Feedback on Granada Symposium

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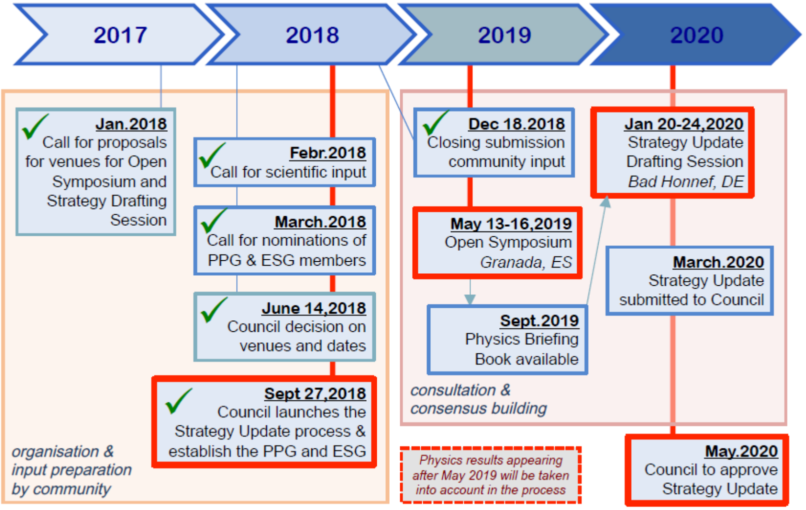
European Strategy for Particle Physics

- European Particle Physics Strategy Update
  - ✓ (periodicity ~5 ans) process: 2018-2020
- Driven by: European Strategy Group
  - ✓ (Chair: H.Abramovicz)
    - Physics Preparatory Group

- Decision making body – CERN Council
- Drafting of the Strategy Update document – responsibility of the European Strategy Group (ESG)
- Scientific Input to the Strategy Update – responsibility of the Physics Preparatory Group (PPG)
- Coordinating body – the Strategy Update Secretariat (SUS)

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?



✓ **Jan.2018**
Call for proposals for venues for Open Symposium and Strategy Drafting Session

✓ **Febr.2018**
Call for scientific input

✓ **March.2018**
Call for nominations of PPG & ESG members

✓ **June 14,2018**
Council decision on venues and dates

✓ **Sept 27,2018**
Council launches the Strategy Update process & establish the PPG and ESG

organisation & input preparation by community

✓ **Dec 18.2018**
Closing submission community input

May 13-16,2019
Open Symposium
Granada, ES

Sept.2019
Physics Briefing Book available

consultation & consensus building

Physics results appearing after May 2019 will be taken into account in the process

Jan 20-24,2020
Strategy Update Drafting Session
Bad Honnef, DE

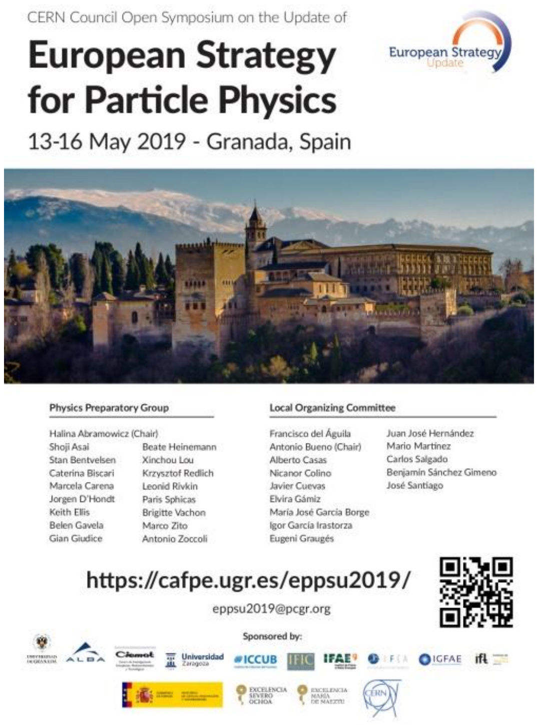
March.2020
Strategy Update submitted to Council

May.2020
Council to approve Strategy Update

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

Symposium

- **CERN Council Open Symposium on the Update of European Strategy for Particle Physics**
- 13-16 May 2019 - Granada, Spain
  - ✓ 603 participants
  - ✓ 160 written documents submitted
  - ✓ Parallel sessions
    - ▪ Electroweak Physics
    - ▪ Flavour Physics and CP violation
    - ▪ Dark Matter and Dark Sector
    - ▪ Accelerator Science and Technology
    - ▪ Beyond the Standard Model at colliders
    - ▪ Strong Interactions
    - ▪ Neutrino Physics
    - ▪ Instrumentation and Computing
  - ✓ ~20 plenary talks



CERN Council Open Symposium on the Update of

European Strategy for Particle Physics

13-16 May 2019 - Granada, Spain

Physics Preparatory Group

Halina Abramowicz (Chair)
Shoji Asai
Stan Bentvelsen
Caterina Biscari
Marcela Carena
Jorgen D'Hondt
Keith Ellis
Belen Gavela
Gian Giudice
Beate Heinemann
Xinchou Lou
Krzysztof Redlich
Leonid Rivkin
Paris Sphicas
Brigitte Vachon
Marco Zito
Antonio Zoccoli

Local Organizing Committee

Francisco del Águila
Antonio Bueno (Chair)
Alberto Casas
Nicanor Colino
Javier Cuevas
Elvira Gámiz
María José García Borge
Igor García Irastorza
Eugeni Graugés
Juan José Hernández
Mario Martínez
Carlos Salgado
Benjamín Sánchez Gimeno
José Santiago

https://cafpe.ugr.es/eppsu2019/

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Sponsored by:

Future lepton colliders

ILC (Japan)

CLIC (CERN)

FCC-ee (CERN)

CEPC (China)

Consensus:
e+e- should be the next priority

Future hadron colliders

FCC-hh (CERN)

HE-LHC (CERN)

SppC (China)

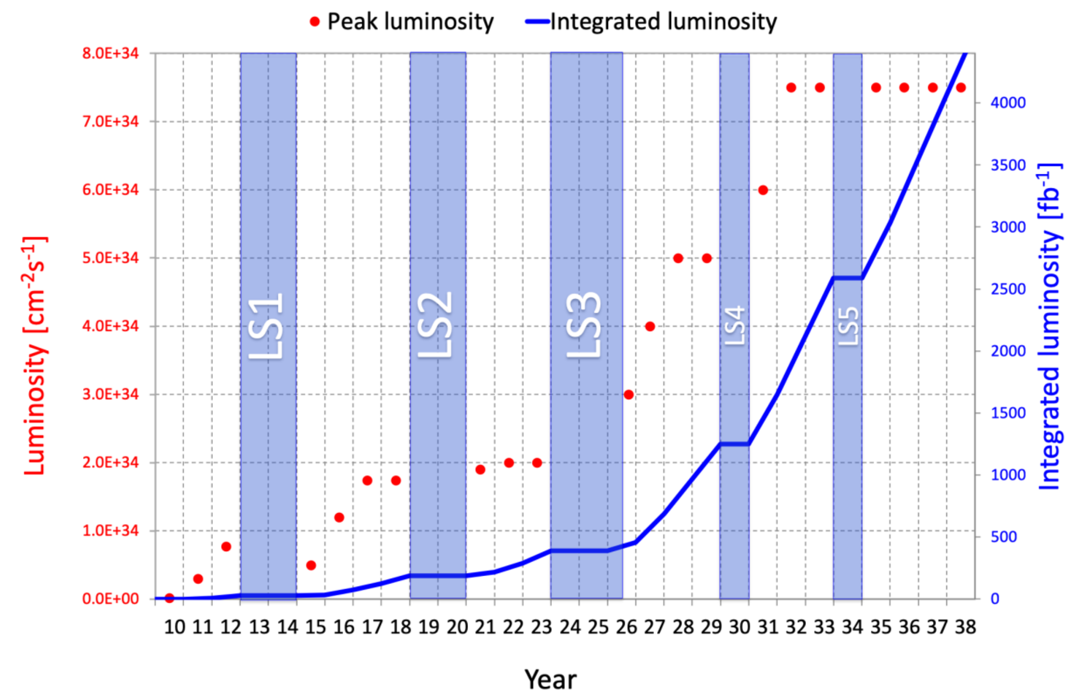
Future e-h colliders

FCC-eh (CERN)

LHeC (CERN)

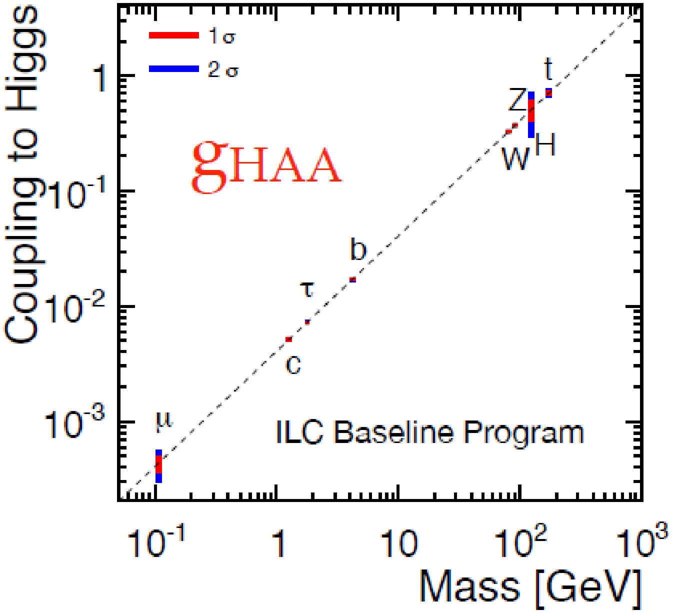
HE-LHeC (CERN)

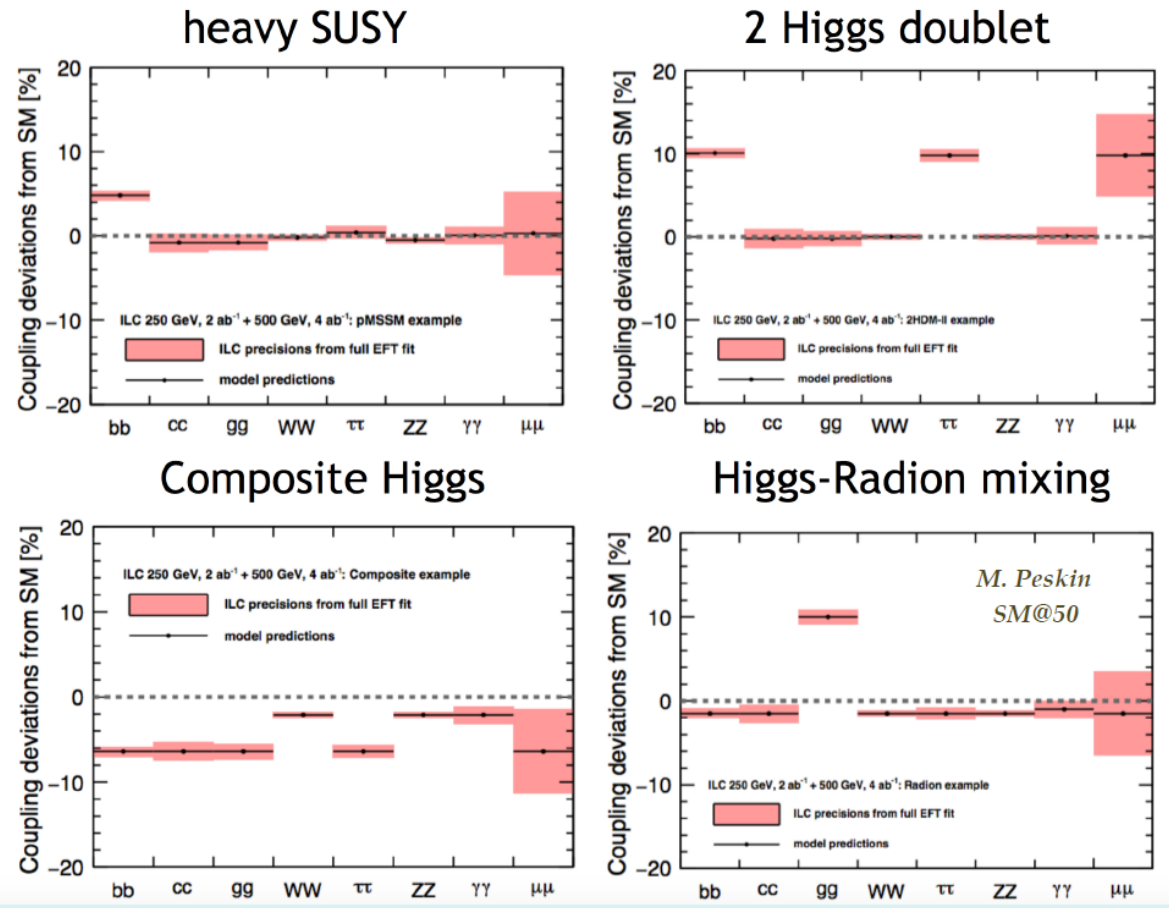
LHC/HL-LHC



HL-LHC:
Data up to ~2038 !

Why studying the Higgs @ the percent level precision ?

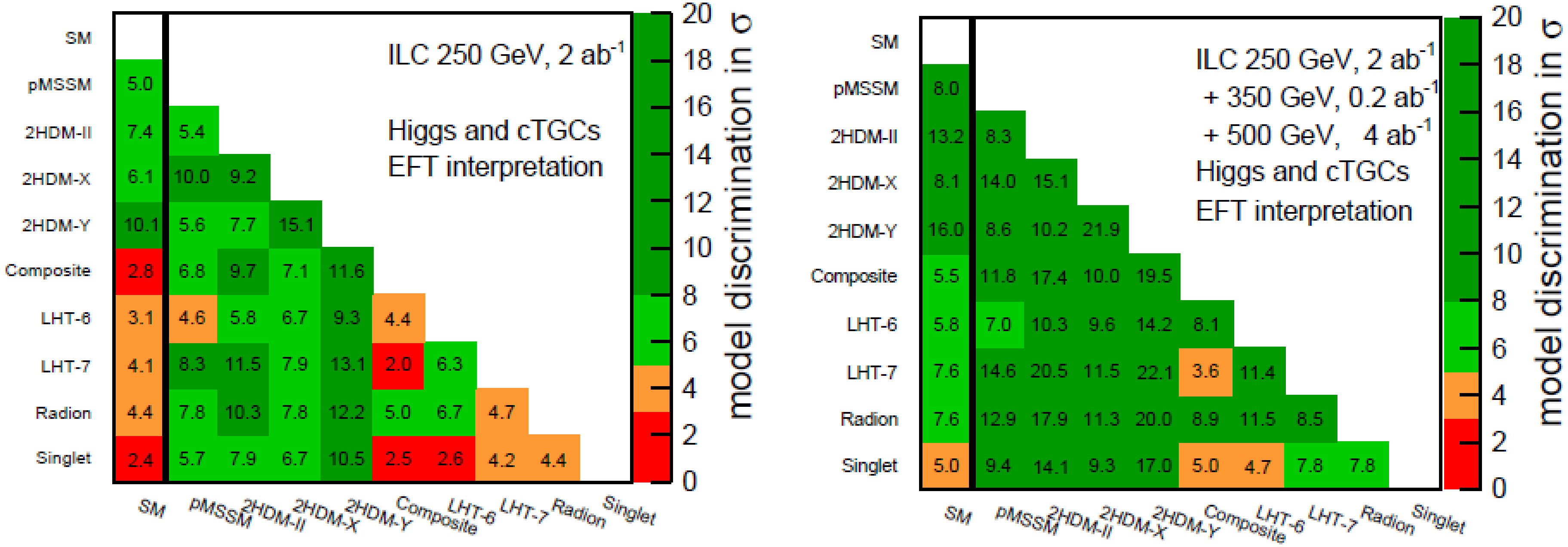




- Mass generation for bosons and fermions (Yukawa couplings)
- Mass, Γ, J^{CP} ⇨ source of CP violation ?
- Triple Higgs coupling: hhh ⇨ Higgs Potential
- H → invisible

Higgs sector is a window for new physics

Why studying Higgs couplings ?



ILC 250 GeV, 2 ab^{-1}

Higgs and cTGCs
EFT interpretation

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.0									
2HDM-II	7.4	5.4								
2HDM-X	6.1	10.0	9.2							
2HDM-Y	10.1	5.6	7.7	15.1						
Composite	2.8	6.8	9.7	7.1	11.6					
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4				
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3			
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7		
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4	

ILC 250 GeV, 2 ab^{-1}
+ 350 GeV, 0.2 ab^{-1}
+ 500 GeV, 4 ab^{-1}
Higgs and cTGCs
EFT interpretation

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	8.0									
2HDM-II	13.2	8.3								
2HDM-X	8.1	14.0	15.1							
2HDM-Y	16.0	8.6	10.2	21.9						
Composite	5.5	11.8	17.4	10.0	19.5					
LHT-6	5.8	7.0	10.3	9.6	14.2	8.1				
LHT-7	7.6	14.6	20.5	11.5	22.1	3.6	11.4			
Radion	7.6	12.9	17.9	11.3	20.0	8.9	11.5	8.5		
Singlet	5.0	9.4	14.1	9.3	17.0	5.0	4.7	7.8	7.8	

Figure 9: Graphical representation of the χ^2 separation of the Standard Model and the models 1–9 described in the text: (a) with 2 ab^{-1} of data at the ILC at 250 GeV; (b) with 2 ab^{-1} of data at the ILC at 250 GeV plus 4 ab^{-1} of data at the ILC at 500 GeV. Comparisons in orange have above 3 σ separation; comparison in green have above 5 σ separation; comparisons in dark green have above 8 σ separation. From [19], with slight modifications to account for the beam polarization scheme in Section 2.

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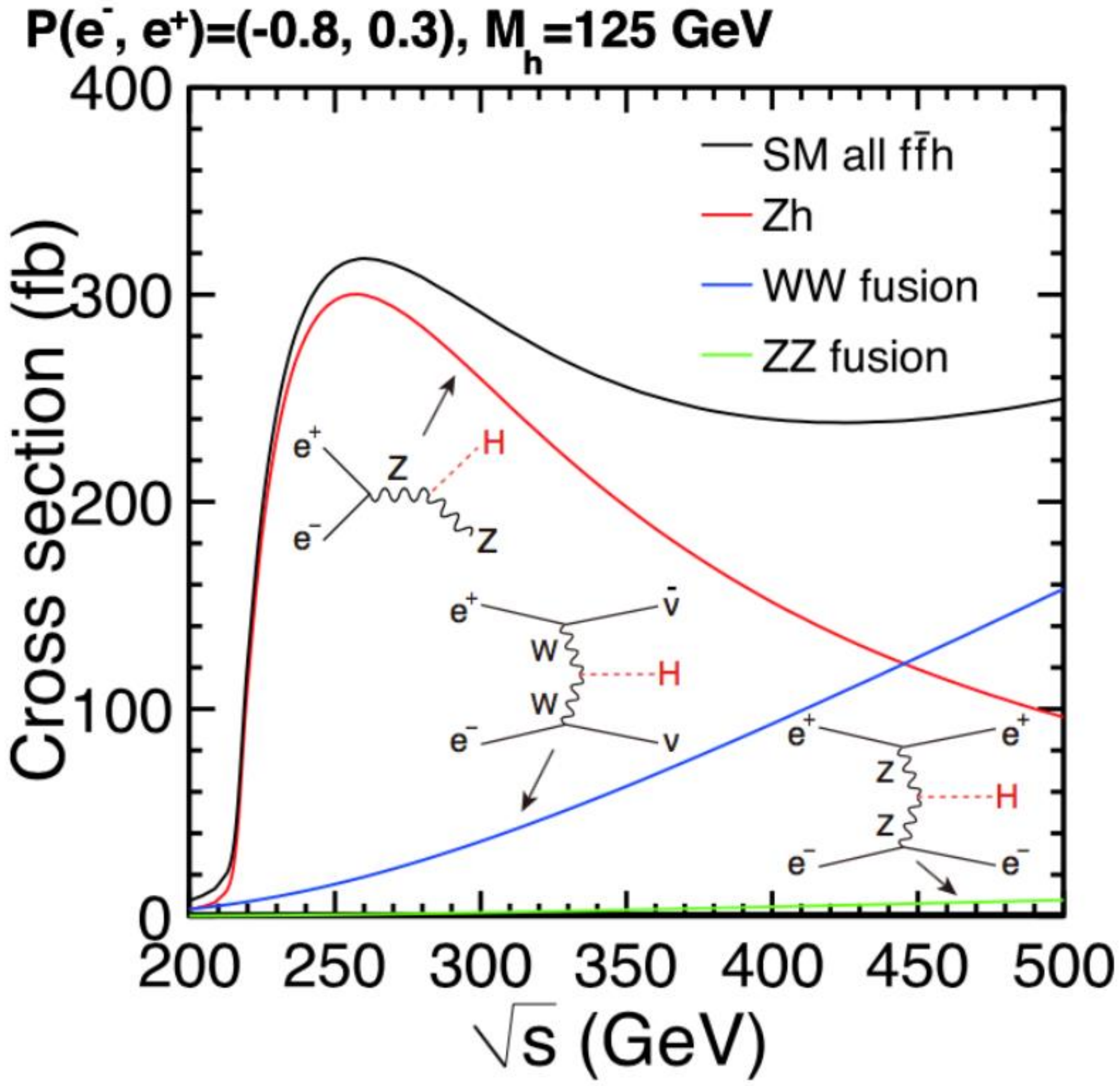
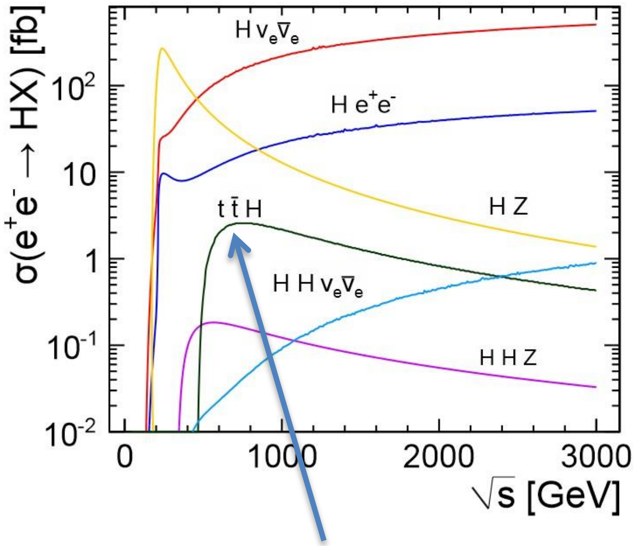
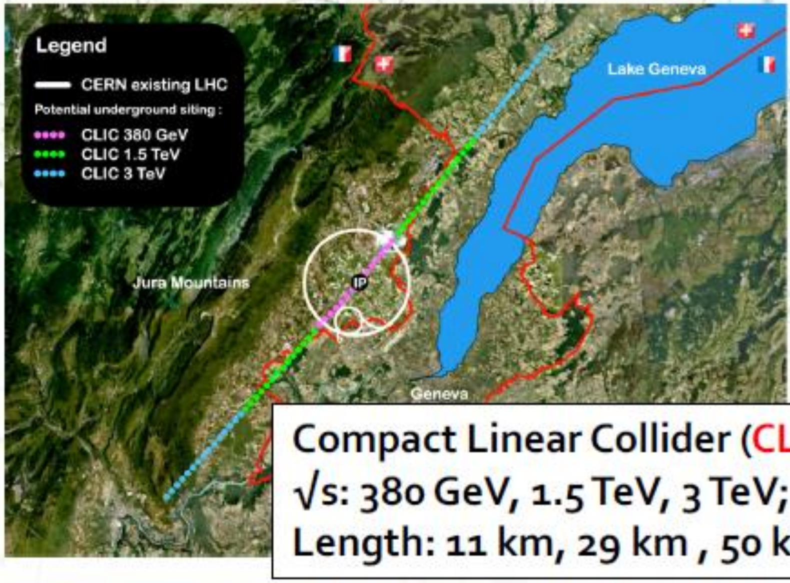
Higgs studies with $e^+e^- \rightarrow Zh$



