Update of European Strategy for Particle Physics

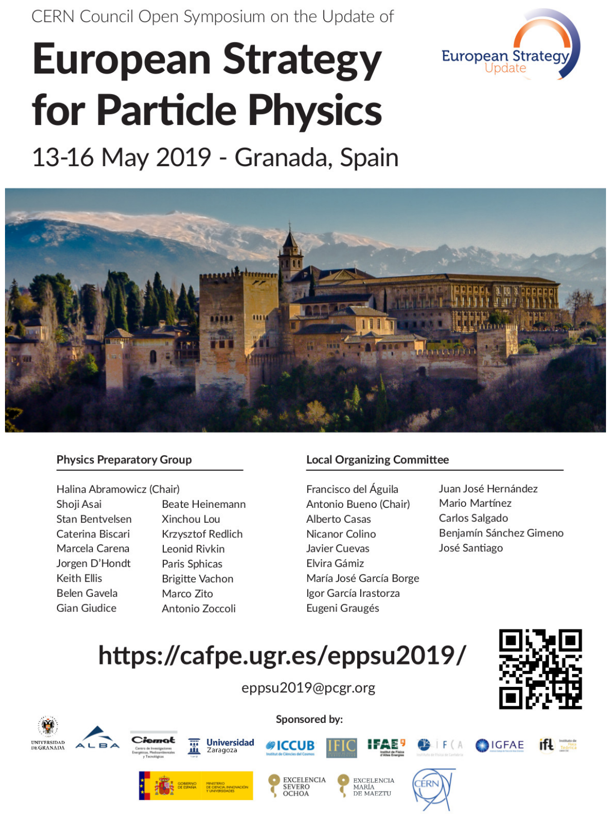
Beate Heinemann

Deutsches Elektronen-Synchrotron (DESY Hamburg) und Albert-Ludwigs Universität Freiburg

QU meeting, May 26th 2019

What is the European Strategy of Particle Physics?

- Last Update: May 2013
- Current Update planned for May 2020
- Important bodies (see backup for lists of members)
    - Physics Preparatory group (PPG): 17 people
        - Organizes Symposium (May 2019) and prepares *briefing book* (Sept. 2019)
        - Provides scientific input to strategy based on input of community
    - European Strategy Group (ESG): Members
        - Drafts the strategy update (Jan. 2020)
    - Strategy secretariat:
        - H. Abramowics (chair), J. D'Hondt, K. Ellis, L. Rivkin
        - Coordinates the process
    - CERN Council:
        - Approves strategy in May 2020
- CERN management is responsible for implementing strategy
- Strategy also serves as important guideline for national funding agencies



~600 participants

Strategy Secretariat

- H. Abramowicz (Chairperson)
- J. D'Hondt (ECFA Chairperson, *ECFA: European Committee for Future Accelerators*)
- K. Ellis (SPC Chairperson, *SPC: Science Policy Committee @ CERN*)
- L. Rivkin (European LDG Chairperson, *LDG: Lab Directors Group*)

- Contact: EPPSU-Strategy-Secretariat@cern.ch

Responsible for the organization of the process.

European Strategy Update

Composition of the PPG

Physics Preparatory Group (PPG), Council appointment, September 2018:

- H. Abramowicz, J. D'Hondt, K. Ellis, L. Rivkin (*Strategy Secretary*)
- C. Biscari (ES), Belen Gavela (ES), Beate Heinemann (DE), Krzysztof Redlich (PL)
- Stan Bentvelsen (NL), Paris Sphicas (GR), Marco Zito (FR), Antonio Zoccoli (IT)
- Gian Giudice (*CERN*)
- Shoji Asai and Xinchou Lou (*delegates from Asia*)
- Marcela Carena and Brigitte Vachon (*delegates from the Americas*)

Responsible to organize the Open Symposium and to deliver to the European Strategy Group (ESG) a Briefing Book.

Names at
http://europeanstrategyupdate.web.cern.ch/composition-esg

Composition of the ESG

European Strategy Group (ESG) composition, adopted by Council, December 2013:

- the Strategy Secretary (acting as Chairperson),
- one representative appointed by each CERN Member State,
- one representative for each of the Laboratories participating in the major European Laboratory Directors' meeting, including its Chairperson,
- the CERN Director-General,
- the SPC Chairperson,
- the ECFA Chairperson.

Responsible to deliver a draft Strategy Update to Council.

Invited:

- the President of the CERN Council,
- one representative from each of the Associate Member States,
- one representative from each Observer State,
- one representative from the European Commission and JINR,
- the Chairpersons of ApPEC, FALC, ESFRI, and NuPECC,
- the members of the Physics Preparatory Group.

Composition of the ESG

Names at
http://europeanstrategyupdate.web.cern.ch/composition-esg

European Strategy Group (ESG) composition, adopted by Council, December 2013:

- the Strategy Secretary (acting as Chairperson),
- one representative appointed by each CERN Member State,
- one representative for each of the Laboratories participating in the major European Laboratory Directors' meeting, including its Chairperson,
- the CERN Director-General,
- the SPC Chairperson,
- the ECFA Chairperson.

For Germany: Siggi Bethke

For DESY: Joachim Mnich

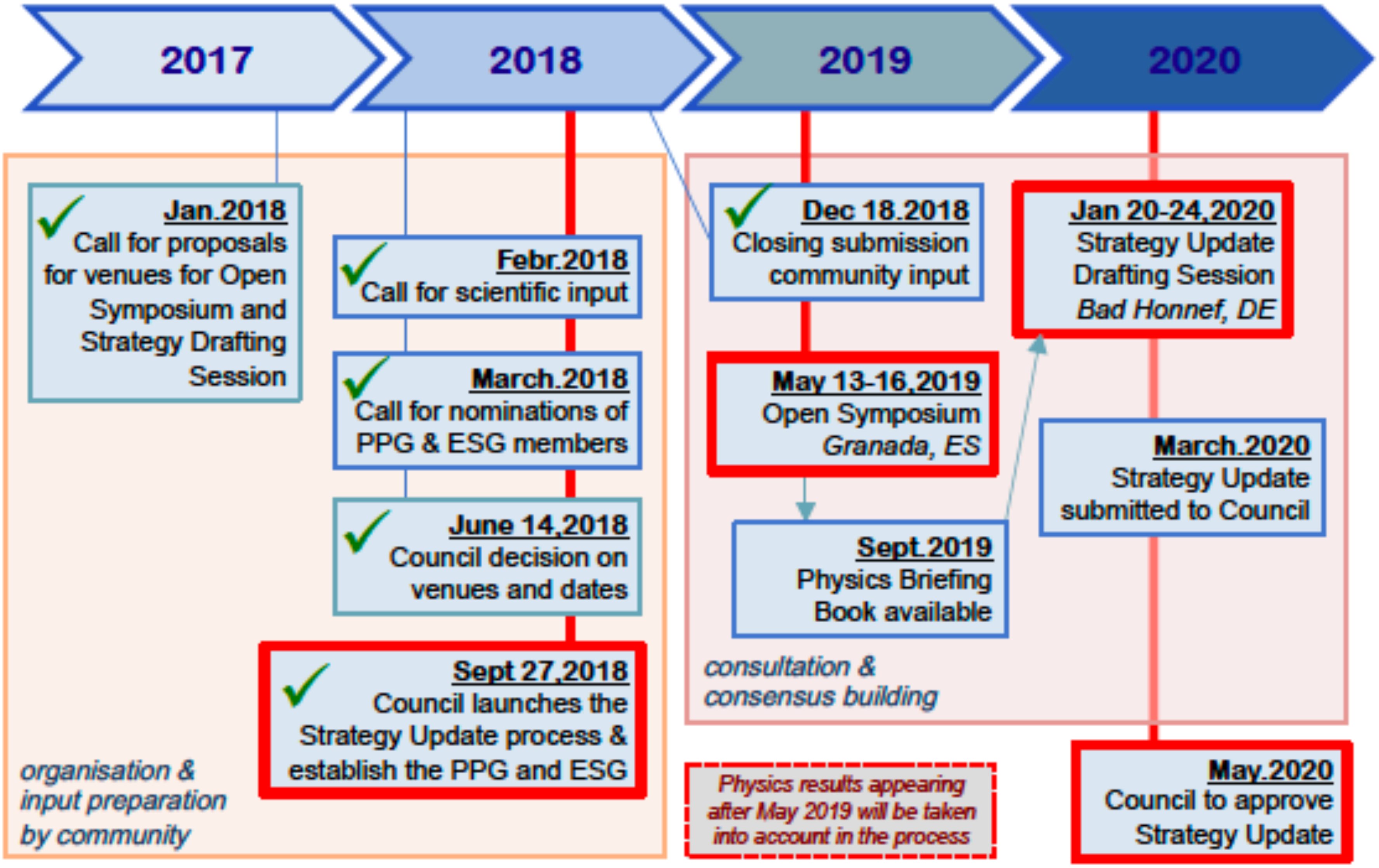
Responsible to deliver a draft Strategy Update to Council.

Invited:

- the President of the CERN Council,
- one representative from each of the Associate Member States,
- one representative from each Observer State,
- one representative from the European Commission and JINR,
- the Chairpersons of ApPEC, FALC, ESFRI, and NuPECC,
- the members of the Physics Preparatory Group.

Incl. BH

Timeline



H. Abramowics

Input received and Sessions in Granada

- Call for inputs issued February 28, 2018 with deadline for submission December 18, 2018
- 160 submissions received

Track ID	Granada sessions	Description	Conveners		
1		Large experiments and projects	PPG/ESG		40
2		National road maps	ESG		42
7	B1	Electroweak Physics (physics of the W, Z, H bosons, of the top quark, and QED)	Keith Ellis	Beate Heinemann	21
8	B2	Flavour Physics and CP violation (quarks, charged leptons and rare processes)	Belen Gavela	Antonio Zoccoli	27
5	B3	Dark matter and Dark Sector (accelerator and non-accelerator dark matter, dark photons, hidden sector, axions)	Marcela Carena	Shoji Asai	27
3	B4	Accelerator Science and Technology	Caterina Biscari	Lenny Rivkin	51
4	B5	Beyond the Standard Model at colliders (present and future)	Gian Giudice	Paris Sphicas	20
10	B6	Strong Interactions (perturbative and non-perturbative QCD, DIS, heavy ions)	Krzysztof Redlich	Jorgen D'Hondt	31
9	B7	Neutrino Physics (accelerator and non-accelerator)	Stan Bentvelsen	Marco Zito	23
6	B8	Instrumentation and Computing	Xinchou Lou	Brigitte Vachon	35
11		Other (communication, outreach, strategy process, technology transfer, individual contributions,...)	ESG		

- The Open Symposium aims to reach a consensus on the *scientific goals* of the community, based on the provided input, and assess the proposed projects and technologies to achieve those goals

- This is to ensure that the ESG is provided with all the necessary input to propose a realistic update of the Strategy – decisions on strategic choices are not expected to be taken this week

