Concluding remarks

Alain Blondel

Corfu 2023 Workshop on Future Colliders

not a summary!

A new era of exploration!

Tevor You
Howard Baer
Stefan Pokorski
Tao Han

We found the Higgs... the SM is 'complete'

– but unexplained facts remain!

Experimentally
-- neutrinos have mass
-- the Universe is made of matter and little or no anti-matter
-- What is dark matter made of?

New particles or phenomena *must exist*!

Furthermore:
-- the mass of the Higgs is exactly in the gap where the SM can be extrapolated to the Planck scale
-- Precision experiments sensitive to heavy physics→ no convincing deviation
-- and LHC has not revealed the 'SM coupled' new physics (Supersymmetry) that had been promised already for LEP!

Yet there are many theoretical questions pending...

Furthermore there are many theoretical questions pending

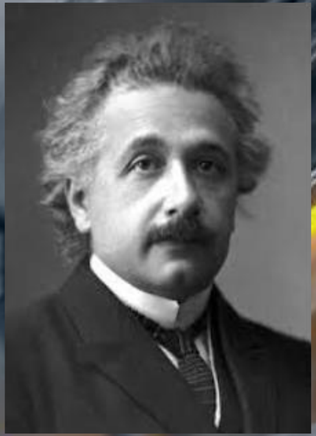
H. Baer

- Higgs mass instability
- strong CP problem
- cosmological constant
- inclusion of gravity
- origin of generations
- dark matter
- dark energy
- baryogenesis

B

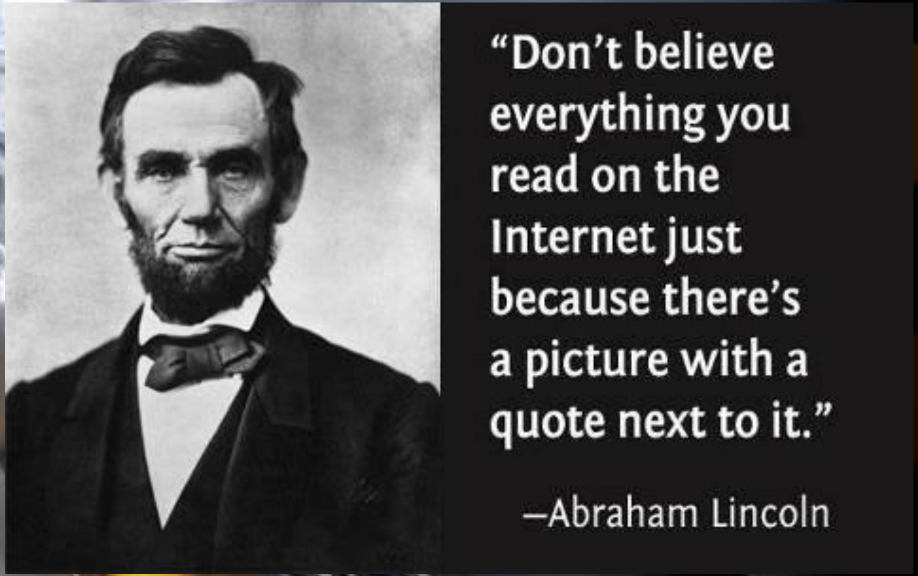
☺ neutrinos have mass

very nice quotes



``Everything should be made as simple as possible, but not simpler"

A. Einstein



The Physics Landscape

It is generally considered that the solution lies at a high energy scale

For the first time since Fermi theory, we do not know the SCALE

and we dont necessarily know the coupling either.

The next facility must be versatile with as broad and powerful reach as possible, as there is no precise target.

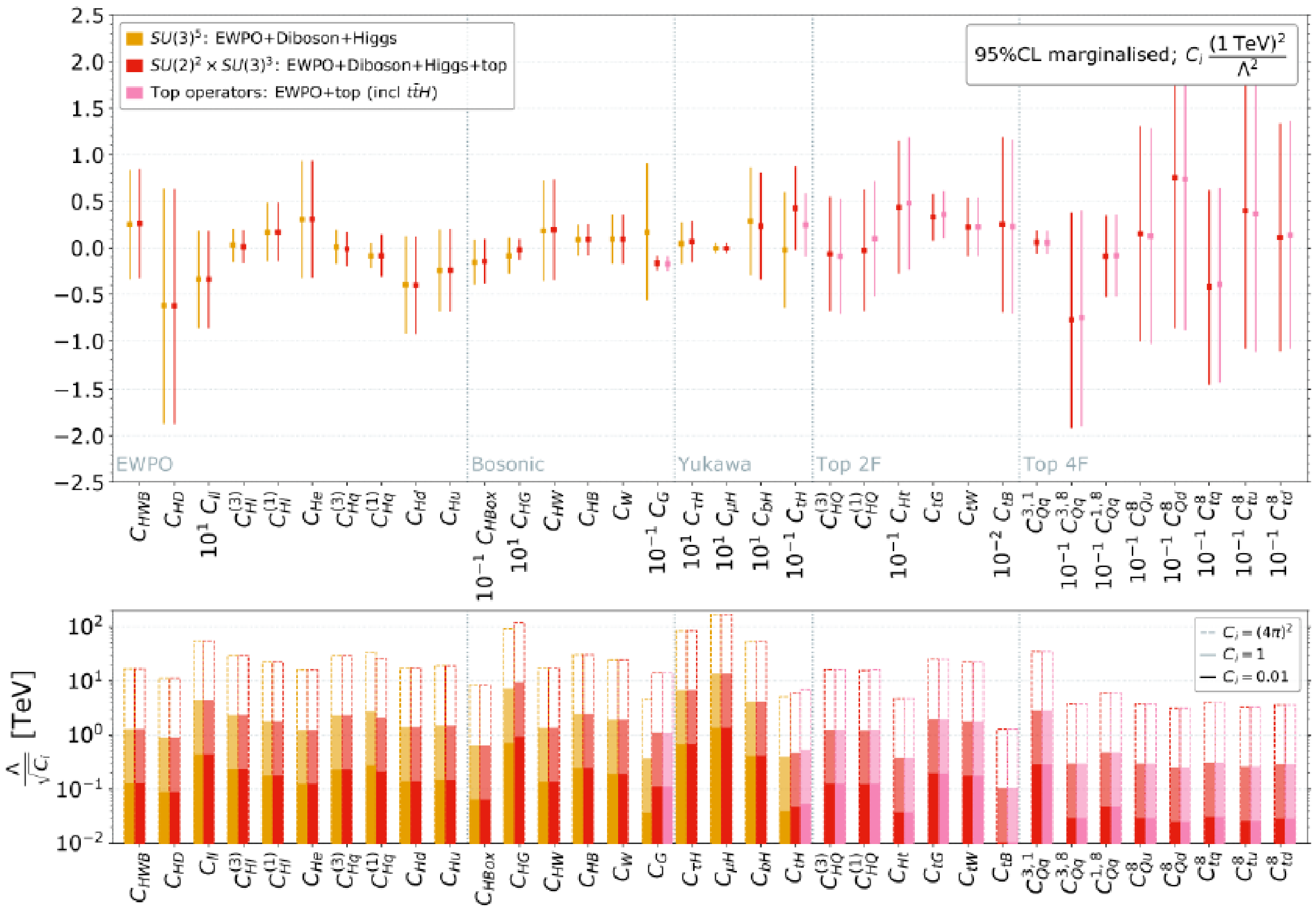
It must be an observatory with

→ more Sensitivity, more Precision, more Energy

Origin of the Standard Model

Tevor You

- **SMEFT** phenomenological framework is the *Fermi theory of the 21st century*



- What are the experimental constraints on the **energy scale** of new physics, $\boldsymbol{\Lambda}$?

- What are the experimental constraints on their **interaction strengths**, $\boldsymbol{c_i}$?

J. Ellis, Madigan, Mimasu, Sanz, TY [2012.02779]

- *e.g.* Combined global fit to **Top**, **Higgs**, **diboson**, and **electroweak** experimental data

How would one turn this into a 'signal?'

Personal comments/questions about EFT/SMEFT

A fashionable parametric way of representing data is to perform EFT/SMEFT analysis

-- there are many advantages to this

-- calculational rigor and practicality by adding higher order operators in the Lagrangian

-- provide good representation of the impact on the various observables in consistent way

-- this is not without raising questions

1. by using c/Λ^2 form, this **assumes that deviations arise from physics at a higher energy scale.**

-- consequently any deviation is seen as evidence for physics at a high scale with $c = \alpha/g/1$?

-- which is not necessarily true (but assumed coupling is often omitted)

-- does'nt this seems like a good engine for fabrication of physics cases for high energy machines?

(NB I do not dislike high energy machines but we should decide on the basis of specific models)

2. the choice and number of operators is consequential and experiment-dependent.

-- It does not represent a particular new physics scenario -- which might have fewer parameters

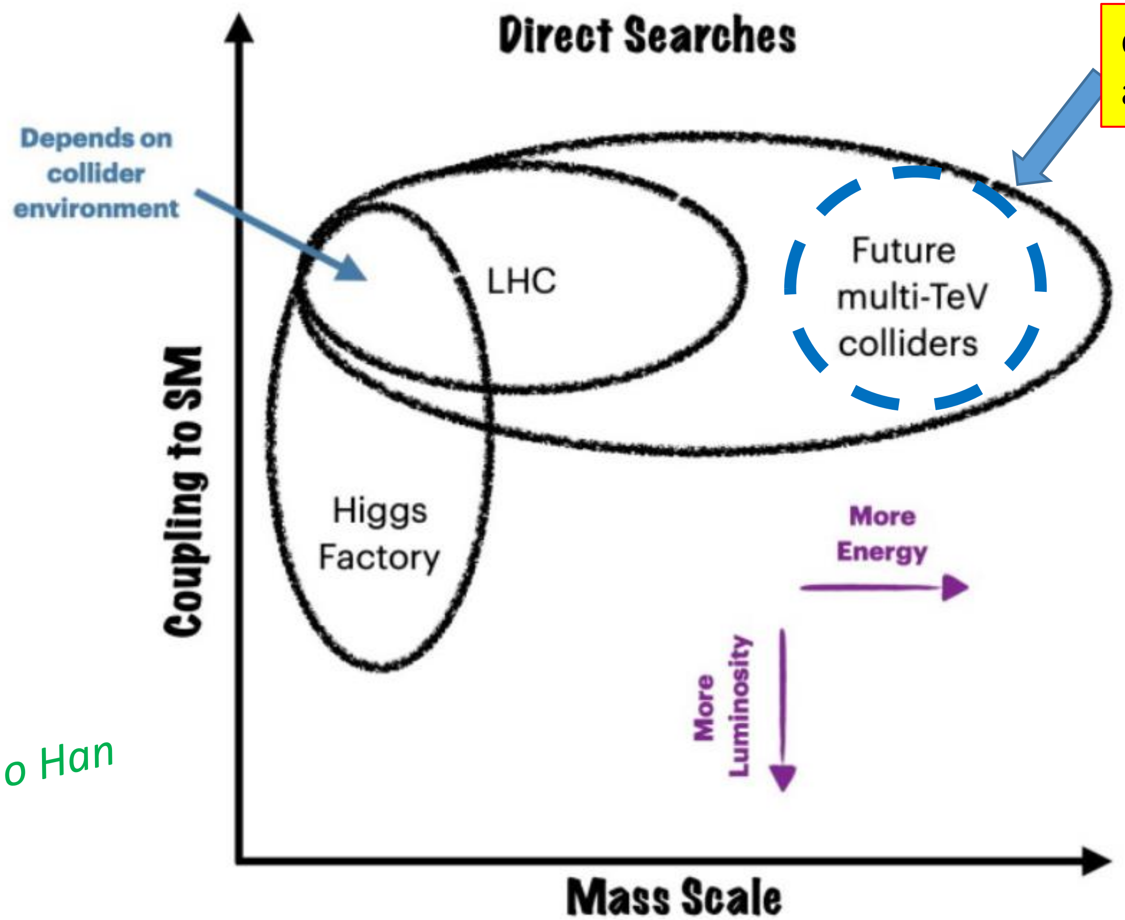
-- How about the look-elsewhere effect? How about 'blindness'? How do we make comparisons?

-- is this the best test one can make?

-- How do we interpret the significance of an effect seen by EFT analysis?

If (unlike me) you have done your homework and know these answers please send me a note/link/paper!

Coupling matters!

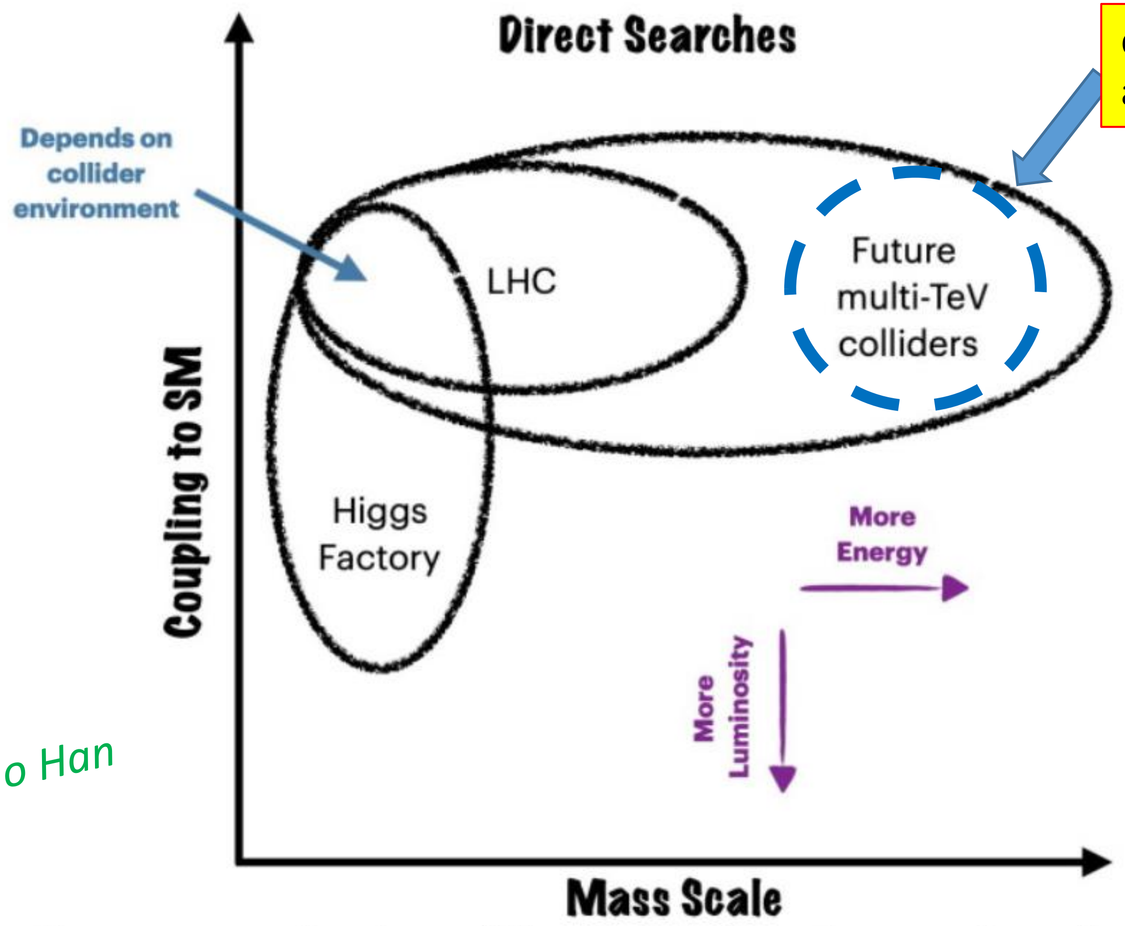


does that mean all multi-TeV colliders are equivalent?

from EF group, shown by Tao Han

Figure 1-2. *The direct coverage of various colliders in the schematic space of coupling to the SM versus mass scale of BSM physics. "Higgs factory" and "multi-TeV colliders" correspond to a generic option among the ones listed in Table 1-1 and Table 1-2 respectively.*

Coupling matters!