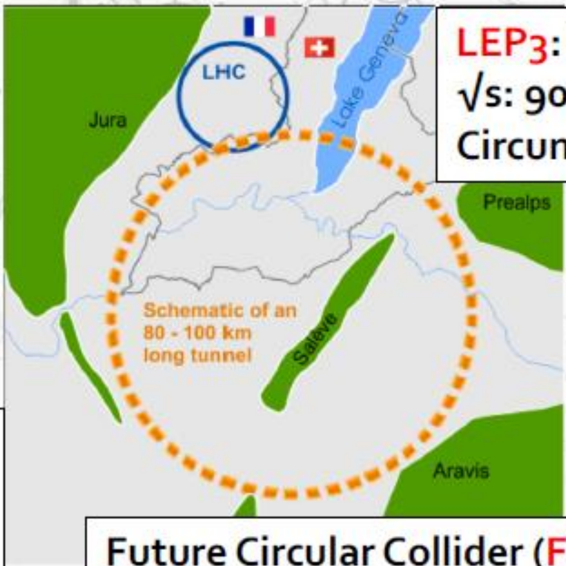


$e^+e^- \rightarrow$ t tbar h

Studies of High-energy e^+e^- Colliders

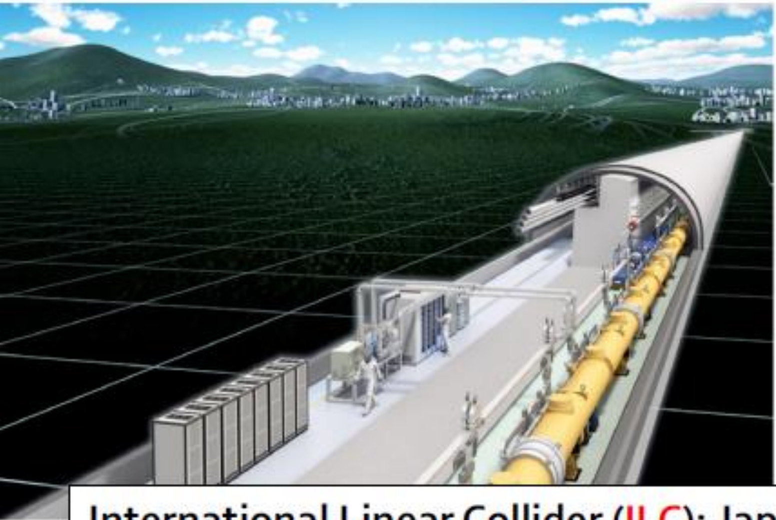


Compact Linear Collider (CLIC): CERN
$\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV;
Length: 11 km, 29 km , 50 km



LEP3: CERN
$\sqrt{s}$: 90 - 240 GeV;
Circumference: 27 km

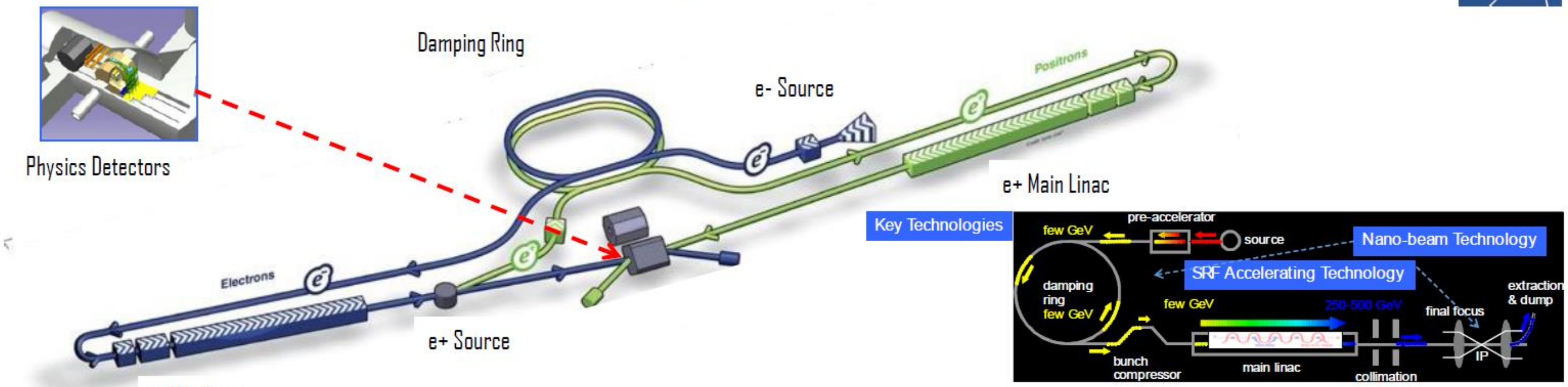
Future Circular Collider (FCC): CERN
e^+e^-, $\sqrt{s}$: 90 - 350 GeV; pp, $\sqrt{s}$: 100 TeV;
Circumference: 97.5 km



International Linear Collider (ILC): Japan
$\sqrt{s}$: 250 – 1000 GeV,
Now concentrating on $\sqrt{s}$ = 250 GeV,
Length: 21 km (250 GeV)

Circular Electron-Positron Collider (CEPC): China
$\sqrt{s}$: 90 – 250 GeV, Circumference: ~100 km

ILC Design Overview



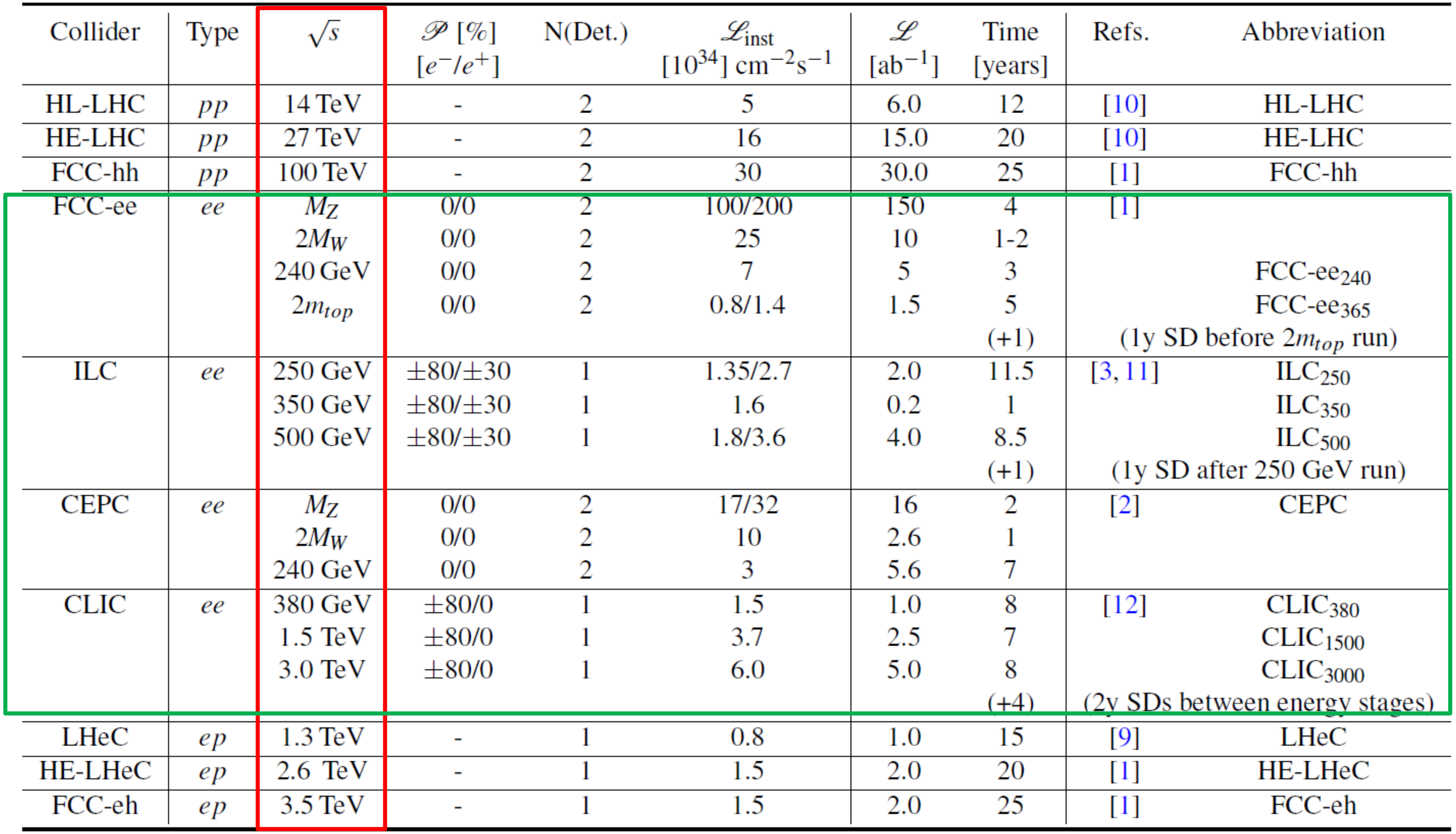
Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	TDR	Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.82	1.8/3.6	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 % (30 %)	80 % (30 %)	80 % (30 %)	80 % (30 %)	80 % (20 %)
Repetition frequency	f_{rep}	Hz	5	5	5	5	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312	1312/2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554	554/366	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	8.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727	727/961	897
Average beam power	P_{ave}	MW	5.3	10.5	10.5	10.5/21	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	729	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	7.7	5.9	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	87.1 %	58.3 %	44.5 %
Energy loss from beamstrahlung	δ_{BS}		2.6 %	2.6 %	0.97 %	4.5 %	10.5 %
Site AC power	P_{site}	MW	129		122	163	300
Site length	L_{site}	km	20.5	20.5	31	31	40

Luminosity upgrade to 10 Hz at 250 also considered

LCs - Granada - May 2019

⇨ Different luminosity options

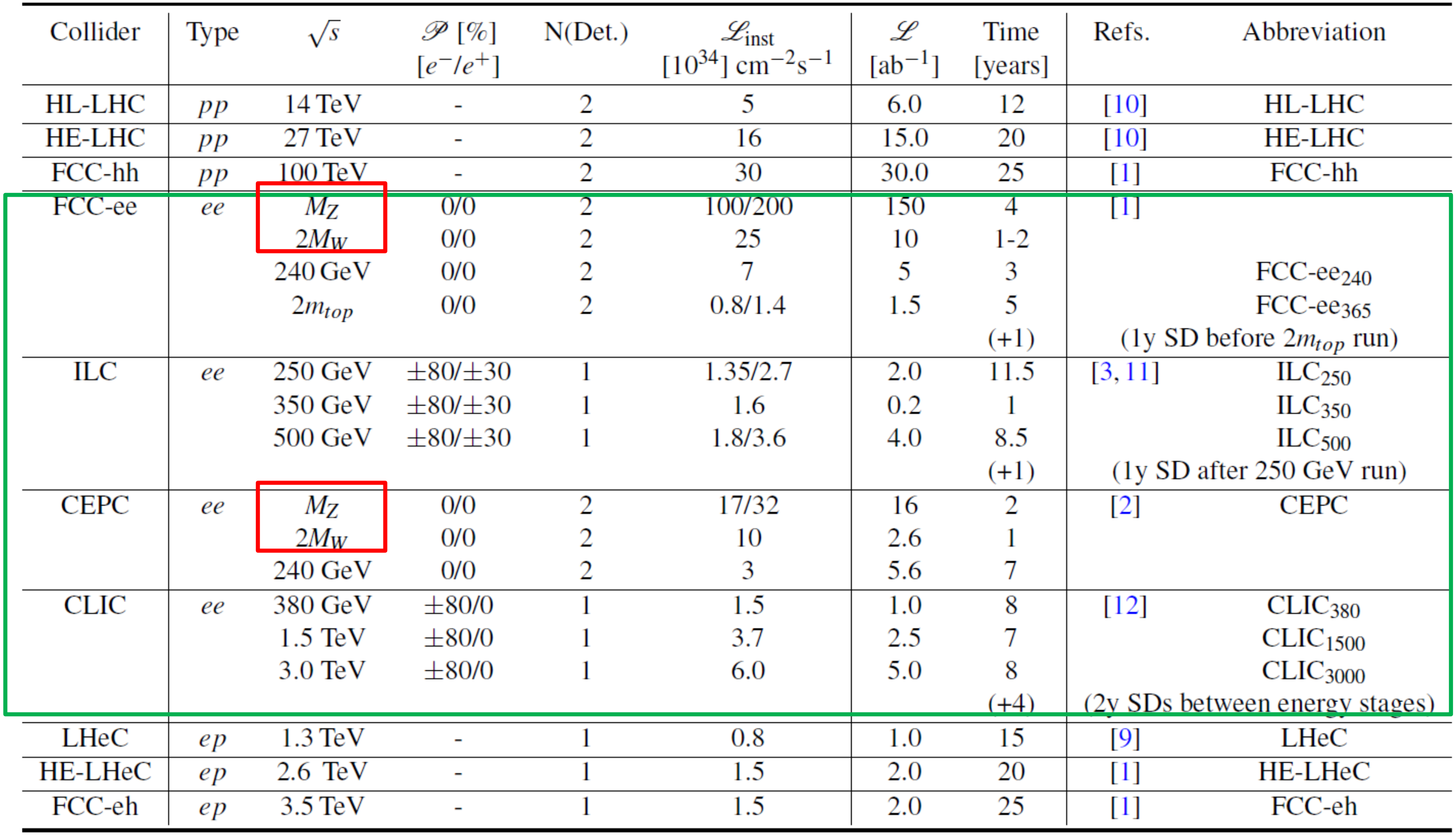
Future collider specifications



Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Common √s~250 GeV ⇨ Zh production
Different high √s capabilities

Future collider specifications



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HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
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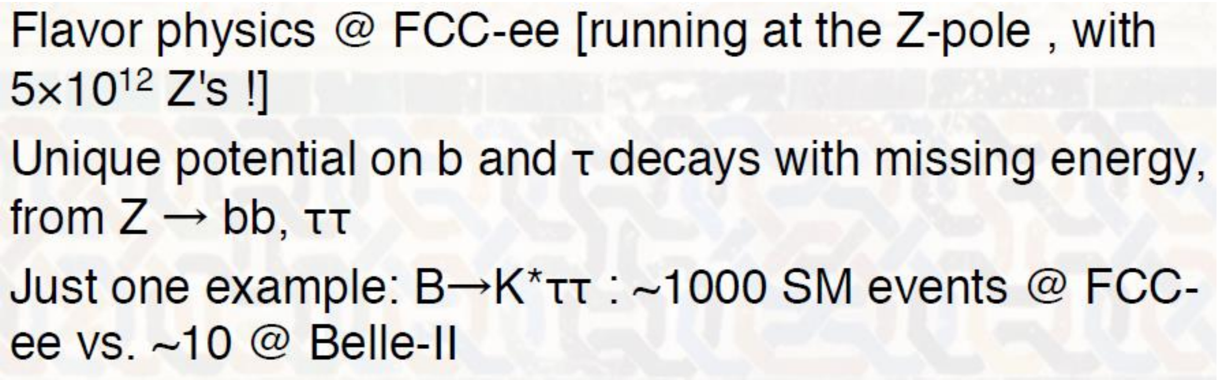
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Z pole program ⇨ Tera-Z
Also possible for ILC (Giga-Z)

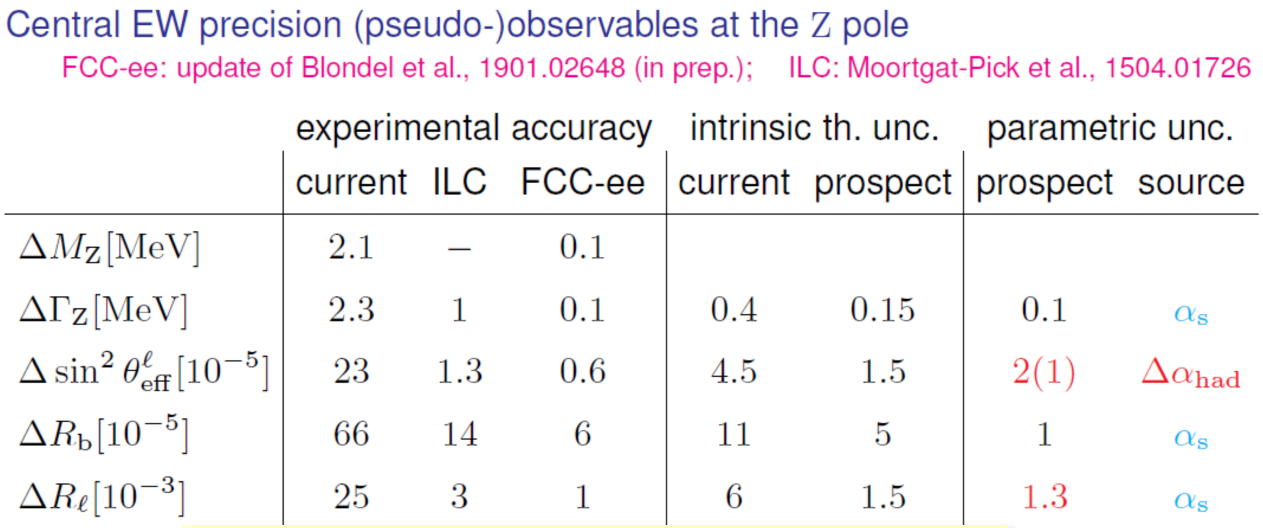
Z pole physics (@ √s = 91 GeV)



Flavor physics @ FCC-ee [running at the Z-pole , with 5×10^{12} Z's !]

Unique potential on b and τ decays with missing energy, from Z → bb, ττ

Just one example: B→K*ττ : ~1000 SM events @ FCC-ee vs. ~10 @ Belle-II



Central EW precision (pseudo-)observables at the Z pole

FCC-ee: update of Blondel et al., 1901.02648 (in prep.); ILC: Moortgat-Pick et al., 1504.01726

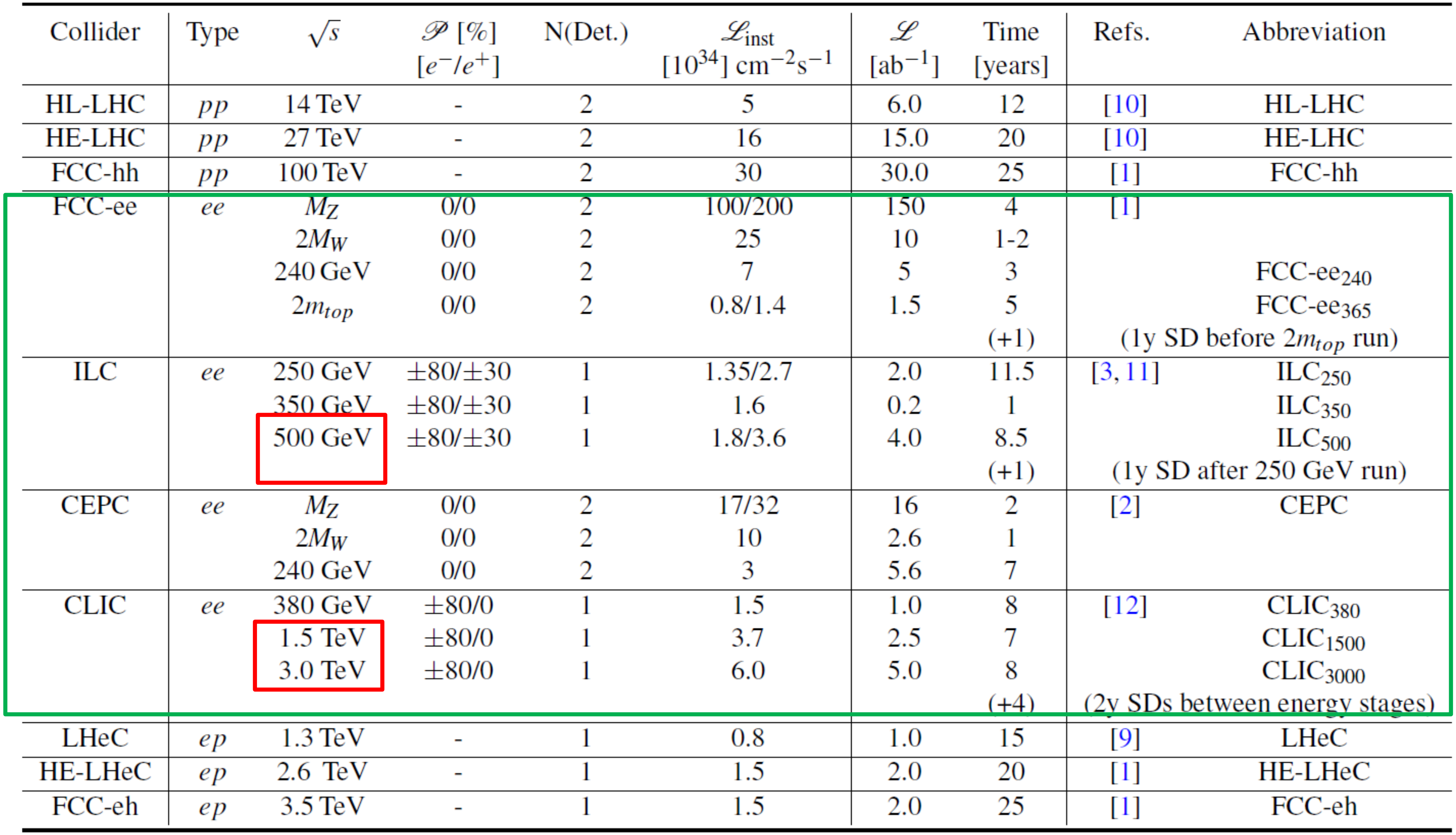
	experimental accuracy			intrinsic th. unc.		parametric unc.	
	current	ILC	FCC-ee	current	prospect	prospect	source
ΔM_Z[MeV]	2.1	–	0.1				
$\Delta\Gamma_Z$[MeV]	2.3	1	0.1	0.4	0.15	0.1	α_s
$\Delta\sin^2\theta^\ell_{\text{eff}}[10^{-5}]$	23	1.3	0.6	4.5	1.5	2(1)	$\Delta\alpha_{\text{had}}$
$\Delta R_b[10^{-5}]$	66	14	6	11	5	1	α_s
$\Delta R_\ell[10^{-3}]$	25	3	1	6	1.5	1.3	α_s

Potential issue: Theoritical uncertainties

Comparisons needed between Tera-Z (FCCee) and Giga-Z (ILC)

Is it decisive in a global SM fit ?