H. Abramowics

<u>8 parallel sessions in Granada: B1-B8</u>

EPPSU 2020

Open Symposium

Parallel Sessions convened by members of the PPG

- Experts invited to summarise submitted input
- Two sessions per theme, separated by half a day
- Focus on a few fundamental questions (posted on Granada website under "Organisation of the Symposium")
- Plenty of time for discussions

Plenary Sessions

- Two half-days to review where we stand and what is expected of the European community, also by communities outside Europe
- Full day of summaries from the parallel session discussions

=> Webcast of Thursday Summary talks
https://webcast.web.cern.ch/event/596

- End product of the Symposium → Briefing Book based on the summaries, compiled by the PPG, assisted by scientific secretaries who will take note of the discussions in each session

H. Abramowics

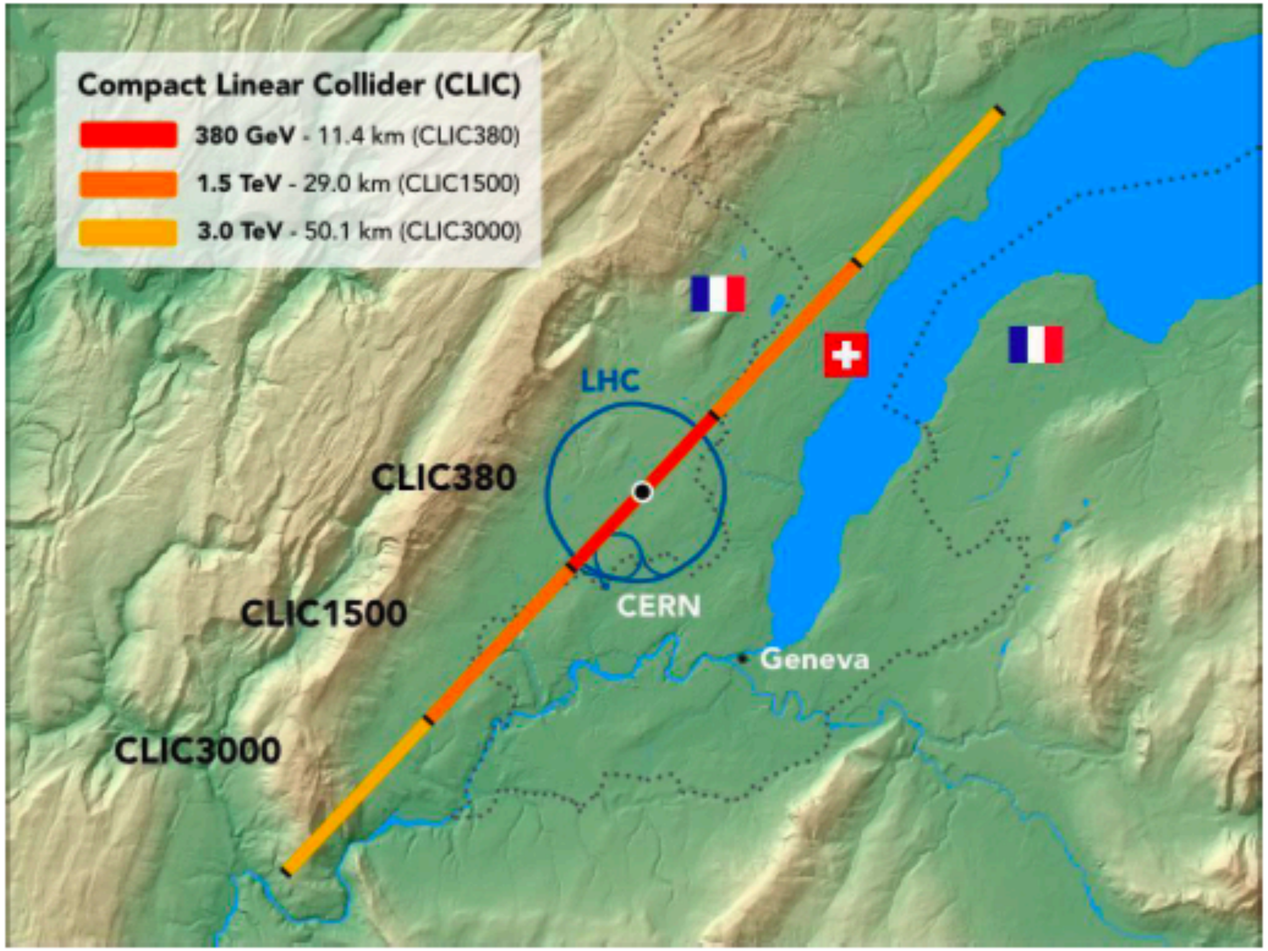
Accelerators

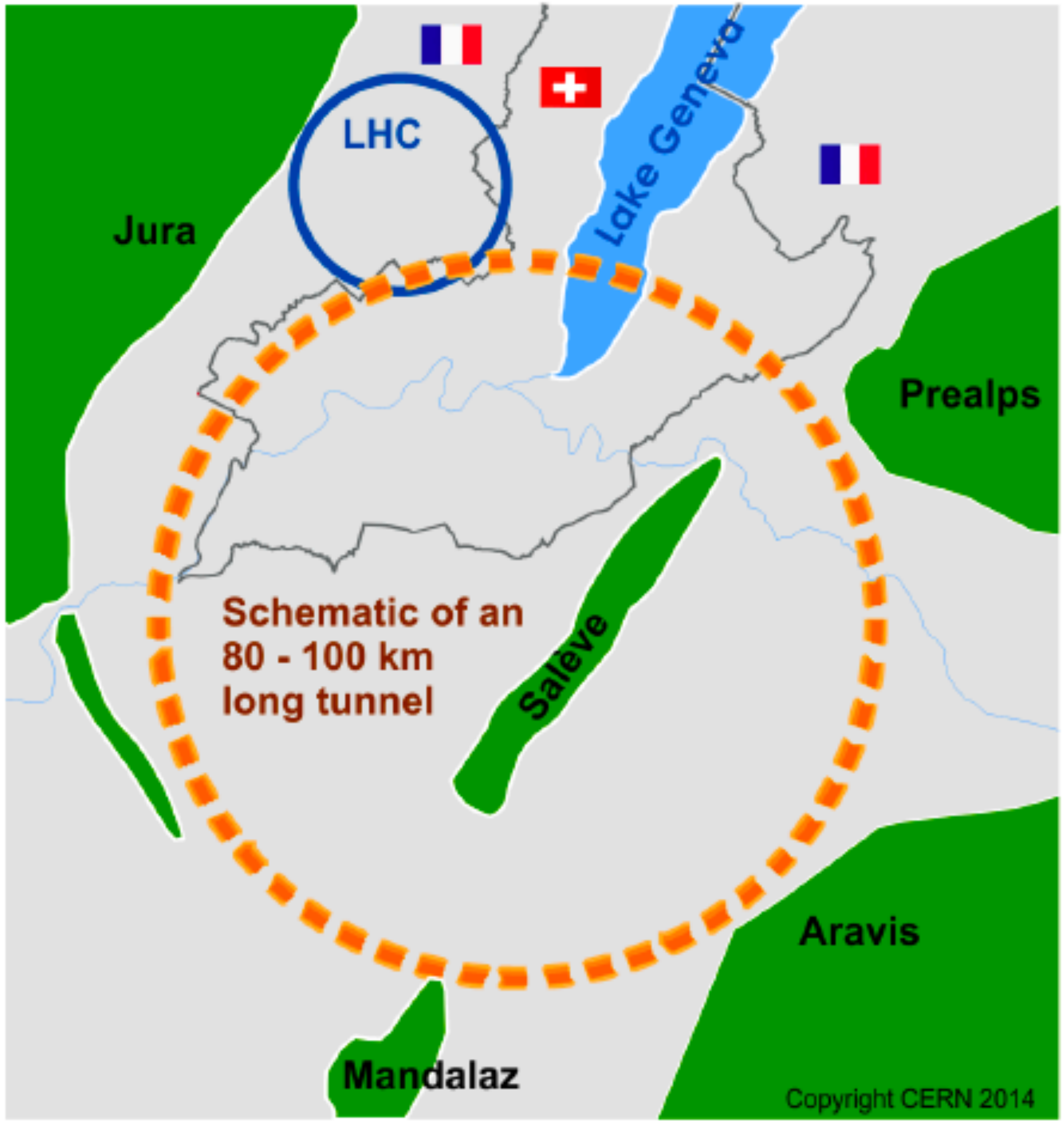
Big Questions

In particular for the Accelerator Science and Technology

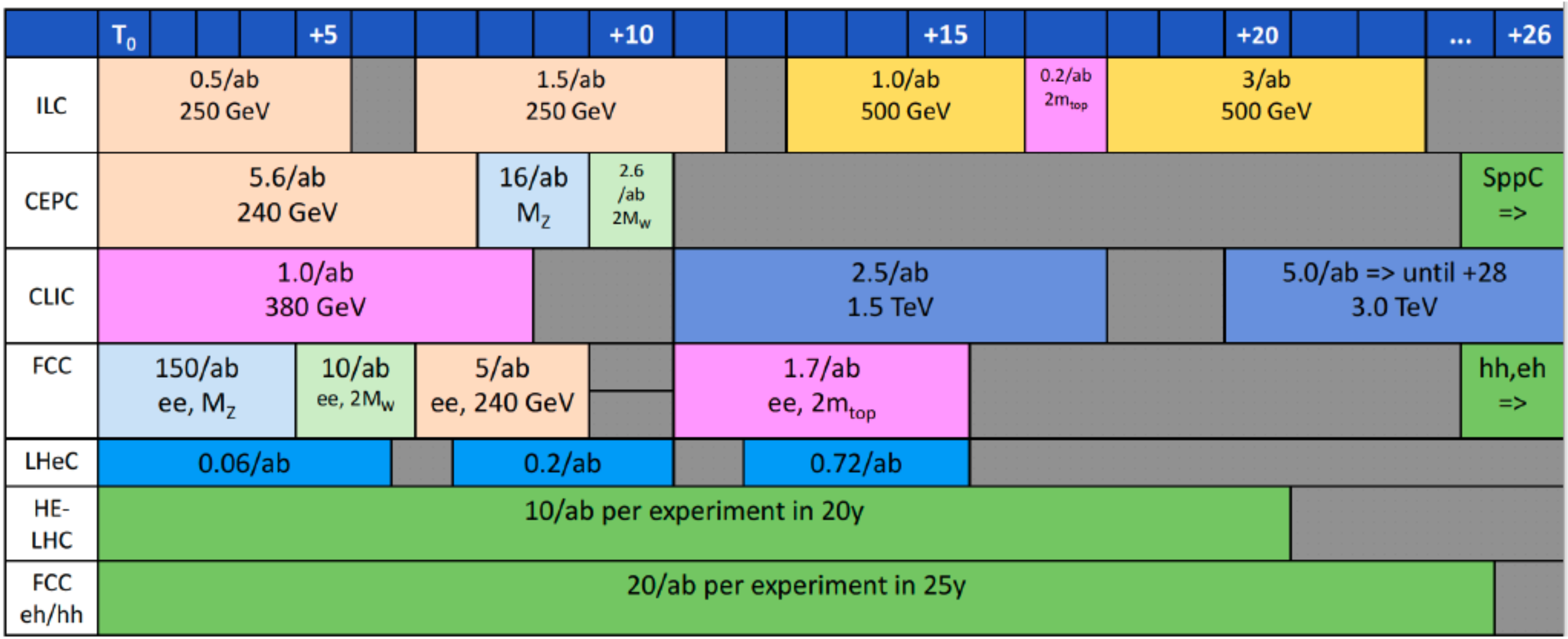
- What is the best implementation for a Higgs factory?
  Choice and challenges for accelerator technology: linear vs. circular?
- Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?
- How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?
- Energy management in the age of high-power accelerators?