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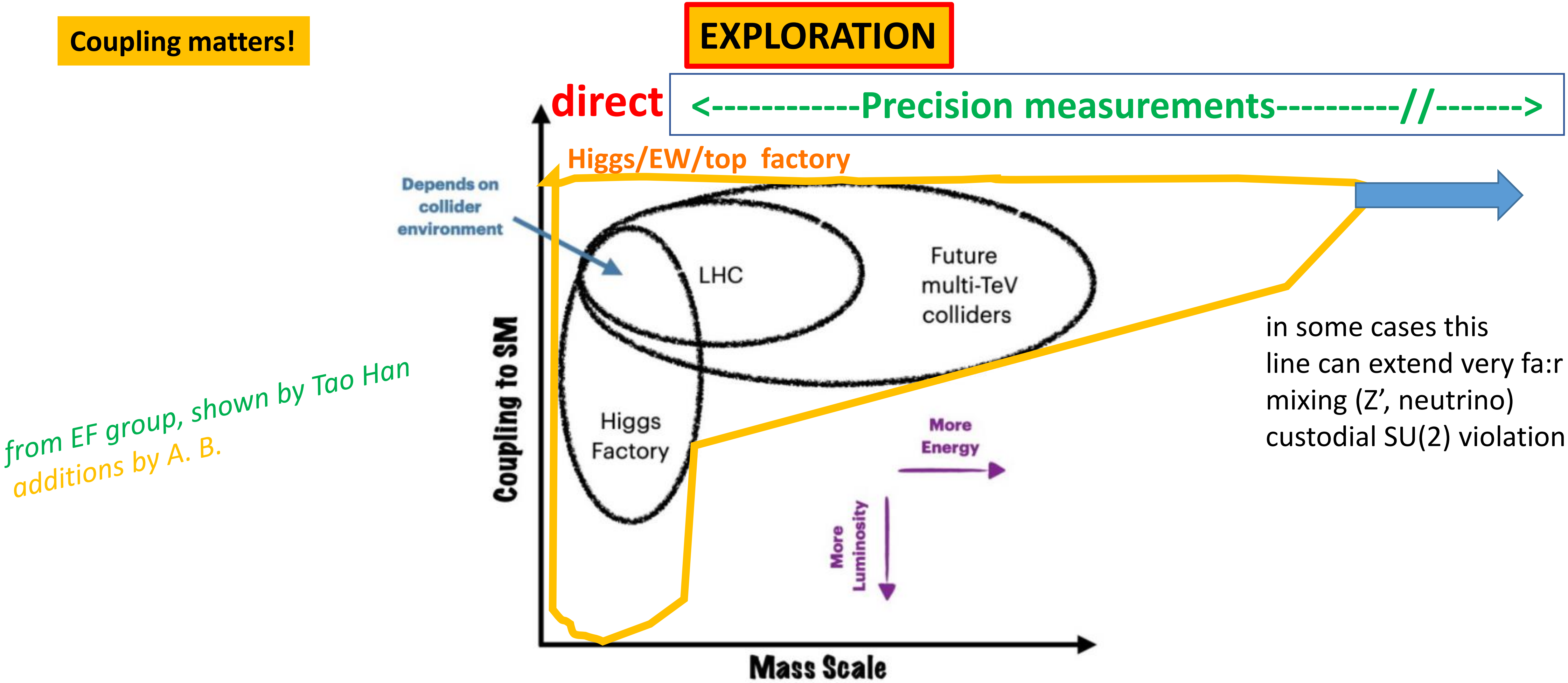

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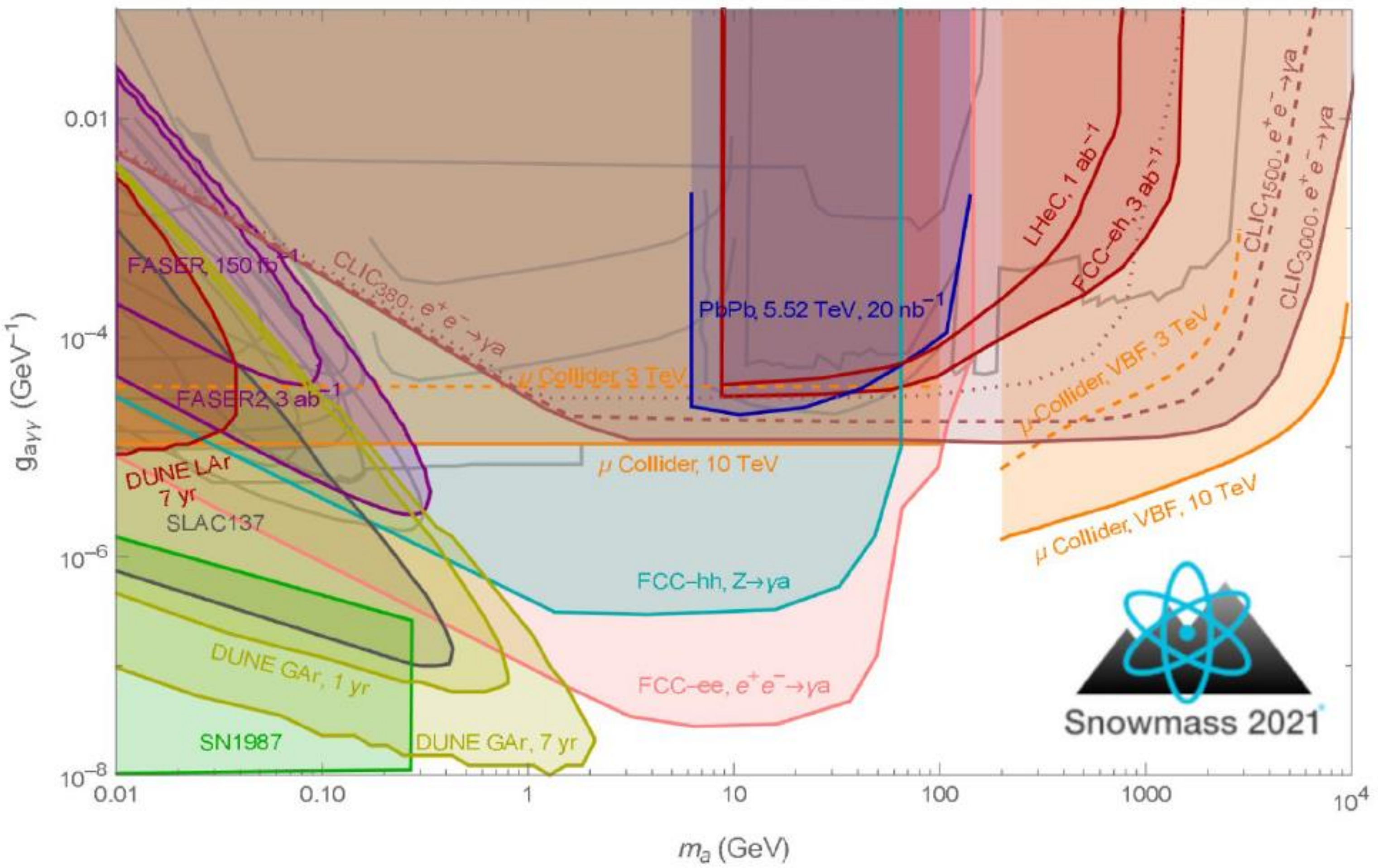
ALPs

Axion like particles coupling to photons are a standard benchmark for the class of feebly interacting particles

They can emerge in a wide range of masses and their parameter space needs several different experiments to be covered efficiently

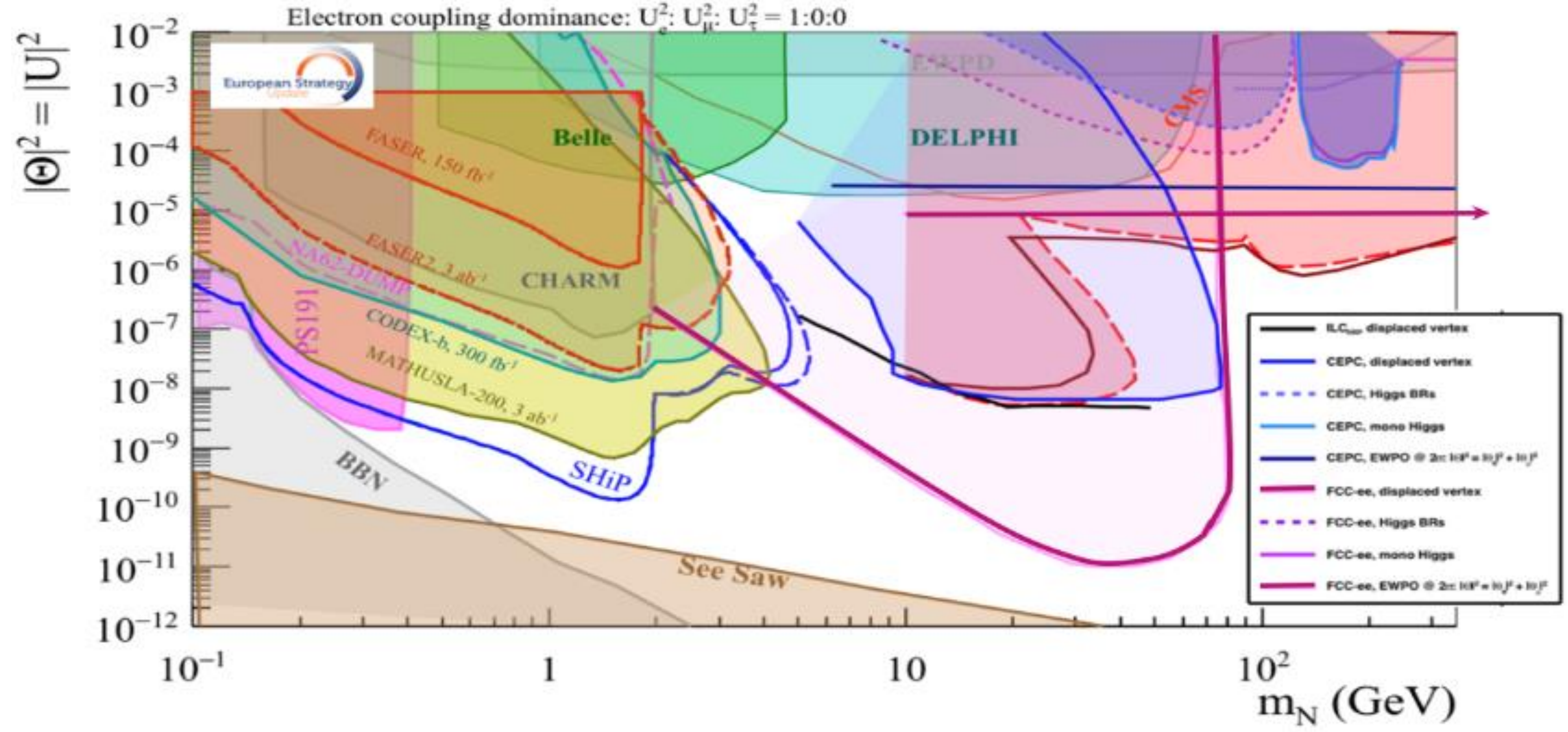
Torre



This picture from the ESPP BB is relevant to Neutrino, Dark sectors and High Energy Frontiers.

FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos

How close can we get to the 'see-saw limit'?



-- the purple line shows the 95% CL limit if no HNL is observed. (here for 10^{12} Z),

-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity from 10^{-3} (now) to 10^{-5} (FCC) mixing all the way to very high HNL masses (500-1000 TeV at least). arxiv:2011.04725

Implementation Task Force on Higgs Factories

Table I - ITF Report – T.Roser, et al, arXiv:2208.06030

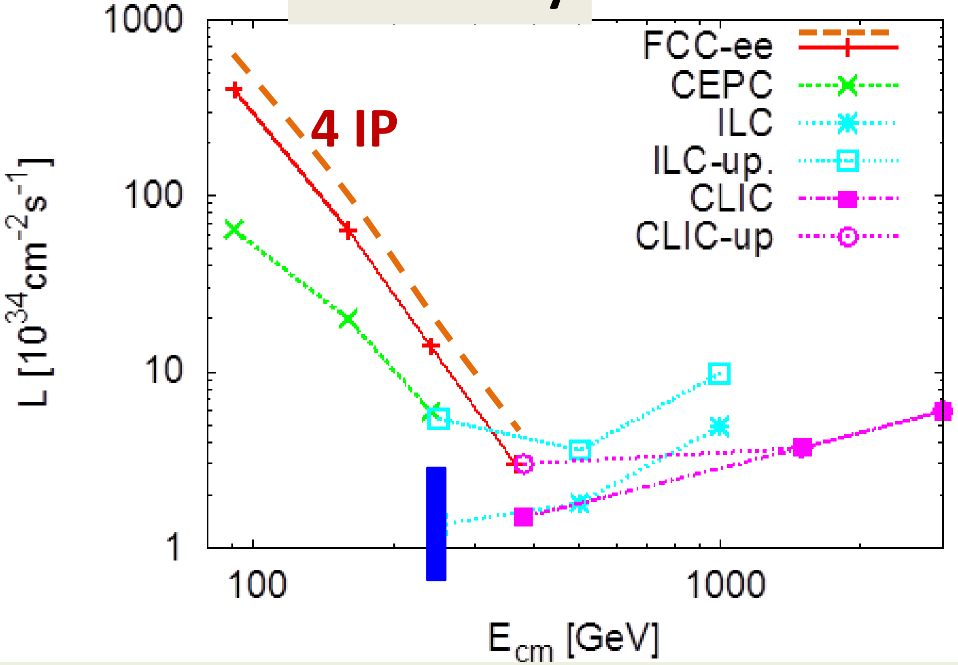
Shiltsev

	Snowmass 2021	CME (TeV)	Lumi per IP/ tot (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
Circular e+e-	FCCee (4 IPs)	0.24	7.7/29	0-2	13-18	12-18	290
	CEPC (2 IPs)	0.24	8.3/17	0-2	13-18	12-18	340
	FermiHF	0.24	1.2	3-5	13-18	7-12	~200
Linear e+e-	ILC	0.25	2.7	0-2	<12	7-12	110
	CLIC	0.38	2.3	0-2	13-18	7-12	150
	C^3	0.25	1.3	3-5	13-18	7-12	150
	HELEN	0.25	1.4	5-10	13-18	7-12	~110
ERL-based	CERC	0.24	78	5-10	19-24	12-30	90
	ReLiC (2 IPs)	0.24	165/330	5-10	>25	7-18	315
	ERLC	0.24	90	5-10	>25	12-18	250
s-chan	XCC-γγ	0.125	0.1	5-10	19-24	4-7	90
	μμ-Higgs	0.13	0.01	>10	19-24	4-7	200

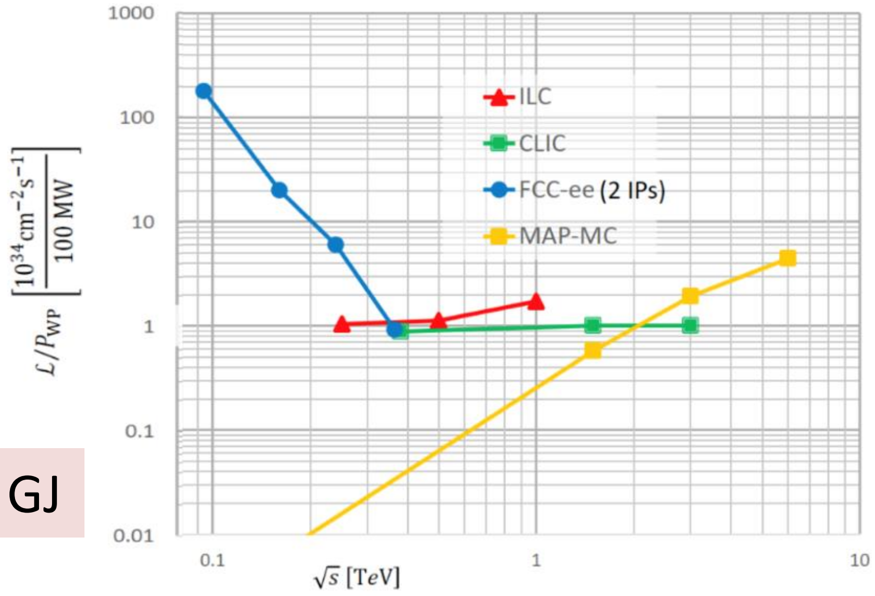
Operational Differences

plots from Briefing Book

Luminosity



Luminosity/Power → Energy efficiency



1 MW.h = 3.6 GJ

Luminosity vs Energy circular below 350 GeV linear above 350 GeV muonC above 2 TeV

efficiency : 9 (5) GJ/Higgs at FCC-ee with 2(4)IP vs 50GJ/Higgs for ILC250 (first 15 years)

