Introduction to the discussion session of the EPPSU25 - GT1

Overview

1. **Summary of the contributions**
2. **Additional information**

GT1 ESPPU session @ IRN Terascale meeting (Nov 13th 2024)

List of contributions included here

LEVEQUE	Jessica	LAPP Annecy	Transition écologique à l'IN2P3	Autres enjeux sociétaux	Intégrer les enjeux environnementaux dans la politique scientifique de l'institut: une nécessité sociétale
BALLI	Fabrice	CEA Saclay/IRFU/DPhP	GTS GT1	Physique sur accélérateurs R&D accélérateurs Nouvelle expérience Higgs BSM / Nouvelle physique Physique électrofaible Saveurs Neutrinos	A multi-TeV muon collider in the LHC tunnel: a realistic path towards breakthroughs in physics with a future high energy particle accelerator at CERN
DELAHAYE	Pierre	GANIL, CAEN, France	GT2 GT1	Physique sur accélérateurs Physique hors-accélérateurs R&D détecteurs Nouvelle expérience BSM / Nouvelle physique Physique électrofaible Saveurs	"PIONEER: A Next-Generation Pion Decay Experiment at PSI"
Bernardi	Gregorio	APC	GTS GT1	Physique sur accélérateurs Théorie/Phénoménologie R&D accélérateurs R&D détecteurs Calcul et données Diffusion scientifique / "outreach" Développement durable Autres enjeux sociétaux Higgs BSM / Nouvelle physique Physique électrofaible Saveurs QCD	The FCC Feasibility study and the FCC-France contributions in view of the future HEP Collider
Marchiori	Giovanni	APC	GT1	Physique sur accélérateurs Higgs	Measurement of Higgs boson couplings at FCC-ee
Kraml	Sabine	LPSC Grenoble	GT1	Physique sur accélérateurs R&D accélérateurs R&D détecteurs Développement durable Autres enjeux sociétaux Higgs	Considerations regarding a Future CERN Collider
Petit	Elisabeth	CPPM	GTS	Physique sur accélérateurs Physique hors-accélérateurs R&D détecteurs Développement durable Autres enjeux sociétaux Higgs BSM / Nouvelle physique Physique électrofaible Saveurs Neutrinos Interdisciplinarité	Contribution des membres du CPPM aux scénarios de la Stratégie Européenne
Zito	Marco	LPNHE	GTS GT1	Physique sur accélérateurs R&D détecteurs Calcul et données Développement durable	LPNHE contribution to the Update of the European Strategy of Particle Physics
PANWAR	Lata	LPNHE - CNRS - Sorbonne Université/ Université Paris Cité	GT1 GT4	QCD	Prospects of QCD and Lund Jet Plane studies at FCC-ee
Delmastro	Marco	LAPP Annecy	GT1	Physique sur accélérateurs Higgs	Measurement of the ZH,H → ZZ* Cross Section at the FCC-ee for the Higgs Width Determination
Delmastro	Marco	LAPP Annecy	R&D Détecteurs GT1	Physique sur accélérateurs R&D détecteurs Nouvelle expérience	Expression d'Intérêt pour le Travail sur les Détecteurs des Futurs Accélérateurs du CERN
Delmastro	Marco	LAPP Annecy	GT1 GT2	Physique sur accélérateurs Higgs Physique électrofaible Saveurs	Expression d'Intérêt pour les mesures de précision au FCC-ee
NORTIER	Florian	IP2I Lyon	GT1 GT2	Physique sur accélérateurs Théorie/Phénoménologie Higgs BSM / Nouvelle physique Physique électrofaible Saveurs	Contribution of the IP2I Theory Group to the ESPPU 2025

https://esppu.in2p3.fr/contribution (To connect: esppu / contributionsESPPU@2024)

List of very recent contributions (not included)

Richard	François	IJCLab	GT1	Théorie/Phénoménologie	Scalar or tensor resonances indicated by LHC data
Faivre	Julien	LPSC	GTS	Développement durable Autres enjeux sociétaux	Countering the biodiversity loss using particle physics research sites
Pöschl	Roman	IJCLab	GT1 GTS	Physique sur accélérateurs Théorie/Phénoménologie R&D accélérateurs R&D détecteurs Higgs Physique électrofaible	The Linear Collider Facility (LCF) - A Vision for the Future of Particle Physics
Kraml	Sabine	LPSC	GT1	Physique sur accélérateurs Théorie/Phénoménologie Calcul et données Diffusion scientifique / "outreach" Nouvelle expérience Higgs BSM / Nouvelle physique Physique électrofaible Saveurs QCD Neutrinos	Reinterpetation and preservation of data and analyses in HEP
Maselek	Rafal	LPSC	GT1	Théorie/Phénoménologie Calcul et données BSM / Nouvelle physique	Artificial Intelligence for BSM searches

About the HL-LHC

- Last high-energy pp collider for decades to come: legacy physics outcome
- Utmost importance to:
  - exploit its full physics potential (Higgs properties, top physics, QCD studies, search for BSM (DM related, LLPs, …), top physics…)
  - continue supporting the planned detector upgrades

About the next project

- Should allow to precisely study the Higgs and EW sectors - what precision is needed?
- A federating collider project at CERN should be funded in a way which is not detrimental to non-collider projects
- Should be built in Europe, but only if it is a world-wide program, or operational in a timely manner with respect to existing or upcoming projects to make competitive measurement
- The energy scale of new physics is unknown
    - Possibly coming from the HL-LHC or other experiments in the coming 10-15 years; could impact the choice
    - May also come only from the Higgs factory itself
    - Privilege a machine occurring within short-term devoted to the Higgs, leave the technological choice for a next collider as open as possible
- Competition with other research fields has become an issue
- Construction costs have increased substantially while the European economy has entered an era dominated by tensions (European governments have become reluctant to engage for large, long term projects)
    - risk of sizable additional delays: loss of attractiveness for younger scientists and of expertise
- Need to take a clear decision at this strategy, as a further delay can compromise the health and attractiveness of the field

About environmental considerations

- Lacking from the last prospectives
- Ethic and exemplarity of the scientific research
  - environmental issues should have the same consideration as we do now for animal experimentation for example
- Need to quantify and compare the impact of each project
- Being proactive & transparent would not only bring a larger adhesion amongst ourselves but would also increase social acceptance
- The current projections of the energy consumption of FCC-ee is higher than the one of LHC
- About 80% of CERN's direct greenhouse gases emissions is due to fluorinated gases
  - replacement of fluorinated gases in the ongoing experiments has to be done when possible
- The impact of the tunnel building is also a challenge
- Effort developed in a dedicated chapter of the midterm report of FCC feasibility study (societal and environmental impacts)
- Technological innovations to achieve high efficiency could also benefit the whole society

About computing

- The volume of data collected by particle physics experiments has increased by around two orders of magnitude per decade, reaching the Hexascale
  - Not slowing down:
    - increasing detector granularity
    - precision timing information
    - larger samples
- Increase in computing needs also driven by to ML/AI-driven data processing
- Energy efficiency will increasingly be as important as financial costs: need to innovate

About personpower & maintaining expertise

- The next major collider project cannot rely only on physicists & engineers involved in LHC collaborations
  - Already committed to running the experiments, analysing current and future datasets and building and commissioning upgrades for the HL-LHC phase
  - Should be supported with additional personpower
- Education and training of young physicists are crucial for the needs of the field and of society at large
  - Need to analyse physics data during the construction of the next collider: maintain full activity in the HL-LHC program
  - Need to maintain and transfer the expertise in electronics, information technology, instrumentation and mechanics, independently of the choice of the future collider
- Expertise of current groups in analysis and detectors is key to getting involved now in the development of the future detectors

About non-collider projects

- Neutrino projects:
  - KM3NET, DUNE, Hyper Kamiokande, NA61/SHINE
  - An innovative short baseline (SBL) experiment at CERN would allow to measure neutrino cross sections at the percent level and to improve the interaction models used to reconstruct the neutrino energy. Such inputs would be extremely valuable to DUNE and HK.
  - Next generation of long baseline (LBL) experiments.
  - Both LBL and SBL projects could effectively re-use existing infrastructures at CERN (SPS, CNGS) and in Europe (KM3NeT)
  - The CERN neutrino platform is also an invaluable asset for R&D on novel neutrino detectors and neutrino beams
- Precision:
  - COMET (J-PARC)
  - Collaboration with the LKB laboratory on QED high precision tests using antiprotonic atoms at ELENA
- Searches for WIMPs and axions
  - For ex. DarkSide, MADMAX
- Continue the interplay between particle physics and biomedical imaging, and support societal applications

About FCC

- FCC feasibility study will be delivered in March 2025. Mid-term report delivered end of 2023
- Current baseline: 4 IPs, run at Z pole, WW threshold, ZH prod. max, top pair threshold + possibly at the H pole (Hee Yukawa)
- Precision on Higgs boson properties and precision electroweak and QCD observables an order of magnitude better than the measurements at HL-LHC and LEP
    - Z pole: Z line shape and EW observables with 50x improved precision, uniquely precise determinations of $\alpha_{QED}(m_Z)$ and $\alpha_S(m_Z)$
    - α_S determination at different E (multiplicity or substructure of jets): important for testing the Renormalization Group Equation in QCD
    - ZH coupling at the /1000 level in baseline scenario (10.8 ab^{-1} @ 240 GeV): measure inclusive ZH xsec; other couplings can be probed by measuring the product of this xsec and the branching fractions for decays to hadronic final states
    - Measure the total Higgs boson production xsec: Higgs boson BRs directly accessible, unlike the LHC (ratios of BRs)
- BSM: feebly interacting particles down to sub-GeV, ALPs, light pseudoscalars, SMEFT, up to 10-100 TeV range
- Possibility of FCC-hh afterwards at 100 TeV (reach of HL-LHC x 10 + H self coupling at 5%) - especially if deviations seen!
- FCC-France community (~60 physicists and engineers), master-projet (IN2P3) FCC-PED since Jan 2020:
    - 12 groups, 11 from IN2P3 Labs and one from IRFU

