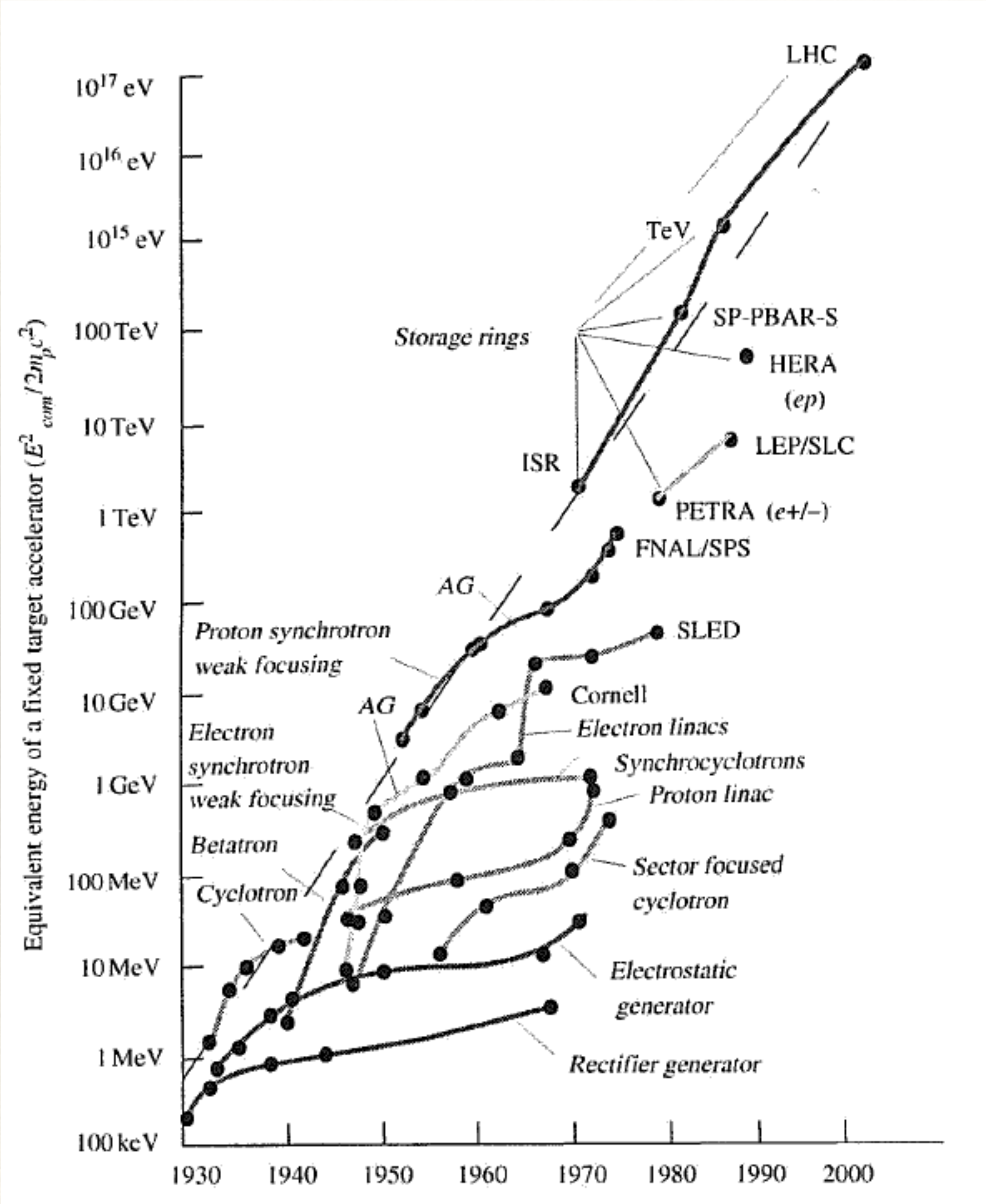
Conclusions

Pisa Future Colliders School,

17-21 September 2018

R. Keith Ellis
IPPP, Durham

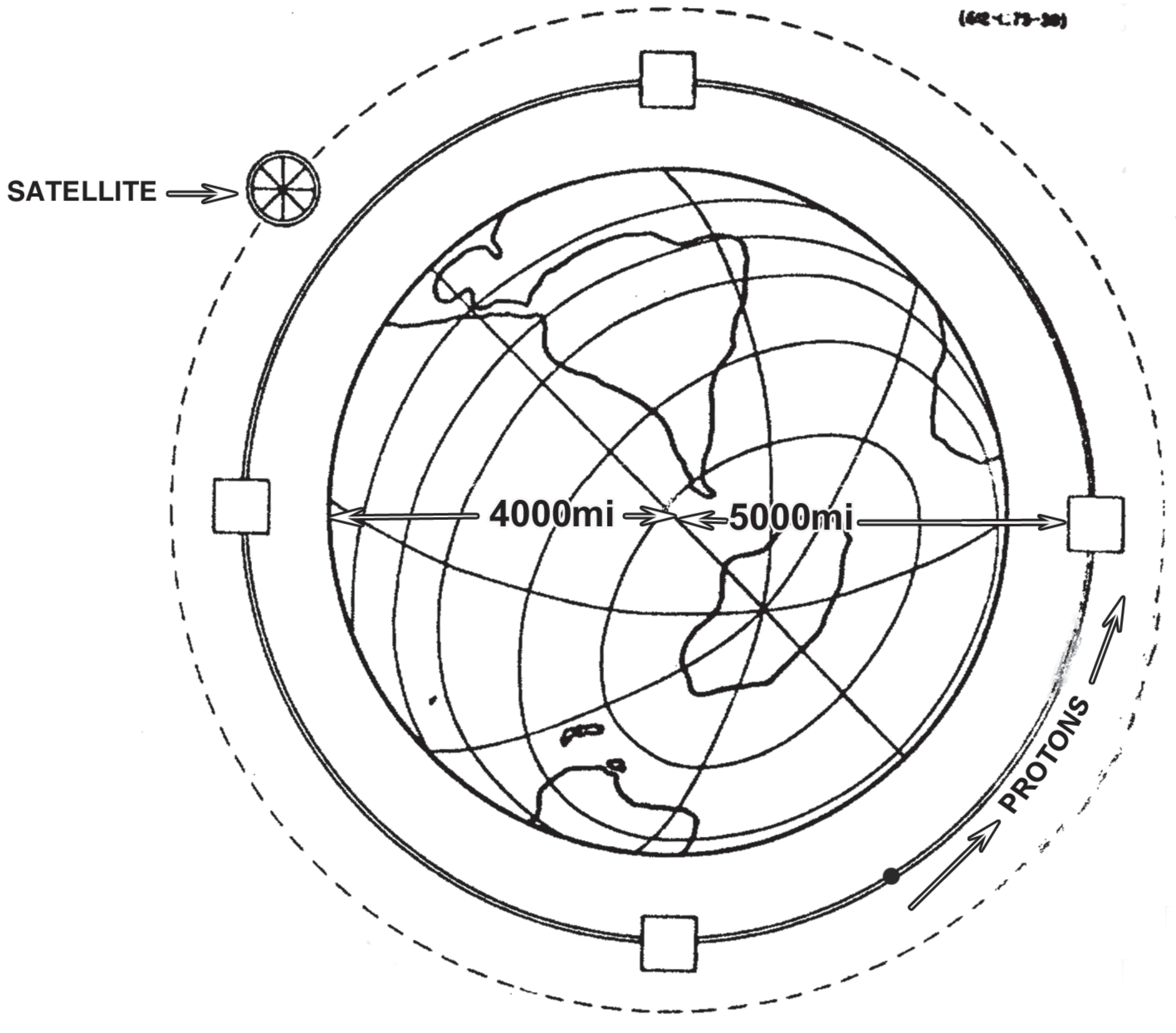
The continuation of a 90-year adventure

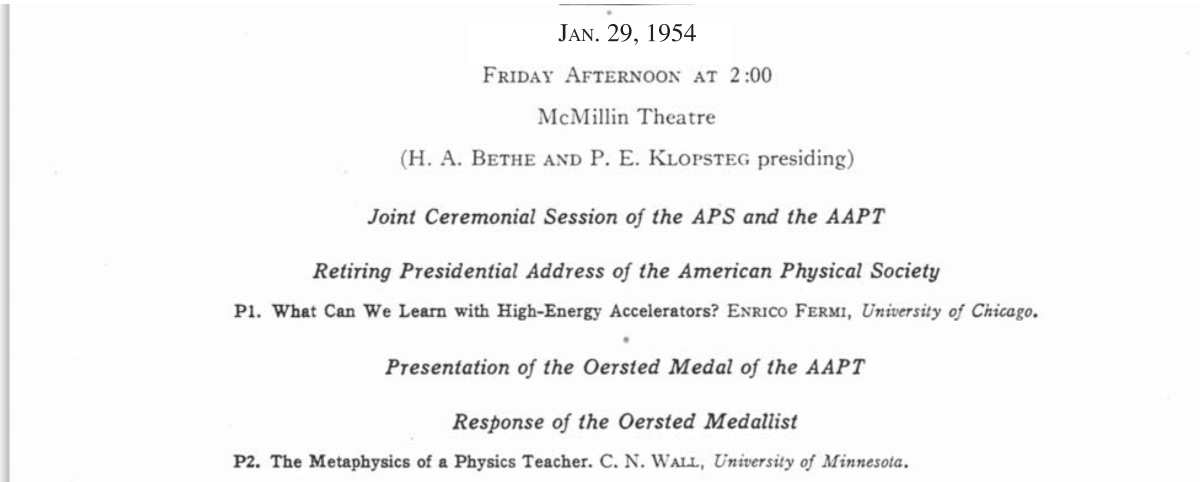


- Accelerator progress over 90 years,
- For the colliders, the energy has been expressed in terms of the energy of an equivalent fixed target machine

Global Accelerator (mark1)

- In January 1954, Enrico Fermi made a presentation in New York, on the occasion of Fermi stepping down as president of the APS, and being replaced by Bethe. The title of the presentation was **What can we learn from High-Energy Accelerators?** The following are quotations from Fermi's notes.
- Fermi starts off by "Congratulate Society on Loosing(sic) mediocre President and getting eccellent(sic) one."
- "But to solve the mysteries, higher energy data are needed."
- "But cosmic rays above 25 GeV only at one per cm^2 at an inconvenient location."
- "For these reasons clamoring for higher and higher energies.."
- "Preliminary design…8000 km, 20,000 gauss" (2 Tesla)
- "Energy of 5x10^6GeV, cost $170 Billion"
- "What we can learn impossible to guess. . .main element surprise. . .some things look for, but see others"
- ". . .Look for multiple production. . .antinucleons.. .strange particles. . .puzzle of long lifetimes. . .large angular momentum?. . .double formation?" (now called associated production) .
- Fermi died in November 1954.




JAN. 29, 1954

FRIDAY AFTERNOON AT 2:00

McMillin Theatre

(H. A. BETHE AND P. E. KLOPSTEG presiding)

Joint Ceremonial Session of the APS and the AAPT

Retiring Presidential Address of the American Physical Society

P1. What Can We Learn with High-Energy Accelerators? ENRICO FERMI, *University of Chicago.*

Presentation of the Oersted Medal of the AAPT

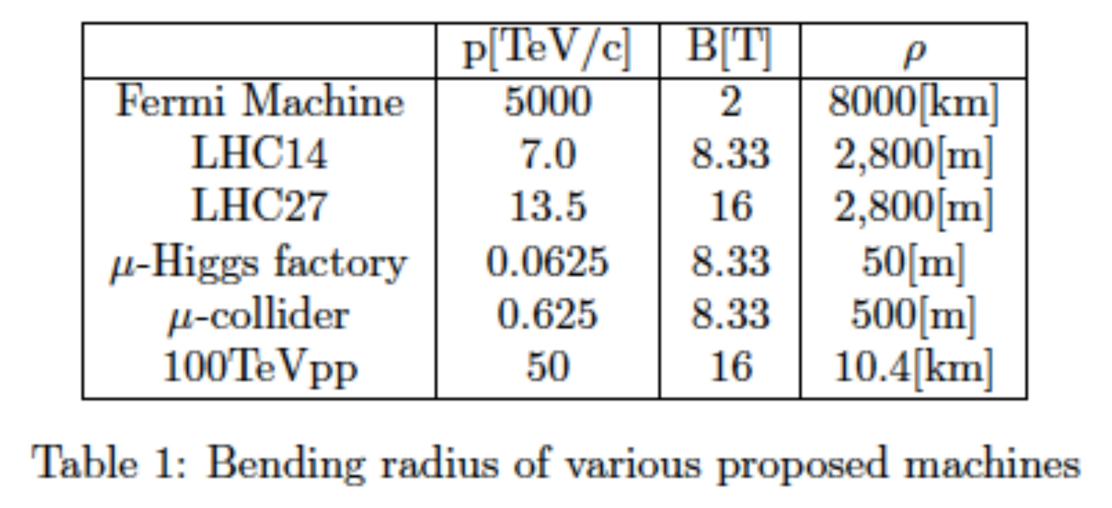
Response of the Oersted Medallist

P2. The Metaphysics of a Physics Teacher. C. N. WALL, *University of Minnesota.*

Bending magnetic field

- A synchrotron has a bending field produced by several magnets
- Field changes as momentum increases to keep particles in fixed orbit. $\frac{mv^2}{\rho} = evB \quad \implies p = eB\rho$
- Balance of centrifugal force and Lorentz force for bending radius ρ

$$\frac{pc}{e}[eV/c] = c[m/s]B[T]\rho[m] \quad \implies (pc/e)[TeV/c] = 0.299B[T]\rho[km]$$



	p[TeV/c]	B[T]	ρ
Fermi Machine	5000	2	8000[km]
LHC14	7.0	8.33	2,800[m]
LHC27	13.5	16	2,800[m]
μ-Higgs factory	0.0625	8.33	50[m]
μ-collider	0.625	8.33	500[m]
100TeVpp	50	16	10.4[km]

Table 1: Bending radius of various proposed machines

Continuous (superconducting) magnetic fields have a practical limitation to ~20-30T.

Higher energies, higher fields

- Norwegian, Rolf Wideroe’s German patent of 1943, (published only in 1953….), introduced the collider concept.
- (The first successful superconducting magnet was built by using niobium wire and achieved a field of 0.71T at 4.2K in 1954).
- Power consumption limits conventional magnets to about ~2T

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM
11. MAI 1953

DEUTSCHES PATENTAMT

PATENTSCHRIFT

№ 876 279

KLASSE 21g GRUPPE 36

W 687 VIIIc / 21g

Dr.-Ing. Rolf Wideröe, Oslo
ist als Erfinder genannt worden

Aktiengesellschaft Brown, Boveri & Cie, Baden (Schweiz)

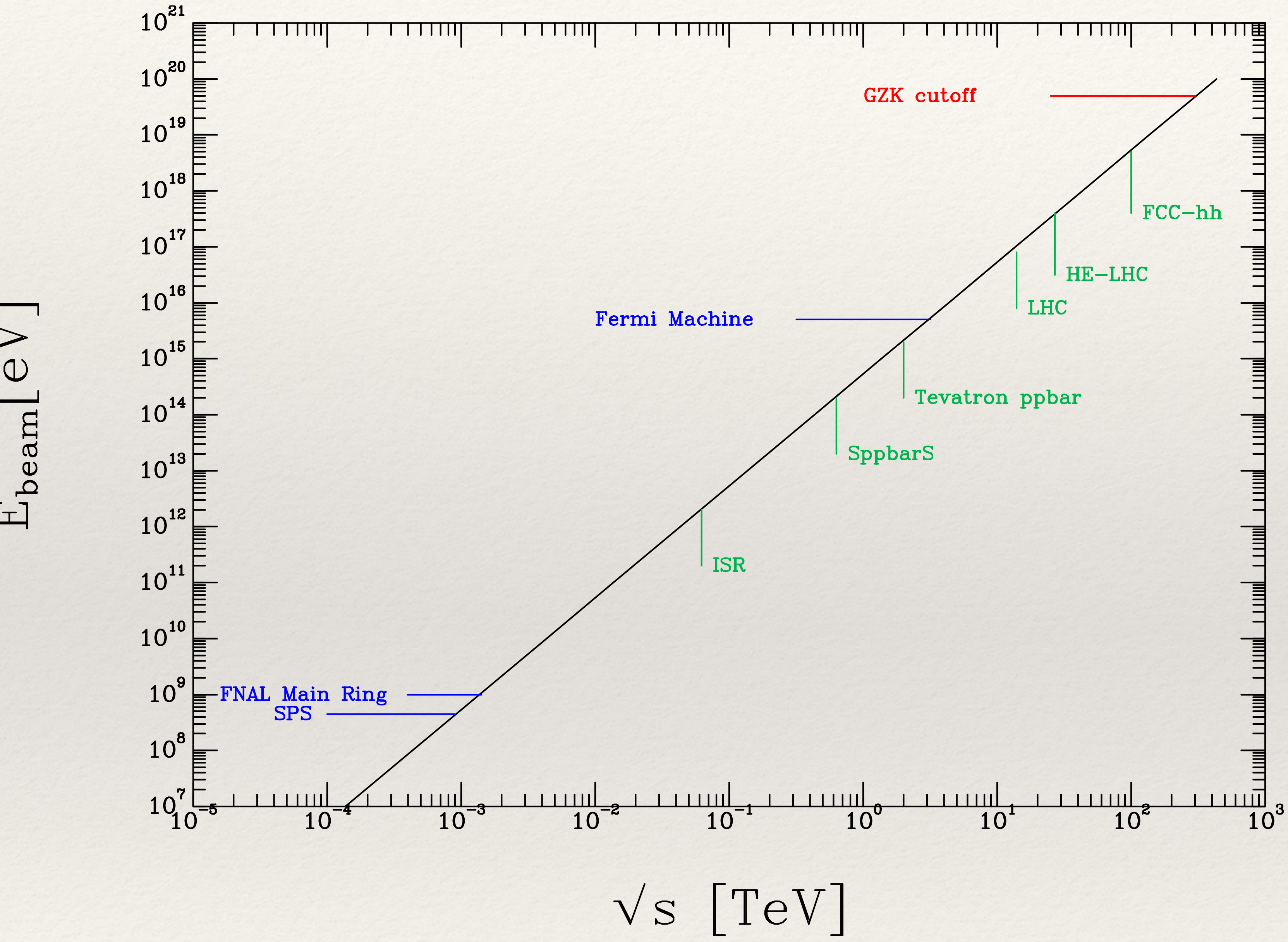
Anordnung zur Herbeiführung von Kernreaktionen

Patentiert im Gebiet der Bundesrepublik Deutschland vom 8. September 1943 an
Patentanmeldung bekanntgemacht am 18. September 1952
Patenterteilung bekanntgemacht am 26. März 1953

Fig. 1: The patent of R.Wideröe introducing colliding beams

Hubner 1206.3948

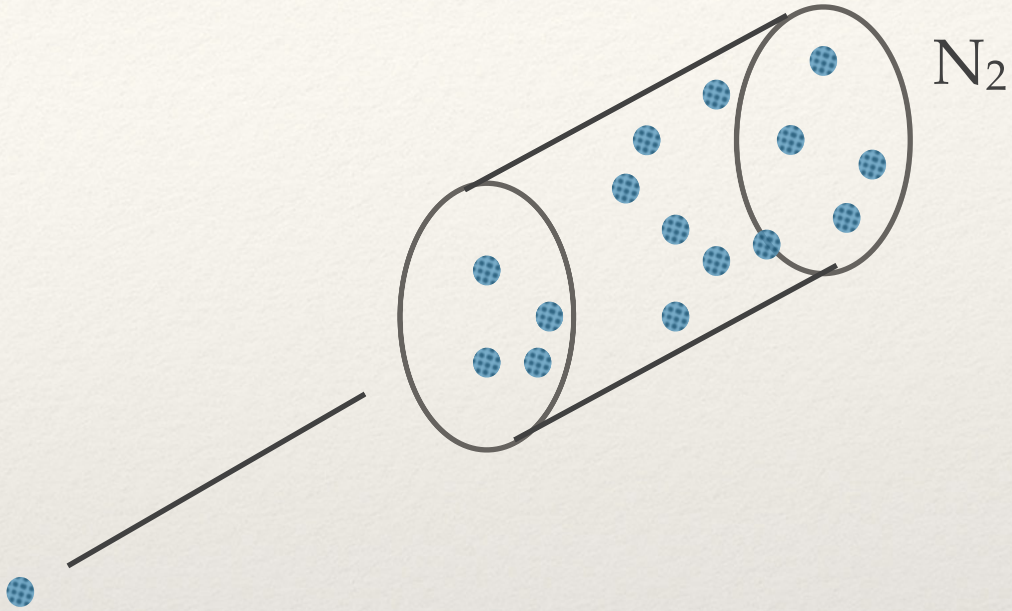
The power of the collider technique



(The Greisen–Zatsepin–Kuzmin limit (GZK limit) is a theoretical upper limit on the energy of cosmic ray protons travelling from other galaxies through the intergalactic medium to our galaxy. The limit is set by slowing-interactions of the protons with the microwave background radiation over long distances (~160 million light-years)).

