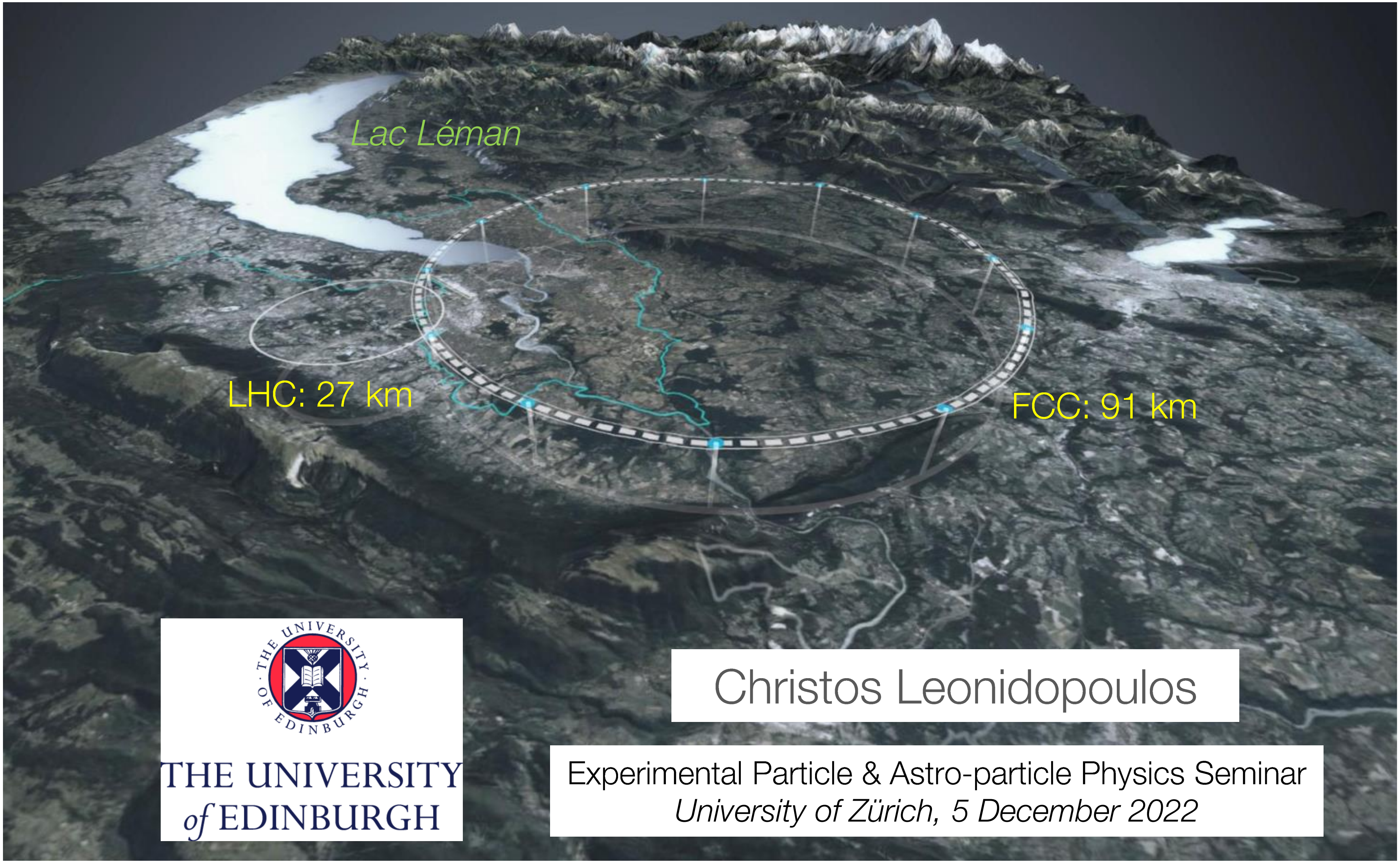
Future Circular Collider & e^+e^-

Physics prospects, TDAQ & Politics



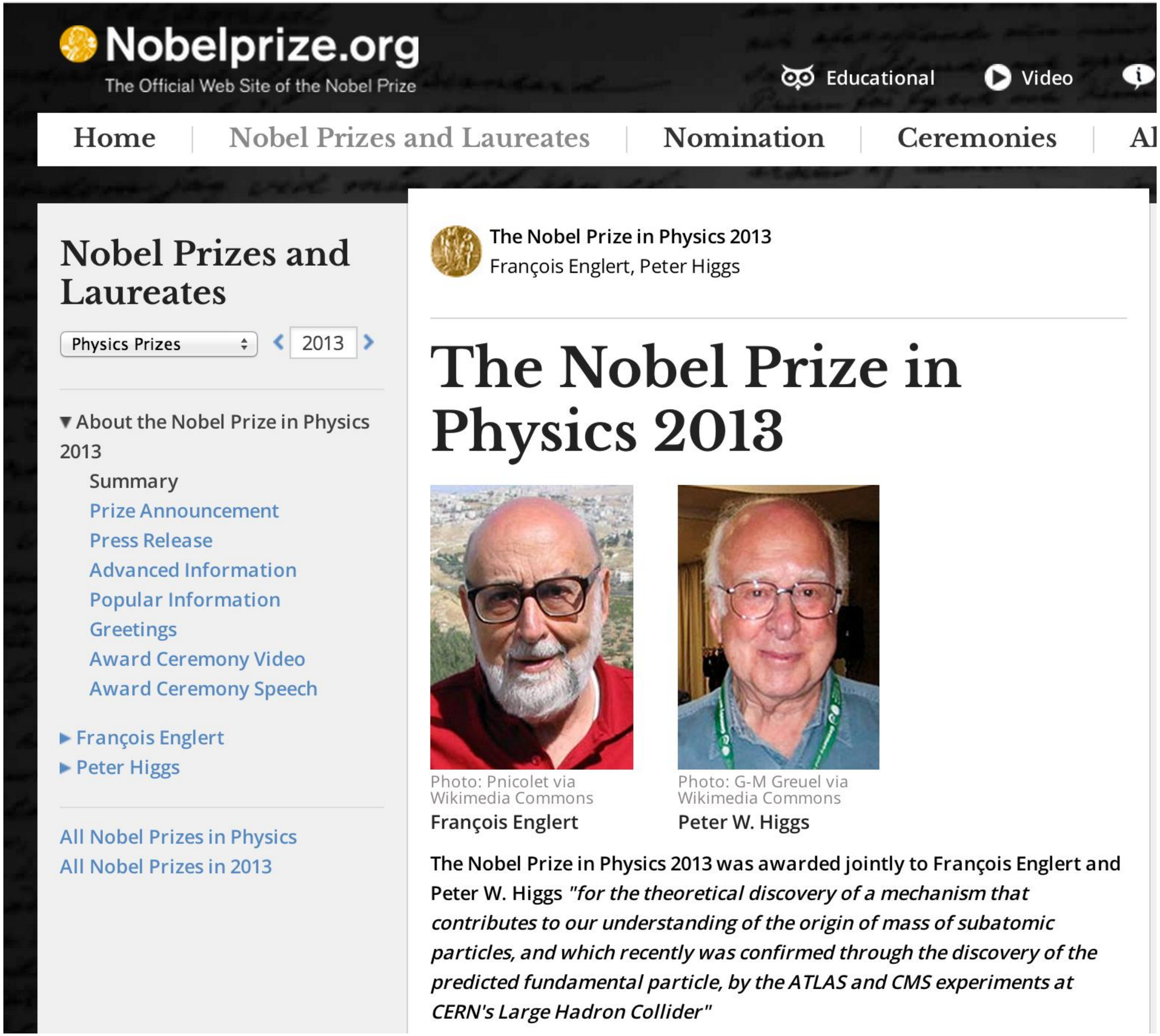
THE UNIVERSITY of EDINBURGH

Christos Leonidopoulos

Experimental Particle & Astro-particle Physics Seminar
University of Zürich, 5 December 2022

4 July 2012

8 October 2013



Nobel Prizes and Laureates

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

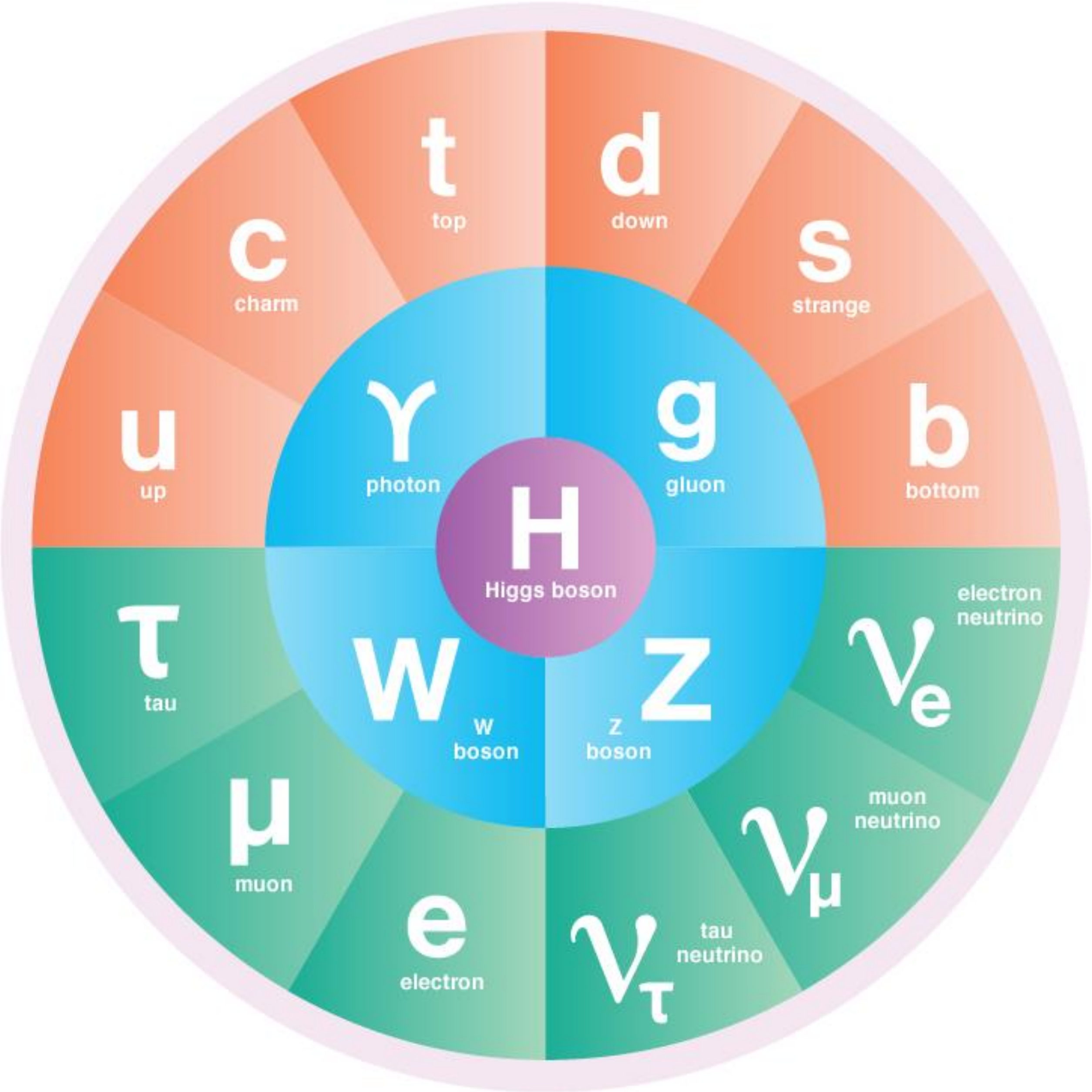
The Nobel Prize in Physics 2013

Photo: Pnicolet via Wikimedia Commons
François Englert

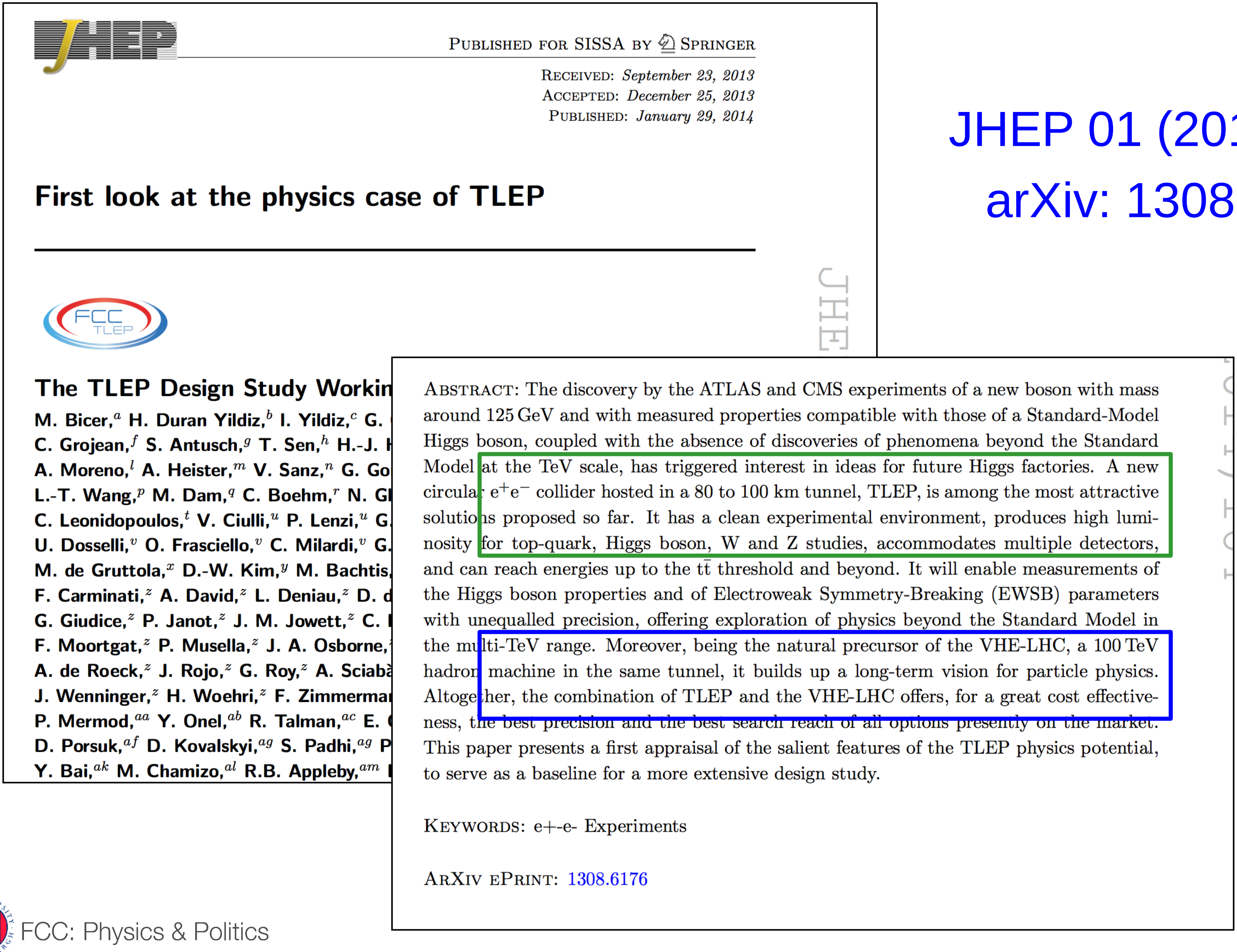
Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

The Completion of the Standard Model



FCCee: a Physics Study



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First look at the physics case of TLEP

The TLEP Design Study Workin

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G.
C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J.
A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Go
L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Gl
C. Leonidopoulos,[t] V. Ciulli,[u] P. Lenzi,[u] G.
U. Dosselli,[v] O. Frasciello,[v] C. Milardi,[v] G.
M. de Gruttola,[x] D.-W. Kim,[y] M. Bachtis,
F. Carminati,[z] A. David,[z] L. Deniau,[z] D. d
G. Giudice,[z] P. Janot,[z] J. M. Jowett,[z] C.
F. Moortgat,[z] P. Musella,[z] J. A. Osborne,
A. de Roeck,[z] J. Rojo,[z] G. Roy,[z] A. Sciabà
J. Wenninger,[z] H. Woehri,[z] F. Zimmerma
P. Mermod,[aa] Y. Onel,[ab] R. Talman,[ac] E.
D. Porsuk,[af] D. Kovalskyi,[ag] S. Padhi,[ag] P
Y. Bai,[ak] M. Chamizo,[al] R.B. Appleby,[am]

Abstract: The discovery by the ATLAS and CMS experiments of a new boson with mass around 125 GeV and with measured properties compatible with those of a Standard-Model Higgs boson, coupled with the absence of discoveries of phenomena beyond the Standard Model at the TeV scale, has triggered interest in ideas for future Higgs factories. A new circular e^+e^- collider hosted in a 80 to 100 km tunnel, TLEP, is among the most attractive solutions proposed so far. It has a clean experimental environment, produces high luminosity for top-quark, Higgs boson, W and Z studies, accommodates multiple detectors, and can reach energies up to the $t\bar{t}$ threshold and beyond. It will enable measurements of the Higgs boson properties and of Electroweak Symmetry-Breaking (EWSB) parameters with unequalled precision, offering exploration of physics beyond the Standard Model in the multi-TeV range. Moreover, being the natural precursor of the VHE-LHC, a 100 TeV hadron machine in the same tunnel, it builds up a long-term vision for particle physics. Altogether, the combination of TLEP and the VHE-LHC offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market. This paper presents a first appraisal of the salient features of the TLEP physics potential, to serve as a baseline for a more extensive design study.

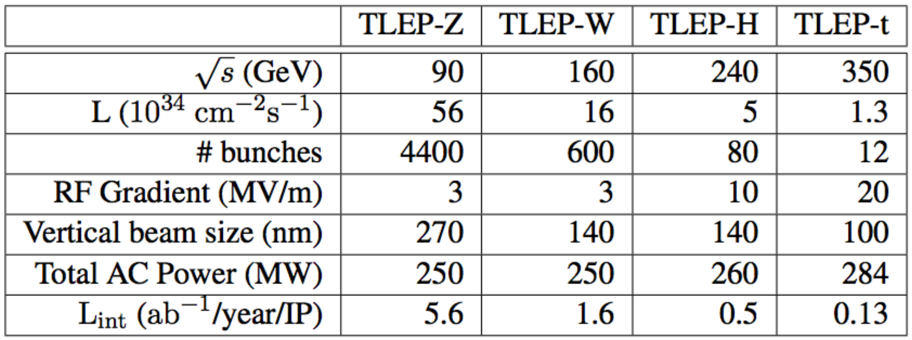
Keywords: e+-e- Experiments

ArXiv ePrint: 1308.6176

JHEP 01 (2014) 164

arXiv: 1308.6176

FCCee: a Physics Study



	TLEP-Z	TLEP-W	TLEP-H	TLEP-t
$\sqrt{s}$ (GeV)	90	160	240	350
L (10^{34} cm^{-2}s^{-1})	56	16	5	1.3
# bunches	4400	600	80	12
RF Gradient (MV/m)	3	3	10	20
Vertical beam size (nm)	270	140	140	100
Total AC Power (MW)	250	250	260	284
L_{int} (ab^{-1}/year/IP)	5.6	1.6	0.5	0.13

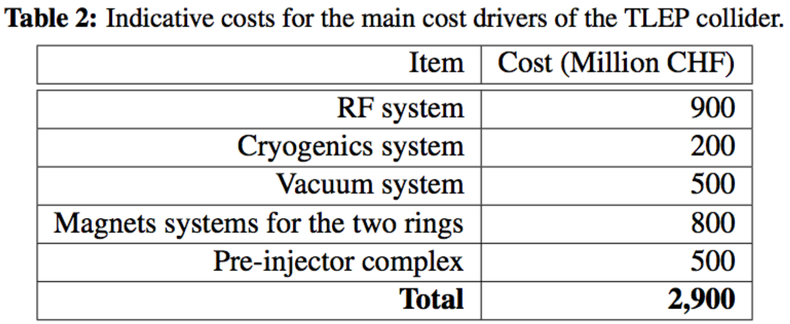
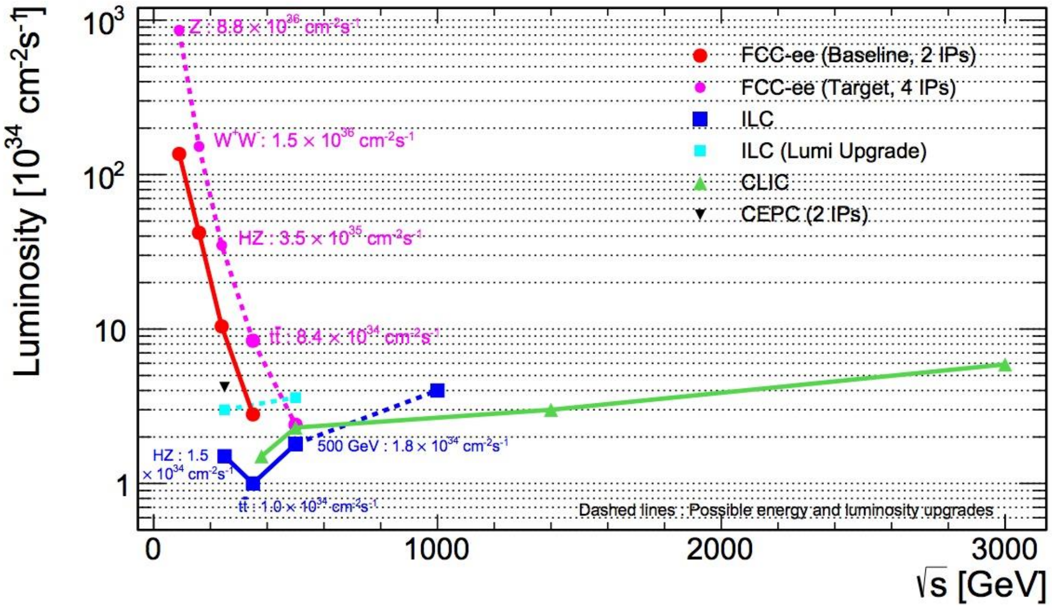


Table 2: Indicative costs for the main cost drivers of the TLEP collider.

