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# Future colliders

UK Input to European Particle Physics Strategy Update

Durham, 04/04/2018



#### proton-proton 14 TeV [3/ab]



	electron-positron	top threshold [100/fb] 380 GeV [500/fb] 1.5 TeV [1.5/ab] 3 TeV [3/ab]
ilc	electron-positron	250 GeV [2/ab] 350 GeV [200/fb] 500 GeV [4/ab]
FEC hh ee he	proton-proton electron-positron electron-proton	100 TeV [30/ab], <u>HE-LHC 27 TeV</u> [15/ab] 91 [5.6/ab/yr], 160 [1.6/ab/yr], 240 [2.5/ab], 365 GeV [130/fb/yr] e(60 GeV) p(50 TeV)
CEPC	proton-proton electron-positron electron-proton	100 TeV as SPPC 91 ["10 x LEP"], 240 GeV [5/ab] e(60 GeV) p(35 TeV)

#### proton-proton

14 TeV [3/ab]



TDR 2013

	250 GeV [2/ab]
electron-positron	350 GeV [200/fb]
	500 GeV [4/ab]

TLEP. 13 CDR 13, YRS '16 March 182 16 100 TeV [30/ab], <u>HE-LHC 27 TeV</u> [15, proton-proton 91 [5.6/ab/yr], 160 [1.6/ab/yr], 240 [2.5/ab], 365 G electron-positron e(60 GeV) p(50 TeV) electron-proton PreCDR'15 CDR Spring 15 182



100 TeV as SPPC proton-proton 91 ["10 x LEP"], 240 GeV [5/ab] electron-positron e(60 GeV) p(35 TeV) electron-proton

#### ► LHC has entered the TeV scale sensitivity range

Selected CMS SUSY Results\* - SMS Interpretation ICHEP '16 - Moriond '17 m-111.1 → m1 SUS-16-014 SUS-16-033 OKMHT P-11.1 - 91 SUS-16-015 SUS-16-036 OKMT2) 10-11-1-10 Z SUS-16-014 SUS-16-033 OKMHT) SUS-16-015 SUS-16-036 OKMT2) m-111.1 → 10 1 SUS-16-016 0( a., ) 10 - 10 j . j - 10 j SUS-16-014 SUS-16-033 O(MHT) PP→11 1.1 → 11 1 SUS-16-015 SUS-16-036 O(MT2) SUS-16-016 0( a., ) PR-10.0.0 -+ 113 SUS-16-019 SUS-16-042 18(A.¢) 10-18 8.8 -112 SUS-16-020 SUS-16-035 2I same-eign PP-188.8-172 SUS-16-022 SUS-16-041 Multilepton PP→11 1 . 1 → 11 2 SUS-16-090 OF PP -18 8 -8 -1 H Z 1004.0 (M<sub>mente</sub> - M <sub>100</sub> = 20 GeV) (M<sub>1</sub> - M<sub>100</sub> = 5 GeV) SUS-16-000 0I 10 → 11 → 102 PP-188.8 -14 1 ÷ii.i → 42, → 44 ¥2 SUS-16-019 SUS-16-042 18(A.e) 200.5 ₩~88.8~92 ~91¥2 ₩~88.8~92 ~91¥2 SUS-16-020 SUS-16-035 2I same-sign x=0.5 SUS-16-020 SUS-16-035 2I same-sign (M\_\_\_\_\_ - M\_\_\_\_\_ = 20 GeV) +88.8 → 44(2 / 2 ) → 44(442)2 +88.8 → 44(2 / 2 ) → 44(442)2 SUS-16-014 SUS-16-033 OKMHT) 2+0.5 SUS-16-022 SUS-16-041 Multilepton 200.5 SUS-16-014 SUS-16-033 OKMHT) SUS-16-015 SUS-16-036 OKMT2) PP-41,1-12 SUS-16-016 0( a., ) PP-41,1-+12 SUS-16-027 SUS-17-031 21 opposite-sign SUS-16-020 SUS-16-051 11 SUS-16-029 SUS-16-049 OI pp-41,1-12 SUS-16-000 OI pp-41,1 → e Ž (Max exclusion for M <sub>Mober</sub> - M <sub>LBA</sub> < 80 GeV) (Max exclusion for M mone - M us < 80 GeV) OI(MT2) CMS Preliminary (Max exclusion for M <sub>linke</sub> - M <sub>Lin</sub> < 00 GeV) (Max exclusion for M <sub>linke</sub> - M <sub>Lin</sub> < 00 GeV) SUS-16-049 08 SUS-16-025 SUS-16-048 21 soft pp -11,1 -+ b11 2<sup>®</sup> (+ body) pp −41,1 → bff 2 (+body) pp −41,1 → bff 2 (+body) (Max exclusion for M <sub>Beller</sub> - M <sub>LBP</sub> < 00 GeV) (Max exclusion for M <sub>Beller</sub> - M <sub>LBP</sub> < 00 GeV) SUS-16-029 SUS-16-049 0 √s = 13TeV SUS-16-091 11 poft SUS-16-020 SUS-16-051 11 m-il.i-z.s-sw.z Tool . PP-41,1-2 b-bW 2 SUS-16-029 SUS-16-049 OI 2-0.5 m-11,1-12 b→bW 2 ORMT25 200.5  $L = 12.9 \text{ fb}^{-1}L = 35.9 \text{ fb}^{-1}$ 11,1→2 b→bW 2 21 opposite-sign -0 S pp -46, b → b Z SUS-16-014 SUS-16-033 OKMHT pp -- 66, 6 -- b Z SUS-16-015 SUS-16-036 OKMT2) PP-60,0-10 SUS-16-016 0( a., ) pp→bb,b→b Z 102 OI m-44.4 →41 q +q (u,d,c,s) SUS-16-014 SUS-16-033 O(MHT) +q (u,d,c,s) 10-44.4 +41 SUS-16-015 SUS-16-036 OVMT2  $\hat{1} - \hat{1}\hat{1}$  $\hat{1} - \hat{1}\hat{1}$  $\hat{1} - \hat{1}\hat{1}$ ..... SUS-16-024 SUS-16-022 x=0.5 Multilecton + 2 same-sion (5 200.95 epton (by enriched z=0.5 i -mvi i x=0.5 oton (tau do For decays with intermediate mass, SUS-16-024 SUS-16-033 Multi March mintermediate = x · m Hother +(1-x)· m - M .... < 40 GeV) US-16-025 DUG-1 21 and (Max exclusion for M 200 400 600 800 1000 1200 1400 2000 0 1600 1800 Mass Scale [GeV]