Future collider specifications



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FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee_{240}
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee_{365}
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC_{250}
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		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC_{500}
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC_{380}
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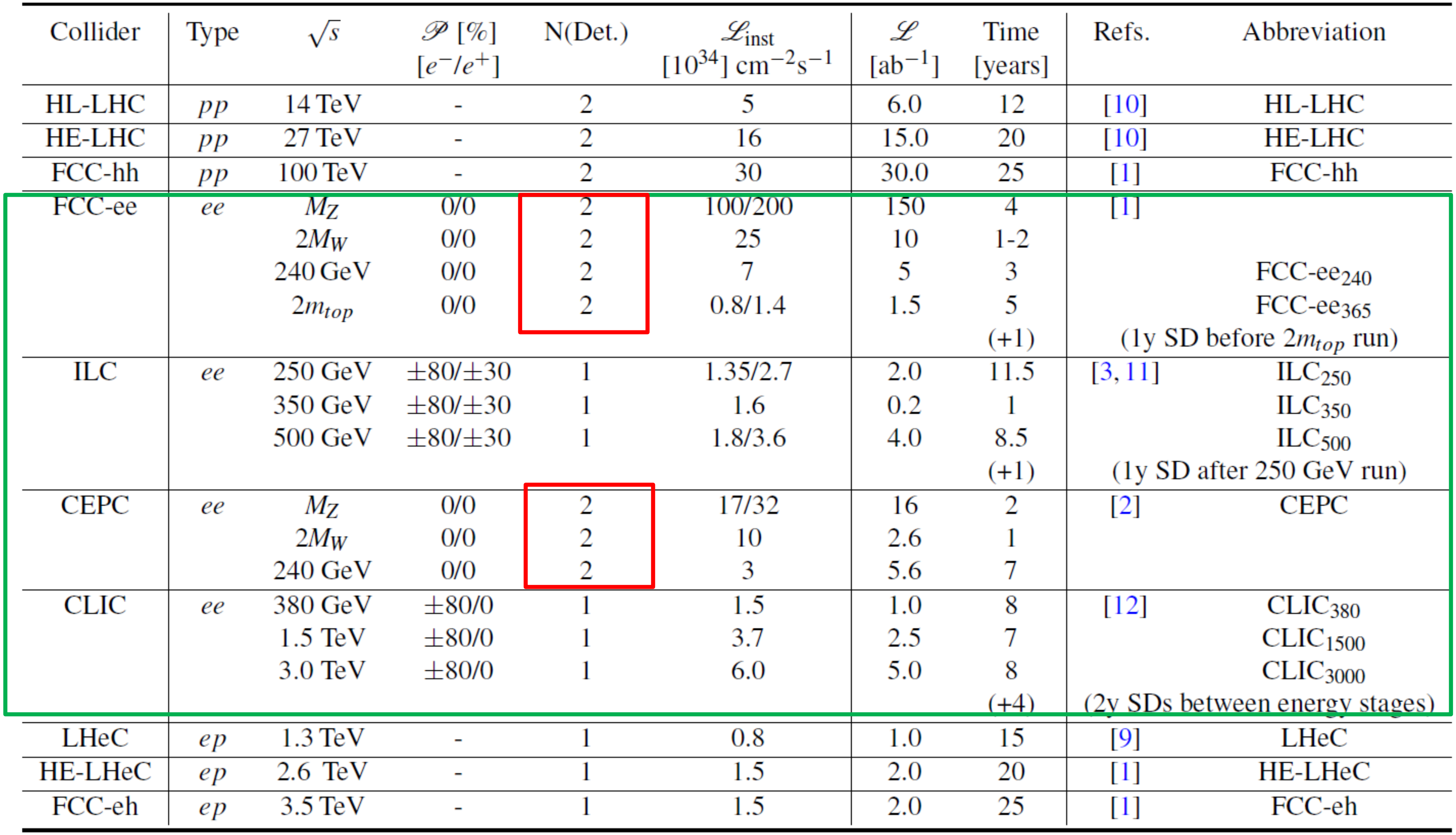
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Linear Colliders ⇨ Higher √s accessible

Future collider specifications



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FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
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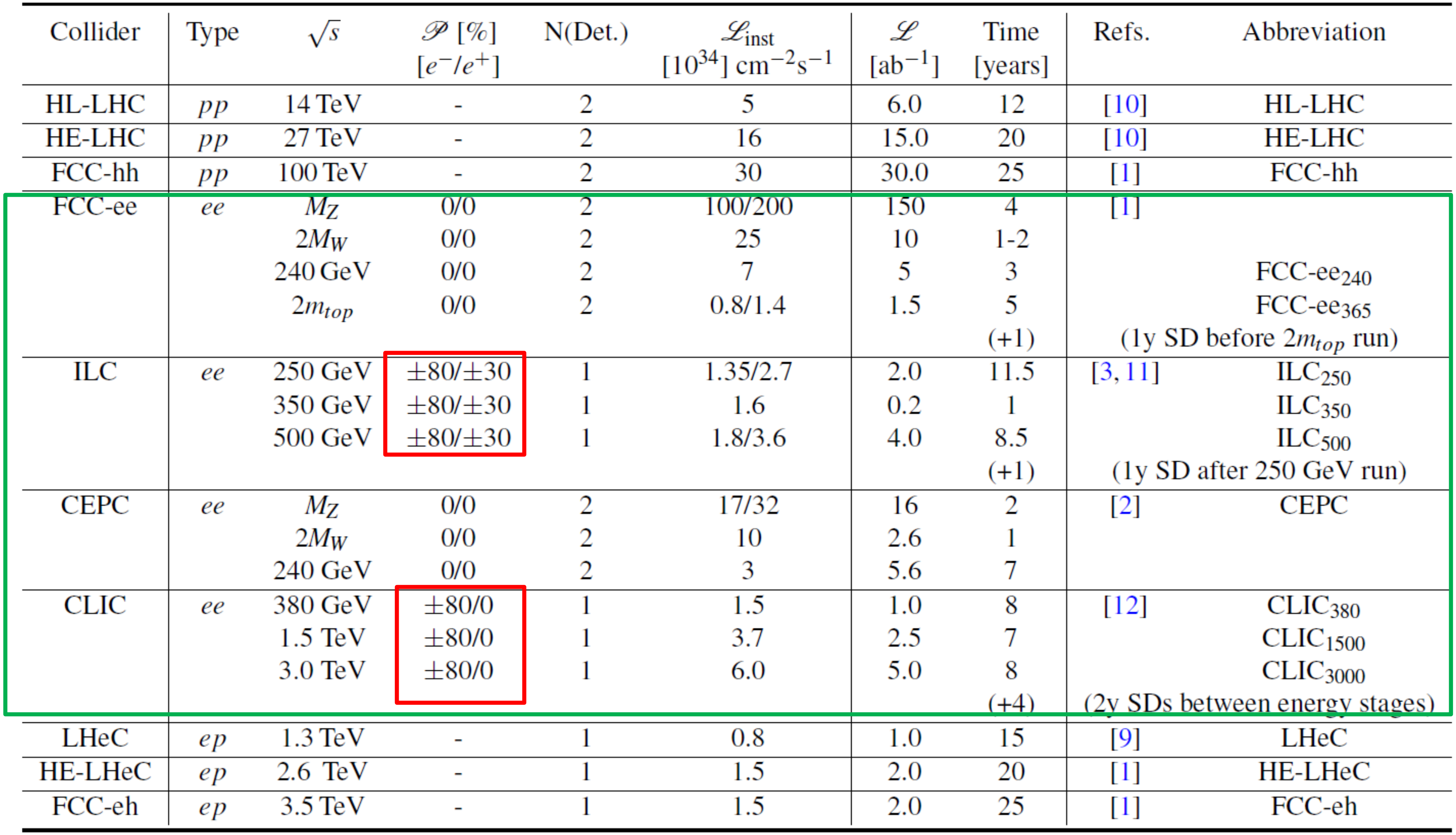
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

2 IPs or more ⇨ only circular

Future collider specifications



Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
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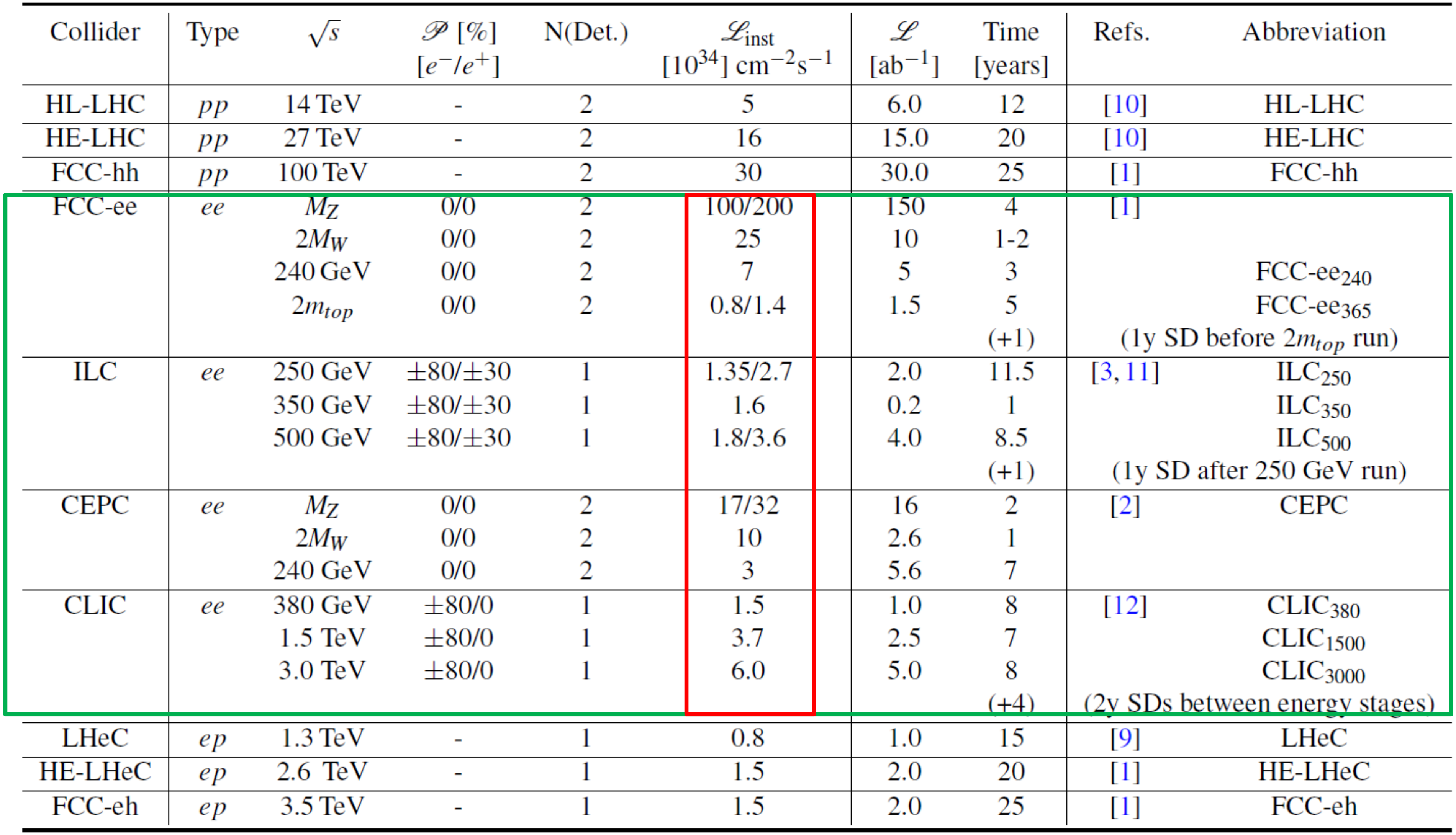
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Beam Polarisation ⇨ only linear colliders

Future collider specifications



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HE-LHC	*pp*	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	*pp*	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	*ee*	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	*ee*	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
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CEPC	*ee*	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	*ee*	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
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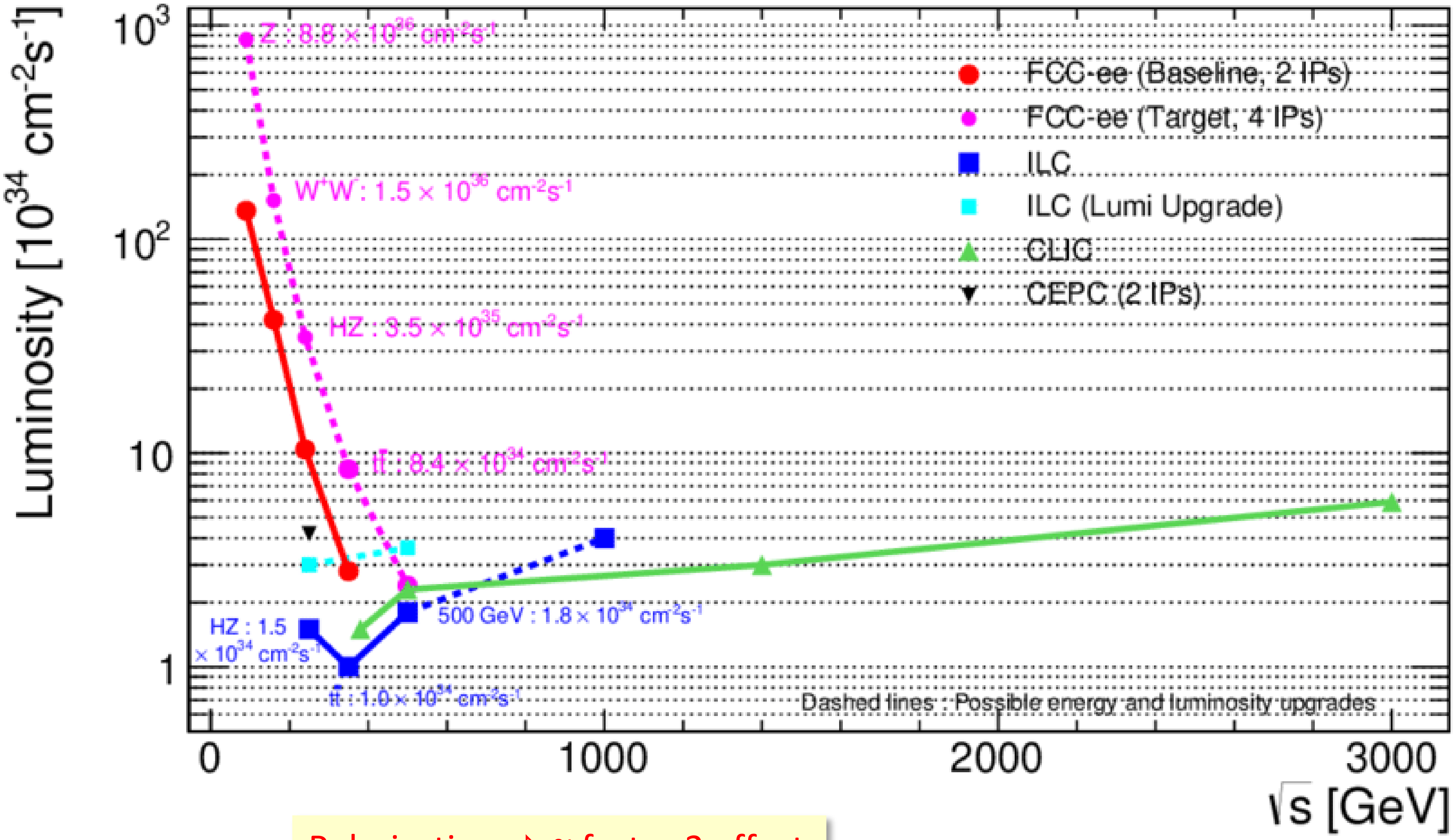
LHeC	*ep*	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	*ep*	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	*ep*	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

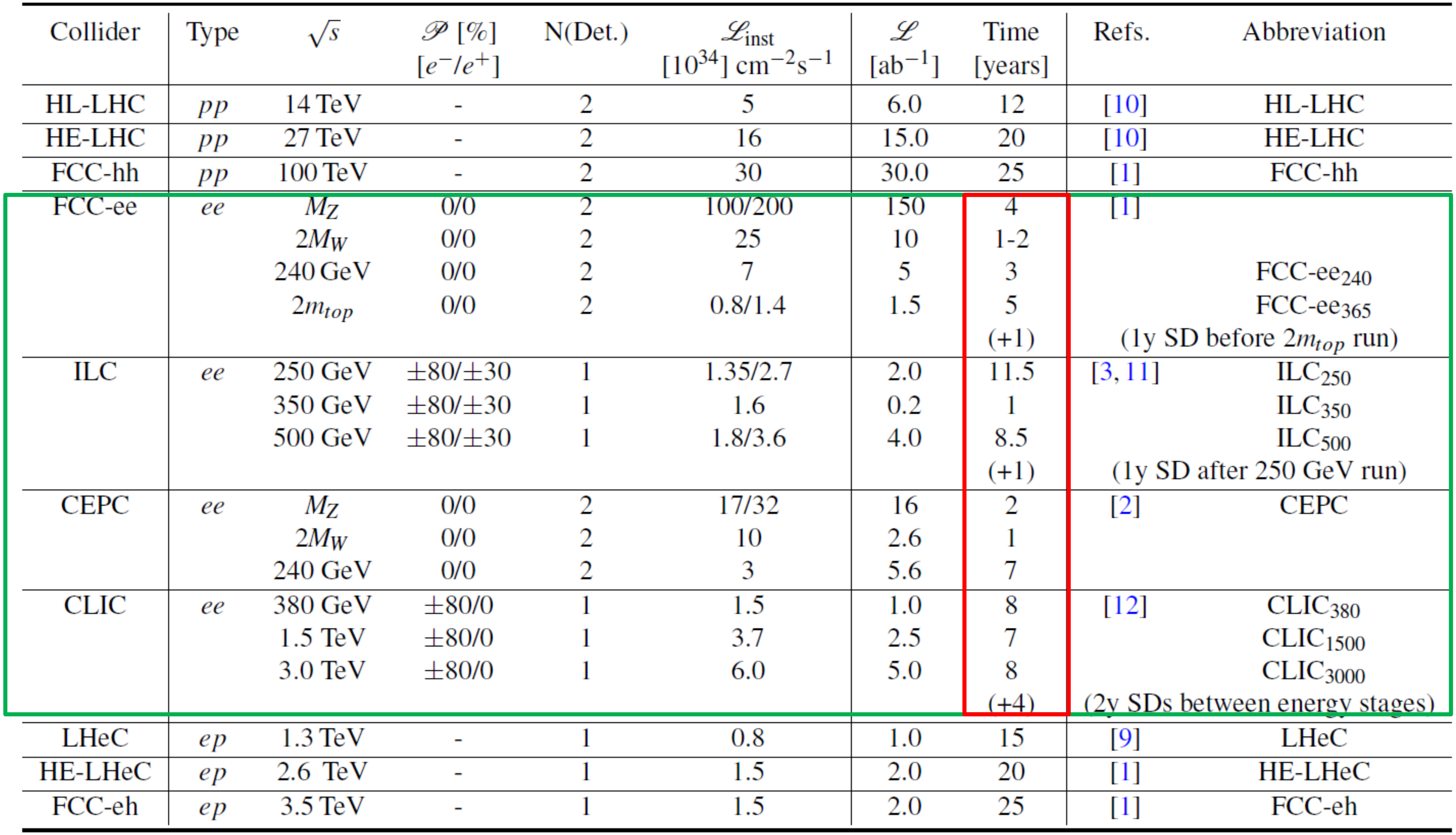
Circular Colliders ⇨ higher luminosity @ 250 GeV

Is luminosity the only figure of merit ?