About FCCee: new physics studies

- Two contributions showing active work ongoing on FCCee
- Combining the measurement on the ZH,H → ZZ_* process, along with the H → ZZ_* branching ratio, allows for the calculation of the total Higgs boson width without any additional theoretical assumptions
  - With an integrated luminosity of 5 ab^{-1} in e^+e^- collisions at $\sqrt{s}$ = 240 GeV, collected by two detectors over three years of data-taking, FCC-ee could measure the natural width of the Higgs boson with a precision of approximately 4%. Considering the new nominal FCC-ee luminosity of 7.5 ab^{-1}, the achievable precision would improve to around 3.3%
  - A similar measurement of VBF H → ZZ_* production at $\sqrt{s}$ = 365 GeV could also be performed and combined to further enhance sensitivity
- The Lund jet plane organizes the emissions in terms of their transverse momentum and angular separation. This approach not only distinguishes between perturbative and non-perturbative QCD regimes but also enhances the ability to study αS
  - more accurate global fits of alphas, improving jet modeling in Monte Carlo simulations and enabling advanced jet tagging techniques.
  - role in optimizing detector designs

About a linear collider

- Can measure the Higgs self-coupling through the direct HH production, with an upgraded linear collider (beyond the baseline 250 GeV)
- For a circular machine, the size of the tunnel fixes the reachable energy boundary: delicate when not knowing yet the next fundamental scale
- Smaller, cheaper machine than FCC:
  - faster to build
  - possibly in parallel with the HL-LHC operation

About a muon collider

- Possibility to re-use the LHC tunnel to accelerate muons (multi-TeV), to collide them in a smaller ring (~10 km circumference)
- Significantly smaller tunnel than FCC
    - More funding for the accelerator and particle physics community (magnets, cooling and RF acceleration techniques) rather than civil engineering
- Higgs factory that rivals with FCC-ee and FCC-hh
    - trilinear Higgs coupling can be determined at 5%; only collider giving access to the quartic coupling via HHH production
- Much smaller energy required than in a proton collider to reach equivalent cross-sections for BSM physics
- Challenges to build such a machine: need dedicated R&D, and notably a demonstrator for the cooling
- Problem of neutrino radiation by the beam, particularly in straight sections, is studied and dedicated solutions are envisaged
    - buying of the land where neutrino-induced radiation occurs, or install dedicated detectors for neutrino physics
- One of the most competitive in terms of energy consumption
- Revolutionize the field while being complementary to other shorter term e+e- machines

Reminder of the context

- ESPPU 2020
  - e+e- as Higgs factory highest priority. Longer term p-p collider at the highest achievable energy
    - ✓ R&D on advanced accelerator technology
    - ✓ Hadron collider @ 100TeV
    - ✓ Timely realisation of ILC compatible with this strategy
  - Innovative R&D
    - ✓ High-field magnet, high-T superconductor, plasma acceleration, high gradient accelerating structures
- ESPPU 2025 ?
  - Preferred option for the next collider at CERN and prioritised alternative options
  - This plan should attract and value international collaboration (and allow Europe to play a key leading role).
- International context
  - ILC in Japan is jeopardised ?
  - CEPC/SppC in China: CDR in 2018, Accelerator TDR released in 12/2023 [3], Detector TDR in 2025.
    - A more and more likely option ?

Refs

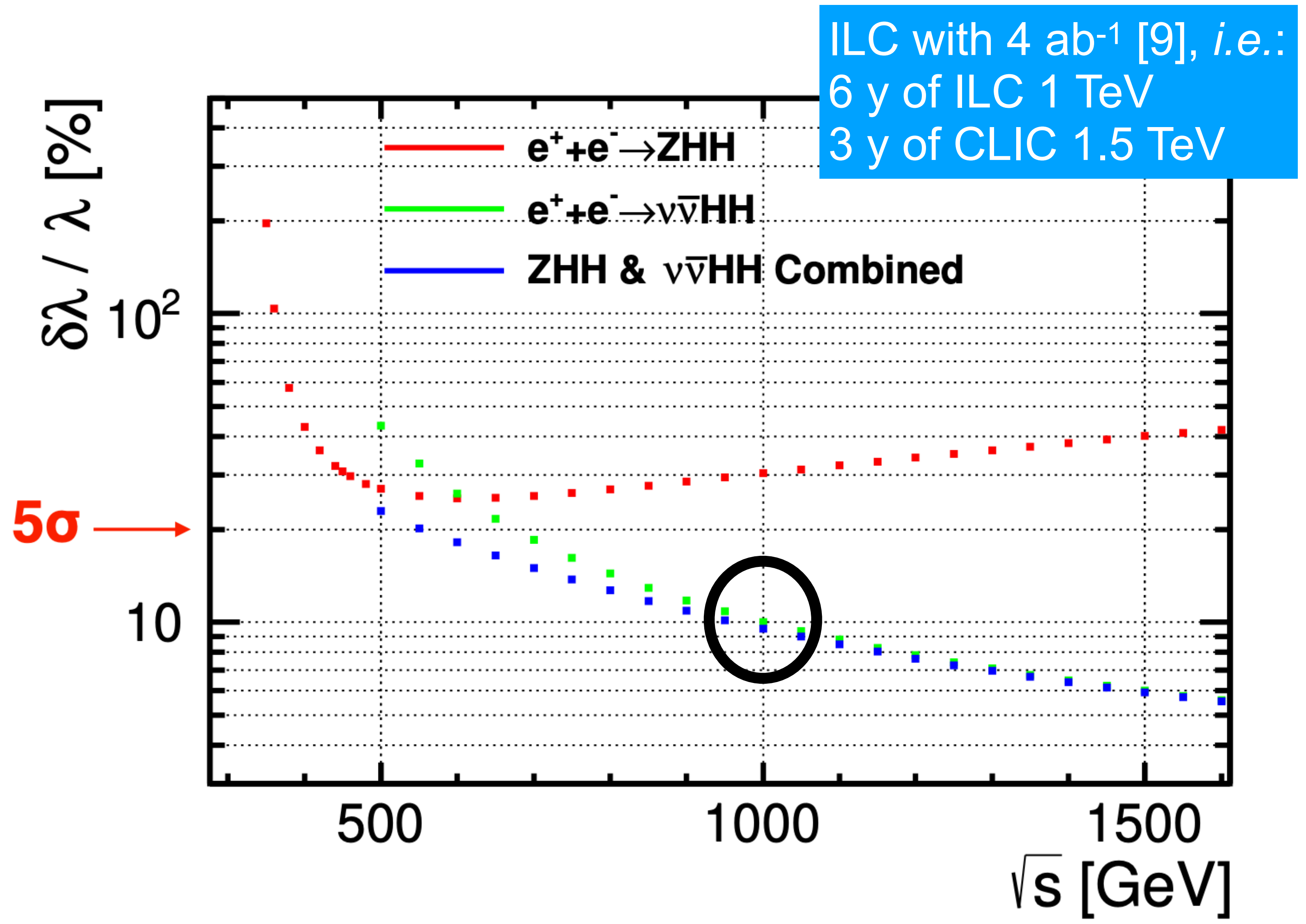
REF	LINK
[1] eeFACT22 (summary)	https://arxiv.org/pdf/2209.05827
[2] ECFA (2024) - FCC	https://indico.in2p3.fr/event/32629/contributions/140465/attachments/87558/132169/FCC-ECFA-WS-Oct2024.pptx
[3] ECFA (2024) - CEPC	https://indico.in2p3.fr/event/32629/contributions/140468/attachments/87594/132224/20241010-ECFA-Paris-CEPC.pdf
[4] CLIC project (2022)	https://arxiv.org/pdf/2203.09186
[5] ECFA (2024) - ILC/CLIC	https://indico.in2p3.fr/event/32629/contributions/140466/attachments/87556/132225/linear-colliders-ecfa-uploaded.pptx
[6] FCC	https://home.cern/science/accelerators/future-circular-collider
[7] FCC costing	https://cds.cern.ch/record/2666742/files/CERN-ACC-2019-0037.pdf
[8] ILC - eeFact22	https://agenda.infn.it/event/21199/contributions/168888/attachments/96229/132499/ILC_AFG_v1.pptx
[9] Higgs Self Coupling e+e-	https://indico.in2p3.fr/event/32629/contributions/140462/attachments/87691/132386/Hself_ECFA_20241011.pdf
[10] Higgs @ future colliders	https://link.springer.com/article/10.1007/JHEP01(2020)139

Higgs reach @ e+ e- colliders (250GeV - 1TeV)

SINGLE H	# Higgs Boson / h	MWh (Wall plug)/ Higgs Boson [1]	Tunnel length	R&D Maturity [1]	Bill (GCHF)
FCC-ee (2IPs) - 240GeV	71.6	4.2	90km	9	11-15 [7]
CEPC (2IPs) - 240GeV	71.6	3.6	100km	9	5 [3]
ILC - 250 GeV (polarised)	15.2	7.3	20km	10	7 [5]
CLIC - 380GeV	12.3	8.7	11km	10	7 [4]
LEP3	15.7		N/A	8	

HH	# vvH / h	MW	Tunnel	Bill (GCHF)
ILC 1TeV	0,014	300	40 km	(7 +) ?* [5]
CLIC 1.5TeV	0,028	364 *	29 km	(7 +) 5 [4]

ILC 1TeV* :this is another ILC (cost unknown)
CLIC 1.5TeV*: consumption can be significantly improved [1]



