The broad physics case of a muon collider

Muon4Future

Nathaniel Craig UCSB







PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva, 21-27 March 1984

as:

what is the origin of mass? what kind of unification may exist beyond the standard model? what is the origin of flavour? is there a deeper reason for gauge symmetry?

We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the pp collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

Satisfied with these successes, we have now to face deeper questions such

2



✓ What is the origin of mass? What kind of unification may exist? What is the origin of flavor? Is there a deeper reason for gauge symmetry?

✓ What is the origin of mass? What kind of unification may exist? What is the origin of flavor? Is there a deeper reason for gauge symmetry? + What is the nature of dark matter?

✓ What is the origin of mass? What kind of unification may exist? What is the origin of flavor? Is there a deeper reason for gauge symmetry? + What is the nature of dark matter? + What is the nature of the neutrino sector?

✓ What is the origin of mass?
What kind of unification may exist?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?
+ What is the nature of dark matter?
+ What is the nature of the neutrino sector?

"The more ambitious goal...is to identify and understand the nature of electroweak symmetry breaking, the asymmetry that is key to the material universe. The Higgs boson is but its herald."

A Higgs! Yet:

-Frank Close

What is the origin of mass?

"The more ambitious goal... is to identify and understand the nature of electroweak symmetry breaking, the asymmetry that is key to the material universe. The Higgs boson is but its herald."

-Frank Close

A Higgs! Yet...

What is the origin of mass?

"The more ambitious goal...is to identify and understand the nature of electroweak symmetry breaking, the asymmetry that is key to the material universe. The Higgs boson is but its herald."



A Higgs! Yet...

-Frank Close

A superconducting analogy:

Low-Tc Superconductors (BCS)