Beam polarization:

circular: transverse → ppm beam energy calibration also (even easier) at muonC

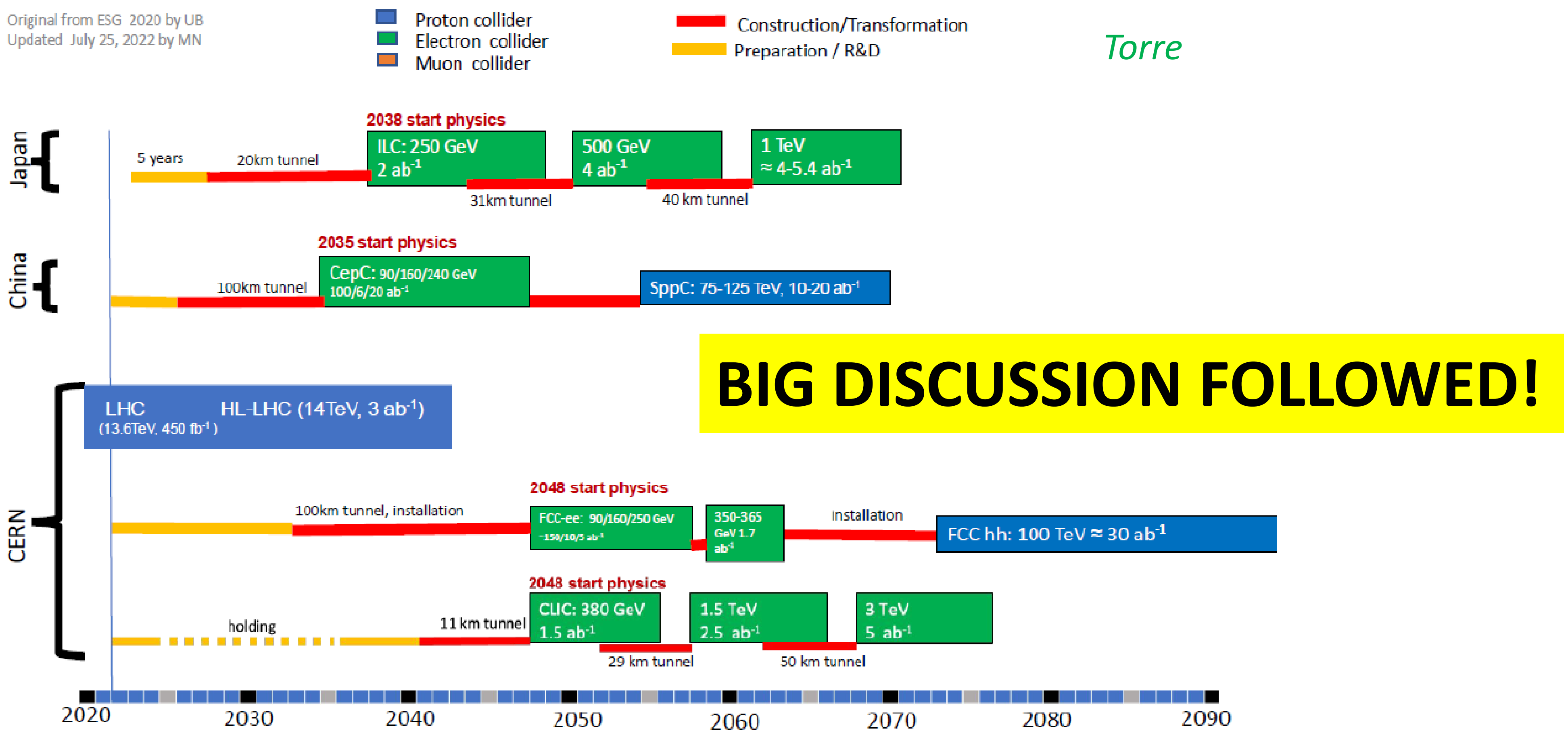
linear: longitudinal : e- ±80% e+ ±30% → additional d.o.fs

Long term energy upgrade circular: pp collider linear: High energy lepton collisions

Interaction points circular: 2-4 linear: 1

Run limited in time by arrival of hadron collider Run is open ended *upgrades are not included in the cost*

Which colliders?



Snowmass Energy Frontier summary, 2211.11084

An “outsider” would argue that the mose time-efficient strategy is to finalize CepC and ILC while CERN works to make FCC-hh real

CRITERION FOR CHOICE BETWEEN STRATEGIES

1. **Lab directors are funded by, and report to, the governments**
   They must make users happy of course and go for the most interesting program
   They must complete approved programs with high priority and success.
   Can not cancel, or delay significantly, approved programs

2. **choice of facility must be adapted to the local lab**
   Existing infrastructure and personnel competence,
   Users community
   Local communities
   e.g. for CERN with >12000 users, a collider with four IP is very desirable

3. **Make sure one is not doing something that might be already done by the time you start**
   some competition is useful, and so is cooperation
   given limited resources best is to ensure collectively good coverage of existing questions

Choice ultimately should follow the principle of
local synergies and global complementarity

The machines ...and the labs

SuperKEKb/BELLEII in ‘early running phase’ & improving. plan upgrade 2029. Guess: taking data until late 30’s
JPARC -neutrino commissioning beam upgrade for T2K with near detector upgrade (for 2024)
U-Tokyo HyperK under construction uses T2K ND and beam line. (~2028) +10 years of beam operation approved
ILC limited funding for R&D. **If and when** approved, construction 10 years. $\mathcal{L}$(250 GeV) = 1.3 10^{34} /cm/s 1IP (2 exp?)

run **LHC** and construction of HL-LHC until **2028**. Commissioning of **HL-LHC** 2029 end of run around 2041
FCC feasibility study approved by council for report in 2025. (Mid term review 2023) ESPP 2026-2028
Higgs- Electroweak factory FCC-ee (4IP) as first step, with **FCC-hh** 100 TeV as ultimate goal
funded from CERN budget (~ 35 MCHF/year over 5 years, including high-field magnet R&D) + collabs
If successful, construction start 2030. EOIs for experimental program to be submitted to strategy in 2025.
“Plan B” R&D programs for ILC, **CLIC acceleration, Muon collider. No collider can start at CERN before 2043-5**

Recently held snowmass process (2020-2022). My take: desire of younger generation to have next generation collider in the US, enthusiasm for Muon collider. Now P5 process –> summer 2023.
Fermilab focus on neutrino (LBNF+DUNE, upgrade with PIPII 2.4MW) until 2038/40.
Strong collaboration with CERN ’sister LAB’ for FCC. R&D towards next facility at Fermilab TBD. Request to P5

IHEP neutrino ➔ Daya Bay, final results published, JUNO(50kton) starts 2024
Astroparticle physics ➔ LHAASO (~CTA in Tibet), satellite experiments
collider ➔ BES (τ/charm e+e- factory) running, physics program requires upgrade of accelerator
➔ CEPC/SPPC (similar to TLEP/VLHC submitted to ESPP 2012 → FCC-ee/hh)
recently recommended by IHEP IAC as nº 1 proposal for IHEP future large infrastructure

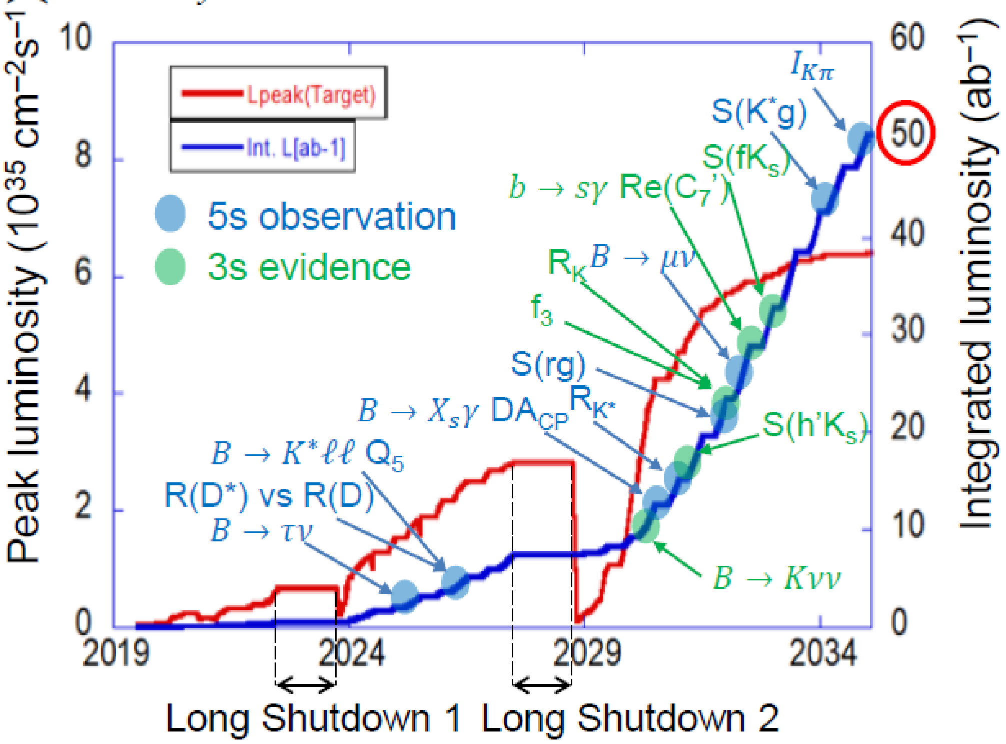
SuperKEKb progress to high luminosity -- key to energy efficiency

Yamauchi, P5 meeting April 2023

Prospects toward 50 ab^{-1}

Boost up the peak luminosity

Squeeze $\sigma_y^* \approx$ 200 nm → 50 nm, and increase $I \approx$ 1 A → 3 A



1. Long shutdown 1 (Jul 2022 – Dec 2023)
   - Detector upgrade
   - Beam background mitigation
   - Improvement of beam injection
2. Run 2 (Dec 2023 –)
   - Extensive machine tuning and studies toward $\mathcal{L} = 2.4 \times 10^{35}$ cm^{-2}s^{-1} (≈ KEKB x 10)
3. Long shutdown 2 (To be confirmed)
   - Need new ideas and technology for upgrade of SuperKEKB interaction region to enable $\mathcal{L} = 6 \times 10^{35}$ cm^{-2}s^{-1} e.g. QCS (final focusing system) upgrade with Nb_3Sn

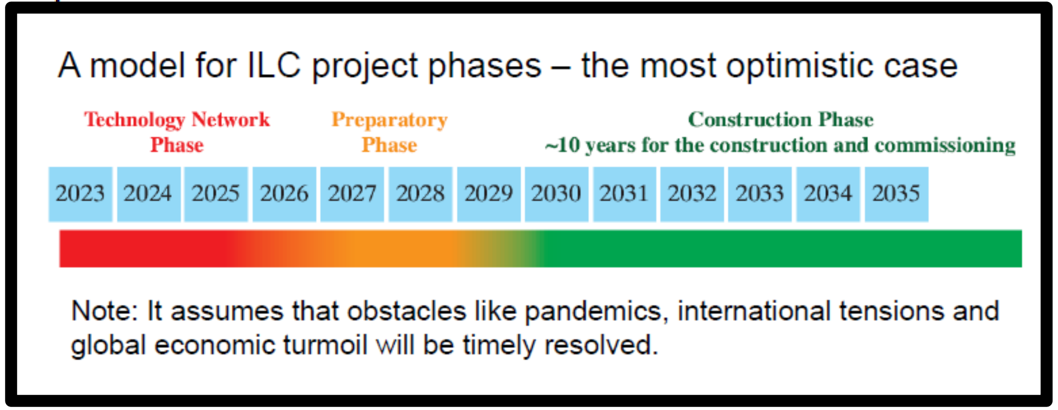
➢ Many challenges and R&D items ahead of us

→ Need more collaborative work in the framework of

- SuperKEKB International Task Force
-

Many physics discoveries are expected.

ILC cannot start construction earlier than 2030 *→
also:
HyperK in construction now, starts ~2028
results for CPV 2 years after



From ESPP 2020 update

"An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage."

"Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

⬇

FCC Feasibility Study (FS) started in 2021 → will be completed in 2025

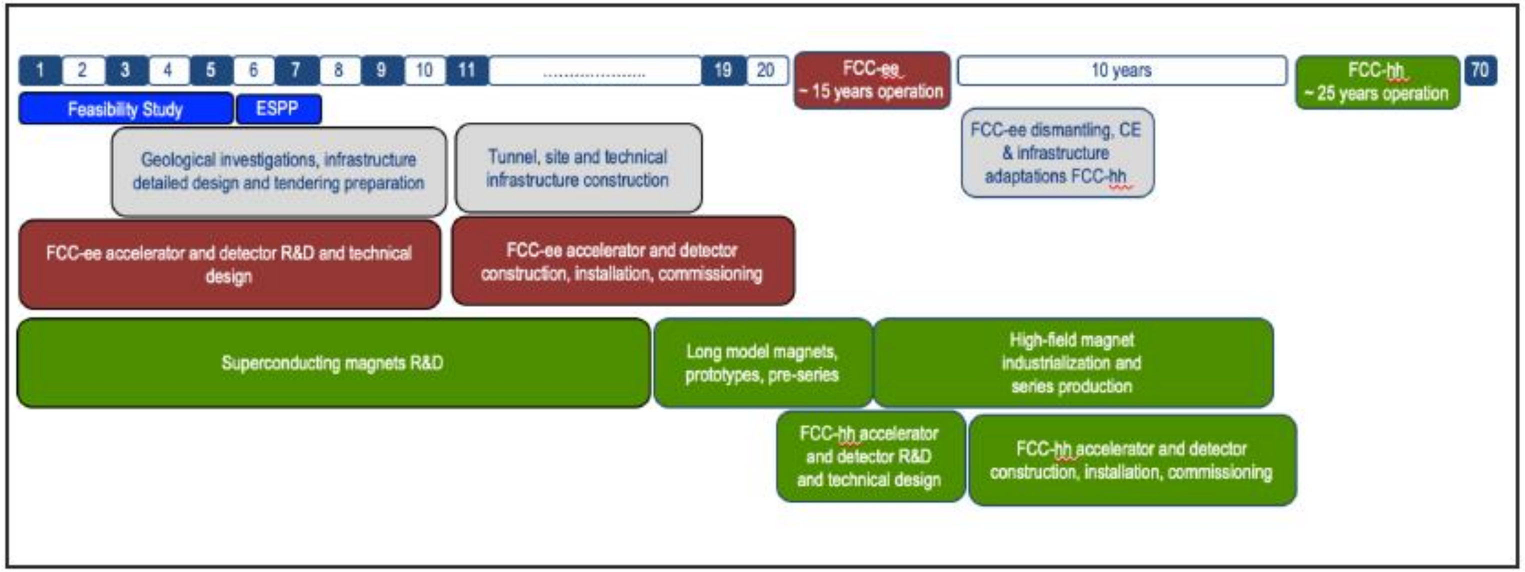
"The European particle physics community should develop an accelerator R&D roadmap focused on the critical technologies needed for future colliders" …. "The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs."

