New Frontiers in Theoretical Physics -

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Collider Physics beyond LHC

Barbara Mele

INFN Roma

Outline

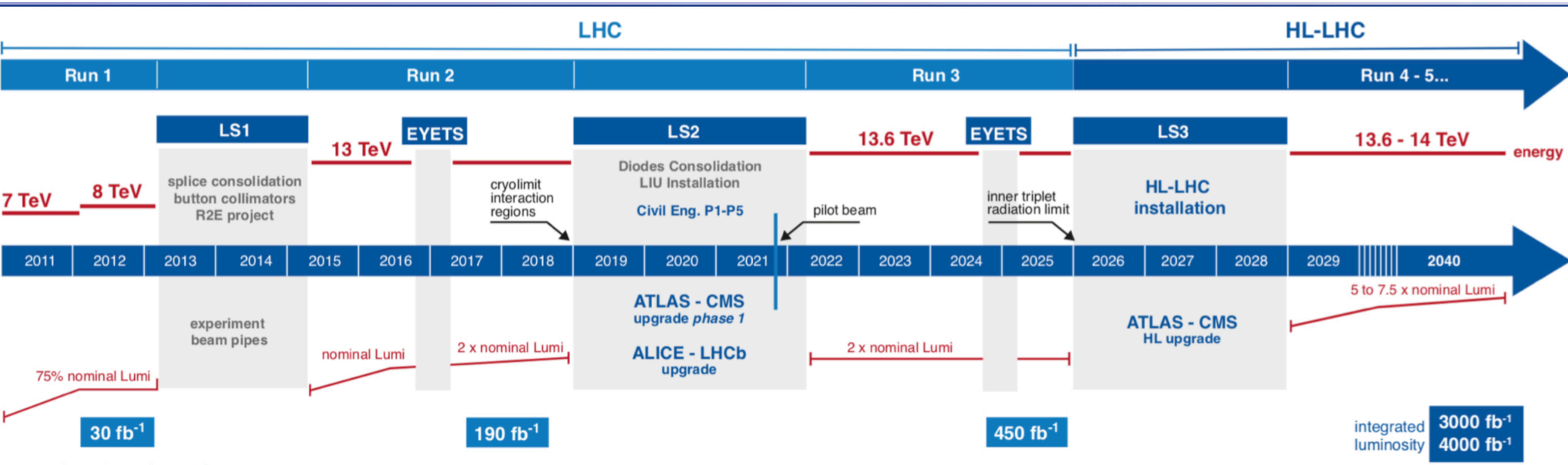
* HEP Theory : present status
* HEP Experiments : main strategies
* quite a few great options for "beyond HL-LHC" Physics !
* extremely rich programme...
  a few examples of physics potential...
* very exciting (and challenging) time for particle physics !

our starting point → LHC [+ HL-LHC]

impressive amount of results !

testing present knowledge of fundamental interactions in many many directions with unforeseen accuracy…

will expand even more in the high-luminosity phase (~2029-~2040)



our present Physics vision...

WHERE DO WE STAND ?

[THEORY + EXP's]

SM works !

* huge amount of LHC data fits SM predictions with amazing (unplanned) level of accuracy !!!

nevertheless…

great (although quite foggy) expectations for new BSM phenomena at colliders !

* two kinds of issues with the SM :

* existence of "external" phenomena :

(quantum ?) Gravity

+ empirical evidences :

- Dark Matter
- Barion asymmetry
- neutrino masses
- . . .

* "internal" poor consistency :

mainly connected to the EWSB/Higgs sector

what's so problematic about the Higgs (TH)

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi^\dagger\phi) - \bar{\psi}_L\Gamma\psi_R\phi - \bar{\psi}_R\Gamma^\dagger\psi_L\phi^\dagger$$

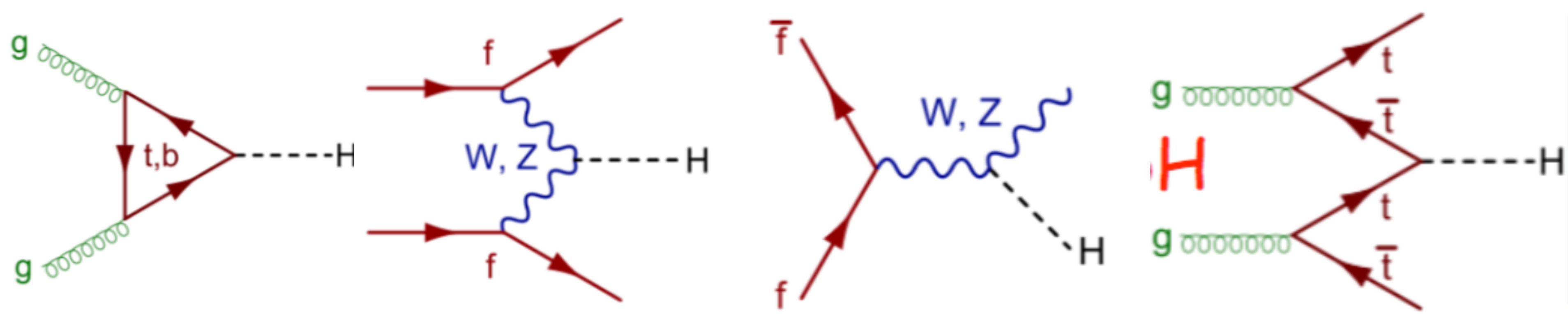
$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \frac{1}{2}\lambda(\phi^\dagger\phi)^2$$

$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

- the only "fundamental" scalar particle (microscopic interpretation ?)
- not protected by symmetries (the less constrained SM sector):
  - naturalness problem : $m_H \sim g \times \Lambda_{cutoff}$
- many different couplings all fixed by masses (?)
  - proliferation of parameters historically leads to breakdown in TH models
- fermion masses/Yukawa's hierarchy (?)
  - have neutrinos a special role ?!!!
- λ determines shape and evolution of Higgs potential → cosmology !

what's so problematic about the Higgs (EXP)

- very challenging experimental studies in general !!!
  - tiny x-sections in direct production from light states → must excite heavy states (t,W,Z) radiating Higgs → small cross sections → harsh separation from backgrounds



- the measured (and unpredicted) m_H value comes as a bonus, since it opens many explorable decay channels (with relatively unsuppressed production x-sections) presently four main strategies

to advance in HEP at colliders

→ → →

four paths to advance in HEP at colliders:

- ✱ by exploring the characteristics of the Higgs sector and confirming/spoiling the SM picture
  (primary relevance since the Higgs sector is so critical !)
- ✱ by searching for new heavy states coupled to the SM,
  [acting as a cut-off for the SM , possibly solving the naturalness issues and/or non-SM phenomena (dark matter, ...)]
  [searched for but not yet found at LHC in minimal version !]
- ✱ by looking for new "DARK" states (i.e.,uncoupled to SM at tree level) either in production or/and heavy-state (H,top...) decays (elusive signatures, may be long-lived p.les)
- ✱ by exploring $\Lambda >> o(1\text{TeV})$ indirect effects through high-accuracy studies of SM x-sections/distributions and searches for rare processes (EFT parametrization)

four paths to advance in HEP at colliders:

* Higgs
* new particles
* "Dark" signals
* indirect effects

* every single method is of fundamental importance to make progress !
* e^+e^- colliders great opportunities in all sectors (cleanness [→ model independence], accuracy…)
* general consensus by now on e^+e^- Higgs factory as next collider to build !

precision needed in Higgs measurements ?

BSM impact on Higgs couplings

- up to few percent for natural model
  not showing up by heavy states production at LHC

	$\Delta g(hVV)$	$\Delta g(ht\bar{t})$	$\Delta g(hb\bar{b})$
Composite Higgs	10%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	tens of %
Mixed-in Singlet	6%	6%	6%

- different patterns of deviations from SM for different NP models

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [38]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [39]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [39]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [39]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [40]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [41]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [42]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [43]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [44]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

arXiv:1710.07621

λ H³ coupling most exposed to BSM !

(impact on vacuum stability, Baryogenesis from cosmological EWPT ?)

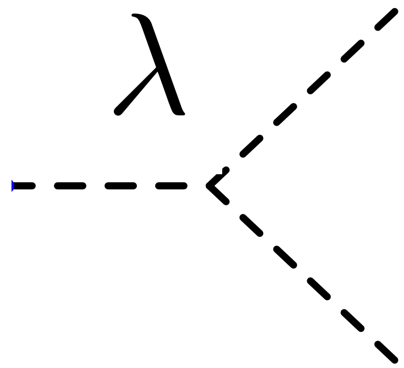
- in the SM :

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda\, v H^3 + \frac{1}{4} \lambda' H^4$$

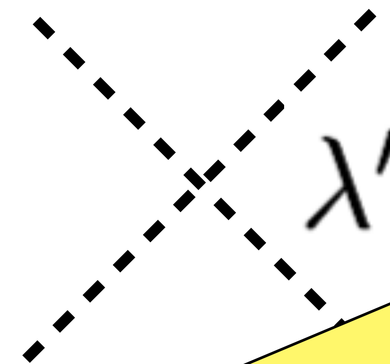
$$\lambda = \lambda' = M_H^2/(2v^2) = 0.13$$

→ m_H directly related to Higgs dynamics !

- direct exploration needs HH in final states (tiny x-sections)



or HHH



out of reach ??

- BSM : Max λ deviations compatible with no other BSM observation:

→ few % to ~20%

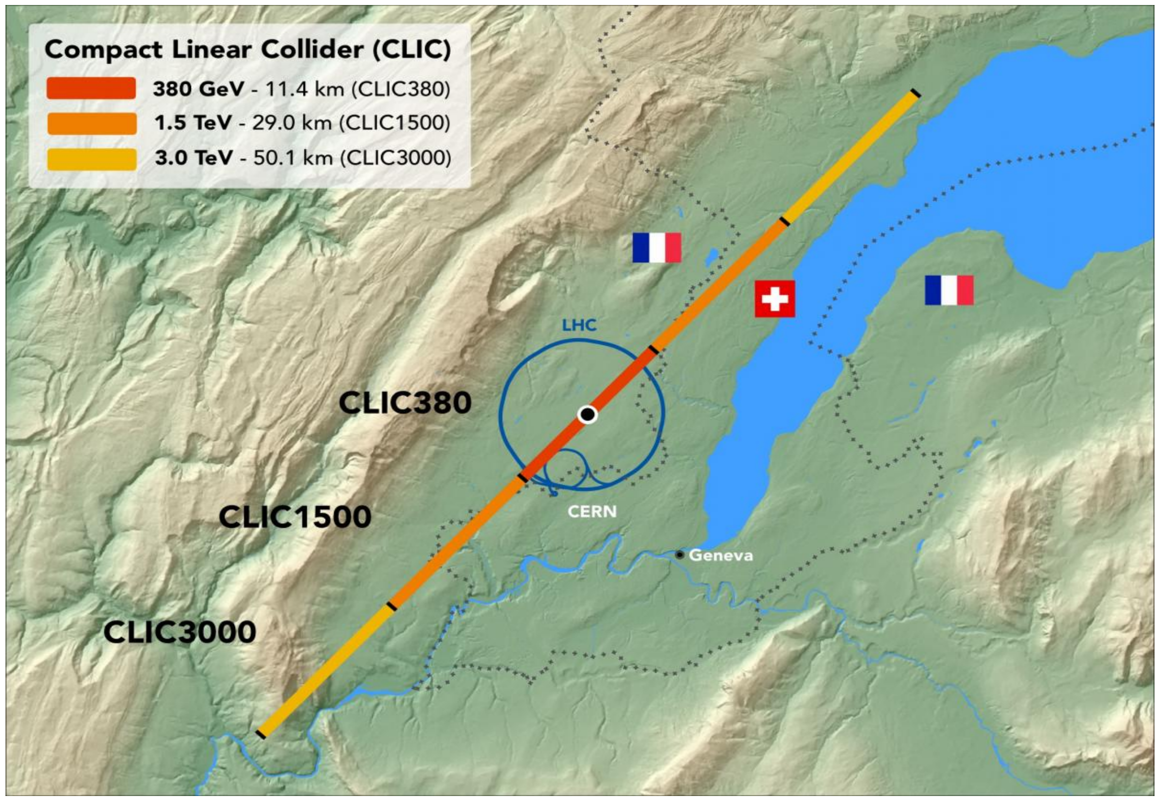
Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^{a}$ $-15\,\%^{b}$
NMSSM	$-25\,\%$

- target for both TH and EXP accuracies !

