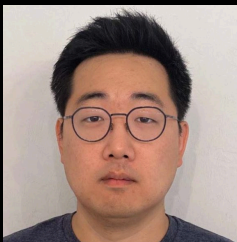


# Recent CMS results on Standard Model Physics

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CIPANP

September 1, 2022



Philip Chang  
University of Florida



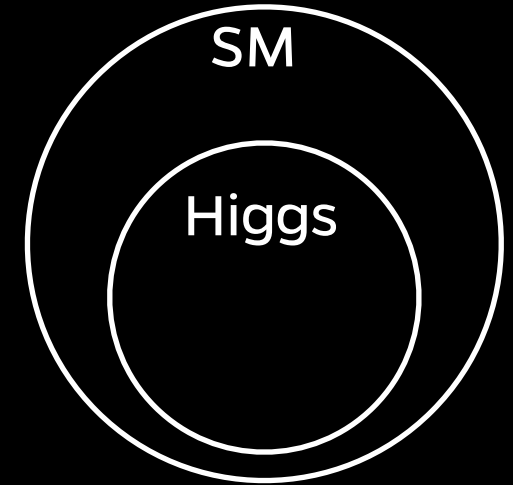
UNIVERSITY of  
FLORIDA

# Higgs physics is broad and I cannot cover all!

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

??

169	<a href="#">HIG-19-016</a>	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	<a href="#">HIG-21-001</a>	Searches for additional Higgs bosons and for vector leptoquarks in $\tau\tau$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	4 August 2022
167	<a href="#">HIG-21-006</a>	Search for CP violation in $t\bar{t}H$ and $H$ production in multilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	4 August 2022
166	<a href="#">HIG-21-003</a>	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	<a href="#">HIG-21-015</a>	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	<a href="#">HIG-21-010</a>	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	<a href="#">HIG-22-001</a>	A portrait of the Higgs boson by the CMS experiment ten years after the discovery	<a href="#">Nature 607 (2022) 60</a>	4 July 2022
162	<a href="#">HIG-20-004</a>	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	<a href="#">HIG-21-002</a>	Search for Higgs boson pairs decaying to $WWWW$ , $WW\tau\tau$ , and $\tau\tau\tau\tau$ in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	21 June 2022
160	<a href="#">HIG-20-013</a>	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	<a href="#">HIG-20-010</a>	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	<a href="#">HIG-20-008</a>	Search for Higgs boson decays into Z and $J/\psi$ and for Higgs and Z boson decays into $J/\psi$ or $\Upsilon$ pairs in pp collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	7 June 2022
157	<a href="#">HIG-21-008</a>	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	<a href="#">HIG-20-007</a>	Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the $\tau\tau$ final state	Accepted by PRD	10 May 2022
155	<a href="#">HIG-20-018</a>	Search for light Higgs bosons from supersymmetric cascade decays in pp collisions at $\sqrt{s} = 13$ TeV	Accepted by EPJC	28 April 2022
154	<a href="#">HIG-19-014</a>	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	<a href="#">HIG-19-010</a>	Measurements of Higgs boson production in the decay channel with a pair of $\tau$ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to EPJC	27 April 2022
152	<a href="#">HIG-20-005</a>	Search for Higgs boson pair production in the four b quark final state in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PRL 129 (2022) 081802</a>	19 February 2022
151	<a href="#">HIG-21-013</a>	First evidence for off-shell production of the Higgs boson and measurement of its width	Submitted to NP	14 February 2022
150	<a href="#">HIG-20-003</a>	Search for invisible decays of the Higgs boson produced via vector boson fusion in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PRD 105 (2022) 092007</a>	27 January 2022



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

2

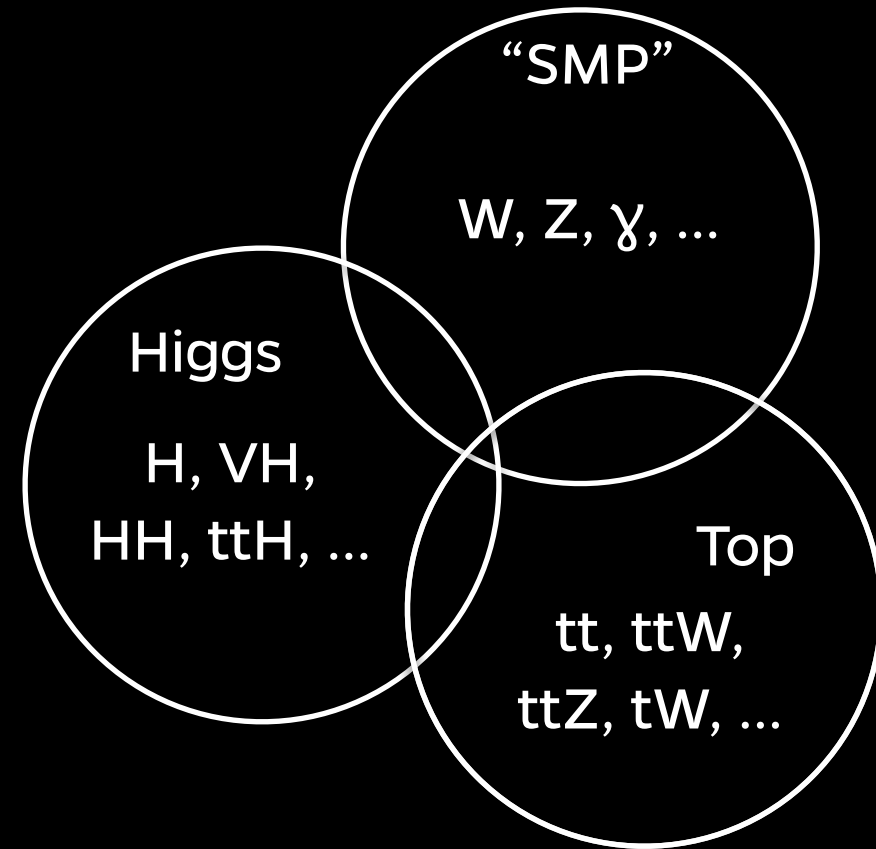
Just this year alone starting January, CMS produced 20 papers!

5

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

# Meaning of “SMP” in CMS

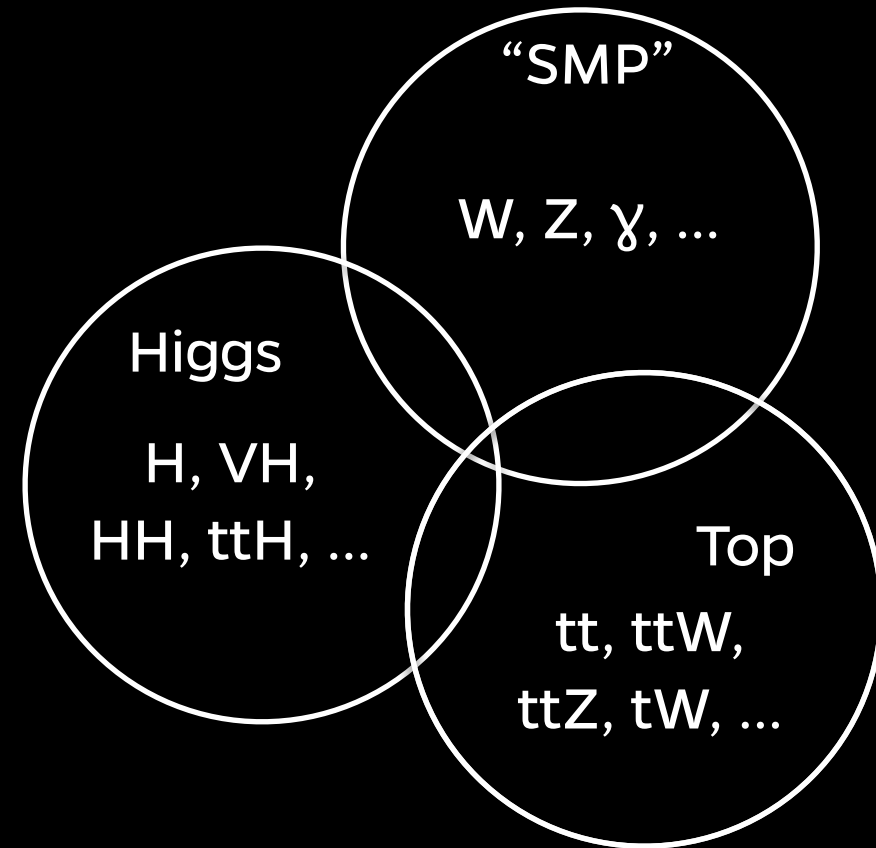
If it has Higgs, it falls to Higgs  
If it has top quark, it falls to top quark  
What's left?  $W, Z, \gamma, \dots$



# 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?  $W, Z, \gamma, \dots$

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



# Recent results

154	<a href="#">SMP-18-014</a>	Precision measurement of the Z boson invisible width in pp collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	14 June 2022
153	<a href="#">SMP-21-013</a>	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	<a href="#">SMP-21-001</a>	Observation of electroweak $W^+W^-$ pair production in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	11 May 2019
151	<a href="#">SMP-20-003</a>	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	<a href="#">SMP-19-009</a>	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	<a href="#">SMP-21-002</a>	Measurement of the Drell-Yan forward-backward asymmetry at high dilepton masses in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 08 (2022) 063</a>	24 February 2022
148	<a href="#">SMP-18-011</a>	Precision measurement of the W boson decay branching fractions in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PRD 105 (2022) 072008</a>	19 January 2022

Focusing on just this year

# Recent results in SMP

154	<a href="#">SMP-18-014</a>	Precision measurement of the Z boson invisible width in pp collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	14 June 2022
153	<a href="#">SMP-21-013</a>	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
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148	<a href="#">SMP-18-011</a>	Precision measurement of the W boson decay branching fractions in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PRD 105 (2022) 072008</a>	19 January 2022