Electroweak breaking

Electroweak restoration







kinetic mixing portal $F^{\mu\nu}$

 ${\cal O}_{\mu
u}$

Neutrinos: the purely weak frontier of the Standard Model

Dark sectors: portals are weak interactions & SM electroweak states





...and exploration after the LHC

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits										S Preliminar
Sta	atus: July 2022							$\int \mathcal{L} dt =$	$(3.6 - 139) \text{ fb}^{-1}$	$\sqrt{s} = 8, 13 \text{ TeV}$
	Model	<i>ℓ</i> , γ	Jets†	E ^{miss} T	∫£ dt[fb	-1]	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell \nu qq$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{c} 0 \ e, \mu, \tau, \gamma \\ 2 \gamma \\ - \\ 2 \gamma \\ multi-channe \\ 1 \ e, \mu \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array}$	$\begin{array}{c} 1-4j \\ -\\ 2j \\ \geq 3j \\ -\\ 2j/1 \\ 2j/1 \\ \geq 1 \\ b_i \geq 1 \\ \geq 2 \\ b_i \geq 3j \end{array}$	Yes - - - Yes Yes Yes	139 36.7 139 3.6 139 36.1 139 36.1 36.1	M _D M _S M _{th} M _{th} G _{KK} mass G _{KK} mass g _{KK} mass g _{KK} mass KK mass		11.2 T 8.6 TeV 9.4 TeV 9.55 TeV 2.3 TeV 2.0 TeV 3.8 TeV 1.8 TeV	$ \begin{array}{l} n = 2 \\ n = 3 \; \text{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\% \\ \text{Tier (1,1), } \mathcal{B}(A^{(1,1)} \to tt) = 1 \end{array} $	2102.10874 1707.04147 1910.08447 1512.02586 2102.13405 1808.02380 2004.14636 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \operatorname{SSM} Z' \to \ell\ell \\ \operatorname{SSM} Z' \to \tau\tau \\ \operatorname{Leptophobic} Z' \to bb \\ \operatorname{Leptophobic} Z' \to tt \\ \operatorname{SSM} W' \to \ell\nu \\ \operatorname{SSM} W' \to \tau\nu \\ \operatorname{SSM} W' \to \taub \\ \operatorname{HVT} W' \to WZ \to \ell\nu \ell' \ell' \operatorname{model} \\ \operatorname{HVT} W' \to WZ \to \ell\nu \ell' \ell' \operatorname{model} \\ \operatorname{HVT} W' \to WH \to \ell\nu bb \operatorname{model} \\ \operatorname{HVT} Z' \to ZH \to \ell \ell / \nu\nu bb \operatorname{model} \\ \operatorname{HNT} Z' \to \mu N_R \end{array}$	2 e, μ 2 τ - 0 e, μ 1 e, μ 1 τ - B 1 e, μ al C 3 e, μ B 1 e, μ al B 0,2 e, μ 2 μ	_ 2 b ≥1 b, ≥2 J _ 2 j / 1 J 2 j (VBF) 1-2 b, 1-0 j 1 J	– Yes Yes Yes Yes j Yes j Yes	139 36.1 36.1 139 139 139 139 139 139 139 139 80	Z' mass Z' mass Z' mass Z' mass W' mass W' mass W' mass W' mass W' mass Z' mass W' mass Z' mass	340 GeV	5.1 TeV 2.42 TeV 2.1 TeV 4.1 TeV 6.0 TeV 5.0 TeV 4.4 TeV 4.3 TeV 3.3 TeV 3.2 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-2021-025 ATLAS-CONF-2021-043 2004.14636 ATLAS-CONF-2022-005 2207.00230 2207.00230 1904.12679
