Exploration of preonic models at the FCC based pp, ep, μp and γp colliders

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ATLAS, LHeC and FCC Collaborations, CERN

* with Y. Acar, U. Kaya and B. Oner

1870’s: Mendeleyev Table

1960’s: Eight-fold Way

Today: Family Replication
Apologies

I have been down in my bed with 39°C fever for the last two days. For this reason
  ❖ I could not attend Tuesday and Wednesday sessions
  ❖ For the same reason I could not prepare this presentation in the best manner (usually, I am preparing the latest version of my presentations in the last 1-2 days).

My presentation covers two topics beyond the «mainstream»:
  ❖ Energy frontier (FCC based) lp colliders
  ❖ Quark and lepton substructure

and I have only 15 minutes.
Preface

Higgs boson discovery – triumph of the SM. But a lot of unsolved problems → BSM models.

1) \(v(R)\) and SM4 are not BSM
   - \(v(R)\) is counterpart of \(d(R)\). Sea-saw provides small «\(v(L)\)» mass.
   - Only minimal SM4 with one Higgs doublet is excluded by the LHC data, 2HDM and doublet-triplet options are still survive. General Chiral Fourth Generation cannot be excluded by the LHC.

2) Standard extensions
   - Fermion sector, i.e. Induced by E(6) GUT ore Little Higgs
   - Gauge sector (predicted by all GUT’s except SU(5)), i.e. Left-Right symmetric models (LR asymmetry posted to Higgs sector, \(\eta_R >> \eta_L\))

3) Radical extension
   - Compositeness: see next slides
   - SUSY: very nice idea, but hundreds free parameters put by hand → thousands if RPV!
   - Extra dimensions
   - …
Contents

1. Introduction
   - SM particle’s and parameter’s inflation, family replication, mixings etc
   - Historical arguments: Periodic Table of Elements, Eight-fold Way
   - “SM” and SUSY at preonic level

2. Manifestations
   - New particles (LQ – Monica D'Onofrio; I8 and I* - this presentation)
   - New interactions (Cl – Monica D'Onofrio, anomalous t – Orhan Çakır)
   - Form-factors (next time)

3. FCC based lepton-hadron and photon-hadron colliders

4. pp, ll, lp comparison

5. Conclusions
1. Introduction

- SM particle’s and parameter’s inflation, family replication, mixings etc
- Historical arguments: Periodic Table of Elements, Eight-fold Way
- “SM” and SUSY at preonic level
Periodic Table of the Elementary* Particles

<table>
<thead>
<tr>
<th>family</th>
<th>(\nu) (direct)</th>
<th>(l)</th>
<th>(u)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt; 2 eV</td>
<td>510.9989461(31) keV</td>
<td>1.8 to 3.0 MeV</td>
<td>4.5 to 5.3 MeV</td>
</tr>
<tr>
<td>2</td>
<td>&lt; 190 keV</td>
<td>105.6583745(24) MeV</td>
<td>1.275(25) GeV</td>
<td>95(5) MeV</td>
</tr>
<tr>
<td>3</td>
<td>&lt; 18.2 MeV</td>
<td>1.77686(12) GeV</td>
<td>173.21(1.22) GeV</td>
<td>4.18(3) GeV</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 39.5 GeV</td>
<td>&gt; 100 GeV</td>
<td>&gt; 700 GeV</td>
<td>&gt; 675 GeV</td>
</tr>
</tbody>
</table>

Also,

- \(m_\gamma = 0 (< 10^{-18} \text{ eV})\)
- \(m_g = 0 (< \text{few MeV})\)
- \(m_w = 80.385(15) \text{ GeV}\)
- \(m_z = 91.1876(21) \text{ GeV}\)
- \(m_H = 125.09 \pm 0.24 \text{ GeV}\)

Scale: \(\eta \approx 247 \text{ GeV}\)

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

We wonder why $m_H = 125 \text{ GeV}$?