# Recent results in SMP

154	SMP-18-016	Precision measurement of the Z boson invisible width in pp collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	14 June 2022
153	SMP-21-013	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	SMP-21-001	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	SMP-20-003	Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan production in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to EPJC	10 May 2022
150	SMP-18-009	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	SMP-21-002	Measurement of the Drell-Yan forward-backward asymmetry at high dilepton masses in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 08 (2022) 083</a>	24 February 2022
148	SMP-18-011	Precision measurement of the W boson decay branching fractions in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PRD 106 (2022) 072008</a>	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	<a href="#">PRD 106 (2022) 080214</a>	17 December 2021
146	SMP-20-013	Evidence for WWVZ vector boson scattering in the decay channel $\ell^+\ell^-qq$ produced in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to PLB	9 December 2021
145	SMP-18-013	Measurements of the associated production of a W boson and a charm quark in proton-proton collisions at $\sqrt{s} = 8$ TeV	Submitted to EPJC	2 December 2021
144	SMP-20-005	Measurement of W <sup>+</sup> differential cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV and effective field theory constraints	<a href="#">PRD 106 (2022) 052003</a>	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	<a href="#">JHEP 02 (2022) 142</a>	10 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	<a href="#">JHEP 01 (2022) 052</a>	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	<a href="#">JHEP 01 (2022) 117</a>	29 September 2021
140	SMP-20-010	Study of quark and gluon jet substructure in Z1jet and dj1et events from pp collisions	<a href="#">JHEP 01 (2022) 188</a>	8 September 2021
139	SMP-20-012	Measurements of the electroweak diboson production cross sections in proton-proton collisions at $\sqrt{s} = 8.02$ TeV using leptonic decays	<a href="#">PRL 127 (2021) 181801</a>	2 July 2021
138	SMP-20-016	Measurement of the electroweak production of Z <sub>1</sub> and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on anomalous quartic gauge couplings	<a href="#">PRD 104 (2021) 072001</a>	21 June 2021
137	SMP-20-009	Measurements of Z bosons plus jets using variables sensitive to double parton scattering in pp collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 10 (2021) 178</a>	30 May 2021
136	SMP-18-013	Measurements of the $pp \rightarrow W^+W^-$ and $pp \rightarrow ZZ$ cross sections at $\sqrt{s} = 13$ TeV and limits on anomalous quartic gauge couplings	<a href="#">JHEP 10 (2021) 174</a>	26 May 2021
135	SMP-17-008	Measurements of angular distribution and momentum ratio distributions in three-jet and Z + two-jet final states in pp collisions	<a href="#">EPJC 81 (2021) 802</a>	17 February 2021
134	SMP-19-006	Hard color-singlet exchange in dijet events in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PRD 104 (2021) 032009</a>	13 February 2021
133	SMP-18-002	Measurement of W <sub>1</sub> production cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on effective field theory coefficients	<a href="#">PRL 126 (2021) 242004</a>	3 February 2021
132	SMP-19-010	Measurements of the differential cross sections of the production of Z1-jets and Z2-jets and of Z boson emission collinear with a jet in pp collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 08 (2021) 285</a>	3 February 2021
131	SMP-18-003	Measurement of the Z boson differential production cross section using its invisible decay mode ( $Z \rightarrow \nu\bar{\nu}$ ) in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 08 (2021) 205</a>	18 December 2020
130	SMP-18-011	Measurement of differential cross sections for Z bosons produced in association with charm jets in pp collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 04 (2021) 159</a>	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 $\sqrt{s} = 13$ TeV	<a href="#">PLB 819 (2021) 136409</a>	11 November 2020
128	SMP-20-006	Measurements of production cross sections of polarized same-sign W boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PLB 812 (2020) 136039</a>	20 September 2020
127	SMP-19-001	Measurements of $pp \rightarrow ZZ$ production cross sections and constraints on anomalous triple gauge couplings at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 81 (2021) 200</a>	2 September 2020
126	SMP-18-004	W <sup>+</sup> W <sup>-</sup> boson pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PRD 102 (2020) 052001</a>	1 September 2020
125	SMP-19-008	Observation of electroweak production of W <sub>1</sub> with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PLB 811 (2020) 115886</a>	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	<a href="#">PLB 812 (2020) 115892</a>	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	<a href="#">PRD 102 (2020) 080212</a>	10 August 2020
122	SMP-19-014	Observation of the production of three massive gauge bosons at $\sqrt{s} = 13$ TeV	<a href="#">PRL 125 (2020) 151805</a>	19 June 2020
121	SMP-18-003	Dependence of inclusive jet production on the anti-k <sub>T</sub> distance parameter in pp collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 12 (2020) 082</a>	11 May 2020
120	SMP-19-012	Measurements of production cross sections of WZ and same-sign WW boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PLB 809 (2020) 136710</a>	4 May 2020
119	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	<a href="#">JHEP 08 (2020) 076</a>	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 $\sqrt{s} = 13$ TeV	<a href="#">PRD 102 (2020) 032002</a>	19 January 2020
117	SMP-18-005	Determination of the strong coupling constant $\alpha_s(m_Z)$ from measurements of inclusive W <sup>+</sup> and Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV	<a href="#">JHEP 08 (2020) 018</a>	9 December 2019
116	SMP-18-015	Evidence for WW production from double-parton interactions in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 80 (2020) 41</a>	13 September 2019
115	SMP-17-010	Measurements of differential Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 12 (2019) 061</a>	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	<a href="#">JHEP 12 (2019) 062</a>	19 July 2019
113	SMP-16-016	Measurements of triple-differential cross sections for inclusive isolated-photon+jet events in pp collisions at $\sqrt{s} = 8$ TeV	<a href="#">EPJC 79 (2019) 969</a>	18 July 2019
112	SMP-18-006	Search for anomalous electroweak production of vector boson pairs in association with two jets in proton-proton collisions at 13 TeV	<a href="#">PLB 798 (2019) 114695</a>	17 May 2019
111	SMP-17-013	Search for the production of W <sup>+</sup> W <sup>-</sup> W <sup>+</sup> W <sup>-</sup> events at $\sqrt{s} = 13$ TeV	<a href="#">PRD 100 (2019) 012004</a>	10 May 2019
110	SMP-17-011	Measurement of electroweak production of a W boson in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 80 (2020) 43</a>	10 March 2019
109	SMP-17-009	Angular separation in nearly back-to-back jet topologies in inclusive 3- and 3+jet events in pp collisions at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 79 (2019) 373</a>	12 February 2019
108	SMP-18-009	Search for W boson decays to three charged pions	<a href="#">PRL 122 (2019) 151802</a>	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	<a href="#">PLB 795 (2019) 281</a>	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 $\sqrt{s} = 13$ TeV	<a href="#">JHEP 04 (2019) 122</a>	10 January 2019
105	SMP-17-001	Measurement of the differential Drell-Yan cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 12 (2019) 059</a>	27 December 2018
104	SMP-17-014	Measurement of associated production of a W boson and a charm quark in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 79 (2019) 269</a>	26 November 2018
103	SMP-17-003	Event shape variables measured using multijet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">JHEP 12 (2018) 117</a>	2 November 2018
102	SMP-17-012	Search for rare decays of Z and Higgs bosons to $\bar{\nu}\nu$ and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 79 (2019) 84</a>	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 $\sqrt{s} = 13$ TeV	<a href="#">JHEP 11 (2018) 113</a>	16 July 2018
100	SMP-16-003	Measurement of differential cross sections for inclusive isolated-photon and photon+jet production in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 79 (2019) 20</a>	2 July 2018
99	SMP-17-005	Measurement of differential cross sections for Z boson pair production in association with jets at $\sqrt{s} = 8$ and 13 TeV	<a href="#">PLB 789 (2018) 19</a>	28 June 2018
98	SMP-16-007	Measurement of the weak mixing angle using the forward-backward asymmetry of Drell-Yan events in pp collisions at 8 TeV	<a href="#">EPJC 79 (2018) 301</a>	3 June 2018
97	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	<a href="#">EPJC 79 (2018) 965</a>	14 April 2018
96	SMP-16-018	Electroweak production of two jets in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 79 (2018) 969</a>	28 December 2017
95	SMP-16-014	Angular correlations for inclusive 2-jet, 3-jet, and 4-jet events in pp collisions at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 79 (2018) 566</a>	14 December 2017
94	SMP-15-009	Measurement of associated Z+charm production in proton-proton collisions at $\sqrt{s} = 8$ TeV	<a href="#">EPJC 78 (2018) 287</a>	6 November 2017
93	SMP-17-002	Measurement of differential cross sections in the $\beta^2$ variable for inclusive Z <sub>1</sub> boson production in pp collisions at $\sqrt{s} = 8$ TeV	<a href="#">JHEP 03 (2018) 172</a>	22 October 2017
92	SMP-16-017	Measurements of the $pp \rightarrow ZZ$ production cross section and the Z $\rightarrow 4\ell$ branching fraction, and constraints on anomalous triple gauge couplings at $\sqrt{s} = 13$ TeV	<a href="#">EPJC 78 (2018) 165</a>	25 September 2017
91	SMP-17-004	Observation of electroweak production of same-sign W boson pairs in the two-jet and two same-sign lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PRL 120 (2018) 081801</a>	18 September 2017
90	SMP-17-006	Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PLB 774 (2017) 682</a>	9 August 2017
89	SMP-16-005	Measurement of the differential cross sections for the associated production of a W boson and jets in proton-proton collisions at $\sqrt{s} = 13$ TeV	<a href="#">PRD 96 (2017) 072005</a>	19 July 2017
88	SMP-15-003	Measurements of jet charge with dijet events in pp collisions at $\sqrt{s} = 8$ TeV	<a href="#">JHEP 10 (2017) 131</a>	18 June 2017
87	SMP-16-011	Measurement of the triple-differential dijet cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on parton distribution functions	<a href="#">JHEP 07 (2017) 146</a>	7 May 2017
86	SMP-15-008	Measurements of the $pp \rightarrow W\gamma$ and $pp \rightarrow ZZ$ cross sections and limits on anomalous quartic gauge couplings at $\sqrt{s} = 8$ TeV	<a href="#">JHEP 10 (2017) 072</a>	3 April 2017
85	SMP-13-008	Search for anomalous couplings in boosted W <sup>+</sup> W <sup>-</sup> Z <sub>1</sub> production in proton-proton collisions at $\sqrt{s} = 8$ TeV	<a href="#">PLB 772 (2017) 21</a>	17 March 2017

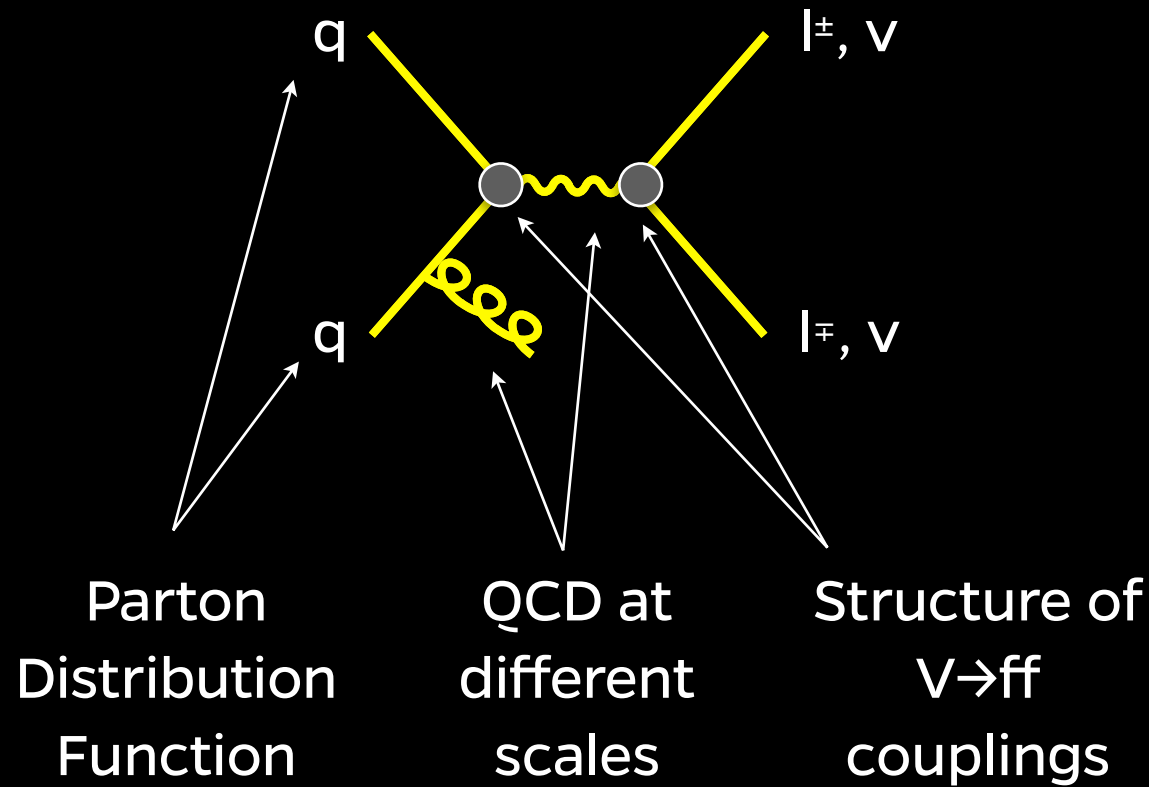
So many since last CIPANP  
so I can't cover all!