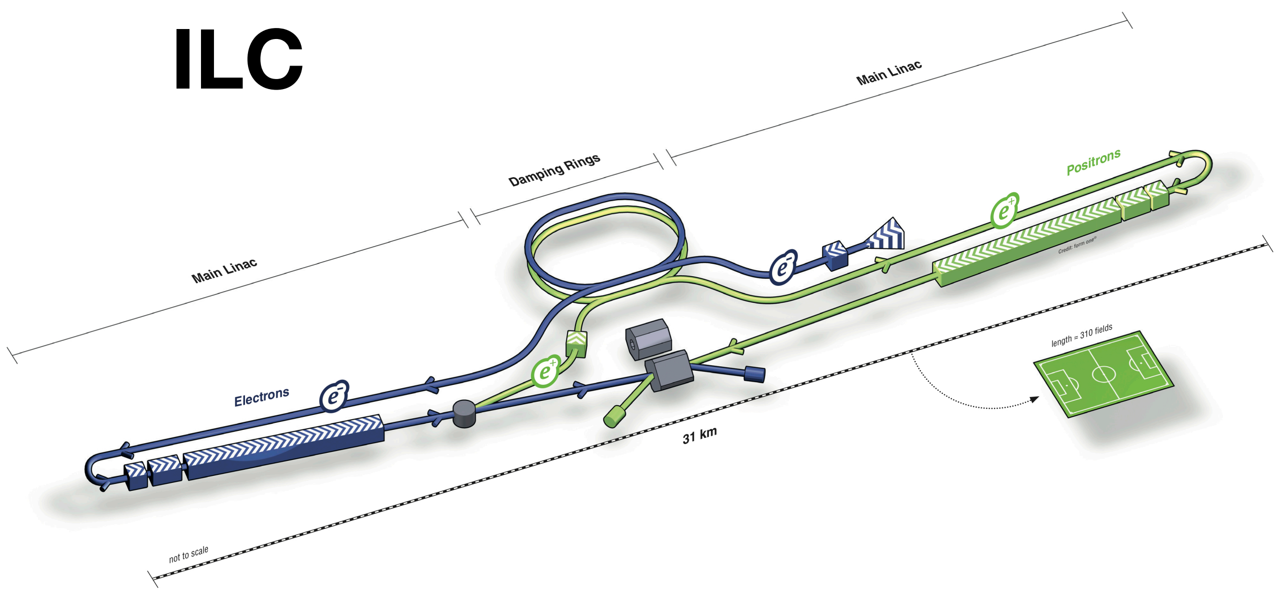
Future Collider main projects

future colliders under consideration

Linear (e⁺e⁻) colliders

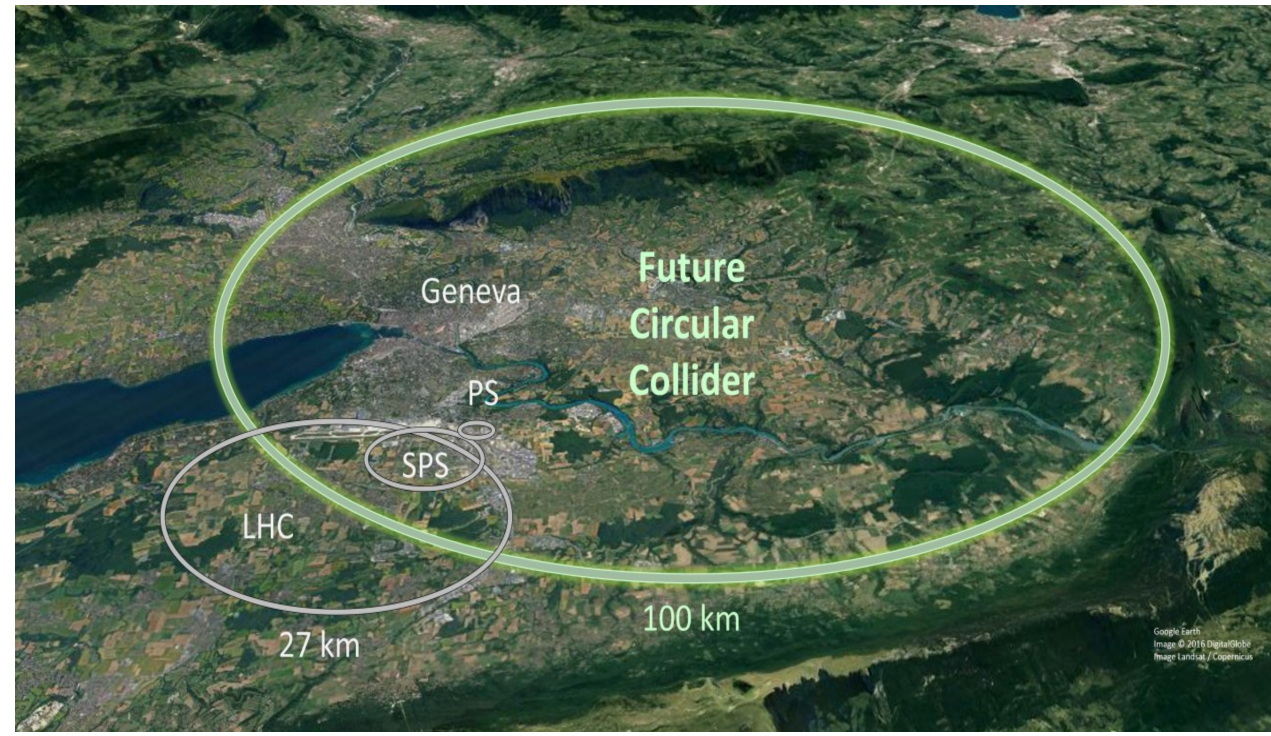


ILC



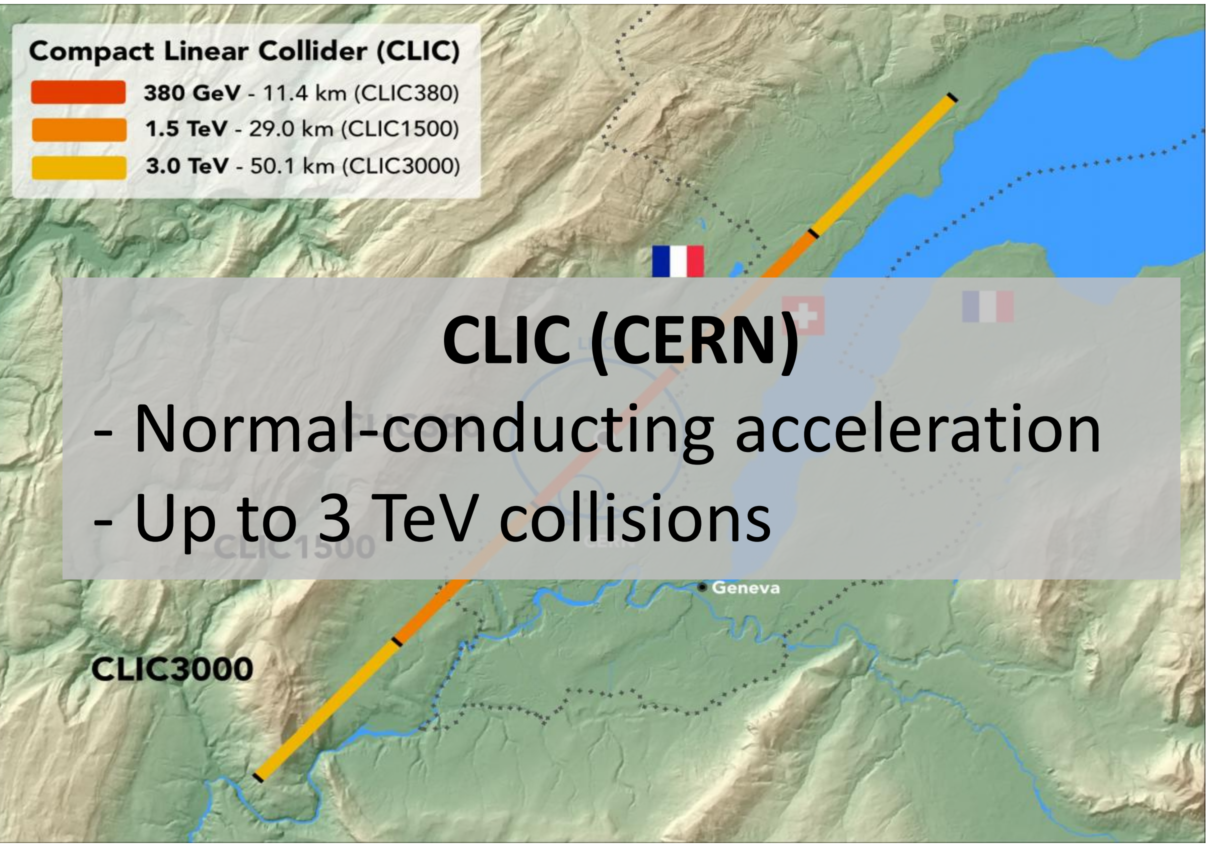
L. Gouskos

Circular (e⁺e⁻/hh) colliders



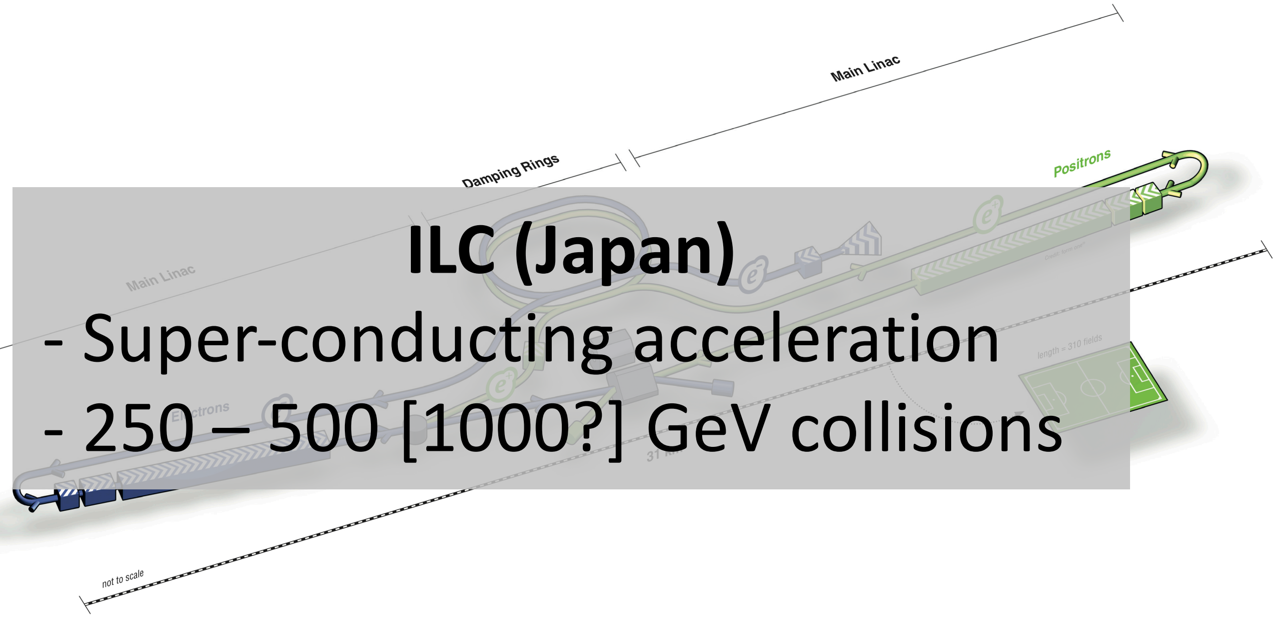
future colliders under consideration

Linear (e^+e^-) colliders



CLIC (CERN)

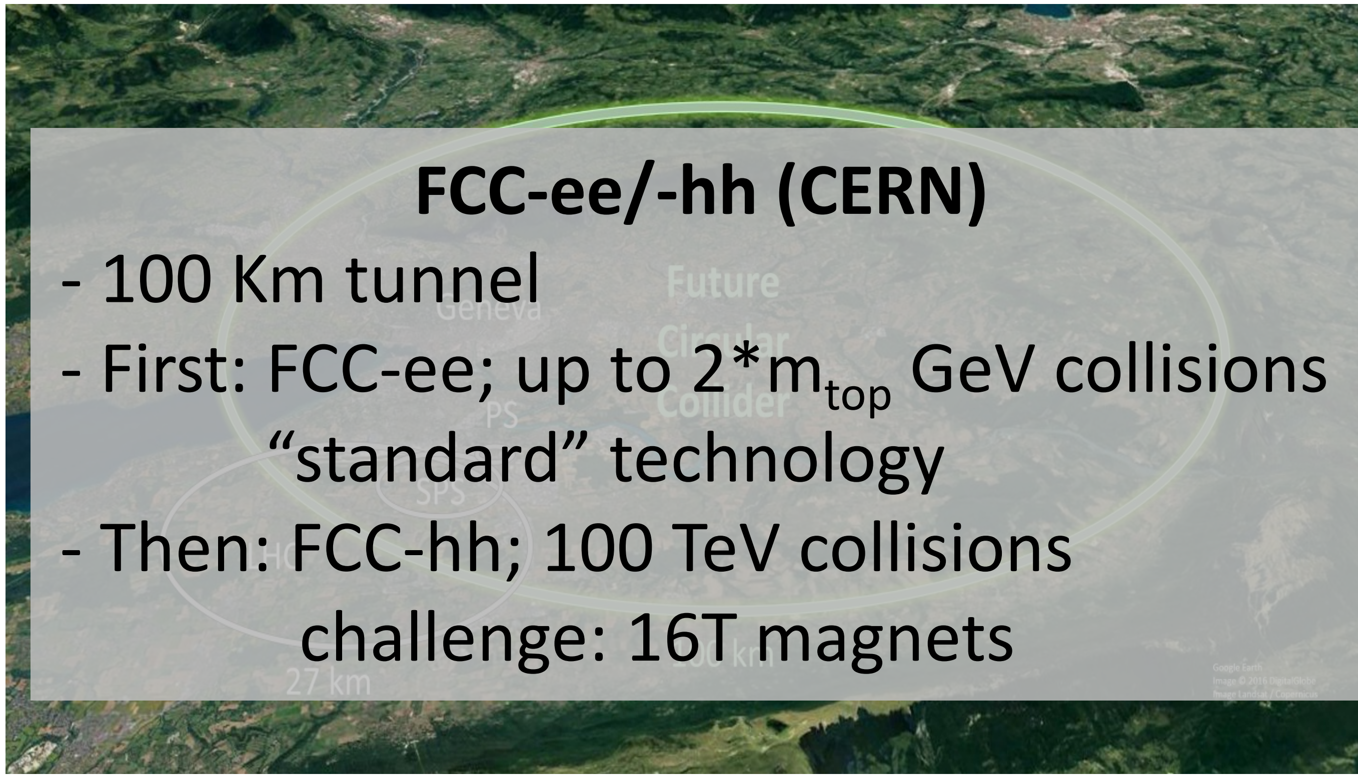
- Normal-conducting acceleration
- Up to 3 TeV collisions



ILC (Japan)

- Super-conducting acceleration
- 250 – 500 [1000?] GeV collisions

Circular (e^+e^-/hh) colliders



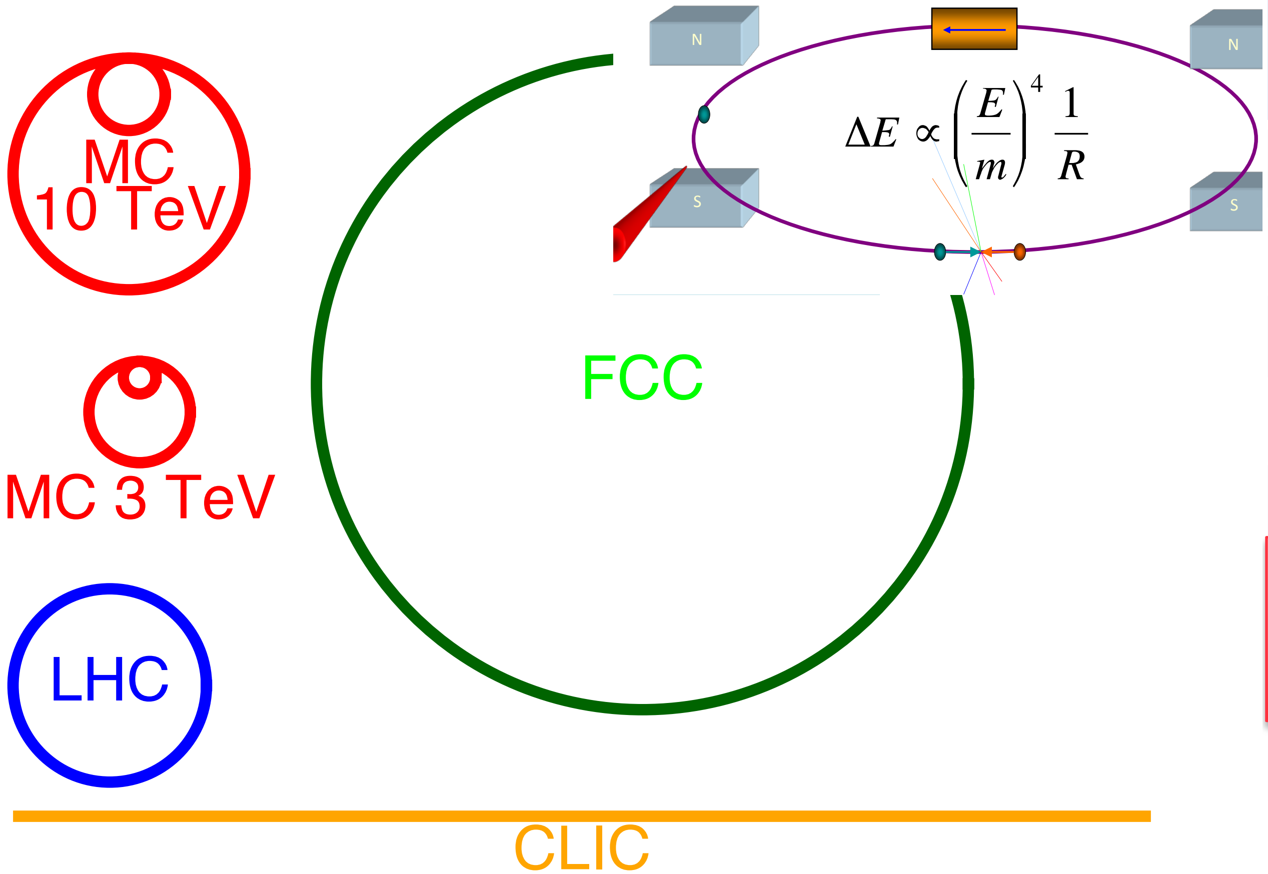
FCC-ee/-hh (CERN)

