Prospects on future energy frontier colliders

Brief overview of talks and discussions in CERN Council Open Symposium on the Update of European Strategy for Particle Physics

13-16 May 2019 - Granada, Spain

Alexander Kupčo
Institute of Physics of Czech Academy of Sciences

ATLAS CZ-SK meeting

June 2019, Prague

EPPSU 2019 meeting

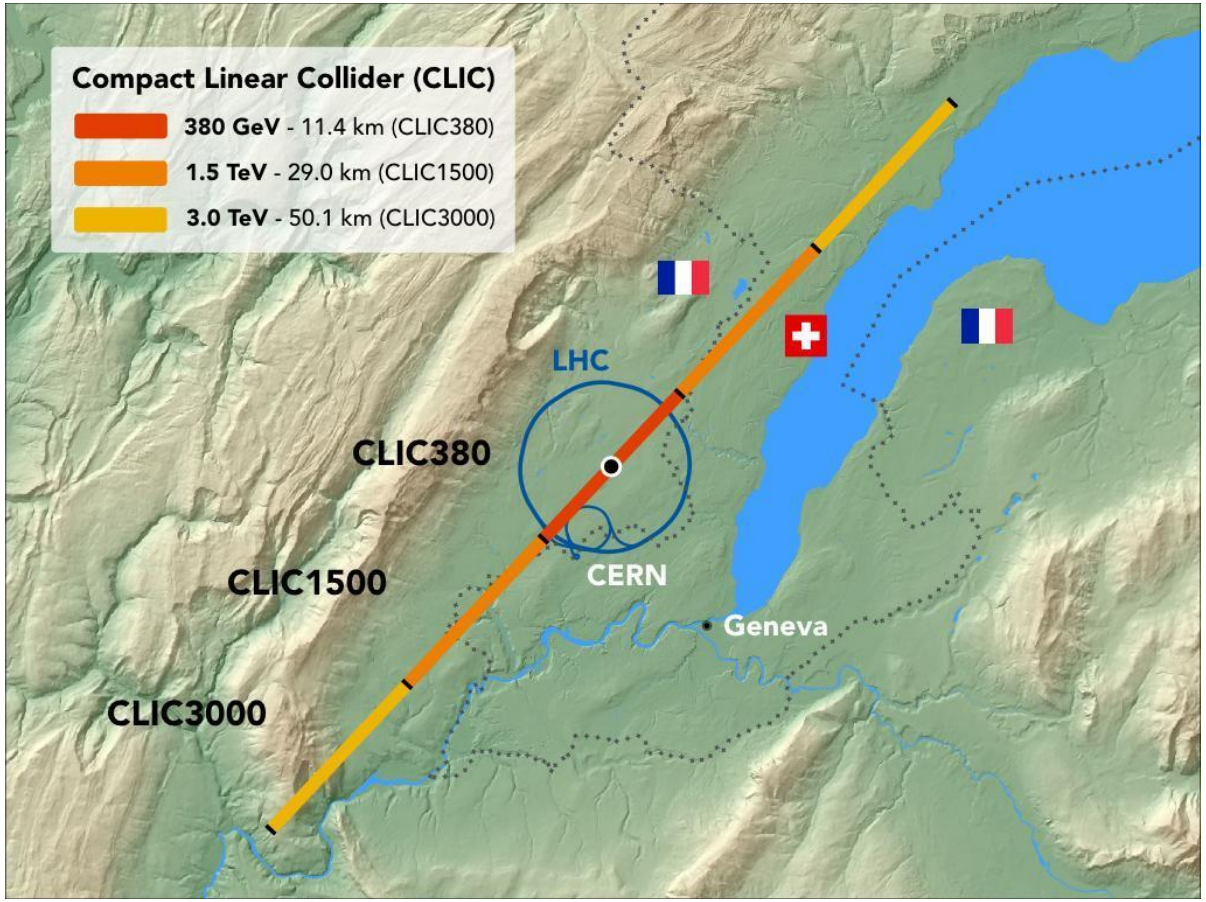
- https://cafpe.ugr.es/eppsu2019/
- Input for this talk
  - C. Biscardi: *Accelerator Summary +* talks in parallel sessions
  - F. Gianotti: *Implementation of the 2013 European Strategy Update*
  - G. Taylor: *Perspective on the European Strategy from Asia*
  - B. Heinemann: *Electroweak Physics (physics of the W, Z, H bosons, of the top quark, and QED)*
- *Submitted input documents*

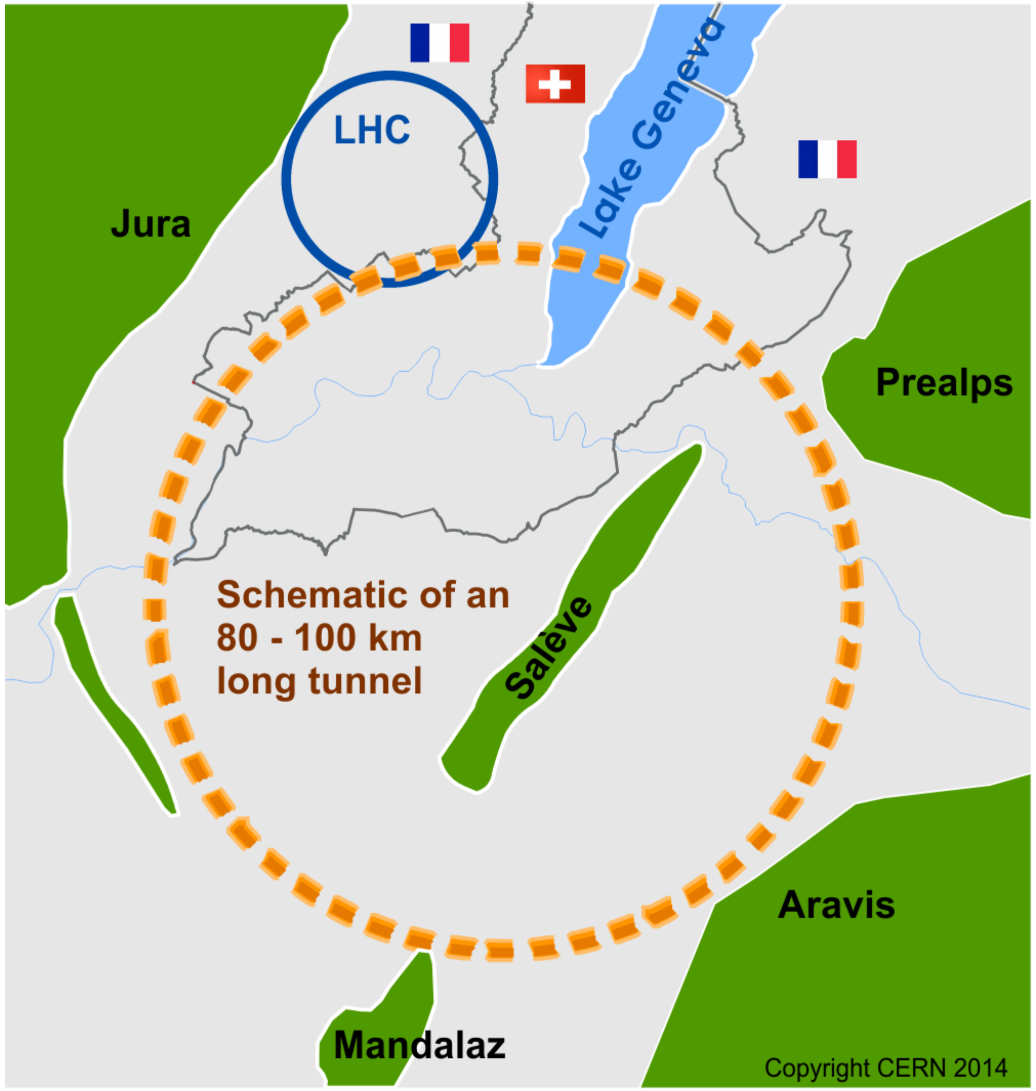
Accelerators summary

Caterina Biscari and Lenny Rivkin, Phil Burrows, Frank Zimmermann

Open Symposium towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain

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





Rationales

CLIC:

Ultimate goal: Achieve multi-TeV electron-positron collisions

- Linear collider with high gradient normal-conducting acceleration
- Overcome the challenges with technologies
- Now: do it in stages for physics and funding

FCC-hh + FCC-ee

Push the energy frontier with protons

- Large ring with high field magnets

Use the FCC-hh tunnel for an electron-positron collider

- The layout and cost is not optimised for FCC-ee proper

LHeC:

Expand the LHC programme with limited cost

ILC:

Ultimate goal: Reach energies of originally 0.5-1 TeV

- Use high gradient superconducting technology
- Now reduce cost to obtain funding

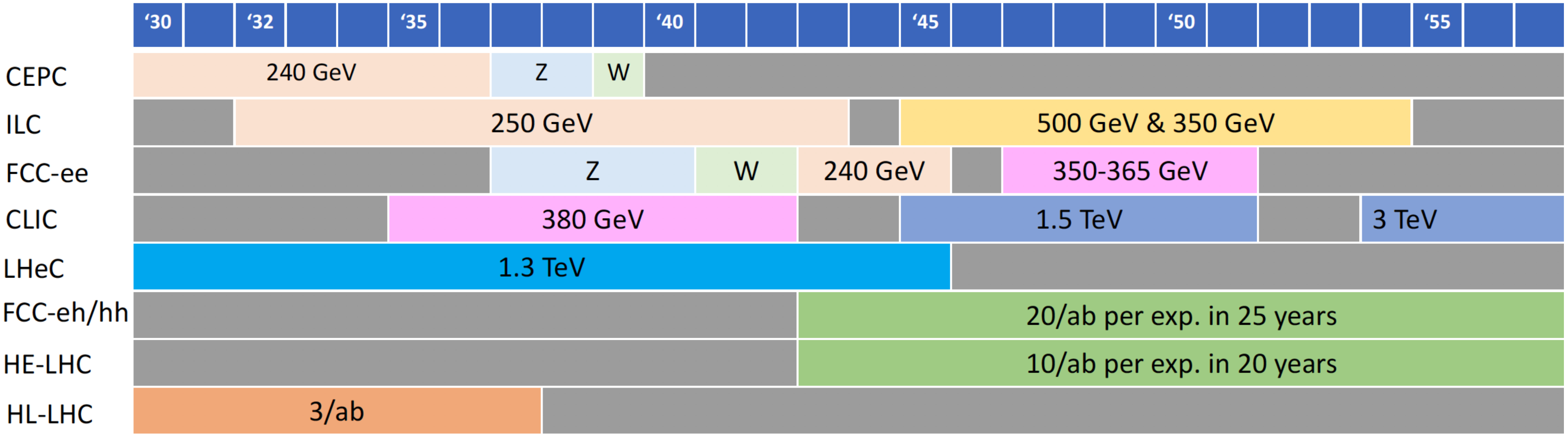
CEPC:

Build a higgs factory with limited energy with a tunnel that could house a hadron collider afterwards

Comparisons

Project	Type	Energy [TeV]	Int. Lumi. $[a^{-1}]$	Oper. Time [y]	Power [MW]	Cost	Annual energy consumption [TWh] CERN today: 1.2 TWh
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade	
		0.5	4	10	163 (204)	7.8 GILCU	
		1.0			300	?	
CLIC	ee	0.38	1	8	168	5.9 GCHF	0.8
		1.5	2.5	7	(370)	+5.1 GCHF	1.7
		3	5	8	(590)	+7.3 GCHF	2.8
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	1.9
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF	
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)	4
HE-LHC	pp	27	20	20		7.2 GCHF	

Proposed Schedules



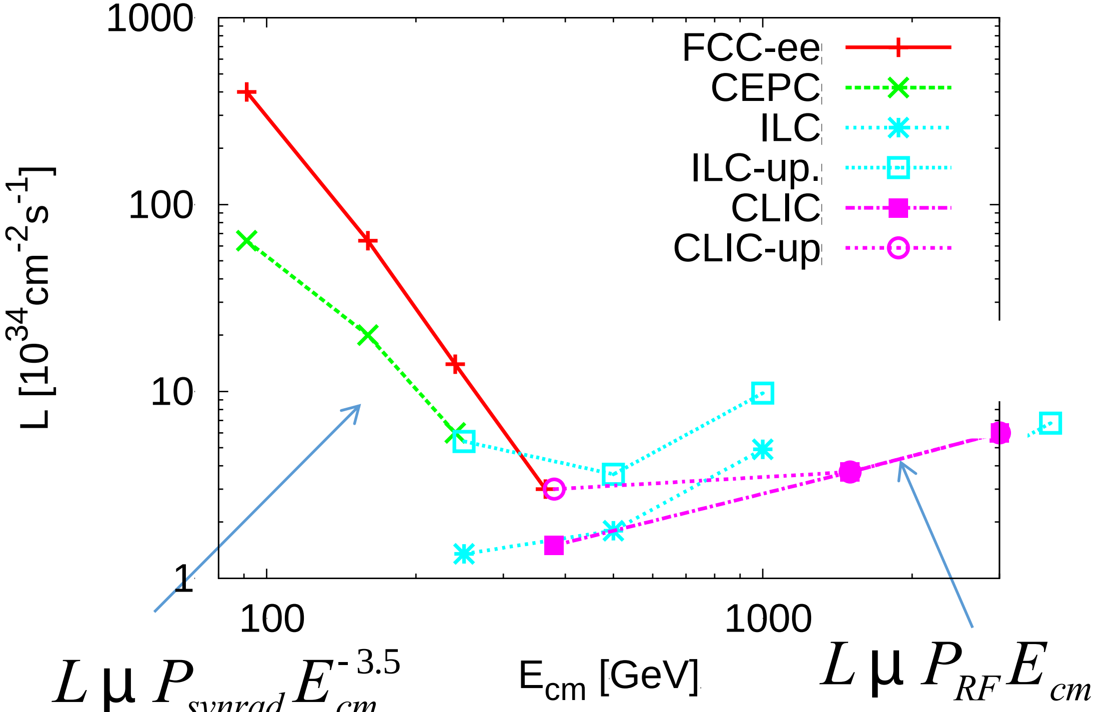
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC		

Proposed dates from projects

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.