Q1: What is the best implementation for a Higgs factory?
Choice and challenges for accelerator technology: linear vs. circular?



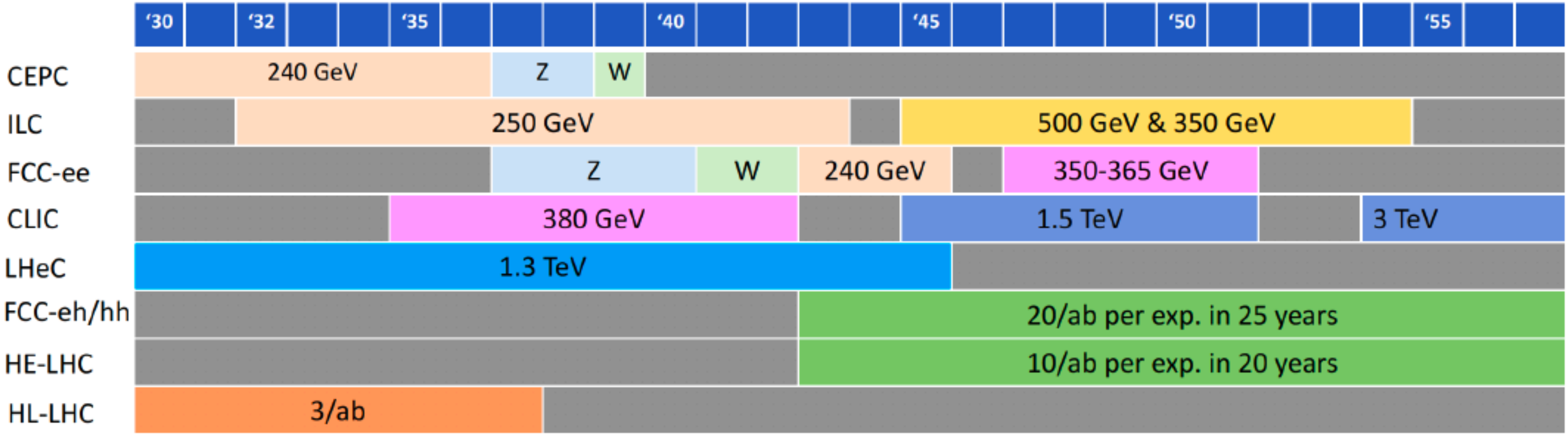


Collider Schedules: starting from T_0



NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3×10^7

Schedules: by calendar year



LHC:
150 MW

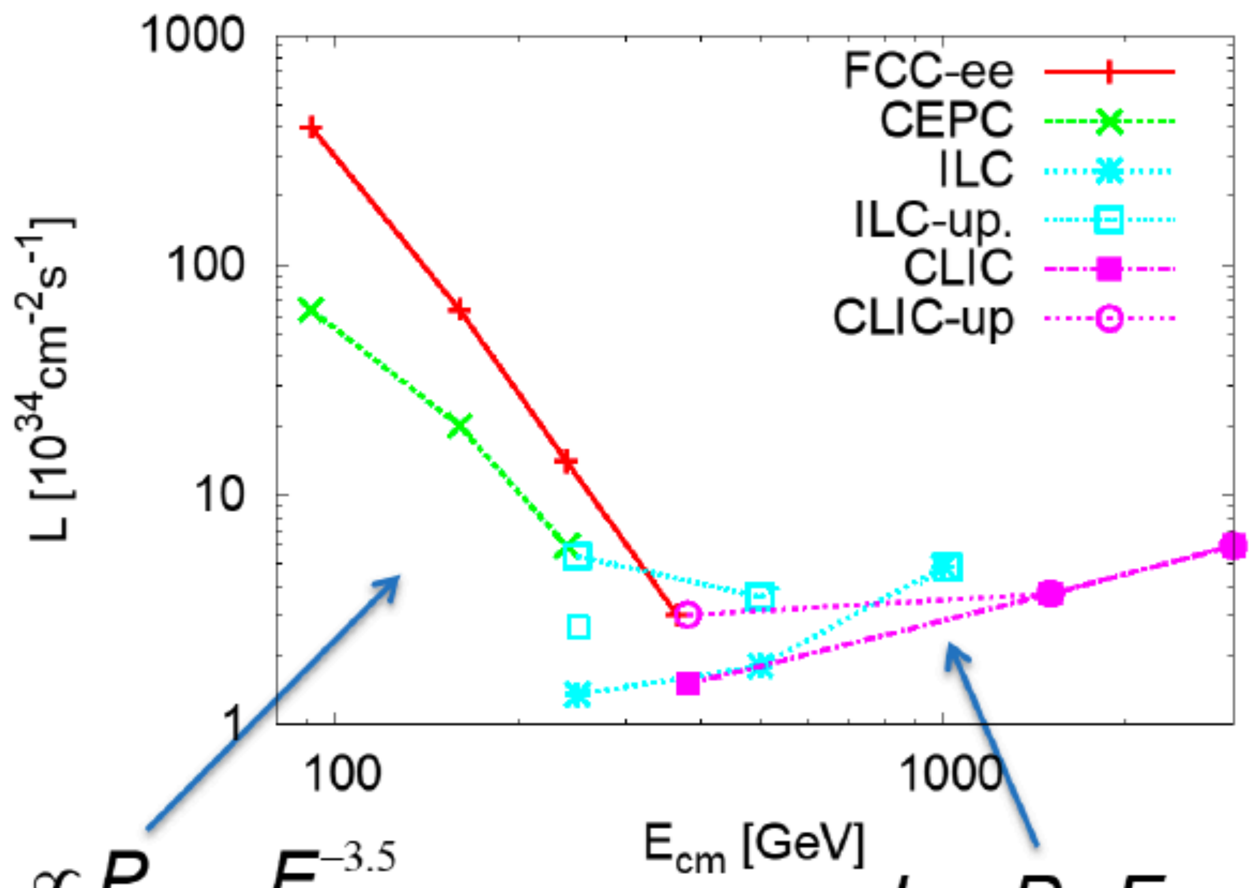
Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

C. Biscari, L. Rivkin

ee Colliders

Ours is a very dynamic field!
(Luminosity upgrades for ILC, CLIC)

Luminosity per facility



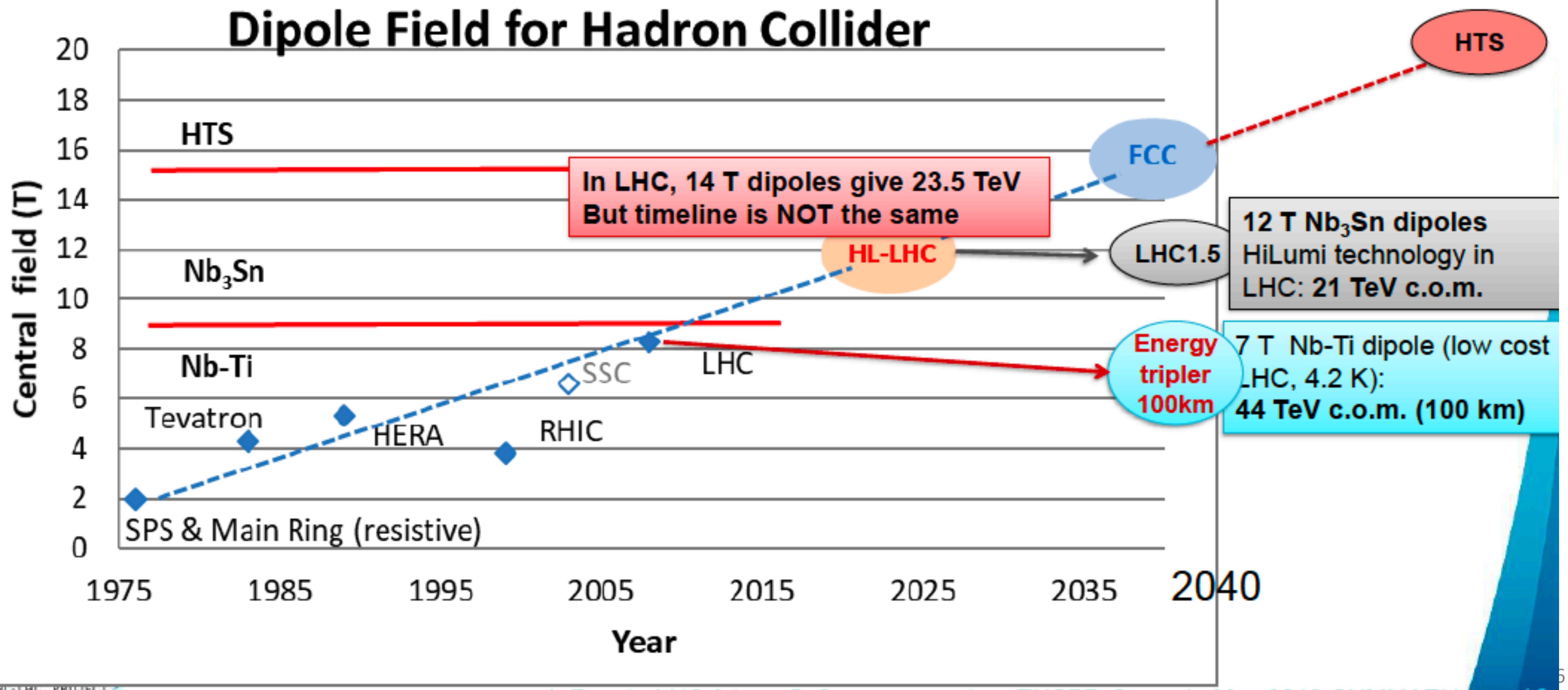
$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF} E_{cm}$

All considered to be mature
⇒Can start construction
within 5-10 years

pp Colliders

Slide by Lucio Rossi



Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CChh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CCee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 – (40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LCee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	4.8- 5.3 (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

*Cost estimates are commonly for "**Value**" (material) only.