Polarisation ⇨ ~ factor 2 effect

Future collider specifications



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HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
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							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
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LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
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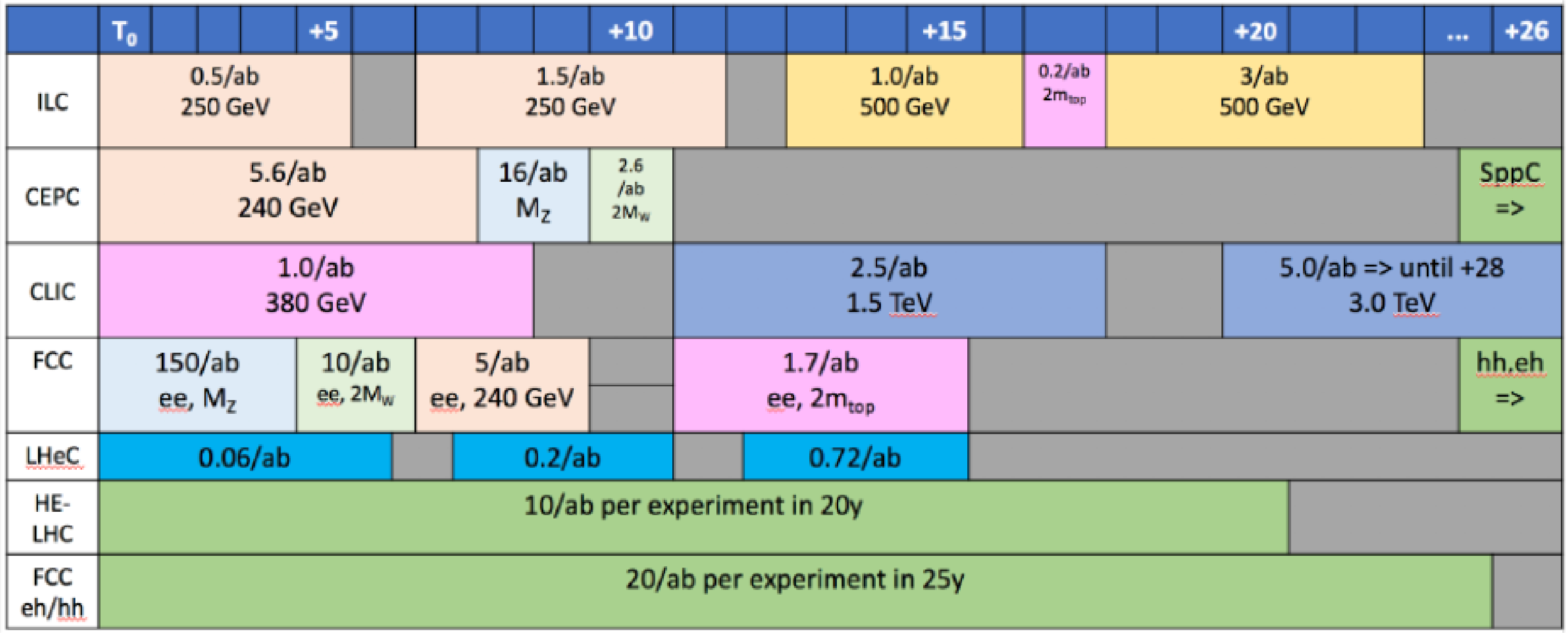
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Is expected lifetime of physicists the main parameter ?

What will be your age of retirement ?



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250 GeV</td><td></td><td colspan="5">1.5/ab
250 GeV</td><td></td><td colspan="4">1.0/ab
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$2m_{top}$</td><td colspan="5">3/ab
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M_Z</td><td>2.6
/ab
$2M_W$</td><td colspan="12"></td><td colspan="2">SppC
=></td></tr>
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ee, $2m_{top}$</td><td colspan="7"></td><td colspan="2">hh,eh
=></td></tr>
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<tr><td>HE-LHC</td><td colspan="20">10/ab per experiment in 20y</td><td colspan="4"></td></tr>
<tr><td>FCC eh/hh</td><td colspan="23">20/ab per experiment in 25y</td><td></td></tr>
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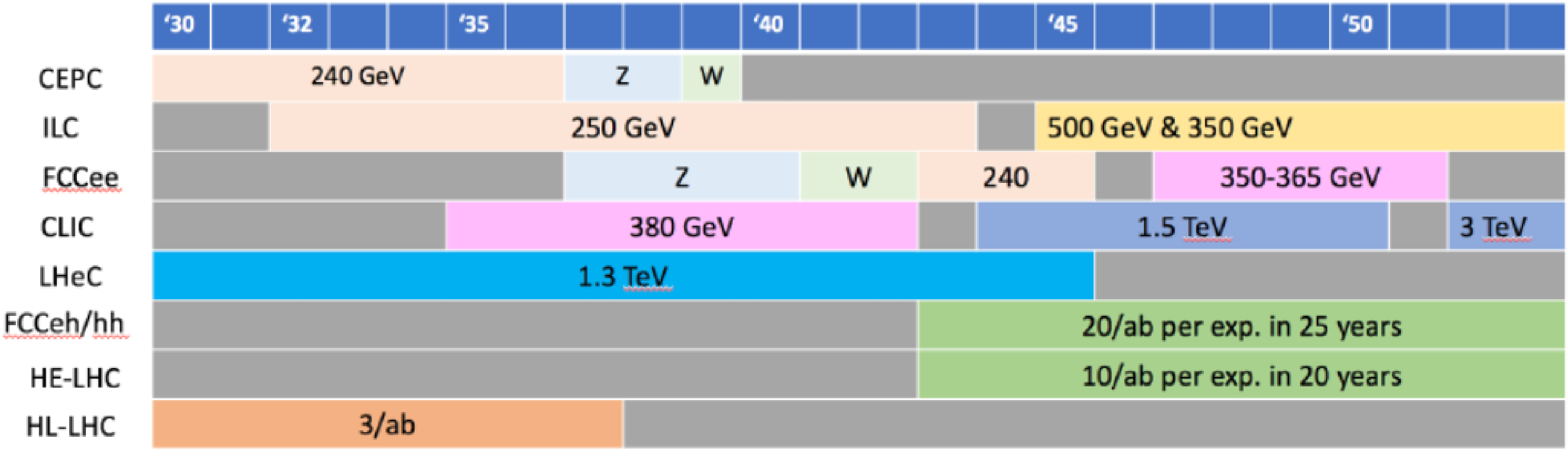

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<tr><td>LHeC</td><td colspan="16">1.3 TeV</td><td colspan="8"></td></tr>
<tr><td>FCCeh/hh</td><td colspan="13"></td><td colspan="11">20/ab per exp. in 25 years</td></tr>
<tr><td>HE-LHC</td><td colspan="13"></td><td colspan="11">10/ab per exp. in 20 years</td></tr>
<tr><td>HL-LHC</td><td colspan="8">3/ab</td><td colspan="16"></td></tr>
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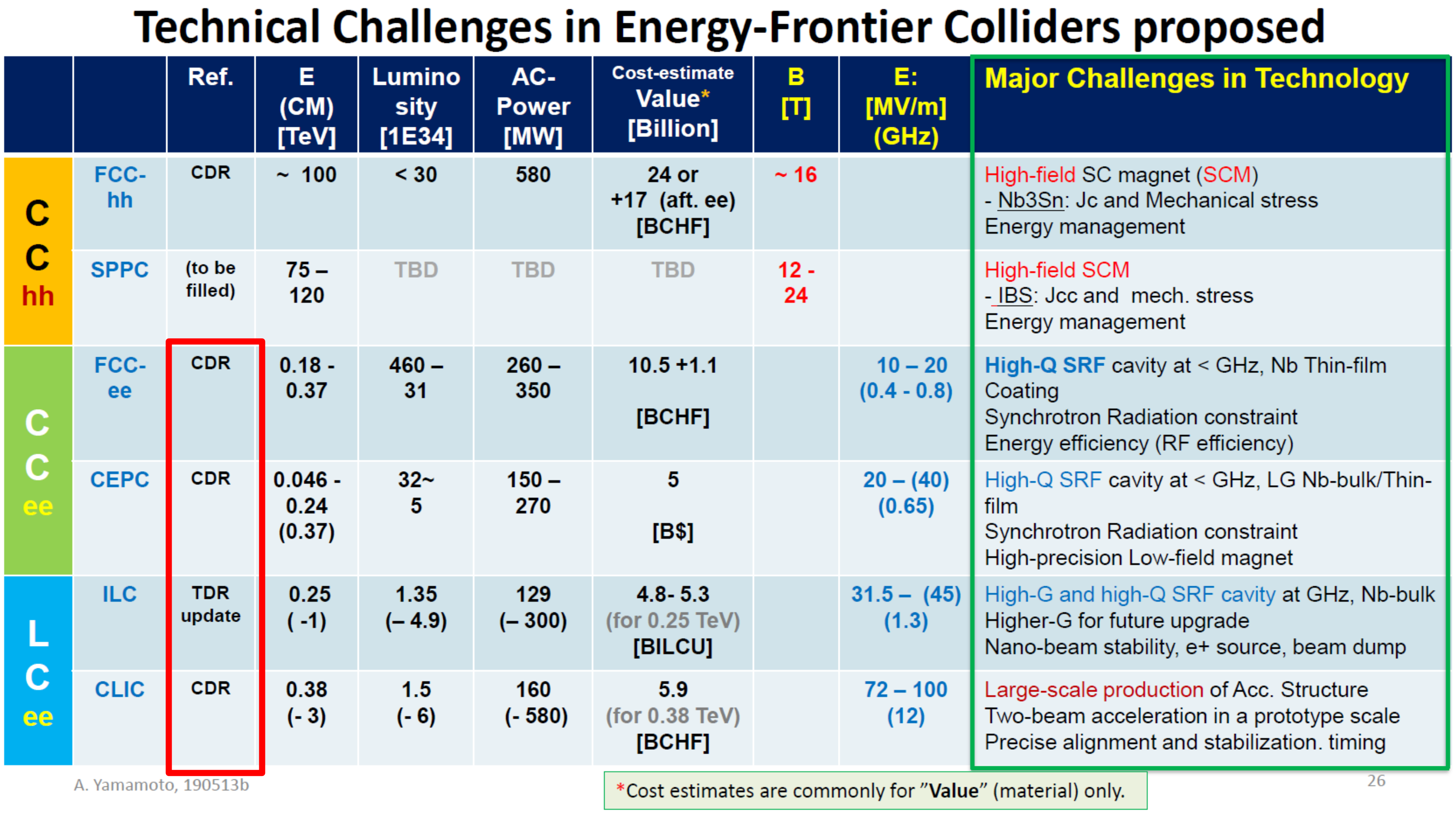
Maturity and technological challenges



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

A. Yamamoto, 190513b

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

26

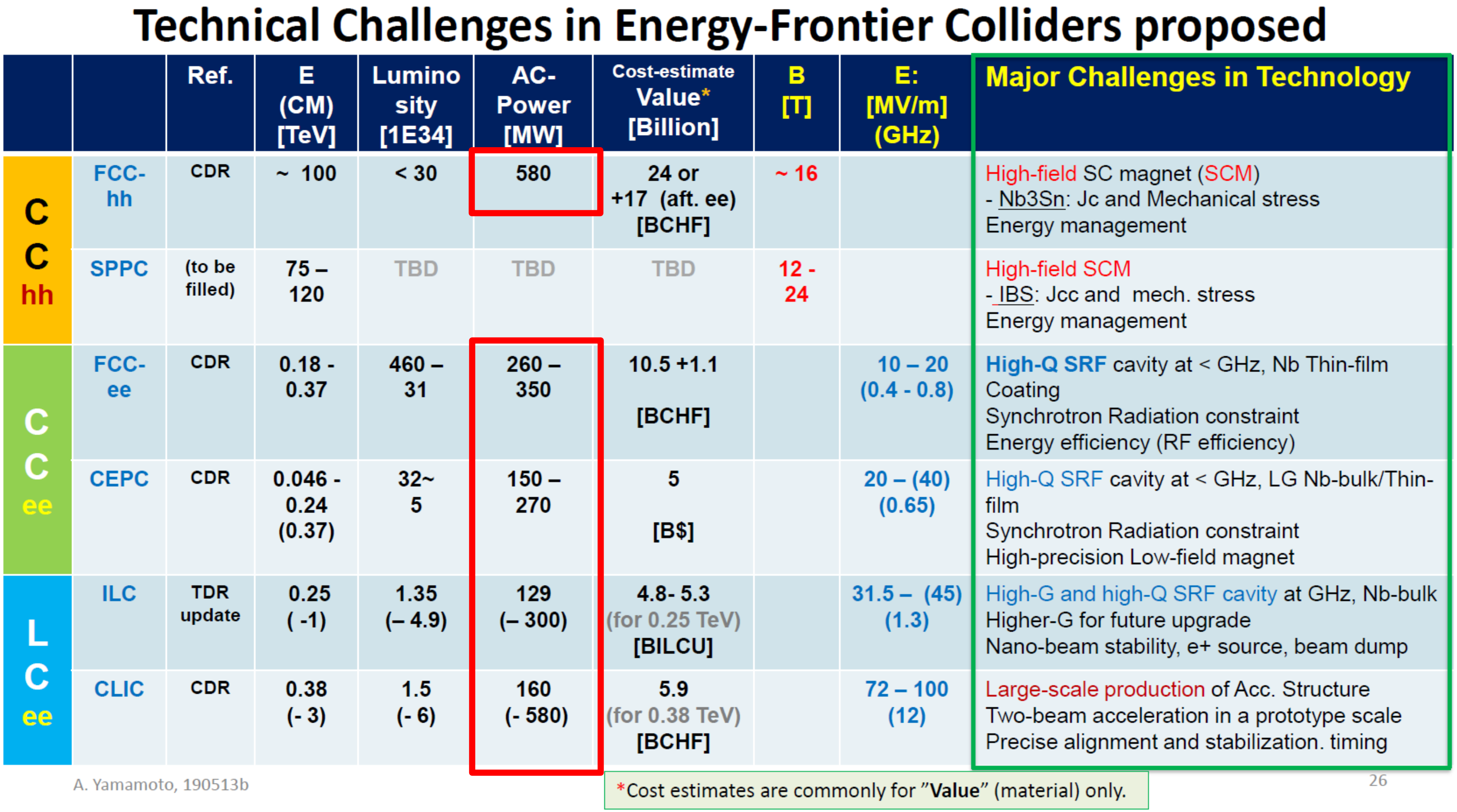
ILC has a TDR

Major Technical Challenges:

Hadron Colliders:
- High-field magnet
- Energy management

Lepton Colliders:
- SRF cavity: High-Q and -G (to prepare for upgrade)
- NRF acc. Struct.: large scale, alignment, tolerance, timing
- Energy management

Maturity and technological challenges



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A. Yamamoto, 190513b

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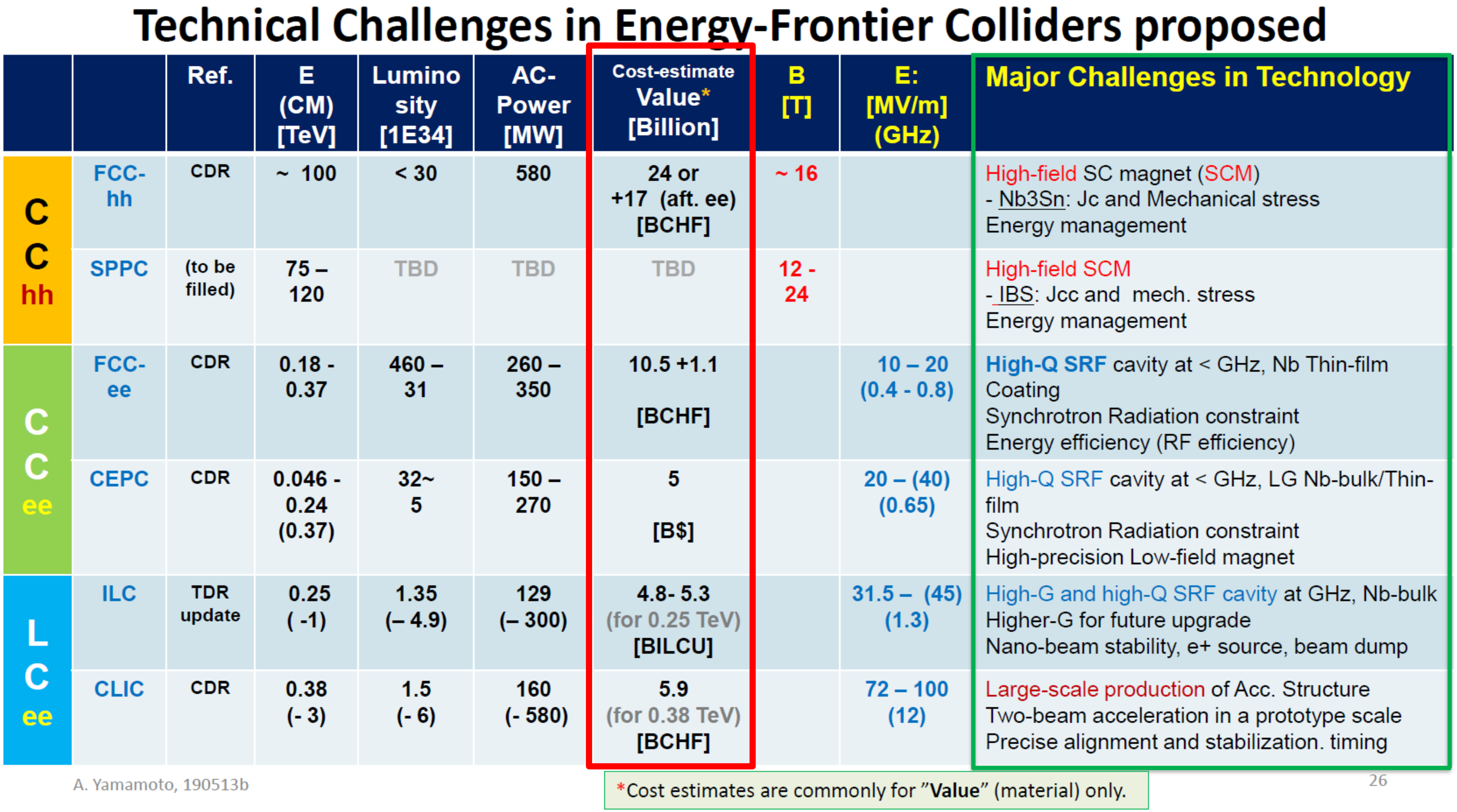
26

LHC ~115 MW
Whole CERN ~ 200 MW

Is a machine beyond ~ 250 MW reasonnable ?

Maturity and technological challenges



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A. Yamamoto, 190513b

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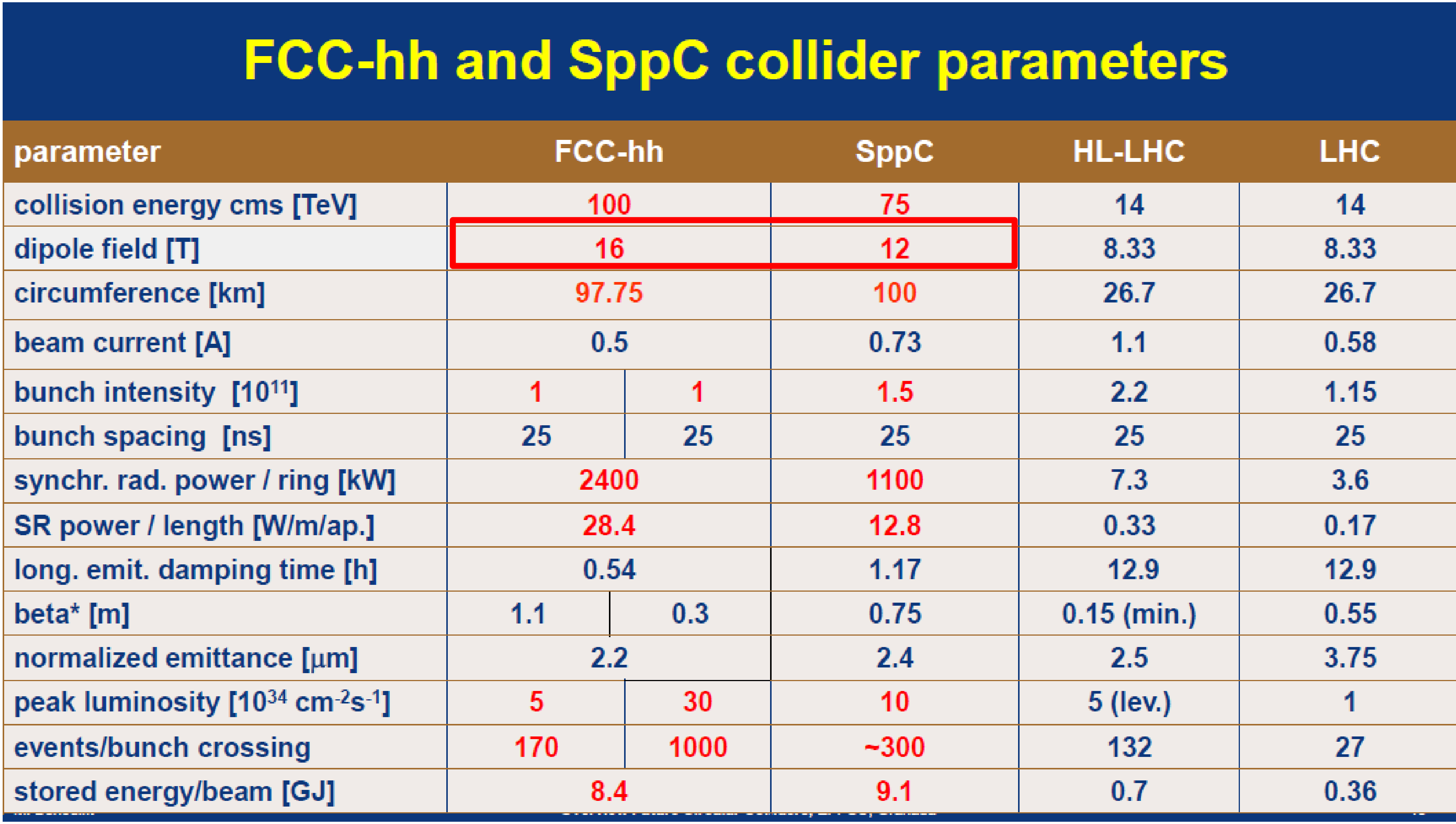
26