Luminosity

Luminosity per facility



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

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

Energy dependence:

At low energies circular colliders trump

- Reduction at high energy due to synchrotron radiation

At high energies linear colliders excel

- Luminosity per beam power roughly constant

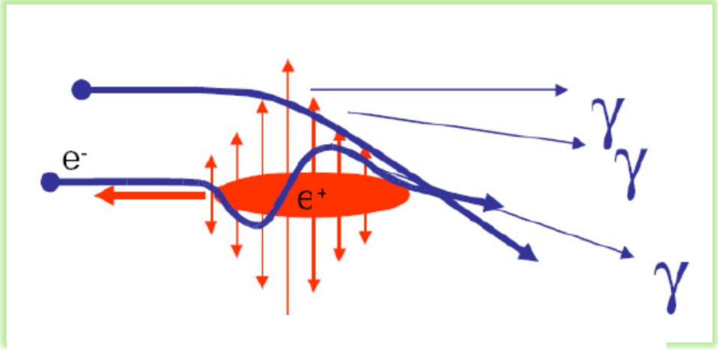
The typical higgs factory energies are close to the cross over in luminosity

Linear collider have polarised beams (80% e$^-$, ILC also 30% e$^+$) and beamstrahlung

- All included in the physics studies

The picture is much clearer at lower or higher energies

Luminosity Spectrum (Physics)



- $\delta E/E$ ~1.5% in ILC
- Grows with E: 40% of CLIC lumi 1% off

Conclusion

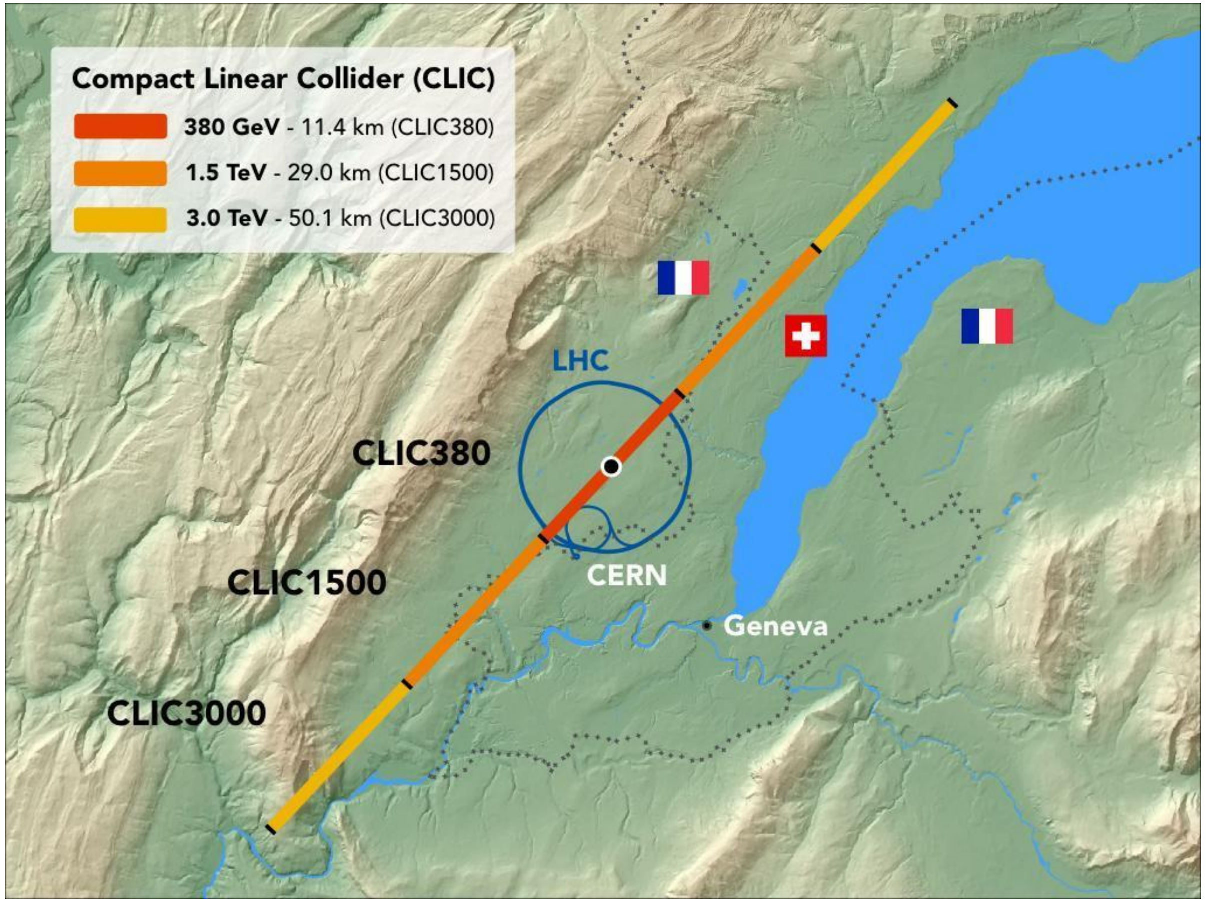
- Four main proposals for higgs factories exist
  - ILC, CLIC, FCC-ee and CEPC
  - FCC-hh and HE-LHC need time for technology development (see Yamamoto's talk)
  - LHeC would also produce some higgs
  - No clear proposal for options like LEP3 or low field magnets in FCC-tunnel
  - Muon and plasma-based colliders will need more time to become realistic alternatives

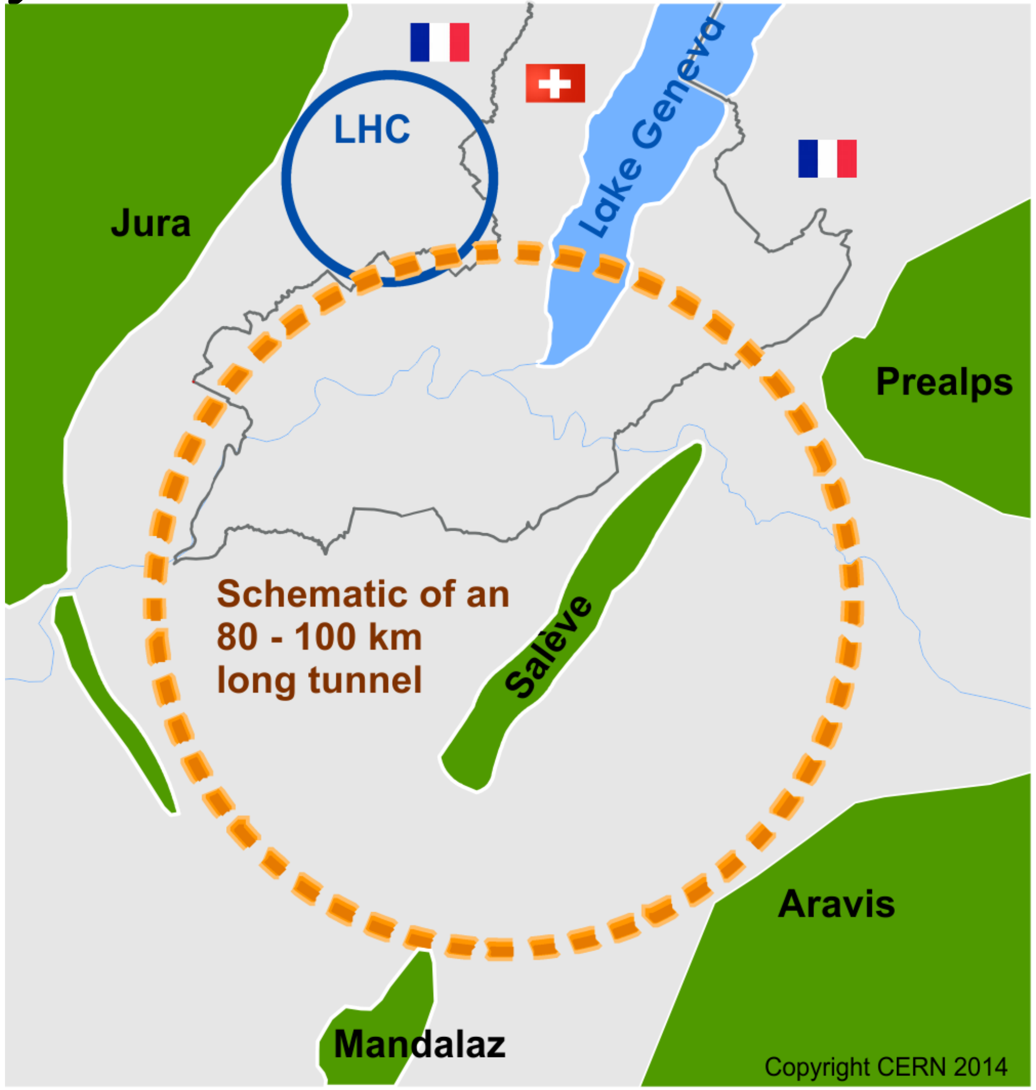
- No feasibility issue is known for any of the proposed higgs factories CLIC, ILC, FCC-ee and CEPC
  - More work has to be done for each of them to ensure performance goal is met
  - Should review in detail them before commitment is made
  - In all cases need several years before construction could start
  - Currently, technology can not help with the choice of the next project

- Cost are high in all
  - 5.9 GCHF for 380 GeV CLIC, 5.3 GILCU for ILC, 11.6 GCHF for FCC-ee, 5 G$ for CEPC

- Physics potential and strategy should be the governing principles

Q2: Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?