ГО	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Vector LQ 3 rd gen	2 e 2 μ 1 τ 0 e, μ ≥2 e, μ , ≥1 τ 0 e, μ , ≥1 τ 1 τ	≥2j ≥2j 2b ≥2j,≥2b r≥1j,≥1b 0-2j,2b 2b	Yes Yes Yes Yes Yes Yes Yes	139 139 139 139 139 139 139 139	LQ mass LQ mass LQ" mass LQ ¹ mass LQ ¹ mass LQ ¹ mass LQ ² mass LQ ³ mass	1.2 1 1.24 1.4 1.26	1.8 TeV 1.7 TeV TeV TeV 43 TeV TeV 1.77 TeV	$\begin{array}{l} \beta = 1\\ \beta = 1\\ \mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1\\ \mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1\\ \mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1\\ \mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1\\ \mathcal{B}(\mathrm{LQ}_3^d \to b\tau) = 0.5, \text{ Y-M coupl.} \end{array}$	2006.05872 2006.05872 2108.07665 2004.14060 2101.11582 2101.12527 2108.07665
Vector-like fermions	$ \begin{array}{ l l l l l l l l l l l l l l l l l l l$	$2e/2\mu/\geq 3e,\mu$ multi-channe $2(SS)/\geq 3e,\mu$ $1e,\mu$ $1e,\mu$ $0e,\mu \geq$ multi-channe	$\begin{array}{l} \mu \ge 1 \ b_i \ge 1 \ j \\ \mu \\ \mu \\ \mu \ge 1 \ b_i \ge 1 \ j \\ \ge 1 \ b_i \ge 3 \ j \\ \ge 1 \ b_i \ge 1 \ j \\ \ge 2b_i \ge 1j_i \ge \end{array}$	– Yes Yes 1J – Yes	139 36.1 36.1 139 36.1 139 139	T mass B mass T _{5/3} mass T mass Y mass B mass τ' mass	1. 1.34 898 GeV	.4 TeV 4 TeV 1.64 TeV 1.8 TeV 1.85 TeV 2.0 TeV	$ \begin{array}{l} & \mathrm{SU(2)\ doublet} \\ & \mathrm{SU(2)\ doublet} \\ & \mathcal{B}(T_{5/3} \rightarrow Wt) = 1,\ c(T_{5/3}Wt) = 1 \\ & \mathrm{SU(2)\ singlet},\ \kappa_T = 0.5 \\ & \mathcal{B}(Y \rightarrow Wb) = 1,\ c_R(Wb) = 1 \\ & \mathrm{SU(2)\ doublet},\ \kappa_B = 0.3 \\ & \mathrm{SU(2)\ doublet} \end{array} $	ATLAS-CONF-2021-024 1808.02343 1807.11883 ATLAS-CONF-2021-040 1812.07343 ATLAS-CONF-2021-018 ATLAS-CONF-2022-044
Excited fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton ν^*	- 1 γ - 3 e,μ 3 e,μ,τ	2 j 1 j 1 b, 1 j –	- - - -	139 36.7 139 20.3 20.3	q [*] mass q [*] mass b [*] mass ℓ [*] mass v [*] mass		6.7 TeV 5.3 TeV 3.2 TeV 3.0 TeV 1.6 TeV	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
Other	Type III Seesaw LRSM Majorana v Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$ Multi-charged particles Magnetic monopoles $\sqrt{s} = 8 \text{ TeV}$	$2,3,4 e, \mu$ 2μ $2,3,4 e, \mu (SS)$ $2,3,4 e, \mu (SS)$ $3 e, \mu, \tau$ $-$ $=$ $5 = 13 \text{ TeV}$	22j 2j various - - - - - - - - -	Yes - Yes - - - - - - - - - - - - -	139 36.1 139 139 20.3 139 34.4	N ⁰ mass N _R mass H ^{±±} mass H ^{±±} mass H ^{±±} mass multi-charged particle mass monopole mass	910 GeV 350 GeV 1.08 Te 400 GeV s	3.2 TeV V 1.59 TeV 2.37 TeV	$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 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-2022-034 1905.10130
	pa		Tull a	ala					Mass scale [TeV]	