- 100 Km tunnel
- First: FCC-ee; up to $2*m_{top}$ GeV collisions
  "standard" technology
- Then: FCC-hh; 100 TeV collisions
  challenge: 16T magnets

CEPC/SppC (China)

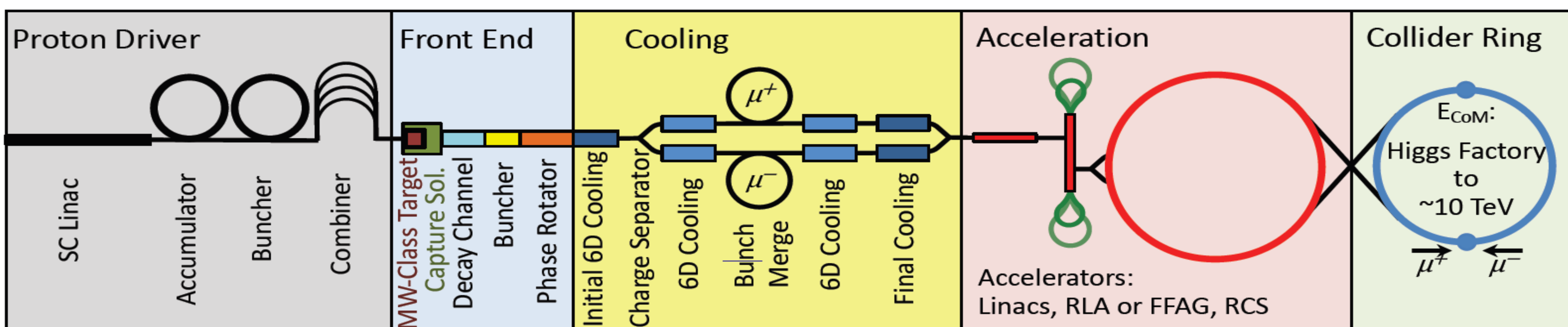
- 100 Km tunnel
- Essentially an FCC-ee/ FCC-hh
- More conservative luminosity scenarios

recently renewed interest also in Muon Colliders



	CME [TeV]	Lumi per IP [10^{34}cm^{-2}s^{-1}]	Years to physics	Cost range [B$]	Power [MW]
FCC-ee	0.24	8.5	13-18	12-18	290
ILC	0.25	2.7	<12	7-12	140
CLIC	0.38	2.3	13-18	7-12	110
ILC	3	6.1	19-24	18-30	400
CLIC	3	5.9	19-24	18-30	550
MC	3	1.8	19-24	7-12	230
MC	10	20	>25	12-18	300
FCC-hh	100	30	>25	30-50	560

[Snowmass Implementation Task Force, 2208.06030]



Short, intense proton bunch

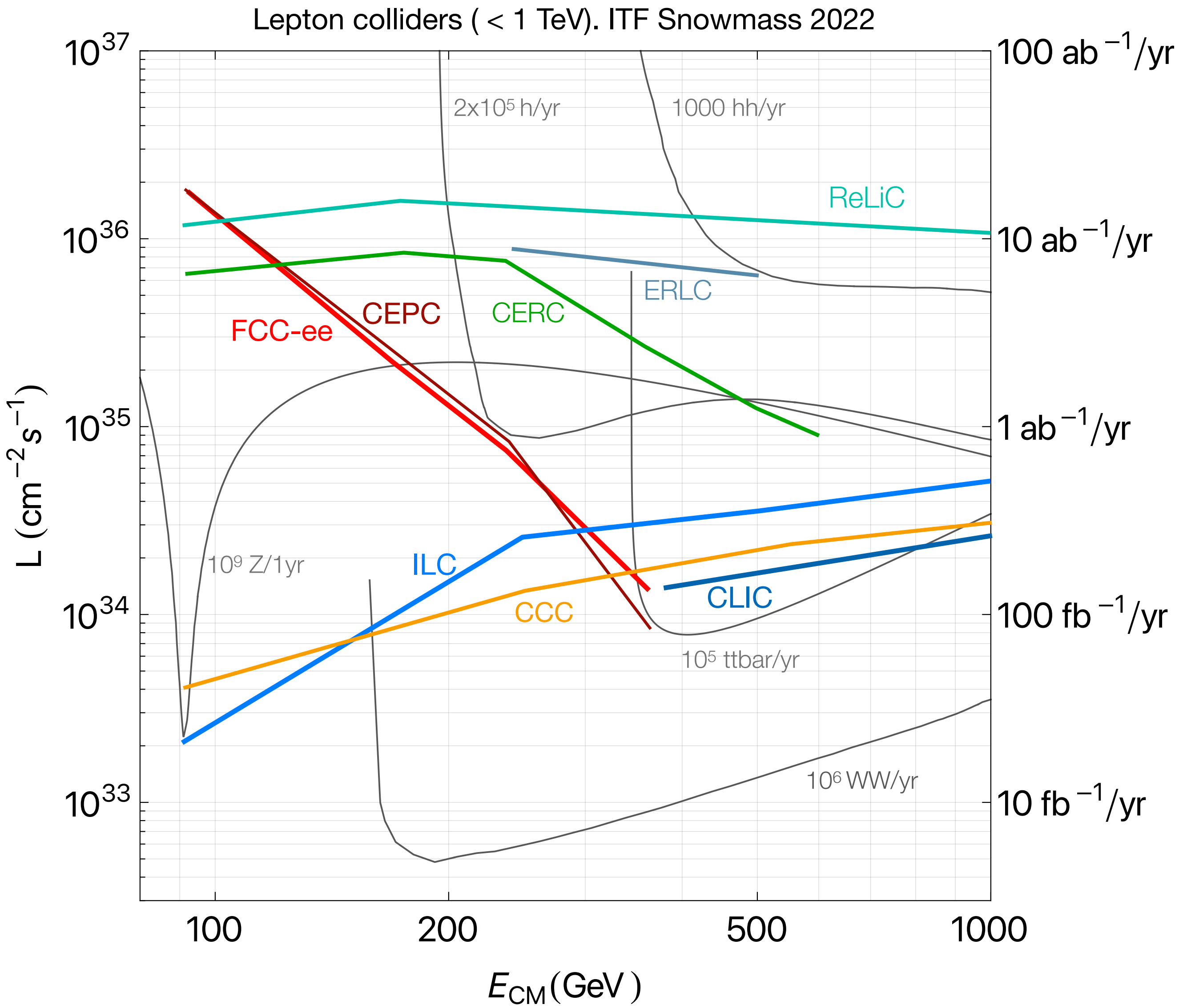
Protons produce pions which decay into muons muons are captured

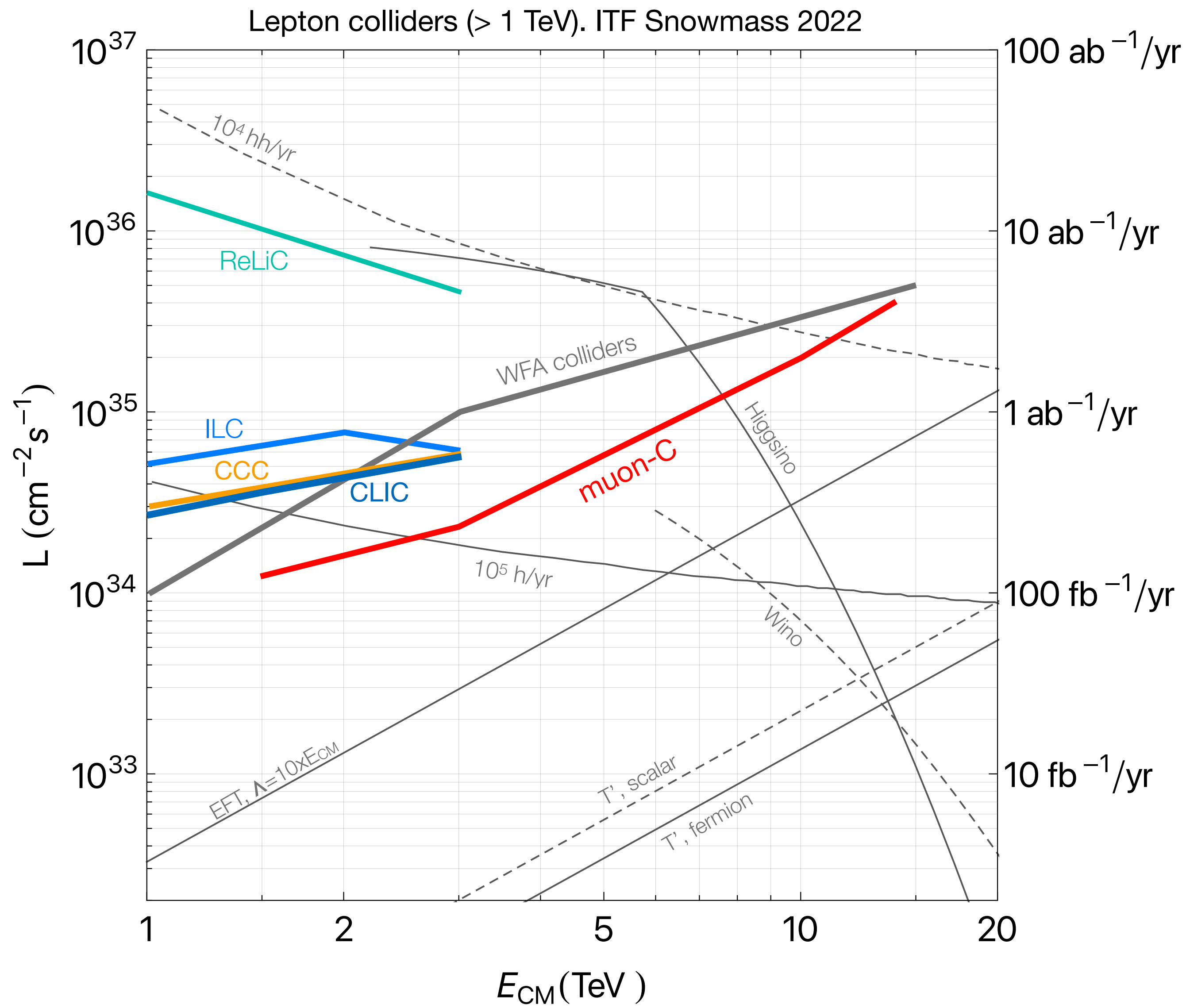
Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

lepton colliders Lumi [√s < 1 TeV or > 1TeV]

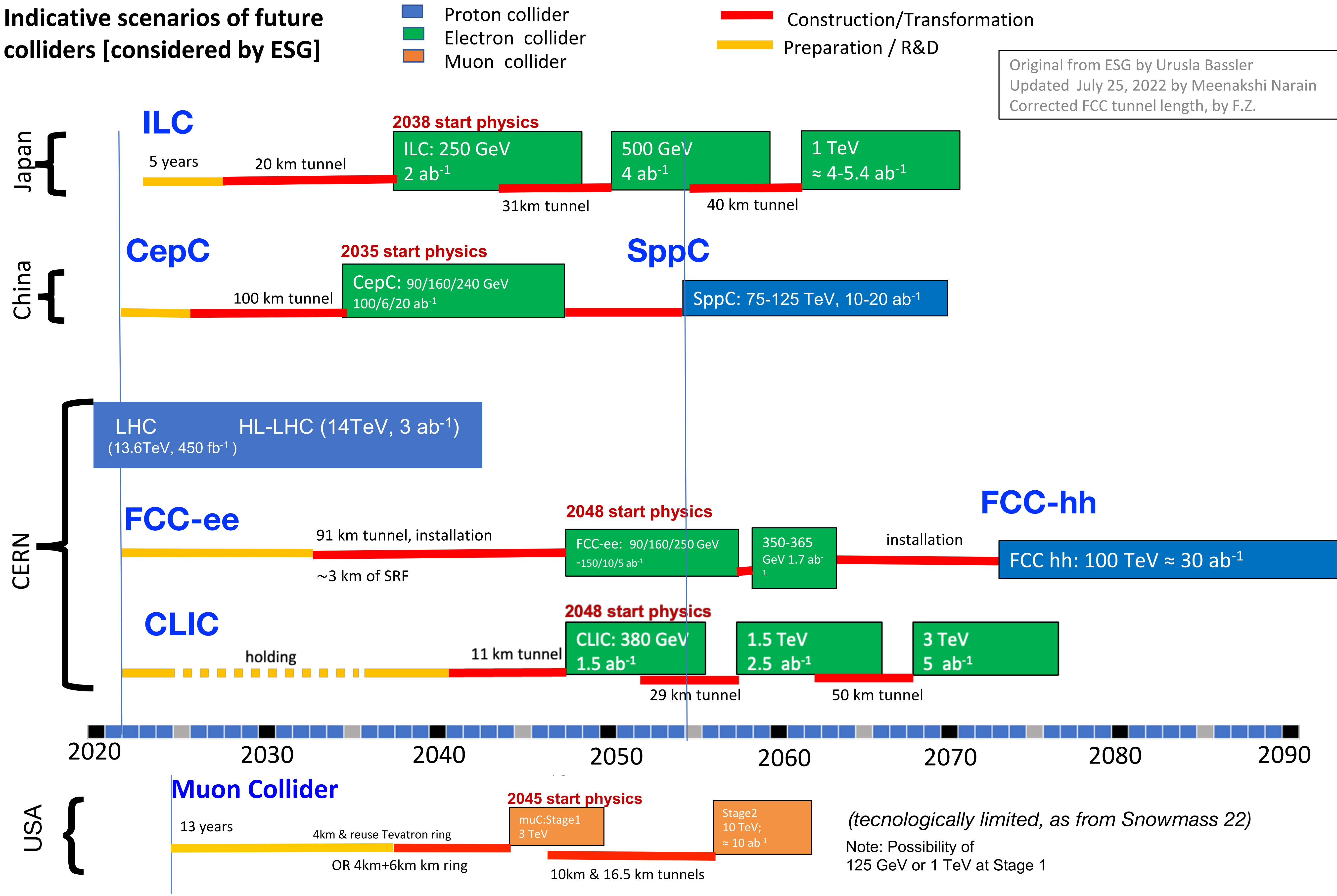




- in Europe, after ESG input → IMCC [Int. MuCol Collaboration]
- in US, after Snowmass studies :
  - MuC physics case → fantastic ! [energy & precision frontier]
  - MuC technical challenges (cooling, BIB,...) → manageable !

