# Recent CMS results on Standard Model Physics

CIPANP September 1, 2022



Philip Chang University of Florida



#### Higgs physics is broad and I cannot cover all!

#### http://cms-results.web.cern.ch/cms-results/ public-results/publications/HIG/index.html

169	HIG-19-016	Measurement of the Higgs boson inclusive and differential fiducial production cross sections in the diphoton decay channel with pp collisions at $\sqrt{s}=$ 13 TeV	Submitted to JHEP	25 August 2022
168	HIG-21-001	Searches for additional Higgs bosons and for vector leptoquarks in $\pi r$ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV	Submitted to JHEP	4 August 2022
167	HIG-21-006	Search for CP violation in ttH and tH production in multilepton channels in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Submitted to JHEP	4 August 2022
166	HIG-21-003	Search for the exotic decay of the Higgs boson into two light pseudoscalars with four photons in the final state in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Submitted to JHEP	2 August 2022
165	HIG-21-015	Search for the Higgs boson decay to a pair of electrons in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Submitted to PLB	30 July 2022
164	HIG-21-010	Search for a charged Higgs boson decaying into a heavy neutral Higgs boson and a W boson in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Submitted to JHEP	4 July 2022
163	HIG-22-001	A portrait of the Higgs boson by the CMS experiment ten years after the discovery	Nature 607 (2022) 60	4 July 2022
162	HIG-20-004	Search for nonresonant Higgs boson pair production in the four leptons plus two b jets final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV	Submitted to JHEP	22 June 2022
161	HIG-21-002	Search for Higgs boson pairs decaying to WWWW, WW $_{TT}$ and $_{TTTT}$ in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Submitted to JHEP	21 June 2022
160	HIG-20-013	Measurements of the Higgs boson production cross section and couplings in the WW boson pair decay channel in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Submitted to EPJC	20 June 2022
159	HIG-20-010	Search for nonresonant Higgs boson pair production in final state with two bottom quarks and two tau leptons in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Submitted to PLB	19 June 2022
158	HIG-20-008	Search for Higgs boson decays into Z and J/ $\psi$ and for Higgs and Z boson decays into J/ $\psi$ or Y pairs in pp collisions at $\sqrt{s}=$ 13 TeV	Submitted to PLB	7 June 2022
157	HIG-21-008	Search for Higgs boson decay to a charm quark-antiquark pair in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Accepted by PRL	11 May 2022
156	HIG-20-007	Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the rr final state	Accepted by PRD	10 May 2022
155	HIG-20-018	Search for light Higgs bosons from supersymmetric cascade decays in pp collisions at $\sqrt{s}=$ 13 TeV	Accepted by EPJC	28 April 2022
154	HIG-19-014	Search for Higgs boson decays to a Z boson and a photon in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Accepted by JHEP	27 April 2022
153	HIG-19-010	Measurements of Higgs boson production in the decay channel with a pair of $ au$ leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV	Submitted to EPJC	27 April 2022
152	HIG-20-005	Search for Higgs boson pair production in the four b quark final state in proton-proton collisions at $\sqrt{s}=$ 13 TeV	PRL 129 (2022) 081802	19 February 2022
151	HIG-21-013	First evidence for off-shell production of the Higgs boson and measurement of its width	Submitted to NP	14 February 2022
150	HIG-20-003	Search for invisible decays of the Higgs boson produced via vector boson fusion in proton-proton collisions at $\sqrt{s}$ = 13 TeV	PRD 105 (2022) 092007	27 January 2022

#### Just this year alone starting January, CMS produced 20 papers!

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	Search for invisible decays of the Higgs boson produced via vector boson fusion in proton-proton collisions at $\sqrt{s}=$ 13 TeV	27 January 2022
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?? SM Higgs

UF

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#### If Higgs Physics is broad than what does it mean for SM Physics?

# Meaning of "SMP" in CMS



If it has Higgs, it falls to Higgs If it has top quark, it falls to top quark What's left? W, Z,  $\gamma$ , ...