\*Observed limits at 95% C.L. - theory uncertainties not included Only a selection of available mass limits. Probe \*up to\* the quoted mass limit for m =0 GeV unless stated otherwise

## Status of LHC measurements

#### rearly stage: constraints can be avoided in non-minimal scenarios

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5	
$\star m_{h1} \; (\text{GeV})$	125.1	125.1	57.83	86.79	33.17	
$m_{h_2} (\text{GeV})$	260.6	228	125.1	125.1	64.99	
$\star m_{h_3} (\text{GeV})$	449.6	311.3	299	291.8	125.1	
$\star \alpha_1$	-0.04375	0.05125	-1.102	-1.075	1.211	
$\star \alpha_2$	0.4151	-0.4969	1.136	0.8628	-1.319	
$\star \alpha_3$	-0.6983	-0.5059	-0.02393	-0.0184	1.118	
$\star v_S \; (\text{GeV})$	185.3	52.3	376.9	241.9	483.2	
$v_A \; (\text{GeV})$	371.3	201.6	236.3	286.1	857.8	
$\lambda$	1.148	1.018	0.869	0.764	0.5086	
$\delta_2$	-0.9988	1.158	-0.4875	-0.4971	0.01418	
$d_2$	1.819	3.46	0.6656	0.9855	0.003885	
$m^2 \; ({ m GeV}^2)$	$5.118 \times 10^4$	$-5.597 \times 10^4$	$2.189 \times 10^4$	$1.173 \times 10^{4}$	$-2.229 \times 10^4$	
$b_2 \; (\text{GeV}^2)$	$-3.193 \times 10^4$	$-5.147 \times 10^4$	$-3.484 \times 10^4$	$-3.811 \times 10^4$	1362	
$b_1 \; (\text{GeV}^2)$	$9.434 \times 10^4$	$5.864 \times 10^4$	$1.623 \times 10^4$	$1.599 \times 10^{4}$	3674	
$a_1 \; (\text{GeV}^3)$	$-1.236 \times 10^{7}$	$-2.169 \times 10^{6}$	$-4.325 \times 10^{6}$	$-2.735 \times 10^{6}$	$-1.255 \times 10^{6}$	
$\mu_{h_1}^C/\mu_{h_1}^T$	0.0127	0.0407	0.365	0.117	0.687	
$\mu_{h_1}$	0.836	0.771	0.0362	0.0958	0.00767	
$\sigma_1 \equiv \sigma(gg \to h_1)$	36.1 [ph]	33 3 [nh]	6.42 [ph]	8.03 [pb]	4.61 [pb]	
$\sigma_1  imes { m BR}(h_1  imes { m I})$	7.55 [pb]	0.01 [fb]				
$\sigma_1  imes \mathrm{BR}(h_1$	$\oplus$ exotic (rare) signatures 0.					
$\sigma_1  imes \mathrm{BR}(h_1$	21.3 [pb] 19.6 [pb] 5.48 [pb] 6.6 [pb] 4.01 [pb]					
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau \tau)$	2.29 [pb]	2.11 [pb]	501 [fb]	659 [fb]	323 [fb]	
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma \gamma)$	83.7 [fb]	77.2 [fb]	2.87 [fb]	9.13 [fb]	0.617  [fb]	

e.g. [Costa, Mühlleitner, Sampaio, Santos `15] scenarios for run-2

#### Conclusions for HEP ? No guaranteed discoveries. Best case(s)?

the SM is flawed

no evidence for exotics yet

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Higgs/top properties are central to BSM and a clear deliverable of any future collider

