

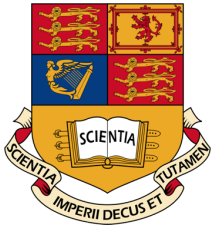
**Imperial College
London**

Physics Landscape

Nicholas Wardle
Imperial College London

ECR Future Collider Forum
4th November 2022
Cambridge University





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Describing the landscape



Describing the landscape

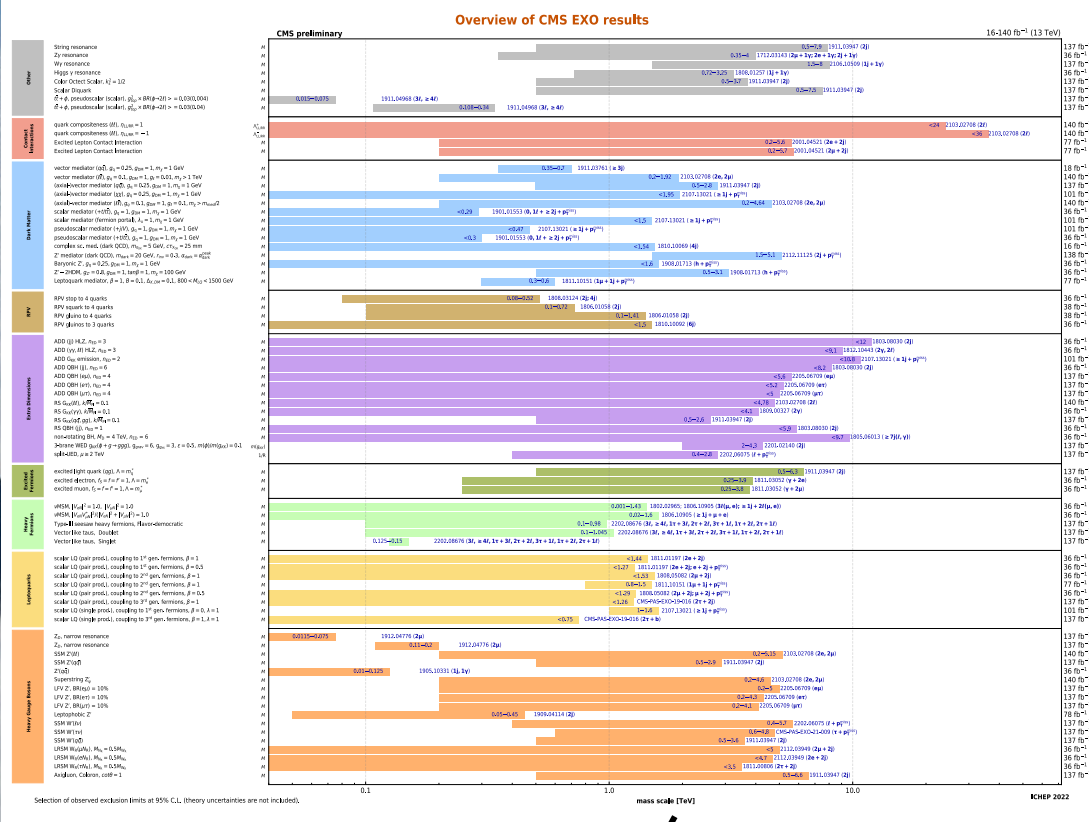
Somehow impossible to ignore the vast span of things that we haven't seen so far ...

ATLAS SUSY Searches* - 95% CL Lower Limits
July 2020

Model	Signature	$[L, dl]$ [fb ⁻¹]	Mass limit	Reference	
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow\tilde{g}\tilde{g}$	0 e, μ 2-6 jets 1-3 jets	E_{T}^{miss} 139 38.1	\tilde{g} [10x Degrad] \tilde{g} [1x, 8x Degrad]	ATLAS-CONF-2019-040 1711.03201
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow\tilde{g}\tilde{g}$	0 e, μ 2-6 jets	E_{T}^{miss} 139	\tilde{g}	ATLAS-CONF-2019-040 ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow\tilde{g}\tilde{g}W$	1 e, μ 2 jets	E_{T}^{miss} 139	\tilde{g}	ATLAS-CONF-2020-047 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow\tilde{g}\tilde{g}WZ$	0 e, μ 7-11 jets	E_{T}^{miss} 139	\tilde{g}	ATLAS-CONF-2020-020 1909.08457
3rd gen. squarks direct production	$\tilde{t}\tilde{t}, \tilde{t}\rightarrow\tilde{t}\tilde{t}$	0-1 e, μ 6 jets	E_{T}^{miss} 79.8 139	\tilde{t} \tilde{t}	ATLAS-CONF-2018-041 1909.08457
	$\tilde{b}\tilde{b}, \tilde{b}\rightarrow\tilde{b}\tilde{b}$	Multiple	E_{T}^{miss} 139	Forbidden	1708.02666, 1711.02801 1909.08457
	$\tilde{b}\tilde{b}, \tilde{b}\rightarrow\tilde{b}\tilde{b}Z$	0 e, μ 2 t	E_{T}^{miss} 139	Forbidden	1908.08122 ATLAS-CONF-2020-031
	$\tilde{b}\tilde{b}, \tilde{b}\rightarrow\tilde{b}\tilde{b}W$	0-1 e, μ ≥ 1 jet	E_{T}^{miss} 139	\tilde{b}	ATLAS-CONF-2020-003, 2004.14060
EW direct	$\tilde{W}\tilde{W}$	0 e, μ 3 jets	E_{T}^{miss} 139	\tilde{W}	ATLAS-CONF-2019-017 1803.10778
	$\tilde{Z}\tilde{Z}$	1 $t + 1 e, \mu$ 2 jets	E_{T}^{miss} 36.1	\tilde{Z}	1805.01649 1805.01649
	$\tilde{H}\tilde{H}$	0 e, μ mono-jet	E_{T}^{miss} 36.1	\tilde{H}	1711.03201 1705.03430
	$\tilde{H}\tilde{H}, \tilde{H}\rightarrow\tilde{H}\tilde{H}$	1-2 e, μ 3 jets	E_{T}^{miss} 139	Forbidden	SUSY-2018-019 SUSY-2018-019
Long-lived particles	$\tilde{L}\tilde{L}$ via WZ	3 e, μ 2 jets	E_{T}^{miss} 139	$\tilde{L}_1^+ \tilde{L}_1^-$	ATLAS-CONF-2020-015 1911.12606
	$\tilde{L}\tilde{L}$ via WW	0-1 e, μ 2 jets	E_{T}^{miss} 139	$\tilde{L}_1^+ \tilde{L}_1^-$	1908.08215
	$\tilde{L}\tilde{L}$ via Wb	2 e, μ 2 jets	E_{T}^{miss} 139	$\tilde{L}_1^+ \tilde{L}_1^-$	2004.10384, 1908.08226 1908.08215
	$\tilde{L}\tilde{L}$ via $\tilde{Z}\tilde{Z}$	2 t 2 jets	E_{T}^{miss} 139	$\tilde{L}_1^+ \tilde{L}_1^-$	1911.06660 1908.08215
RPV	$\tilde{L}\tilde{L}$ via $\tilde{Z}\tilde{Z}$	0 e, μ $\geq 3 b$	E_{T}^{miss} 36.1	\tilde{L}	1906.04030 ATLAS-CONF-2020-040
	Direct $\tilde{L}_1^+ \tilde{L}_1^-$ prod., long-lived \tilde{L}_1^+	Disapp. trk	E_{T}^{miss} 36.1	\tilde{L}_1^+	1712.02118 ATL-PHYS-PUB-2017-019
	Stable \tilde{R} -hadron	Multiple	E_{T}^{miss} 36.1	\tilde{R}	1902.01636, 1808.04095 1710.04991, 1808.04095
	Metastable \tilde{R} -hadron, $\tilde{R}\rightarrow\tilde{g}\tilde{g}$	Multiple	E_{T}^{miss} 36.1	\tilde{R}	1710.04991, 1808.04095