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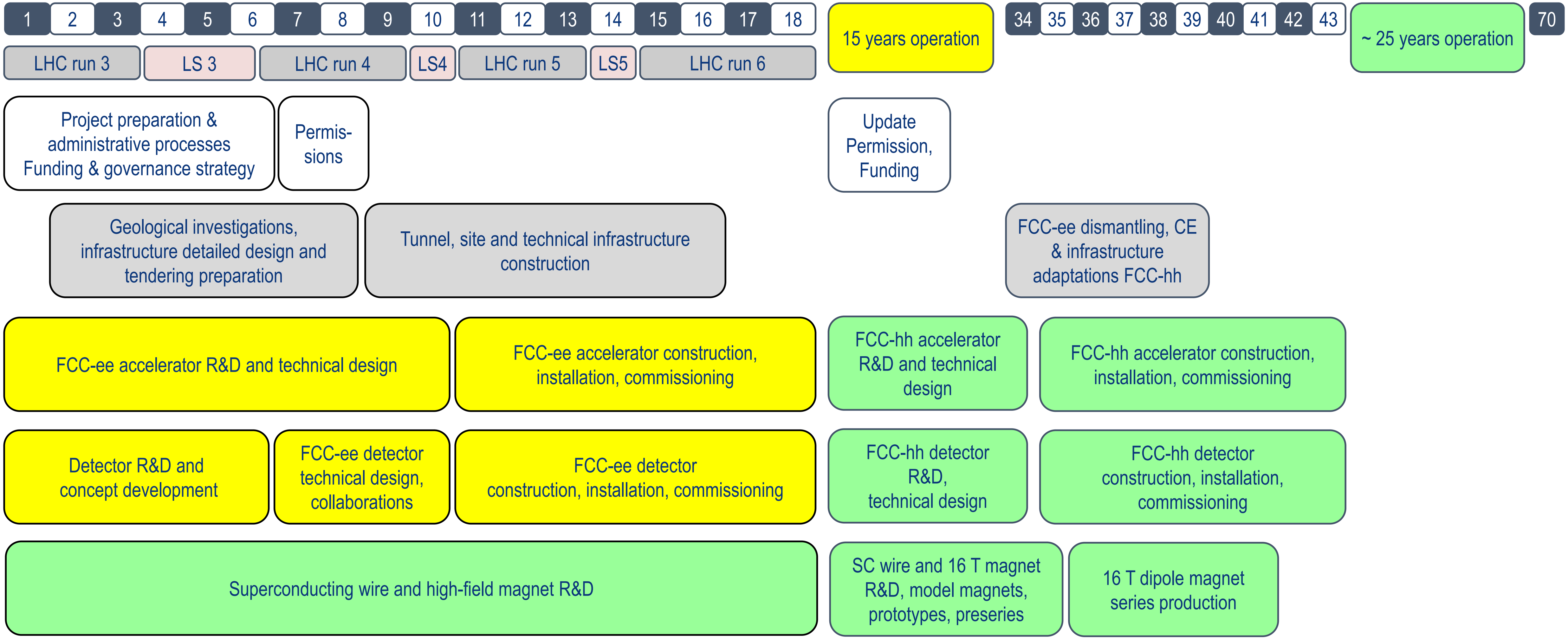
FCC integrated project technical schedule



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

15 years operation

34 35 36 37 38 39 40 41 42 43

~ 25 years operation

70

LHC run 3

LS 3

LHC run 4

LS4

LHC run 5

LS5

LHC run 6

Project preparation & administrative processes Funding & governance strategy

Permis-sions

Update Permission, Funding

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

FCC integrated project is fully aligned with HL-LHC exploitation and provides for seamless continuation of HEP in Europe with highest performance EW factory followed by highest energy hadron collider.

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

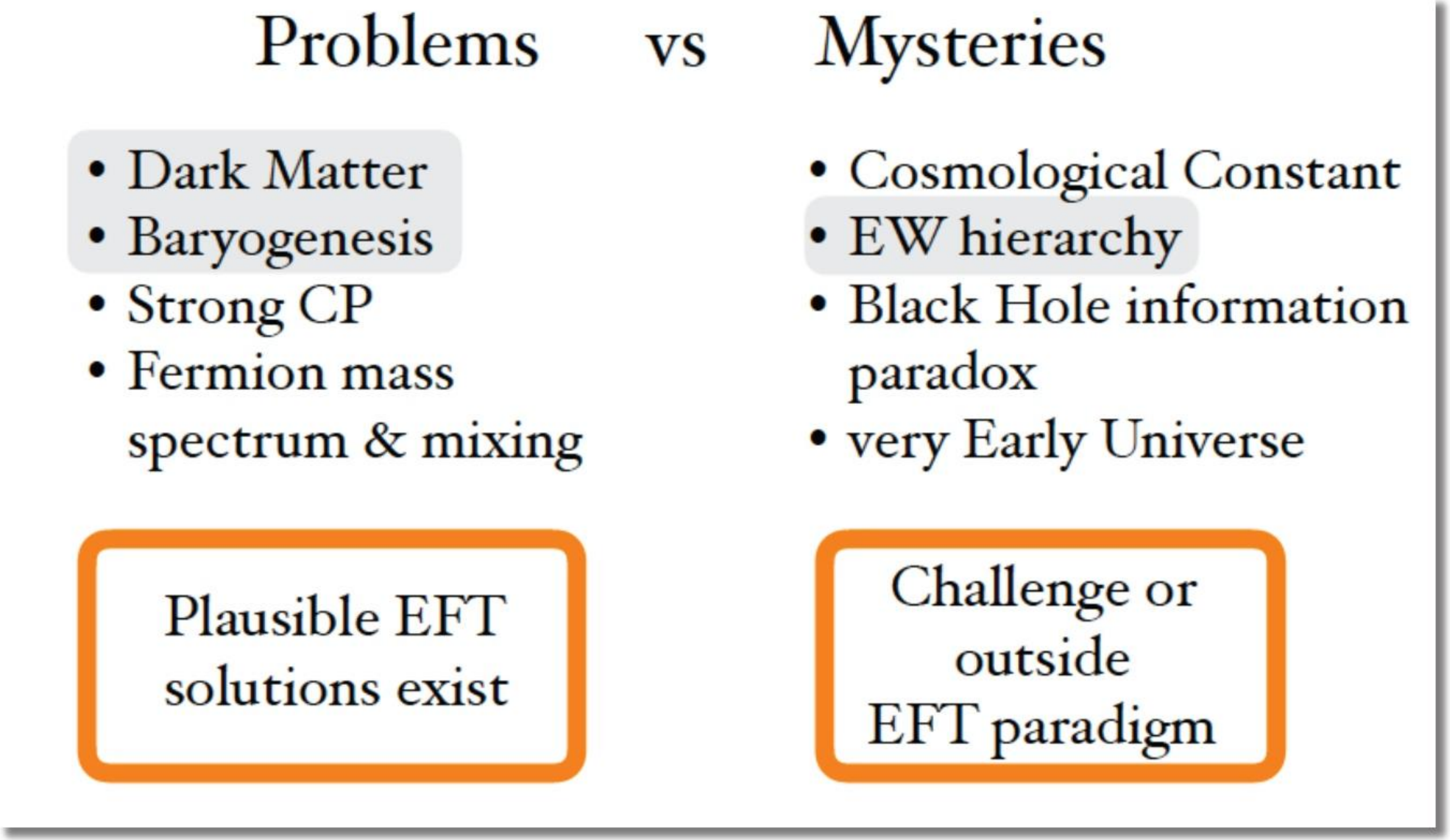
HE-LHC 27 TeV

- Needs some 1700 large magnets in Nb_3Sn (1200 dipole 15 m long) operating at **16 T**. (same as FCC-hh)
- It needs a new generation of Nb_3Sn, beyond HiLumi (like FCC-hh): the 23 y timeline presented is realistic (21 for the magnets) but t_0 is probably 2025 or more because of SC development.
- **The set up of a SC Open Lab for fostering development of superconductors (F. Bordry and L. Bottura proposal) is critical for HEP HC progress.**
- A further upgrade to 42 TeV in HTS at 25 T possible to envisage for longer time. 24 T dipole is the long term goal also of the Chinese SppC.
  (Recently an HTS 32 T special solenoid and a commercial HTS 26 T NMR solenoid have been announced!)

Summary: Electroweak Session

Conveners: Keith Ellis and Beate Heinemann
Scientific Secretaries: Fabio Maltoni and Aleandro Nisati
Open Symposium towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain

What and Why?



Problems vs Mysteries

- Dark Matter
- Baryogenesis
- Strong CP
- Fermion mass spectrum & mixing

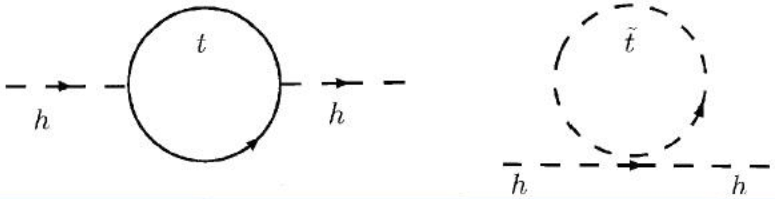
Plausible EFT solutions exist

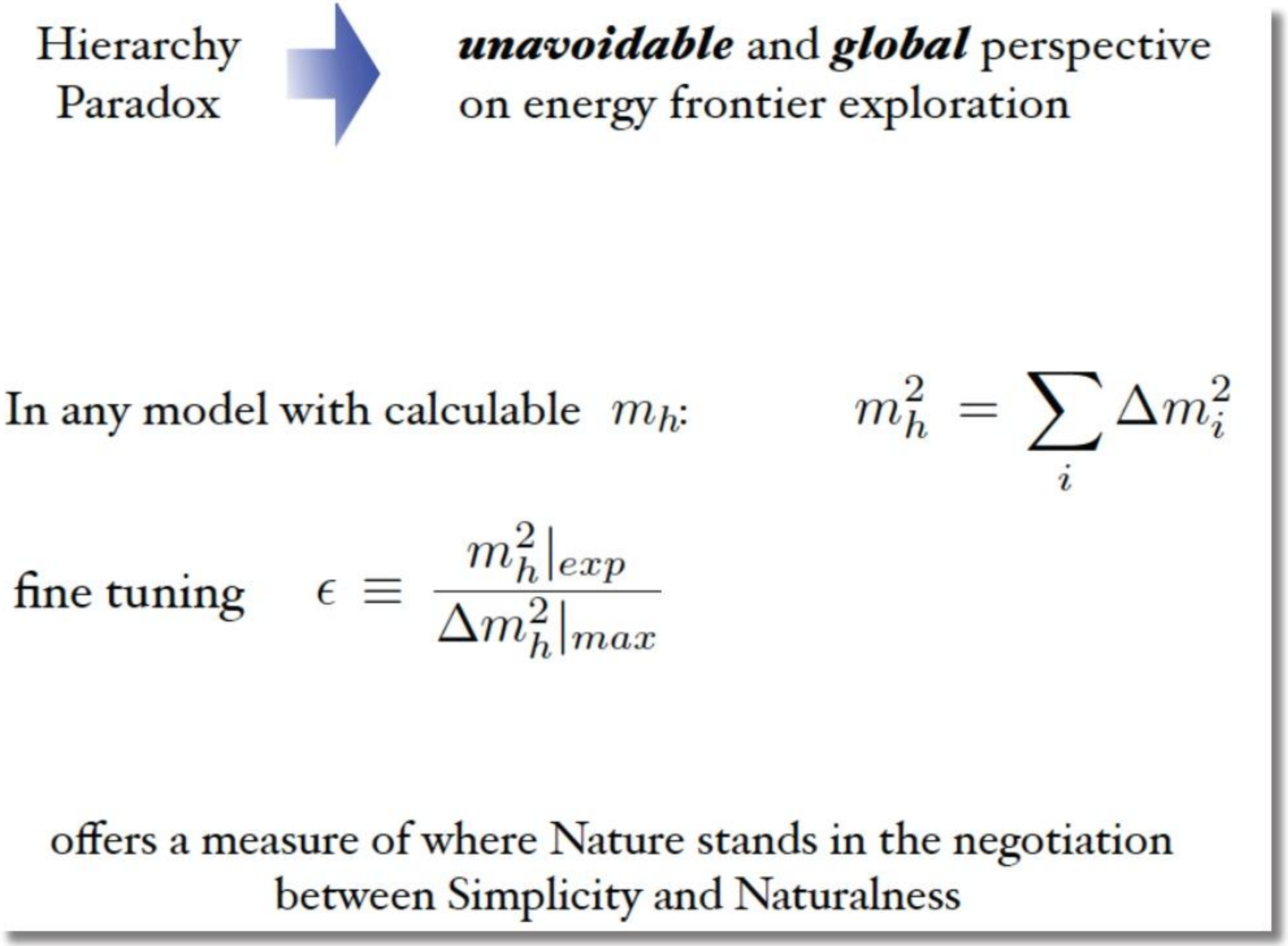
- Cosmological Constant
- EW hierarchy
- Black Hole information paradox
- very Early Universe