⬇

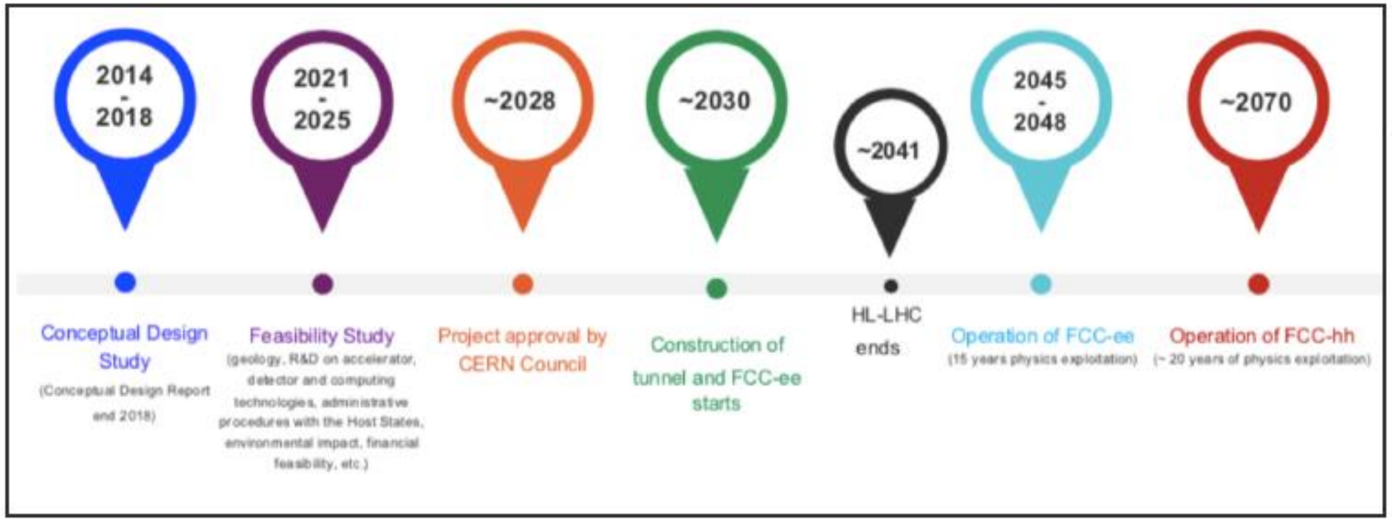
Accelerator R&D roadmap developed (→ now being executed). CERN pursue R&D on high-field magnets, SCRF, proton-driven plasma wakefield acceleration, and R&D and design studies for CLIC and muon colliders to prepare alternative options to FCC if the latter is not pursued.

FCC estimated timeline

FUTURE CIRCULAR COLLIDER



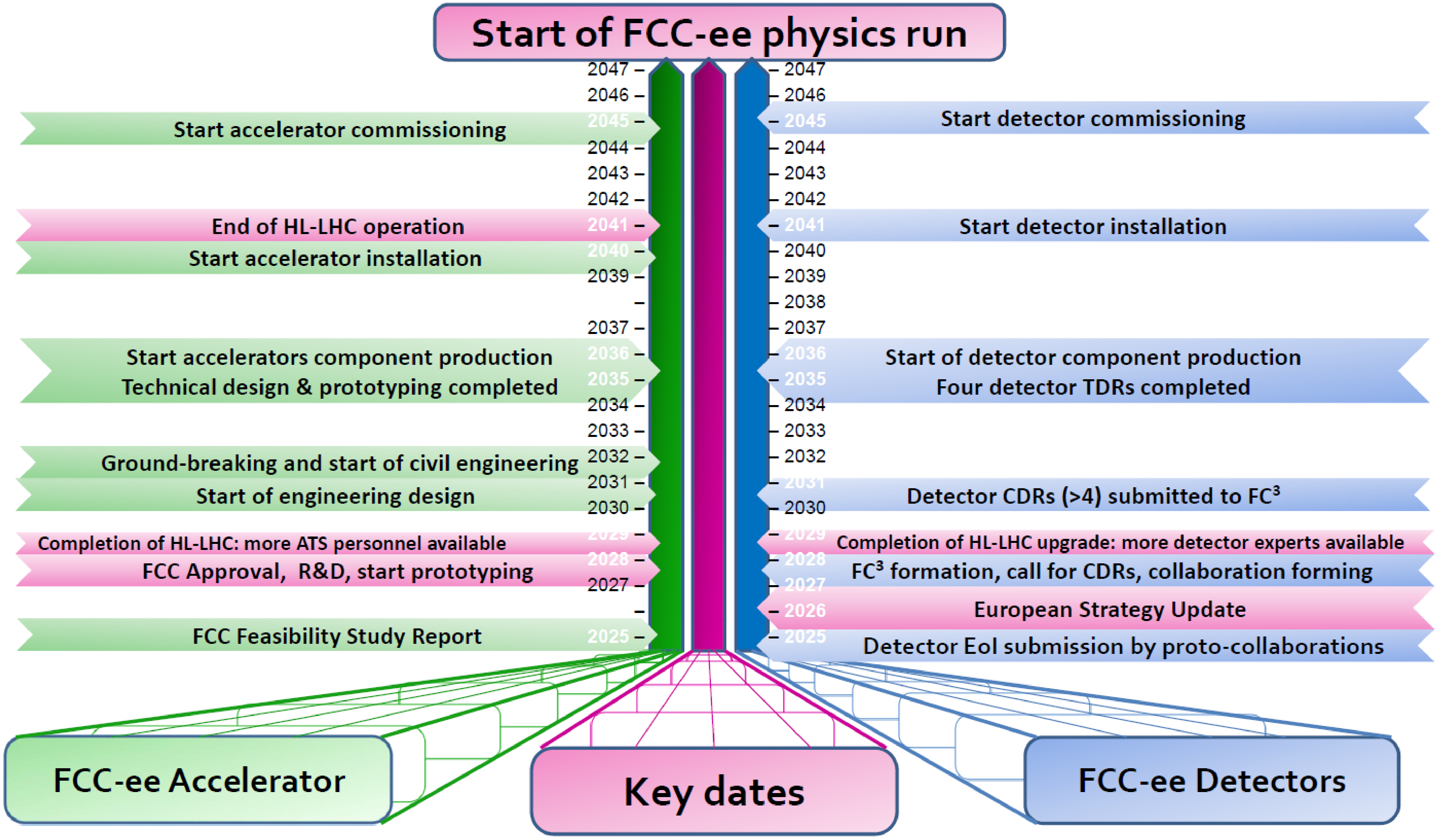
Technical schedule:
FCC-ee could start operation **in 2040 or earlier**



Realistic schedule takes into account:

- ❑ past experience in building colliders at CERN
- ❑ CERN Council approval timeline
- ❑ that HL-LHC will run until ~ 2041

→ **ANY future collider at CERN cannot start physics operation before 2045-2048** (but construction will proceed in parallel to HL-LHC operation)



Start of FCC-ee physics run
2047
2046
2045
2044
2043
2042
2041
2040
2039
2038
2037
2036
2035
2034
2033
2032
2031
2030
2029
2028
2027
2026
2025
Start accelerator commissioning
End of HL-LHC operation
Start accelerator installation
Start accelerators component production
Technical design & prototyping completed
Ground-breaking and start of civil engineering
Start of engineering design
Completion of HL-LHC: more ATS personnel available
FCC Approval, R&D, start prototyping
FCC Feasibility Study Report
Start detector commissioning
Start detector installation
Start of detector component production
Four detector TDRs completed
Detector CDRs (>4) submitted to FC³
Completion of HL-LHC upgrade: more detector experts available
FC³ formation, call for CDRs, collaboration forming
European Strategy Update
Detector EoI submission by proto-collaborations
FCC-ee Accelerator
Key dates
FCC-ee Detectors

FUTURE CIRCULAR COLLIDER

Optimised Placement and Layout

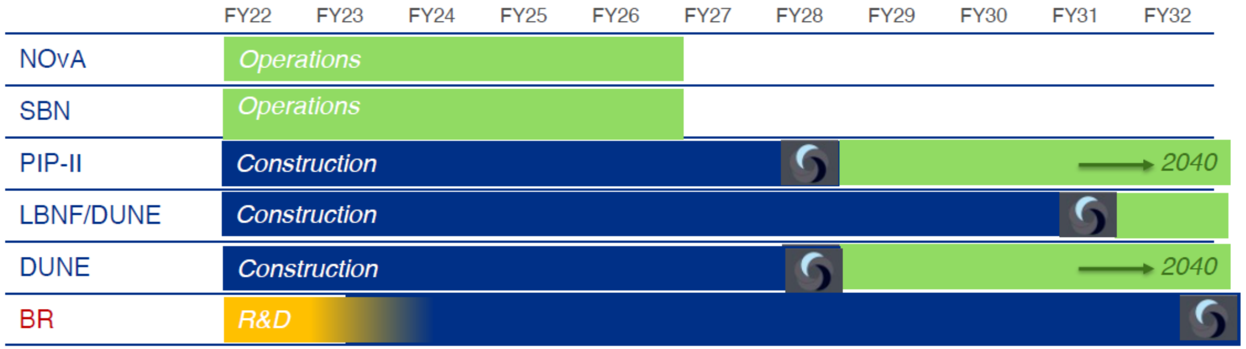
8-site baseline “PA31”

Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2143 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**91.1 km**

- 8 sites – less use of land, <40 ha instead 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP
- **Exchanges with ~40 local communes in preparation**

Neutrino Science

Vision: US/Fermilab is universally acknowledged as the world leader in neutrino science for decades to come



➔Construction of full LBNF+ DUNE program (2.4MW x 40kton) until ~2038-40

Collider : Strong involvement of Fermilab in FCC for R&D and prototyping
R&D for future facility@FNAL TBD by P5

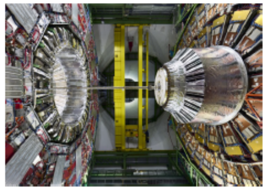
NB as pointed out in discussions at Corfu, strong synergy (multiMW proton beam) and history with muon collider in the US

S&T

Collider Science

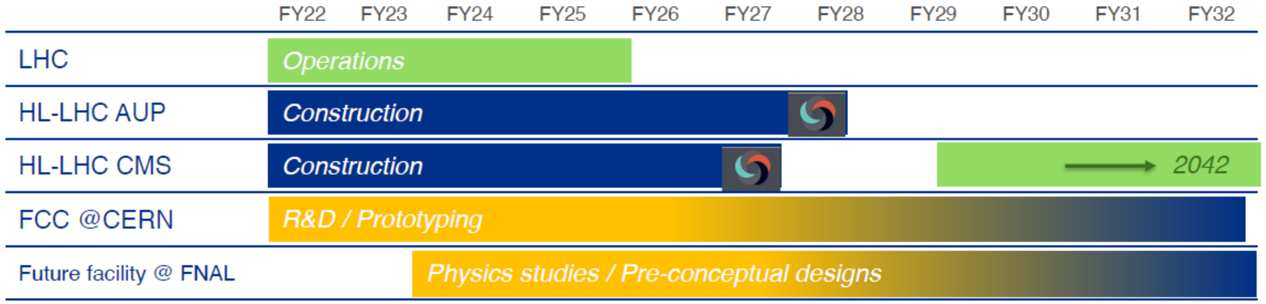
Vision: Fermilab continues to be the leading U.S. center for CMS and second leading center in the world after our partner CERN

CERN is our European sister laboratory and our strong partner in many areas



Major decadal goals

- Maximize science from LHC Runs 2 and 3 data – ROC is back in Operations!
- Execute HL-LHC AUP and CMS Detector Upgrade Projects
- Advance R&D towards FCC @CERN



Moving Forward

- Assuming the approval of FCC in ~2028, we can expect **DOE CD-0 in ~2029** and creation of the US FCC Project Office to follow (like for the LHC process).
  - CD-0 & CD-1 is within the 10-year window of consideration by this P5 committee.
- While a formal US FCC Project office can only be formed following CD-0 (which must wait for a formal approval of the FCC project), it is critical that the community **comes together now to develop a strategic and coherent US program**.
  - The formation of a US proto-collaboration **now** that can prioritize, scope and channel the U.S. efforts into a coherent effort on FCC-ee accelerators is necessary.
  - Funding for **targeted accelerator R&D at a range of upto $12-20M per year** in the early phase and subsequently ramping up following the approval of FCC
  - Scale of the targeted R&D similar to the past US-LARP program.
- Early engagement and investments in accelerator/detector R&D is crucial to seed our role in the global initiatives and allow the U.S. to be in a position of strength and be **significant stakeholders** in future international projects.

V. Shiltsev, FCC-US meeting 24-26 April 2023

Summary –

- Higgs Factory is slated to be the next high priority Energy Frontier project following the completion of HL-LHC.
- FCCee is one of the most feasible HF options… it has challenges (power consumption, cost, etc) but the concept is based on well-understood accelerator technology and greatly benefit from synergies with existing and planned accelerators and ongoing technology developments.
- We seek the P5 approval and recommendation:

*Motivated by the strong scientific importance of FCC as a Higgs factory, and the initiatives at CERN to host it including the FCC feasibility study, **the U.S. must promptly engage**, at appropriate levels, **in targeted accelerator and detector design** and prepare the groundwork to projectize these efforts in anticipation of the FCC approval in 2028.*

Muon Collider

see presentation by Tao Han

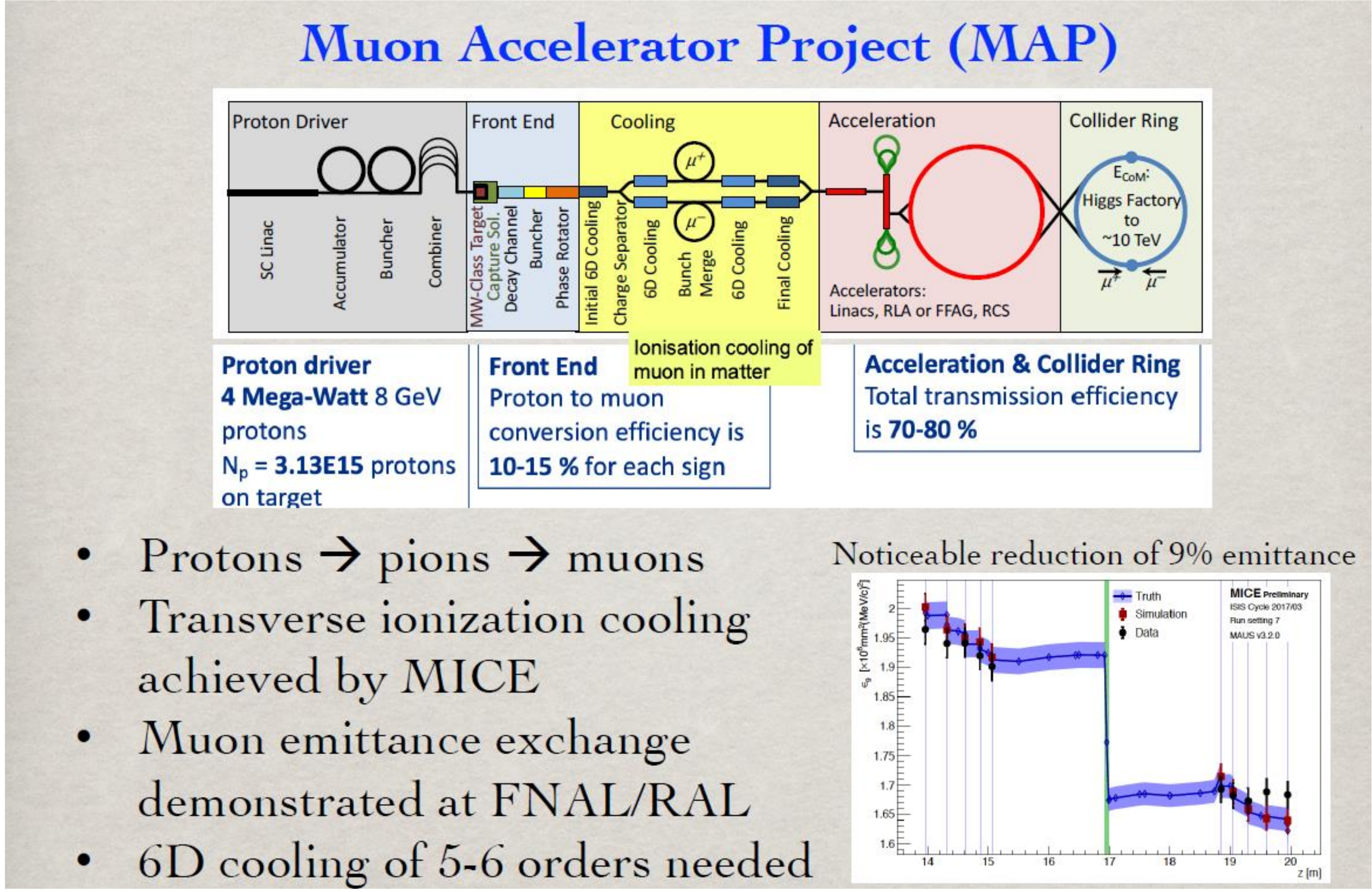
e+e- colliders are difficult to design and operate at energies above 3 TeV; in particular the energy consumption becomes prohibitive and cost also. Plasma acceleration is difficult to achieve for positrons, etc. etc.

