FUTURE e+e- COLLIDERS

circular or linear?

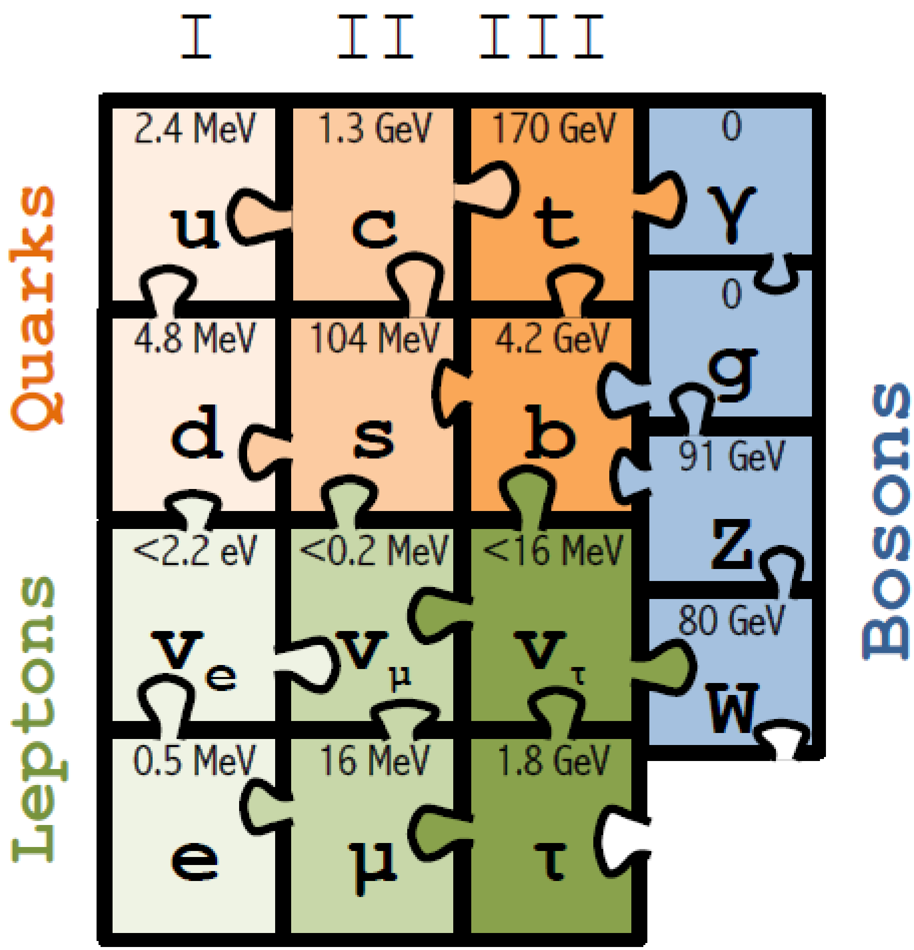
Sensitivity

Precision

Energy

Particle physics has arrived at an important moment of its history

1989-1999: top mass predicted (LEP, mostly Z mass&width)
top quark discovered (Tevatron)
t'Hooft and Veltman get Nobel Prize 1999

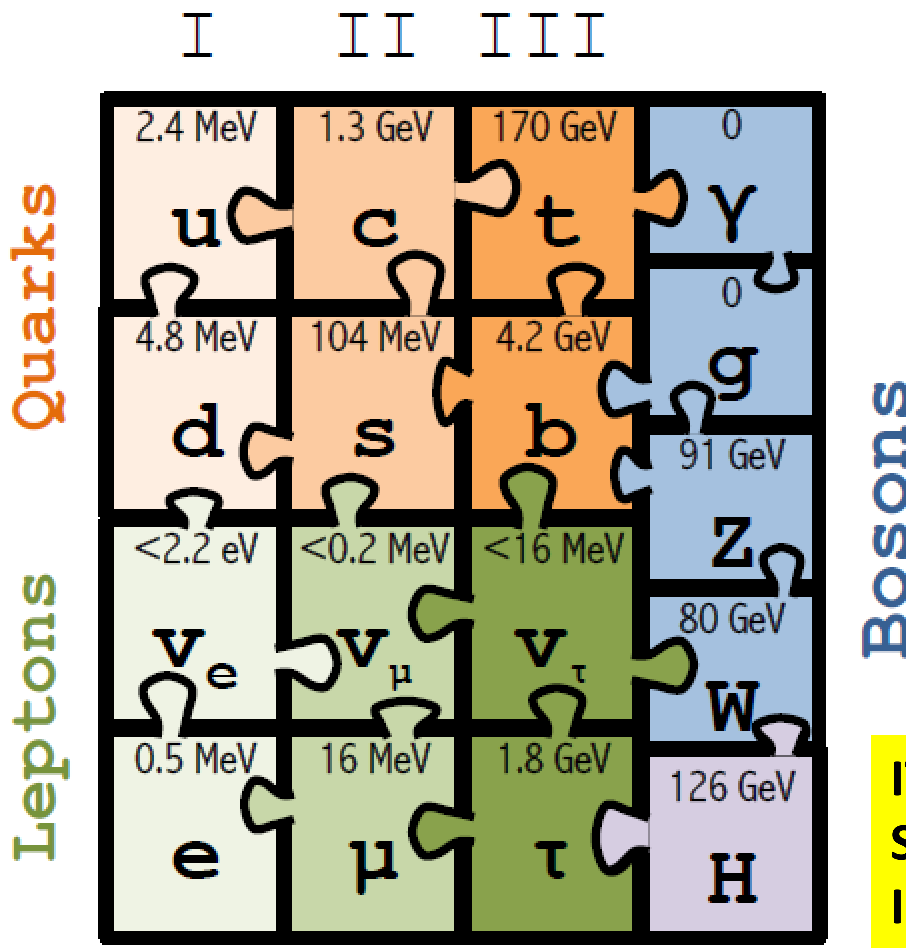


(c) Sfyrla

1997-2013 Higgs boson mass cornered (LEP H, M_Z etc +Tevatron m_t , M_W)

Higgs Boson discovered (LHC)

Englert and Higgs get Nobel Prize 2013

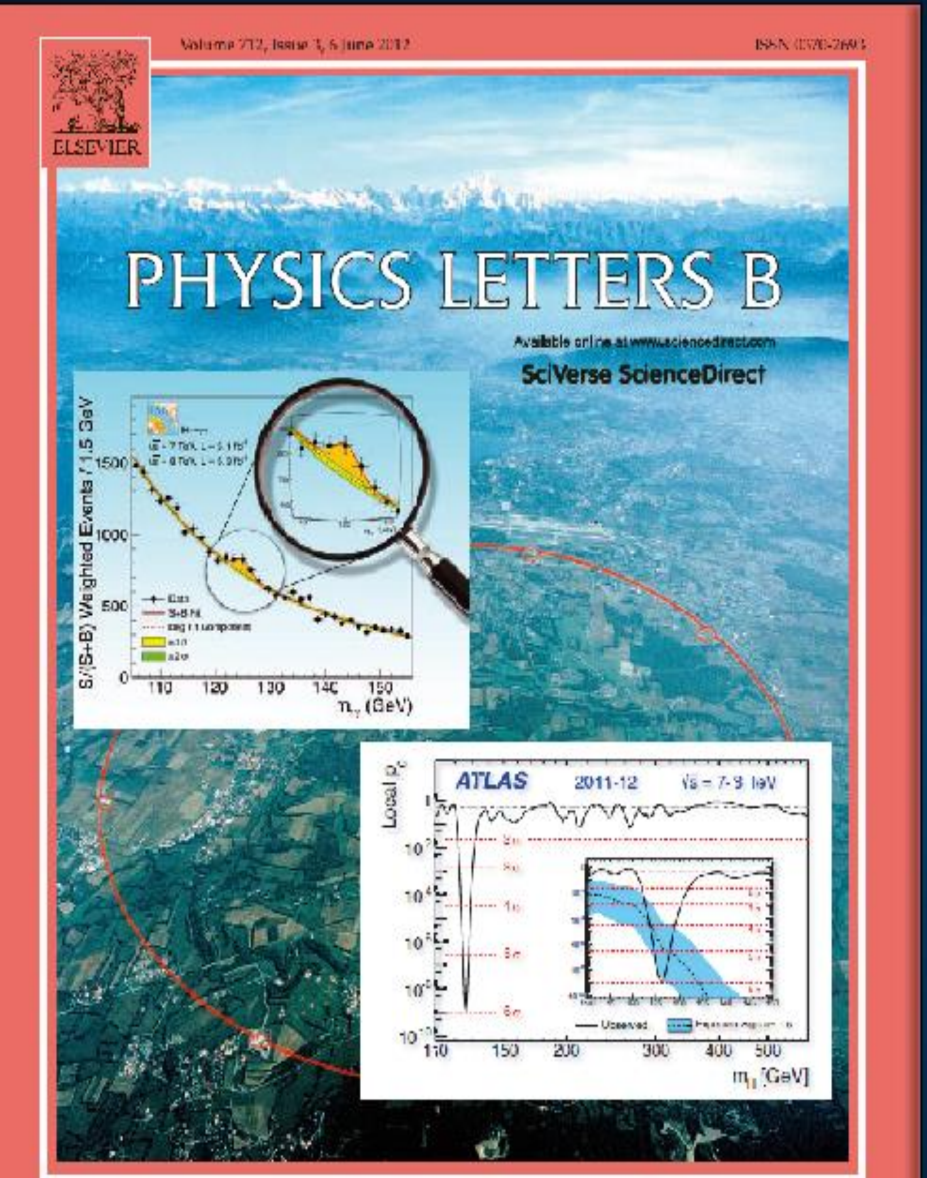


(c) Sfyrla

IT LOOKS LIKE THE STANDARD MODEL IS COMPLETE.....

NB in fact we know from oscillations and cosmology that all 3 neutrino masses are less than ~0.1 eV

SEVEN YEARS AGO ALREADY



The Standard Model is a very consistent and complete theory.

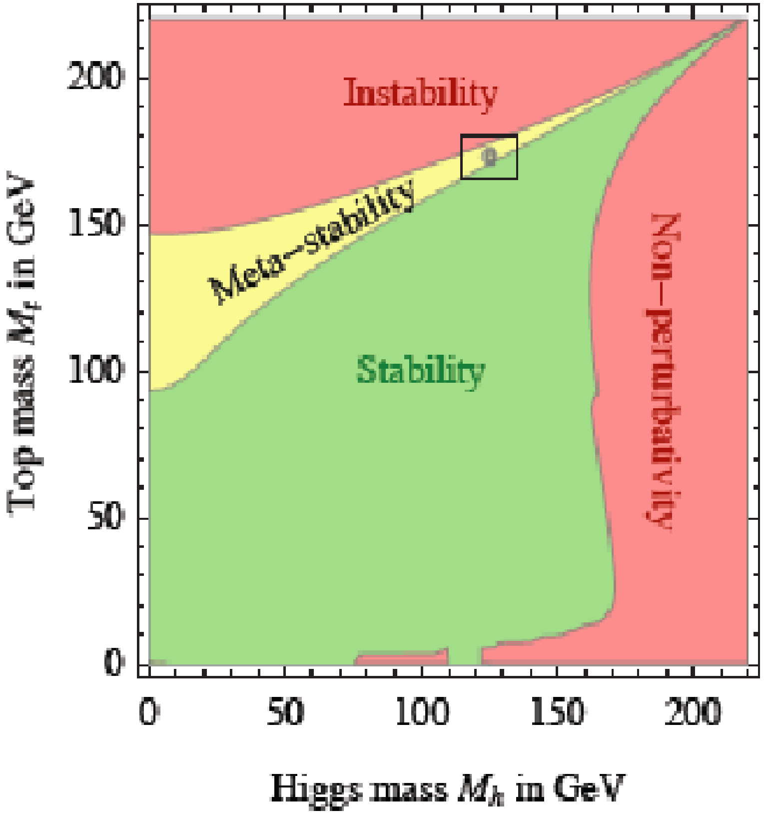
It explains all known collider phenomena and almost all particle physics (except ν's)

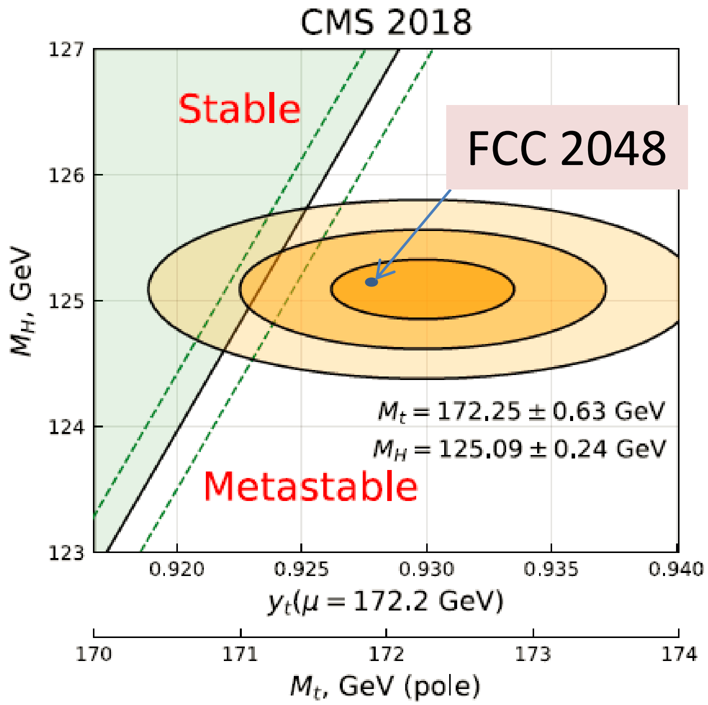
– this was beautifully verified at LEP, SLC, Tevatron and the LHC.

-- the EWPO radiative corrections predicted top and Higgs masses

assuming SM *and nothing else*

we can even extrapolate the Standard Model all the way to the the Plank scale :





Asymptotic safety of gravity and the Higgs boson mass

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12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\text{min}} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\text{min}} < m_H < m_{\text{max}} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

Key words:
Asymptotic s
PACS: 04.60.