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### Meaning of "SMP" in CMS



Minor exception: jets only final states are still in SMP (i.e. QCD studies are included)





#### **Recent results**



154	<u>SMP-18-014</u>	Precision measurement of the Z boson invisible width in pp collisions at $\sqrt{s}=$ 13 TeV	Submitted to PLB	14 June 2022
153	<u>SMP-21-013</u>	Observation of same-sign WW production from double parton scattering in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Accepted by PRL	6 June 2022
152	<u>SMP-21-001</u>	Observation of electroweak W <sup>+</sup> W <sup>-</sup> pair production in association with two jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV	Submitted to PLB	11 May 2019
151	<u>SMP-20-003</u>	Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan production in proton-proton collisions at $\sqrt{s}$ = 13 TeV	Submitted to EPJC	10 May 2022
150	<u>SMP-19-009</u>	Measurement of differential cross sections for the production of a Z boson in association with jets in proton-proton collisions at $\sqrt{s}=$ 13 TeV	Submitted to PRD	5 May 2022
149	<u>SMP-21-002</u>	Measurement of the Drell-Yan forward-backward asymmetry at high dilepton masses in proton-proton collisions at $\sqrt{s}=$ 13 TeV	JHEP 08 (2022) 063	24 February 2022
148	<u>SMP-18-011</u>	Precision measurement of the W boson decay branching fractions in proton-proton collisions at $\sqrt{s}=$ 13 TeV	PRD 105 (2022) 072008	19 January 2022

#### Focusing on just this year



### **Recent results in SMP**

154	<u>SMP-18-014</u>	Precision measurement of the Z boson invisible width in pp collisions at $\sqrt{s}=$ 13 TeV	Submitted to PLB	14 June 2022
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### **Recent results in SMP**

So many since last CIPANP	•
so I can't cover all!	