Precision

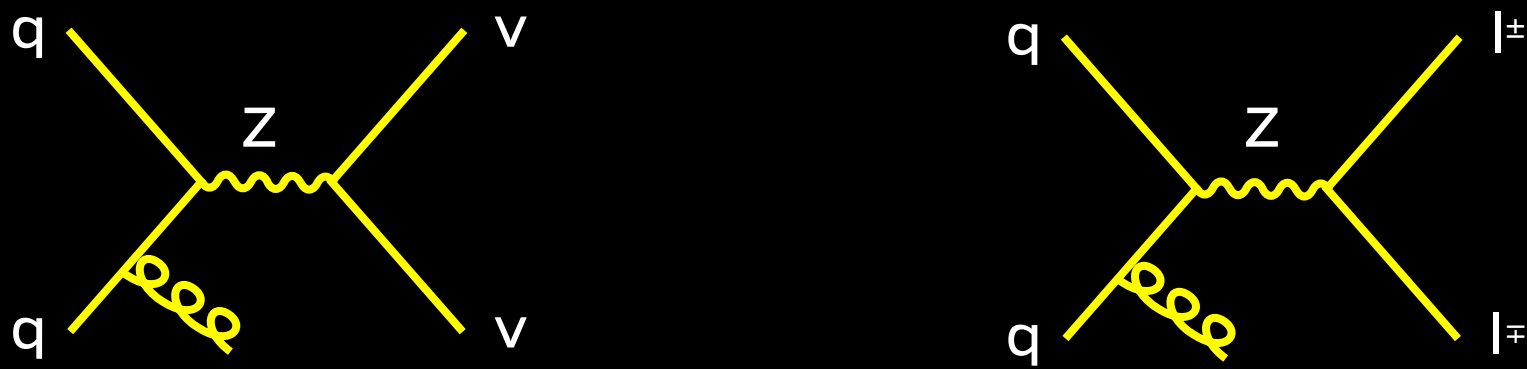
Searches



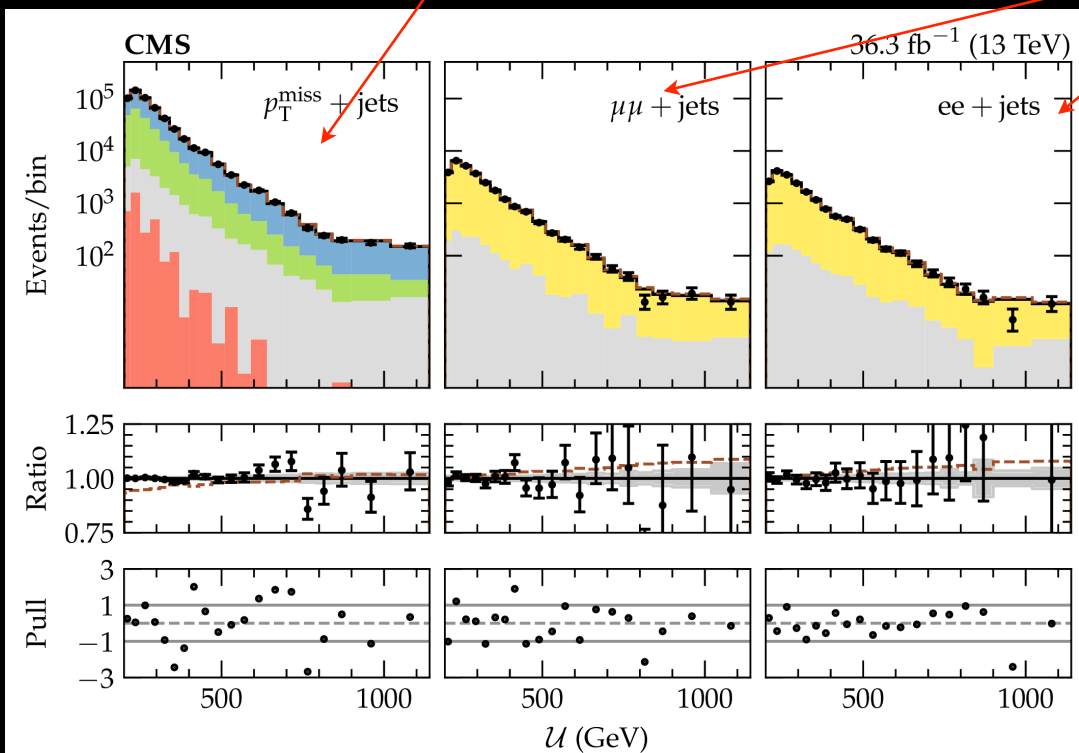
# Precision measurements



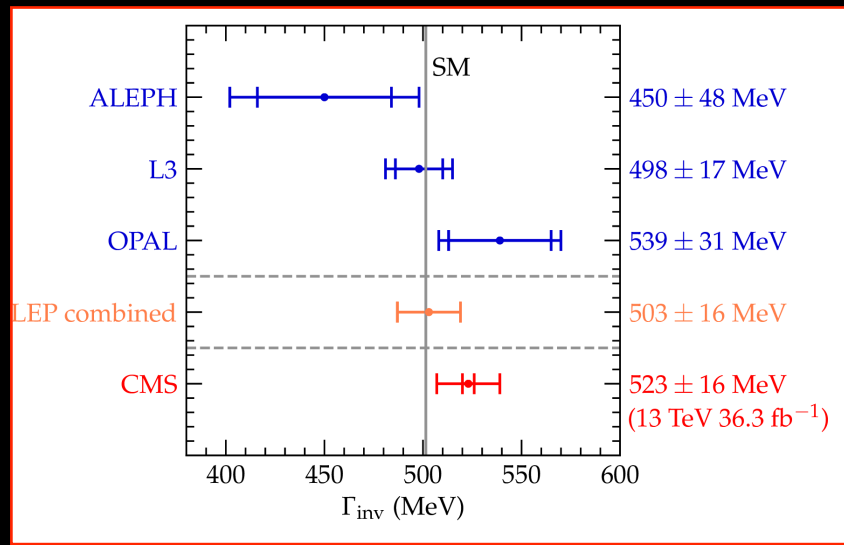
# Z boson branching ratio to invisible particles



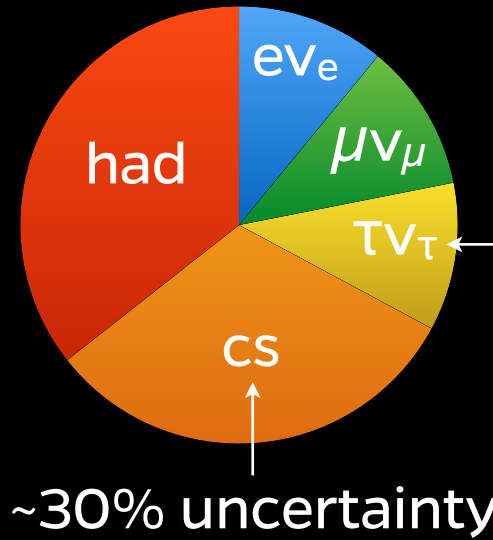
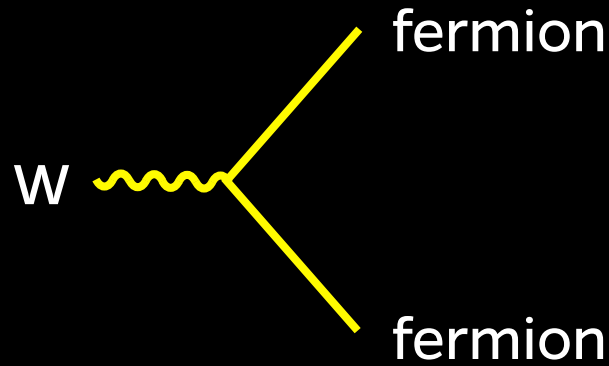
- Data
- SM pre-fit
- SM post-fit
- Z( $\rightarrow \nu\nu$ ) + j
- W( $\rightarrow lv$ ) + j
- Minor bgrd
- QCD multijet
- Z/ $\gamma^*$ ( $\rightarrow ll$ ) + j



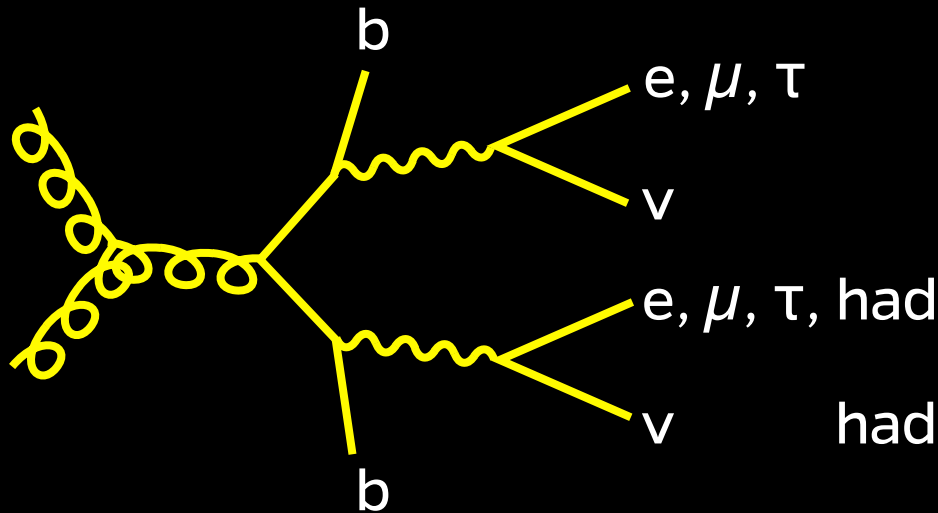
$$\Gamma(Z \rightarrow \nu\nu) = \frac{\text{Rate}(Z \rightarrow \nu\nu)}{\text{Rate}(Z \rightarrow ll)} \Gamma(Z \rightarrow ll)$$



# W boson branching ratios



Large Electron-positron (LEP) Collider results had  $2.8\sigma$  higher  $\tau\nu_\tau$  BR



Slice and dice into final states:  
ee, eμ, μμ, eτ, μτ, e/μ + had

Then, measure the rate

Use top-quark pair production process

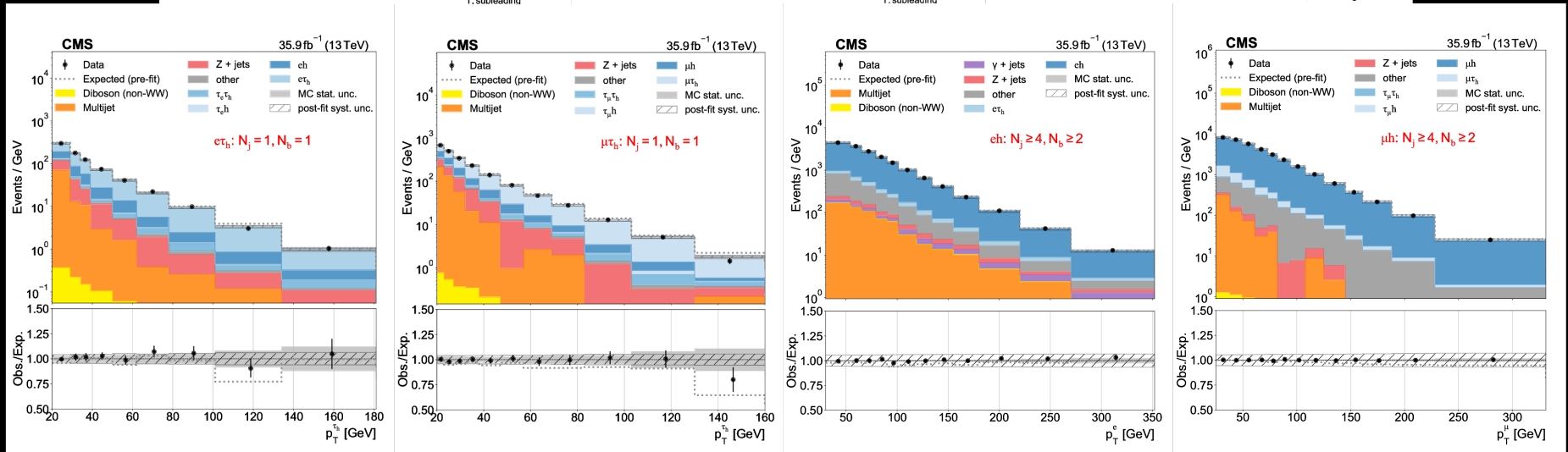
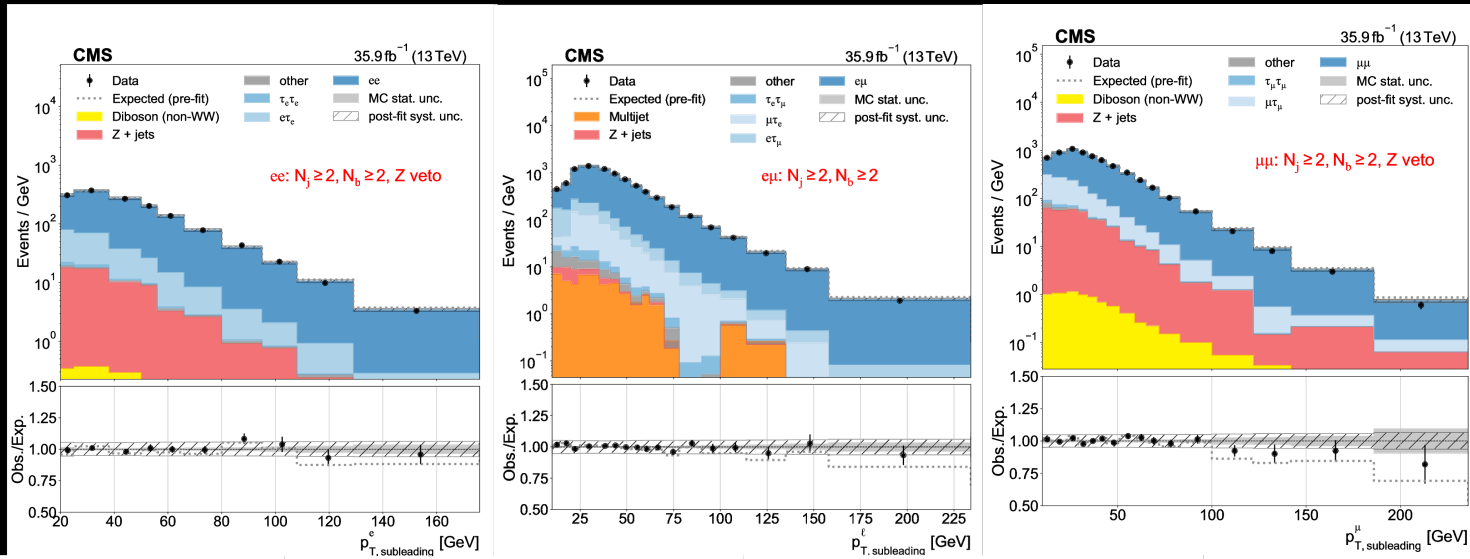
BR(Top quark → Wb) ~ 100%