→ → → " We want a MuC ! "

projects possible timelines



how to assess a large-scale project

project → [beam species, energy, lumi, technology]

- Physics potential (direct, indirect) *(mainly discussed here)*
- feasibility → maturity → technical risk
- innovation
- construction/operation costs (vs constraints from funding agencies)
- power consumption
- start-up time
- total operation time (staging, expandibility)
- location vs infrastructures vs politics (global context !)
- HEP (both regional and global) community support
- fraction of present HEP community involved

how to assess a large-scale ...ct

project → [beam species, energy ... gy]

- Physics potential (direct, indirect ... sed here)
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- start-up tim...
- total op... aging, expandibility)
- locat... uctures vs politics (global context !)
- ... onal and global) community support
- ... present HEP community involved

a global adventure !

focus on FCC

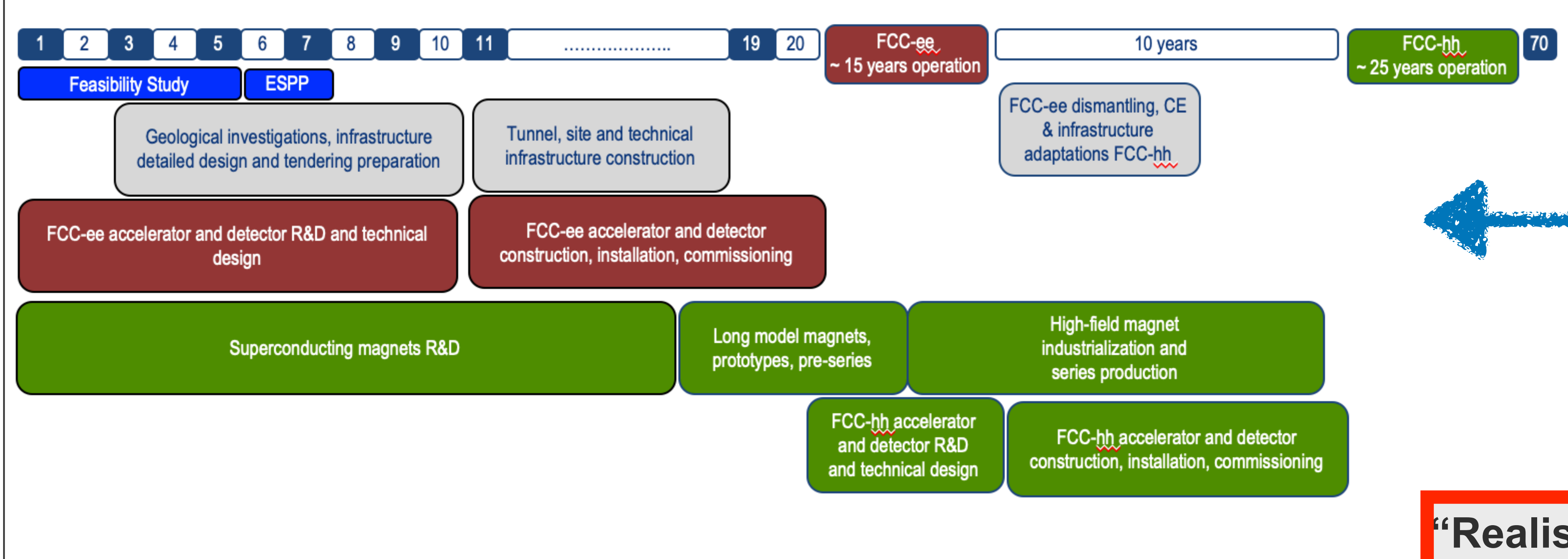
FUTURE CIRCULAR COLLIDER

FCC research infrastructure for the 21st cent

A new 91 km tunnel to host multiple colliders
100 – 300 m under ground, 8 surface sites
FCC-ee: electron-positron @ 91, 160, 240, 365 GeV
FCC-hh: proton-proton @ 100 TeV, and heavy-ions (Pb) @39 TeV
FCC-eh: electron-proton@ 3.5 TeV

FCC estimated timeline

[F. Gianotti]



Technical schedule: FCC-ee could start physics operation **in 2040 or earlier**

1st stage collider, FCC-ee: electron-positron collisions 90-360 GeV
Construction: 2033-2045 → Physics operation: 2048-2063

2nd stage collider, FCC-hh: proton-proton collisions at ≥ 100 TeV
Construction: 2058-2070 → Physics operation: ~ 2070-2095

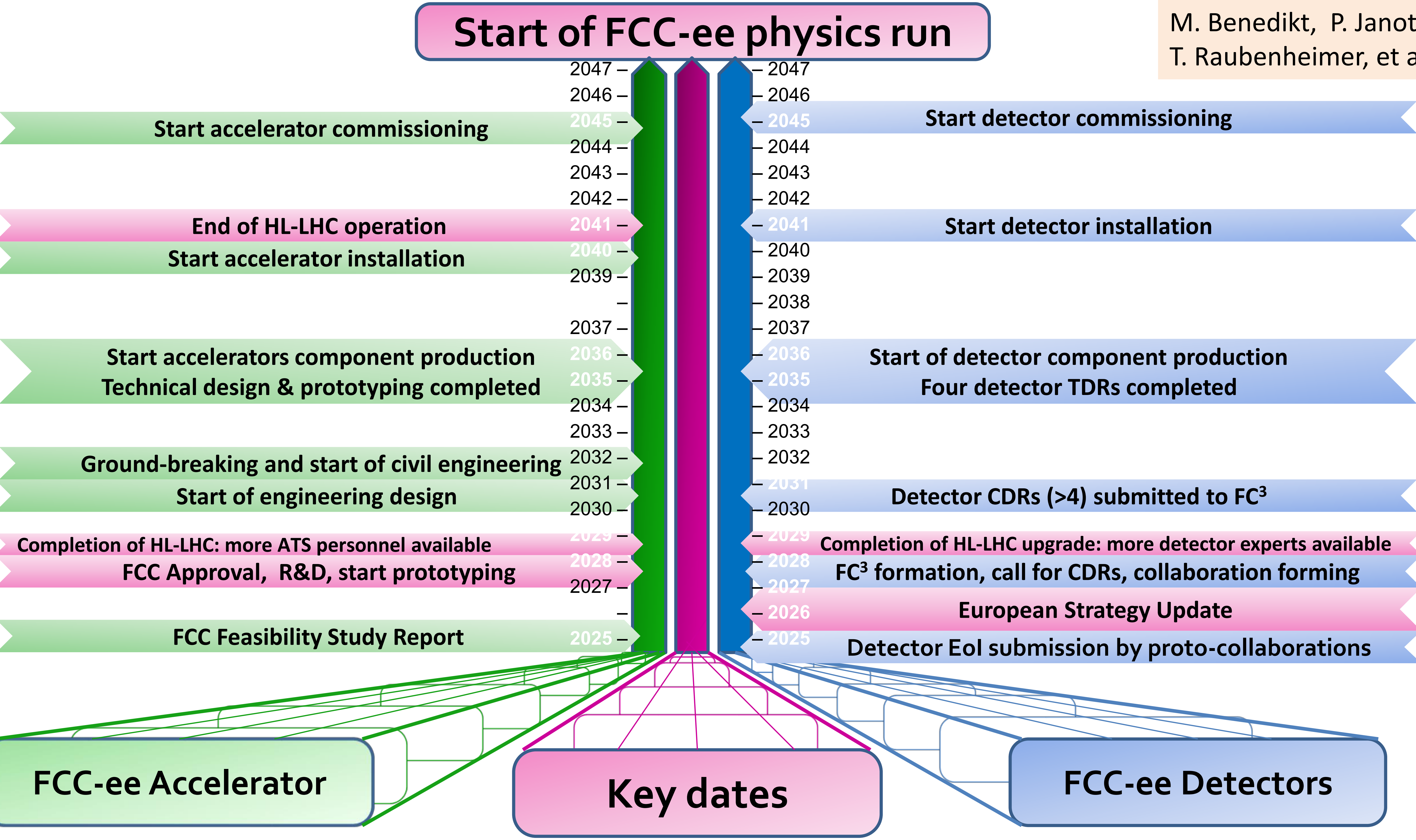
"Realistic" schedule takes into account:
- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until ~ 2041

→ **ANY future collider at CERN cannot start physics operation before ~ 2045** (but construction will proceed in parallel to HL-LHC operation)

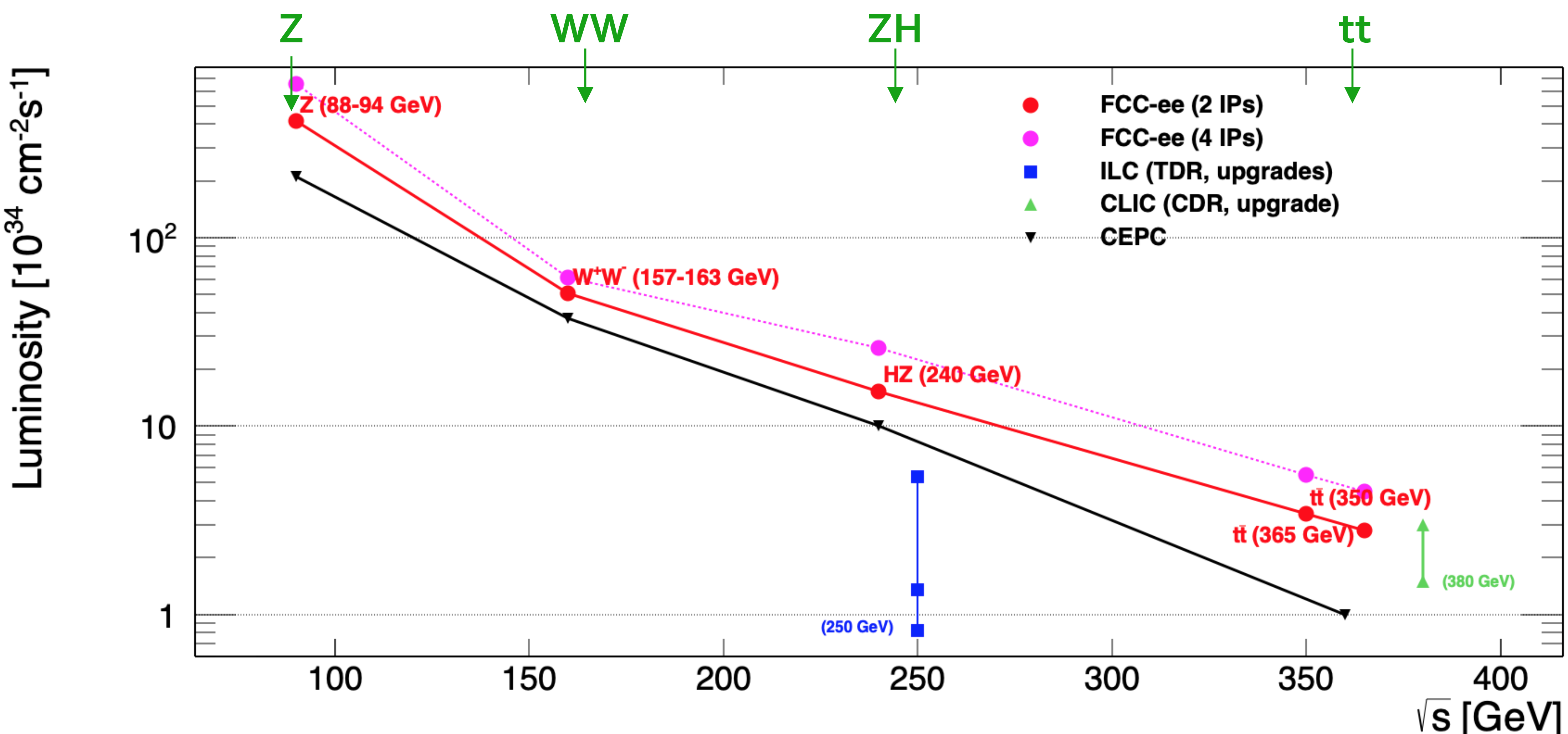
Care should be taken when comparing to other proposed facilities, for which in some cases only the (optimistic) technical schedule is shown

FCC-ee implementation schedule

M. Benedikt, P. Janot
T. Raubenheimer, et a



FCC-ee: Lumi and event # at different stages



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

Event statistics (with 2 IPs, x1.7 for 4 IPs now official baseline)

in each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day

exact sequence and duration for stages to be elaborated !

SUPERB FCC-ee physics programme !!