√s ~ 250 GeV machine ⇨ ~ 5-6 Billions except FCCee ~ 12 B

FCCee + FCChh ~ 29 B

Costly upgrades and or options

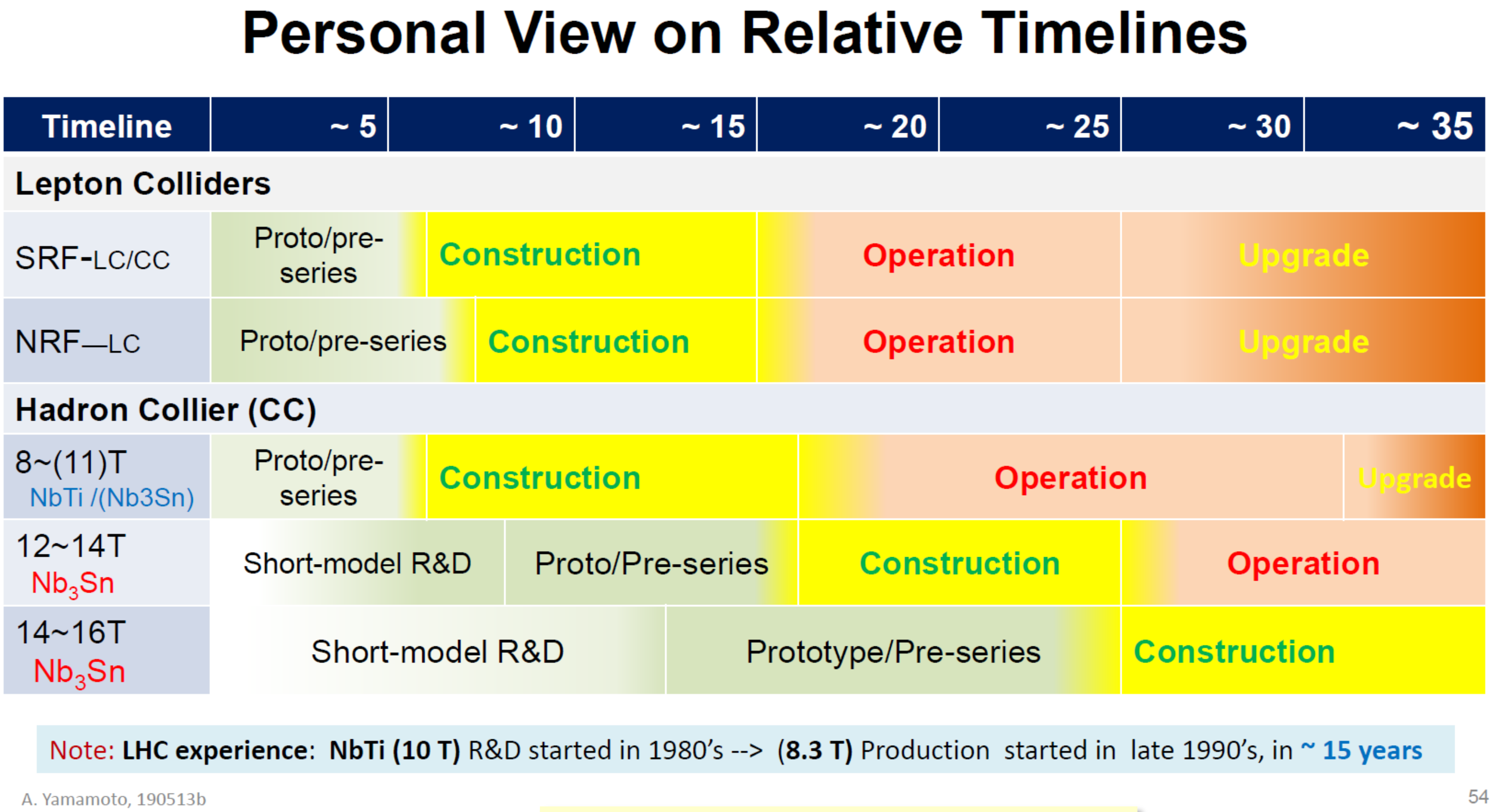


FCC-hh and SppC collider parameters

parameter	FCC-hh		SppC	HL-LHC	LHC
collision energy cms [TeV]	100		75	14	14
dipole field [T]	16		12	8.33	8.33
circumference [km]	97.75		100	26.7	26.7
beam current [A]	0.5		0.73	1.1	0.58
bunch intensity [10^{11}]	1	1	1.5	2.2	1.15
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		1100	7.3	3.6
SR power / length [W/m/ap.]	28.4		12.8	0.33	0.17
long. emit. damping time [h]	0.54		1.17	12.9	12.9
beta* [m]	1.1	0.3	0.75	0.15 (min.)	0.55
normalized emittance [µm]	2.2		2.4	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	10	5 (lev.)	1
events/bunch crossing	170	1000	~300	132	27
stored energy/beam [GJ]	8.4		9.1	0.7	0.36

16 T magnet to reach 100 TeV @ FCChh

Hadron Collider Magnets (FCC-hh)



Personal 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 Collier (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	**Construction**		**Operation**			**Upgrade**
12~14T Nb$_3$Sn	Short-model R&D	Proto/Pre-series		**Construction**		**Operation**	
14~16T Nb$_3$Sn	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, 190513b

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16 T = 25 years before production …

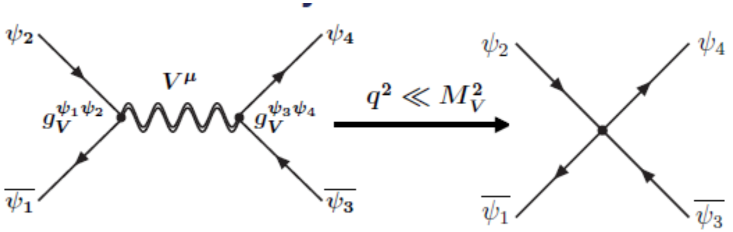
e+e- Higgs physics program

- Kappa framework versus EFT
  - ✓ κ framework : relative deviation from SM value

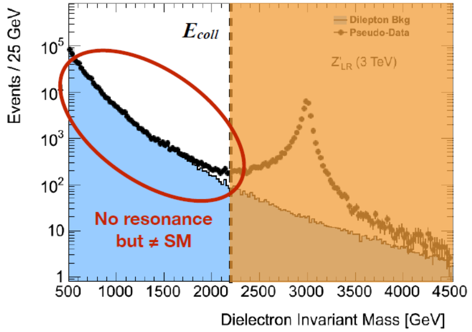
$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

$$\mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2} \qquad \kappa_H^2 \equiv \sum_j \frac{\kappa_j^2 \Gamma_j^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

  - ✓ Effective field Theory (SMEFT)
    - Formalism to test new physics



(e.g *Z'* effects in dilepton spectrum)

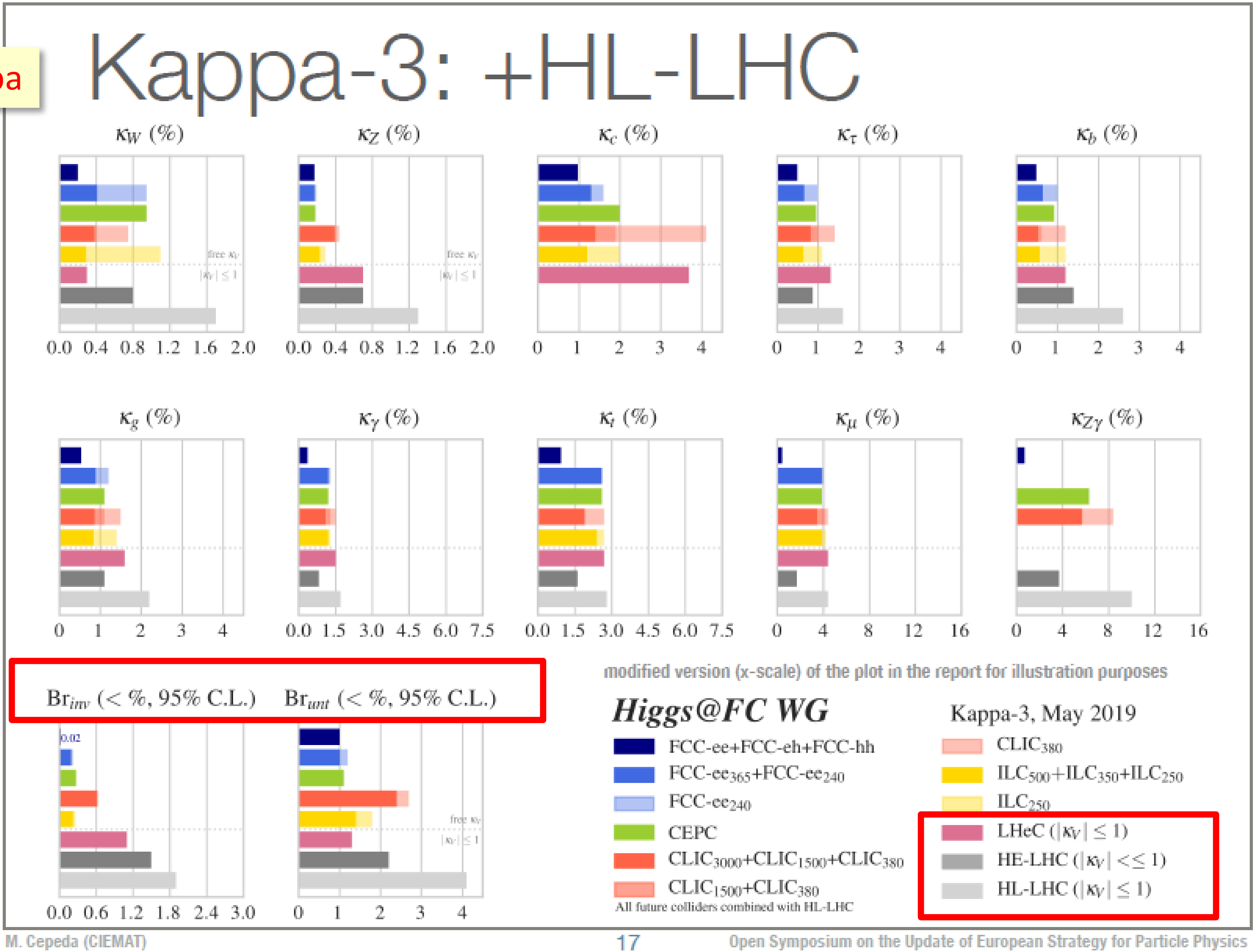


$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{Z'} + \mathcal{L}_{\mathrm{SM}-Z'} \xrightarrow{q^2 \ll M_V^2} \mathcal{L}_{\mathrm{Eff}}$$

    - Polarisation effects « included »
- Model independant in e^+e^- colliders
  - ✓ direct access to full width of higgs boson
  - ✓ HL-LHC Hypothesis: $|\kappa_V|$ =< 1
- Different levels of simulation/reco
  - ✓ From Full simulation to parametric models (DELPHES, etc.)
- 20% differences are likely to be unsignificant !

Be cautious with comparisons !

Kappa



Kappa-3: +HL-LHC

modified version (x-scale) of the plot in the report for illustration purposes

Higgs@FC WG

Kappa-3, May 2019

- 🟦 FCC-ee+FCC-eh+FCC-hh
- 🟦 FCC-ee$_{365}$+FCC-ee$_{240}$
- 🟦 FCC-ee$_{240}$
- 🟩 CEPC
- 🟥 CLIC$_{3000}$+CLIC$_{1500}$+CLIC$_{380}$
- 🟥 CLIC$_{1500}$+CLIC$_{380}$
- 🟥 CLIC$_{380}$
- 🟨 ILC$_{500}$+ILC$_{350}$+ILC$_{250}$
- 🟨 ILC$_{250}$
- 🟥 LHeC ($|\kappa_V| \leq 1$)
- ⬛ HE-LHC ($|\kappa_V| <\leq 1$)
- ⬜ HL-LHC ($|\kappa_V| \leq 1$)

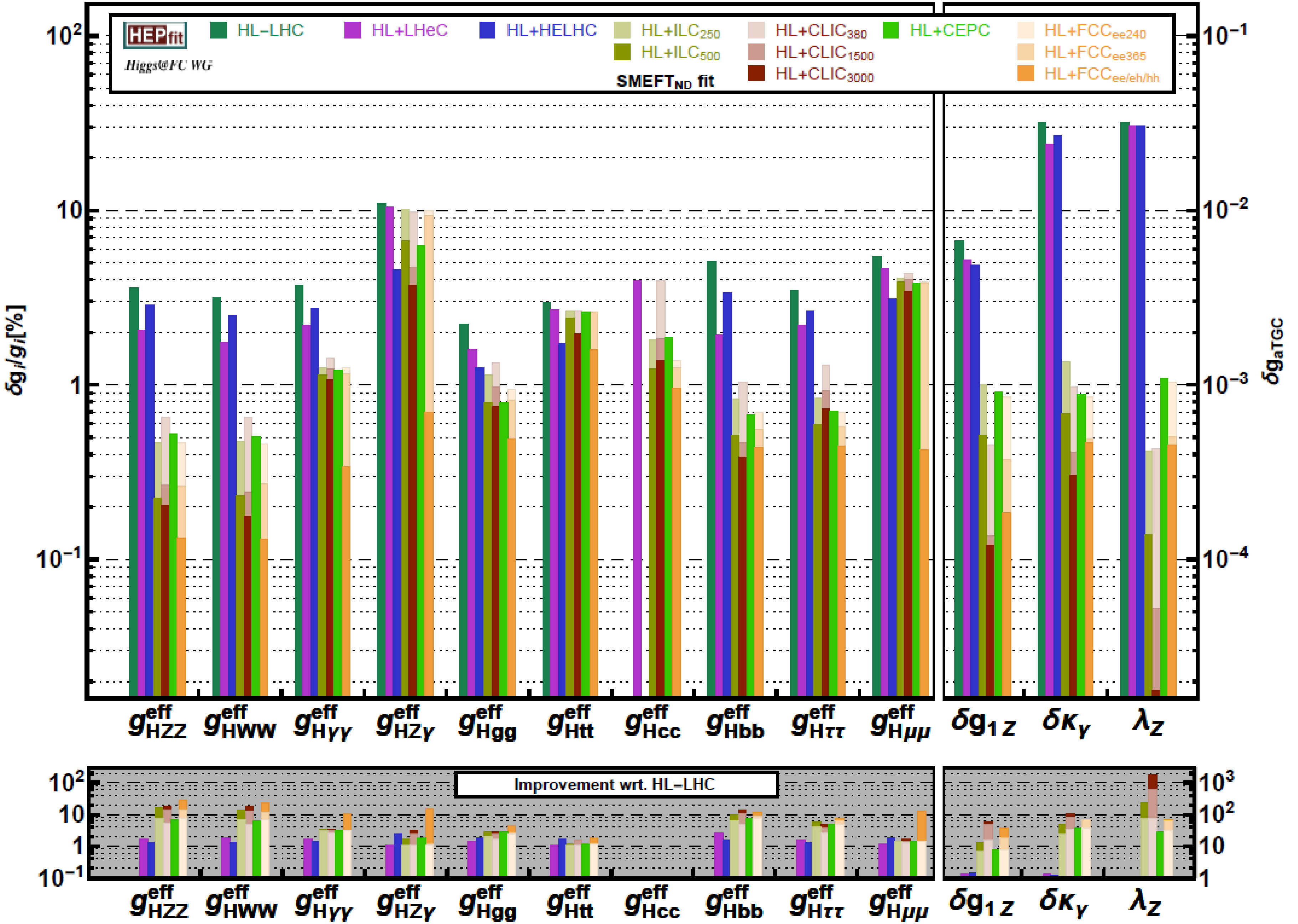
All future colliders combined with HL-LHC

M. Cepeda (CIEMAT) 17 Open Symposium on the Update of European Strategy for Particle Physics

Invisible / Untagged

e+e- colliders: direct measurement of h -> invisible through full width

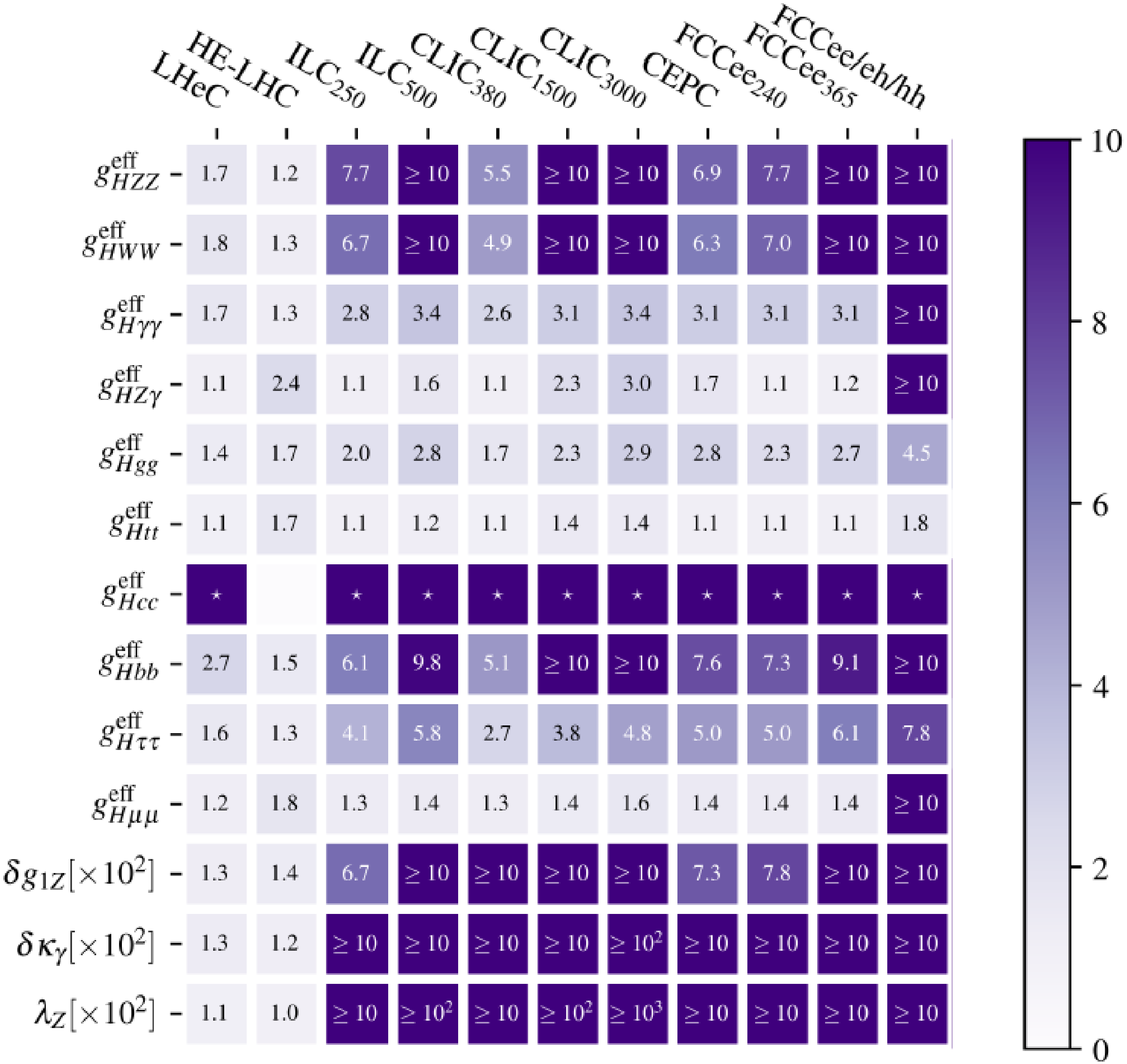
$|\kappa_V|$ =< 1


HEPfit
Higgs@FC WG
HL-LHC
HL+LHeC
HL+HELHC
HL+ILC250
HL+ILC500
HL+CLIC380
HL+CLIC1500
HL+CLIC3000
HL+CEPC
HL+FCCee240
HL+FCCee365
HL+FCCee/eh/hh
SMEFTND fit
δgi/gi[%]
δgaTGC
10²
10
1
10⁻¹
10⁻¹
10⁻²
10⁻³
10⁻⁴
geff HZZ
geff HWW
geff Hγγ
geff HZγ
geff Hgg
geff Htt
geff Hcc
geff Hbb
geff Hττ
geff Hμμ
δg1Z
δκγ
λZ
Improvement wrt. HL-LHC
10²
10
1
10⁻¹
10³
10²
10
1

SMEFT

Improvement with respect to HL-LHC

SMEFT



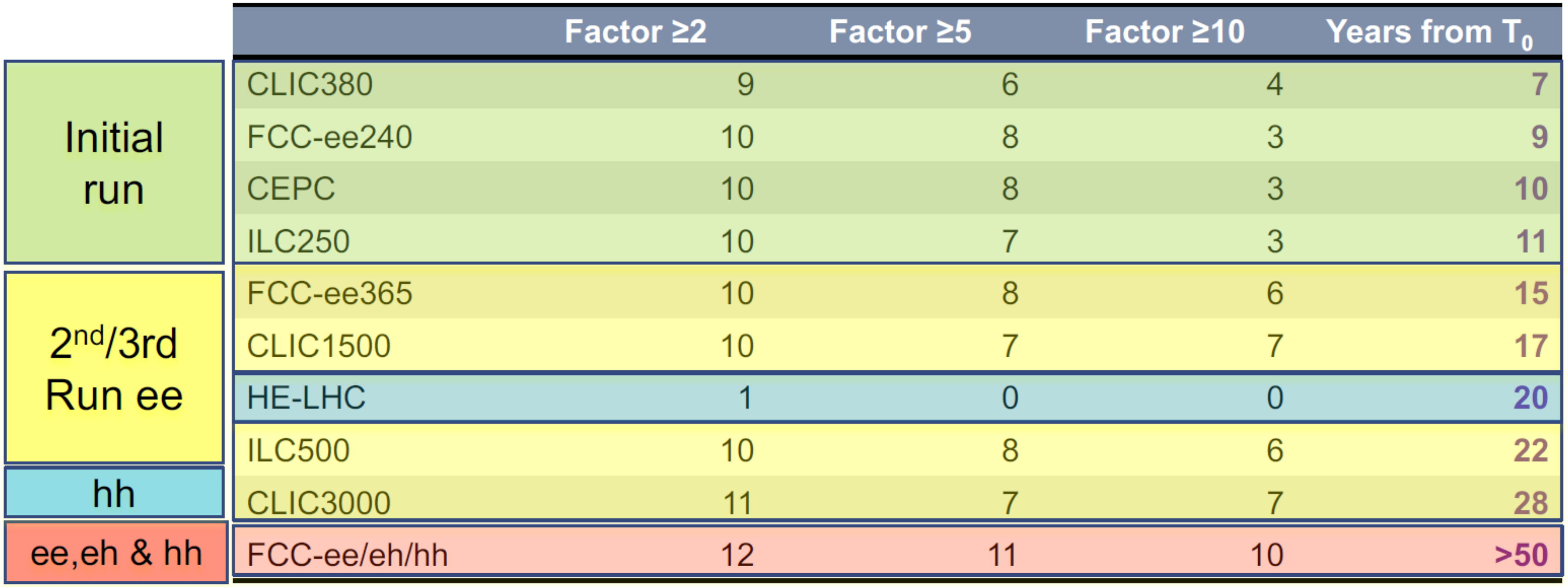
	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{\mathrm{eff}}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{\mathrm{eff}}_{HZ\gamma}$	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}	$\star$		$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{\mathrm{eff}}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{\mathrm{eff}}_{H\mu\mu}$	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

($\star$) not measured at HL-LHC

SMEFT

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
2nd/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
2nd/3rd Run ee	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

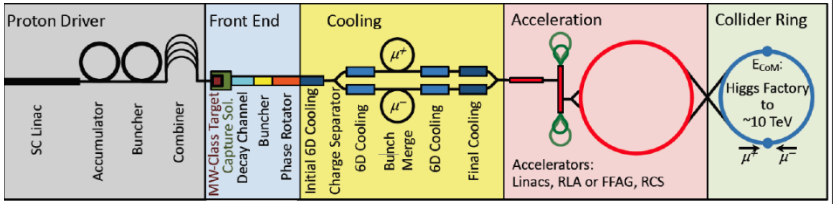
13 quantities in total

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

The 4 e^+e^- projects are very comparable in performances…

Other approaches ?