Current and future colliders have c.o.m energies fixed above that of the Fermi Machine, thanks to the colliding beam technique and the development of superconducting magnets.

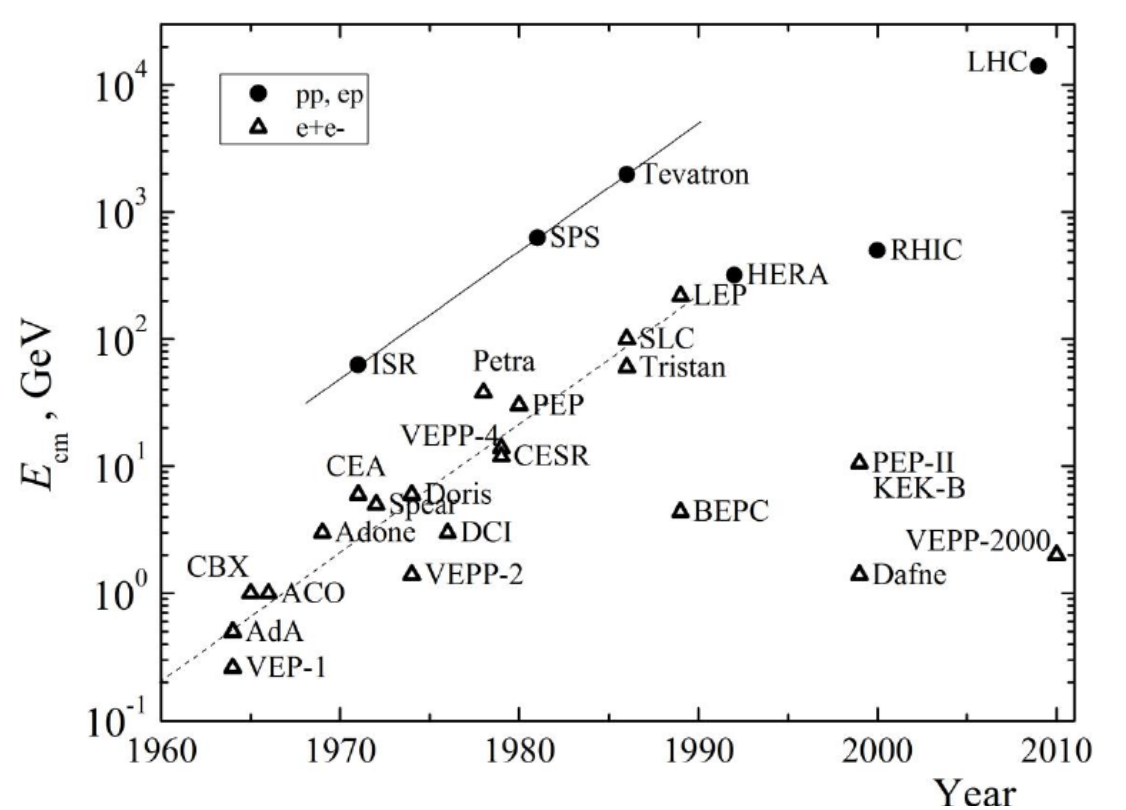
Luminosity

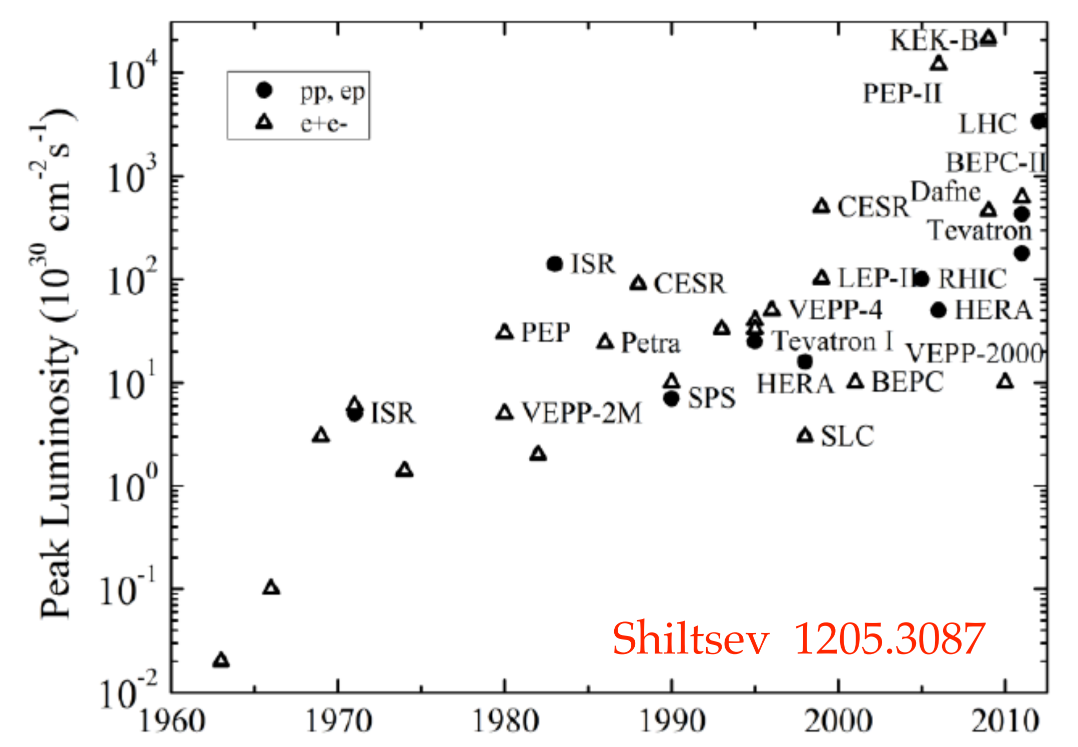


- Cylindrical bunches have a cross sectional area A and contain N_1, N_2 particles
- A given particle in Bunch 1 will interact with a fraction $N_2\frac{\sigma_{int}}{A}$
- Total number of such interactions is $\frac{N_1N_2\sigma_{int}}{A}$
- If the frequency of bunch interactions is f, then the interaction rate is $R = f\frac{N_1N_2}{A}\sigma_{int}$
- Defining $R = \mathscr{L}\sigma_{int}$ the luminosity per bunch is $\mathscr{L} = f\frac{N_1N_2}{A}$
- More sophisticated calculation for Gaussian beams, colliding head-on, N_b number of bunches gives $\mathscr{L} = f\frac{N_1N_2N_b}{4\pi\sigma_x\sigma_y}$
- σ_x, σ_y are the transverse sizes of the Gaussian.

Credo

- Accelerator-based particle physics is the fundamental core of our subject - allows us to perform reproducible experiments.
- Historical precedent: 100-fold increase in energy for both hadron and lepton colliders (in ~60 years) accompanied by a similar increase in luminosity.
- Progress in the field will continue to require colliders with high energy and high luminosity.
- Does our advanced technological civilisation have another high-energy collider in its future? Certainly, yes.
- How, when and where?

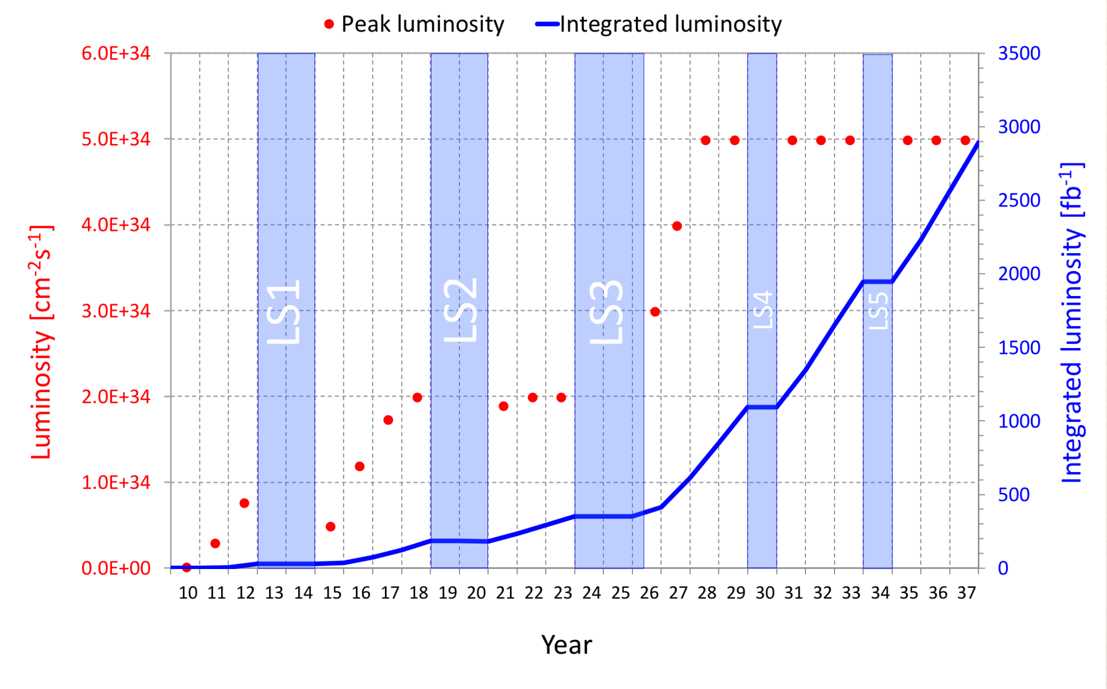




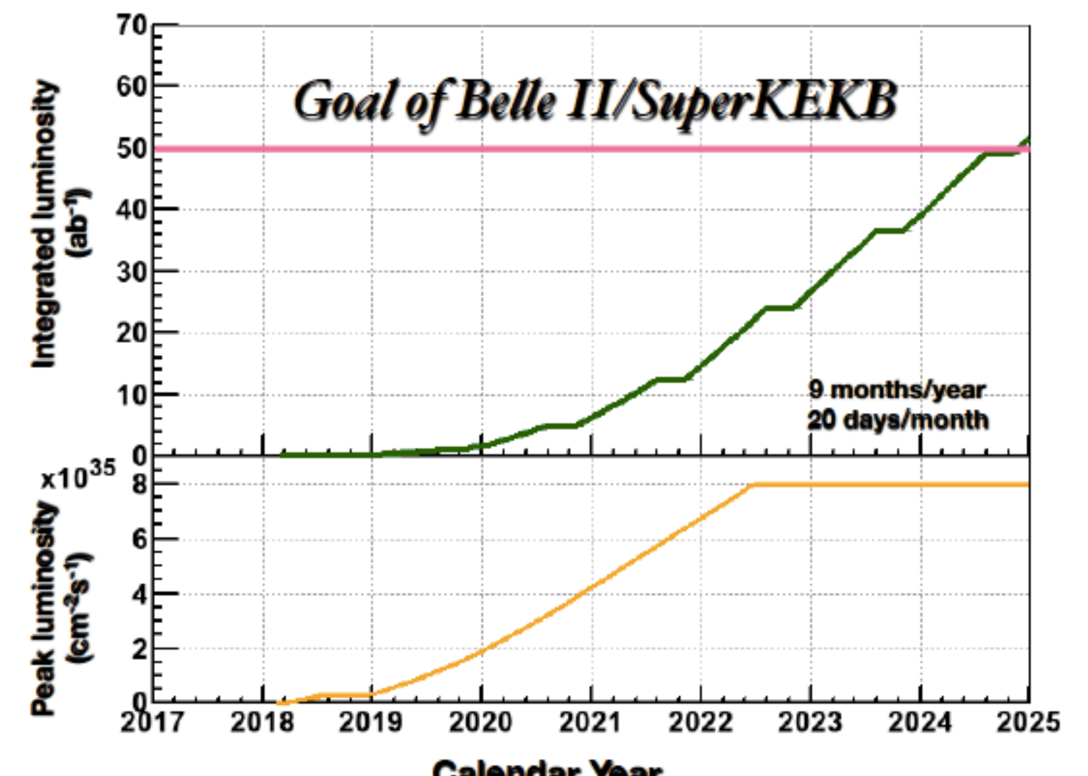
Shiltsev 1205.3087

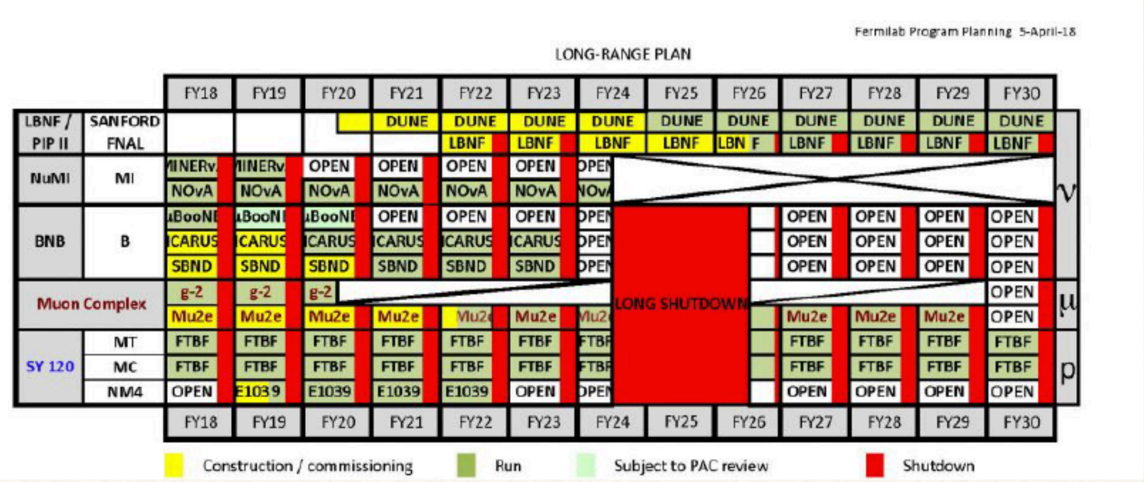
Credo, part II

- The “short-term” future looks good too.
- HL-LHC will run from 2026-2037 (~20 years=half of an academic career).
    - HL-LHC includes dipole & quadrupole magnets based on Nb_3Sn and crab cavities, both of which are important technical steps for the future.
- SuperKEKB now in operation, goal 50ab^{-1}
- Exploration of the rare as well as the high energy, c.f. DUNE, start 2025



SuperKEKB luminosity projection





Fermilab Program Planning 5-April-18

LONG-RANGE PLAN

		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
LBNF / PIP II	SANFORD				DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	
	FNAL					LBNF	LBNF	LBNF	LBNF	LBN F	LBNF	LBNF	LBNF	LBNF	
NuMI	MI	MINERv	MINERv	OPEN	OPEN	OPEN	OPEN	OPEN							ν
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA							
BNB	B	µBooN	µBooN	µBooN	OPEN	OPEN	OPEN	OPEN	LONG SHUTDOWN		OPEN	OPEN	OPEN	OPEN	
		ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	OPEN			OPEN	OPEN	OPEN	OPEN	
		SBND	SBND	SBND	SBND	SBND	SBND	OPEN			OPEN	OPEN	OPEN	OPEN	
Muon Complex		g-2	g-2	g-2										OPEN	μ
		Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e			Mu2e	Mu2e	Mu2e	OPEN	
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	FTBF	FTBF	p
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	FTBF	FTBF	
	NM4	OPEN	E1039	E1039	E1039	E1039	OPEN	OPEN			OPEN	OPEN	OPEN	OPEN	
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	

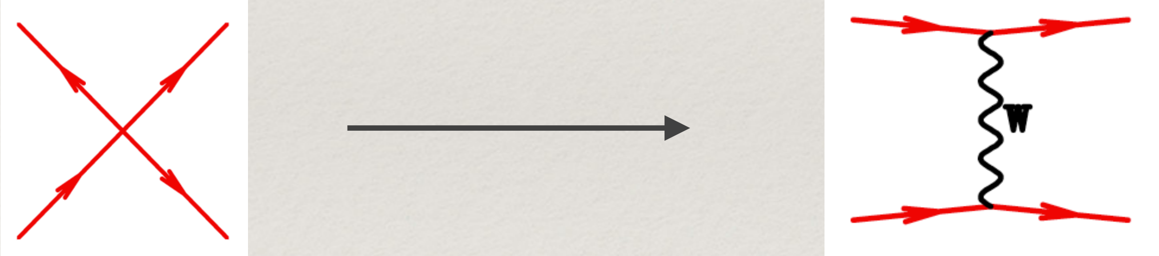
🟨 Construction / commissioning 🟩 Run 🟩 Subject to PAC review 🟥 Shutdown

A question of scale?

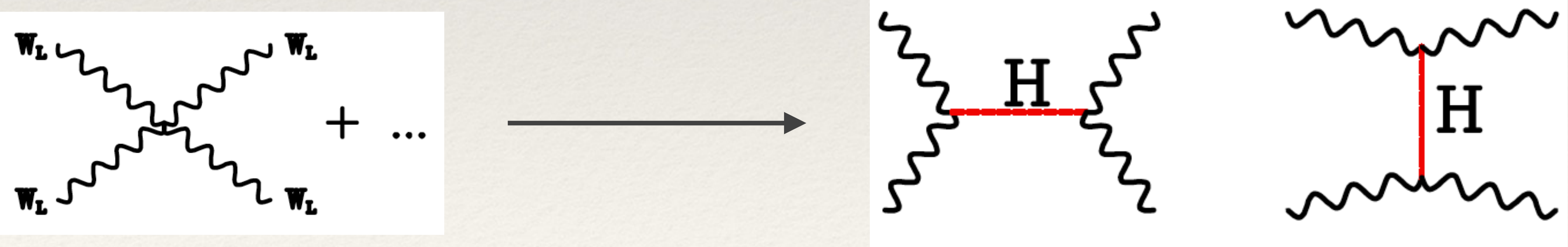
- In planning for future colliders it would be helpful to have an idea of the energy scale of potential next discoveries.
- This was very helpful in making the case for the LHC.
- No-lose theorems implied that below about 1 TeV,
  - There had to be either new physics (Higgs boson)
  - Or strong interaction dynamics.

No-lose completion of the standard model

- To complete the standard model we have been aided by no-lose theorems, based on perturbative unitarity.
- Before some critical energy $\sqrt{s_c}$, new physics must enter,
- either a new particle which keeps the theory perturbative.
- or, new physics to describe the non-perturbative regime.