* **Higgs** : $e^+e^- \to H\,Z$ → m_{Higgs}, Γ_{Higgs}; Higgs couplings; self-coupling

* **Top** : $e^+e^- \to t\ t_{bar}$ → m_{top}, Γ_{top}; EW top couplings

* **"intensity frontier"** : $e^+e^- \to Z,\ WW$ [→ super LEP]

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

  * **direct searches of "light new physics"** →
    - Axion-like particles, dark photons, Heavy Neutral Leptons
    - long lifetimes - LLPs

  * **Flavor Factory** (10^{12} bb/cc; $1.7\times10^{11}\,\tau\tau$)

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

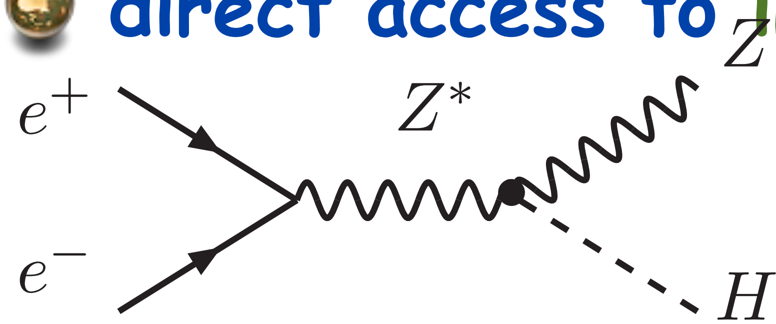
    → Belle II x 15

    tau physics →
    - τ-based EWPOs
    - lept. univ. violation tests

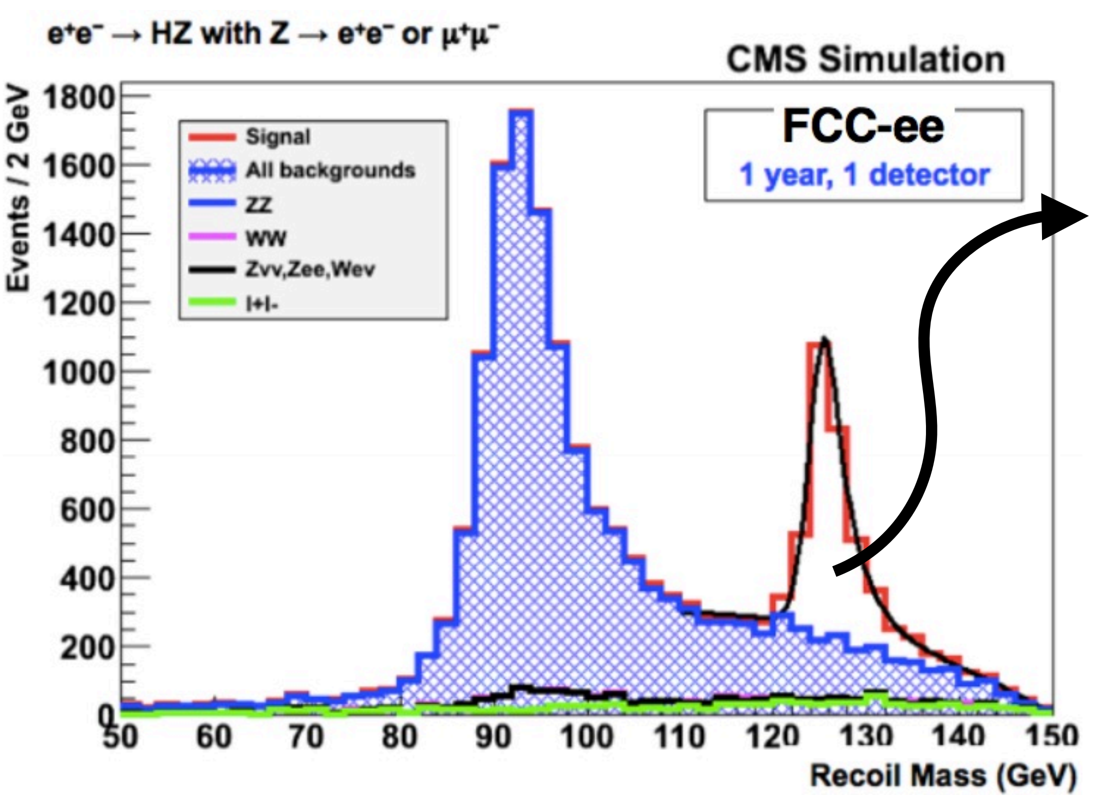
ee → HZ allows model-independent g_{HXX} measurem.s

[both circular and linear colliders]

- selected by just identifying Z decay products
  → absolute σ_{tot} (~g_{HZZ}^2) measurement → model independent g_{HZZ}
- direct access to inv. H decays, H → cc, H → ss (?), H → gg



by identifying Higgs final states X
→ absolute measurement of BR_X
→ g_{HXX}



N(ZH) ∝ σ(ZH) ∝ g_{HZZ}^2

- sub-% accuracy of couplings to W, Z, b, τ
- % accuracy of couplings to gluon and charm

expected $\delta g_{Hii}/g_{SM}$ (Snowmass summary)

Higgs Factories

Energy Frontier Higgs Factory First Stages

EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings: Tree	Gauge Couplings: Loop induced	Higgs Width	λ_3
LHC/HL-LHC	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$\mathcal{O}(1)$
Higgs Factory + HL-LHC: ILC/C^3 250	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$ *	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$
Higgs Factory + HL-LHC: CLIC 380	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$
Higgs Factory + HL-LHC: FCC-ee 240	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$
Higgs Factory + HL-LHC: CEPC 240	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$

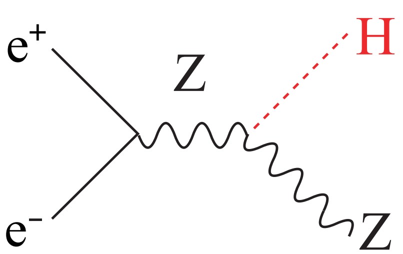
Order of Magnitude for Fractional Uncertainty

★ $\lesssim \mathcal{O}(10^{-3})$ ◆ $\mathcal{O}(.01)$ ◆ $\mathcal{O}(.1)$ ◆ $\mathcal{O}(1)$ □ $> \mathcal{O}(1)$

[slide from P. Janot]

Higgs self-coupling at FCC-ee $\lambda\ H^3$

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



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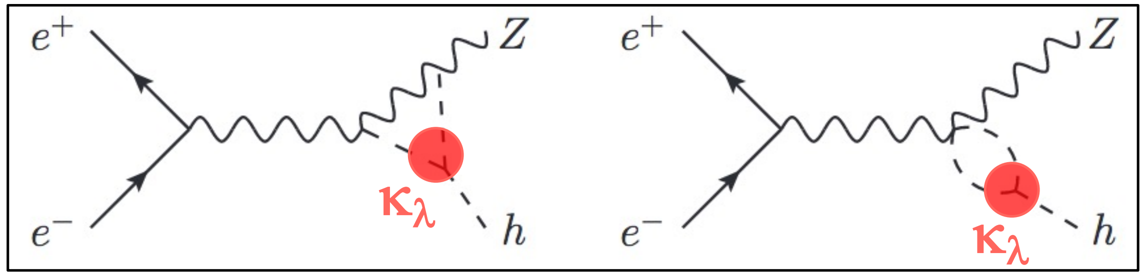
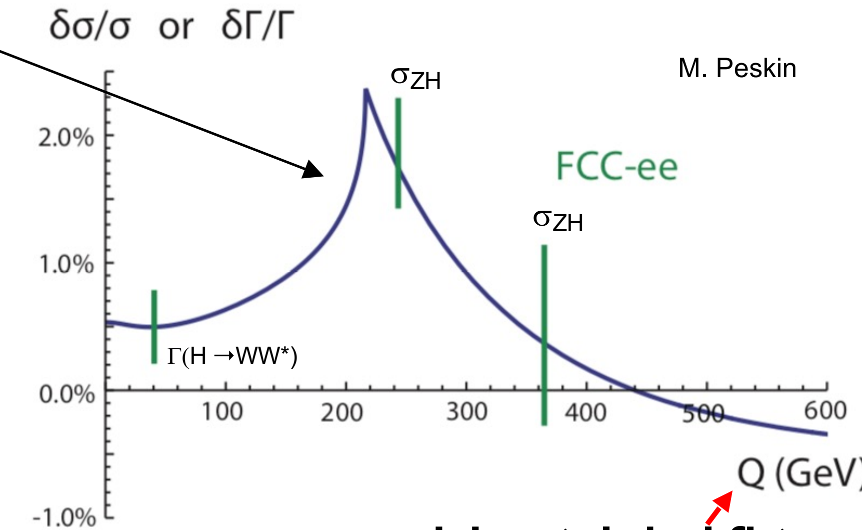
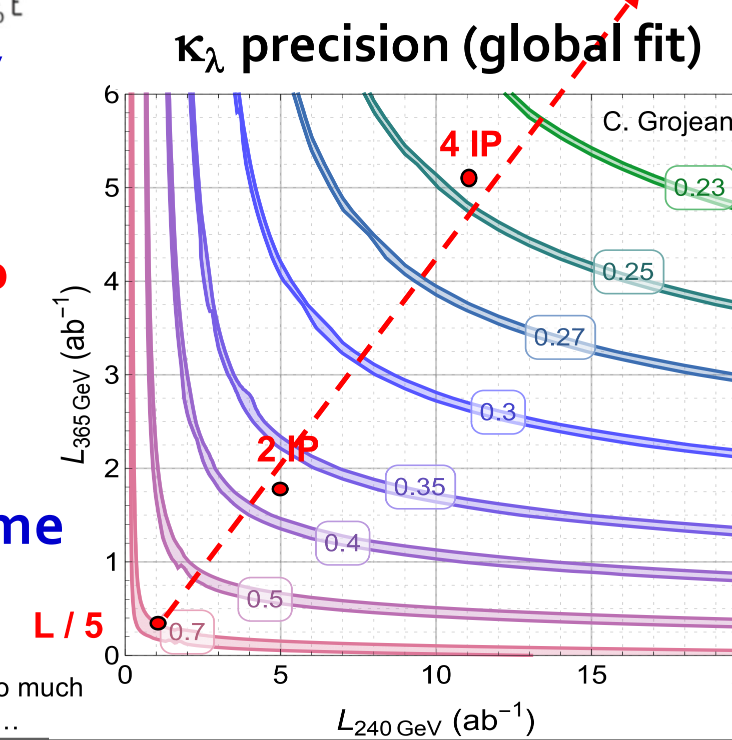




- **Estimate with present run plan and 2 IPs: $\geq 2\sigma$ from $\kappa_\lambda = 0$**
  - Analyses will improve, but no hope with 5 times less luminosity

(Discovery)

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

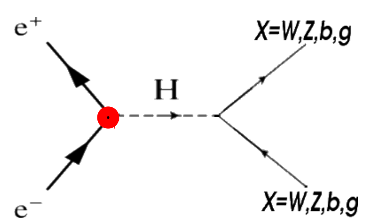


HL-LHC alone cannot do much in a global EFT fit …

22

including FCC-hh → direct HH production → $\delta\kappa_\lambda \sim$ few %

access to electron Yukawa !!!



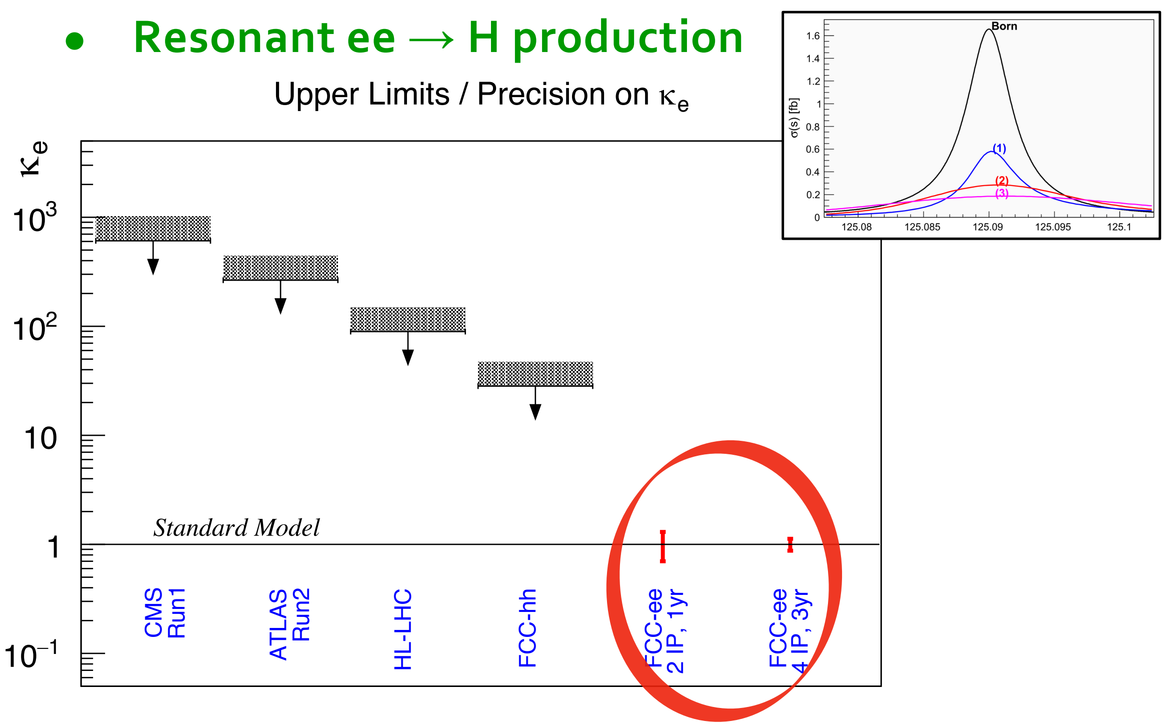
$\sigma(e^+e^-\to H)$ = 1.64 fb

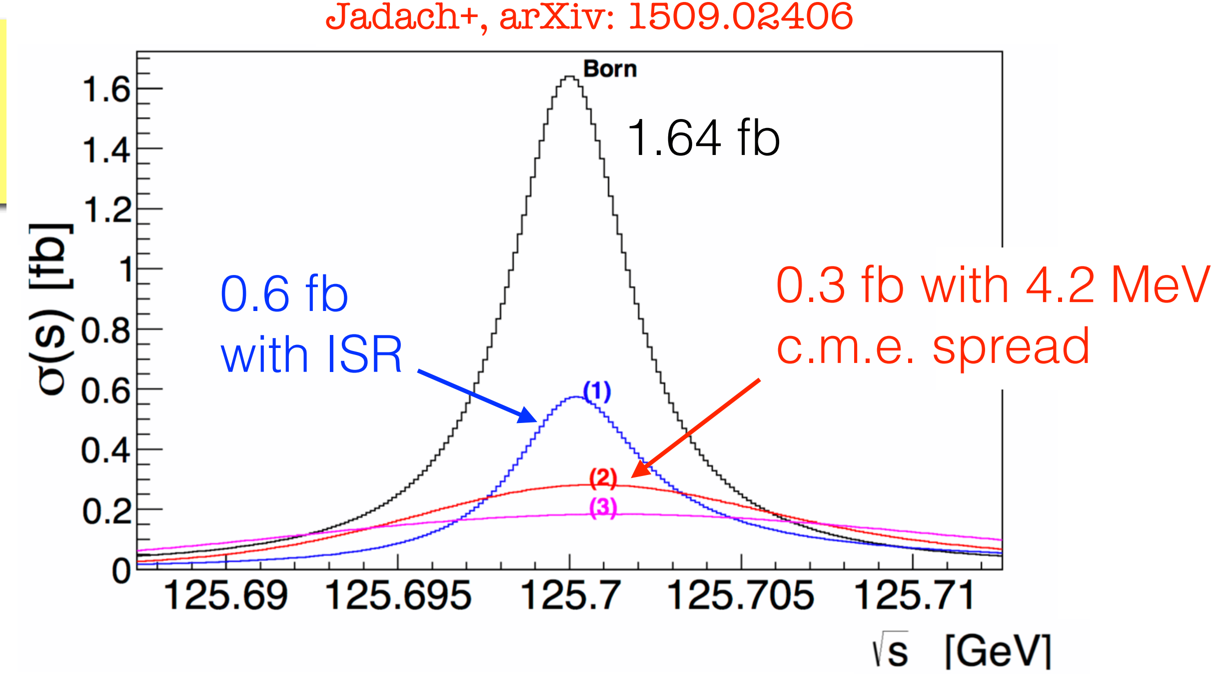
$\sigma_{spread+ISR}(e^+e^-\to H)=0.17\times\sigma(e^+e^-\to H)$=290 ab