But do not worry on accidental values of SM fermion masses and mixings …; i.e. $m(e)/m(t) \sim 10^{-5}$
More than 50 fundamental particles and 26 free parameters in the minimal SM3 indicates that the Standard Model is manifestation of more fundamental theory.

Physics met similar situation two times in the past:

<table>
<thead>
<tr>
<th>Stages</th>
<th>1870s-1930s</th>
<th>1950s-1970s</th>
<th>1970s-2020s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Constituent Inflation</td>
<td>Chemical Elements</td>
<td>Hadrons</td>
<td>Quarks, leptons</td>
</tr>
<tr>
<td>Systematic</td>
<td>Periodic Table</td>
<td>Eight-fold Way</td>
<td>Family replication</td>
</tr>
<tr>
<td>Confirmed Predictions</td>
<td>New elements</td>
<td>New Hadrons</td>
<td>BSM particles</td>
</tr>
<tr>
<td>Clarifying Experiments</td>
<td>Rutherford</td>
<td>SLAC DIS</td>
<td>LHC or rather FCC</td>
</tr>
<tr>
<td>Building Blocks</td>
<td>Proton, neutron, electron</td>
<td>Quarks</td>
<td>Preons?</td>
</tr>
<tr>
<td>Energy Scale</td>
<td>MeV</td>
<td>GeV</td>
<td>TeV?</td>
</tr>
<tr>
<td>Impact on Technology</td>
<td>Exceptional</td>
<td>Indirect</td>
<td>Exceptional?</td>
</tr>
</tbody>
</table>

- Periodic Table of the Elements was clarified by Rutherford's experiment
- Hadron inflation has resulted in quark model
- This analogy implies the preonnic structure of the SM fermions
WHY PREONIC MODELS?

- The composite models are particularly interesting for the continued "simplification" and describe nature in terms of its most fundamental building blocks.

- These fundamental constituents were called PREONS by Pati and Salam.

- Family replication and especially SM fermion mixings can be considered as indication of preonic structure of matter.

- Could provide a solution to some of the aforementioned problems with an effective model at the preonic level.

- Quark-lepton compositeness is a well-known BSM scenario and the preonic models predict;
  - Excited leptons and quarks, leptogluons, leptoquarks, diquarks, dileptons, color sextet quarks etc
  - Contact Interactions, anomalous interactions of SM fermions and bosons, form-factors
“SM” and SUSY at preonic level

If space-time structure is not changed, then SU(3)\times SU(2)\times U(1) gauge symmetry, as well as SUSY, should be realized at preonic level *

First case means that W, Z and (probably) H bosons are point-like ...

Second case means that each SM particle has:
- four «SUSY» partners in fermion-scalar (FS) models
- and eight «SUSY» partners in three-fermion (FFF) models
...

* Actually at pre-preonic level as mentioned by Professor Abdus SALAM during our private conversation in October 1989. I understood his reasons 10 years later.
(My first departure from the Soviet Union was made possible by the invitation of Abdus Salam.)
2. Manifestations

- New particles (LQ – Monica D'Onofrio; e8, μ8 and μ* - this presentation)
- New interactions (CI – Monica D'Onofrio, anomalous t – Orhan Çakır)
- Formfactors (next time)
Since $W$, $Z$ and (probably) $H$ bosons are point-like, then following manifestations should be considered:

- Excited leptons: $l_p$, $p_p$
- Excited quarks: $p_p$, $γ_p$
- Color octet leptons: $l_p$, $p_p$
- Exotic colored quarks: $p_p$
- Contact interactions: $l_p$, $p_p$
- Anomalous interactions of SM leptons and quarks: $p_p$, $l_p$, $l_l$
- Form-factors: $l_p$
- ...

