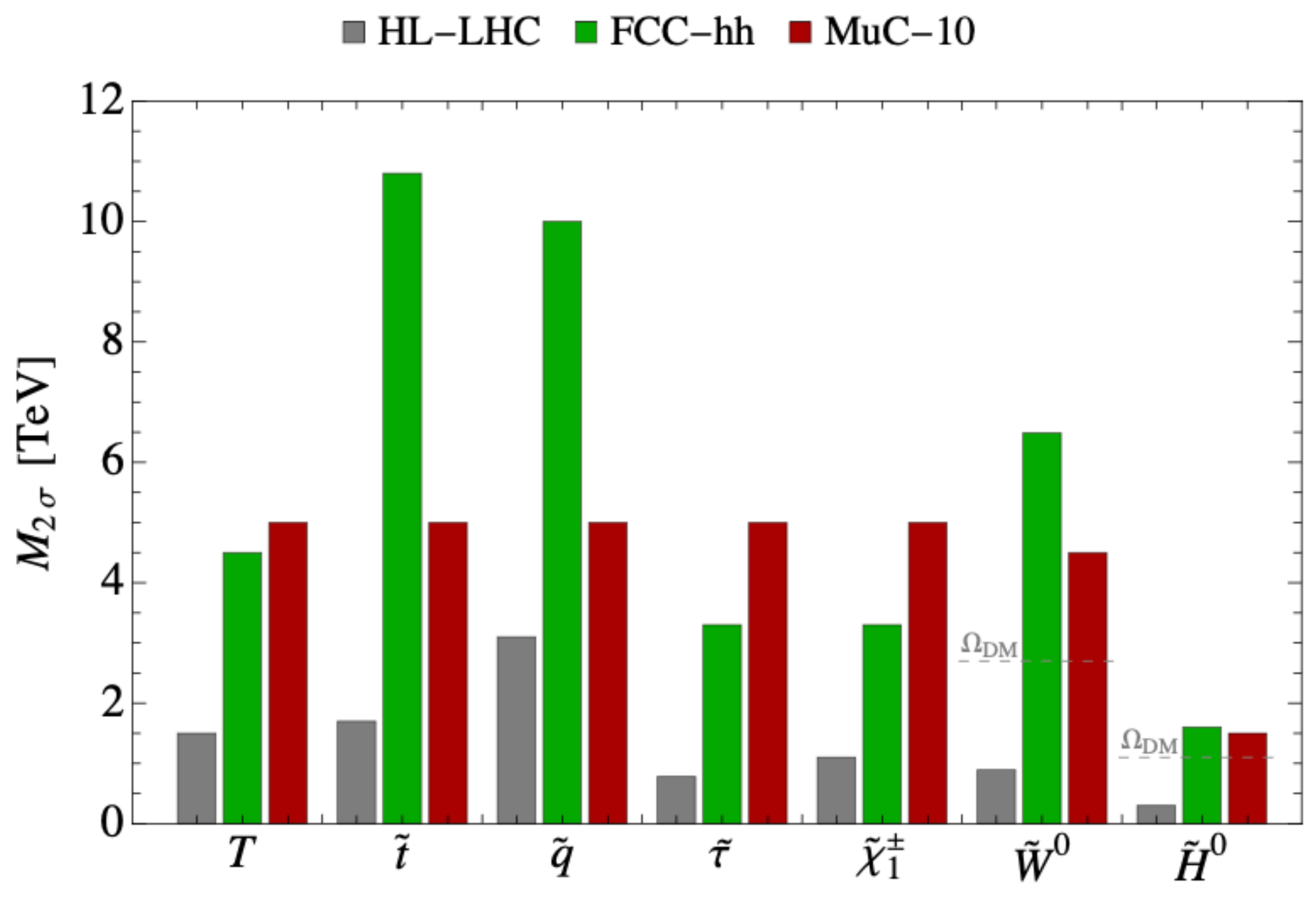
Reach on the trilinear coupling (and more) extremely competitive.

Energy

s-channel pair production



A few months of run could be sufficient for a discovery.



$$\delta\kappa_g = \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

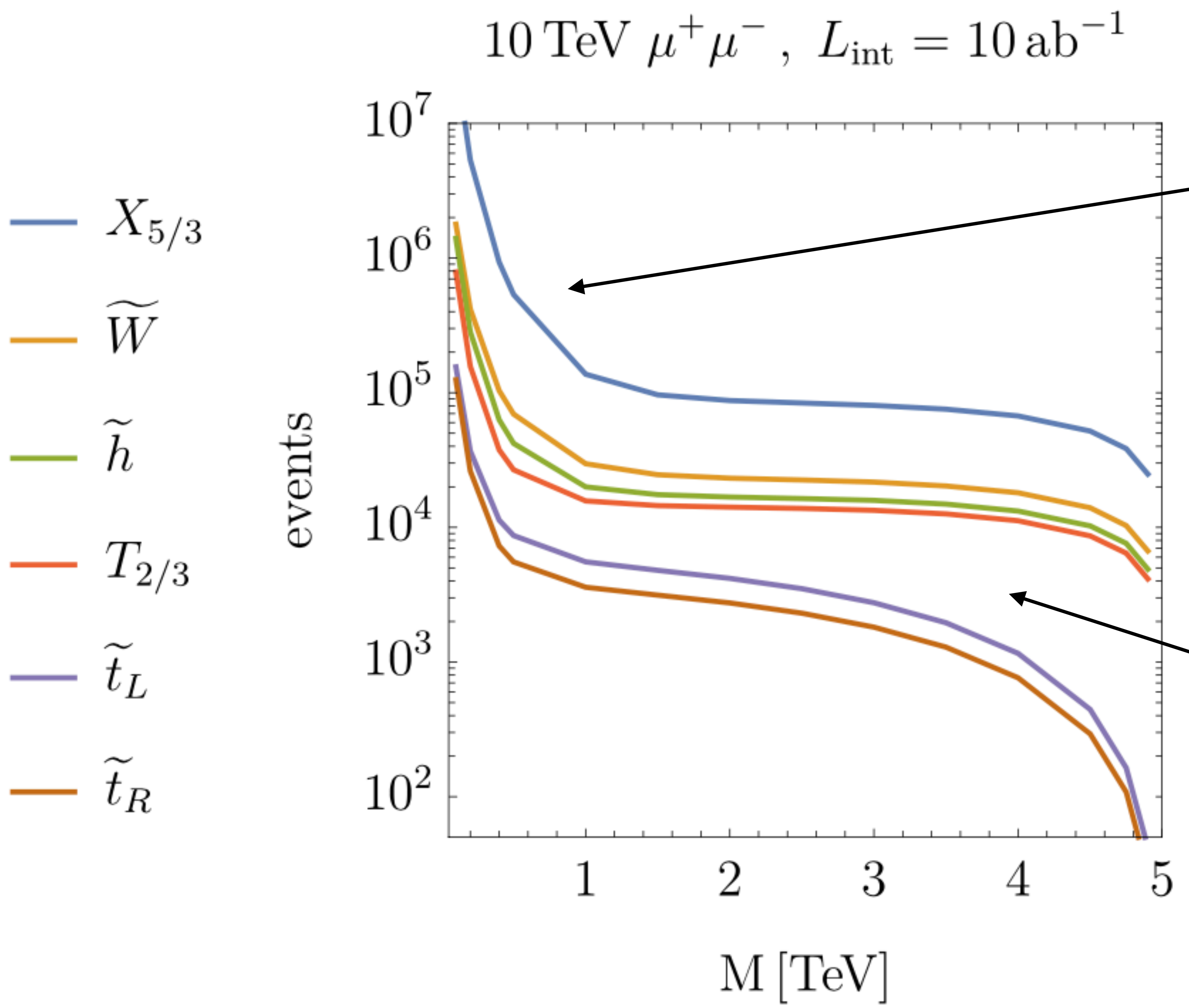
Matching Higgs precision:

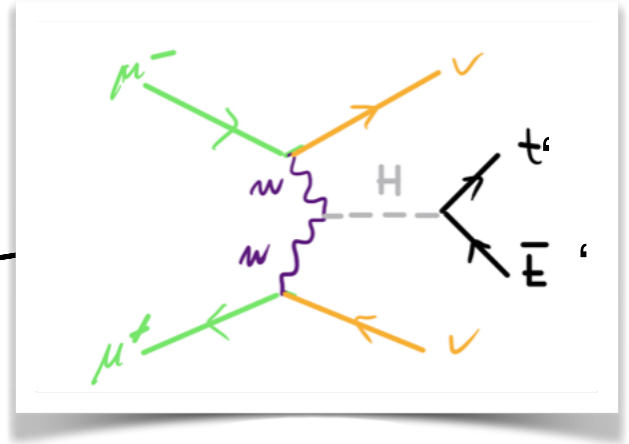
$$m_{\tilde{t}} \gtrsim 1.5\,\mathrm{TeV}\sqrt{\frac{0.67\%}{\delta\kappa_g^{\max}}}.$$

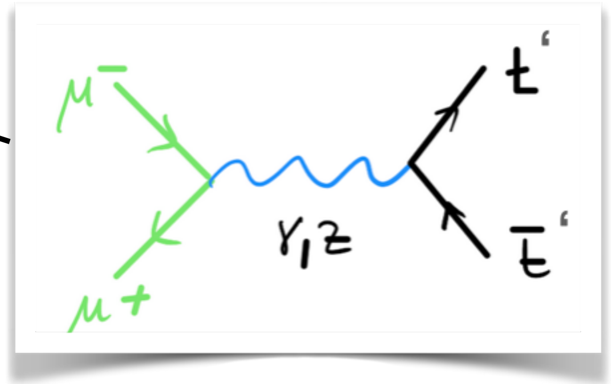
[2504.21417 The Muon Collider]

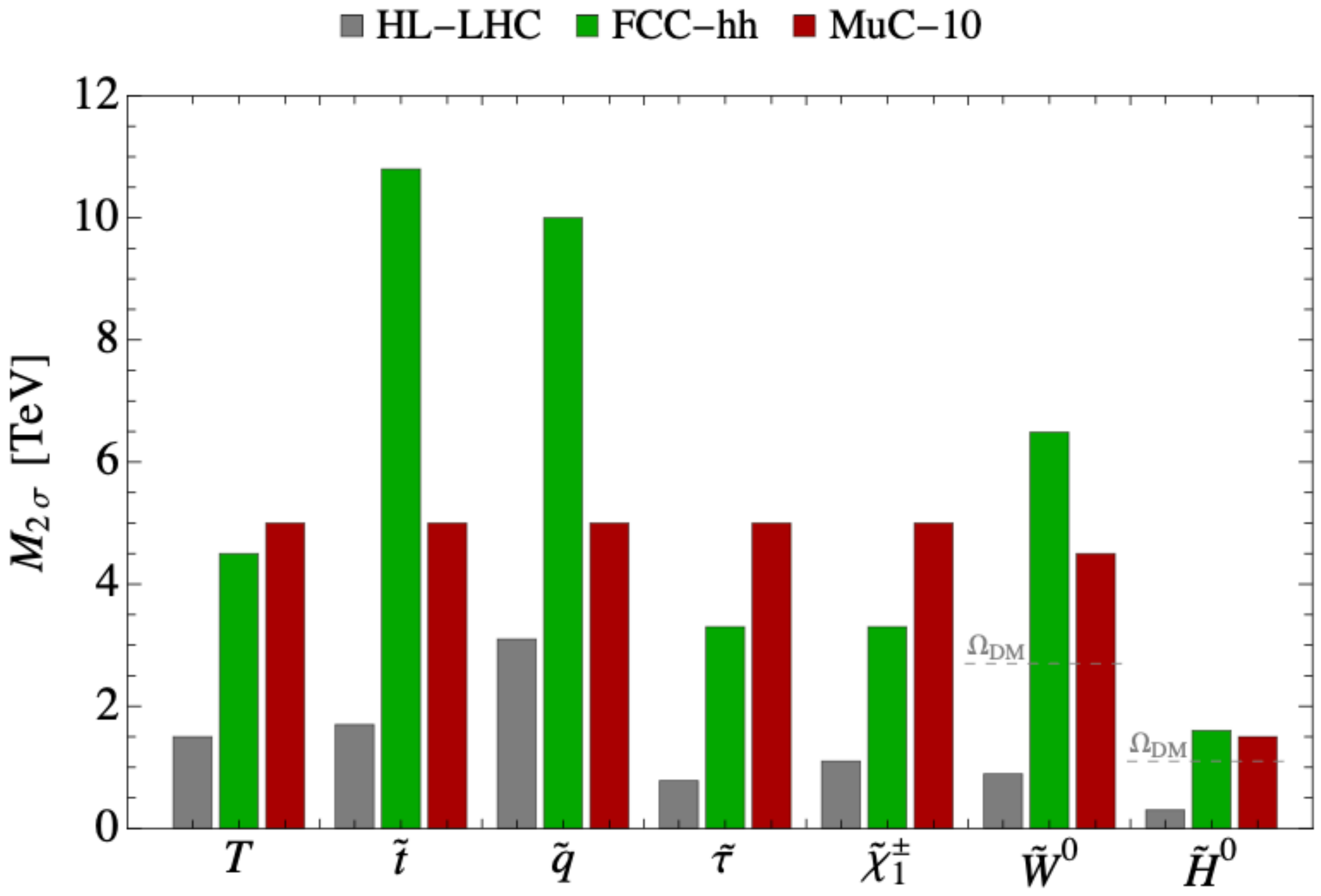
Energy

s-channel pair production









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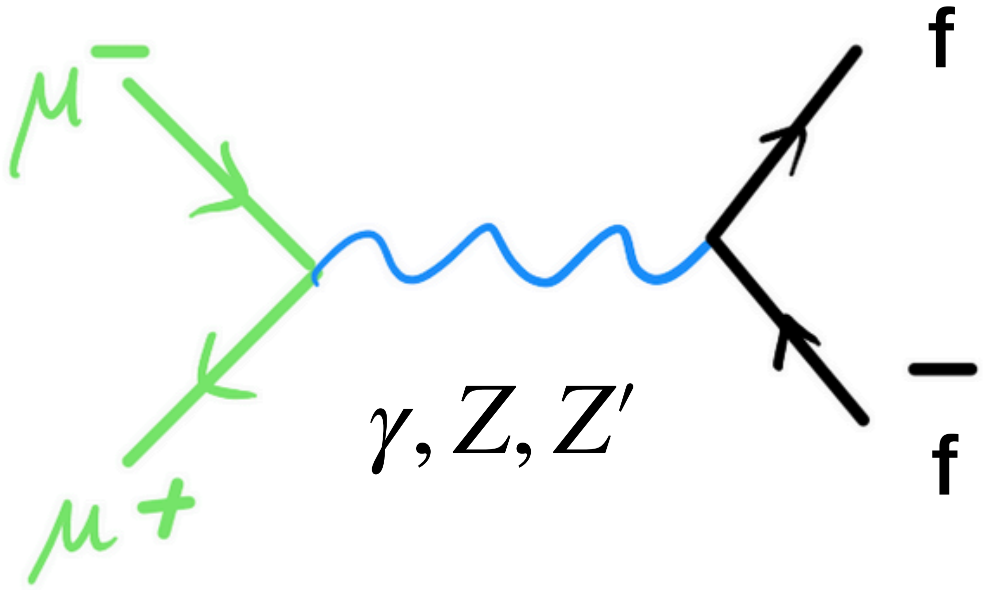
Matching Higgs precision:

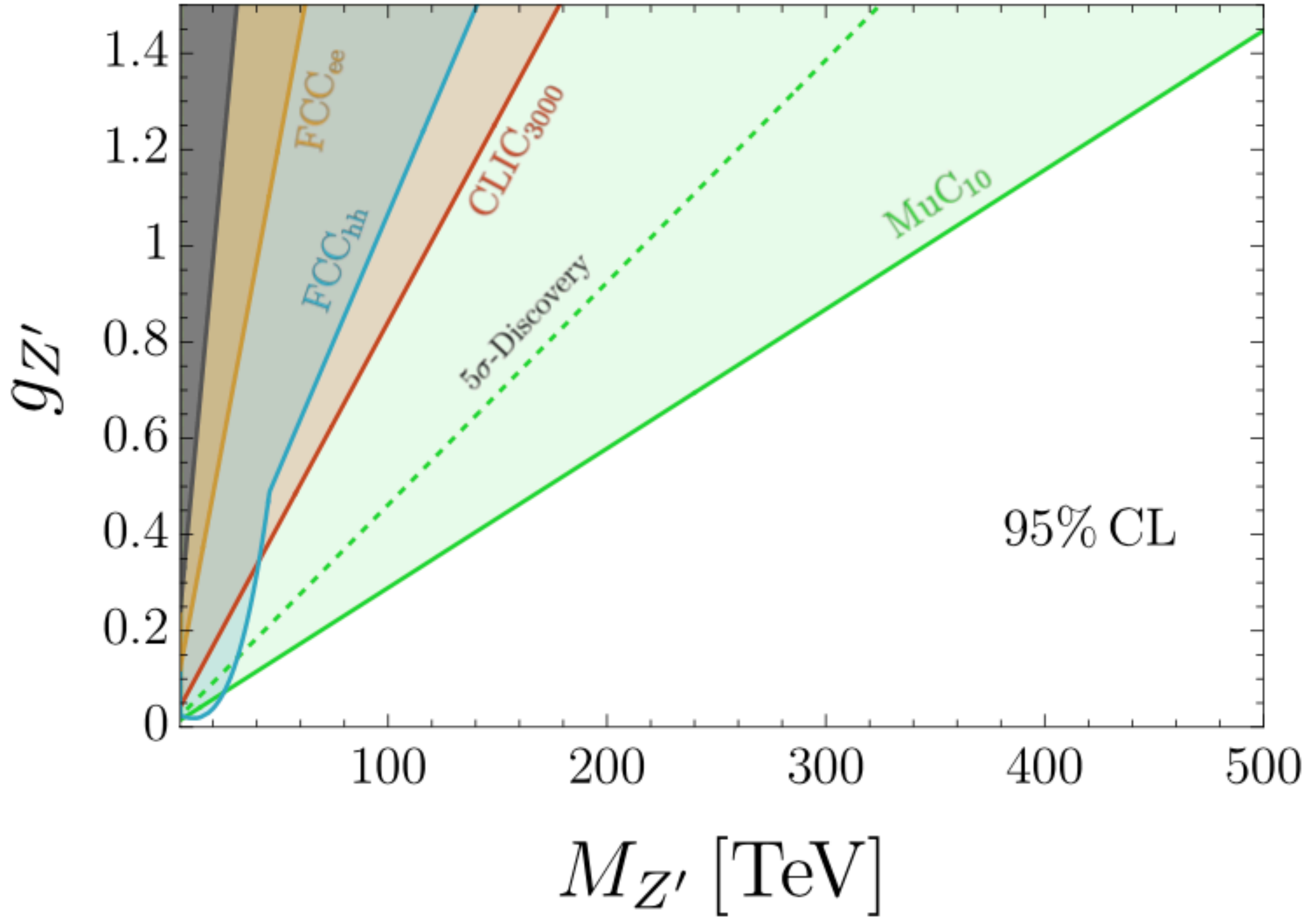
$$\delta\kappa_g=\frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2}+\frac{m_t^2}{m_{\tilde{t}_2}^2}-\frac{m_t^2X_t^2}{m_{\tilde{t}_1}^2\,m_{\tilde{t}_2}^2}\right)$$

$$m_{\tilde{t}}\gtrsim 1.5\,\mathrm{TeV}\sqrt{\frac{0.67\%}{\delta\kappa_g^{\rm max}}}.$$

Precision from energy

BSM interpretation: Z'





Muon collider reach on a new neutral current interaction mediated by a heavy Z′ gauge boson coupled to the SM Hypercharge. The 10 TeV MuC mass reach for discovery is around 100 TeV for a coupling of the order of the SM EW gauge couplings. The mass reach for exclusion extends far higher, up to 500 TeV for the maximal value of the gZ′ coupling, gZ′ ≃ 1.5, allowed by perturbativity.

[2504.21417 The Muon Collider]

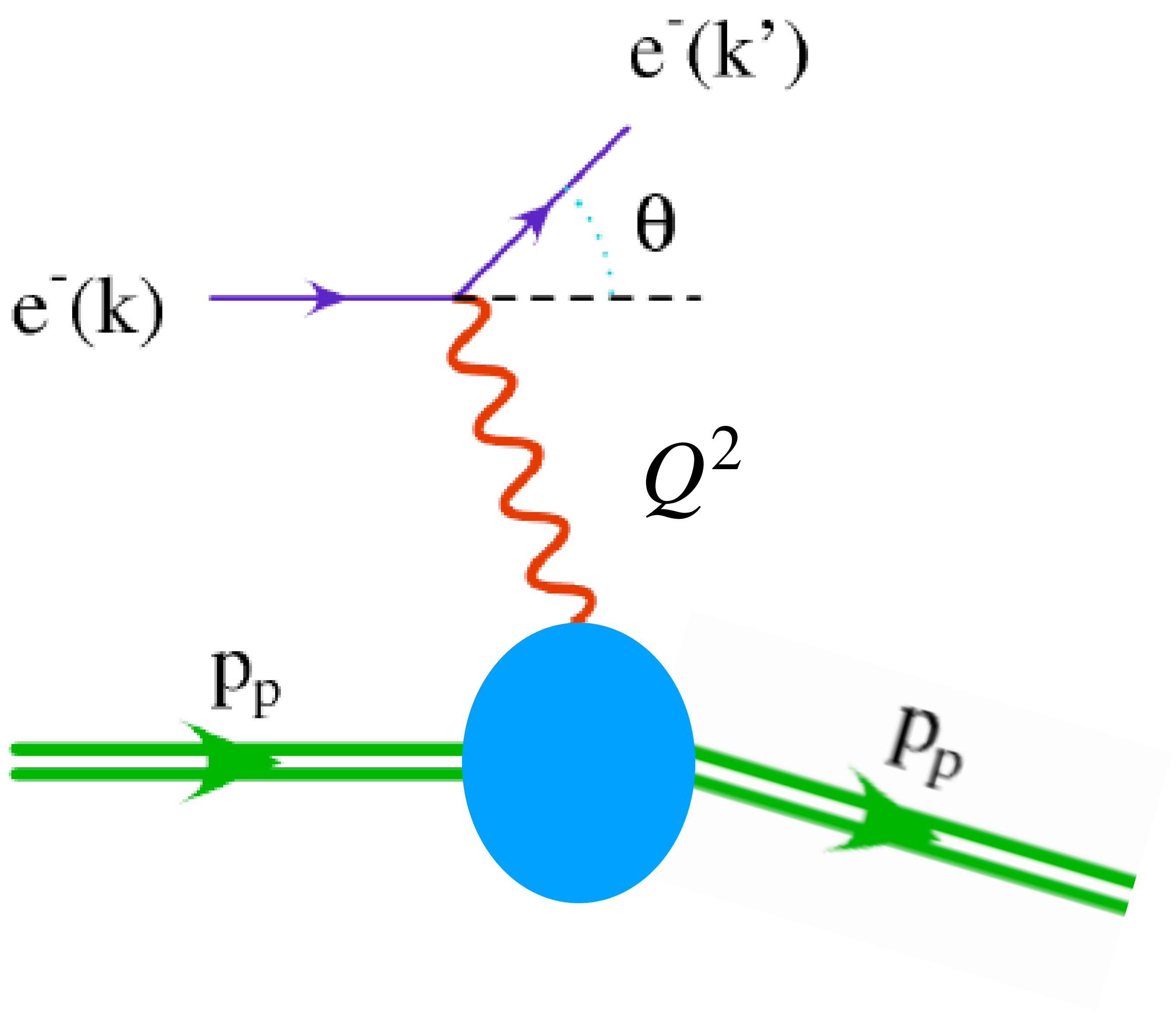
Precision from energy

BSM interpretation: Higgs compositeness

Precision from energy

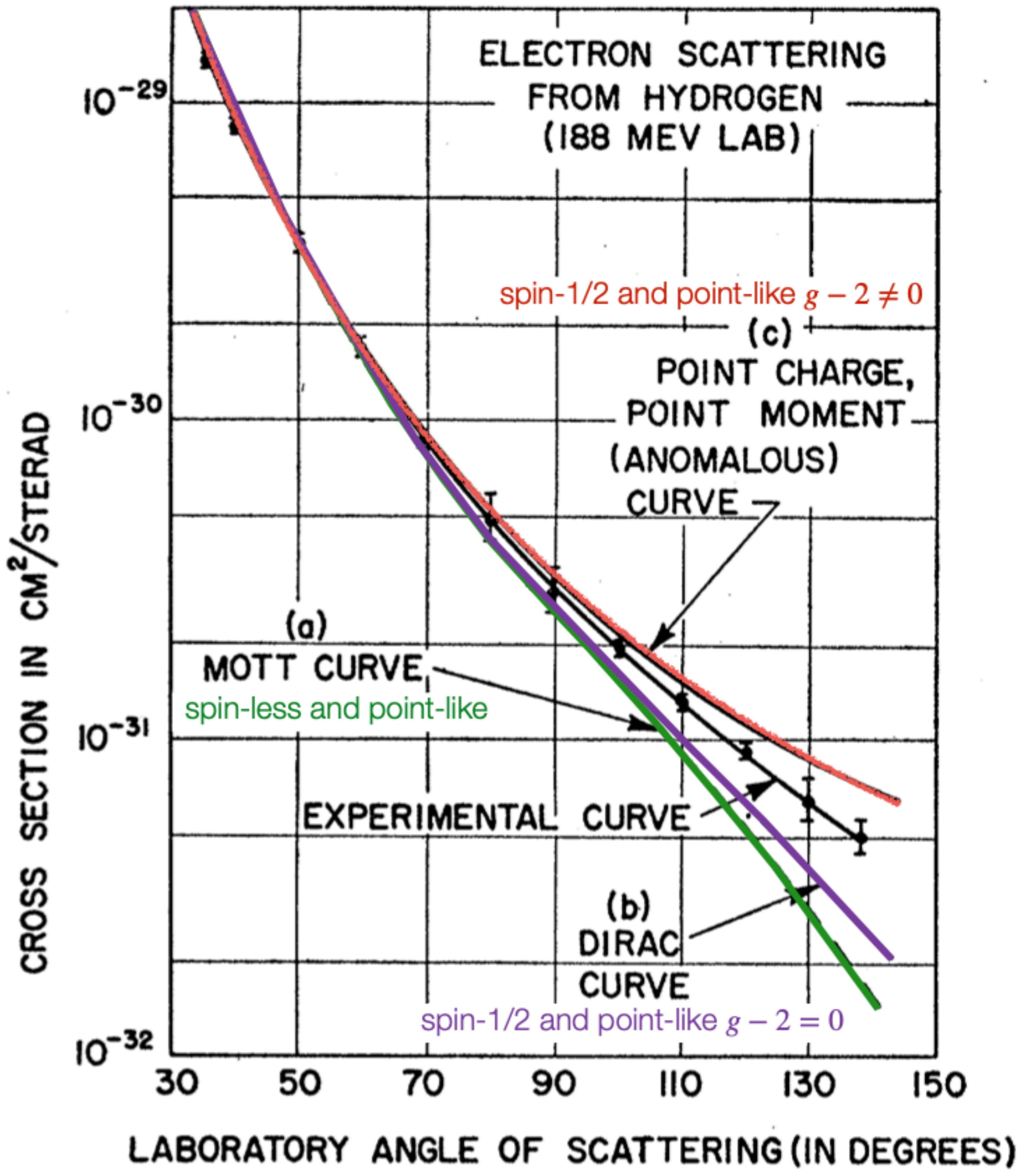
BSM interpretation: Higgs compositeness

Remember the 1961 Nobel Prize:
internal structure of the proton



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

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



[2504.21417 The Muon Collider]

Precision from energy

BSM interpretation: Higgs compositeness

[2504.21417 The Muon Collider]

Precision from energy

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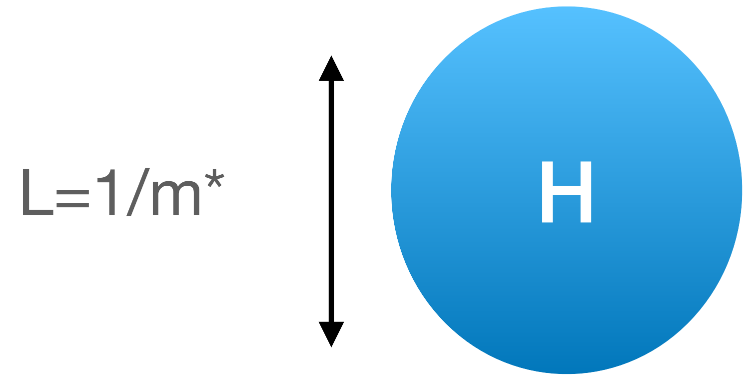
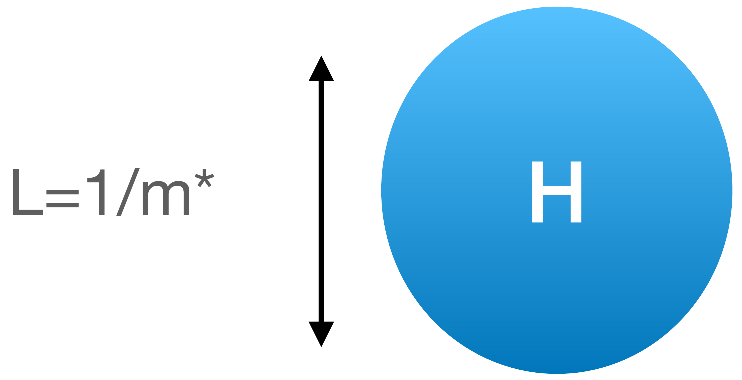
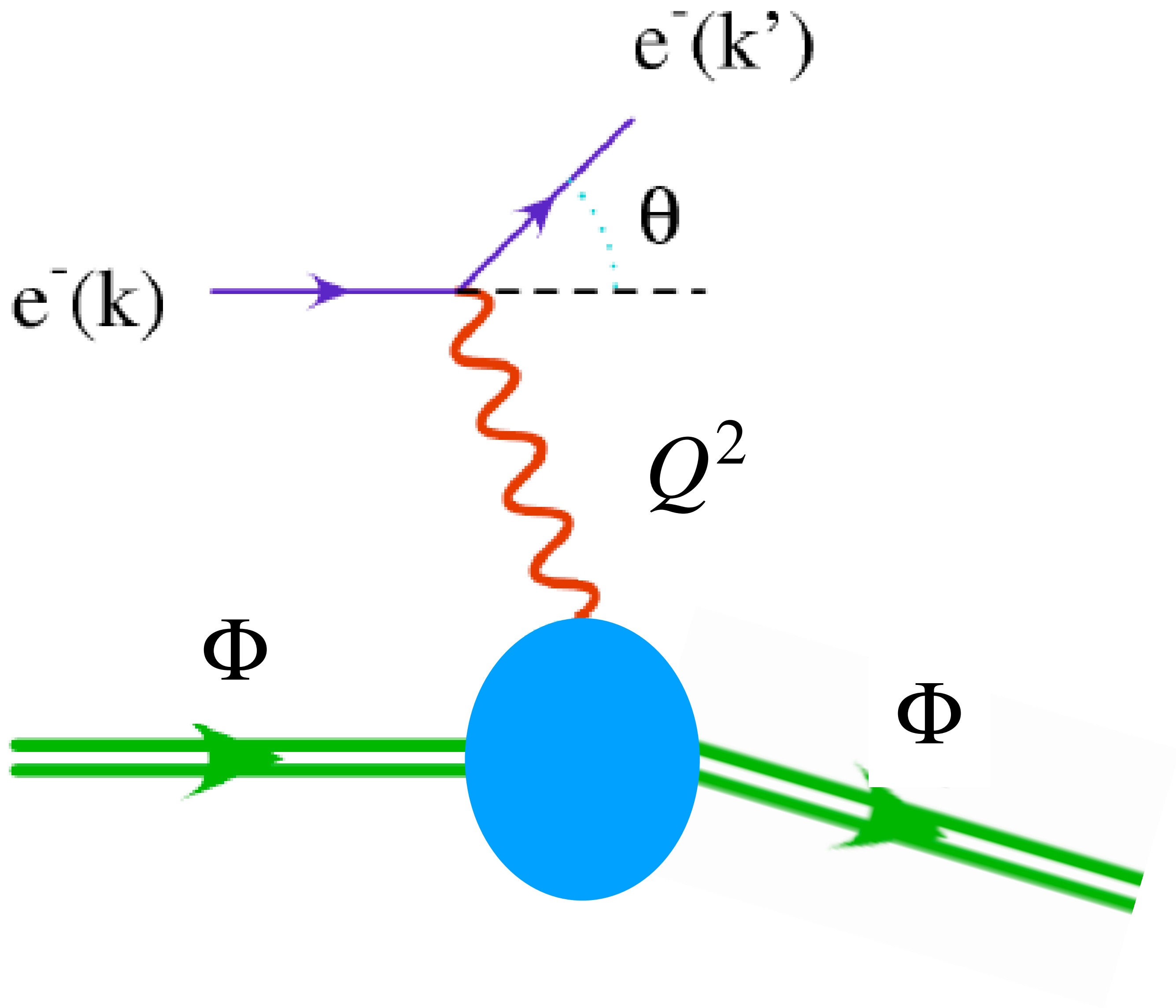