Item	Cost (Million CHF)
RF system	900
Cryogenics system	200
Vacuum system	500
Magnets systems for the two rings	800
Pre-injector complex	500
Total	**2,900**



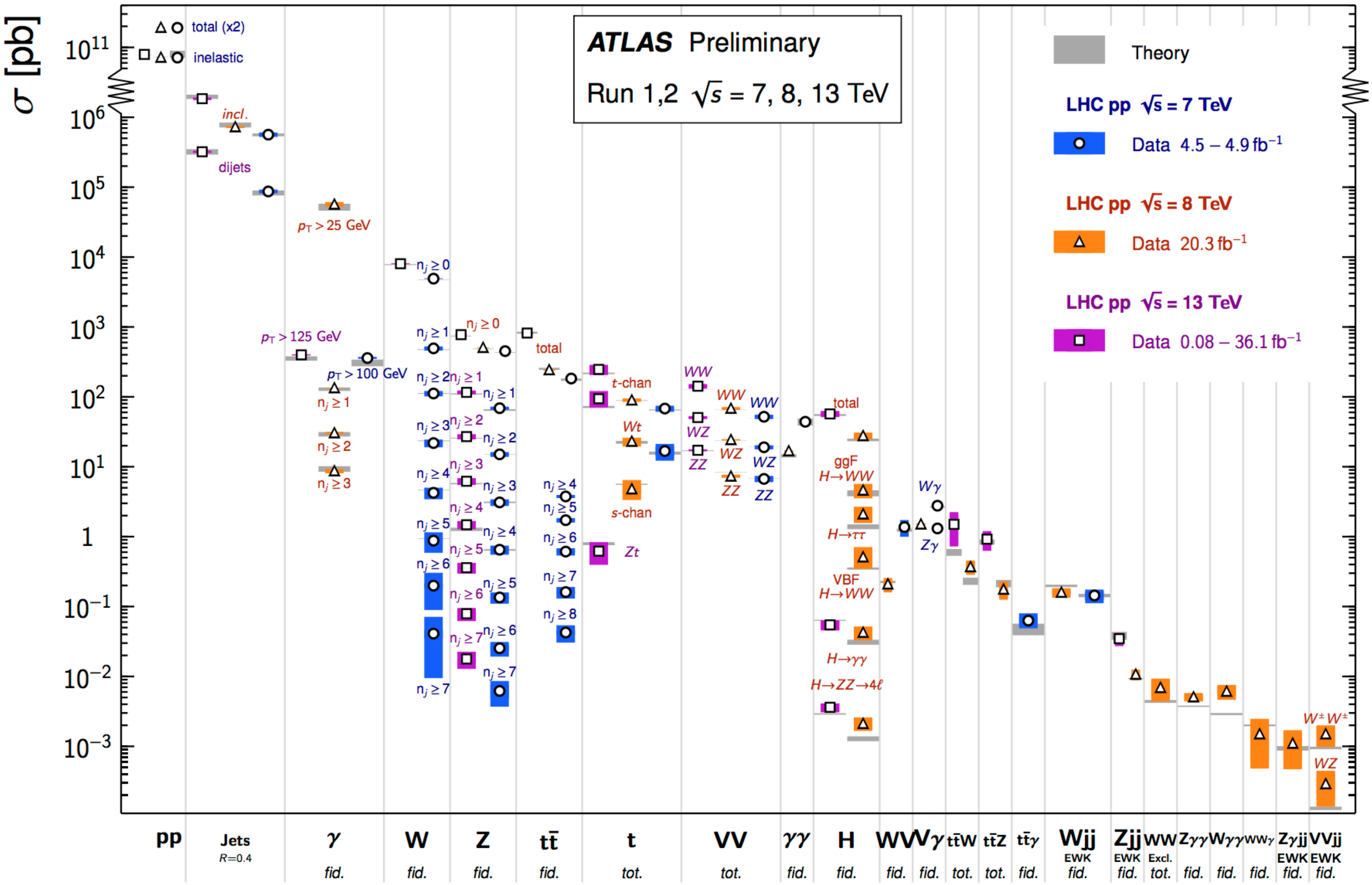
JHEP 01 (2014) 164

arXiv: 1308.6176

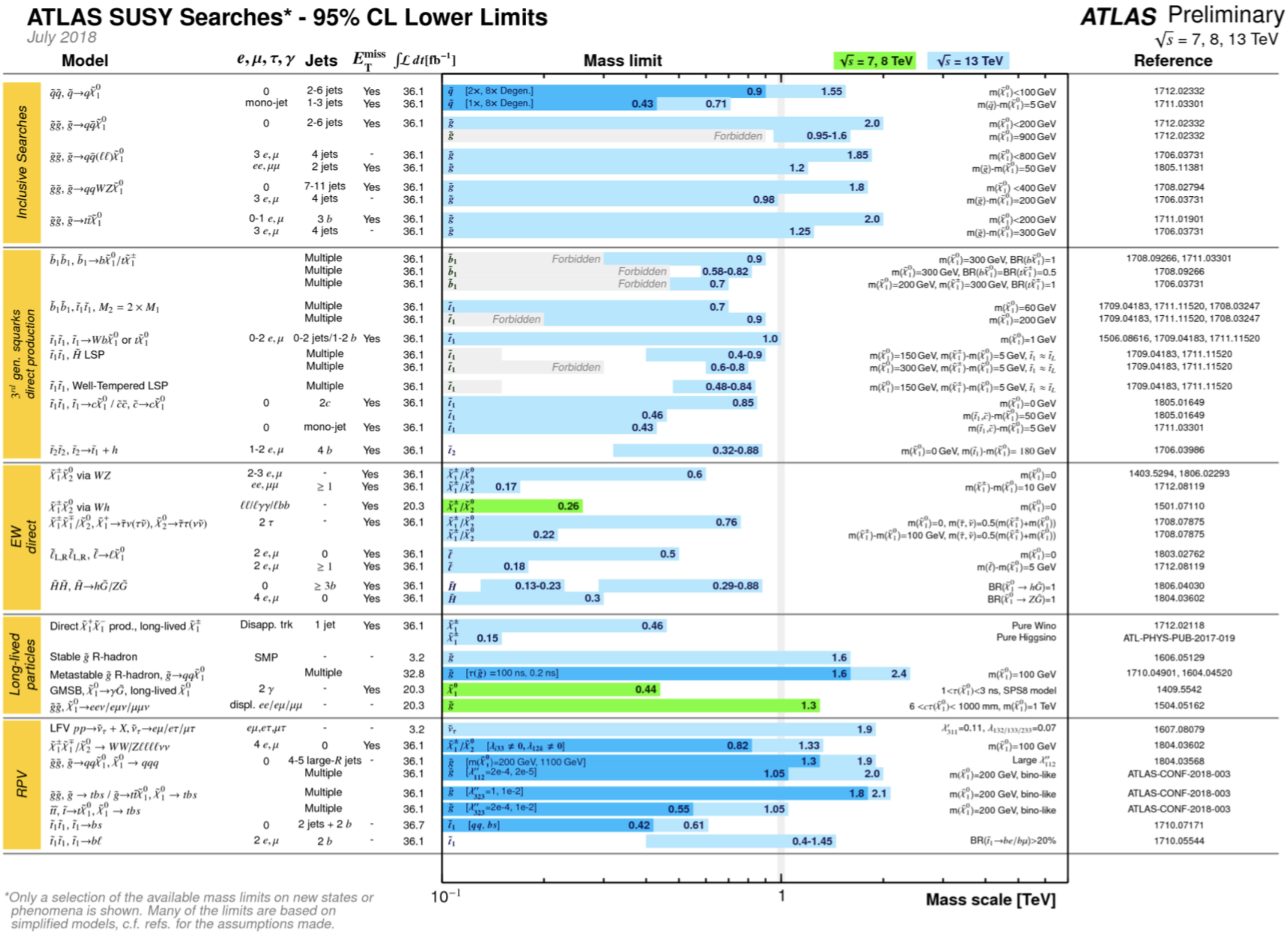
Figure 1: *Target luminosities as a function of center-of-mass energy for future circular (FCC-ee, CEPC) and linear (ILC, CLIC) e^+e^- colliders under consideration.*

Do we *really* need another collider?

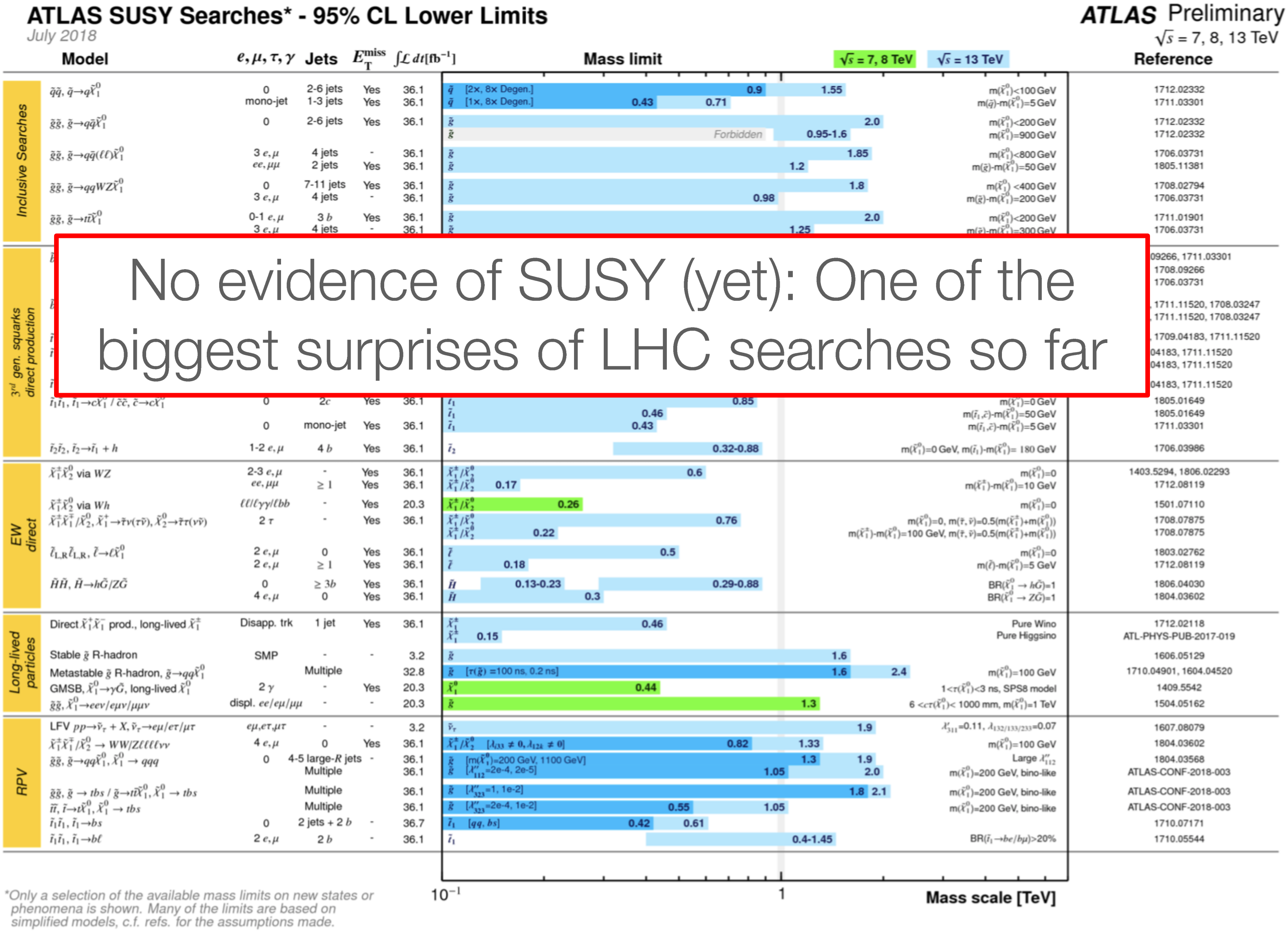
Precision SM Measurements



Summary of SUSY searches



Summary of SUSY searches



ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	$\tilde{q}$ [2x, 8x Degen.] 0.9 1.55 $\tilde{q}$ [1x, 8x Degen.] 0.43 0.71	$m(\tilde{\chi}_1^0)$<100 GeV $m(\tilde{q})$-$m(\tilde{\chi}_1^0)$=5 GeV	1712.02332 1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0 $\tilde{g}$ Forbidden 0.95-1.6	$m(\tilde{\chi}_1^0)$<200 GeV $m(\tilde{\chi}_1^0)$=900 GeV	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ $ee,\mu\mu$	4 jets 2 jets	- Yes	36.1 36.1	$\tilde{g}$ 1.85 $\tilde{g}$ 1.2	$m(\tilde{\chi}_1^0)$<800 GeV $m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=50 GeV	1706.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 3 e,μ	7-11 jets 4 jets	Yes -	36.1 36.1	$\tilde{g}$ 1.8 $\tilde{g}$ 0.98	$m(\tilde{\chi}_1^0)$ <400 GeV $m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=200 GeV	1708.02794 1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ 3 e,μ	3 b 4 jets	Yes -	36.1 36.1	$\tilde{g}$ 2.0 $\tilde{g}$ 1.25	$m(\tilde{\chi}_1^0)$<200 GeV $m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=300 GeV	1711.01901 1706.03731
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{c}$ 0.85 $\tilde{t}_1$ 0.46	$m(\tilde{\chi}_1^0)$=0 GeV $m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)$=50 GeV	1805.01649 1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ $ee,\mu\mu$	- ≥ 1	Yes Yes	36.1 36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17	$m(\tilde{\chi}_1^0)$=0 $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=10 GeV	1403.5294, 1806.02293 1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26	$m(\tilde{\chi}_1^0)$=0	1501.07110
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$) $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=100 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	1708.07875 1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ 2 e,μ	0 ≥ 1	Yes Yes	36.1 36.1	$\tilde{\ell}$ 0.5 $\tilde{\ell}$ 0.18	$m(\tilde{\chi}_1^0)$=0 $m(\tilde{\ell})$-$m(\tilde{\chi}_1^0)$=5 GeV	1803.02762 1712.08119
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 4 e,μ	$\geq 3b$ 0	Yes Yes	36.1 36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88 $\tilde{H}$ 0.3	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1 BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1806.04030 1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46 $\tilde{\chi}_1^\pm$ 0.15	Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	$m(\tilde{\chi}_1^0)$=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, $m(\tilde{\chi}_1^0)$=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33	$m(\tilde{\chi}_1^0)$=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets Multiple	-	36.1 36.1	$\tilde{g}$ [$m(\tilde{\chi}_1^0)$=200 GeV, 1100 GeV] 1.3 1.9 $\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	Large λ''_{112} $m(\tilde{\chi}_1^0)$=200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g}\to tbs / \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

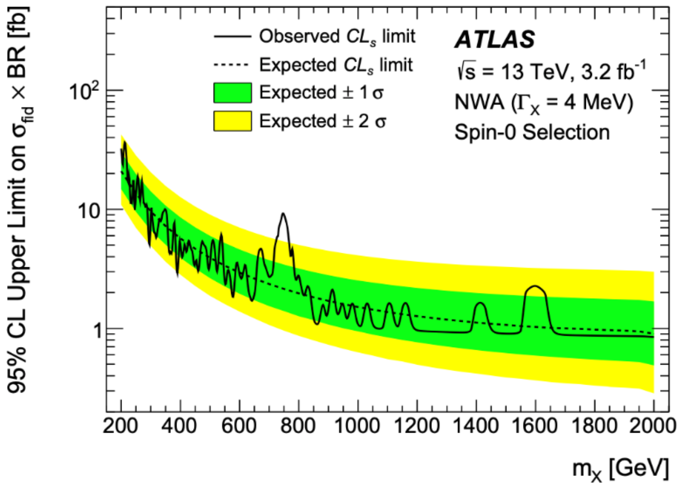
**Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*

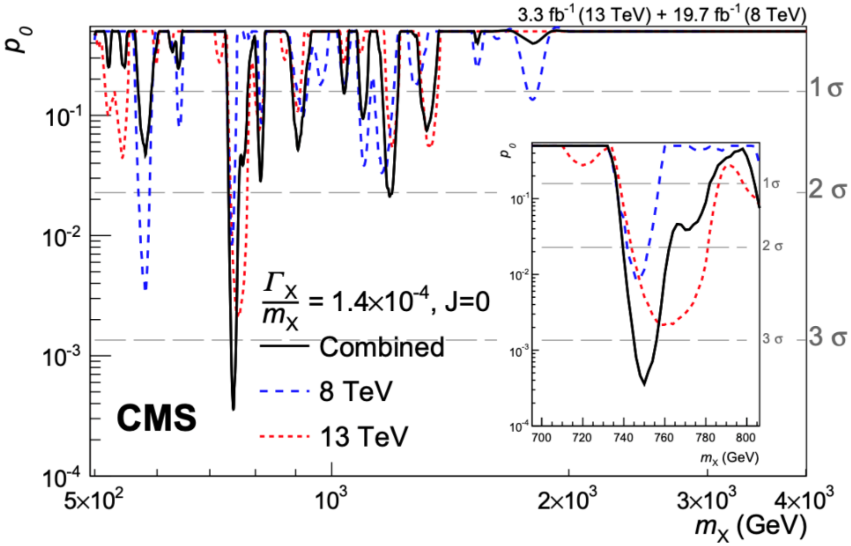
No evidence of SUSY (yet): One of the biggest surprises of LHC searches so far


IS THAT ALL THERE IS ?

Diphoton resonance

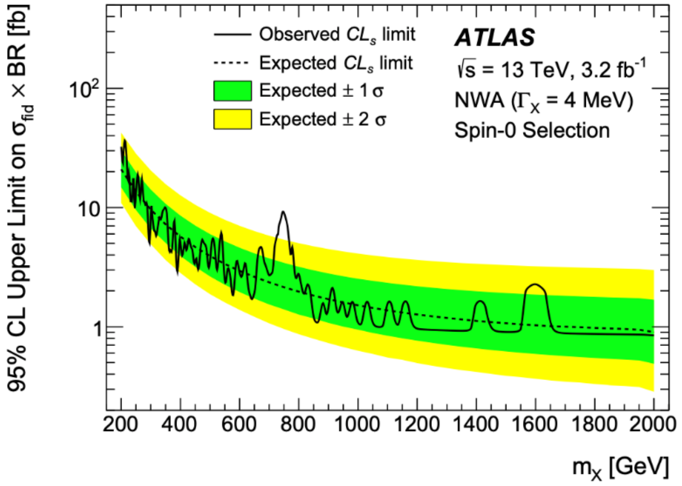
December 2015

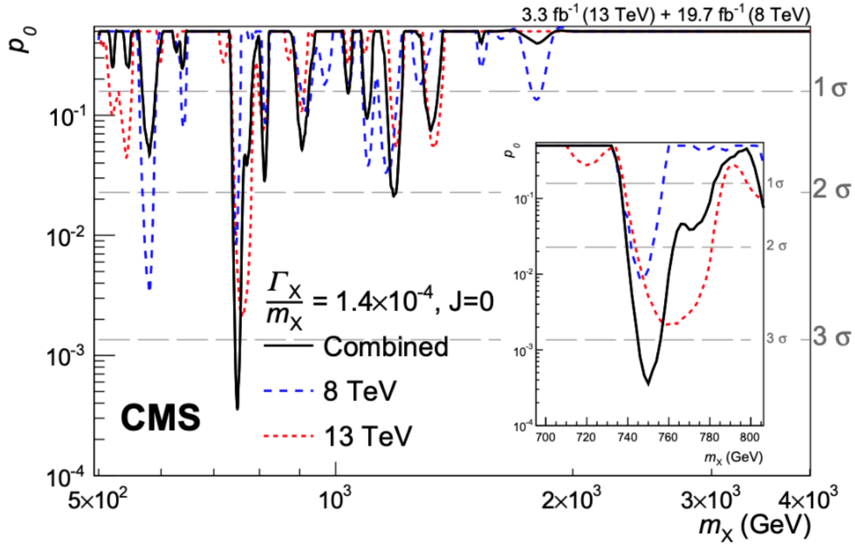




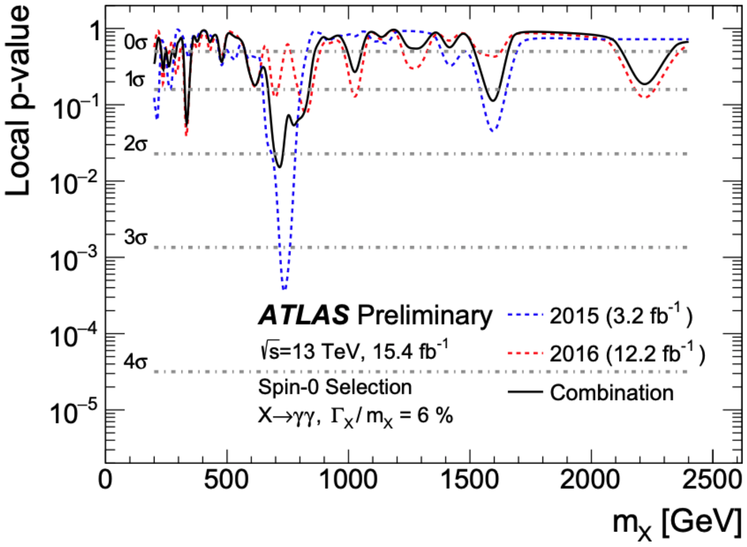
Diphoton resonance

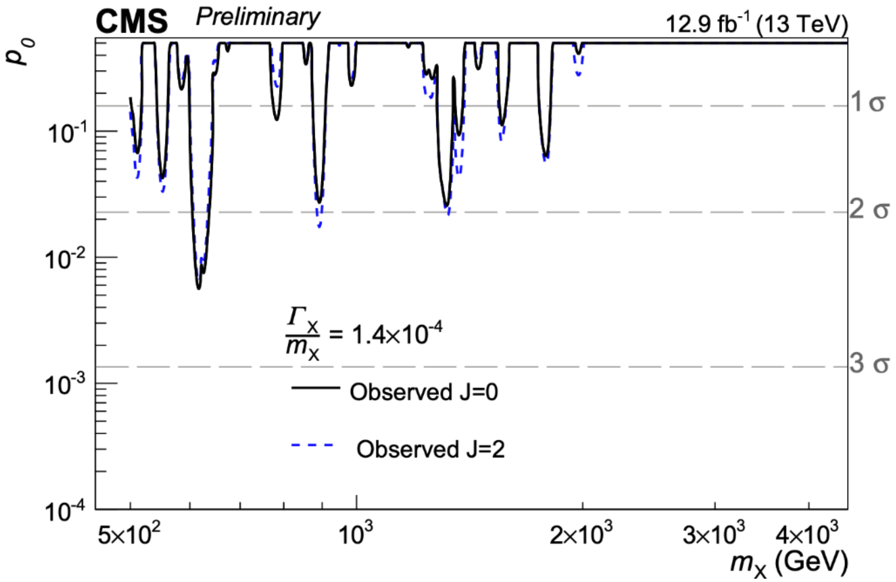
December 2015





August 2016





Theoretical confusion

Nima Arkani-Hamed:
“It’s striking that we’ve thought about these things for 30 years and we have not made one correct prediction”

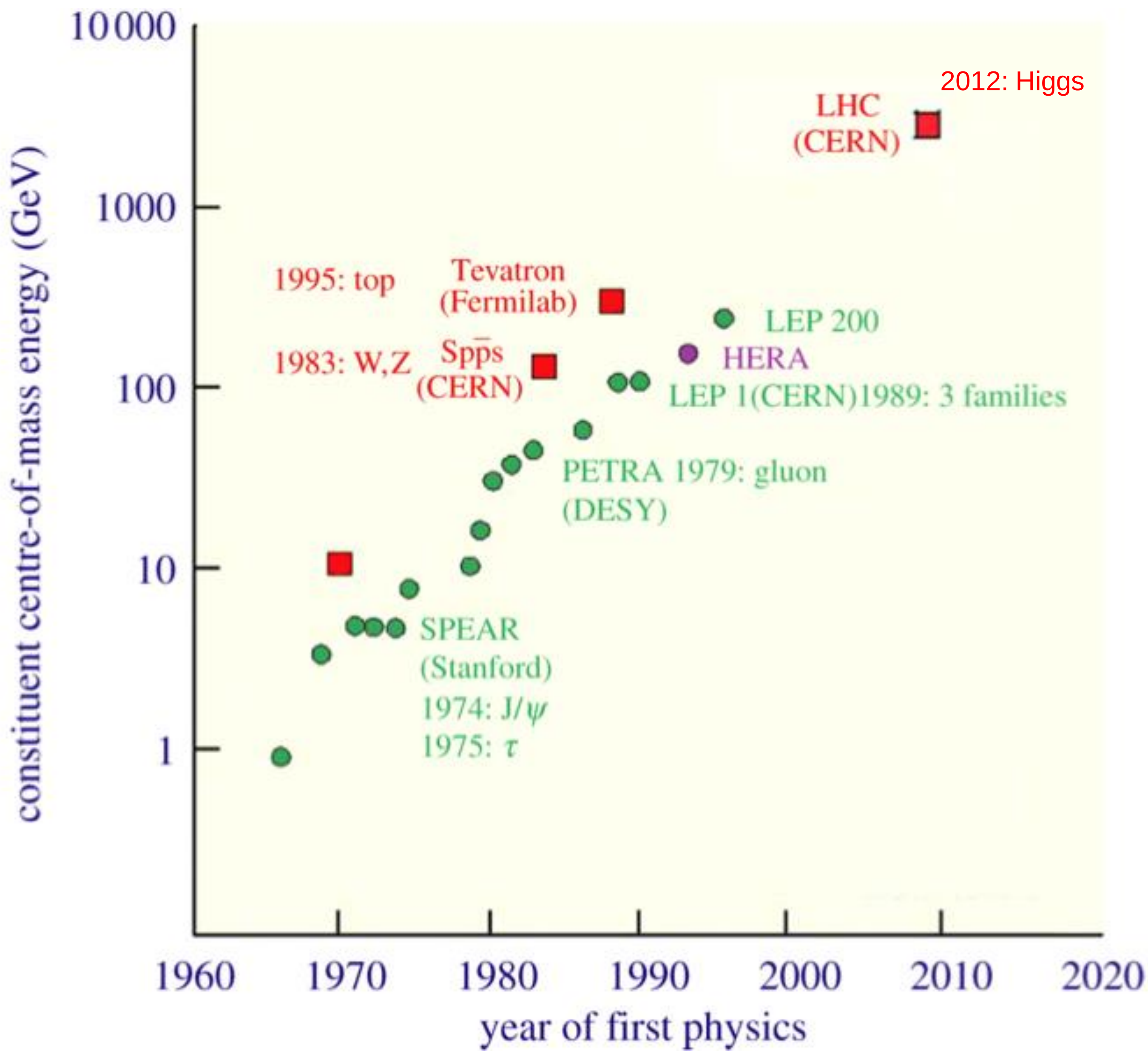
Theoretical confusion

Nima Arkani-Hamed:
“It’s striking that we’ve thought about these things for 30 years and we have not made one correct prediction”

- The days of “guaranteed” discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- …But the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP’s progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Michelangelo Mangano

Colliders: decades-long experience



European Strategy for Particle Physics: 2020

“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 p-p collider at the highest achievable energy.”

“Europe, together with its international partners, should investigate the technical & 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 EWK 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.”