Necessity of W-boson

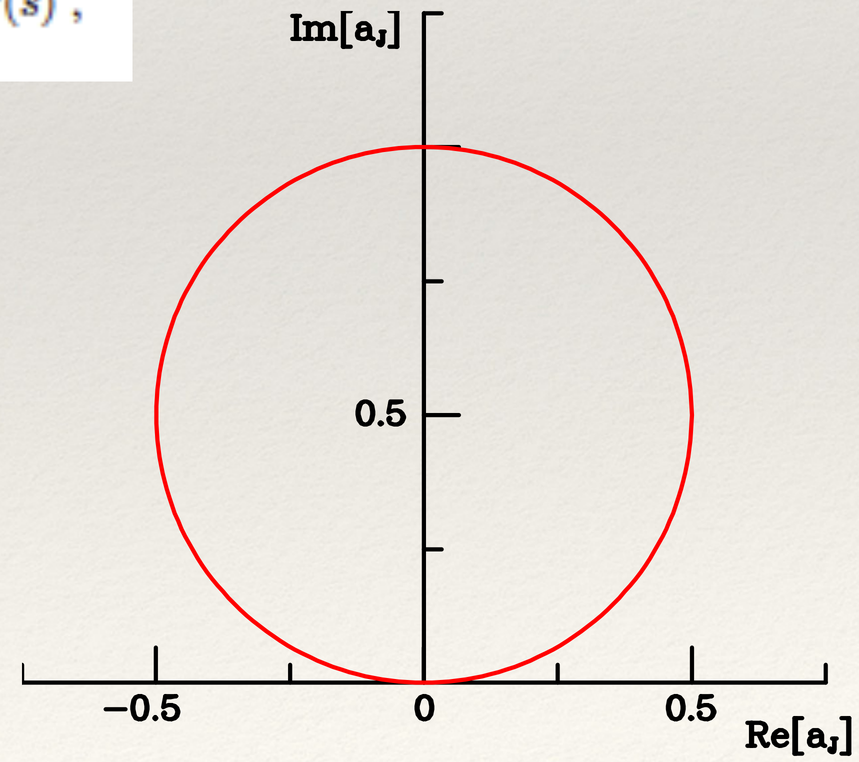


Necessity of H-boson

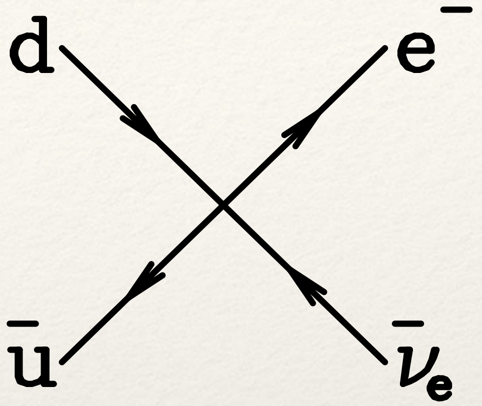
Now that the standard model is complete, there are no further no-lose theorems.
In principle, the standard model could be valid to the Planck scale.

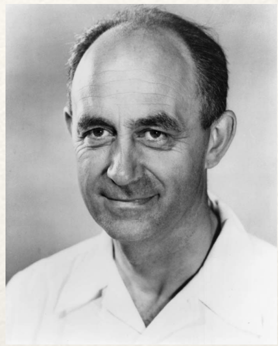
Partial Wave Unitarity

- Partial wave expansion $$T(s,t) = 16\pi \sum_J (2J+1)\, a_J(s)\, P_J(\cos\theta)$$
- Lowest partial wave $$a_0 = \frac{1}{32\pi}\int_{-1}^{1} d(\cos\theta)\, T(s,\cos\theta)$$
- Expression for cross section $$\sigma = \frac{16\pi}{s}\sum_J (2J+1)\,|a_J(s)|^2 \,.$$
- Optical theorem $$\sigma = \frac{1}{s}\,\mathrm{Im}\; T(s,0) = \frac{16\pi}{s}\sum_J (2J+1)\,\mathrm{Im}\; a_J(s)\,,$$
- Resultant bound on a $$|a_J|^2 = \mathrm{Im}\; a_J$$
- Unitarity circle $$\mathrm{Re}\; a_J^2 + \left(\mathrm{Im}\; a_J - \frac{1}{2}\right)^2 = \frac{1}{4}$$
- Constraint $$Re\; a_0 < \frac{1}{2}$$



Perturbative Unitarity constraint on Fermi theory

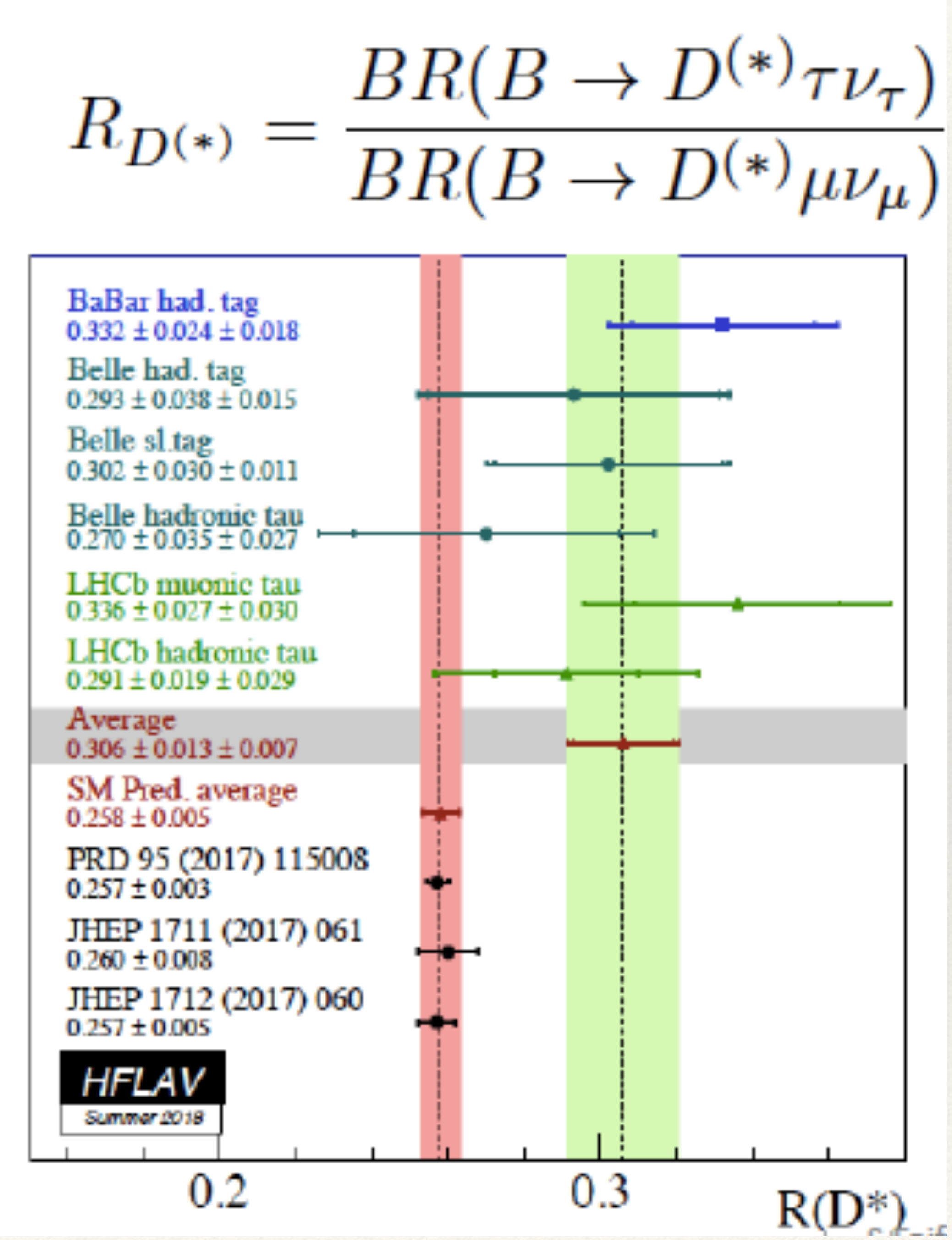




- In Fermi's theory of beta decay the Lagrangian is, $\mathscr{L} = \frac{G_f}{\sqrt{2}} \bar{u}(p_u)\gamma^\mu \gamma_L u(p_d)\; \bar{u}(p_e)\gamma_\mu \gamma_L u(p_\nu)$
- At high energy the amplitude is $T(s, \cos\theta) = \frac{G_f}{\sqrt{2}} s\,(1 - \cos\theta)$
- So the result for the J=0 partial wave is $a_0 = \frac{G_f}{\sqrt{2}} \frac{s}{16\pi}$
- Constraint $a_0 < \frac{1}{2}$ gives $s_{critical} < \frac{8\pi\sqrt{2}}{G_F}$
- So that the constraint of perturbative unitarity places the limit on the Fermi theory of $\sqrt{s_{critical}} < 1.75$ TeV This constraint is satisfied by the discovery of the W-boson with mass 81.4 GeV
- A similar argument applied to WW scattering implies for the mass of Higgs boson

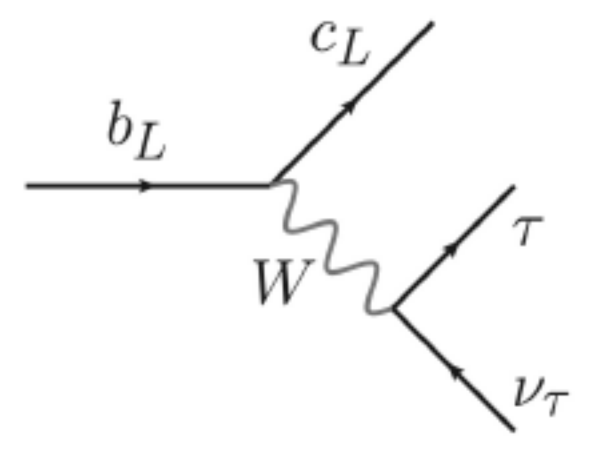
$$M_H < \sqrt{\left(\frac{8\sqrt{2}\pi}{3G_f}\right)} \approx 1 TeV$$

BSM physics?—B-physics Anomalies - tree level



$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$

Fajfer:ICHEP

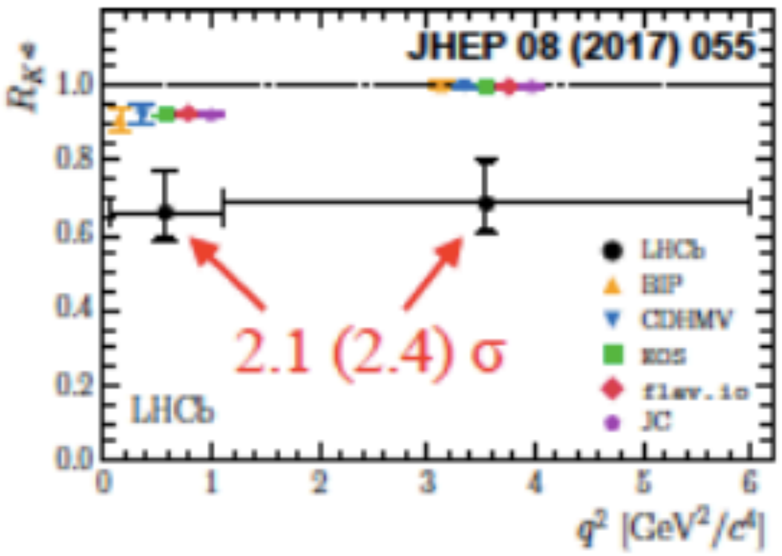


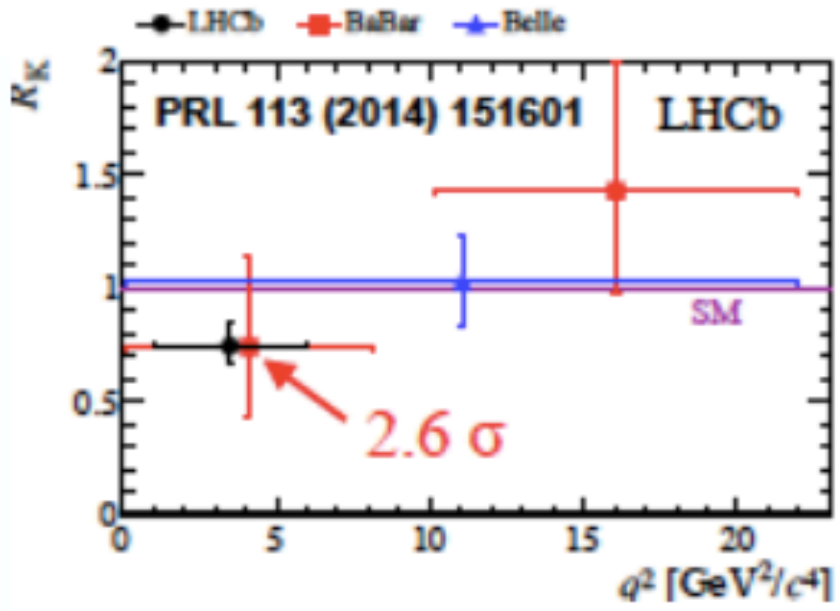
- 3.8 sigma anomaly in a tree process

BSM physics: B physics anomalies –R_{K^*} and R_K (loop level)

Fajfer:ICHEP2018

$$R_{K^{(*)}} = \left.\frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}\right|_{q^2 \in [q^2_{min}, q^2_{max}]}$$





- Flavor changing neutral current processes $b \to s\ell\bar{\ell}$
- Also 3 sigma deviation in P5primed, a variable constructed in such a way that theoretical uncertainties cancel out and are under control.

Could B-physics be suggesting a new scale?

- The B-physics anomalies have not yet reached the level of 5 sigma.
- If they were to persist, perturbative unitarity can be used to set the scale of the new physics, just as it did for the Fermi theory.
- Unfortunately the loop-level perturbative unitarity constraints are not very stringent.
- Using the operator $\mathscr{L} = \frac{1}{\Lambda_{D*}^2} 2\bar{c}_L \gamma^\mu b_L \ \bar{\tau}_L \gamma_\mu \nu_L \ + \ \frac{1}{\Lambda_{R_{K^*}}^2} 2\bar{s}_L \gamma^\mu b_L \ \bar{\mu}_L \gamma_\mu \mu_L$
- Perturbative unitarity limits are $s_c^{D^*} = 9.2\ \text{TeV}$ and $s_c^{R_{K^*}} = 84\ \text{TeV}$

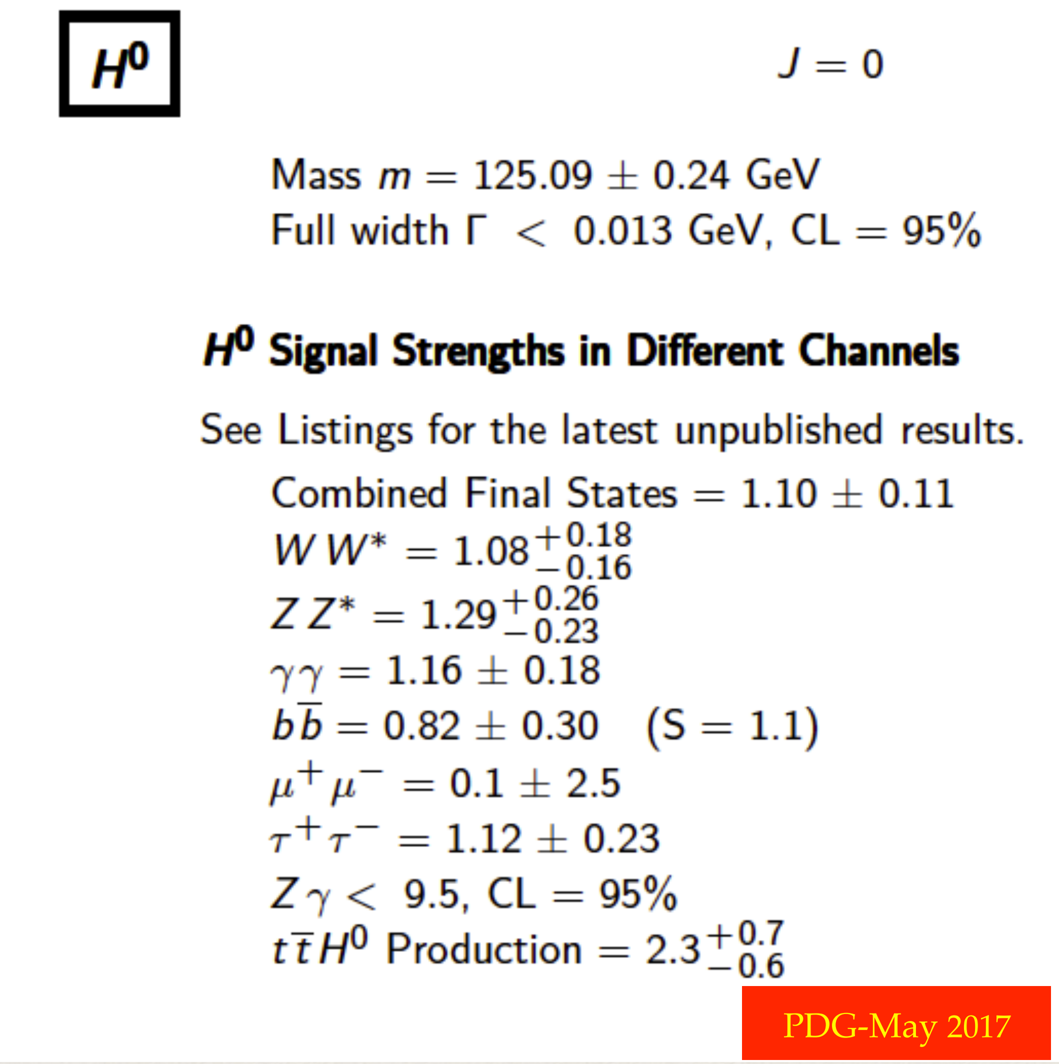
Allanach et al, 1710.0636, Di Luzio, Nardecchia, 1706.01868,

The next project

- Every new machine needs to have a guaranteed deliverable, as well as the potential for serendipitous discovery.
- As a temporary goal, let us decide to find out as much about the Higgs boson as we can, and rate potential new machines on that basis.
- Everything changes if we see something new at the 1TeV scale.

Higgs Physics provides guaranteed deliverables

- Mass of Higgs
- Total Width of Higgs
- Couplings of Higgs to all? particles
- (Higgs invisible width)
- Trilinear coupling of Higgs
- Composite or elementary?



