FCC based Lepton-Hadron and Photon-Hadron Colliders: Luminosity And Physics

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* with A. Akay, Y. Acar, S. Beser, U. Kaya and B. Oner

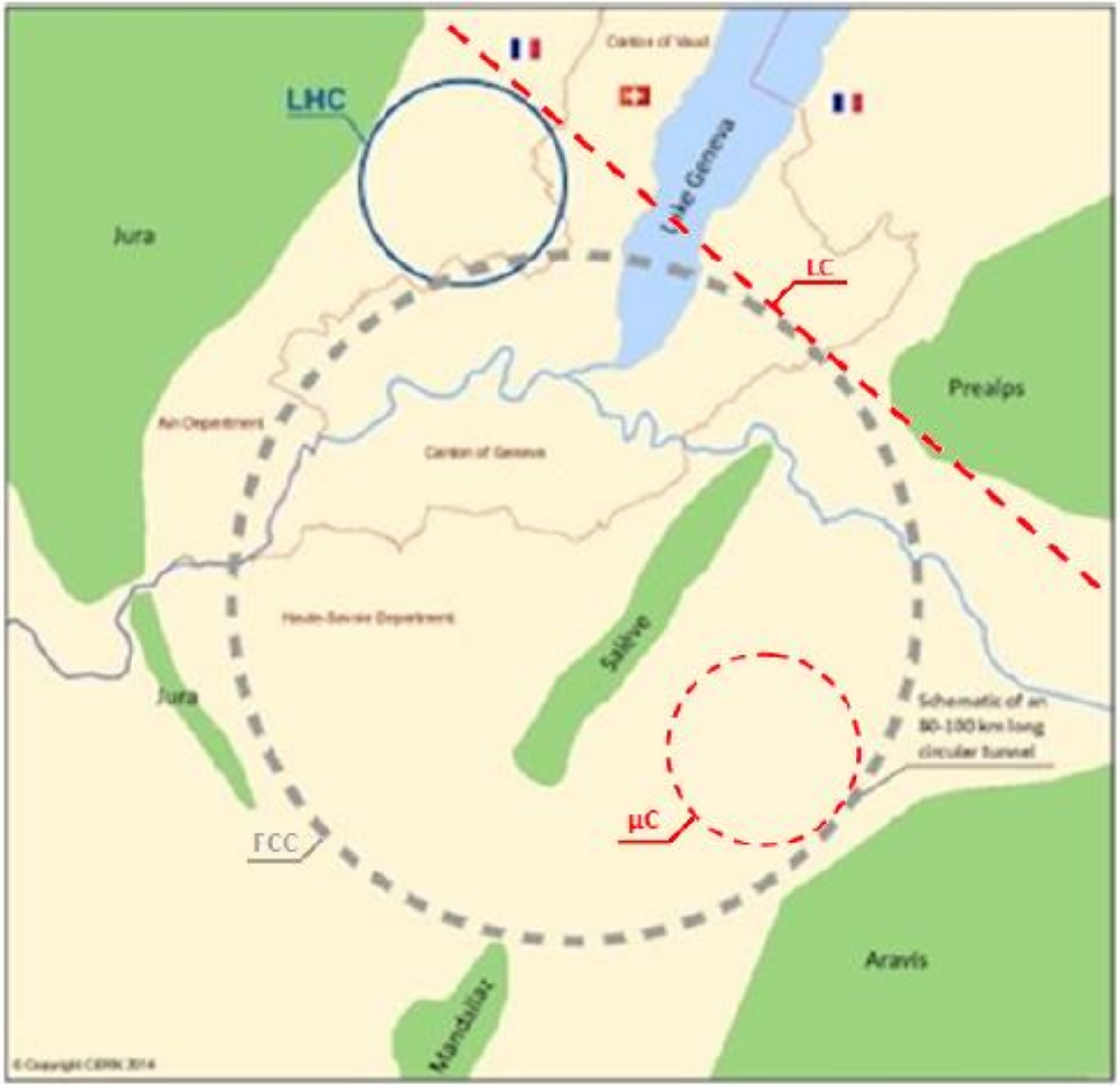
> ***What is the science of tomorrow? Pretty awesome!***
> ***"Power of particles of the substance" engaged in the business ...***
> ***Mehmet Akif ERSOY, Safahat (1919)***
> ***The author of the words of the Turkish National Anthem***

- Turkey is an Associate Member of CERN since April 2015
- Azerbaijan has applied for associate membership in September 2015
- TOBB ETÜ is member of FCC Collaboration since September 2015

Construction of future electron-positron colliders (or dedicated electron linac) and muon colliders tangential to Future Circular Collider will give opportunity to utilize highest energy proton and nucleus beams for lepton-hadron and photon-hadron collisions.

LC×FCC = LC + FCC
+ ep + eA
$+ \gamma p + \gamma A + \mathrm{FEL}\,\gamma A$

$\mu C \times FCC = \mu C + FCC$
$+ \mu p + \mu A$



Max Klein’s presentation – lumi frontier; this presentetion – energy frontier

Contents

Linac-Ring Type Colliders

- Second Way to TeV Scale
- LHC, ILC and ILC×LHC comparison

Physics

- SM: Triumph and Challenges
- BSM: standard extensions
- BSM: radical extensions
- BSM: «unexpected» new physics

FCC based ep, eA, μp, μA, γp, γA and FEL γA colliders

Dreams for 2030'ies

Linac-Ring Type Colliders

- Second Way to TeV Scale
- LHC, ILC and ILC×LHC comparison

Plenary ECFA – CERN (25-26 November 2010)

https://indico.cern.ch/event/111130/contribution/27/material/slides/1.pdf

ECFA EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

EIGHTY-EIGHTH PLENARY ECFA MEETING

25-26 November 2010, CERN

THE CORNESTONE OF THE TAC PROJECT: LINAC-RING TYPE SUPER-CHARM FACTORY

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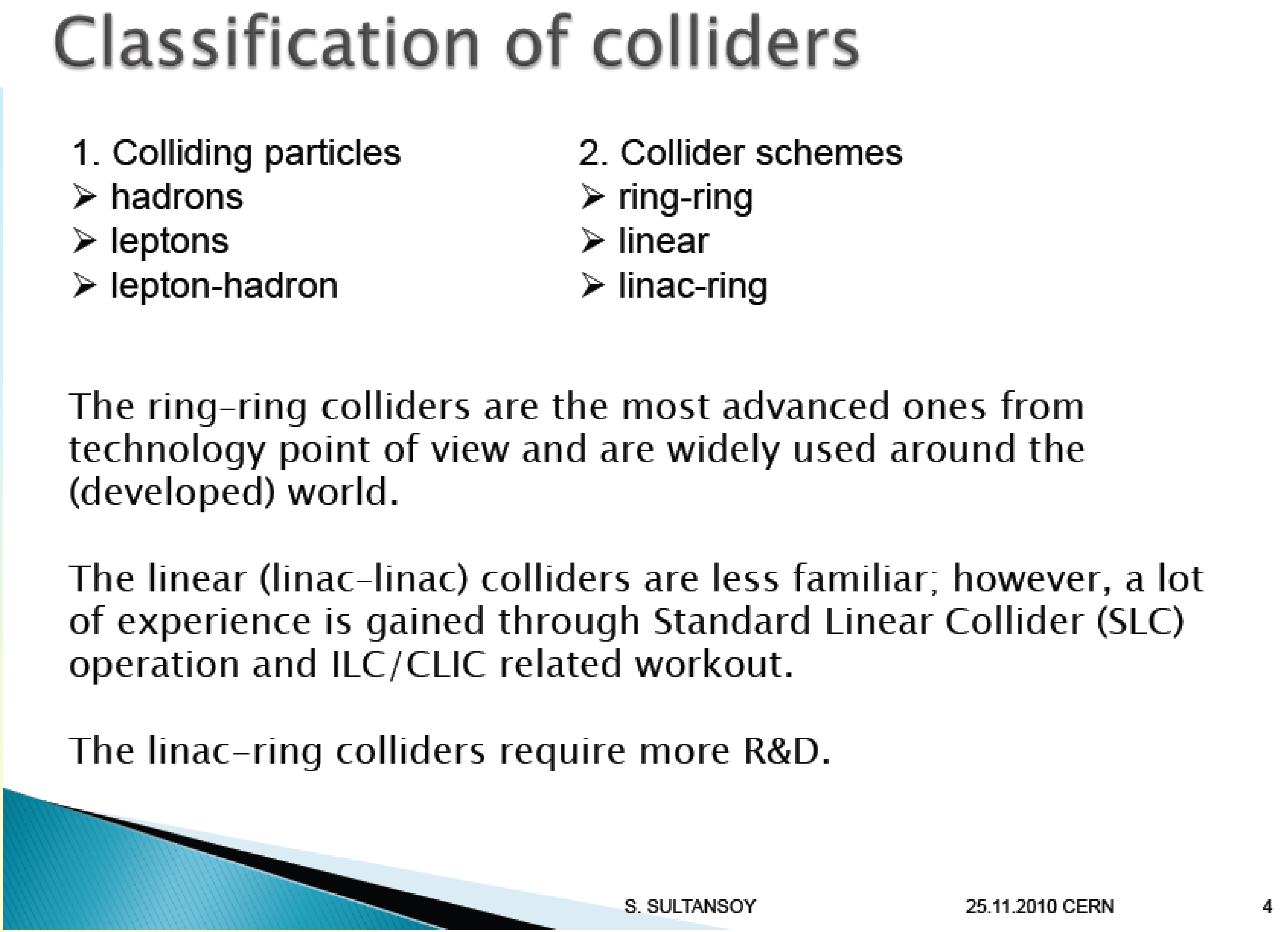
S. SULTANSOY 25.11.2010 CERN 1



Classification of colliders

1. Colliding particles
- hadrons
- leptons
- lepton-hadron

2. Collider schemes
- ring-ring
- linear
- linac-ring

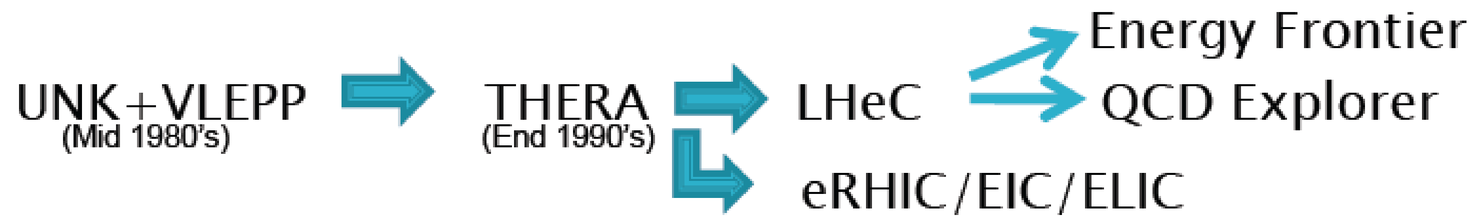
The ring-ring colliders are the most advanced ones from technology point of view and are widely used around the (developed) world.

The linear (linac-linac) colliders are less familiar; however, a lot of experience is gained through Standard Linear Collider (SLC) operation and ILC/CLIC related workout.

The linac-ring colliders require more R&D.

Linac-ring type colliders: two directions*

Lepton-hadron and photon-hadron colliders:



UNK+VLEPP
(Mid 1980's)

THERA
(End 1990's)

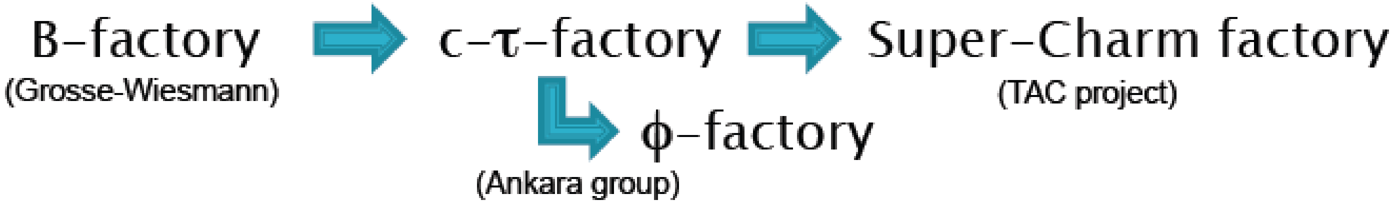
LHeC

Energy Frontier

QCD Explorer

eRHIC/EIC/ELIC

Factories:



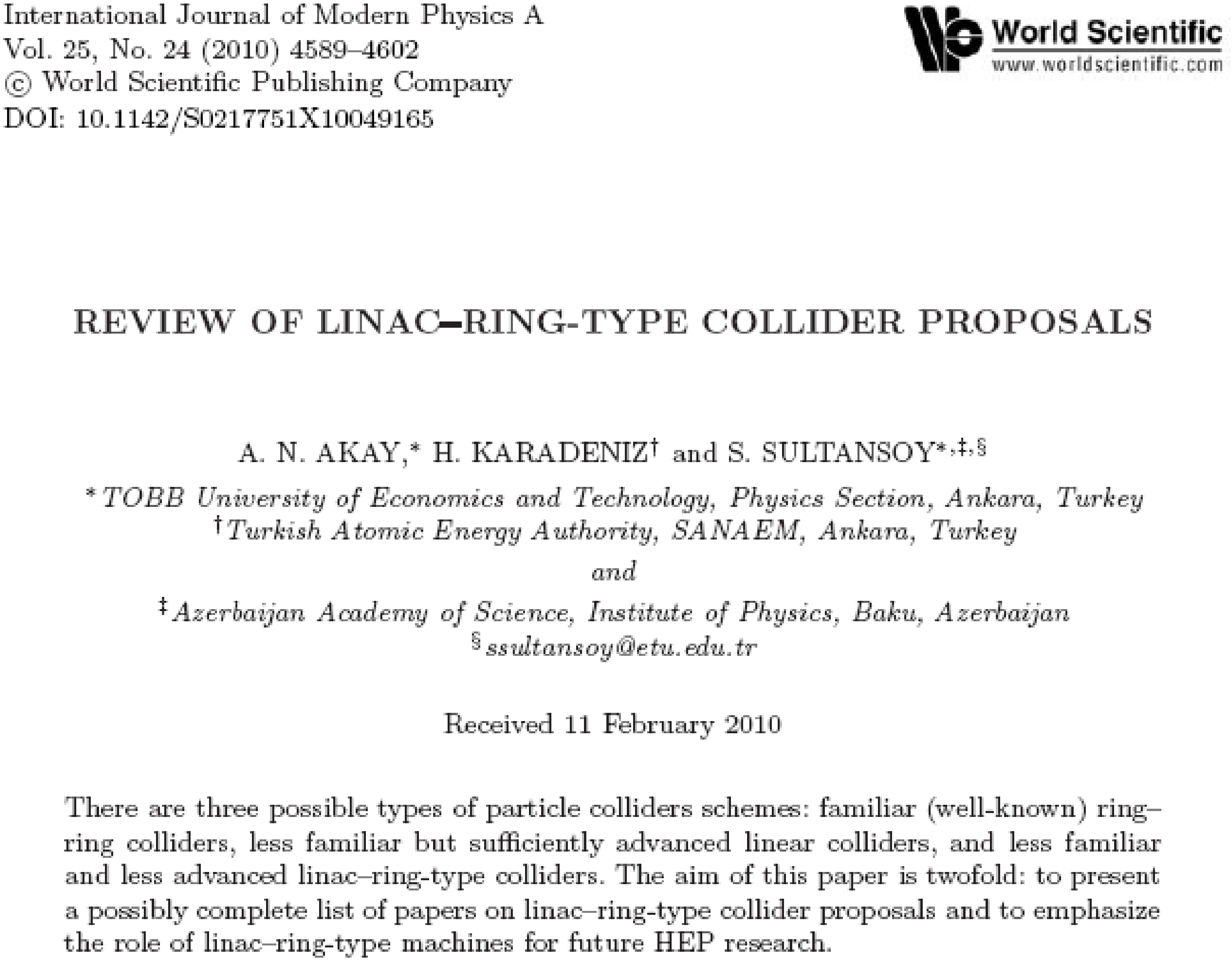
B-factory
(Grosse-Wiesmann)

c-τ-factory

Super-Charm factory
(TAC project)

ϕ-factory
(Ankara group)

* For details and ref's see: A. Akay, H. Karadeniz and S. Sultansoy, Review of Linac-Ring-Type Collider Proposals, Int. J. Mod. Phys. A 25 (2010) 4589