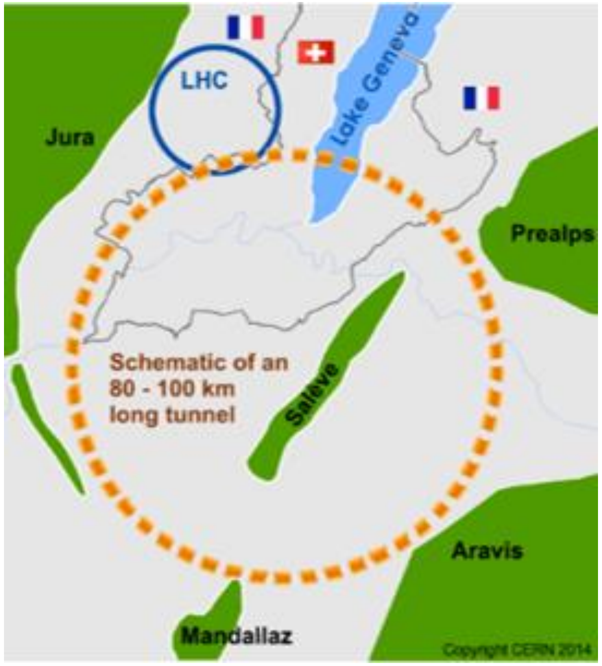
- FS: to be carried out 2021-25
- Mid-term review in Autumn 23
- Will cover the integrated program (FCCee & FCChh)

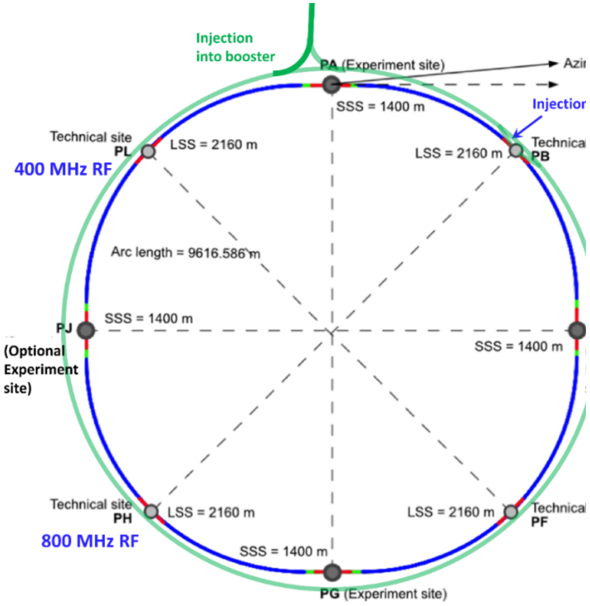
The Integrated FCC project

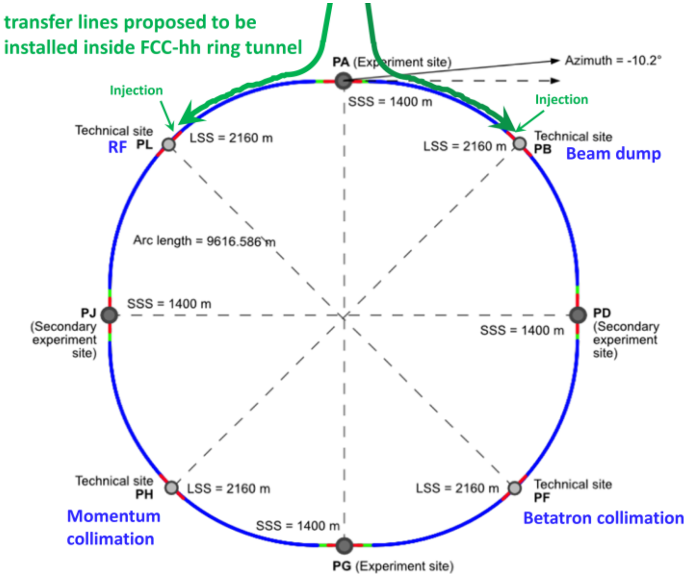
Integrated FCC (ee+hh) like LEP & LHC

Comprehensive long-term program maximising physics

- Stage-1: FCCee (Z, W, H, t) as Higgs, EWK and top factory
- Stage-2: FCChh (100 TeV) as natural continuation at energy frontier with ion and e-p options
- Complementary physics
- Common civil engineering & technical infrastructure, exploiting CERN's know-how & infrastructure
- Seamless continuation of collider program after completion of HL-LHC







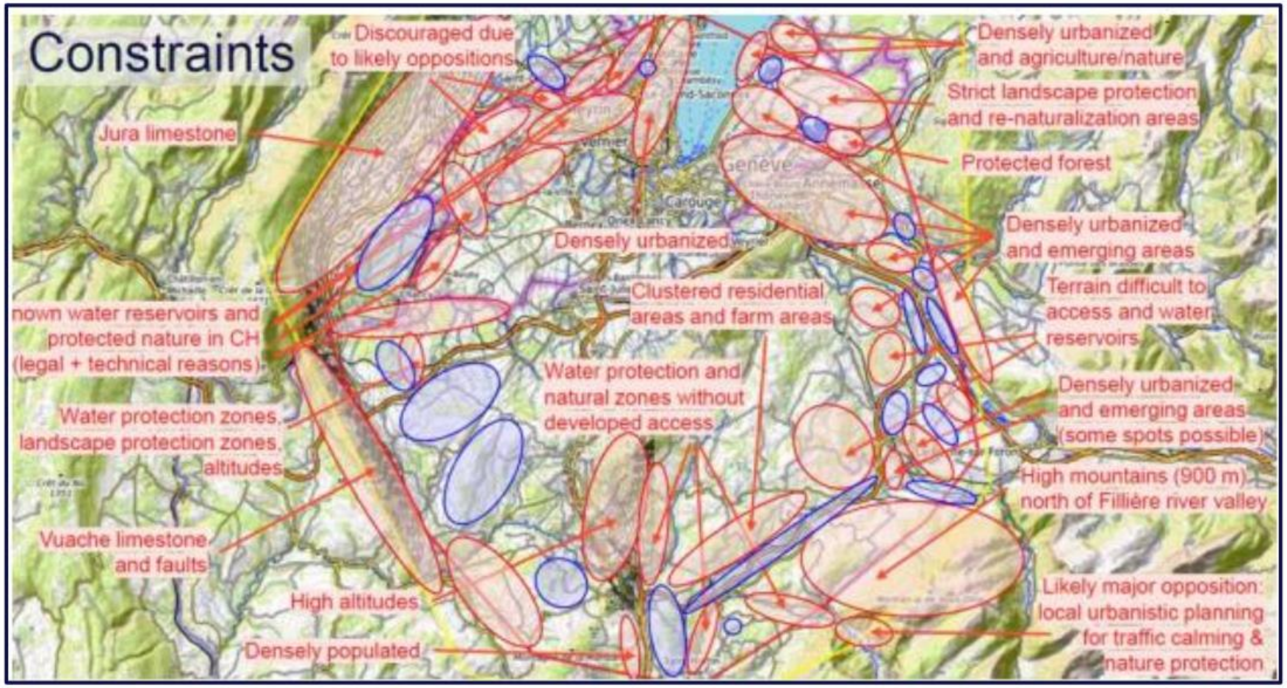
Timeline

- 2023: Mid-term review (update on FCCee & hh physics cases)
- 2028: Council decision on FCC (?)
- 2032-40: Tunnel excavation
- 2039-45: Accelerator & experiments installation
- 2041: End of HL-LHC (with 3 $ab^{-1}$of data accumulated)
- 2045-60: FCCee physics programme
- 2070-90++: FCChh physics programme

- No removal of LHC infrastructure needed prior to FCC start
- Also options for PbPb, ep and e-Pb running

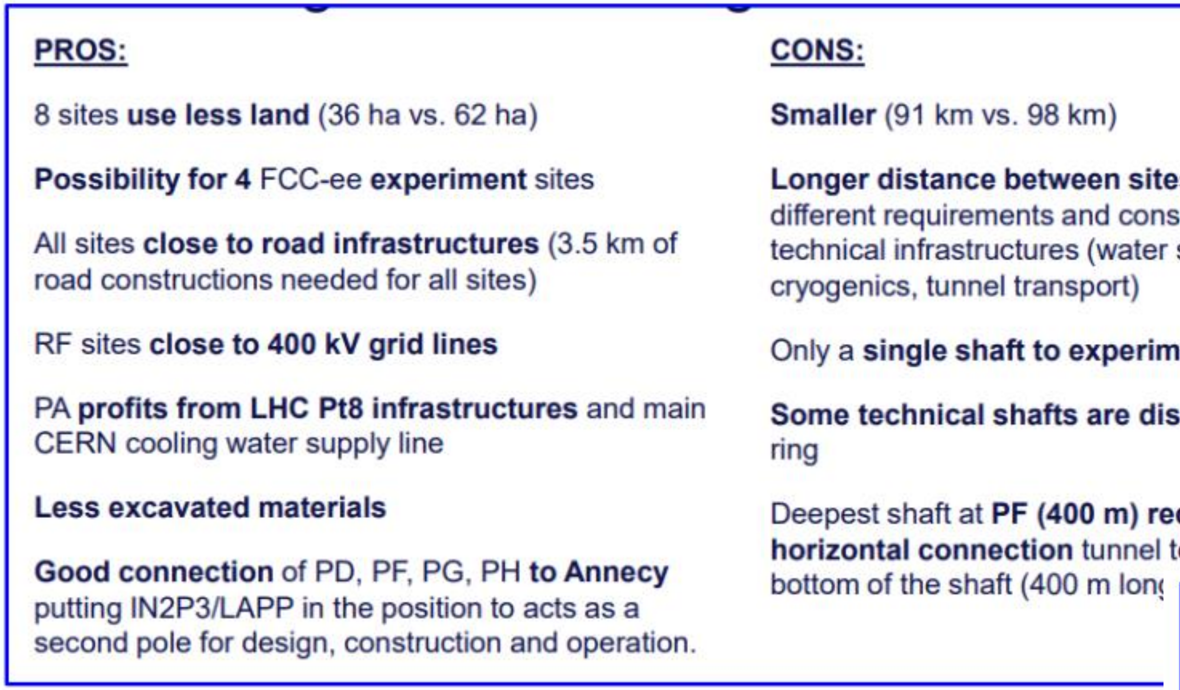
Placement

- More than 100 possible alignments studied recently
- Comparison of all these options was done using rigorous multi-criteria process in order to arrive at reasonable & transparent outcome



Placement

- Finally an 8-point configuration was deemed optimal
- Four-fold periodicity allows for 4 experimental sites/IPs



PROS:

8 sites **use less land** (36 ha vs. 62 ha)

Possibility for 4 FCC-ee **experiment** sites

All sites **close to road infrastructures** (3.5 km of road constructions needed for all sites)

RF sites **close to 400 kV grid lines**

PA **profits from LHC Pt8 infrastructures** and main CERN cooling water supply line

Less excavated materials

Good connection of PD, PF, PG, PH **to Annecy** putting IN2P3/LAPP in the position to acts as a second pole for design, construction and operation.

CONS:

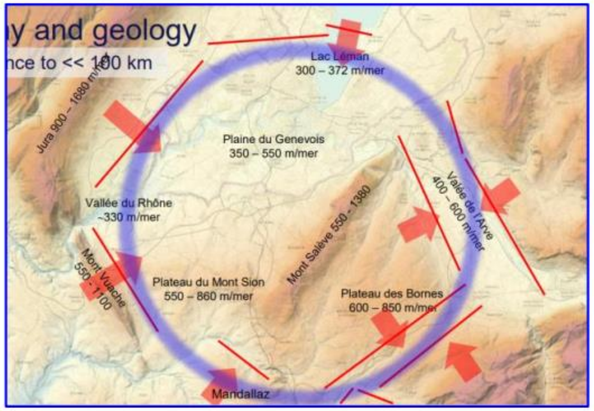
Smaller (91 km vs. 98 km)

Longer distance between sites generates different requirements and constraints for technical infrastructures (water supply, electricity, cryogenics, tunnel transport)

Only a **single shaft to experiment** cavern

Some technical shafts are displaced along the ring

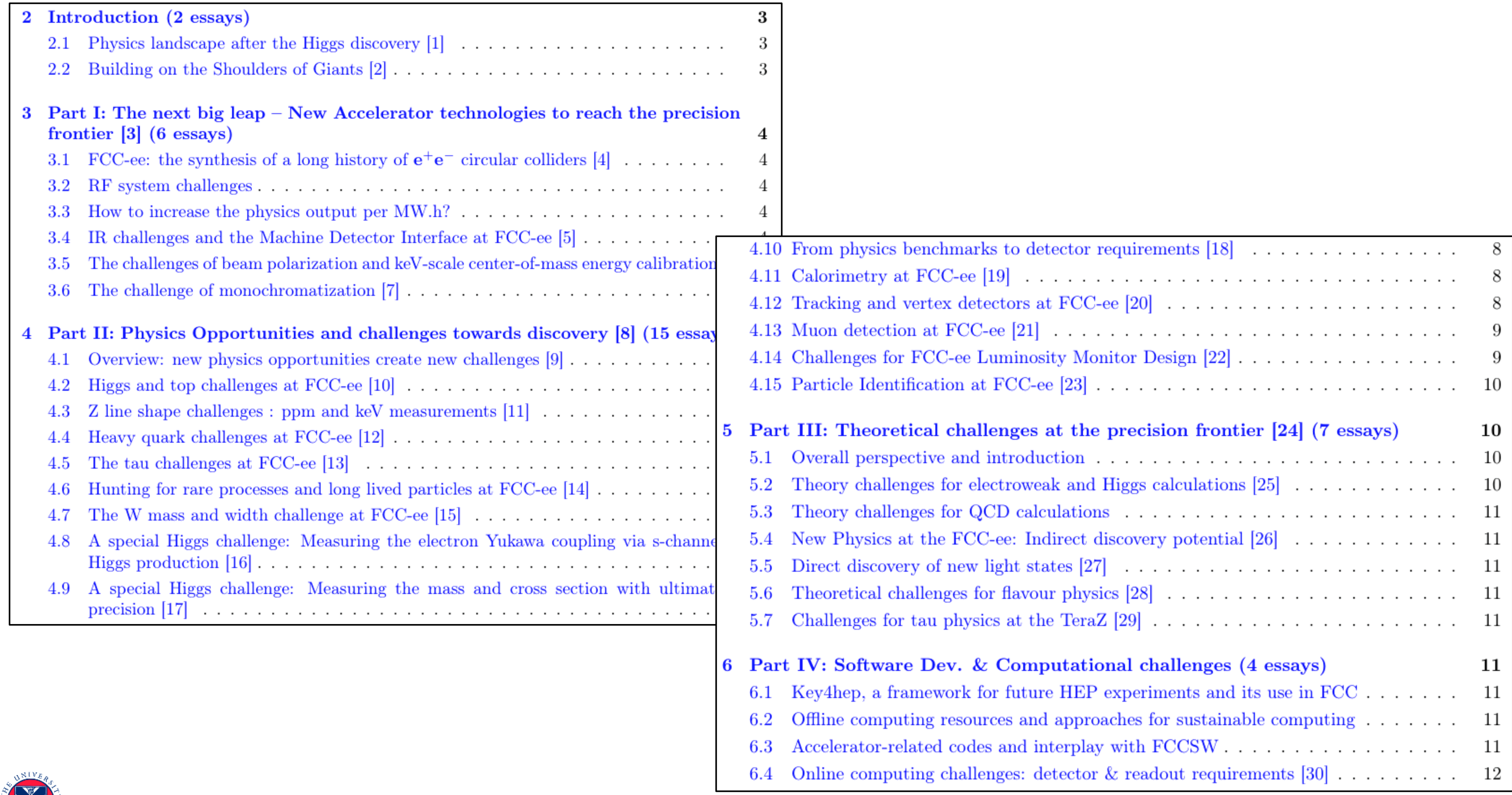
Deepest shaft at **PF (400 m) requires a horizontal connection** tunnel to the ring at the bottom of the shaft (400 m lon



The Physics Case

“A future Higgs & EWK Factory”

- EPJ+ special issue with 34 papers covering physics, theory, accelerator, detectors, software & online aspects of FCCee



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3.1 FCC-ee: the synthesis of a long history of $\mathbf{e^+e^-}$ circular colliders [4] 4

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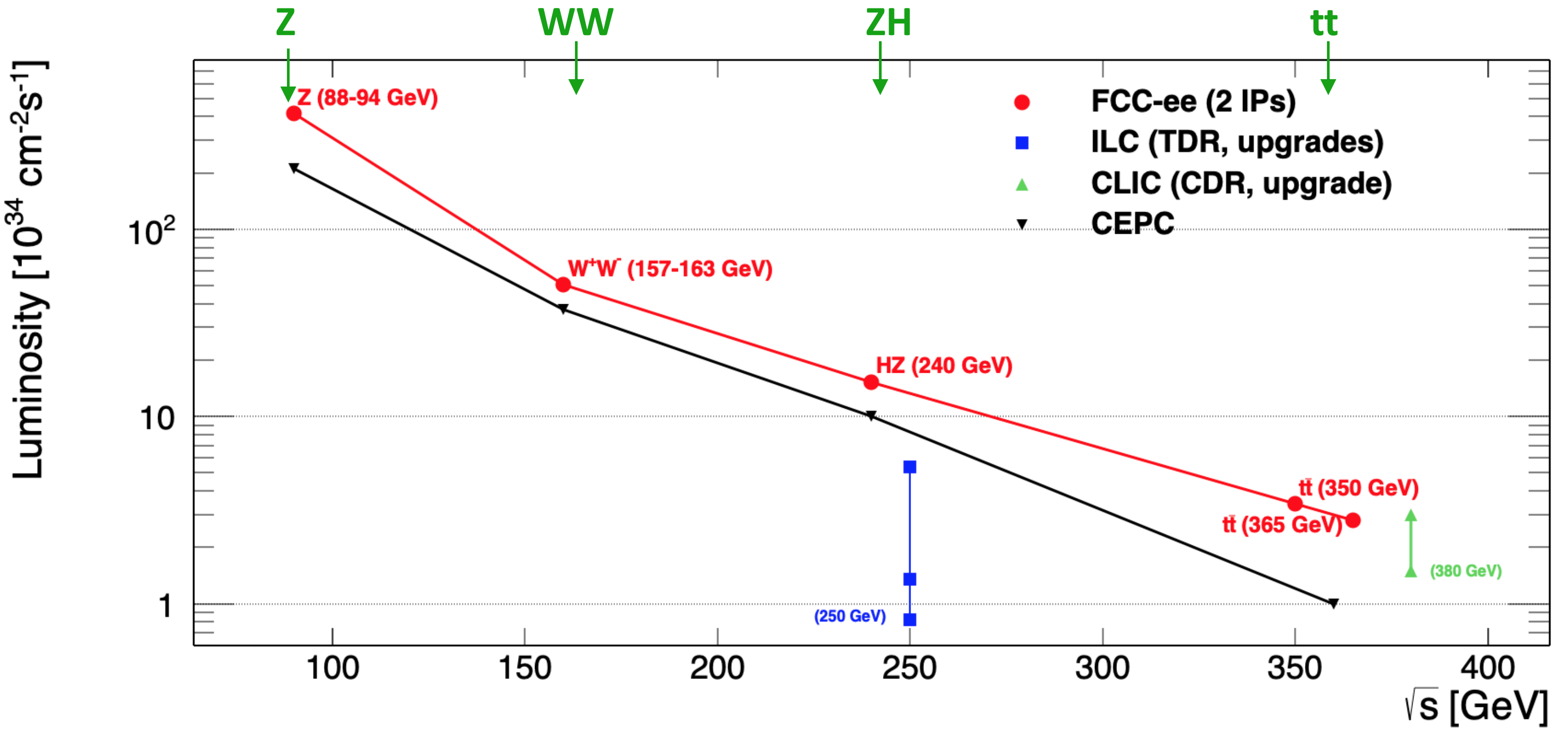
“A future Higgs & EWK Factory”

- Full energy scan to access all heavy SM particles
- Highest luminosity
- Highest $\sqrt{s}$ precision



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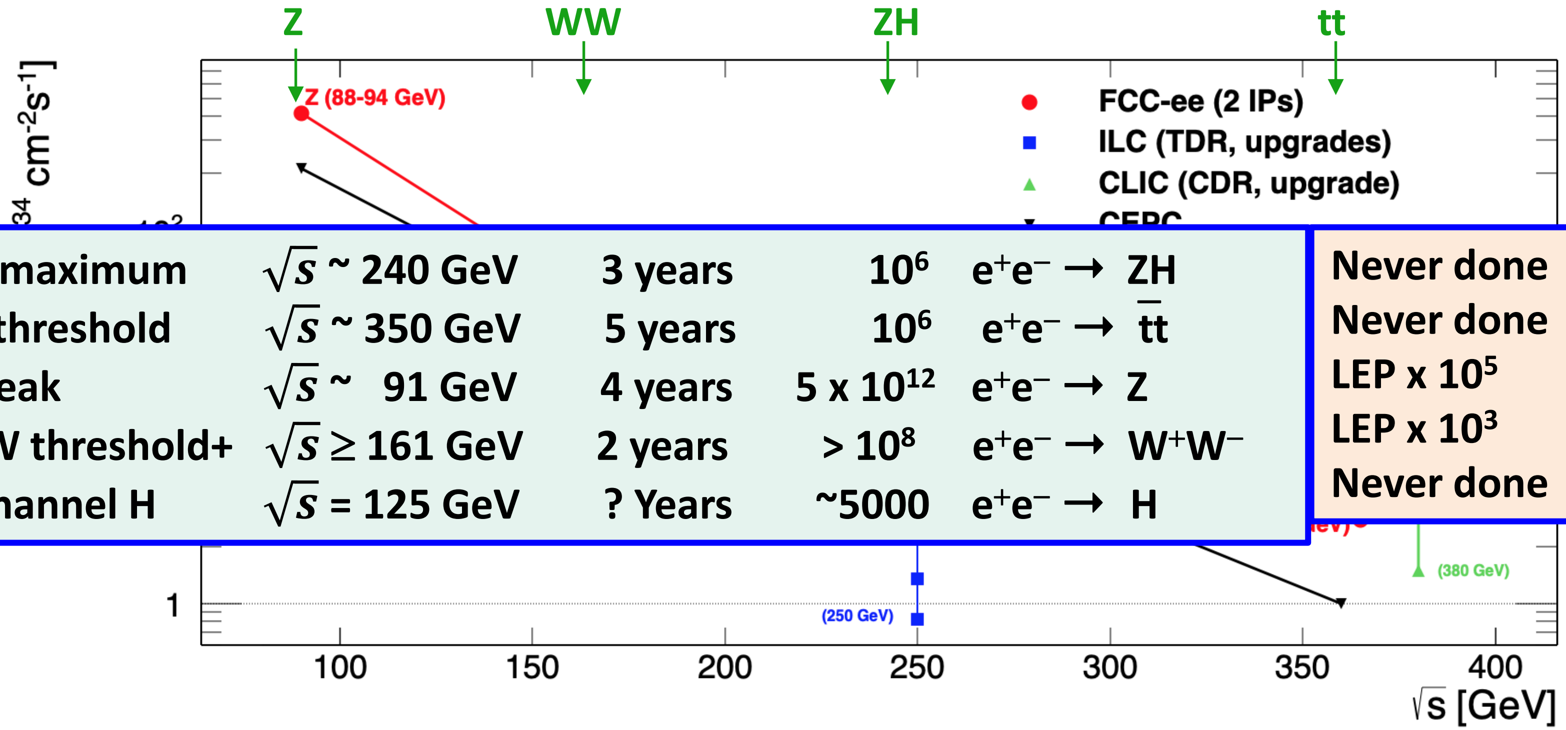


						$\sqrt{s}$ errors
ZH maximum	$\sqrt{s}$ ~ 240 GeV	3 years	10^6	$e^+e^- \rightarrow ZH$	**Never done**	2 MeV
$t\bar{t}$ threshold	$\sqrt{s}$ ~ 350 GeV	5 years	10^6	$e^+e^- \rightarrow t\bar{t}$	**Never done**	5 MeV
Z peak	$\sqrt{s}$ ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \rightarrow Z$	**LEP x 10^5**	< 100 keV
WW threshold+	$\sqrt{s} \geq$ 161 GeV	2 years	$> 10^8$	$e^+e^- \rightarrow W^+W^-$	**LEP x 10^3**	< 300 keV
s-channel H	$\sqrt{s}$ = 125 GeV	? Years	~5000	$e^+e^- \rightarrow H$	**Never done**	< 200 keV

“A future Higgs & EWK Factory”

”Higgs Factory” Programme

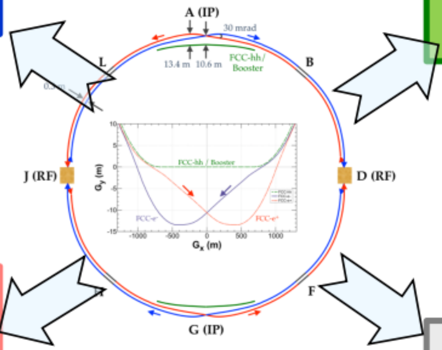
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- $5\mathrm{x}10^{12}$ Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; $1.7\mathrm{x}10^{11}$ ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays

- CKM matrix, CP measurements, ”flavour anomaly” studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