154	SMP-18-014	Precision measurement of the Z boson invisible width in on collisions at $\sqrt{s}=13$ TeV	Submitted to PLB	14 June 2022
45	500 31 613	Observation of some size MW architeling four deable notice contrained in maters and a collision at $\tilde{k}=42$ YeV	Langeled by DRI	d have 2022
135	amenaria	Contraction of sampling in the production from double particle scattering in proceeding to incontraction at $\chi_0 = 12$ meV	NUMPER OF THE	0.5410 2022
152	SMP-21-001	Observation of electroweak W"W" pair production in association with two jets in proton-proton collisions at $\sqrt{y}$ = 13 TeV	Submitted to PLB	11 May 2019
151	SMP-20-003	Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan production in proton-proton collisions at $\sqrt{x}$ = 13 TeV	Submitted to EPJC	10 May 2022
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148	SMP-18-011	Precision measurement of the W boson decay branching fractions in proton-proton collisions at $\sqrt{s}=$ 13 TeV	PRD 105 (2022) 072008	19 January 2022
147	SMP-20-015	Measurement of the production cross section for Z + b jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV	PRD 105 (2022) 092014	17 December 2021
146	SMP-20-013	Evidence for WWWZ vector boson scattering in the decay channel $\ell_{\lambda}$ on produced in association with two lets in proton-proton collisions at $\sqrt{\kappa}=13$ TeV	Submitted to PLB	9 December 2021
			0.1	
145	0402-10-010	we associated production of a wide solution and a channing state in proton-proton containers at $\sqrt{r} = 0$ rev	SUBMITING ID EP-JC	2 Depember 2021
144	SMP-20-005	Measurement of $W^{\pm}\gamma$ differential cross sections in proton-proton collisions at $\sqrt{r} = 13$ TeV and effective field theory constraints	PRD 105 (2022) 052003	27 November 2021
143	SMP-20-011	Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at $\sqrt{s}=$ 13 TeV	JHEP 62 (2022) 142	19 November 2021
142	SMP-20-014	Measurement of the inclusive and differential WZ production cross sections, polarization angles, and triple gauge couplings in pp collisions at $\sqrt{s}=$ 13 TeV	JHEP 07 (2022) 032	21 October 2021
141	SMP-20-007	Measurement of double-parton scattering in inclusive production of four jets with low transverse momentum in proton-proton collisions at $\sqrt{s}=$ 13 TeV	JHEP 01 (2022) 177	29 September 2021
140	SMP-20-010	Study of quark and gluon jet substructure in Z+jet and dijet events from pp collisions	JHEP 01 (2022) 188	8 September 2021
139	SMP-20-012	Measurements of the electroweak diboson production cross sections in proton-proton collisions at $\sqrt{\epsilon}=$ 5.02 TeV using leptonic decays	PRL 127 (2021) 191801	2 July 2021
		Measurement of the electroweak production of Z <sub>2</sub> and two jets in proton-proton collisions at $\sqrt{g}$ = 13 TeV and constraints on anomalous quartic gauge		
138	SMP-20-016	couplings	PRD 104 (2021) 072001	21 June 2021
137	SMP-20-009	Measurements of Z bosons plus jets using variables sensitive to double parton scattering in pp collisions at 13 TeV	JHEP 10 (2021) 176	30 May 2021
136	SMP-19-013	Measurements of the $pp \rightarrow W^2 \gamma \gamma$ and $pp \rightarrow Z \gamma \gamma$ cross sections at $\sqrt{\hat{r}}$ = 13 TeV and limits on anomalous quartic gauge couplings	JHEP 10 (2021) 174	26 May 2021
135	SMP-17-008	Measurements of angular distance and momentum ratio distributions in three-jet and Z + two-jet final states in pp collisions	EPUC 81 (2021) 852	17 February 2021
134	SMP-19-006	Hard color-singlet exchange in dijet events in proton-proton collisions at $\sqrt{e}=$ 13 TeV	PRD 104 (2021) 032009	13 February 2021
133	8MP-19-012	Neasurement of Wy conduction cross section in preton-proton collisions at $\sqrt{5} = 13$ TeV and constraints on effective Sold theory coefficients	PRI 126 (2021) 252002	3 February 2021
- 66	5000 - 1.0-500A	$\mathbf{M}_{\mathbf{x}} = \mathbf{M}_{\mathbf{x}} + $	LOW DOC 1606 1 LADOUDA	51 minutes all 21
132	SMP-19-010	measurements or the offerential cross sections of the production of Z+jets and y+jets and of Z boson emission collinear with a jet in pp collisions at $\sqrt{r} = 13$ TeV	JHEP 06 (2021) 285	3 February 2021
	SMP-18-003	Measurement of the Z boson differential production cross section using its invisible decay mode (Z $\rightarrow s\bar{v}$ ) in proton-proton collisions at $\sqrt{s}$ = 13 TeV	JHEP 05 (2021) 205	16 December 2020