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REVIEW OF LINAC–RING-TYPE COLLIDER PROPOSALS

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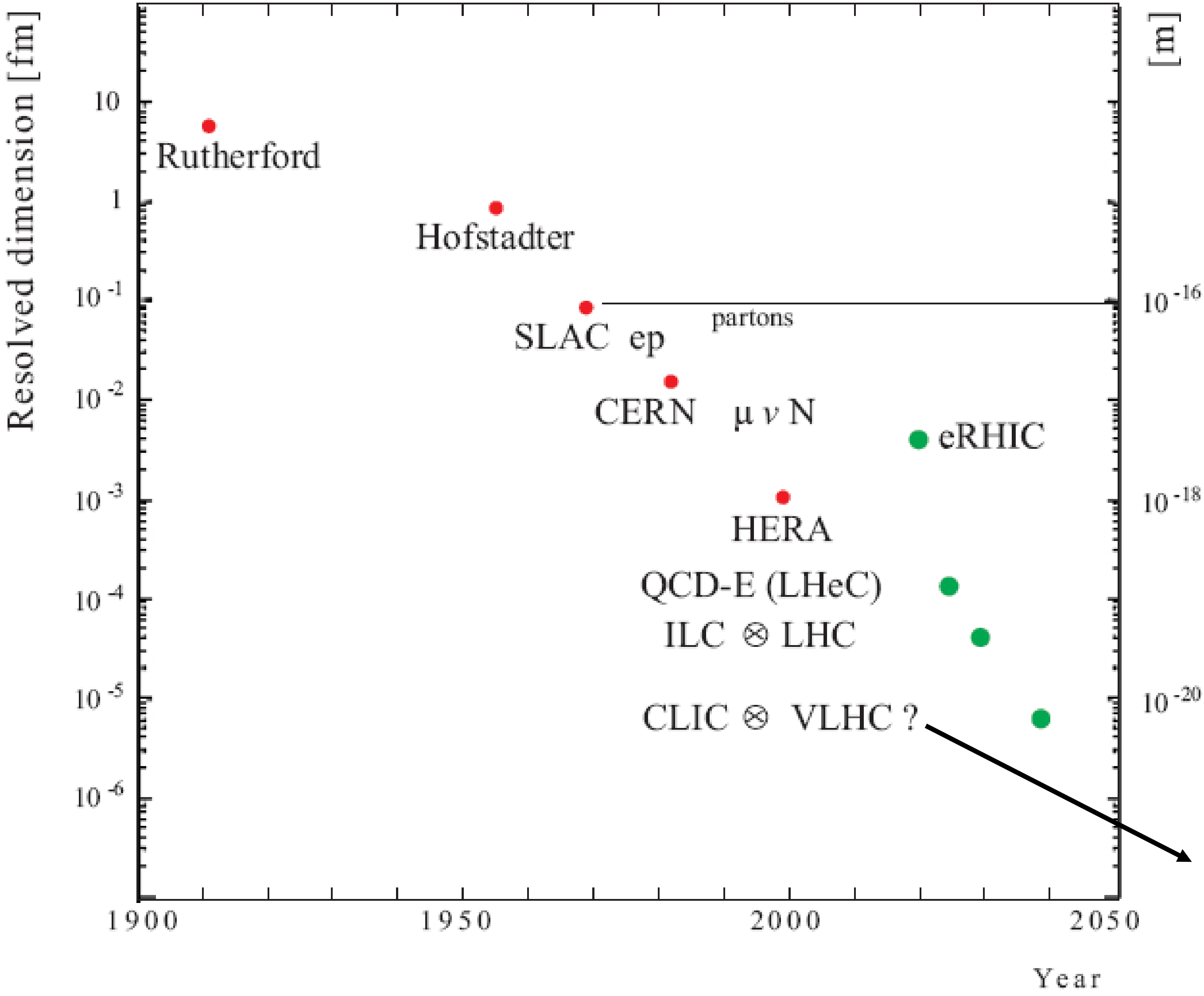
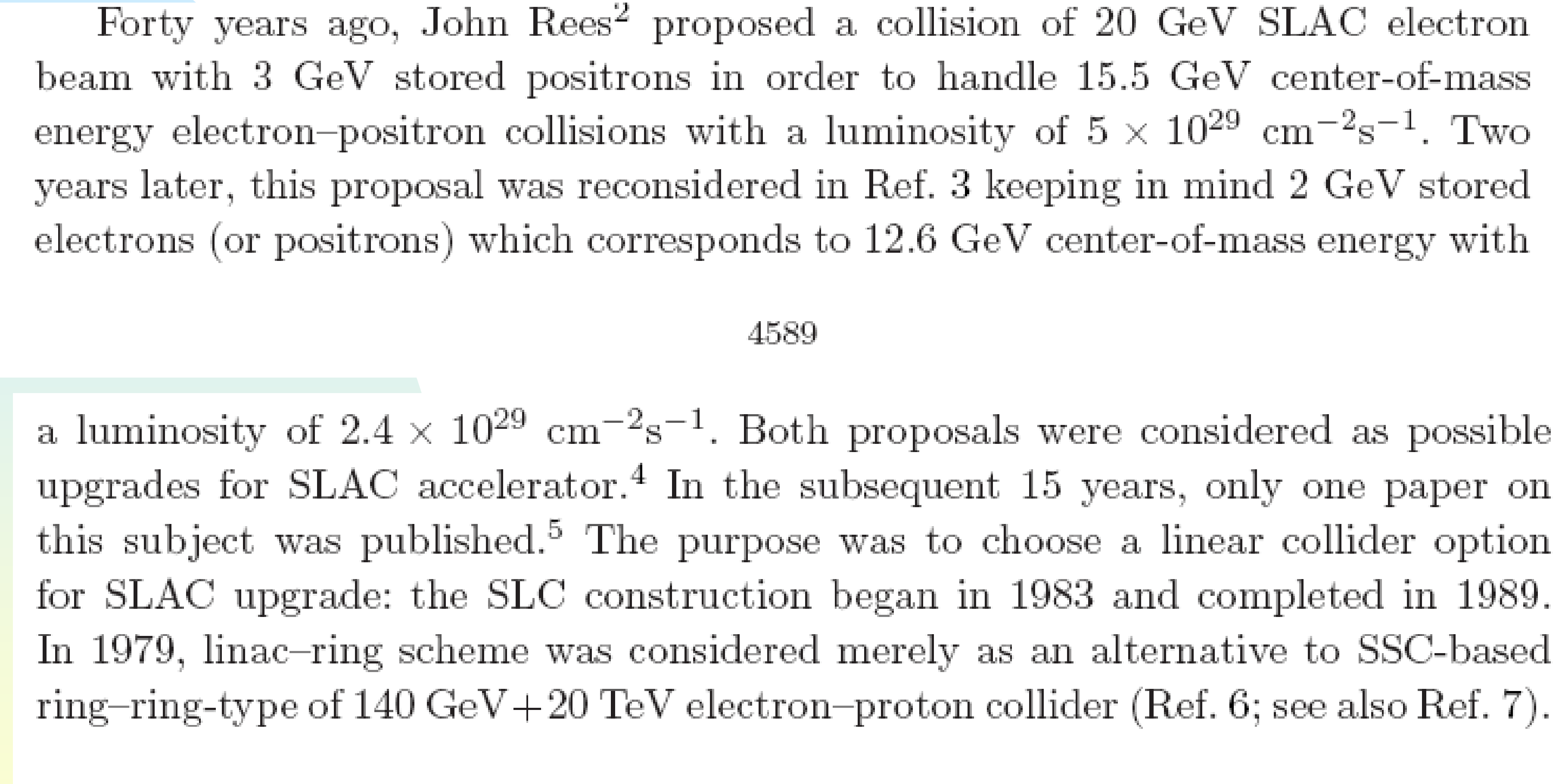
There are three possible types of particle colliders schemes: familiar (well-known) ring–ring colliders, less familiar but sufficiently advanced linear colliders, and less familiar and less advanced linac–ring-type colliders. The aim of this paper is twofold: to present a possibly complete list of papers on linac–ring-type collider proposals and to emphasize the role of linac–ring-type machines for future HEP research.



LC×FCC

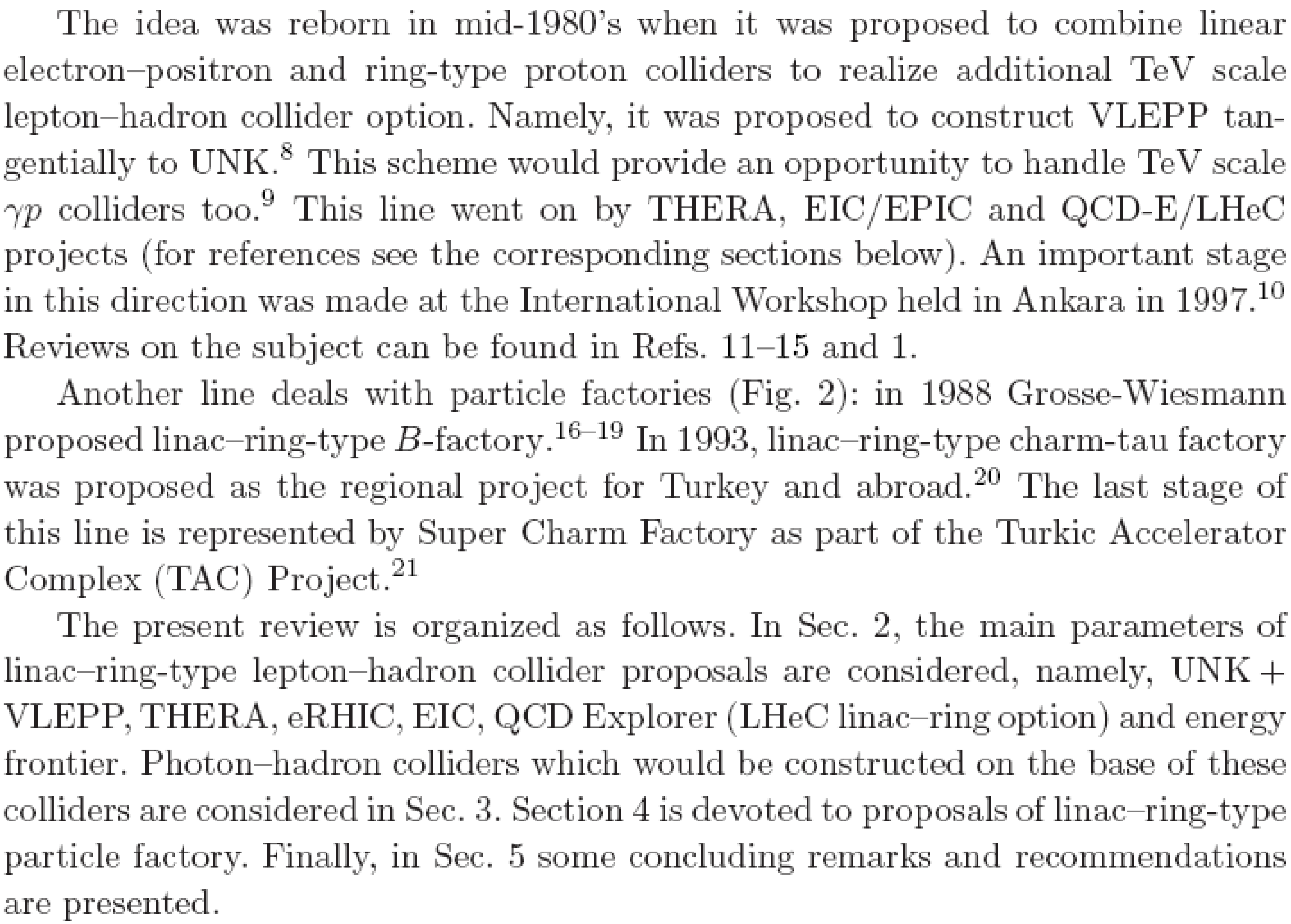
Fig. 1. The development of the resolution power of the experiments exploring the inner structure of matter over time from Rutherford experiment to CLIC ⊗ VLHC.



Forty years ago, John Rees[2] proposed a collision of 20 GeV SLAC electron beam with 3 GeV stored positrons in order to handle 15.5 GeV center-of-mass energy electron–positron collisions with a luminosity of 5×10^{29} cm^{-2}s^{-1}. Two years later, this proposal was reconsidered in Ref. 3 keeping in mind 2 GeV stored electrons (or positrons) which corresponds to 12.6 GeV center-of-mass energy with

4589

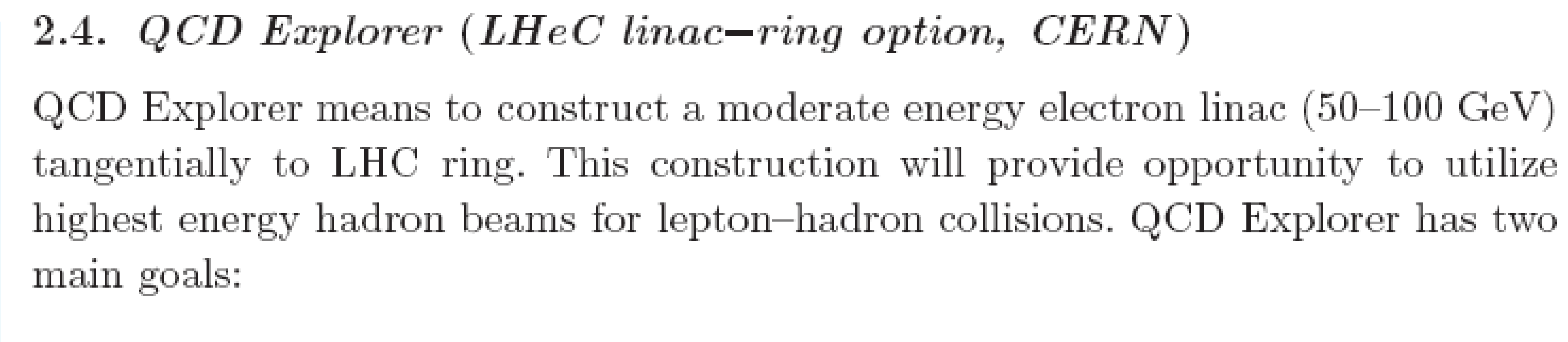
a luminosity of 2.4×10^{29} cm^{-2}s^{-1}. Both proposals were considered as possible upgrades for SLAC accelerator.[4] In the subsequent 15 years, only one paper on this subject was published.[5] The purpose was to choose a linear collider option for SLAC upgrade: the SLC construction began in 1983 and completed in 1989. In 1979, linac–ring scheme was considered merely as an alternative to SSC-based ring–ring-type of 140 GeV+20 TeV electron–proton collider (Ref. 6; see also Ref. 7).



The idea was reborn in mid-1980's when it was proposed to combine linear electron–positron and ring-type proton colliders to realize additional TeV scale lepton–hadron collider option. Namely, it was proposed to construct VLEPP tangentially to UNK.[8] This scheme would provide an opportunity to handle TeV scale γp colliders too.[9] This line went on by THERA, EIC/EPIC and QCD-E/LHeC projects (for references see the corresponding sections below). An important stage in this direction was made at the International Workshop held in Ankara in 1997.[10] Reviews on the subject can be found in Refs. 11–15 and 1.

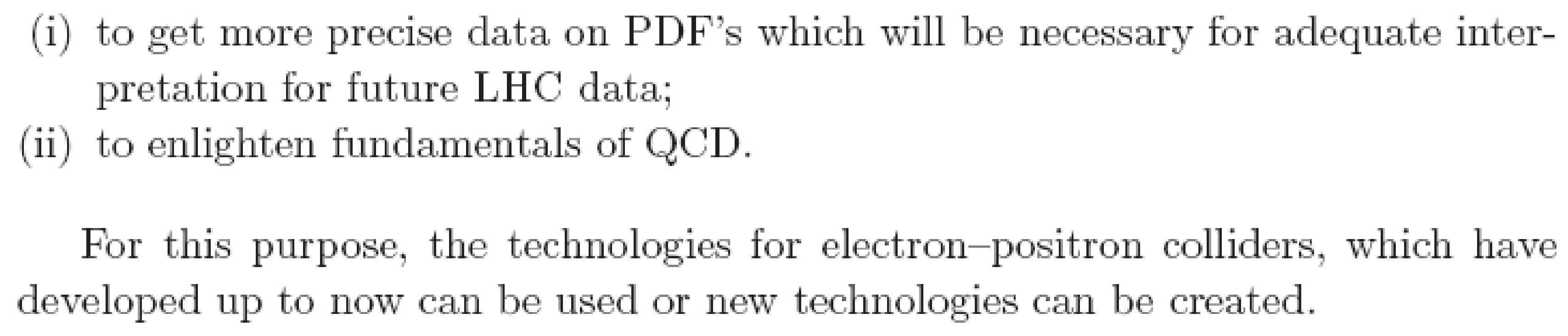
Another line deals with particle factories (Fig. 2): in 1988 Grosse-Wiesmann proposed linac–ring-type B-factory.[16–19] In 1993, linac–ring-type charm-tau factory was proposed as the regional project for Turkey and abroad.[20] The last stage of this line is represented by Super Charm Factory as part of the Turkic Accelerator Complex (TAC) Project.[21]

The present review is organized as follows. In Sec. 2, the main parameters of linac–ring-type lepton–hadron collider proposals are considered, namely, UNK + VLEPP, THERA, eRHIC, EIC, QCD Explorer (LHeC linac–ring option) and energy frontier. Photon–hadron colliders which would be constructed on the base of these colliders are considered in Sec. 3. Section 4 is devoted to proposals of linac–ring-type particle factory. Finally, in Sec. 5 some concluding remarks and recommendations are presented.