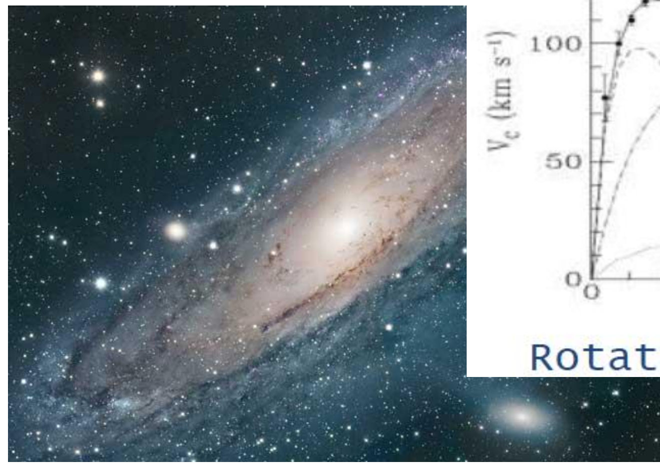
Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

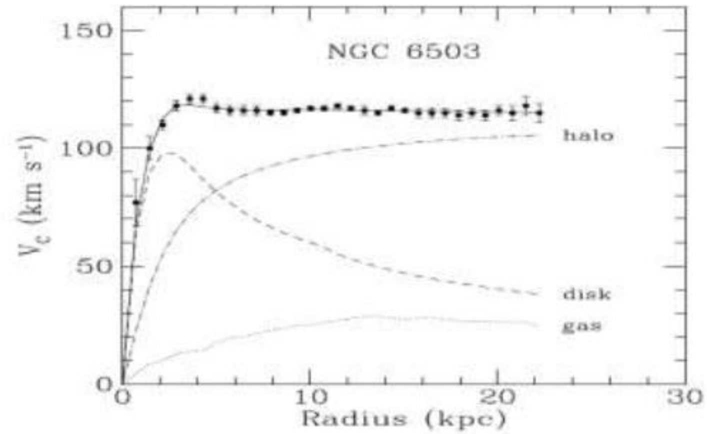
Is it the end?

We cannot explain:

Dark matter

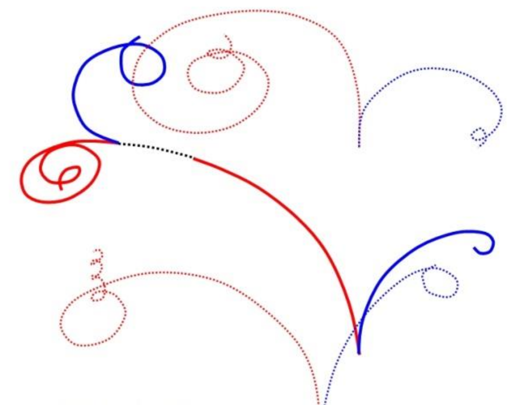
Standard Model particles constitute only 5% of the energy in the Universe





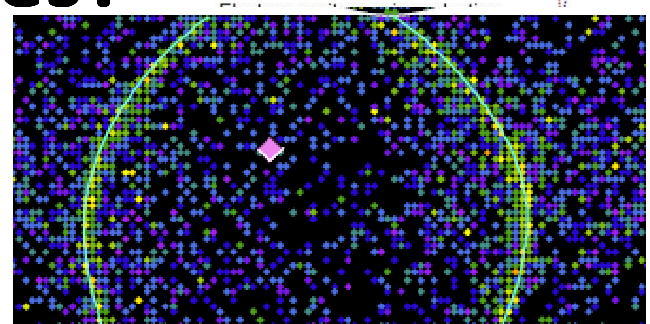
Rotation curve for Galaxy

Were is antimatter gone?



What makes neutrino masses?

Not a unique solution in the SM --
Dirac masses (why so small?)
Majorana masses (why not Dirac?)
Both (the preferred scenarios, see-saw…) ?
➔ heavy right handed neutrinos?



Is it the end?

Certainly not!

-- Dark matter

-- Baryon Asymmetry in Universe

-- Neutrino masses

these facts require particle physics explanations.

To which, one can add many theoretical questions on the SM

are experimental proofs that there is more to understand.

We must continue our quest, but HOW?

Direct observation of new particles (but not only!)

New phenomena (ex: Neutral currents, neutrino oscillations, CP violation..)

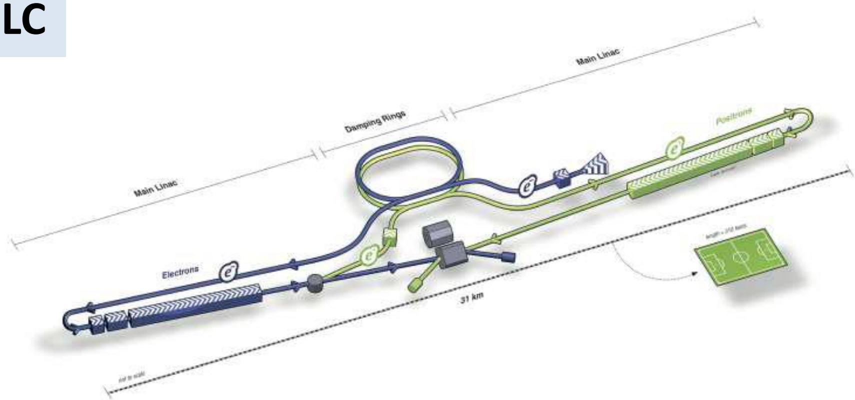
Deviations from precise predictions

(ref. Uranus to Neptune, Mercury's perihelion,
top and Higgs predictions from LEP/SLC/Tevatron/B factories, g-2, etc…)

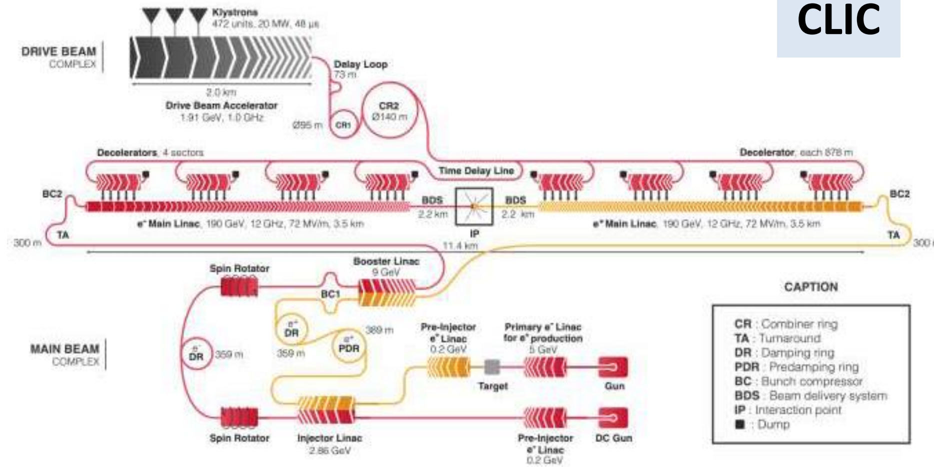
HIGGS FACTORIES

Higgs provides a very good reason why we need a lepton (e+e- or μμ) collider

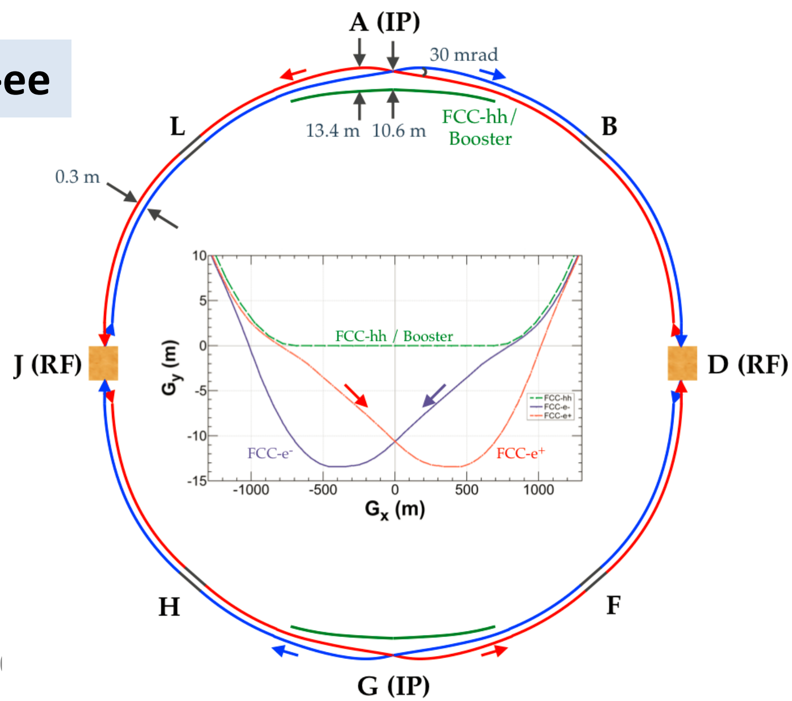
ILC



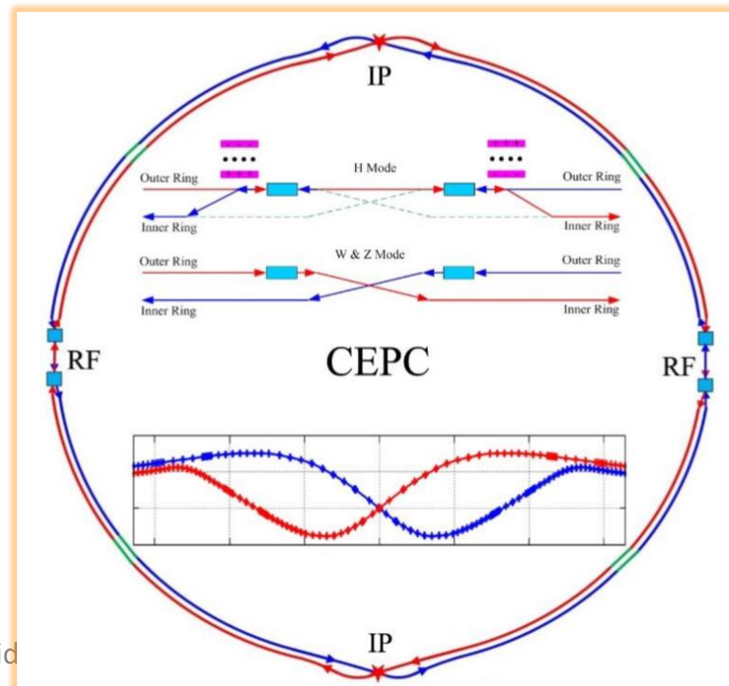
CLIC

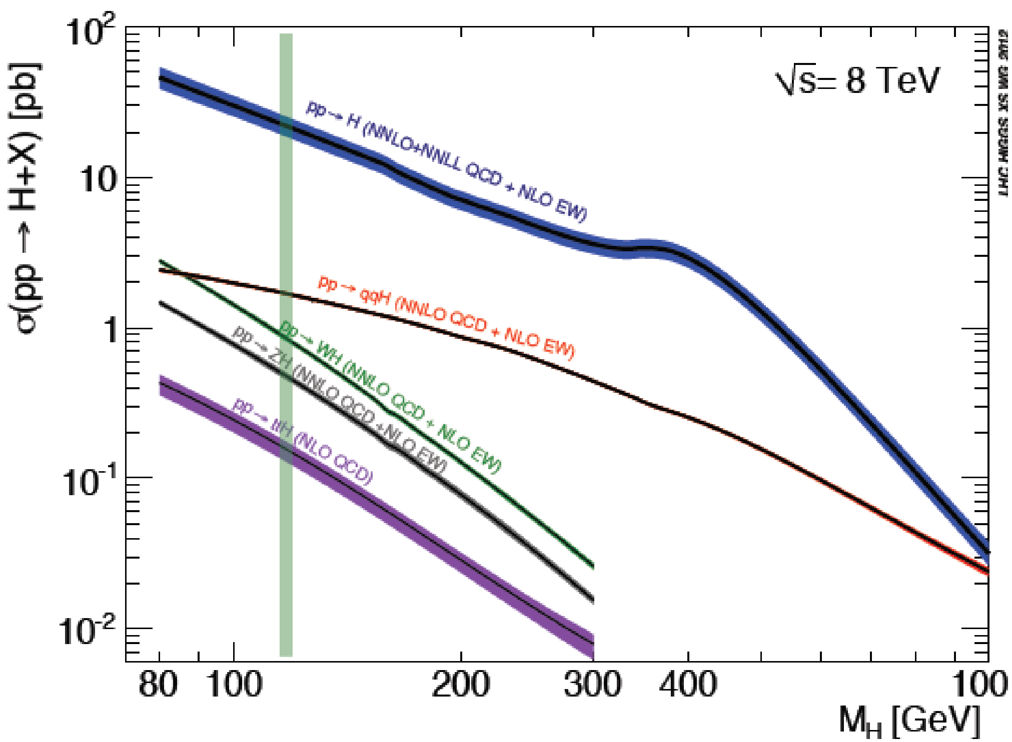


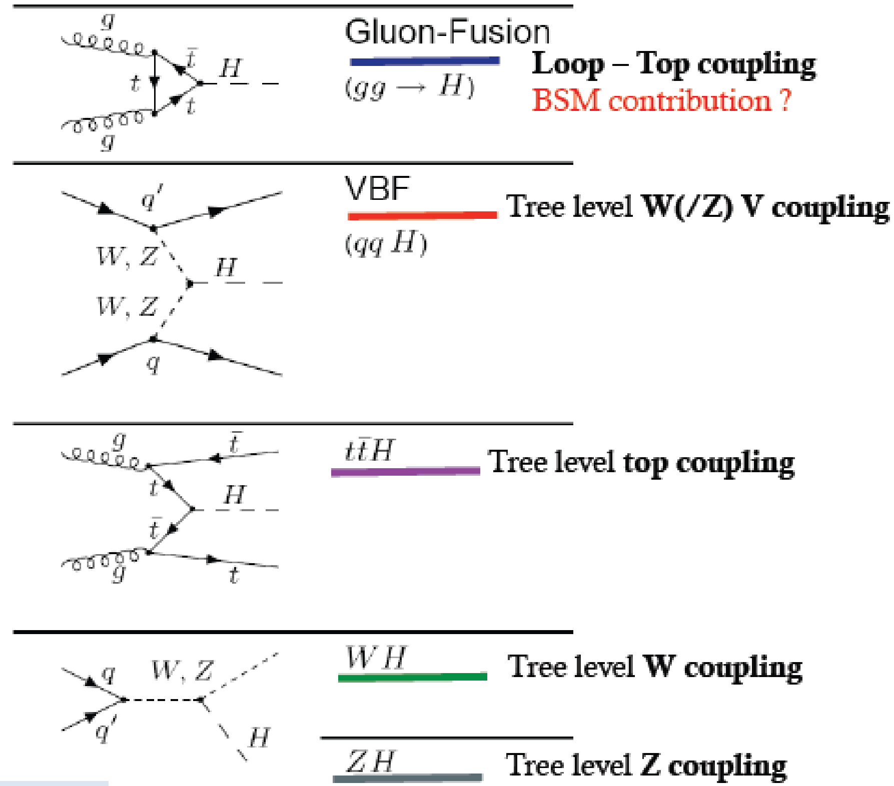
FCC-ee



CEPC







THE LHC is a Higgs Factory…BUT

several tens of Million Higgs already produced… > than most Higgs factory projects.

$$\sigma_{i\to f}^{\ \text{observed}} \propto \sigma_{prod} \frac{(g_{Hi})^2(g_{Hf})^2}{\Gamma_H}$$

relative error scales with 1/purity and 1/√efficiency of signal

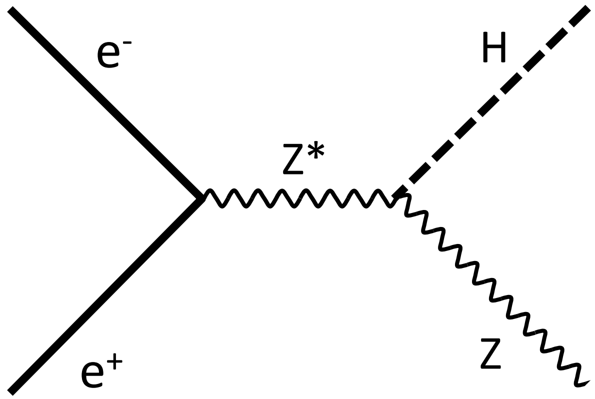
difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown (invisible channels) → must do physics with ratios.