130	SMP-19-011	Measurement of differential cross sections for Z bosons produced in association with charm jets in pp collisions at $\sqrt{s}=$ 13 TeV	JHEP 04 (2021) 109	7 December 2020
129	SMP-20-008	Search for the rare decay of the W boson into a pion and a photon in proton-proton collisions at $\sqrt{x}=$ 13 TeV	PLB 819 (2021) 136409	11 November 2020
129	SMP.20.006	Measurements of production cross sections of polarized same-sion W boson min in secretation with two lats in notion-protoc collision of $K = 49$ TeV	PLB 812 (2020) 136319	20 September 2020
120	0007-20-050		PLD 012 320201 120210	20 окритов 2020
127	SMP-19-001	Measurements of pp $\rightarrow$ ZZ production cross sections and constraints on anomalous triple gauge couplings at $\gamma^{\rm g}=$ 13 TeV	EPUC 81 (2021) 200	2 September 2020
126	8MP-18-004	$W^+W^-$ boson pair production in proton-proton collisions at $\sqrt{s}$ = 13 TeV	PRD 102 (2020) 092001	1 September 2020
125	SMP-19-008	Observation of electroweak production of Wy with two jets in proton-proton collisions at $\sqrt{r}=$ 13 TeV	PLB 811 (2020) 135988	24 August 2020
124	SMP-20-001	Evidence for electroweak production of four charged leptons and two jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV	PLB 812 (2020) 135992	17 August 2020
123	SMP-18-012	Measurements of the W boson rapidity, helicity, double-differential cross sections, and charge asymmetry in pp collisions at 13 TeV	PRD 102 (2020) 092012	10 August 2020
122	SMP-19-014	Observation of the production of three massive gauge bosons at $\sqrt{s}=$ 13 TeV	PRI, 125 (2020) 151802	19 June 2020
1.11	910 16 0/2	Dependence of inclusive lat production on the apti- $b_{\rm c}$ distance parameter in an collisions of $\beta_{\rm c}=11$ TeV	NED 13 (3030) 092	11 May 2020
120	349-19-012	Measurements of production cross sections of WZ and same-sign www boson pairs in association with two jets in proton-proton costsions at $\sqrt{y}$ = 13 lev	PLB 809 (2020) 135710	4 May 2020
	SMP-18-007	Measurement of the cross section for electroweak production of a Z boson, a photon and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on anomalous quartic couplings	JHEP 06 (2020) 076	23 February 2020
118	SMP-19-004	Measurement of the associated production of a Z boson with charm or bottom quark jets in proton-proton collisions at $\sqrt{z}=$ 13 TeV	PRD 102 (2020) 032007	19 January 2020
		Determination of the strong coupling constant as(mr) from measurements of inclusive W <sup>±</sup> and Z boson production cross sections in proton-proton collisions		
117	3MP-16-010	at $\sqrt{r} \equiv$ 7 and 8 TeV	JHEP 06 (2020) 018	9 December 2019
116	SMP-18-015	Evidence for WW production from double-parton interactions in proton-proton collisions at $\sqrt{s}=$ 13 TeV	EPJC 80 (2020) 41	13 September 2019
115	SMP-17-010	Measurements of differential Z boson production cross sections in proton-proton collisions at $\sqrt{s}=$ 13 TeV	"HEP 12 (2019) 061	9 September 2019
114	SMP-18-008	Search for anomalous triple gauge couplings in WW and WZ production in lepton + jet events in proton-proton collisions at $\sqrt{s}$ = 13 TeV	JHEP 12 (2019) 062	19 July 2019
113	SMP-16-016	Measurements of triple-differential cross sections for inclusive isolated-photon+jet events in pp collisions at $\sqrt{s}=0$ TeV	EPUC 79 (2019) 969	18 July 2019
112	SMP-18-006	Search for anomalous electroweak production of vector boson pairs in association with two lets in proton-proton collisions at 13 TeV	PLB 798 (2019) 134985	17 May 2019
	9MD 47.012	Search for the production of $W^{\pm}W^{\pm}W^{\pm}$ quarter at $\sqrt{c} = 43$ TeV	PPD 100 (2019) 012004	10 May 2019
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110	<u>SMP-17-011</u>	Measurement of electroweak production of a W boson in association with two jets in proton-proton collisions at $\sqrt{s}=13$ TeV	EPJC 80.(2020) 43	10 March 2019
109	SMP-17-009	Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3-jet events in pp collisions at $\sqrt{s}=$ 13 TeV	EP.JC 79 (2019) 773	12 February 2019
108	SMP-18-009	Search for W boson decays to three charged pions	PRL 122 (2019) 151802	30 January 2019
107	SMP-18-001	Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at $\sqrt{s}$ = 13 TeV	PLB 795 (2019) 281	14 January 2019