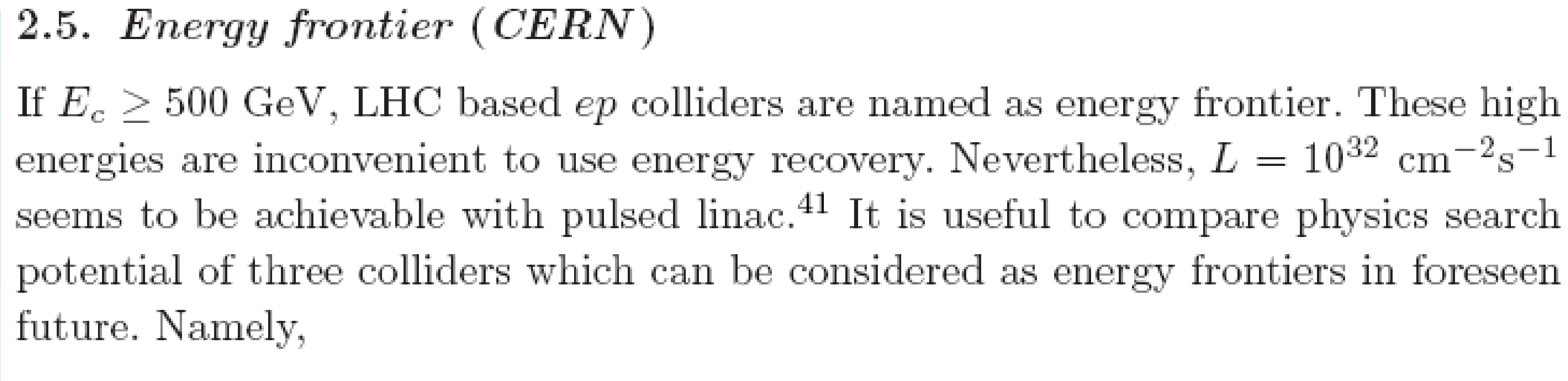
2.4. *QCD Explorer (LHeC linac–ring option, CERN)*

QCD Explorer means to construct a moderate energy electron linac (50–100 GeV) tangentially to LHC ring. This construction will provide opportunity to utilize highest energy hadron beams for lepton–hadron collisions. QCD Explorer has two main goals:



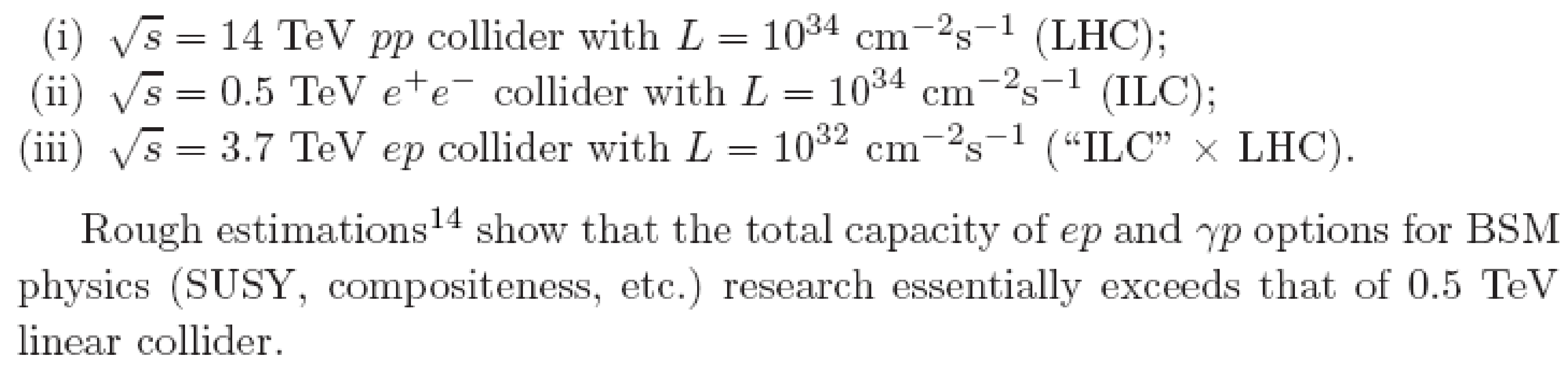
(i) to get more precise data on PDF's which will be necessary for adequate interpretation for future LHC data;
(ii) to enlighten fundamentals of QCD.

For this purpose, the technologies for electron–positron colliders, which have developed up to now can be used or new technologies can be created.



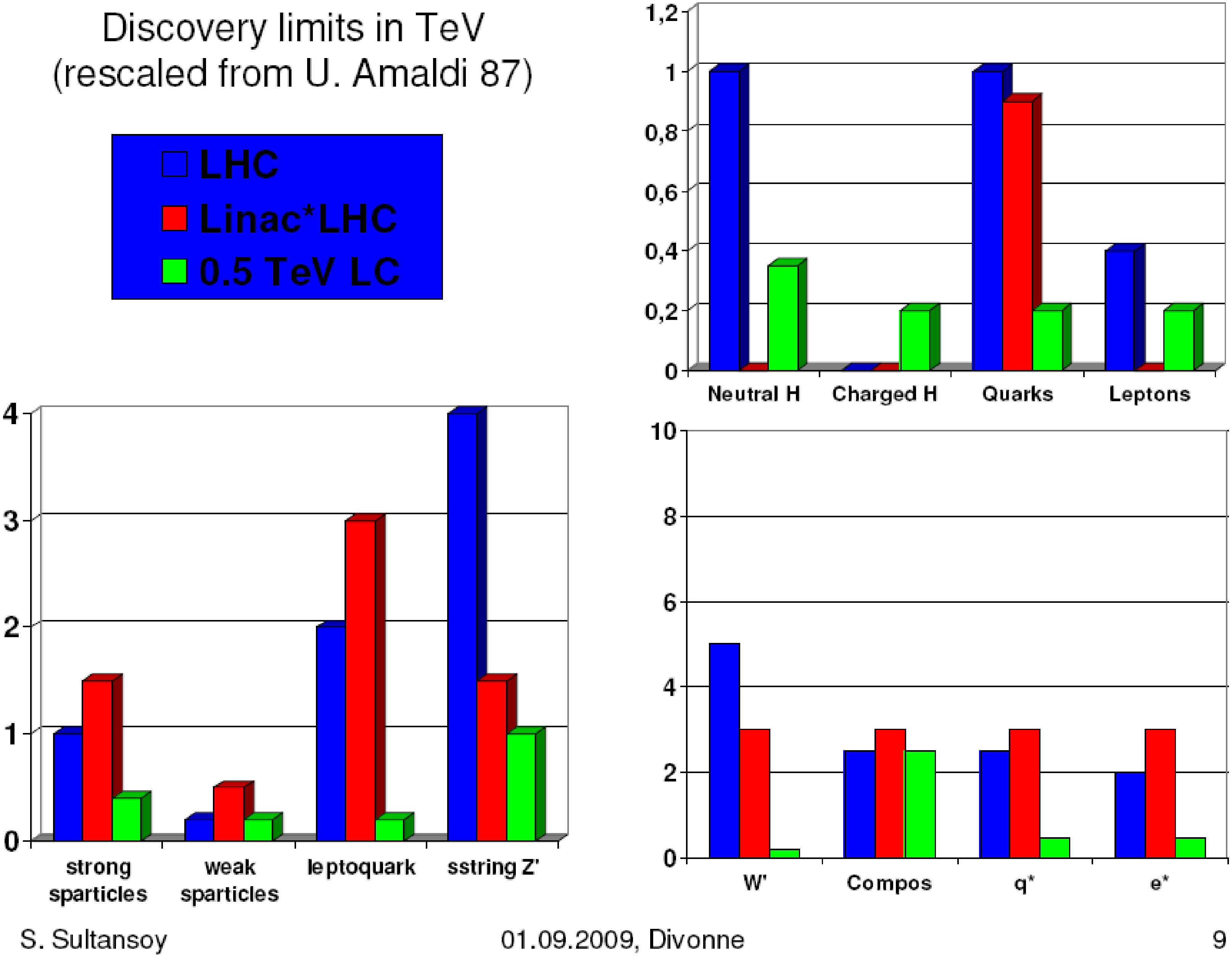
2.5. *Energy frontier (CERN)*

If $E_c \geq 500$ GeV, LHC based *ep* colliders are named as energy frontier. These high energies are inconvenient to use energy recovery. Nevertheless, $L = 10^{32}$ cm^{-2}s^{-1} seems to be achievable with pulsed linac.[41] It is useful to compare physics search potential of three colliders which can be considered as energy frontiers in foreseen future. Namely,



(i) $\sqrt{s} = 14$ TeV *pp* collider with $L = 10^{34}$ cm^{-2}s^{-1} (LHC);
(ii) $\sqrt{s} = 0.5$ TeV e^+e^- collider with $L = 10^{34}$ cm^{-2}s^{-1} (ILC);
(iii) $\sqrt{s} = 3.7$ TeV *ep* collider with $L = 10^{32}$ cm^{-2}s^{-1} (“ILC” × LHC).

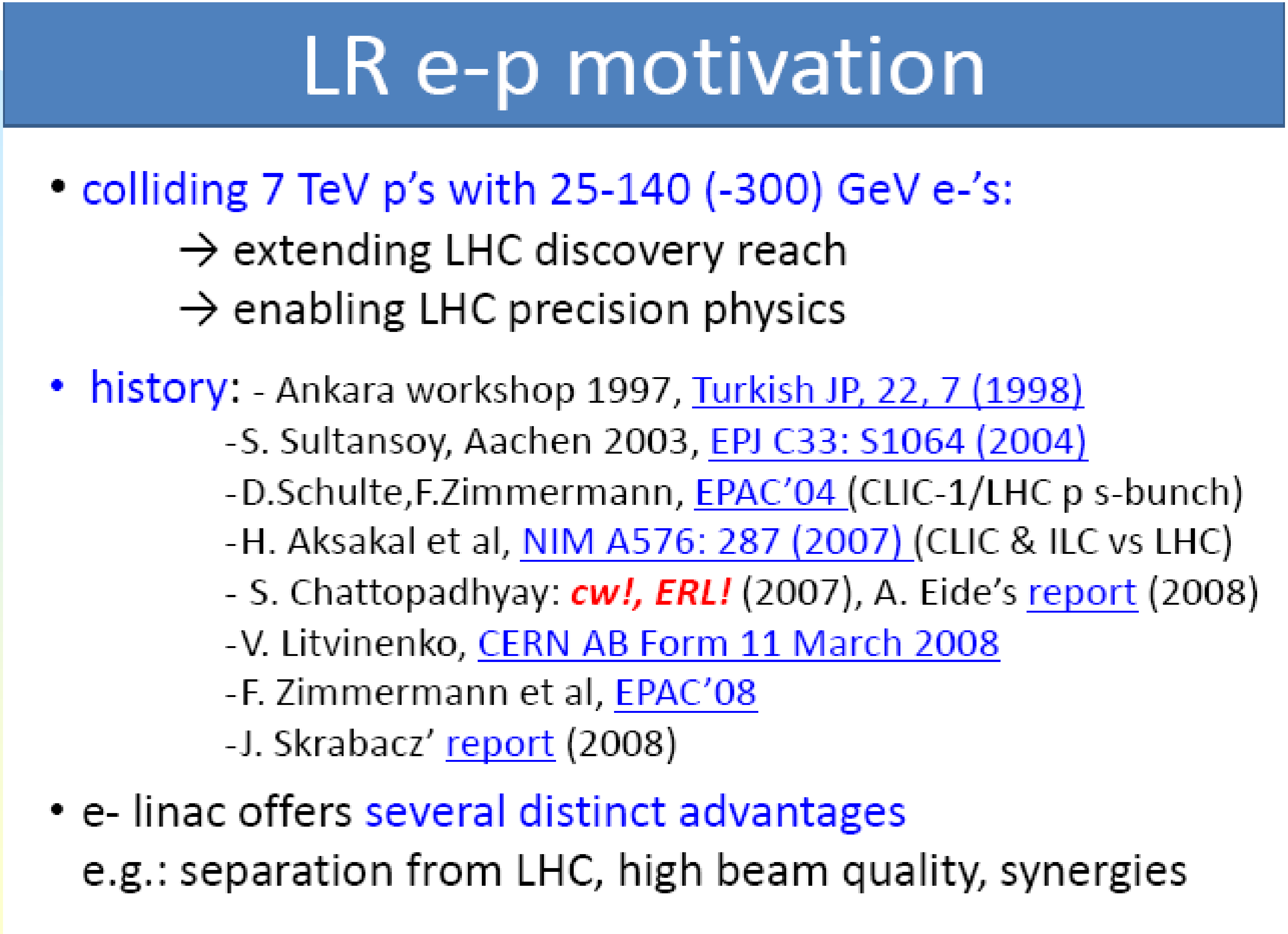
Rough estimations[14] show that the total capacity of *ep* and γp options for BSM physics (SUSY, compositeness, etc.) research essentially exceeds that of 0.5 TeV linear collider.



Discovery limits in TeV (rescaled from U. Amaldi 87)

S. Sultansoy 01.09.2009, Divonne 9

(F. Zimmermann, 1st ECFA-CERN LHeC Workshop, 02.09.2008)

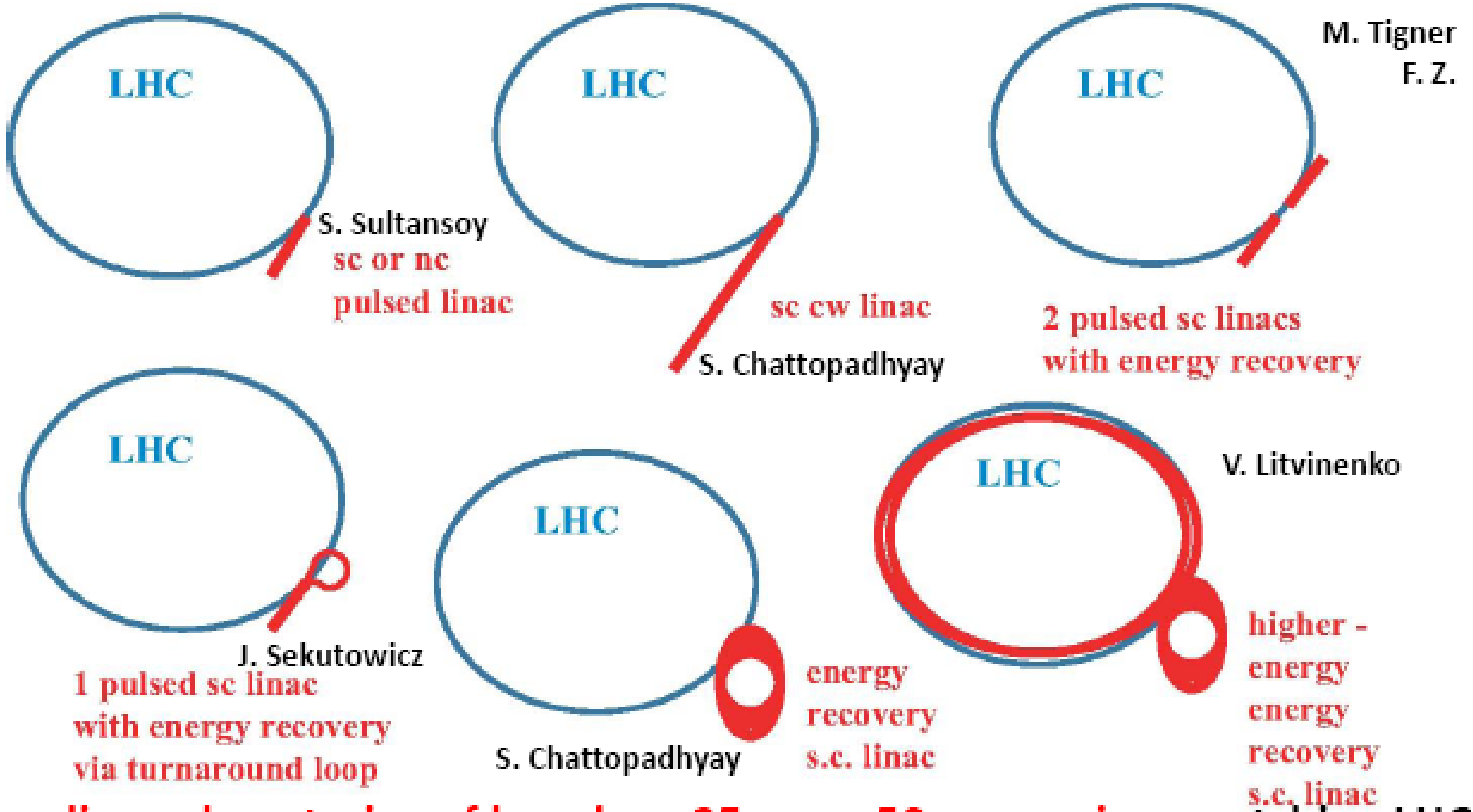


LR e-p motivation

- colliding 7 TeV p's with 25-140 (-300) GeV e-'s:
  - → extending LHC discovery reach
  - → enabling LHC precision physics
- history: - Ankara workshop 1997, Turkish JP, 22, 7 (1998)
  - -S. Sultansoy, Aachen 2003, EPJ C33: S1064 (2004)
  - -D.Schulte,F.Zimmermann, EPAC'04 (CLIC-1/LHC p s-bunch)
  - -H. Aksakal et al, NIM A576: 287 (2007) (CLIC & ILC vs LHC)
  - - S. Chattopadhyay: ***cw!, ERL!*** (2007), A. Eide's report (2008)
  - -V. Litvinenko, CERN AB Form 11 March 2008
  - -F. Zimmermann et al, EPAC'08
  - -J. Skrabacz' report (2008)
- e- linac offers several distinct advantages
  e.g.: separation from LHC, high beam quality, synergies

(F. Zimmermann, 1st ECFA-CERN LHeC Workshop, 02.09.2008)

LR scenarios

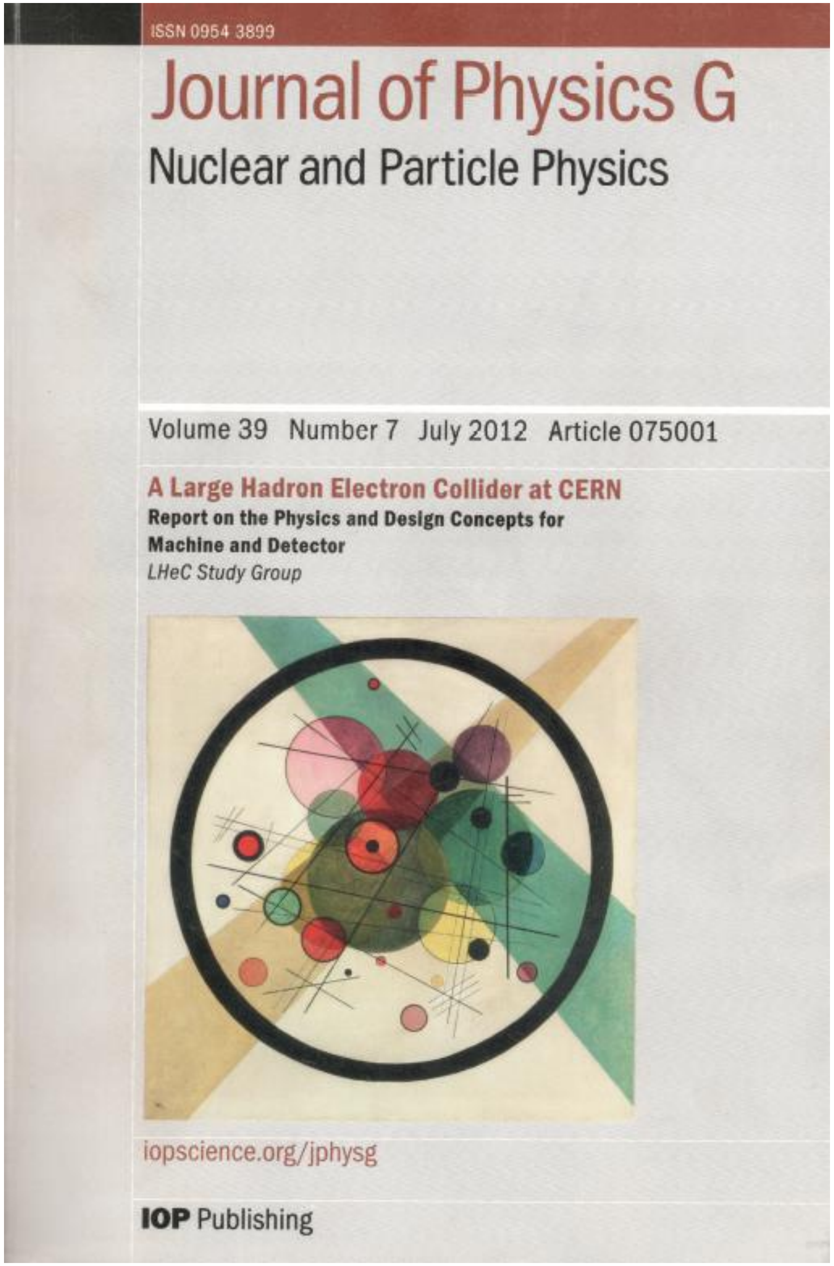


s.c. linac , long trains of bunches, 25-ns or 50-ns spacing, matching LHC p beam (*PLACET: stable*); long pulse or cw → high luminosity; optional energy recovery → higher luminosity; 1.3 GHz (ILC) or 700 MHz (SPL)

LHeC/QCD-E:

A Large Hadron electron Collider at CERN. Webpage:
http://lhec.web.cern.ch/
Mirror site:
http://www.ep.ph.bham.ac.uk/exp/LHeC/

CDR is published in Journal of Physics G: Nuclear and Particle Physics
Volume 39, Number 7, July 2012.