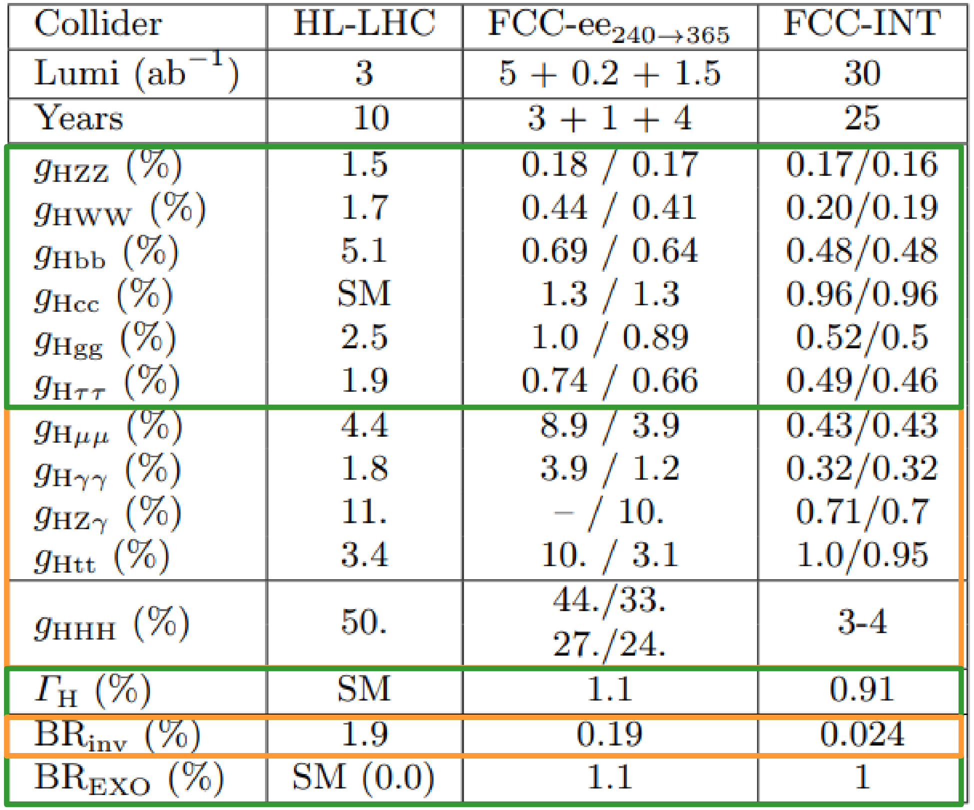
Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes – LLPs

Mogens Dam, FCC Week 2002 (Paris)

Precision Higgs measurements



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
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{\mathrm{HZ}\gamma}$ (%)	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
$\mathrm{BR}_{\mathrm{inv}}$ (%)	1.9	0.19	0.024
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM (0.0)	1.1	1

ee

pp

ee

pp

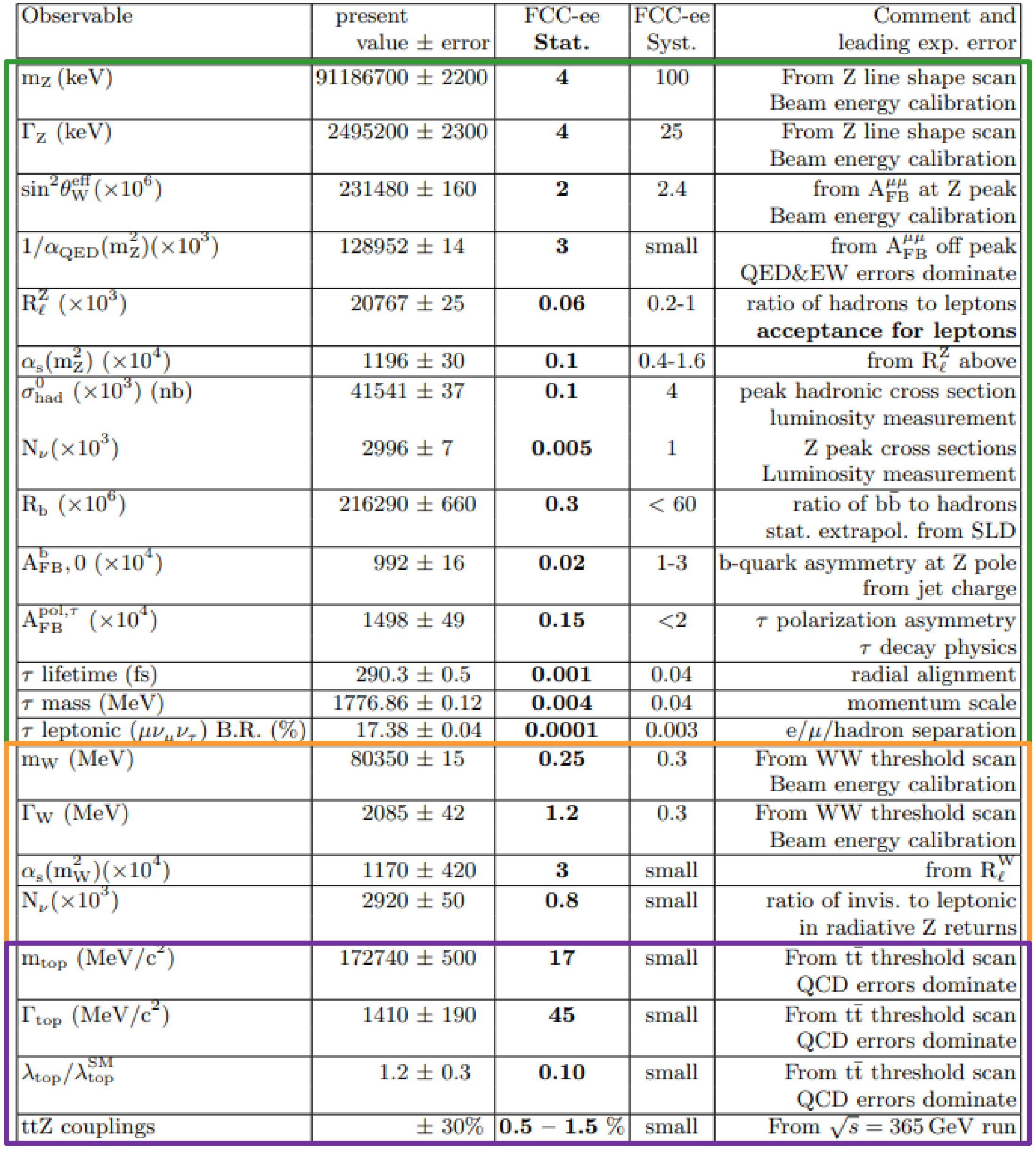
ee

arXiv:2106.13885

- FCCee measures g_{ZZH} to 0.2% (absolute, model independent) from σ_{ZH}
  - Fixes all other couplings
- FCChh produces 10B Higgs bosons, 100M $t\bar{t}H$, 20M HH pairs
  - Determines $g_{H\mu\mu}, g_{H\gamma\gamma}, g_{HZ\gamma}, BR(H\to \text{inv})$
- FCCee measures ttZ couplings

Unique FCCee/FCChh complementarity

Precision EWK measurements



Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	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 polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	**0.5 – 1.5** %	small	From $\sqrt{s} = 365\,\text{GeV}$ run

Z

W

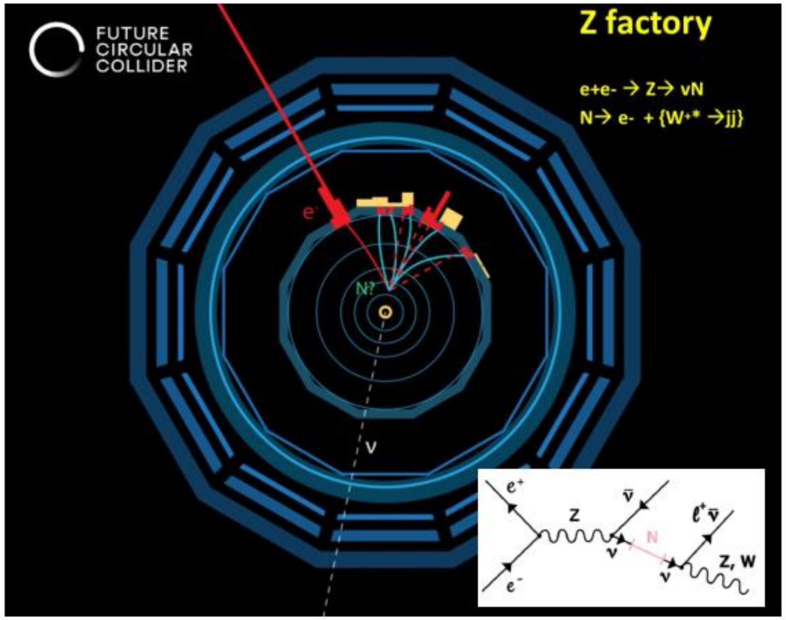
top

arXiv:2106.13885

FCCee: direct BSM searches

FCCee: not just a precision machine!

- Huge statistics opens the window for search of forbidden (or extremely rare) decays
- Lepton flavour violation
  - Examples: $Z \to \tau\mu$ in 5T Z decays, or $\tau \to \mu\nu/e\nu$ in 200B τ decays
  - Also: $B^0 \to K^{*0}\tau^+\tau^-$ (see excitement in recent LHCb anomalies)
  - Unique flavour physics potential at FCCee with huge Z statistics
- Dark Matter searches: invisible decays of Z and Higgs
- Light, weakly-interacting particles provide elegant solutions to DM puzzle



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- 10^6 tt

TeV scale

- Long-term program with immense breadth & richness
- 50+ years of physics
- O(10) experimental collaborations
- O(10k) scientific publications

- Enormous statistics: 10^{12} bb, cc; $1.7x10^{11}$ ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays

- CKM matrix, CP measurements, ”flavour anomaly” studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

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- Signatures: long lifetimes – LLPs

Mogens Dam, FCC Week 2002 (Paris)

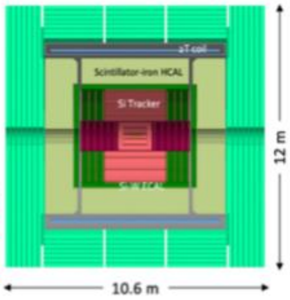
Detectors & TDAQ

Detectors & Instrumentation

- Primary goal of the detector R&D branch is to demonstrate, as input to the next ESPPU, that detectors can be built that match the precision physics potential of the FCC
- European Strategy stresses importance of strong focus on instrumentation
- Common R&D issues with near- and mid-term projects: goal is to exploit synergies and work on common deliverables
- Extremely important to offer long-term prospect for engineers & detector physicists
- Ongoing effort to establish R&D collaborations

FCCee Detectors

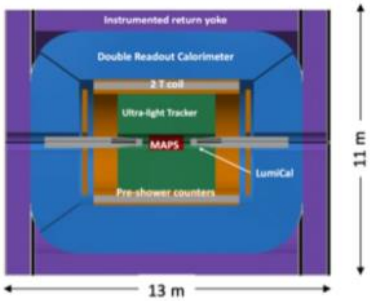
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Engineering needed to make able to operate with continous beam (no pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations?
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

- Robust software stack
  - Now ported (wrapped) to FCCSW

IDEA



- Less established design
  - But still ~15y history: 4th Concept
- Developed by very active community
  - Prototype construction / test beam compains
  - Italy, Korea,…
- Is IDEA really two concepts? Or will it be?
  - w, w/o crystals

- Software under active development
  - Being ported to FCCSW

Noble Liquid ECAL based

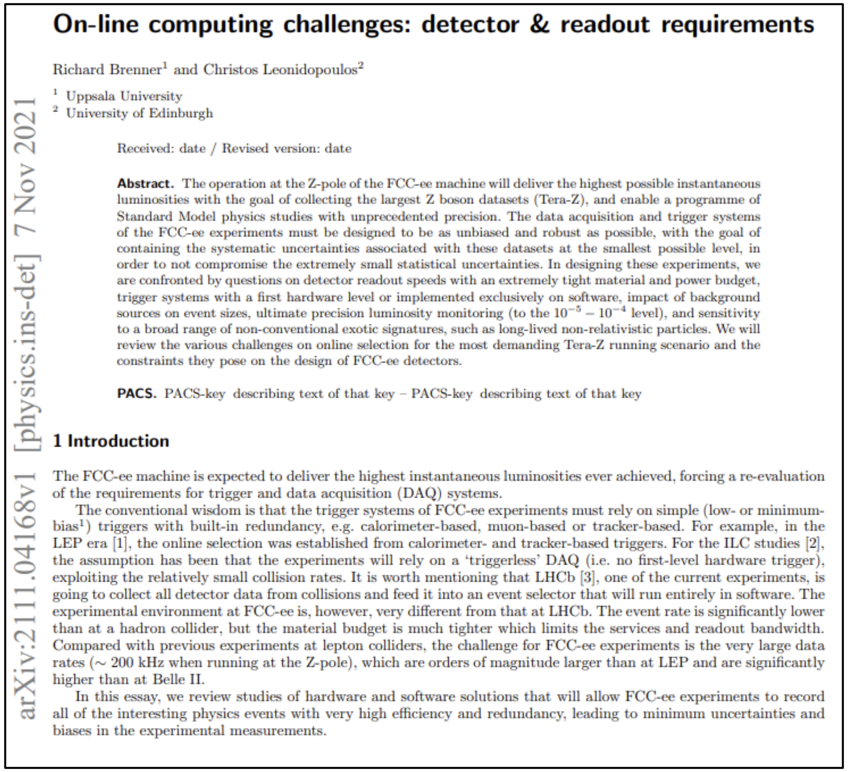
- A design in its infancy
- High granul Noble Liquid ECAL is the core
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

- Full simulation of ECAL available in FCCSW

Mogens Dam

Online Computing Challenges

Detector & readout requirements for future e^+e^-colliders



On-line computing challenges: detector & readout requirements

Richard Brenner[1] and Christos Leonidopoulos[2]

[1] Uppsala University
[2] University of Edinburgh

Received: date / Revised version: date

Abstract. The operation at the Z-pole of the FCC-ee machine will deliver the highest possible instantaneous luminosities with the goal of collecting the largest Z boson datasets (Tera-Z), and enable a programme of Standard Model physics studies with unprecedented precision. The data acquisition and trigger systems of the FCC-ee experiments must be designed to be as unbiased and robust as possible, with the goal of containing the systematic uncertainties associated with these datasets at the smallest possible level, in order to not compromise the extremely small statistical uncertainties. In designing these experiments, we are confronted by questions on detector readout speeds with an extremely tight material and power budget, trigger systems with a first hardware level or implemented exclusively on software, impact of background sources on event sizes, ultimate precision luminosity monitoring (to the $10^{-5} - 10^{-4}$ level), and sensitivity to a broad range of non-conventional exotic signatures, such as long-lived non-relativistic particles. We will review the various challenges on online selection for the most demanding Tera-Z running scenario and the constraints they pose on the design of FCC-ee detectors.

PACS. PACS-key describing text of that key – PACS-key describing text of that key

1 Introduction

The FCC-ee machine is expected to deliver the highest instantaneous luminosities ever achieved, forcing a re-evaluation of the requirements for trigger and data acquisition (DAQ) systems.

The conventional wisdom is that the trigger systems of FCC-ee experiments must rely on simple (low- or minimum-bias[1]) triggers with built-in redundancy, e.g. calorimeter-based, muon-based or tracker-based. For example, in the LEP era [1], the online selection was established from calorimeter- and tracker-based triggers. For the ILC studies [2], the assumption has been that the experiments will rely on a 'triggerless' DAQ (i.e. no first-level hardware trigger), exploiting the relatively small collision rates. It is worth mentioning that LHCb [3], one of the current experiments, is going to collect all detector data from collisions and feed it into an event selector that will run entirely in software. The experimental environment at FCC-ee is, however, very different from that at LHCb. The event rate is significantly lower than at a hadron collider, but the material budget is much tighter which limits the services and readout bandwidth. Compared with previous experiments at lepton colliders, the challenge for FCC-ee experiments is the very large data rates (~ 200 kHz when running at the Z-pole), which are orders of magnitude larger than at LEP and are significantly higher than at Belle II.

In this essay, we review studies of hardware and software solutions that will allow FCC-ee experiments to record all of the interesting physics events with very high efficiency and redundancy, leading to minimum uncertainties and biases in the experimental measurements.

A few thoughts based on invited FCC essay on online computing challenges for future e^+e^-colliders accepted by EPJ+ (jointly with Richard Brenner)

"Focus Point on A Future Higgs & Electroweak Factory (FCC): Challenges towards Discovery"

arXiv:2111.04168

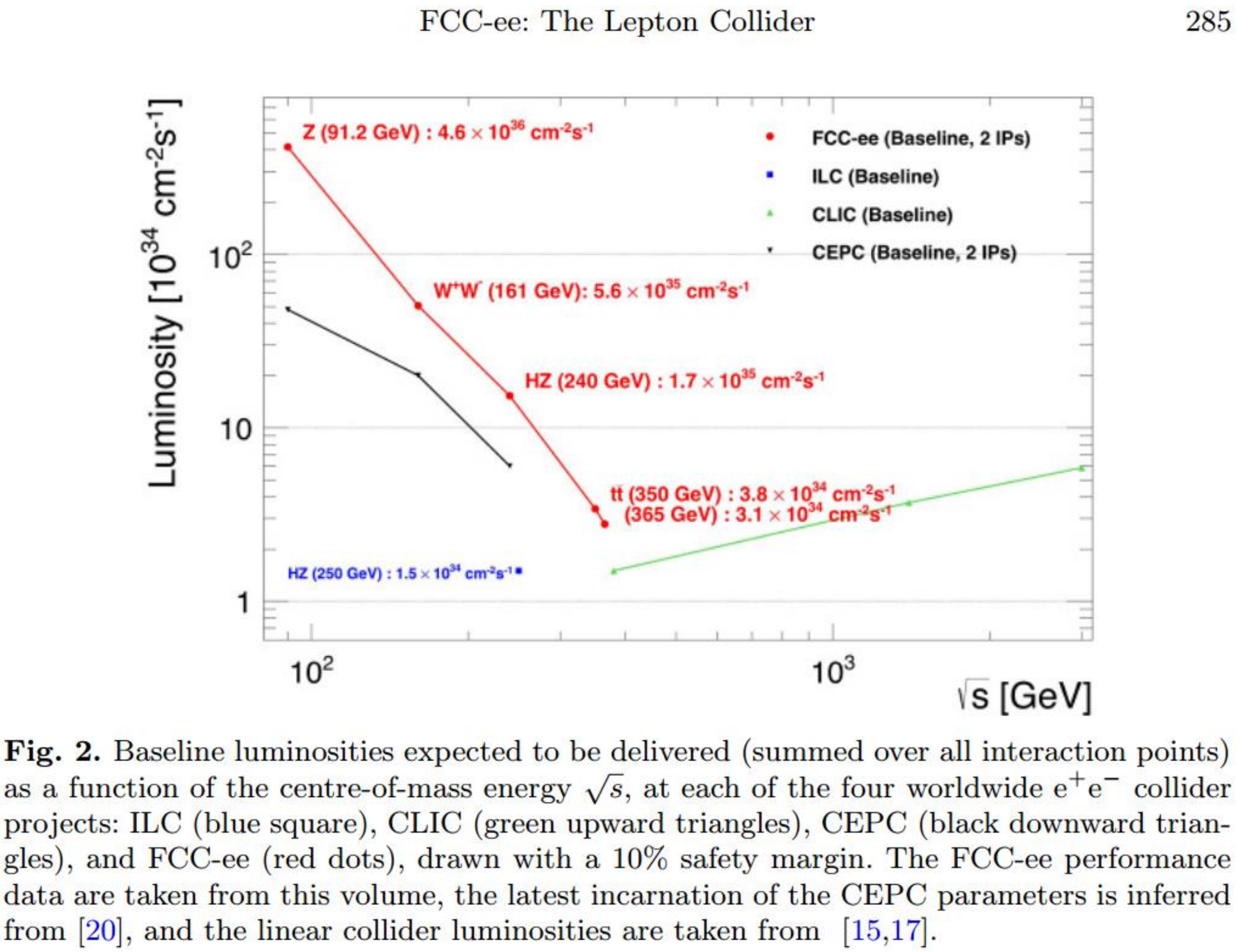
Online challenges: what do others do?

Conventional wisdom: rely on simple triggers with built-in redundancy

- LEP: when life was simple. Calo-, muon- or tracker-based selection
- ILC: “trigger-less” DAQ (aka: no custom hardware for Level-1 filtering)
- LHCb: collecting all detector data from all collisions, and feed into event selection (run entirely on software)
  - But: material budget at future e^+e^- colliders limits readout bandwidth & services

“Good artists copy; Great artists steal”

Instantaneous luminosities: FCCee



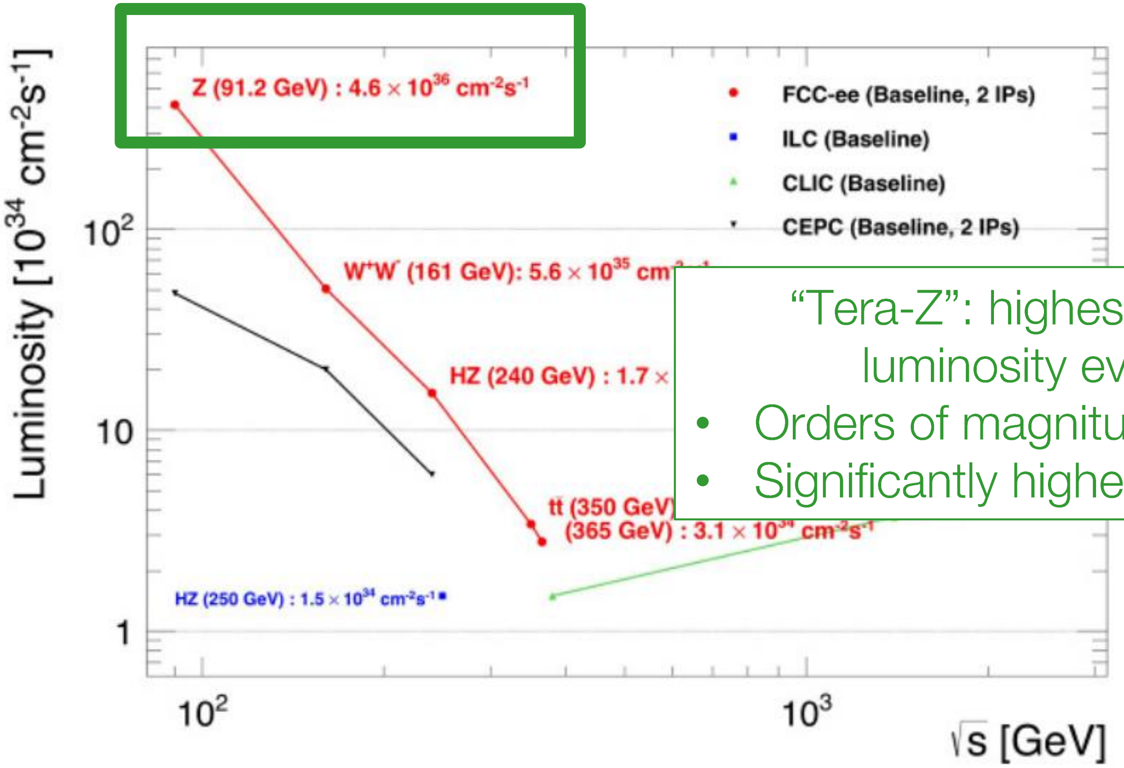
FCC-ee: The Lepton Collider 285

Fig. 2. Baseline luminosities expected to be delivered (summed over all interaction points) as a function of the centre-of-mass energy $\sqrt{s}$, at each of the four worldwide e^+e^- collider projects: ILC (blue square), CLIC (green upward triangles), CEPC (black downward triangles), and FCC-ee (red dots), drawn with a 10% safety margin. The FCC-ee performance data are taken from this volume, the latest incarnation of the CEPC parameters is inferred from [20], and the linear collider luminosities are taken from [15,17].

FCC CDR vol.2: `https://link.springer.com/article/10.1140%2Fepjst%2Fe2019-900045-4`

Instantaneous luminosities: FCCee

FCC-ee: The Lepton Collider 285



"Tera-Z": highest instantaneous luminosity ever achieved

- Orders of magnitude higher than LEP
- Significantly higher than Belle-II

Fig. 2. Baseline luminosities expected to be delivered (summed over all interaction points) as a function of the centre-of-mass energy $\sqrt{s}$, at each of the four worldwide e^+e^- collider projects: ILC (blue square), CLIC (green upward triangles), CEPC (black downward triangles), and FCC-ee (red dots), drawn with a 10% safety margin. The FCC-ee performance data are taken from this volume, the latest incarnation of the CEPC parameters is inferred from [20], and the linear collider luminosities are taken from [15,17].