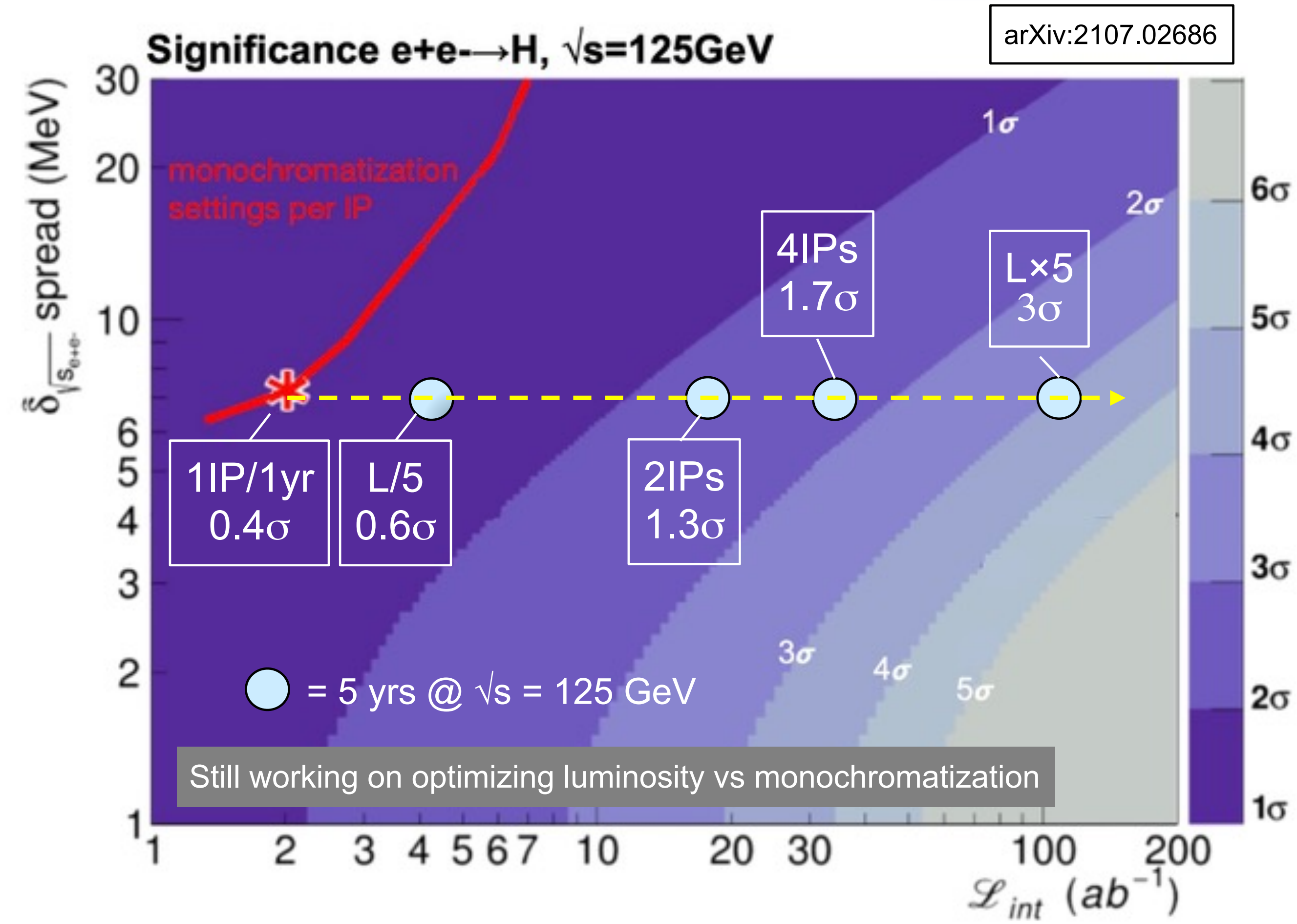
20 ab⁻¹ / year at $\sqrt{s}$ = 125 GeV *(not in baseline FCC-ee)*

Monochromatization $\sigma_{\sqrt{s}} \sim 1\text{-}2 \times \Gamma_H \sim$ 6 to 10 MeV

- **Resonant ee → H production**







- **2σ excess in one year with 2 IP**
- **±15% precion on κ_e in 3 years with 4 IP**
  - ➔ **Not feasible at ILC or CLIC**

w. 10/ab

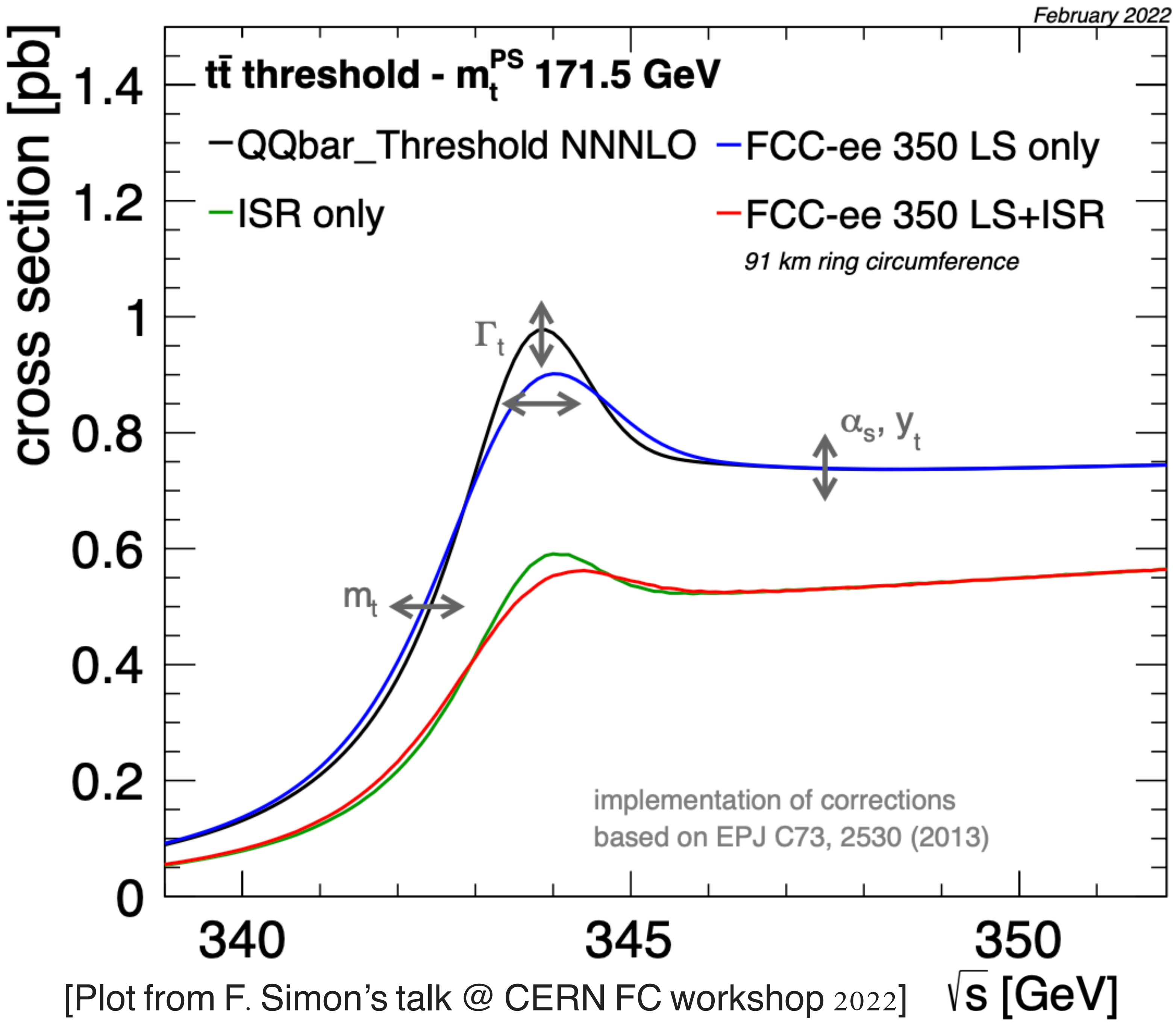
$H\to gg$	$H\to WW^*\to \ell\nu\,2j;\ 2\ell\,2\nu;\ 4j$	$H\to ZZ^*\to 2j\,2\nu;\ 2\ell\,2j;\ 2\ell\,2\nu$	$H\to b\bar{b}$	$H\to\tau_{had}\tau_{had};\ c\bar{c};\ \gamma\gamma$	Combined
1.1σ	$(0.53\otimes 0.34\otimes 0.13)\sigma$	$(0.32\otimes 0.18\otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$	1.3σ

w/ 10/ab: S~55, B~2400 → 1.1σ

FCC-ee at tt^{bar} threshold (top Factory !)

- up to per-mille accuracy on x-sections and asymmetries !
- access to top mass and width, and strong and Yukawa top couplings
- exps aims at

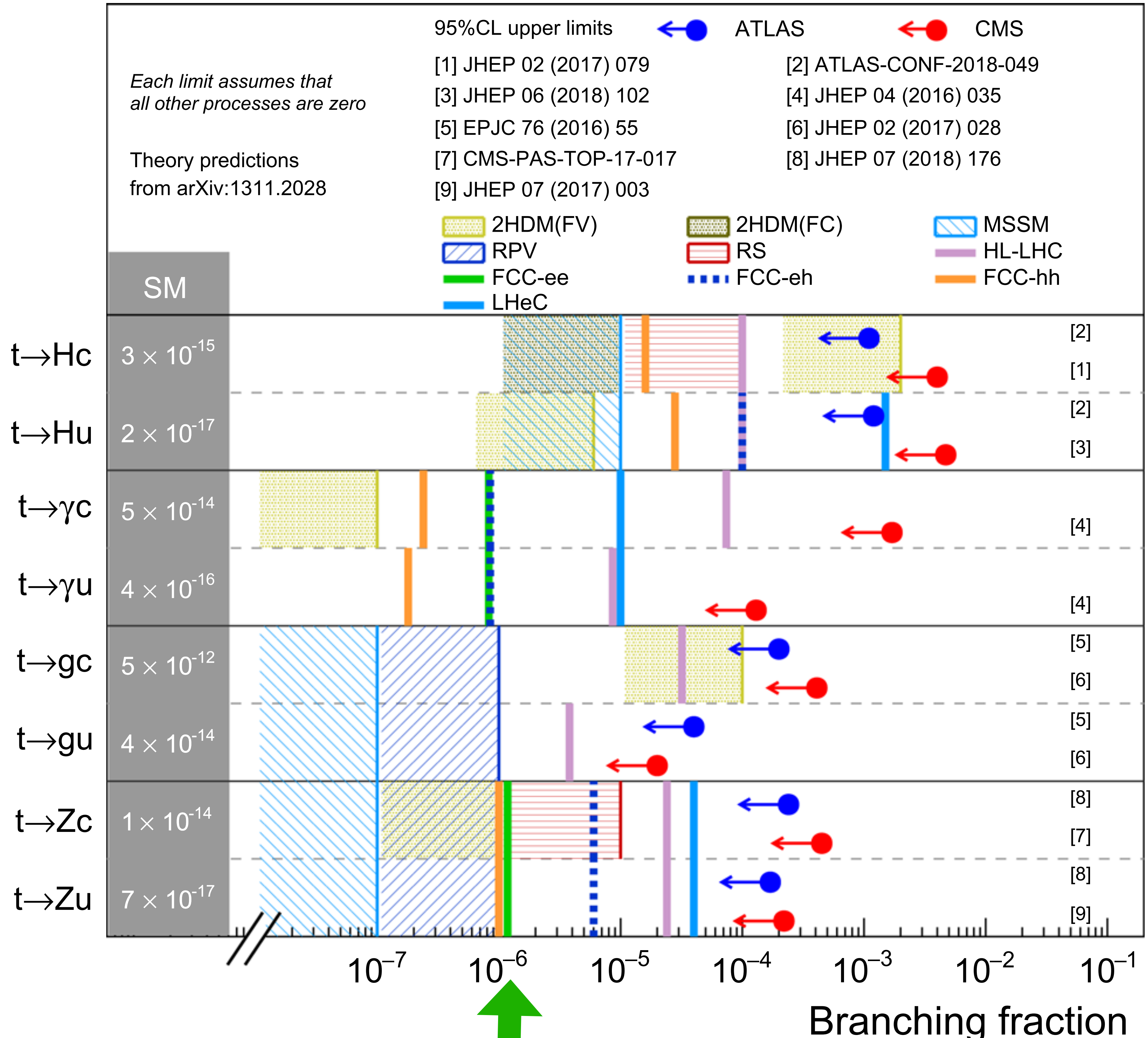
  $\delta m_t \sim 20$ MeV
- challenge for theory!!



[Plot from F. Simon's talk @ CERN FC workshop 2022]

bounds on top FCNC from 10^6 ttbar

Future Circular Collider Conceptual Design Report Volume 1



EW param.s at FCC-ee [Tera-Z] → 5×10^{12} Z

- stat precision up to 1000 times better than LEP
- (exp) syst precision "10÷50" times better
- total precision currently limited by TH systematics (!!!)