H^0 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.29^{+0.26}_{-0.23}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\overline{b} = 0.82 \pm 0.30$ (S = 1.1)
$\mu^+\mu^- = 0.1 \pm 2.5$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 9.5$, CL = 95%
$t\overline{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

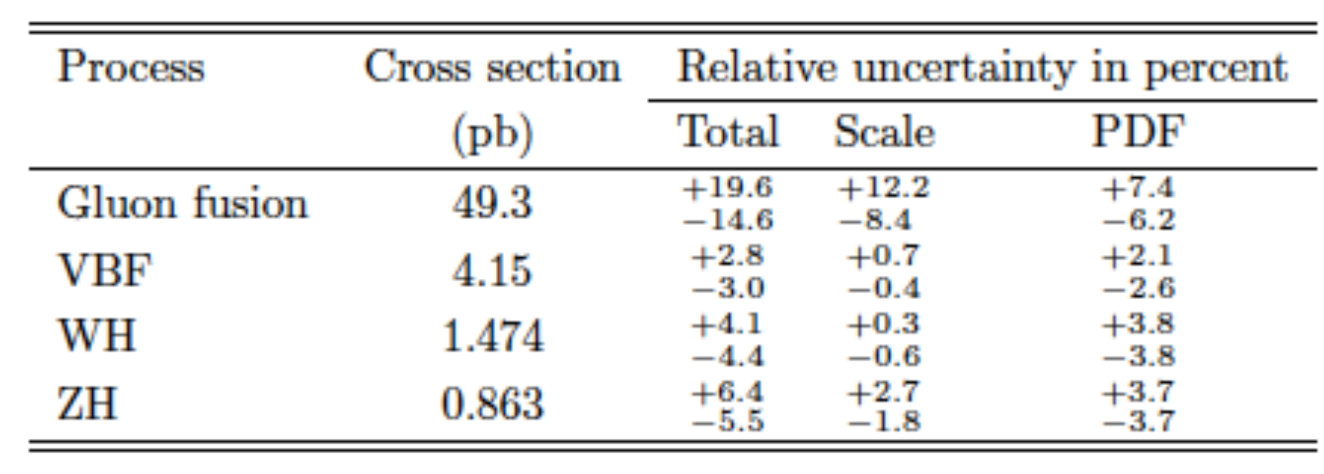
PDG-May 2017

$$\mathcal{V}(\phi^\dagger\phi) = \lambda\,(\phi^\dagger\phi)^2 - \mu^2\phi^\dagger\phi\ .$$

$$\mathcal{L}_{\rm Higgs} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}M_h h^2 - \lambda_3\left(\frac{M_h^2}{2v}\right)h^3 - \lambda_4\left(\frac{M_h^2}{8v^2}\right)h^4$$

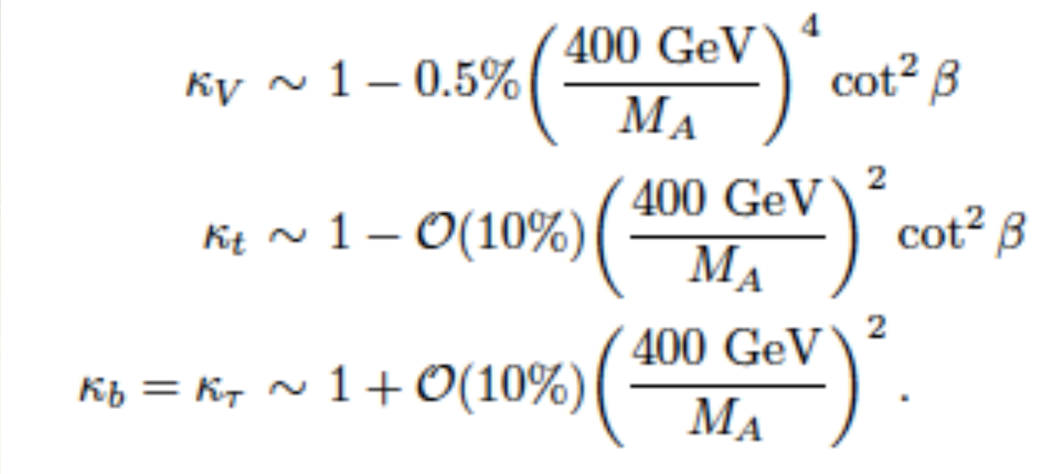
SM: $\lambda_3 = 1, \lambda_4 = 1$

How precisely do we need to know Higgs couplings?



Process	Cross section (pb)	Relative uncertainty in percent		
		Total	Scale	PDF
Gluon fusion	49.3	$^{+19.6}_{-14.6}$	$^{+12.2}_{-8.4}$	$^{+7.4}_{-6.2}$
VBF	4.15	$^{+2.8}_{-3.0}$	$^{+0.7}_{-0.4}$	$^{+2.1}_{-2.6}$
WH	1.474	$^{+4.1}_{-4.4}$	$^{+0.3}_{-0.6}$	$^{+3.8}_{-3.8}$
ZH	0.863	$^{+6.4}_{-5.5}$	$^{+2.7}_{-1.8}$	$^{+3.7}_{-3.7}$

- A hard question
- As precisely as possible?
- As precisely as theoretical errors on couplings?
- Beyond the level of sensitivity associated with the non-observation of BSM particles at the LHC?
- eg MSSM



$$\kappa_V \sim 1 - 0.5\% \left(\frac{400\ \text{GeV}}{M_A}\right)^4 \cot^2\beta$$

$$\kappa_t \sim 1 - \mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2 \cot^2\beta$$

$$\kappa_b = \kappa_\tau \sim 1 + \mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2 .$$

Higgs and Flavor

$$y_F = \frac{\sqrt{2} m_f}{v}$$

- Proportionality

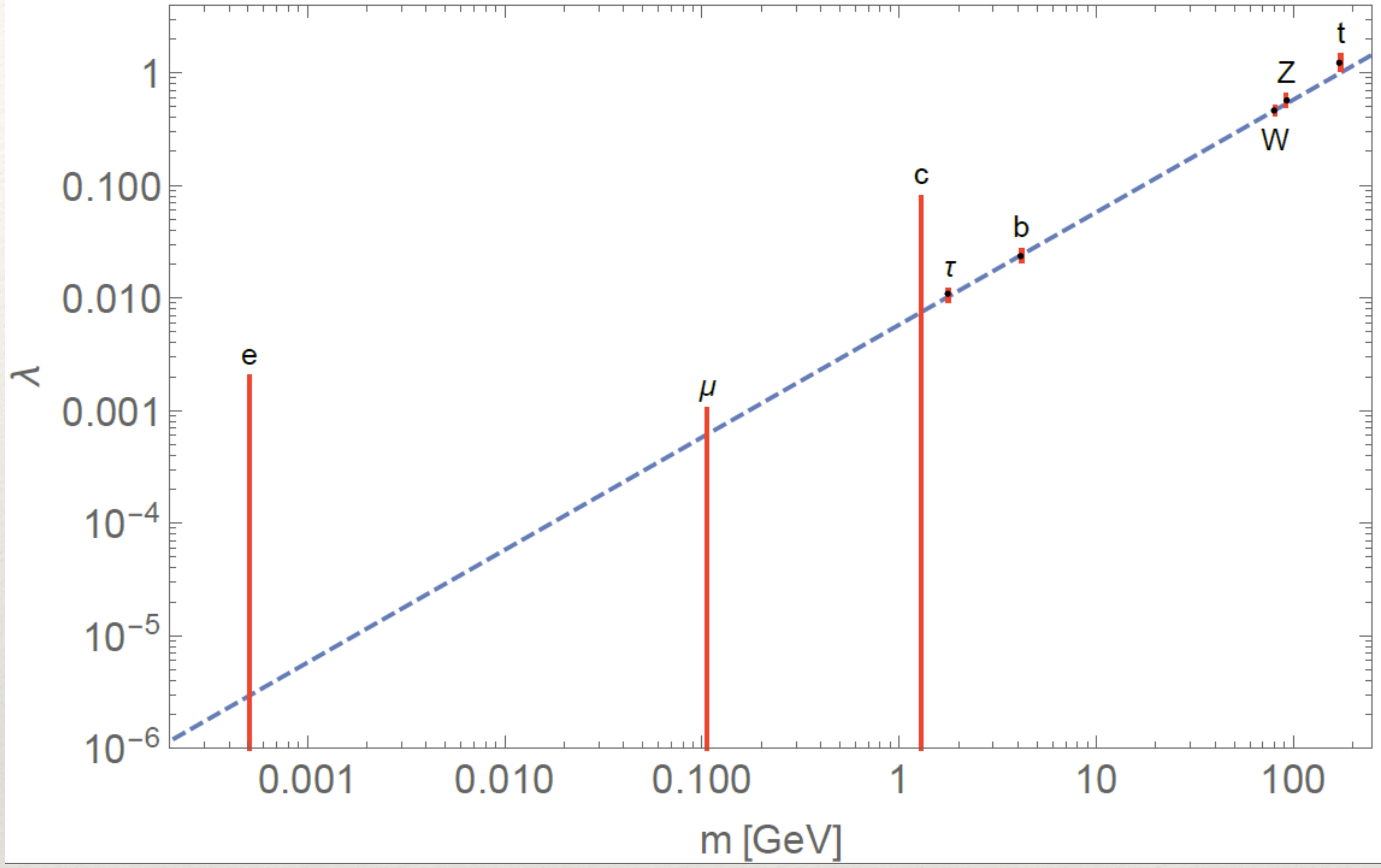
$$y_i / y_j = m_i / m_j$$

- Factor of proportionality

$$y_i / m_i = \sqrt{2} / v$$

- Diagonality

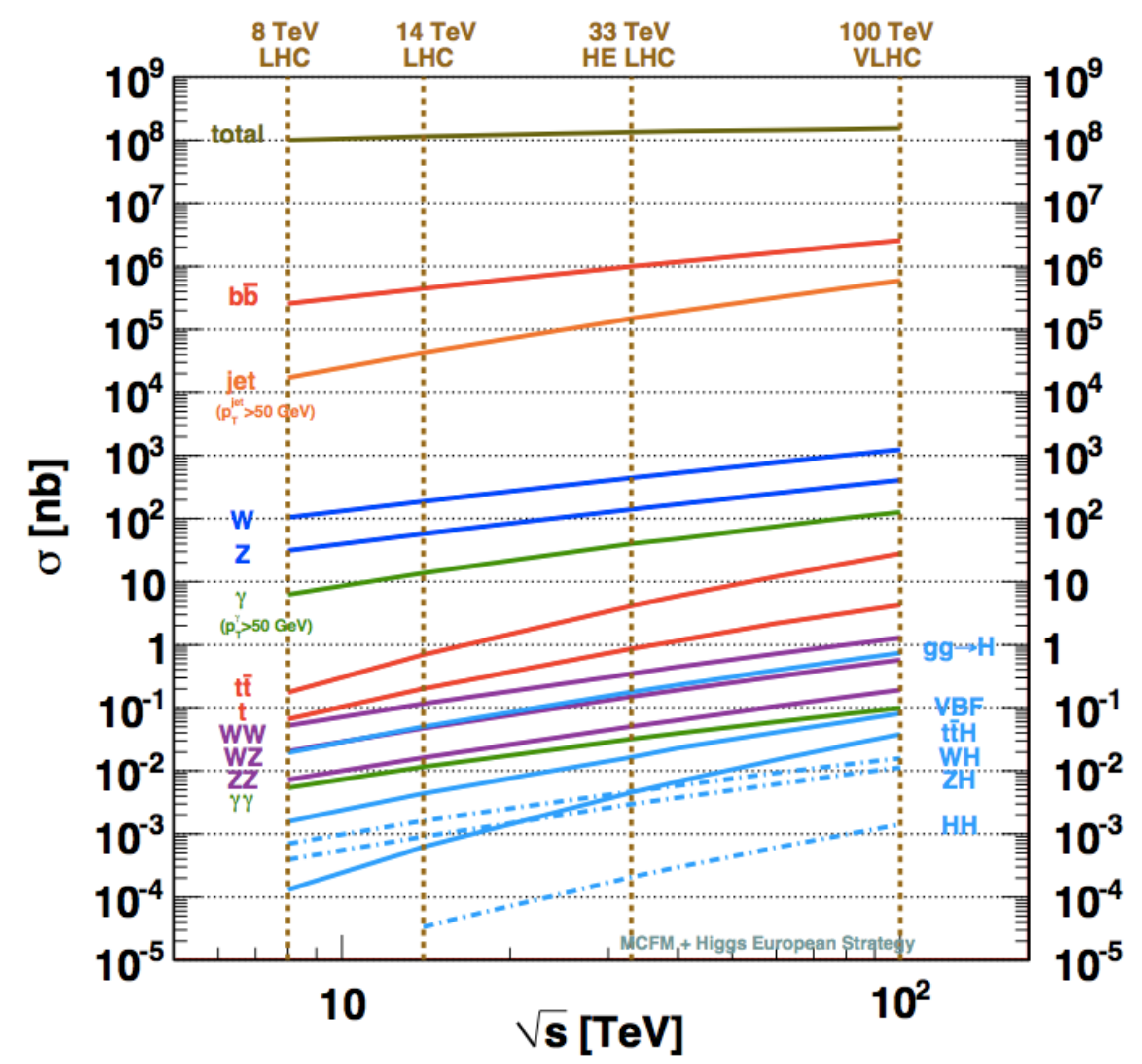
$$y_{ij} = 0 \text{ for } i \neq j$$

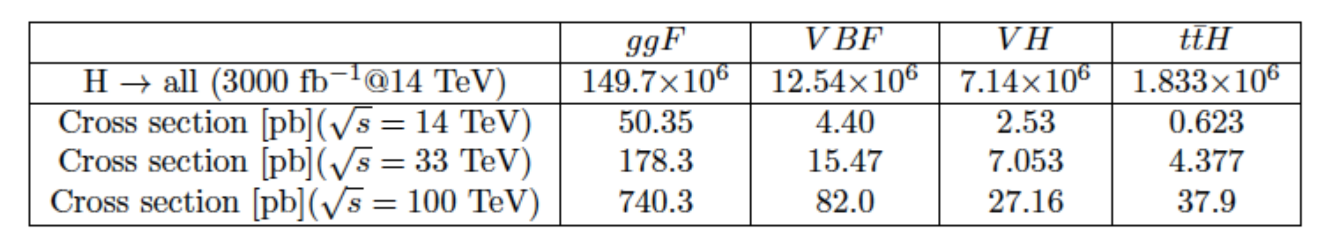


Yossi Nir private communication.

Hadron colliders as Higgs Factories

- Real factories vs lepton colliders
- Millions rather than thousands of H-bosons
- Signal to background
- Growth with energy (esp. ttH).
- Access to Higgs pair production.





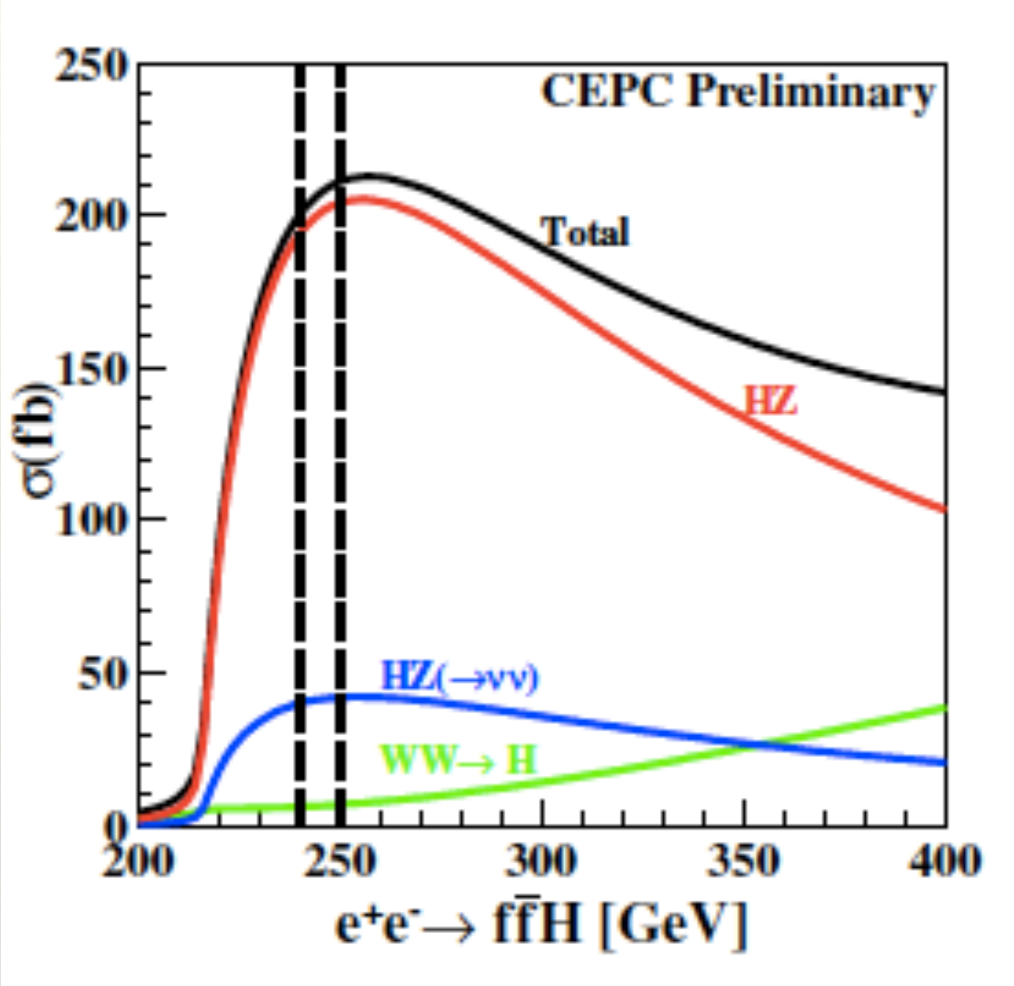
	ggF	VBF	VH	$t\bar{t}H$
H → all (3000 fb^{-1}@14 TeV)	149.7×10^6	12.54×10^6	7.14×10^6	1.833×10^6
Cross section [pb]($\sqrt{s} = 14$ TeV)	50.35	4.40	2.53	0.623
Cross section [pb]($\sqrt{s} = 33$ TeV)	178.3	15.47	7.053	4.377
Cross section [pb]($\sqrt{s} = 100$ TeV)	740.3	82.0	27.16	37.9

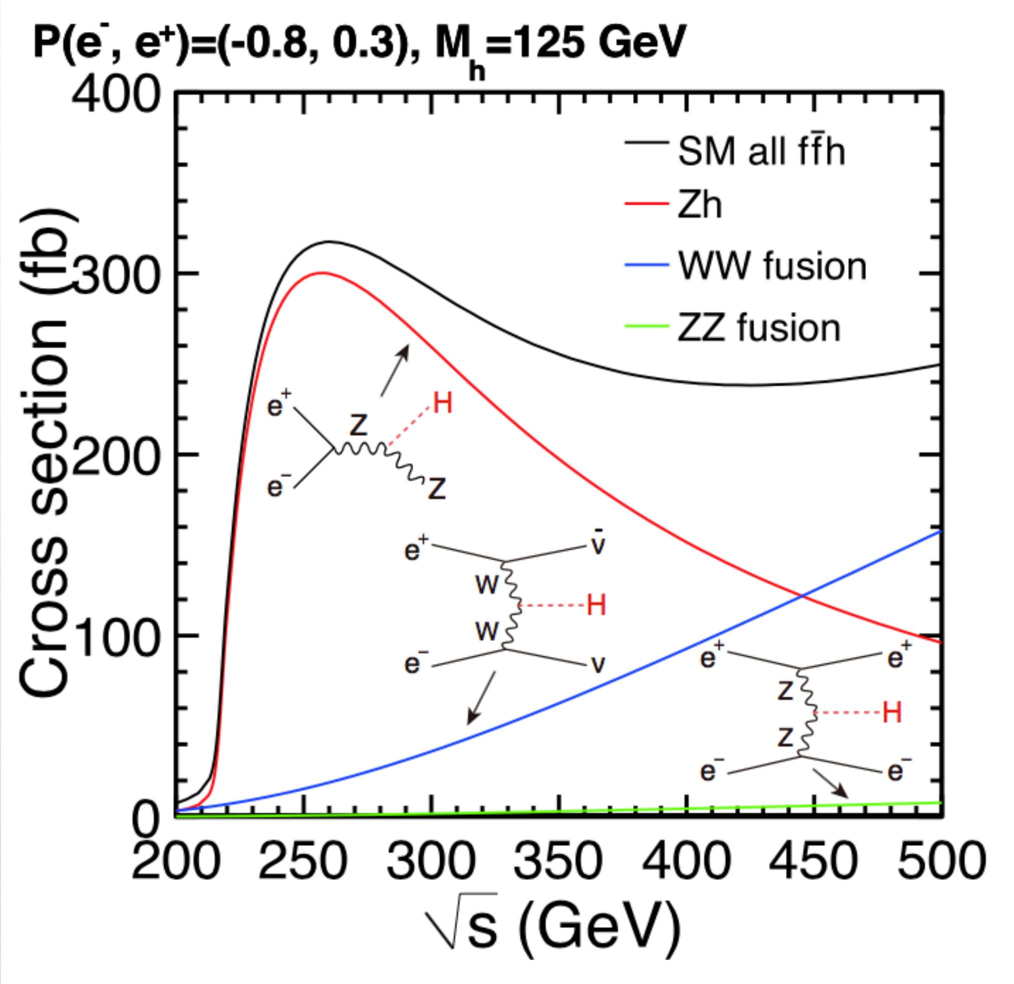
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/

