# Theory motivation: opportunities & challenges

Ken Mimasu King's College London UK Future Collider Town Hall, University of Birmingham 6<sup>th</sup> of July 2022



## Colliders are explorers

### Collider experiments: why do we do it?

- Discover the elementary building blocks of nature
- Establish the fundamental laws that govern their interactions
- Understand the origin and history of our universe

### Exploration is our natural instinct

- Colliders are the tool to explore the smallest scales
- Counterparts to telescopes & space programmes
- Each analysis is a new experiment
- New discoveries from the LHC every year

**2023 highlights:** 4 top quark production, evidence for  $h \to Z\gamma$ , LHC neutrinos, new exotic hadrons,...

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**BSM** 

[James Webb Space Telescope]

Theory motivation for future colliders

2







## The LHC's success

#### "Completed" the Standard Model



[Symmetry magazine]

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#### Explored the TeV scale

#### AC Hoovy Derticle Coerchest 05% CL Upper Evolution Limits

Model	<i>ℓ</i> ,γ	Jets†	$E_{T}^{miss}$	∫£ dt[fb	Limit		1	Reference
ADD $G_{KK}$ + , ADD non-rest ADD QBH ADD BH mult RS1 $G_{KK} \rightarrow$ Bulk RS $G_{KK}$ Bulk RS $G_{KK}$ Bulk RS $g_{KK}$ 2UED / RPP	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{ccc} \gamma & 1-4j \\ & -\\ & 2j \\ \geq 3j \\ & -\\ nnel \\ & 2j/1J \\ \geq 1b, \geq 1J, \\ & \geq 2b, \geq 3 \end{array}$	Yes - - - Yes 2j Yes j Yes	139 36.7 139 3.6 139 36.1 139 36.1 36.1	La Tev	11.2 T 8.6 TeV 9.4 TeV 9.55 TeV 4 5 TeV	e $n = 2$ n = 3  HLZ NLO n = 6 $n = 6, M_D = 3 \text{ TeV, rot BH}$ $k/\overline{M}_{Pl} = 0.1$ $k/\overline{M}_{Pl} = 1.0$ $k/\overline{M}_{Pl} = 1.0$ $\Gamma/m = 15\%$ Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	2102.10874 1707.04147 1910.08447 1512.02586 2102.13405 1808.02380 2004.14636 1804.10823 1803.09678
SSM $Z' \rightarrow \ell\ell$ SSM $Z' \rightarrow \tau$ Leptophobic SSM $W' \rightarrow \ell$ SSM $W' \rightarrow \ell$ SSM $W' \rightarrow \ell$ SSM $W' \rightarrow \ell$ SSM $W' \rightarrow \ell$ HVT $W' \rightarrow W$ HVT $W' \rightarrow W$ HVT $W' \rightarrow W$ HVT $Z' \rightarrow Z$ LRSM $W_R \rightarrow \ell$	$\begin{array}{cccc} & 2 \ e, \mu \\ & 2 \ \tau \\ Z' \rightarrow bb & - \\ Z' \rightarrow tt & 0 \ e, \mu \\ \gamma & 1 \ e, \mu \\ \gamma & 1 \ \tau \\ b & - \\ VZ \rightarrow \ell \nu \ qq \ \text{model B} & 1 \ e, \mu \\ VZ \rightarrow \ell \nu \ \ell' \ \ell' \ \text{model C} & 3 \ e, \mu \\ VH \rightarrow \ell \nu bb \ \text{model B} & 1 \ e, \mu \\ H \rightarrow \ell \ell / \nu v