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Rates & event sizes at colliders

- Three (or four) parameters here
  - Rate of interesting physics to record
  - Event size
  - Data throughput (ie. Read-out & write-out data volume/time)

- Key TDAQ parameter: data throughput, not rate!
  - Capacity: data volume per unit time =

    (event size) × (interesting physics rate)
  - Determining readout & write-out capacity of system

Rates & event sizes at LHC

Experiment	Rate	Event size	Throughput
Detector Readout			
ATLAS/CMS Run 1/2	100 kHz	1 MB	100 GB/s
LHCb Run 1/2	1 MHz	100 kB	100 GB/s
ATLAS/CMS Run 4 –	O(500 kHz)	4 MB (PU = 200)	2 TB/s
LHCb Run 4 –	40 MHz	100 kB	4 TB/s
Throughput to disk			
ATLAS/CMS Run 1/2	1-2 kHz	1 MB	1-2 GB/s
LHCb Run 1/2	10 kHz	100 kB	1 GB/s
ATLAS/CMS Run 4 –	5 kHz	4 MB (PU = 200)	20 GB/s
LHCb Run 4 –	20 kHz – ?	100 kB	2 GB/s

Notes:

- Figures refer to order-of-magnitude estimates
- Generally, disk space capacity is the actual bottleneck here, not trigger rate or output to disk

Rates & event sizes at FCCee (Z-pole)

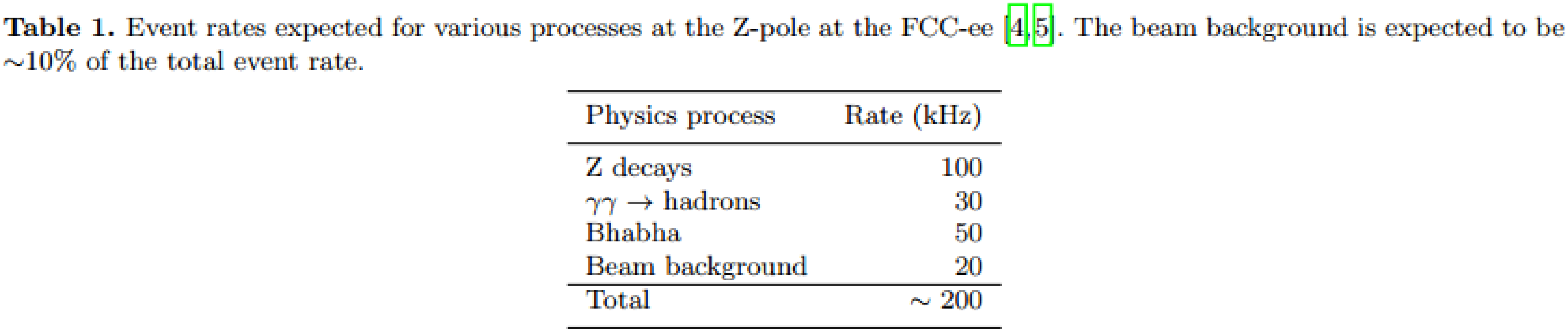

Table 1. Event rates expected for various processes at the Z-pole at the FCC-ee [4,5]. The beam background is expected to be ~10% of the total event rate.

Physics process	Rate (kHz)
Z decays	100
$\gamma\gamma \rightarrow$ hadrons	30
Bhabha	50
Beam background	20
Total	~ 200

Basic assumptions

- Store all interesting physics with ~100% efficiency
- Beam background: not a major consideration for DAQ

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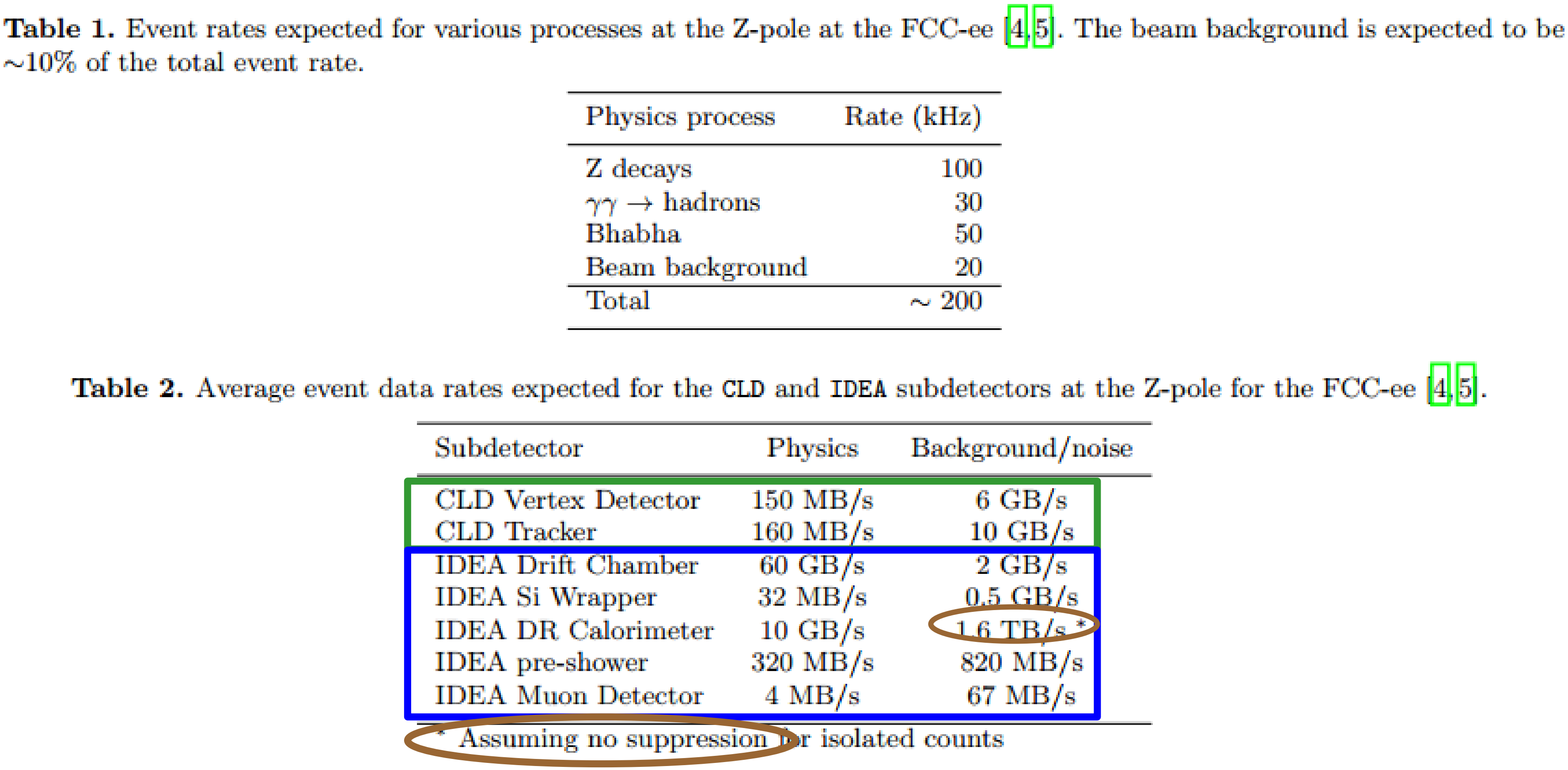
Rates & event sizes at FCCee (Z-pole)



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Total	$\sim$ 200

Table 2. Average event data rates expected for the `CLD` and `IDEA` subdetectors at the Z-pole for the FCC-ee [4,5].

Subdetector	Physics	Background/noise
CLD Vertex Detector	150 MB/s	6 GB/s
CLD Tracker	160 MB/s	10 GB/s
IDEA Drift Chamber	60 GB/s	2 GB/s
IDEA Si Wrapper	32 MB/s	0.5 GB/s
IDEA DR Calorimeter	10 GB/s	1.6 TB/s *
IDEA pre-shower	320 MB/s	820 MB/s
IDEA Muon Detector	4 MB/s	67 MB/s

* Assuming no suppression for isolated counts

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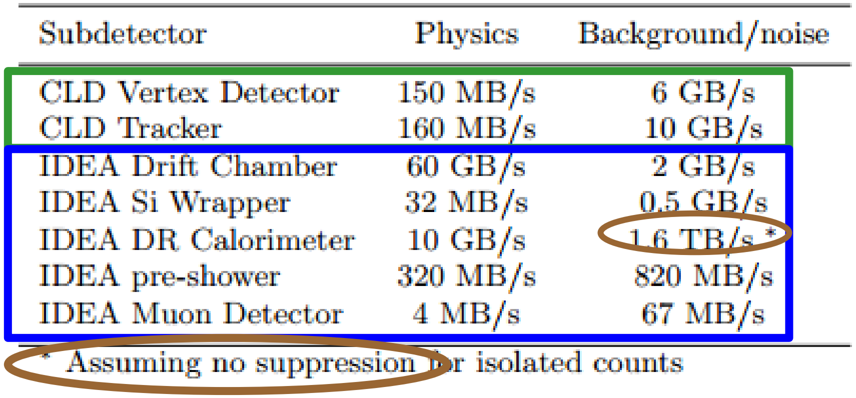
Rates & event sizes at FCCee (Z-pole)

Table 1. Event rates expected for various processes at the Z-pole at the FCC-ee [4,5]. The beam background is expected to be ~10

- With an appropriate zero-suppression scheme, the major contribution to the average event size for the IDEA detector is from physics, and it should be possible to keep the main backgrounds (e.g. synchrotron radiation) under control at a relatively small fraction of the total event rate
- Zero-suppression requires continuous calibration in semi-real time, smooth/stable running conditions, robust monitoring



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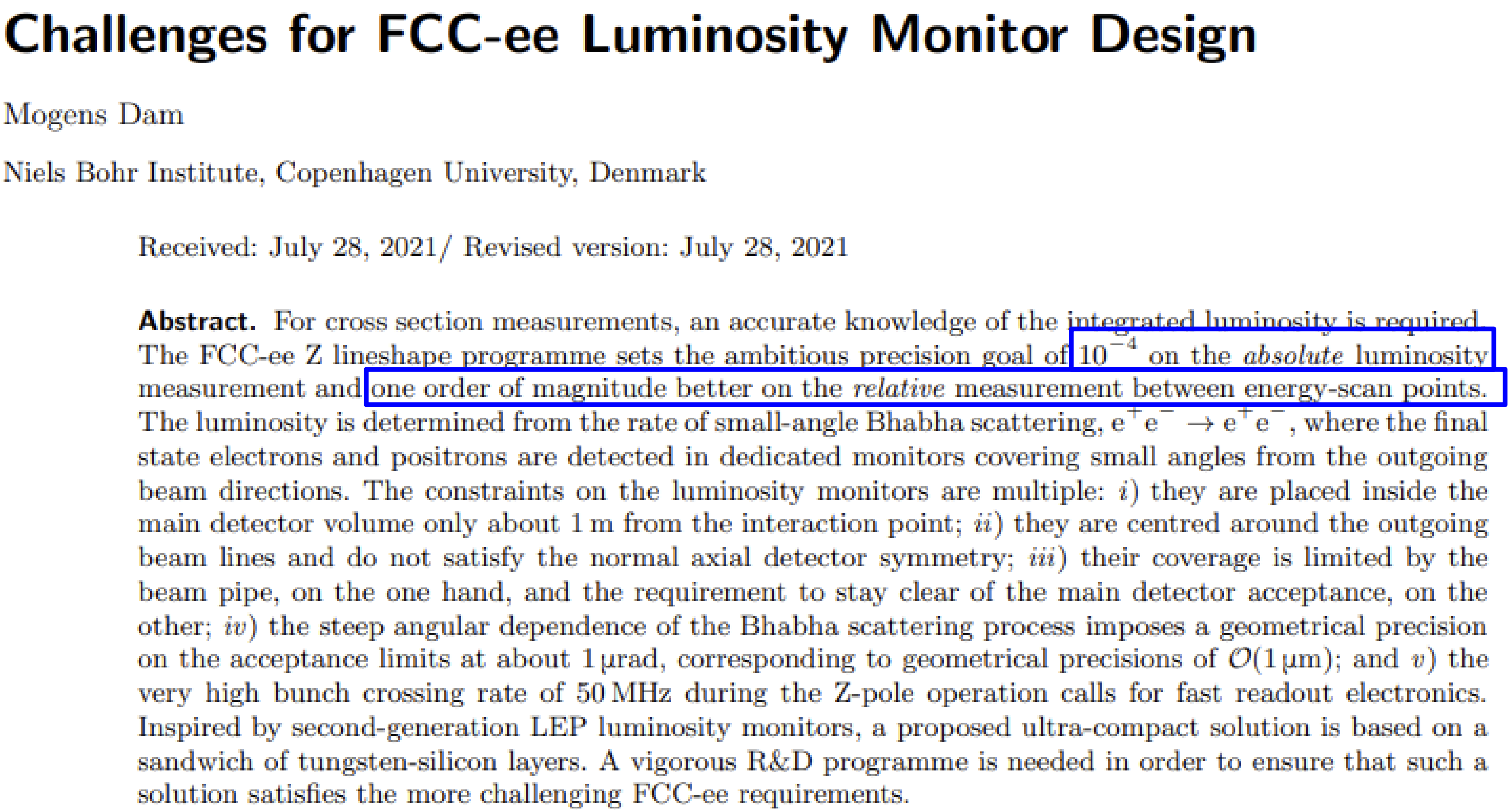
Luminosity monitoring



Challenges for FCC-ee Luminosity Monitor Design

Mogens Dam

Niels Bohr Institute, Copenhagen University, Denmark

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Abstract. For cross section measurements, an accurate knowledge of the integrated luminosity is required. The FCC-ee Z lineshape programme sets the ambitious precision goal of 10^{-4} on the *absolute* luminosity measurement and one order of magnitude better on the *relative* measurement between energy-scan points. The luminosity is determined from the rate of small-angle Bhabha scattering, $e^+e^- \to e^+e^-$, where the final state electrons and positrons are detected in dedicated monitors covering small angles from the outgoing beam directions. The constraints on the luminosity monitors are multiple: *i*) they are placed inside the main detector volume only about 1 m from the interaction point; *ii*) they are centred around the outgoing beam lines and do not satisfy the normal axial detector symmetry; *iii*) their coverage is limited by the beam pipe, on the one hand, and the requirement to stay clear of the main detector acceptance, on the other; *iv*) the steep angular dependence of the Bhabha scattering process imposes a geometrical precision on the acceptance limits at about 1 μrad, corresponding to geometrical precisions of $\mathcal{O}(1\,\mu\mathrm{m})$; and *v*) the very high bunch crossing rate of 50 MHz during the Z-pole operation calls for fast readout electronics. Inspired by second-generation LEP luminosity monitors, a proposed ultra-compact solution is based on a sandwich of tungsten-silicon layers. A vigorous R&D programme is needed in order to ensure that such a solution satisfies the more challenging FCC-ee requirements.

arXiv:2107.12837

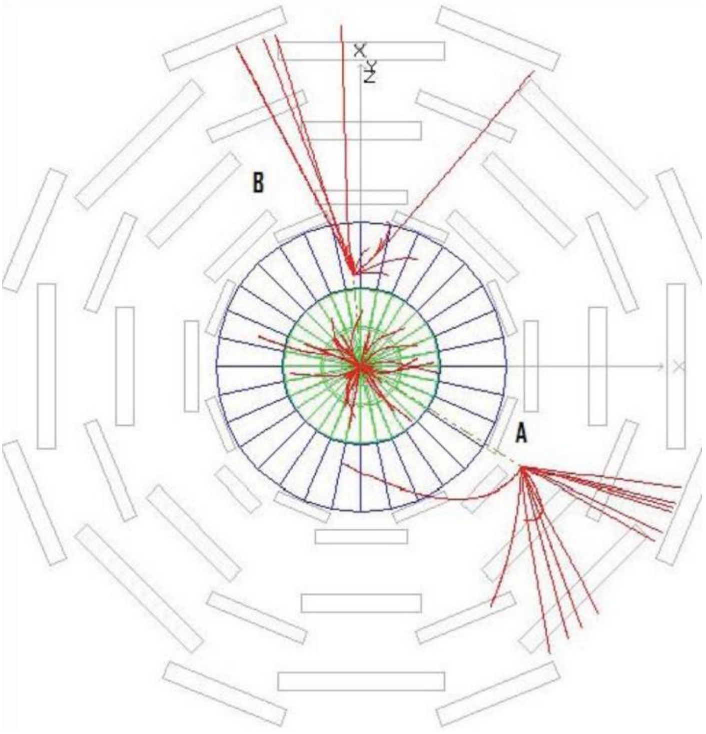
Trigger-less design?

- A software-based solution provides flexibility that cannot be matched by traditional first-level hardware-based filtering systems
- For a future e^+e^- collider, the major challenge is the very high luminosity (especially at the Z-pole). R&D studies assume zero-suppression will be routinely applied at read-out. However, this necessitates not only careful calibration (&alignment), but also a technical solution that can be deployed online and updated in semi-real time.
- Smooth & stable running conditions and robust monitoring system are of paramount importance
- Detector choices can have a major impact on TDAQ design. It is important to balance detector requirements against operational considerations & constraints on TDAQ when designing future experiments.

Trigger-less design? #2

- Tracking: Time-Projection Chambers (TPC) which is favoured by tracking experts for lightweight design cannot be read out every 20 ns. A TPC-based detector would require hardware-based filtering system
- Calorimetry: a fine-granularity but noisy calorimeter may lead to non-straightforward zero-suppression. A high-noise calorimeter that contributes significantly to average event data rates would interfere with optimisation of trigger efficiency of electromagnetic showers.

Long-Lived Particles



- Dark Sector models give rise to long-lived signatures
- Challenge for TDAQ with appearing/disappearing tracks that do not point to primary vertex
- Selection of LLP events in real-time usually not a priority in design phase of experiments. Complexity of signature makes it harder to find good metrics for design specs
- Timing info of every hit would allow studies of out-of-bunch/out-of-time particles.
- Hardware track triggering requires instrumentation on tracker
- Important to have clear strategy for LLP searches. Require distant detectors? integrate in TDAQ?

Political considerations

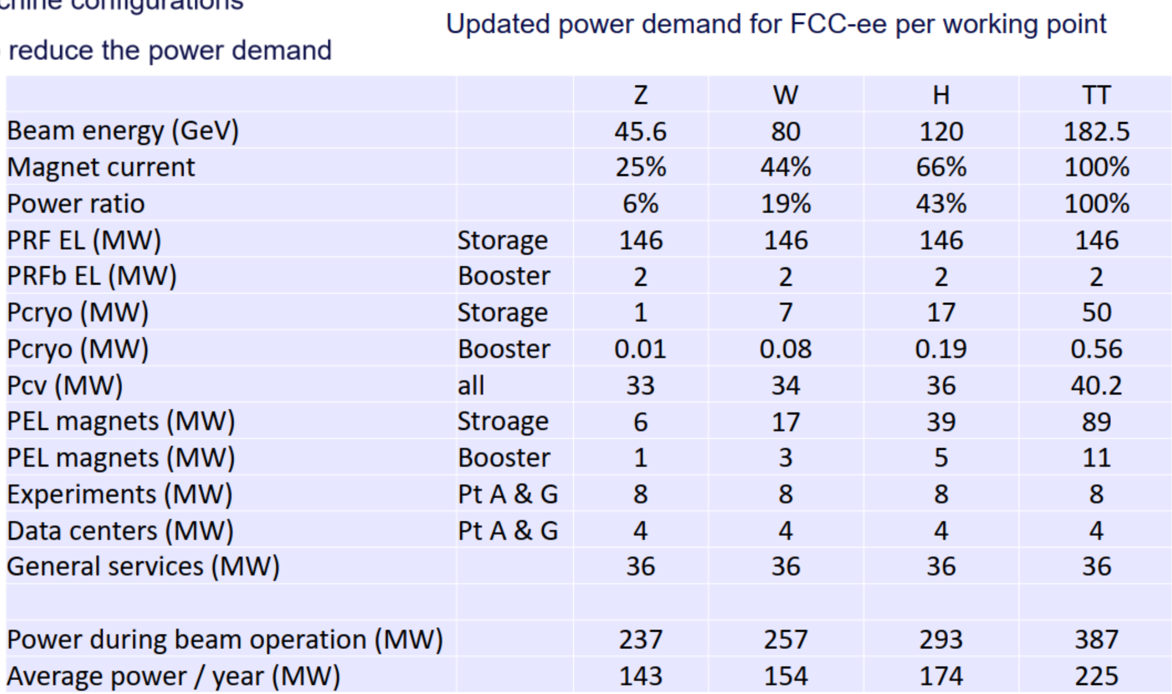
Political considerations

- Environment
- Funding
- Beyond Physics

Environment

J P Burnet, *Update of the Power Demand for FCC-ee*

- Update of the power demand / main loads for FCC-ee
- Distribution of the power demand by points and by the beam energies
- Estimation of energy consumption per machine configurations
- Optimization of the accelerator systems to reduce the power demand
- Ways to reduce the energy consumption



Updated power demand for FCC-ee per working point

		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Magnet current		25%	44%	66%	100%
Power ratio		6%	19%	43%	100%
PRF EL (MW)	Storage	146	146	146	146
PRFb EL (MW)	Booster	2	2	2	2
Pcryo (MW)	Storage	1	7	17	50
Pcryo (MW)	Booster	0.01	0.08	0.19	0.56
Pcv (MW)	all	33	34	36	40.2
PEL magnets (MW)	Stroage	6	17	39	89
PEL magnets (MW)	Booster	1	3	5	11
Experiments (MW)	Pt A & G	8	8	8	8
Data centers (MW)	Pt A & G	4	4	4	4
General services (MW)		36	36	36	36
Power during beam operation (MW)		237	257	293	387
Average power / year (MW)		143	154	174	225

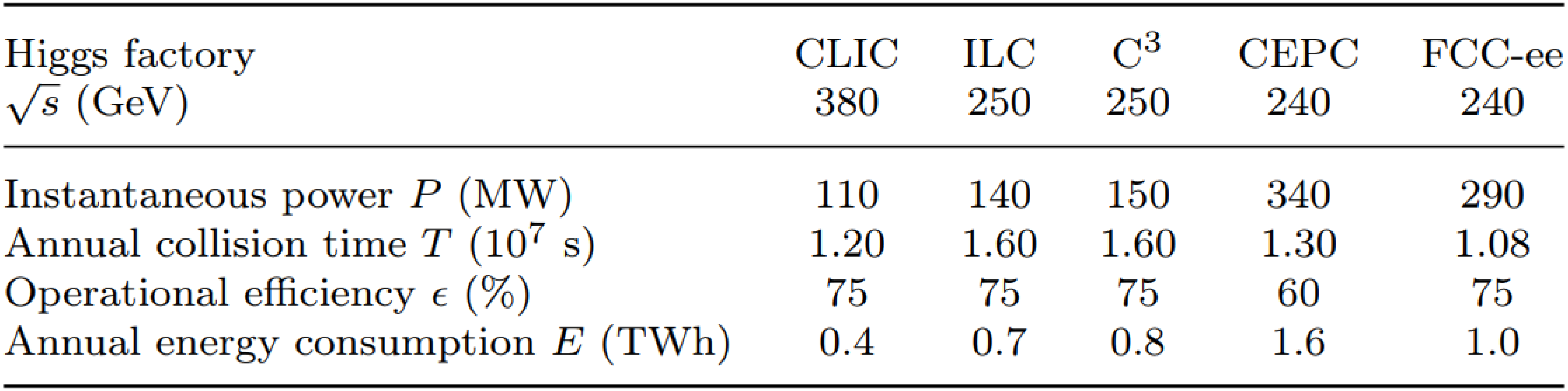
<u>Big Five:</u>
RF
Cryo
Booster Magnets
Collider Magnets
Cooling & Ventilation

Plus others: general services, computing, …

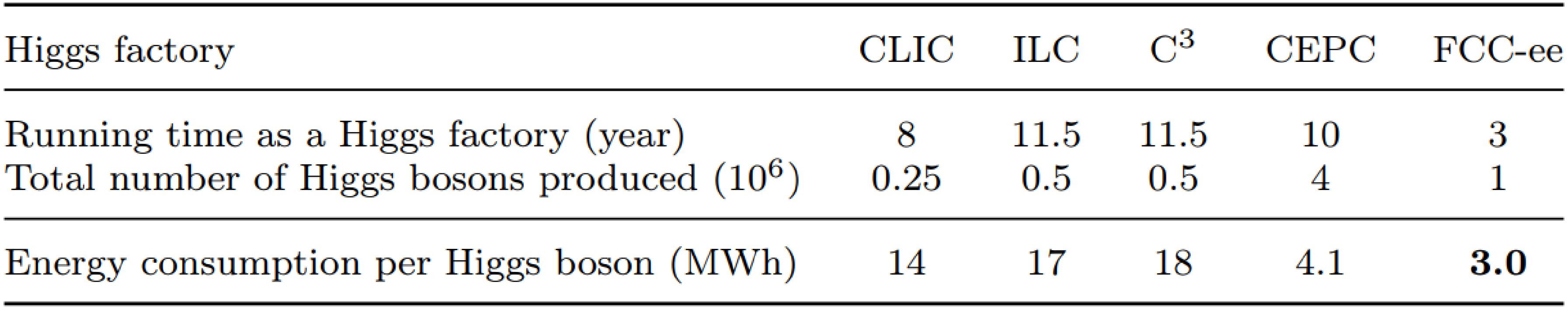
- Is FCCee (240): 174 MW more energy-hungry than ILC(240): 140 MW/yr or CLIC(380): 110 MW/yr ?
- Not so quick! ILC/CLIC produce 2-4 times fewer Higgs, with 3-6x longer running times