There are no $W^*$, $Z^*$, $W_8$, $Z_8$ and so on.
3. **FCC based lepton-hadron and photon-hadron colliders**

- $ep$ and $eA$
- $\gamma p$ and $\gamma A$
- $\mu p$ and $\mu A$ (ultimate sgrts(S) $\approx$ 63 TeV !!!)
- FEL $\gamma A$

For details, see:

- presentation at 2nd FCC Week, Rome
  [http://indico.cern.ch/event/438866/contributions/1085135/](http://indico.cern.ch/event/438866/contributions/1085135/)

- and Y. Acar et al., «**FCC Based Lepton-Hadron and Photon-Hadron Colliders: Luminosity and Physics**»
Construction of future electron-positron colliders (or dedicated electron linac) and muon colliders (or dedicated muon ring) tangential to Future Circular Collider will give opportunity to **utilize highest energy proton and nucleus beams** for **lepton-hadron** and **photon-hadron** collisions.

\[
\text{LC} \times \text{FCC} = \text{LC} + \text{FCC} + e p + e A + \gamma p + \gamma A + \text{FEL } \gamma A
\]

\[
\mu C \times \text{FCC} = \mu C + \text{FCC} + \mu p + \mu A
\]
# LC×FCC based ep colliders

## Table IV. Main parameters of ILC×FCC based ep collider.

<table>
<thead>
<tr>
<th>$E_e (GeV)$</th>
<th>$\sqrt{s} (TeV)$</th>
<th>$L_{ep}, cm^{-2}s^{-1}$</th>
<th>$D_e$</th>
<th>$\xi_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>7.08</td>
<td>$2.26 \times 10^{30}$</td>
<td>1.0</td>
<td>$1.09 \times 10^{-3}$</td>
</tr>
<tr>
<td>500</td>
<td>10.0</td>
<td>$2.94 \times 10^{30}$</td>
<td>0.5</td>
<td>$9.40 \times 10^{-4}$</td>
</tr>
<tr>
<td>$E_e (GeV)$</td>
<td>$\sqrt{s} (TeV)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>7.08</td>
<td>$55.0 \times 10^{30}$</td>
<td>24</td>
<td>$1.09 \times 10^{-3}$</td>
</tr>
<tr>
<td>500</td>
<td>10.0</td>
<td>$70.0 \times 10^{30}$</td>
<td>12</td>
<td>$9.40 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

## Table V. Main parameters of ILC×FCC based ep collider corresponding to the disruption limit $D_e = 25$.

<table>
<thead>
<tr>
<th>$E_e (GeV)$</th>
<th>$\sqrt{s} (TeV)$</th>
<th>$N_p (10^{11})$</th>
<th>$L_{ep}, cm^{-2}s^{-1}$</th>
<th>$\xi_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>7.08</td>
<td>2.3</td>
<td>$57 \times 10^{30}$</td>
<td>$1.09 \times 10^{-3}$</td>
</tr>
<tr>
<td>500</td>
<td>10.0</td>
<td>4.6</td>
<td>$149 \times 10^{30}$</td>
<td>$9.40 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

## Table VII. Main parameters of PWFA-LC×FCC based ep collider.

<table>
<thead>
<tr>
<th>$E_e (GeV)$</th>
<th>$\sqrt{s} (TeV)$</th>
<th>$L_{ep}, cm^{-2}s^{-1}$</th>
<th>$D_e$</th>
<th>$\xi_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>7.08</td>
<td>$3.44 \times 10^{30}$</td>
<td>1.00</td>
<td>$5.47 \times 10^{-4}$</td>
</tr>
<tr>
<td>500</td>
<td>10.0</td>
<td>$2.58 \times 10^{30}$</td>
<td>0.50</td>
<td>$5.47 \times 10^{-4}$</td>
</tr>
<tr>
<td>1500</td>
<td>17.3</td>
<td>$1.72 \times 10^{30}$</td>
<td>0.17</td>
<td>$5.47 \times 10^{-4}$</td>
</tr>
<tr>
<td>5000</td>
<td>31.6</td>
<td>$0.86 \times 10^{30}$</td>
<td>0.05</td>
<td>$5.47 \times 10^{-4}$</td>
</tr>
<tr>
<td>$E_e (GeV)$</td>
<td>$\sqrt{s} (TeV)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>7.08</td>
<td>$82.6 \times 10^{30}$</td>
<td>24</td>
<td>$5.47 \times 10^{-4}$</td>
</tr>
<tr>
<td>500</td>
<td>10.0</td>
<td>$61.9 \times 10^{30}$</td>
<td>12</td>
<td>$5.47 \times 10^{-4}$</td>
</tr>
<tr>
<td>1500</td>
<td>17.3</td>
<td>$41.3 \times 10^{30}$</td>
<td>4.0</td>
<td>$5.47 \times 10^{-4}$</td>
</tr>
<tr>
<td>5000</td>
<td>31.6</td>
<td>$20.8 \times 10^{30}$</td>
<td>1.2</td>
<td>$5.47 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