# W boson branching ratios

ee

eμ

μμ



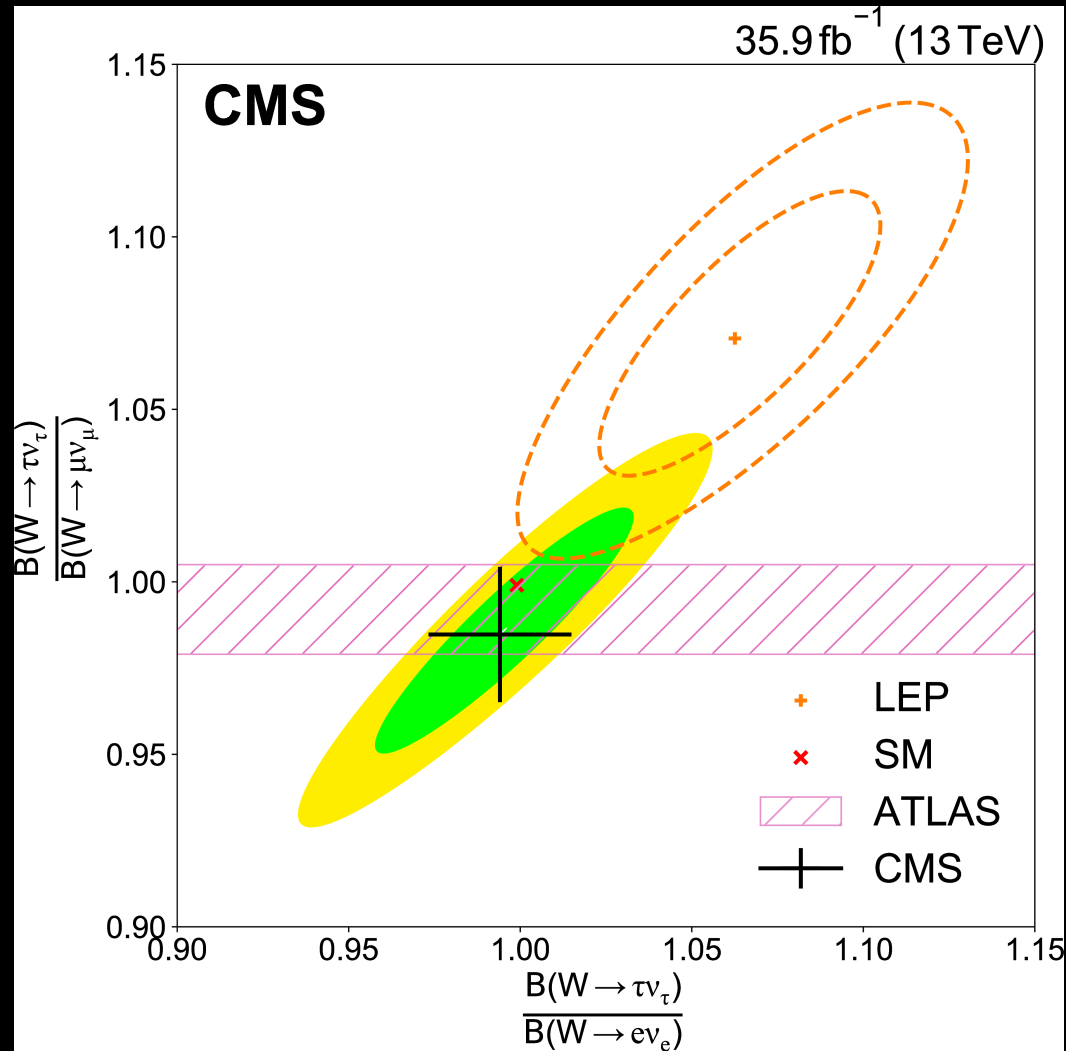
eτ

μτ

ehad

μhad

# W boson branching ratios



Confirms SM

# W boson branching ratios

Phys. Rev. D 105 (2022) 072008

Use measured hadronic  
branching ratio

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

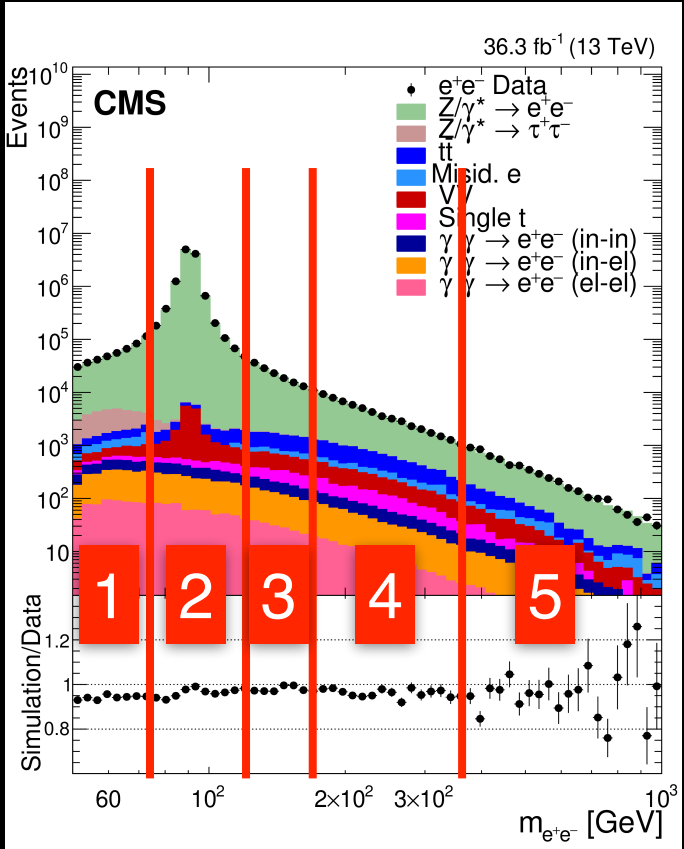
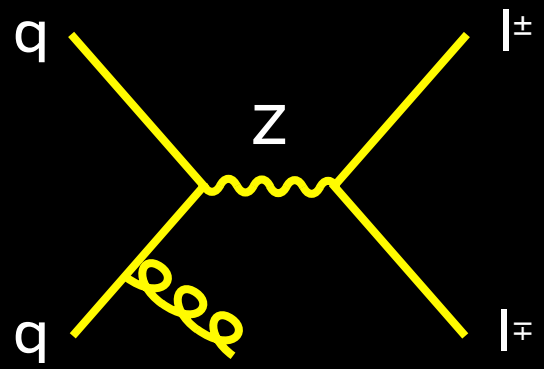
$$\frac{\mathcal{B}(W \rightarrow q\bar{q}')}{1 - \mathcal{B}(W \rightarrow q\bar{q}')} = \sum_{\substack{i=(u,c), \\ j=(d,s,b)}} |V_{ij}|^2 \left[ 1 + \sum_{i=1}^4 c_i \left( \frac{\alpha_s}{\pi} \right)^i + c_{EW}(\alpha) + c_{mix}(\alpha\alpha_s) \right]$$

$ V_{cs} $
$0.967 \pm 0.011$

↑  
Fixing other parameters from world  
average values from PDG, one can  
obtain  $|V_{cs}|$  value indirectly

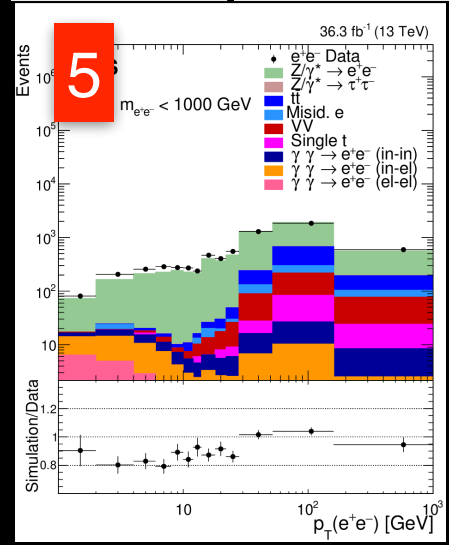
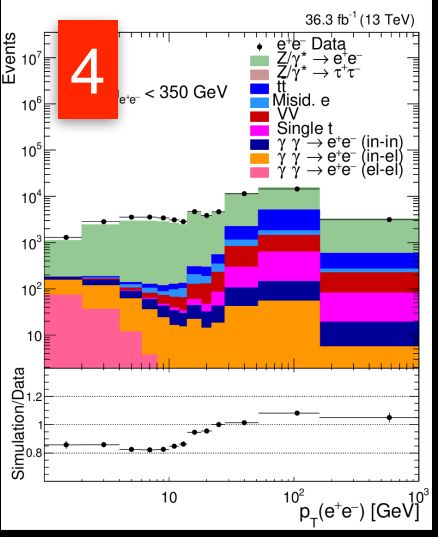
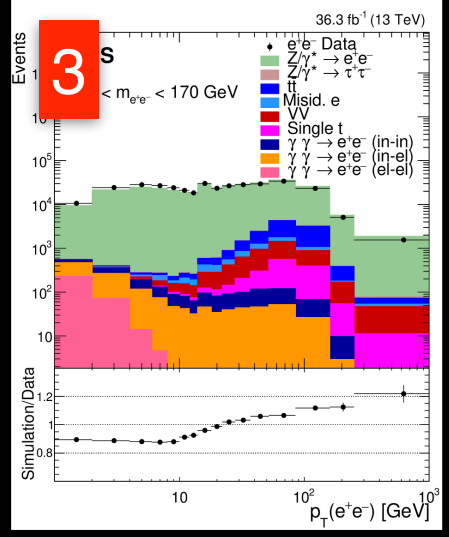
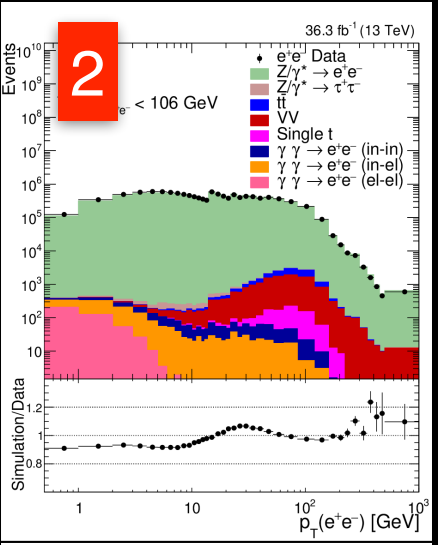
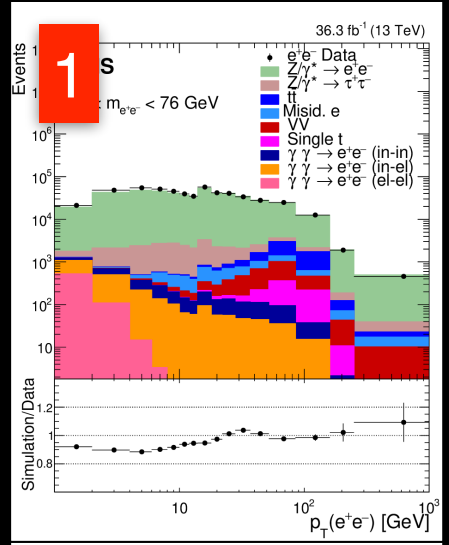
(Although indirect), precise  $V_{cs}$  measurement provided