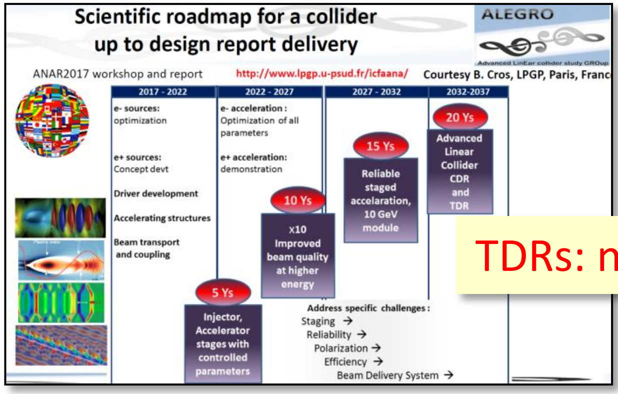
- **Muon colliders**



TDRs: not before ~2035

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged
  - But at this moment not mature enough for a proposal
- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - Should not miss this opportunity

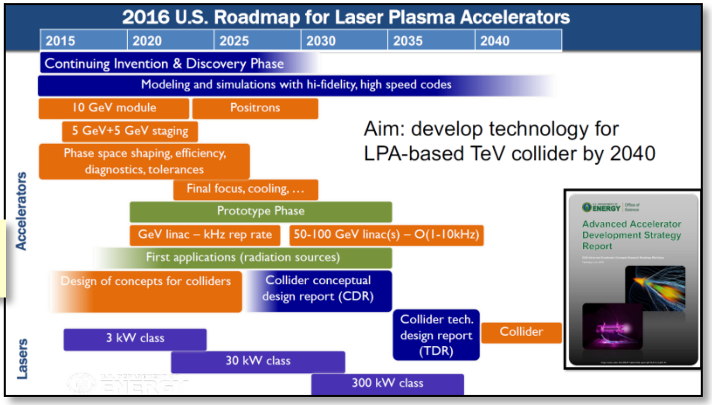
- **Plasma acceleration**
  - **Main advantage: large accelerating gradients:** 1 GV/m average,



Scientific roadmap for a collider up to design report delivery

ANAR2017 workshop and report http://www.lpgp.u-psud.fr/icfaana/ Courtesy B. Cros, LPGP, Paris, Franc

TDRs: not before ~2035



2016 U.S. Roadmap for Laser Plasma Accelerators

Aim: develop technology for LPA-based TeV collider by 2040

Although the road is long towards a collider, the results so far merit further significant investments

Many key achievements in last decade (and a half) in plasma based acceleration using lasers, electron and proton drivers

- Focus is now on high brightness beams, tunability, reproducibility, reliability, and high average power

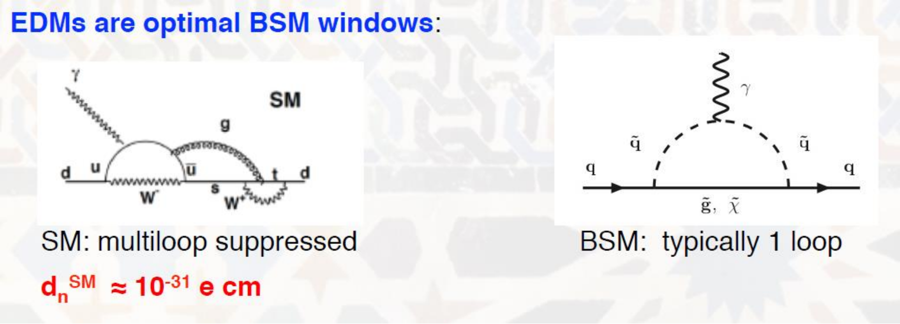
Summary (and personnal opinions)

- Consensus for a 250 GeV e^+e^- machine
  - ✓ 4 viable projects with similar performances in Higgs sector
  - ✓ Large political and funding uncertainties
  - ✓ Large scale projects reaching a glass ceiling ?
- CERN’s future is a major concern in the community
  - ✓ Which main project ?
    - Funding limitations up to ~ 2028 (HL-LHC)
    - Only one R&D program ? (FCC or CLIC)
    - Constant budget ?
  - ✓ New model for CERN ?
    - Leading role for projects outside CERN ?
    - Leading role for accelerator R&D
- The salvation may (will) come from diversification
  - ✓ Intensity frontier & Flavour physics
    - Belle II & LHC-b
    - Tau-charm factories
  - ✓ Beam dump experiments
  - ✓ Dark matter searches
  - ✓ Multi-messengers astroparticles
  - ✓ New accelerator technologies (muons, plasma, etc.)

backup

Flavours: light sector (not covered…)

- Electric Dipole Moment (EDM)
  - ✓ Neutron: ILL, ESS, PIK, PSI, TRIUMF, SNS, LANL, JPARC, etc.
  - ✓ proton



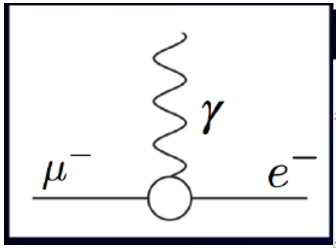
EDMs are optimal BSM windows:

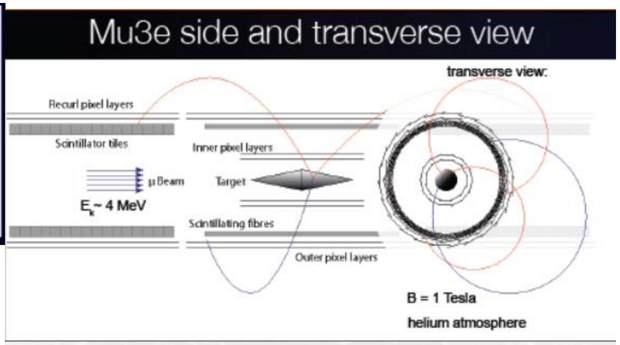
SM: multiloop suppressed

$d_n^{SM} \approx 10^{-31}$ e cm

BSM: typically 1 loop

- Lepton Flavour Violation (LFV)
  - ✓ MU2E, COMET, MEG





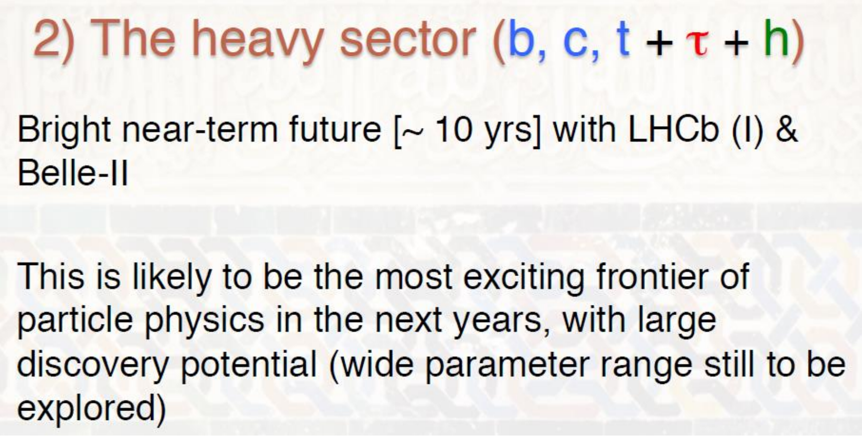
Mu3e side and transverse view

- Rare Kaon decays
  - ✓ KOTO (J-PARC), KLEVER (CERN)

⇨Can probe very high scales $\Lambda > 10^4$ TeV

Future of flavour physics

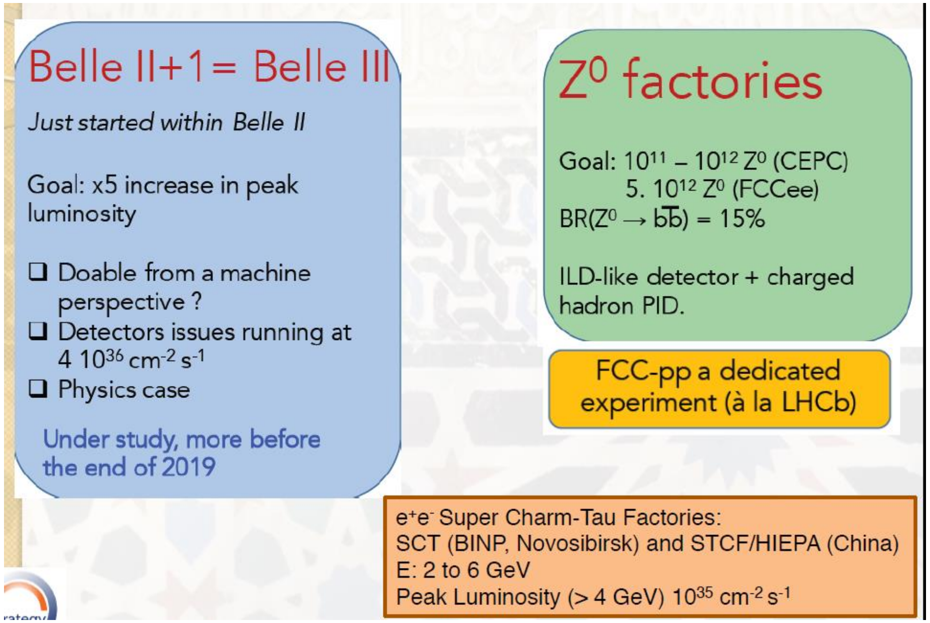
- LHCB & BelleII



2) The heavy sector (b, c, t + τ + h)

Bright near-term future [~ 10 yrs] with LHCb (I) & Belle-II

This is likely to be the most exciting frontier of particle physics in the next years, with large discovery potential (wide parameter range still to be explored)



Belle II+1= Belle III

Just started within Belle II

Goal: x5 increase in peak luminosity

- ☐ Doable from a machine perspective ?
- ☐ Detectors issues running at 4 10^{36} cm^{-2} s^{-1}
- ☐ Physics case

Under study, more before the end of 2019

Z^0 factories

Goal: $10^{11} - 10^{12}$ Z^0 (CEPC)
5. 10^{12} Z^0 (FCCee)
BR($Z^0 \rightarrow b\bar{b}$) = 15%

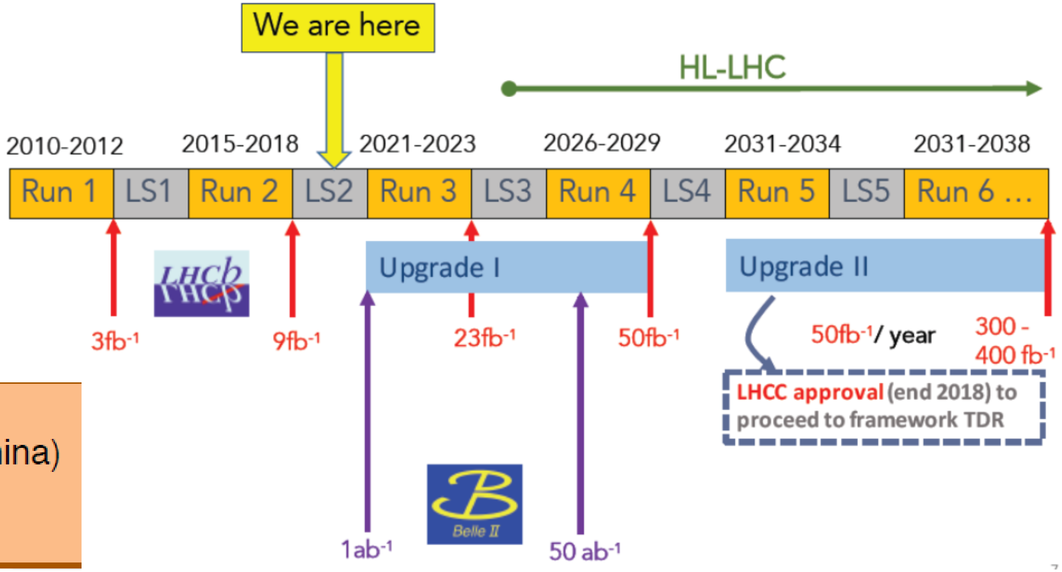
ILD-like detector + charged hadron PID.

FCC-pp a dedicated experiment (à la LHCb)

e^+e^- Super Charm-Tau Factories:
SCT (BINP, Novosibirsk) and STCF/HIEPA (China)
E: 2 to 6 GeV
Peak Luminosity (> 4 GeV) 10^{35} cm^{-2} s^{-1}

- Charm factories
- Tau factories
  - ✓ LFV in tau decays
  - ✓ Lepton universality

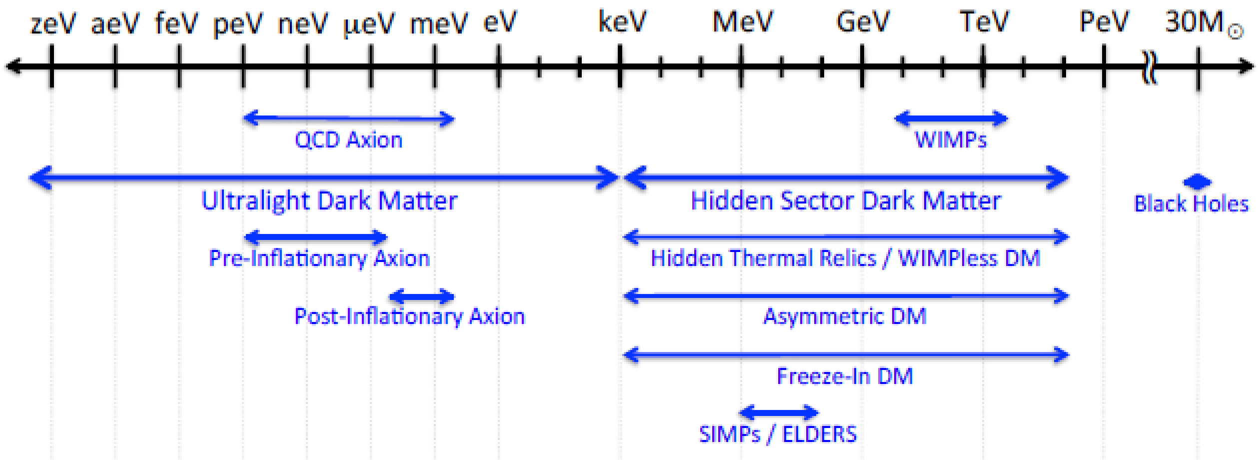
e^+e^- Super Charm-Tau Factories:
SCT (BINP, Novosibirsk) and STCF/HIEPA (China)
E: 2 to 6 GeV
Peak Luminosity (> 4 GeV) 10^{35} cm^{-2} s^{-1}



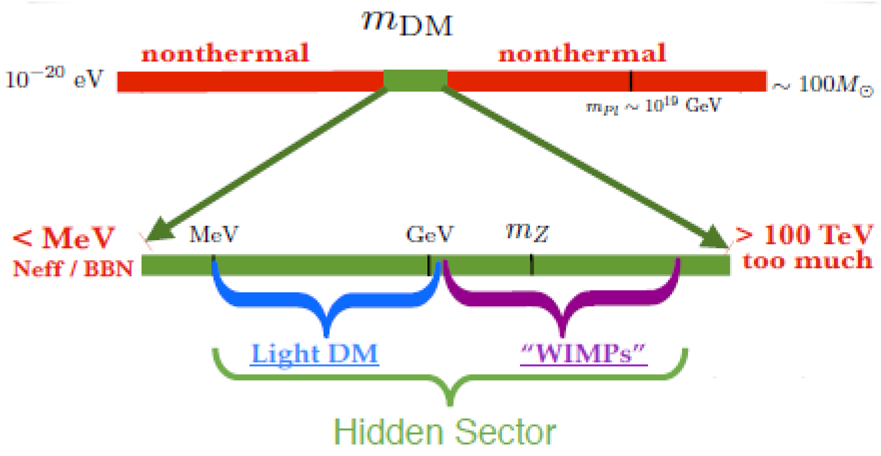
LHCC approval (end 2018) to proceed to framework TDR

Dark matter searches

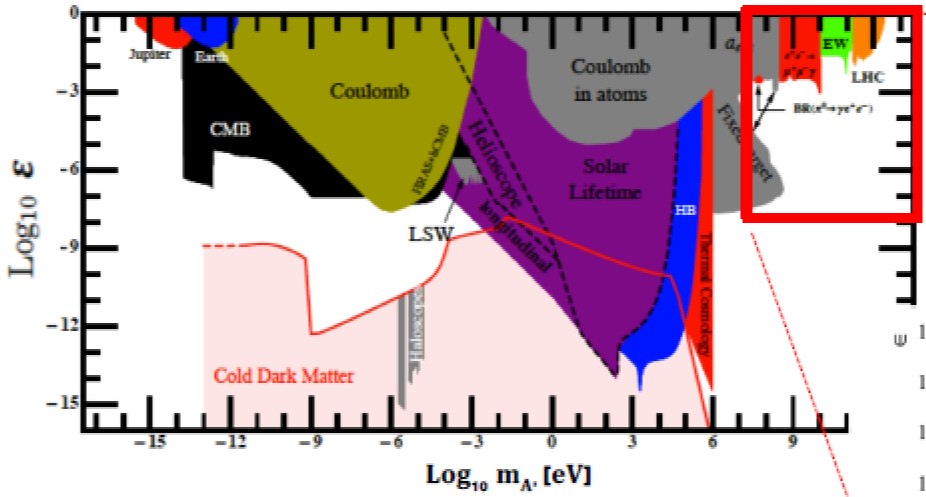
Too small mass
⇒ won't "fit"
in a galaxy!



From MACHOs
searches



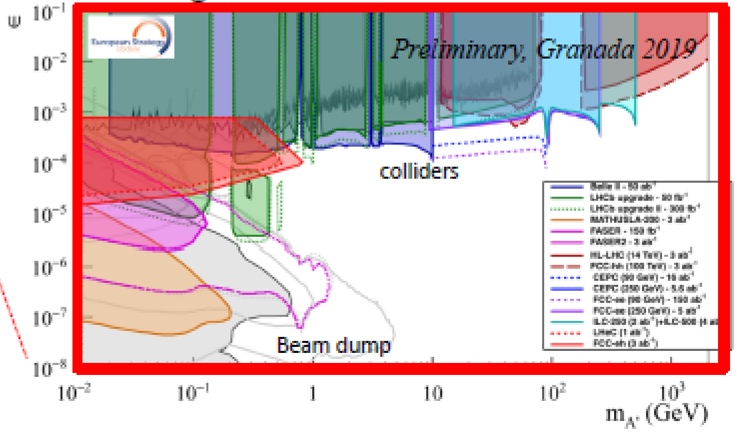
Vector portal: current limits in the ℰ versus Dark Photon mass plane



⇦ MeV-TeV range accelerators' domain (range compatible with the hypothesis of DM as thermal relic)

⇩

All together



Improvements by several orders of magnitude both in low-mass low-coupling regime (beam-dump) and in high-mass large-coupling regime (colliders). ⇨

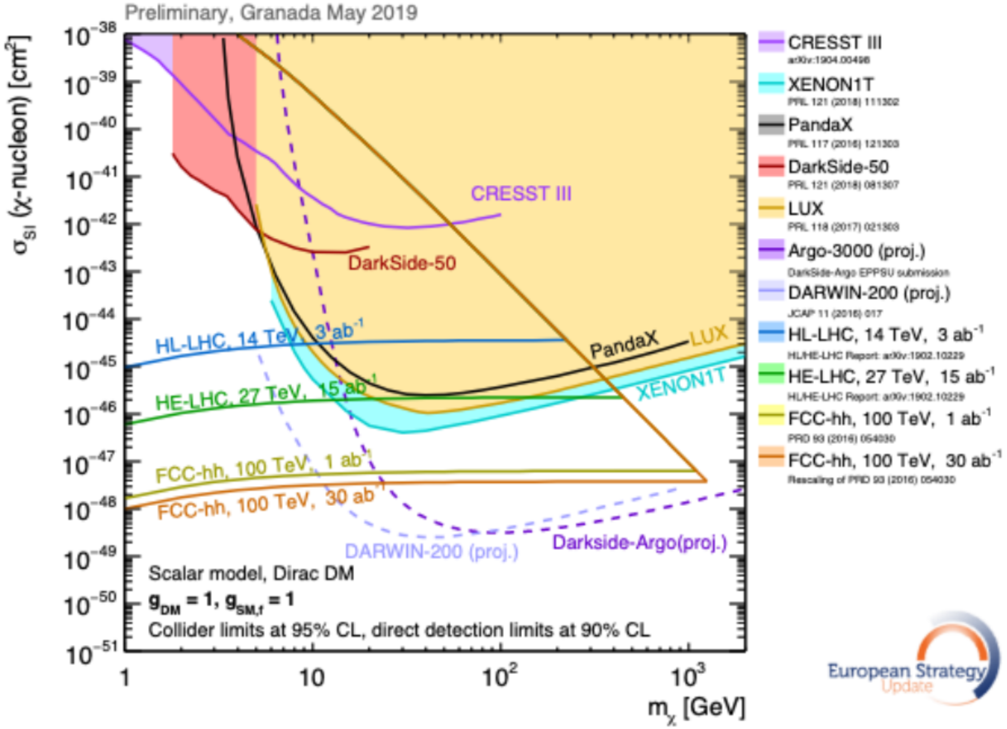
Nice complementarity between beam-dump and colliders' experiments

Summary plot for direct detection/colliders

Example of Complementary reach for future colliders and future DD for benchmarks considered (this case: scalar mediator)

C. Doglioni's Talk

See P. Sphicas' talk

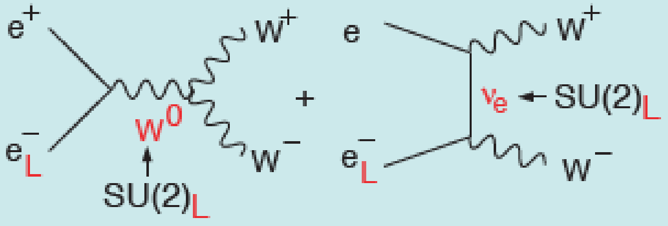


- A collider discovery will need confirmation from DD/ID for cosmological origin
- A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction
- A future collider program that increases sensitivity to invisible particles coherently with DD/ID serves this purpose

Power of Beam Polarization

Fujii, Pheno2014

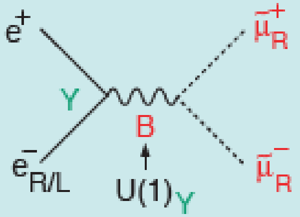
W^+W^- *(Largest SM BG in SUSY searches)*



In the symmetry limit, $\sigma_{WW} \to 0$ for e_R^- !