Higgs production mechanism

“higgstrahlung” process close to threshold

Production xsection has a maximum at near threshold ~200 fb

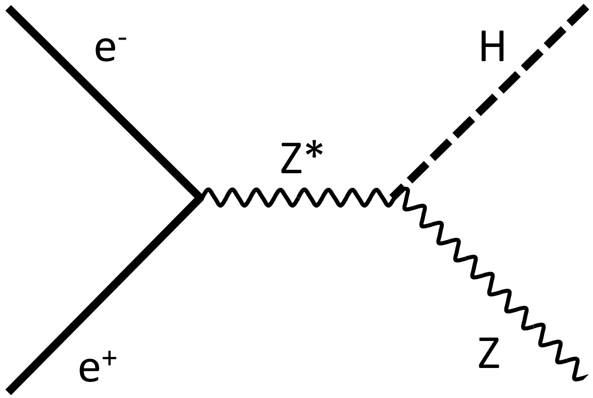
$10^{34}/cm^2/s$ ➔ 20’000 HZ events per year.



Z – tagging
by missing mass

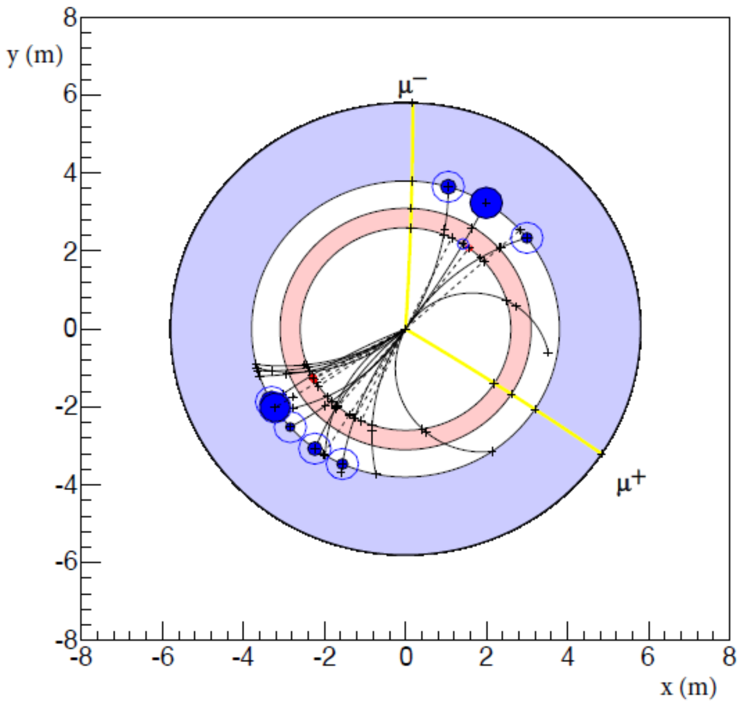
For a Higgs of 125GeV, a centre of mass energy of 240-250 GeV is optimal
➔ kinematical constraint near threshold for high precision in mass, width, selection purity

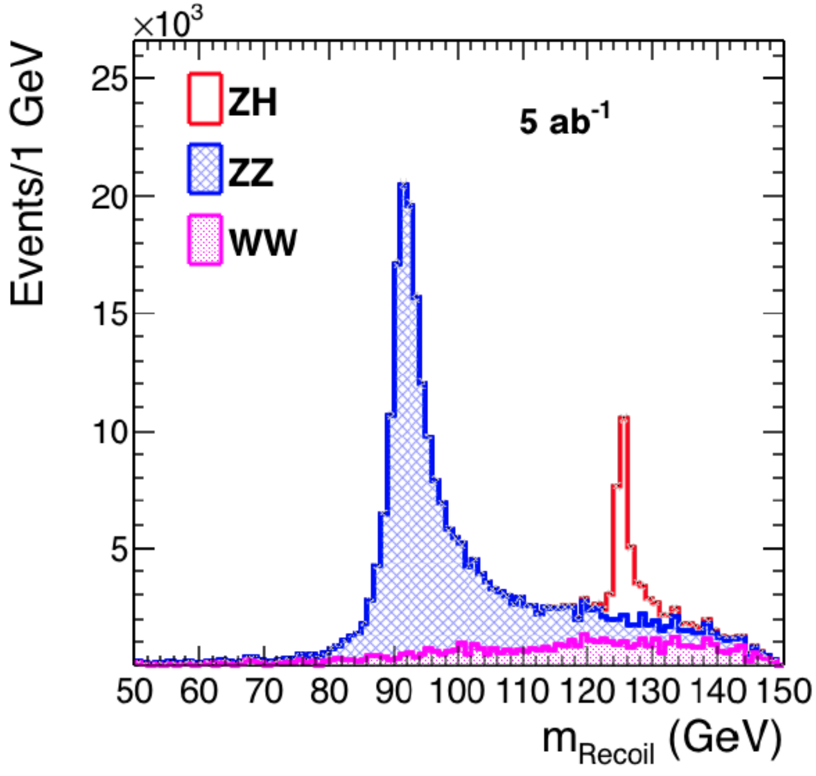
e+e- : Z – tagging by missing mass



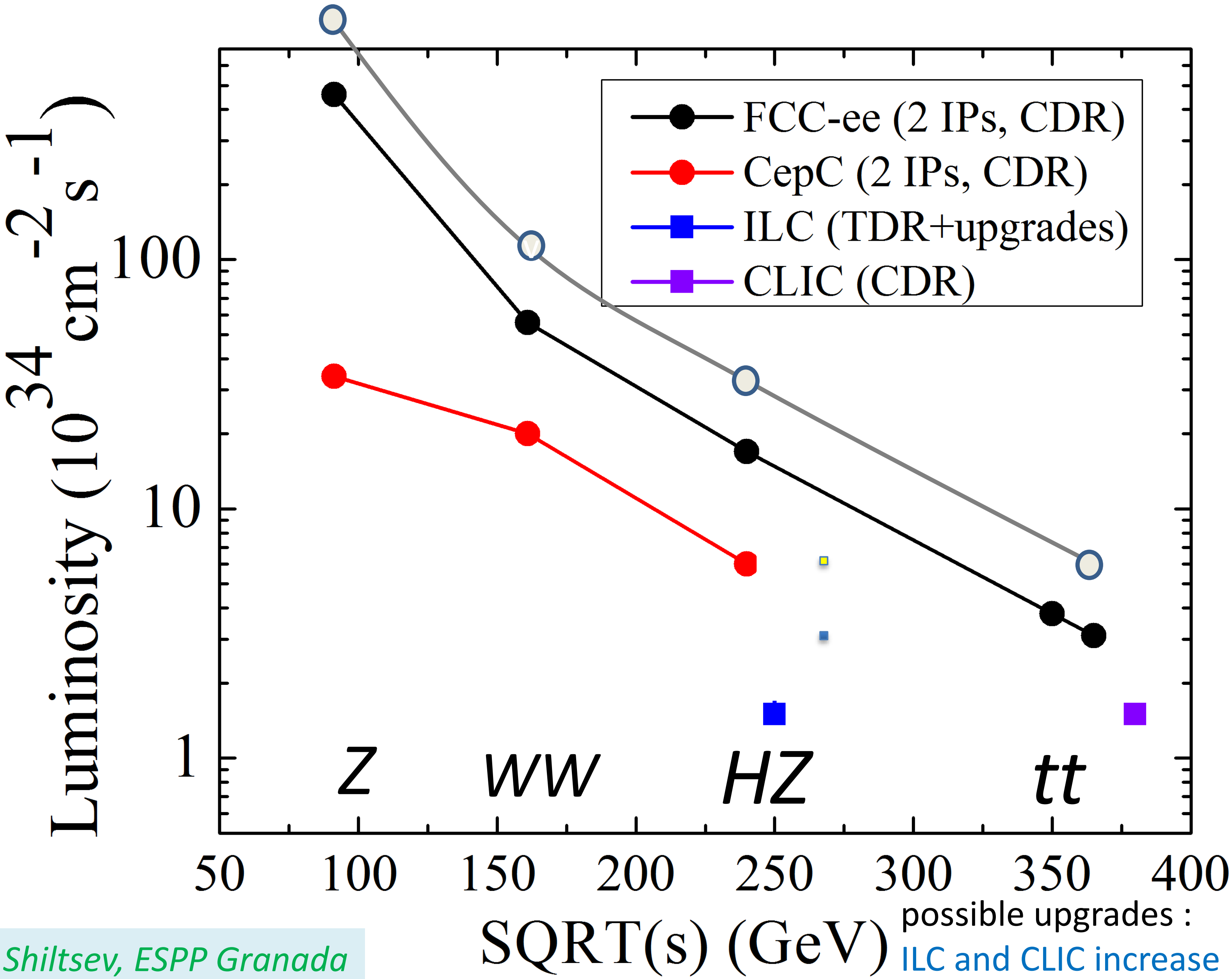
total rate $\propto g_{HZZ}^2$
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$
➔ **measure total width** Γ_H

g_{HZZ} to ±0.2% and many other partial widths
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold





not all the same : *e+e-* Higgs Factories: Circular vs Linear



Shiltsev, ESPP Granada

possible upgrades :

ILC and CLIC increase rep rate + Nb

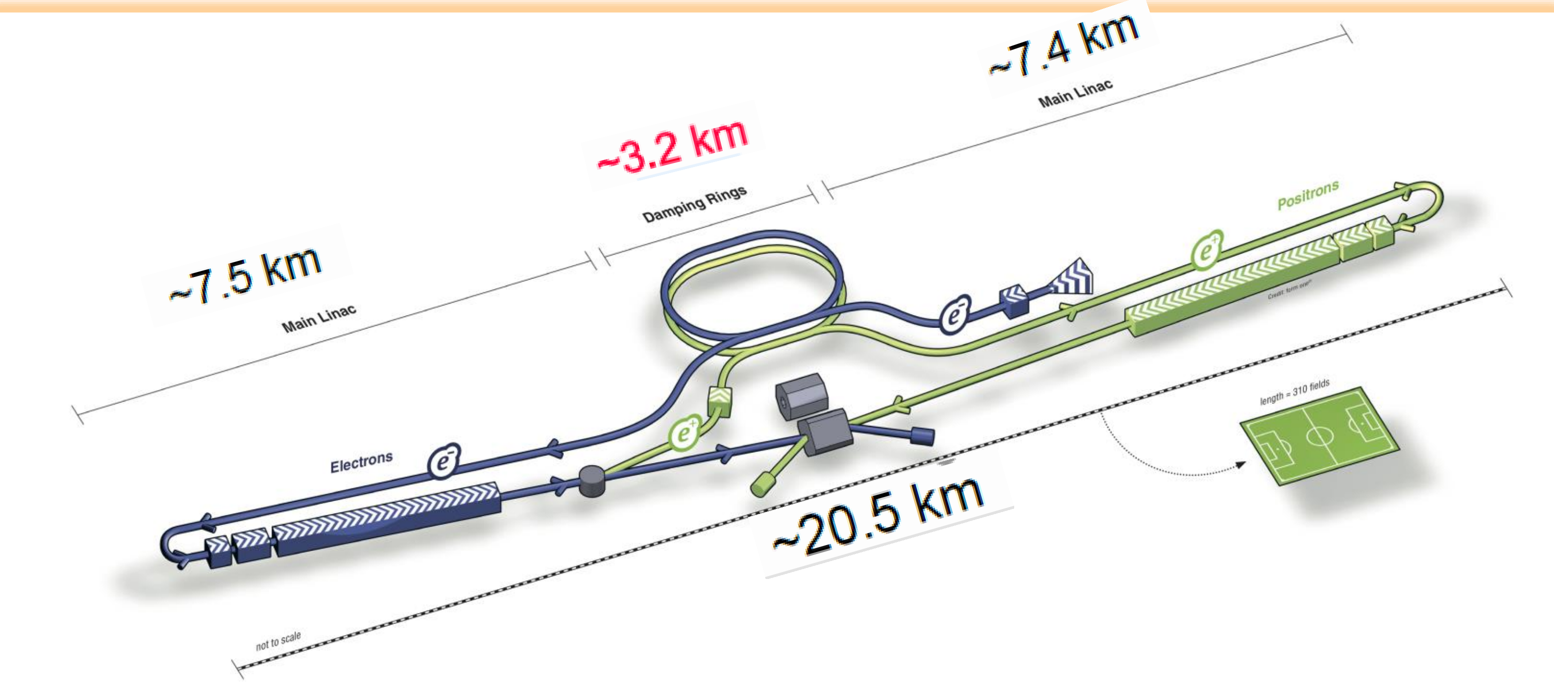
FCC-ee from 2 to 4 IP

International Linear Collider

Input #77

arXiv:1306.6328

TDR



Key facts:

20 km, including 5 km of Final Focus

SRF 1.3 GHz, **31.5 MV/m**, 2 K

130 MW site power @ 250 GeV ECM

Cost estimate **700 B JPY***

** ± 25% err, includes labor cost*

R&D still ongoing for

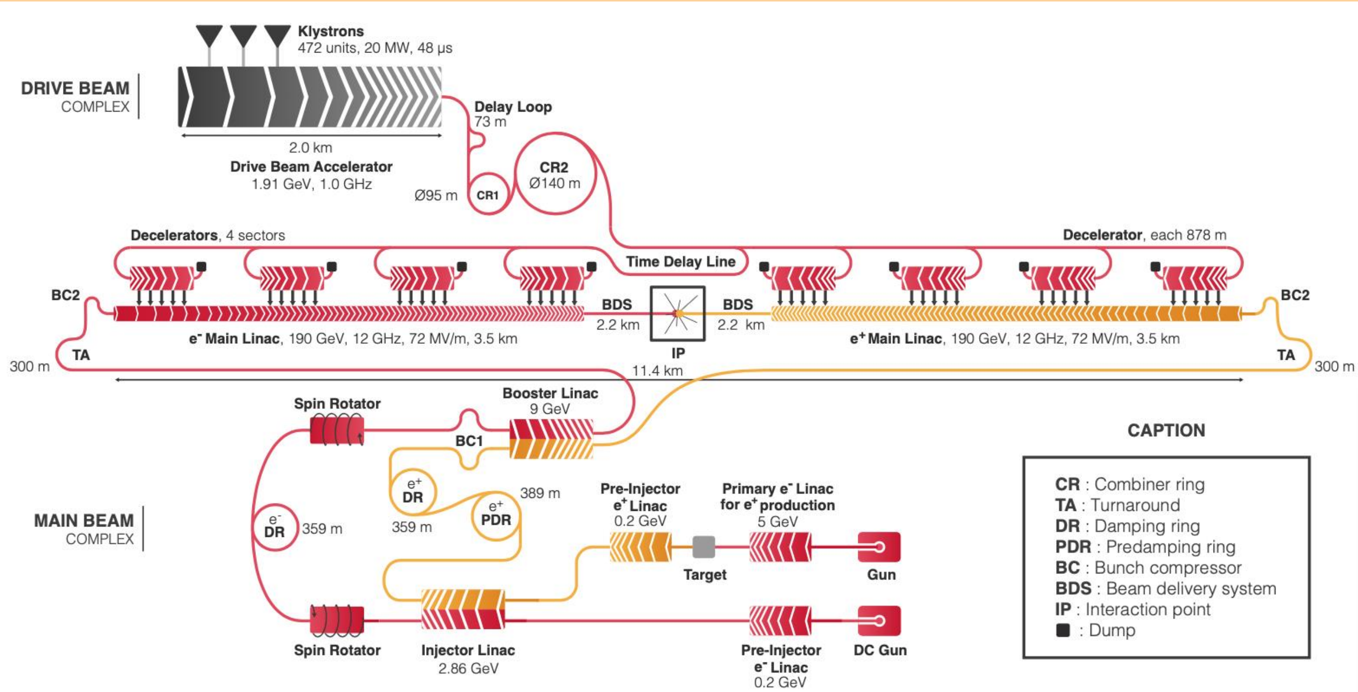
- beam quality needed for operation only achieved with low intensity
- positron source is still not fully solved