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

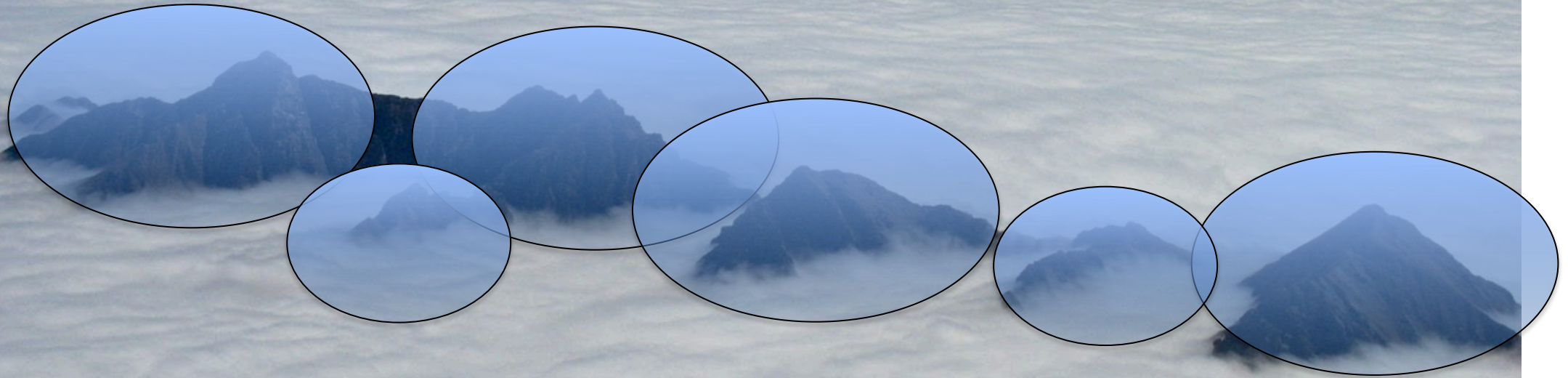
ATLAS Preliminary
 $\sqrt{s} = 13$ TeV



I'll do my best to not repeat [Mika's Talk](#) from April but the landscape hasn't changed (too much) since then

Describing the landscape

I'll cover a few interesting features (bumps or deviations) ...

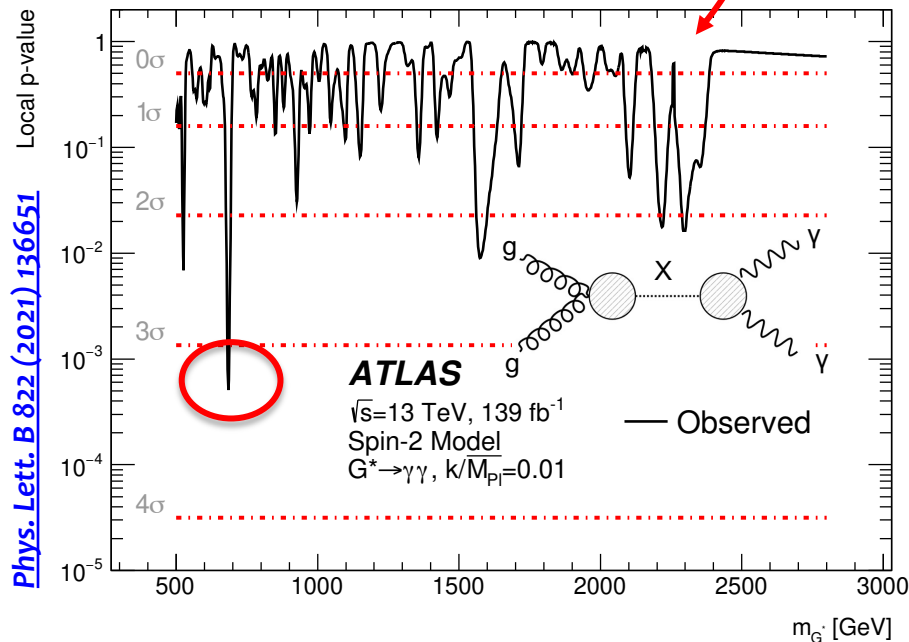


... And i'll do my best to not repeat [Mika's Talk](#) from April - but the landscape hasn't changed (too much) since then

Interesting Bumps

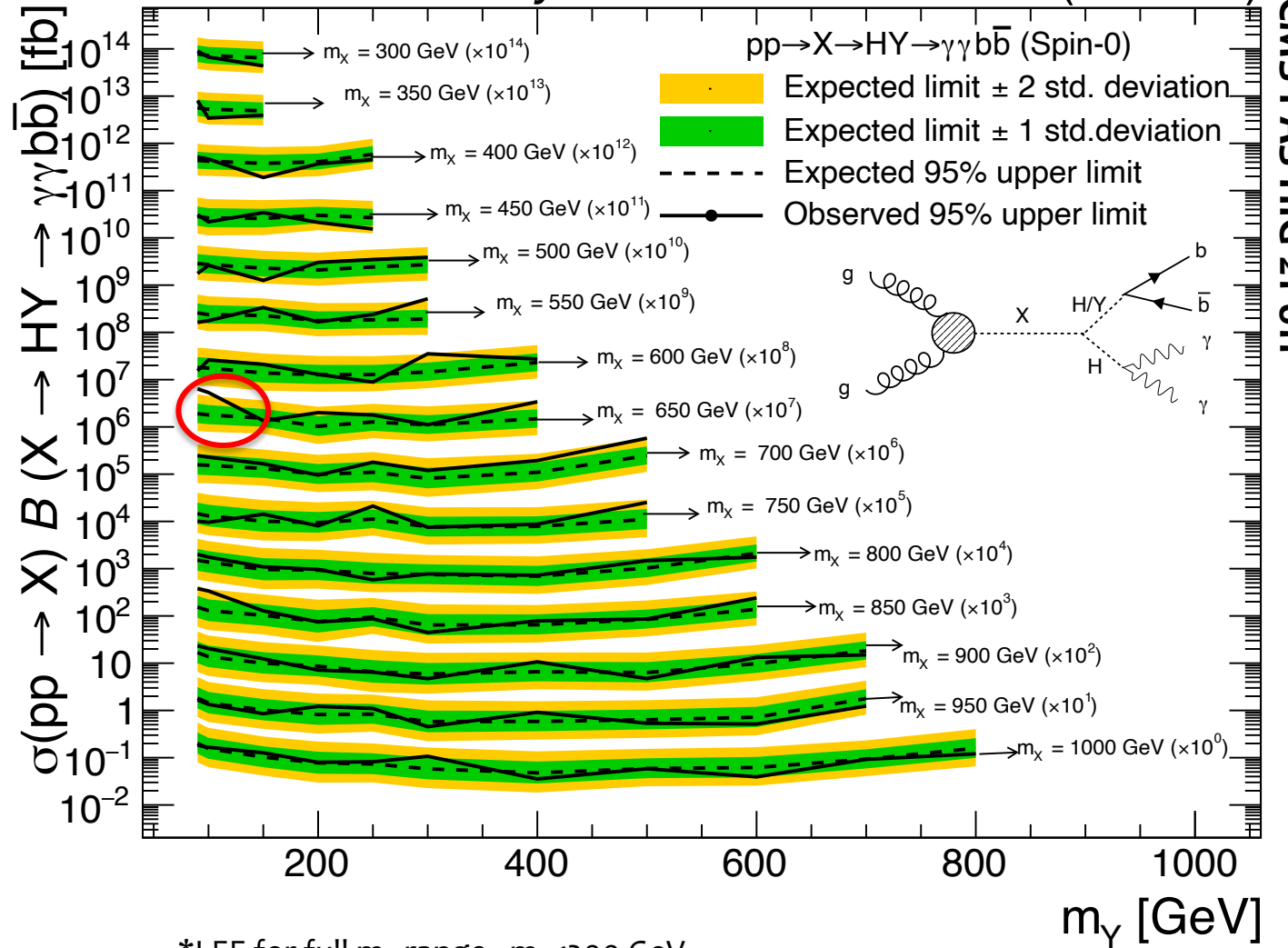
$X \rightarrow H(\gamma\gamma)Y(bb)$ Excess for $m_X=650$ GeV,
 $m_Y=90$ GeV $\rightarrow 3.8\sigma$ local (2.6σ global*)