From [10] (2020)
HE-LHC δλ/λ ≈ 10-20%
15/ab ≈ 20 years

Z pole - ttbar @ e+ e- colliders

Z pole [σ ≈ 50 nb]	# pb^{-1} / h	MWh / pb^{-1}
FCC-ee (2IPs)	13032.0	0.02
CEPC (2IPs)	13680.0	0.02
ILC - 91 GeV	7.6	14.68
CLIC - 91 GeV (*)	13.0	8.26

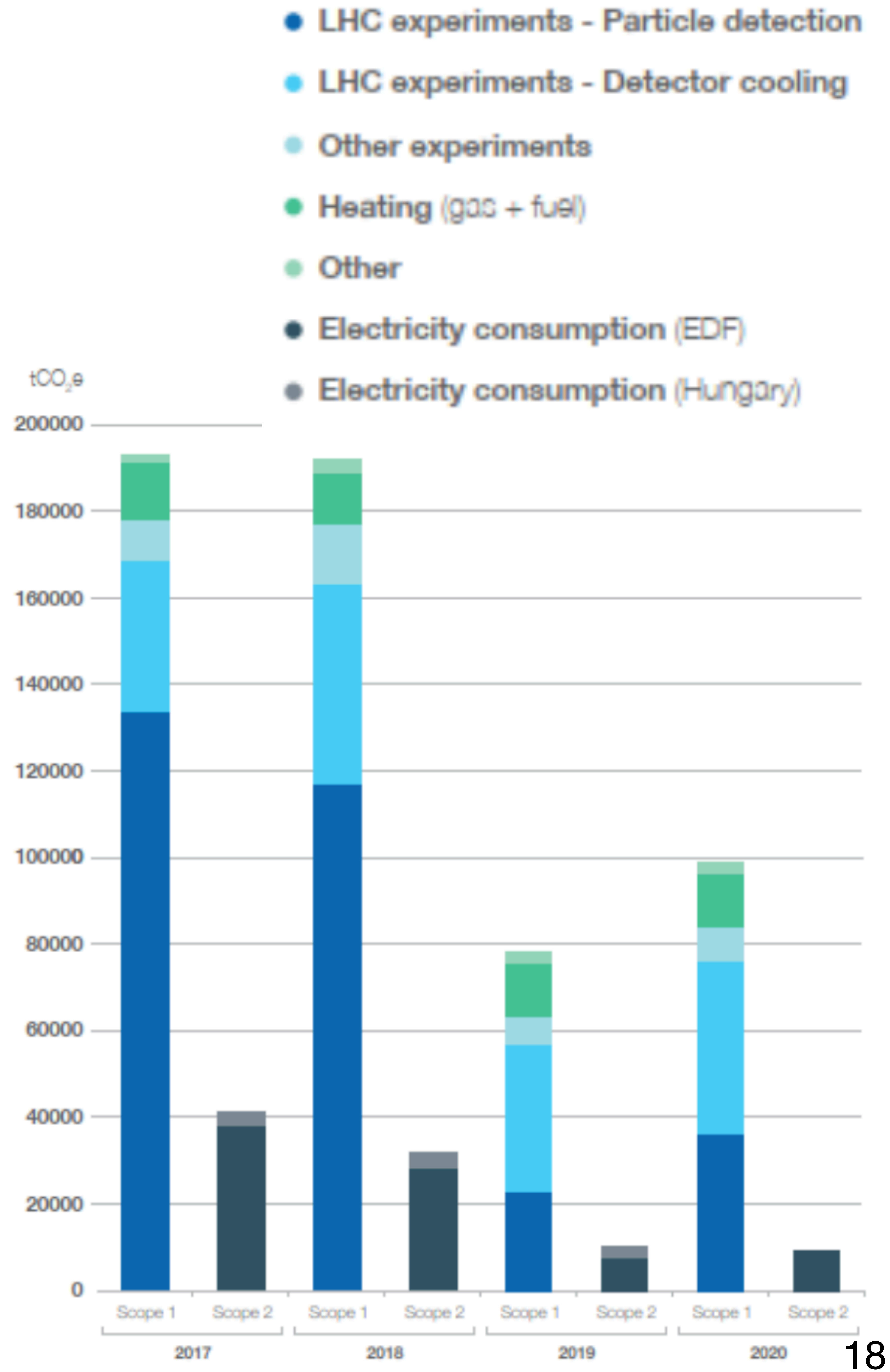
(*): with a dedicated run configuration at startup

ttbar threshod	# pb^{-1} / h
FCC-ee (2IPs)	90,0
CEPC (2IPs)	57,6
ILC - 365 GeV	56,2
CLIC - 380 GeV	82,8

e+ e- colliders
Carbon footprint

	# Higgs Boson / h	Electricity TWh / year [1]	Electricity tCO2eq for 20 years (1)	Tunnel construction tCO2eq (2)
FCC-ee (2IPs) - 240GeV	71.6	1.5	875’000	900’000
CEPC (2IPs) - 240GeV	71.6	0.9	525’000	1’000’000
ILC - 250 GeV	15.2	0.8	467’000	200’000
CLIC - 380GeV	12.3	0.6	350’000	110’000
LEP3	15.7			Existing tunnel

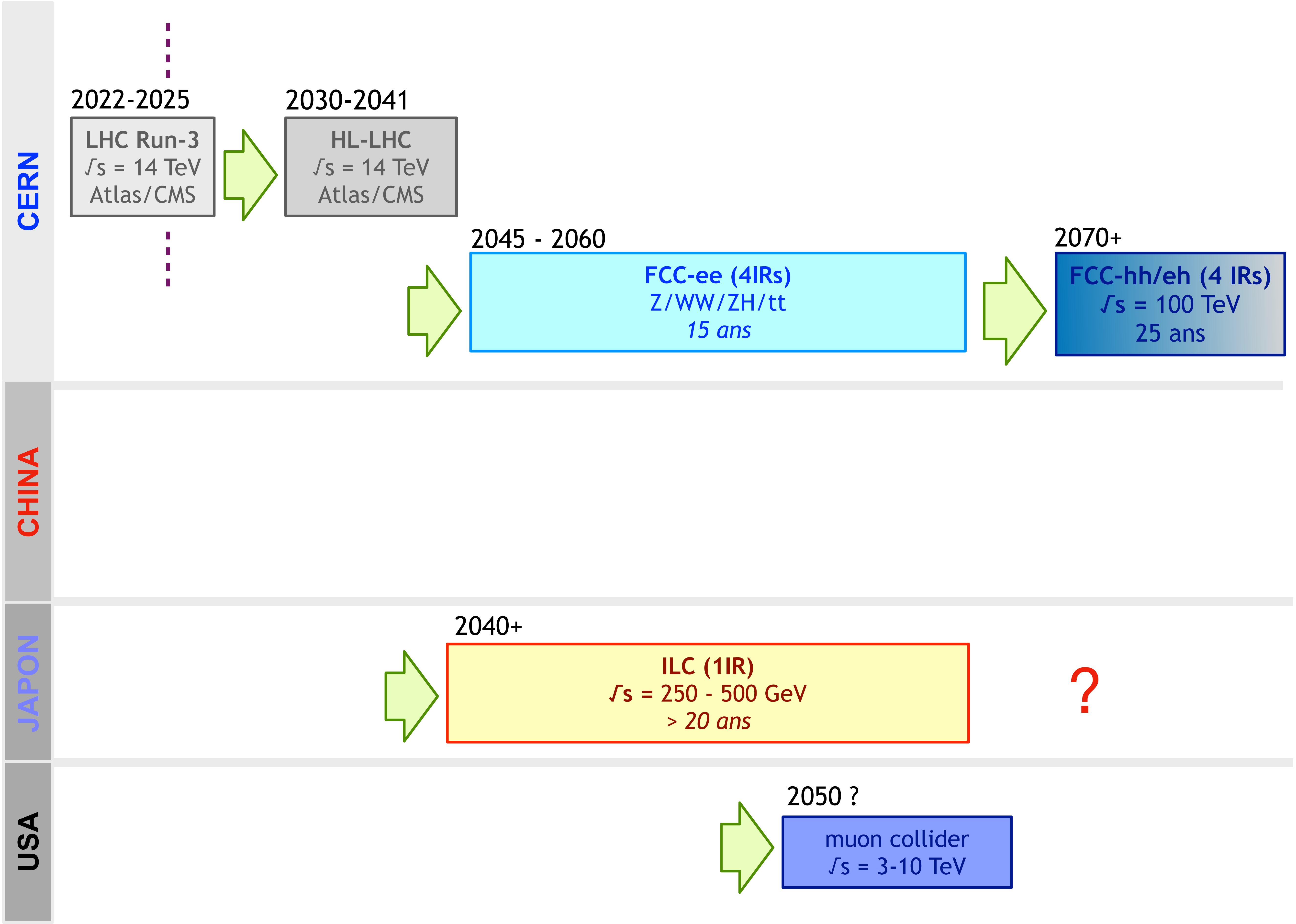
(1) Assuming recent electricity mix at CERN (mostly nuclear). May be very different elsewhere.
(2) Assuming 10’000 tCO2eq/km of tunnel. Estimations vary a lot. See for example here.
(3) LHC green-house emissions largely dominated by detector gas leaks (CO2, methane, SF6 etc…). 5 years of LHC = 1 FCC tunnel [tCO2eq] !