Muon colliders have been proposed in 1970s in Novosibirsk, and revived in 1992 in the US (Bob Palmer, A. Sessler, A. Tollestrup) The concept was spearheaded in the US. A possible first step is a neutrino factory. A scoping study was carried out at CERN.

A small emittance high intensity muon beam requires one of two methods:
-- standard from pion decay. (presently studied)
-- from 45 GeV e+ beam on e- target (e+e- → μ+μ-)
requires huge intensity e+ bunches. **LEMMA**
(first ideas do not work well enough by ... miles)

The present design contains many parameters beyond known feasibility esp. magnets
-- in particular high field magnets for target
and final state 6D cooling
-- final magnets for the high energy accelerator

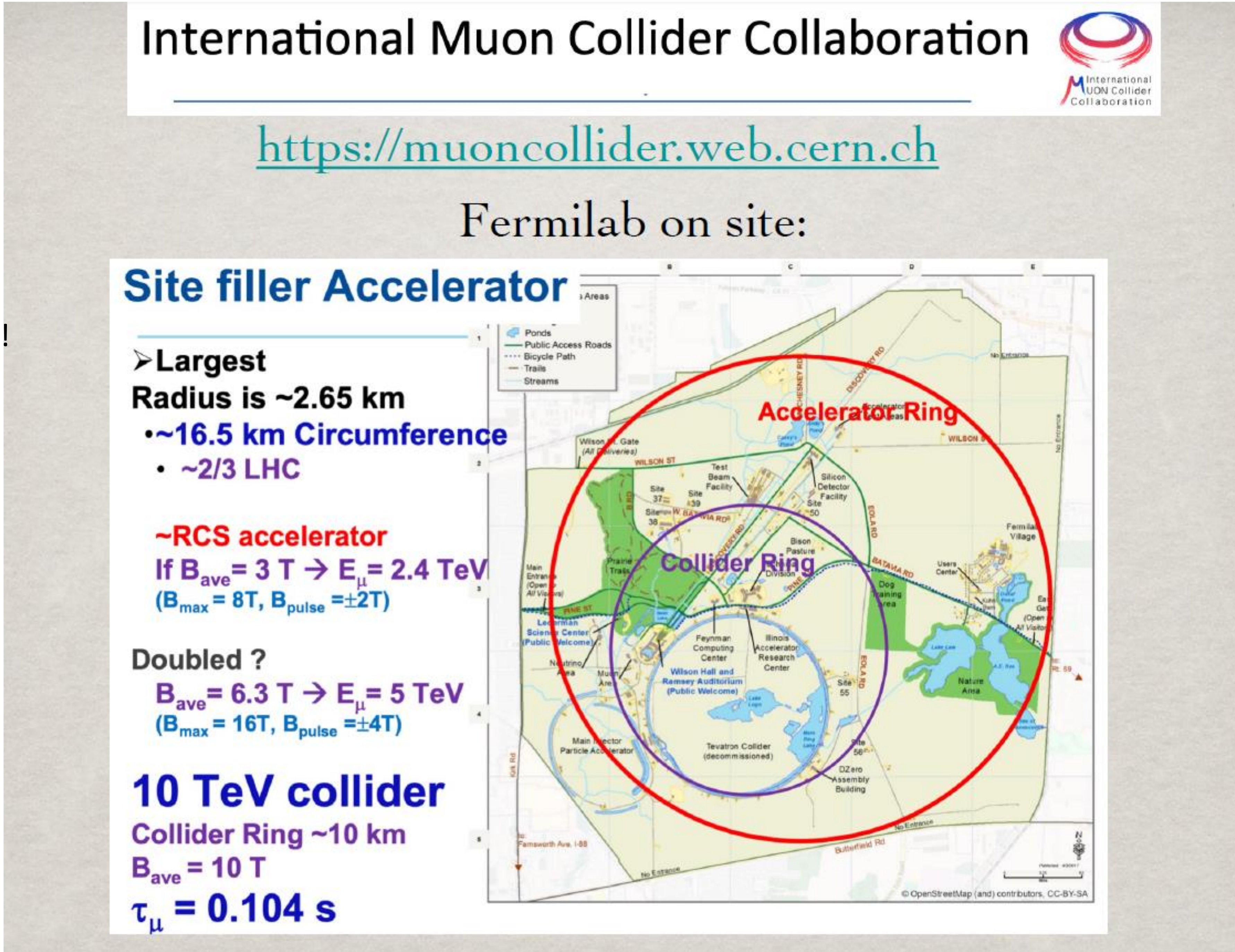
either as single unit or as a chain of magnetic elements
in mutual interaction (MICE). High intensity!



Fitting a 5 TeV muon accelerator
on FNAL site is not feasible
with today’s parameters
(need 16T fields)
5 TeV linac?

this has to be easier in the FCC tunnel!
(lower field)

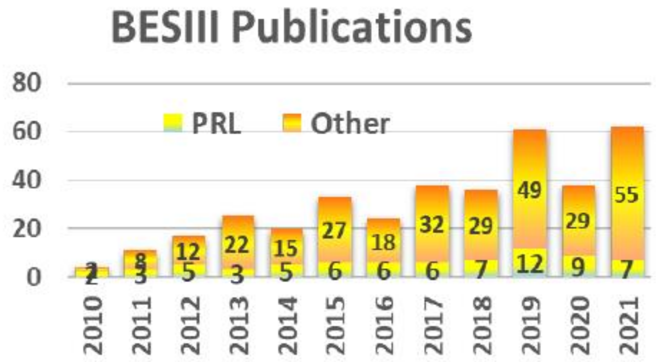
Considerable R&D and new ideas needed!

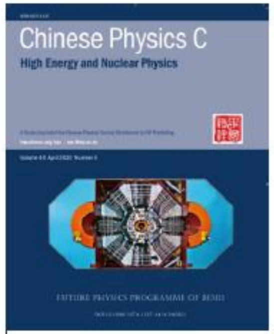


BEPCII/BESIII: 2009-2030

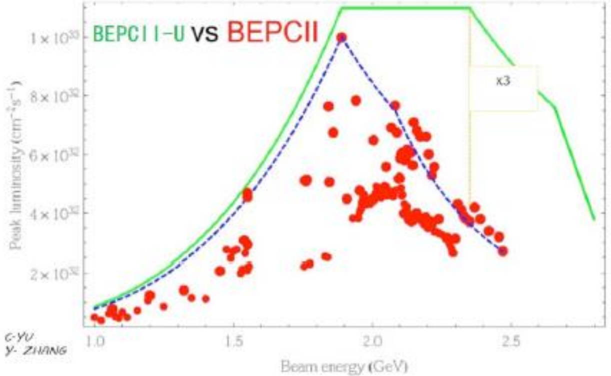
Yifang Wand
IHEP road map
Snowmass 2022

- Fruitful physics results
- Rich physics program requiring > 40 fb^{-1}, corresponding to ~15 yrs@curr. lumi.
- Upgrade to be completed in 2024:
  - Luminosity × ~3 ➔ squeeze the beam size by adding a new RF cavity per beam
  - Replace the two SC quadrupole magnets near the IP to increase the maximum beam energy from 2.45 to 2.8 GeV ➔ for charmed baryons

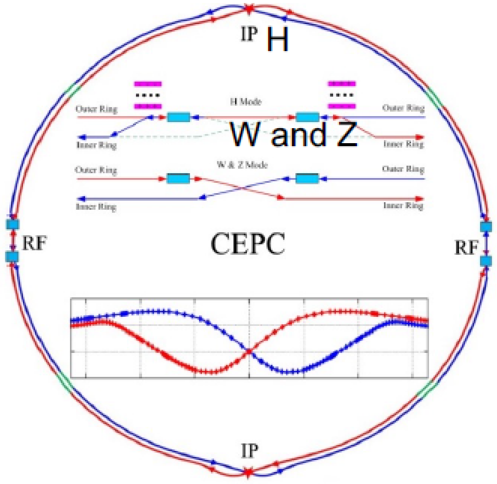




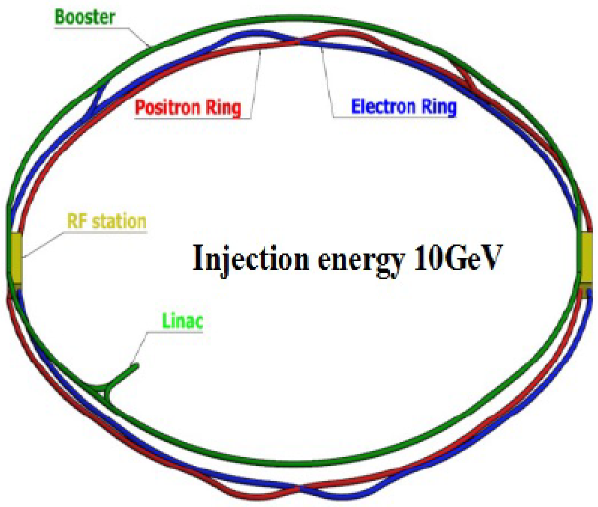
Future physics program of BESIII



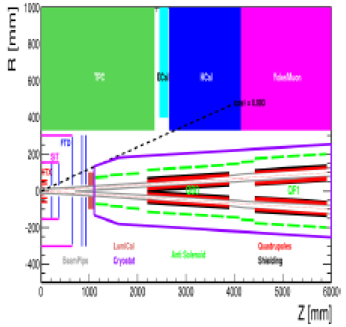
CEPC Layout



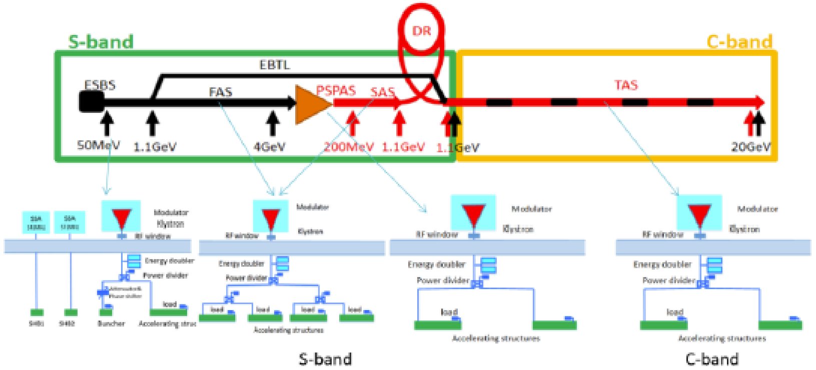
Collider ring (100km)

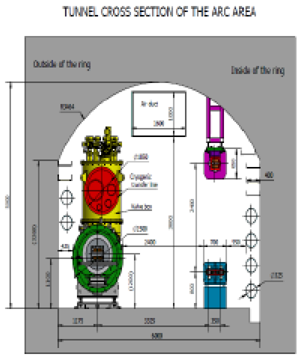


Booster ring (100km)



Operation mode		ZH	Z	W⁺W⁻	tt
$\sqrt{s}$ [GeV]		~240	~91.2	158-172	~360
L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	CDR (2018)	3	32	10	
	Latest	5.0	115	16	0.5





Very similar(inspired) to FCC design.
main differences
-- lower power/luminosity
-- proton and lepton colliders cohabitate

Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z, ttbar; Compatible to pp collider

Back to « outsider »:

-- it is important to realize that there is no world-wide body that has authority to synchronize all laboratories. ICFA, unlike ECFA which is a CERN council official committee, is only a 'club' of international directors and representatives.

-- Labs are busy with approved programs (and they should be). SuperKEKb and HyperK, HL-LHC, LBNF/DUNE, BEPC/JUN there is a waiting line of about 10 years

-- Unlike CERN, IHEP in China has considerable investment in non-collider physics -- CEPC→ huge scope increae.

-- CERN next collider date of 2045/8 takes into account need to run HL-LHC until 2041, *and*

to have sufficient personnel to prepare FCC operations

to accumulate enough CERN funding

This date can be brought earlier with contributions/participation from abroad,

as requested by US colleagues in P5 process.

An essential consideration: energy consumption and Carbon footprint

The hopefully short term shortages of energy (and cost increase) in Europe should not hide the more lasting issue of global warming.

-- reduce energy consumption

Including not only the beam power but the whole facility consumption (overhead) *Stapnes*

in fact sould reduce also local transport

-- improve performance to maximize the

physics output (number of usable Higgs bosons produced) per consumed energy

-- make sure the Carbon footprint is as small as possible

physics output (number of usable Higgs bosons produced) per Carbon footprint.

-- make sure machine has flexibility to run when electricity is cheap and carbon-free (seasonal mix of electricity)

Facility with high luminosity, several IPs, and based in country with low-carbon electricity scores much better

This is the case for FCC-ee at CERN *Abramov, AB*

This remains true when the Carbon footprint of the construction is taken into account.

R&D for Improved SRF Performance & Sustainability

Steinar Stapnes

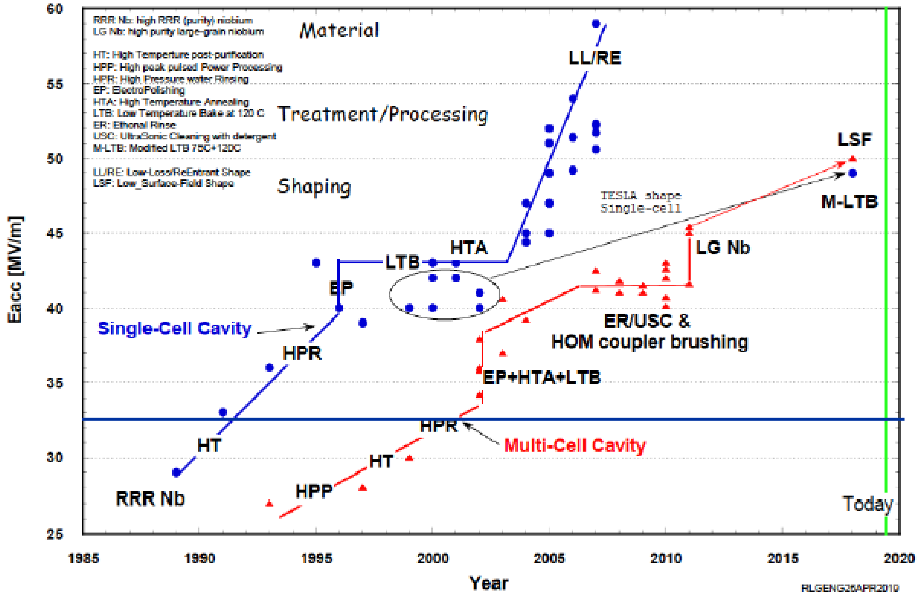
Better surface treatments and cavity shapes improve cavity performance. Lots of progress in last 10 years

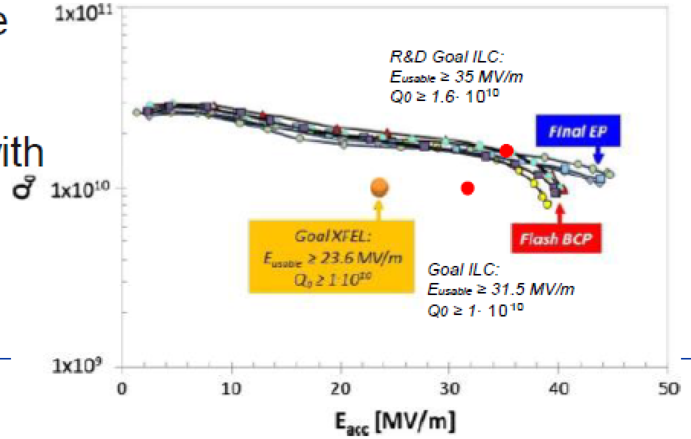
Raise gradient: fewer cavities for same beam energy
Short term goal: 31.5MV/m -> 35MV/m
Medium term goal: 45MV/m
Lab record: 59MV/m

Improve Q_0: reduce cryogenic losses
(1W @ 2K requires ~750W AC power!)
Short term goal: 1E10 -> 2E10

New treatments reduce / avoid need for electropolishing treatments (involving aggressive chemicals)

R&D into replacement of bulk niobium cavities with Nb or Nb_3Sn coated copper:
reduce niobium consumption,
increase performance (arXiv:2203.09718)