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Nuclear and Particle Physics

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN
Report on the Physics and Design Concepts for Machine and Detector
LHeC Study Group

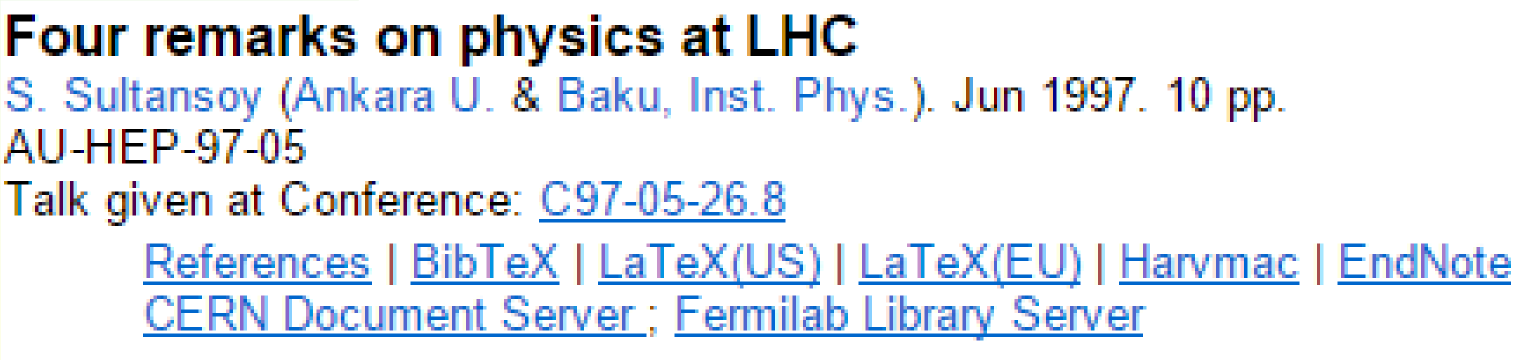
iopscience.org/jphysg

IOP Publishing

Physics

- SM: Triumph and Challenges
- BSM: standard extensions
- BSM: radical extensions
- BSM: «unexpected» new physics

Upgraded from:



Four remarks on physics at LHC

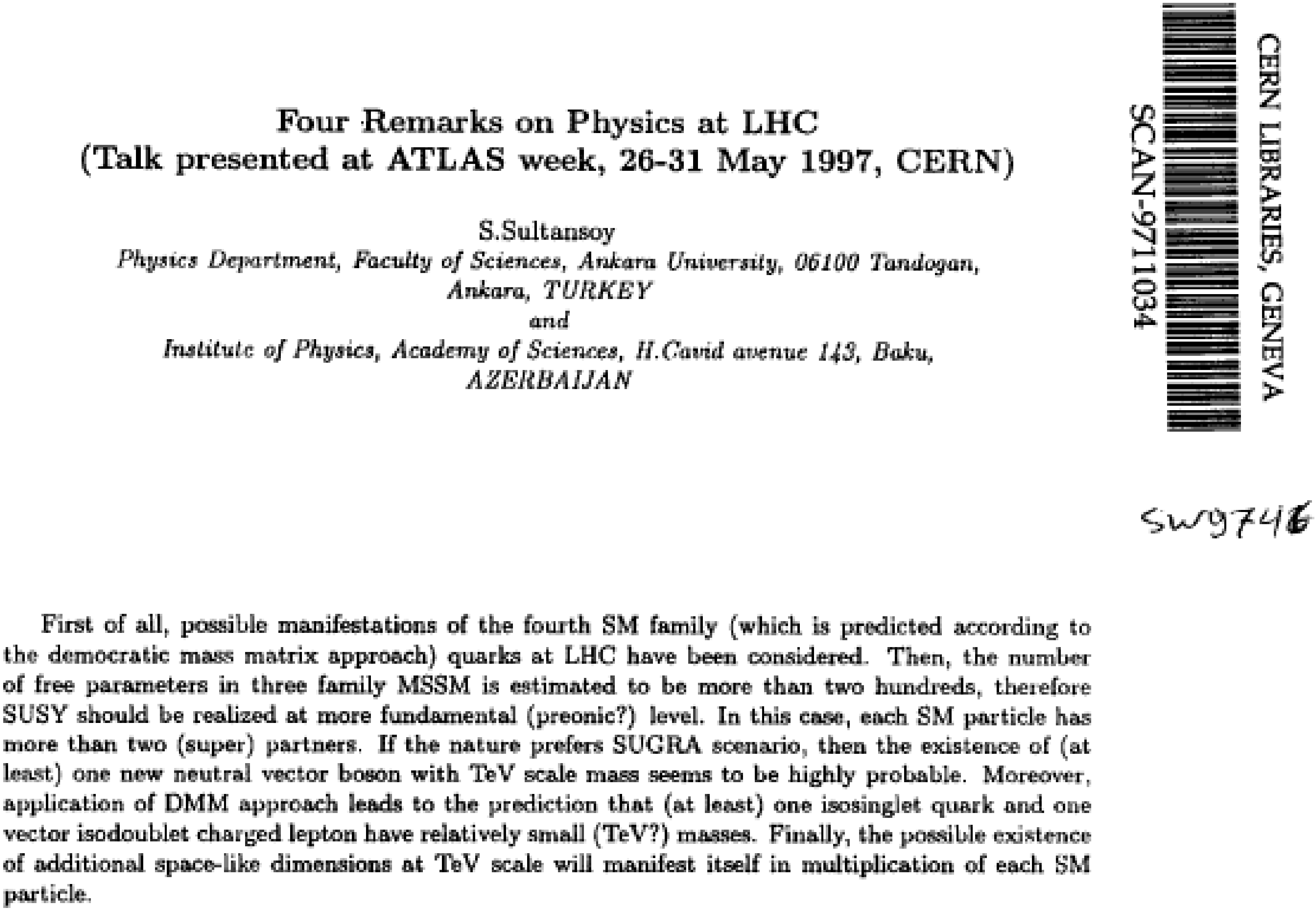
S. Sultansoy (Ankara U. & Baku, Inst. Phys.). Jun 1997. 10 pp.

AU-HEP-97-05

Talk given at Conference: C97-05-26.8

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

CERN Document Server ; Fermilab Library Server



Four Remarks on Physics at LHC
(Talk presented at ATLAS week, 26-31 May 1997, CERN)

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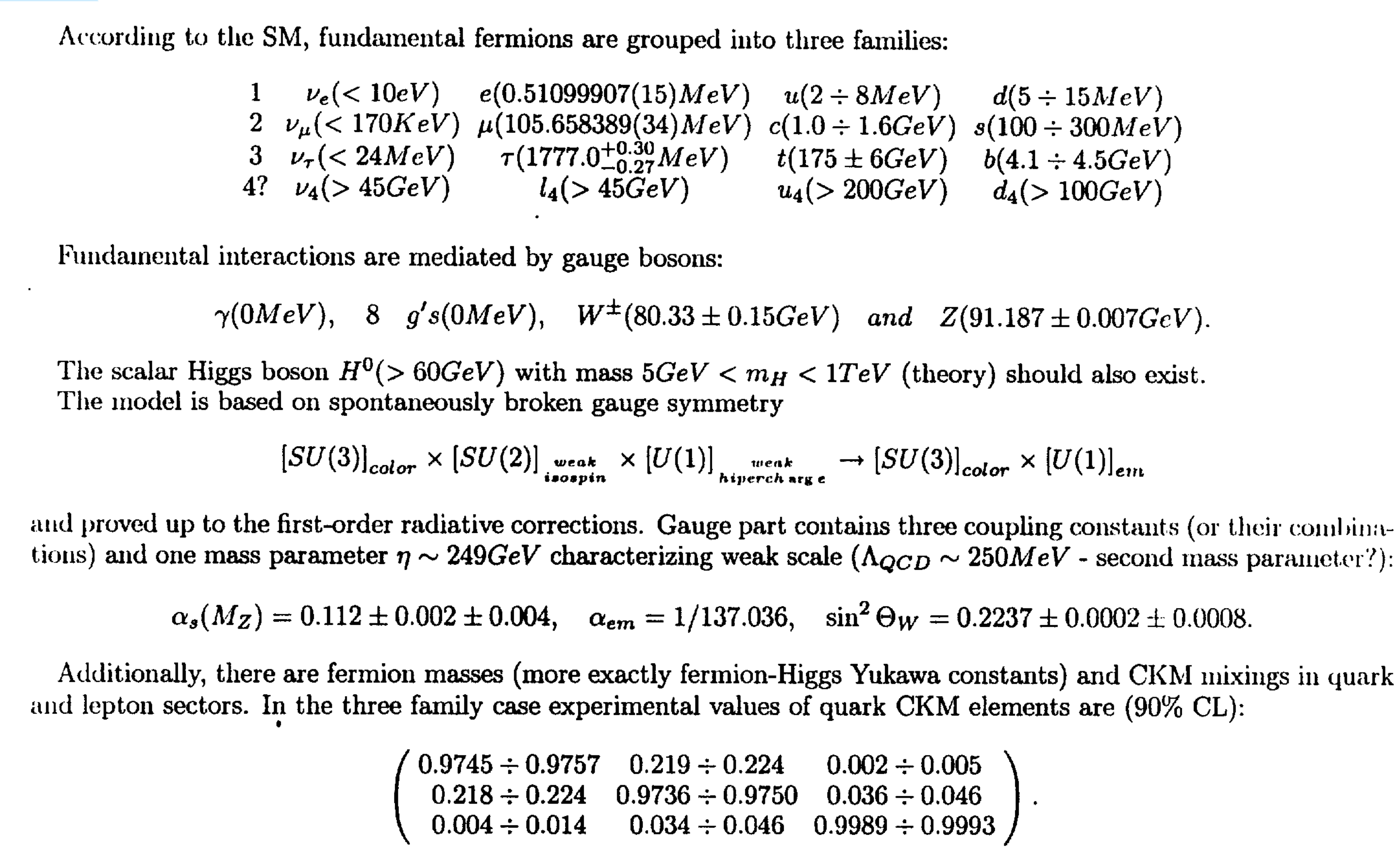
First of all, possible manifestations of the fourth SM family (which is predicted according to the democratic mass matrix approach) quarks at LHC have been considered. Then, the number of free parameters in three family MSSM is estimated to be more than two hundreds, therefore SUSY should be realized at more fundamental (preonic?) level. In this case, each SM particle has more than two (super) partners. If the nature prefers SUGRA scenario, then the existence of (at least) one new neutral vector boson with TeV scale mass seems to be highly probable. Moreover, application of DMM approach leads to the prediction that (at least) one isosinglet quark and one vector isodoublet charged lepton have relatively small (TeV?) masses. Finally, the possible existence of additional space-like dimensions at TeV scale will manifest itself in multiplication of each SM particle.

SM: Triumph and Challenges

Standard Model according PDG 1996



According to the SM, fundamental fermions are grouped into three families:

1	$\nu_e(< 10eV)$	$e(0.51099907(15)MeV)$	$u(2 \div 8MeV)$	$d(5 \div 15MeV)$
2	$\nu_\mu(< 170KeV)$	$\mu(105.658389(34)MeV)$	$c(1.0 \div 1.6GeV)$	$s(100 \div 300MeV)$
3	$\nu_\tau(< 24MeV)$	$\tau(1777.0^{+0.30}_{-0.27}MeV)$	$t(175 \pm 6GeV)$	$b(4.1 \div 4.5GeV)$
4?	$\nu_4(> 45GeV)$	$l_4(> 45GeV)$	$u_4(> 200GeV)$	$d_4(> 100GeV)$

Fundamental interactions are mediated by gauge bosons:

$$\gamma(0MeV), \quad 8 \quad g's(0MeV), \quad W^\pm(80.33 \pm 0.15GeV) \quad and \quad Z(91.187 \pm 0.007GeV).$$

The scalar Higgs boson $H^0(> 60GeV)$ with mass $5GeV < m_H < 1TeV$ (theory) should also exist.
The model is based on spontaneously broken gauge symmetry

$$[SU(3)]_{color} \times [SU(2)]_{\substack{weak\\isospin}} \times [U(1)]_{\substack{weak\\hipercharge}} \rightarrow [SU(3)]_{color} \times [U(1)]_{em}$$

and proved up to the first-order radiative corrections. Gauge part contains three coupling constants (or their combinations) and one mass parameter $\eta \sim 249GeV$ characterizing weak scale ($\Lambda_{QCD} \sim 250MeV$ - second mass parameter?):

$$\alpha_s(M_Z) = 0.112 \pm 0.002 \pm 0.004, \quad \alpha_{em} = 1/137.036, \quad \sin^2\Theta_W = 0.2237 \pm 0.0002 \pm 0.0008.$$

Additionally, there are fermion masses (more exactly fermion-Higgs Yukawa constants) and CKM mixings in quark and lepton sectors. In the three family case experimental values of quark CKM elements are (90% CL):

$$\begin{pmatrix} 0.9745 \div 0.9757 & 0.219 \div 0.224 & 0.002 \div 0.005 \\ 0.218 \div 0.224 & 0.9736 \div 0.9750 & 0.036 \div 0.046 \\ 0.004 \div 0.014 & 0.034 \div 0.046 & 0.9989 \div 0.9993 \end{pmatrix}.$$

Periodic Table of the Elementary* Particles

family	ν *(direct)*	***l***	***u***	***d***
1	**< 2 eV**	**510.998928(11) keV**	**1.8 to 3.0 MeV**	**4,5 to 5.3 MeV**
2	**< 190 keV**	**105.6583715(35) MeV**	**1.275(25) GeV**	**95(5) MeV**
3	**< 18.2 MeV**	**1.77686(12) GeV**	**173.21(1.22) GeV**	**4.18(3) GeV**
4	**> 39.5 GeV**	**> 100 GeV**	**> 700 GeV**	**> 675 GeV**

Also,

$m_\gamma = 0$ ($< 10^{-18}$ eV)

$m_g = 0$ (< few MeV)

$m_W = 80.385(15)$ GeV

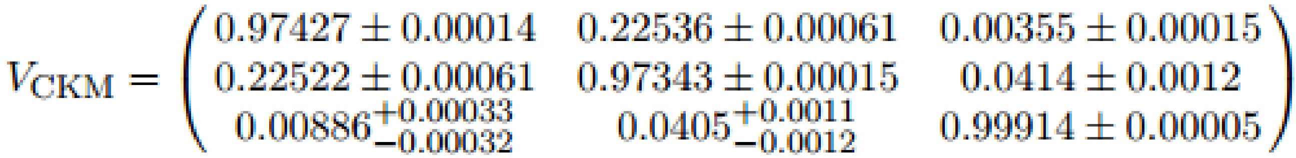
$m_Z = 91.1876(21)$ GeV

$m_H = 125.09 \pm 0.24$ GeV

PDG 2014

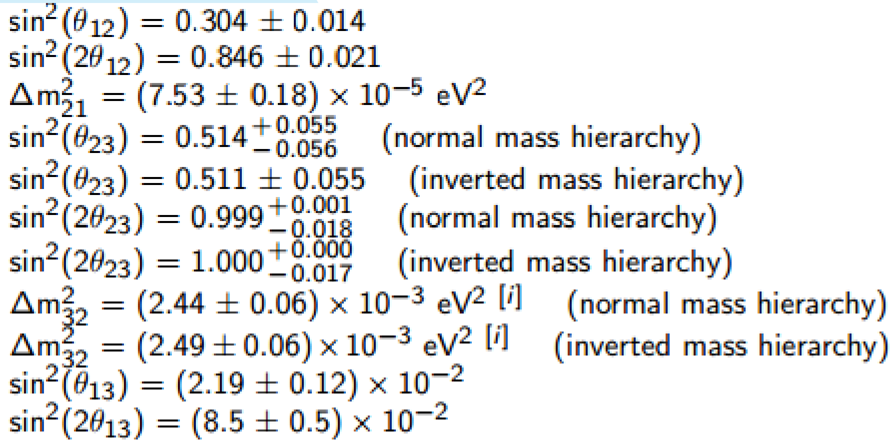
Scale: $\eta \approx 247$ GeV

* *Elementary in the SM framework. At least one more level (preons) should exist.*



$$V_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00014 & 0.22536 \pm 0.00061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{pmatrix}$$