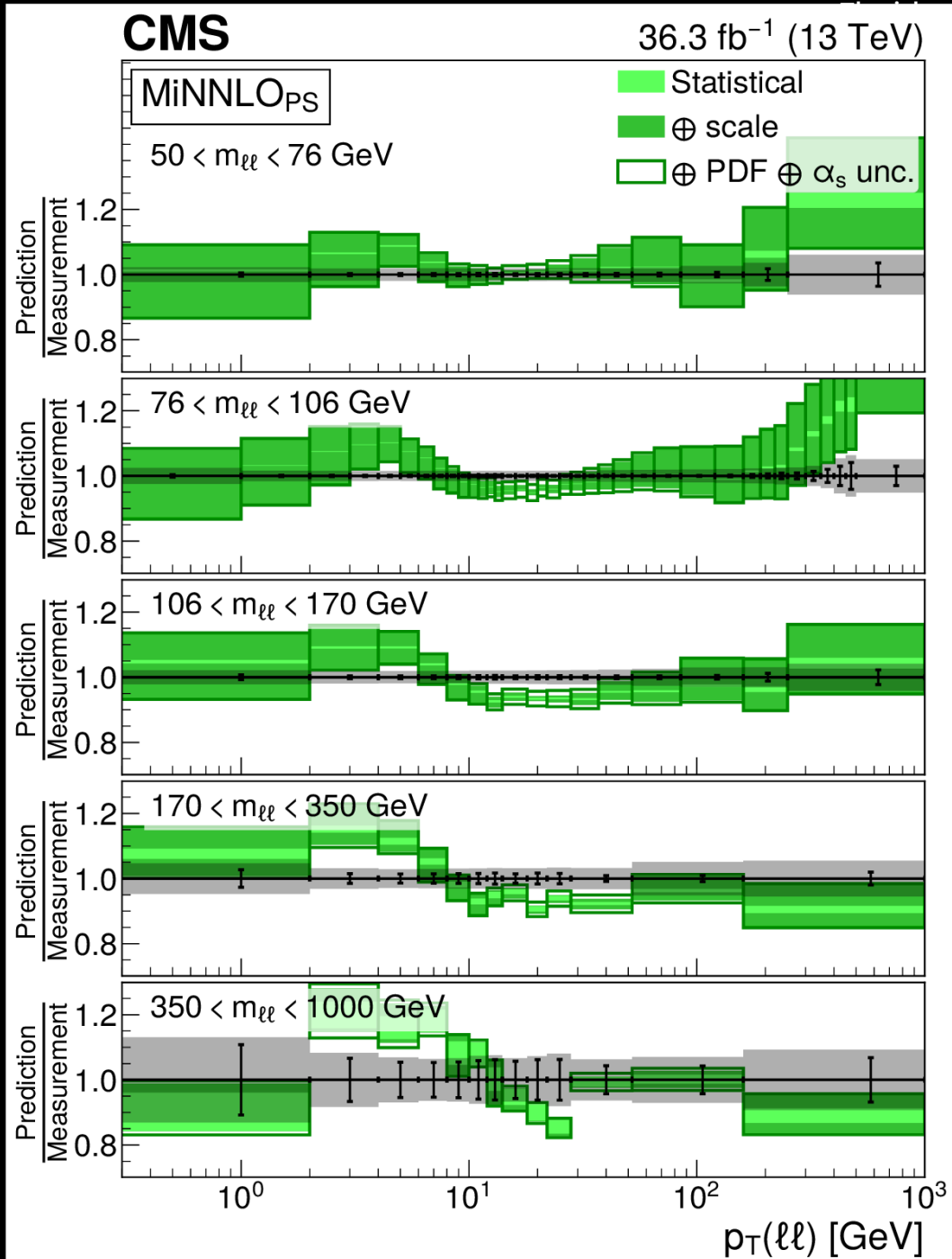
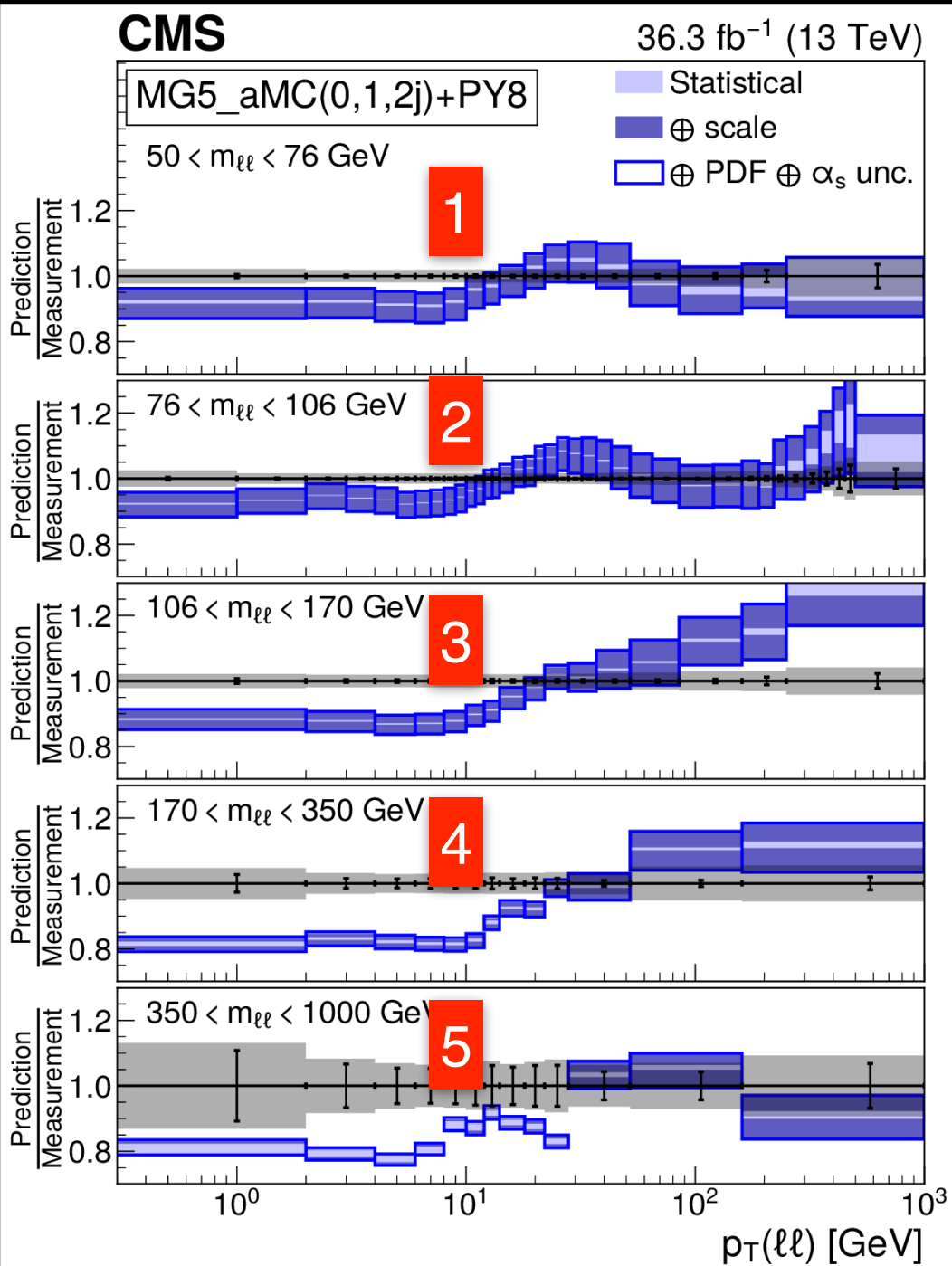
# $M_{\parallel}$ VS. $P_{T,\parallel}$