106	SMP-18-002	Measurements of the pp $\rightarrow$ WZ inclusive and differential production cross section and constraints on charged anomalous triple gauge couplings at $\sqrt{s} =$ 13	JHEP-04.(2019).122	10 January 2019
			NED 10 (0010) 077	71 Dec. 1
160	<u>900-17-001</u>	measurements of the universities of the access access in proton-proton consistents at $\sqrt{x} \equiv 13$ MV	when he here and a sold	21 Geoember 2018
104	SMP-17-014	Measurement of associated production of a W boson and a charm quark in proton-proton collisions at $\sqrt{x}=$ 13 TeV	EPSC 79 (2019) 269	26 November 2018
103	SMP-17-003	Event shape variables measured using multijet final states in proton-proton collisions at $\sqrt{\hat{r}}=$ 13 TeV	JHEP 12 (2018) 117	2 November 2018
102	SMP-17-012	Search for rare decays of Z and Higgs bosons to $J/y$ and a photon in proton-proton collisions at $\sqrt{s}=$ 13 TeV	EPJC 79 (2019) 94	23 October 2018
101	SMP-16-010	Measurements of the differential jet cross section as a function of the jet mass in dijet events from proton-proton collisions at $\sqrt{r}=$ 13 TeV	JHEP 11 (2018) 113	16 July 2018
100	SMP-16-003	Measurement of differential cross sections for inclusive isolated-photon and photon+jets production in proton-proton collisions at $\sqrt{s}=$ 13 TeV	EPUC 79 (2019) 20	2 July 2018
59	SMP-17-005	Measurement of differential cross sections for Z boson pair production in association with jets at $\sqrt{r}=$ 8 and 13 TeV	PLB 789 (2019) 19	28 June 2018
52	SMP-16-007	Measurement of the weak minim anois using the forward-backward asymmetry of Drell-Yan events in on collisions at 8 TeV	EP.IC 78 (2018) 701	3.June 2018
	SMP.16 015	Measurement of differential cross sections for Z bases production is second tion with late to action protocollisions at $-5-45$ TeV	EB.IC 78 (2018) 955	54 4448 2010
	SMP-16-015	Measurement of differential cross sections for Z boson production in association with jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV	EPUC 78 (2018) 985	14 April 2018
97 96	SMP-16-015 SMP-16-018	Measurement of differential cross sections for Z boson production in association with jets in proton-proton collisions at $\sqrt{s} = 13$ TeV Electroweak production of two jets in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV	EP.JC 78 (2018) 965 EP.JC 78 (2018) 569	14 April 2018 28 December 2017
97 96 95	SMP-16-015 SMP-16-018 SMP-16-014	Measurement of differential cross sections for 2 beam production is association with jobs in proton-proton collisions at $\sqrt{c} = 13$ TeV Electroweak production of two jots in association with a 2 beam in proton-proton collisions at $\sqrt{c} = 13$ TeV Azimuthal combinitions for inclusive 3-jot, 3-jot, and 4-jot events in go collisions at $\sqrt{c} = 13$ TeV	EPUC 78 (2018) 085 EPUC 78 (2018) 089 EPUC 78 (2018) 585	14 April 2018 28 December 2017 14 December 2017
97 96 95 94	SMP-16-015 SMP-16-018 SMP-16-014 SMP-15-009	Measurement of affirming areas sections for Zheose production in association with pix in proton-points collision at $\sqrt{c} = 13$ TeV Electrowark production of the join in association with a Zheosen in proton-points collisions at $\sqrt{c} = 13$ W Animelia contains for industry 2 pix, 2 pix, and of a proton-points collisions at $\sqrt{c} = 13$ W Measurement of associated Zenham protons protons proton collisions at $\sqrt{c} = 13$ W	EP.JC 78 (2015) 985 EP.JC 78 (2015) 589 EP.JC 78 (2015) 585 EP.JC 78 (2015) 287	14 April 2018 28 December 2017 14 December 2017 6 November 2017
97 96 95 94 93	SMP-16-015 SMP-16-018 SMP-16-014 SMP-15-009 SMP-17-002	Measurement of affirmential cross sections for 2 boson production in association with join in proton-proton collisions at $\sqrt{c} = 13$ TeV Electrowary productions of the join in an accounting with 2 bosons in proton-proton collisions at $\sqrt{c} = 13$ TeV Admittal correlations for inclusive 2 joint 2 joint and 4 joint events in proton for a 2 To TeV Measurement of affirmential cross sections in the $\phi^2$ variable for inclusive 2 joints proton-protocolisions at $\sqrt{c} = 13$ TeV	EP.42.78 (2018) 085 EP.42.78 (2018) 089 EP.42.78 (2018) 586 EP.42.78 (2018) 287 AHEP 08 (2018) 172	14 April 2018 28 December 2017 14 December 2017 6 November 2017 22 October 2017