Neutrino mixings



$\sin^2(\theta_{12}) = 0.304 \pm 0.014$

$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2

$\sin^2(\theta_{23}) = 0.514^{+0.055}_{-0.056}$ (normal mass hierarchy)

$\sin^2(\theta_{23}) = 0.511 \pm 0.055$ (inverted mass hierarchy)

$\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$ (normal mass hierarchy)

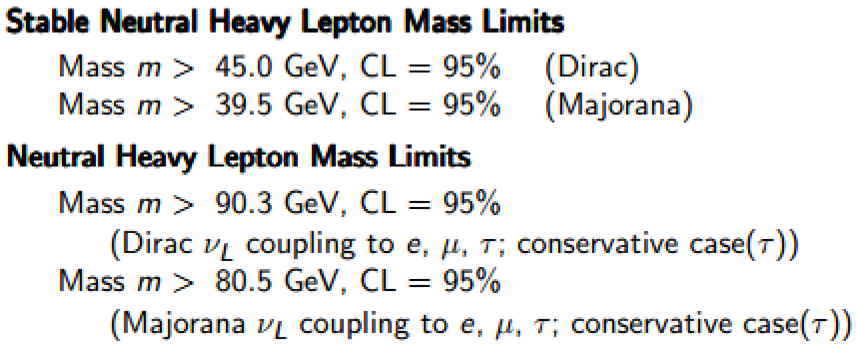
$\sin^2(2\theta_{23}) = 1.000^{+0.000}_{-0.017}$ (inverted mass hierarchy)

$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}$ eV^2 [i] (normal mass hierarchy)

$\Delta m^2_{32} = (2.49 \pm 0.06) \times 10^{-3}$ eV^2 [i] (inverted mass hierarchy)

$\sin^2(\theta_{13}) = (2.19 \pm 0.12) \times 10^{-2}$

$\sin^2(2\theta_{13}) = (8.5 \pm 0.5) \times 10^{-2}$



Stable Neutral Heavy Lepton Mass Limits

Mass $m >$ 45.0 GeV, CL = 95% (Dirac)

Mass $m >$ 39.5 GeV, CL = 95% (Majorana)

Neutral Heavy Lepton Mass Limits

Mass $m >$ 90.3 GeV, CL = 95%

(Dirac ν_L coupling to e, μ, τ; conservative case(τ))

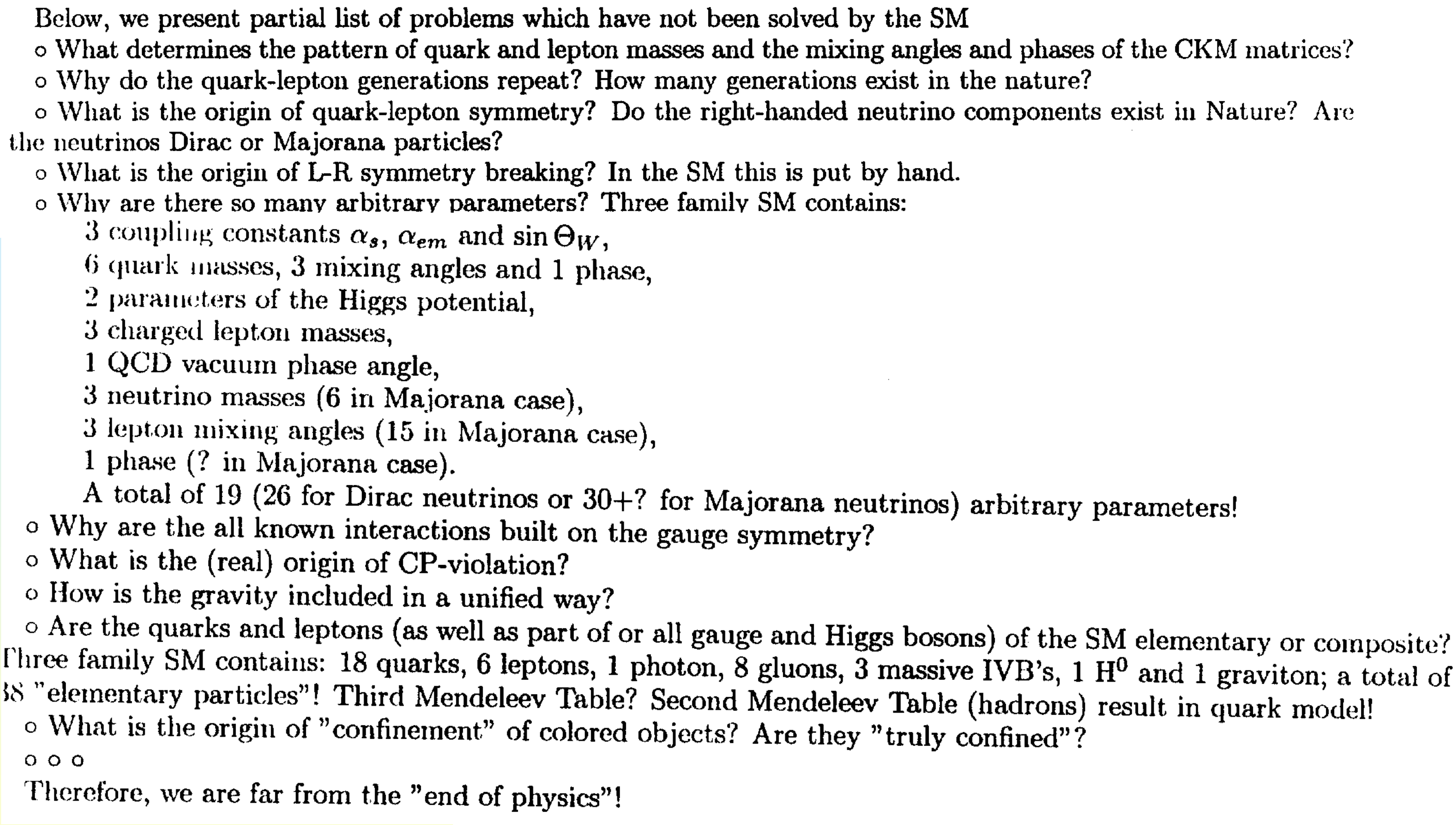
Mass $m >$ 80.5 GeV, CL = 95%

(Majorana ν_L coupling to e, μ, τ; conservative case(τ))

We wonder why **m_H = 125 GeV?**

But do not worry on accidental values of SM fermion masses and mixings …; i.e. **m(e)/m(t) ~ 10^{-5}**

Unanswered Questions



Below, we present partial list of problems which have not been solved by the SM

- What determines the pattern of quark and lepton masses and the mixing angles and phases of the CKM matrices?
- Why do the quark-lepton generations repeat? How many generations exist in the nature?
- What is the origin of quark-lepton symmetry? Do the right-handed neutrino components exist in Nature? Are the neutrinos Dirac or Majorana particles?
- What is the origin of L-R symmetry breaking? In the SM this is put by hand.
- Why are there so many arbitrary parameters? Three family SM contains:

  3 coupling constants α_s, α_{em} and $\sin\Theta_W$,
  6 quark masses, 3 mixing angles and 1 phase,
  2 parameters of the Higgs potential,
  3 charged lepton masses,
  1 QCD vacuum phase angle,
  3 neutrino masses (6 in Majorana case),
  3 lepton mixing angles (15 in Majorana case),
  1 phase (? in Majorana case).
  A total of 19 (26 for Dirac neutrinos or 30+? for Majorana neutrinos) arbitrary parameters!
- Why are the all known interactions built on the gauge symmetry?
- What is the (real) origin of CP-violation?
- How is the gravity included in a unified way?
- Are the quarks and leptons (as well as part of or all gauge and Higgs bosons) of the SM elementary or composite? Three family SM contains: 18 quarks, 6 leptons, 1 photon, 8 gluons, 3 massive IVB's, 1 H^0 and 1 graviton; a total of 38 "elementary particles"! Third Mendeleev Table? Second Mendeleev Table (hadrons) result in quark model!
- What is the origin of "confinement" of colored objects? Are they "truly confined"?

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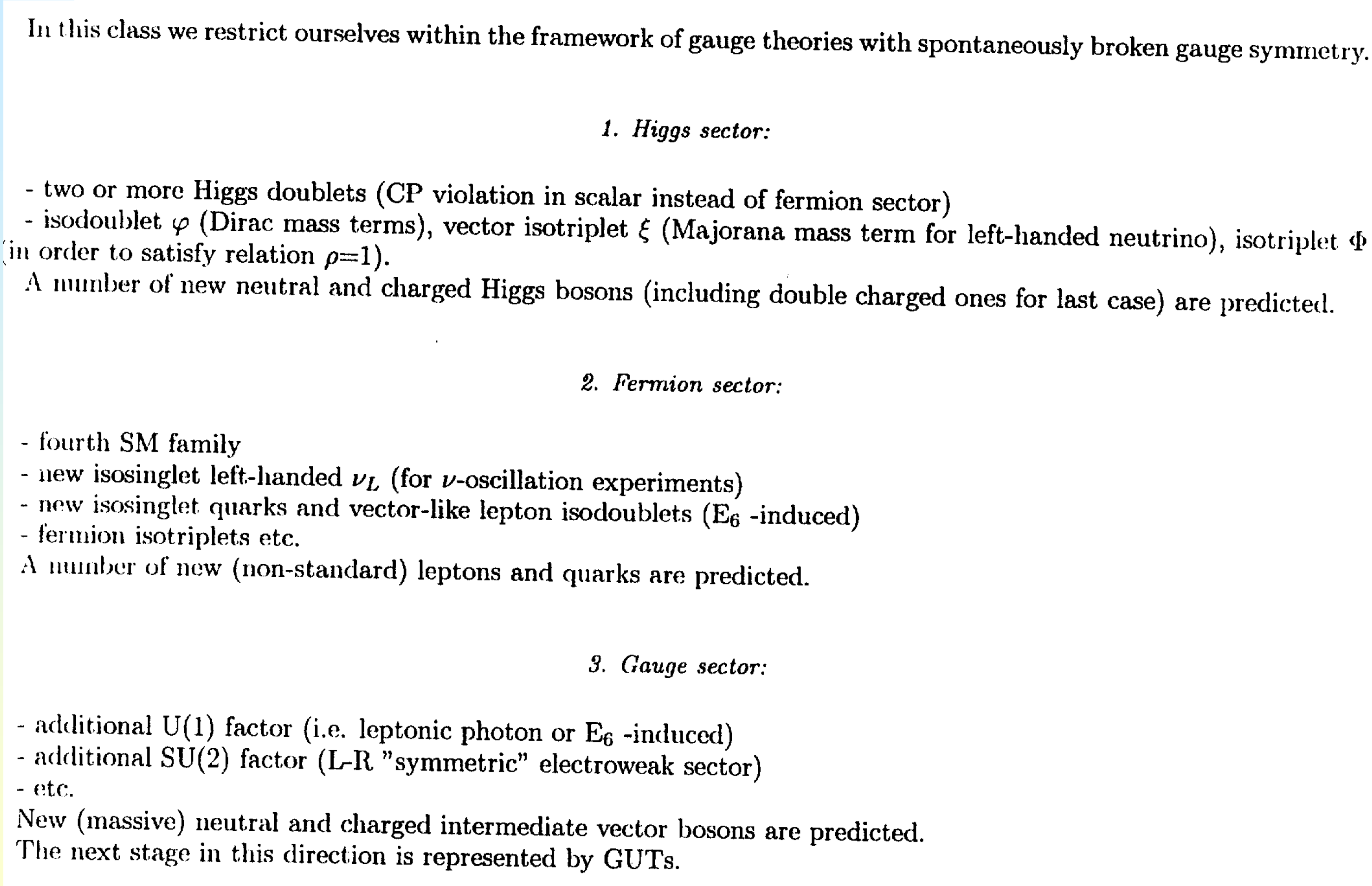
Therefore, we are far from the "end of physics"!

Standard extensions of the Standard Model



In this class we restrict ourselves within the framework of gauge theories with spontaneously broken gauge symmetry.

1. Higgs sector:

- two or more Higgs doublets (CP violation in scalar instead of fermion sector)
- isodoublet φ (Dirac mass terms), vector isotriplet ξ (Majorana mass term for left-handed neutrino), isotriplet Φ (in order to satisfy relation ρ=1).

A number of new neutral and charged Higgs bosons (including double charged ones for last case) are predicted.

2. Fermion sector:

- fourth SM family
- new isosinglet left-handed ν_L (for ν-oscillation experiments)
- new isosinglet quarks and vector-like lepton isodoublets (E_6 -induced)
- fermion isotriplets etc.

A number of new (non-standard) leptons and quarks are predicted.

3. Gauge sector:

- additional U(1) factor (i.e. leptonic photon or E_6 -induced)
- additional SU(2) factor (L-R "symmetric" electroweak sector)
- etc.

New (massive) neutral and charged intermediate vector bosons are predicted.
The next stage in this direction is represented by GUTs.

Radical extensions of the Standard Model

This class includes two well-known directions: Compositness and SUSY.

1. Compositness:

- composite Higgs
- composite quarks and leptons
- composite W and Z
- composite γ and g's ?

A number of new exotic particles (leptoquarks, leptogluons, exited fermions and bosons etc.) and interactions (including residual ones) are predicted.

2. SUSY:

- three family MSSM
- four family MSSM
- SUSY GUTs
- SUGRA

Spectrum of fundamental particles is enriched with inclusion of superpartners.

3. "Unexpected" new physics

- new space-time dimensions
- ?

All extensions (with exceptions of minimal SU(5) and SO(10) GUTs) predict a rich spectrum of new particles and/or interactions at TeV scale. Therefore an exploration of this region will require all possible types of colliding beams.

Today

Minimal SM4 is excluded by Higgs data. However, SM4 with extended Higgs sector is not excluded. Therefore, LHC should continue the search for fourth family quarks and leptons

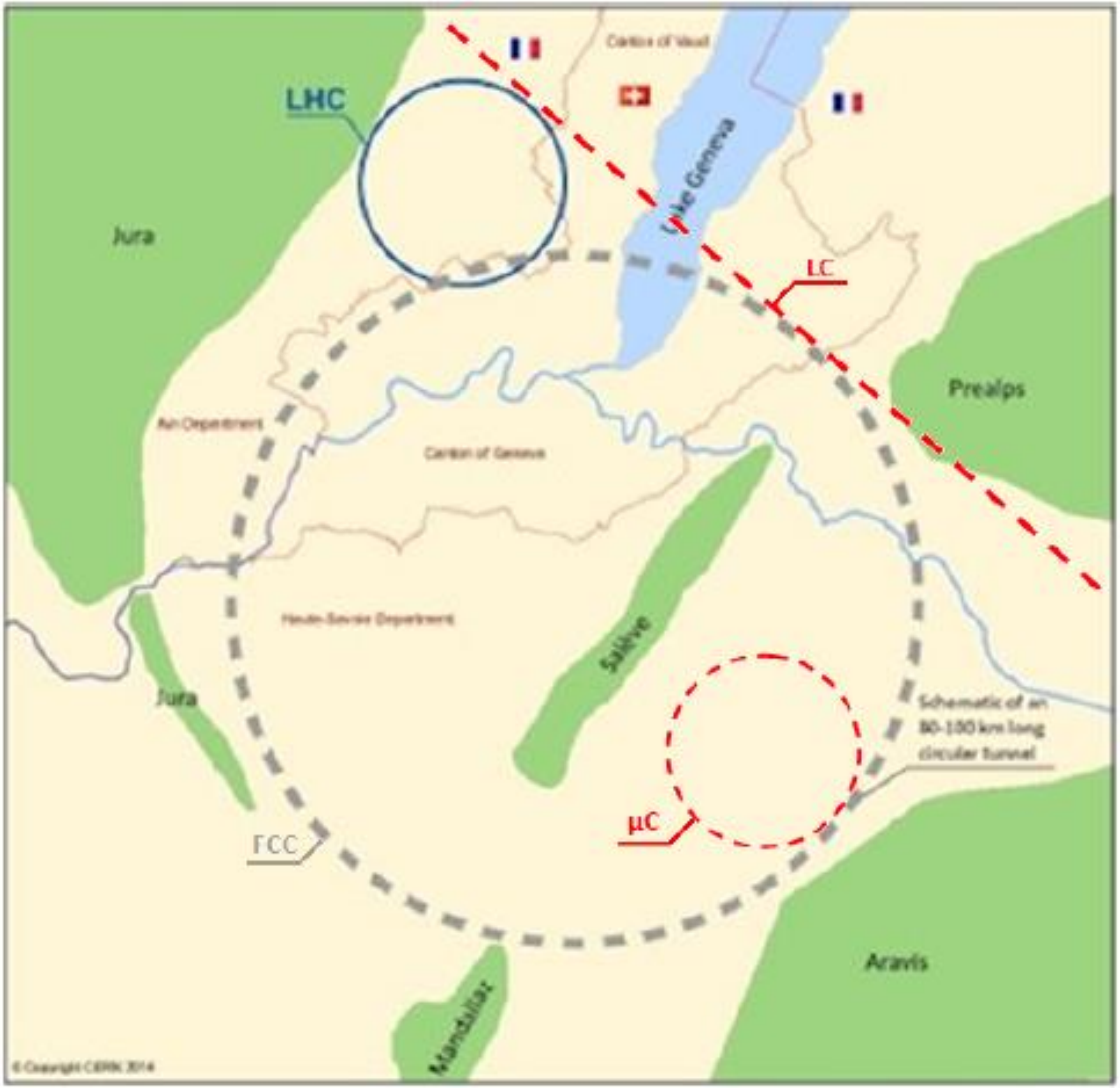
New space-time dimensions (as well as mini black holes) became rutine part of the LHC research program

MSSM3 is almost excluded by the LHC data. It should be noted that it includes more than 200 free parameters (extremely large price for solving hiyerarchy problem). It is the time to turn to SUSY at preonic level…

Possible indications of BSM physics:

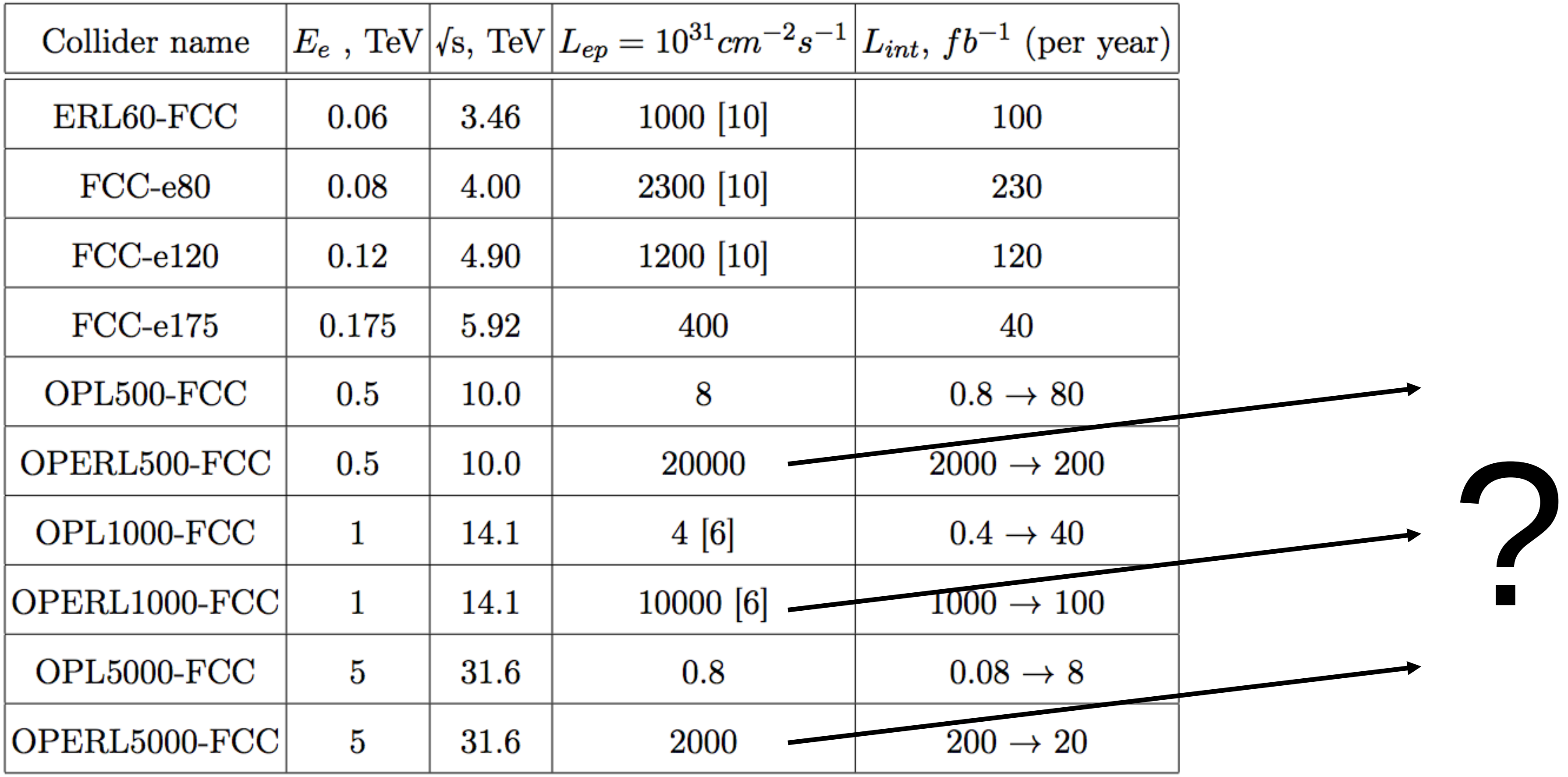
- IceCube PeV neutrino events
- LHC excess at m($\gamma\gamma$)$\sim$750 GeV (seen by ATLAS, but CMS?)

FCC based
ep, eA,
µp, µA,
γp, γA
and FEL γA
colliders



FCC Based ep Colliders **arXiv:1510.08284** **[hep-ex]**

Table III: Main parameters of the FCC based *ep* colliders



Collider name	E_e , TeV	$\sqrt{s}$, TeV	$L_{ep} = 10^{31} cm^{-2} s^{-1}$	L_{int}, fb^{-1} (per year)
ERL60-FCC	0.06	3.46	1000 [10]	100
FCC-e80	0.08	4.00	2300 [10]	230
FCC-e120	0.12	4.90	1200 [10]	120
FCC-e175	0.175	5.92	400	40
OPL500-FCC	0.5	10.0	8	0.8 → 80
OPERL500-FCC	0.5	10.0	20000	2000 → 200
OPL1000-FCC	1	14.1	4 [6]	0.4 → 40
OPERL1000-FCC	1	14.1	10000 [6]	1000 → 100
OPL5000-FCC	5	31.6	0.8	0.08 → 8
OPERL5000-FCC	5	31.6	2000	200 → 20

[10] F. Zimmermann, "Challenges for Highest Energy Circular Colliders", KEK Accelerator Seminar, 31 July 2014, Tsukuba, Japan.

[6] U. Kaya, M. Sahin, S. Sultansoy, "Majorana Neutrino and WR at TeV scale ep Colliders", (2015), arXiv:1502.04115v2[hep-ph].

FCC Based μp Colliders arXiv:1510.08284 **[hep-ex]**

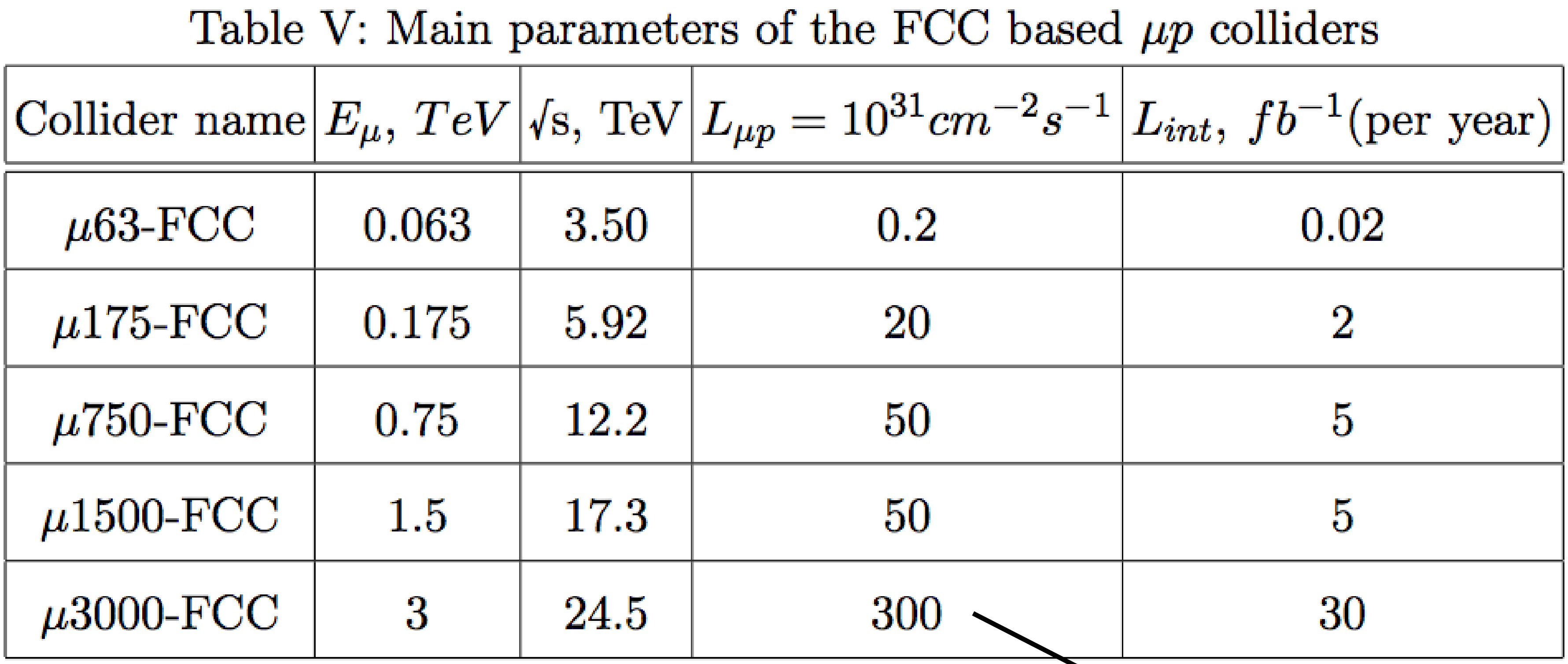


Table V: Main parameters of the FCC based μp colliders

Collider name	E_μ, TeV	$\sqrt{s}$, TeV	$L_{\mu p} = 10^{31} cm^{-2} s^{-1}$	L_{int}, fb^{-1}(per year)
μ63-FCC	0.063	3.50	0.2	0.02
μ175-FCC	0.175	5.92	20	2
μ750-FCC	0.75	12.2	50	5
μ1500-FCC	1.5	17.3	50	5
μ3000-FCC	3	24.5	300	30

?

ILC x FCC ep colliders

arXiv:1602.03089 [physics.acc-ph]

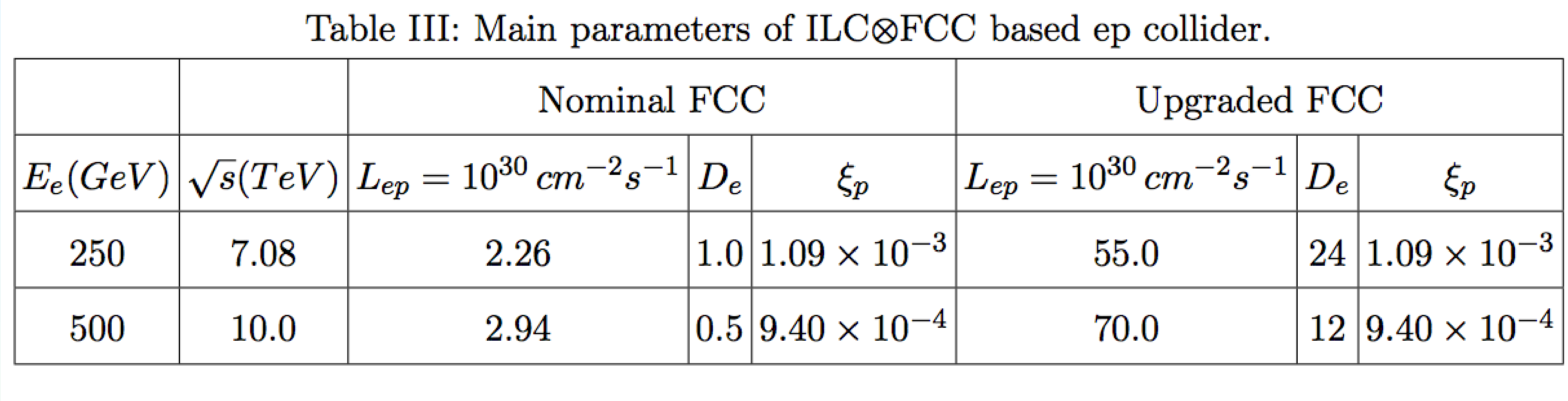


Table III: Main parameters of ILC⊗FCC based ep collider.

		Nominal FCC			Upgraded FCC		
$E_e(GeV)$	$\sqrt{s}(TeV)$	$L_{ep}=10^{30}\,cm^{-2}s^{-1}$	D_e	ξ_p	$L_{ep}=10^{30}\,cm^{-2}s^{-1}$	D_e	ξ_p
250	7.08	2.26	1.0	1.09×10^{-3}	55.0	24	1.09×10^{-3}
500	10.0	2.94	0.5	9.40×10^{-4}	70.0	12	9.40×10^{-4}

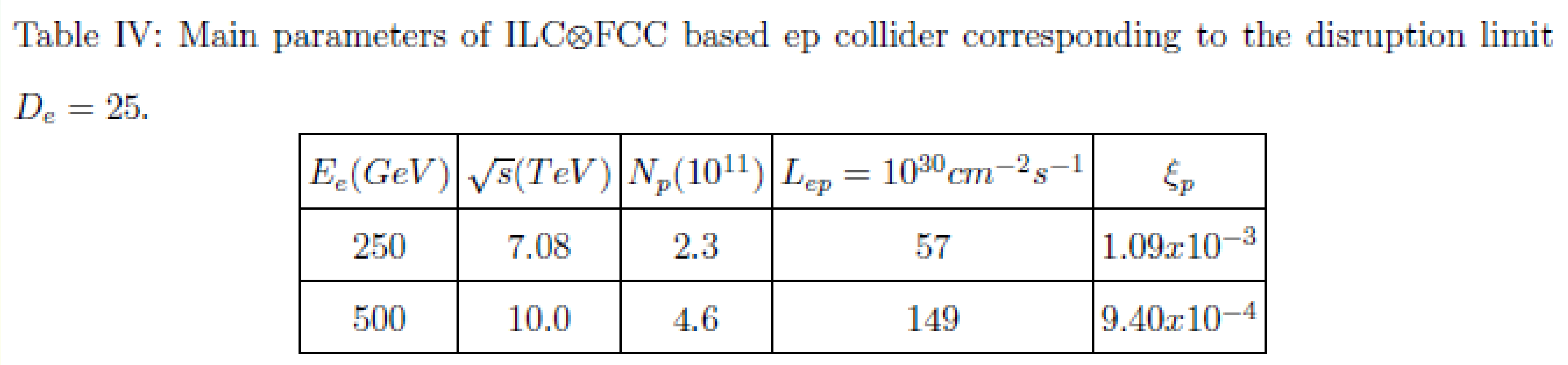


Table IV: Main parameters of ILC⊗FCC based ep collider corresponding to the disruption limit $D_e=25$.

$E_e(GeV)$	$\sqrt{s}(TeV)$	$N_p(10^{11})$	$L_{ep}=10^{30}cm^{-2}s^{-1}$	ξ_p
250	7.08	2.3	57	$1.09x10^{-3}$
500	10.0	4.6	149	$9.40x10^{-4}$

PWFA-LC x FCC ep colliders

arXiv:1602.03089 [physics.acc-ph]

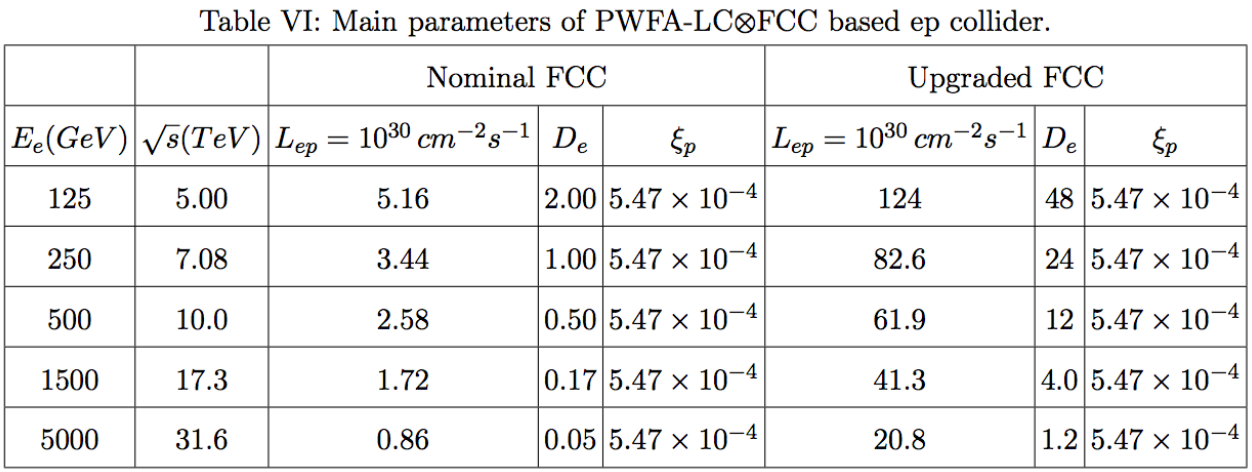


Table VI: Main parameters of PWFA-LC⊗FCC based ep collider.