bb \ \text{model B} & 0, 2 \ e, \mu \\ \mu N_R & 2 \ \mu \end{array}$	- 2 b ≥1 b, ≥2 - ≥1 b, ≥1 2 j / 1 J 2 j (VBF) 1-2 b, 1-0 1 J	– – J Yes Yes J – Yes J – Yes j Yes j Yes j Yes	139 36.1 36.1 139 139 139 139 139 139 139 139 80	<pre>/ mass / mass / mass / mass / mass // mass</pre>	5.1 TeV 6.0 TeV 5.0 TeV 4 4 TeV 4.3 TeV 5.0 TeV 5.0 TeV	$\Gamma/m = 1.2\%$ $g_V = 3$ $g_V c_H = 1, g_f = 0$ $g_V = 3$ $g_V = 3$ $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$	1903.06248 1709.07242 1805.09299 2005.05138 1906.05609 ATLAS-CONF-2021-02 ATLAS-CONF-2021-04 2004.14636 ATLAS-CONF-2022-00 2207.00230 2207.00230 1904.12679
Cl qqqq Cl ℓℓqq Cl eebs Cl μμbs Cl tttt	_ 2 e, μ 2 e 2 μ ≥1 e,μ	2 j - 1 b 1 b ≥1 b, ≥1	– – – j Yes	37.0 139 139 139 36.1	1.8 TeV 2.0 TeV 2.57 TeV		<b>21.8 TeV</b> $\eta_{LL}^-$ <b>35.8 TeV</b> $\eta_{LL}^-$ $g_* = 1$ $ C_{4t}  = 4\pi$	1703.09127 2006.12946 2105.13847 2105.13847 1811.02305
Axial-vector n Pseudo-scala Vector med. A Pseudo-scala	ned. (Dirac DM) $0 e, \mu, \tau$ r med. (Dirac DM) $0 e, \mu, \tau$ Z'-2HDM (Dirac DM) $0 e, \mu$ r med. 2HDM+a multi-char	$\begin{array}{ccc} \gamma & 1-4j\\ \gamma & 1-4j\\ & 2b\\ \end{array}$	Yes Yes Yes	139 139 139 139	med 2.1 TeV med 376 GeV 376 GeV 3.1 Te med 560 GeV	N	$g_q$ =0.25, $g_\chi$ =1, $m(\chi)$ =1 GeV $g_q$ =1, $g_\chi$ =1, $m(\chi)$ =1 GeV tan $\beta$ =1, $g_Z$ =0.8, $m(\chi)$ =100 GeV tan $\beta$ =1, $g_\chi$ =1, $m(\chi)$ =10 GeV	2102.10874 2102.10874 2108.13391 ATLAS-CONF-2021-036
Scalar LQ 1 <sup>st</sup> Scalar LQ 2 <sup>nd</sup> Scalar LQ 3 <sup>rd</sup> Scalar LQ 3 <sup>rd</sup> Scalar LQ 3 <sup>rd</sup> Scalar LQ 3 <sup>rd</sup> Scalar LQ 3 <sup>rd</sup> Vector LQ 3 <sup>rd</sup>	$\begin{array}{cccc} gen & & 2 \ e \\ gen & & 2 \ \mu \\ gen & & 1 \ \tau \\ gen & & 0 \ e, \mu \\ gen & & \geq 2 \ e, \mu, \geq \\ gen & & 0 \ e, \mu, \geq \\ gen & & 1 \ \tau \end{array}$	$ \begin{array}{c} \geq 2 \ j \\ \geq 2 \ j \\ \geq 2 \ j, \geq 2 \ l \\ \geq 2 \ j, \geq 2 \ l \\ 1 \ \tau \ \geq 1 \ j, \geq 1 \ l \\ \tau \ 0 - 2 \ j, 2 \\ 2 \ b \end{array} $	Yes Yes Yes O Yes O – b Yes Yes	139 139 139 139 139 139 139 139	Q mass       1.8 TeV         Q mass       1.7 TeV         Q mass       1.2 TeV         Q mass       1.2 TeV         Q mass       1.2 TeV         Q mass       1.2 TeV         Q mass       1.4 B TeV         Q mass       1.26 TeV         Q mass       1.26 TeV         Q mass       1.27 TeV		$\begin{split} \beta &= 1\\ \beta &= 1\\ \mathcal{B}(\mathrm{LQ}_3^u \to b\tau) &= 1\\ \mathcal{B}(\mathrm{LQ}_3^u \to t\nu) &= 1\\ \mathcal{B}(\mathrm{LQ}_3^d \to t\tau) &= 1\\ \mathcal{B}(\mathrm{LQ}_3^d \to b\nu) &= 1\\ \mathcal{B}(\mathrm{LQ}_3^V \to b\tau) &= 0.5, \text{ Y-M coupl.} \end{split}$	2006.05872 2006.05872 2108.07665 2004.14060 2101.11582 2101.12527 2108.07665