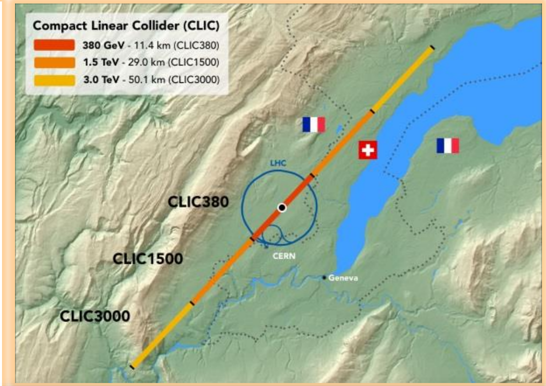
\+ Accelerating field still improving

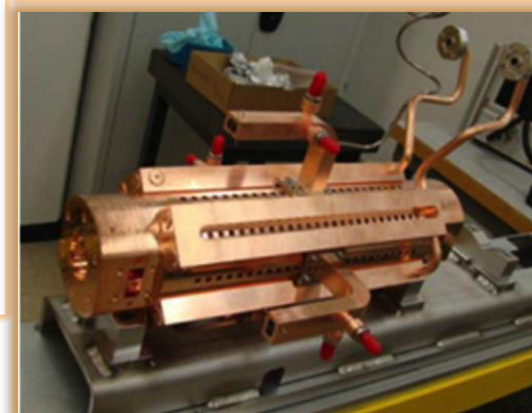
Compact LInear Collider

Input #146

arXiv:1209.2543 CDR







Key facts:

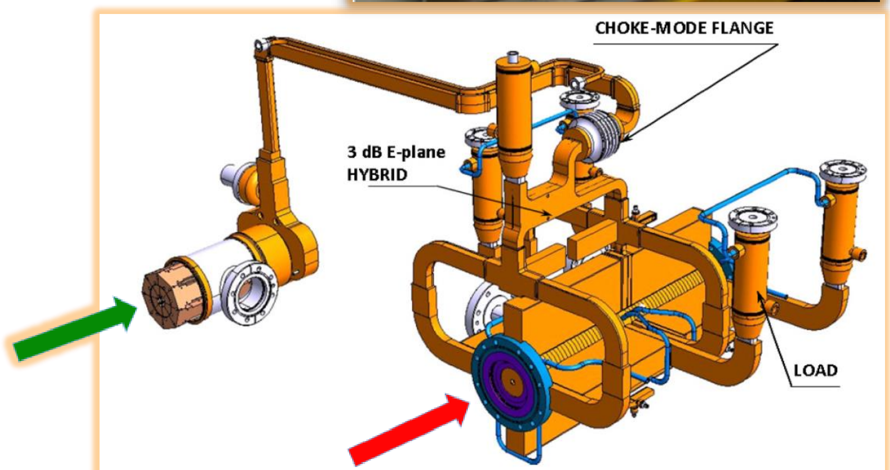
11 km main linac @ 380 GeV c.m.e.

NC RF **72 MV/m**, two-beam scheme

168 MW site power (~9MW beams)

Cost est. **5.9 BCHF** ± 25%

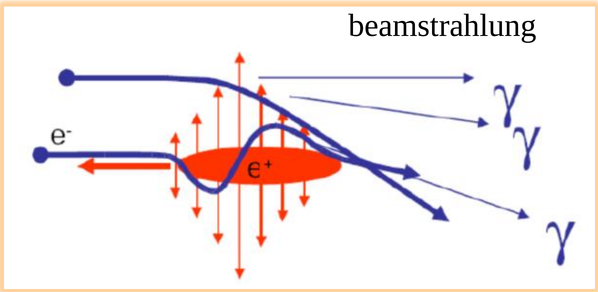
Beams requested are even smaller than at ILC



Challenges of Linear Colliders Higgs Factories

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y} \quad \sim 10^{34}$$

Luminosity Spectrum
(Physics)



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

Beam Current
(RF power limited, beam stability)

- **Challenging *e+* production (two schemes)**
- CLIC high-current drive beam bunched at 12 GHz

(klystrons + 1.4 BCHF)

Beam Quality
(Many systems)

- Record small DR emittances
- 0.1 µm BPMs
- IP beam sizes

ILC 8nm/500nm

CLIC 3nm/150nm

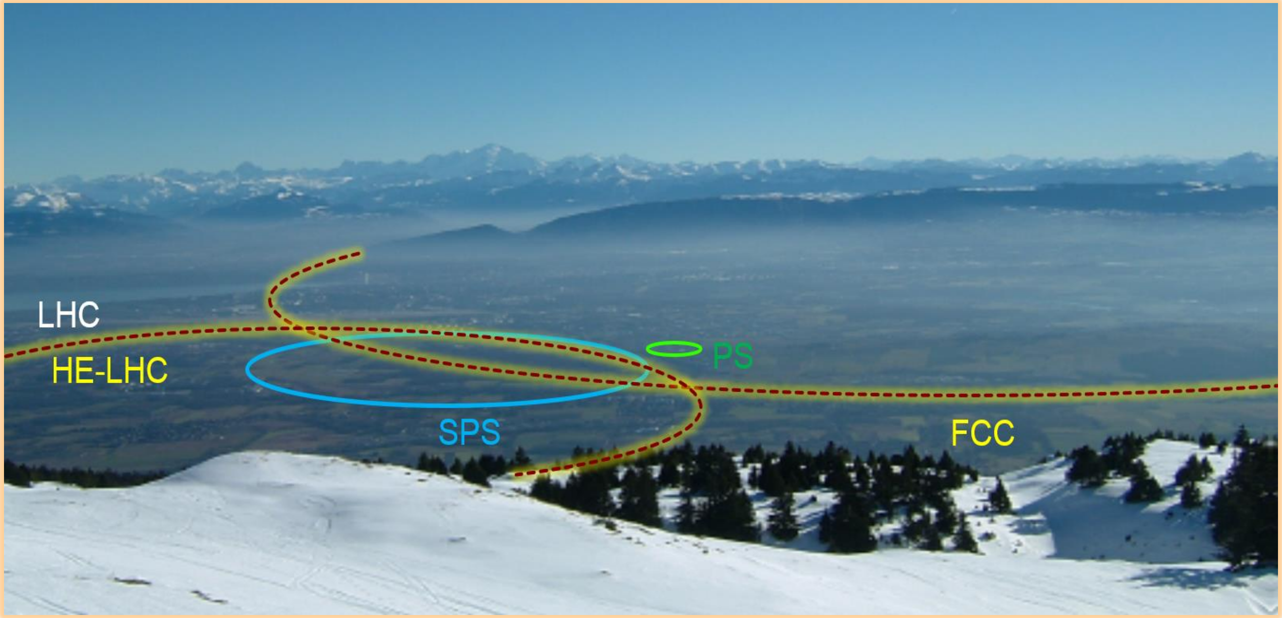
Linear Colliders *e+e-* Higgs Factories

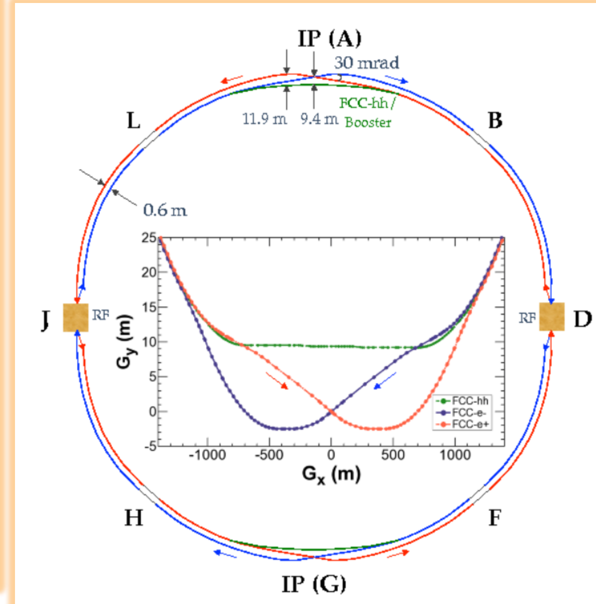
- **Advantages:**
  - Based on mature technology (Normal Conducting RF, SRF)
  - Mature designs: ILC TDR, CLIC CDR and test facilities
  - **Polarization (ILC: 80%-30% ; CLIC 80% - 0%) (but not essential, see later)**
  - Expandable to higher energies (ILC to 0.5 and 1 TeV, CLIC to 3 TeV)
  - Well-organized international collaboration (LCC) → "we're ready"
  - Wall plug power ~130-170 MW (i.e. <= LHC)
- **Pay attention to:**
  - Cost more than LHC ~(1-1.5) LHC
  - LC luminosity < ring (e.g., FCC-ee), and energy upgrades at the cost:
    - e.g. factor of 4 for ILC: *x2* $N_{bunches}$ and *5 Hz → 10 Hz* **(what about positrons?)**
  - Limited LC experience (SLC). two-beam scheme (CLIC) is novel, klystron backup?
  - Wall plug power may grow >LHC for *lumi* / E upgrades
  - positron target
  - upgrades are quite expensive! 1 TeV ILC → 17B$ 3 TeV CLIC -> 18.4B$.
  - only one collision point.

Circular e+e- Higgs Factories

Input #132

FCC-ee CDR (2018)





Key facts:

100 km tunnel, three rings (*e-*, *e+*, booster)

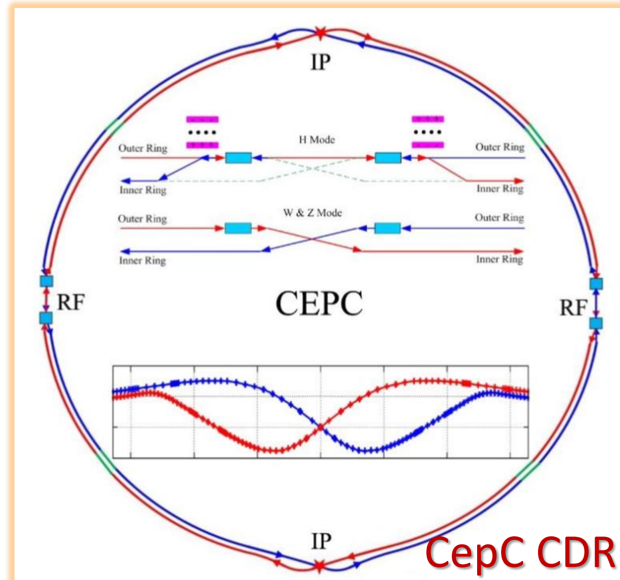
SRF power to beams 100 MW (60 MW in CepC)

Total site power <300MW (tbd)

Cost est. *FCCee* 10.5 BCHF (+1.1BCHF for tt)

of which 7BCHF is infrastructure that will be used for future hadron collider FCC-hh

(< 6BCHF cited in the *CepC CDR*)

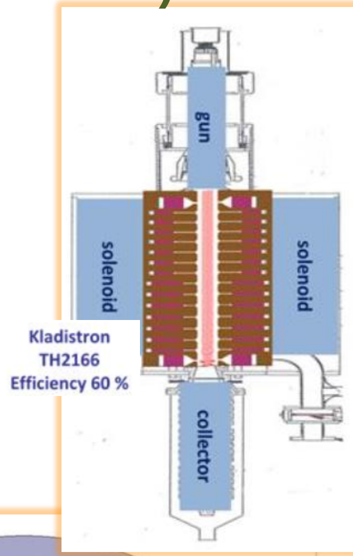


CepC CDR

Input #51 arXiv:1809.00285

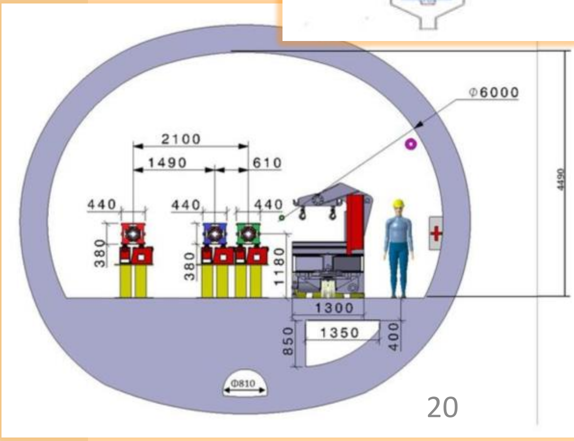
e+e- Ring Higgs Factories

- ***Advantages:***
  - **Based on mature technology (SRF) and rich experience → low risk**
  - High(er) luminosity and ratio luminosity/cost; up to 4 IPs, **EW factories**
  - 100 km tunnel can be reused for a ***pp* collider** in the future
  - **Transverse polarization (τ~ 18 min at *tt*) for *E* calibration O(100keV)**
  - CDRs addressed key design points, mb ready for ca 2039 start
  - Very strong and broad **Global FCC Collaboration**