7

...and exploration after the LHC

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits										S Preliminary
Sta	atus: July 2022							$\int \mathcal{L} dt = (3)$	$1.6 - 139) \text{ fb}^{-1}$	\sqrt{s} = 8, 13 TeV
	Model	ℓ,γ	Jets†	E ^{miss}	∫£ dt[fb	-1]	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu q$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{c} 0 \ e, \mu, \tau, \gamma \\ 2 \gamma \\ - \\ 2 \gamma \\ multi-channe \\ q \\ 1 \ e, \mu \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array}$	1 – 4 j – 2 j ≥3 j – el 2 j / 1 J ≥1 b, ≥1 J/2 ≥2 b, ≥3 j	Yes - - - Yes 2j Yes Yes	139 36.7 139 3.6 139 36.1 139 36.1 36.1	M _D M _S M _{th} M _{th} G _{KK} mass G _{KK} mass g _{KK} mass g _{KK} mass KK mass	2.0 1.8 T	11.2 Te 8.6 TeV 9.4 TeV 9.55 TeV 2.3 TeV 7eV 3.8 TeV eV	$ n = 2 n = 3 HLZ NLO n = 6 n = 6, M_D = 3 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), B(A^{(1,1)} \rightarrow tt) = 1 $	2102.10874 1707.04147 1910.08447 1512.02586 2102.13405 1808.02380 2004.14636 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \operatorname{SSM} Z' \to \ell\ell \\ \operatorname{SSM} Z' \to \tau\tau \\ \operatorname{Leptophobic} Z' \to bb \\ \operatorname{Leptophobic} Z' \to tt \\ \operatorname{SSM} W' \to \ell\nu \\ \operatorname{SSM} W' \to \tau\nu \\ \operatorname{SSM} W' \to vt \\ \operatorname{HVT} W' \to WZ \to \ell\nu qq \operatorname{mo} \\ \operatorname{HVT} W' \to WZ \to \ell\nu \ell\ell' t' \operatorname{m} \\ \operatorname{HVT} W' \to WH \to \ell\nu bb \operatorname{mo} \\ \operatorname{HVT} Z' \to ZH \to \ell\ell/\nu bb \operatorname{mo} \\ \operatorname{LRSM} W_R \to \mu N_R \end{array}$	$\begin{array}{c} 2 \ e, \mu \\ 2 \ \tau \\ - \\ 0 \ e, \mu \\ 1 \ e, \mu \\ 1 \ \tau \\ - \\ del \ B \\ 1 \ e, \mu \\ odel \ C \\ 3 \ e, \mu \\ del \ B \\ 1 \ e, \mu \\ odel \ B \\ 2 \ \mu \\ 2 \ \mu \end{array}$	_ 2 b ≥1 b, ≥2 J _ 2 j / 1 J 2 j (VBF) 1-2 b, 1-0 j 1 J	– Yes Yes Yes Yes Yes Yes Yes	139 36.1 36.1 139 139 139 139 139 139 139 139 80	Z' mass Z' mass Z' mass Z' mass W' mass W' mass W' mass W' mass W' mass Z' mass W _R mass	2 2.* GeV	5.1 TeV 4.2 TeV 4.1 TeV 6.0 TeV 5.0 TeV 4.4 TeV 4.3 TeV 3.3 TeV 3.2 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-2021-025 ATLAS-CONF-2021-043 2004.14636 ATLAS-CONF-2022-005 2207.00230 2207.00230 1904.12679
D7	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Vector LQ 3 rd gen	$2 e 2 \mu 1 \tau 0 e, \mu \ge 2 e, \mu, \ge 1 \tau 0 e, \mu, \ge 1 \tau 1 \tau$	$ \begin{array}{c} \geq 2 j \\ \geq 2 j \\ 2 b \\ \geq 2 j, \geq 2 b \\ \tau \geq 1 j, \geq 1 b \\ \tau = 1 j, 2 b \\ 0 - 2 j, 2 b \\ 2 b \end{array} $	Yes Yes Yes - Yes Yes Yes	139 139 139 139 139 139 139 139	LQ mass LQ mass LQ" mass LQ [#] mass LQ [#] mass LQ ⁴ mass LQ ⁴ mass LQ ³ mass	1.8 T 1.7 Te 1.2 TeV 1.24 TeV 1.43 TeV 1.26 TeV 1.26 TeV	eV V ≥V	$\begin{split} \beta &= 1\\ \beta &= 1\\ \mathcal{B}(\mathrm{LQ}_3^u \to b\tau) &= 1\\ \mathcal{B}(\mathrm{LQ}_3^u \to t\nu) &= 1\\ \mathcal{B}(\mathrm{LQ}_3^d \to t\tau) &= 1\\ \mathcal{B}(\mathrm{LQ}_3^d \to b\nu) &= 1\\ \mathcal{B}(\mathrm{LQ}_3^d \to b\tau) &= 0.5, \text{ Y-M coupl.} \end{split}$	2006.05872 2006.05872 2108.07665 2004.14060 2101.11582 2101.12527 2108.07665
Vector-like fermions	$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	2 <i>e</i> /2 <i>µ</i> /≥3 <i>e</i> ,, multi-channe X 2(SS)/≥3 <i>e</i> ,, 1 <i>e</i> , <i>µ</i> 1 <i>e</i> , <i>µ</i> 0 <i>e</i> , <i>µ</i> multi-channe	$\begin{array}{ll} \mu \geq 1 \ b, \geq 1 \ j \\ el \\ \mu \geq 1 \ b, \geq 1 \ j \\ \geq 1 \ b, \geq 3 \ j \\ \geq 1 \ b, \geq 1 \ j \\ \geq 2b, \geq 1 \ j, \geq 1 \\ el \\ \geq 1 \ j \end{array}$	– Yes Yes IJ – Yes	139 36.1 36.1 139 36.1 139 139	T mass B mass T _{5/3} mass T mass Y mass B mass τ' mass	1.4 TeV 1.34 TeV 1.64 TeV 1.8 Tr 1.85 T 2.0 898 GeV	/ eV eV TeV	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 fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton ν^*	- 1 γ - 3 e,μ 3 e,μ,τ	2 j 1 j 1 b, 1 j –	- - - -	139 36.7 139 20.3 20.3	q* massq* massb* massl* massv* mass	1.6 TeV	6.7 TeV 5.3 TeV 3.2 TeV 3.0 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0$ TeV $\Lambda = 1.6$ TeV	1910.08447 1709.10440 1910.0447 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana v Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Multi-charged particles Magnetic monopoles $\sqrt{s} = 8$ TeV	2,3,4 e, μ 2 μ 2,3,4 e, μ (S 2,3,4 e, μ (S 3 e, μ , τ 	2j 2 j S) various S)	Yes Yes TeV	139 36.1 139 139 20.3 139 34.4	N ⁰ mass N _R mass H ^{±±} mass 350 H ^{±±} mass 40 multi-charged particle mass monopole mass	910 GeV GeV 1.08 TeV 00 GeV 1.59 TeV 2	3.2 TeV 37 TeV	$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ DY production DY production DY production, $\mathcal{B}(H_L^{+\pm} \rightarrow \ell \tau) = 1$ 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-2022-034 1905.10130
		partial data	full da	ata		10 ⁻¹	1	1() Mass scale [TeV]	