Challenge or outside EFT paradigm

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

R. Rattazzi

Measures of fine tuning

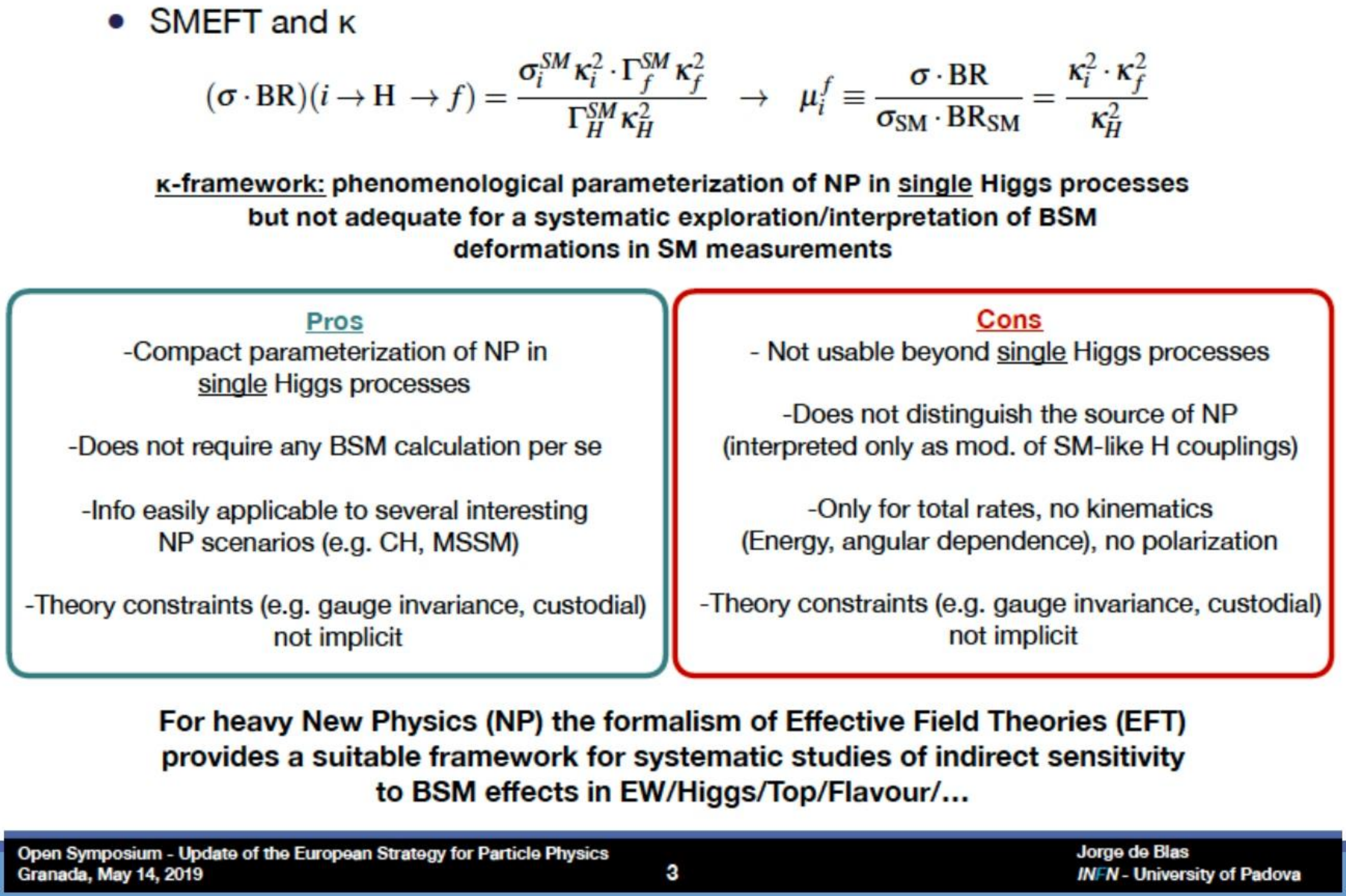
- **Direct searches: depends on top partner constraints in model (e.g. SUSY varieties, composite H, twin H)**
  - **LHC now:** $\epsilon \lesssim 10^{-2} - 1$
  - **FCC-hh:** $\epsilon \lesssim 10^{-4} - 10^{-2}$ (if nothing)
- **Higgs observables:** $\boldsymbol{\epsilon \sim \delta g/g}$
- **Electroweak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

Higgs and EWK precision observables can test naturalness beyond direct searches

Big Questions

1. **How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?**
2. **How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?**
3. **What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?**
4. **What is the best path towards measuring the Higgs potential?**

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

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/...

Open Symposium - Update of the European Strategy for Particle Physics
Granada, May 14, 2019

3

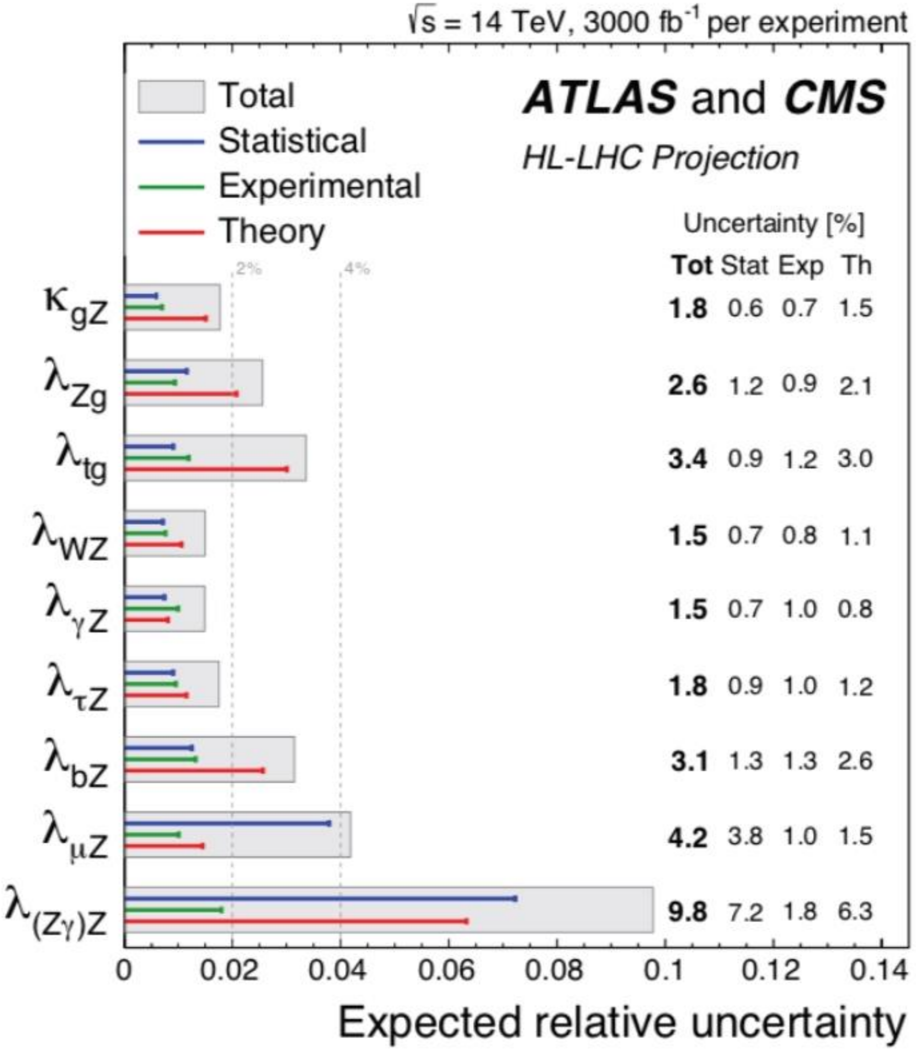
Jorge de Blas
INFN - University of Padova

Include BSM in kappa via :

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

J. De Blas

HL-LHC Higgs measurement projections



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_{gZ}	**1.8**	0.6	0.7	1.5
λ_{Zg}	**2.6**	1.2	0.9	2.1
λ_{tg}	**3.4**	0.9	1.2	3.0
λ_{WZ}	**1.5**	0.7	0.8	1.1
$\lambda_{\gamma Z}$	**1.5**	0.7	1.0	0.8
$\lambda_{\tau Z}$	**1.8**	0.9	1.0	1.2
λ_{bZ}	**3.1**	1.3	1.3	2.6
$\lambda_{\mu Z}$	**4.2**	3.8	1.0	1.5
$\lambda_{(Z\gamma)Z}$	**9.8**	7.2	1.8	6.3

Some remarks:

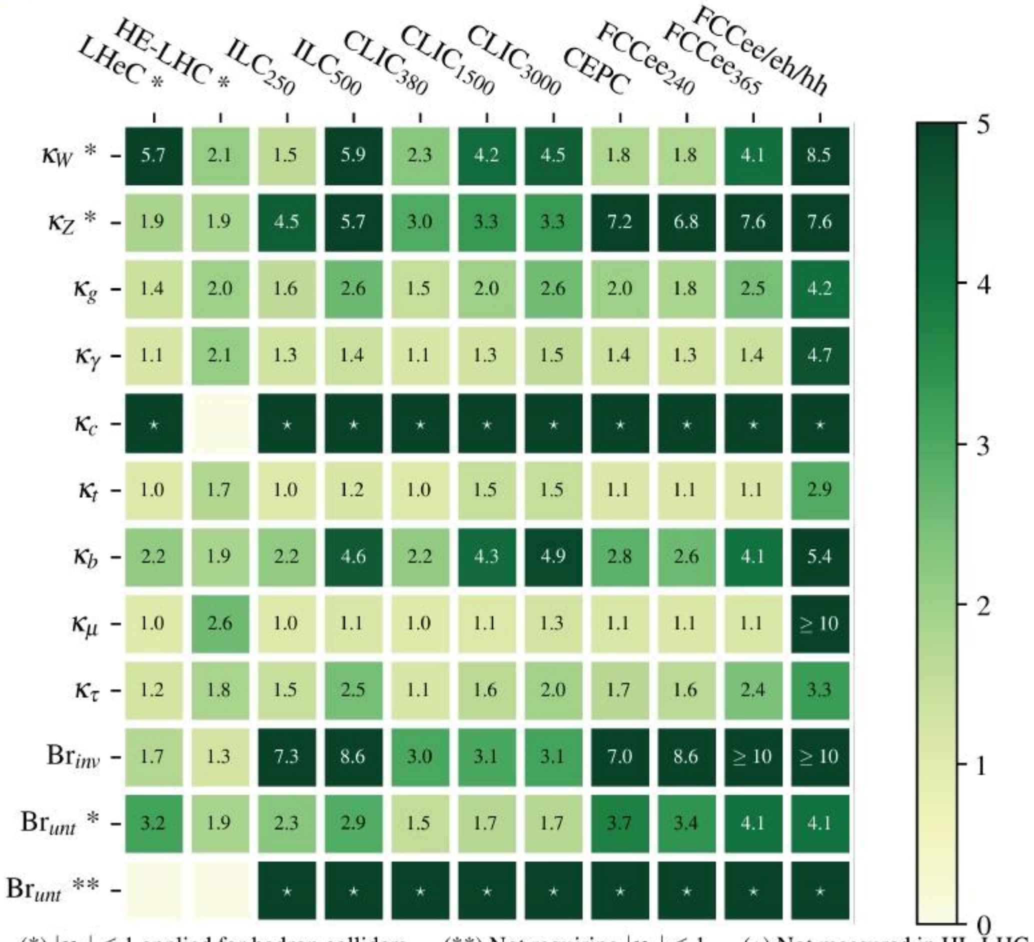
- **Combination benefits from extensive analysis experience of ATLAS and CMS since 2012 Higgs discovery**
- **Precision dominated by theoretical uncertainties for most decay modes**
  - **Scaled by factor 2 compared to present uncertainties**
- **Measurement of absolute couplings model-dependent**
  - **Measure also ratios to reduce model-dependence**