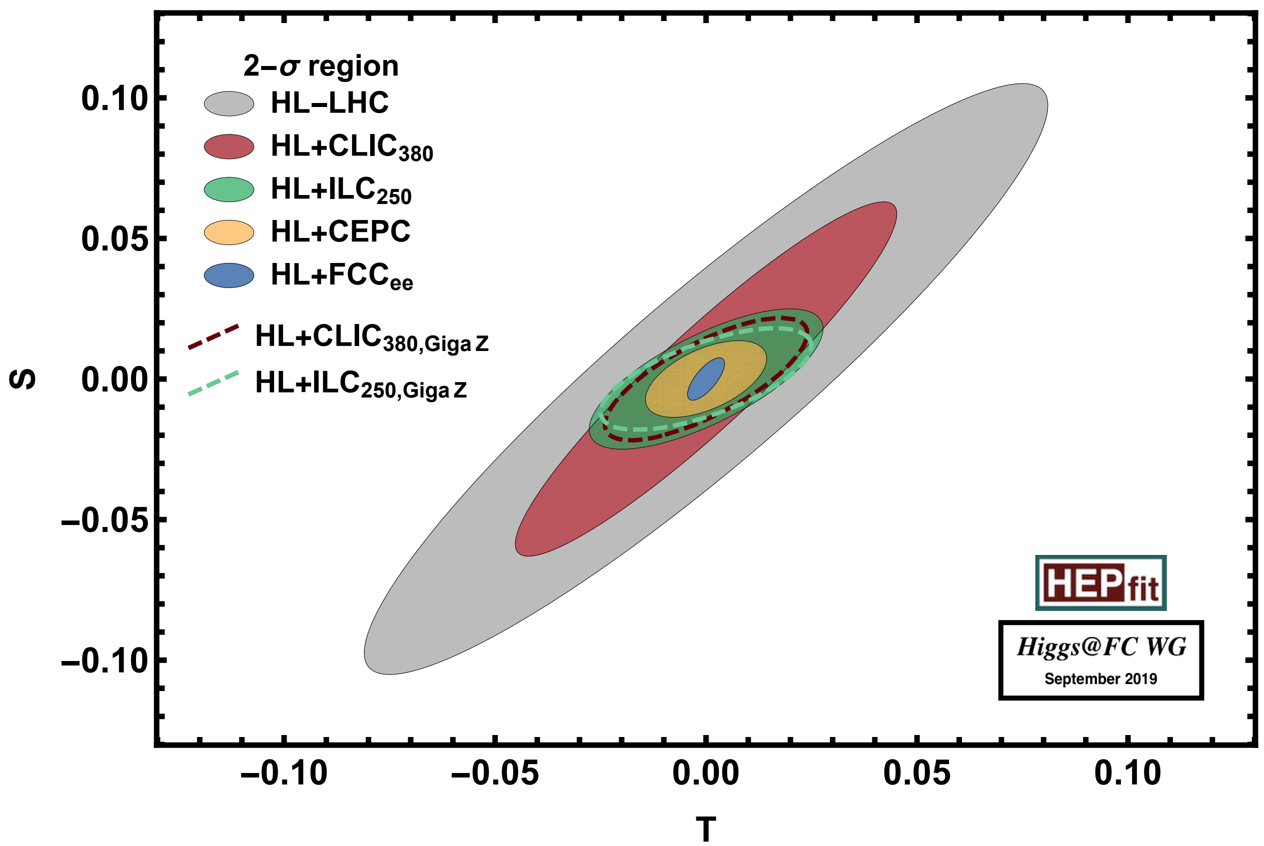
Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \to \gamma\gamma$ cross section to 0.002%
N_ν ($\times10^3$) from σ_{had}	2996.3 ± 7.4	0.007	1	0.2	Lineshape QED unfolding $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$
R_ℓ ($\times10^3$)	20766.6 ± 24.7	0.04	1	0.2 ?	Lepton angular distribution (QED ISR/FSR/IFI, EW corrections)
$\alpha_s(m_Z)$ ($\times10^4$) from R_ℓ	1196 ± 30	0.1	1.5	0.4 ?	Higher order QCD corrections for Γ_{had}
R_b ($\times10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, ...)

[P. Janot's talk @ CERN FC workshop 2022]

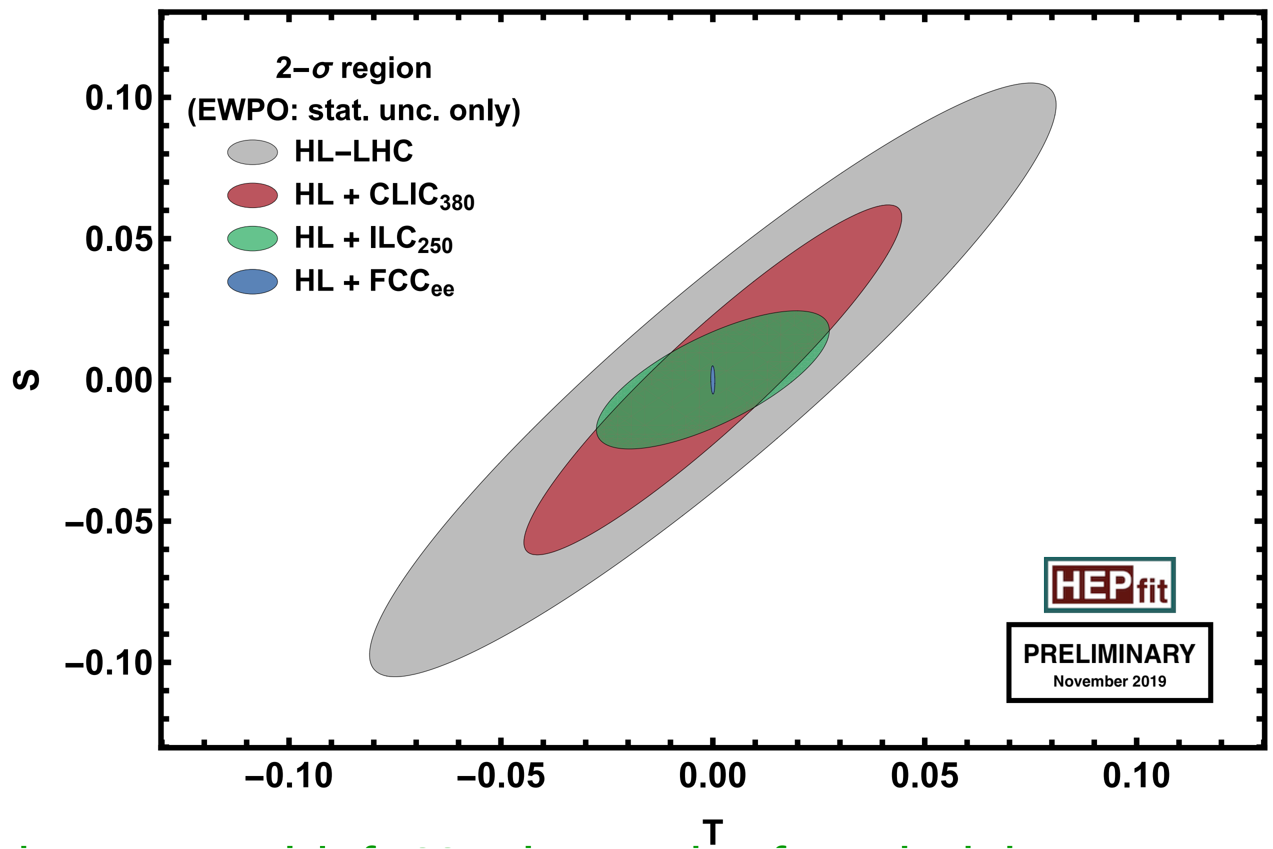
Global EW fits at FCC-ee

2106.13885

w/. stat.+ param. + th-exp syst.



w/ stat. and param. only



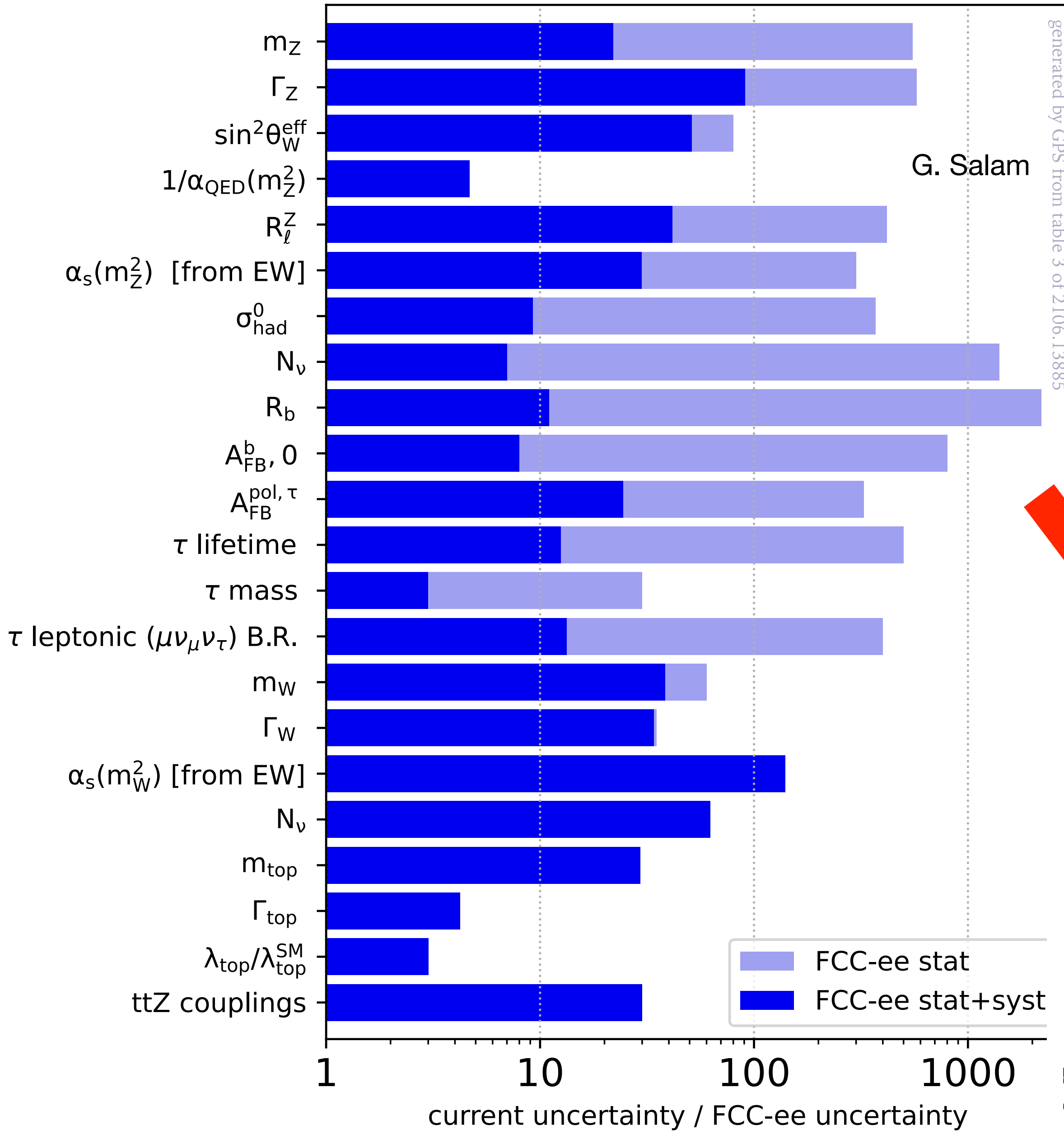
- oblique S,T,U parameters as an indirect probe of NP
- improve mass reach in indirect search for NP

  [$S \sim 10^{-2} \rightarrow M \sim 70$ TeV]
- in general, increase by X in accuracy gives increase

  by $\sqrt{X}$ in mass reach !!

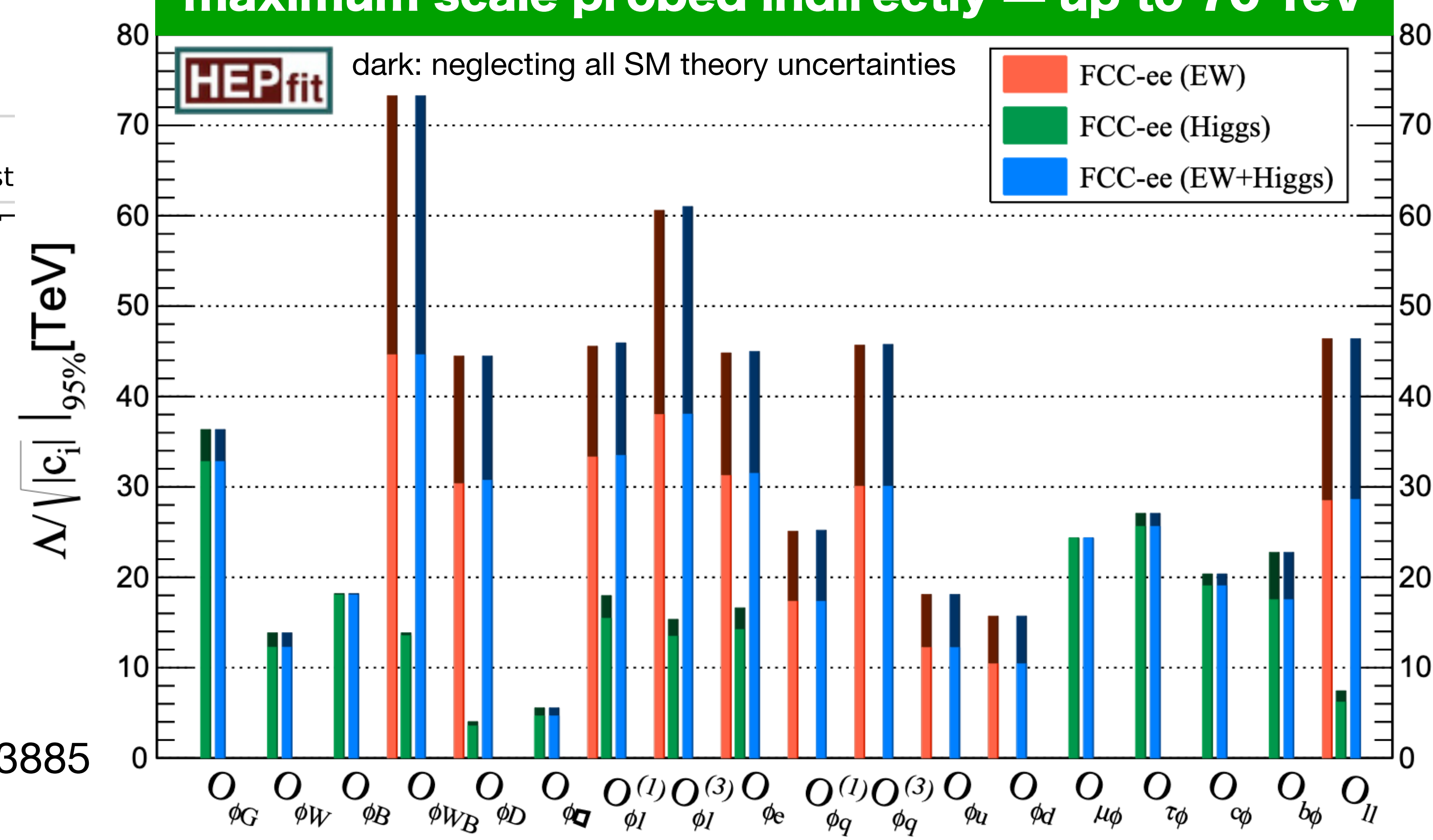
Precision vs Energy reach

FCC precision gain



4÷5 increase in EFT energy reach at FCC-ee !

maximum scale probed indirectly — up to 70 TeV



2106.13885

✱ crucial to improve systematics !