		Nominal FCC			Upgraded FCC		
$E_e(GeV)$	$\sqrt{s}(TeV)$	$L_{ep} = 10^{30}\, cm^{-2}s^{-1}$	D_e	ξ_p	$L_{ep} = 10^{30}\, cm^{-2}s^{-1}$	D_e	ξ_p
125	5.00	5.16	2.00	5.47×10^{-4}	124	48	5.47×10^{-4}
250	7.08	3.44	1.00	5.47×10^{-4}	82.6	24	5.47×10^{-4}
500	10.0	2.58	0.50	5.47×10^{-4}	61.9	12	5.47×10^{-4}
1500	17.3	1.72	0.17	5.47×10^{-4}	41.3	4.0	5.47×10^{-4}
5000	31.6	0.86	0.05	5.47×10^{-4}	20.8	1.2	5.47×10^{-4}

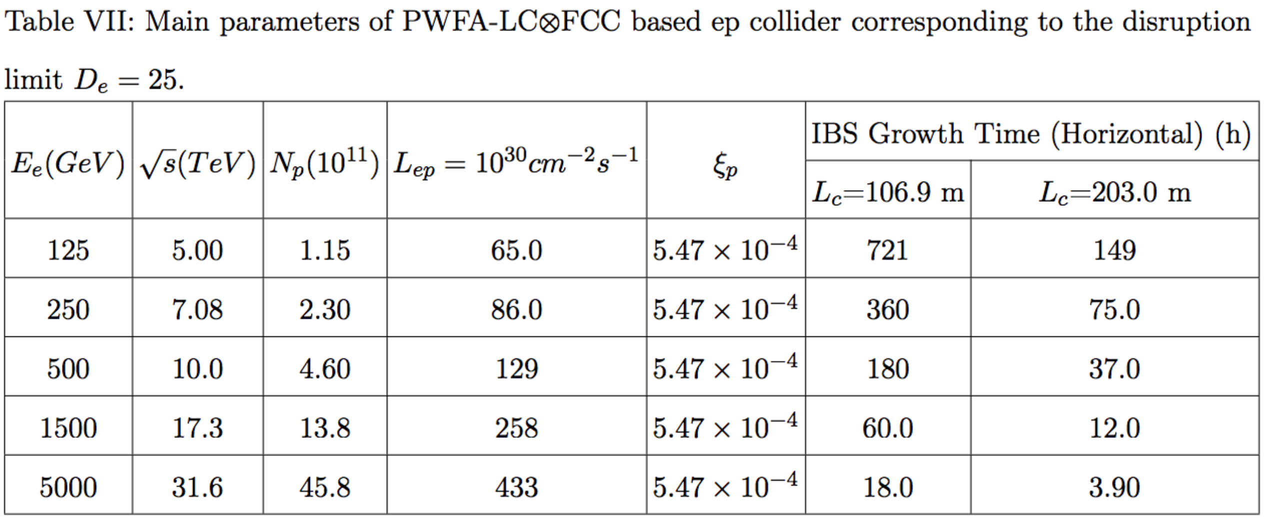
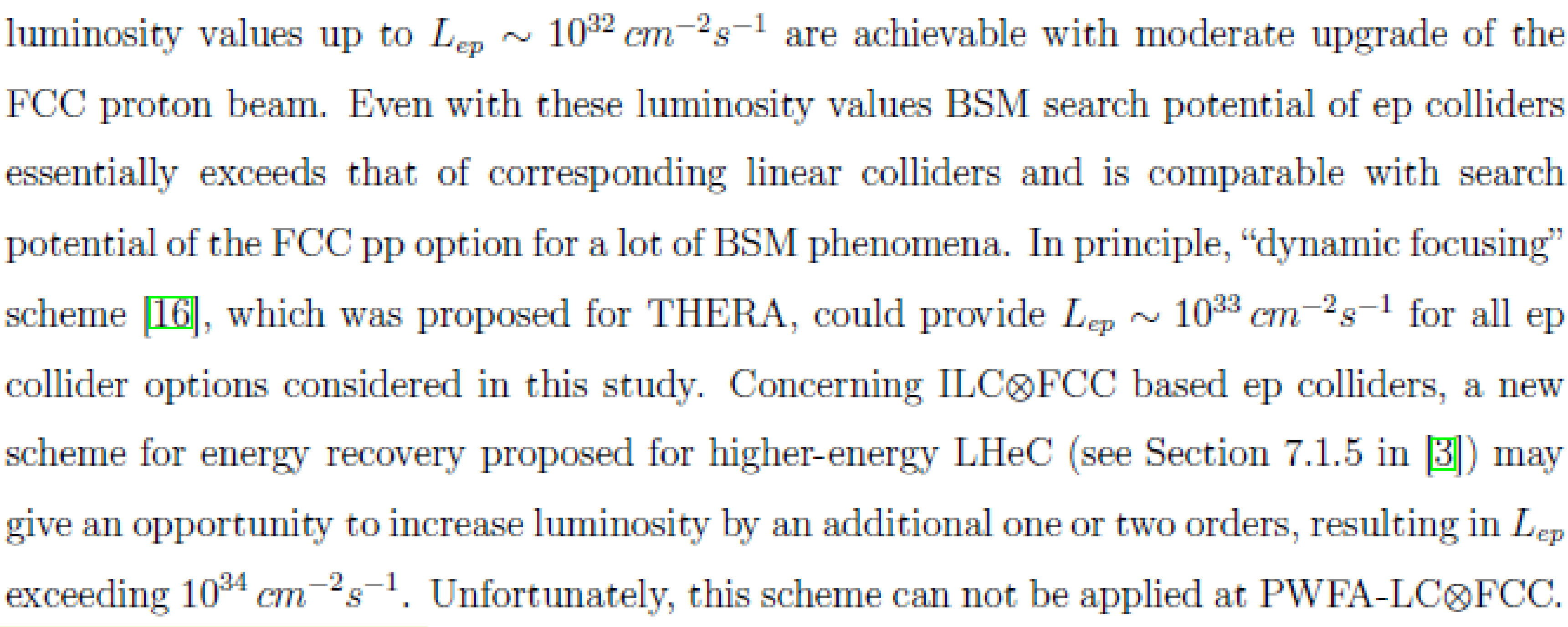


Table VII: Main parameters of PWFA-LC⊗FCC based ep collider corresponding to the disruption limit $D_e = 25$.

$E_e(GeV)$	$\sqrt{s}(TeV)$	$N_p(10^{11})$	$L_{ep} = 10^{30}cm^{-2}s^{-1}$	ξ_p	IBS Growth Time (Horizontal) (h)	
					L_c=106.9 m	L_c=203.0 m
125	5.00	1.15	65.0	5.47×10^{-4}	721	149
250	7.08	2.30	86.0	5.47×10^{-4}	360	75.0
500	10.0	4.60	129	5.47×10^{-4}	180	37.0
1500	17.3	13.8	258	5.47×10^{-4}	60.0	12.0
5000	31.6	45.8	433	5.47×10^{-4}	18.0	3.90

arXiv:1602.03089 [physics.acc-ph]

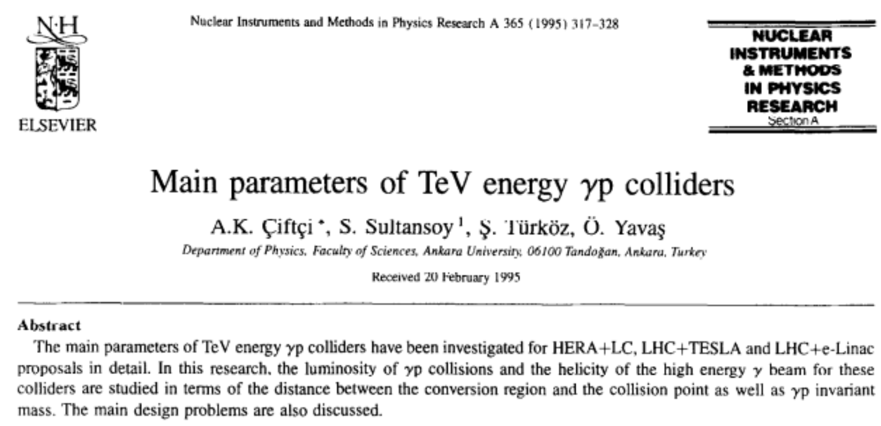
For ILC×FCC and PWFA-LC×FCC based ep colliders:



luminosity values up to $L_{ep} \sim 10^{32}\,cm^{-2}s^{-1}$ are achievable with moderate upgrade of the FCC proton beam. Even with these luminosity values BSM search potential of ep colliders essentially exceeds that of corresponding linear colliders and is comparable with search potential of the FCC pp option for a lot of BSM phenomena. In principle, "dynamic focusing" scheme [16], which was proposed for THERA, could provide $L_{ep} \sim 10^{33}\,cm^{-2}s^{-1}$ for all ep collider options considered in this study. Concerning ILC⊗FCC based ep colliders, a new scheme for energy recovery proposed for higher-energy LHeC (see Section 7.1.5 in [3]) may give an opportunity to increase luminosity by an additional one or two orders, resulting in L_{ep} exceeding $10^{34}\,cm^{-2}s^{-1}$. Unfortunately, this scheme can not be applied at PWFA-LC⊗FCC.

LC×FCC based γp and γA colliders

This machines can be realised only on the base of linac-ring type ep and eA colliders
$\sqrt{s}(\gamma p)\sim 0.9\sqrt{s}(ep)$ and $L(\gamma p)\sim 0.6L(ep)$



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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Main parameters of TeV energy γp colliders

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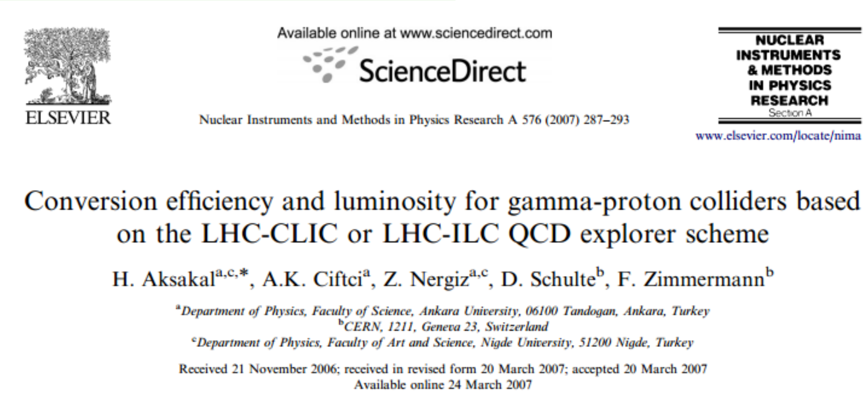
Received 20 February 1995

Abstract

The main parameters of TeV energy γp colliders have been investigated for HERA+LC, LHC+TESLA and LHC+e-Linac proposals in detail. In this research, the luminosity of γp collisions and the helicity of the high energy γ beam for these colliders are studied in terms of the distance between the conversion region and the collision point as well as γp invariant mass. The main design problems are also discussed.



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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
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Conversion efficiency and luminosity for gamma-proton colliders based on the LHC-CLIC or LHC-ILC QCD explorer scheme

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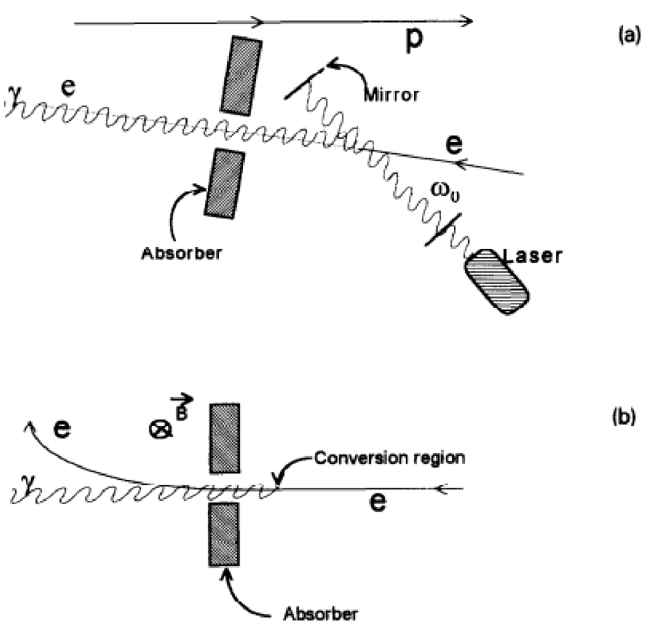
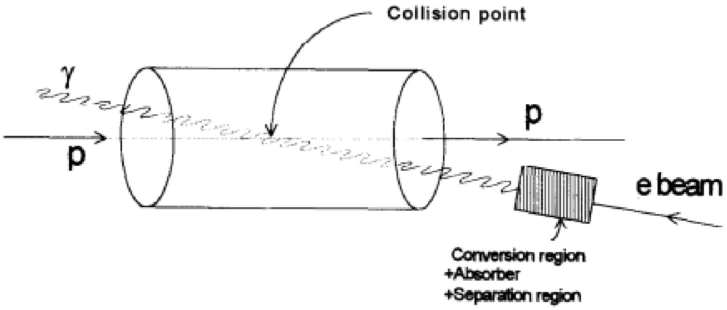
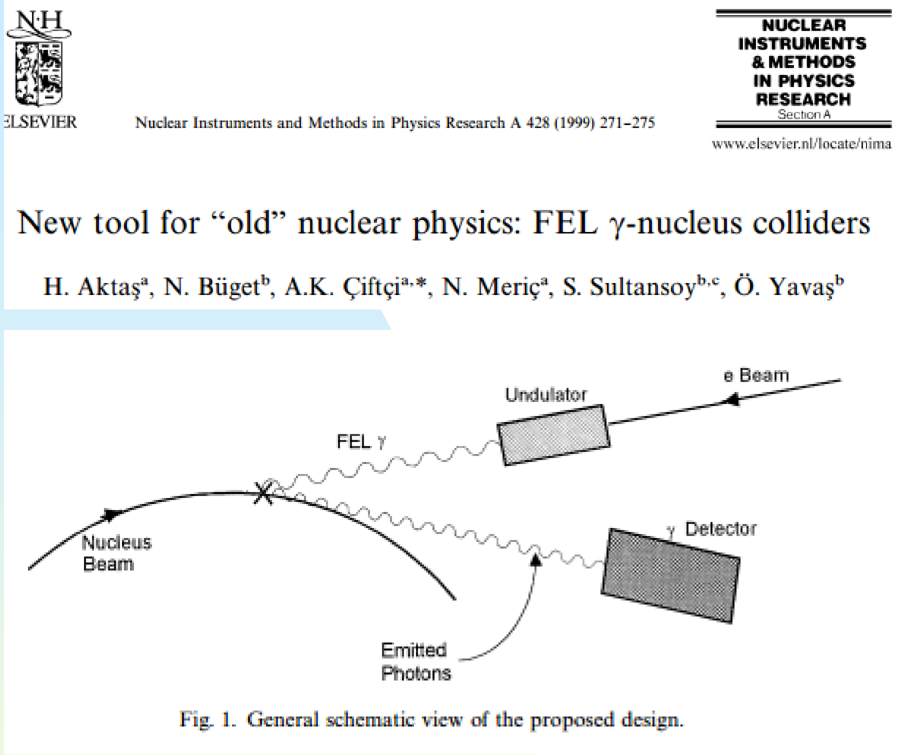


Fig. 16. Schematic view of the part of the design between the conversion region and the detector. (a) Horizontal plane, (b) vertical plane.



FEL γA colliders



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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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New tool for “old” nuclear physics: FEL γ-nucleus colliders

H. Aktaş[a], N. Büget[b], A.K. Çiftçi[a,*], N. Meriç[a], S. Sultansoy[b,c], Ö. Yavaş[b]

Fig. 1. General schematic view of the proposed design.

keV energy FEL photons will be seen as a «laser» beam in the MeV energy range in the rest frame of the nucleus.

In the nucleus rest frame the energy of FEL photon is multiplied by $2\gamma(\mathrm{N})$, where $\gamma(\mathrm{N})$ is the Lorentz factor of the nucleus:
$\gamma(\mathrm{N})\sim3000$ for LHC
$\gamma(\mathrm{N})\sim20{,}000$ for LHC

Excited nucleus will turn to the ground state at a distance $l=\gamma(\mathrm{N})\tau(\mathrm{N})c$ from the collision point, where $\tau(\mathrm{N})$ is the lifetime of the excited state in the nucleus rest frame and c is the speed of light. As an example, for the 4847.2 keV excitation of 208Pb nucleus at FCC l=4×10(-4) m. Therefore, the detector should be placed close to the collision region. The 5 MeV energy photons emitted in the rest frame of the nucleus will be seen in the detector as high energy photons with energies up to 200 GeV.

Effective tool for nuclear spectroscopy…

Dreams for 2030'ies:
multi-TeV center of mass energy at constituent level

Hadron colliders:

FCC pp with√s = 100 TeV
+ FCC AA

Lepton colliders:

CLIC ee with√s = 3 TeV and/or PWFA-LC ee with√s = 10 TeV
+ $\gamma e + \gamma\gamma$

μC μμ with√s = 6 TeV

Lepton-Hadron:

LC×FCC based ep with√s = 30 TeV
+ eA + $\gamma p + \gamma A$

μC×FCC based μp with√s = 30 TeV
+ μA

For correct HEP strategy we need:

- Systematic study (accelerator, physics and detector aspects) for the FCC based ep, eA, μp, μA, γp, γA and FEL γA colliders.

- Comparison of physics search potentials of hadron, lepton and lepton-hadron colliders for different BSM phenomena: e8 example will be presented by Umit Kaya at this session.

In order to do these:

- FCC subgroup on lh and γh colliders (may be DESY leaded) a'la FCC-ee.

- Dedicated Workshops a'la FCC-ee etc.

In this content comparison of

ERL60×FCC with $\sqrt{s} = 3.46\ \text{TeV}$ and $L = 10^{34\text{-}35}\ \text{cm}^{-2}\ \text{s}^{-1}$

ILC×FCC with $\sqrt{s} = 10\ \text{TeV}$ and $L = 10^{33\text{-}34}\ \text{cm}^{-2}\ \text{s}^{-1}$

PWFA-LC×FCC with $\sqrt{s} = 30\ \text{TeV}$ and $L = 10^{32\text{-}33}\ \text{cm}^{-2}\ \text{s}^{-1}$

will be useful.

FCC based lh and γh colliders, especially γA option, will provide deeper understanding of QCD basics and in general strong interactions from quark to nuclei level.

FCC based ep (μp) collider will be powerful tool for BSM physics connected to first (second) family leptons and quarks.

….