[2504.21417 The Muon Collider]

Precision from energy
BSM interpretation: Higgs compositeness



What is the equivalent for the Higgs?



[2504.21417 The Muon Collider]

Precision from energy

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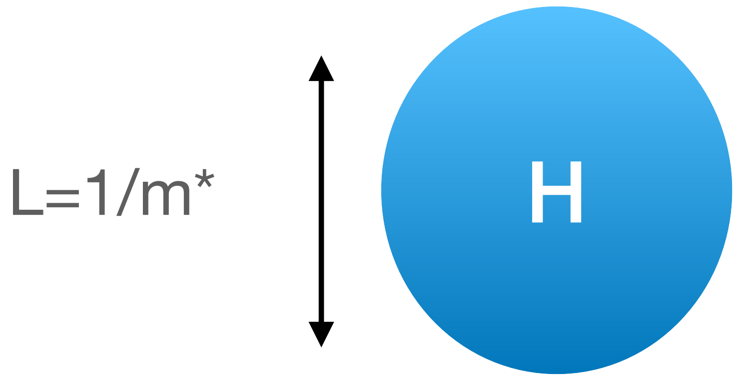

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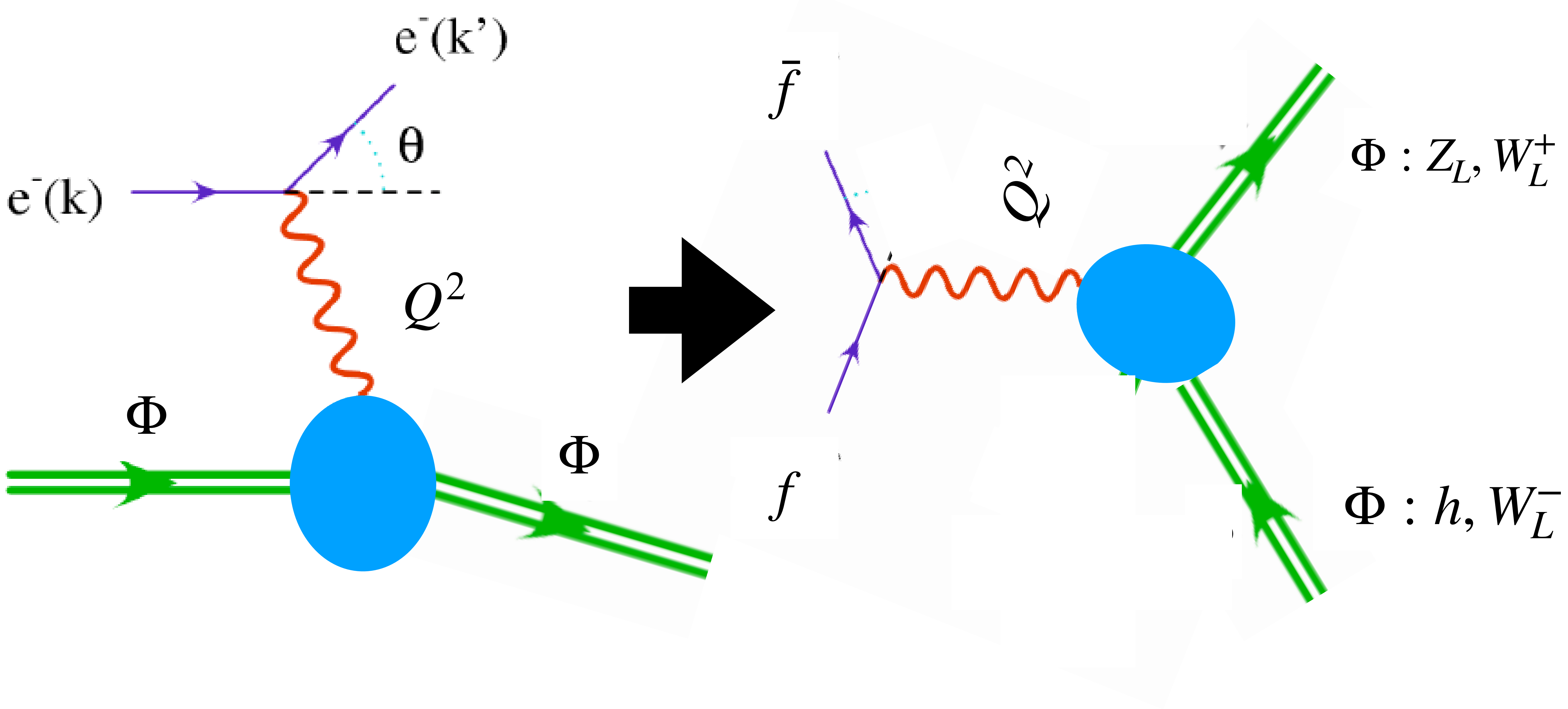
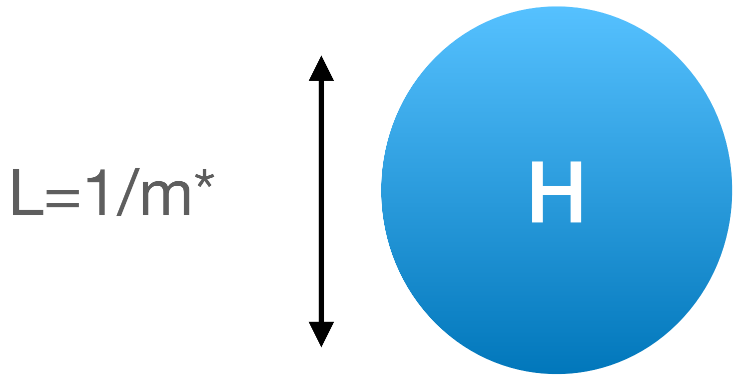


[2504.21417 The Muon Collider]

Precision from energy

BSM interpretation: Higgs compositeness



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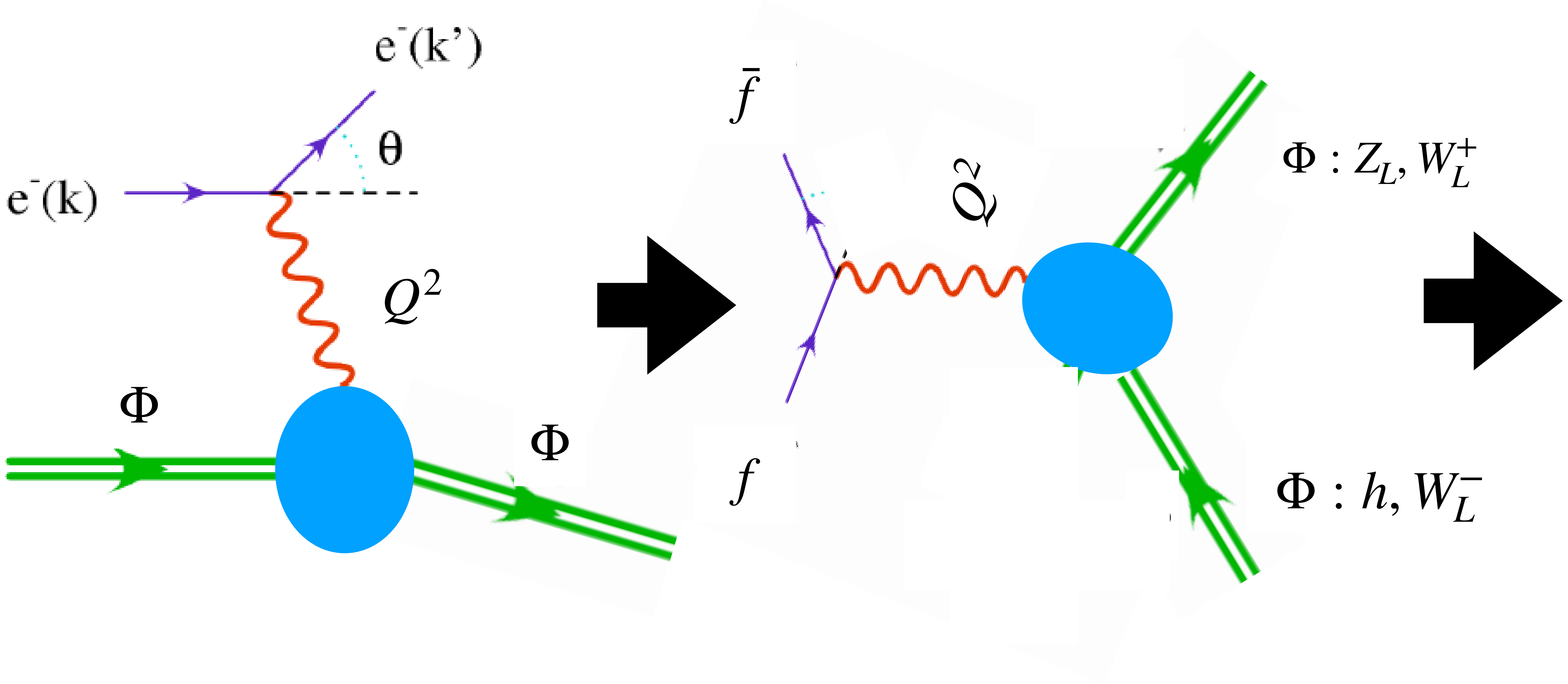
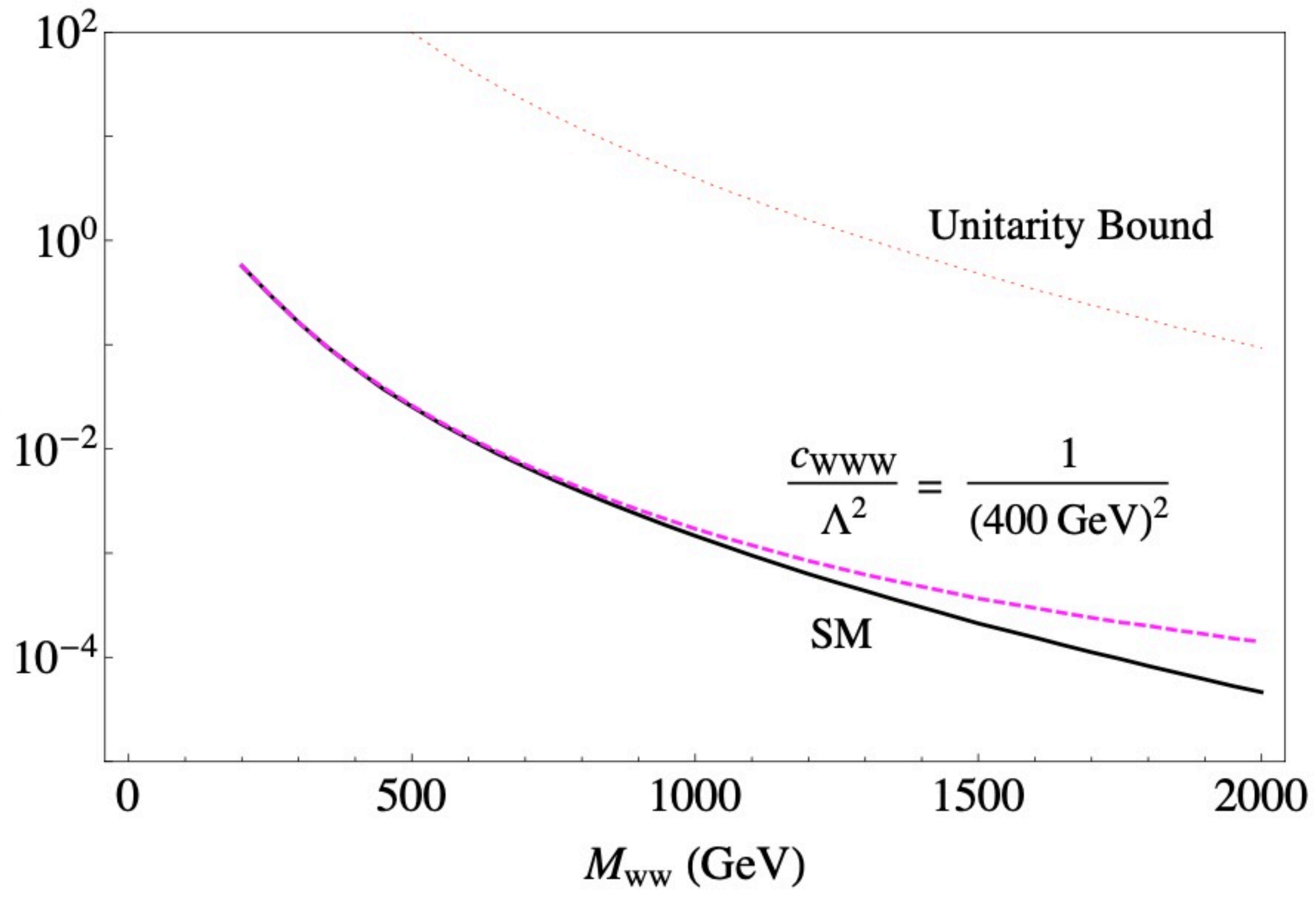
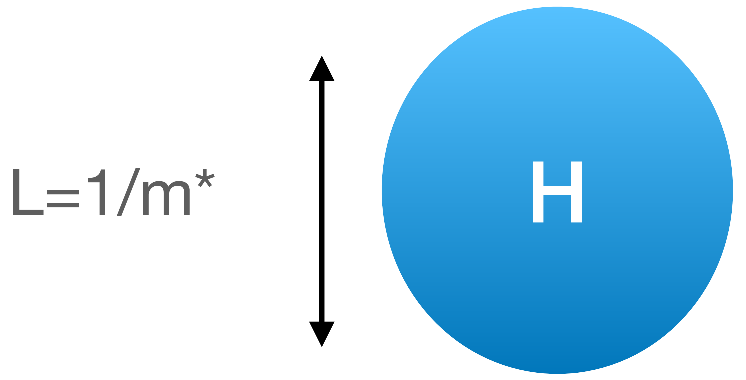