A. Yamamoto, 190513b

C. Biscari, L. Rivkin

ee and pp colliders:

Personal (A. Yamamoto) View on Relative Timelines

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF—LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collider (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	

Note: **LHC experience: NbTi (10 T)** R&D started in 1980's --> **(8.3 T)** Production started in late 1990's, in ~ 15 years

A. Yamamoto 190512b 18

pp collider schedule depends critically on progress in high field magnet R&D

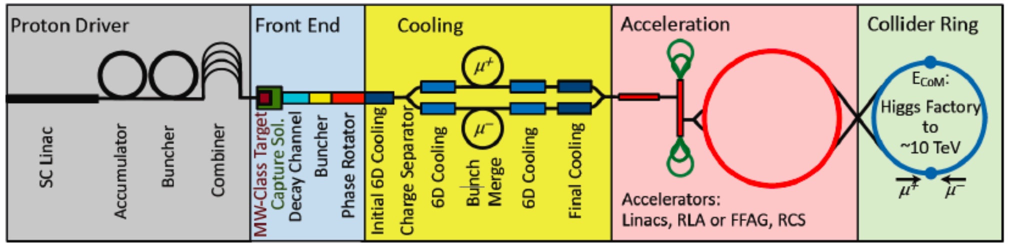
C. Biscari, L. Rivkin

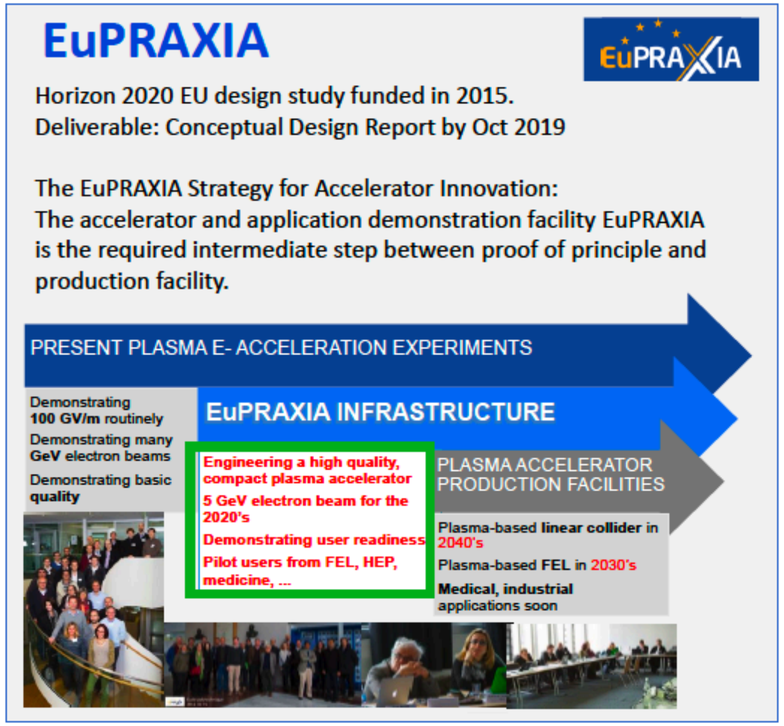
Further (Far?) Future

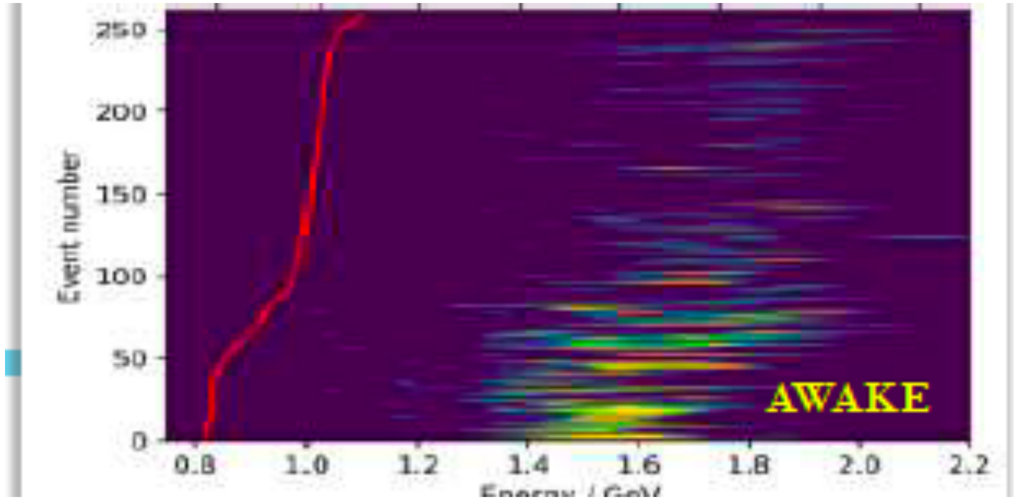
Very interesting R&D projects

- Muon collider:
  - from proton beam (rcooling success: MICE)
  - from e+e- production (LEMMA)
- Plasma wakefield acceleration:
  - High gradients possible: ~100 GV/m
  - R&D progressing well but many challenges

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.







Views from Americas and Asia

Young-Kee Kim for the Americas

Conclusions: Towards 2020 ESG

- Support of Americas' current plan
  - Importance of current high-priority projects such as HL-LHC, DUNE, …
- Beyond mid-2020's
  - Scientific drivers of the current plans are still valid
  - More capable facilities and broader programs
  - R&D of enabling technologies for future (accelerator, detector and computing)
- Support of facilities and activities outside of Europe
  - DUNE/LBNF, SNOLAB, CMB-S4, EIC, ….
  - A statement in the ESG document plays a significant role for success of facilities outside of Europe that serves the European / worldwide community
- The American community
  - will continue with its strong partnership with Europe
  - would like to see positive steps toward a new collider: an e+e- collider might be the first one to be realized: O(1000) American community

Open Symposium – European Strategy Update, 2019-05-15, Granada   Young-Kee Kim, University of Chicago   31

Geoffrey Taylor for Asia

Asian (and personal) View

- Diversity is Critical to thrive in all environments, including HEP.
  - *Big and small facilities/experiments, at various stages of development and operation*
- Push for e+e- colliders, both Linear and Circular, as soon as possible.
  - *Linear Collider: ILC*
    - 1 Collision point
  - *Circular Collider: CepC*
    - 2 Collision points
- Push for FCC tunnel to be ready at completion of HL-LHC
  - *Stage the energy frontier with best option magnets available for early 2040's*
  - *?? Default: ~8T LHC magnets optimised for price*
    - Minimum energy: >50TeV
    - Magnet upgrade foreseen.
  - *ep and ion-ion options available*
  - *4 collision points*
  - *Upgrade path to higher energy after 20 years operation?*

See A. Yamamoto, L. Rossi, V. Shiltzev talks this symposium

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale   Geoffrey Taylor "Perspective on the European Strategy from Asia", EPPSU2019, Granada   43   European Strategy Update

Conclusions and Outlook I

Gigantic amount of information reviewed at Symposium in Granada

- Many excellent talks and a lot of time for discussion
- Input of LHC experiments via Yellow Reports was critical!
- Discussions were constructive and focused on scientific aspects
    - Finances and schedule also touched on though
    - Some complaints about existence of parallel sessions

Discussions in Granada form basis of “Briefing Book”

- In some cases some additional information being collected
- Release by PPG planned for **Sept. 10th**

Conclusions and Outlook II

Discussions points during Granada on may topics, e.g.

- Is it critical to have ee collider next?
- Do we want pp collider in not too distant future? Even maybe in 100km tunnel with NbTi magnets to start with?
- Should CERN invest more in astrophysics?
- How to ensure support of theory for precision calculations?
- How to collaborate better with industry for detector development?
- …

European Strategy Group will continue these discussions

- Regular meetings of ESG are going on already in parallel to PPG work
- Contact your national representative in case of thoughts/worries etc.
- Final drafting session in Jan. 2020

Backup Slides

Electroweak Physics

Answers to Big Questions

1. **How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?**
   - Current colliders: ~1-3% for 3rd gen fermions and gauge bosons, 4% to μ, 50% to itself
   - Future colliders: factors of ~2-10 better (!) + $\kappa_c \sim 2\%$ + model-independent $\sigma(ZH)$
2. **How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?**
   - Important to make sure precision H measurements (δg_Z) not limited by these
   - Themselves probe new physics in interesting and complementary way
3. **What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?**
   - A lot of progress needed! Plan exists but lots of work/people needed!!
   - In some cases, new ideas are needed => and unclear when/if new ideas come
4. **What is the best path towards measuring the Higgs potential?**
   - Di-Higgs and single Higgs production are sensitive to derivative $d^3V/d^3\phi$ near minimum
   - Seems conceivable to determine it with sufficient precision to test 1st order EWΦT

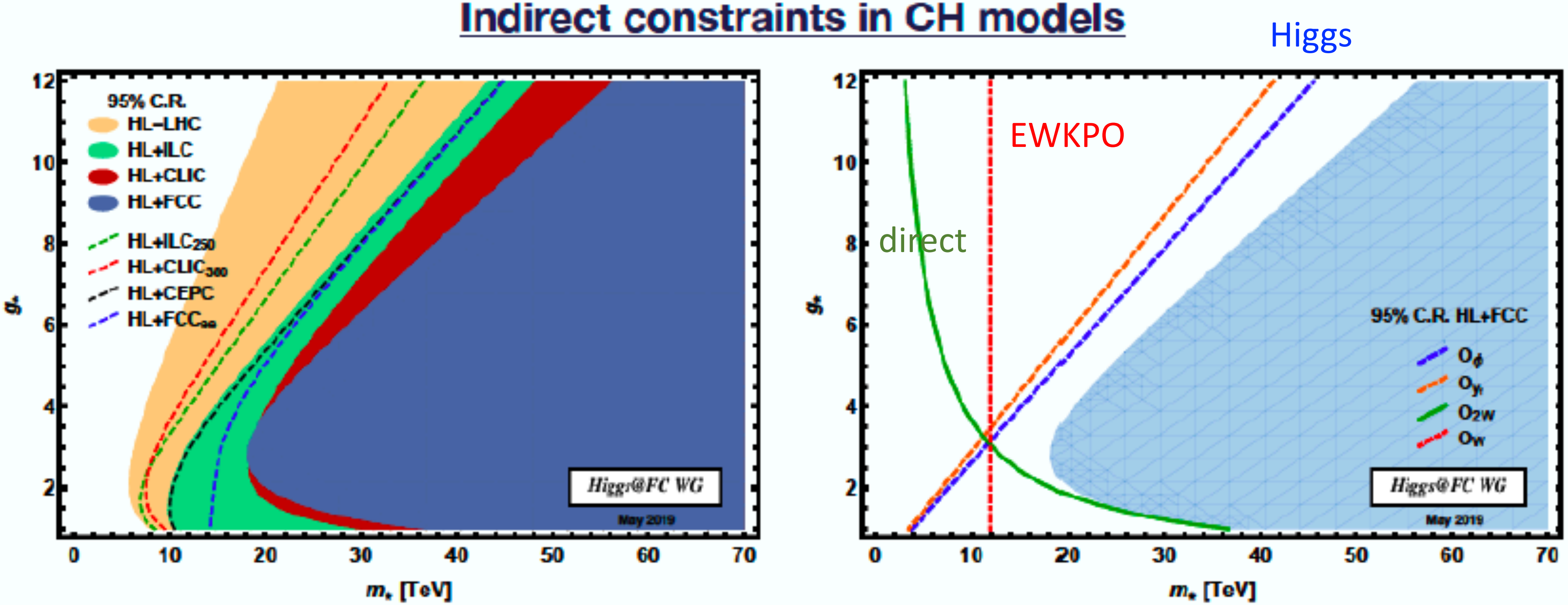
The Big Questions (BQs)