#### Conclusions for HEP ? No guaranteed discoveries. Best case(s)?

#### direct vs indirect precision? energy coverage?

#### the SM is flawed

no evidence for exotics yet

big part of WG studies focus on Higgs physics Higgs/top properties are central to BSM and a clear deliverable of any future collider

Higgs mass, couplings, (width),...

#### Conclusions for HEP ? No guaranteed discoveries. Best case(s)?

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Higgs properties are central to BSM and a clear deliverable of any future collider

### Effective Field Theory

 $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{i} \frac{c_i}{\Lambda^2} \mathcal{O}_i$ 

[Buchmüller, Wyler `87] [Hagiwara, Peccei, Zeppenfeld, Hikasa `87] [Giudice, Grojean, Pomarol, Rattazzi `07] [Grzadkowski, Iskrzynski, Misiak, Rosiek `10]

59 B-conserving operators  $\otimes$  flavor  $\otimes$  h.c., d=6 2499 parameters (reduces to 76 with N<sub>f</sub>=1)



Higgs mass precision can be limitation of coupling fit precision

**Higgs mass** 

$$\delta_W = 6.9 \cdot \delta m_h, \quad \delta_Z = 7.7 \cdot \delta m_h$$

[Almeida, Lee, Pokorski, Wells `13]



Higgs mass precision can be limitation of coupling fit precision

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$$\delta_W = 6.9 \cdot \delta m_h, \quad \delta_Z = 7.7 \cdot \delta m_h$$

[Almeida, Lee, Pokorski, Wells `13]

► through leptonic recoil in  $Z \rightarrow \mu^+\mu^$ the Higgs mass can be constrained to 14 MeV [LCC Physics Working Group `18]



Higgs mass

## Status of LHC measurements



everything is consistent with the SM Higgs hypothesis (so far) but what are the implications for new physics/future colliders?

# **HL-LHC** projections



uniform coupling weak boson modifier  $\kappa_v$ 

## FCC-hh projections



large relative improvement for ttH (pdfs & phasespace)

# FCC-hh projections



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[Durieux, Grojean, Gu, Wang `17]

# Coupling projections: HL-LHC

#### precision reach of the 12-parameter fit in Higgs basis



see also [LCC working group `18], [CEPC working group `17]

Precision environment of a lepton colliders allows to pin down gauge-Higgs sector at the per mille level in case of the Z [Durieux, Grojean, Gu, Wang `17]

# Coupling projections: HL-LHC

#### precision reach of the 12-parameter fit in Higgs basis



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- Precision environment of a lepton colliders allows to pin down gauge-Higgs sector at the per mille level in case of the Z
- ► CLIC energy coverage beneficial to pin down high energy behavior of electroweak sector e.g.  $c_{Z\Box} g^2 Z_{\mu} \partial_{\nu} Z_{\mu\nu}$

LHC blind spots: Higgs potential

# ► dimension 6 deformations of the Higgs potential $V(H^{\dagger}H)_6 \supset c_6/\Lambda^2(H^{\dagger}H)^3$

modify Higgs self-interactions. Large top-threshold interference.



## LHC blind spots: Higgs potential



### LHC blind spots: HH @ 100 TeV





## LHC blind spots: HH @ 100 TeV





# LHC blind spots: HH @ e<sup>+</sup> e<sup>-</sup>

direct probe of Higgs self
 interactions possible for higher
 energies

$$\Delta \lambda / \lambda = 40\%$$
 at  $\sqrt{s} = 1.4 \,\text{TeV}$ ,  
 $\Delta \lambda / \lambda = 22\%$  at  $\sqrt{s} = 3 \,\text{TeV}$ .

► recent EFT fit to Zh(h) production show sensitivity to  $e^+e^-$ →Zhh  $[\langle (\delta\sigma)^2 \rangle]^{1/2} = 2.4\% \oplus 5\%$  EFT systematics,  $\sigma/(SM) = 1 + 0.56c_6 + \cdots$ self-coupling extraction becomes possible at 500 GeV at ~14%

## Summary

- community is active in making the case for the next generation of colliders
- ► (HL-)LHC input to strategy is crucial

complementarity in searches for light resonances/dark matter

constrain blind directions vice versa

FCC(hh)/... although at an early stage in planning clearly has the highest energy reach

identify BSM parameter space after LHC