$$\frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

Precision from energy

BSM interpretation: Higgs compositeness



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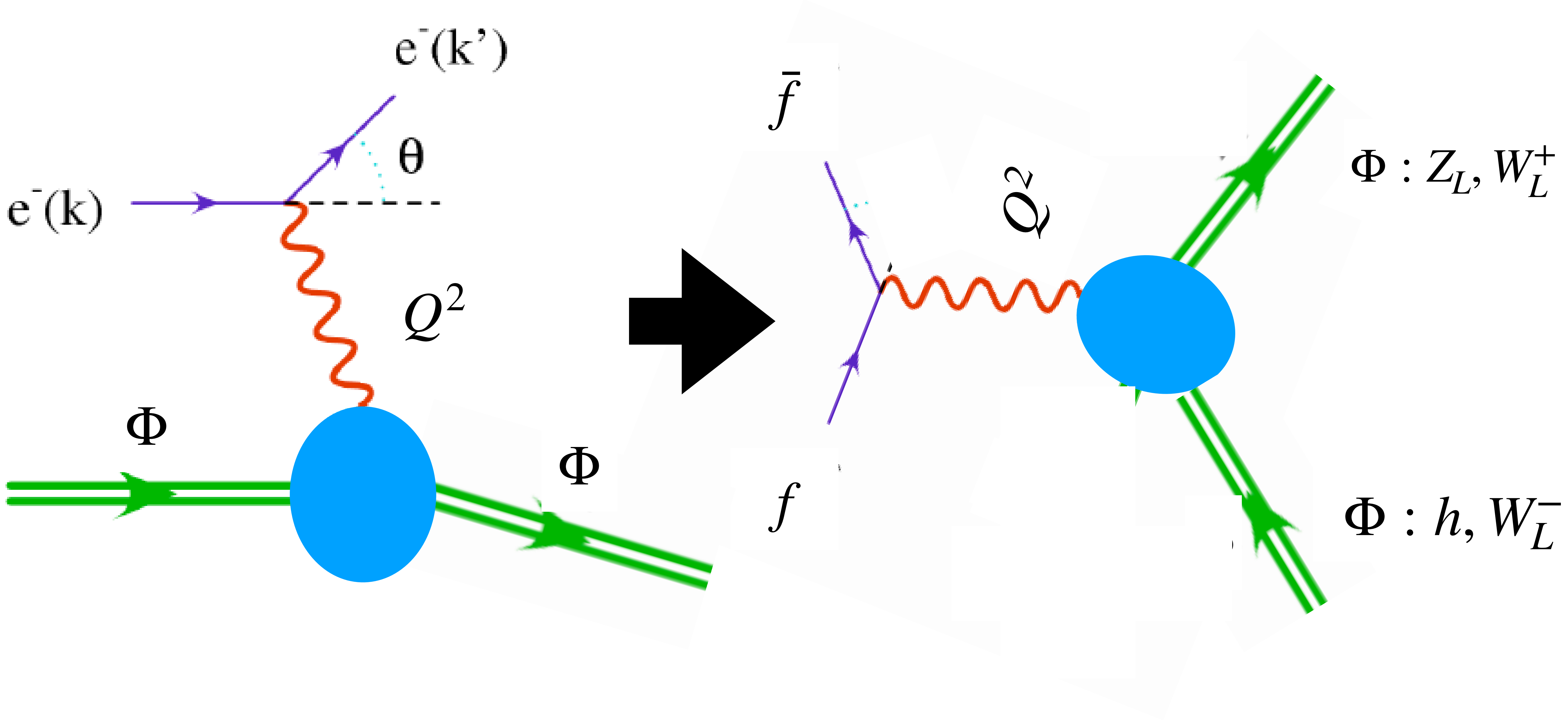
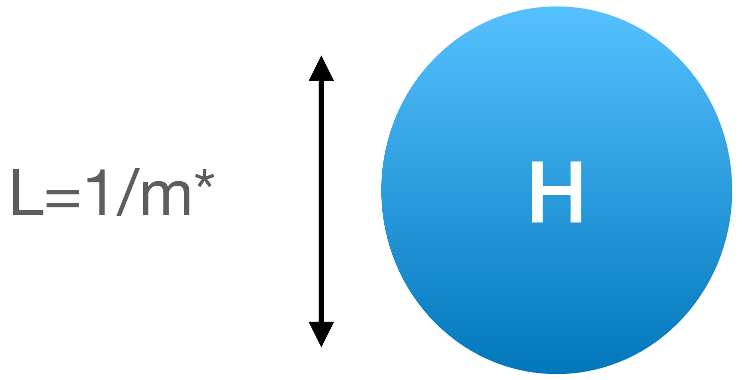
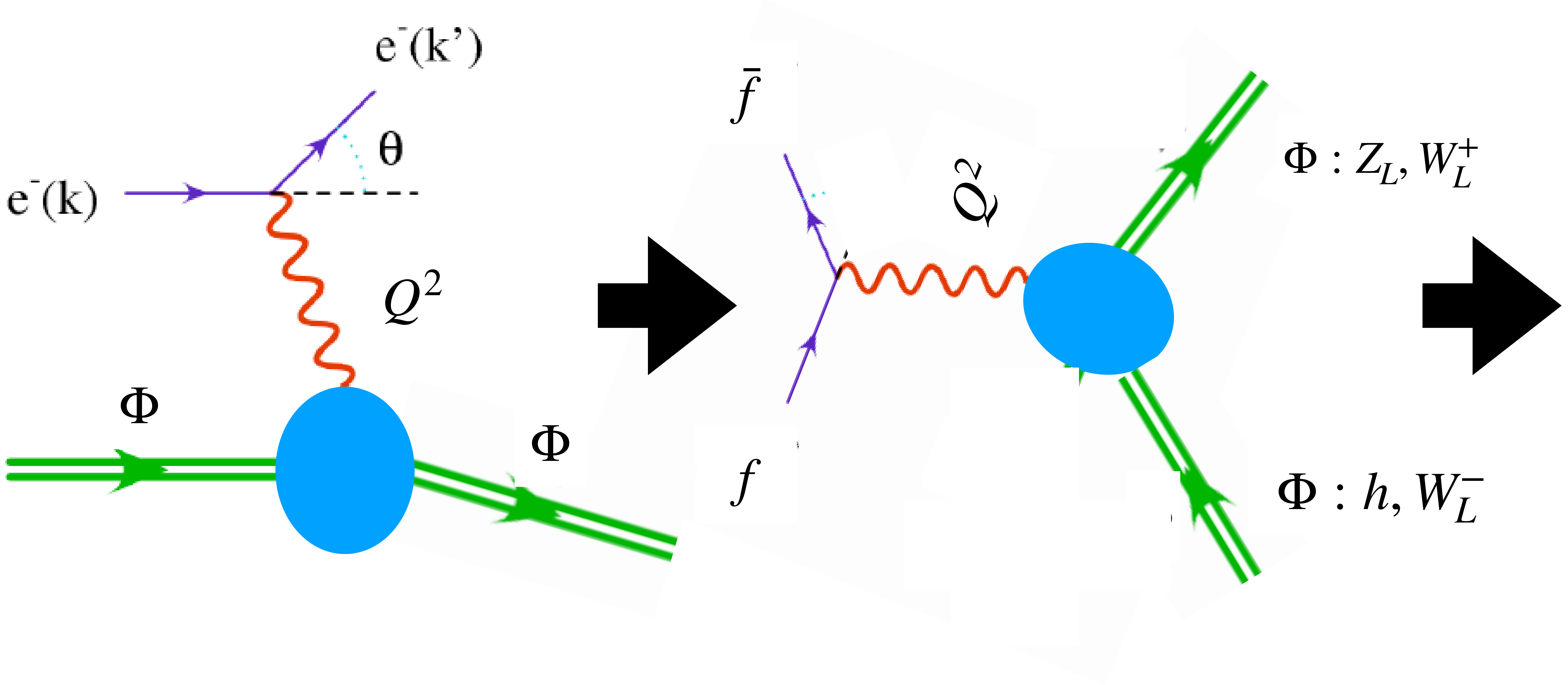
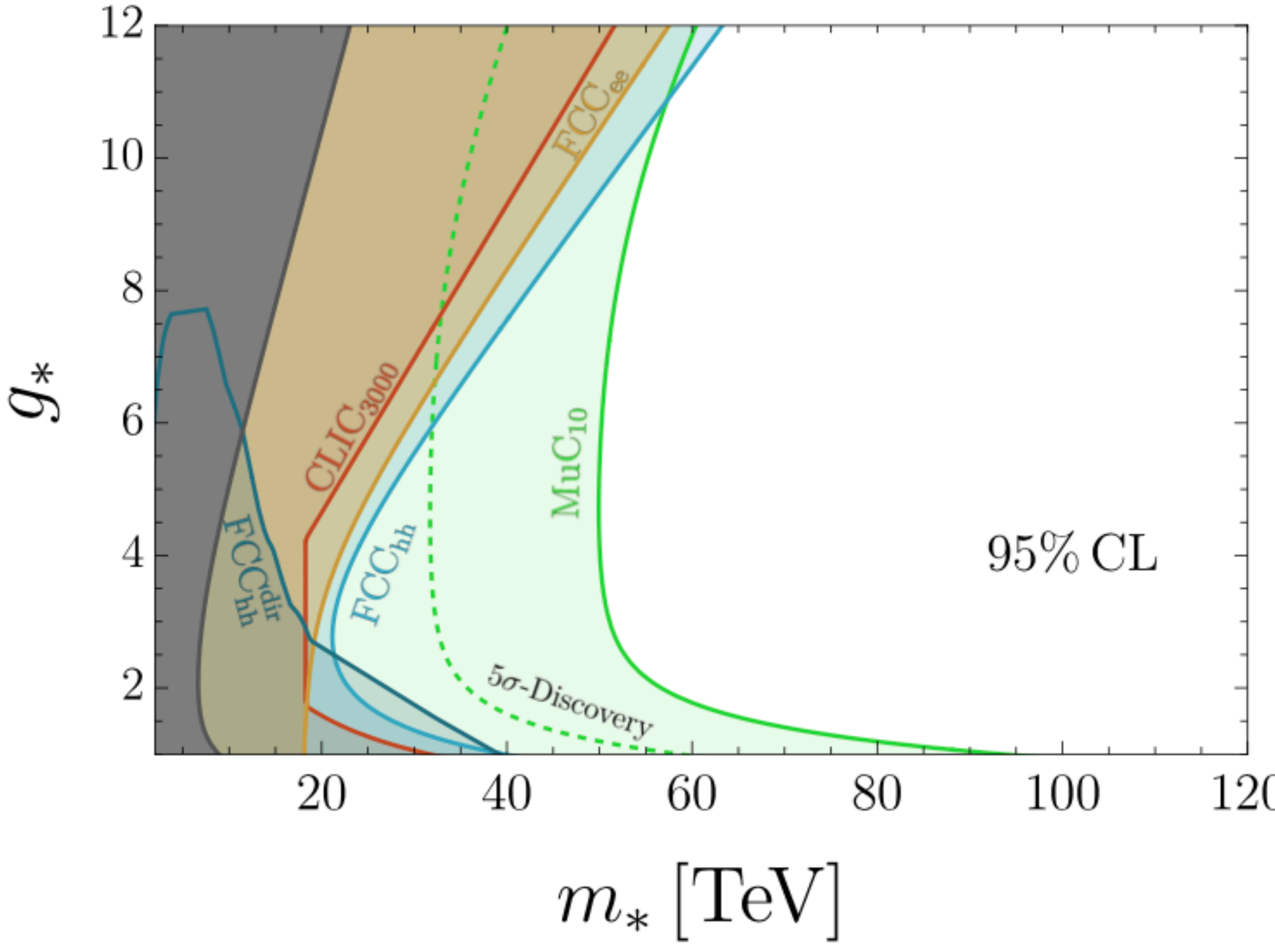


Precision from energy
BSM interpretation: Higgs compositeness



What is the equivalent for the Higgs?