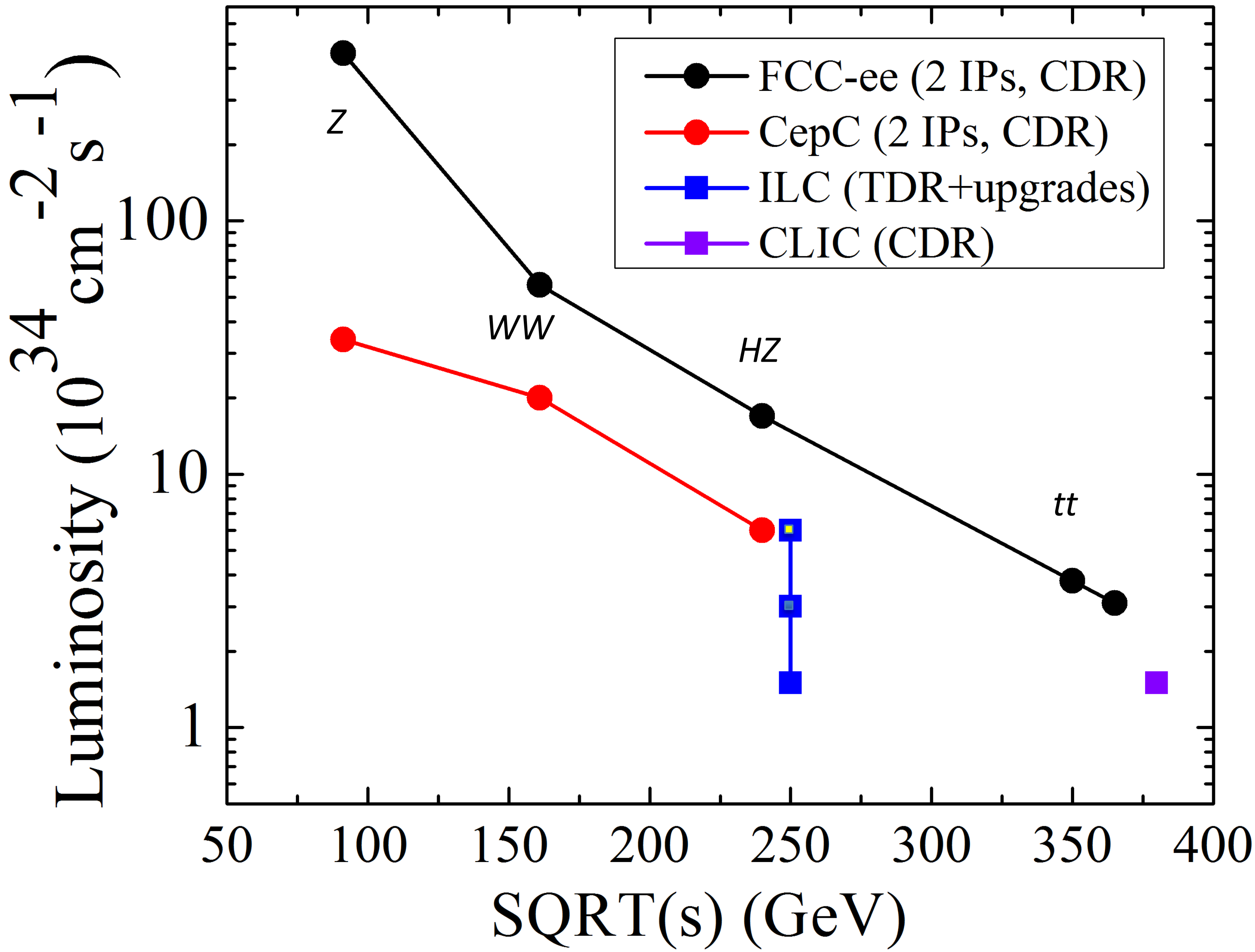


Strategic R&D ahead :

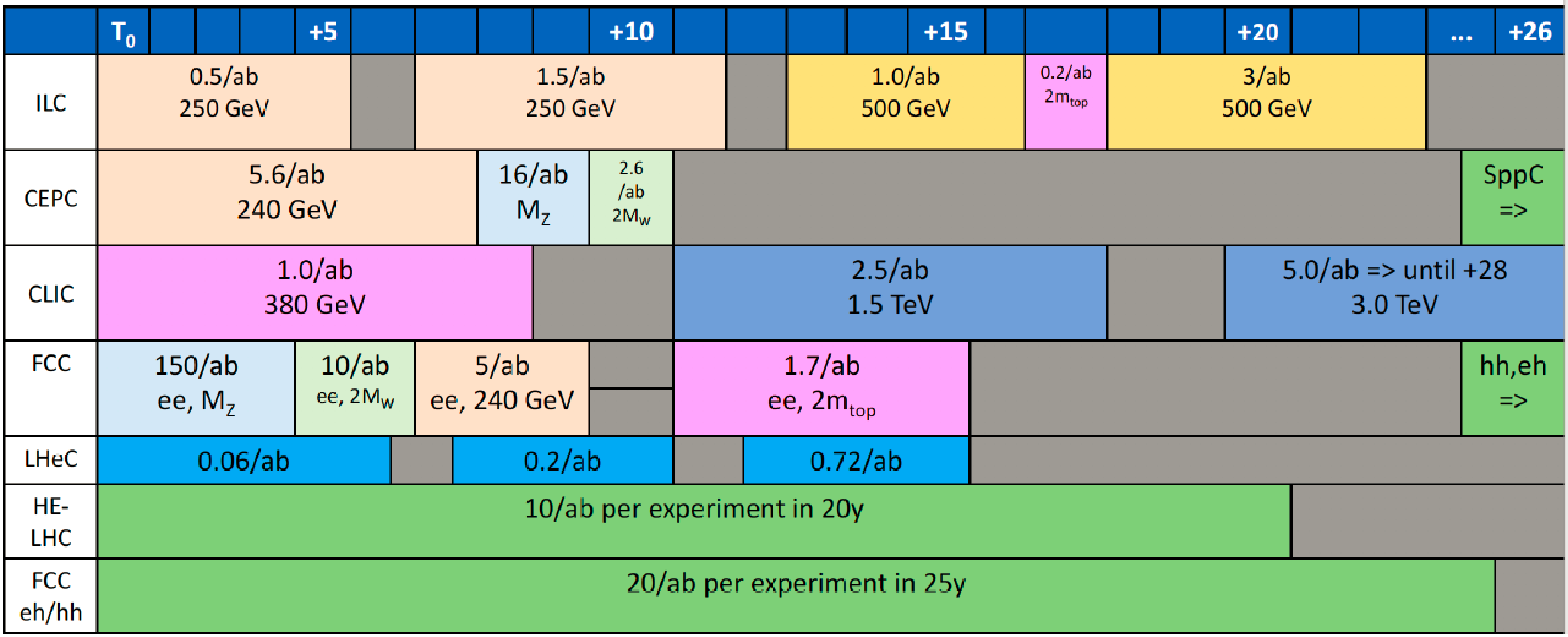
- High efficiency RF sources:
  - Klystron 400/800 MHz η from 65% to >85%
- High efficiency SRF cavities:
  - 10-20 MV/m and high Q_0; Nb-on-Cu, Nb_3Sn
- Crab-waist collision scheme:
  - *Super KEK-B* nanobeams experience will help
- Energy Storage and Release R&D:
  - Magnet energy re-use > 20,000 cycles
- Efficient Use of Excavated Materials:
  - 10^7 m^3 out of 100 km tunnel
- Cost performance optimization



e+e- Higgs Factories: Circular vs Linear



RUN PLANS OF VARIOUS FACILITIES



NB: number of seconds/year differs: ILC $1.6x10^7$, FCC-ee & CLIC: $1.2x10^7$, CEPC: $1.3x10^7$

Notes and caveats:

-- Run plan for FCC-ee is 2IP, baseline, includes TeraZ and m_W measurement.

Flexible: Higgs run can be chosen to be at the start, giving 5ab-1 in 4 years.

-- run plan for CLIC assumes upgrades of 5-7 BCHF every 9 years (probably ~factor 2 too fast)

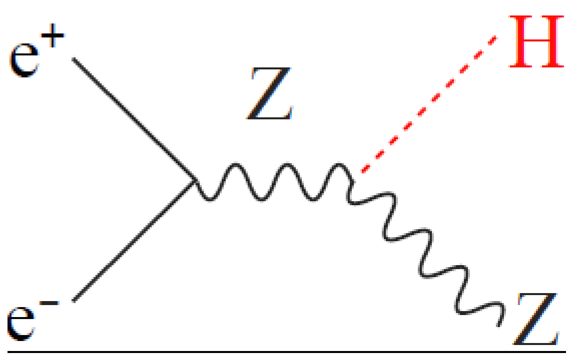
-- run plan for ILC includes upgrades beyond TDR

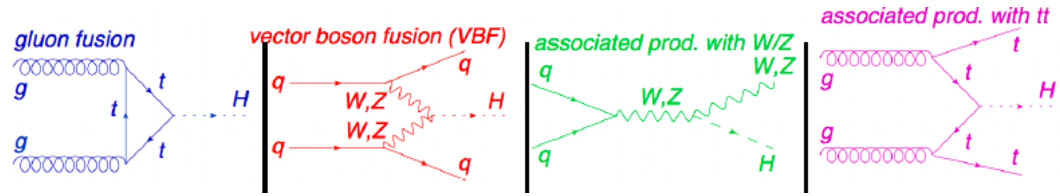
Typically 1 years at FCC-ee = 10 years at ILC.

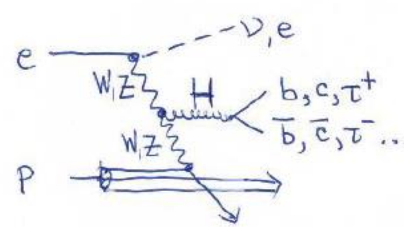
The FCC integrated program FCC (ee and hh, ep) by way of

synergy and complementarity

will provide the most complete and model-independent studies of the Higgs boson







ee provides 10^6 ZH + 10^5 Hvv evts

-- Model-Independent Γ_H determination

-- g_{HZZ} Higgs coupling to Z at 0.17%

→fixed candle for all measurements

(WW, bb, $\tau\tau$, cc, gg etc… <% level)

→ even possibly Hee coupling!

also first 40% effect of g_{HHH} from loop effect

(22% with 4 IPs)

pp provides 2.10^{10} Higgs !

(Using **ee** 'candle') will provide

-- model-independent ttH coupling to <1%

-- rare decays ($\mu\mu$, $\gamma\gamma$, $Z\gamma$ …)

-- invisible width to 5 10^{-4} BR

-- Higgs self coupling g_{HHH} to 5%

ep will produce 2.5 10^6 Higgs

(using **ee** 'candle') **further improves**

on several measurements esp. g_{HWW} coupling

Superb complementarity!

kappa-3 scenario	HL-LHC+								
	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
κ_W (%)	1.1	0.29	0.75	0.4	0.38	0.95	0.95	0.41	0.2
κ_Z(%)	0.29	0.23	0.44	0.39	0.39	0.18	0.19	0.17	0.17
κ_g(%)	1.4	0.84	1.5	1.1	0.86	1.1	1.2	0.89	0.53
κ_γ (%)	1.3	1.2	1.5∗	1.3	1.1	1.2	1.3	1.2	0.36
$\kappa_{Z\gamma}$ (%)	11.∗	11.∗	11.∗	8.4	5.7	6.3	11.∗	10.	0.7
κ_c (%)	2.	1.2	4.1	1.9	1.4	2.	1.6	1.3	0.97
κ_t (%)	2.7	2.4	2.7	1.9	1.9	2.6	2.6	2.6	0.95
κ_b (%)	1.2	0.57	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ (%)	4.2	3.9	4.4∗	4.1	3.5	3.9	4.	3.9	0.44
κ_τ (%)	1.1	0.64	1.4	0.99	0.82	0.96	0.98	0.66	0.49
BR_{inv} (<%, 95% CL)	0.26	0.22	0.63	0.62	0.61	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.8	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.
self coupling %	--	27/35	--	36	9	--	--	35	<5

yellow: based on ZH cross-section measurements
white : based on analyis of HH production

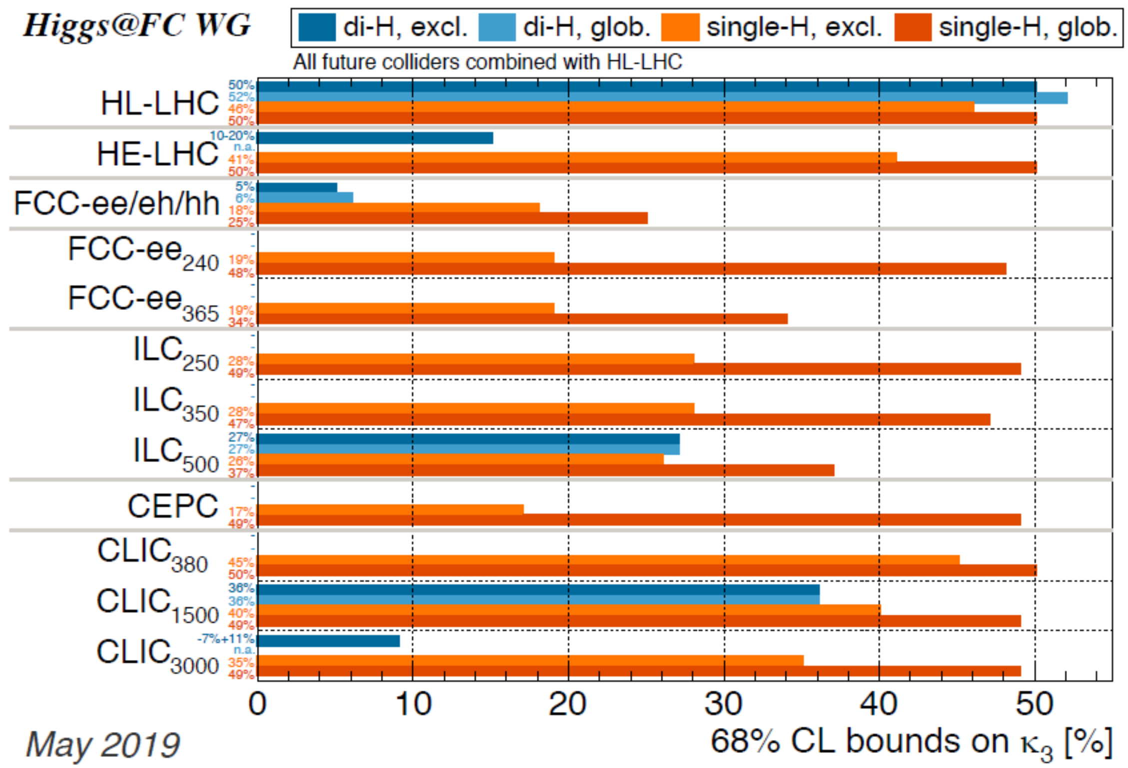
Sensitivity to λ: via single-H and di-H production

Di-Higgs:

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

Single-Higgs:

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



NOT «JUST» A HIGGS FACTORY!