P. Azzi

Improvements w.r.t. HL-LHC

M. Cepeda

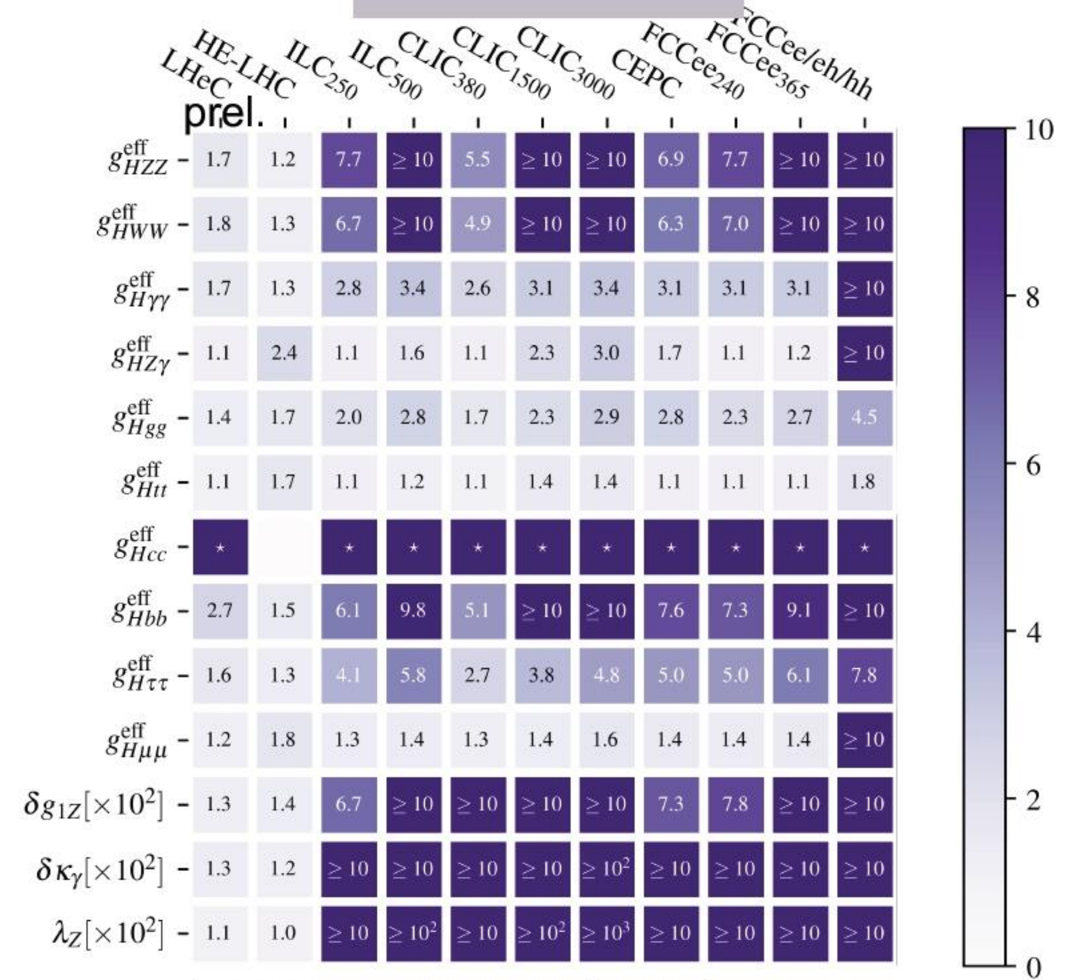
Kappa-framework



	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

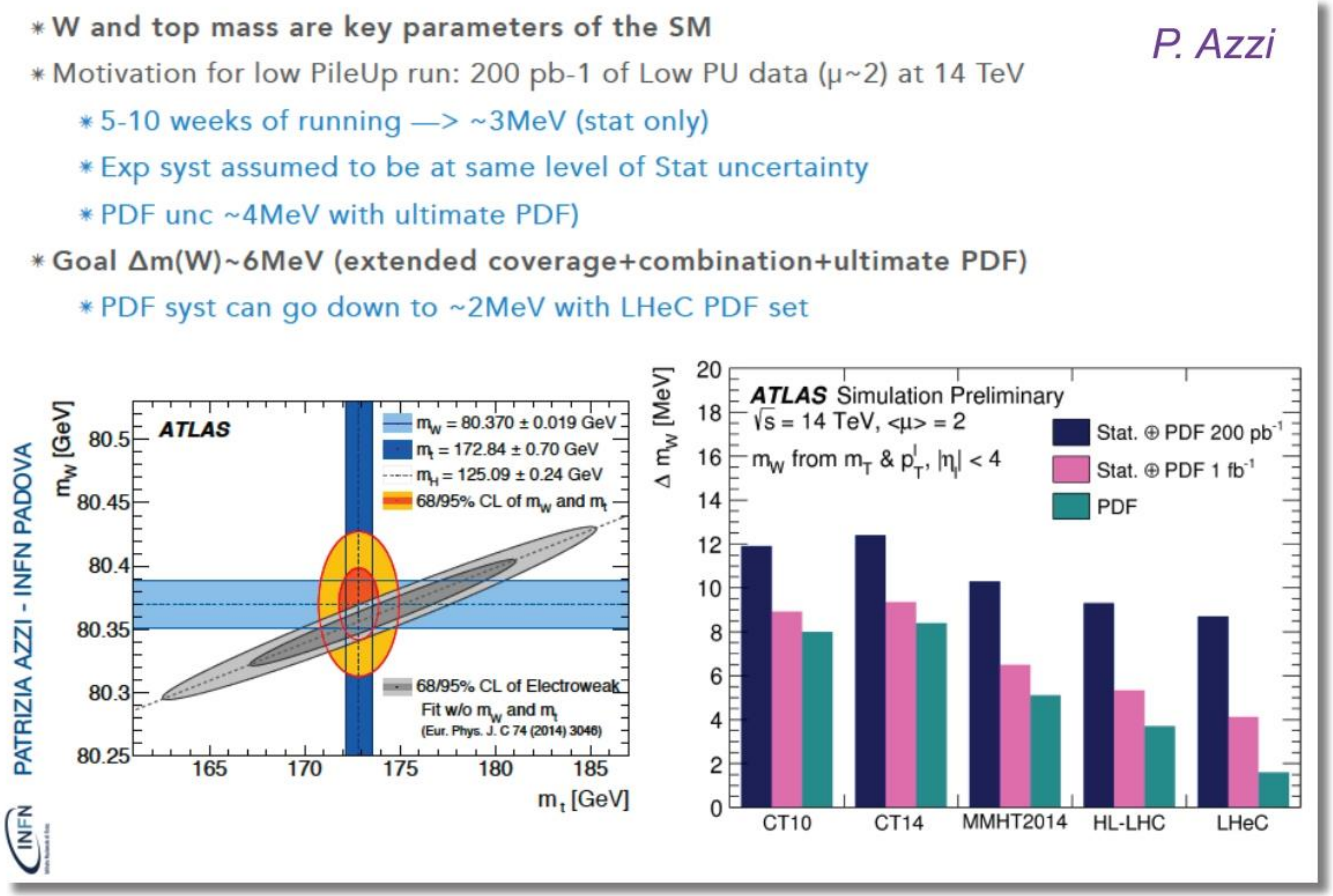


	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	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

Question 2:
How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?

What can HL-LHC do?



P. Azzi

- W and top mass are key parameters of the SM
- Motivation for low PileUp run: 200 pb-1 of Low PU data (μ~2) at 14 TeV
  - 5-10 weeks of running —> ~3MeV (stat only)
  - Exp syst assumed to be at same level of Stat uncertainty
  - PDF unc ~4MeV with ultimate PDF)
- Goal Δm(W)~6MeV (extended coverage+combination+ultimate PDF)
  - PDF syst can go down to ~2MeV with LHeC PDF set

PATRIZIA AZZI - INFN PADOVA

W mass:

- goal is ~6 MeV
- PDF precision important

Top mass:

- Several methods explored
- Precision range: 0.2-1.2 GeV
- Relation to pole mass unclear for most precise methods

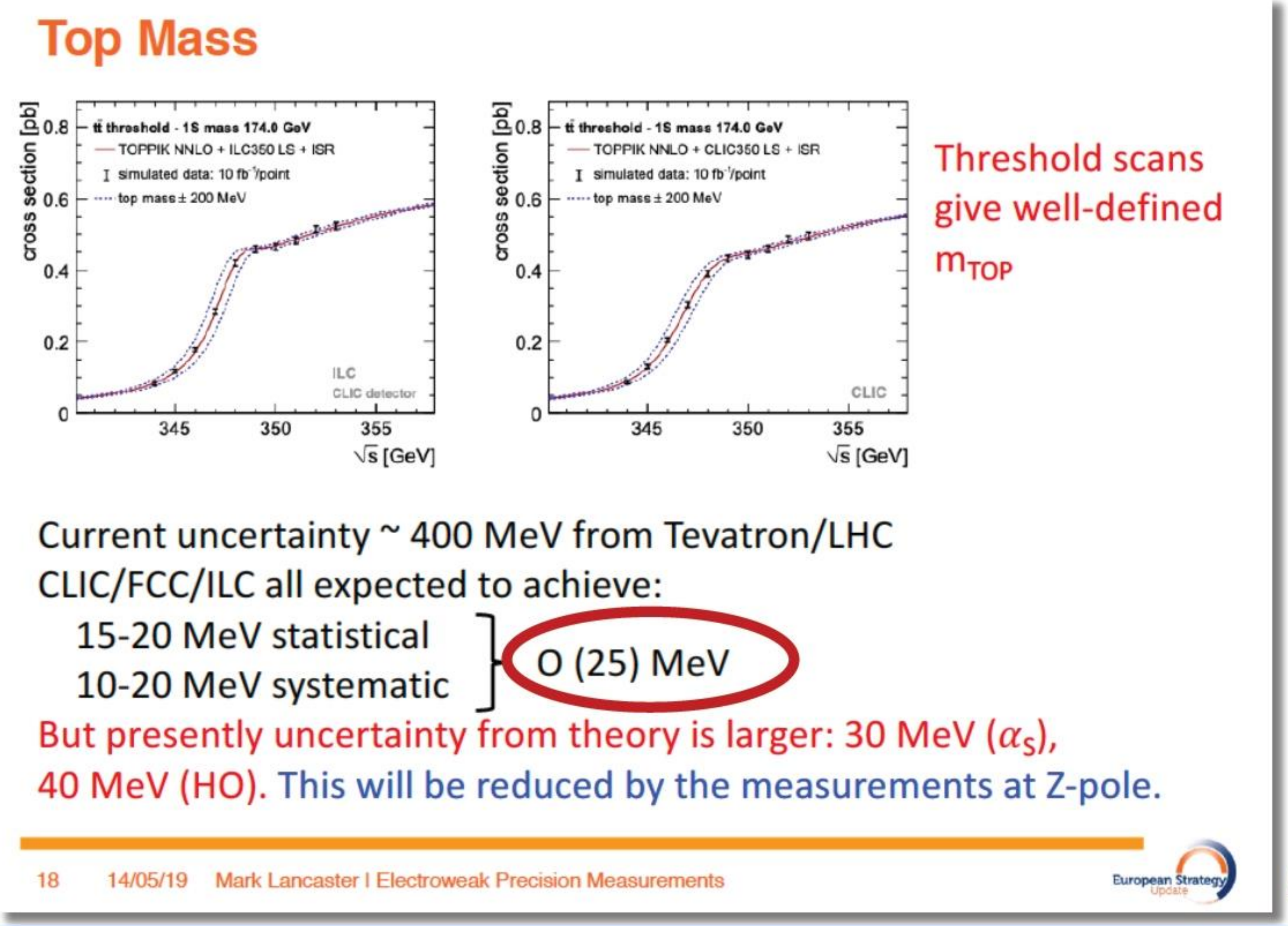
Method:	$t\bar{t}$ lepton+jets	t-channel single top	$m_{SV\ell}$	J/ψ	$\sigma_{t\bar{t}}$
Δm_{top} (GeV):	0.17	0.45	0.62	0.50	1.2

Standard →ℓ+jets measurement

Statistically dominated

Limited by theory uncertainty and luminosity measurement

Top precision at Future Colliders



Top Mass

Threshold scans give well-defined m_{TOP}

Current uncertainty ~ 400 MeV from Tevatron/LHC
CLIC/FCC/ILC all expected to achieve:
15-20 MeV statistical
10-20 MeV systematic

$\left.\begin{array}{l}\text{15-20 MeV statistical}\\\text{10-20 MeV systematic}\end{array}\right\}$ O (25) MeV

But presently uncertainty from theory is larger: 30 MeV (α_S), 40 MeV (HO). This will be reduced by the measurements at Z-pole.