P. Sphicas

- **The four big questions for BSM (@colliders):**
  - To what extent can we tell whether the Higgs is fundamental or composite?
    - EWSB/NewReson, SUSY
  - Are there new interactions or new particles around or above the electroweak scale?
    - EWSB/NewReson, SUSY, Ext-H/FlavorDyn, DM, FIPs
  - What cases of thermal relic WIMPs are still unprobed and can be fully covered by future collider searches?
    - DM, FIPs, SUSY
  - To what extent can current or future accelerators probe feebly interacting sectors?
    - FIPs, SUSY

Indirect constraints on Composite Higgs

Indirect constraints in CH models



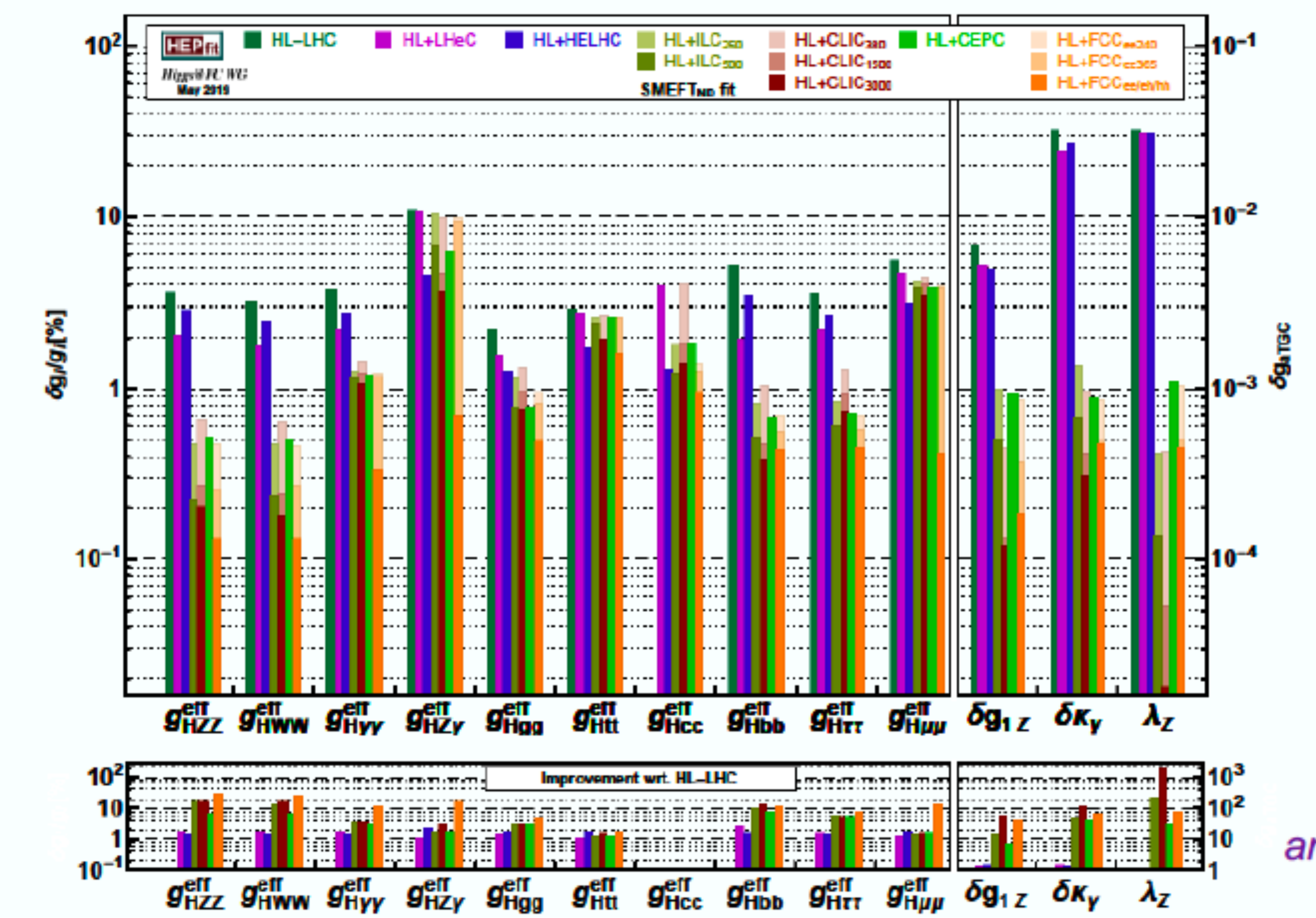
Simplified CH benchmark: 1 coupling (g*) - 1 scale (m*)

$$\frac{c_{\phi,6,y_f}}{\Lambda^2} = \frac{g_\star^2}{m_\star^2}, \qquad \frac{c_{W,B}}{\Lambda^2} = \frac{1}{m_\star^2}, \qquad \frac{c_{2W,2B,2G}}{\Lambda^2} = \frac{1}{g_\star^2}\frac{1}{m_\star^2},$$

$$\frac{c_T}{\Lambda^2} = \frac{y_t^4}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{\gamma,g}}{\Lambda^2} = \frac{y_t^2}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{\phi W,\phi B}}{\Lambda^2} = \frac{g_\star^2}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{3W,3G}}{\Lambda^2} = \frac{1}{16\pi^2}\frac{1}{m_\star^2}$$

J. de Blas

Comparison of Colliders: EFT



Effective Higgs couplings

- Constraints approach 0.1% precision for gauge bosons
- Major improvement w.r.t. HL-LHC for many colliders for fermions

Trilinear gauge couplings

- Will achieve precision 10^{-3}-10^{-4}
- About 2-3 orders of magnitude better than LEP

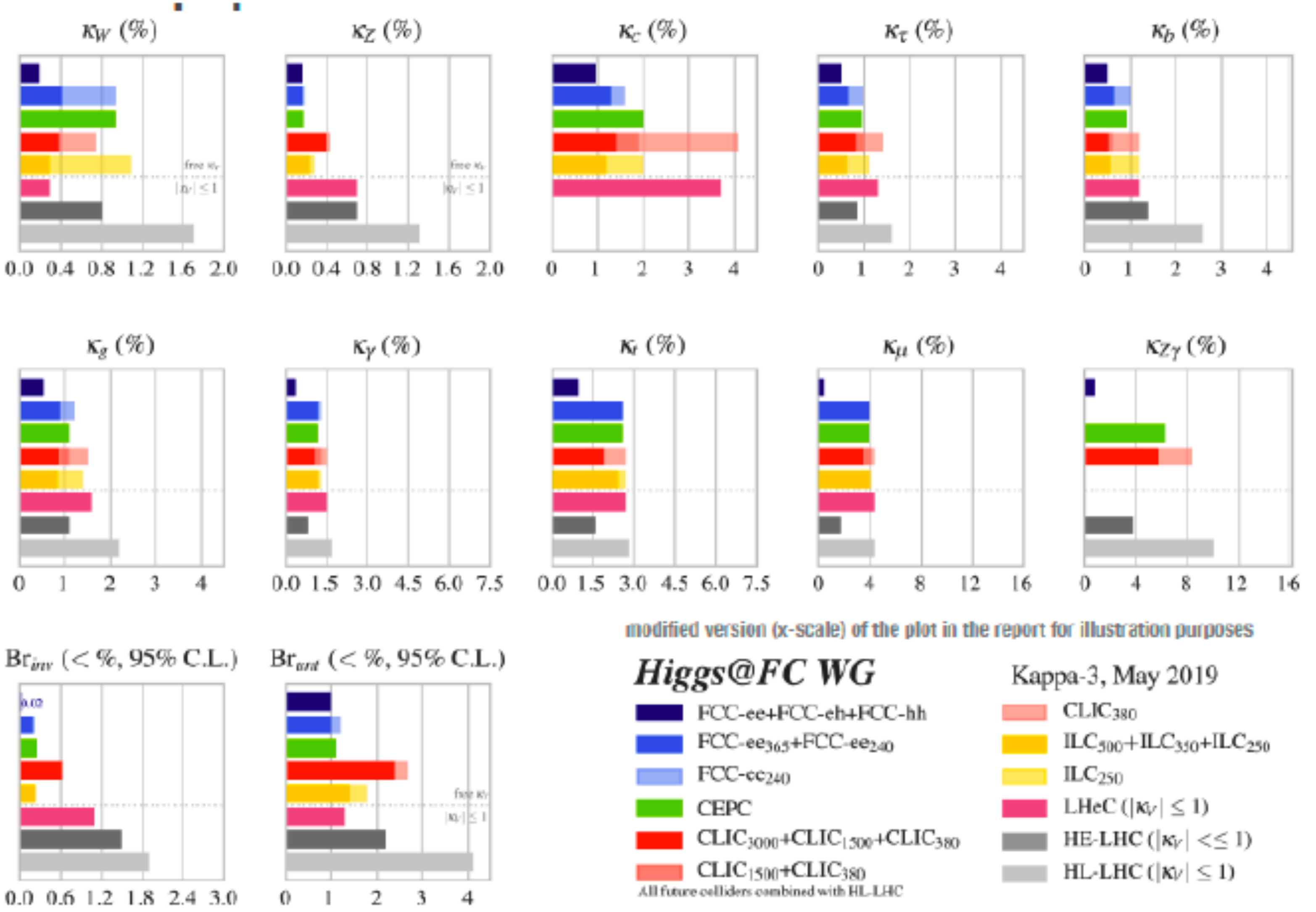
arXiv:1905.03764

Comparison of Colliders: kappa-framework

Some observations:

- **HL-LHC achieves precision of ~1-3% in most cases**
  - In some cases model-dependent
- **Proposed e^+e^- and ep colliders improve w.r.t. HL-LHC by factors of ~2 to 10**
- **Initial stages of e^+e^- colliders have comparable sensitivities (within factors of 2)**
- **ee colliders constrain $BR \rightarrow untagged$ w/o assumptions**
- **Access to κ_c at ee and eh**

arXiv:1905.03764



of "largely" improved H couplings (EFT)

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2^{nd}/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
2^{nd}/3rd Run ee	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

13 quantities in total

NB: number of seconds/year differs: ILC $1.6\text{x}10^7$, FCC-ee & CLIC: $1.2\text{x}10^7$, CEPC: $1.3\text{x}10^7$

Theory uncertainties for EWK physics

ILC and FCC-ee have great potential for high-precision Z, WW, and Higgs physics

Can theory provide the necessary precision?