courtesy of H. Bachacou

A. Defined as our preferred scenario

1. FCC option



Bill

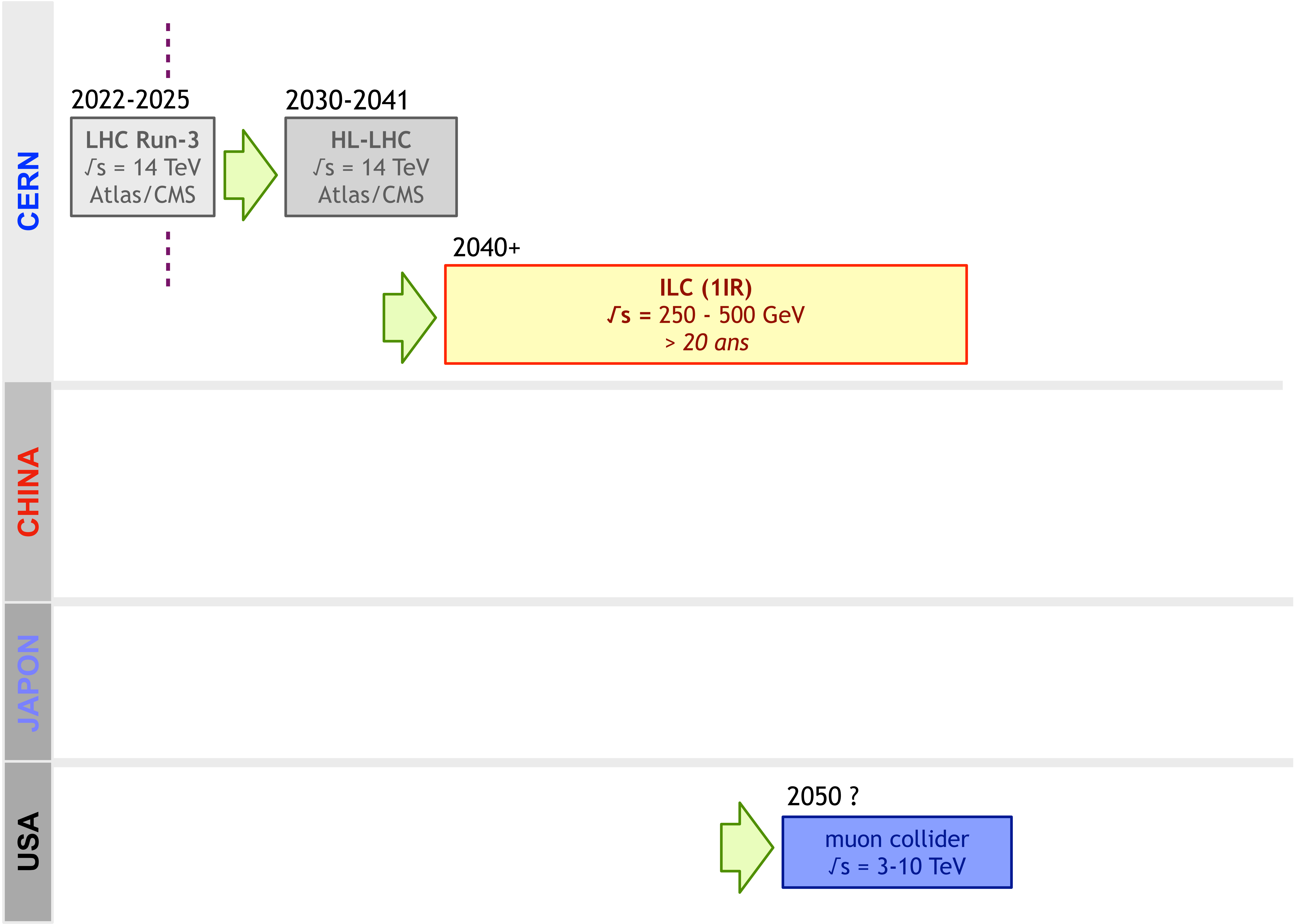
FCC ee: 15 GCHF [7*]

FCC hh: + 20-25 GCHF [7*]

From [7] correcting with current cost from CERN FCC web page (15GCHF)

A. Defined as our preferred scenario

2. ILC option

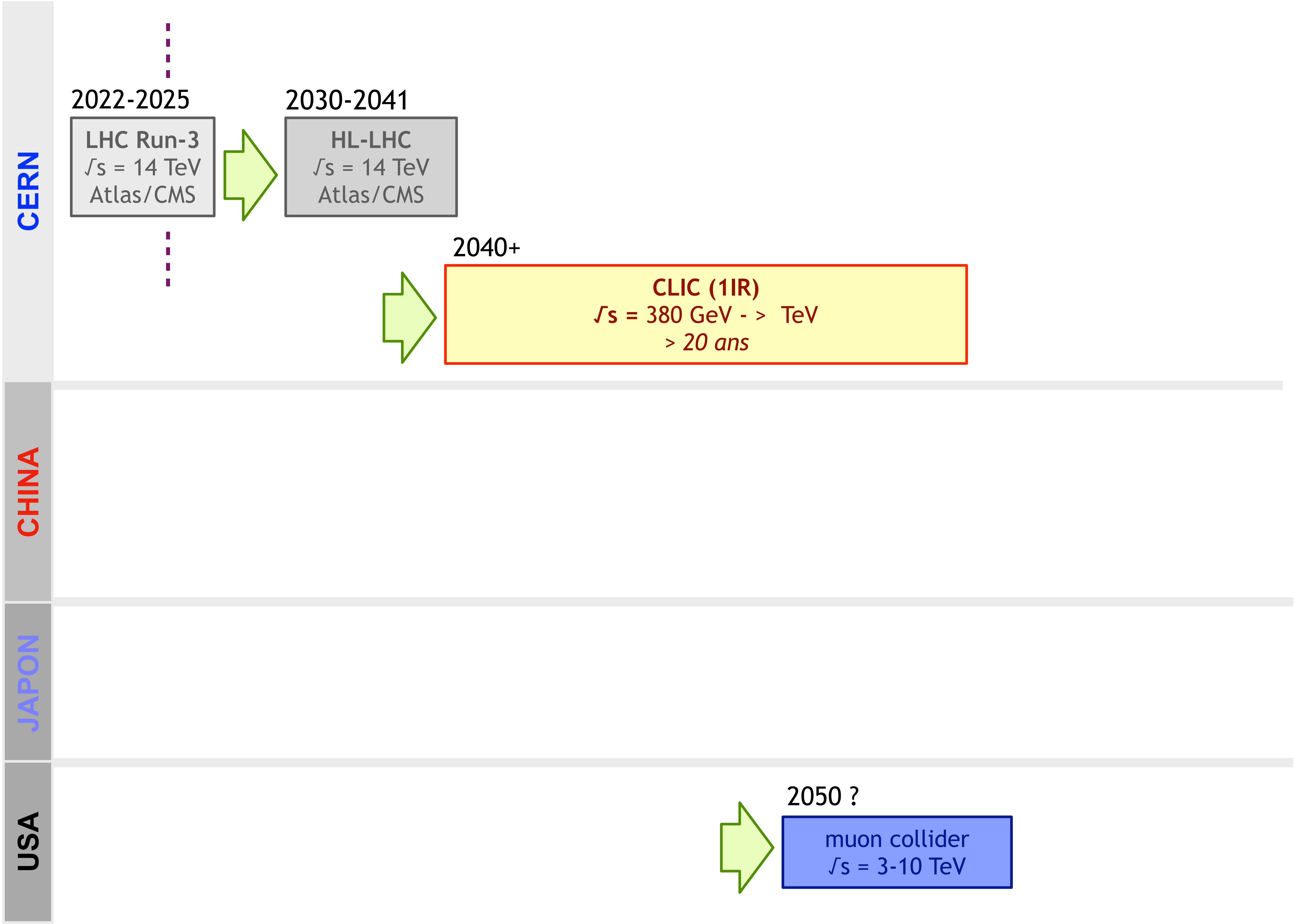


Bill

ILC <=500GeV: 12 GCHF [5]