18 14/05/19 Mark Lancaster I Electroweak Precision Measurements

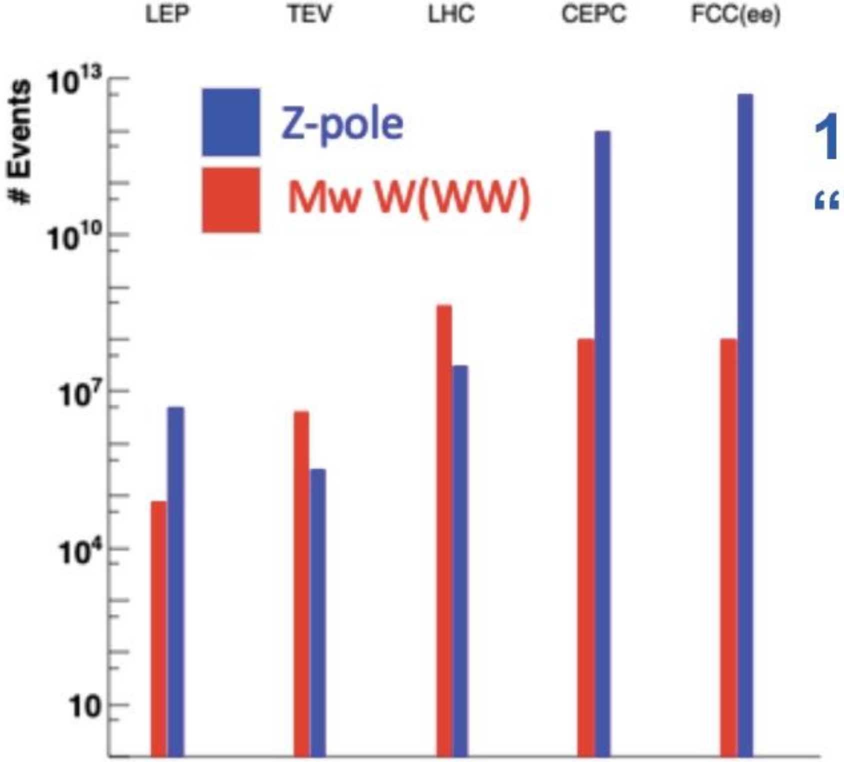
European Strategy Update

Collider plans:

- FCC-ee plans 5y run at $\sqrt{s} \approx 2m_{top}$ after 9y run at 240 GeV
- CEPC currently not planning on top programme
- CLIC 1st stage at 380 GeV includes top programme
- ILC plans run at $\sqrt{s} \approx 2m_{top}$ after about 15y

M. Lancaster

Electroweak Observables at Future Colliders

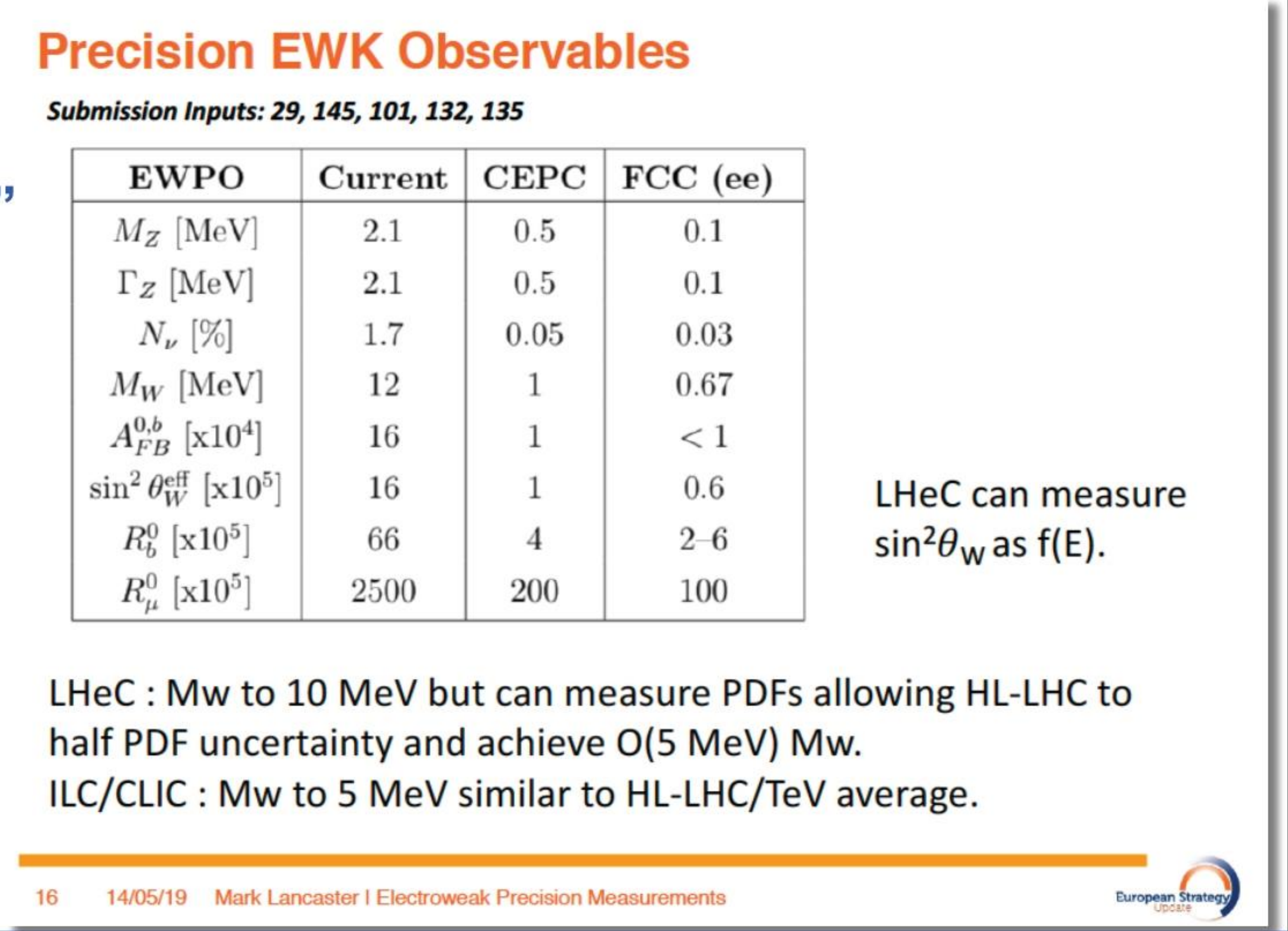


10^{12} Z's "Tera-Z"

M. Lancaster

ILC:

- **"Giga-Z" running not part of baseline but maybe later**



Precision EWK Observables

Submission Inputs: 29, 145, 101, 132, 135

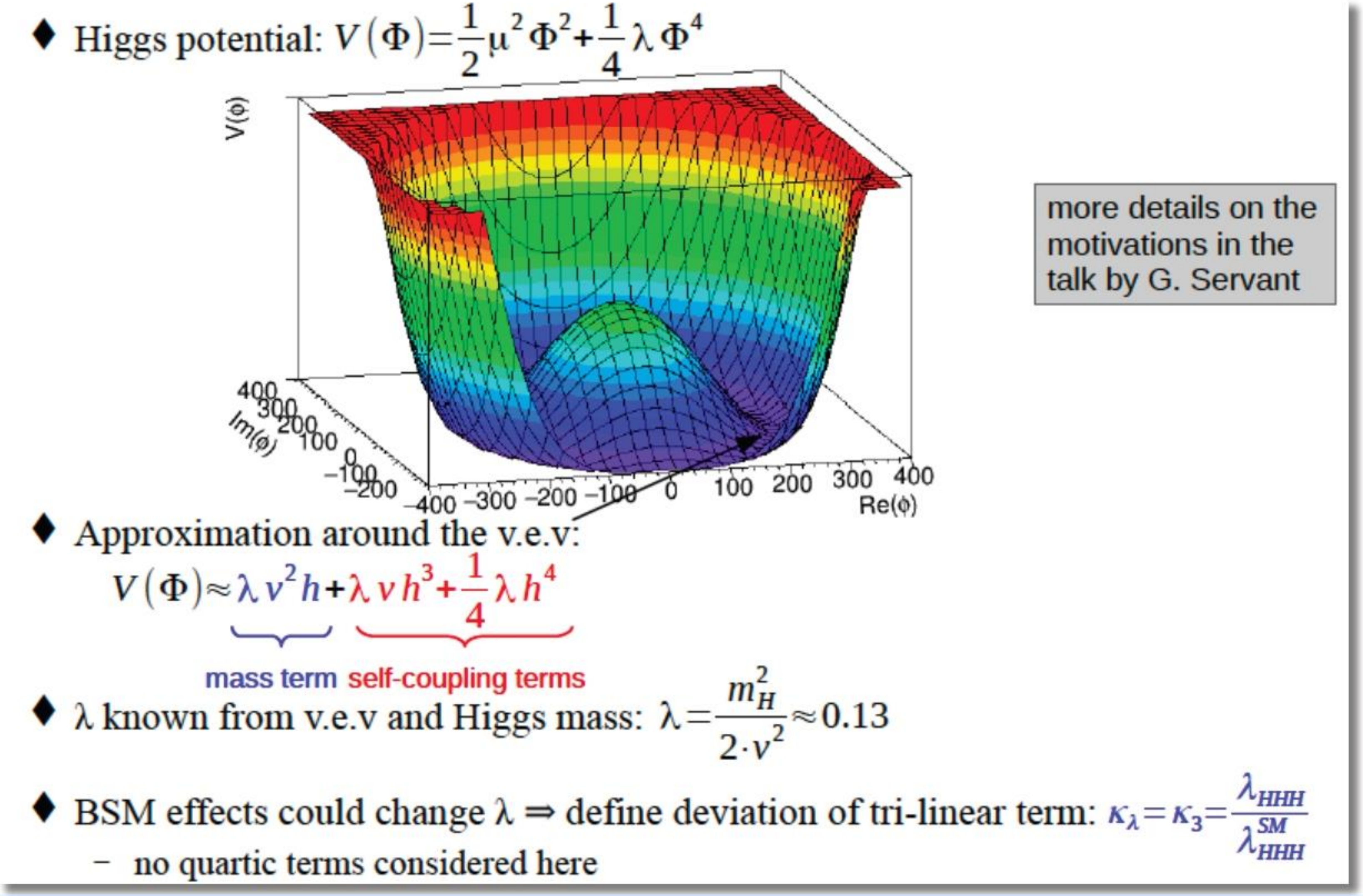
EWPO	Current	CEPC	FCC (ee)
M_Z [MeV]	2.1	0.5	0.1
Γ_Z [MeV]	2.1	0.5	0.1
N_ν [%]	1.7	0.05	0.03
M_W [MeV]	12	1	0.67
$A_{FB}^{0,b}$ [x10^4]	16	1	< 1
$\sin^2\theta_W^{\rm eff}$ [x10^5]	16	1	0.6
R_b^0 [x10^5]	66	4	2–6
R_μ^0 [x10^5]	2500	200	100

LHeC can measure $\sin^2\theta_W$ as f(E).

LHeC : Mw to 10 MeV but can measure PDFs allowing HL-LHC to half PDF uncertainty and achieve O(5 MeV) Mw.
ILC/CLIC : Mw to 5 MeV similar to HL-LHC/TeV average.

Question 4:
What is the best path towards measuring the Higgs potential?