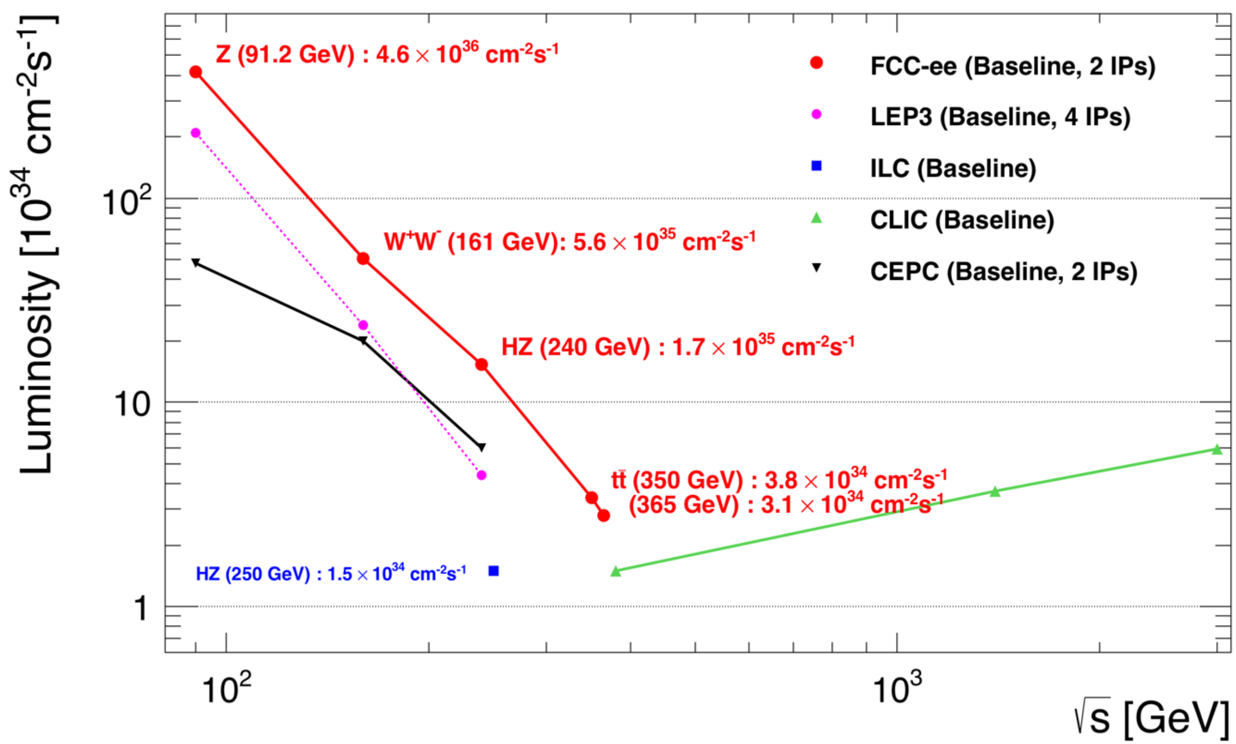
By running at the Z pole, W pair threshold and top threshold,
the FCC plans to perform an extensive improvement of EW measurement by factor 20 -100 on many observables.

Should reveal the presence of SM-coupled particles (if operator in $1/\Lambda^2$) up to 70 TeV
and non-decoupling effects (breaking SM symmetry) to much higher energies

An Electroweak Factory!

FCC-ee

Z WW HZ tt



Event statistics :

					E_{CM} errors:
Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$	e+e- → Z	LEP x 10^5	100 keV
WW threshold	E_{cm} : 161 GeV	10^8	e+e- → WW	LEP x 2.10^3	300 keV
ZH threshold	E_{cm} : 240 GeV	10^6	e+e- → ZH	Never done	1 MeV
$t\bar{t}$ threshold	E_{cm} : 350 GeV	10^6	e+e- → $t\bar{t}$	Never done	2 MeV

Great energy range for the heavy particles of the Standard Model.

Beam Polarization

Circular colliders offer transverse polarization that builds naturally.

→ beam energy calibrations from spin resonance at 10^{-6} precision.

$m_{J/\psi}$ = 3096.900±0.002±0.006 MeV (VEPP-4M), m_Z =91.1867 ±0.0023 (LEP)

polarization process is limited by beam energy spread which grows as $\sigma_E \propto E^2/\sqrt{\rho}$

better in a large ring → can reach both Z region and WW pair threshold.

This is unique to circular colliders (ee and $\mu\mu$)

➔ expect precisions on m_Z (100ke) Γ_Z (< 100 keV) m_W (600 keV) $\sin^2\theta_w^{eff}$ ($6\ 10^{-6}$)

Obtaining longitudinal center-of-mass spin polarization requires spin rotation which is more delicate, energy dependent and will reduce luminosity

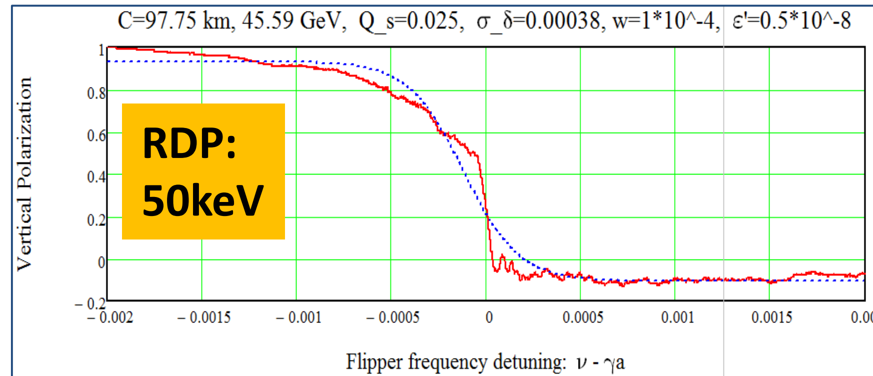
Linear colliders have the advantage that longitudinally polarized beams are available from the electron source. This enhances some helicity physics sensitivity esp. via the A_{LR} measurement at the Z run.

In general the **longitudinal polarization does not give anything that cannot be ortained otherwise with sufficient statistics,** and FCC-ee decided to focus on the energy calibration

FCC-ee Beam Polarization and Energy Calibration

Simulations show transverse polarization at Z (with wigglers) & WW energies
→ Energy calibration by resonant depolarization (RDP) feasible every 10' on pilot bunches
UNIQUE to Circular Colliders

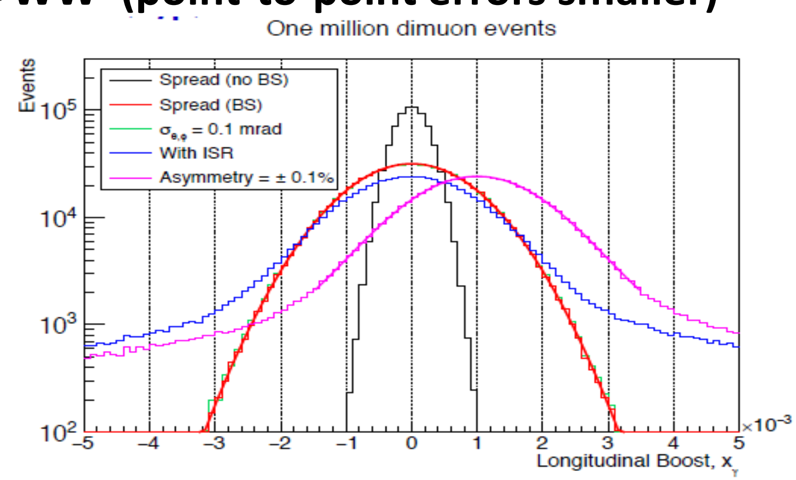
-- Continuous E_{CM} calibration at Z and W
Polarimeter, wigglers, RF kicker
Only one RF section at these energies



260 seconds sweep of depolarizer frequency

-- **E_{CM} effects** : beamstrahlung (62 keV),
Synchrotron radiation in arcs
RF errors, aligment errors etc….
all are compensated by RF within small errors

➔ **Total E_{CM} uncertainty of 100 keV @Z and 300 keV @WW (point-to-point errors smaller)**



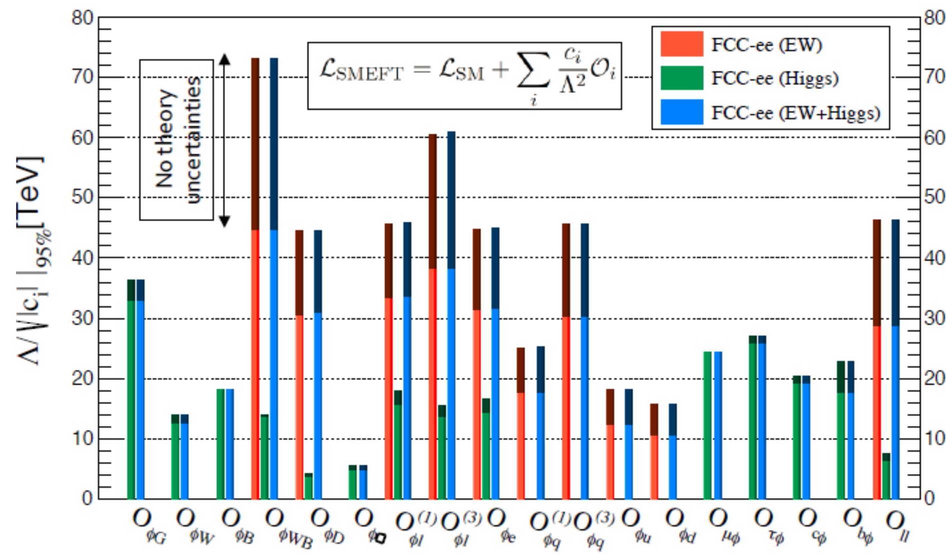
Energy spread and CM boost will be measured with e+e- → μμ events (10^6 /5min @Z) ➔ 45 keV precision

→ **high redundancy for precision measurements**

Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV/c^2)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20767 ± 25	0.06	0.2-1	ratio of hadrons to leptons acceptance for leptons
$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6	from R_ℓ^Z above [29]
R_b ($\times 10^6$)	216290 ± 660	0.3	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [30]
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement
N_ν($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$($\times 10^6$)	231480 ± 160	3	2 - 5	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128952 ± 14	4	small	from $A_{FB}^{\mu\mu}$ off peak [20]
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics
m_W (keV/c^2)	80350000 ± 15000	600	300	From WW threshold scan Beam energy calibration
Γ_W (keV)	2085000 ± 42000	1500	300	From WW threshold scan Beam energy calibration
$\alpha_s(m_W)$($\times 10^4$)	1170 ± 420	3	small	from R_ℓ^W [31]
N_ν($\times 10^3$)	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	20	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	40	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.08	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	<2%	small	From E_{CM} = 365GeV run

Pecision EW measurements: is the SM complete?



-^- EFT D6 operators (some assumptions)

-^- Higgs and EWPOs are complementary

-^- top quark mass and couplings essential!

(the 100km circumference is optimal for this)

<-- many systematics are preliminary and should improve with more work.

<-- tau b and c observables still to be added

<-- complemented by high energy FCC-hh

Theory work is critical and initiated

DR presentation

ok

Theoretical challenges

FCC proposes a HUGE step in statistical precision w.r.t. LEP/SLC/Tevatron/LHC
(up to factor sqrt(N)~400 improvement)
Also rare processes at the level of <**10^{-12}** of Z decays (10^{-8} for W, 10^{-6} for H and top)

→ need to know rare SM processes at that kind of level!

Experiment (i.e. accelerator physics + experimental physics) will work hard to make sure that this is matched by experimental systematics and experimental backgrounds

This is a huge challenge for the theoretical community!

QED
QCD (incl. quark masses)
EW
Multi-loop calculations and exponentiation

THIS IS EXPLICITELY INSCRIBED IN THE ESPP SUBMISSIONS AS CRITICAL CHALLENGE

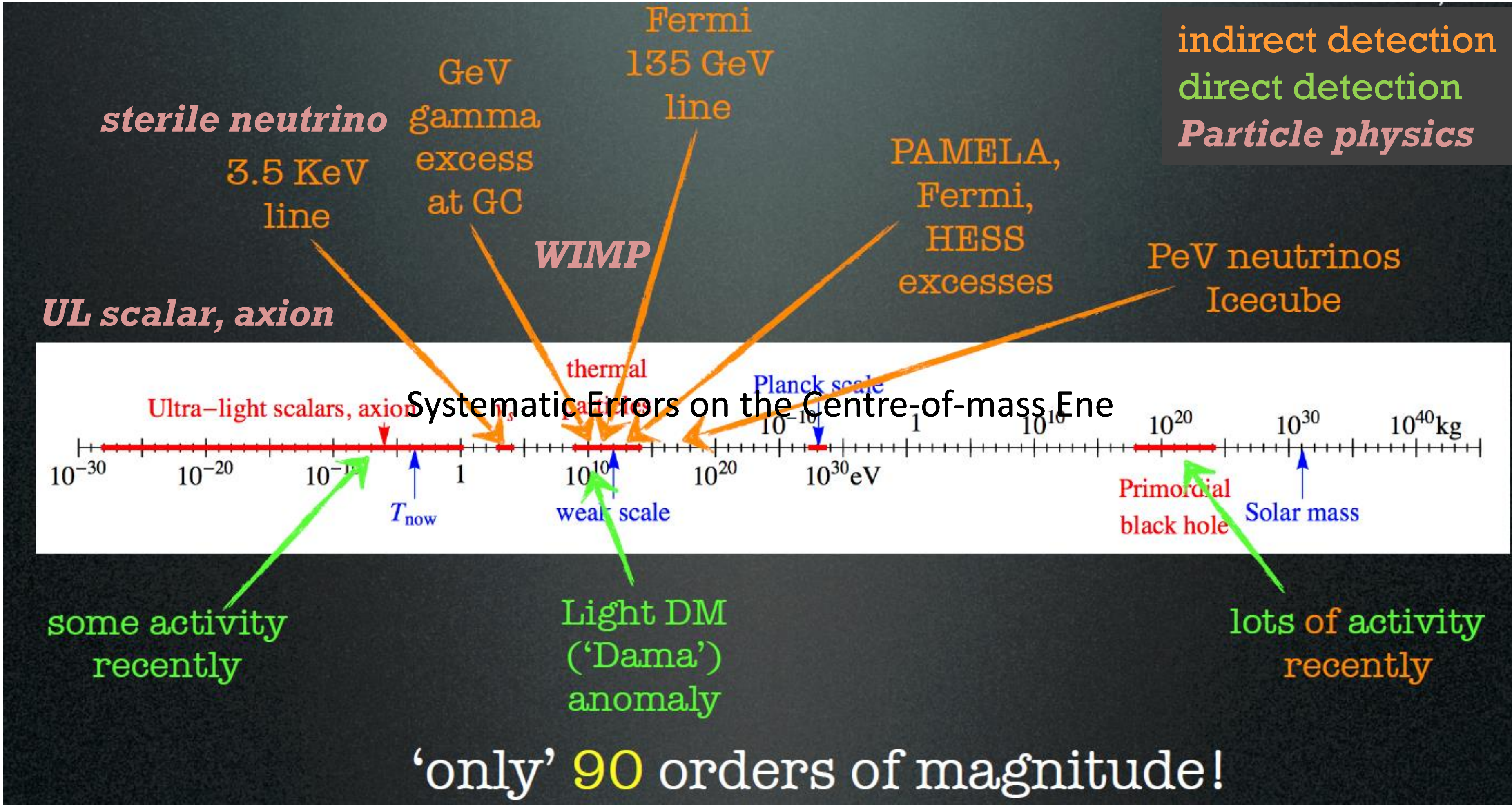
Insufficient level of theoretical precision and accuracy.	Full exploitation of machine's capabilities depends on accurate theoretical predictions of SM phenomena at levels where higher-order contributions become significant.	Set up an international collaboration, leveraging existing world-wide HEP computing infrastructures, to develop the tools and to carry out the necessary computations. This effort is assumed to require substantial committed engagement of personnel by the collaborating institutes during the design, construction and operation phases.