Singlet scalar $(1,1)_0$ Doublet scalar (1,2)_{1/2} Doublet scalar $(1,2)_{3/2}$



7

Muon Colliders for the EWK Era

Muon colliders blur the dichotomy of probing micsocopic phenomena with **precision** or **energy**.



Muon annihilation

deploys the entire energy of the collider



Moreover, muon collider energy in a (relatively) clean environment provides precision from energy.



Vector boson fusion

leverages the muon's virtual boson content





Muon Colliders as EWK Laboratories

[Han, Ma, Xie, 2007.14300]



Longitudinal polarizations play a key role, making an extraordinary laboratory for EWSB



Dominant signals and backgrounds both have electroweak cross sections

How do muons illuminate the physics vision?

What S the Origin \mathbf{O}^{\dagger} Mass





What is the BCS Theory of EWSB?

Theories that predict the Higgs mass & EWSB provide sharp targets for new physics.



Direct targets set by the observed Higgs mass (e.g. supersymmetry)



What is the BCS Theory of EWSB?

Theories that predict the Higgs mass & EWSB provide sharp targets for new physics.

Compositeness leaves fingerprints in EFT:

 $\mathcal{O}_{2W} = (D_{\mu}W^{\mu\nu,a})^2$

$$\mathcal{O}_{2B} = \left(\partial_{\mu}B^{\mu\nu}\right)^2$$

 $\mathcal{O}_W = ig(H^{\dagger}\sigma^a D_{\mu}H)D^{\nu}W^a_{\mu\nu}$

 $\mathcal{O}_B = ig'(H^{\dagger}D_{\mu}H)\partial^{\nu}B_{\mu\nu}$

$$\mathcal{O}_{tD} = (\bar{t}\gamma^{\mu}t)(\partial^{\nu}B_{\mu\nu})$$

Splendid example of precision from energy... (See also [Buttazzo, Franceschini, Wulzer 2012.11555])







Electroweak Breaking

Our current experimental knowledge of the Higgs potential is far from the cartoon we usually show...



(If you like this way of presenting Higgs self-coupling precision, feel free to use it w/ credit to R. Petrossian-Byrne.)





14



Electroweak Breaking

[Accettura et al. 2303.08533]



HL-LHC

μ**C (10 TeV)**



The birth and death of the Universe?





[2015 NSAC LRP / 1501.06477]

First-order electroweak phase transition?

Vacuum stability?

Electroweak Symmetry?