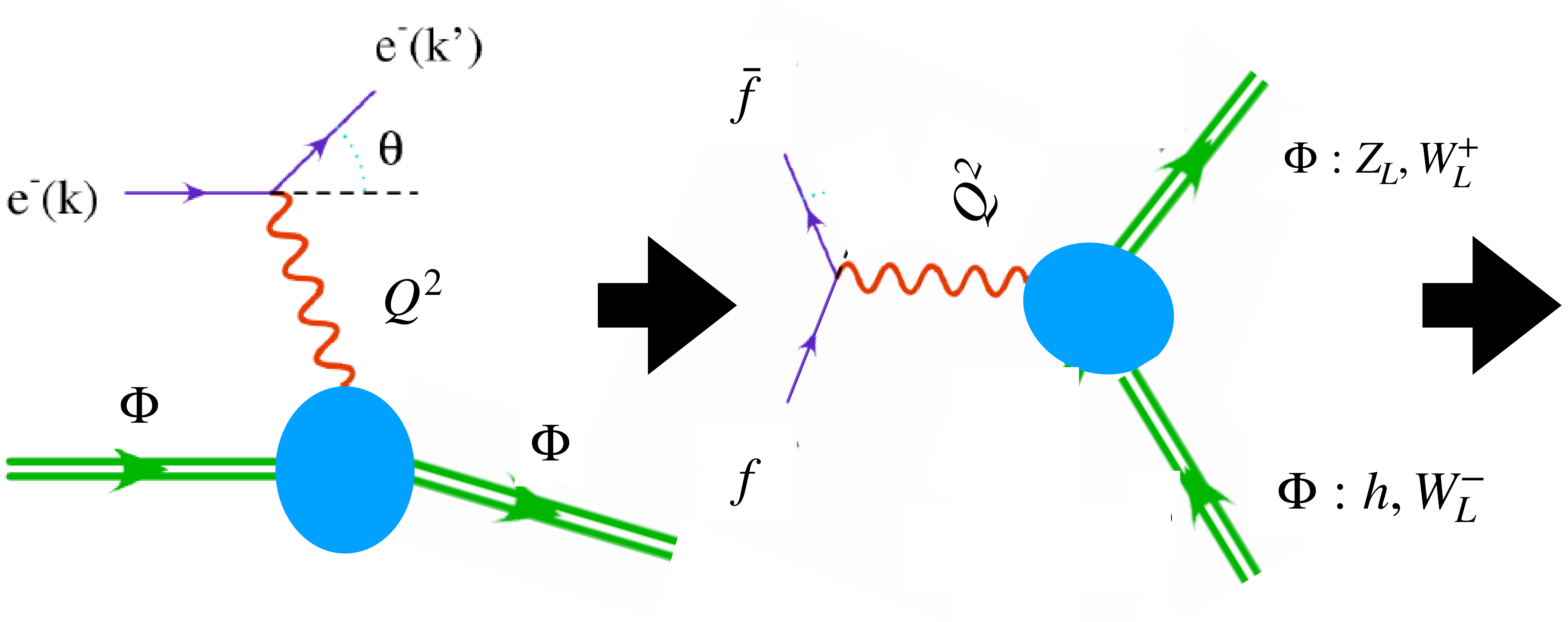


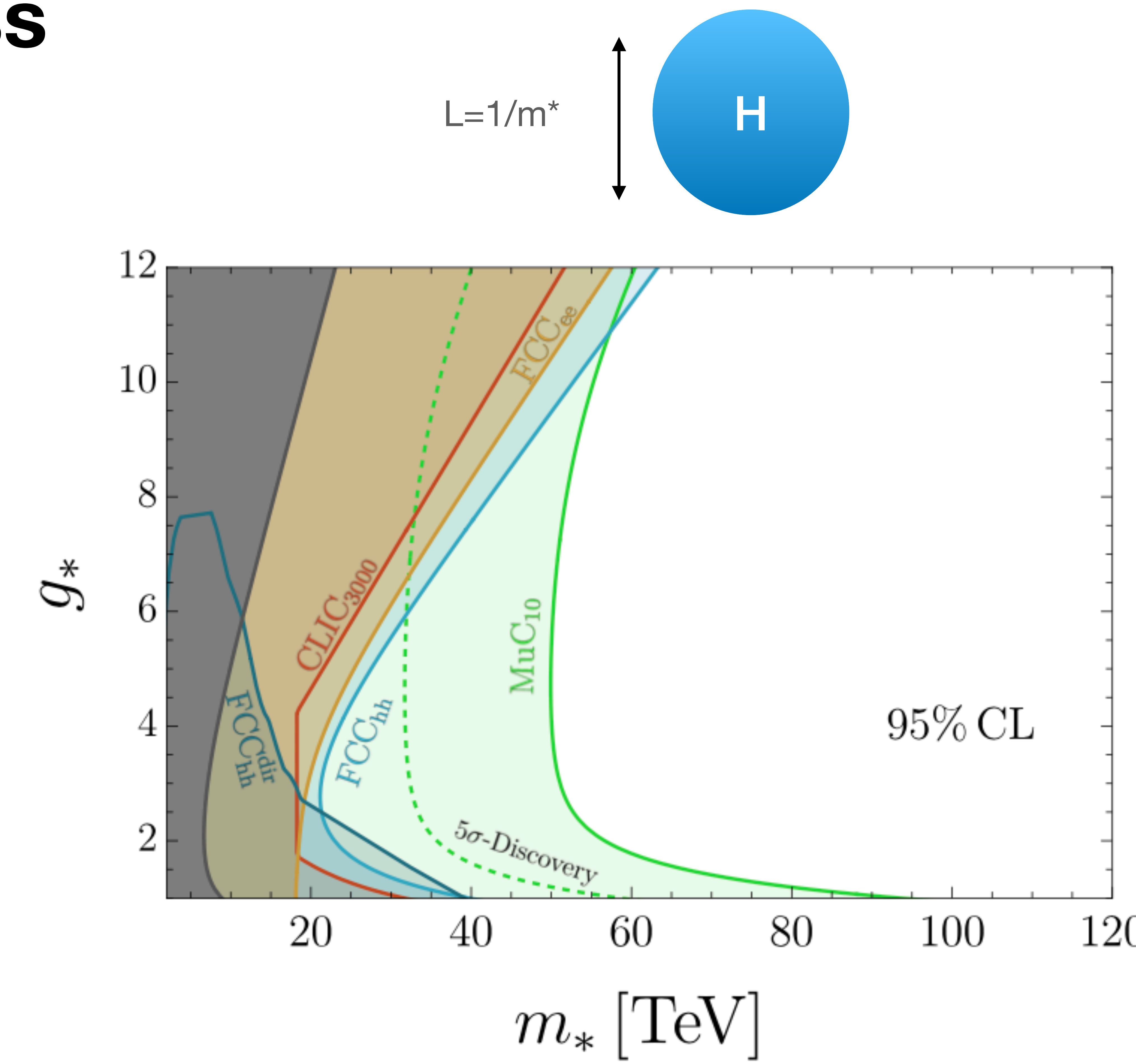
[2504.21417 The Muon Collider]

Precision from energy

BSM interpretation: Higgs compositeness

What is the equivalent for the Higgs?



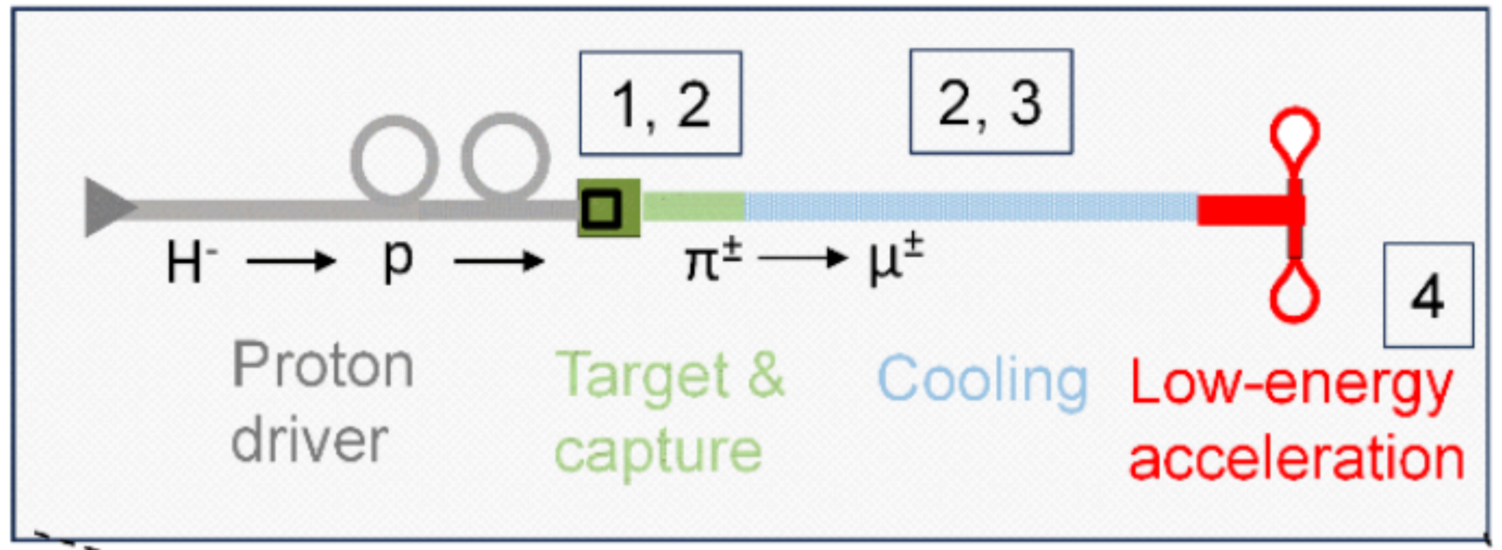


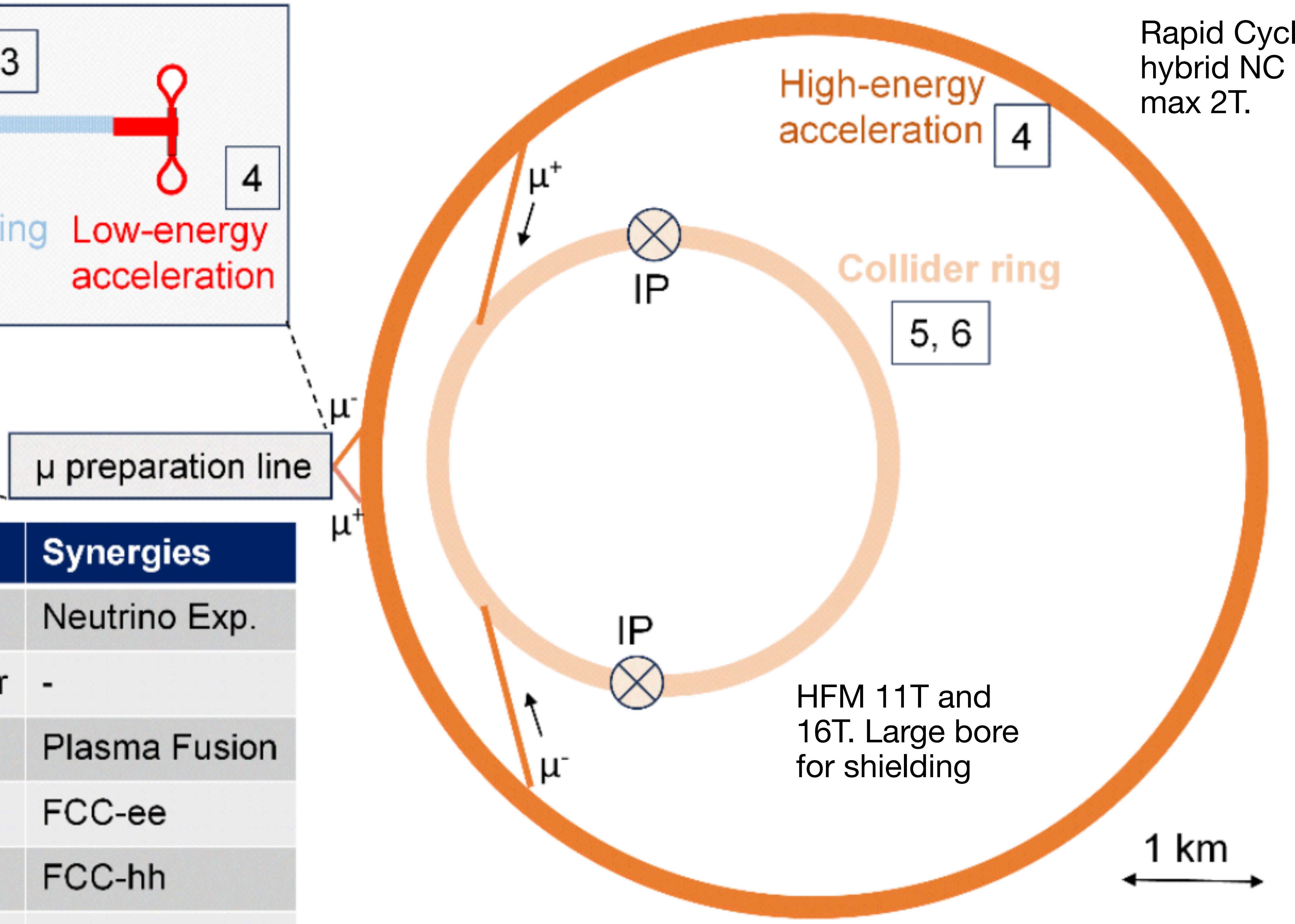
95% reach on the Composite Higgs scenario from high-energy measurements in di- boson and di-fermion final states. The green contour display the sensitivity from “Universal” effects related with the composite nature of the Higgs boson and not of the top quark.

[2504.10295 Stratakis]

Dream ⇔ reality ?

The key accelerator challenges

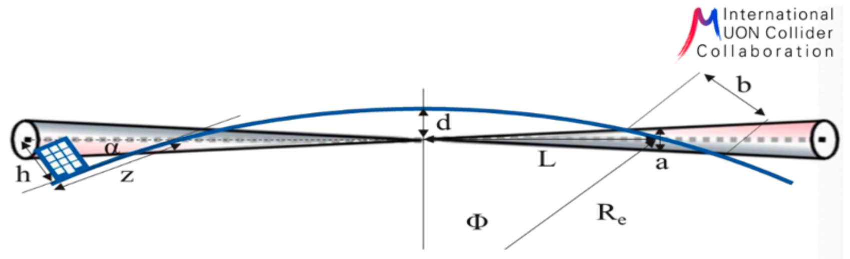


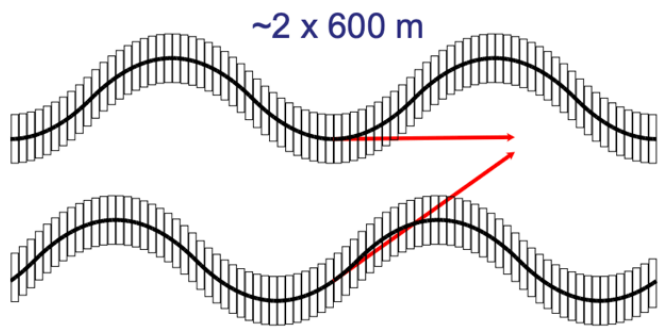


Rapid Cyclic Syncrotron : hybrid NC and SC magnets max 2T.

HFM 11T and 16T. Large bore for shielding

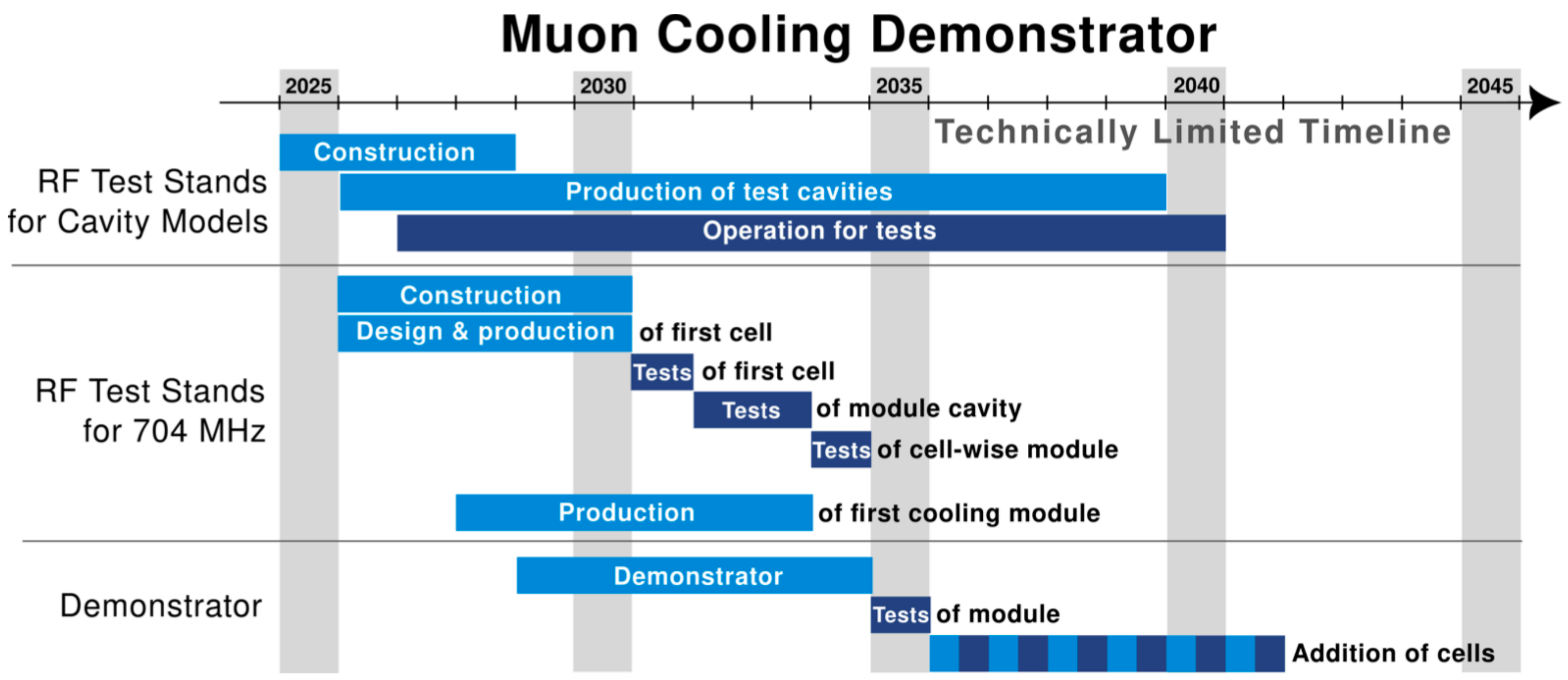
Area	Challenge	Approach	Synergies
1	High-Power Targetry	R&D	Neutrino Exp.
2	Cooling Technology	Demonstrator	-
3	High-Field Solenoids	R&D	Plasma Fusion
4	High-Gradient SRF	Prototyping	FCC-ee
5	High-Field Dipoles	R&D	FCC-hh
6	Neutrino Mitigation	R&D	-