$\hookrightarrow$ Optimists: "Yes. No show-stoppers seen, great progress can be anticipated."

Sceptics: "Enormous challenge! Conceptual progress difficult to extrapolate."

Some warnings:

- Produce solid and conservative uncertainty estimates!
- Always combine experimental and theoretical uncertainties!
- Employ different theoretical strategies and exp. analyses as much as possible! (e.g. for α_s, $\Delta\alpha_{had}$)

The greatest challenges: (+ many more very demanding tasks)

- Z:
  - ⋄ full EW 2-loop calculation for off-shell $e^+e^- \to f\bar{f}$ + theoretically sound concept of pseudo-obervables
  - ⋄ massive 3-loop calculations for $1 \to 2$ decays and μ decay
- WW:
  - ⋄ NNLO threshold EFT calculation for $e^+e^- \to WW$
- Higgs:
  - ⋄ full EW 2-loop calculation for off-shell $e^+e^- \to ZH$
  - ⋄ massless 4-/5-loop QCD calculations for $1 \to 2$ decays

$\hookrightarrow$ Certainly takes another generation of bright minds!

S. Dittmaier

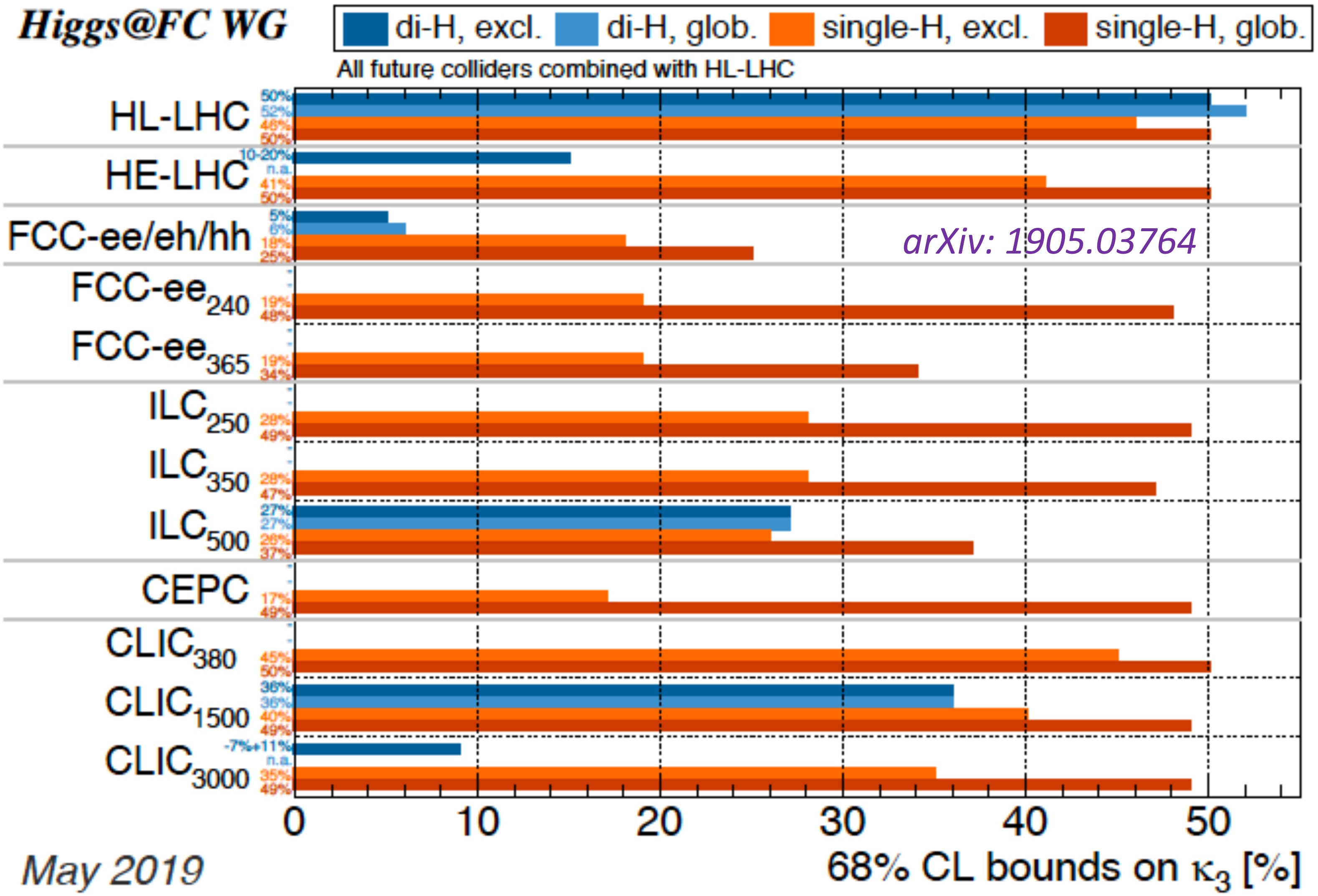
Sensitivity to λ: via single-H and di-H production

Di-Higgs:

- HL-LHC: ~50% or better?
- Improved by HE-LHC (~15%), ILC_{500} (~27%), $CLIC_{1500}$ (~36%)
- Precisely by $CLIC_{3000}$ (~9%), FCC-hh (~5%),
- Robust w.r.t other operators

Single-Higgs:

- Global analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC
  - ~21% if FCC-ee has 4 detectors
- Exclusive analysis: too sensitive to other new physics to draw conclusion



Beyond the Standard Model (at colliders)

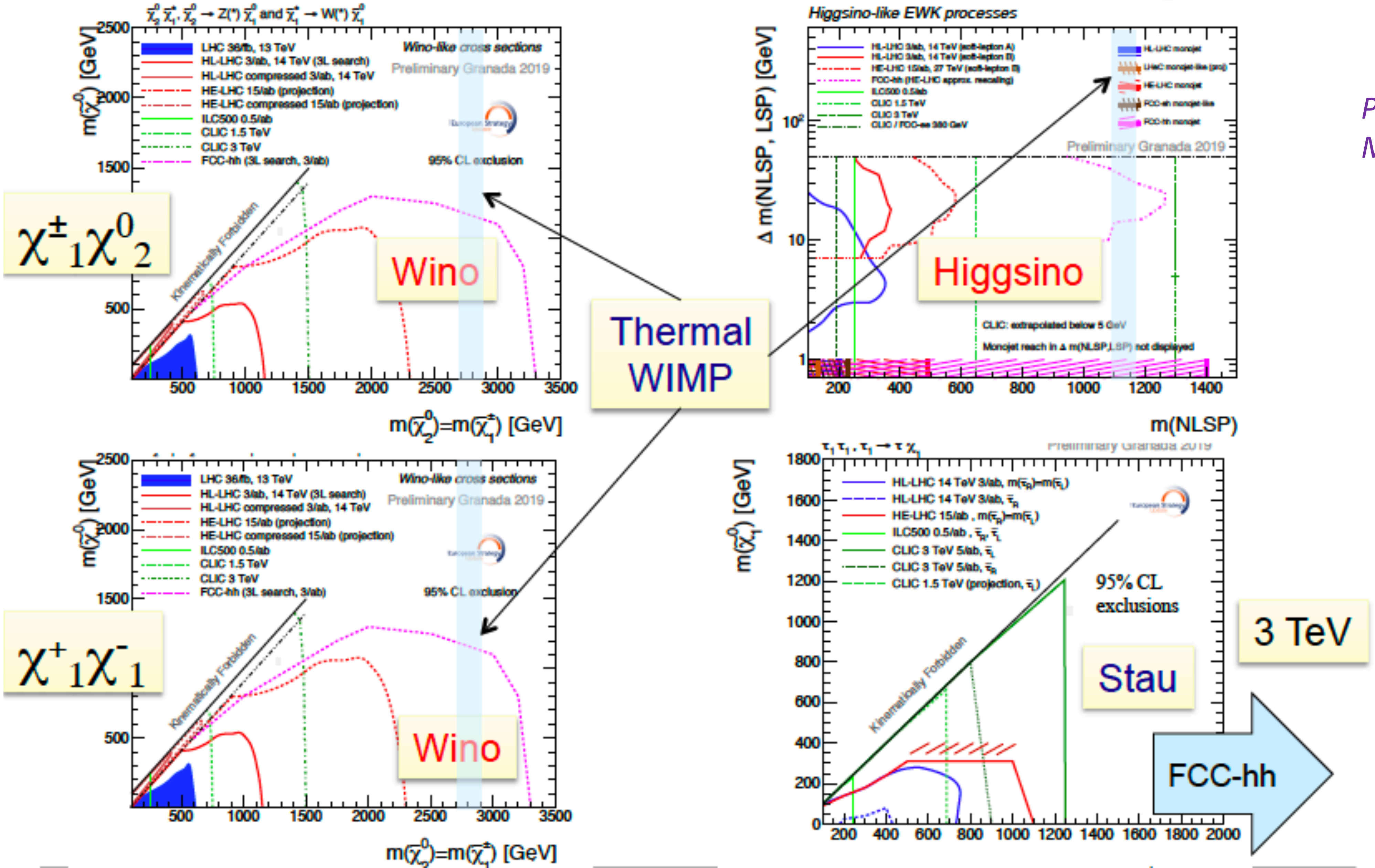
Open Symposium on the Update of European Strategy for Particle Physics

Gian Giudice and Paris Sphicas
For the BSM group
J. Alcaraz, C. Doglioni, G. Lanfranchi, M. D'Onofrio, M. McCullough, G. Perez, P. Roloff, V. Sanz, A. Weiler, A. Wulzer

May 16, 2019

- **Introduction**
  - **Some cautionary comments**
  - **The big questions (& some smaller questions)**
- **The [partial] answers to the Big Questions**
  - **And some answers to the Smaller Questions**
- **Outlook**

SUSY: EWK sector



Plots by
M. D'Onofrio

High Luminosity LHC

The Yellow Reports released end of 2018/early 2019 served as foundation for all discussions

- The huge effort in putting these together was very much appreciated!
- All new colliders are measured w.r.t. HL-LHC, i.e. the question is “what do they add?”

Many other interesting talks

- Introductory talks
  - Current European Strategy (F. Gianotti)
  - Accelerators: past, present and (far) future
  - Technologies: instrumentation and computing
- Parallel sessions and summary talks of the 8 topics
- Other communities
  - Astrophysics (APPEC) and nuclear physics (NUPPEC)
  - American and Asian views on EPPSU
- …

Improvements w.r.t. HL-LHC

M. Cepeda

Kappa-framework

	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC

EFT-framework

prel.