BG Suppression

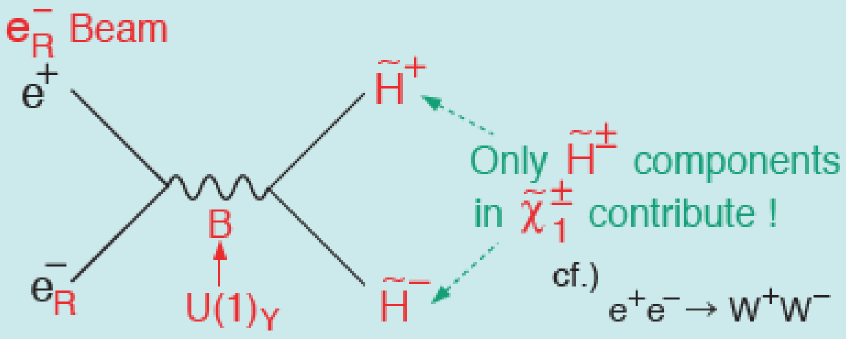
Slepton Pair



$Y_L = -1/2 : e_L^-$
$Y_R = -1 \quad : e_R^-$

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

Chargino Pair



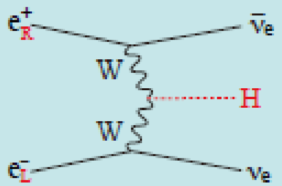
Only $\tilde H^\pm$ components in $\tilde\chi_1^\pm$ contribute !

cf.) $e^+e^- \to W^+W^-$

$$\tilde\chi_1^\pm = \bigcirc \cdot \tilde W^\pm + \bullet \cdot \tilde H^\pm$$
$$\bullet = \langle \tilde H^\pm | \tilde\chi_1^\pm \rangle$$

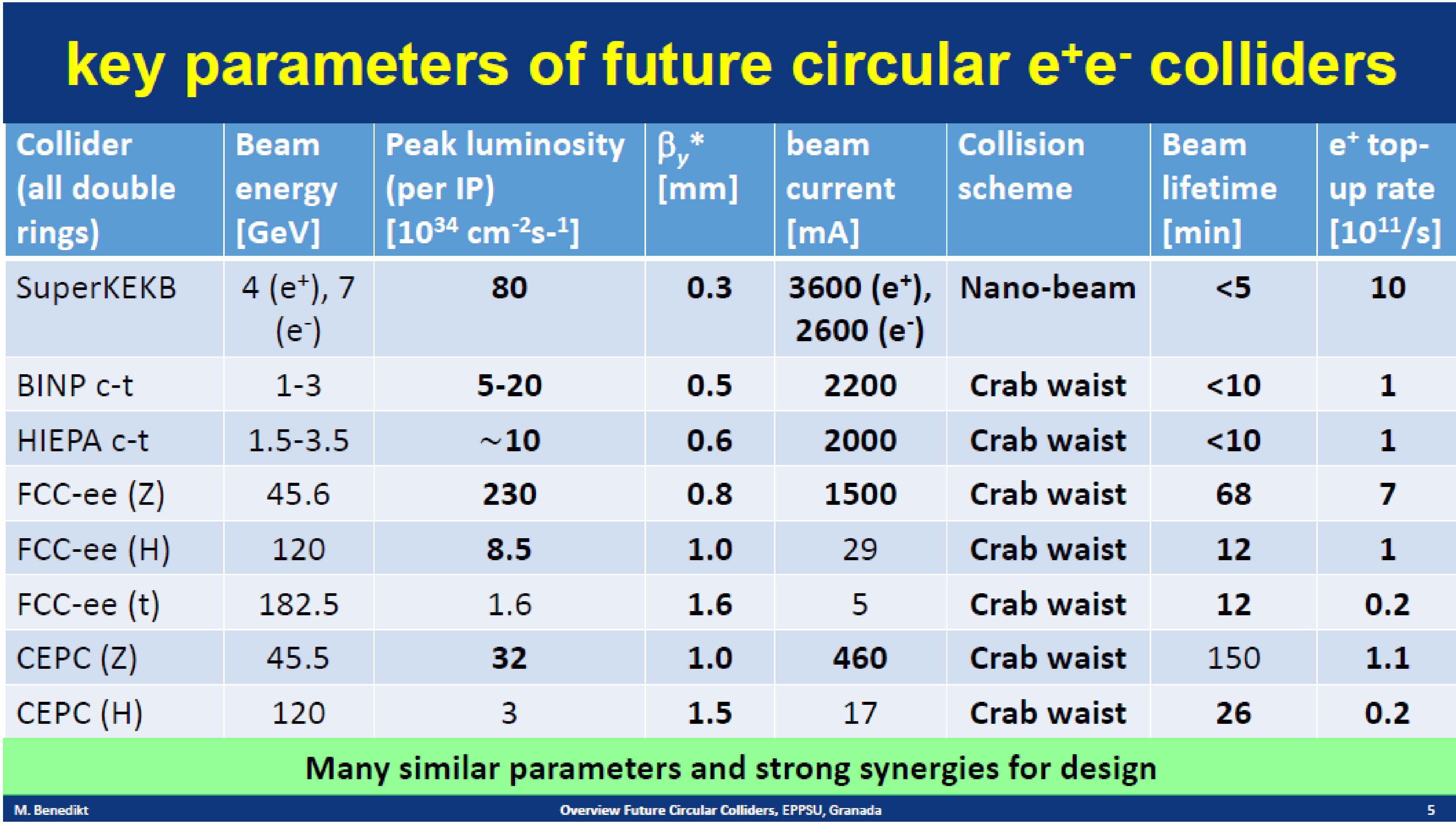
Decomposition

WW-fusion Higgs Prod.



	ILC
Pol (e⁻)	-0.8
Pol (e⁺)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

Signal Enhancement



key parameters of future circular e^+e^- colliders

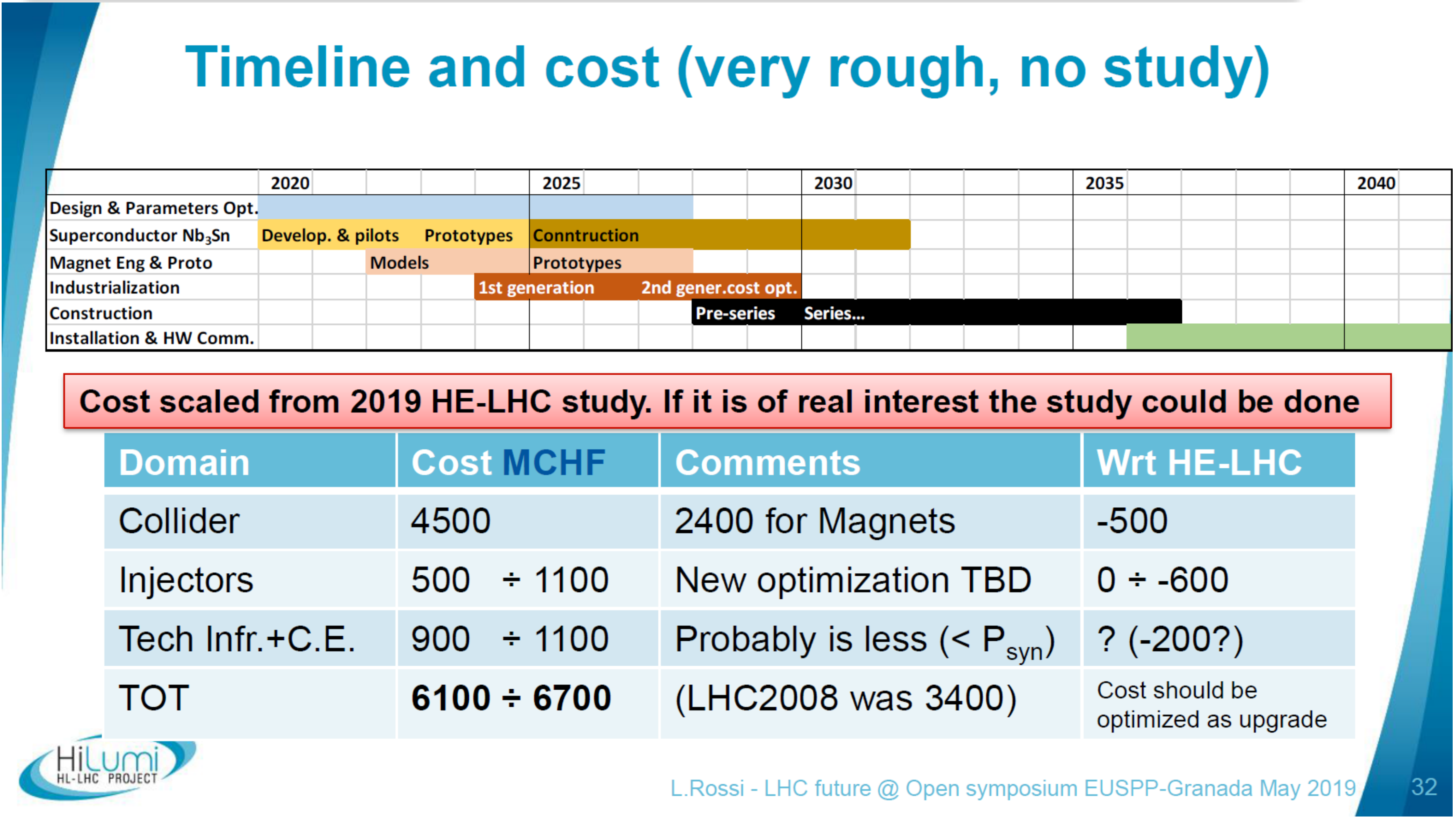
Collider (all double rings)	Beam energy [GeV]	Peak luminosity (per IP) [10^{34} cm^{-2}s^{-1}]	β_y^* [mm]	beam current [mA]	Collision scheme	Beam lifetime [min]	e^+ top-up rate [10^{11}/s]
SuperKEKB	4 (e^+), 7 (e^-)	**80**	**0.3**	**3600 (e^+), 2600 (e^-)**	**Nano-beam**	**<5**	**10**
BINP c-t	1-3	**5-20**	**0.5**	**2200**	**Crab waist**	**<10**	**1**
HIEPA c-t	1.5-3.5	**~10**	**0.6**	**2000**	**Crab waist**	**<10**	**1**
FCC-ee (Z)	45.6	**230**	**0.8**	**1500**	**Crab waist**	**68**	**7**
FCC-ee (H)	120	**8.5**	**1.0**	29	**Crab waist**	**12**	**1**
FCC-ee (t)	182.5	1.6	**1.6**	5	**Crab waist**	**12**	**0.2**
CEPC (Z)	45.5	**32**	**1.0**	**460**	**Crab waist**	150	**1.1**
CEPC (H)	120	3	**1.5**	17	**Crab waist**	**26**	**0.2**

Many similar parameters and strong synergies for design

M. Benedikt Overview Future Circular Colliders, EPPSU, Granada 5

HE-LHC

- 33 TeV c.o.m. : 20 T magnets (2010 Malta Workshop)
- 27 TeV c.o.m. : 16 T magnets (FCC baseline magnet)
- 21 TeV c.o.m. : LHC1.5, based on 12 T magnets



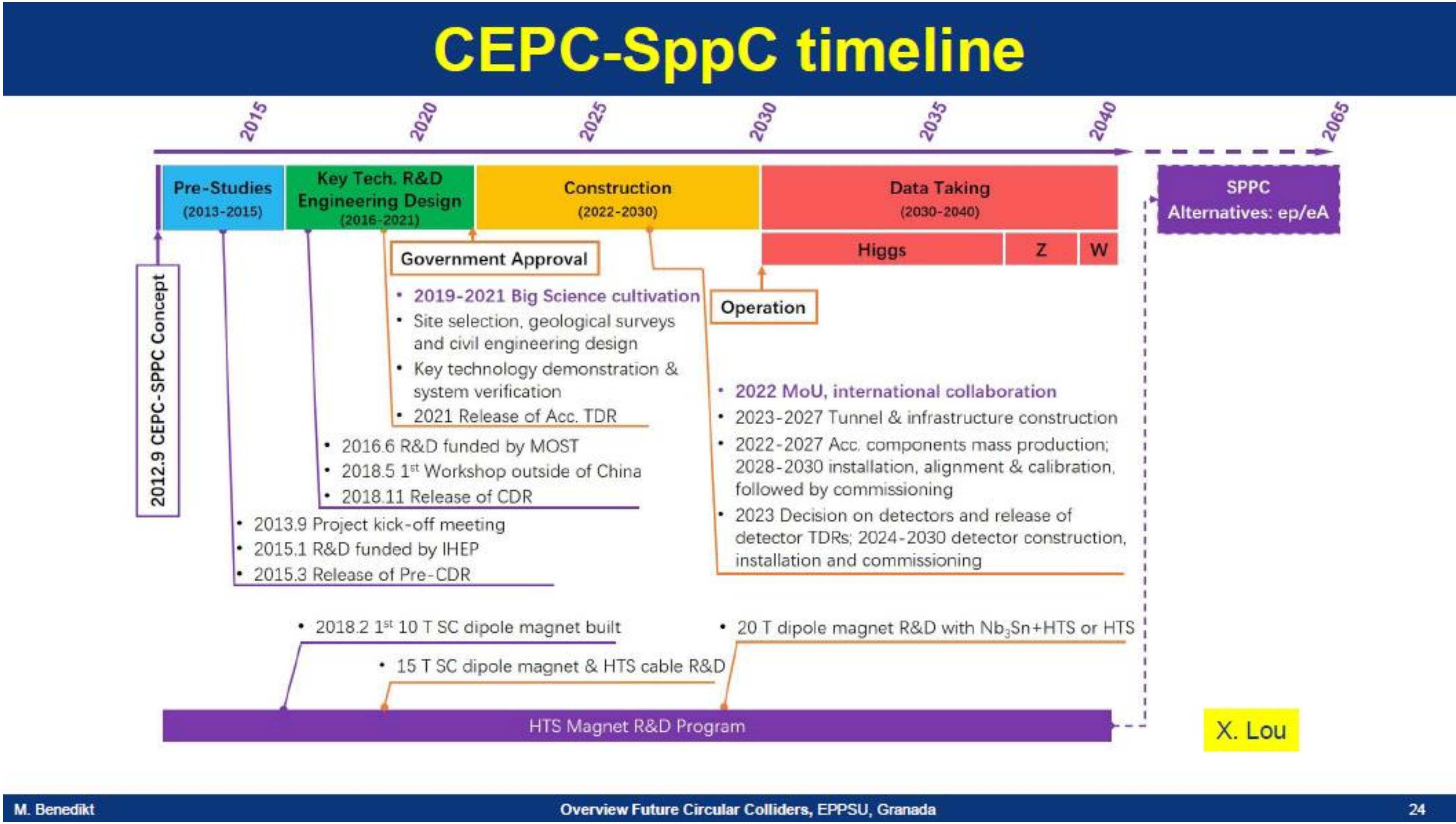
Timeline and cost (very rough, no study)

	2020	2025	2030	2035	2040
Design & Parameters Opt.	🟦	🟦			
Superconductor Nb$_3$Sn	Develop. & pilots Prototypes	Conntruction	🟨		
Magnet Eng & Proto	Models	Prototypes			
Industrialization	1st generation	2nd gener.cost opt.			
Construction		Pre-series	Series...	■	
Installation & HW Comm.				🟩	🟩

Cost scaled from 2019 HE-LHC study. If it is of real interest the study could be done

Domain	Cost MCHF	Comments	Wrt HE-LHC
Collider	4500	2400 for Magnets	-500
Injectors	500 ÷ 1100	New optimization TBD	0 ÷ -600
Tech Infr.+C.E.	900 ÷ 1100	Probably is less (< P_{syn})	? (-200?)
TOT	**6100 ÷ 6700**	(LHC2008 was 3400)	Cost should be optimized as upgrade

L.Rossi - LHC future @ Open symposium EUSPP-Granada May 2019



CEPC-SppC timeline

2012.9 CEPC-SPPC Concept

Pre-Studies (2013-2015)

Key Tech. R&D Engineering Design (2016-2021)

Construction (2022-2030)

Data Taking (2030-2040)

Higgs | Z | W

SPPC Alternatives: ep/eA

Government Approval

- **2019-2021 Big Science cultivation**
- Site selection, geological surveys and civil engineering design
- Key technology demonstration & system verification
- 2021 Release of Acc. TDR

Operation

- **2022 MoU, international collaboration**
- 2023-2027 Tunnel & infrastructure construction
- 2022-2027 Acc. components mass production; 2028-2030 installation, alignment & calibration, followed by commissioning
- 2023 Decision on detectors and release of detector TDRs; 2024-2030 detector construction, installation and commissioning

- 2016.6 R&D funded by MOST
- 2018.5 1st Workshop outside of China
- 2018.11 Release of CDR

- 2013.9 Project kick-off meeting
- 2015.1 R&D funded by IHEP
- 2015.3 Release of Pre-CDR

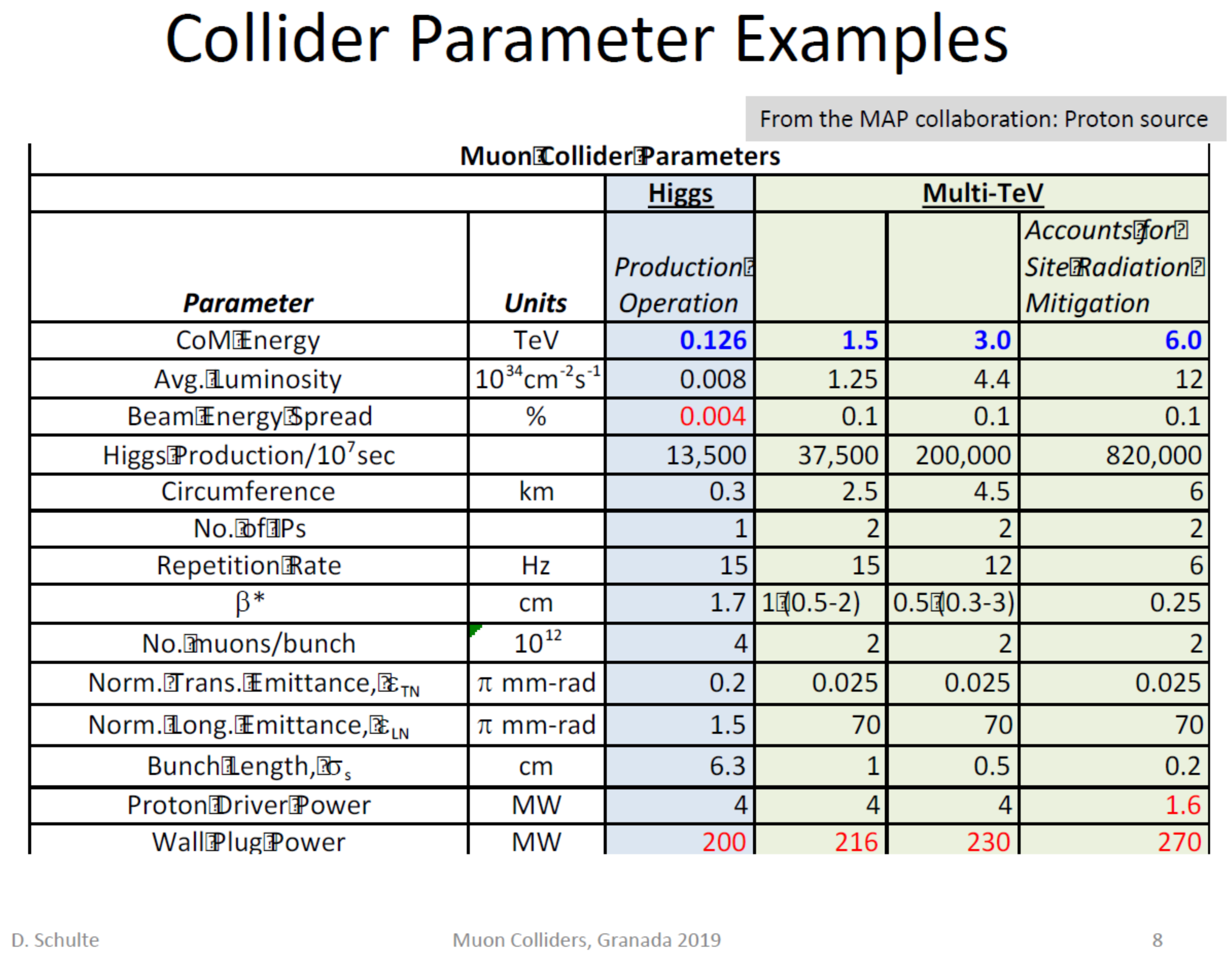
- 2018.2 1st 10 T SC dipole magnet built
- 15 T SC dipole magnet & HTS cable R&D
- 20 T dipole magnet R&D with Nb_3Sn+HTS or HTS