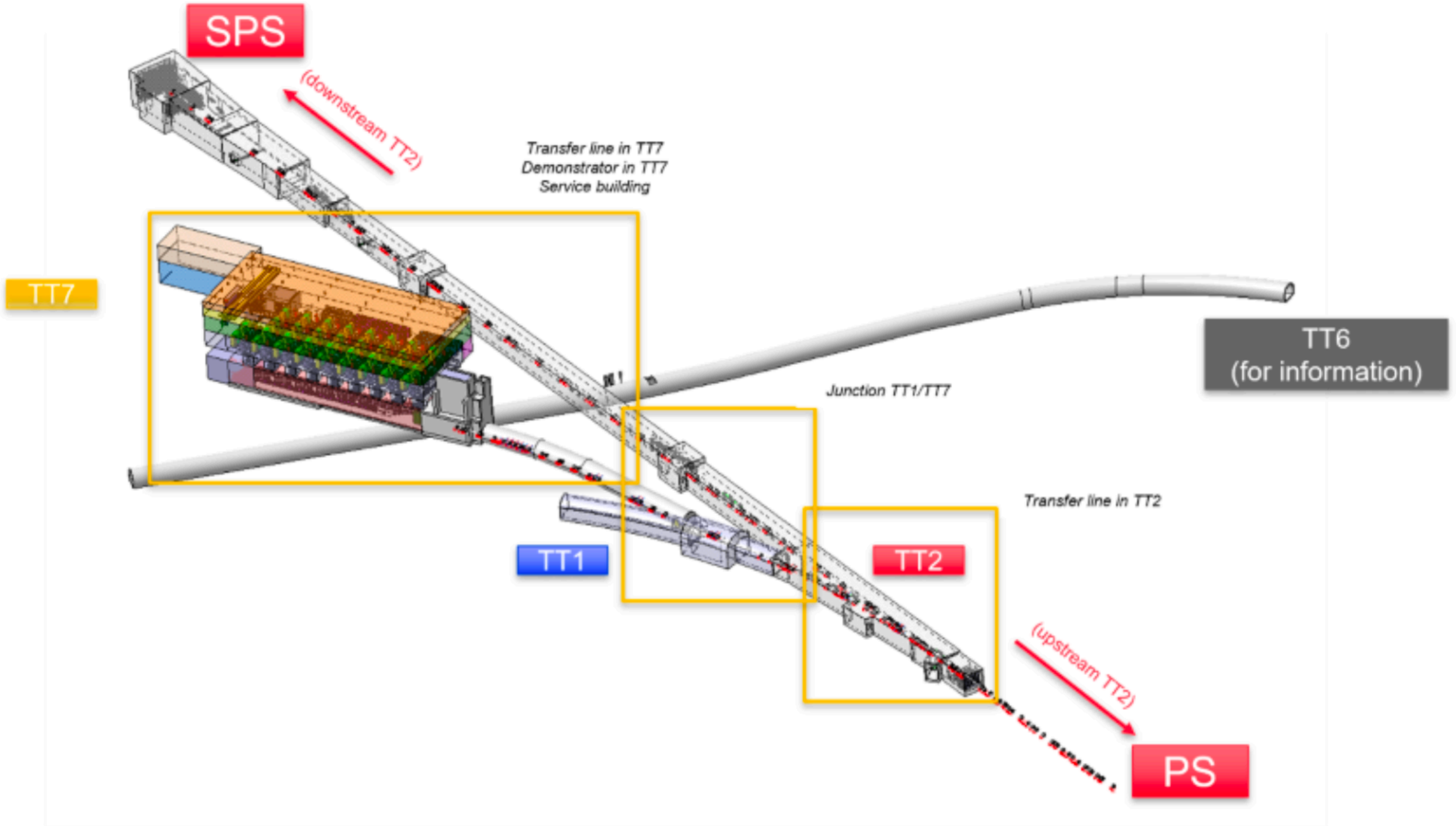




Dream ⇔ reality ?

Demonstrator at CERN





Year	I	II	III	IV	V	VI	VII	VIII	IX	X
One-Cell Module										
Staff	4	4.50	7	7	5.5	4.5	0	0	0	0
Post doc	5	6	5	5	5	4	0	0	0	0
Student	1	1	1	0	0	0	0	0	0	0
Material (kCHF)	600	2250	3900	4800	4350	700	0	0	0	0
Multi-Cell Module										
Staff	0	0	0	5.5	5.5	6	7	7	7.5	7
Post doc	0	0	0	3	4	4	5	6	6	6
Student	0	0	0	0	0	0	0	0	0	0
Material (kCHF)	0	0	0	300	1500	7200	11200	12700	9900	6300
TT7										
Staff	0	0	0	4.7	4.7	7	8.5	8.7	7.2	6.5
Post doc	0	0	0	4	5	5	5	6	6	6
Student	0	0	0	0	0	0	0	0	0	0
Material (kCHF)	0	0	0	300	2000	7200	14700	19700	21900	6300
TOTALS										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5

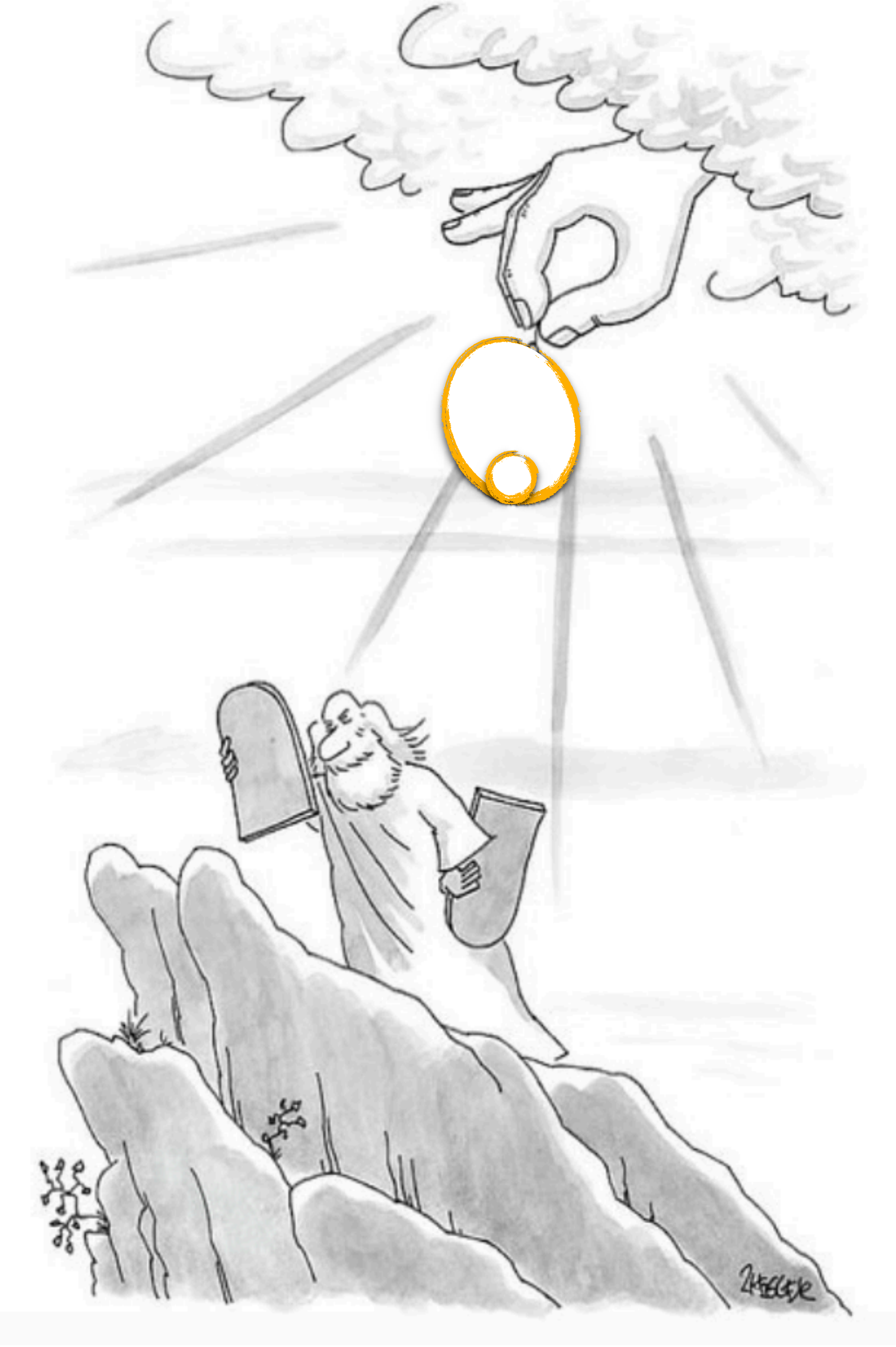
Three different sites have been considered for the implementation at CERN of a muon ionisation cooling demonstrator. They would all receive beam extracted from the PS as the optimal energy for muon production is in the range 5 – 20 GeV. A plan has been devised spanning 10 years.

Summary

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

- For the **future**, i.e. after 2050, we are evaluating the options. The most mature and feasible project for CERN is an e+e- “weak-scale factory” in a new 91 Km circular tunnel and then the pp option in the 70’s.

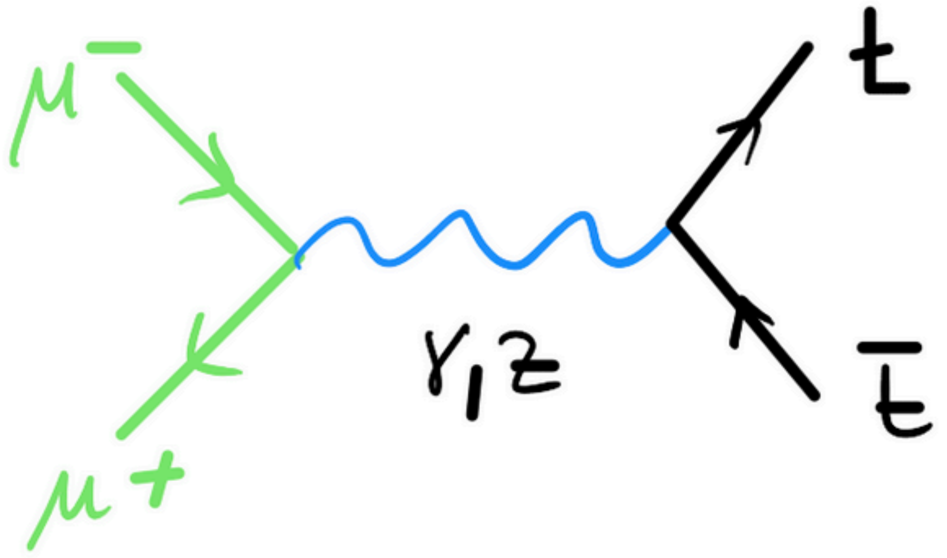
- A **futuristic** collider based on accelerating muons could open a new era in HEP experiments, with an exciting physics case. The technology needs to and should be demonstrated. An R&D plan is ready.



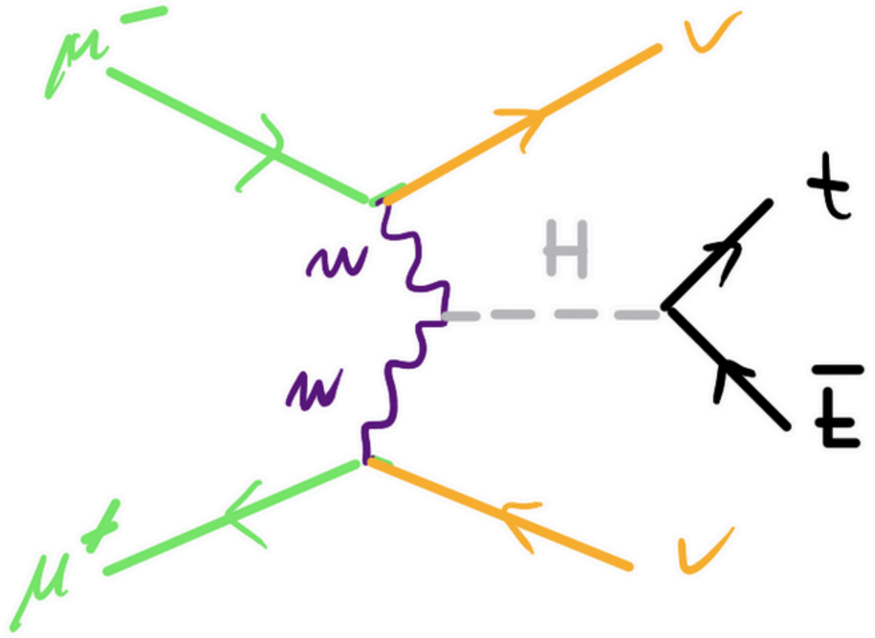
[Costantini et al. 2005.10289]

Precision from energy

SMEFT analysis

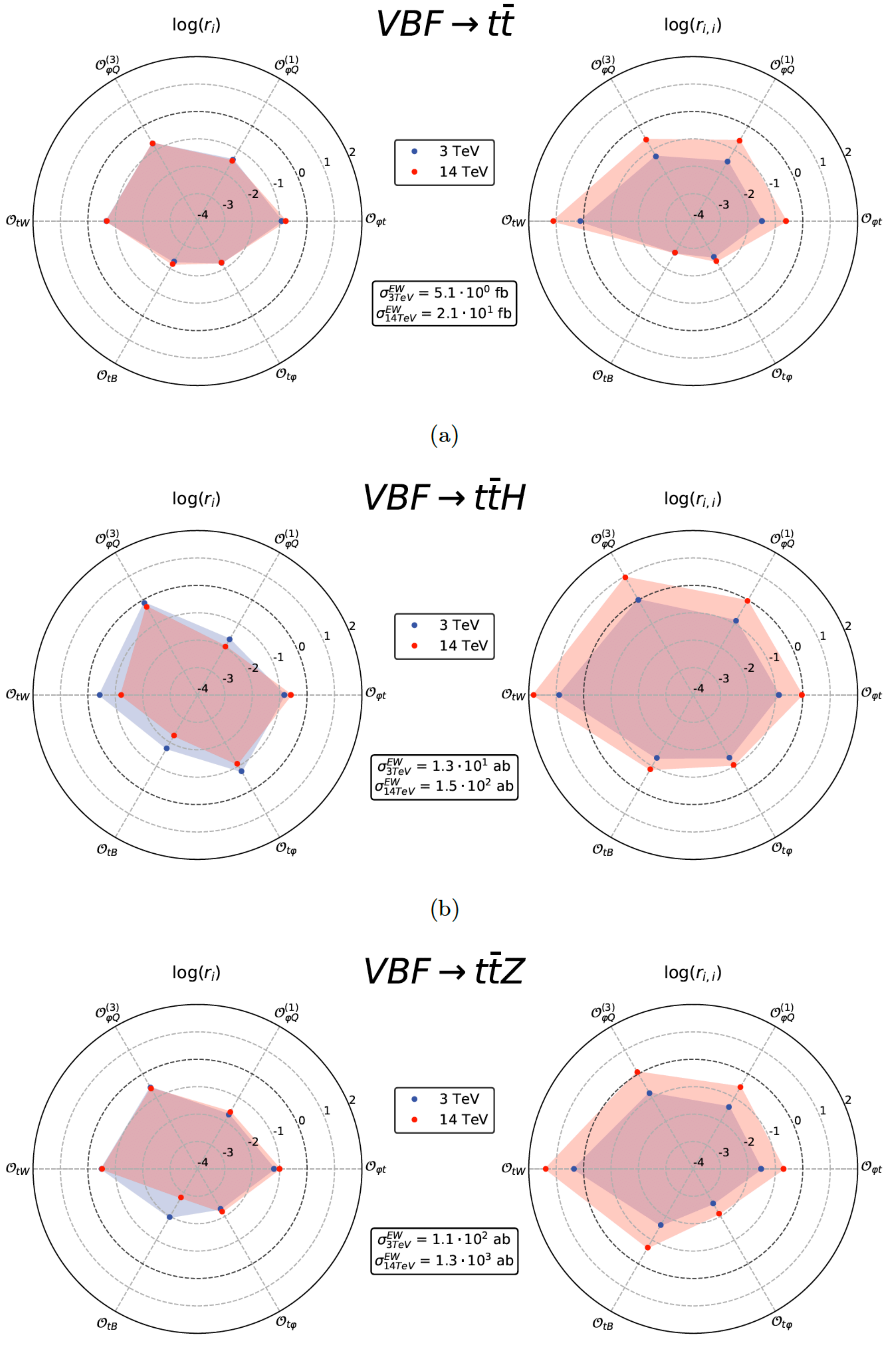


VS



Annihilation can probe $t\bar{t}\gamma, t\bar{t}Z$ couplings at very high energy with a large statistics.