FCC Week 2022

Environment: energy consumption



Higgs factory $\sqrt{s}$ (GeV)	CLIC 380	ILC 250	C^3 250	CEPC 240	FCC-ee 240
Instantaneous power P (MW)	110	140	150	340	290
Annual collision time T (10^7 s)	1.20	1.60	1.60	1.30	1.08
Operational efficiency ϵ (%)	75	75	75	60	75
Annual energy consumption E (TWh)	0.4	0.7	0.8	1.6	1.0



Higgs factory	CLIC	ILC	C^3	CEPC	FCC-ee
Running time as a Higgs factory (year)	8	11.5	11.5	10	3
Total number of Higgs bosons produced (10^6)	0.25	0.5	0.5	4	1
Energy consumption per Higgs boson (MWh)	14	17	18	4.1	**3.0**

arXiv:2208.10466

Environment: energy consumption

Higgs factory $\sqrt{s}$ (GeV)	CLIC 380	ILC 250	C^3 250	CEPC 240	FCC-ee 240

Instantaneous pow
Annual collision ti
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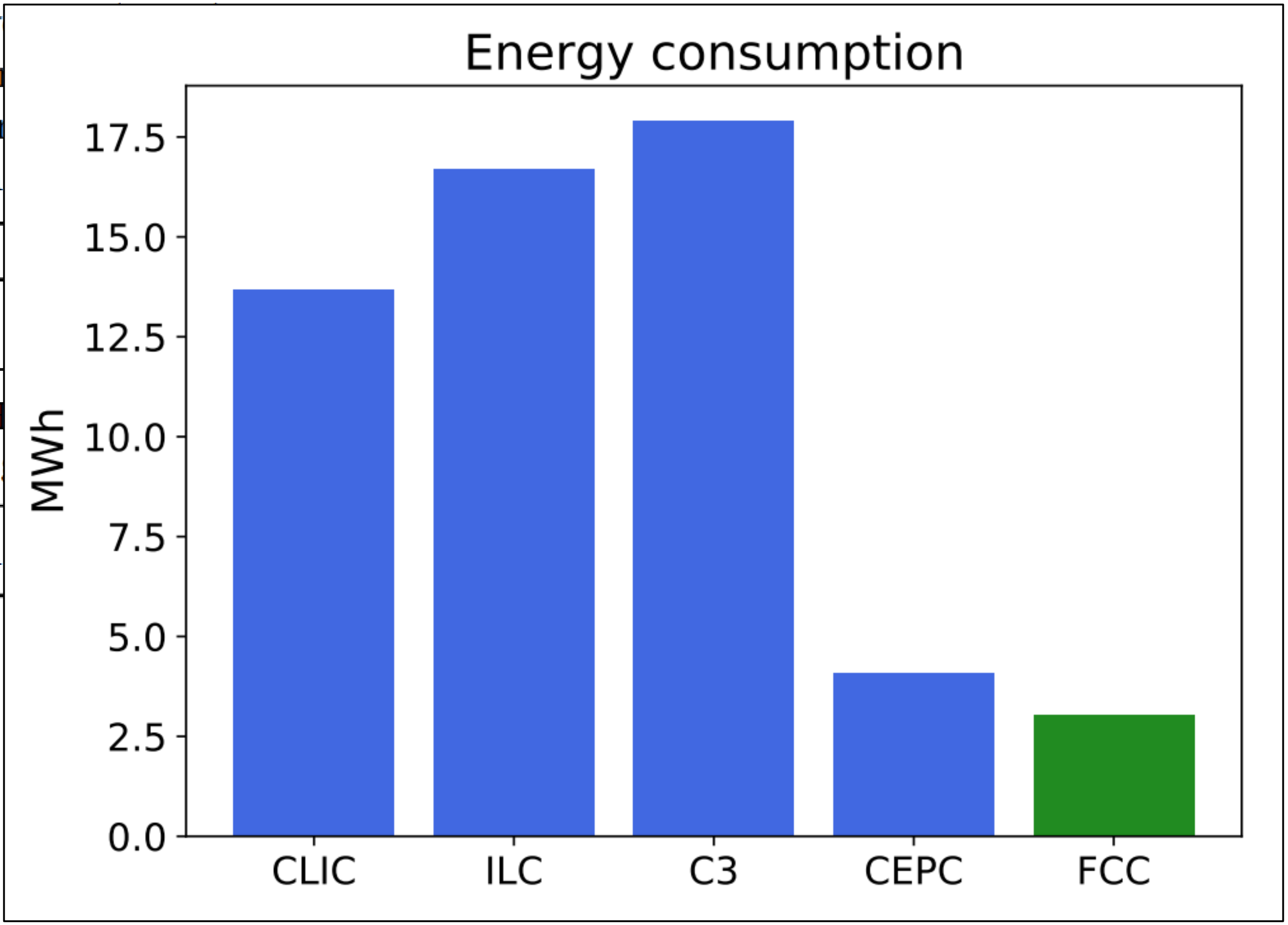
Higgs factory

Running time as a H
Total number of Hig

Energy consumption



arXiv:2208.10466

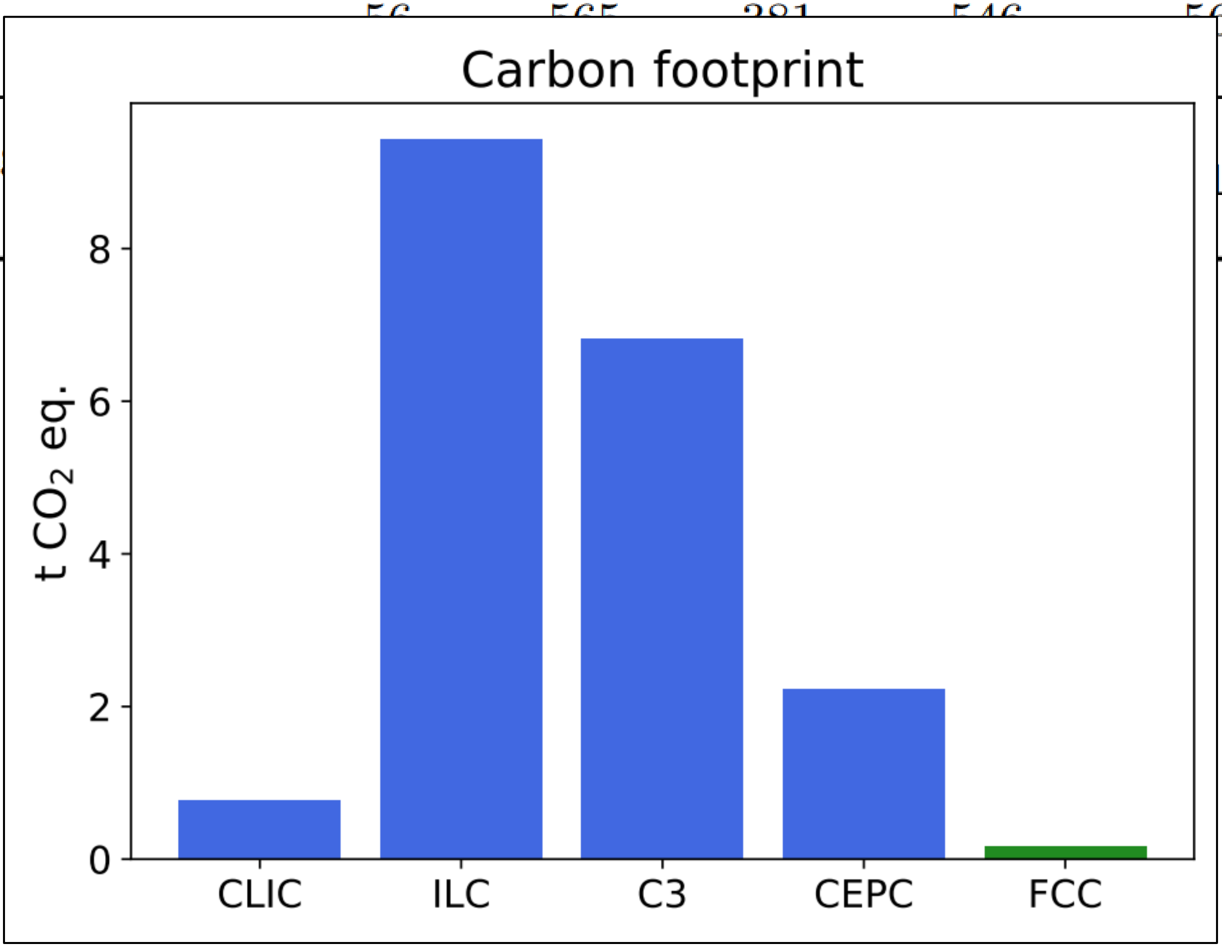
Environment: carbon footprint

Higgs factory Operated from	CLIC CERN	ILC KEK	C^3 FNAL	CEPC China	FCC-ee CERN
Carbon intensity (kg CO_2 eq. / MWh)	56	565	381	546	56
Carbon footprint per Higgs boson (t CO_2 eq.)	0.8	9.4	6.8	2.2	**0.17**

arXiv:2208.10466

Environment: carbon footprint

Higgs factory Operated from	CLIC CERN	ILC KEK	C^3 FNAL	CEPC China	FCC-ee CERN
Carbon intensity (kg CO_2 eq. / MWh)	56	565	381	546	56
Carbon footprint per Hi (t CO_2 eq.)					**17**

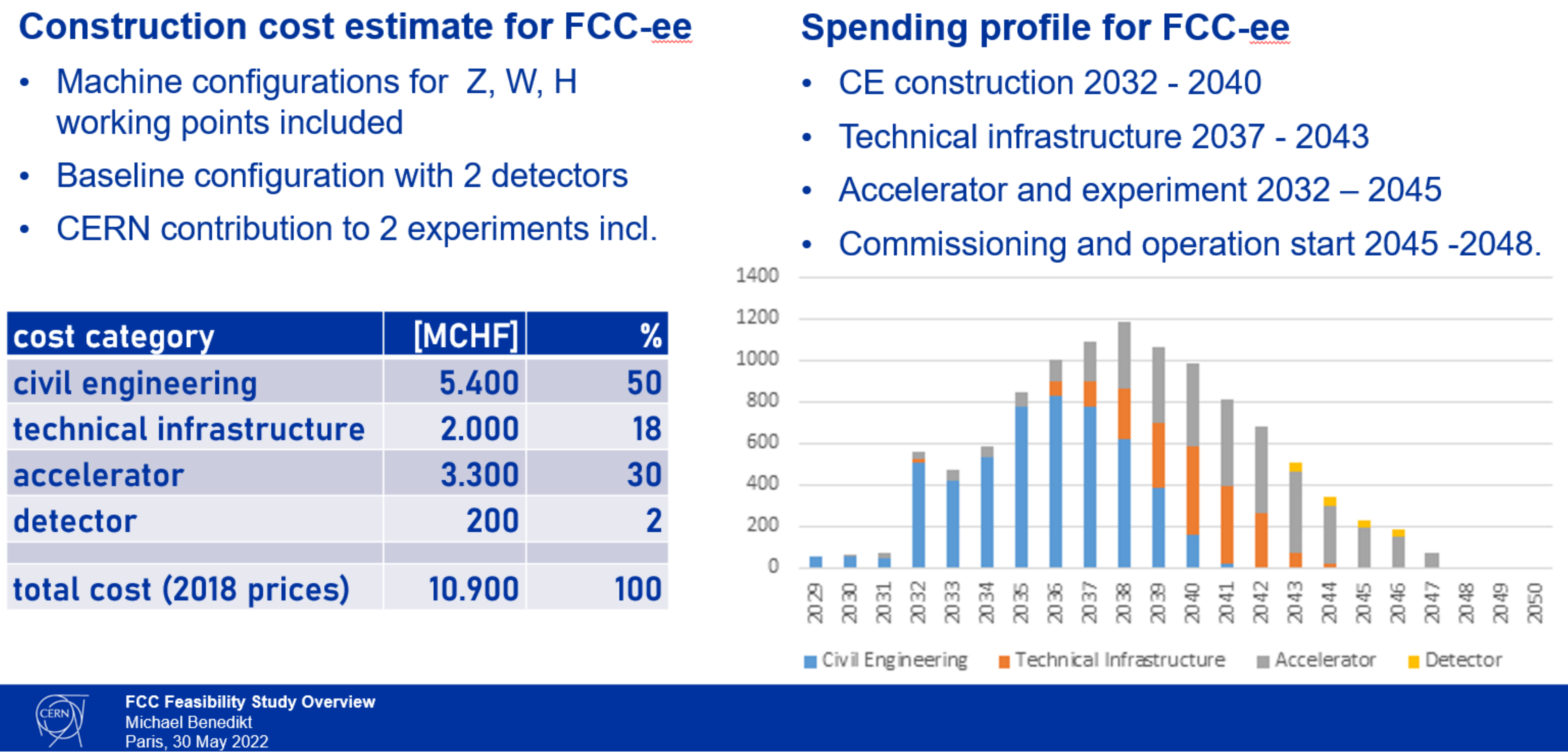


arXiv:2208.10466

Funding

- Funding for FCC FS secured in CERN's Medium-Term Plan: 100 MCHF (~ 20 MCHF/year over 5 years)
  - 1st stage: tunnel & FCCee
- Additional funding for magnet R&D: 120 MCHF/6 years
  - Sustained R&D on High-Field Magnets, for a seamless start of the 2nd stage (FCC-hh)

FCC 1st stage cost profile



Construction cost estimate for FCC-ee

- Machine configurations for Z, W, H working points included
- Baseline configuration with 2 detectors
- CERN contribution to 2 experiments incl.

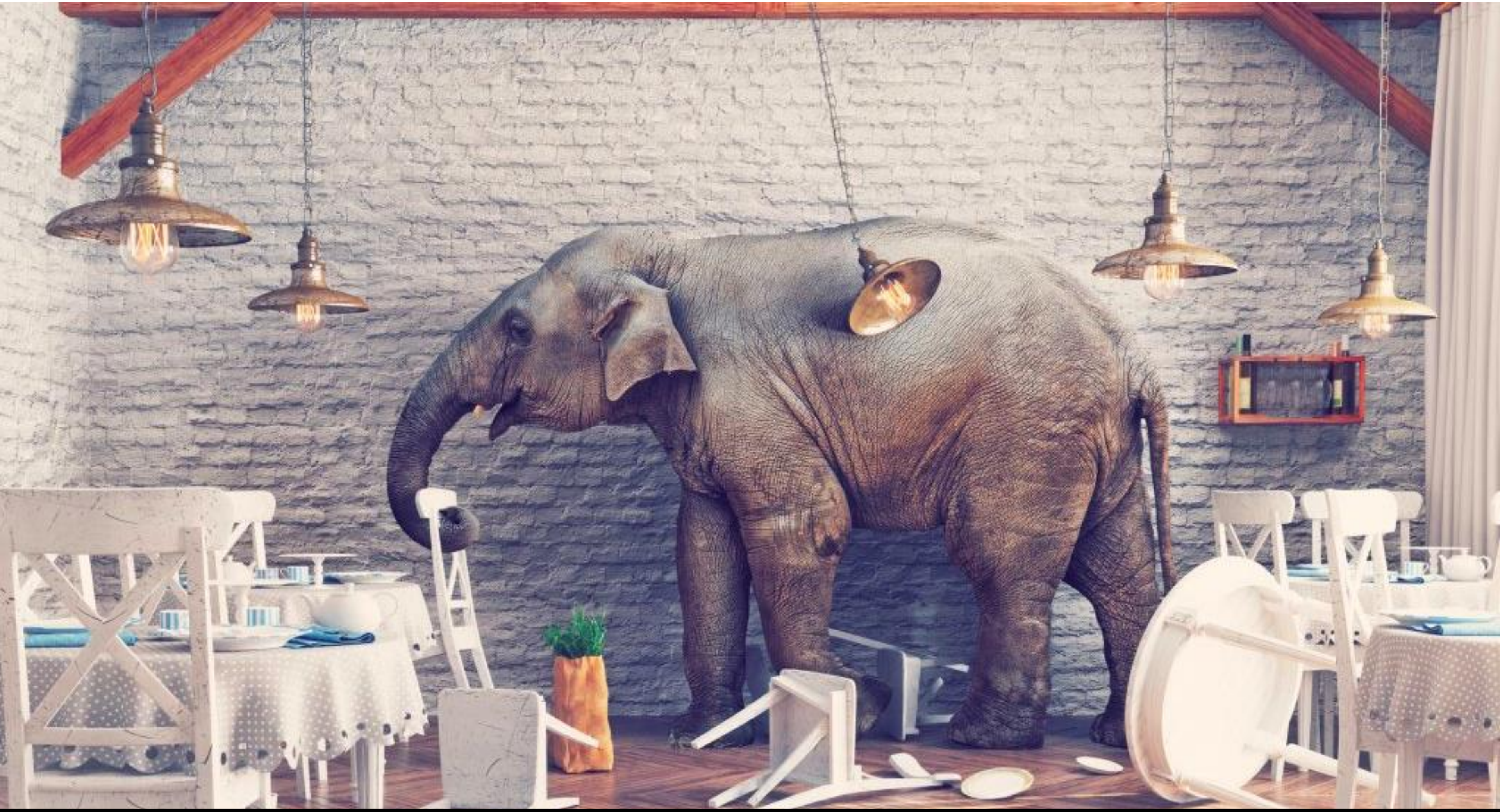
cost category	[MCHF]	%
civil engineering	5.400	50
technical infrastructure	2.000	18
accelerator	3.300	30
detector	200	2
total cost (2018 prices)	10.900	100

Spending profile for FCC-ee

- CE construction 2032 - 2040
- Technical infrastructure 2037 - 2043
- Accelerator and experiment 2032 – 2045
- Commissioning and operation start 2045 -2048.

FCC Feasibility Study Overview
Michael Benedikt
Paris, 30 May 2022

Financial feasibility: spending profile for the tunnel and FCC-ee machine developed and needed resources versus time defined
Ongoing discussions with Host States and Council



Substantial resources (~ 5 BCHF) needed from outside CERN’s budget

- Large part in-kind contributions from non-Member States
- Special contributions from Host States and other Member States
- European Commission
- Private funding?

FCC: beyond Physics

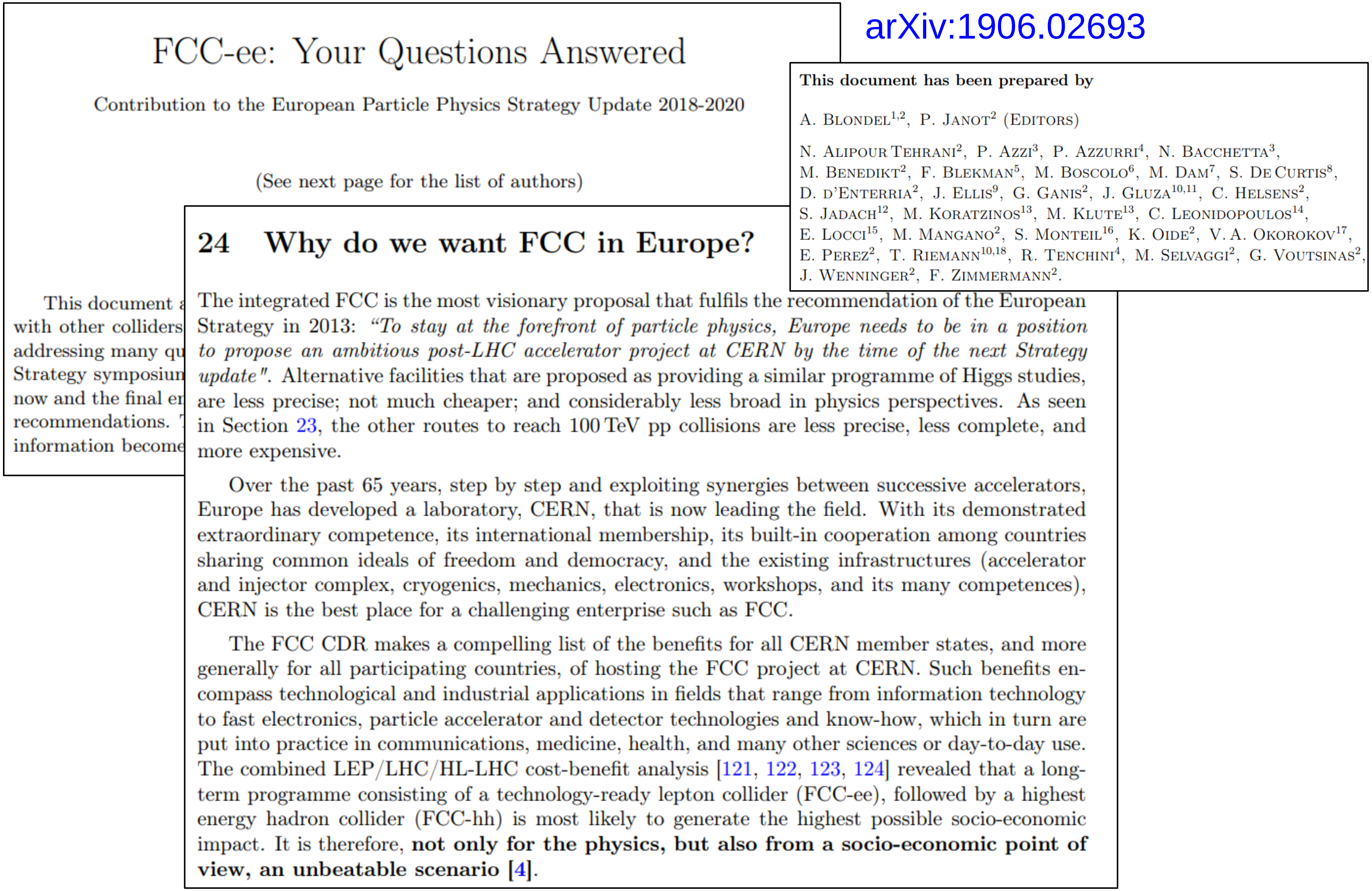
- CERN has been the leader in scientific & technological vision for the last 70 years
- Excellence is extremely hard to achieve. But very easy to loose
- European tradition of global collaboration & open science values

A lesson from the past: SSC

- A 87-km ring, 20-TeV collider that was not meant to be
- Cancelled in 1993 after $2.5B and 20% of excavation completed due to increased costs
- US has contributed significantly larger amounts to LHC that would have cost to complete SSC construction

Why Europe

arXiv:1906.02693



FCC-ee: Your Questions Answered

Contribution to the European Particle Physics Strategy Update 2018-2020

(See next page for the list of authors)

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This document has been prepared by

A. Blondel[1,2], P. Janot[2] (Editors)

N. Alipour Tehrani[2], P. Azzi[3], P. Azzurri[4], N. Bacchetta[3], M. Benedikt[2], F. Blekman[5], M. Boscolo[6], M. Dam[7], S. De Curtis[8], D. d'Enterria[2], J. Ellis[9], G. Ganis[2], J. Gluza[10,11], C. Helsens[2], S. Jadach[12], M. Koratzinos[13], M. Klute[13], C. Leonidopoulos[14], E. Locci[15], M. Mangano[2], S. Monteil[16], K. Oide[2], V. A. Okorokov[17], E. Perez[2], T. Riemann[10,18], R. Tenchini[4], M. Selvaggi[2], G. Voutsinas[2], J. Wenninger[2], F. Zimmermann[2].

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24 Why do we want FCC in Europe?

The integrated FCC is the most visionary proposal that fulfils the recommendation of the European Strategy in 2013: *"To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update"*. Alternative facilities that are proposed as providing a similar programme of Higgs studies, are less precise; not much cheaper; and considerably less broad in physics perspectives. As seen in Section 23, the other routes to reach 100 TeV pp collisions are less precise, less complete, and more expensive.

Over the past 65 years, step by step and exploiting synergies between successive accelerators, Europe has developed a laboratory, CERN, that is now leading the field. With its demonstrated extraordinary competence, its international membership, its built-in cooperation among countries sharing common ideals of freedom and democracy, and the existing infrastructures (accelerator and injector complex, cryogenics, mechanics, electronics, workshops, and its many competences), CERN is the best place for a challenging enterprise such as FCC.