## Table VIII. Main parameters of PWFA-LC×FCC based ep collider corresponding to the disruption limit $D_e = 25$.

<table>
<thead>
<tr>
<th>$E_e (GeV)$</th>
<th>$\sqrt{s} (TeV)$</th>
<th>$N_p (10^{11})$</th>
<th>$L_{ep}, cm^{-2}s^{-1}$</th>
<th>$\xi_p$</th>
<th>IBS Growth Time (Horizontal) (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>5.00</td>
<td>1.15</td>
<td>$65.0 \times 10^{30}$</td>
<td>$5.47 \times 10^{-4}$</td>
<td>721</td>
</tr>
<tr>
<td>250</td>
<td>7.08</td>
<td>2.30</td>
<td>$86.0 \times 10^{30}$</td>
<td>$5.47 \times 10^{-4}$</td>
<td>360</td>
</tr>
<tr>
<td>500</td>
<td>10.0</td>
<td>4.60</td>
<td>$129 \times 10^{30}$</td>
<td>$5.47 \times 10^{-4}$</td>
<td>180</td>
</tr>
<tr>
<td>1500</td>
<td>17.3</td>
<td>13.8</td>
<td>$258 \times 10^{30}$</td>
<td>$5.47 \times 10^{-4}$</td>
<td>60.0</td>
</tr>
<tr>
<td>5000</td>
<td>31.6</td>
<td>45.8</td>
<td>$433 \times 10^{30}$</td>
<td>$5.47 \times 10^{-4}$</td>
<td>18.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$L_c=106.9$ m</th>
<th>$L_c=203.0$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>721</td>
<td>149</td>
</tr>
<tr>
<td>360</td>
<td>75.0</td>
</tr>
<tr>
<td>180</td>
<td>37.0</td>
</tr>
<tr>
<td>60.0</td>
<td>12.0</td>
</tr>
<tr>
<td>18.0</td>
<td>3.90</td>
</tr>
</tbody>
</table>
LC\(\times\)FCC based \(\gamma p\) colliders

These machines can be realised only on the base of linac-ring type \(ep\) colliders

\[ \sqrt{s(\gamma p)} \sim 0.9 \sqrt{s(ep)} \quad \text{and} \quad L(\gamma p) \sim 0.6L(ep) \]

According to VMD \(\gamma A\) means \(pA\) collider. Formation of the quark-gluon plasma at very high temperatures but relatively low parton densities
FCC based $\mu p$ colliders

<table>
<thead>
<tr>
<th>Collider Name</th>
<th>$\sqrt{s}$, TeV</th>
<th>$L_{\mu p}$, $cm^{-2}s^{-1}$ (Avg.)</th>
<th>$\xi_p$</th>
<th>$\xi_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu63$-FCC</td>
<td>3.50</td>
<td>$0.2 \times 10^{31}$</td>
<td>$1.8 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\mu750$-FCC</td>
<td>12.2</td>
<td>$50 \times 10^{31}$</td>
<td>$1.1 \times 10^{-1}$</td>
<td>$3.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\mu1500$-FCC</td>
<td>17.3</td>
<td>$50 \times 10^{31}$</td>
<td>$1.1 \times 10^{-1}$</td>
<td>$8.3 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Ultimate: $\mu20000$-FCC, $\sqrt{s} = 63$ TeV, $L = 10^{33}$ cm$^{-2}$ s$^{-1}$