$X \rightarrow \gamma\gamma$ 3.29σ (1.36σ) local (global)
 @ $m_X=684$ GeV



Phys. Lett. B 822 (2021) 136651

CMS Preliminary 138 fb⁻¹ (13 TeV)

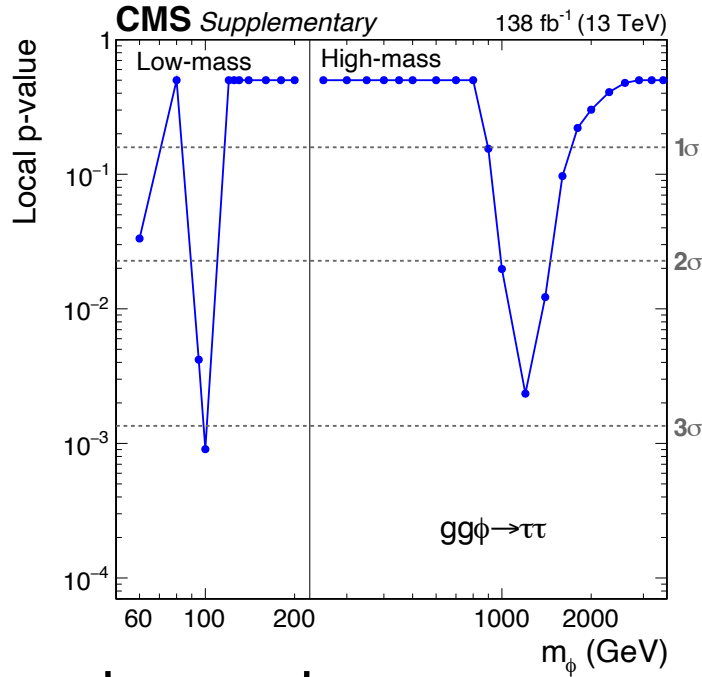


*LEE for full m_X range, $m_Y < 200$ GeV

CMS-PAS-HIG-21-011

Related Bumps?

HIG-21-001: Search for $A/H \rightarrow \tau\tau$

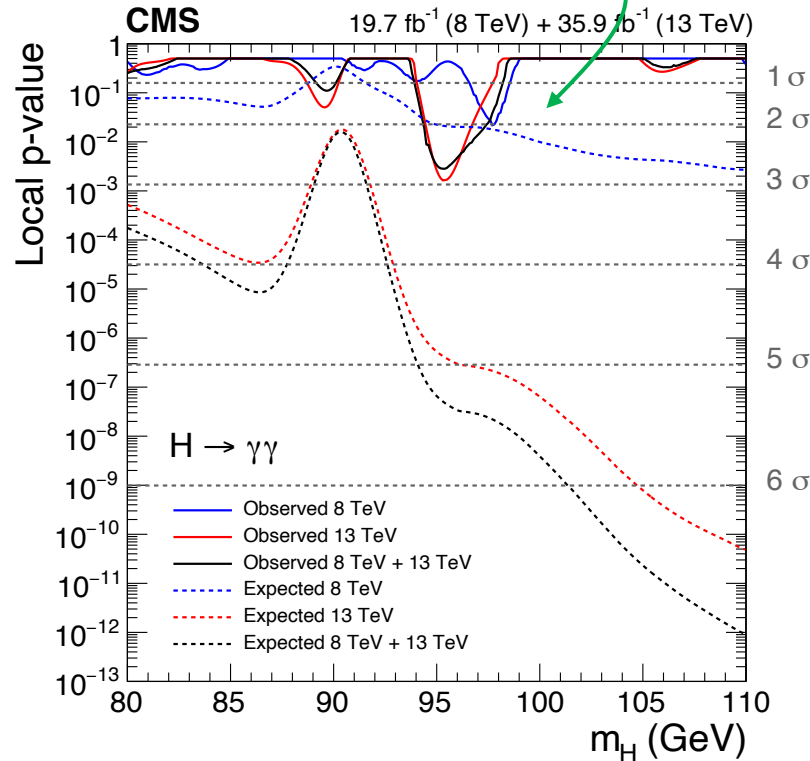


100 GeV: 3.1 σ (local)
/ 2.7 σ (global)

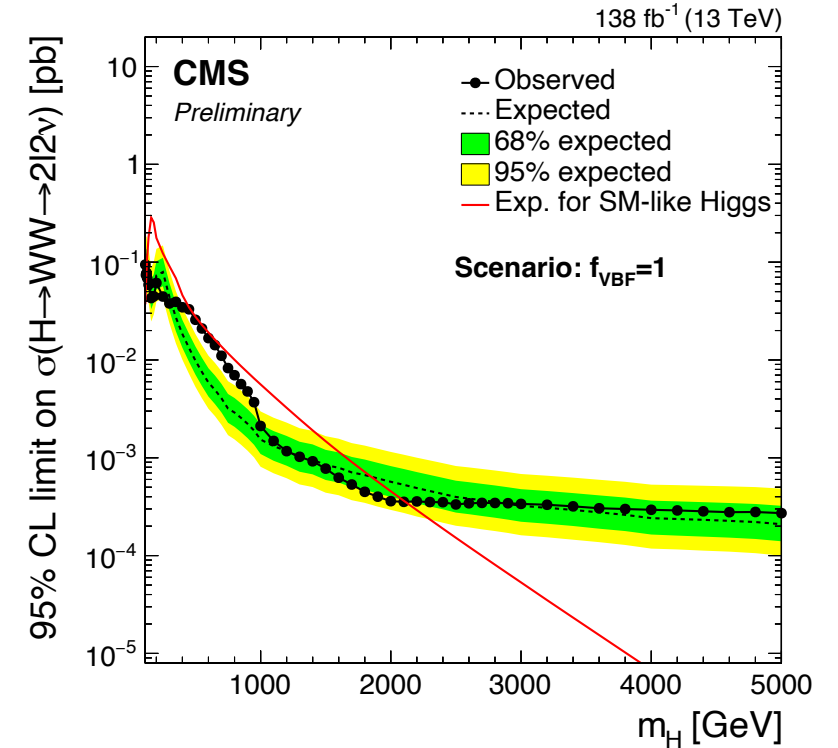
1.2 TeV: 2.8 σ (local)
/ 2.4 σ (global)