97 96 95 94 93 92	SMP-16-015 SMP-16-018 SMP-16-014 SMP-15-009 SMP-17-002 SMP-16-017	Measurement of differential cross sections for 2 beans production in association with jets in proton-proton collisions at $\sqrt{c} = 13$ TeV Electrowark production of two jets in association with a 2 beans in proton-proton collisions at $\sqrt{c} = 13$ TeV Administration constitutions for inclusion 2 jets 3 jets 4 jets and 4 jet events in proton collisions at $\sqrt{c} = 13$ TeV Measurement of associated 2*sharm production in proton-proton collisions at $\sqrt{c} = 15$ TeV Measurement of differential cross sections in the 6 <sup>4</sup> visual for inclusive 2 beans proton-proton collisions at $\sqrt{c} = 15$ TeV Measurement of differential cross sections in the 6 <sup>4</sup> visual for inclusive 2 beans protonerised in proton-proton collisions at $\sqrt{c} = 15$ TeV Measurement of the graph cross sections in the 6 <sup>4</sup> visual for inclusive 2 beans protonerised in proton-protonerised in proton-protonerised in the graph crossing the collision of the collision of the graph crossing the graph crossing the collision of the graph crossing the collision of the graph crossing the collision of the graph crossing the collision of the graph crossing the	EE30278-2015-265 EE30278-2015-368 EE30278-2015-368 EE30278-2015-368 EE30278-2015-387 JHEP-30-2012015-172	14 April 2018 28 December 2017 14 December 2017 6 November 2017 22 October 2017 25 September 2017
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97 96 95 94 93 92 91	SMP-16-018 SMP-16-018 SMP-16-014 SMP-16-009 SMP-17-062 SMP-16-017 SMP-16-017	Measurement of afferendial corest sections for 2 because production is association with joint is proton-proton collisions at $\sqrt{c} = 13$ TeV Electrowark production of the joint in association with 2 bases in proton-proton collisions at $\sqrt{c} = 13$ TeV Admittal correlations for inclusive 2 joint, 3 pict, and 4 pict reversits in pro collisions at $\sqrt{c} = 13$ TeV Measurement of differential cross sections in the $d^+$ variable for inclusive 2 bases in production in pp collisions at $\sqrt{c} = 15$ TeV Measurement of differential cross sections in the $d^+$ variable for inclusive 2 bases production in pp collisions at $\sqrt{c} = 15$ TeV Measurement of the production cross sections in the $d^-$ variable for inclusive 2 bases production in pp collisions at $\sqrt{c} = 15$ TeV Measurements of a gray – ZZ production cross sections and the Z – 4 for knoice for factors, and constraints on anomalous triple gauge couplings at $\sqrt{c} = 13$ TeV	EPUC 28 (2018) 585 EPUC 28 (2018) 589 EPUC 28 (2018) 589 EPUC 28 (2018) 589 EPUC 28 (2018) 587 HEPUC 28 (2018) 172 EPUC 28 (2018) 165 PSUL 28 (2018) 165	14 April 2018 28 December 2017 14 December 2017 0 November 2017 22 October 2017 25 September 2017 18 September 2017
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97 95 94 93 92 91 91	8002-16-313 8002-16-319 8002-16-314 8002-16-313 8002-17-332 8002-17-334 8002-17-334	Measurement of differential orass sections for Z basin production is association with join is proton-points collision at $\zeta_0 = 13$ TW Electrowark production of the spin in associations with a Z basin in proton-points collision at $\zeta_0 = 13$ TW Automatical correlations for inclusive 2.4, 3 jet, and 4 per events in proton-points collision at $\zeta_0 = 13$ TW Measurement of associated 2.4-buts productions in proton-points collisions at $\zeta_0 = 13$ TW Measurement of additional 2.4-buts productions for inclusive 2.5 and proton-points collisions at $\zeta_0 = 15$ W Measurement of additional cores sections in the $\zeta^2$ - variable for inclusive 2 basin production in part collisions at $\zeta_0 = 15$ W Measurement of a light-media cores sections in the $\zeta^2$ - variable for inclusive 2 basin production in proton-points with $\zeta_0 = 15$ W Measurement of a section-point $\zeta_0 = 10$ TW Measurement of values and $\zeta_0 = 10$ associations are associated as a section of the term of term of the term of ter	EP32 78 (2019) 885 EP32 78 (2019) 896 EP32 78 (2019) 896 EP32 78 (2019) 886 EP32 78 (2019) 887 EP32 78 (2019) 887 EP32 78 (2019) 887 EP32 78 (2019) 884 EP33 78 (2019) 884 EP33 78 (2019) 884	14 Agril 2018 28) December 2017 14 December 2017 0 November 2017 22: October 2017 25: September 2017 18: September 2017 8: August 2017
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#### Precision