However, VBF can access a much larger set of dim=6 operators with very interesting energy-growth behaviors (yet with lower statistics).

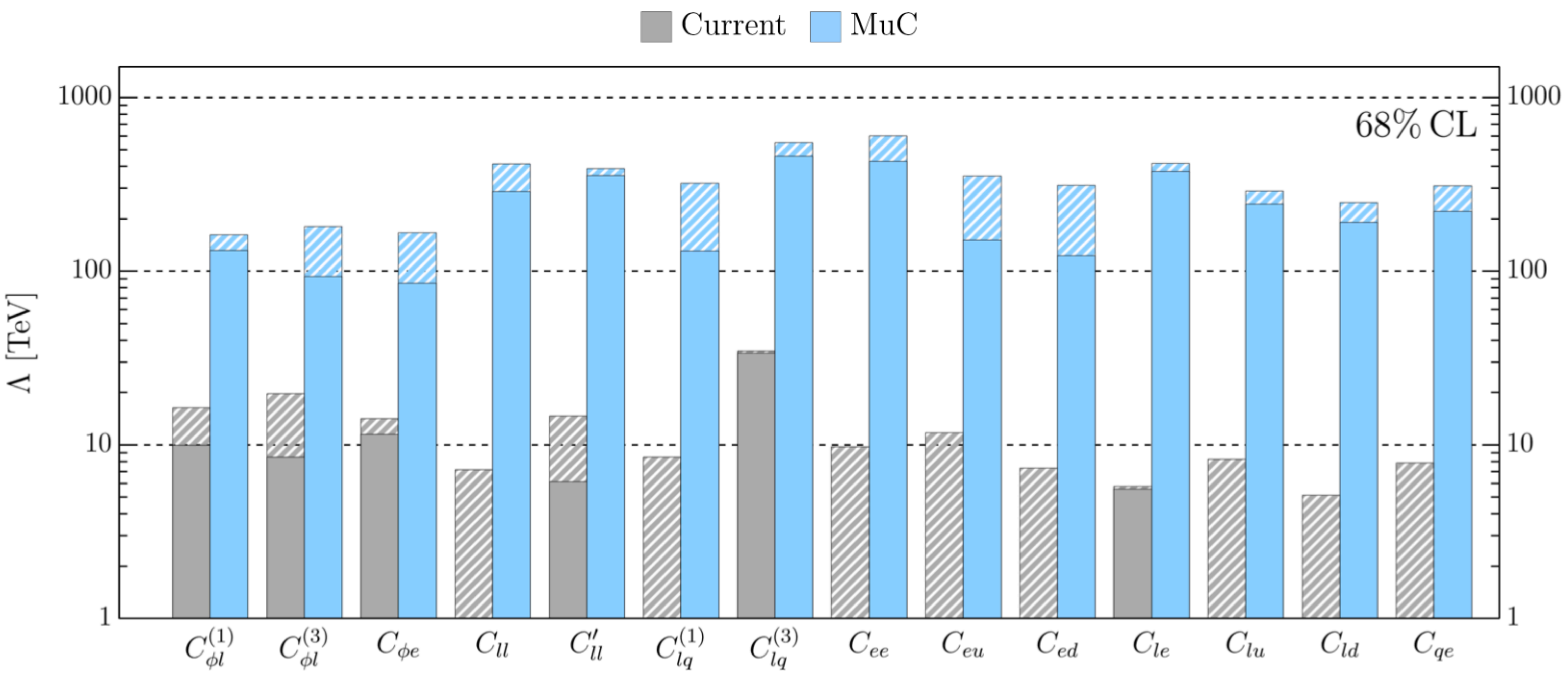


(a)
(b)
(c)

[2504.21417 The Muon Collider]

Precision from energy

SMEFT analysis

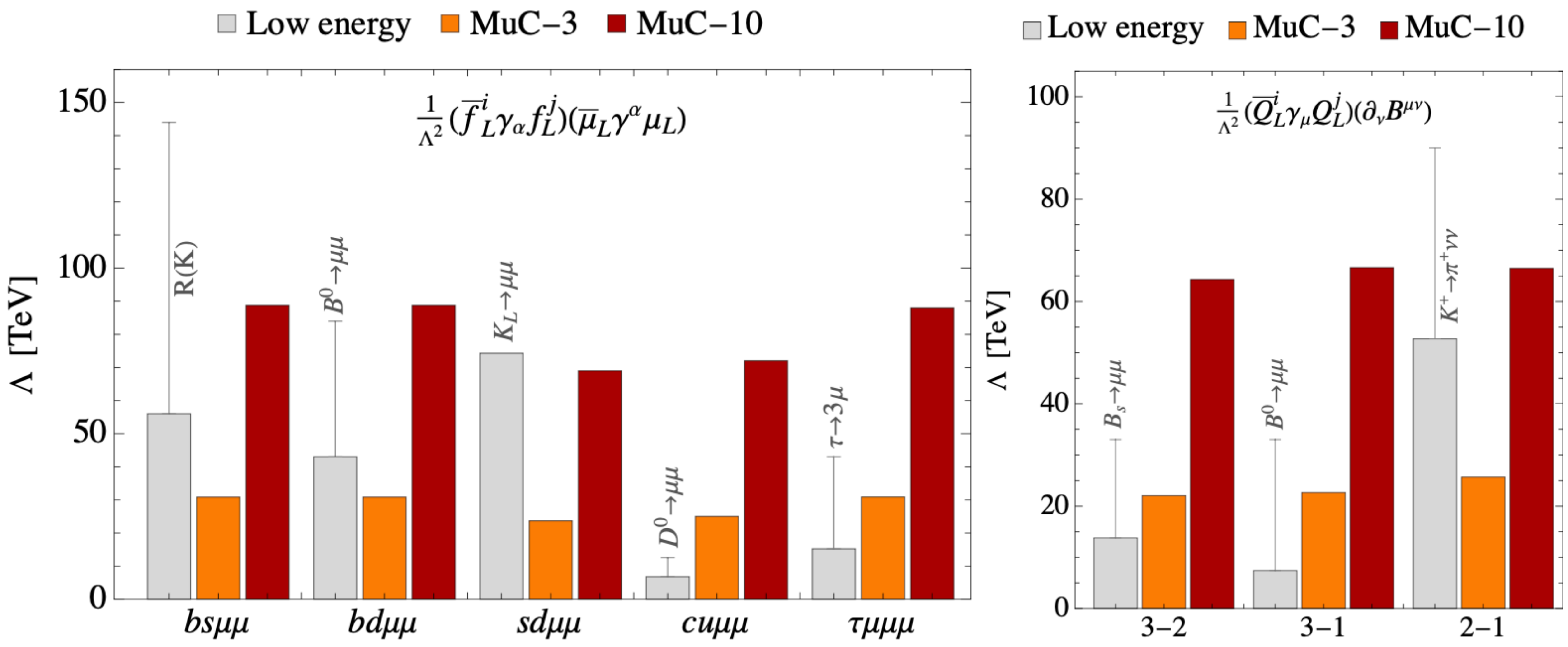


Fit to the CP-even flavour-blind Warsaw basis operators that grow with the energy and interfere with the SM in di-fermion and di-boson production at the MuC. The MuC projections (blue bars) from the measurements of these observables are compared with current knowledge (gray bars).

[2504.21417 The Muon Collider]

Precision from energy

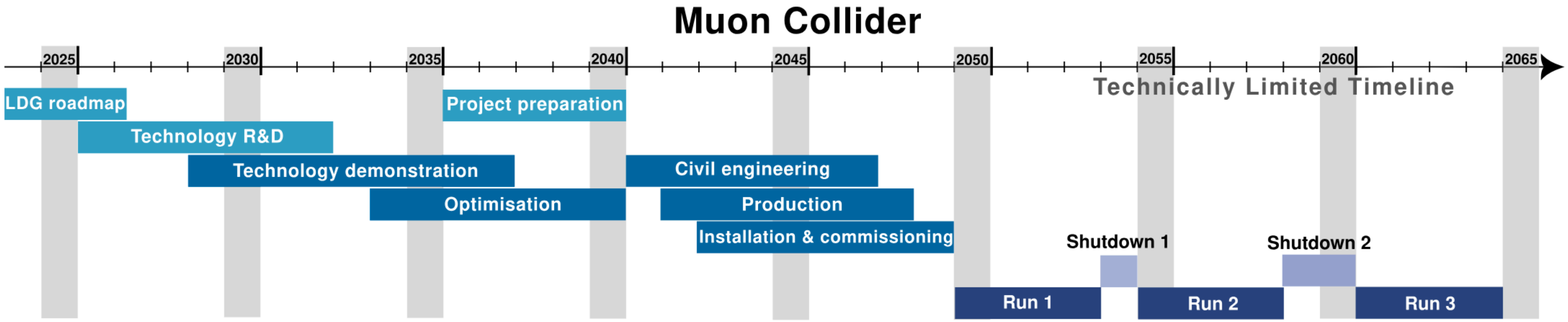
SMEFT: qqll operators



Sensitivity reach in the effective scale Λ [TeV] of effective operators containing a quark or lepton flavour-violating current, coupled to either a muon current (left panel) or a flavour-blind gauge current (right panel). The gray bands show the present constraints from meson and tau decays, while the gray lines are the expected future sensitivity at the end of LHCb upgrade II, Belle II, and NA62 runs.

Dream ⇔ reality ?

Path

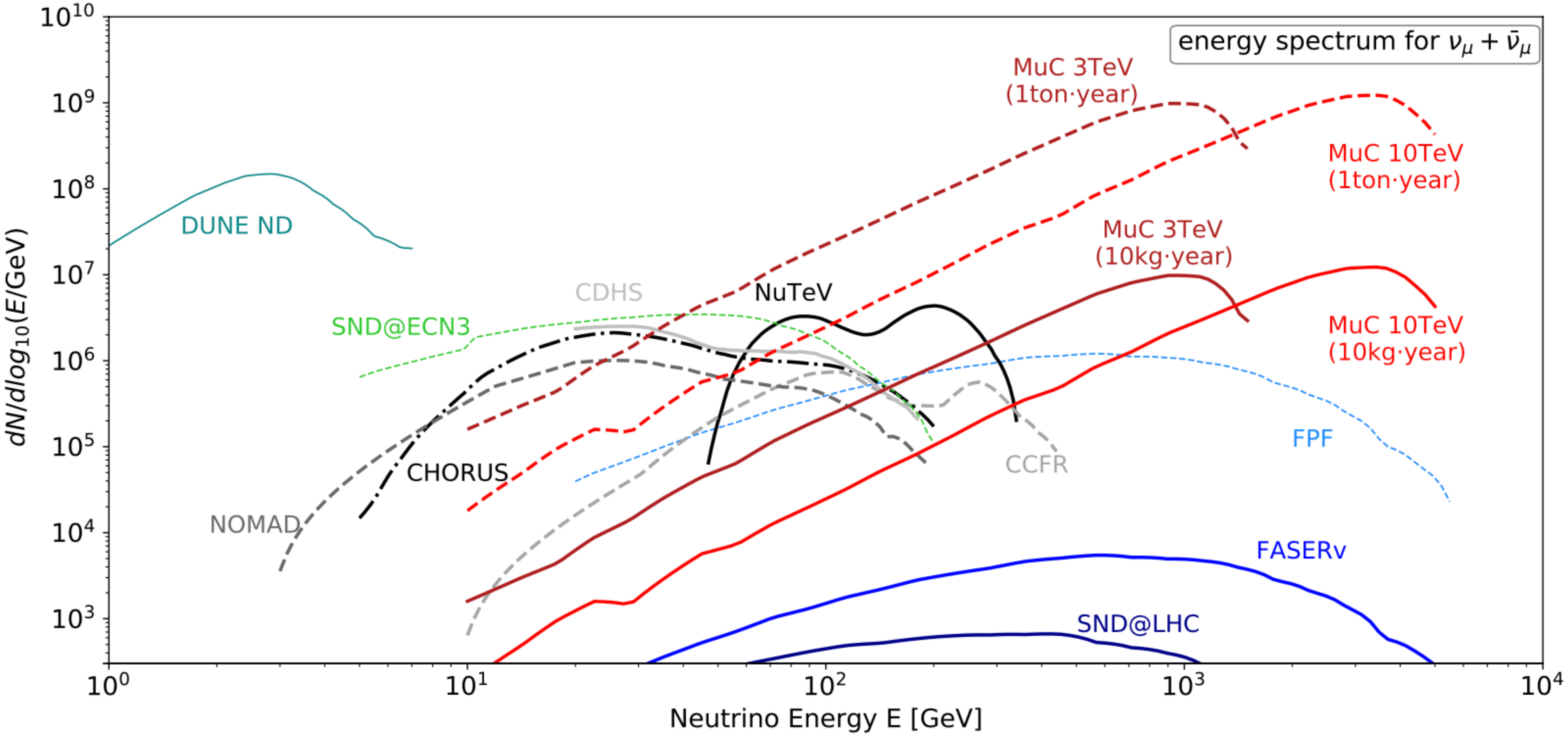


– The muon production and cooling technology and its demonstration in a test facility. At this moment it is expected that this development can be mature enough for a decision in 15 years provided sufficient funding is made available.

– The magnet technologies, in particular HTS superconductor technology. At this moment, it is expected that the different HTS solenoids for the muon production and cooling are available within 15 years; the same is expected for the fast-ramping magnets. For the collider ring, one can expect 11 T Nb3Sn magnets with an aperture of 16 cm to be mature. Higher performant HTS or hybrid collider ring magnets may take longer.

– The detector and its technologies that impact the efficiency of background suppression and the quality of the measurements. At this moment, it is expected this technology to be mature in 15 years.