A. Defined as our preferred scenario

3. CLIC option



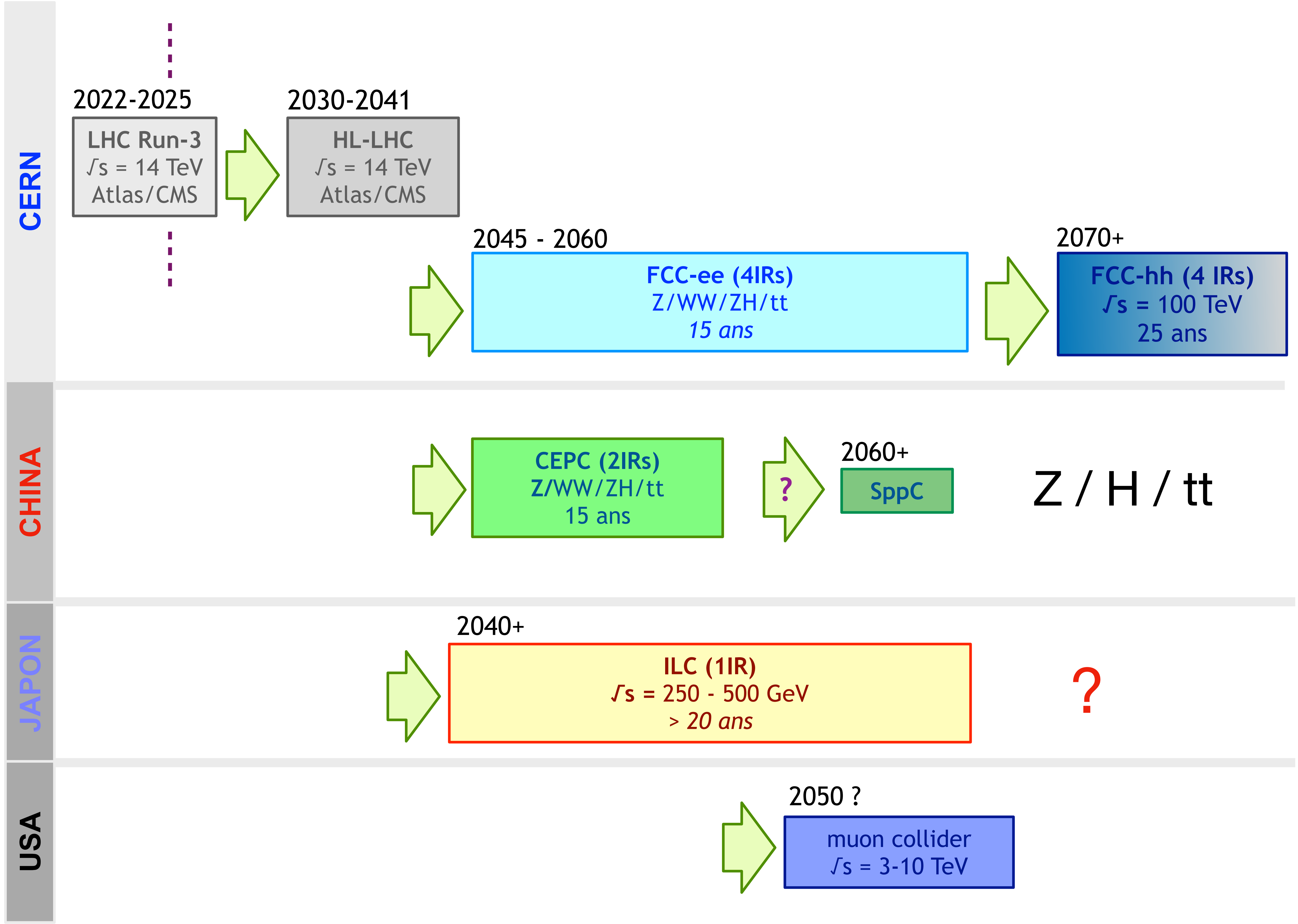
Bill

CLIC (0.4TeV): 7 GCHF

CLIC (1.5TeV): +5 GCHF

B. Scenario with CEPC

1. We don’t care ?



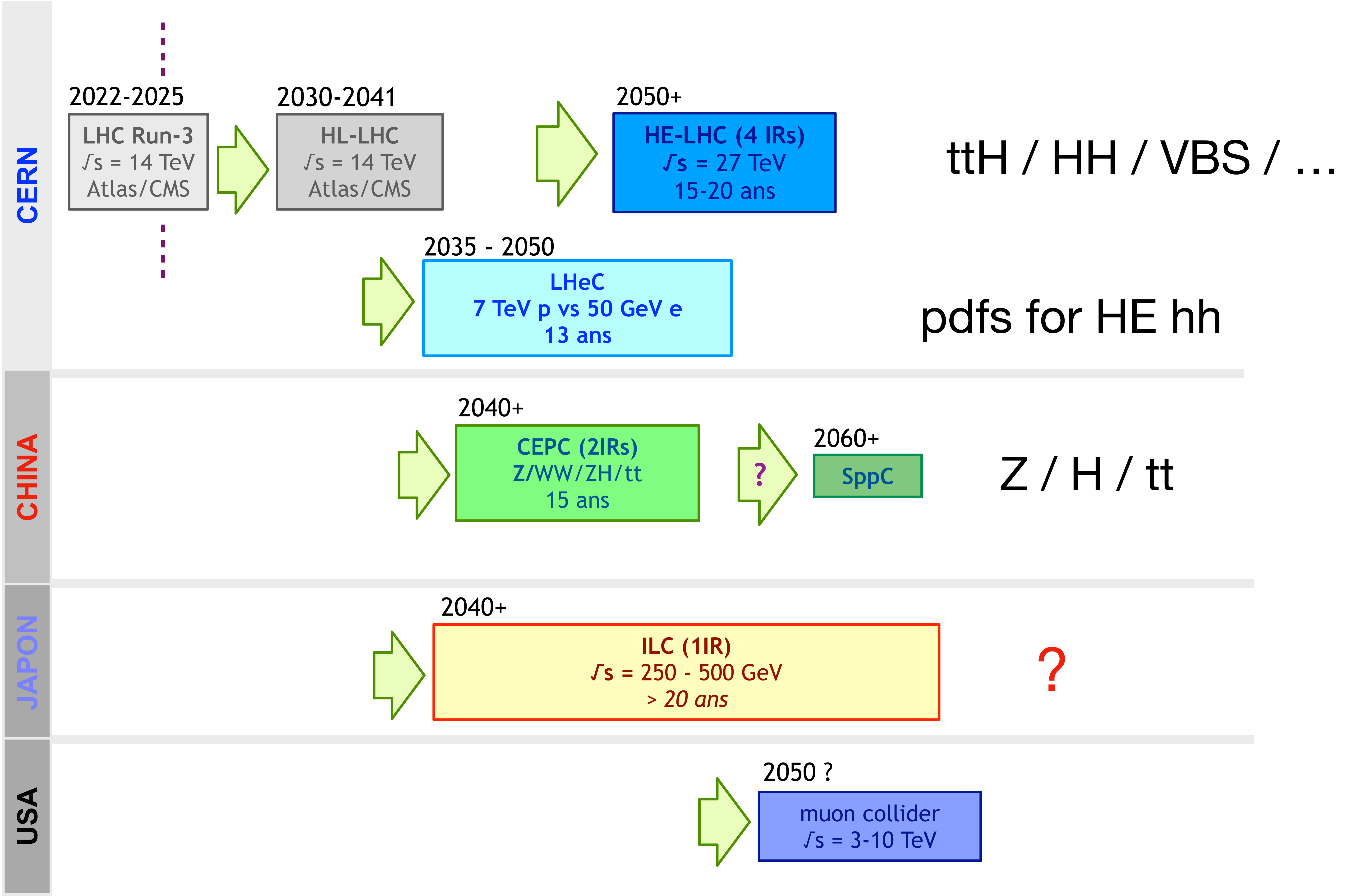
Bill

FCC ee: 15 GCHF [7*]

FCC hh: + 20-25 GCHF [7*]

B. Scenario with CEPC

2. Europe with a complementary hadronic program



Bill

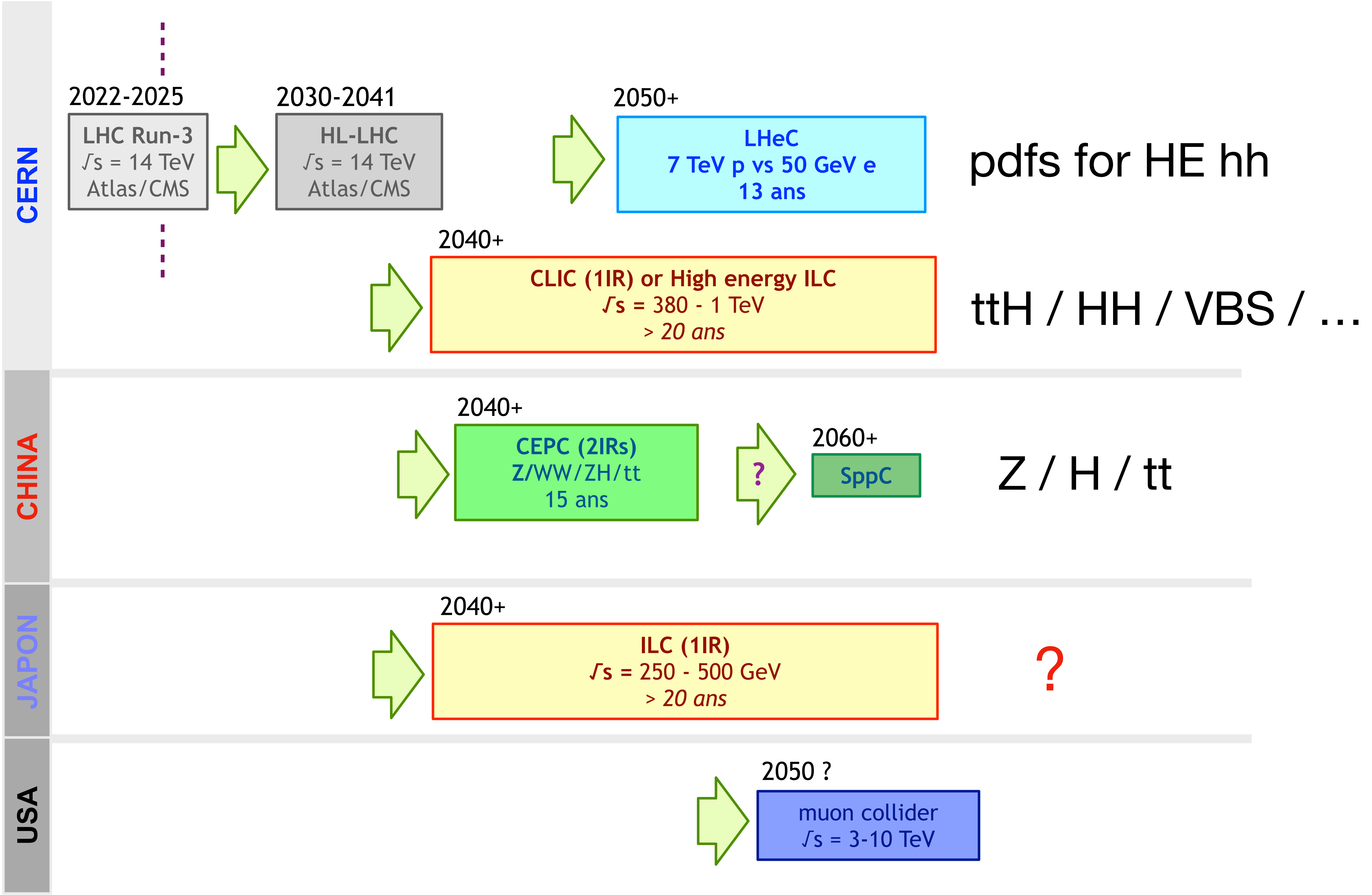
LHeC: 1-2 GCHF ?