The FCC CDR makes a compelling list of the benefits for all CERN member states, and more generally for all participating countries, of hosting the FCC project at CERN. Such benefits encompass technological and industrial applications in fields that range from information technology to fast electronics, particle accelerator and detector technologies and know-how, which in turn are put into practice in communications, medicine, health, and many other sciences or day-to-day use. The combined LEP/LHC/HL-LHC cost-benefit analysis [121, 122, 123, 124] revealed that a long-term programme consisting of a technology-ready lepton collider (FCC-ee), followed by a highest energy hadron collider (FCC-hh) is most likely to generate the highest possible socio-economic impact. It is therefore, **not only for the physics, but also from a socio-economic point of view, an unbeatable scenario [4].**

A few words on China

Collider efforts in China

CEPC:

- Circular electron positron collider
- 50 - 100 km ring
- 90 - 250 GeV
- Z and Higgs factory

SPPC:

- Super pp Collider
- In the same ring as CEPC

Yifang Wang

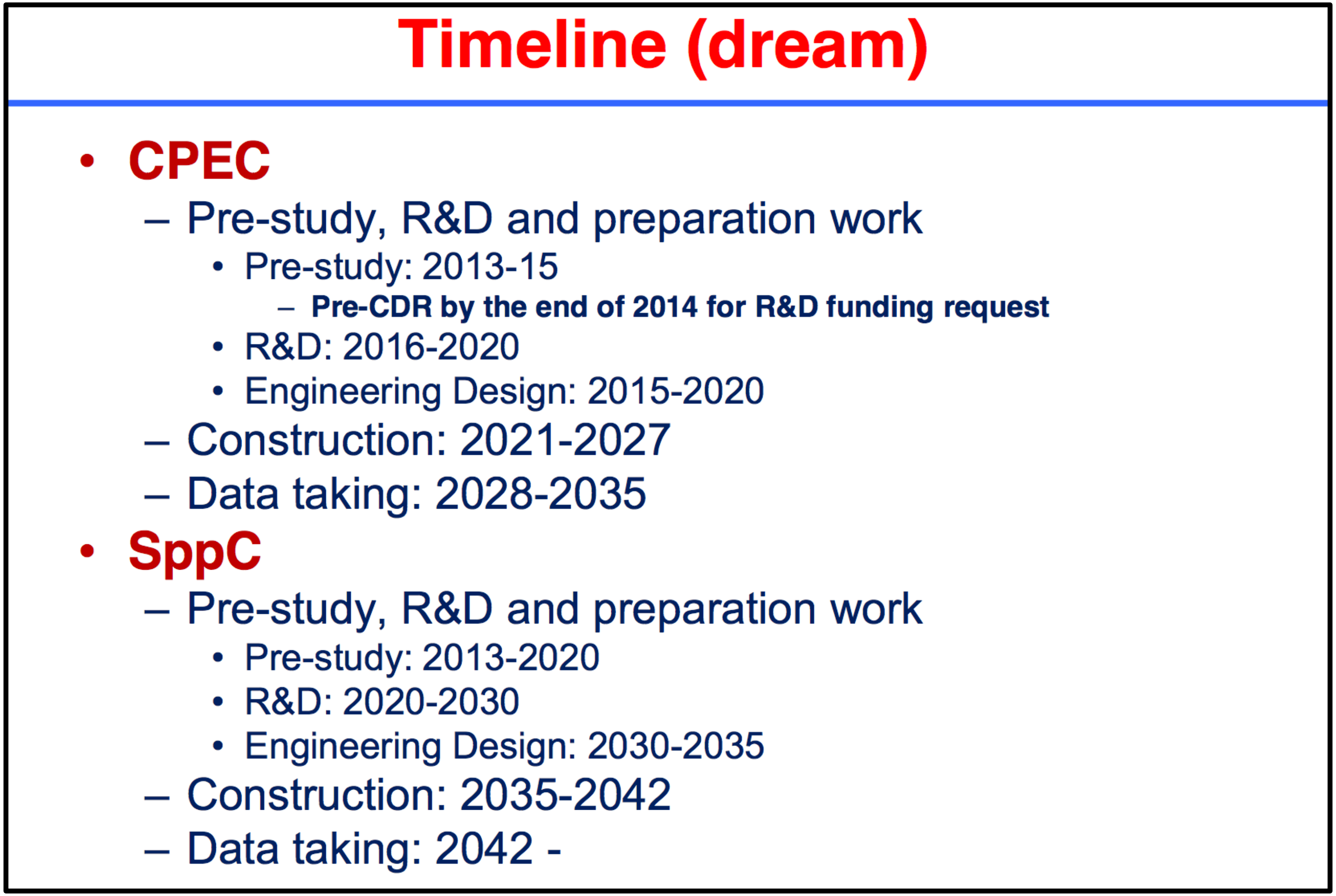
CEPC Design –Higgs Parameters

Parameter	Design Goal
Particles	e+, e-
Center of mass energy	2*120 GeV
Luminosity (peak)	>2*10^34/cm^2s
No. of IPs	2

CEPC Design – Z-pole Parameters

Parameter	Design Goal
Particles	e+, e-
Center of mass energy	2*45.5 GeV
Integrated luminosity (peak)	>10^34/cm^2s
No. of IPs	2
Polarization	to be considered in the second round of design

A few words on China



Timeline (dream)

- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
      - **Pre-CDR by the end of 2014 for R&D funding request**
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2021-2027
  - Data taking: 2028-2035
- **SppC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - Construction: 2035-2042
  - Data taking: 2042 -

A few words on China

Major advantages

- Low cost
- Ambition

My personal opinion

- If Europe (&US) does not step up, have no doubts that China will get there

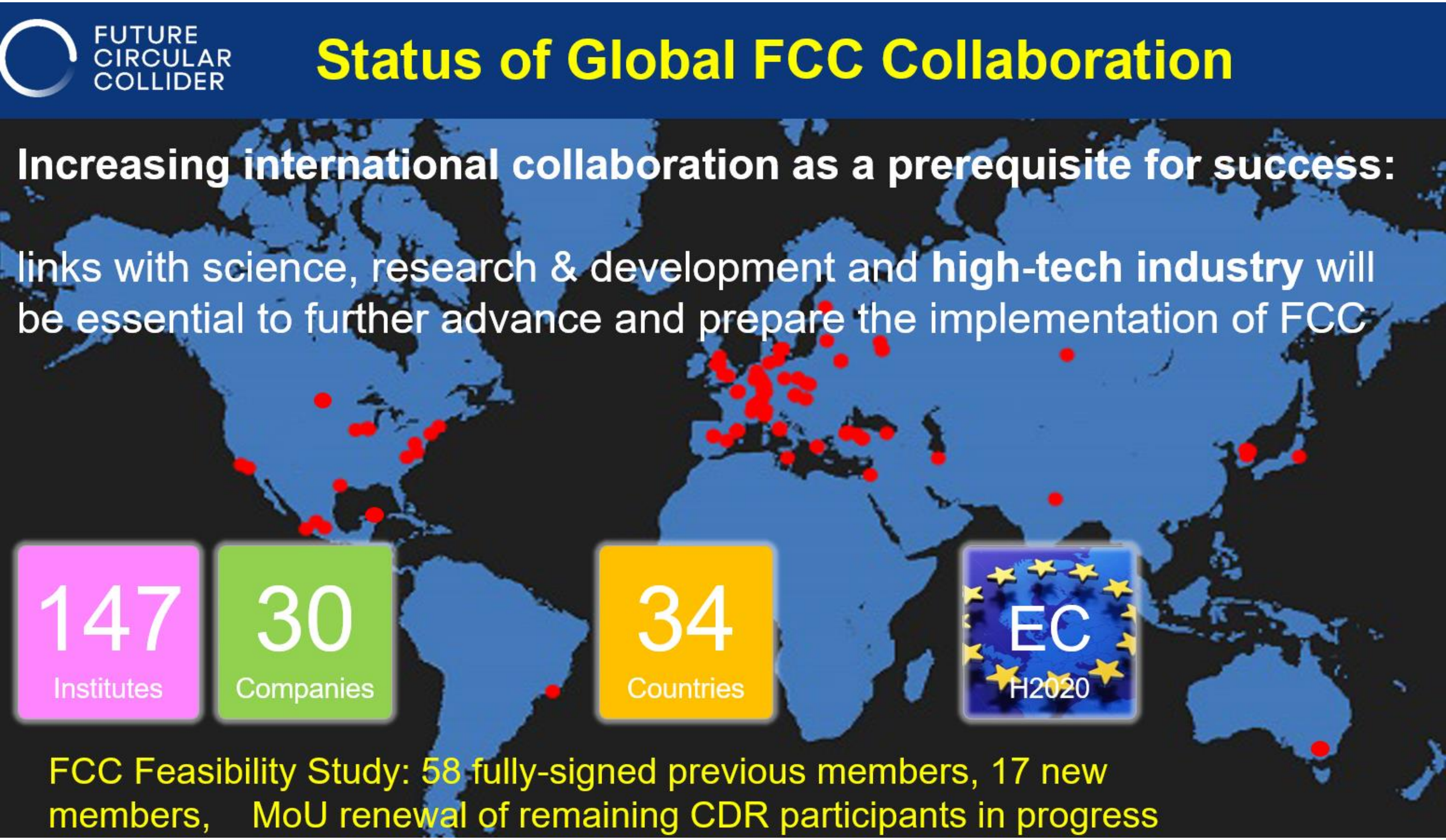
Epilogue

Summary

- After a very successful decades-long physics program that established the SM we are exhausting the theoretical clues and we must pursue experimental exploration
- The integrated FCC project with lepton & hadron colliders offers an immensely rich physics program extending till the end of the 21st century
- Program very ambitious, rewarding (huge statistics) but challenging: technology R&D and control of systematics will be key to success
- FCC is the best, most comprehensive & most environmentally friendly option among collider proposals
- Europe: the place of open science & global collaboration

Bonus Slides

FCC: International Collaboration



FUTURE
CIRCULAR
COLLIDER

Status of Global FCC Collaboration

Increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

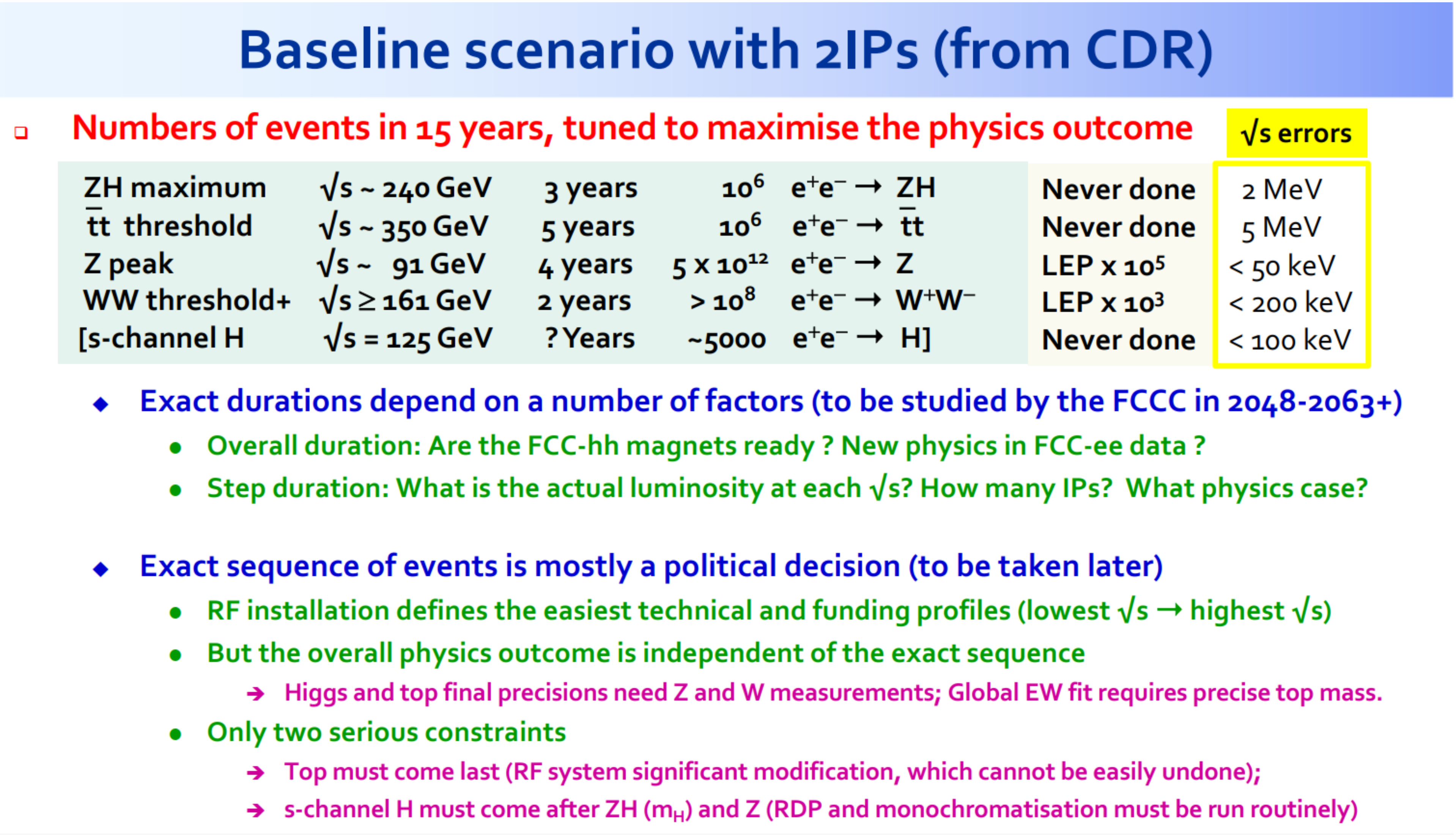
147	30	34	EC
Institutes	Companies	Countries	H2020

FCC Feasibility Study: 58 fully-signed previous members, 17 new members, MoU renewal of remaining CDR participants in progress

Feasibility Study (2021-25) objectives

- ☐ demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- ☐ pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- ☐ optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies;
- ☐ elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- ☐ development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- ☐ identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- ☐ consolidation of the physics case and detector concepts for both colliders.

Sequence of energy runs



Baseline scenario with 2IPs (from CDR)

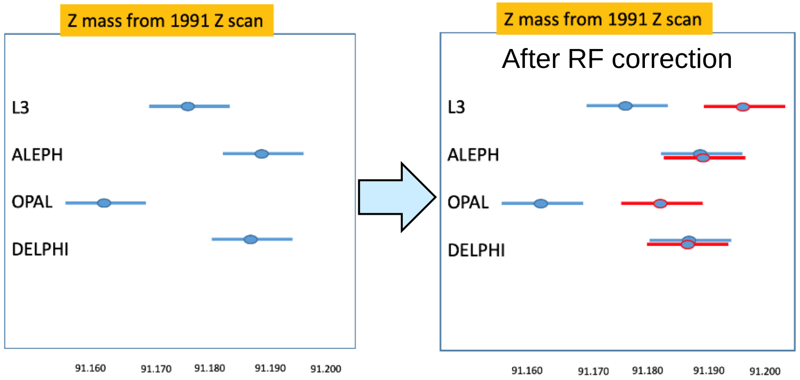
- Numbers of events in 15 years, tuned to maximise the physics outcome

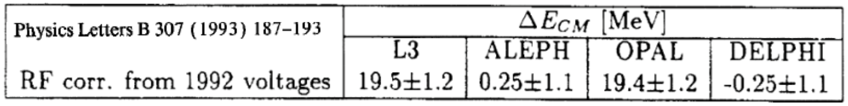
						$\sqrt{s}$ errors
ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s} \sim 350$ GeV	5 years	10^6	$e^+e^- \to t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	5×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 50 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$	LEP x 10^3	< 200 keV
[s-channel H	$\sqrt{s} = 125$ GeV	? Years	~5000	$e^+e^- \to H$]	Never done	< 100 keV

- Exact durations depend on a number of factors (to be studied by the FCCC in 2048-2063+)
  - Overall duration: Are the FCC-hh magnets ready ? New physics in FCC-ee data ?
  - Step duration: What is the actual luminosity at each $\sqrt{s}$? How many IPs? What physics case?
- Exact sequence of events is mostly a political decision (to be taken later)
  - RF installation defines the easiest technical and funding profiles (lowest $\sqrt{s} \to$ highest $\sqrt{s}$)
  - But the overall physics outcome is independent of the exact sequence
    - ➔ Higgs and top final precisions need Z and W measurements; Global EW fit requires precise top mass.
  - Only two serious constraints
    - ➔ Top must come last (RF system significant modification, which cannot be easily undone);
    - ➔ s-channel H must come after ZH (m_H) and Z (RDP and monochromatisation must be run routinely)

The case for four interaction points

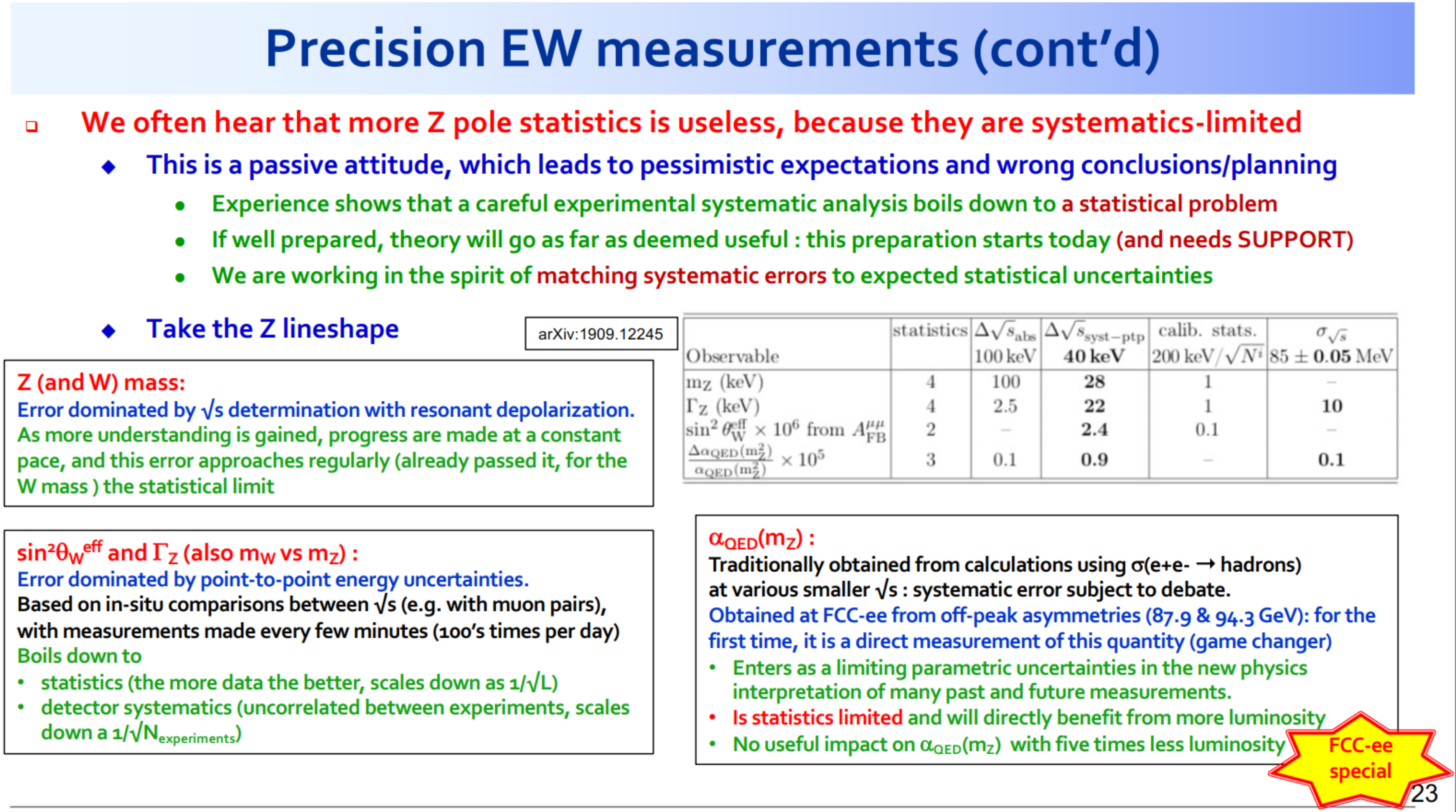
- One of the many advantages of circular colliders: can serve several IP
  - Overall gain in luminosity and in luminosity/MW (greener collider)
    - Many measurements are statistics limited – some are tantalizingly close with only 2 IP
      - ➔ E.g., Higgs self-coupling ; Search for HNL; Flavour anomalies; etc.
  - Variety of detector requirements may not be satisfied by one or even two detectors
    - E.g., High precision, high granularity, high stability, geometric accuracy, PID, cost constraints
      - ➔ Having four IP allows for a range of detector solutions to cover all FCC-ee opportunities
  - Four IP provide an attractive challenge for all skills in the field of particle physics
  - Redundancy is invaluable in uncovering hidden systematic biases or conspiracy of errors
    - E.g., m_Z discrepancy at LEP in 1991
      - ➔ Found to be an effect of RF phases and voltages
    - Could have remained unnoticed for ever
      - ➔ With only ALEPH and DELPHI
      - ➔ Or with only L3 and OPAL





Physics Letters B 307 (1993) 187–193	ΔE_{CM} [MeV]			
	L3	ALEPH	OPAL	DELPHI
RF corr. from 1992 voltages	19.5±1.2	0.25±1.1	19.4±1.2	-0.25±1.1

Systematics



Precision EW measurements (cont'd)

- **We often hear that more Z pole statistics is useless, because they are systematics-limited**
  - **This is a passive attitude, which leads to pessimistic expectations and wrong conclusions/planning**
    - **Experience shows that a careful experimental systematic analysis boils down to a statistical problem**
    - **If well prepared, theory will go as far as deemed useful : this preparation starts today (and needs SUPPORT)**
    - **We are working in the spirit of matching systematic errors to expected statistical uncertainties**
  - **Take the Z lineshape**

arXiv:1909.12245

Observable	statistics	$\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ **40 keV**	calib. stats. 200 keV/$\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{\mathrm{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	**0.9**	–	**0.1**

Z (and W) mass:
Error dominated by $\sqrt{s}$ determination with resonant depolarization.
As more understanding is gained, progress are made at a constant pace, and this error approaches regularly (already passed it, for the W mass) the statistical limit

$\sin^2\theta_W^{eff}$ and Γ_Z (also m_W vs m_Z) :
Error dominated by point-to-point energy uncertainties.
Based on in-situ comparisons between $\sqrt{s}$ (e.g. with muon pairs), with measurements made every few minutes (100's times per day)
Boils down to
- statistics (the more data the better, scales down as $1/\sqrt{L}$)
- detector systematics (uncorrelated between experiments, scales down a $1/\sqrt{N_{experiments}}$)

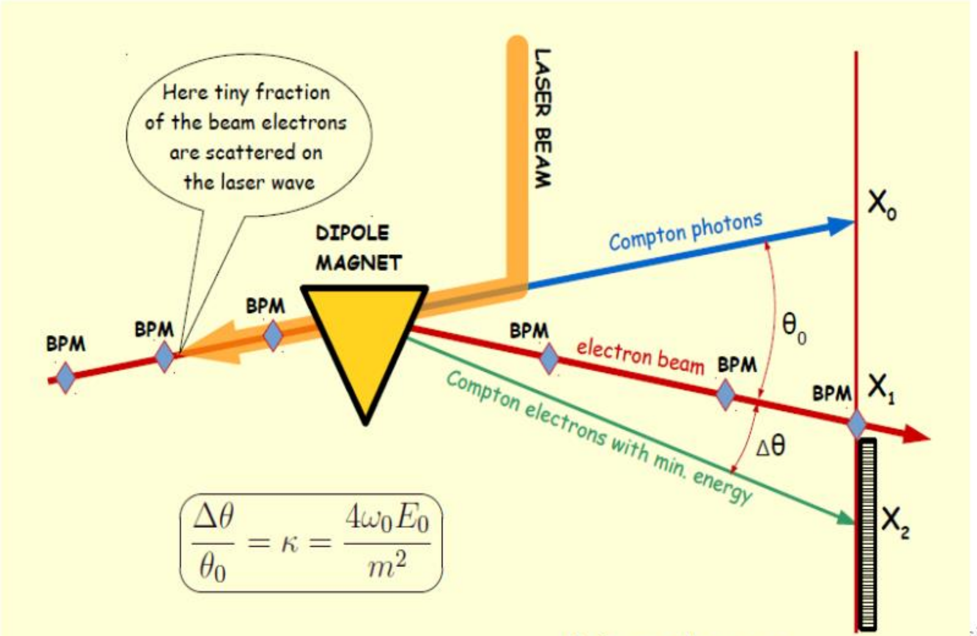
$\alpha_{QED}(m_Z)$:
Traditionally obtained from calculations using σ(e+e- → hadrons) at various smaller $\sqrt{s}$: systematic error subject to debate.
Obtained at FCC-ee from off-peak asymmetries (87.9 & 94.3 GeV): for the first time, it is a direct measurement of this quantity (game changer)
- Enters as a limiting parametric uncertainties in the new physics interpretation of many past and future measurements.
- Is statistics limited and will directly benefit from more luminosity
- No useful impact on $\alpha_{QED}(m_Z)$ with five times less luminosity