#### Searches

8

#### **Precision measurements**





# Z boson branching ratio to invisible particles









Use top-quark pair production process BR(Top quark  $\rightarrow$  Wb) ~ 100%







Phys. Rev. D 105 (2022) 072008 *µµ* 



еτ

μτ

ehad

 $\mu$ had



Phys. Rev. D 105 (2022) 072008



**Confirms SM** 



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#### Use measured hadronic

branching ratio

#### Depends on $\alpha_s$ at $M_W$ and CKM elements

$$\frac{\mathcal{B}(W \to q\overline{q}')}{1 - \mathcal{B}(W \to q\overline{q}')} = \sum_{\substack{i=(u,c), \\ j=(d,s,b)}} |V_{ij}|^2 \left[1 + \sum_{i=1}^4 c_i \left(\frac{\alpha_S}{\pi}\right)^i + c_{EW}(\alpha) + c_{mix}(\alpha\alpha_S)\right]$$



Fixing other parameters from world average values from PDG, one can obtain |V<sub>cs</sub>| value indirectly

(Although indirect), precise V<sub>cs</sub> measurement provided







#### Soft-gluon resummation p

# Fixed order perturbative QCD

15

2205.04897

































Fraction of L, R, O will add up to 1  $f_L + f_R + f_O = 1$ 

So parametrize in two 2D  $f_L - f_R v. f_0$ 

### Importance of vector boson scattering





credit: J. Manjarres

VBS sensitive to Higgs mechanism

















#### Variable Description Invariant mass of the two tagging jets pair $m_{ii}$ Pseudorapidity separation between the two tagging jets $\Delta \eta_{ii}$ $p_{\mathrm{T}}^{\mathbf{j}_1}$ $p_{\rm T}$ of the highest $p_{\rm T}$ jet $p_{\mathrm{T}}^{\mathbf{j}_2}$ $p_{\rm T}$ of the second-highest $p_{\rm T}$ jet $p_{\mathrm{T}}^{\ell\ell}$ $p_{\rm T}$ of the lepton pair Azimuthal angle between the two leptons $\Delta \phi_{\ell\ell}$ $Z_{\ell_1}$ Zeppenfeld variable of the highest $p_{\rm T}$ lepton Zeppenfeld variable of the second-highest $p_{\rm T}$ lepton $Z_{\ell}$ $m_{\mathrm{T}}^{\ell_1}$

Transverse mass of the  $(p_T^{\ell_1}, p_T^{\text{miss}})$  system



Trained deep neural network machine learning algorithm to identify events that is more similar to VBS events

**First observation of VBS** opposite-sign WW 5.6 $\sigma_{obs}$  (5.2 $\sigma_{exp}$ )











~similar cross section as tttt

The final states are getting more intertwined than ever

#### Summary



At the LHC SM physics is being tested in various ways

For processes with large cross section we are slicing and dicing the data

For processes with small cross sections we are now finding SM processes that produce O(100 GeV) particles up to multiplicities of three and four. (e.g. WWW, 4-top)

In the future, HL-LHC will provide us large dataset to improve precision measurements

And also allow some of the rarest processes with large multiplicities to be probed