Soft-gluon  
resummation

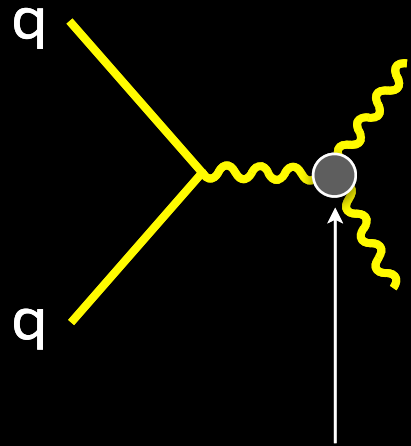
Fixed order  
perturbative QCD





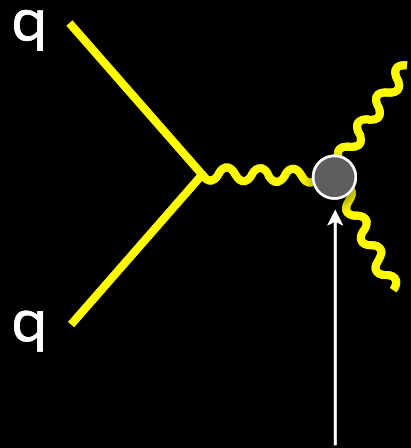


# Rare process searches/measurements

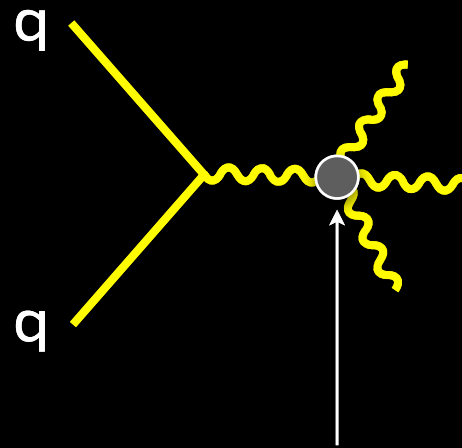


Triple gauge interactions

# Rare process searches/measurements

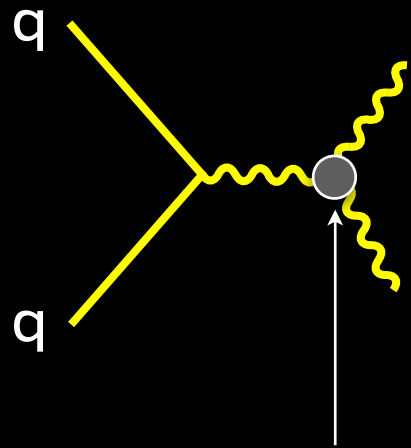


Triple gauge interactions

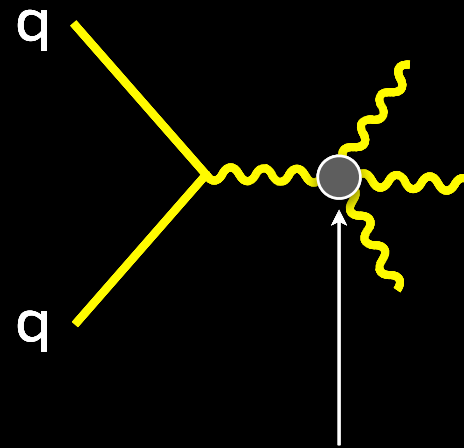


Quartic gauge interactions

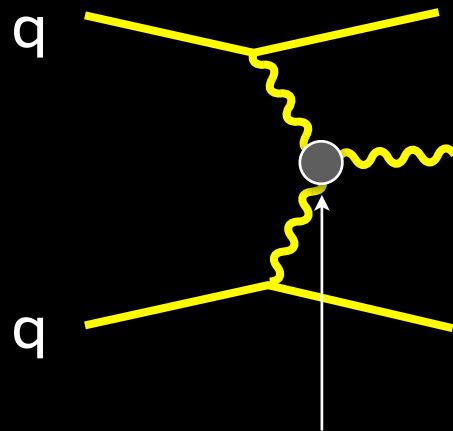
# Rare process searches/measurements



Triple gauge interactions

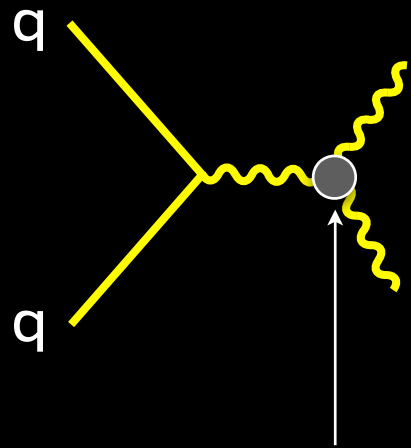


Quartic gauge interactions

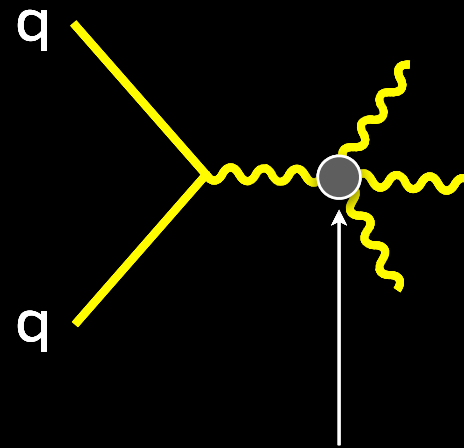


Triple gauge interactions

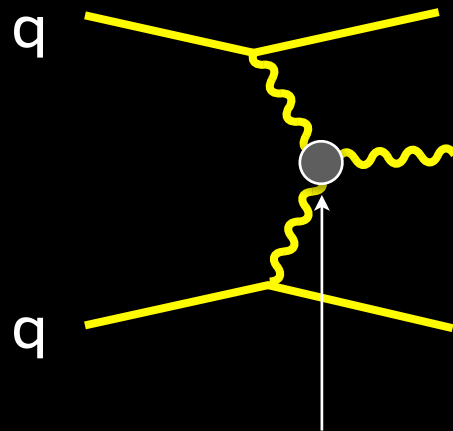
# Rare process searches/measurements



Triple gauge interactions

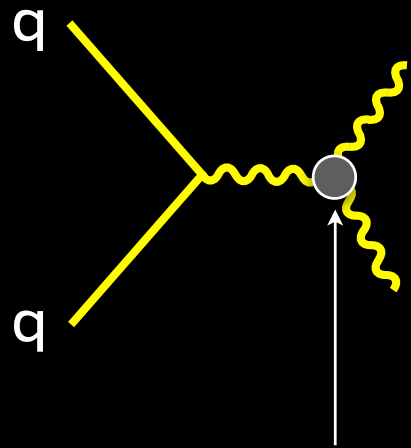


Quartic gauge interactions

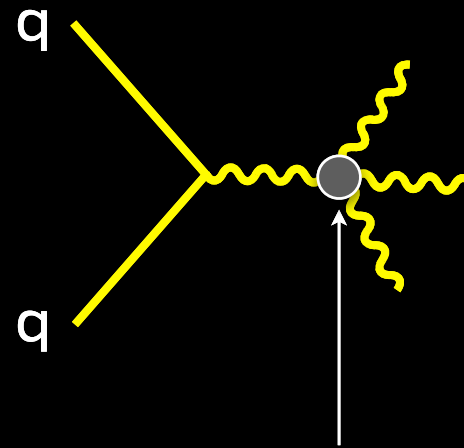


Triple gauge interactions

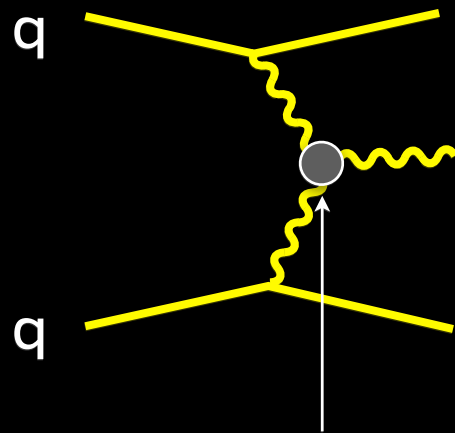
# Rare process searches/measurements



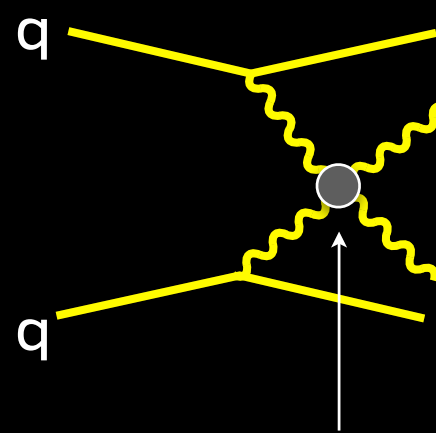
Triple gauge interactions



Quartic gauge interactions

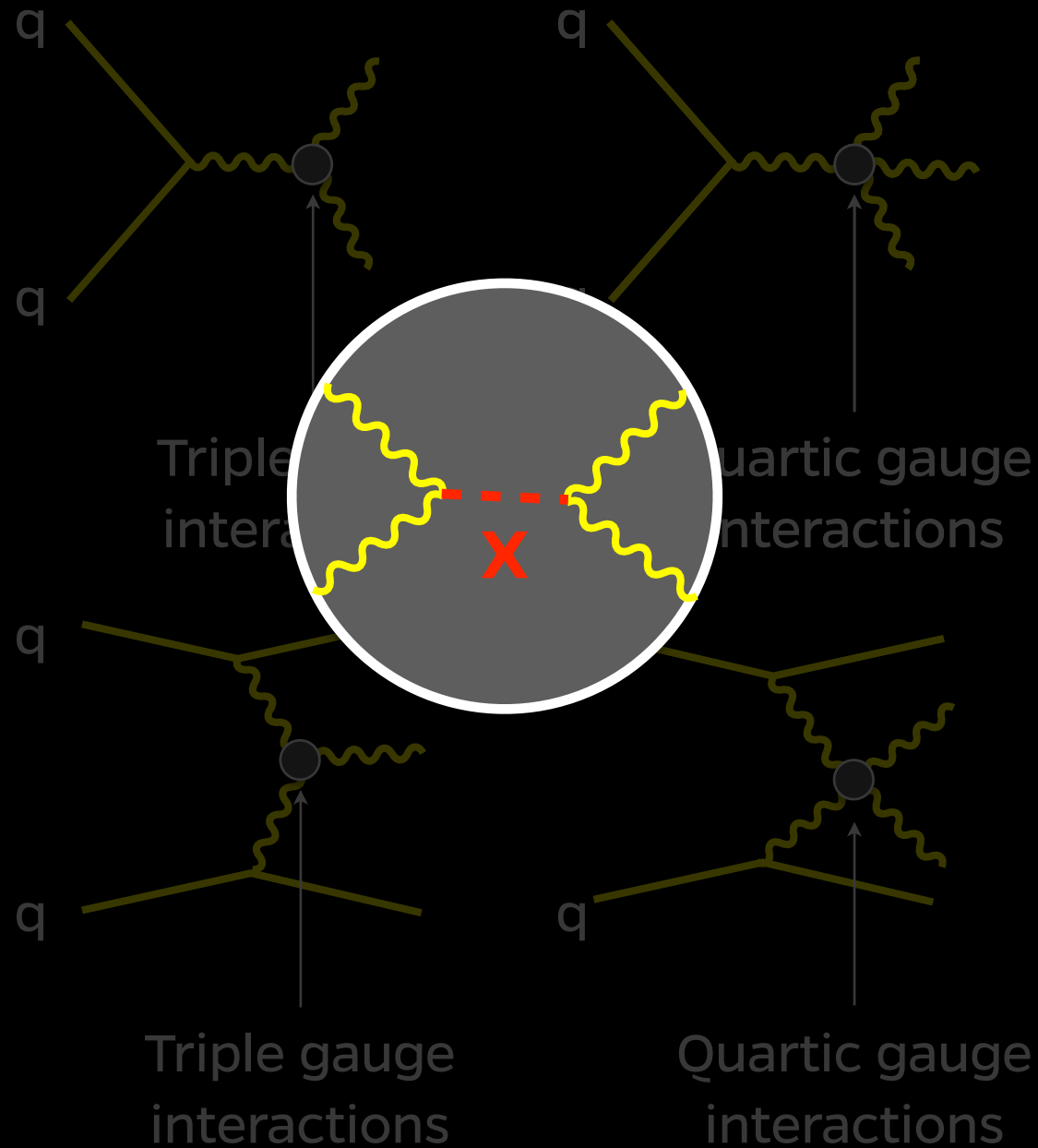


Triple gauge interactions

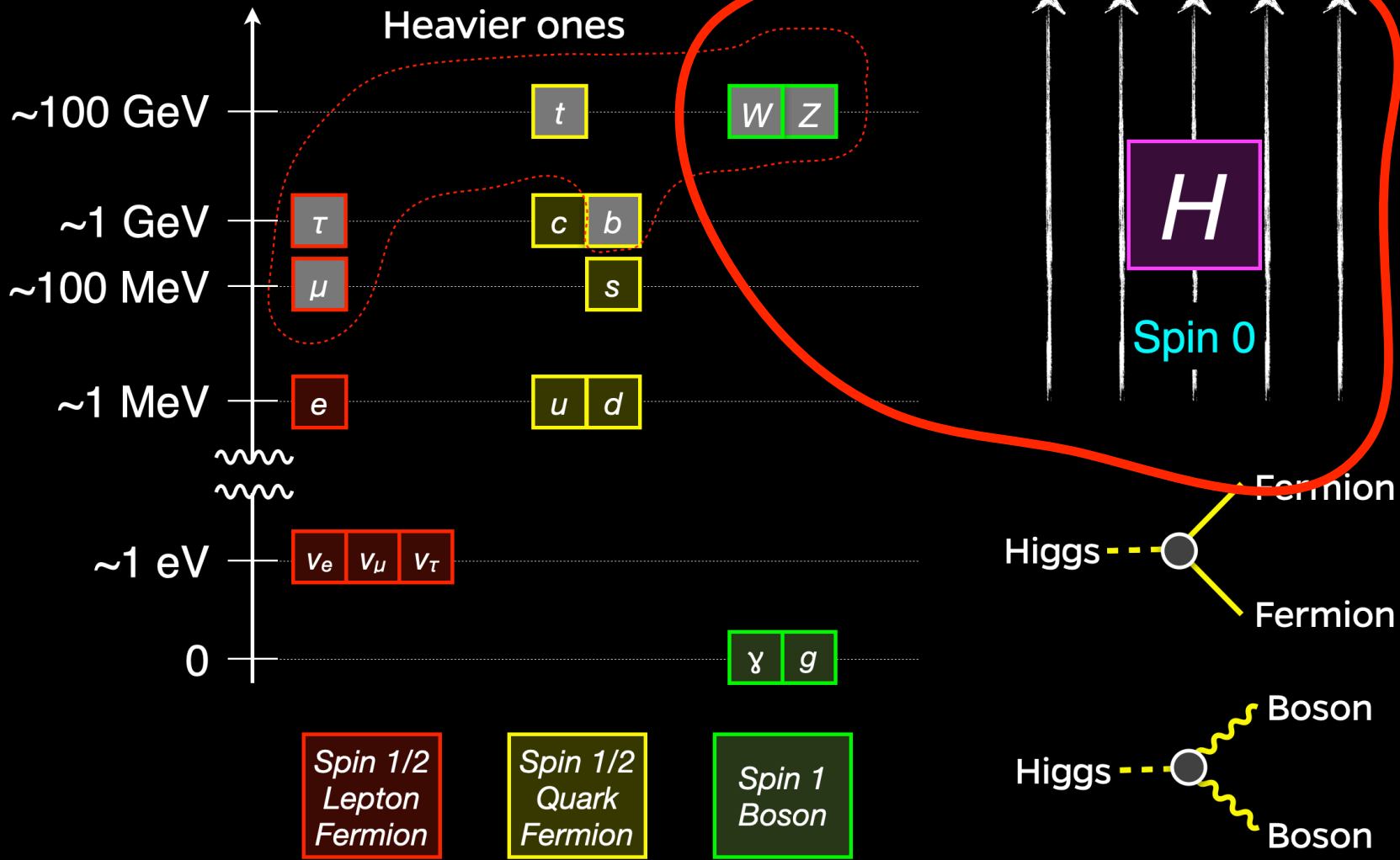


Quartic gauge interactions

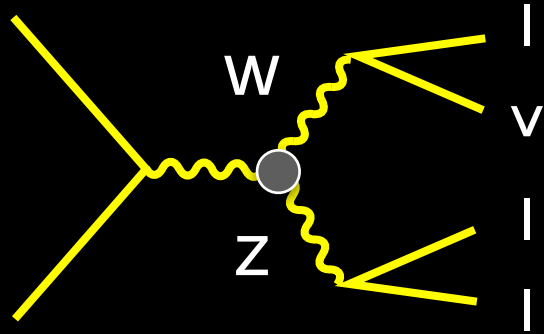
# Rare process searches/measurements



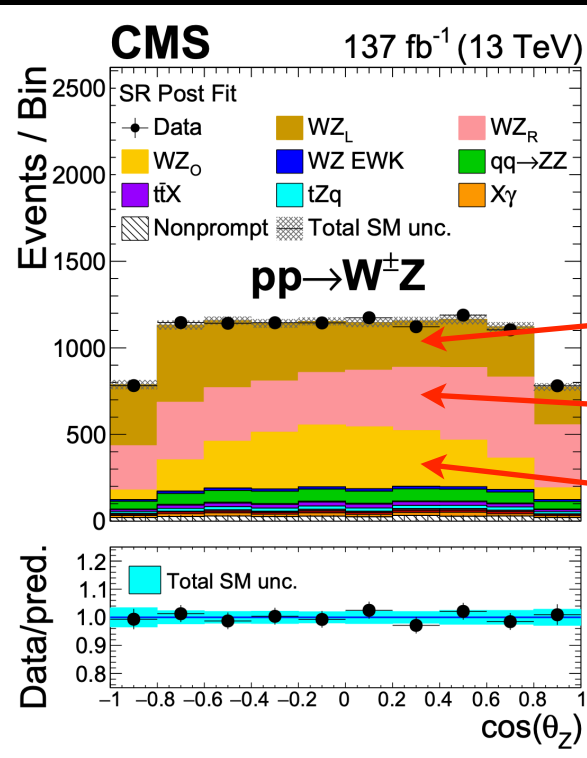
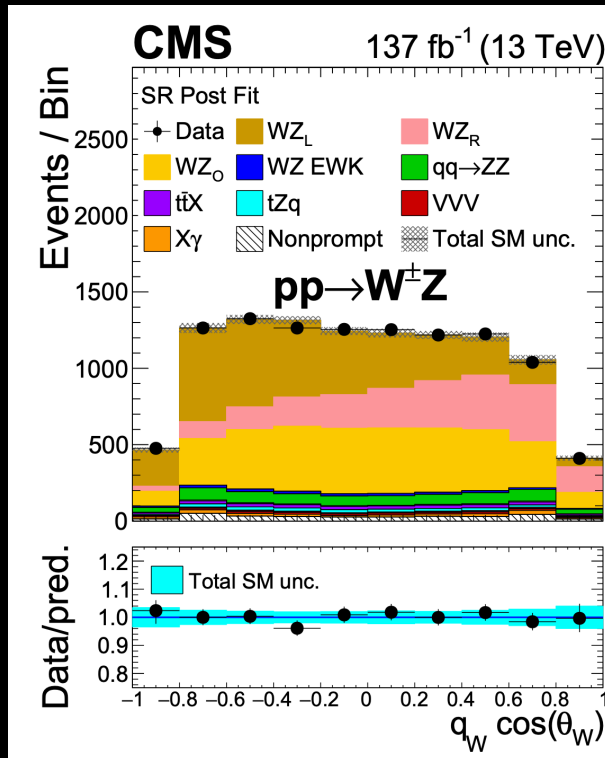
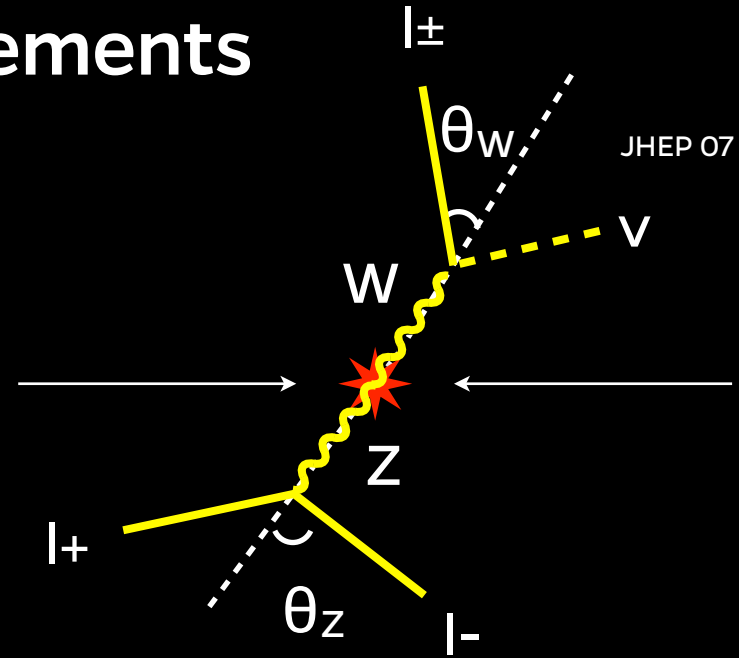
# SM particle masses