HE-LHC: 9 GCHF [7*]

From [7] correcting with current cost from CERN FCC web page (15GCHF)

B. Scenario with CEPC

3. Europe with a complementary e-e+ high energy program



Bill

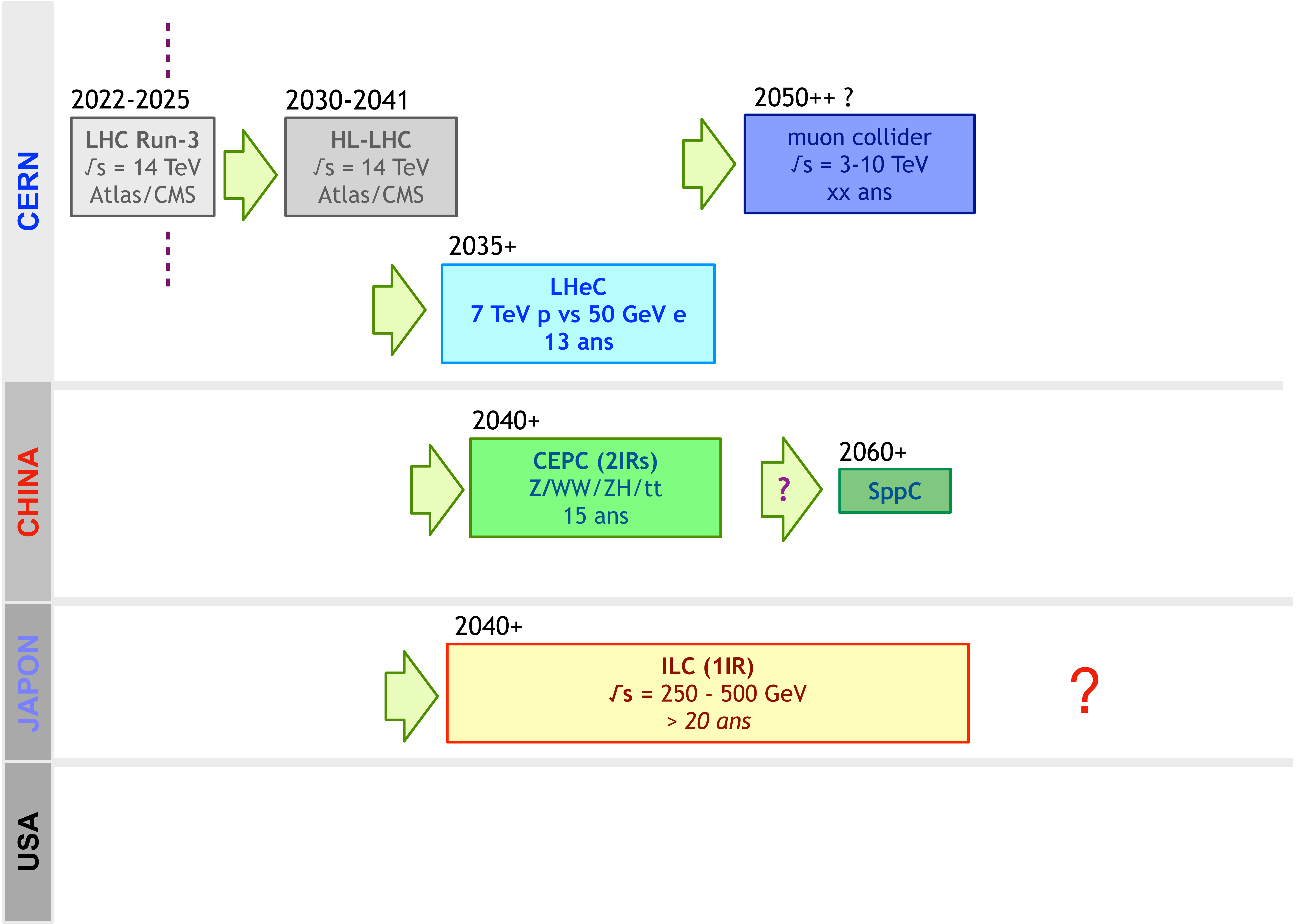
LHeC: 1-2 GCHF ?

CLIC (0.4TeV): 7 GCHF

CLIC (1.5TeV): +5 GCHF

B. Scenario with CEPC

4. Europe with a complementary μ-μ+ high energy program



Bill

LHeC: 1-2 GCHF ?