Higgs Boson Physics

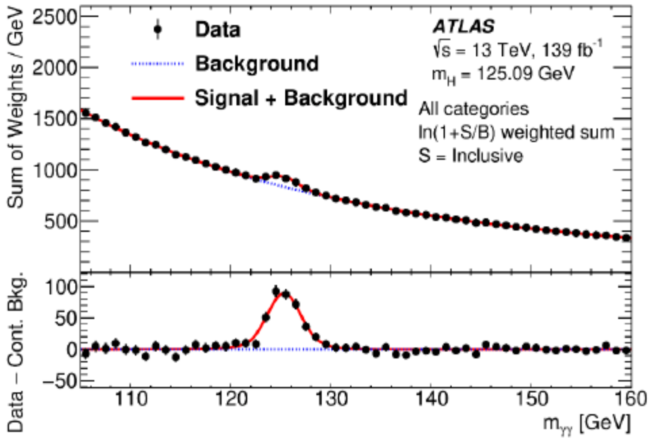
presently intense activity at ATLAS and CMS even for rare (γγ, μμ, Zγ)

signal normalization limited by knowledge of

- luminosity,
- gluon structure functions,
- Higgs-gluon coupling and more fundamentally
- **total Higgs width**

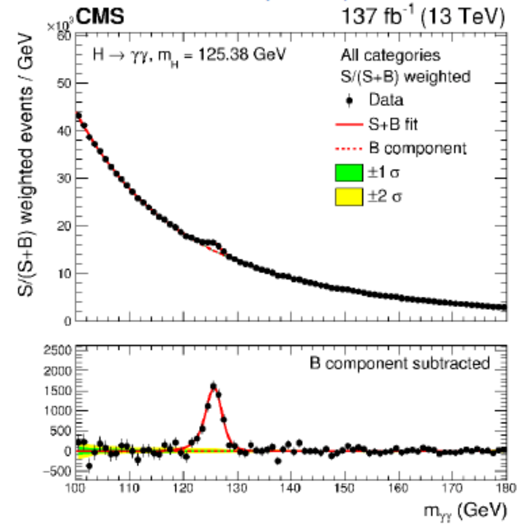
Cross sections extracted by fitting signal and background models to mass spectrum of data

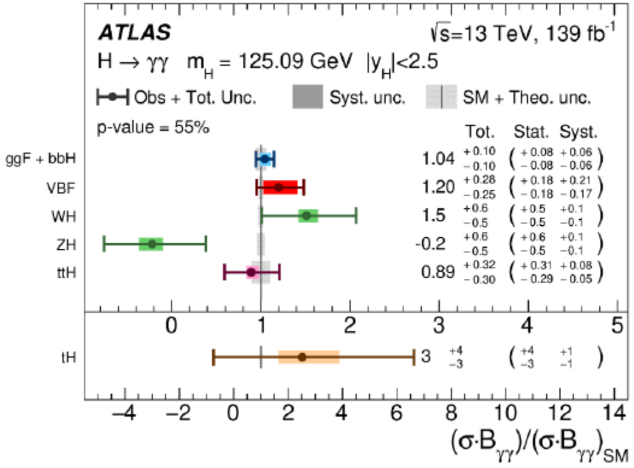
arXiv:2207.00348



CortuFA: Workshop on Future Accelerators

JHEP 07 (2021) 027





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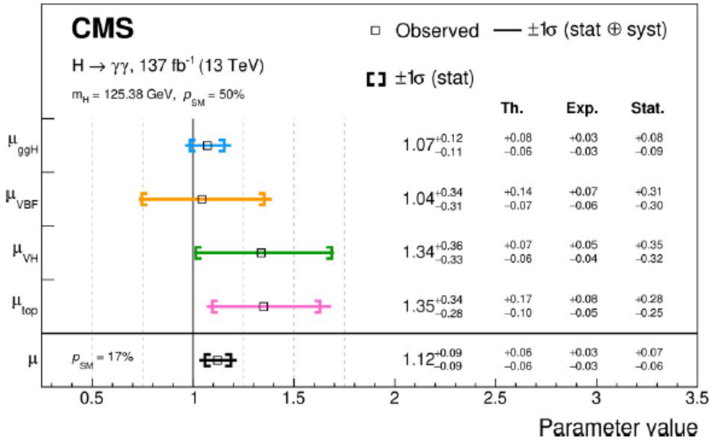


JHEP 07 (2021) 027

- Total cross sections measured are at 10% level from both ATLAS and CMS.
- Systematic uncertainties smaller or comparable to the statistical uncertainties

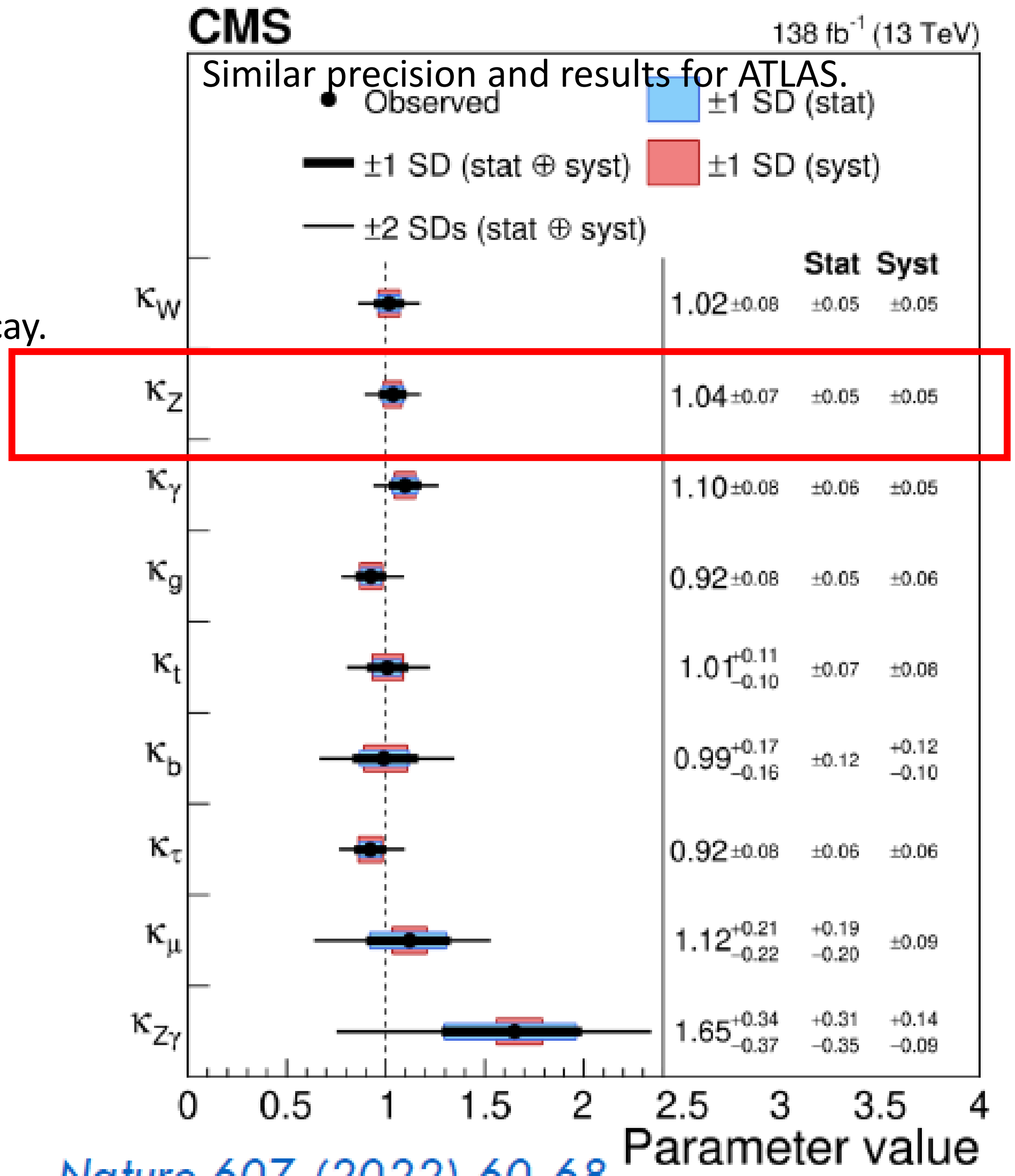
Higgs Boson Physics

Couplings to top and gluon are obtained
from total rate constraint (ttH, ggH production)

ZZ and WW channels by both initial state (VBF) and decay.

The most precise channel is H→ ZZ

Suggest to give one set of results for other channels as
ratio to ZZ, since this will coupling will be fixed
by Higgs factories operating at HZ production maximum

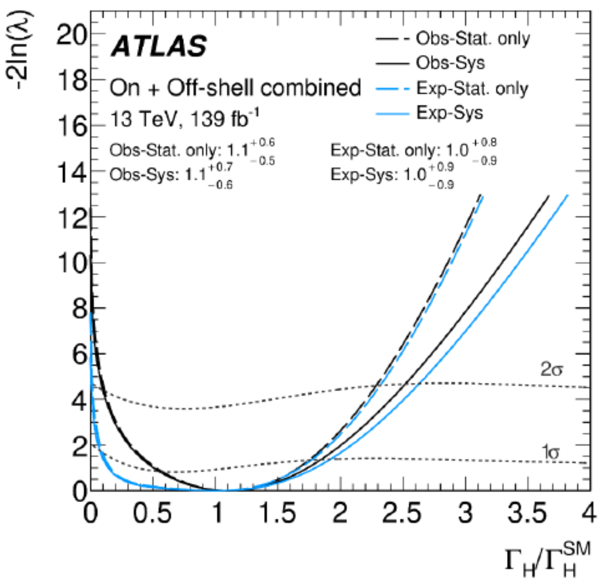


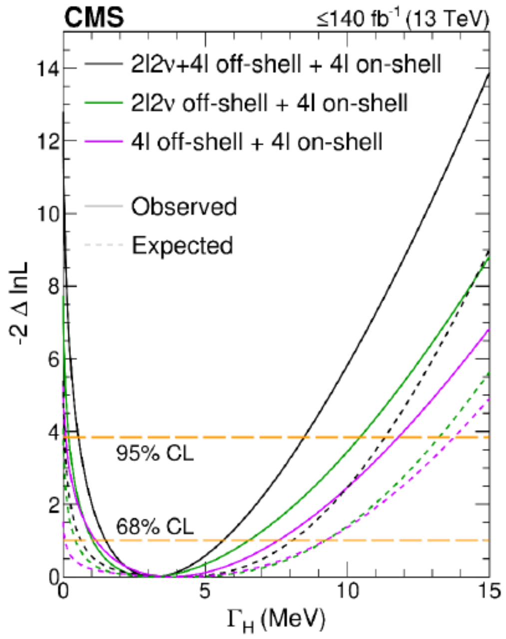
Nature 607 (2022) 60-68

Higgs Boson Physics

Higgs width

- Difficult for direct measurement of Higgs width due to detector resolution
  - Detector resolution (1-2GeV) >> Higgs width Γ_H (4.1MeV)
- Indirect measurement with $H \to ZZ$ channel by comparing on-shell and off-shell productions $\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\mu_{off-shell}}{\mu_{on-shell}}$





$$\Gamma_H = 4.6\,^{+2.6}_{-2.5}\ MeV\ @\ 68\%\ C.L.$$

$$\Gamma_H = 3.2\,^{+2.4}_{-1.7}\ MeV\ @\ 68\%\ C.L.$$

Even with HL-LHC the measurement of the Higgs boson total width will be limited to at best $\Delta\Gamma_{Higgs} / \Gamma_{Higgs}$ ~10 % level.

Target is rather 1% at e+e- Higgs Factory

Jenny List
Lukas Gourgos

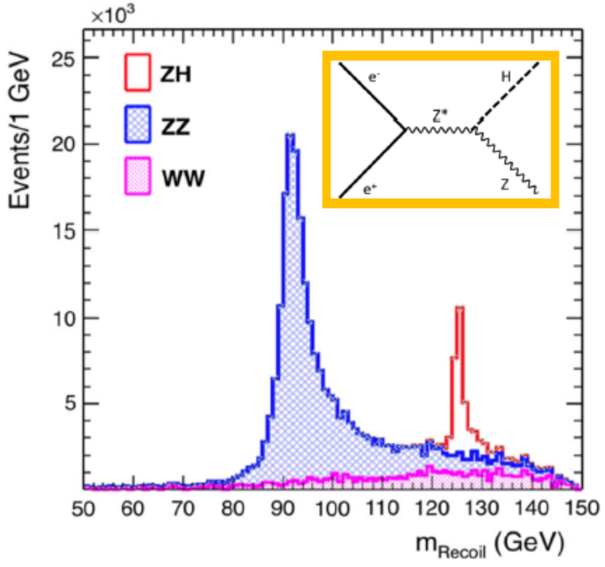
Higgs Boson width

In **e+e- colliders** operating around ZH cross-section maximum (240-250 GeV) total cross-section can be precisely measd by measuring Z production with a recoil mass consistent with the Higgs boson mass, **regardless of the Higgs decay mode.**
This provides a model independent determination of the total width and other direct branching ratios.

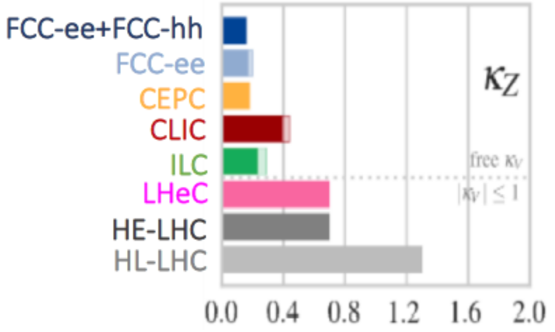
Model-independent measurements

- ZH production in e^+e^-
  - Unbiased tagging of Higgs boson
    - via Z→LL, m_{recoil}, E_{beam} constraints

$$m^2_{\text{Recoil}} = s + m^2_Z - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$



- Strategy:
  - First: measure ZH production
    - rate ~g_{HZZ}^2 → $\delta(g_{HZZ})/g_{HZZ}$~0.1%
  - Then: measure ZH(→ZZ)
    - rate ~$g_{HZZ}^4/\Gamma(H)$ → $\delta(\Gamma(H))/\Gamma(H)$~1%



- Unique in e^+e^- machines in ZH
- "standard candle" for other Higgs measurements (incl. FCC-hh)

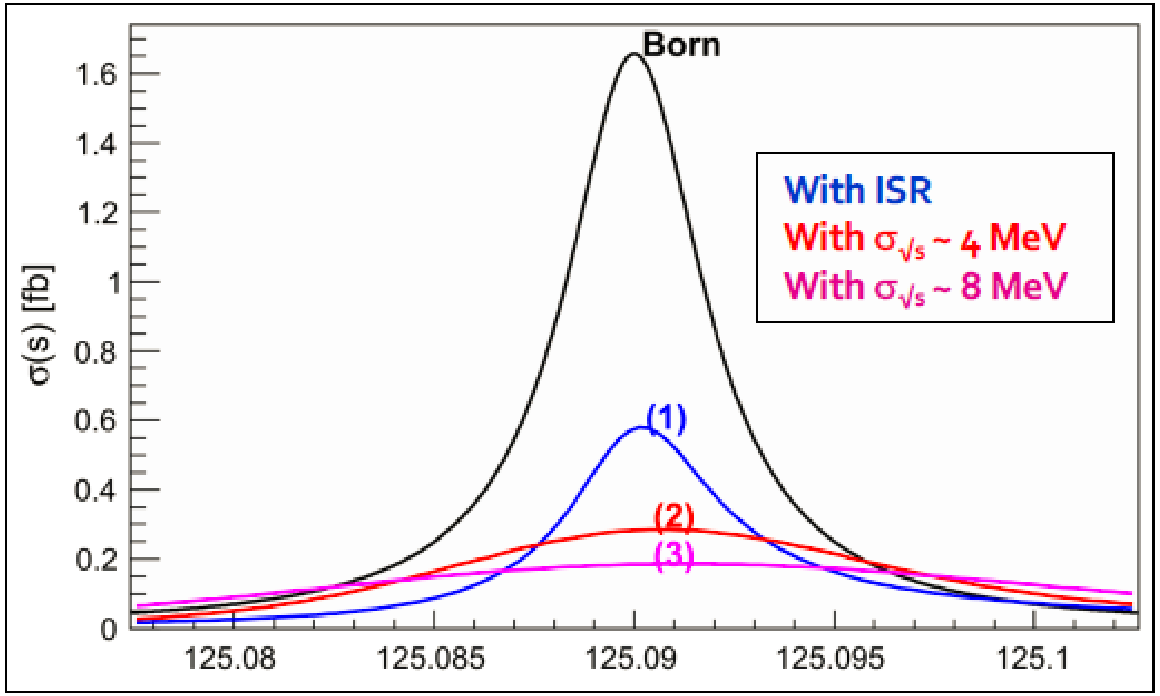
of particular interest:

H→ gg A color singlet of pure gluons!