Low energy Higgs factories

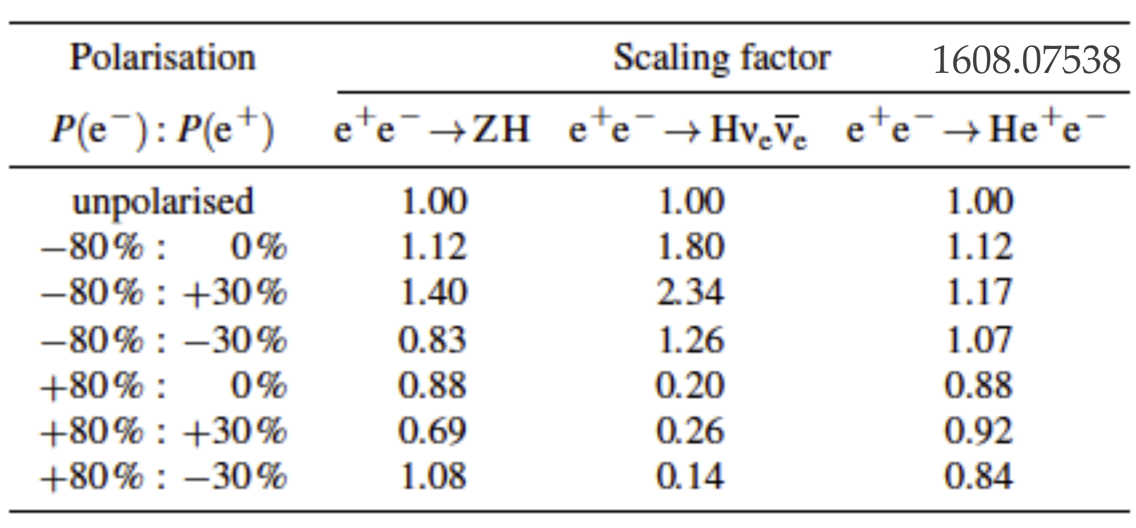
- The physics of electron positron colliders is independent of whether the machine is circular or linear.
- What differs is the luminosity (and possibly polarization in the case of the linear collider).
- Muon collider has access to s-channel production.

e+e- collider generalities: Higgs physics





- WW fusion production ten times smaller at 250 than 500.
- ~40% increase in ZH cross section with polarization(-0.8,+0.3)
- Polarization is useful to identify certain sub-processes.



1608.07538

Polarisation	Scaling factor		
$P(e^-):P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$	$e^+e^- \to He^+e^-$
unpolarised	1.00	1.00	1.00
−80% : 0%	1.12	1.80	1.12
−80% : +30%	1.40	2.34	1.17
−80% : −30%	0.83	1.26	1.07
+80% : 0%	0.88	0.20	0.88
+80% : +30%	0.69	0.26	0.92
+80% : −30%	1.08	0.14	0.84

We will have a much better idea of this tables by the end of the year and maybe we already do (cf Kado).

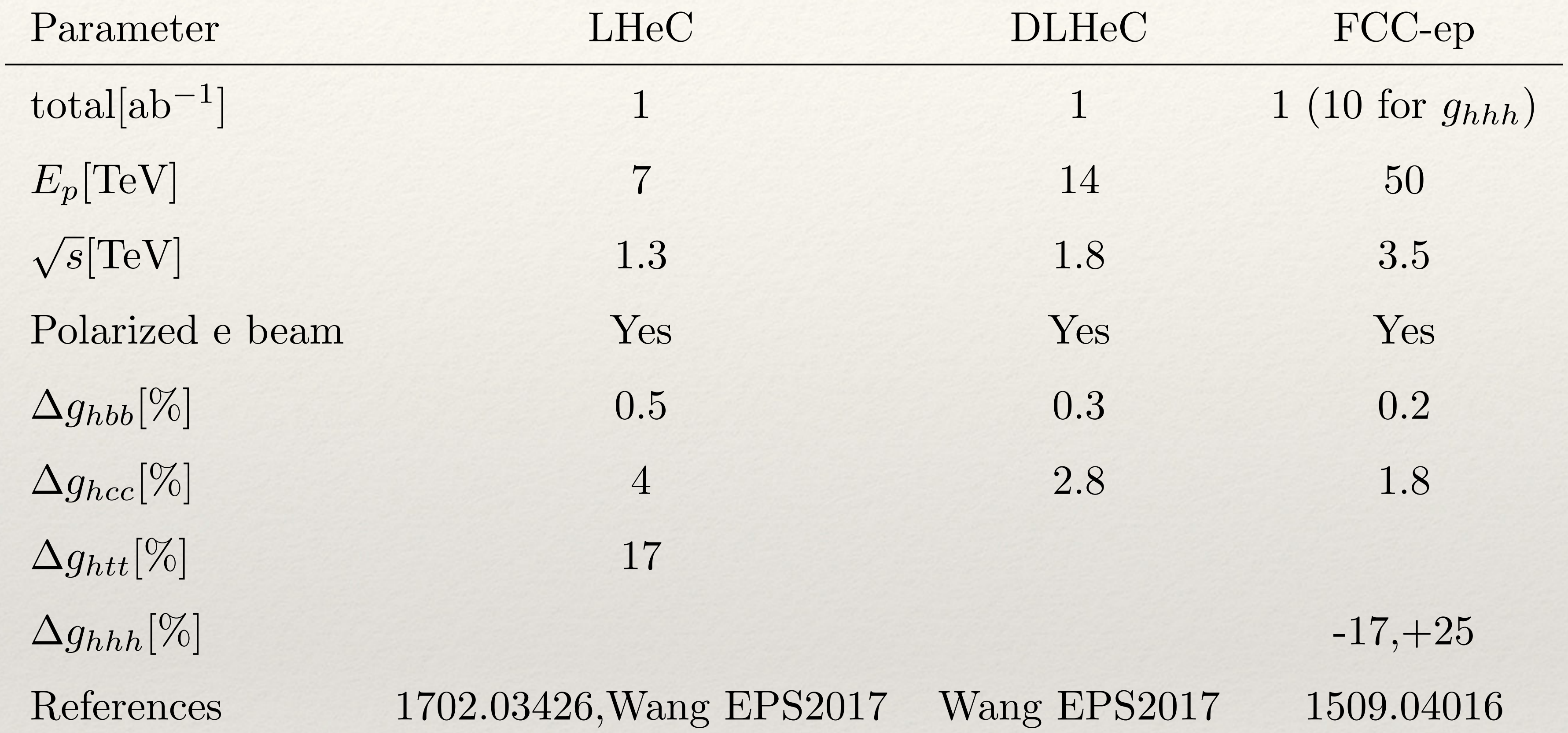
Comparison of precision on Higgs couplings

Parameter	HL-LHC	FCC-ee	FCC-ee	ILC	CLIC	CEPC	μ-Coll
$\sqrt{s}$[TeV]	14	350	240	250	1400	240	125
Lum/IP[E34]	5	1.9	8.5	1.35	1.5	2	0.01?
total[ab^{-1}]	3+(3)	1.3+1.3	5+5	2	1.5	2+2	0.002?
years[Sn'm'ss]	6	6.8	5.9	15	10	10	2?
Δm_h[MeV]	$\sim$ 100			14	47	5.9	0.06
Γ_h[%]	-	1.2	2.4	3.9	3.7	2.7	3.6
Δg_{hZZ}[%]	4	0.15	0.16	0.38	0.8	0.26	
Δg_{hWW}[%]	4.5	0.19	0.85	1.8	0.9	1.2	2.2
Δg_{hbb}[%]	11	0.42	0.88	1.8	1.0	1.3	2.3
$\Delta g_{h\tau\tau}$[%]	9	0.54	0.94	1.9	1.7	1.4	2.3
$\Delta g_{h\gamma\gamma}$[%]	4.1	1.5	1.7	1.1	5.7	4.7	5
Δg_{hcc}[%]	-	0.71	0.71	2.4	2.3	1.7	10
Δg_{hgg}[%]	6.5	0.8	0.80	2.2	1.8	1.5	-
Δg_{htt}[%]	8.5	-	-	-	4.2	-	-
$\Delta g_{h\mu\mu}$[%]	7.2	6.2	6.4	5.6	14.1	8.6	2.1
$\Delta\Gamma_{\text{invis}}$[%]	$\sim$10			0.32			
Δg_{hhh}[%]	-400,1200	-	-	-	40	-	
References	ATL-PHYS-PUB -2014-016	1308.6176	1308.6176	1710.07621 1711.00568	1608.07538	IHEP-CEPC-DR -2015-01	1304.5270 1308.2143

Many questionable and/or dated numbers!

Table inspired by talk of M Klute, Higgs couplings,2015

Higgs physics at lepton-proton colliders



Parameter	LHeC	DLHeC	FCC-ep
total[ab^{-1}]	1	1	1 (10 for g_{hhh})
E_p[TeV]	7	14	50
$\sqrt{s}$[TeV]	1.3	1.8	3.5
Polarized e beam	Yes	Yes	Yes
Δg_{hbb}[%]	0.5	0.3	0.2
Δg_{hcc}[%]	4	2.8	1.8
Δg_{htt}[%]	17		
Δg_{hhh}[%]			-17,+25
References	1702.03426,Wang EPS2017	Wang EPS2017	1509.04016

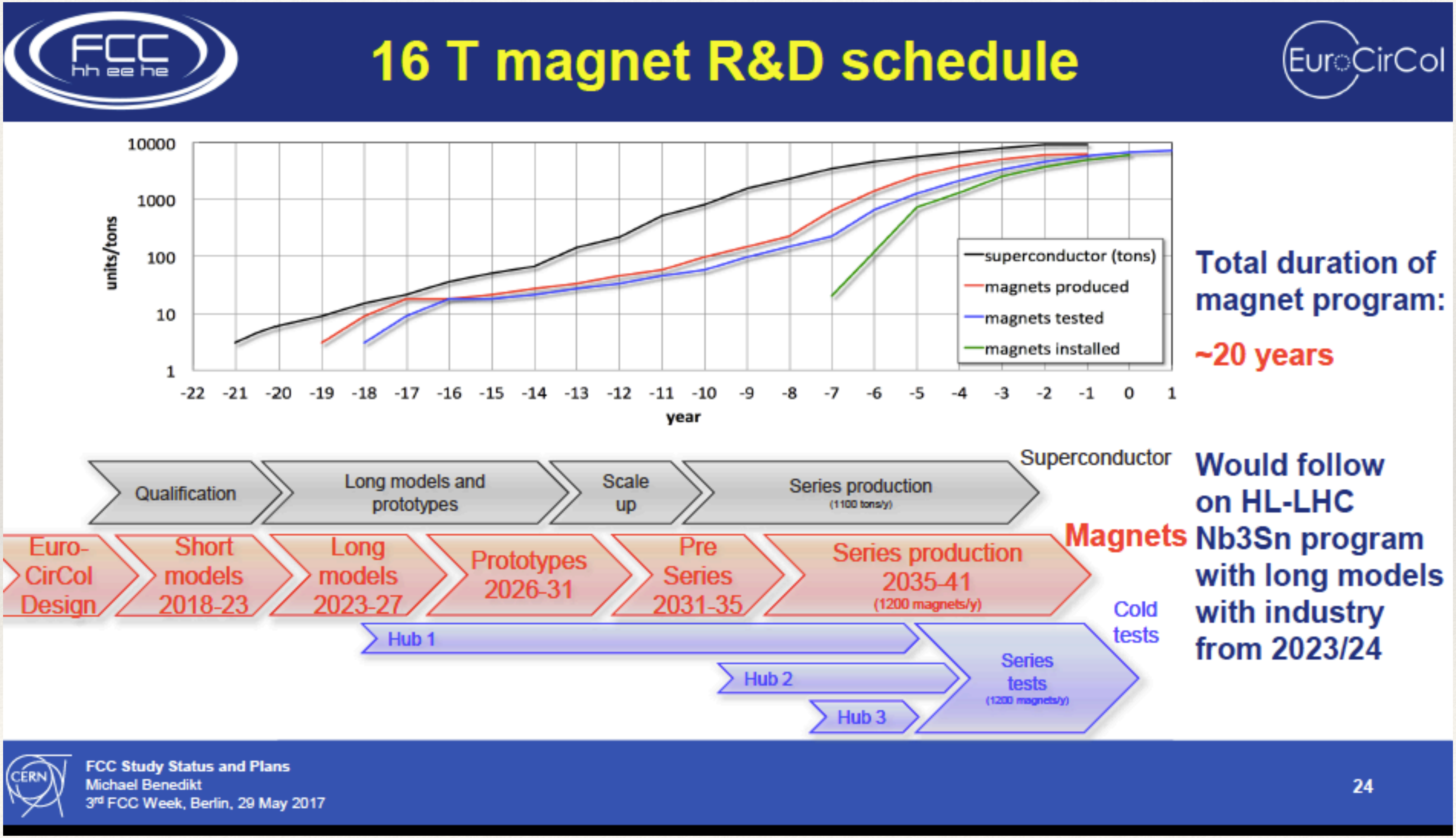
- Limited study of potential of these machines for Higgs physics

Hadron-colliders

How fast can we proceed to higher energy at LHC

- Given the apparent absence so far of new physics so far, (with less than 2% of final data sample fully analyzed), one might wish to move to higher energy ASAP.
- The possibility of going to 15 TeV (with the current magnets operated at higher field) late in Run 3 is being studied.
- the feasibility and cost of substituting some fraction of the magnets, (say 1/3), with higher field magnets to go beyond 15 TeV is being studied.

16 Tesla Technically-driven magnet schedule



16 T magnet R&D schedule

Total duration of magnet program:

~20 years

Would follow on HL-LHC Nb3Sn program with long models with industry from 2023/24

FCC Study Status and Plans
Michael Benedikt
3rd FCC Week, Berlin, 29 May 2017

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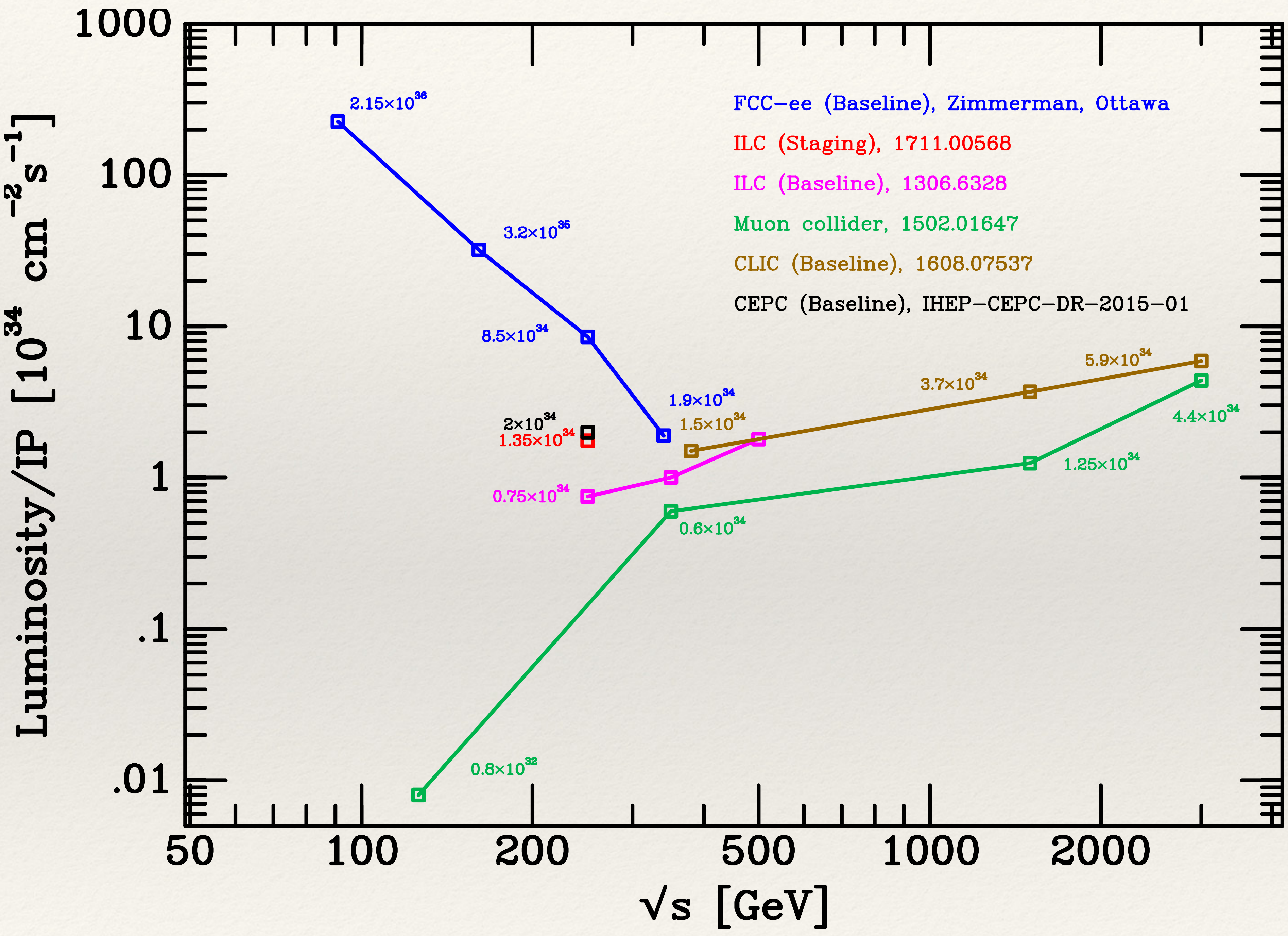
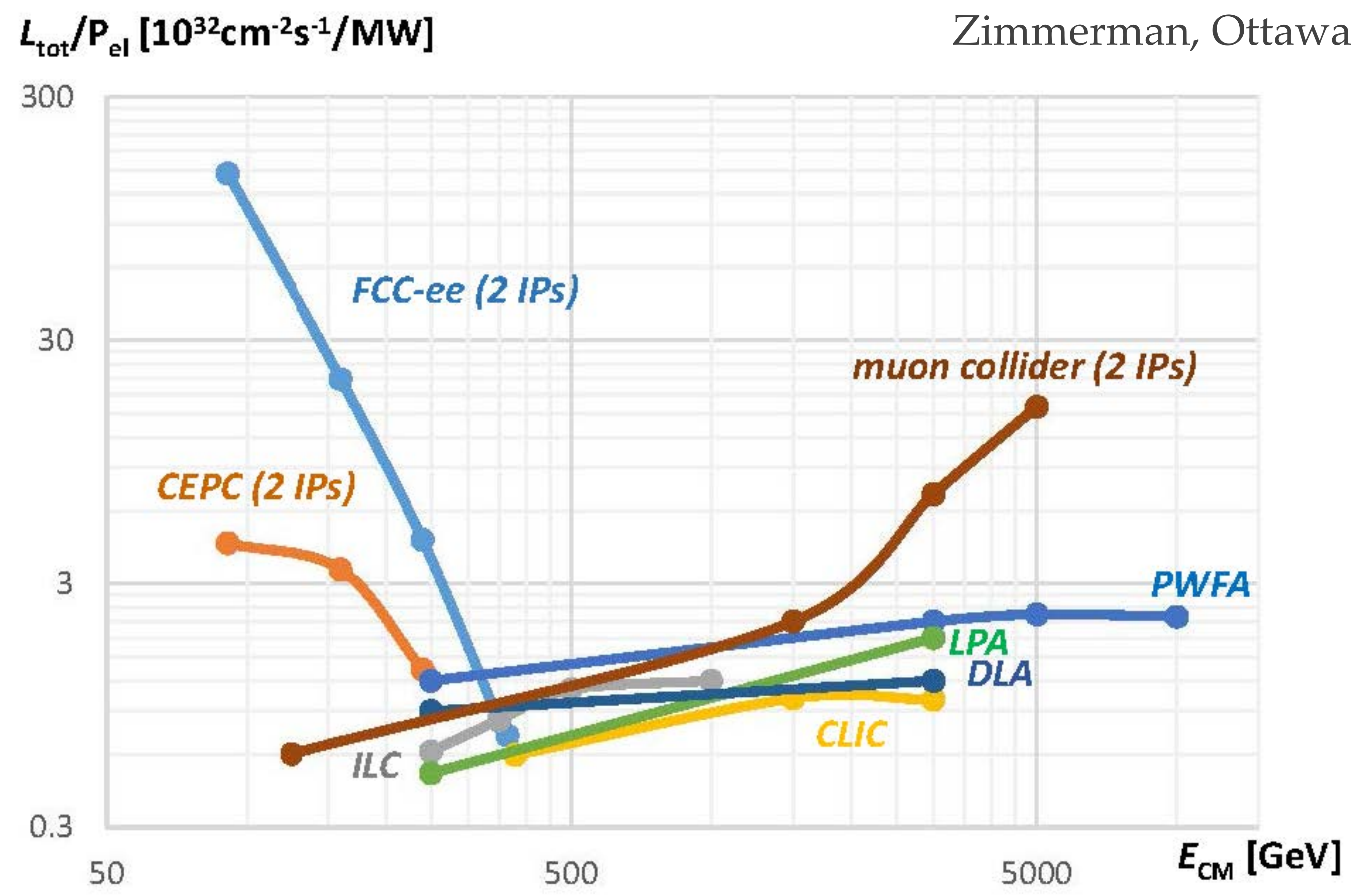
Lepton-colliders