PLB 793 (2019) 320: Search for low mass $h \rightarrow \gamma\gamma$

95 GeV: 2.8 σ (local) / 1.3 σ (global)



HIG-20-016: Search for high mass $H \rightarrow WW$

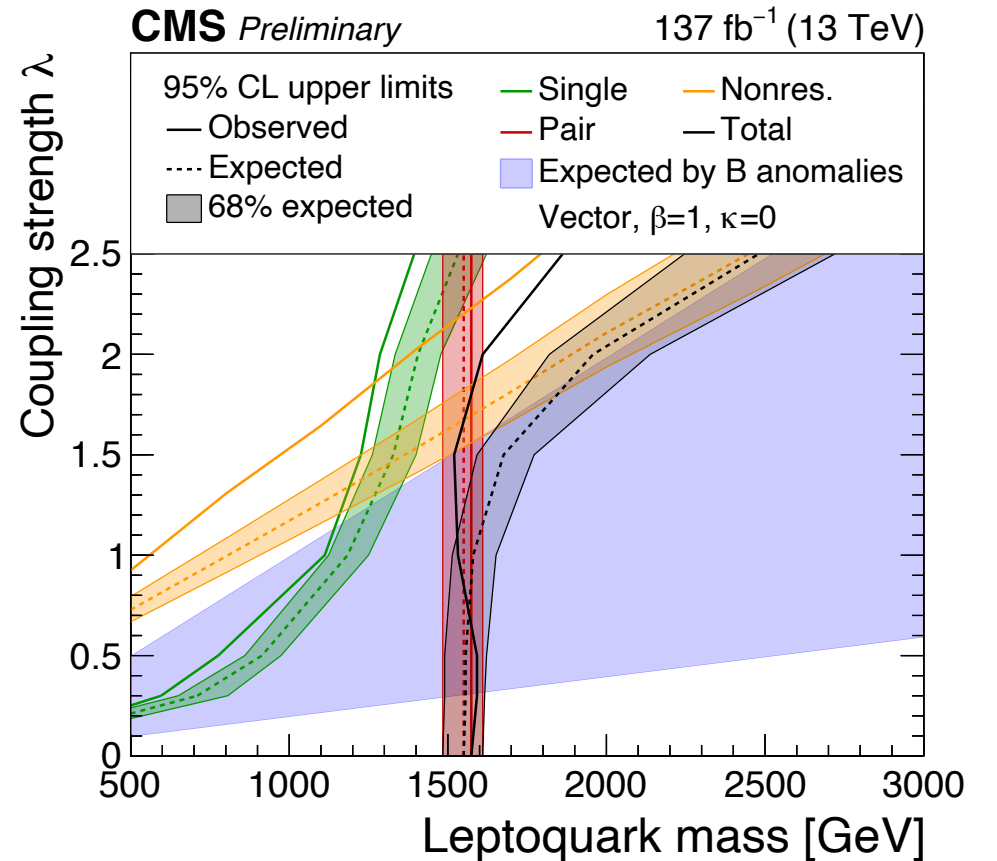
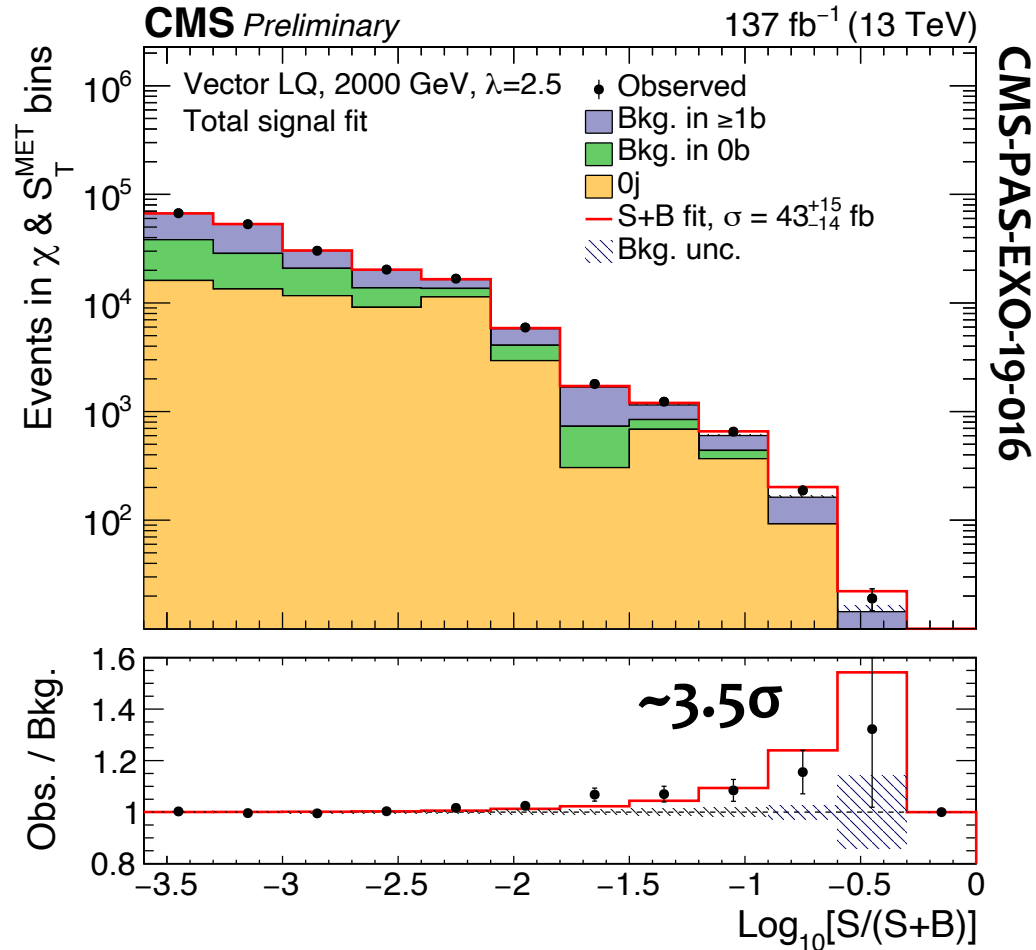
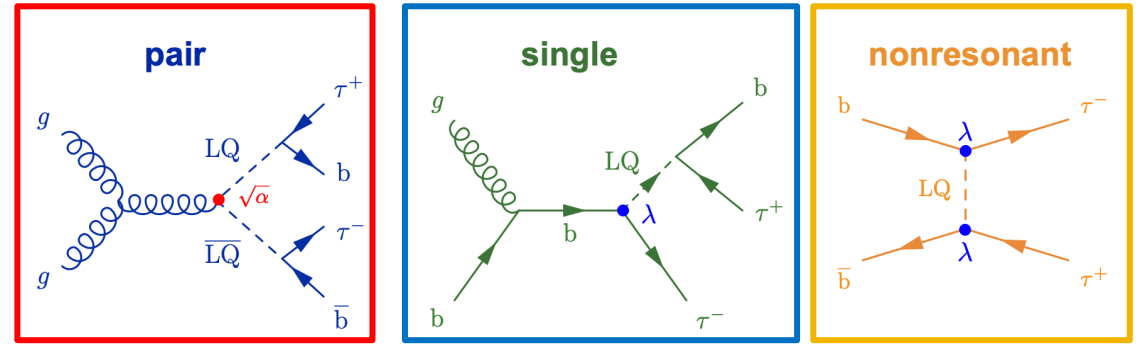


Excess (largely in VBF prod) at **650 GeV – 3.8 σ (local) 2.6 σ (global)**

What's up with 650 & 90 GeV?