HTS Magnet R&D Program

X. Lou

M. Benedikt Overview Future Circular Colliders, EPPSU, Granada 24

Muon colliders



Collider Parameter Examples

From the MAP collaboration: Proton source

Muon Collider Parameters

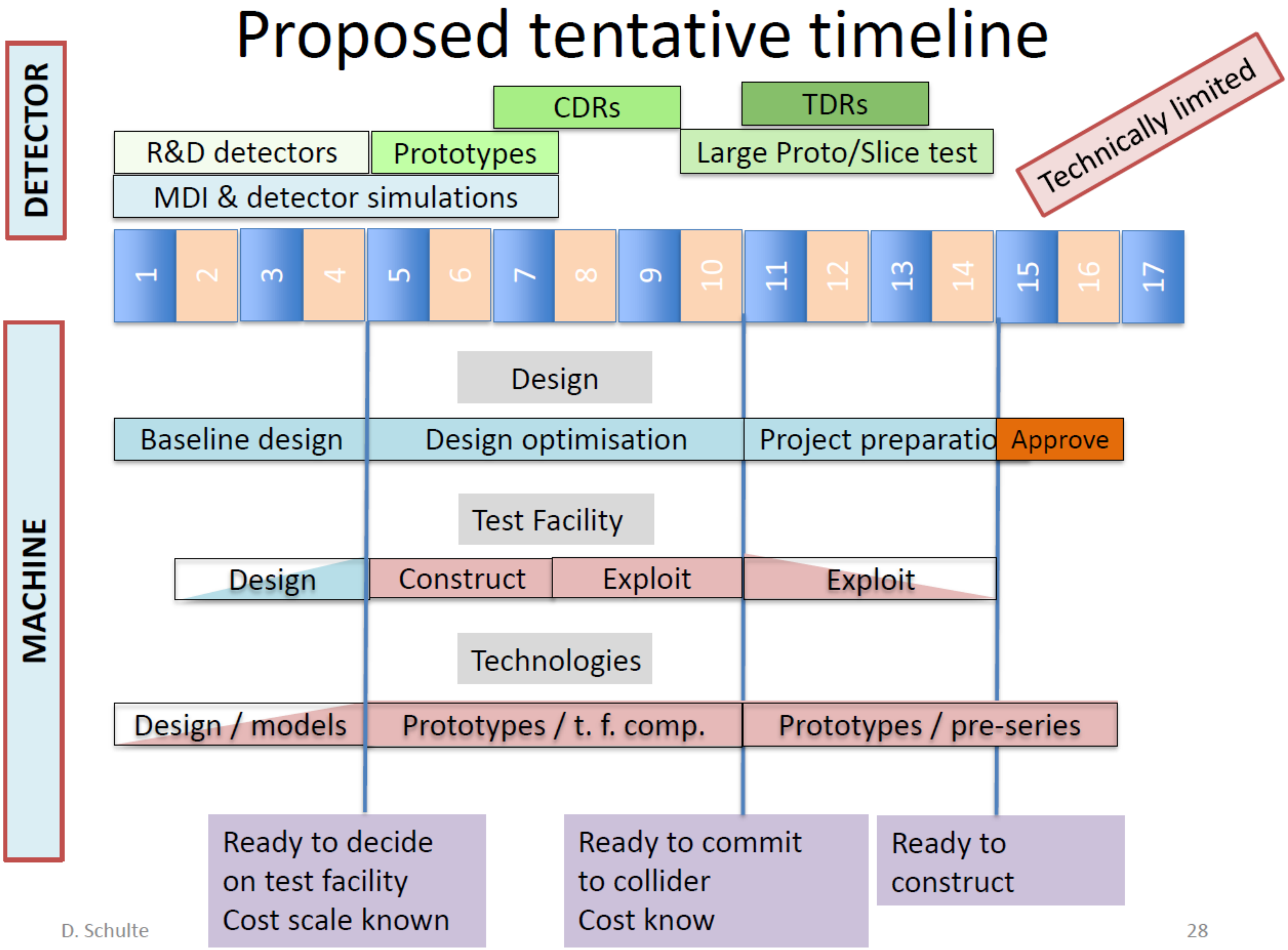
		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

D. Schulte

Muon Colliders, Granada 2019

8

Muon colliders



Proposed tentative timeline

DETECTOR

CDRs

TDRs

Technically limited

R&D detectors

Prototypes

Large Proto/Slice test

MDI & detector simulations

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

MACHINE

Design

Baseline design | Design optimisation | Project preparatio | Approve

Test Facility

Design | Construct | Exploit | Exploit

Technologies

Design / models | Prototypes / t. f. comp. | Prototypes / pre-series

Ready to decide on test facility Cost scale known

Ready to commit to collider Cost know

Ready to construct

D. Schulte

28

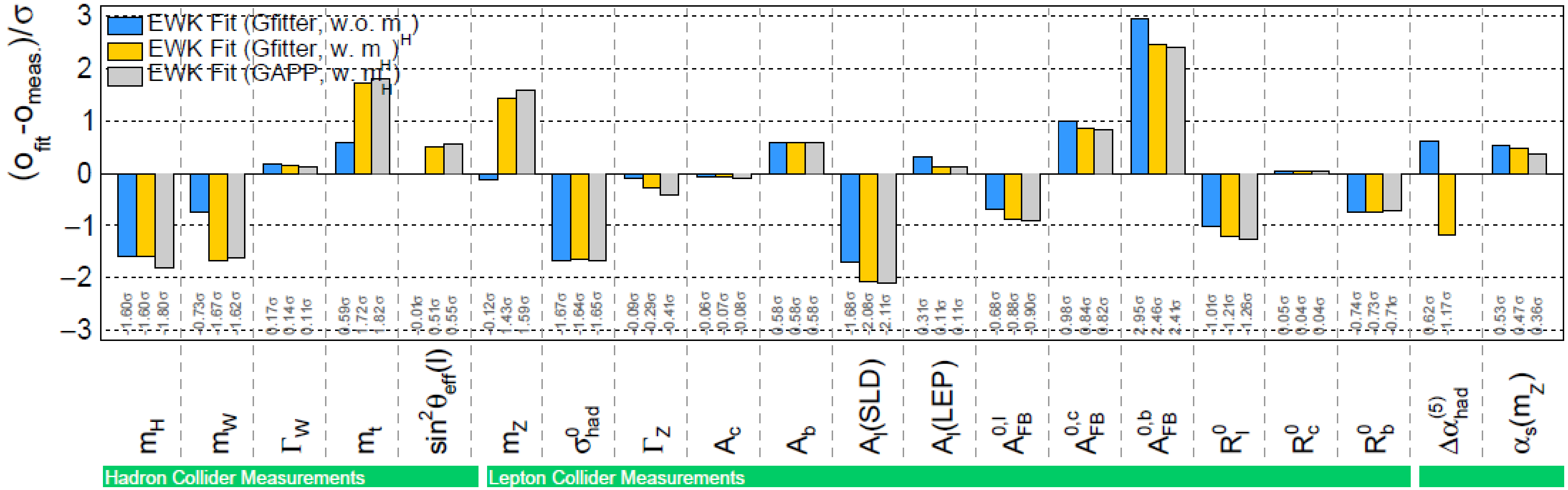
7-10 YEARS FROM NOW

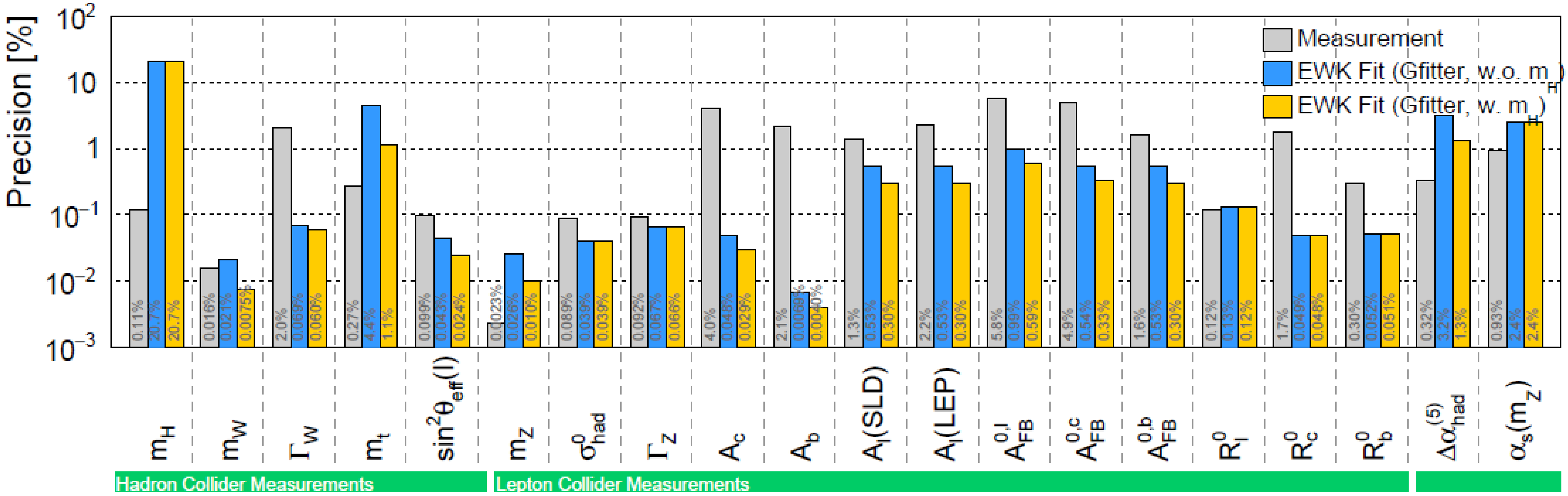
WITH PROPOSED ACTIONS / R&D DONE / TECHNICALLY LIMITED

- ***ILC:***
  - Some change in cost (~6-10%)
  - All agreements by 2024, then
  - **Construction** (2024-2033)
- ***CLIC:***
  - TDR & preconstr. ~2020-26
  - **Construction** (2026-2032)
  - 2 yrs of commissioning
- ***CepC:***
  - Some change in cost & power
  - TDR and R&D (2018-2022)
  - **Construction** (2022-2030)
- ***FCC-ee:***
  - Some change in cost & power
  - **Preparations** 2020-2029
  - Construction 2029-2039
- ***HE-LHC:***
  - **R&D and prepar'ns** 2020-2035
  - Construction 2036-2042
- ***FCC-hh*** (w/o FCC-ee stage)***:***
  - **16T magnet prototype** 2027
  - Construction 2029-2043
- ***μ^+-μ^- Collider :***
  - **CDR completed** 2027, cost known
  - Test facility constructed 2024-27
  - Tests and TDR 2028-2035

Current status of (not only) EW precision physics

Erler, Schott '19





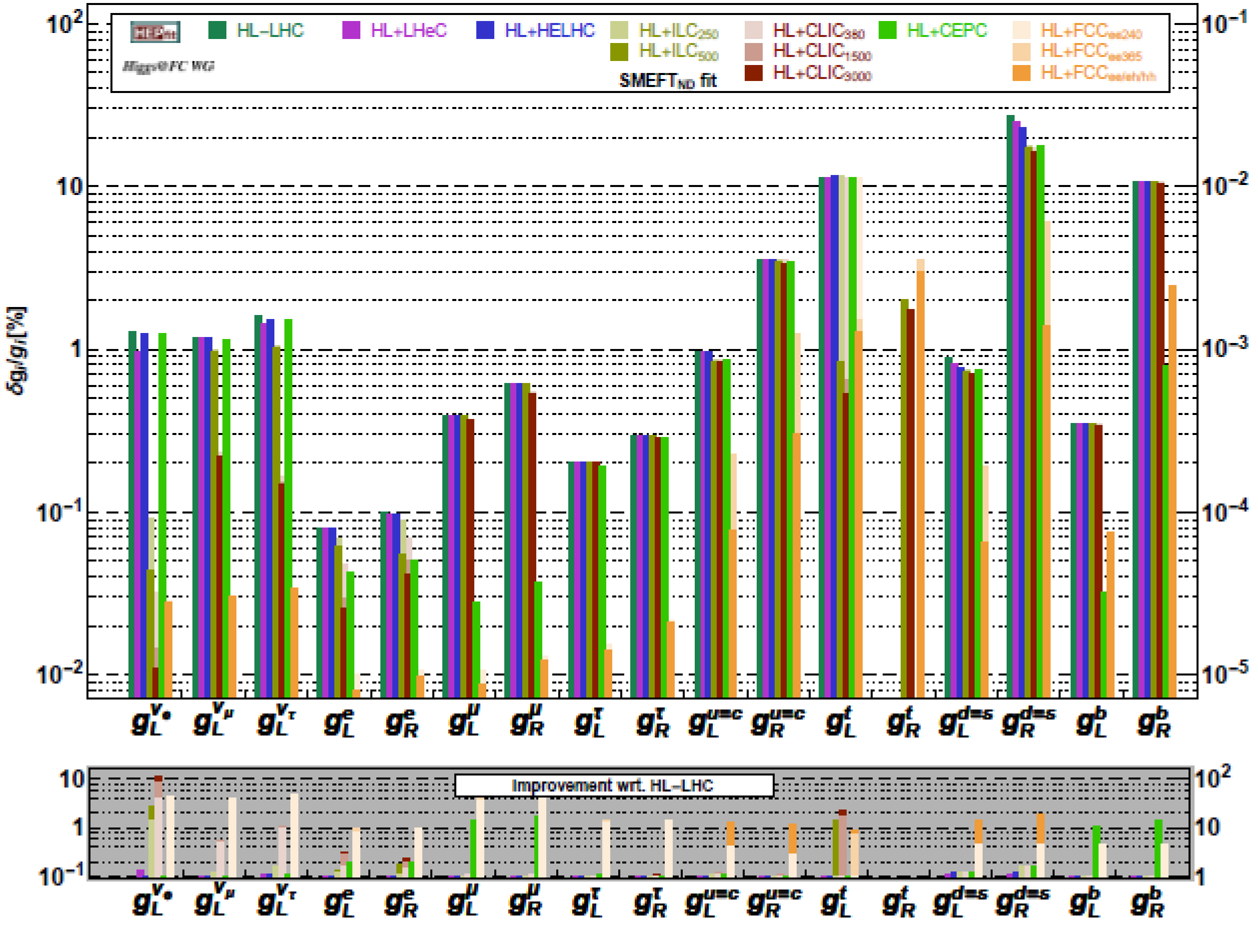
⇒ Future increase in precision is great experimental and theory challenge!

Z pole

- Caveat: No complete studies done @ ILC/CEPC

The other "half" of the 30+ EFT parameters: EW Zff couplings

From the SAME SMEFT$_{ND}$ fit

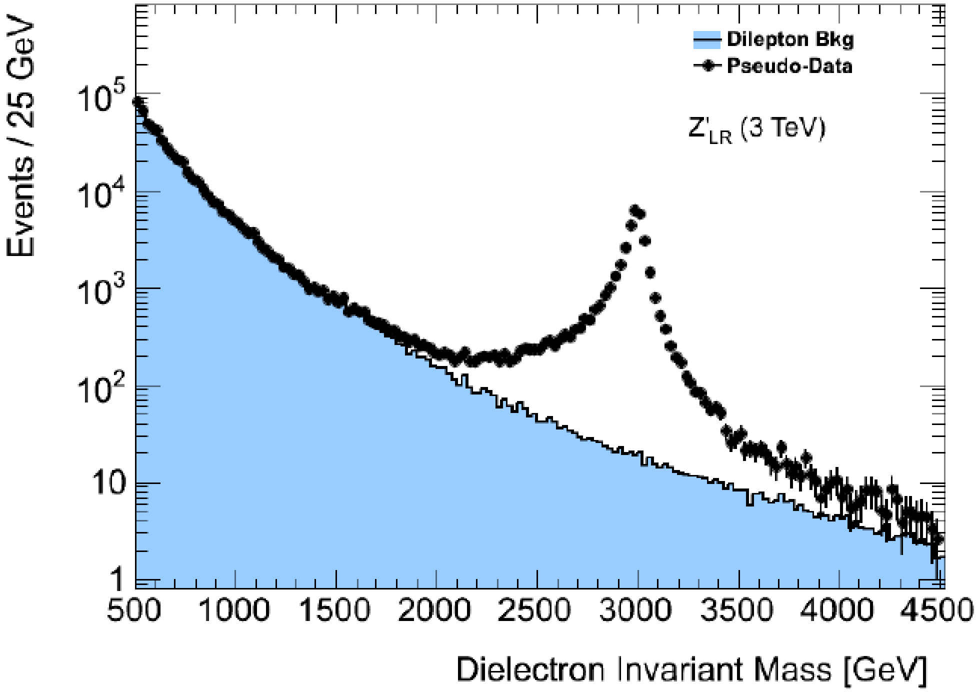


Effective Field Theory description of New Physics

- BSM Effective Field Theories (EFT) are, by construction, a formalism for indirect tests of new physics

What direct searches look for

(e.g Z' search in dilepton spectrum)



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'} + \mathcal{L}_{{\rm SM}-Z'}$$

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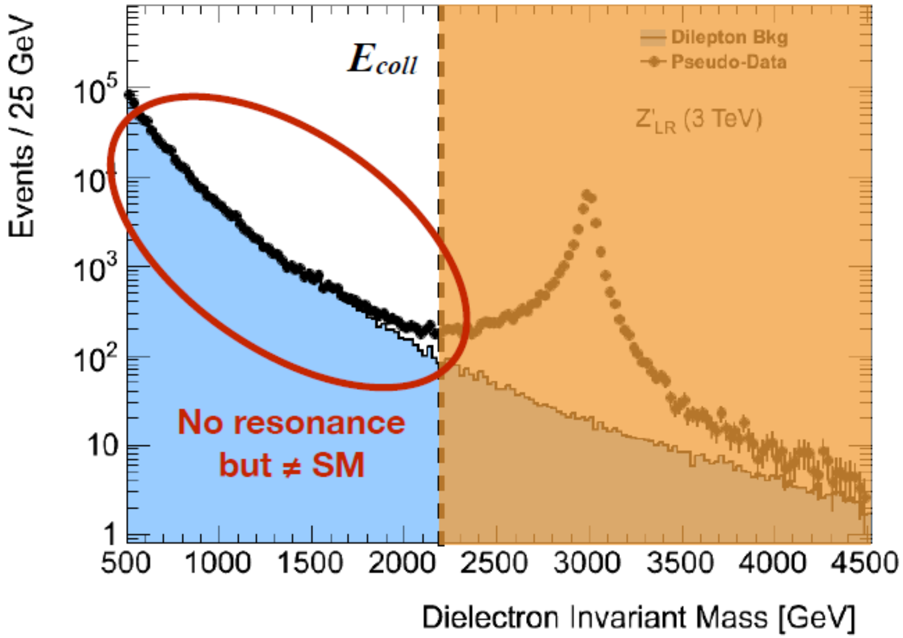
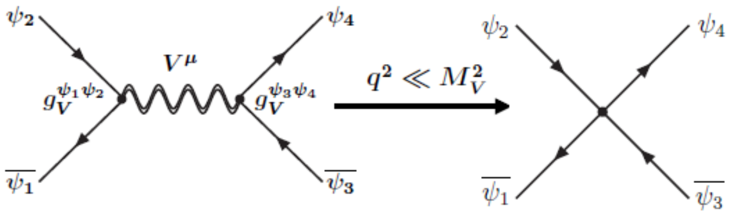


If $E_{coll} < M_{Z'}$ one can still test *virtual effects* of NP looking for "deformations" in SM measurements

For $E_{coll} << M_{Z'}$ these low-energy effects can be well described by effective interactions



In general, the whole set of such possible deformations can be studied with minimal reference to the nature of the UV theory

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'} + \mathcal{L}_{{\rm SM}-Z'} \xrightarrow{q^2 \ll M_V^2} \mathcal{L}_{\rm Eff}$$

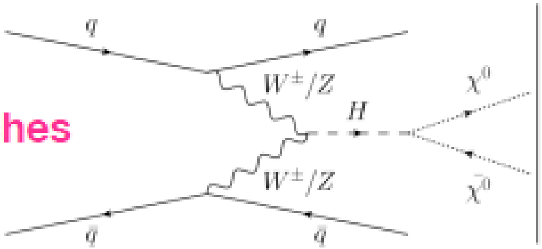
SMEFT: $\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$

SM particles & symm.

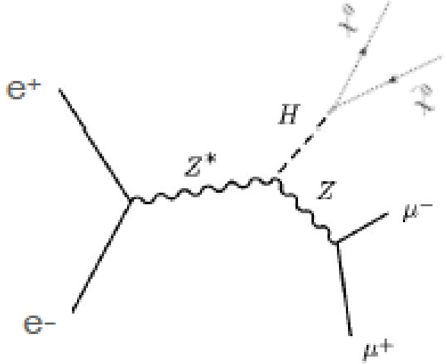
NP decouples for $\Lambda \to \infty$ $\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i$ $[\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$

Observ. Effects $q = v, E < \Lambda$

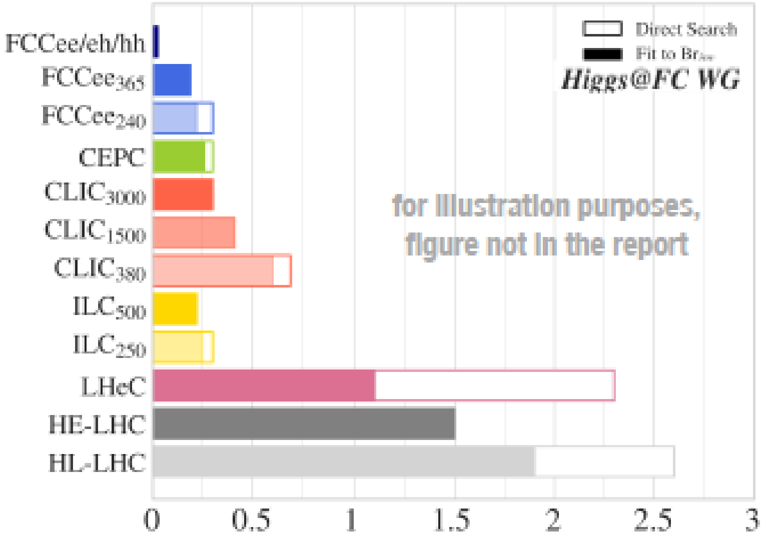
Invisible Width



- **Connection between the Higgs boson and dark matter searches**
- In the SM, $BR_{SM,\,inv} = BR(H\to4\nu) = 0.11\%$
- Current LHC limits ~ 15-20% @ 95%CL
- Direct searches for Invisible width: fundamentally different in a hadron collider (MET uncertainties) and a lepton collider (Z recoil)
    - **Lepton colliders would improve upon HL-LHC limits by an order of magnitude**
    - **FCC-hh : another order of magnitude: values below the SM**



Collider	95% CL upper bound on BR_{inv} [%]		
	Direct searches	kappa-3 fit	Fit to BR_{inv} only
HL-LHC	2.6	1.9	1.9
HL-LHC & HE-LHC		1.5	1.5
FCC-hh	0.025	0.024	0.024
HL-LHC & LHeC	2.3	1.1	1.1
CEPC	0.3	0.27	0.26
FCC-ee$_{240}$	0.3	0.22	0.22
FCC-ee$_{365}$		0.19	0.19
ILC$_{250}$	0.3	0.26	0.25
ILC$_{500}$		0.22	0.22
CLIC$_{380}$	0.69	0.63	0.60
CLIC$_{1500}$		0.62	0.41
CLIC$_{3000}$		0.61	0.30



for illustration purposes, figure not in the report