FCC-ee special

23

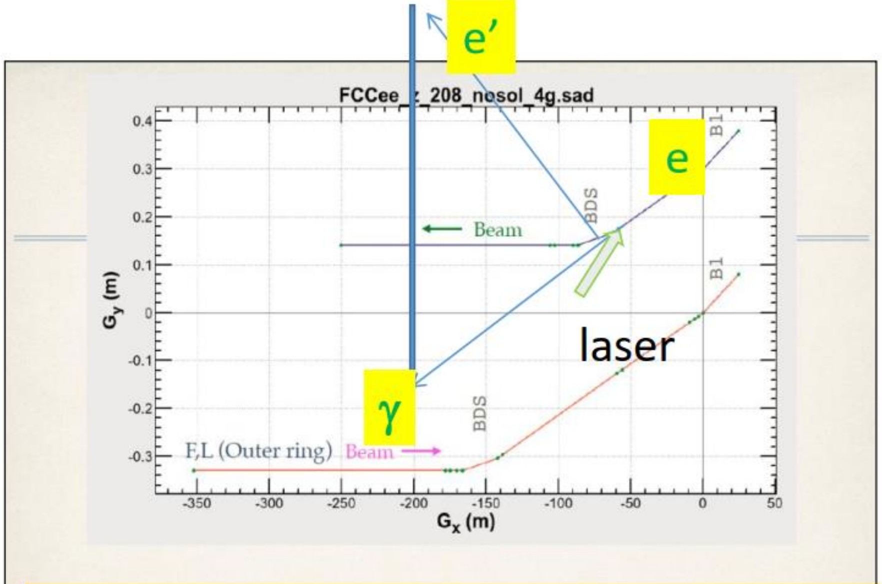
Polarimeters

2 Polarimeters, for e+ and e-   Use of both electron and photons recoil → measurement of 3D beam polarizatior
Backscattered Compton γ +e → γ + e   532 nm (2.33 eV) laser; detection of photon and electron.
Change upon flip of laser circular polarization → beam Polarization ±0.01 per second
End point of recoil electron → beam energy monitoring ± 4 MeV per second   (Muchnoi, Aurelien Martens)



$$\frac{\Delta\theta}{\theta_0} = \kappa = \frac{4\omega_0 E_0}{m^2}$$

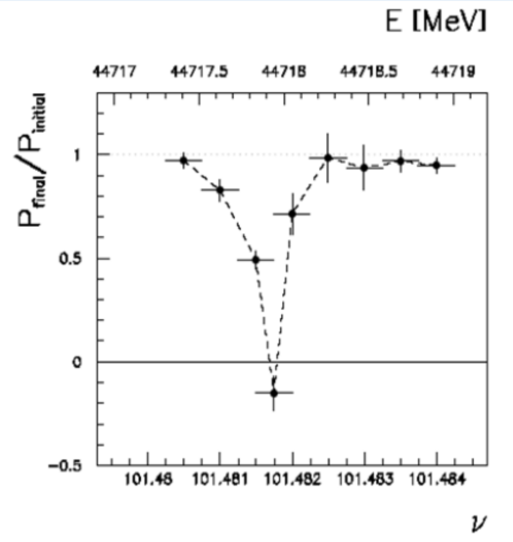
Munchnoy



install photon-electron IP on inner ring in RF straights *(Oide)*

Polarimeters

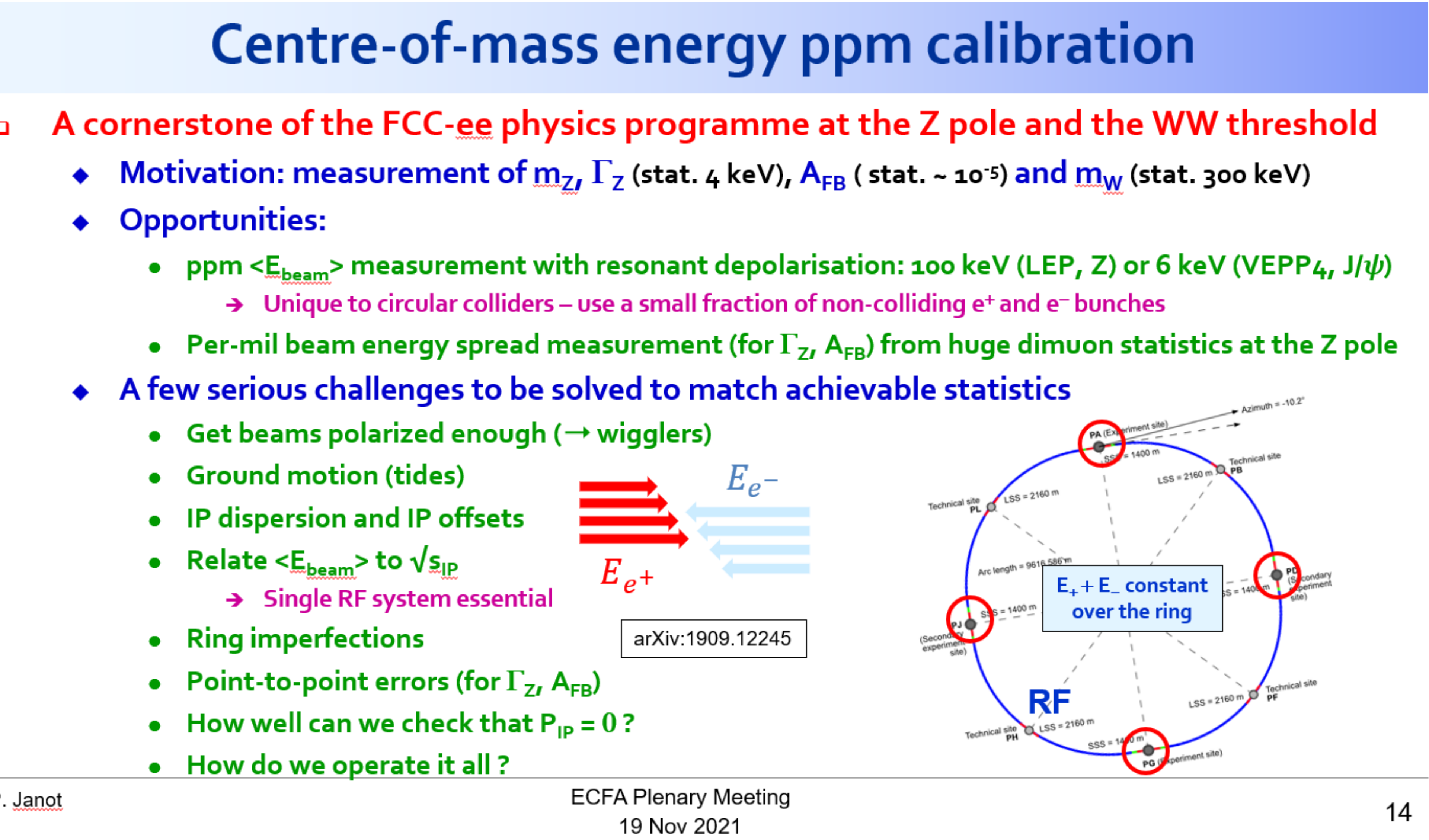
Transverse beam polarization provides beam energy calibration by resonant depolarization



→ low level of polarization is required (~10% is sufficient)
→ at Z & W pair threshold comes naturally $\sigma_E \propto E^2/\sqrt{\rho}$
→ at Z use of asymmetric wigglers at beginning of fills since polarization time is otherwise very long (250h→ ~1h)
→ should be used also at ee → H(126)
→ use 'single' non-colliding bunches and calibrate continuously during physics fills to avoid issues encountered at LEP
→ Compton polarimeters for e+ and e- each
→ should calibrate at energies corresponding to half-integer spin tune
→ must be complemented by analysis of «average E_beam-to-E_CM» relationship

For beam energies higher than ~90 GeV can use ee → Z γ or ee → WW events to calibrate E_{CM} at ±1-5 MeV level: m_H (~3 MeV) and m_{top} (~10-20 MeV) measts

Energy beam calibration



Centre-of-mass energy ppm calibration

- A cornerstone of the FCC-ee physics programme at the Z pole and the WW threshold
  - Motivation: measurement of m_Z, Γ_Z (stat. 4 keV), A_{FB} (stat. ~ 10^{-5}) and m_W (stat. 300 keV)
  - Opportunities:
    - ppm $\langle E_{beam} \rangle$ measurement with resonant depolarisation: 100 keV (LEP, Z) or 6 keV (VEPP4, J/ψ)
      - → Unique to circular colliders – use a small fraction of non-colliding e^+ and e^- bunches
    - Per-mil beam energy spread measurement (for Γ_Z, A_{FB}) from huge dimuon statistics at the Z pole
  - A few serious challenges to be solved to match achievable statistics
    - Get beams polarized enough (→ wigglers)
    - Ground motion (tides)
    - IP dispersion and IP offsets
    - Relate $\langle E_{beam} \rangle$ to $\sqrt{s_{IP}}$
      - → Single RF system essential
    - Ring imperfections
    - Point-to-point errors (for Γ_Z, A_{FB})
    - How well can we check that $P_{IP} = 0$?
    - How do we operate it all ?

arXiv:1909.12245

$E_+ + E_-$ constant over the ring

. Janot

ECFA Plenary Meeting
19 Nov 2021

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Flavour, Tau, QCD, Rare/BSM

- **TeraZ offers four additional pillars to the FCC-ee physics programme**

Flavour physics programme

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., $b \to s\tau\tau$

QCD programme

- Enormous statistics with $Z \to \ell\ell$, qq(g)
- Complemented by 100,000 $H \to gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Often statistics-limited
$5.\ 10^{12}$ Z is a minimum

Tau physics programme

- Enormous statistics: $1.7\ 10^{11}$ $\tau\tau$ events
- Clean environment, boost, vertexing
- Much improved measurement of mass, lifetime, BR's

1. τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
2. Lepton universality violation tests
3. PMNS matrix unitarity
4. Light-heavy neutrino mixing

Rare/BSM processes, e.g. Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m_Z

- Signature: long lifetimes (LLP's)
- Other ultra-rare Z (and W) decays

1. Axion-like particles
2. Dark photons
3. Heavy Neutral Leptons

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Accelerator options

	$\sqrt{s}$	L /IP ($cm^{-2}\,s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	230 x10^{34} 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep **Fcc-eh**	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb **Fcc-eh**	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

FUTURE
CIRCULAR
COLLIDER

Stage 1: updated parameters

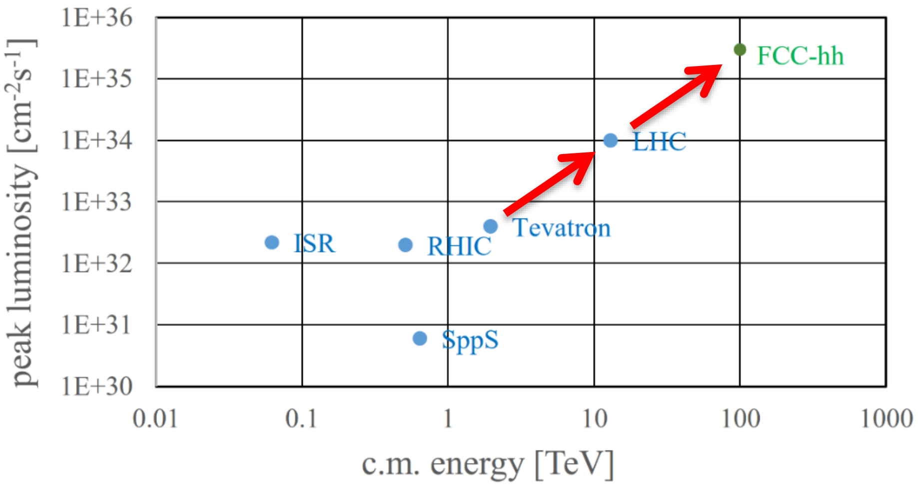
K. Oide, D. Shatilov,

Parameter [4 IPs, 91.2 km,T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity $[10^{11}]$	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP $[10^{34}\ cm^{-2}s^{-1}]$	182	19.4	7.3	1.33
total integrated luminosity / year $[ab^{-1}/yr]$	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

Stage 2: FCC-hh (pp) collider parameters

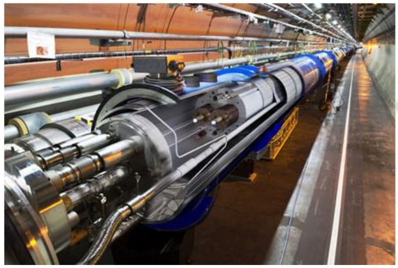
parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	~17 (~16 comb.function)		8.33	8.33
circumference [km]	91.2		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [µm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36

FCC-hh: highest collision energies

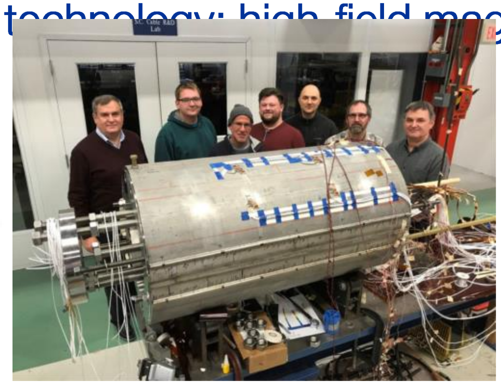


- order of magnitude performance increase in both energy & luminosity
- 100 TeV cm collision energy (vs 14 TeV for LHC)
- 20 ab-1 per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)
- similar performance increase as from Tevatron to LHC
- key technology: high field magnets

from
LHC technology
8.3 T NbTi dipole



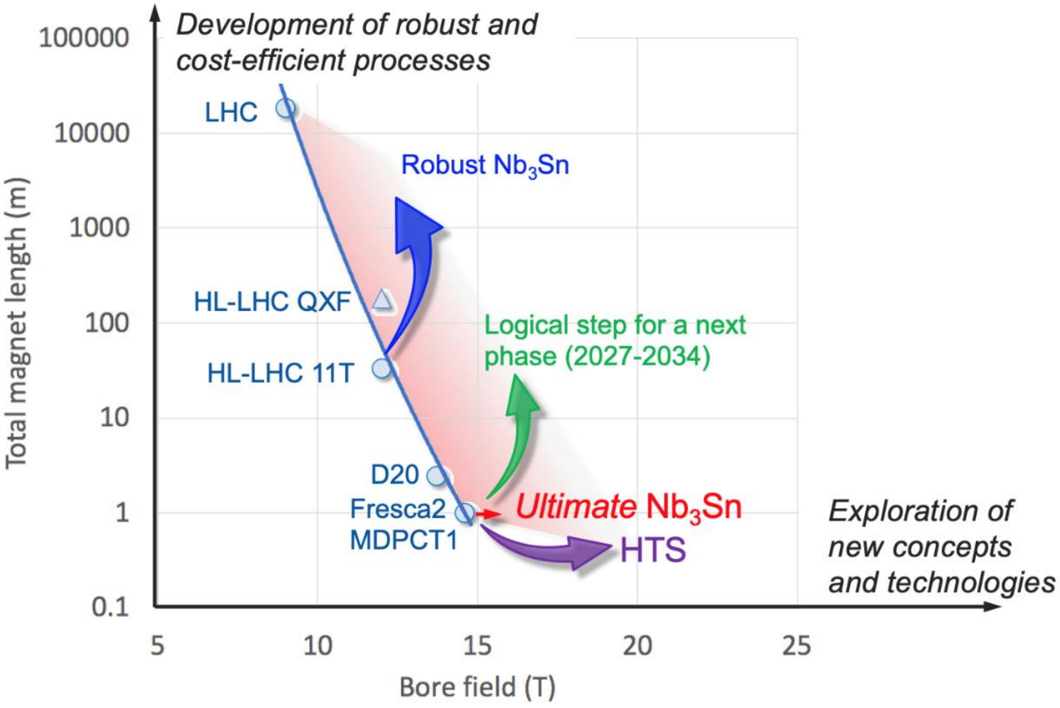
via
HL-LHC technology
12 T Nb$_3$Sn quadrupole



FNAL dipole demonstrator
4-layer cosϑ
14.5 T Nb$_3$Sn
in 2019

High-field magnets R&D: 1st steps towards FCC-hh

In parallel to FCC Study, HFM development program as long-term separate R&D project



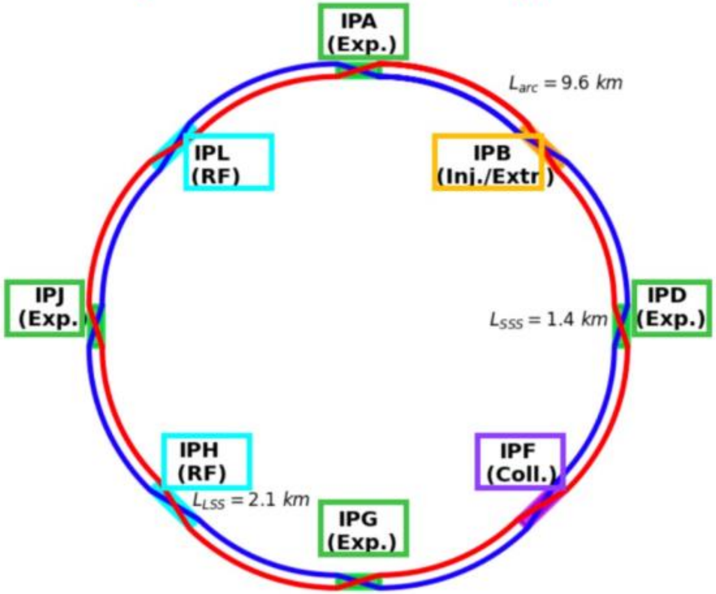
Main R&D activities:

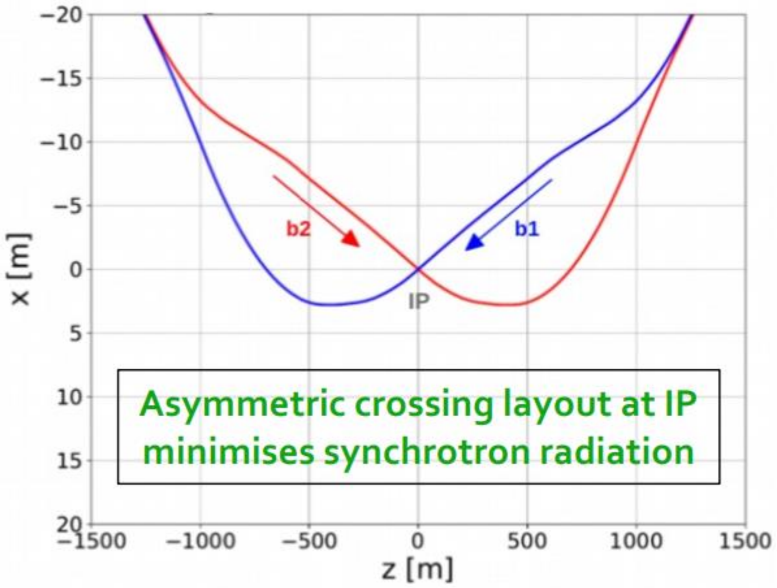
- ❑ materials: goal is ~16 T for Nb_3Sn, at least ~20 T for HTS inserts
- ❑ magnet technology: engineering, mechanical robustness, insulating materials, field quality
- ❑ production of models and prototypes: to demonstrate material, design and engineering choices, industrialisation and costs
- ❑ infrastructure and test stations: for tests up to ~ 20 T and 20-50 kA

Global collaborations already established during FCC CDR phase.

Synchrotron radiation (as in the CDR)

- Of course, the 100 MW from synchrotron radiation mostly go in the arcs





Asymmetric crossing layout at IP minimises synchrotron radiation

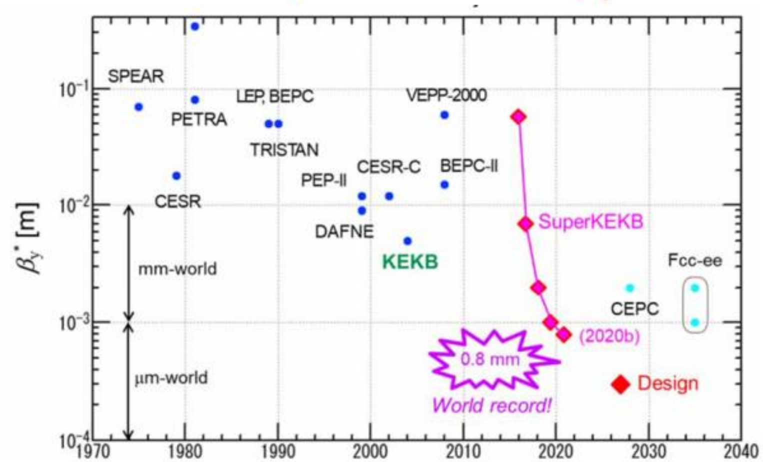
- SR photons from the last bend followed through the interaction region and the CLD tracker
  - Full GEANT4 simulation predicts no hits in the detector from SR all the way to $\sqrt{s}$ = 125 GeV
    - At $\sqrt{s}$ = 365 GeV, hits in the central tracker suppressed by additional shielding. VTX 1st layer occupancy ~ 10^{-4}
      - → Being revisited as we speak (including the need for shielding) with the old and new IR designs
      - → Effect of synchrotron radiation in the IDEA drift chamber will follow

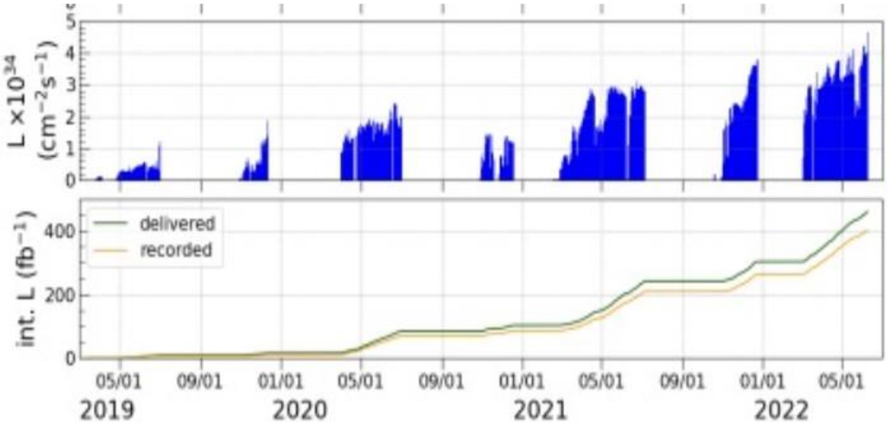
SuperKEKB as a FCC-ee demonstrator

- Tested successfully FCC-ee-type "virtual crab waist collisions

K. Oide, Phys. Rev. Accel. Beams 19, 111005)

- Run routinely with smallest β_y^* ever considered for FCC-ee: 1mm and 0.8mm



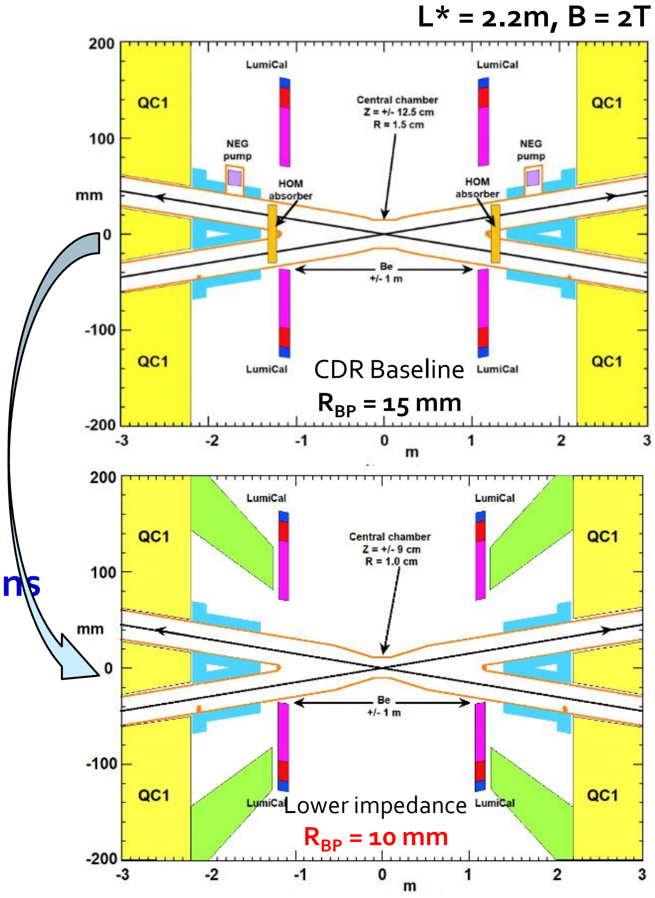


- World-record luminosity of $4.71\times10^{34}\ cm^{-2}s^{-1}$, and counting.

- e^+ production rate similar to FCC-ee: feasibility shown
  - Top-up injection with short beam lifetime (< 10 mins) demonstrated

The FCC-ee interaction region

- Need to progress from “conceptual” to “feasible” design
  - Engineering mechanical design & assembly concept
    - Including support and access for detector elements
  - Heat load assessment
  - Alignment tolerances and vibration control
  - Conceptual design of IR elements / systems
  - Dealing with backgrounds, beam loss, radiation
- Recent reduction of beam-pipe radius to 10 mm
  - Lower impedance
  - Low backgrounds generate low occupancy
    - Detection layer possibly situated inside the beam pipe?
  - Higher efficiency b/c tagging against light quarks & gluons
- B = 2T well adapted to FCC-ee momentum range
  - Study to increase it to 3T at high energies ongoing



L* = 2.2m, B = 2T

CDR Baseline

R_{BP} = 15 mm

Lower impedance

R_{BP} = 10 mm