Luminosity at lepton colliders



Lepton colliders

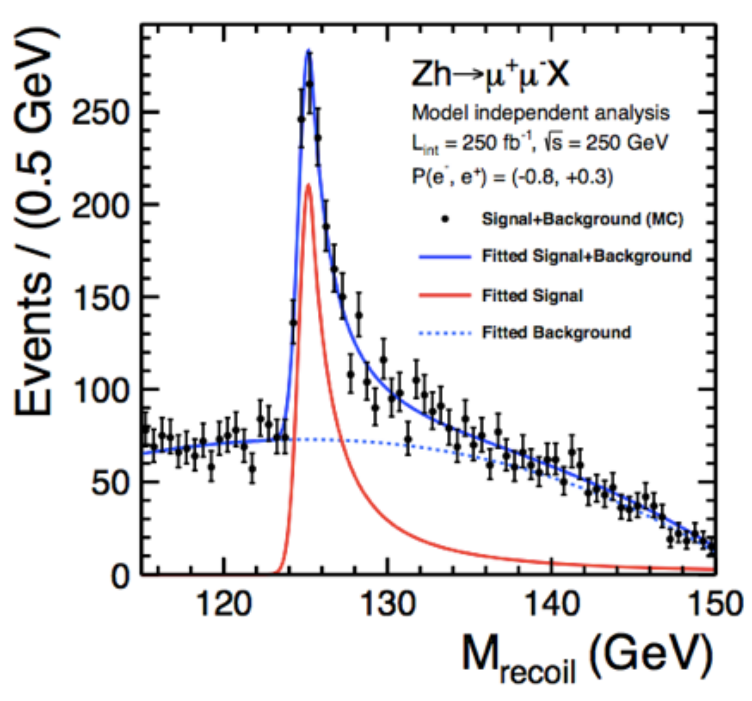
- Luminosity per Megawatt, wall plug power



Zimmerman, Ottawa

Measuring the total width at e+e- collider

$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

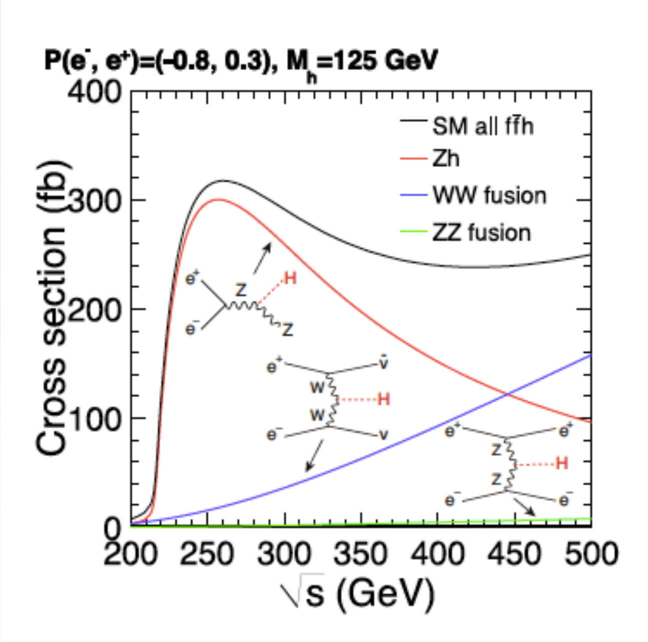


- It is possible to identify a Higgs event without looking at the Higgs at all.
- Total width is given by the quotient of partial width and branching to a given final state.

$$\Gamma_{tot} = \frac{\Gamma(H \to ZZ)}{\mathrm{BR(H \to ZZ)}} = \frac{\sigma(e^+e^- \to ZH)\Gamma(H \to ZZ)}{\sigma(e^+e^- \to ZH) \cdot \mathrm{BR(H \to ZZ)}}$$

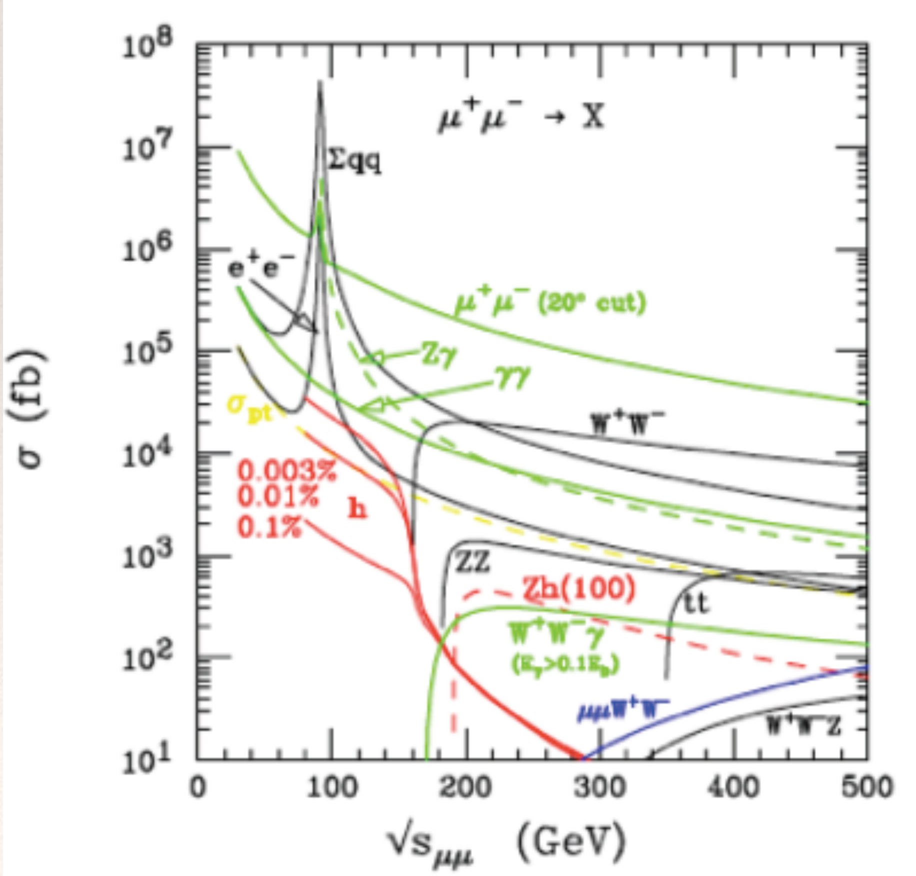
- The partial width is controlled by the HZZ coupling, just like the total cross section $\Gamma(H \to ZZ) \propto \sigma_{HZ}$
- The total width can be measured with the same precision as

$$\frac{\sigma^2_{HZ}}{\sigma_{HZ} \cdot BR(H \to ZZ)}$$



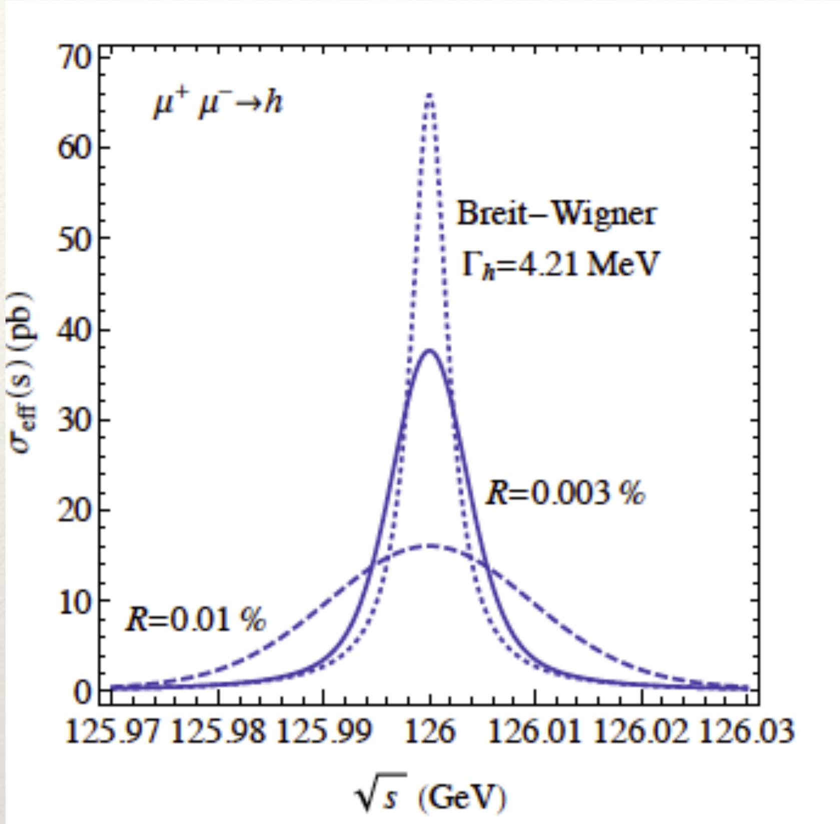
Muon collider Higgs Factory

- Compact, fits on CERN site; Higgs factory ring radius 50m.
- Advantages associated with circular geometry
- Multipass acceleration, multipass collisions, more than one detector
- Narrow energy spread, negligible synchrotron radiation. Higgs signal depends on resolution.
- Picobarn cross section for s-channel Higgs production, direct measurement scan of Higgs width.
- Follow on program, neutrino factory, no energy constraints limiting scaling to Multi-TeV energy.



Muon collider

- Effective production cross section, $\sigma(\mu^+\mu \rightarrow H, \sqrt{s}=125\mathrm{GeV}) = \sim 15\mathrm{pb}$, but dependent on resolution.
- cf, $\sigma(e^+e^- \rightarrow ZH, \sqrt{s}=240\mathrm{GeV}) = 200\text{-}300\mathrm{fb}$
- Ring size small, presenting the hope that cost scales with size.
- Detector issues, decaying beam particle, “machine detector interface”.
- Follow on program, Nustorm, Intense muon beams for Lepton-Flavour violation, neutrino factory, high energy muon collider.….



Gaussian energy spread $\Delta = R\sqrt{s}/\sqrt{2}$

$$\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}} = \frac{1}{\sqrt{2\pi}\Delta}\exp\left[\frac{-(\sqrt{\hat{s}}-\sqrt{s})^2}{2\Delta^2}\right],$$

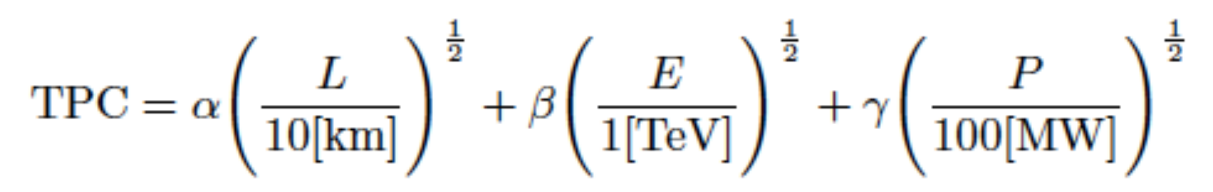
$$\sigma_{\rm eff}(s) = \int d\sqrt{\hat{s}}\,\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}}\sigma(\mu^+\mu^- \to h \to X)$$
$$\propto \begin{cases} \Gamma_h^2 B/[(s-m_h^2)^2+\Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B\exp\left[\frac{-(m_h-\sqrt{s})^2}{2\Delta^2}\right]\left(\frac{\Gamma_h}{\Delta}\right)/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$

Economics: the dismal science

V. Shiltsev, arXiv:1404.4097

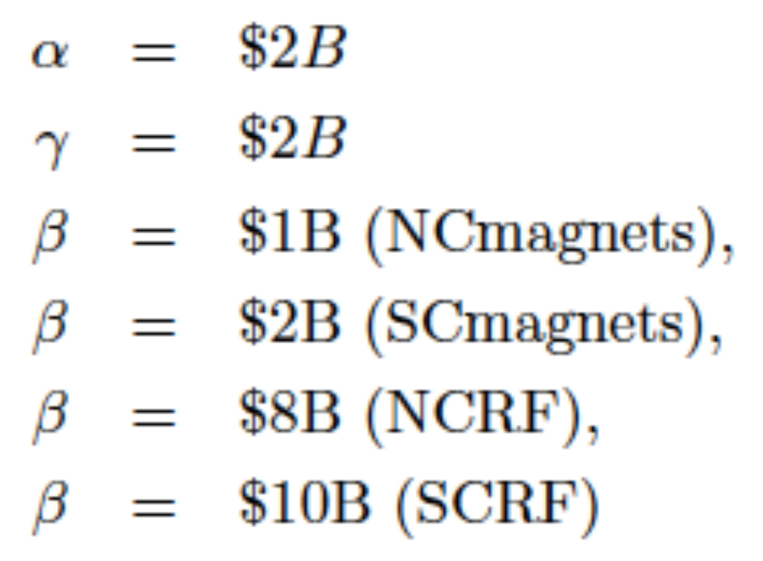
Phenomenological Model of Accelerator costs

- Total project cost [TPC] divided into three components



$$\mathrm{TPC} = \alpha\left(\frac{L}{10[\mathrm{km}]}\right)^{\frac{1}{2}} + \beta\left(\frac{E}{1[\mathrm{TeV}]}\right)^{\frac{1}{2}} + \gamma\left(\frac{P}{100[\mathrm{MW}]}\right)^{\frac{1}{2}}$$

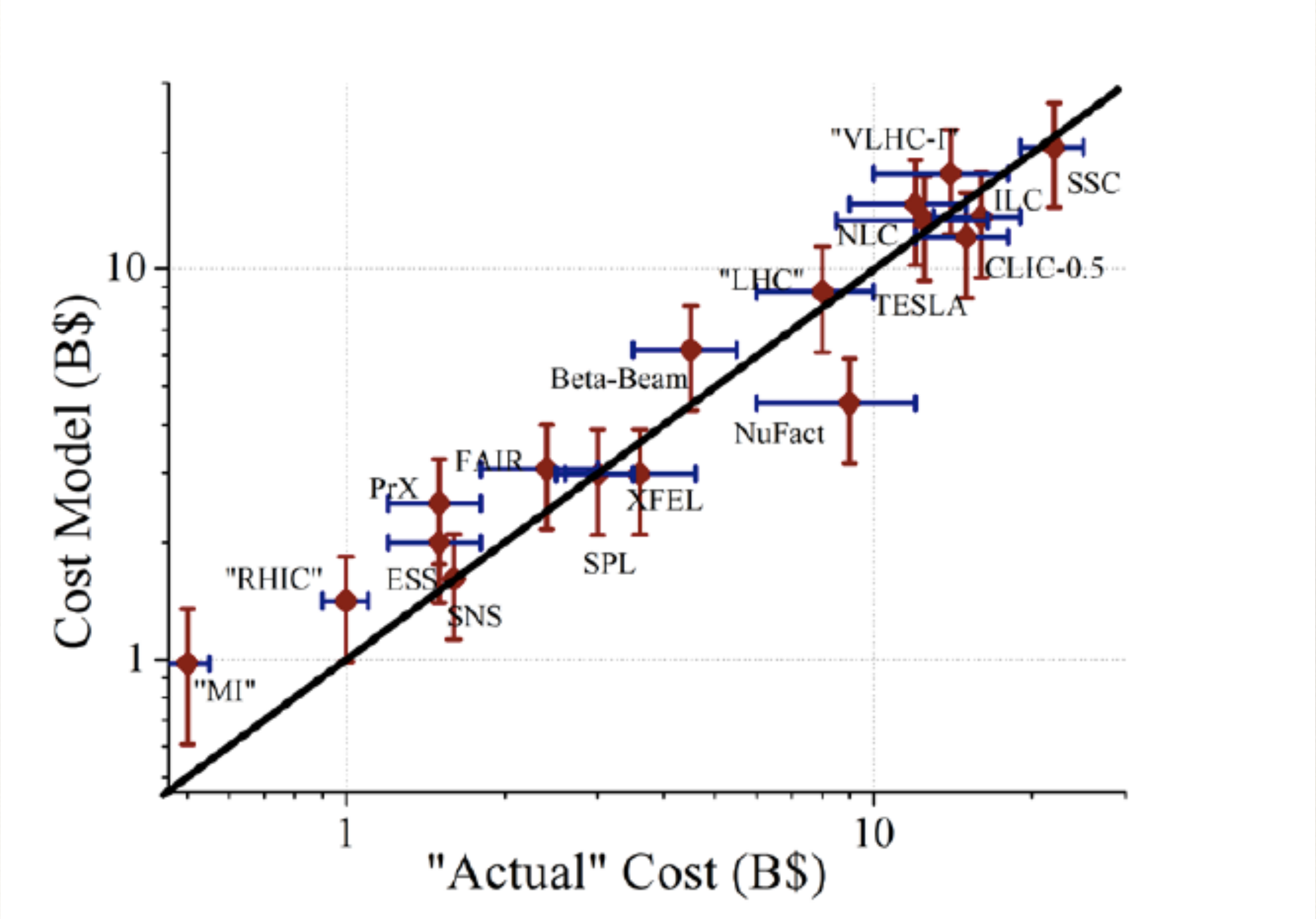
- Civil Engineering and construction
- Accelerator components
- Facility Infrastructure
- Phenomenological formula parametrised in terms of tunnel length[L], centre-of-mass Energy[E] and total site AC power [P]
- Coefficient beta is technology dependent



$$\begin{array}{lcl}
\alpha & = & \$2B \\
\gamma & = & \$2B \\
\beta & = & \$1\mathrm{B}\ (\mathrm{NCmagnets}), \\
\beta & = & \$2\mathrm{B}\ (\mathrm{SCmagnets}), \\
\beta & = & \$8\mathrm{B}\ (\mathrm{NCRF}), \\
\beta & = & \$10\mathrm{B}\ (\mathrm{SCRF})
\end{array}$$

Validation of cost model

- USaccounting≈ 3xEuropean accounting
- Model good to about 30%
- Lots of inverted commas around Actual!