VLQ $TT \rightarrow Z$ VLQ $BB \rightarrow W$ VLQ $T_{5/3}T_{5/3}$ VLQ $T \rightarrow Ht$ VLQ $Y \rightarrow W$ VLQ $B \rightarrow Ht$ VLQ $T' \rightarrow Z\tau$	$\begin{array}{cccc} Tt + X & 2e/2\mu/\geq 3\\ Vt/Zb + X & multi-char \\   T_{5/3} \rightarrow Wt + X & 2(SS)/\geq 3\\ /Zt & 1 e, \mu\\ b & 1 e, \mu\\ 0 & 0 e, \mu\\ TH\tau & multi-char \end{array}$	$e,\mu \ge 1 \text{ b}, \ge 1$ nnel $e,\mu \ge 1 \text{ b}, \ge 1$ $\ge 1 \text{ b}, \ge 3$ $\ge 1 \text{ b}, \ge 1$ $\ge 2\text{ b}, \ge 1\text{ j}, \ge$ nnel $\ge 1 \text{ j}$	j – j Yes j Yes j Yes 1J – Yes	139 36.1 36.1 139 36.1 139 139	mass     1.4     TeV       mass     1.34     TeV       5/3 mass     1.64 TeV       mass     1.64 TeV       mass     1.85 TeV       mass     2.0 TeV       mass     898 GeV		SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ SU(2) singlet, $\kappa_T = 0.5$ $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ SU(2) doublet, $\kappa_B = 0.3$ SU(2) doublet	ATLAS-CONF-2021-024 1808.02343 1807.11883 ATLAS-CONF-2021-040 1812.07343 ATLAS-CONF-2021-018 ATLAS-CONF-2022-044
Excited quark Excited quark Excited quark Excited quark Excited lepton Excited lepton	$\begin{array}{ccc} q^* \to qg & - \\ q^* \to q\gamma & 1\gamma \\ b^* \to bg & - \\ 0 \ell^* & 3e, \mu \\ 0 \gamma^* & 3e, \mu, \end{array}$	2 j 1 j 1 b, 1 j 7 –	- - - -	139 36.7 139 20.3 20.3	mass     3.2 Te       mass     3.2 Te       mass     3.0 Te       mass     1.6 TeV	6.7 TeV 5.3 TeV eV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1910.08447 1709.10440 1910.0447 1411.2921 1411.2921
Type III Sees LRSM Majora Higgs triplet / Higgs triplet / Higgs triplet / Multi-charged Magnetic mon	aw 2,3,4 e, na $v$ 2 $\mu$ $I^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ 2,3,4 e, $\mu$ $I^{\pm\pm} \rightarrow \ell \ell$ 2,3,4 e, $\mu$ $I^{\pm\pm} \rightarrow \ell \tau$ 3 e, $\mu$ , particles – nopoles – <b>s = 8 TeV</b> $\sqrt{s} = 13 \text{ TeV}$	$\mu \geq 2 j$ $2 j$ $(SS) various$ $(SS) $	Yes  Yes  - - 3 TeV	139 36.1 139 139 20.3 139 34.4	<sup>0</sup> mass     910 GeV <sub>R</sub> mass     3.2 Te <sup>±±</sup> mass     350 GeV <sup>±±</sup> mass     1.08 TeV <sup>±±</sup> mass     400 GeV <sup>±±</sup> mass     1.59 TeV       onopole mass     2.37 TeV		$m(W_R) = 4.1$ TeV, $g_L = g_R$ DY production DY production DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ DY production, $ q  = 5e$ DY production, $ g  = 1g_D$ , spin 1/2	2202.02039 1809.11105 2101.11961 ATLAS-CONF-2022-010 1411.2921 ATLAS-CONF-2022-030 1905.10130