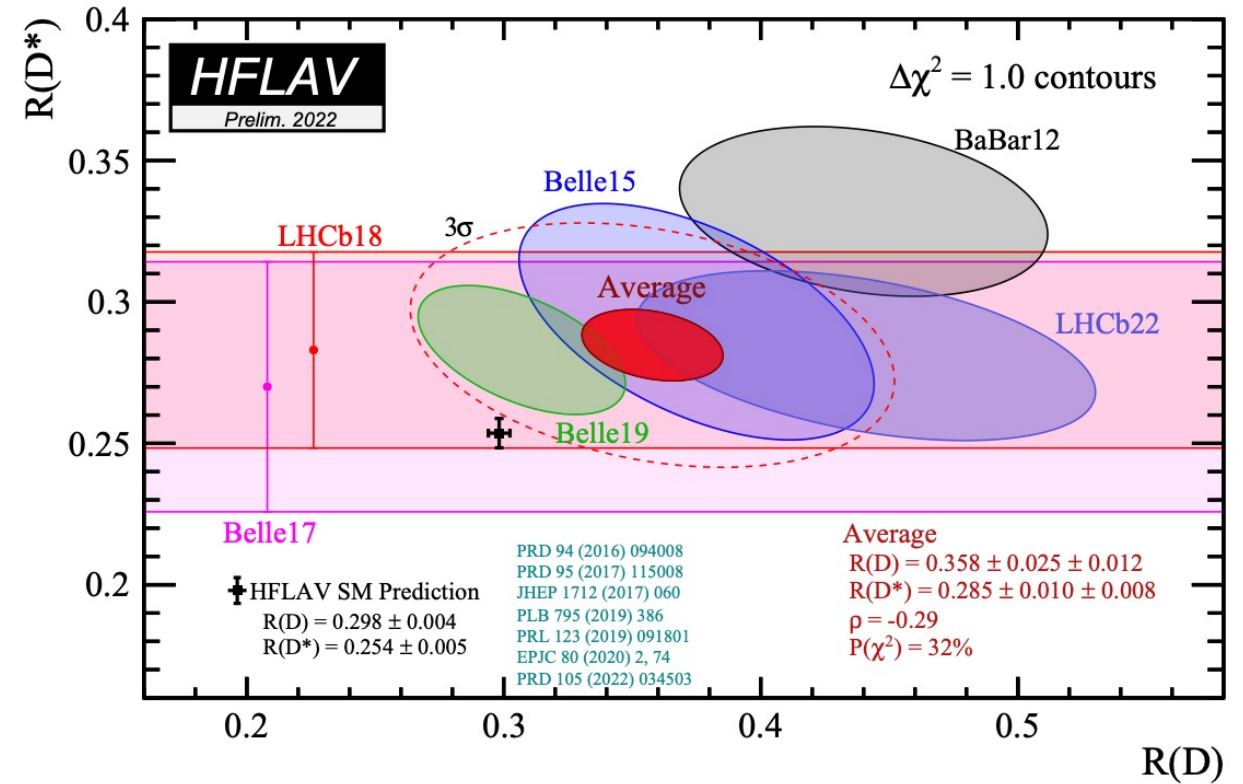
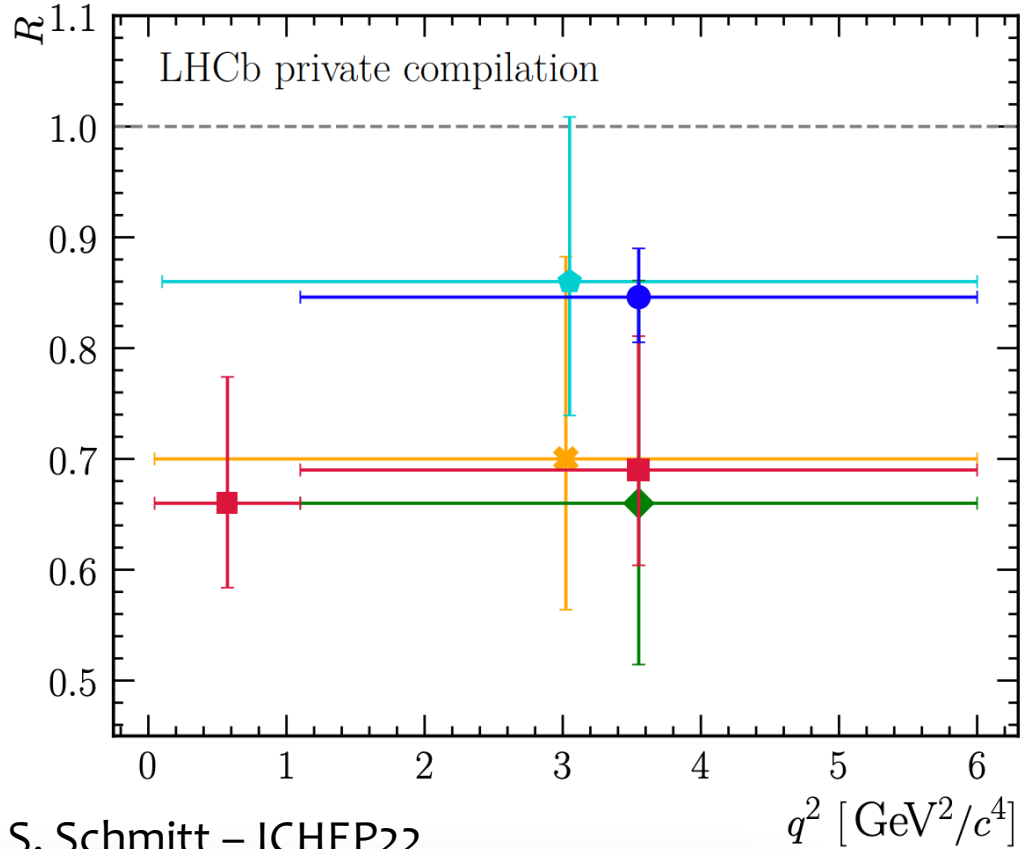
3rd Gen LQ bumps

Searches for new physics with large couplings to 3rd gen quarks and leptons motivated by B-anomalies