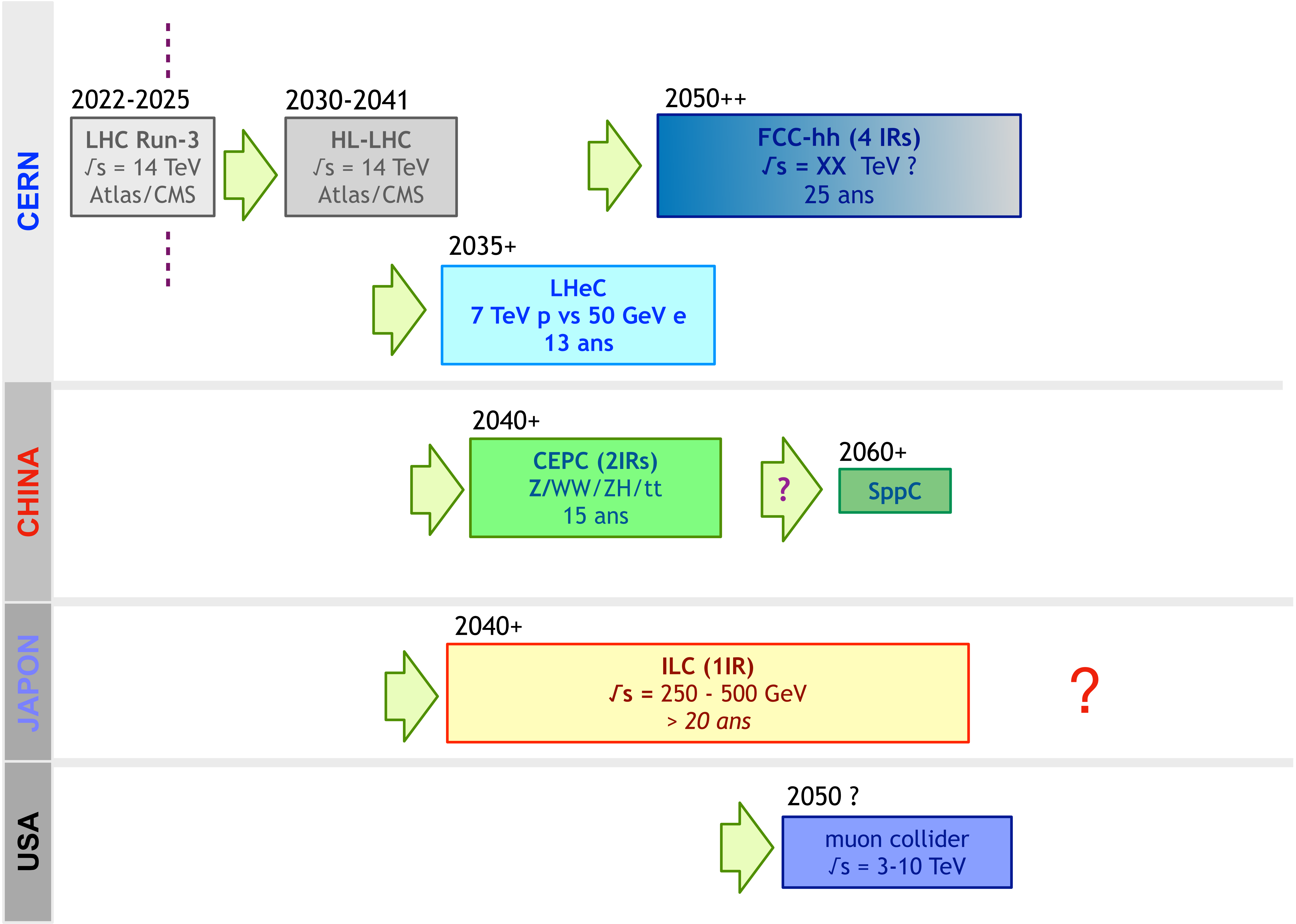
Muon-Collider: ?? GCHF

High risk- high gain

LHeC to bridge the gap between HL-HLC and muon collider

B. Scenario with CEPC

5. Europe directly to pp 100 TeV



Bill

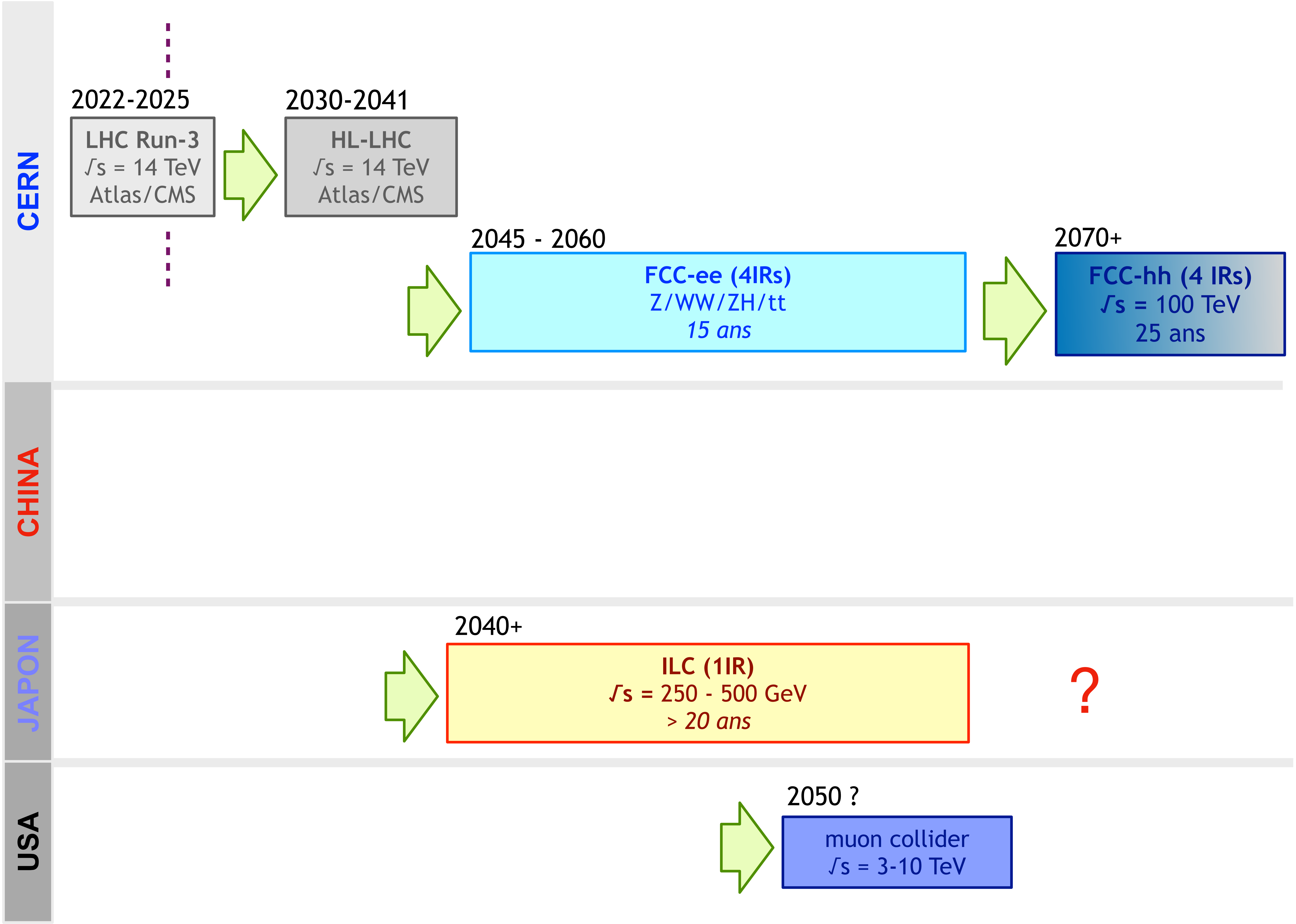
LHeC: 1-2 GCHF ?

FCC-hh: 30 GCHF [7*]

From [7] correcting with current cost from CERN FCC web page (15GCHF)

C. Scenario with BSM @ (HL-)LHC

1. We don't care



Bill

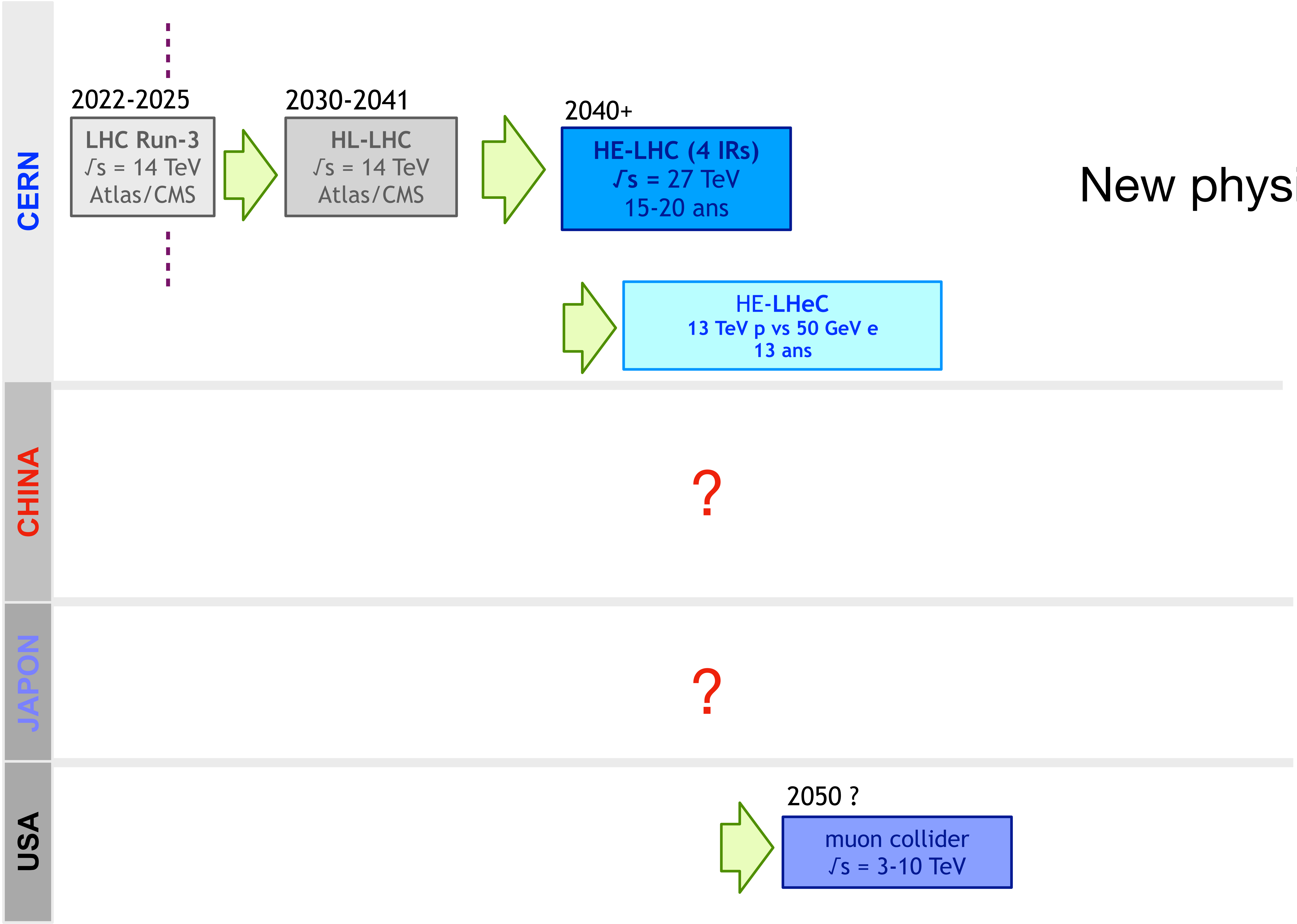
FCC ee: 15 GCHF [7*]

FCC hh: + 20-25 GCHF [7*]

From [7] correcting with current cost from CERN FCC web page (15GCHF)

C. Scenario with BSM @ (HL-)LHC

2. Europe directly to pp 27 TeV



New physics

Bill

LHeC: 1-2 GCHF ?

HE-LHC: 9 GCHF [7*]

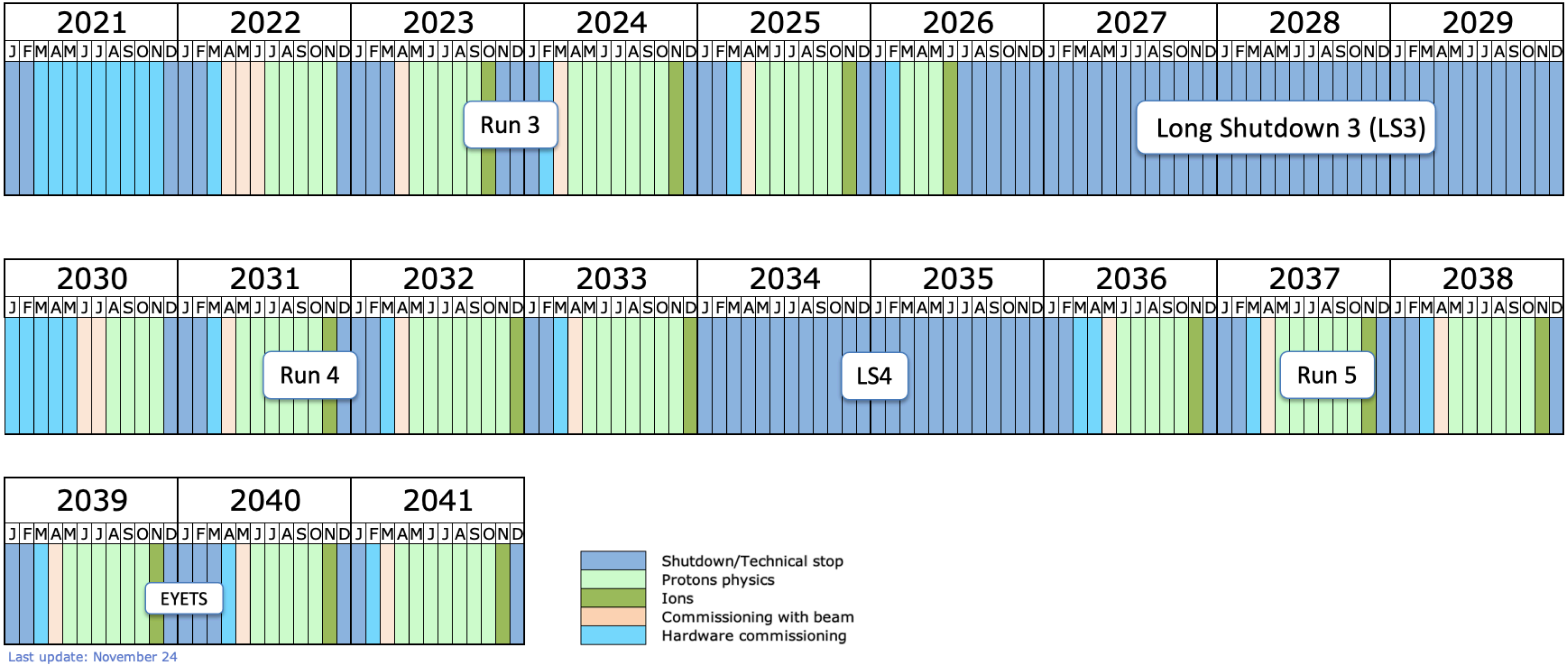
From [7] correcting with current cost from CERN FCC web page (15GCHF)