# WZ polarization measurements



Three charged lepton final state



Left-polarized  
Right-polarized  
Longitudinal

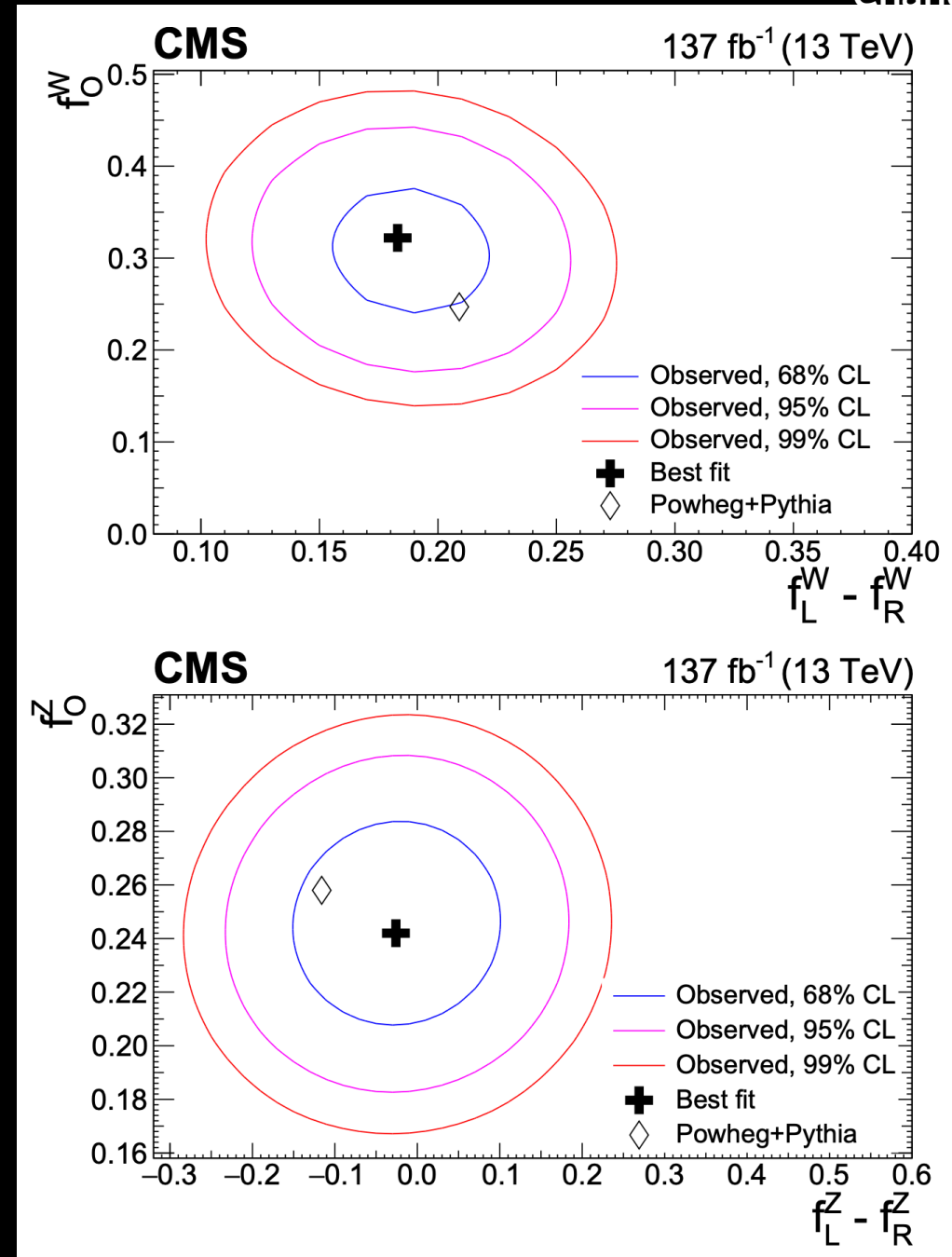


Fraction of L, R, 0 will add up to 1

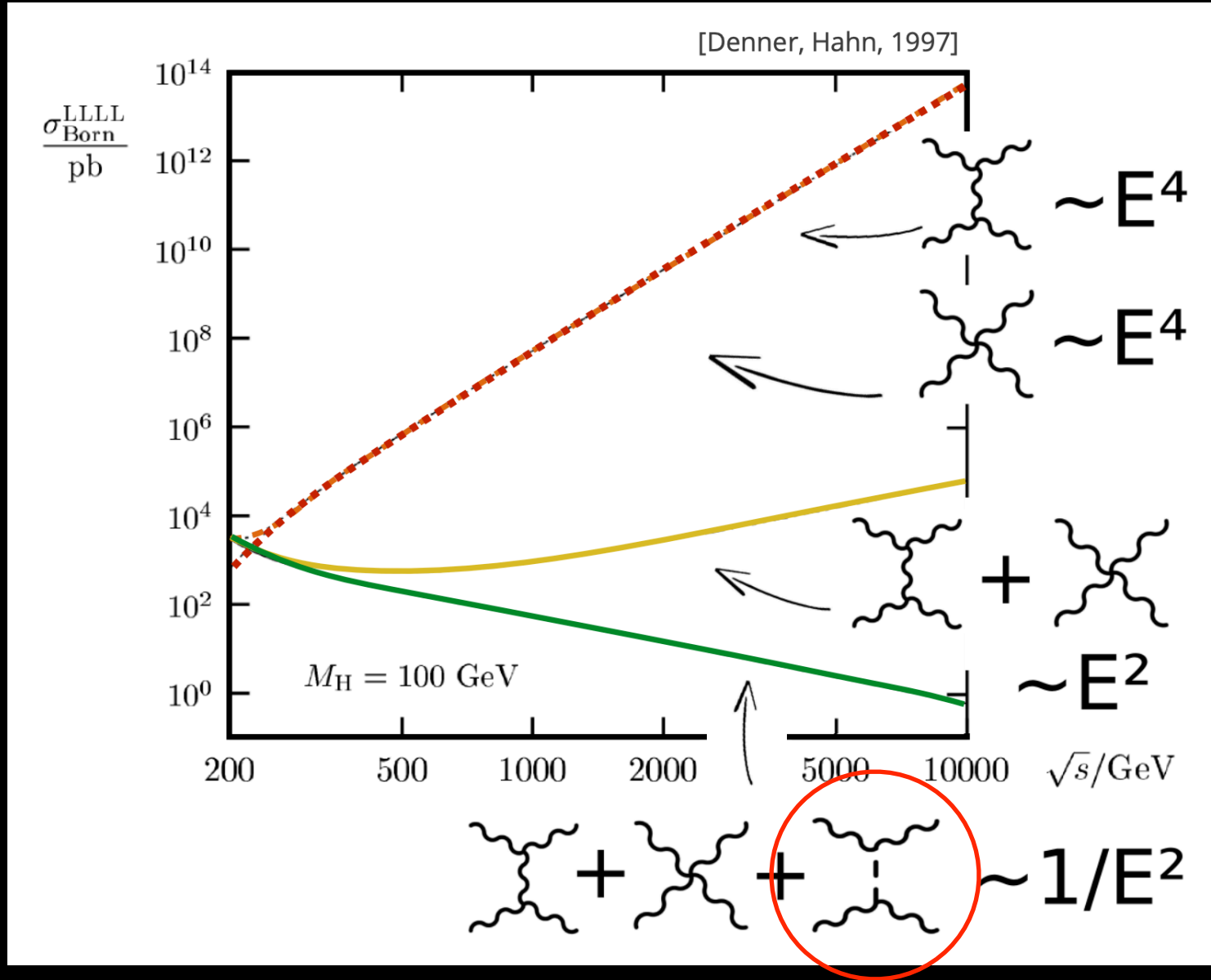
$$f_L + f_R + f_0 = 1$$

So parametrize in two 2D

$$f_L - f_R \text{ v. } f_0$$



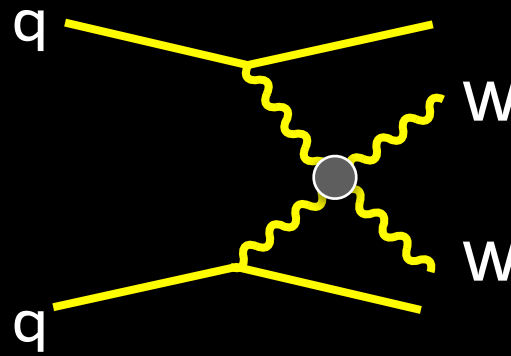
# Importance of vector boson scattering



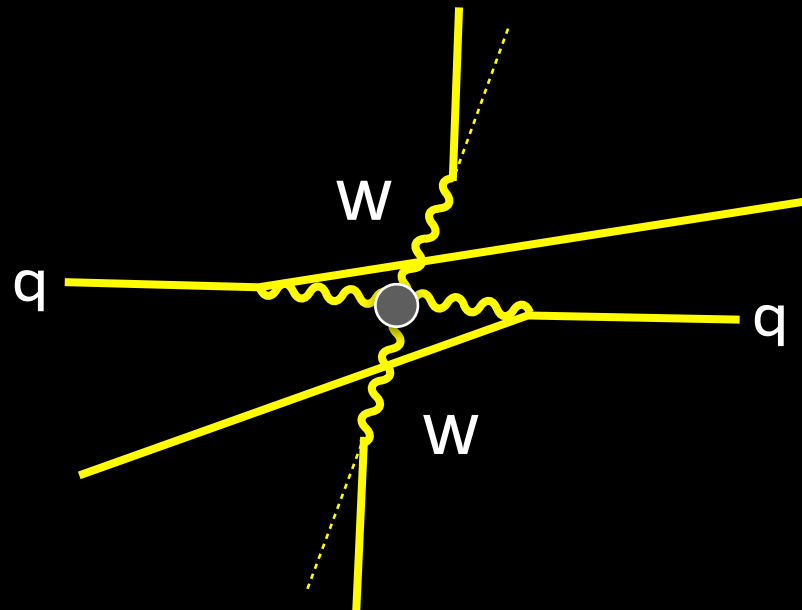
credit: J. Manjarres

VBS sensitive to Higgs mechanism

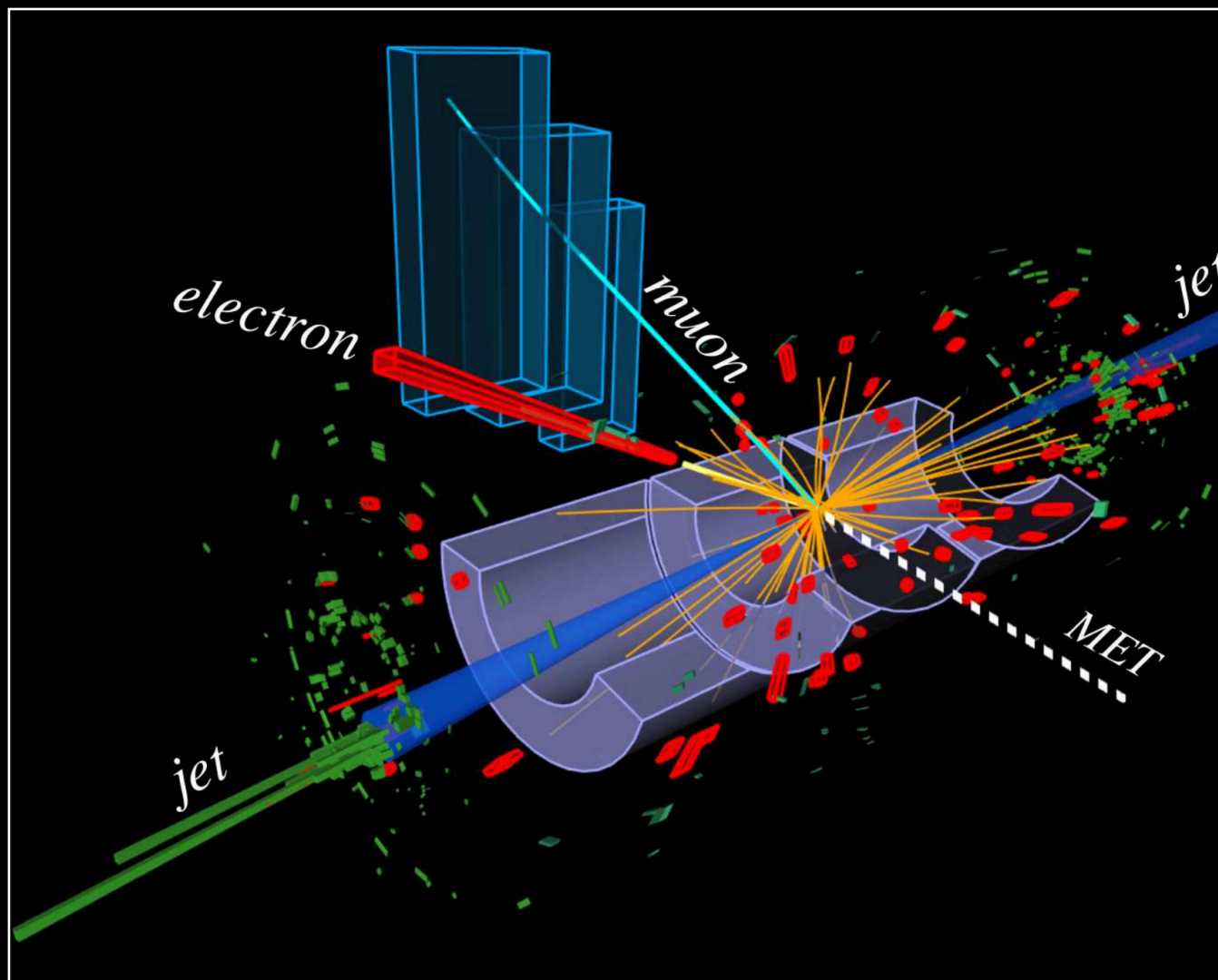
# WW scattering



# WW scattering



# WW scattering



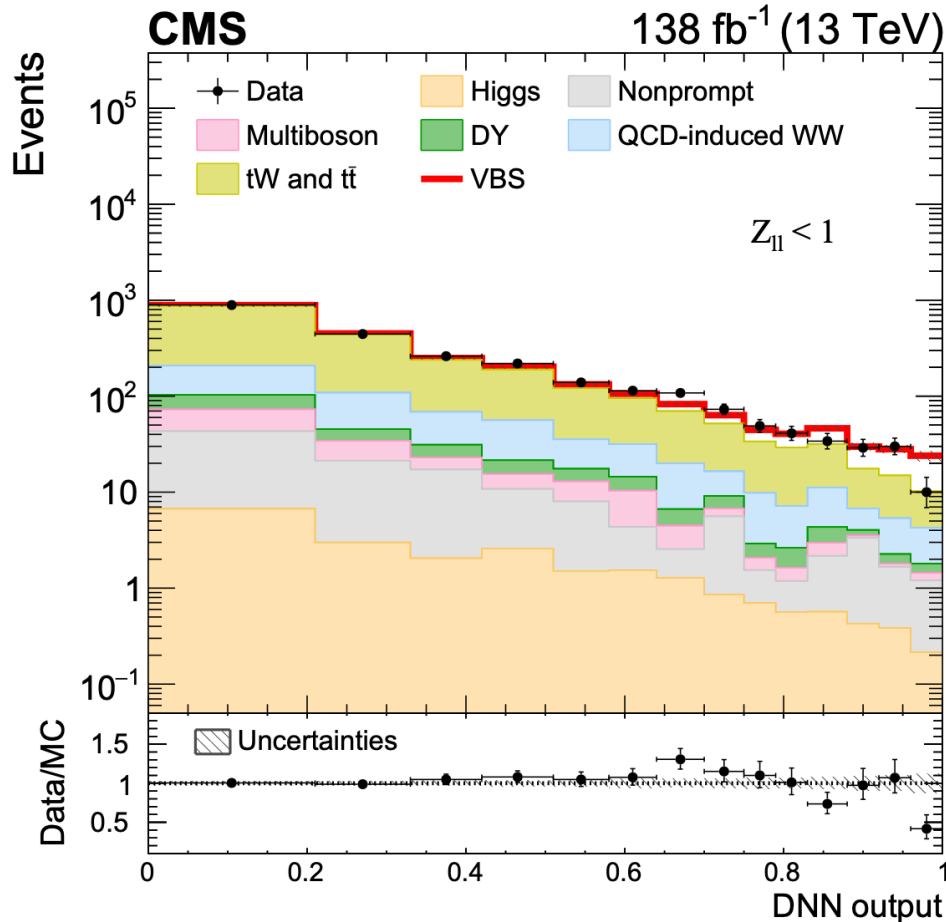
1412.2641

# WW scattering

2205.05711

Variable	Description
$m_{jj}$	Invariant mass of the two tagging jets pair
$\Delta\eta_{jj}$	Pseudorapidity separation between the two tagging jets
$p_T^{j_1}$	$p_T$ of the highest $p_T$ jet