Speaking of anomalies

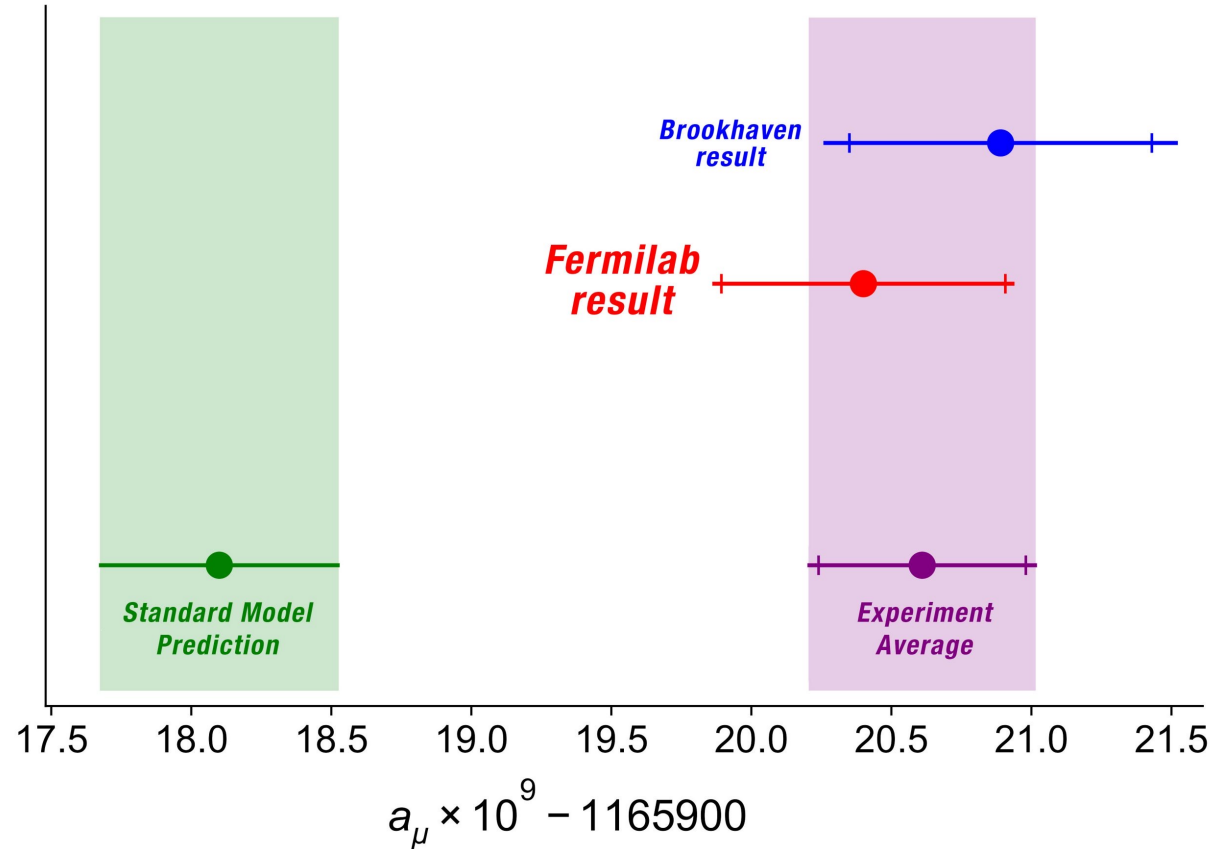
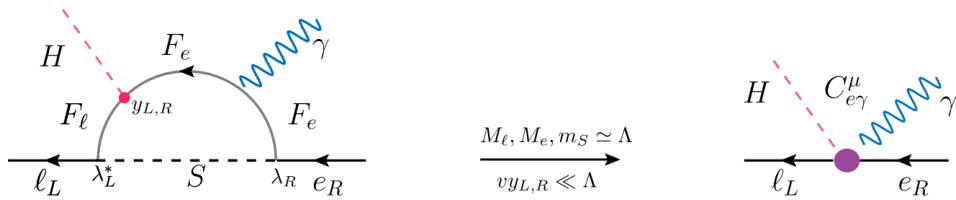
- ◆ R_K [Nat. Phys. 18, 277–282 (2022)]
- ◆ $R_{K_S^0}$ [PRL 128, No. 19]
- ◆ $R_{K^{*+}}$ [PRL 128, No. 19]
- ◆ R_{pK} [JHEP 05 (2020) 040]
- ◆ $R_{K^{*0}}$ [JHEP 08 (2017) 055]



G. Ciezarek - LHC Seminar Oct 22

Setting the scale of NP?

One of the most striking results in our field is in the muon anomalous magnetic moment



FNAL news page

From perturbative unitarity constraints on NP interpretations of $g-2$ results ([Phys. Rev. D 104, 055035 \(2021\)](#).)

“...in order to resolve the new physics origin of the SMEFT operators behind Δa_μ one would need to probe high-energy scales **up to the PeV**”

“.. simplified models [...] still imply new on-shell states below **200 TeV**”