V. Shiltsev, arXiv:1404.4097

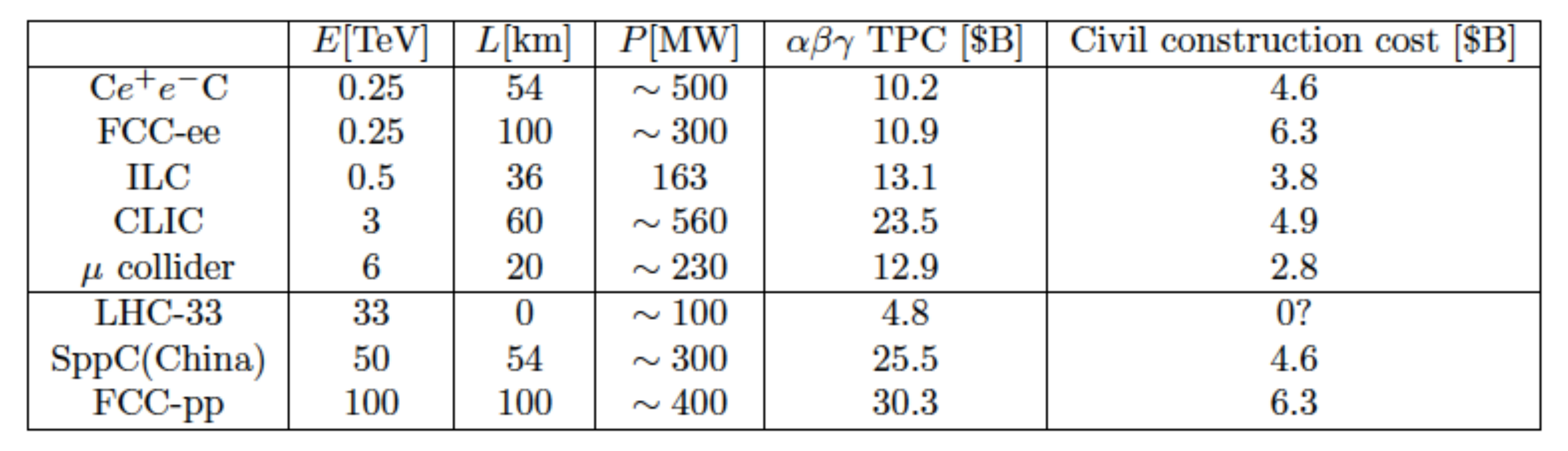
How much is plausible/possible?

- The CERN subscription is about $1B/year. (20% higher now).
- World-wide spending is about $3B/year, of which only a fraction is available for projects
- Spending $1B/year over ten years would allow us to complete a $10B project.

V. Shiltsev, arXiv:1404.4097

Estimated costs of future facilities

- Costs are in American accounting, i.e. including all labour costs. In European accounting this would be a factor ~2-2.5 smaller.



	E[TeV]	L[km]	P[MW]	$\alpha\beta\gamma$ TPC [$B]	Civil construction cost [$B]
Ce^+e^-C	0.25	54	~ 500	10.2	4.6
FCC-ee	0.25	100	~ 300	10.9	6.3
ILC	0.5	36	163	13.1	3.8
CLIC	3	60	~ 560	23.5	4.9
μ collider	6	20	~ 230	12.9	2.8
LHC-33	33	0	~ 100	4.8	0?
SppC(China)	50	54	~ 300	25.5	4.6
FCC-pp	100	100	~ 400	30.3	6.3

These are Shiltsev’s numbers, in no way approved by any of the proponents of these machines.

- Power usage is substantial. Rate of energy usage,~1 kW/person.
- A small nuclear power station gives 500MW of power.

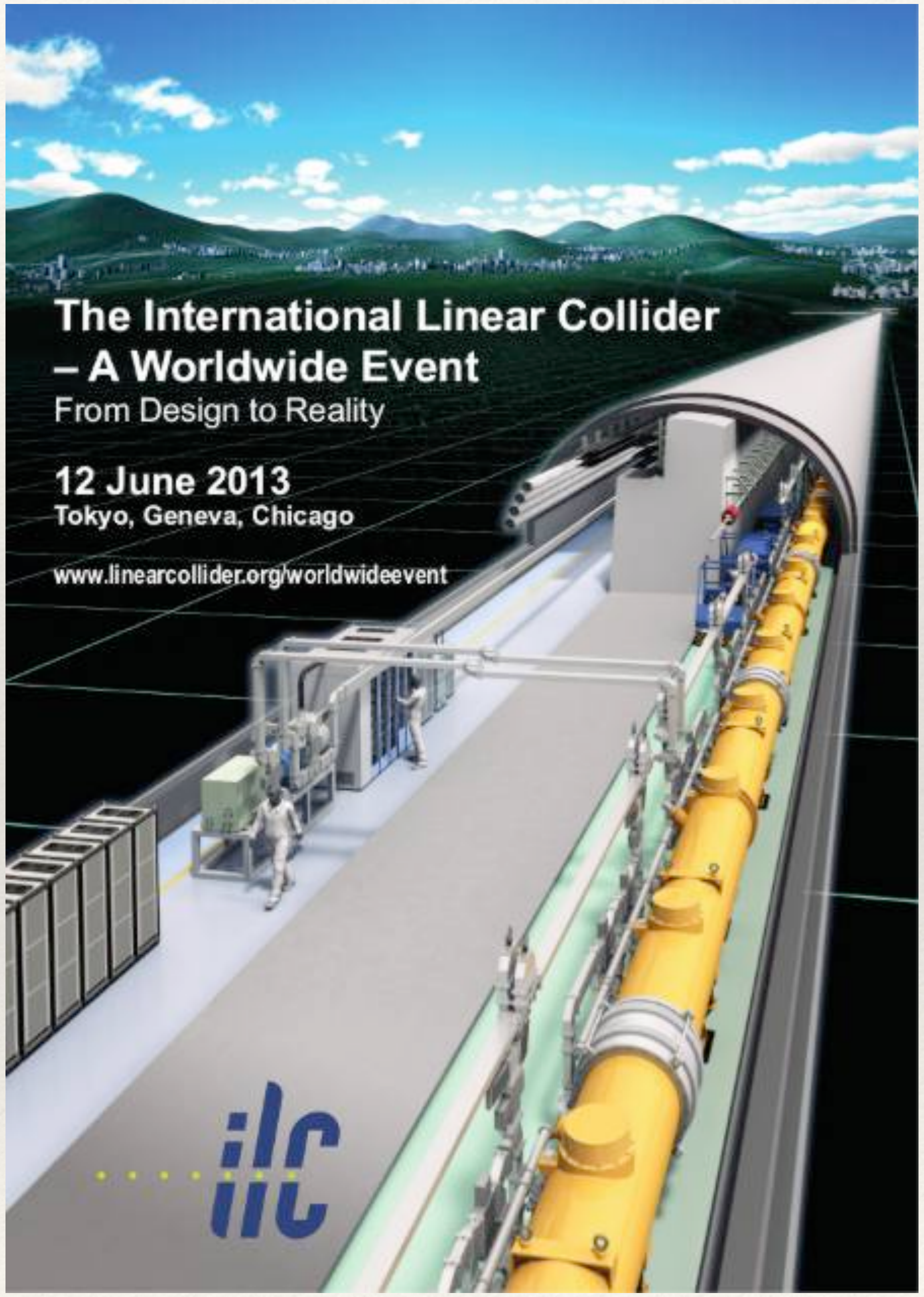
Paramters for CepC,ILC,HE-LHC,SppC have now changed.

HE-LHC advantages

- The tunnel is already there.
- Communality of Magnet R&D program with FCC-hh
- Achievable with current level of CERN budget?

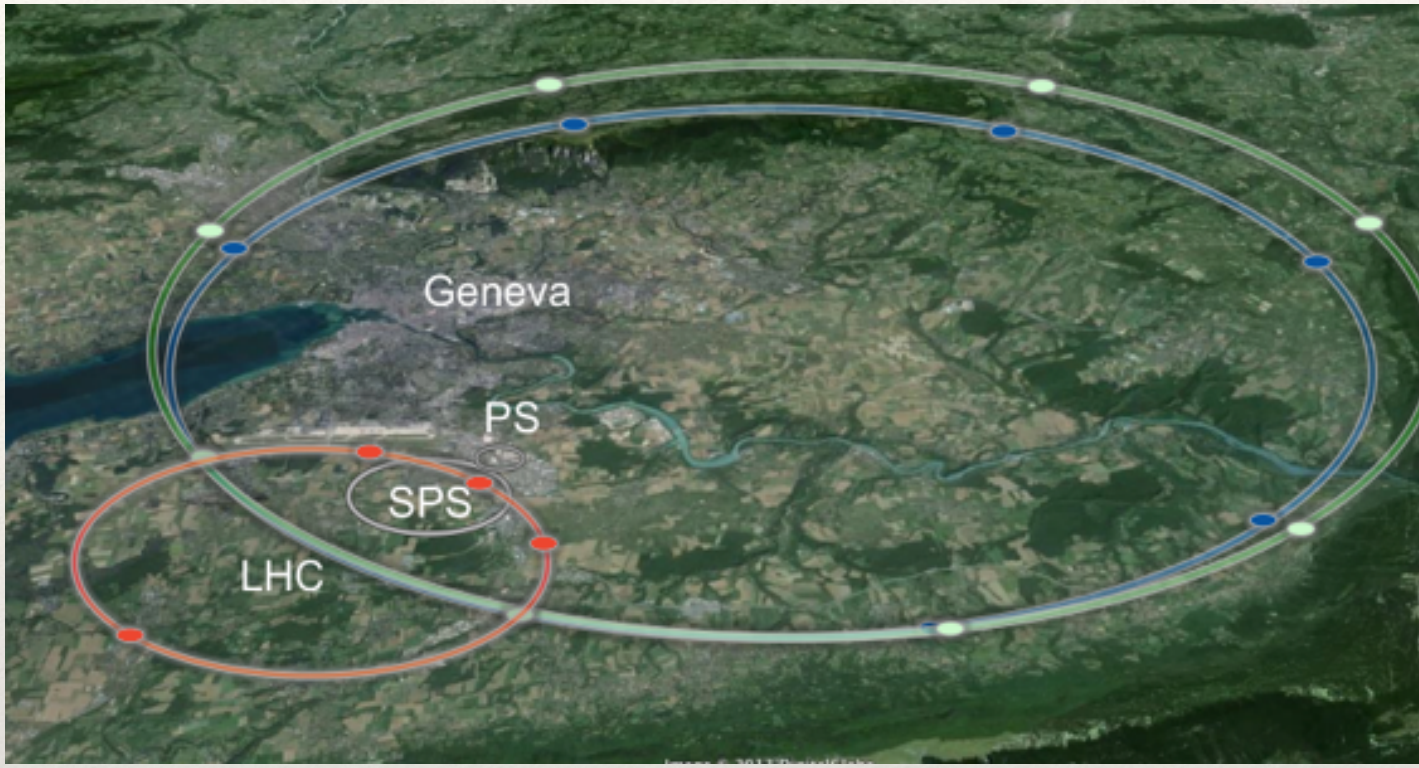
ILC advantages

- A very challenging machine, which now benefits from 20 years of R&D.
- Measurement of Higgs width, using missing mass technique (Common to all e+e- colliders).
- Polarization increases ZH cross section 40% and helps in analysis.
- Japan may pay a substantial fraction of the cost.



FCC(e+e-) Advantages

- Luminosity (superior to ILC).
- Access to physics at the √s=91,240,350 GeV
- Tunnel for further use
- TDR in 2018.
- c.f. CEPC, although limitation on energy consumption gives lower projected luminosity

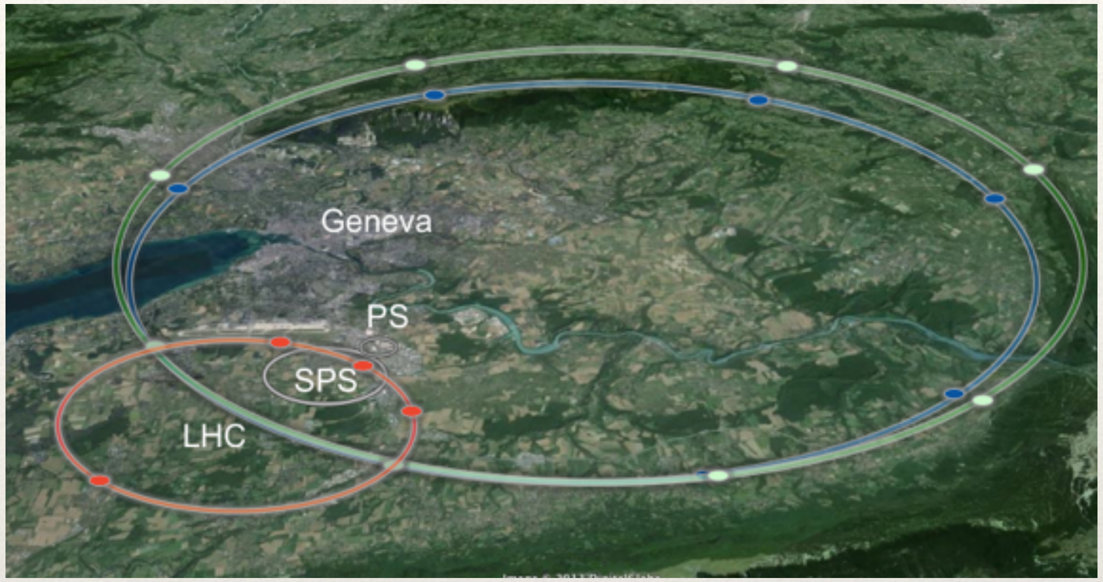


CLIC Advantages

- All the advantages of other e+e- machines, including polarization.
- Possible path to high energy, projected energies, $\sqrt{s}$=380,1500,3000 GeV

Parameter	Unit			
C.ofM. energy	GeV	380	1500	3000
L/year	fb^{-1}	180	444	720

FCC(hh) advantages



- Large jump in energy
- The highest energy hadron-hadron machines have always been considered discovery machines, and have not failed us, (SppS (W,Z), Tevatron (Top), LHC(Higgs).

Muon collider advantages

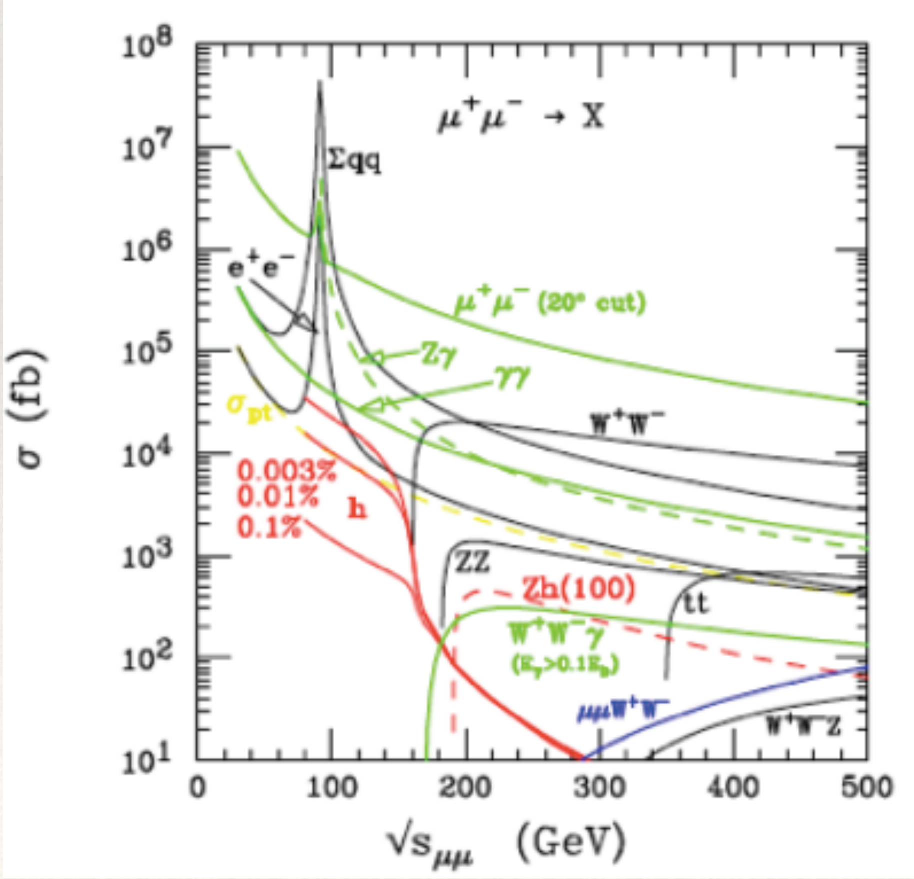
- R&D program, with physics at every step, Nustorm, Higgs factory, Neutrino Factory, High-energy lepton collider.
- Access to high energy lepton collider.
- Small size, leading to possibility of small civil construction, perhaps lower cost.

LHC-ep advantages

- the only possible TeV scale collider one can build in Europe at affordable cost in the next decade
- it brings fundamental new physics for the 2030's
- it maximises the LHC physics return
- it opens a wide perspective for accelerator R and D, energy recovery linac.
- prospect for some Higgs physics in a cleaner environment than LHC.
- A complementary machine for all energies, collide 60GeV polarized beam with HL-LHC, HE-LHC,FCC-hh.

Muon collider Higgs Factory

- Compact, fits on CERN/Fermilab site
- Advantages associated with circular geometry
- Multipass acceleration, multipass collisions, more than one detector
- Narrow energy spread, negligible synchrotron radiation. Higgs signal depends on resolution.
- Enhanced cross section for s-channel Higgs production, direct measurement scan of Higgs width.
- A separate ring for every energy (Z,H,ttbar)?
- No obvious constraints limiting scaling to Multi-TeV energy.