[ATLAS experiment]





## We want more



Dear Santa Claus,

We have been good these past decades. Please could you now bring us

- a dark matter candidate
- an explanation for the fermion masses
- an explanation of matter-antimatter asymmetry
- an axion, to solve the strong CP problem
- a solution to fine tuning the EW scale
- a solution to fine tuning the cosmological constant

Thank you, Particle Physicists ps: please, no anthropics

> Gavin Salam, FCC Physics Workshop, Krakow, 2023]

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### Puzzles, problems, naturalness,...

In many different sectors (EW, flavour, dark,...)

### The data is pointing us towards

• Higher scales & weaker couplings

• i.e. more collider energy & better precision

### **Opportunity for further exploration**

 Testing QFT/SM in the uncharted territory of energy & precision is groundbreaking in & of itself

Do not know what we will find beyond LHC reach

 Observing known objects with better precision is reason enough for new experiments in most fields

## Higgs: the key player

Involved in many of nature's puzzles

- **Directly:** hierachy/naturalness, flavour/ fermion masses, stability of universe,...
- Potentially: matter anti-matter asymmetry, portal to dark sector,...
- Future colliders must target precise determination of Higgs properties
- HL-LHC:  $\frac{\delta g_h}{g_h} \sim 0.05 = \left(\frac{v}{\Lambda_{NP}}\right)^2$  $\Rightarrow \Lambda_{NP} \sim 1 \text{ TeV}$
- Covered by LHC reach? (model dependent)

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# Higgs potential

Today, its shape is basically unknown  $V(h) = \frac{1}{2}m_h^2h^2 + \lambda_3h^3 + \lambda_4h^4 + \cdots$ 

Precise shape has many implications

- Nature of the EW phase transition:  $1^{st}/2^{nd}$  order?  $\Rightarrow$  Baryogenesis How did the Higgs field evolve in the early universe into the EW broken phase? Is it responsible for generating the matter-antimatter asymmetry of the universe?
- Potential stochastic gravitational wave background signature at e.g. LISA
- [<u>Caprini et al.; JCAP 04 (2016) 001]</u> (Meta)stability of the EW vacuum phase How do we even exist and could our ground state have a finite lifetime?
- Modifications to V(h) imply new states coupled to the Higgs

## Measuring $\lambda_3$ is the no-lose theorem of the FC programme

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## E(C)-ee

- Unique, precision Higgs/EW/top factory
- Semi-direct measurement of Higgs width with mild assumptions
- Connection to dark sector: invisible Higgs decay channels
- Clear feasible pathway to FCC-hh
- Challenge & opportunity [Blondel et al.; Contribution to EPPSU]
- Precision goals require a huge leap in theoretical calculations 3/4 loop QCD/EW corrections, beyond current reach
- High priority item to train next generation of theorists (~500 person/years)

7

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# Precision programme, lays foundation & targets for FCC-hh • Like LEP did for the LHC with EWPO $\Rightarrow$ paved way for Higgs discovery • Tera Z: 3 million LEPs worth of Z bosons [Blondel & Janot; Eur. Phys. J. Plus 137 (2022) 1, 92]



## FCC-hh

- e.g. flavour anomalies
- "Complete coverage" for canonical BSM scenarios

[Ellis et al.; Physics briefing book for ESU]



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## HCC-hh

### Discover & test rare processes

- High-energy & high-multiplicity
- Precision measurements of multi top quark production
- High-multiplicity production of Higgs/Top/EW bosons

#### Directly/indirectly measure new interactions

- **Prime target:**  $\lambda_3$  from di-Higgs production
- Quartic Higgs coupling from triple-Higgs production
- EW top quark couplings, *tthh* interaction,...

### Exploring terra incognita

- Cannot know what lies around the corner, our luck might change... Keep an open mind and build the collider!

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[<u>Maltoni, Mantani, KM; JHEP 10 (2019) 004</u>]

 $\overline{W/Z}/\gamma/h$ 

 $W/Z/\gamma/h$ 

(a)  $t\bar{t}X$ 

elle

 $Z/\gamma/h$ 

 $W/Z/\gamma/h$ 

 $W/Z/\gamma/h$ 

(b) tXj

LOOG









## Muon collider

Radically new collider technology

- Combines clean final state with high energy :  $\sqrt{s}$  ~ 10 TeV

Comparable physics case to FCC-ee/hh



Significant R & D required to determine feasibility

Long timescale  $\Leftrightarrow$  possibly high rewards in offshoot technologies 

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 $\mu^{-}\bullet$ 





See also: "no-lose theorem" for new physics scenarios associated to muon g-2 anomaly

[<u>Capdevilla et al.; PRD 105 (2022) 1, 015028</u>]









Search for new physics in at the decaTeV scale

> Explore uncharted territory precision & energy

## Thanks for your attention

Measure the Higgs boson self coupling

Origin of mass

EW phase transition

Quantum leap in experimental & theoretical precision

> Revolutionise accelerator technology

Probing naturalness

Origin of flavour

Nature of the dark sector



## References, further reading

<u>Public lecture: Does the world need a future collider and why? (YouTube)</u>

European strategy for particle physics homepage

<u>European Comittee for Future Accelerators (ECFA) homepage</u>

FCC-ee: your questions answered FCC-ee overview

<u>SM theory for FCC-ee: Tera Z stage</u>

FCC-hh conceptual design report

FCC week 2023 conference webpage

"Muon colliders" input to the ESU

Muon collider forum report (Snowmass

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<u>t</u>	<u>Snowmass FCC study</u>
2	<u>FCC physics workshop 2023 web</u>
/	<u>"Towards a muon collider"</u>
)	"The muon smasher's guide"