BACKUP SLIDES

C. Adolphsen et al., “The International Linear Collider Technical Design Report-Volume 3. II”; arXiv:1306.6328 (2013).

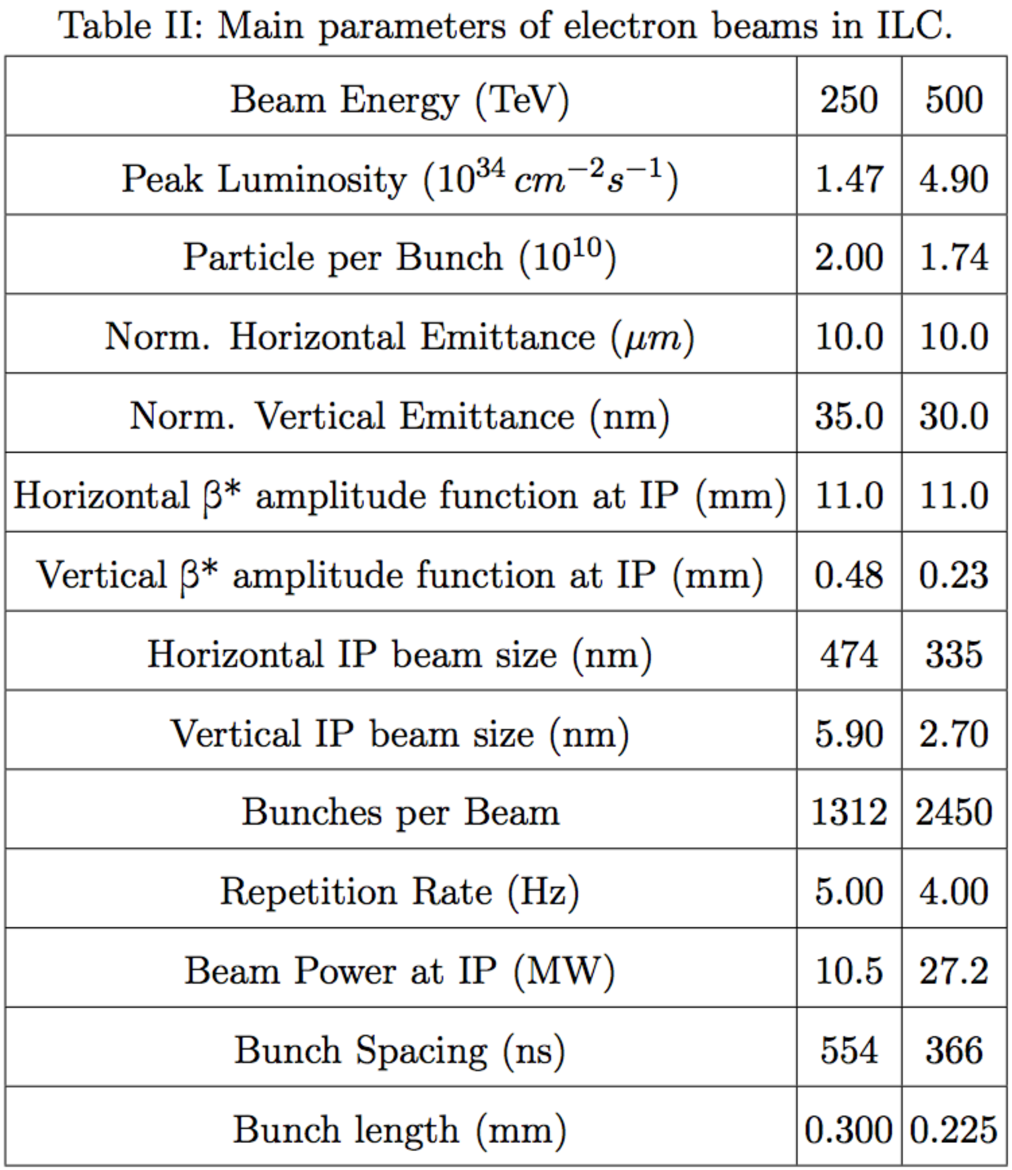

Table II: Main parameters of electron beams in ILC.

Beam Energy (TeV)	250	500
Peak Luminosity ($10^{34}\,cm^{-2}s^{-1}$)	1.47	4.90
Particle per Bunch (10^{10})	2.00	1.74
Norm. Horizontal Emittance (μm)	10.0	10.0
Norm. Vertical Emittance (nm)	35.0	30.0
Horizontal β^* amplitude function at IP (mm)	11.0	11.0
Vertical β^* amplitude function at IP (mm)	0.48	0.23
Horizontal IP beam size (nm)	474	335
Vertical IP beam size (nm)	5.90	2.70
Bunches per Beam	1312	2450
Repetition Rate (Hz)	5.00	4.00
Beam Power at IP (MW)	10.5	27.2
Bunch Spacing (ns)	554	366
Bunch length (mm)	0.300	0.225

J-P. Delahaye et al. , “A Beam Driven Plasma-wakefield Linear Collider from Higgs Factory to Multi-TeV”, Proceedings of IPAC 2014, page 3791.

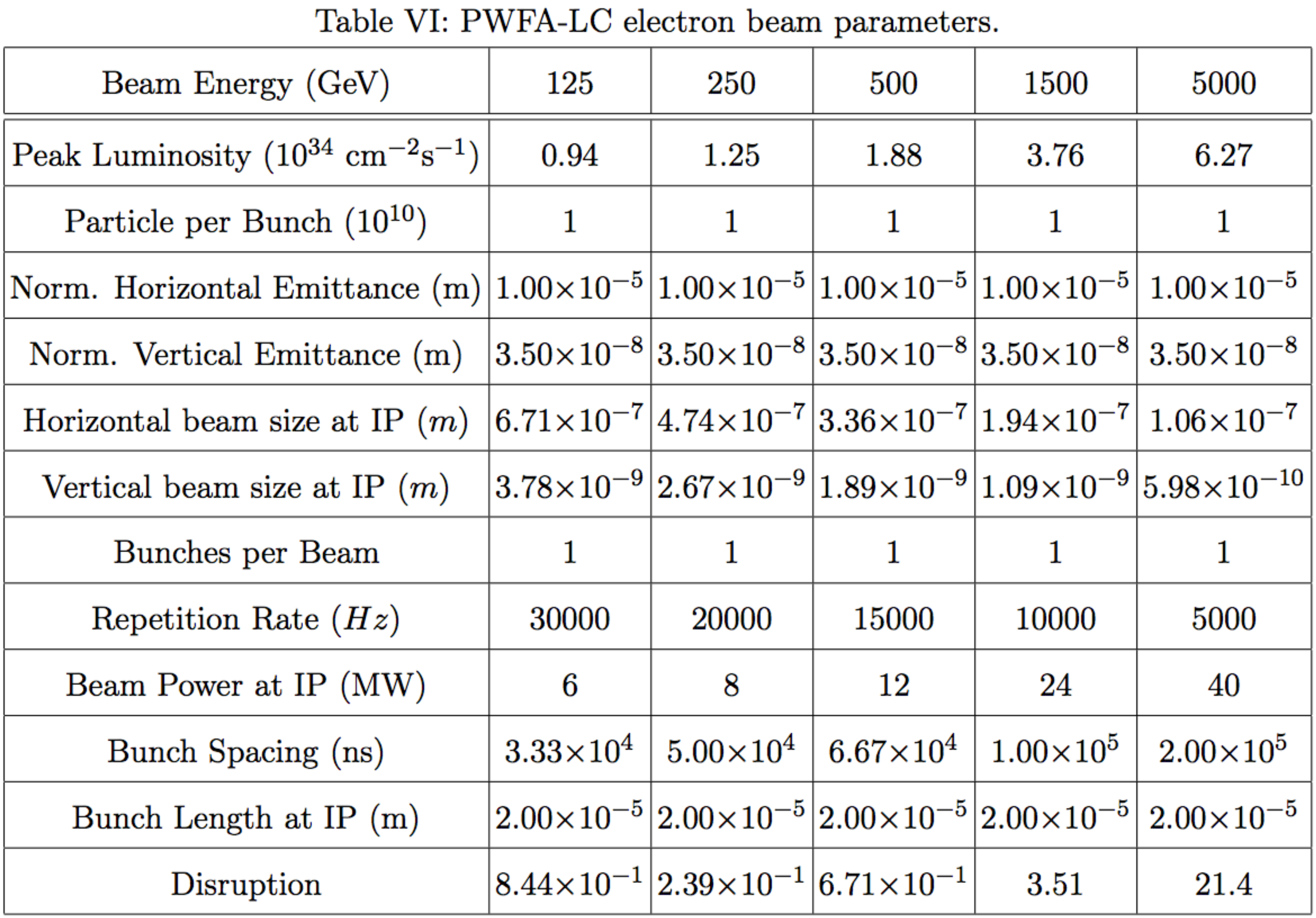

Table VI: PWFA-LC electron beam parameters.

Beam Energy (GeV)	125	250	500	1500	5000
Peak Luminosity (10^{34} cm^{-2}s^{-1})	0.94	1.25	1.88	3.76	6.27
Particle per Bunch (10^{10})	1	1	1	1	1
Norm. Horizontal Emittance (m)	1.00×10^{-5}	1.00×10^{-5}	1.00×10^{-5}	1.00×10^{-5}	1.00×10^{-5}
Norm. Vertical Emittance (m)	3.50×10^{-8}	3.50×10^{-8}	3.50×10^{-8}	3.50×10^{-8}	3.50×10^{-8}
Horizontal beam size at IP (m)	6.71×10^{-7}	4.74×10^{-7}	3.36×10^{-7}	1.94×10^{-7}	1.06×10^{-7}
Vertical beam size at IP (m)	3.78×10^{-9}	2.67×10^{-9}	1.89×10^{-9}	1.09×10^{-9}	5.98×10^{-10}
Bunches per Beam	1	1	1	1	1
Repetition Rate (Hz)	30000	20000	15000	10000	5000
Beam Power at IP (MW)	6	8	12	24	40
Bunch Spacing (ns)	3.33×10^{4}	5.00×10^{4}	6.67×10^{4}	1.00×10^{5}	2.00×10^{5}
Bunch Length at IP (m)	2.00×10^{-5}	2.00×10^{-5}	2.00×10^{-5}	2.00×10^{-5}	2.00×10^{-5}
Disruption	8.44×10^{-1}	2.39×10^{-1}	6.71×10^{-1}	3.51	21.4

J. P. Delahaye et al., "A staged muon accelerator facility for neutrino and collider physics”, Proc. of 2014 International Particle Accelerator Conference, p. 1872 (2015).

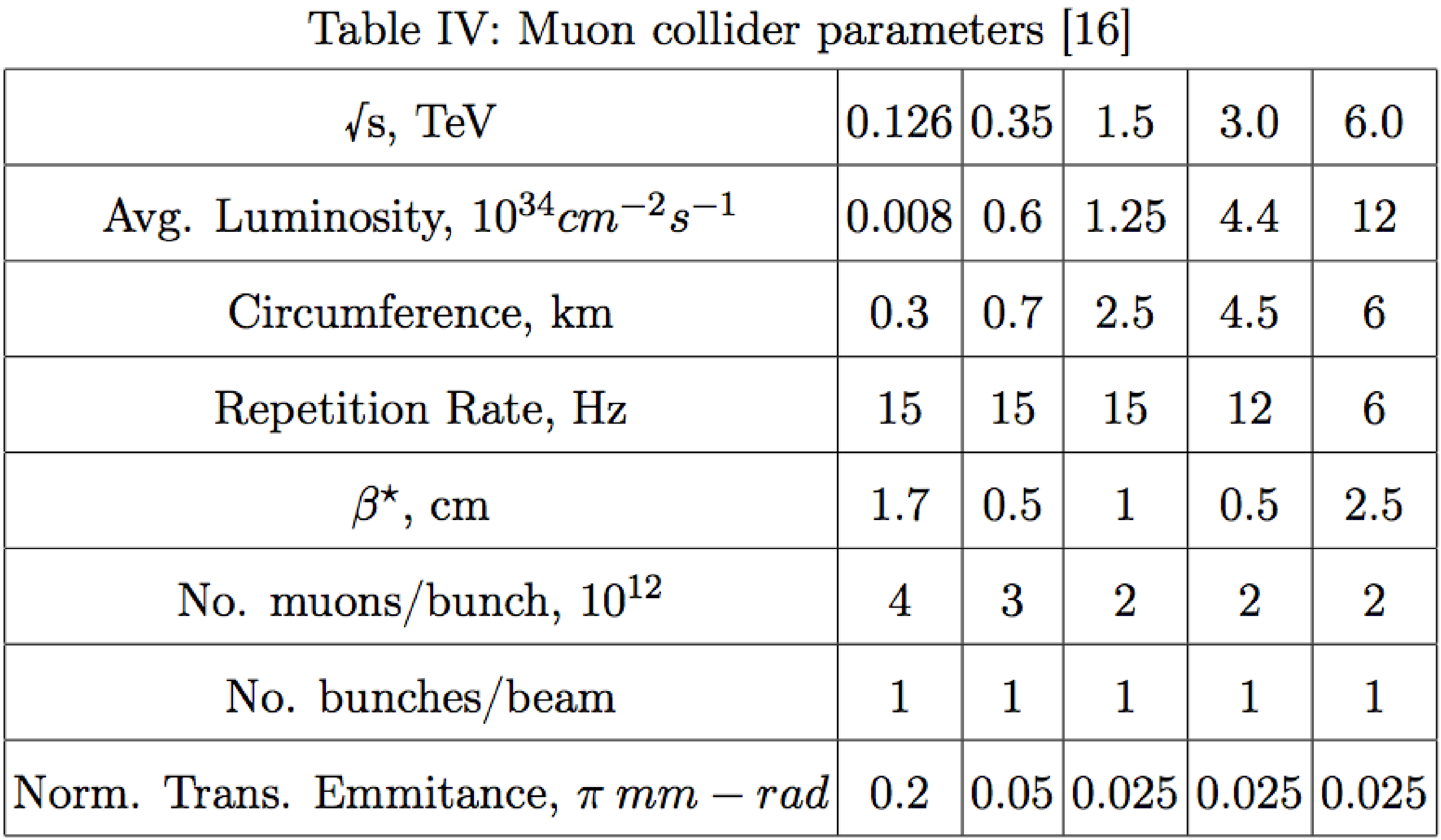

Table IV: Muon collider parameters [16]

$\sqrt{s}$, TeV	0.126	0.35	1.5	3.0	6.0
Avg. Luminosity, $10^{34} cm^{-2} s^{-1}$	0.008	0.6	1.25	4.4	12
Circumference, km	0.3	0.7	2.5	4.5	6
Repetition Rate, Hz	15	15	15	12	6
$\beta^{\star}$, cm	1.7	0.5	1	0.5	2.5
No. muons/bunch, 10^{12}	4	3	2	2	2
No. bunches/beam	1	1	1	1	1
Norm. Trans. Emmitance, $\pi\, mm - rad$	0.2	0.05	0.025	0.025	0.025

FCC parameters

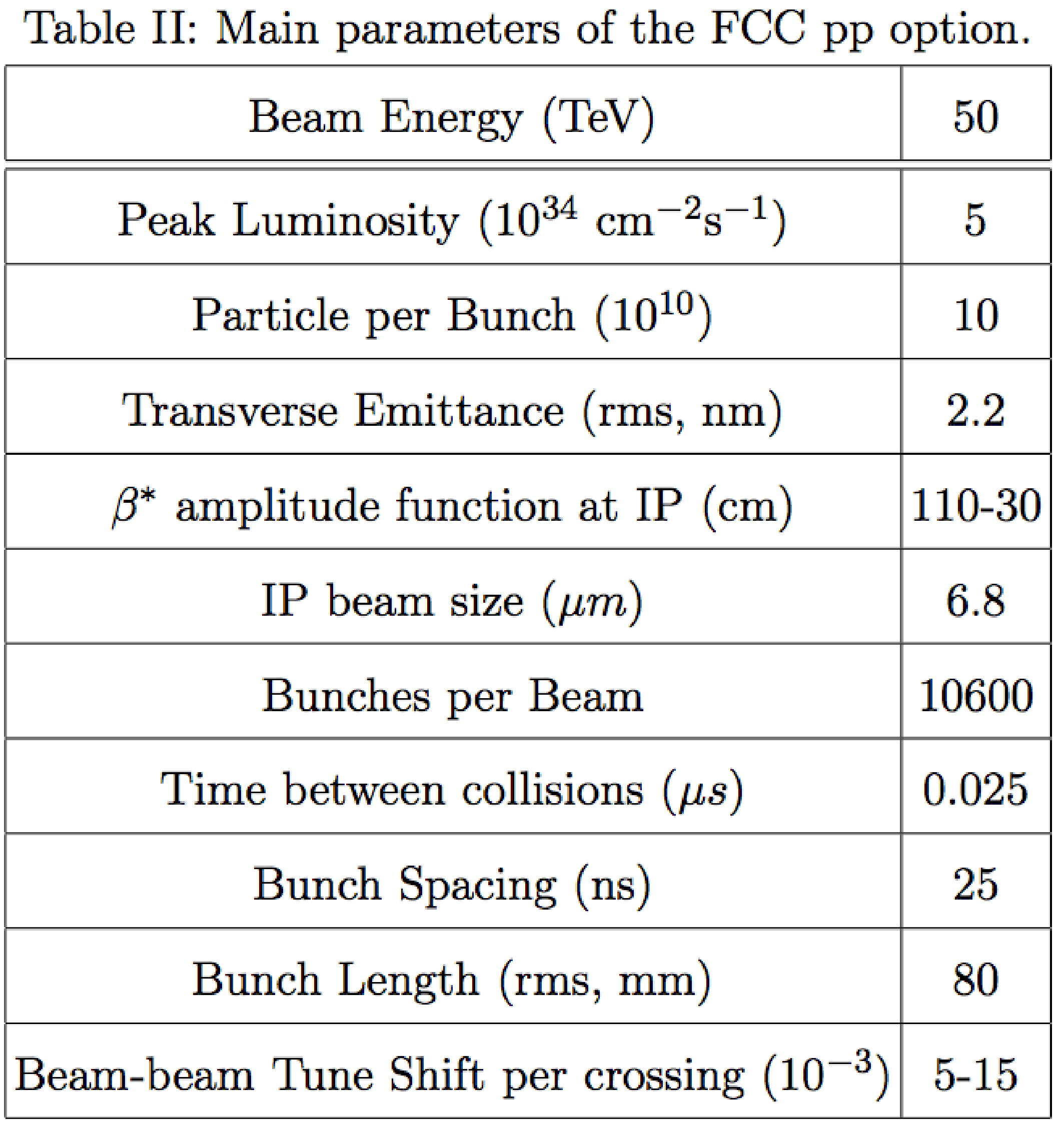

Table II: Main parameters of the FCC pp option.

Beam Energy (TeV)	50
Peak Luminosity (10^{34} cm^{-2}s^{-1})	5
Particle per Bunch (10^{10})	10
Transverse Emittance (rms, nm)	2.2
β^* amplitude function at IP (cm)	110-30
IP beam size (μm)	6.8
Bunches per Beam	10600
Time between collisions (μs)	0.025
Bunch Spacing (ns)	25
Bunch Length (rms, mm)	80
Beam-beam Tune Shift per crossing (10^{-3})	5-15