$p_T^{j_2}$	$p_T$ of the second-highest $p_T$ jet
$p_T^{\ell\ell}$	$p_T$ of the lepton pair
$\Delta\phi_{\ell\ell}$	Azimuthal angle between the two leptons
$Z_{\ell_1}$	Zeppenfeld variable of the highest $p_T$ lepton
$Z_{\ell_2}$	Zeppenfeld variable of the second-highest $p_T$ lepton
$m_T^{\ell_1}$	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



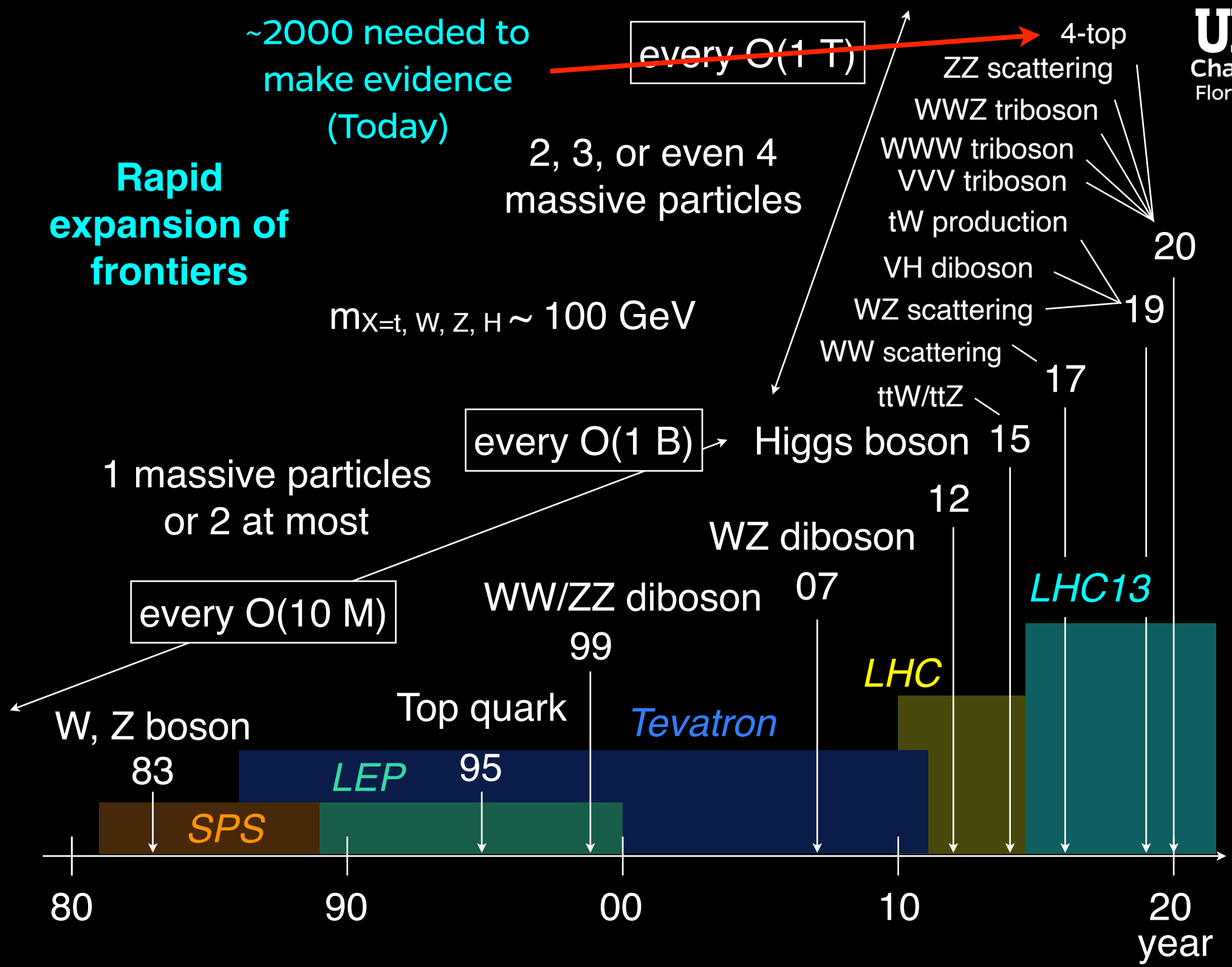
First observation of VBS  
opposite-sign WW  
 $5.6\sigma_{\text{obs}}$  ( $5.2\sigma_{\text{exp}}$ )

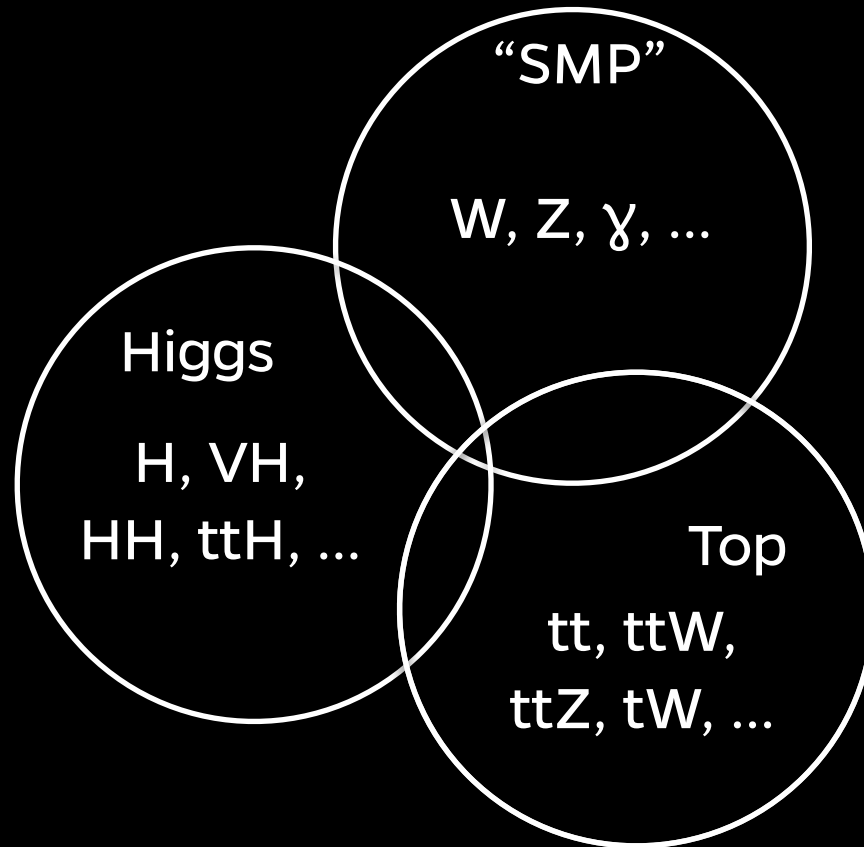
**Rapid expansion of frontiers**

~2000 needed to make evidence  
(Today)

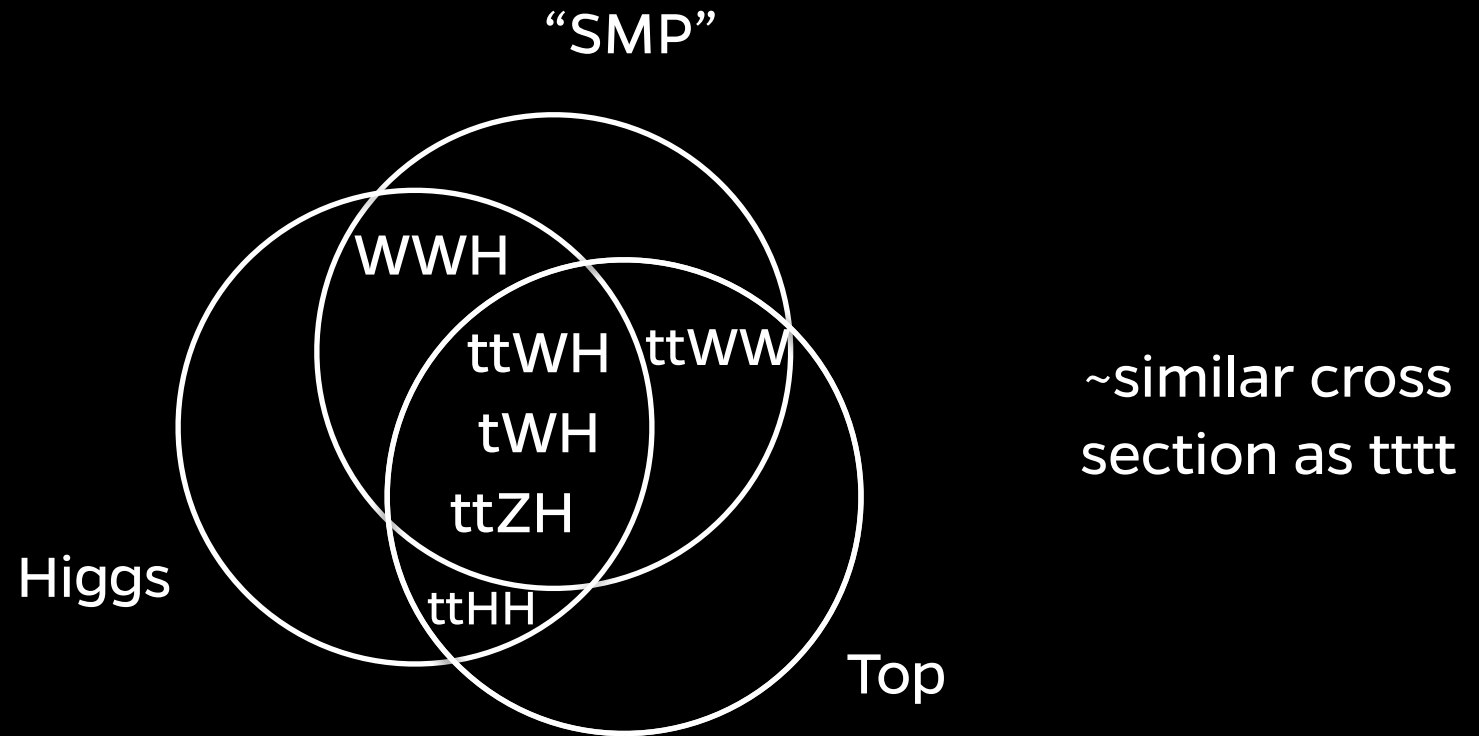
2, 3, or even 4 massive particles

$m_{X=t, W, Z, H} \sim 100 \text{ GeV}$









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  $O(100 \text{ GeV})$  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