1502.03454

Schematic of muon complex

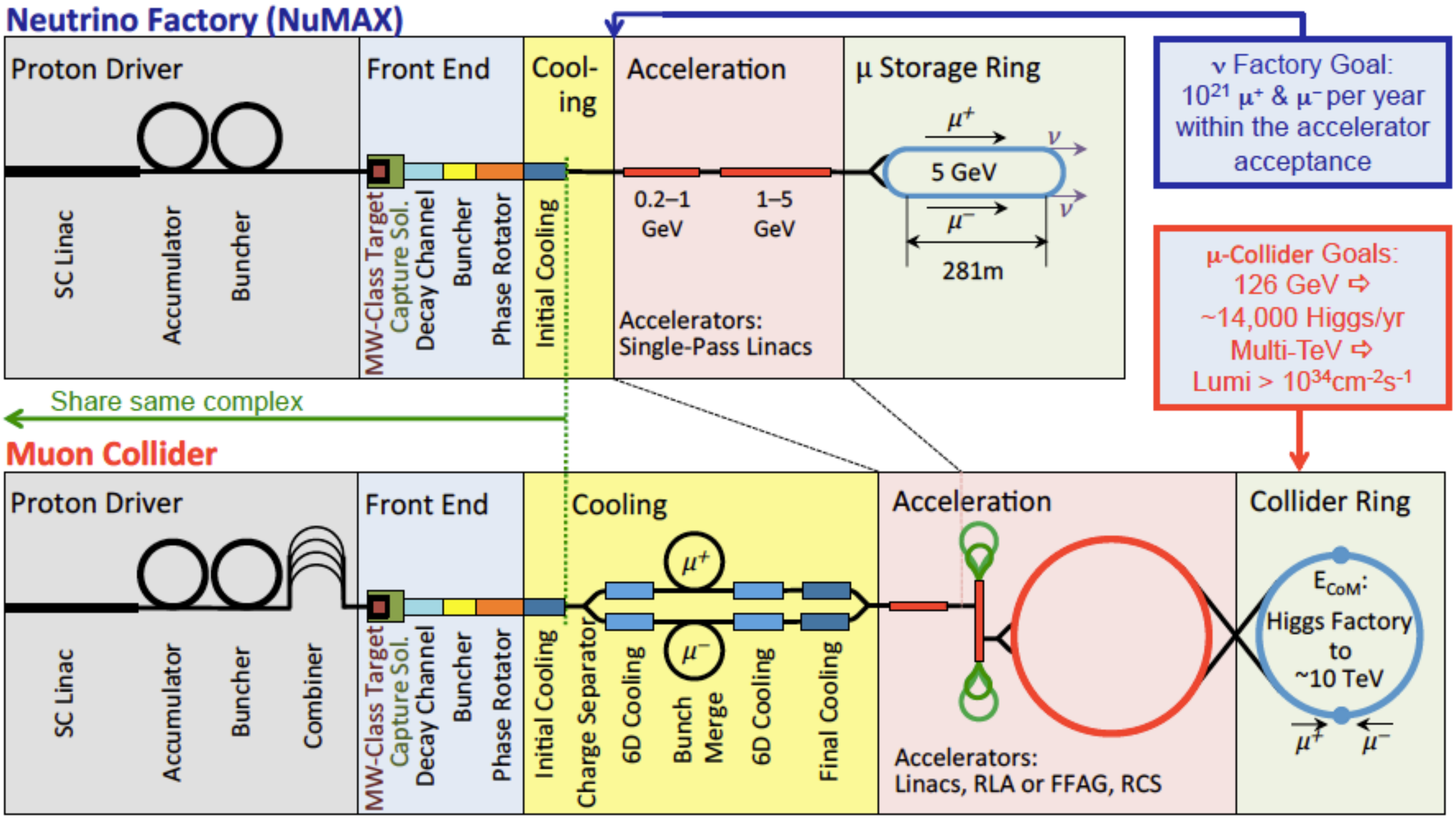
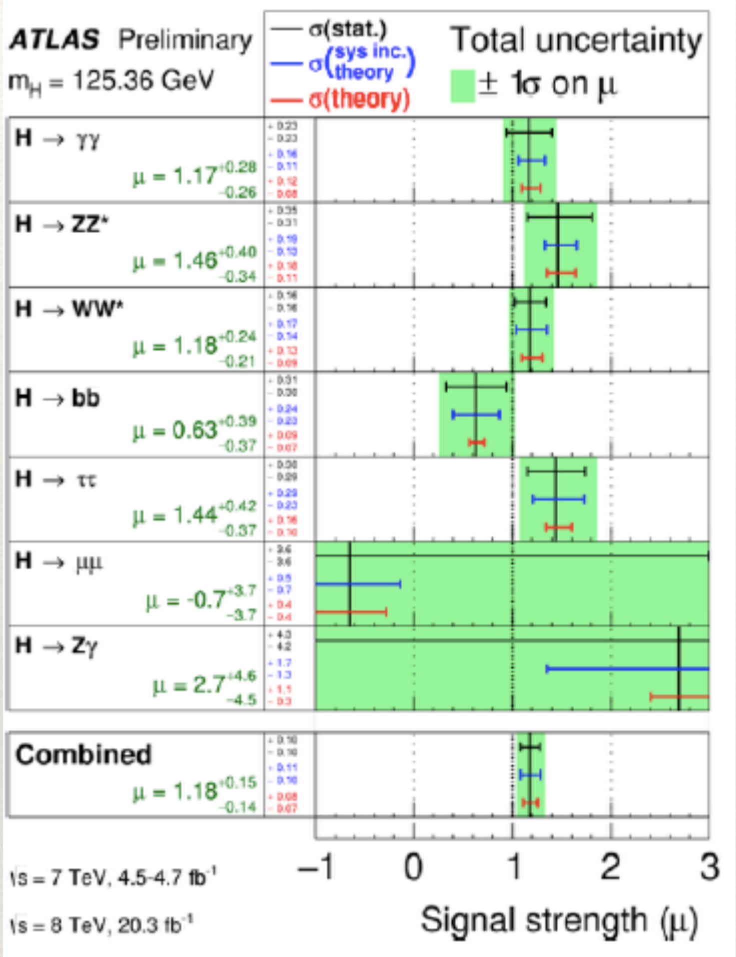


Figure 1: A block diagram showing the key systems needed for a long-baseline neutrino factory capability and a muon collider capability. Much of the infrastructure for each capability could be shared, thus enabling a cost effective multipurpose facility.

Muon-collider Higgs Factory

- Coupling $g_{H\mu\mu}$ not yet measured.
- Muon cooling needs a demonstration of technological feasibility (MICE experiment, LEMMA proposal).
- No access to t-t-H and H-H-H couplings
- Decay backgrounds at High energy

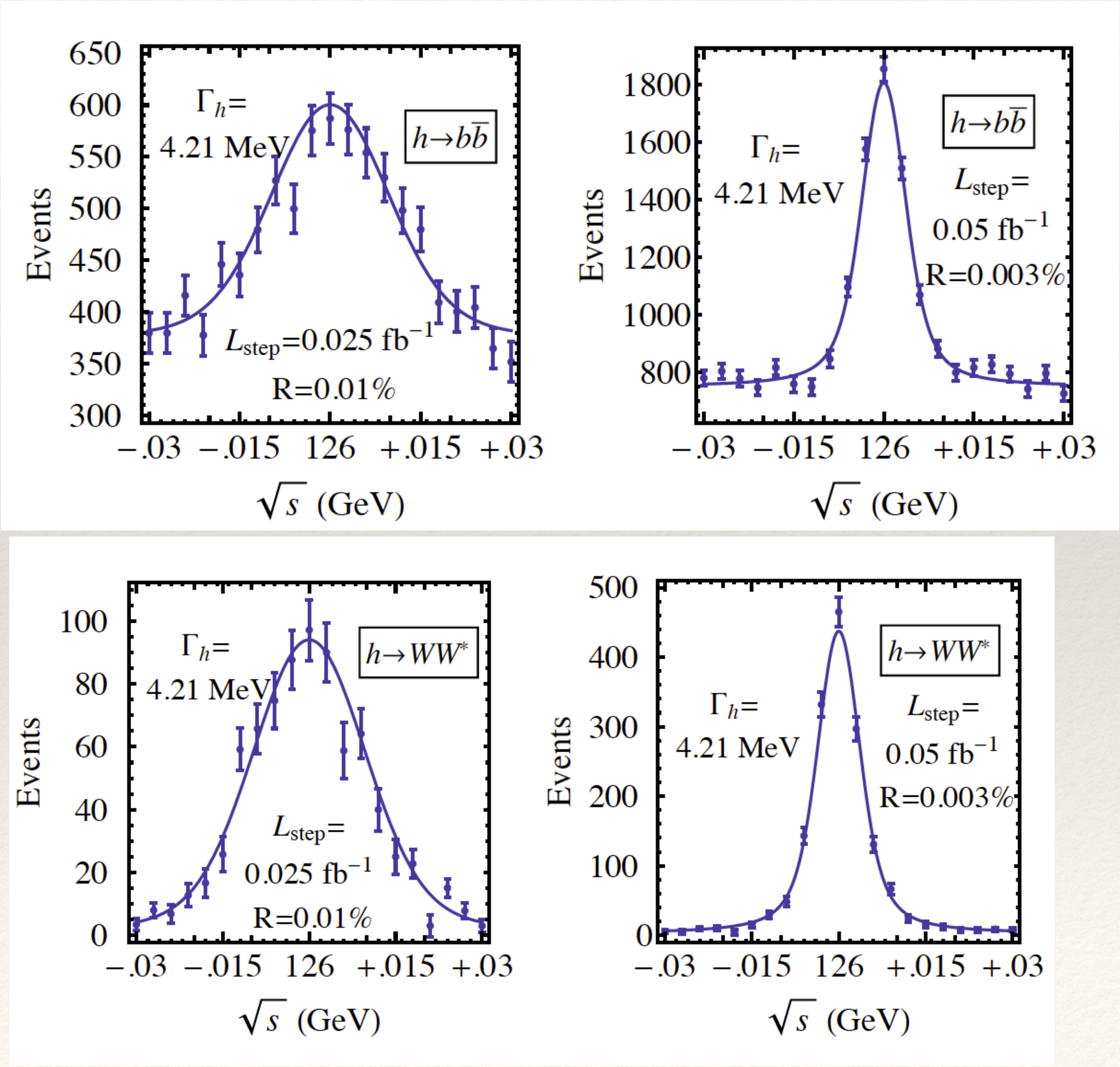


ATLAS-CONF-2015-044

Measuring the Higgs width at Muon collider

1210.7803

With a beam energy resolution of R=0.01% (0.003%) and integrated luminosity of 0.5 fb-1, a muon collider would enable us to determine the Standard-Model-like Higgs width to 0.35 MeV by combining two complementary channels of the WW^* and b\bar b final states



Cern machine parameter list.

- To aid in the strategy update process, the CERN accelerator people have produced a document
- Machine parameters and projected luminosity: performance of proposed future colliders at CERN.
- Realistic assumptions about availability and luminosity
- Beyond the “Snowmass year” approximation.

Projections for the CERN hadron machines

Parameter	Unit	FCC-hh	HE-LHC	HL-LHC	LHC
C.ofM.Energy	TeV	100	27	14	14
Bunch population	10^{11}	1	2.2	1.12	1.15
Peak Events/ crossing	-	170(1000)	460	135	27
Luminosity/ day	fb^{-1}	2.0(8.0)	5.0	1.9	0.4
Luminosity/ year(160 days)	fb^{-1}	250(1000)	500	350	55

The next 50 years

Muon Collider

ILC

Muon-Higgs Factory ?

LHeC

LHC HL-LHC FCC(pp) FCC(ee) ?

? ? ?

CepC

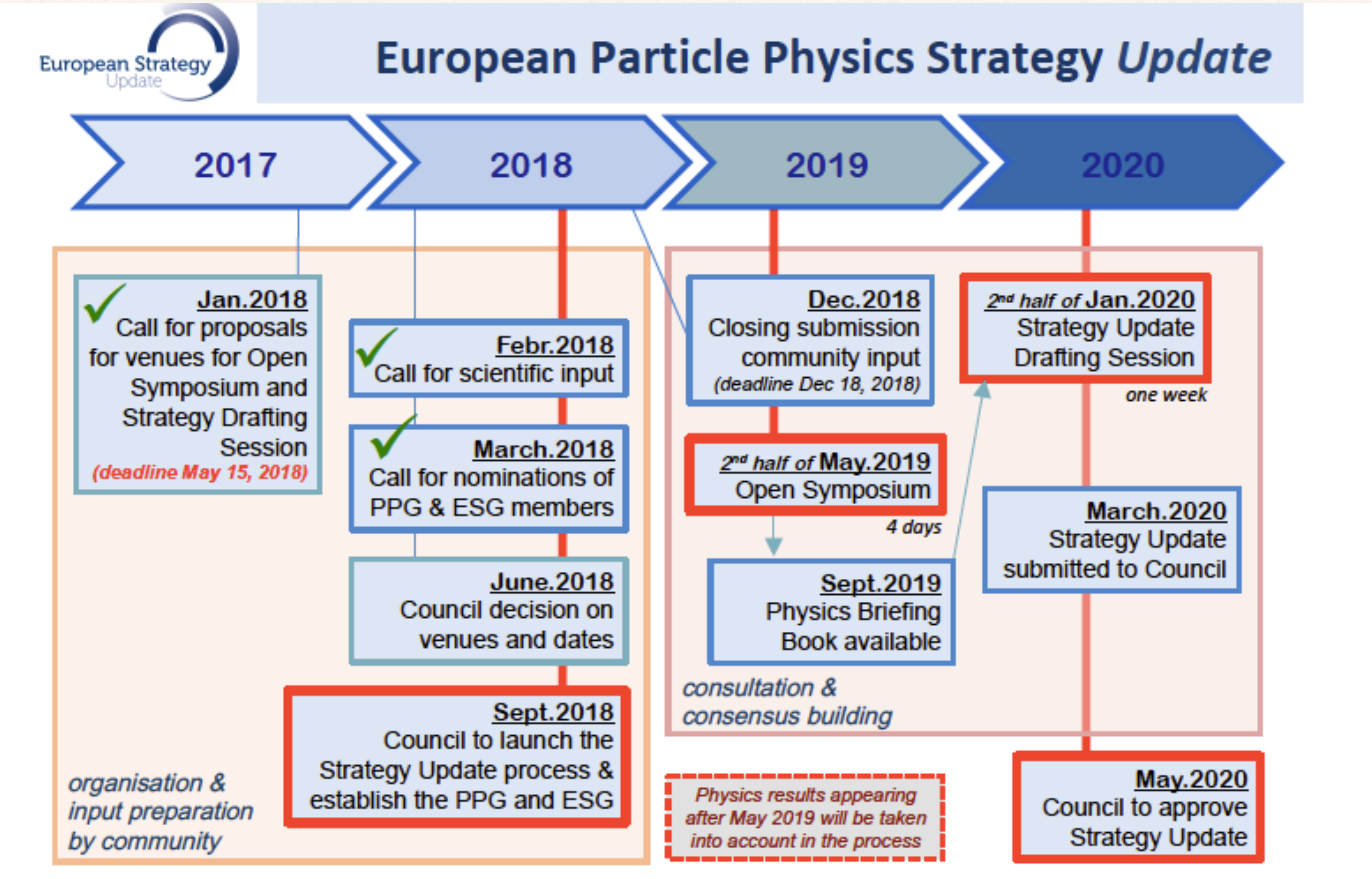
SppC

CLIC(380) CLIC

2018

It is your job to set the time-line!

However you are not alone.



European Strategy Update

European Particle Physics Strategy *Update*

2017 | 2018 | 2019 | 2020

✓ **Jan.2018**
Call for proposals for venues for Open Symposium and Strategy Drafting Session
(deadline May 15, 2018)

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

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

June.2018
Council decision on venues and dates

Sept.2018
Council to launch the Strategy Update process & establish the PPG and ESG

organisation & input preparation by community

Dec.2018
Closing submission community input
(deadline Dec 18, 2018)

***2nd half of* May.2019**
Open Symposium
4 days

Sept.2019
Physics Briefing Book available

consultation & consensus building

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

***2nd half of* Jan.2020**
Strategy Update Drafting Session
one week

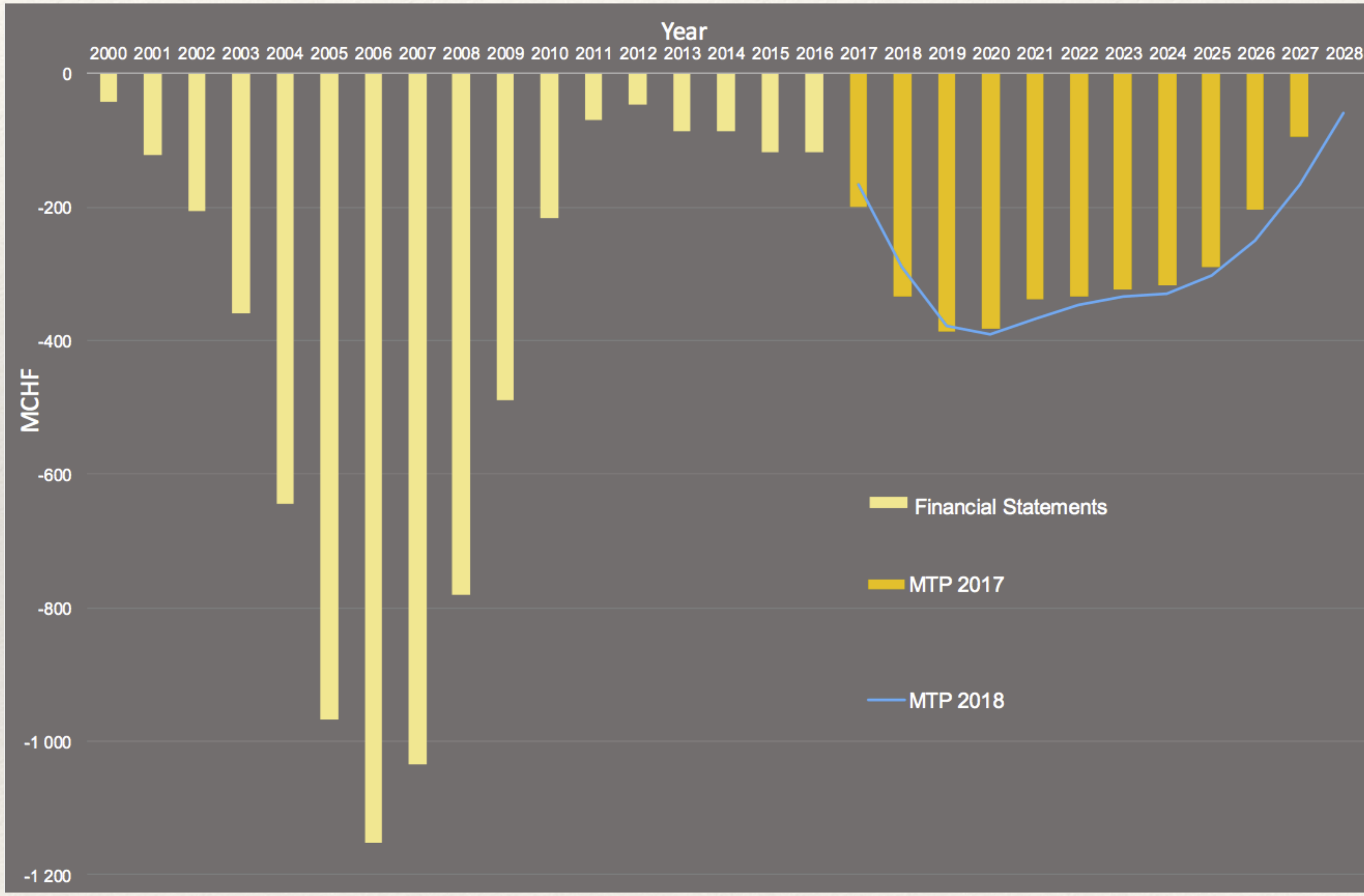
March.2020
Strategy Update submitted to Council

May.2020
Council to approve Strategy Update

- You may want to take note of the open symposium/town meeting in May 2019.

Real decisions to be made

- Cern is entering into a 6-7 year period of financial deficit to pay for the HL-LHC upgrade.
- Because of the financial situation, there is not money to support both magnet R&D and CLIC TDR preparation, to be ready to start a project in 2027-2028



Conclusions

- Human ingenuity (colliders, superconducting magnets) have allowed the field to progress. There is no reason to think that the reservoir of human ingenuity has run dry.
- Our field has made bold decisions in the past, ISR, SppbarS, Tevatron and LHC.
- Vigorous R&D on alternative acceleration techniques is mandatory.
- We have real decisions to make soon.

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