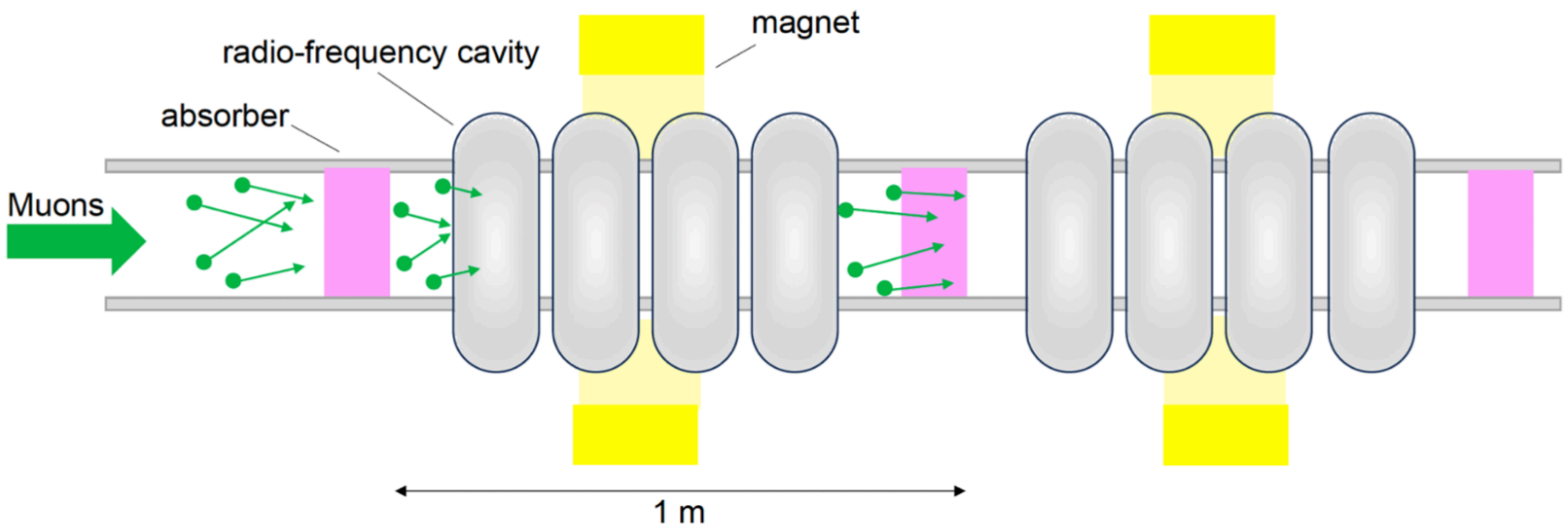
Neutrino physics



The energy spectrum of neutrino interactions produced by the 3 TeV and 10 TeV MuC in one year for past and planned neutrino experiments. The solid and dashed lines assume, respectively, a small 10 kg and a realistic 1 ton target mass.

Dream ⇔ reality ?

The key accelerator challenges



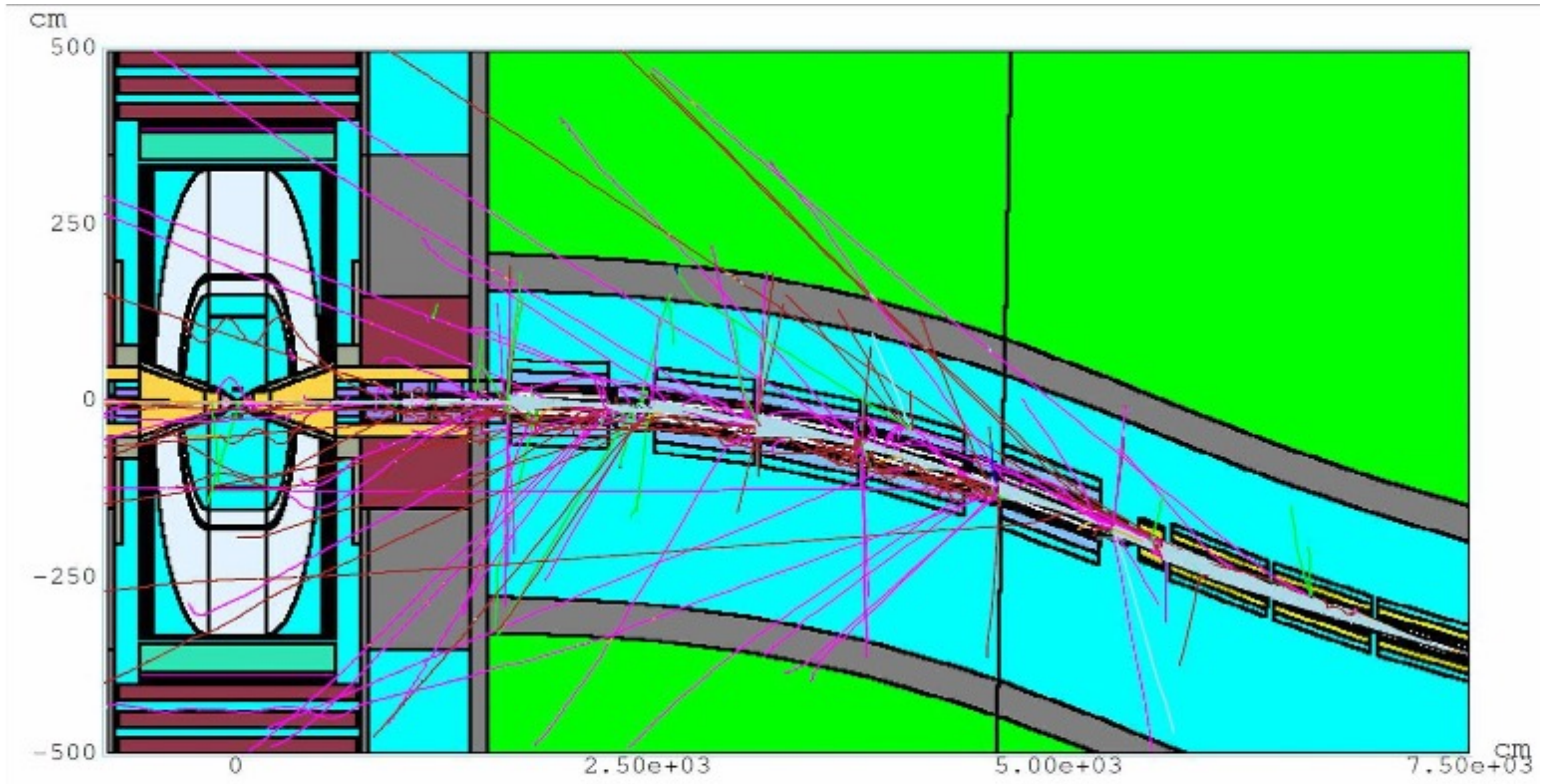
The conventional approach involves a 1-km-long cooling section that reduces both transverse and longitudinal emittances of the beam (6D cooling), followed by a 200 m segment for transverse cooling only (4D cooling).

Recent advancements in superconducting solenoids allow for fields up to 32 T, with the potential for over 40 T in the future at different high magnetic field user facilities.

Future efforts should focus on integrating these technological advancements into the design. Additionally, conducting more extensive optimization studies could yield significant improvements.

Dream ⇔ reality ?
Detector design: BIB

μ- -> e- νμνe causing bremsstrahlung, incoherent electron production, muon pair production in EM showers which then end up either in the detector or producing particles due to decays or additional interaction



Extensive full simulations have provided convincing evidence that these effects can be curbed.

Dream ⇔ reality ?

Two possible designs

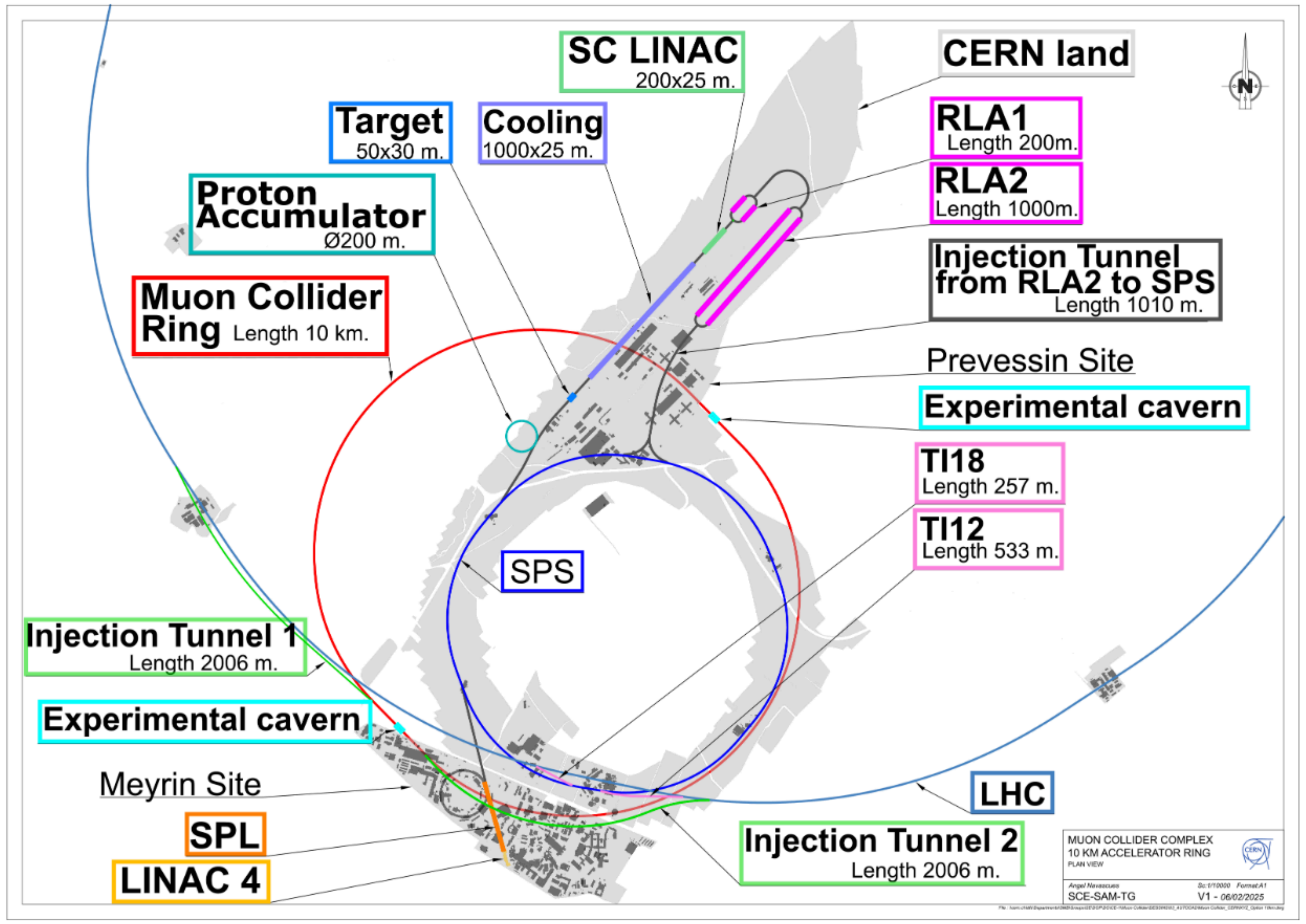
E $\mathscr{L}$

Parameter	Symbol	Unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{\text{target}}$	ab^{-1}	1	10	10	10
Estimated luminosity	$\mathcal{L}_{\text{estimated}}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	2.1	21	5 (tbc)	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	µm	3	0.9	tbc	0.9
Protons on target/bunch	N_{p}	10^{14}	5	5	5	5
Proton energy on target	E_{p}	GeV	5	5	5	5

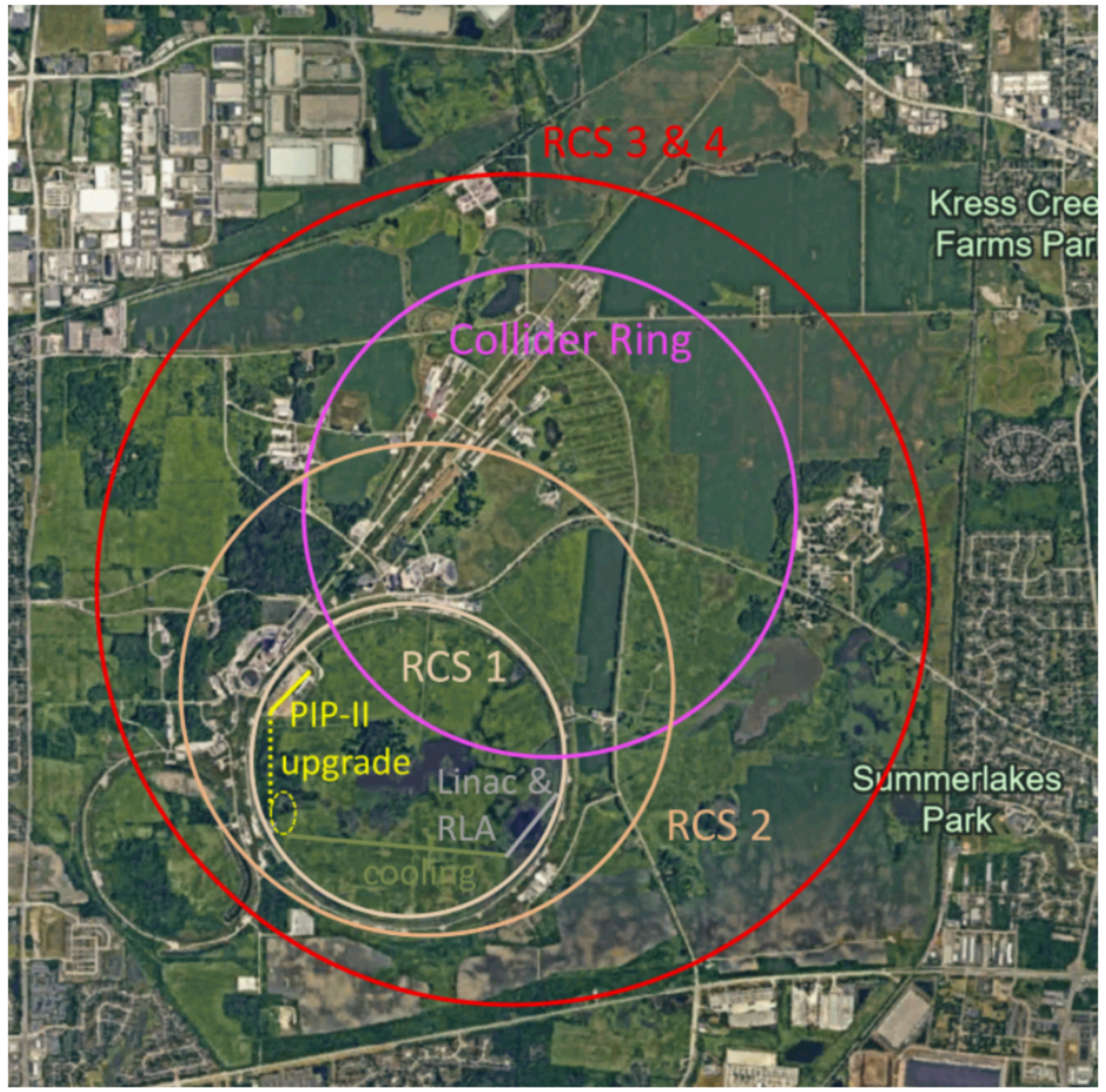
Dream ⇔ reality ?

Two possible sites

CERN



FNAL



At CERN the SPS and LHC tunnels could be reused.