Local EFT of the Higgs does not have electroweak symmetry given e.g. extra EWSB or heavy particles acquiring >1/2 mass from Higgs. Many examples viable, fully covered by 10 TeV μ C. [Banta, Cohen, NC, Lu, Sutherland, 2110.02967]







17



Experimentally demonstrate Goldstone equivalence



Electroweak Restoration, **Electroweak Radiation**

Electroweak radiation: Sudakov suppression of non-emission probability becomes significant @ 10 TeV...

$$\exp\left[-\operatorname{Casimir} \times \frac{g^2}{16\pi^2} \log^2\left(\frac{E_{\rm cm}^2}{m_W^2}\right)\right] \approx \exp\left[-1\right]$$

[Wulzer; Chen, Glioti, Rattazzi, Ricci, Wulzer 2202.10509]]



,*b*,..

What is the origin of flavor?

First high-energy accelerator to primarily collide second-generation fermions.

Direct access to hypothetical new particles associated with flavor structure

Indirect access to flavor structure via lepton flavor violating operators



An outstanding probe of explanations for B flavor anomalies, indicative of complementarity w/ future signs of flavor violation. [Huang, Queiroz, Rodejohann, 2101.04956; Huang, Sana, Queiroz, Rodejohann, 2103.01617, Asadi, Capdevilla, Cesarotti, Homiller 2104.05720]







What is the nature of dark matter?

An ideal laboratory for producing & detecting weakly-interacting dark matter.

We know DM is there; coincidence of Ω_b , Ω_{dm} suggests interactions beyond gravitational



[Han, Liu, Wang, Wang, 2009.11287, lumi updated for μ SG], see also [Capdevilla, Meloni, Simoniello, Zurita 2102.11292; Bottaro, Buttazzo et al. 2107.09688 & 2205.04486]

"Minimal dark matter"

(Electroweak multiplet w/ neutral lightest particle)

Muon Collider 5σ Reach ($\sqrt{s} = 3, 6, 10, 14, 30, 100$ TeV)







[Ruhdorfer, Salvioni, Weiler 191 \bigcirc 4170]



Dark Portals: µC Beam Dump?





[Cesarotti, Homiller, Mishra, Reece 2202.12302]













Nature of the Neutrino Sector: Heavy Neutral Leptons



[Li, Liu, Lyu 2301.07117]

 10^{4}

µC/vF Complementarity



[Delahaye et al. 1803.07431]

High-energy Neutrinos?



[Han, Ma, Xie, 2007.14300] 10⁰

Neutrino radiation for high-energy fixed target? Akin to FASER ν but w/ well-known neutrino flavor composition & spectrum, narrow beam.

Neutrino-neutrino or neutrino-charged lepton collisions? Probe neutrino interactions, dark sector portals, ...

Compelling complementarity

E.g. next-gen. electron EDM experiments sensitive to ~20 TeV particles in Barr-Zee diagrams; same diagram probed in muon colliders



(See also: [Homiller, Lu, Reece 2203.08825]

Any new physics contributions to Muon g-2 efficiently probed at muon colliders [Capdevilla, Curtin, Kahn, Krnjaic, 2006.16277; Buttazzo & Paradisi, 2012.02769; Capdevilla, Curtin, Kahn, Krnjaic, 2101.10334; Chen, Wang, Yao 2102.05619; Yin, Yamaguchi 2012.03928]







MIT TMATE . 1.

-

Conclusions









Conclusions

High-energy muon colliders offer the energy, precision, and interactions needed to realize the promise of the electroweak era.



High-energy muon colliders offer the energy, precision, and interactions needed to realize the promise of the electroweak era.

From development to operation, a muon collider will build countless bridges to the diverse frontiers of high-energy physics.



Conclusions





High-energy muon colliders offer the energy, precision, and interactions needed to realize the promise of the electroweak era.

From development to operation, a muon collider will build



Conclusions



High-energy muon colliders offer the energy, precision, and interactions needed to realize the promise of the electroweak era.

From development to operation, a muon collider will build countless bridges to the diverse frontiers of high-energy physics.

Conclusions

The muons are calling, and we must go.