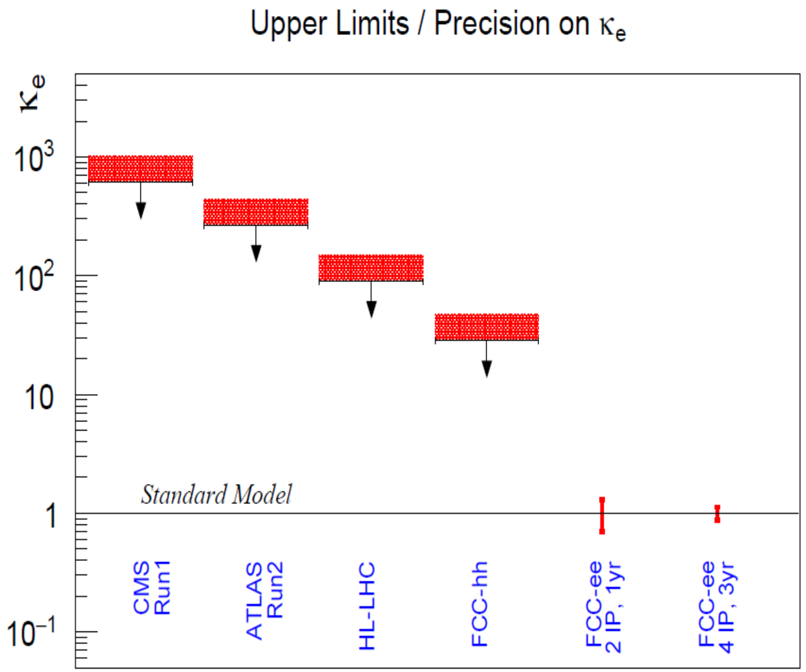
ee→ H at rest (s-channel production) requires monochromatization (circular only)

extremely difficult.

Something unique for FCC-ee: electron Yukawa coupling



Jadach & Kycia arXiv:1509.02406



e+e- → H @ 125.xxx GeV requires

-- Higgs mass known to <3 MeV from 240 GeV run (probably OK)

-- **Huge luminosity** (same optics as Z machine)

-- **monochromatization** (opposite sign dispersion using magnetic lattice) to reduce σ_{ECM}

-- **continuous monitoring and adjustment of E_{CM}** to MeV precision (transv. Polar.)

-- an extremely sensitive event selection against backgrounds as pointed out by *Sophie Renner*

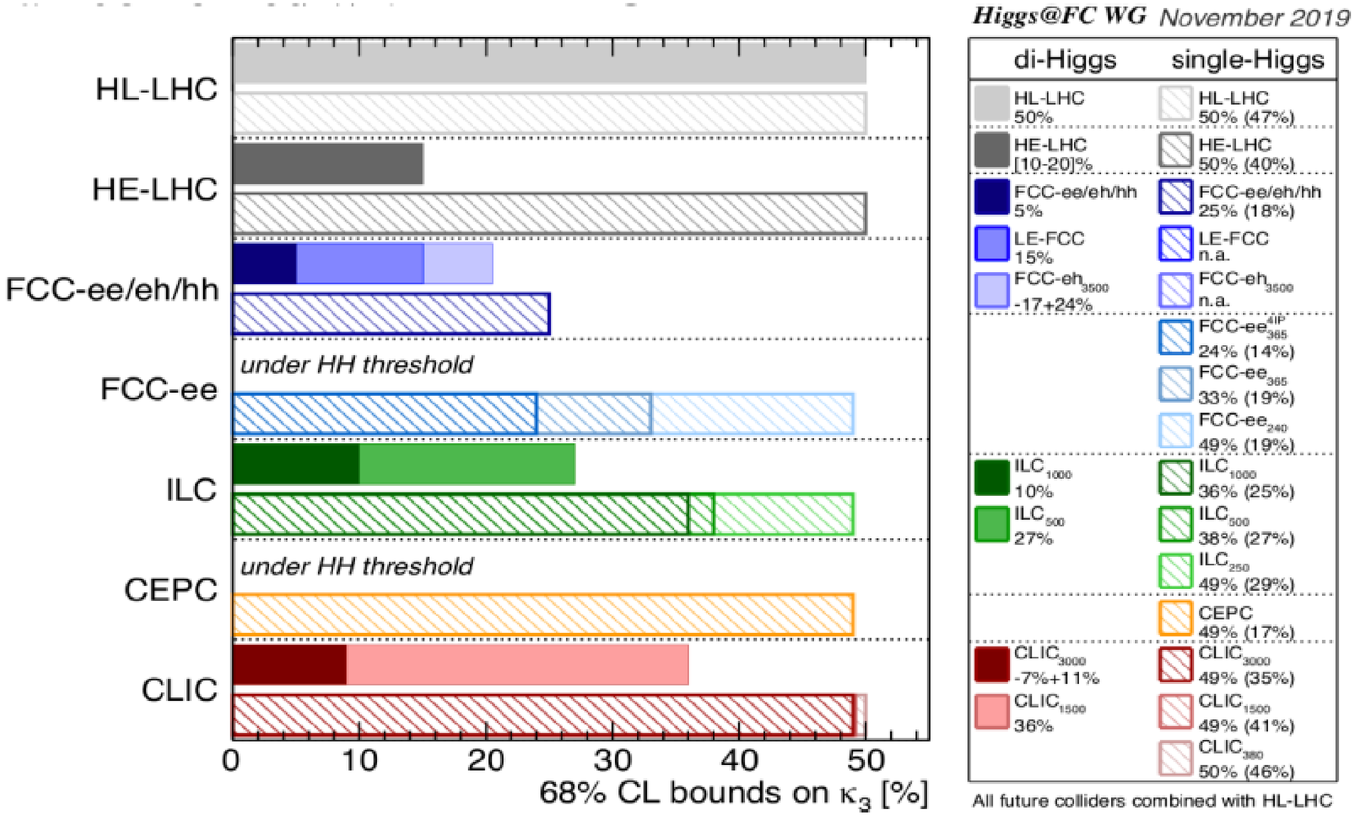
several precision measurements are much better at hh than e+e-

μμ
γγ
Zγ
tt
HHH

Complementarity between e+e- and hh machines!

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95
g_{HHH} (%)	50.	44./33. 27./24.	3-4
Γ_H (%)	SM	1.1	0.91
BR_{inv} (%)	1.9	0.19	0.024
BR_{EXO} (%)	SM (0.0)	1.1	1

Higgs-self coupling: Grand summary



- HL-LHC: Confirm the existence of Higgs-self coupling @ 95% CL [if exists]
- FCC-ee: achieve <20% uncertainty via single-H measurements
- CLIC/ILC: observe HH interaction [5σ → 20% uncertainty]
- FCC Full program: 5% unc. [start probing quantum corrections on H potential]

➔ careful when comparing HHH coupling between high energy facilities (e+e- vs μμ vs pp), analysis is at very different level of complexity (and optimism)

Z factory physics -- 10 TeraZ = 10^{13} Z produced!

-- this is a strong point of circular collider where close to 10^{13} Z would be produced and continuous beam energy calibration at the level of 50-100 keV

-- a formidable program of precision EWPOs, flavour and QCD

completely complementary to Higgs measurements for sensitivity to New Physics
See list and comments in my presentation, flavour examples in presentation by *Sophie Renner*
S,T-parameter with sensitivity to physics at ~70 TeV (EFT) for weak coupling particles
sensitivity to active-sterile neutrino mixing

Highlight measurements

-- m_Z and Γ_Z at few keV (stat)
-- W mass to ~0.3 MeV or better (present best is 10 MeV)
-- $\alpha_{QCD}(m_Z)$ to ± 0.0002 or better
-- $\alpha_{QED}(m_Z)$ to $\pm$ 3 10^{-5} or better ← specific to 5$10^{12}$ Z
-- $\sin^2\theta^{eff}(m_Z)$ to $\pm$ 2 10^{-6} or better with several different methods
-- Rb potentially to $\pm$ 0.3 10^{-6} (stat) → syst. to be pursued.
-- tau lepton lifetime and branching ratios → GF_τ to 2$10^{-5}$
-- several HF measurements unique to TeraZ (tau physics, Bs→ $\tau\nu$, $B \to K(*)\ \tau+\tau-$ etc..

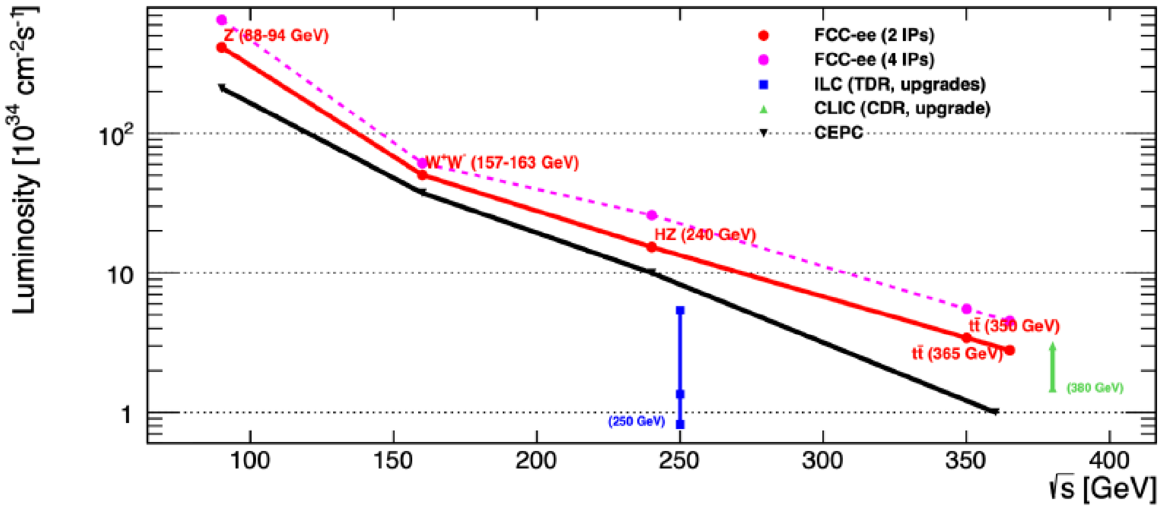
will require a coordinated effort to improve theoretical calculations to the level of statistical errors!

General comments: high precision requires special care on detector construction and alignment procedure

➔ it would be great to give sensitivity limits using specific models

FCC-ee is a flavour factory

Renner



FCC Snowmass report, 2203.06520

Numbers for decays of 5×10^{12} Z^0s:

Lenz & Monteil, 2207.11055

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

$O(10^{11})$ B mesons

About 15 times larger than Belle II dataset

Combines the advantages of B factories and LHCb: highly boosted particles in a clean environment

Renner

B decays into τs after Belle II and HL-LHCb

$$B \to K \tau^+ \tau^-$$

SM branching ratio: $(1.44 \pm 0.15) \times 10^{-7}$ HPQCD, 1306.0434

Current limits: 5 orders of magnitude above SM

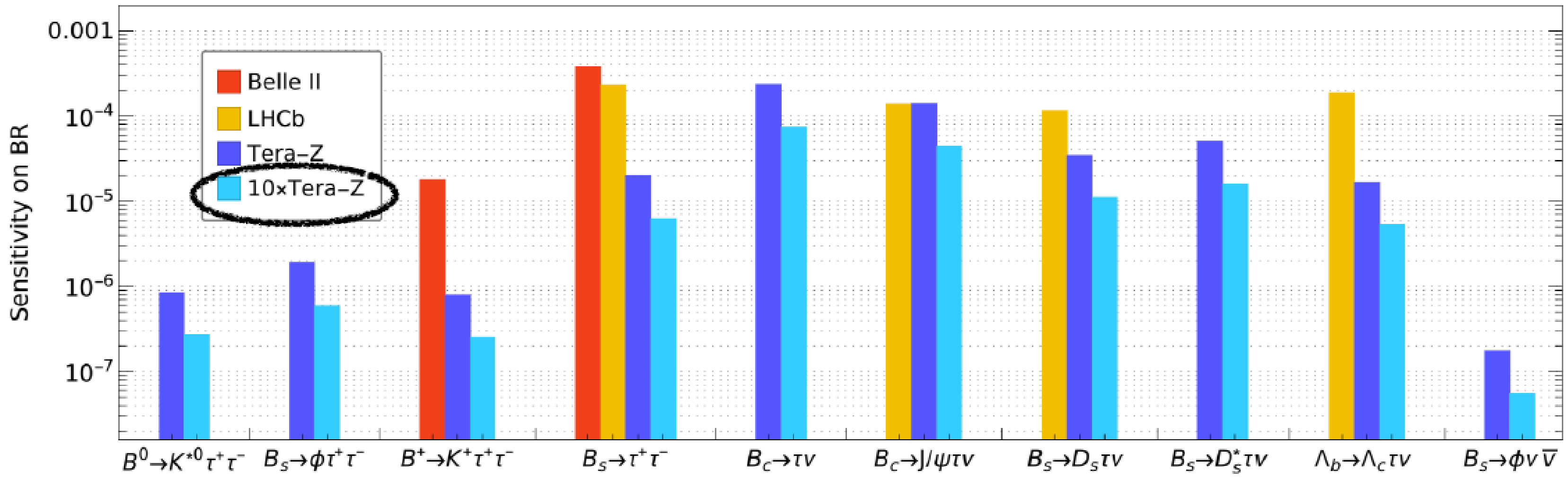
After Belle II: $BR \leq 10^{-4} - 10^{-5}$

$$B_s \to \tau^+ \tau^-$$

Bobeth, 1405.4907

$$\mathrm{Br}\left(B_s \to \tau^+\tau^-\right)_{\mathrm{SM}} = (7.73 \pm 0.49) \times 10^{-7}$$

$$\mathrm{Br}\left(B_s \to \tau^+\tau^-\right)_{\mathrm{EXP}} \leq 6.8 \times 10^{-3}$$ LHCb, 1703.02508



Ho, Jiang, Kwok, Li, Liu 2212.02433

Detectors

Many presentations of great quality, between HL-LHC upgrades and ILC/CLIC/CEPC and FCC-ee

reflect on some fundamental freatures

-- HL-LHC upgrades focus on surviving pile-up

-- High granularity

-- implementation of timing

-- Higgs factory detectors

-- starting point with the **ILC and CLIC detectors**, pulsed, high resolution wrt CMS/ATLAS

-- triggerless operation

-- **New for FCC-ee and CEPC** → lower energy operation (not a TeV detector) → cheaper!