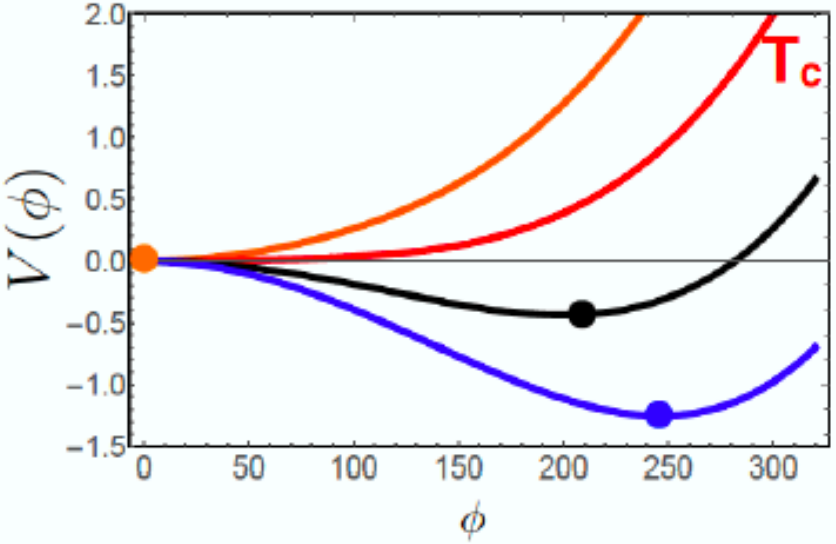
	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
g^{eff}_{Htt}	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
g^{eff}_{Hcc}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{eff}_{H\mu\mu}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured in HL-LHC

Electroweak potential

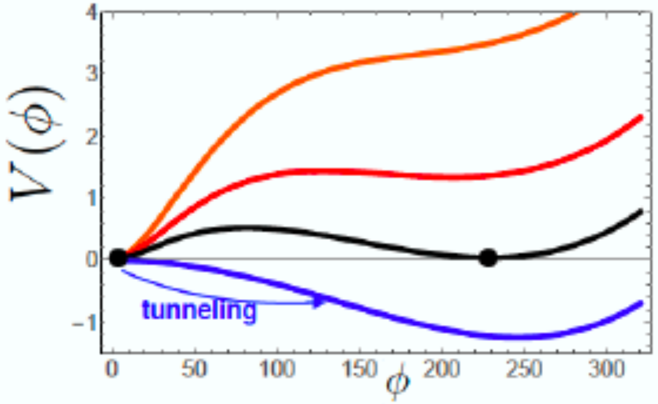
HEATING UP THE STANDARD MODEL .

EW sym. restored at T≳130 GeV through a smooth crossover



No departure from thermal equilibrium

First-order EW phase transition .



Barrier separates 2 degenerate minima

2 phases can coexist

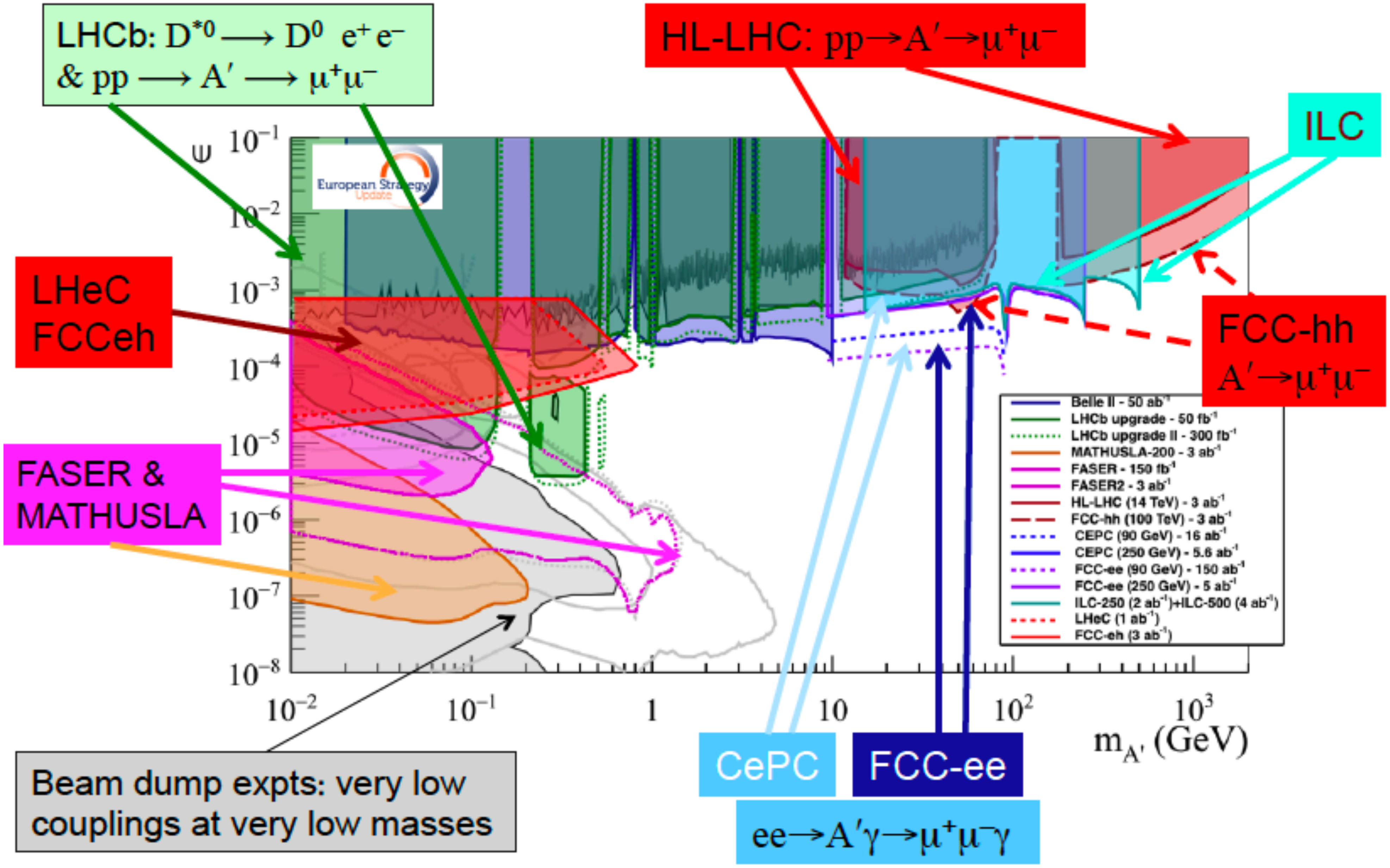
Nucleation, expansion and collision of Higgs bubbles

> Framework for EW baryogenesis !

> Stochastic bgd of gravitational waves detectable at LISA !

G. Servant

Feebly Interacting Particles (FIPs)



s.c. magnet technology

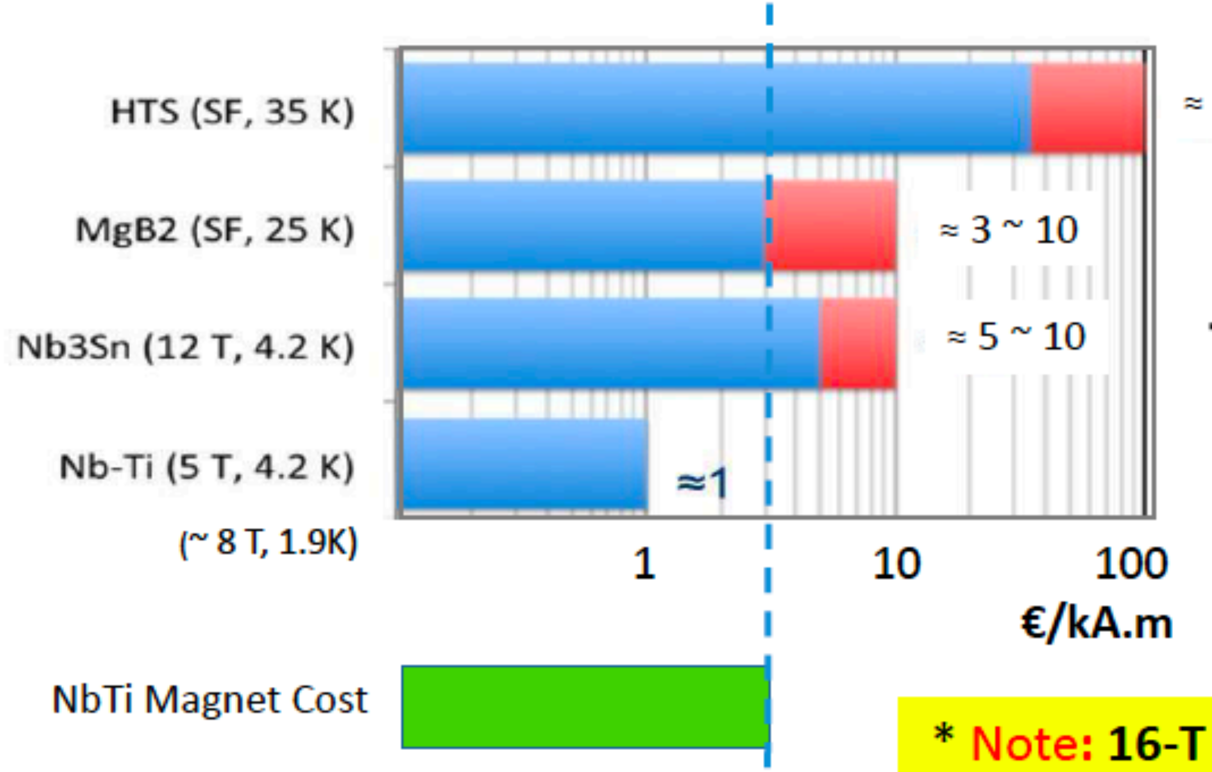
- Nb_3Sn superconducting magnet technology for hadron colliders, still requires **step-by-step** development to reach **14, 15, and 16 T**.
- It would require the following **time-line** (in my personal view):
  - **Nb_3Sn, 12~14 T:** 5~10 years for short-model R&D, and the following 5~10 years for prototype/pre-series with industry. It will result in **10 – 20 yrs** for the construction to start,
  - **Nb_3Sn, 14~16 T:** 10-15 years for short-model R&D, and the following 10 ~ 15 years for protype/pre-series with industry. It will result in **20 – 30 yrs** for the construction to start, (consistently to the FCC-integral time line).
  - **NbTi , 8~9 T:** proven by LHC and **Nb_3Sn, 10 ~ 11 T** being demonstrated. It may be feasible for the construction to begin in > ~ 5 years.
- **Continuing R&D effort** for high-field magnet, present to future, should be critically **important**, to realize highest energy frontier hadron accelerators in future.