Nima

At higher masses -- or at smaller couplings?

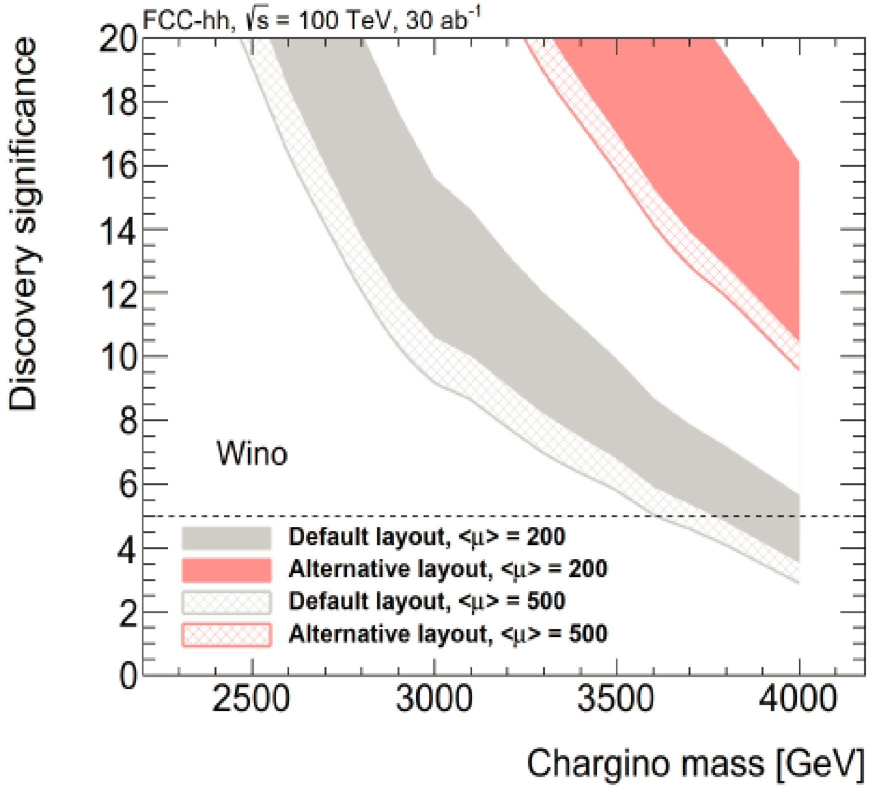
Dark Matter exists. It is made of very long lived neutral particle(s).

Plausible candidates:

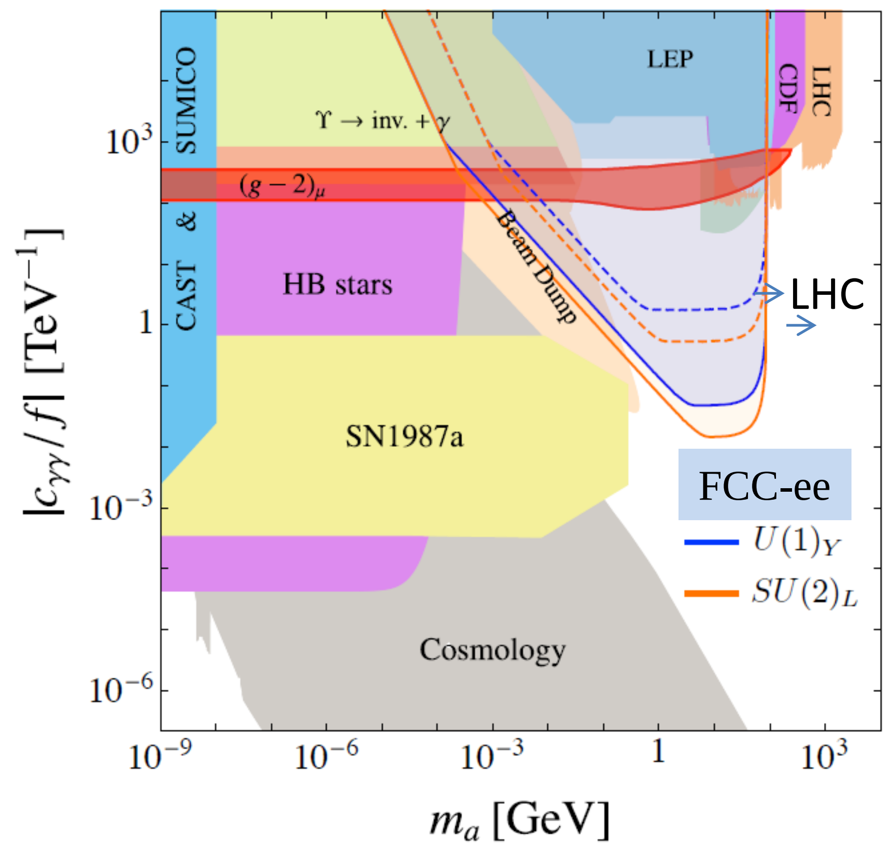


Cirelli

DM neutralino search at the FCC-hh



FCC-ee Z Axion-like particle

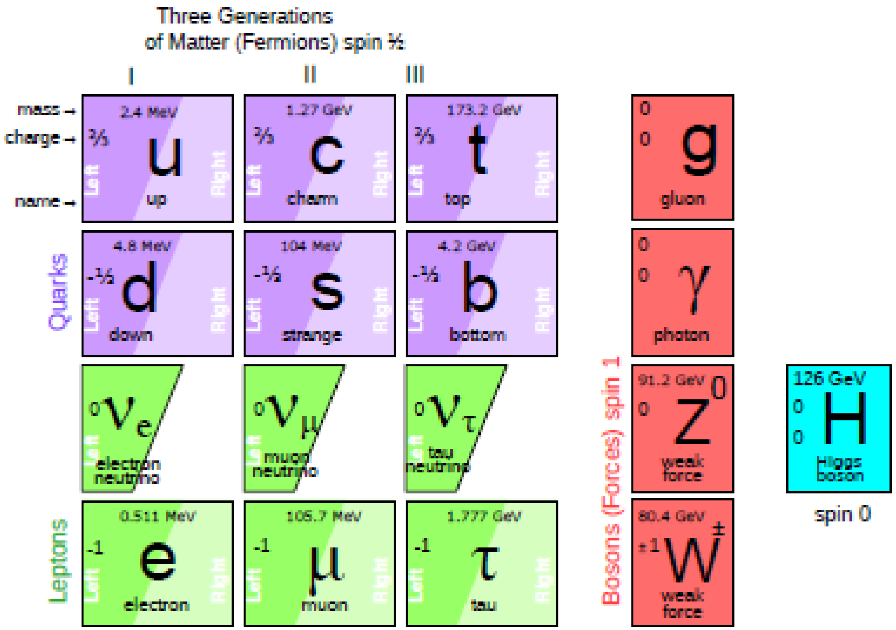


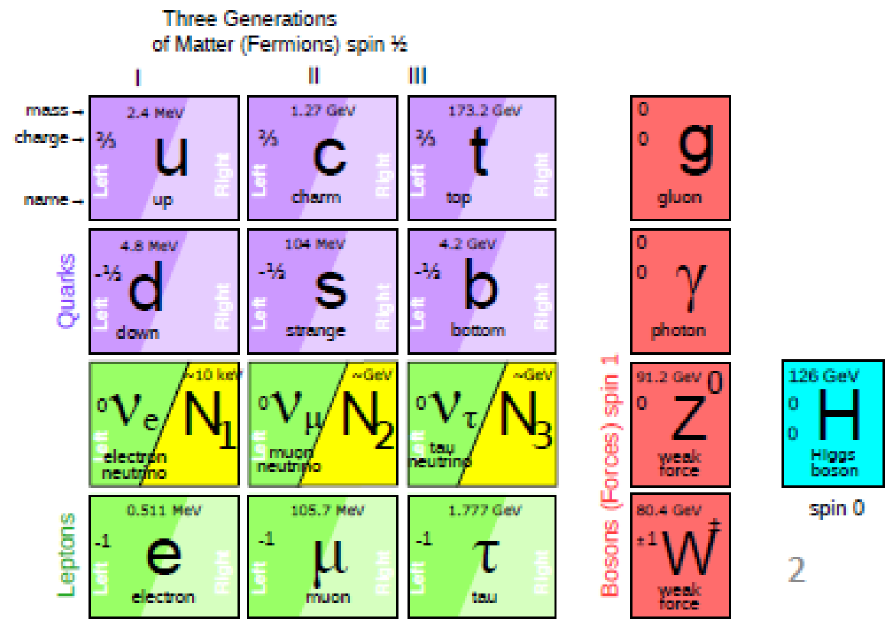
"FCC-hh covers the full mass range for the discovery of these WIMP Dark Matter candidates"

Z→ γa with a→γγ
FCC-ee (solid lines)
Run-2 of the LHC with 300 fb^{-1} (dashed)

«The Z run of FCC-ee is particularly fertile for discovery of particles with very small couplings»

at least 3 pieces are still missing





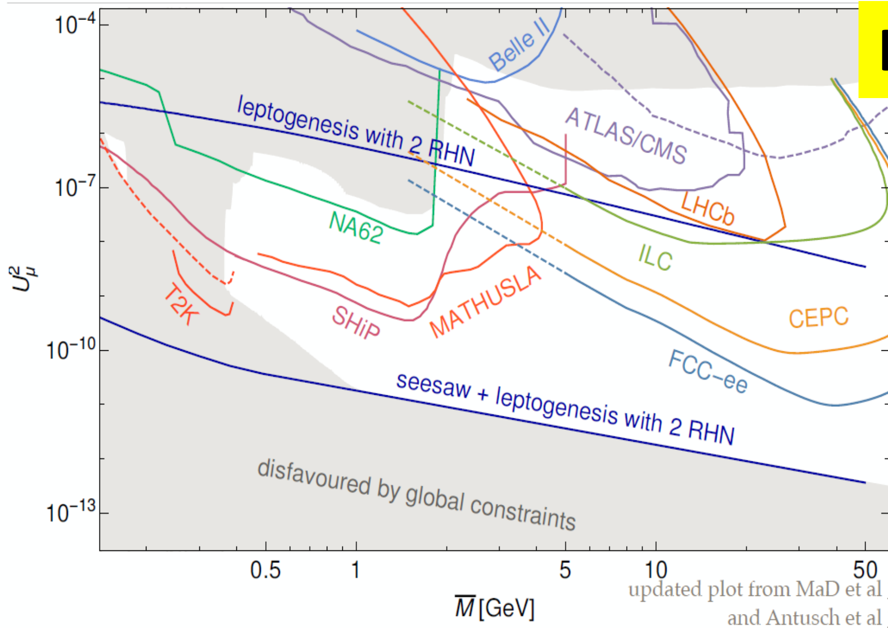
Since 1998 it is established that neutrinos have mass (oscillations) and this very probably implies new degrees of freedom

➔ «sterile», very small coupling to known particles

completely unknown masses (eV to ZeV), nearly impossile to find.

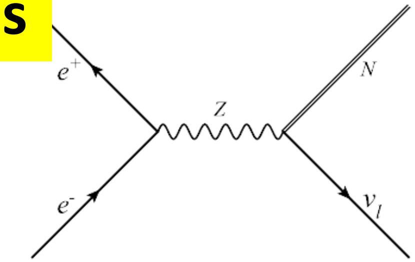
.... but could perhaps explain all: DM, BAU,ν-masses

Heavy neutrinos



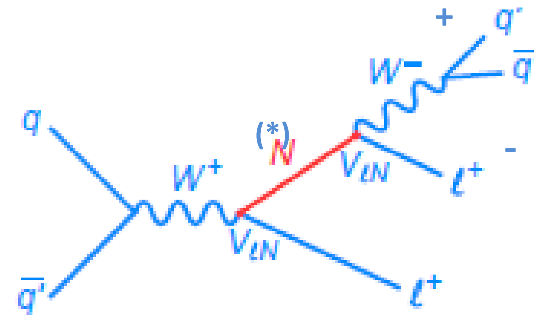
updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

FCC-ee Z

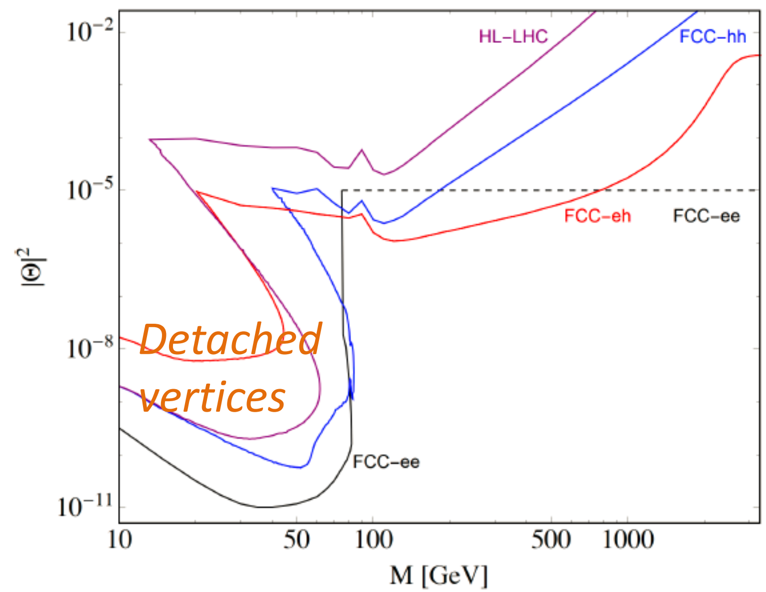


or $l^{\pm}\nu$

FCC-hh



FCC-ee
-- EWPO : sensitivity 10^{-5} up to very high masses
-- high sensitivity to single N(→ $l_2^{\pm}$W) in Z decay
FCC-hh
-- production in W-> $l_1^{\pm}$ + N(→ $l_2^{\pm}$ W)
with initial and final lepton charge and flavour
FCC e-p
-- production in CC $e^{\pm}$ p → X N(→ $l^{\pm}$W) high mass
<u>Complementarity:</u>
discovery + studies of FNV and LFV!