FCC-ee searches for BSM feebly coupled p.les

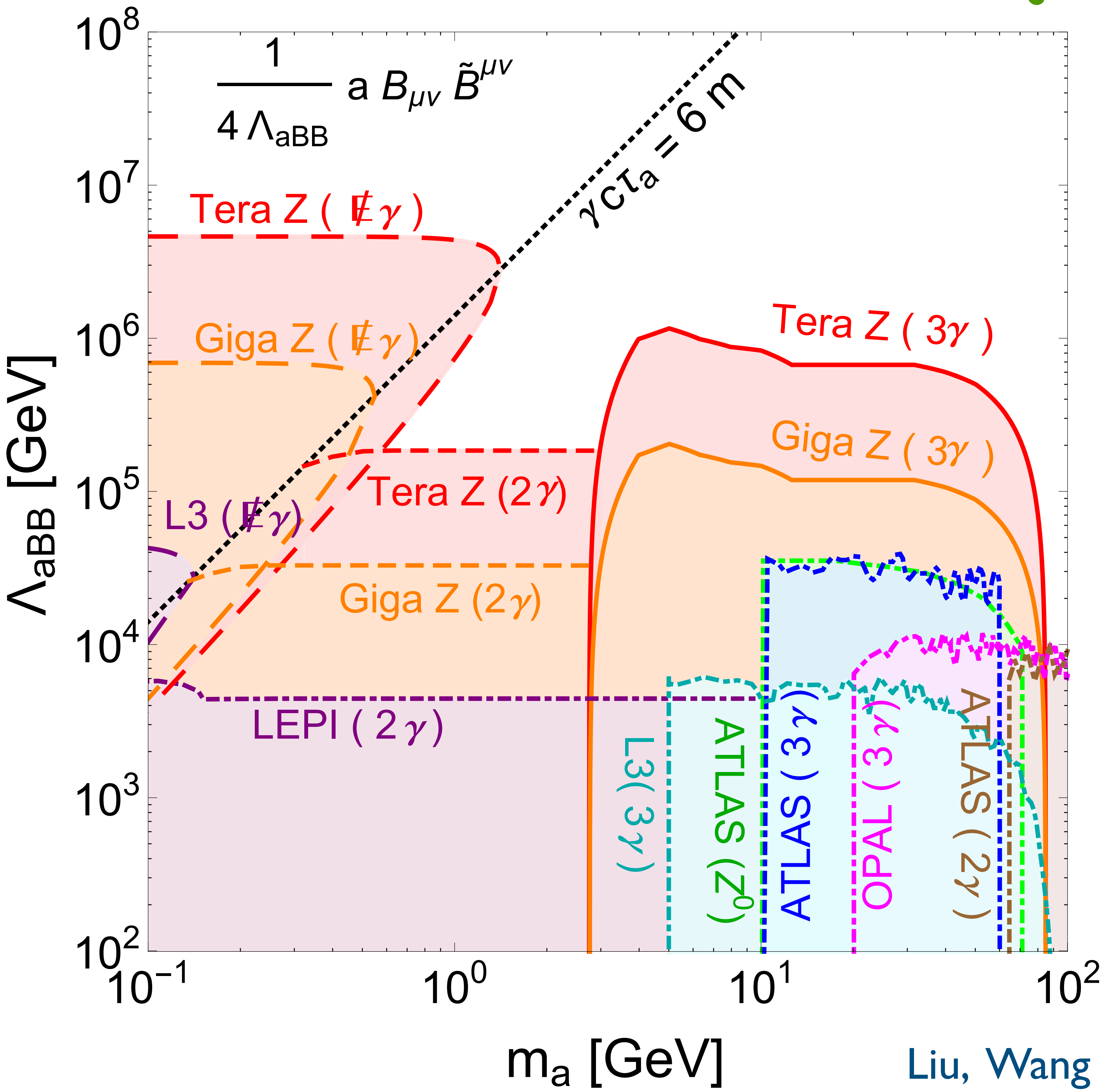
can benefit from huge Z-pole luminosity !

* Heavy Neutral Leptons
* Light SUSY scenarios and scenarios with light scalars
* Axion-like particles (ALP)
* Z′, dark photons and other light-mediator scenarios
* Exotic Higgs boson decays

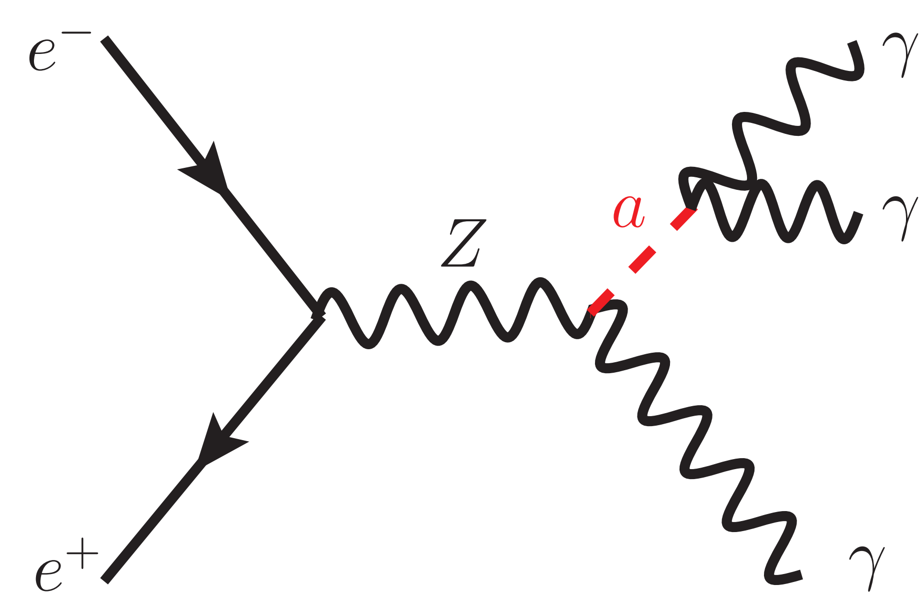
[models inspired by dark matter, baryon asymmetry, neutrino masses ...]

* also involving Long Lived Particles !

Exotic Z decays



* **Axion-like particles :**
  Tera/Giga Z widely extend present LEP/LHC bounds !

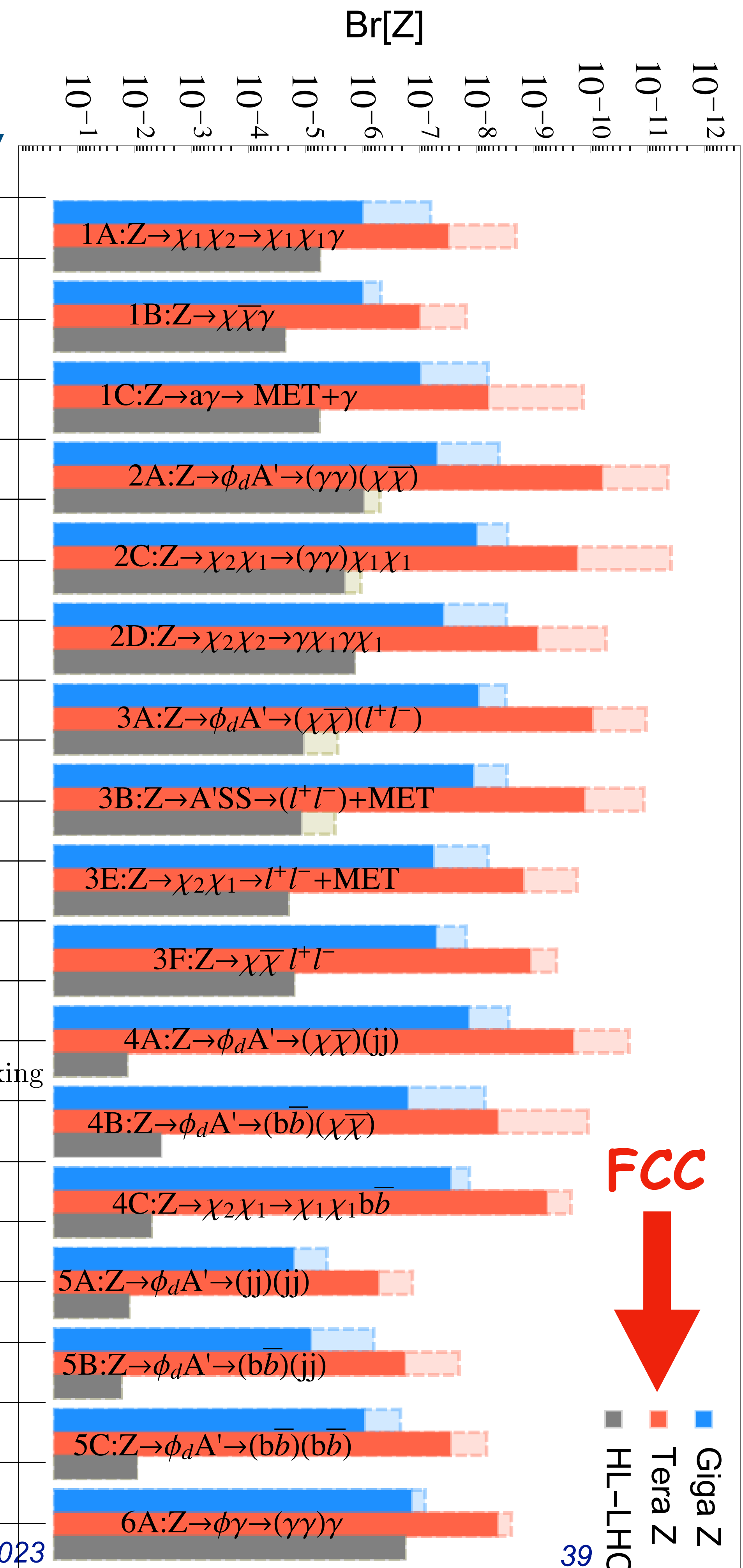


Liu, Wang, Wang, Xue, 1712.07237

✱ long list of models/signatures

Liu, Wang ,Wang, Xue, 1712.07237

exotic decays	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	1A: $\frac{1}{\Lambda_{1A}}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$ (MIDM)
	$Z \to \chi\bar{\chi}\gamma$	0	1B: $\frac{1}{\Lambda_{1B}^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu}$ (RayDM)
	$Z \to a\gamma \to (\not{E})\gamma$	1	1C: $\frac{1}{4\Lambda_{1C}}aB_{\mu\nu}\tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	1D: $\epsilon^{\mu\nu\rho\sigma}A'_\mu B_\nu \partial_\rho B_\sigma$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A'$,$\phi_d \to (\gamma\gamma)$, $A' \to (\bar{\chi}\chi)$	2	2A: Vector portal
	$Z \to \phi_H\phi_A$, $\phi_H \to (\gamma\gamma)$, $\phi_A \to (\bar{\chi}\chi)$	2	2B: 2HDM extension
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1	2C: Inelastic DM
	$Z \to \chi_2\chi_2$, $\chi_2 \to \gamma\chi_1$	0	2D: MIDM
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A'$, $A' \to (\ell^+\ell^-)$, $\phi_d \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	3B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	3D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\ell^+\ell^-$	0	3E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM
$Z \to (JJ)(JJ)$	$Z \to \phi_d A', \phi_d \to jj, A' \to jj$	2	5A: Vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to jj$	2	5B: vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to b\bar{b}$	2	5C: vector portal + Higgs portal
$Z \to \gamma\gamma\gamma$	$Z \to \phi\gamma \to (\gamma\gamma)\gamma$	1	6A: ALP, Higgs portal



Let's assume we find a deviation in H couplings...

- Deviation from SM: $\delta \sim v^2/M^2$
  - M scale of new physics
  - $M \sim 1 - 10$ TeV $\rightarrow \delta \sim 6 - 0.06\%$

* in order to figure out what's going on we will need an energy-frontier facility to explore the corresponding M scale in a direct way.
* R&D for future high-energy colliders (new technologies ?)
  hadron collider beyond LHC ?
  higher energy linear collider ? multi-TeV muon collider ?
  plasma acceleration ?

FCC-hh : 30 ab^{-1} at 100 TeV

* mass reach in BSM searches ~ (4÷6) x $M_{[HL-LHC]}$

* for multiple-heavy-p.le final states n(H,W,Z,t) N_{100}/N_{14} >100 (e.g. ~500 for ttH, ~400 for HH)

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

* much higher gain at high-P_T and large invariant masses !

FCC potential vs crucial sectors

arXiv:1906.02693, FCC-ee: Your questions answered

e^+e^- collisions (√s from m_Z to 3 TeV) — pp collisions (28/37/48 TeV and 100 TeV)

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

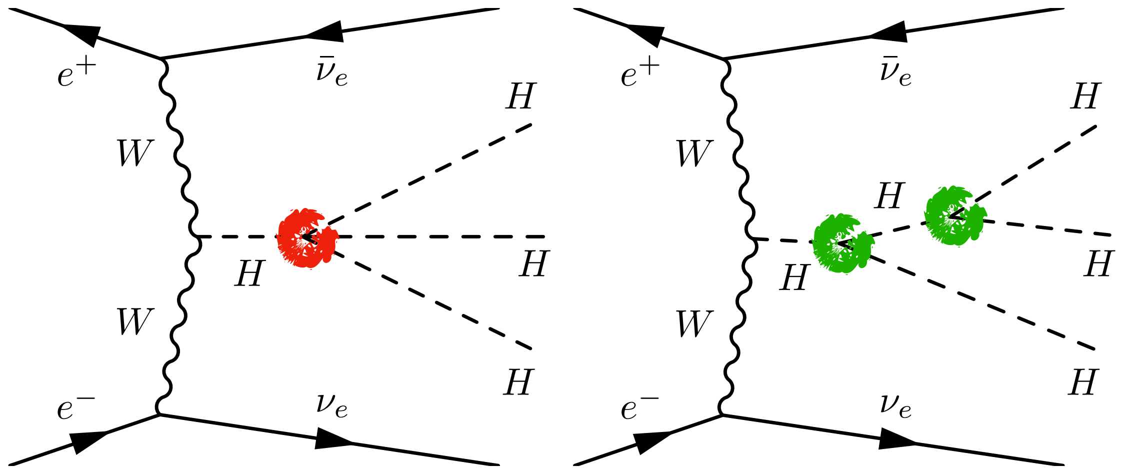
Green = Unique to FCC; **Blue = Best with FCC**; **(*) = if FCC-hh is combined with FCC-ee**; **Pink = Best with other colliders**

Further FCC options : PbPb, e-p, e-Pb

	$\sqrt{s}$	L /IP ($cm^{-2}\,s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	230 x10^{34} 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5 x 10^{34}	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep **Fcc-eh**	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb **Fcc-eh**	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

multi-TeV MuCol could measure λ'H⁴ !!

$$V_h = \frac{m_h^2}{2} h^2 + (1 + \kappa_3)\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1 + \kappa_4)\lambda_{hhhh}^{SM} h^4$$



$$\mu^+\mu^- \to HHH\nu\bar{\nu}, \ (\nu = \nu_e, \nu_\mu, \nu_\tau)$$

($\kappa_i \rightarrow \delta_i$)

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

(2003.13628)

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

Outlook

- ✱ an e^+e^- circular collider running at ZH, tt , WW, Z, (H) with L ~ $10^{(34-36)}$ $cm^{-2}s^{-1}$ can go beyond (HL-) LHC reach in many many different physics sectors...

- ✱ it is "not just" a wonderful Higgs precision probe !

- ✱ EWPT : order of magnitudes improvements wrt LEP
  (badly needed : advances in theory accuracies !)

- ✱ ideal setup for discovering (very) weakly interacting particles

- ✱ whatever deviation from SM predictions will be observed will require an Energy Frontier machine to be clarified !

- ✱ presently a few options...no one technogically mature yet...