For pre-decor of «ultimate» $\mu p$ collider see:
S. Sultansoy «The PostHERA era: Brief review of future lepton hadron and photon hadron colliders», DESY-99-159

More details will be presented at the 3rd FCC Week, Berlin
4. FCC based \(pp, ll, lp\) comparison

- *Color octet electron*
- *Color octet muon*
- *Excited muon*
In models with colored preons, leptogluons have the same status as excited leptons and leptoquarks.

For **color octet electron** comparative analysis, see:

Umit Kaya «Color Octet Electrons @ FCC-hh, CLIC, FCC-he». Presented at «FCC Physics, Detector and Accelerator Workshop @ Istanbul», 11-12 March 2016. [https://indico.cern.ch/event/405973/contributions/1852964](https://indico.cern.ch/event/405973/contributions/1852964)


For **color octet muon** see: Y. Acar, U. Kaya and B. Öner (in preparation)

Color octet leptons in preonic models

Strongly interacting partners of the SM leptons.
Model example:

Leptons: In the framework of fermion-scalar models, leptons would be a bound state of one fermionic preon and one scalar anti-preon,
\[ l = (F \bar{S}) = 1 \oplus 8 \]
then each SM lepton has one colour octet partner. In a three fermion model, the colour decomposition
\[ l = (FFF) = 1 \oplus 8 \oplus 8 \oplus 10 \]
predicts the existence of two colour octet and one colour decouplet partners.

Quarks: In fermion-scalar models, anti-quarks are consist of one fermionic and one scalar preons which means that each SM anti-quark has one coloured sextet partner,
\[ \bar{q} = (FS) = 3 \oplus 6. \]

According to the three fermion models
\[ q = (F\bar{F}F) = 3 \oplus 3 \oplus 6 \oplus 15 \]
therefore, for each SM quark one anti-triplet, one anti-sextet and one 15-plet partners are predicted.

In this study, they choose fermion-scalar model.

| Electric charges of scalar and fermionic preons |
|-----------------|----------|
| \( S_1 \)       | 0        |
| \( F_1 \)       | 0        |
| \( F_2 \)       | -1       |
| \( S_2 \)       | 1/3      |

\[ \nu_e = (F_1 \bar{S}_1), \quad e = (F_2 \bar{S}_1) \]
\[ \bar{d} = (F_1 S_2), \quad \bar{u} = (F_2 S_2) \]
LAGRANGIAN AND DECAY WIDTH FOR COLOR OCTET LEPTONS

- The interaction lagrangian of color octet leptons (denoted by $l_8$) with their corresponding lepton (denoted by $l$);

\[ L_{Int} = \frac{1}{2\Lambda} \sum_l \bar{\psi}_{l_8} g_s F_{\mu\nu}^a \sigma^{\mu\nu} (\eta_L \psi_{l,L} + \eta_R \psi_{l,R}) + h.c. \]

- $\eta_L$ and $\eta_R \rightarrow$ chirality factors
- $\psi_{l,L}$ and $\psi_{l,R}$ denote left and right spinor components of lepton
- $F_{\mu\nu}^a \rightarrow$ gluon field strength tensor
- $\sigma_{\mu\nu} \rightarrow$ antisymmetric tensor
- $g_s \rightarrow$ strong coupling constant

\[ \Gamma_{l_8} = \frac{\alpha_s(M_{l_8}) M_{l_8}^3}{4\Lambda^2} \]

- $\Lambda \rightarrow$ compositeness scale
PRODUCTION CROSS SECTION OF $e_8$ @ FCC-pe

RESONANT PRODUCTION

$\Lambda = \text{Me}_8$

$\Lambda = 100$ TeV
SIGNALS AND BACKGROUNDS

Transverse momentum distribution of **jet** for signals and backgrounds at **ERL60-FCC**