Scenario summary

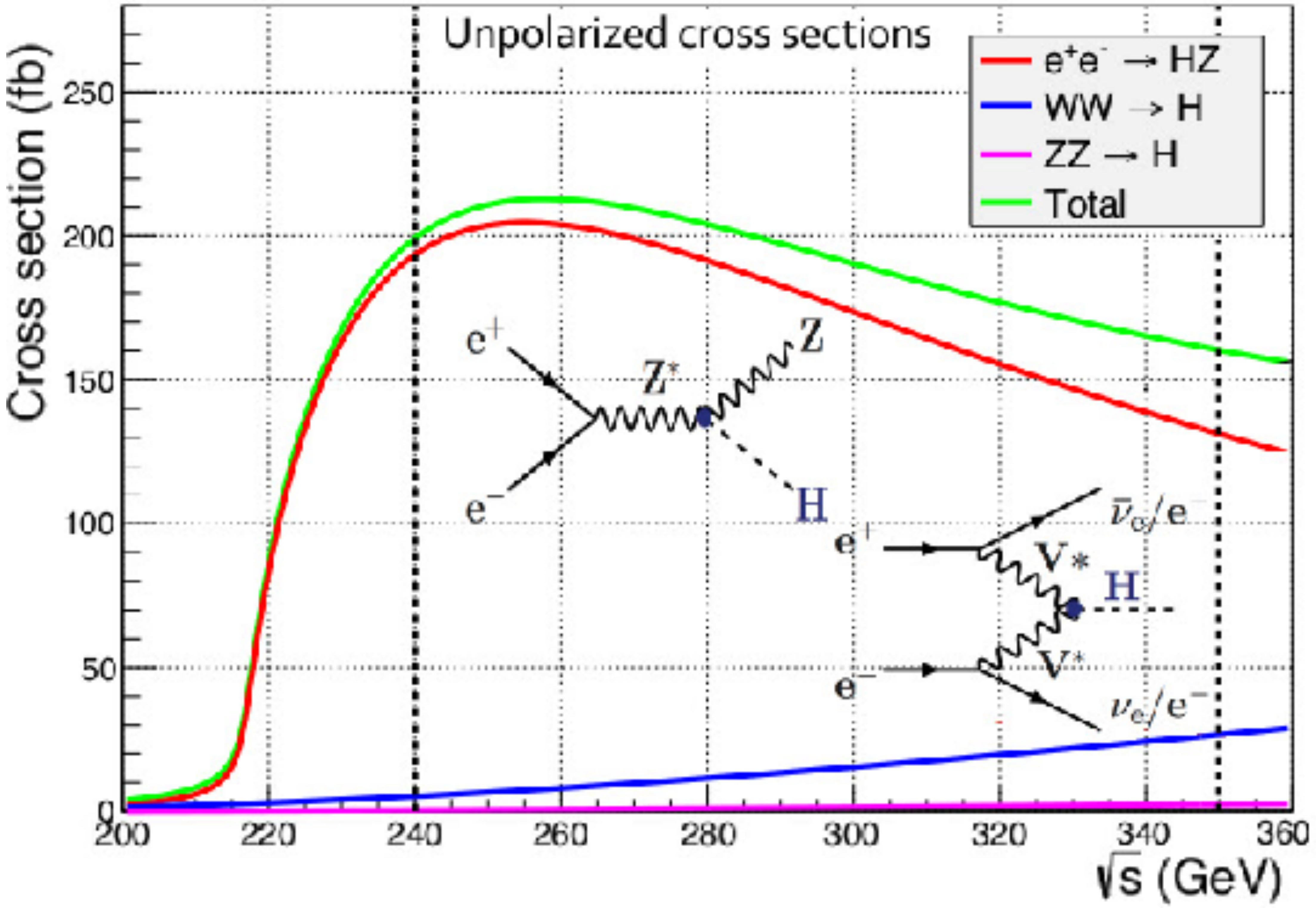
A. European only and/or preferred option
   1. FCC
   2. ILC
   3. CLIC
B. In CEPC gets confirmed soonish and/or fall-back plan if A is not competitive or feasible
   1. (FCC not really a fallback plan)
   2. HE-LHC + LHeC
   3. High energy Linear collider facility
   4. Muon Collider + LHeC (high risk)
   5. Fast FCC-hh at xx TeV (only in the advent of CEPC)
C. New physics (HL-)LHC in tails of distributions
   1. (FCC full program)
   2. HE-LHC + LHeC
   3. Something else ?

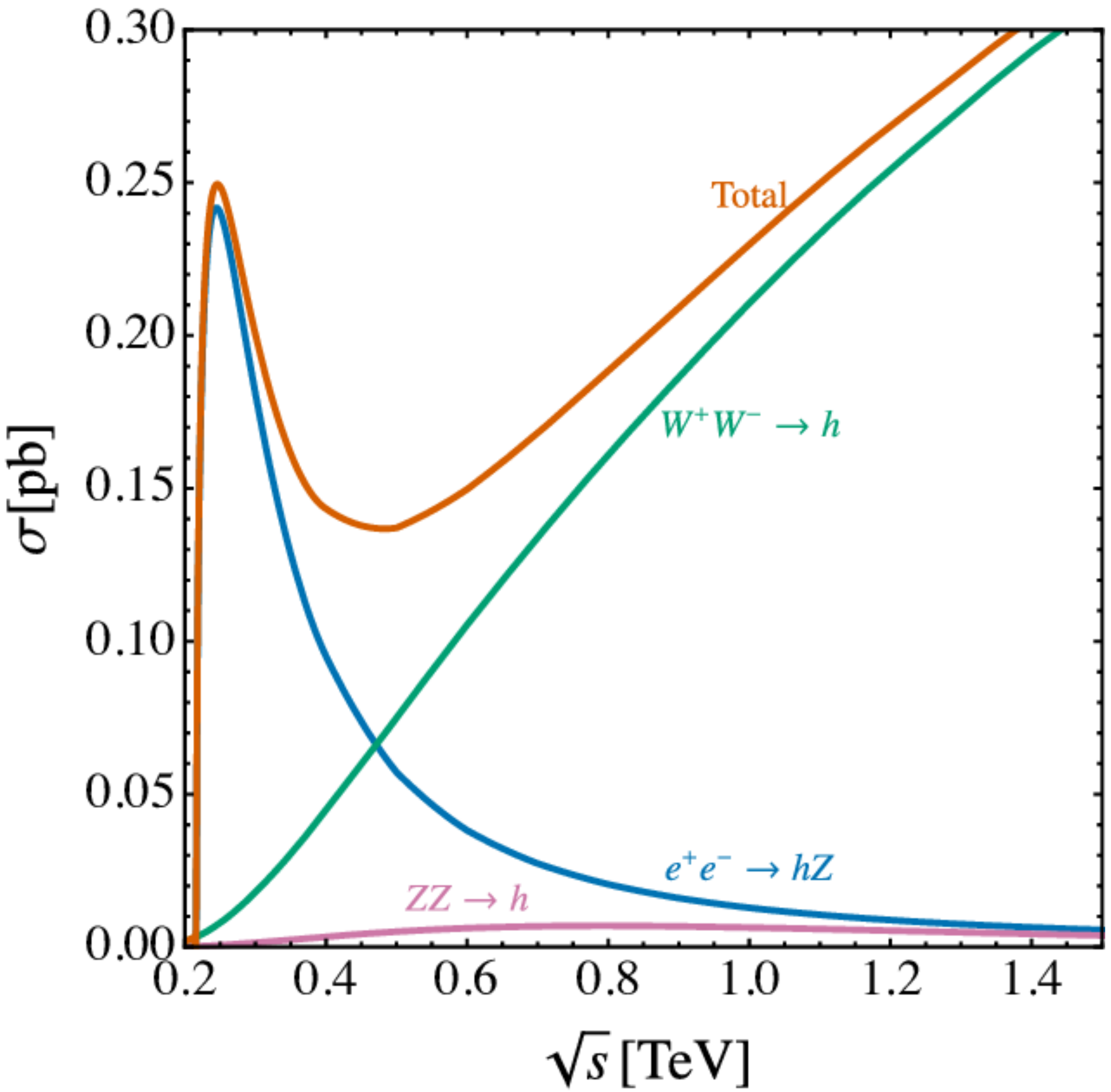
Backup

HL-LHC current plan



xsec e+e- colliders (unpolarised)





Maturity from [1] eeFact 22 summary

Collider	Design Maturity	R&D Maturity
ILC-250	10	9-10
ILC-500	10	9-10
ILC-1000	6-7	6-7
CLIC-380	9	10
CLIC-1500	8	9-10
CLIC-3000	8	8-9
C3-250	3	3
C3-550	3	2
C3-Nb_3Sn	1	0
HELEN	3 (ML)	2 (SRF)
ReLiC	3	4
ERLC	3	4
XCC $\gamma\gamma$	2	2
HE&HL $\gamma\gamma$	0	0

Collider	Design Maturity	R&D Maturity
FCC-ee	9	9
CEPC	9	9
CERC	3	4
LEP3	3	8
EPCCF	3	8
MC-HF	3	2