Intensify HTS accelerator magnet development

Courtesy: F. Bordry, L. Bottura, A. Devred

Relative Cost Comparison for High-field SC and Magnet

- An approach for cost consideration:
  - Superconductor cost to be 30 % of the total cost for the LHC NbTi dipole magnet assembled.
  - It gives a general guideline for acceptable superconductor cost.
  - The currently available HTS cost is still too far, exept for Iron-based-SC (IBS) potential



<u>Goal for</u> Nb_3Sn for FCC or HE-LHC:

- **3.5 €/kA.m at 16 T and 1.9 K**
- Corresponding to 500...600 €/kg,
  - a factor 2.5 ~ 3 lower than the present cost 1300 ~ 1500 EUR/kg for HL-LHC (RRP)

* Note: **16-T** magnet requires x 2 conductor to that of **14 T.**

Interpretation of Higgs Measurements

- SMEFT and κ

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

κ-framework: phenomenological parameterization of NP in single Higgs processes but not adequate for a systematic exploration/interpretation of BSM deformations in SM measurements

Include BSM in kappa via :

$$\Gamma_H=\frac{\Gamma_H^{\mathrm{SM}}\cdot\kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$

Pros

-Compact parameterization of NP in single Higgs processes

-Does not require any BSM calculation per se

-Info easily applicable to several interesting NP scenarios (e.g. CH, MSSM)

-Theory constraints (e.g. gauge invariance, custodial) not implicit

Cons

- Not usable beyond single Higgs processes

-Does not distinguish the source of NP (interpreted only as mod. of SM-like H couplings)

-Only for total rates, no kinematics (Energy, angular dependence), no polarization

-Theory constraints (e.g. gauge invariance, custodial) not implicit

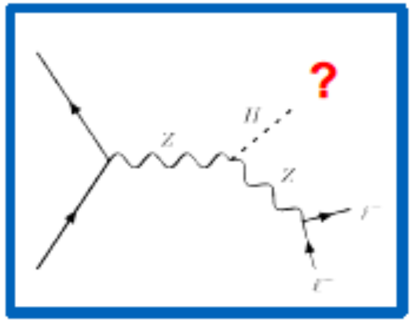
For heavy New Physics (NP) the formalism of Effective Field Theories (EFT) provides a suitable framework for systematic studies of indirect sensitivity to BSM effects in EW/Higgs/Top/Flavour/...

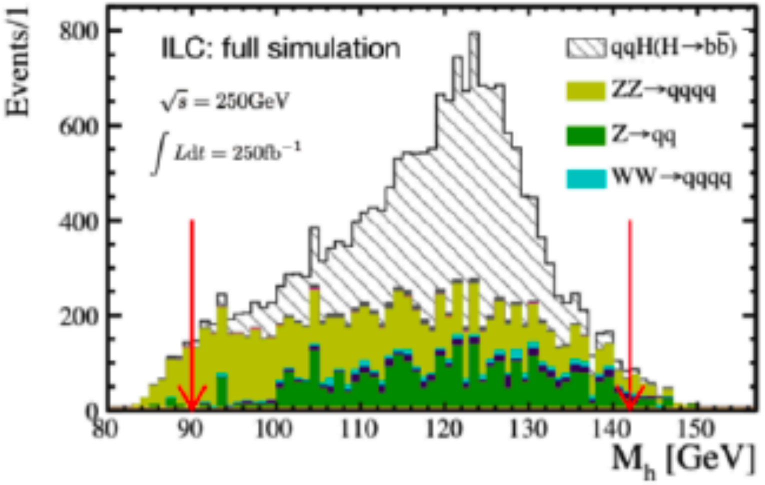
J. De Blas

Higgs width and/or untagged decays

Unique feature of lepton-lepton colliders:

- **Detecting the Higgs boson without seeing decay: “recoil method”**
- **Measure ZH cross section with high precision without assumptions on decay**
- **Often interpreted as quasi-direct measurement of width**





$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

In kappa-framework: $\Gamma_H = \dfrac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$

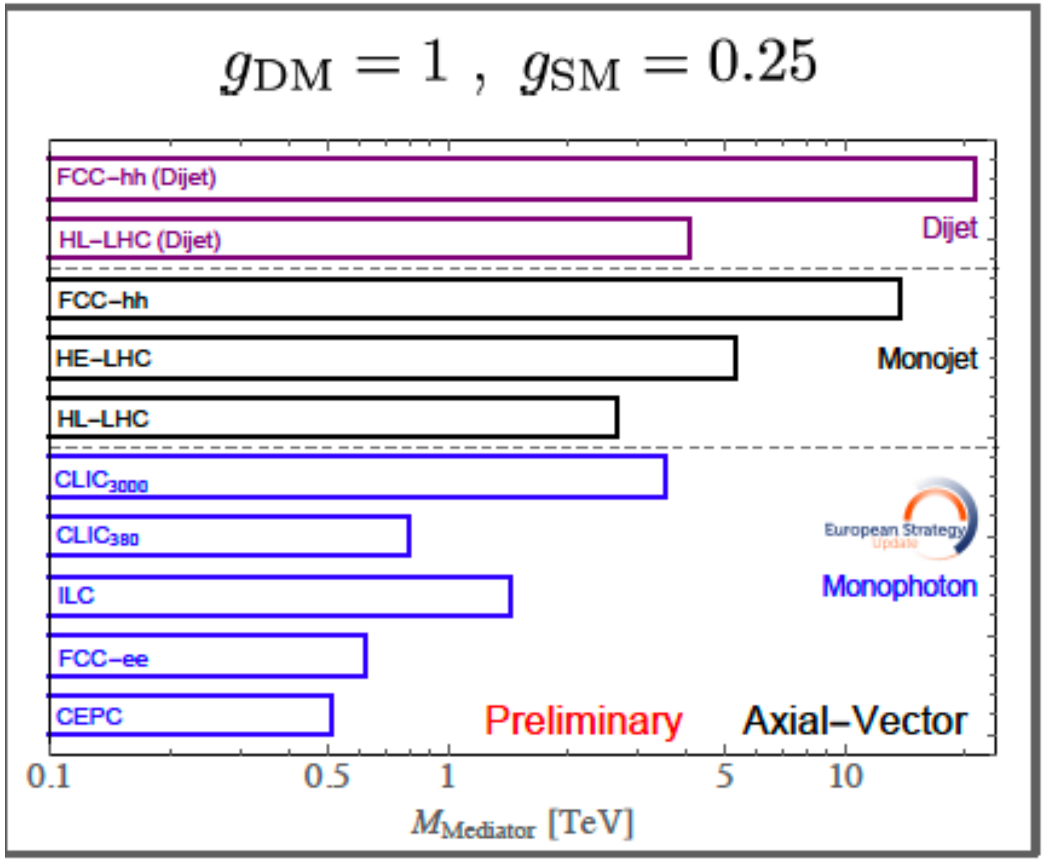
=> Will probe width with 1-2% precision

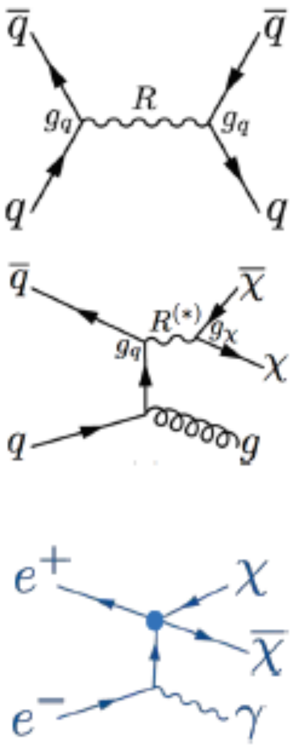
Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [85]	2.6
CLIC_{1500}	2.6	κ-framework [85]	1.7
CLIC_{3000}	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, BR$(H \to Z, b\bar{b}, WW)$ [90]	1.8
$\mathrm{FCC\text{-}ee}_{240}$	2.7	κ-framework [1]	1.9
$\mathrm{FCC\text{-}ee}_{365}$	1.3	κ-framework [1]	1.2

arXiv:1905.03764

Simplified Models: axial vector

- **Light DM, m_χ=1GeV**





pp: assumes mediator couplings to quarks only.
- 750 GeV, HL-LHC
- 1.5 TeV, HE-LHC
- 3.9 TeV for FCC-hh

Dependence on couplings!

ee: assumes mediator couplings to leptons only. Also in EFT limit, so can be easily rescaled for modified couplings.

Note: taking EFT scale as free parameter, M_{DM} reach ~kinematic reach of collider.

C. Doglioni

Significant model dependence. UV models may have comparable quark and lepton couplings. If both present, can also use dilepton resonances.

Simplicity vs Naturalness

The two Chief Systems

Simplicity ↑

I. The SM is valid up to $\Lambda_{UV} \gg TeV$

- B, L and Flavor: beautifully in accord with observation
- Higgs mass & C.C. hierarchy point beyond naturalness
    - multiverse
    - cosmological relaxation, Nnaturalness, ...
    - failure of EFT ideology (UV/IR connection)

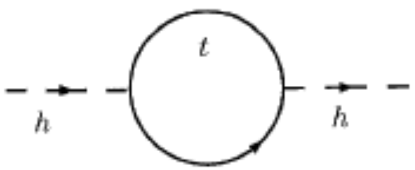
II. Naturalizing New Physics appears at $\Lambda_{UV} \sim 1\,\text{TeV}$

- Constraints on B, L, Flavor & CP met by clever model building

↓ Naturalness

R. Rattazzi

Measuring Naturalness



Hierarchy Paradox ➔ ***unavoidable*** and ***global*** perspective on energy frontier exploration

In any model with calculable m_h: $$m_h^2 = \sum_i \Delta m_i^2$$

fine tuning $$\epsilon \equiv \frac{m_h^2|_{exp}}{\Delta m_h^2|_{max}}$$

offers a measure of where Nature stands in the negotiation between Simplicity and Naturalness

Measures of fine tuning

- **Direct searches: depends on top partner constraints in model (e.g. SUSY varieties, composite H, twin H)**
  - **LHC now:** $\epsilon \lesssim 10^{-2} - 1$
  - **FCC-hh:** $\epsilon \lesssim 10^{-4} - 10^{-2}$ (if nothing)
- **Higgs observables:** $\epsilon \sim \delta g/g$
- **Electroweak precision:** $\epsilon \sim 10^2 \times \delta S/S$

Higgs and EWK precision observables can test naturalness beyond direct searches

R. Rattazzi

What else do we learn from Higgs?

Question	κ_V	κ_3	κ_g	κ_γ	λ_{hhh}	σ_{hZ}	BR_{inv}	BR_{und}	κ_ℓ	μ_{4f}	$\text{BR}_{\tau\mu}$	Γ_h
Is h Alone?	+	+			+	+				+		+
Is h elementary?	+	+	+	+		+						
Why $m_h^2 \ll m_{\text{Pl}}^2$?	+	+					+	+		+		+
1st order EWPT?			+	+	+	+				+		
CPV?		+(CP)										
Light singlets?							+	+	+	+		+
Flavor puzzles?		+							+		+	

BH, Y. Nir, arXiv:1905.00382

Many problems of particle physics today relate to Higgs observables