Higgs Potential: measurement of self-coupling



- Higgs potential: $V(\Phi)=\frac{1}{2}\mu^2\Phi^2+\frac{1}{4}\lambda\Phi^4$
- Approximation around the v.e.v:

$$V(\Phi)\approx\underbrace{\lambda v^2 h}_{\text{mass term}}+\underbrace{\lambda v h^3+\frac{1}{4}\lambda h^4}_{\text{self-coupling terms}}$$

- λ known from v.e.v and Higgs mass: $\lambda=\frac{m_H^2}{2\cdot v^2}\approx 0.13$
- BSM effects could change λ ⇒ define deviation of tri-linear term: $\kappa_\lambda=\kappa_3=\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$
  - no quartic terms considered here

more details on the motivations in the talk by G. Servant

E. Petit

Measurement of Higgs Self-Coupling

Di-Higgs processes at hadron colliders:

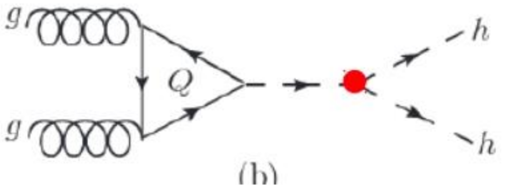
- $\sigma(HH) \approx 0.01 \times \sigma(H)$
- Important to use differential measurements

Di-Higgs processes at lepton colliders

- ZHH or VBF production complementary

Single-Higgs production sensitive through loop effects, e.g. for $\kappa_\lambda = 2$:

- Hadron colliders: ~3%
- Lepton colliders: ~1%



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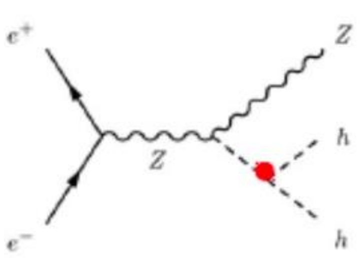
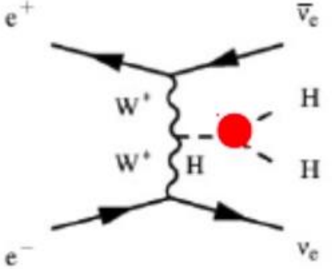
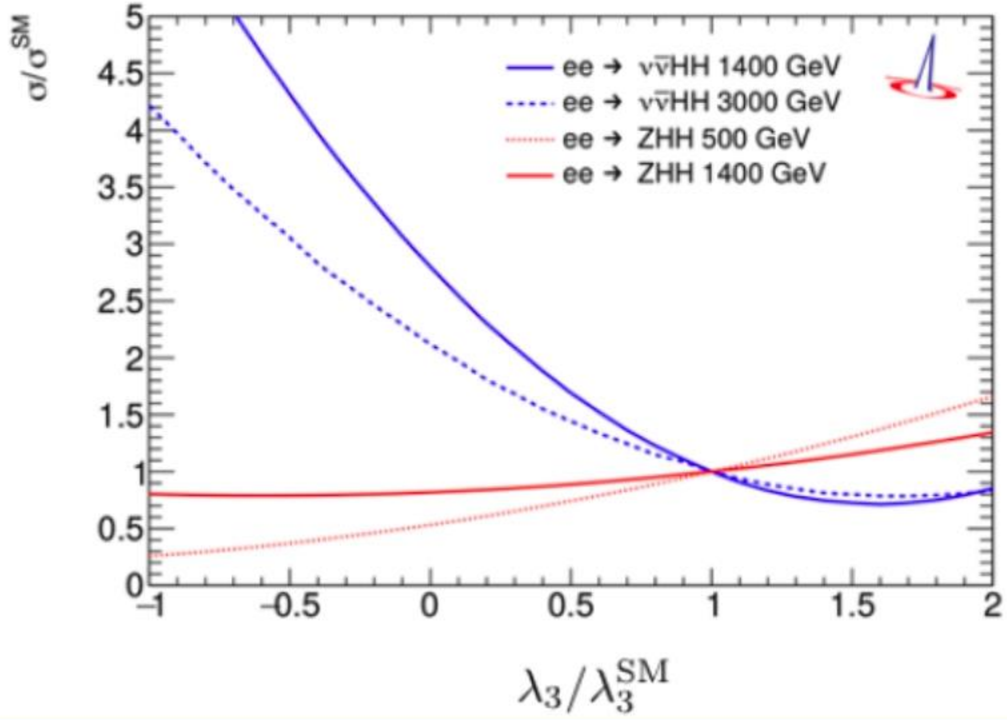
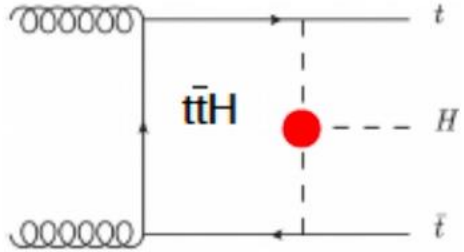
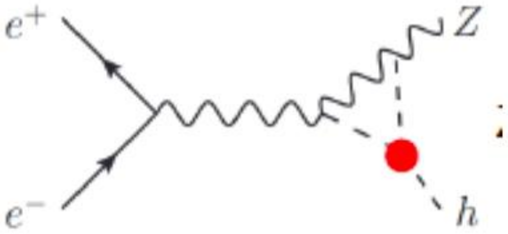










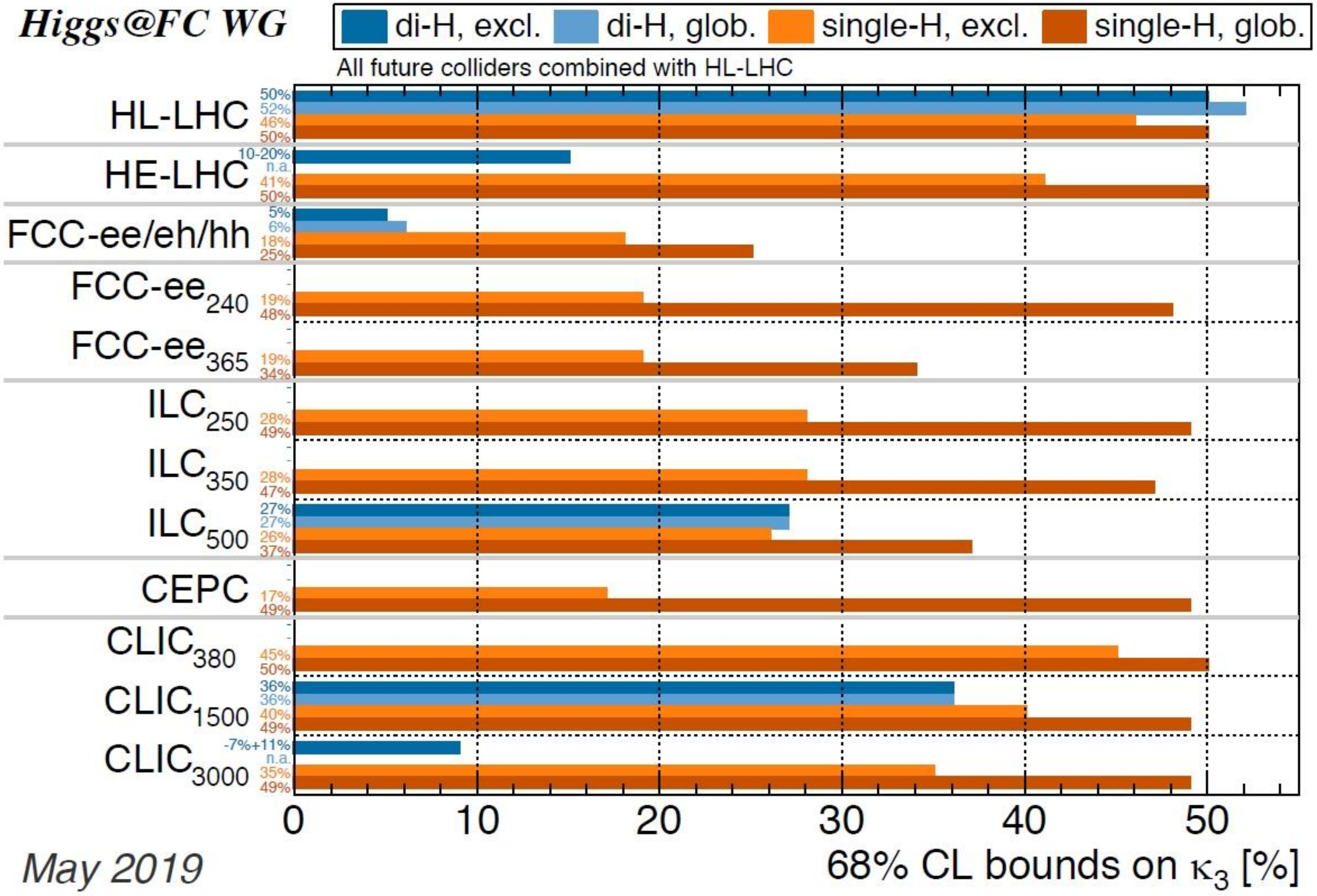
Sensitivity to λ: via single-H and di-H production

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**



May 2019

Question 3:
What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?

Theoretical Uncertainties: production

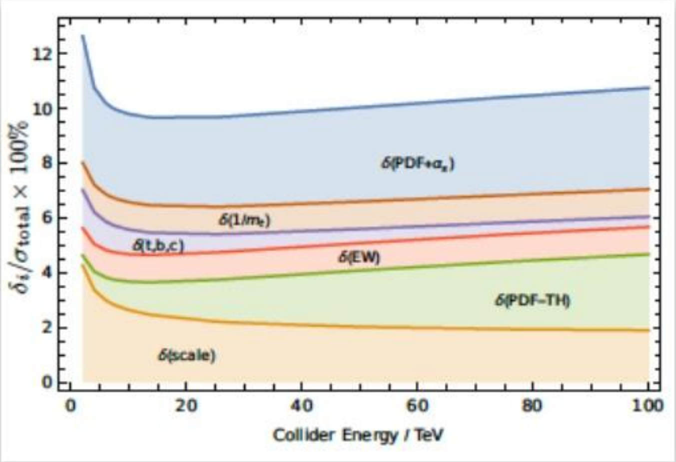
Production at hadron colliders

- For HL-LHC uncertainties expected to be improved by factor 2 w.r.t. current
- HE-LHC: another factor of 2
- FCC-hh: well below 1%

Requires e.g.

- Improved PDFs
- Higher precision calculations
- Improved non-perturbative aspects
- …

ggF: many small sources of uncertainties that add up

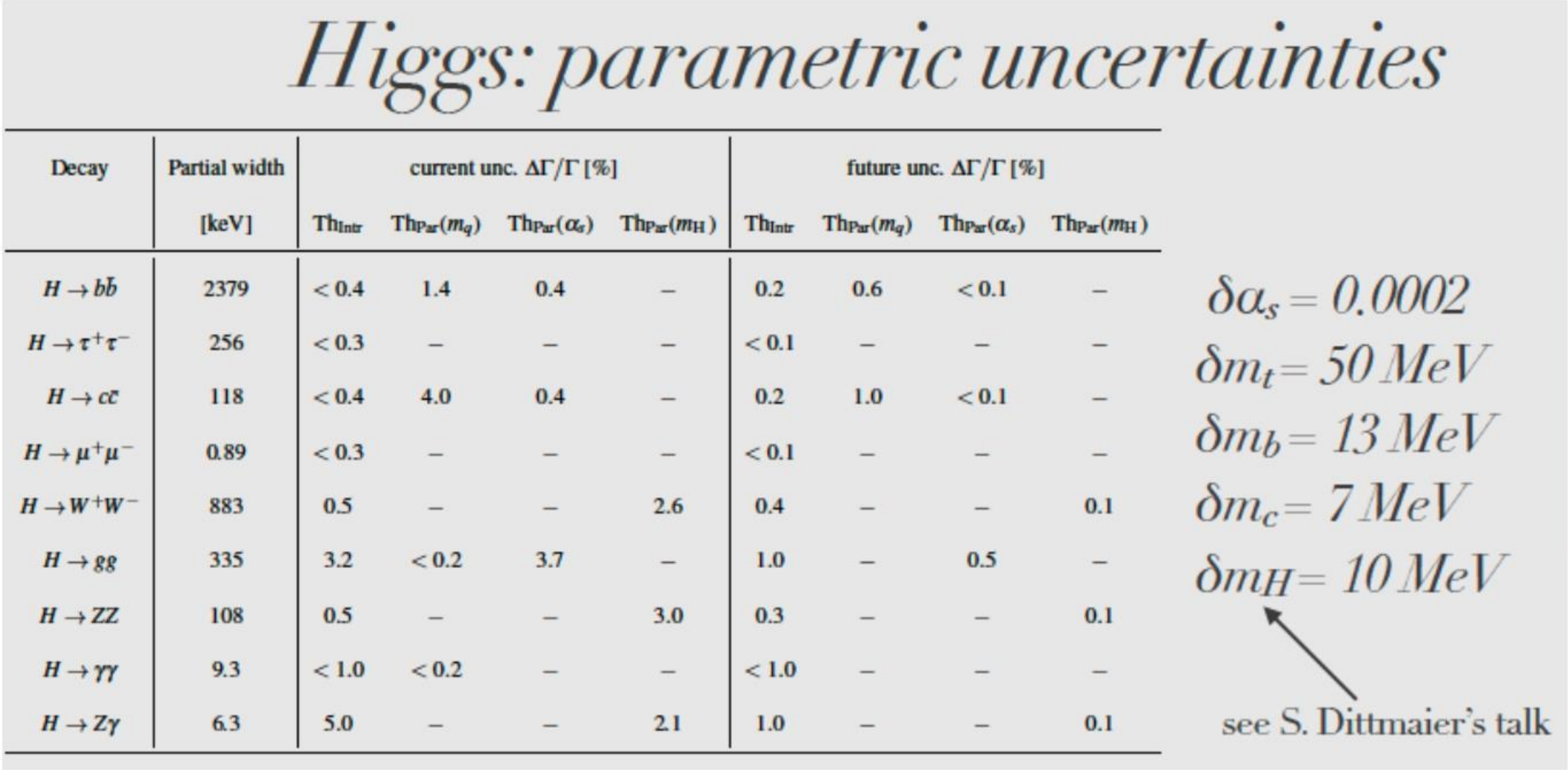


> Improving substantially on any of the current sources of uncertainty represents a major theoretical challenge that should be met in accordance with our ability to utilise said precision and with experimental capabilities. The
>
> . . .
>
> It is obvious that the future precision of experimental measurement of Higgs boson properties will challenge the theoretical community. Achieving a significant improvement of our current theoretical understanding of the Higgs boson and its interactions will inspire us to push the boundaries of our capabilities to predict and extract information. New ways of utilising