-- main novelty is Z factory physics

-- CW operation (20 ns bunch spacing) → cooling, gas tracker, **TPC very difficult**

-- flavour physics → PID mandatory

-- high accuracy for fiducial volume, luminosity and life-time measurements

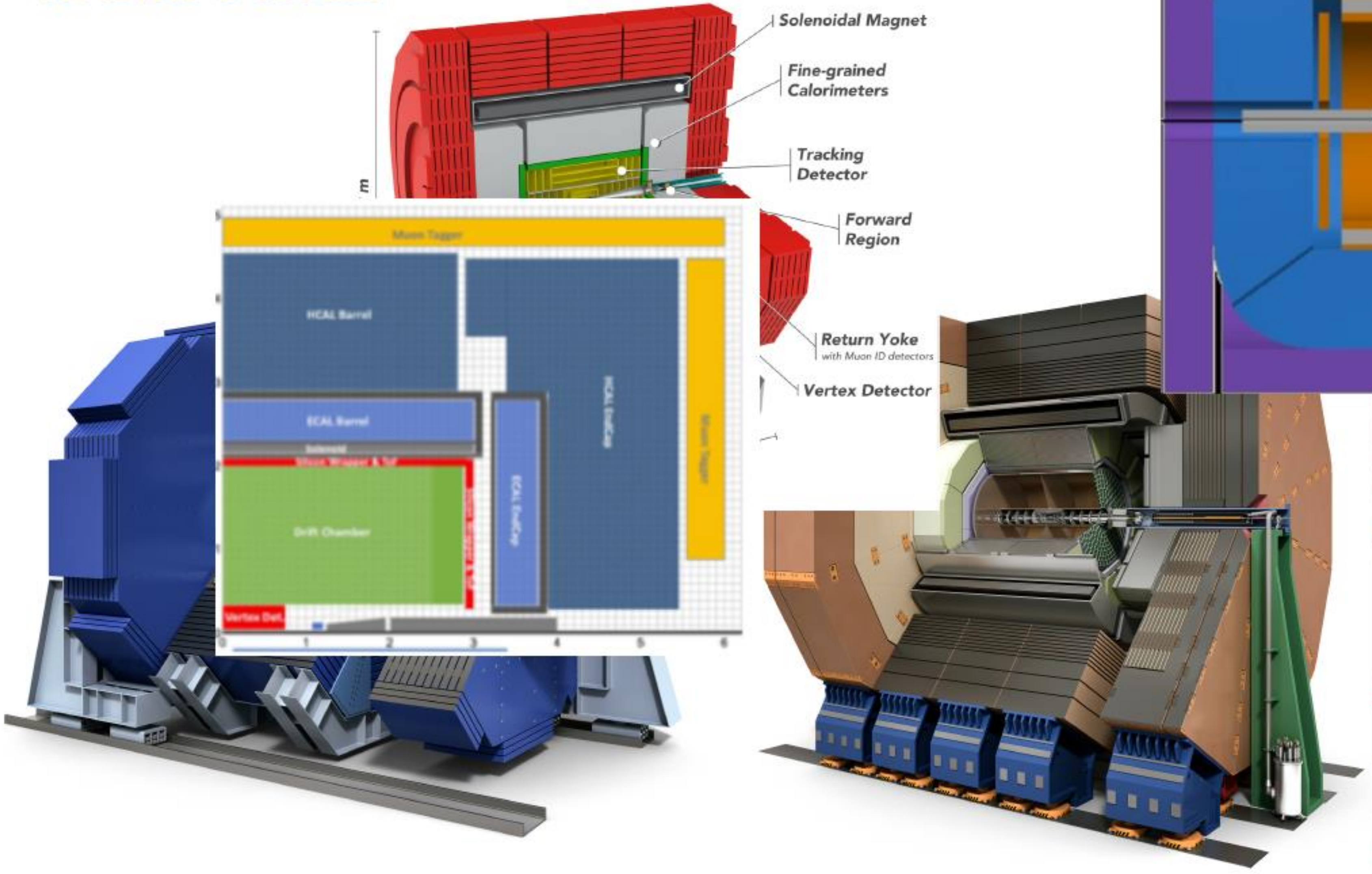
-- mechanical accuracy and in situ alignment pushed to micron levels

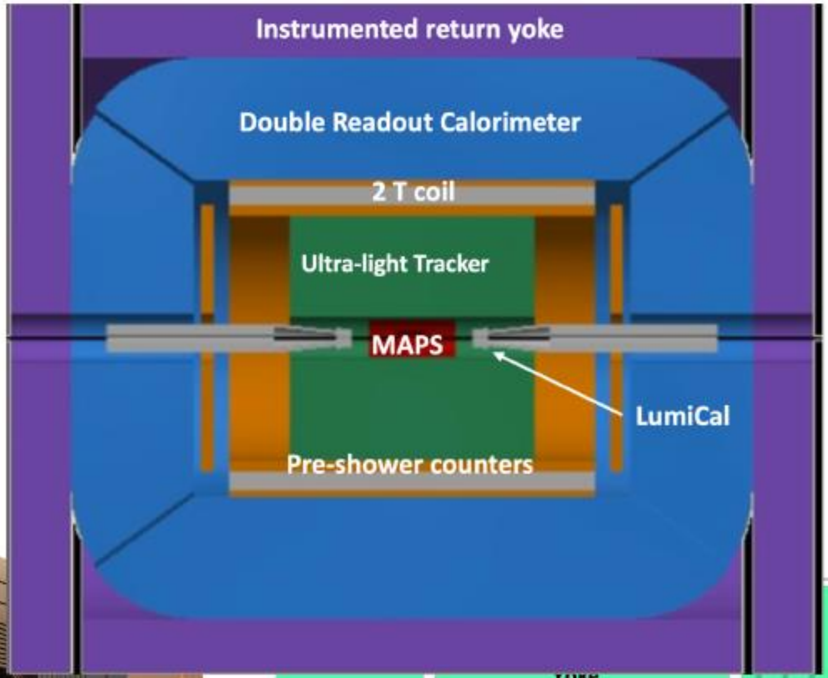
-- in turn would benefit linear projects (eg H→ ss search)

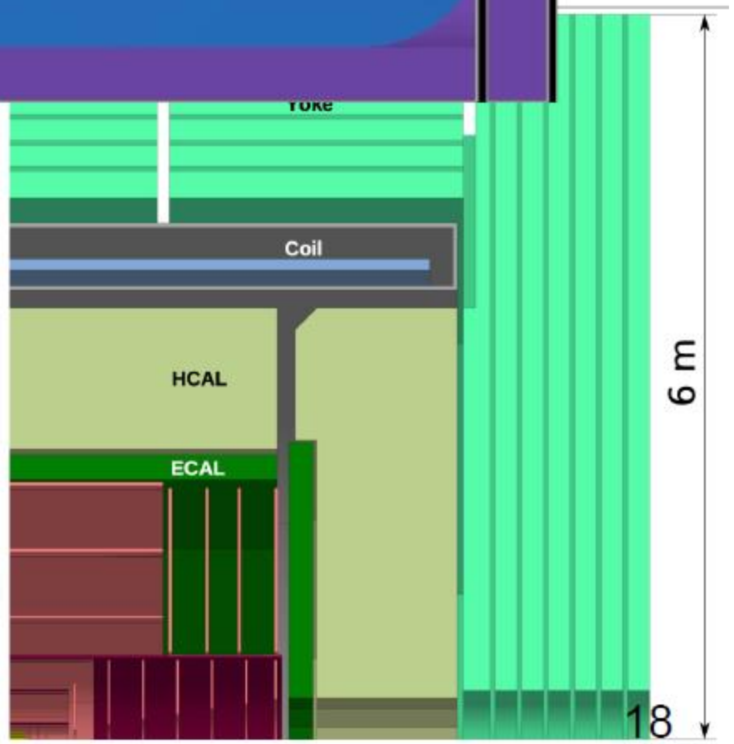
--

Higgs Factory Detector Concepts

for linear & circular







e^+e^- collider beam parameters

Linear

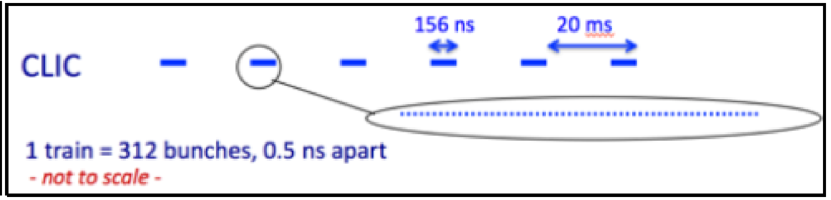
Parameter	ILC 250 GeV	ILC 500 GeV	CLIC 380 GeV	CLIC 1.5 TeV	CLIC 3 TeV
Luminosity L ($10^{34}cm^{-2}sec^{-1}$)	1.35 (2.7)	1.8	1.5	3.7	5.9
L > 99% of √s ($10^{34}cm^{-2}sec^{-1}$)	1.0	1.0	0.9	1.4	2.0
Repetition frequency (Hz)	5	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	1312	1312	352	312	312
Beam size at IP σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	300	300	70	44	44

ILC: Crossing angle 14 mrad, e^- polarization ±80%, e^+ polarization ±30%
CLIC: Crossing angle 20 mrad, e^- polarization ±80%

Very small beams + high energy => beamstrahlung

Very small bunch separation at CLIC drives timing requirements for detector

Very low duty cycle at ILC/CLIC allows for:
Triggerless readout
Power pulsing



Circular

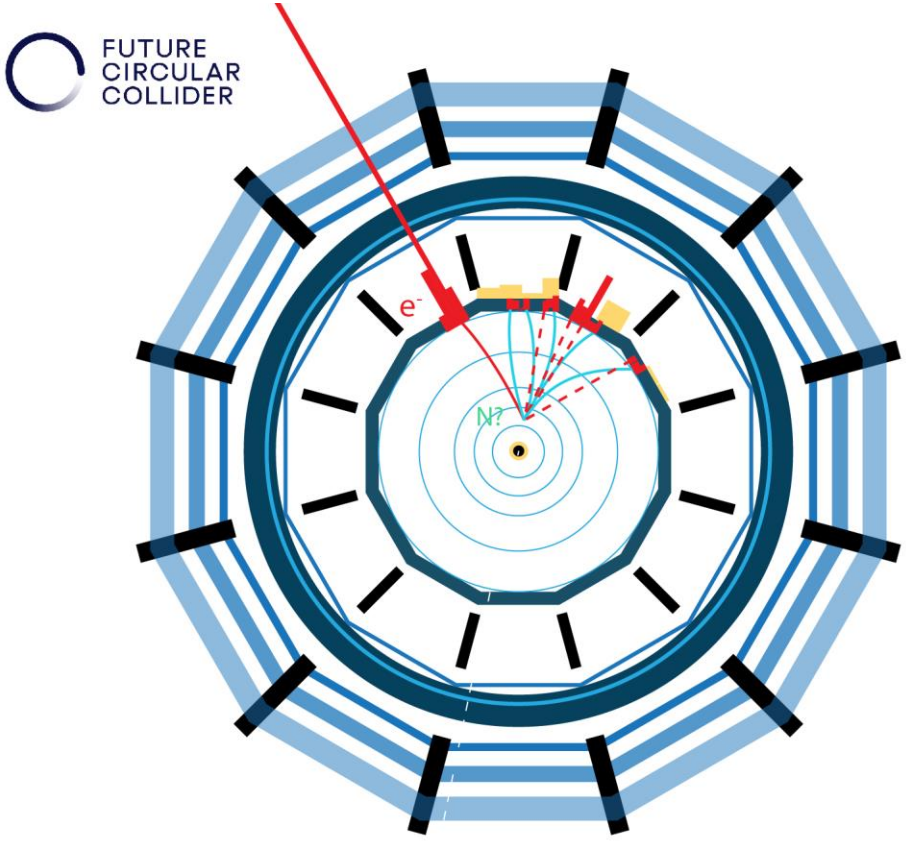
	FCC-ee Z	FCC-ee WW	FCC-ee Higgs	FCC-ee ttbar
√s [GeV]	91.2	80	240	365
Luminosity / IP ($10^{34}cm^{-2}s^{-1}$) [4IP]	182	19.4	7.3	1.33
no. of bunches / beam	10000	880	248	40
Bunch separation (ns)	25	300	1000	6000
Horizontal rms IP spot size [μm]	8	21	14	39
Vertical rms IP spot size [nm]	34	66	36	69

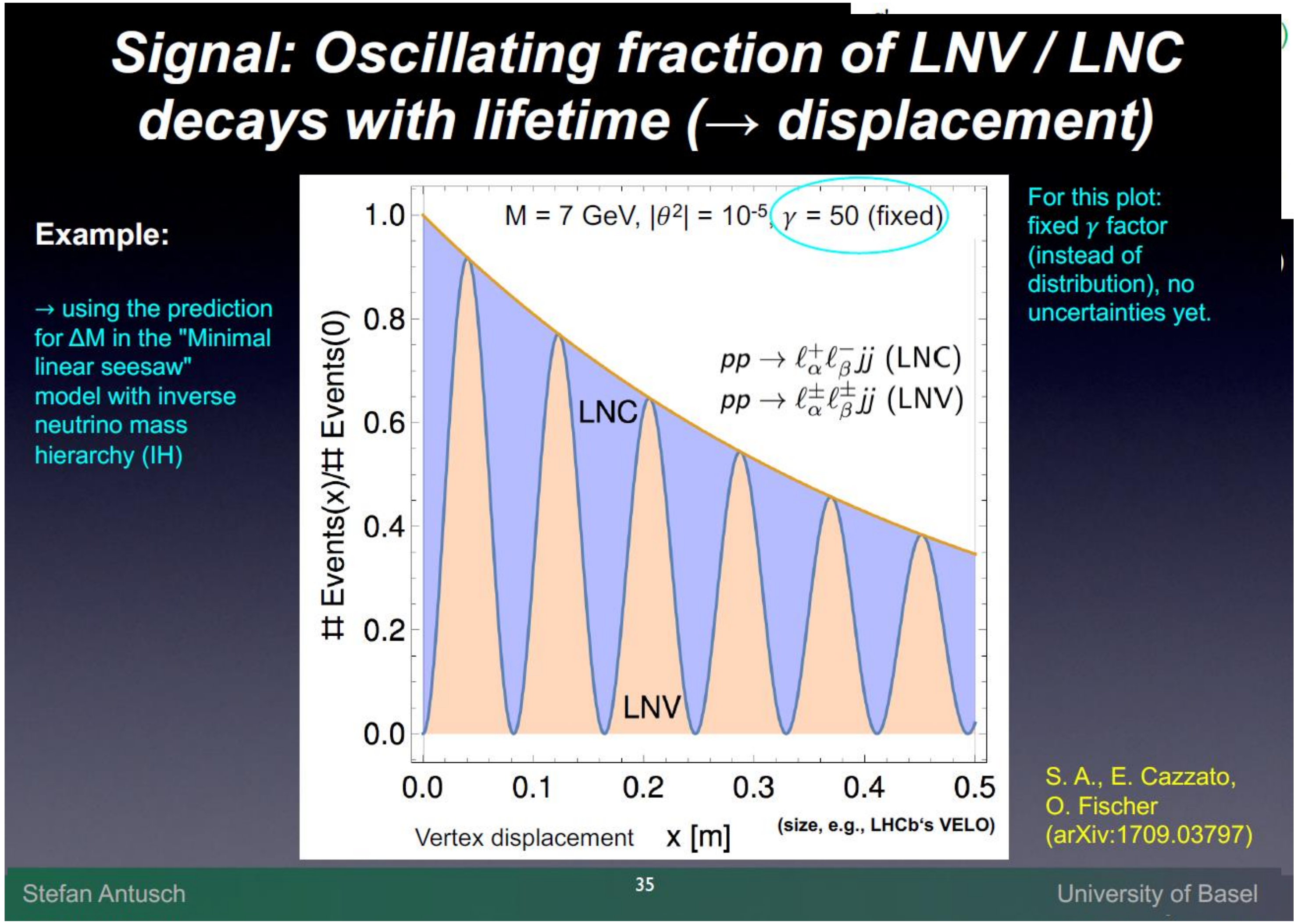
Beam transverse polarisation
=> beam energy can be measured to very high accuracy (~50 keV, 1ppm)

At Z-peak, very high luminosities and **very high e^+e^- cross section (40 nb)**
- ⇒ **Statistical accuracies at 10^{-4} -10^{-5} level** ⇒ **drives detector performance requirements**
- ⇒ **Small systematic errors required** to match
- ⇒ This also drives requirement on **data rates** (physics rates ~100 kHz)
- ⇒ Triggerless (streaming) readout likely possible

Beam-induced background, from beamstrahlung + synchrotron radiation
- Most significant at 365 GeV
- Well mitigated through MDI design and detector design

Dont forget neutrinos and dark matter!





S. Antusch pointed out that 3 families extend the allowed phase space to much higher mixing angles that 1 family see-saw!

and introduced the possibility of **heavy neutrino charge oscillations!**

Conclusions

Although/because we dont relly know what to expect, the situation is really exciting

The possibility of a Future Collider becoming a real project is coming closer.

From detector design to high precision calculations, a serious preparation over many years will trigger many new ideas, tricks, methods and collaborations with new people.

Although I missed the party last night to prepare this ‘summary’ (which was not one)
I would like to thank all the speakers and I am grateful to the organizers for inviting me.


THANK YOU!