The capability to probe massive neutrino mechanisms for generating the matter-antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders. (from the neutrino town meeting report to the ESPP)

FLAVOUR OBSERVABLES

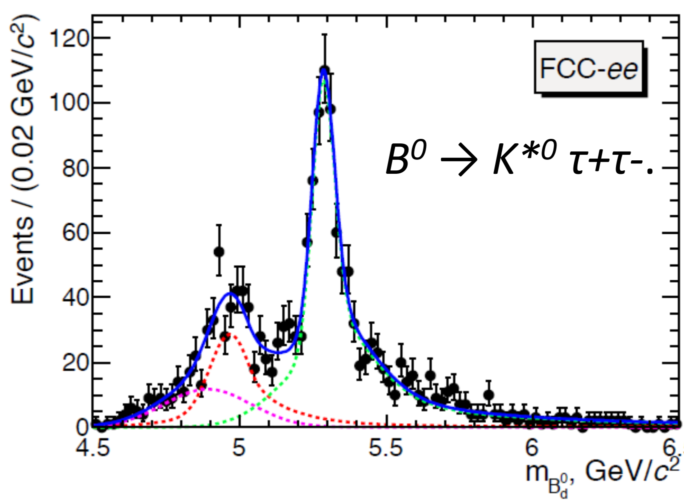
Z run → 10^{12} $b\bar{b}$ events and 10^{11} $\tau\bar{\tau}$ events → significant improvements w.r.t. BELLE II
-- higher energy leptons→ better e/μ/π separation
-- lifetime, braching ratios, rare decays, tests of Universality

Table 7.1: Expected production yields of heavy-flavoured particles at Belle II (50 ab^{-1}) and FCC-ee.

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	550	170

study of rare B decays and test of flavour universality

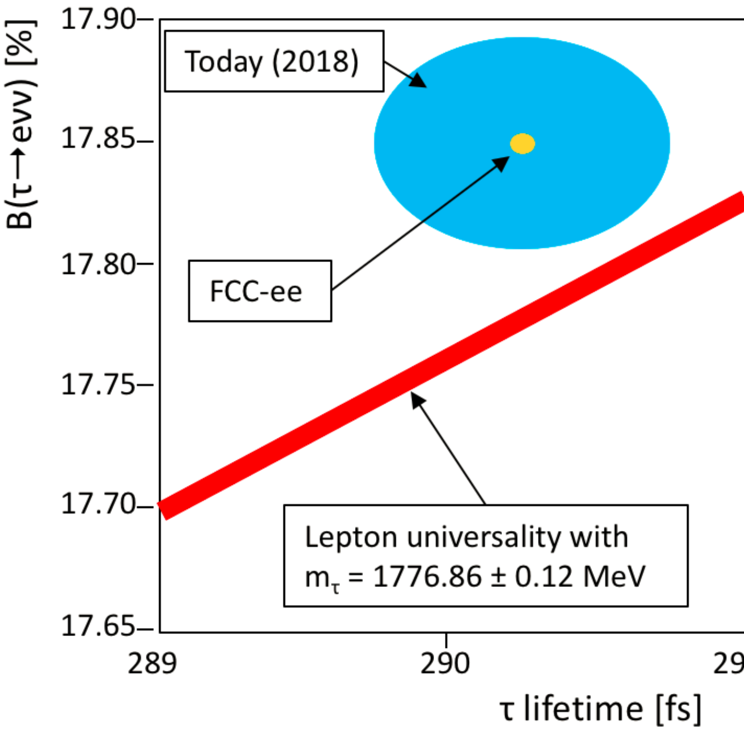
Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	~ 2 000	~ 10	n/a (5)
LHCb Run I	150	-	~ 15 (–)
LHCb Upgrade	~ 5000	-	~ 500 (50)
FCC-ee	~ 200000	~ 1000	~1000 (100)



τ physics

Improve Lepton flavour violation sensitivity by 3 orders of magnitude

$$\mathcal{B}(Z \to \tau^{\pm}\ell^{\mp}) < 10^{-9} \text{ @ } 95\% \text{ C.L.}$$



tau branching ratios are a good **test of Universality** of the α - ν_α CC coupling α= e μ τ

➔ sensitive to light-heavy neutrino mixing

(Can someone re-measure the tau mass better?)

and many more….

Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF [%]	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04

«systematics will be at least this good»

→ to be studied further!

FCC-ee discovery potential and Highlights

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements
-- ~20-100 fold improved precision on many EW quantities (equiv. to factor 5-10 in mass)
m_Z, m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , $\alpha_{QED}(m_z)$ α_s (m_z m_W m_τ), Higgs and top quark couplings
model independent «fixed candle» for Higgs measurements

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
-- ex FCNC ($Z \to \mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ BR in 2 10^{11} $Z \to \tau\tau$
+ flavour physics (10^{12} bb events) ($B \to s\tau\tau$ etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons, ALPS, etc…

+ and many opportunities in – e.g. QCD (α_s @ 10^{-4}, fragementations, $H \to gg$) etc….

NB Not only a «Higgs Factory»! «Z factory» and «top» are important for 'discovery potential'

Limits of Linear $e+e$- Colliders

- Both ILC and CLIC offer staged approach to ultimate E

- The limits are set by:

  Cost

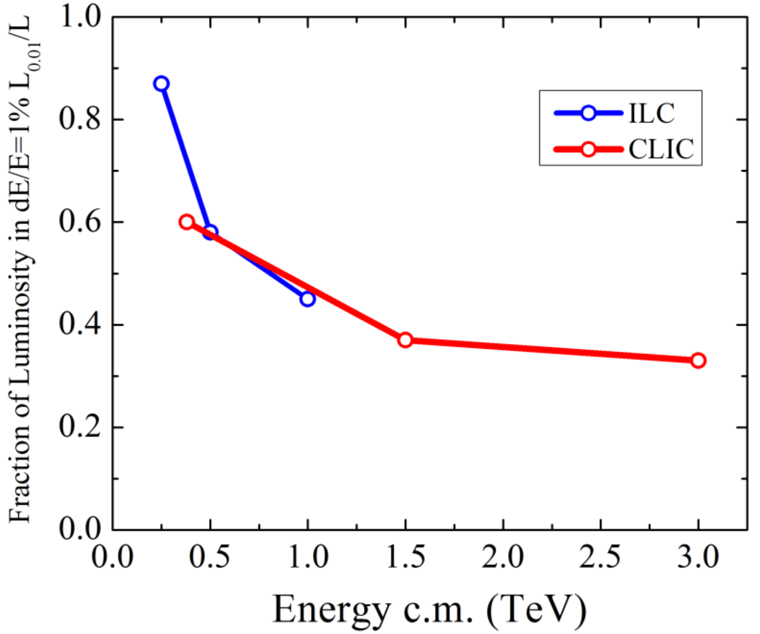
  Electric power required

  Total length

  Beamstrahlung

ILC TDR 1 TeV 17 B$ ±25%
CLIC CDR 3 TeV 18.3BCHF ±25%

Luminosity Dilution by Beamstrahlung



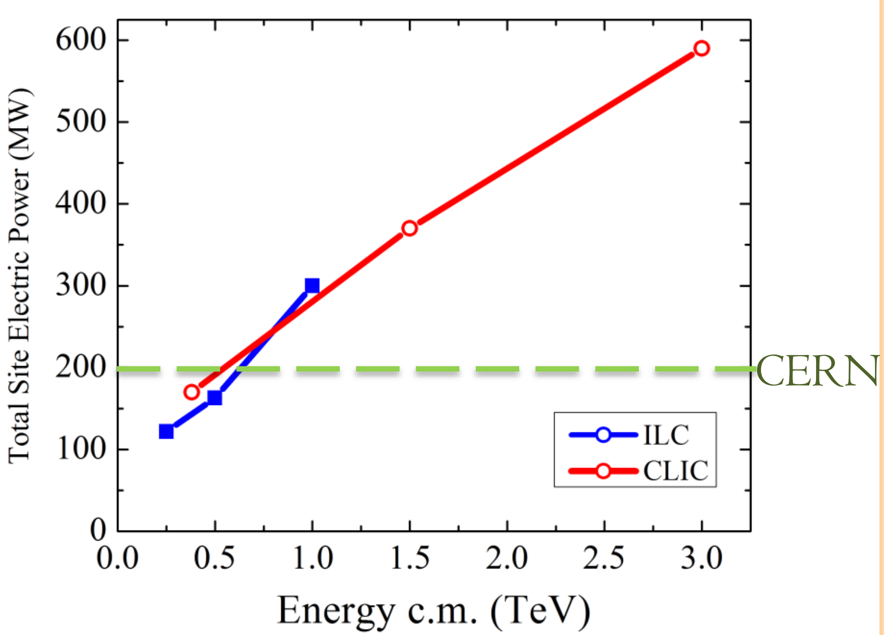
Beamstrahlung rms energy spread :

$$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z}\right)\frac{N^2}{\sigma_x^2}$$

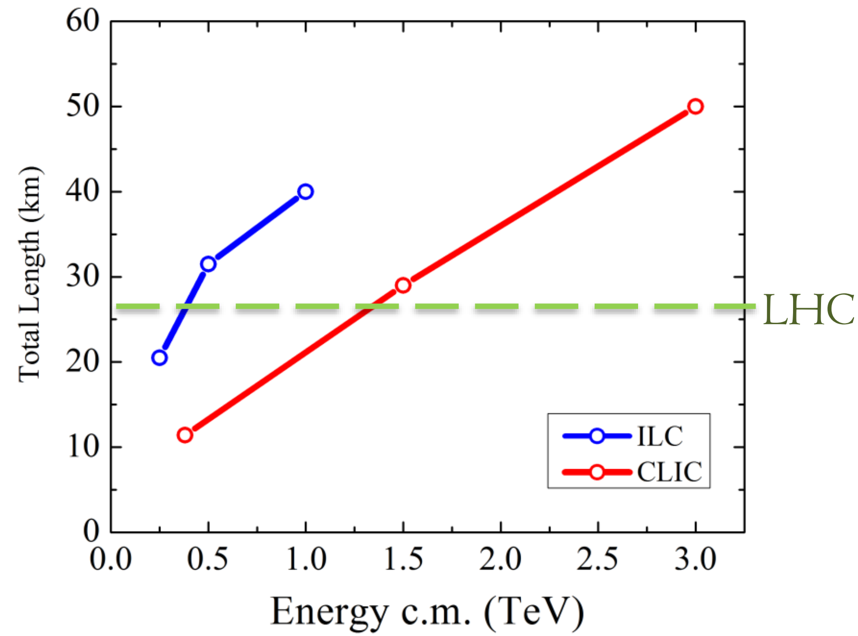
→ Luminosity :

$$L \propto P_{beam}\sqrt{\frac{\delta}{\gamma\varepsilon_y}}H_D$$

Total Facility Site Power Required

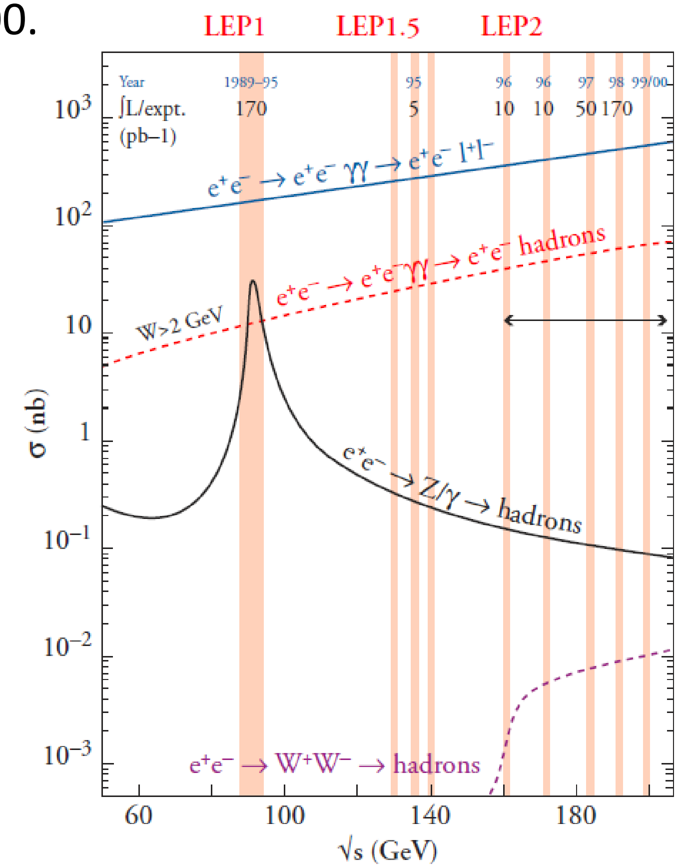


Total Facility Length



At high energies a e+e- colliders, a large part of the physics occurs by the vector boson fusion and gamma-gamma collisions.
In addition the energy spread grows very fast if one wants to keep luminosity
>50% for a 10 TeV linear collider based on plasma wake acceleration
➔ physics at multi-TeV e+e- looks more and more like hadron collider.
The LHC told us that the experiments could do discovery physics -- and some precision, too.
➔ In fact this is observed in higgs physics where the study
of Higgs self coupling is better done at FCC-hh than CLIC3000.

➔ hadron colliders are likely to remain the best way to reach high ECM parton-parton collisions for the foreseable future.



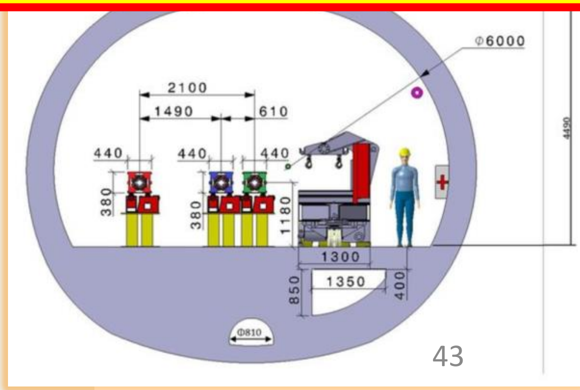
e+e- Ring Higgs Factories

- ***Advantages:***
  - **Based on mature technology (SRF) and rich experience → low risk**
  - High(er) luminosity and ratio luminosity/cost; up to 4 IPs, **EW factories**
  - 100 km tunnel can be reused for a ***pp* collider** in the future
  - **Transverse polarization (τ~ 18 min at *tt*) for *E* calibration O(100keV)**
  - CDRs addressed key design points, mb ready for ca 2039 start

According to the FCC study, there is **no** sensible high energy hadron collider plan at CERN (or elsewhere) after HL-LHC, that does not involve a larger tunnel of > 80km.

Affordability is obtained within an integrated program starting with an e+e- collider «Higgs and Electroweak factory»
This, luckily, has an extremely strong discovery program.
Anything else does less physics, is more expensive, or both.

  - *Super KEK-B* nanobeams experience will help
- Energy Storage and Release R&D:
  - Magnet energy re-use > 20,000 cycles
- Efficient Use of Excavated Materials:
  - 10^7 m^3 out of 100 km tunnel
- Cost performance optimization



conclusion:

The Physics Landscape

We are in a fascinating situation: where to look and what will we find?

For the first time since Fermi theory, <u>WE HAVE NO SCALE</u>

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

➔ <u>more Sensitivity, more Precision, more Energy</u>

<u>There is general agreement that an e+e- collider is part of our future but lets also make sure that we have a hadron collider in the program!</u>

Questions ? https://arxiv.org/abs/1906.02693