Not everything is said and done yet

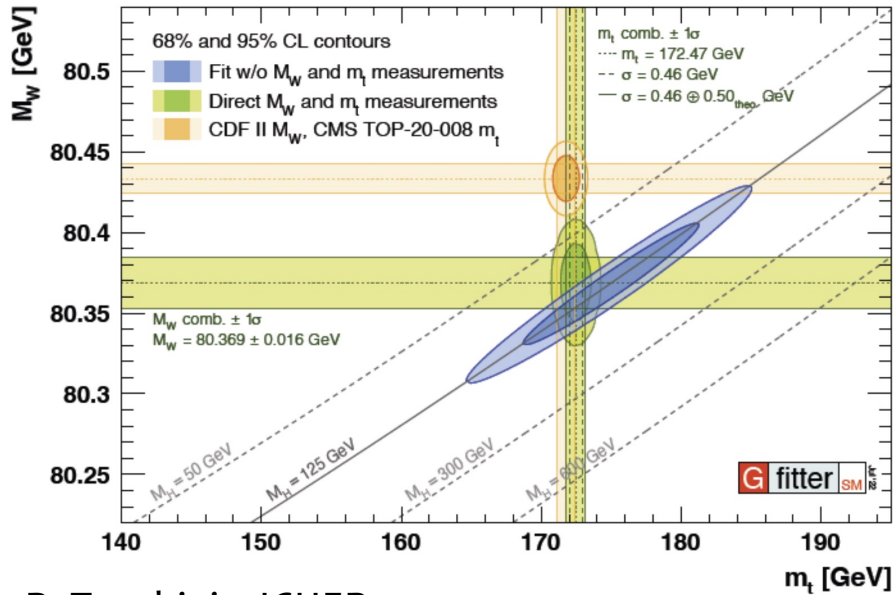
LHC RUN 3

BEAMS, DETECTORS, ACTION



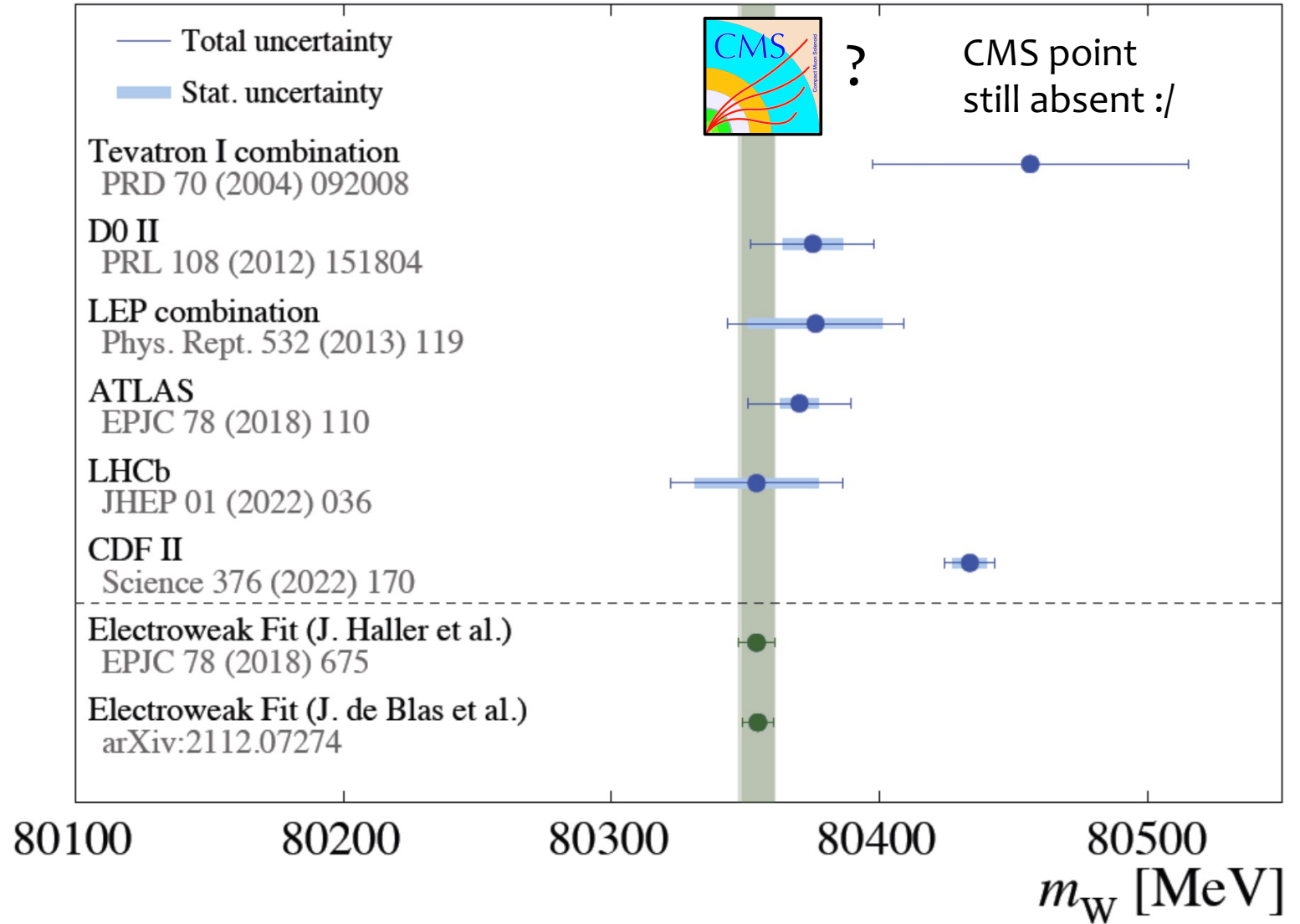
W mass

Understanding our precision W-mass measurements together will take **more data and more time** (exp-vs-exp & exp-vs-theory)



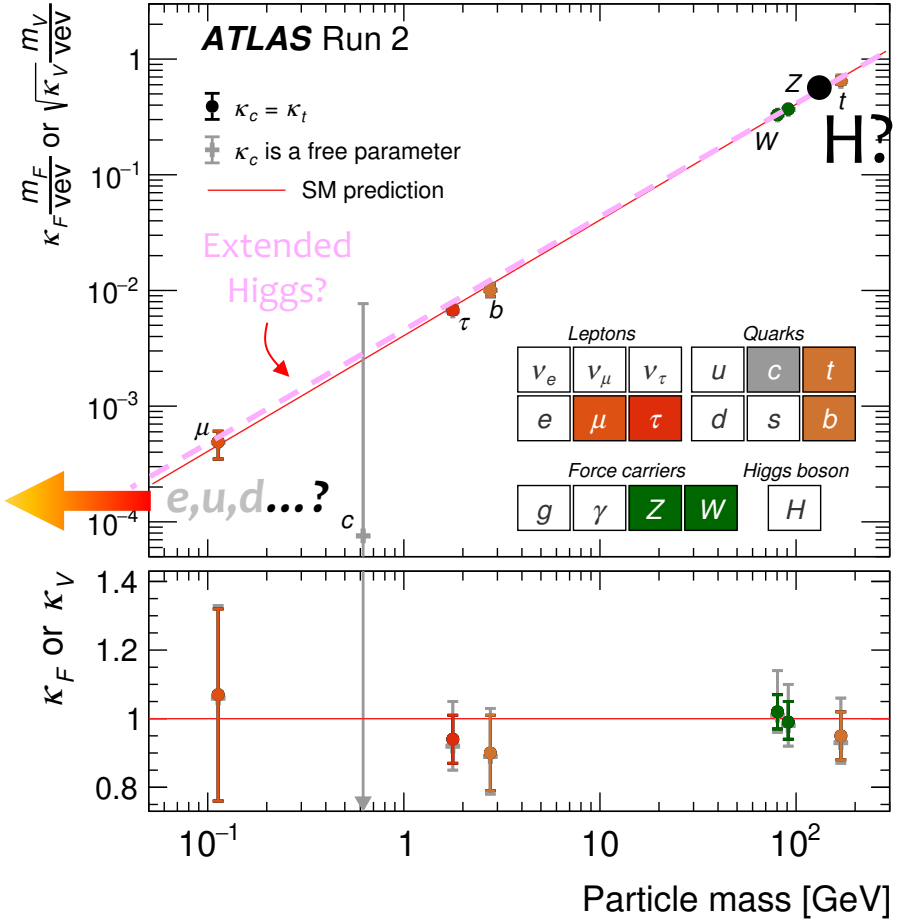
R. Tenchini – ICHEP 2022

LHCB-FIGURE-2022-003



Higgs Physics

10 years of Higgs boson measurements still leave room for new physics!