Transverse momentum distribution of **electron** for signals and backgrounds at **OPL1000-FCC**

Normalised pseudo-rapidity distribution of **jet** for signals and backgrounds at **ERL60-FCC**

Normalised pseudo-rapidity distribution of **electron** for signals and backgrounds at **OPL1000-FCC**
Discovery limits for color octet electron ($\Lambda = m_{e^8}$)

If FCC will discover $e_8$, LC×FCC will give opportunity to determine Lorentz structure of $e_8$-e-g vertex using longitudinal polarization of electron beam, as well as to probe compositeness scale up to hundreds TeV.

Otherwise, PWFA-LC×FCC will discover $e_8$, if its mass is below 25 TeV.

**Similar situation for a lot of BSM phenomena (i.e. LQ, RPV, I* etc)**
A. e8 is discovered by FCC but not observed at e-FCC

B. e8 is discovered by FCC and observed at e-FCC

**Determination of Λ:**

1) FCC discover e8 with 5 TeV mass

2) e-FCC measure cross section as $\sigma \sim 2.50 \text{ fb}$

Therefore, compositeness scale is $\Lambda \approx 100 \text{ TeV}$
Discovery limits for color octet muon ($\Lambda = m_{\mu 8}$)
Discovery limits for excited muon ($\Lambda = m_{\mu^*}$)
5. Conclusions

LC-FCC and μ-FCC will provide great search potential for a lot of BSM phenomena.

Their potentials are far beyond that of ERL60-FCC and ll colliders and sometimes exceed the FCC pp potential

γ options will essentially enlarge the LC-FCC potential

Concerning QCD basics, x up to $10^{-7}$ will be measured at $Q^2 \approx 100$ GeV$^2$

...

Possible stages for FCC hl colliders are presented in the next slide
Frank’s presentation

FCC-he key parameters

$e^\pm$ energy = 60 GeV

$p$ energy = 50 TeV (or equiv. $A$ energy)

# IPs = 1, goal $L \geq 10^{34}$ cm$^{-2}$ s$^{-1}$

to measure Higgs self coupling

spot size determined by $p$

options for FCC-he:

1) $e^-$ from LHeC (or other) ERL

2) $e^\pm$ from FCC-ee

(if co-existing with FCC $hh$)

2) LC-FCC, including gamma options

3) $\mu$-FCC
Thank You for your attention.

Any questions or comments?

This work is supported by TÜBİTAK under grant No 114F337
BACKUP SLIDES
The PostHERA era: Brief review of future lepton hadron and photon hadron colliders

S. Sultansoy (DESY & Ankara U. & Baku, Inst. Phys.)

Oct 1999 - 19 pages

DESY-99-159, AU-HEP-99-02
e-Print: hep-ph/9911417 | PDF

Abstract
Options for future lp, IA, gamma-p, gamma-A and FEL gamma-A colliders are discussed

CONTENTS
1. INTRODUCTION

2. FIRST STAGE: TESLA®HERA, LEP®LHC and $\mu$–ring®TEVATRON
   2.1. TESLA®HERA complex
       i) ep option
       ii) pp option
       iii) eA option
       iv) $\gamma A$ option
       v) FEL $\gamma A$ option
   2.2. LEP®LHC
       i) ep option
       ii) eA option
   2.3. $\mu$–ring®TEVATRON

3. SECOND STAGE: Linac®LHC and $\sqrt{s}=3$ TeV $\mu p$
   3.1. Linac®LHC
       i) ep option
       ii) pp option
       iii) eA option
       iv) $\gamma A$ option
       v) FEL $\gamma A$ option
   3.2. $\sqrt{s}=3$ TeV $\mu p$

4. THIRD STAGE: e–ring®VLHC, LSC®ELOISATRON and multi-TeV $\mu p$
   4.1. e–ring®VLHC
   4.2. LSC®ELOISATRON
   4.3. Multi-TeV $\mu p$

5. CONCLUSION