+ *extreme kinematics [boosted, off-shell…]*

F. Caola

Theoretical Uncertainties: partial widths



Higgs: parametric uncertainties

Decay	Partial width [keV]	current unc. $\Delta\Gamma/\Gamma$ [%] Th$_{\mathrm{Intr}}$	Th$_{\mathrm{Par}}(m_q)$	Th$_{\mathrm{Par}}(\alpha_s)$	Th$_{\mathrm{Par}}(m_H)$	future unc. $\Delta\Gamma/\Gamma$ [%] Th$_{\mathrm{Intr}}$	Th$_{\mathrm{Par}}(m_q)$	Th$_{\mathrm{Par}}(\alpha_s)$	Th$_{\mathrm{Par}}(m_H)$
$H \to b\bar{b}$	2379	< 0.4	1.4	0.4	–	0.2	0.6	< 0.1	–
$H \to \tau^+\tau^-$	256	< 0.3	–	–	–	< 0.1	–	–	–
$H \to c\bar{c}$	118	< 0.4	4.0	0.4	–	0.2	1.0	< 0.1	–
$H \to \mu^+\mu^-$	0.89	< 0.3	–	–	–	< 0.1	–	–	–
$H \to W^+W^-$	883	0.5	–	–	2.6	0.4	–	–	0.1
$H \to gg$	335	3.2	< 0.2	3.7	–	1.0	–	0.5	–
$H \to ZZ$	108	0.5	–	–	3.0	0.3	–	–	0.1
$H \to \gamma\gamma$	9.3	< 1.0	< 0.2	–	–	< 1.0	–	–	–
$H \to Z\gamma$	6.3	5.0	–	–	2.1	1.0	–	–	0.1

$\delta\alpha_s = 0.0002$ <= very hard but doable at M_Z

$\delta m_t = 50\ MeV$ <= OK at e^+e^- threshold scan

$\delta m_b = 13\ MeV$ <= OK

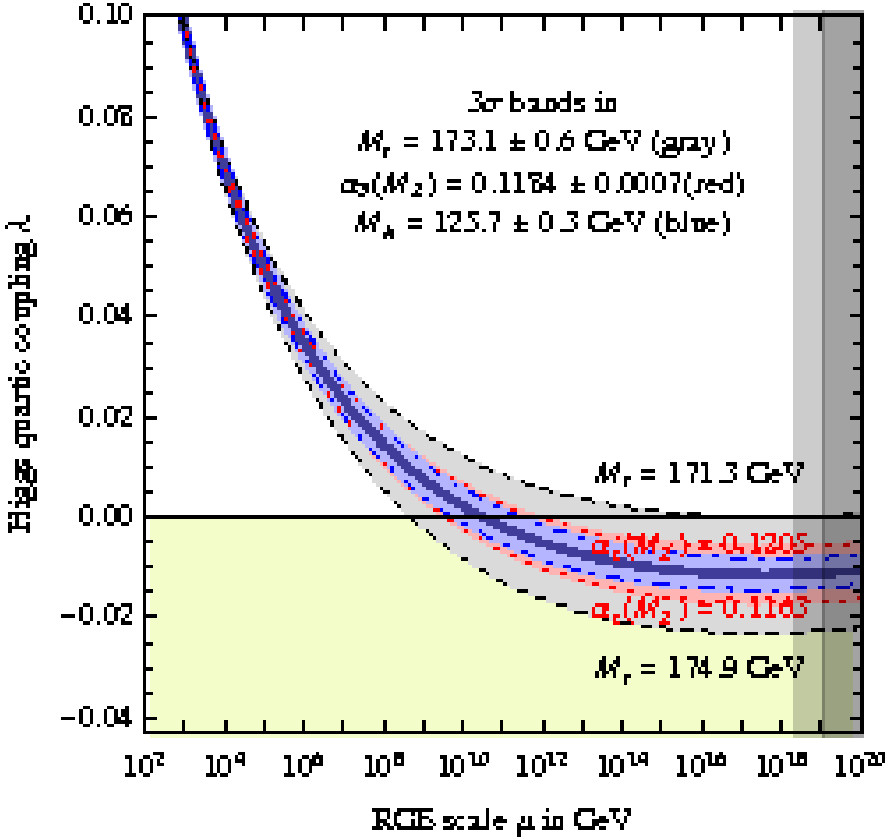
$\delta m_c = 7\ MeV$ <= OK

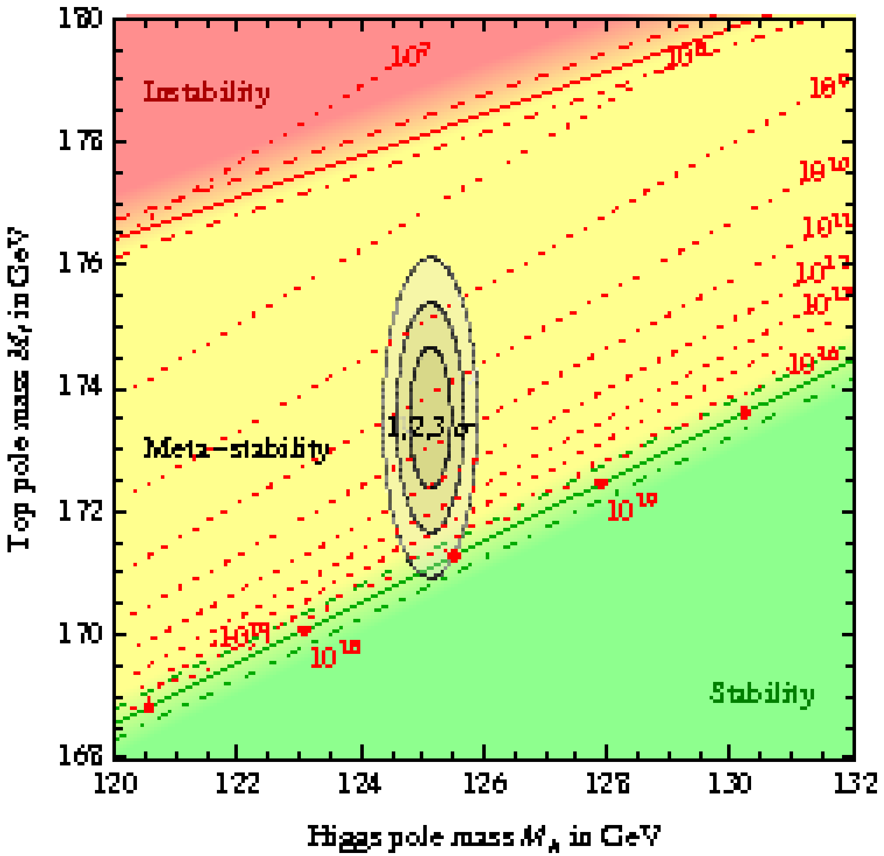
$\delta m_H = 10\ MeV$

see S. Dittmaier's talk

F. Caola

Higgs and top mass and vacuum stability





J. R. Espinosa – PoS TOP2015 (2016) 043, arXiv:1512.01222

With more precision, we may get more clear picture on indication of scale of new physics

Some points from the discussion sessions

- M. Spiro – strong support for FCC-ee followed by FCC-hh
- K. Jacobs – against FCC-ee, wants to go for FCC-hh directly and as soon as possible
- Many expressed an opinion that FCC is too large and and too long project at that we should go for linear e+e- accelerator

Summary

- volba budoucího urychlovače v Evropě není lehká
- po fyzikální stránce se mi nejvíc líbí volba FCC-ee následovaná FCC-hh (kombinace přesných EWK měření na ee a větší objevitelský potenciál FCC-hh)
- mnoho otázek - projekt je mimo současné finanční možnosti CERN, dlouhá časová škála, je vědecký program dostatečně atraktivní, aby přitáhl nadkritické množství vědců a hlavně studentů?

Backup

Higgs width and/or untagged decays

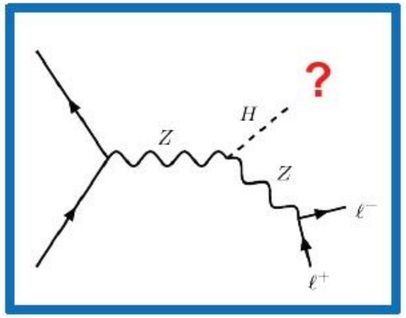
Unique feature of lepton-lepton colliders:

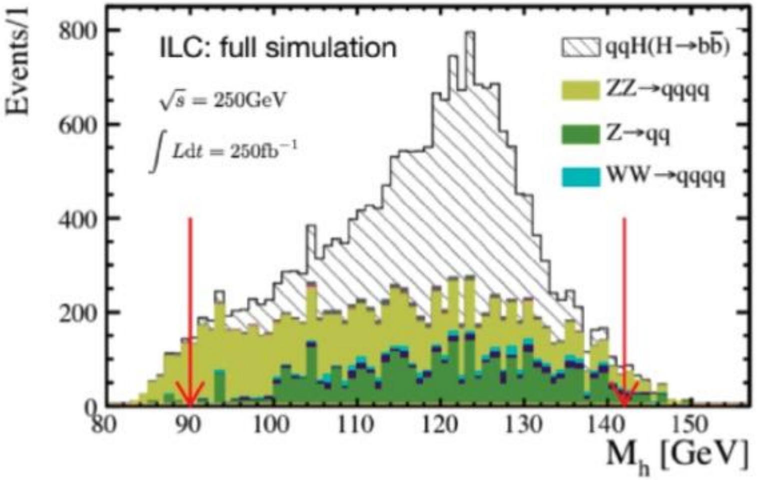
- **Detecting the Higgs boson without seeing decay: "recoil method"**
- **Measure ZH cross section with high precision without assumptions on decay**
- **Often interpreted as quasi-direct measurement of width**

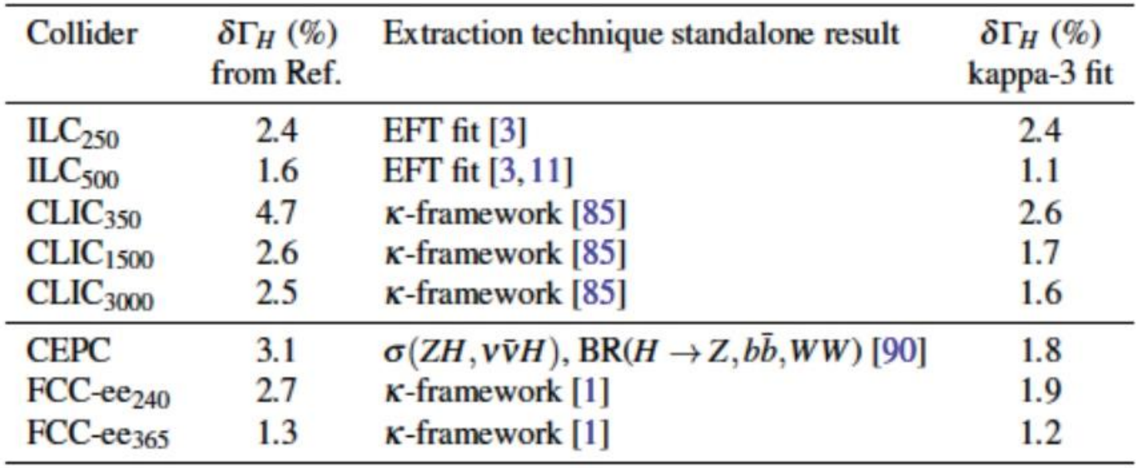
$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

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

=> 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
FCC-ee$_{240}$	2.7	κ-framework [1]	1.9
FCC-ee$_{365}$	1.3	κ-framework [1]	1.2

arXiv:1905.03764