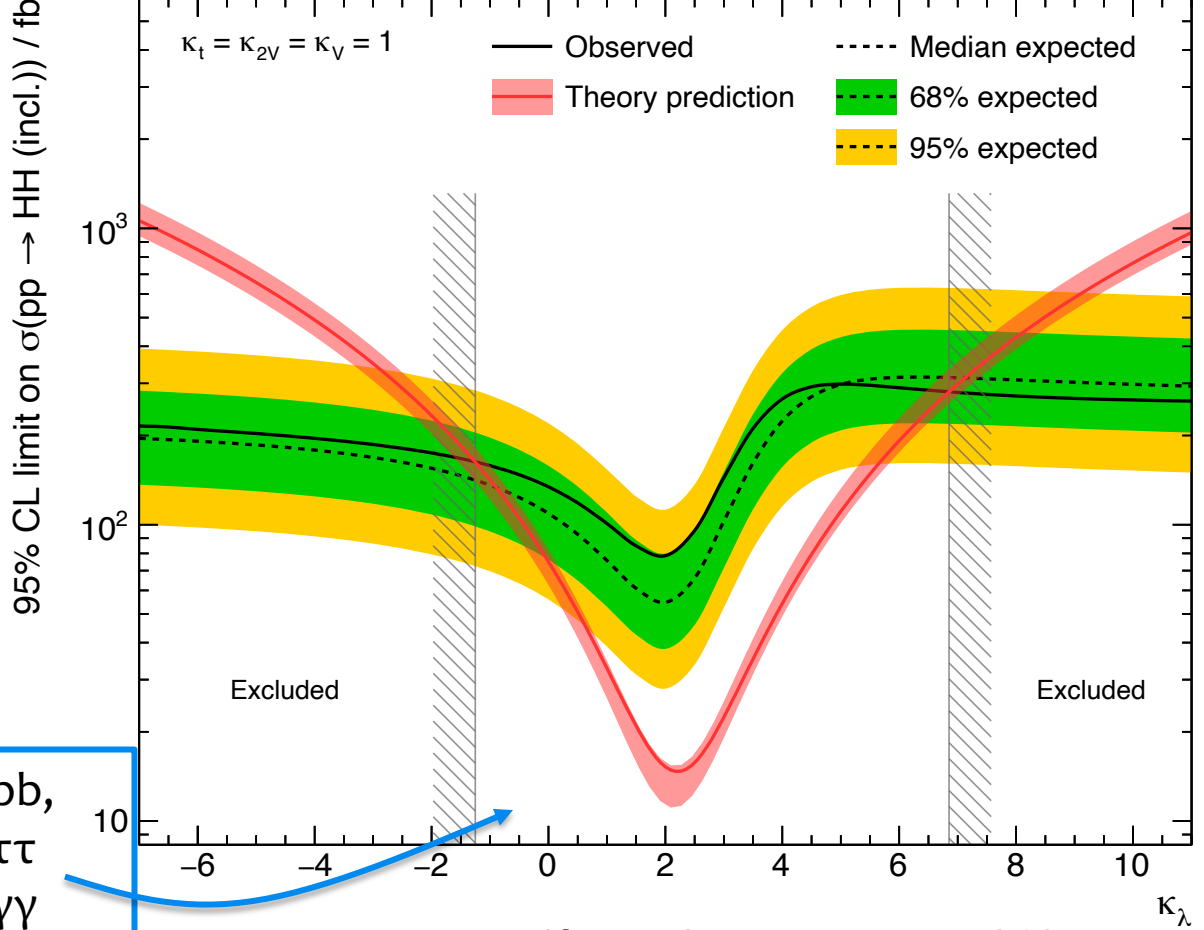


Nature volume 607 (2022)

- HH → bbbb,
- HH → bbττ
- HH → bbγγ
- HH → bbZZ(4l)
- HH → multilep.

CMS

138 fb⁻¹ (13 TeV)



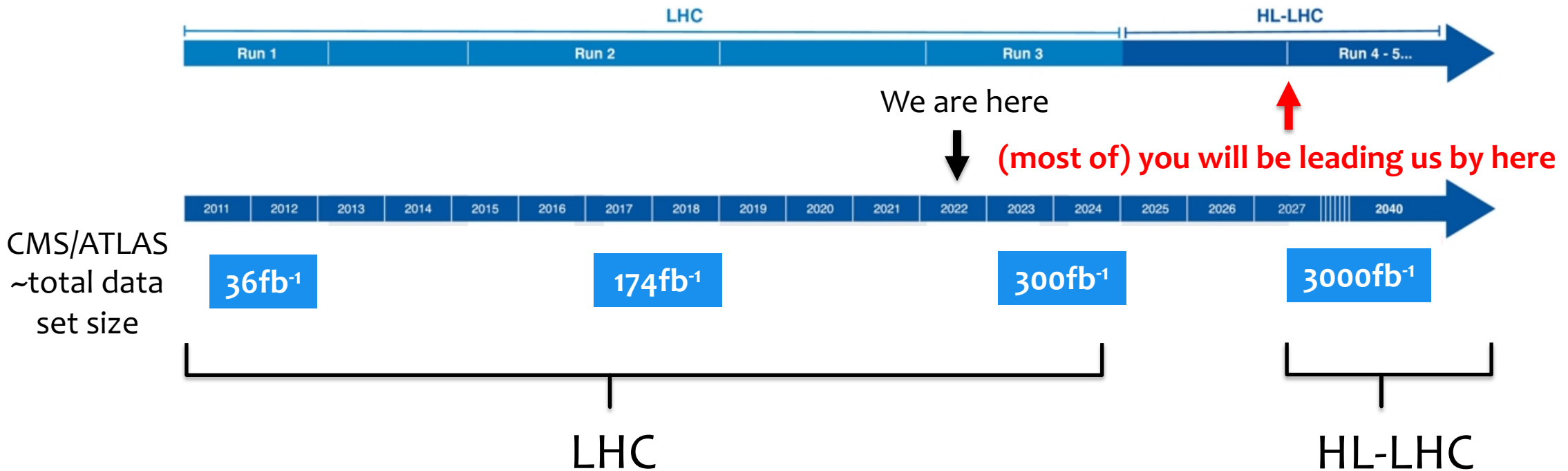
Nature volume 607 (2022)

Measuring self-coupling to 50% would be interesting for understanding early-universe evolution (Phys. Rev. D 97, 075008 (2018))

We've barely begun with the LHC

After Run-3 of the LHC, the next phase is the **high-luminosity (HL)-LHC**

~20X the data we have today!

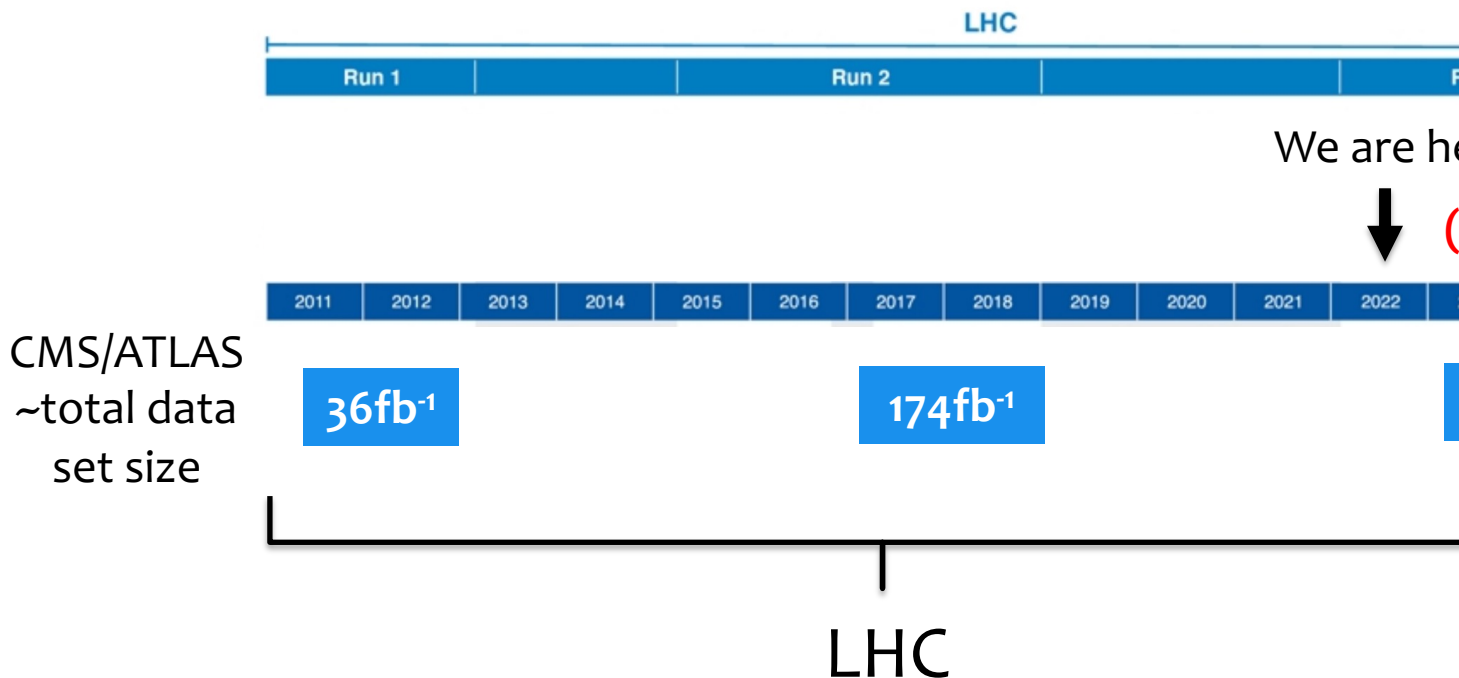


Expect **> 160M H-bosons / 120k HH pairs** Per-expt by the end of the **HL-LHC** !

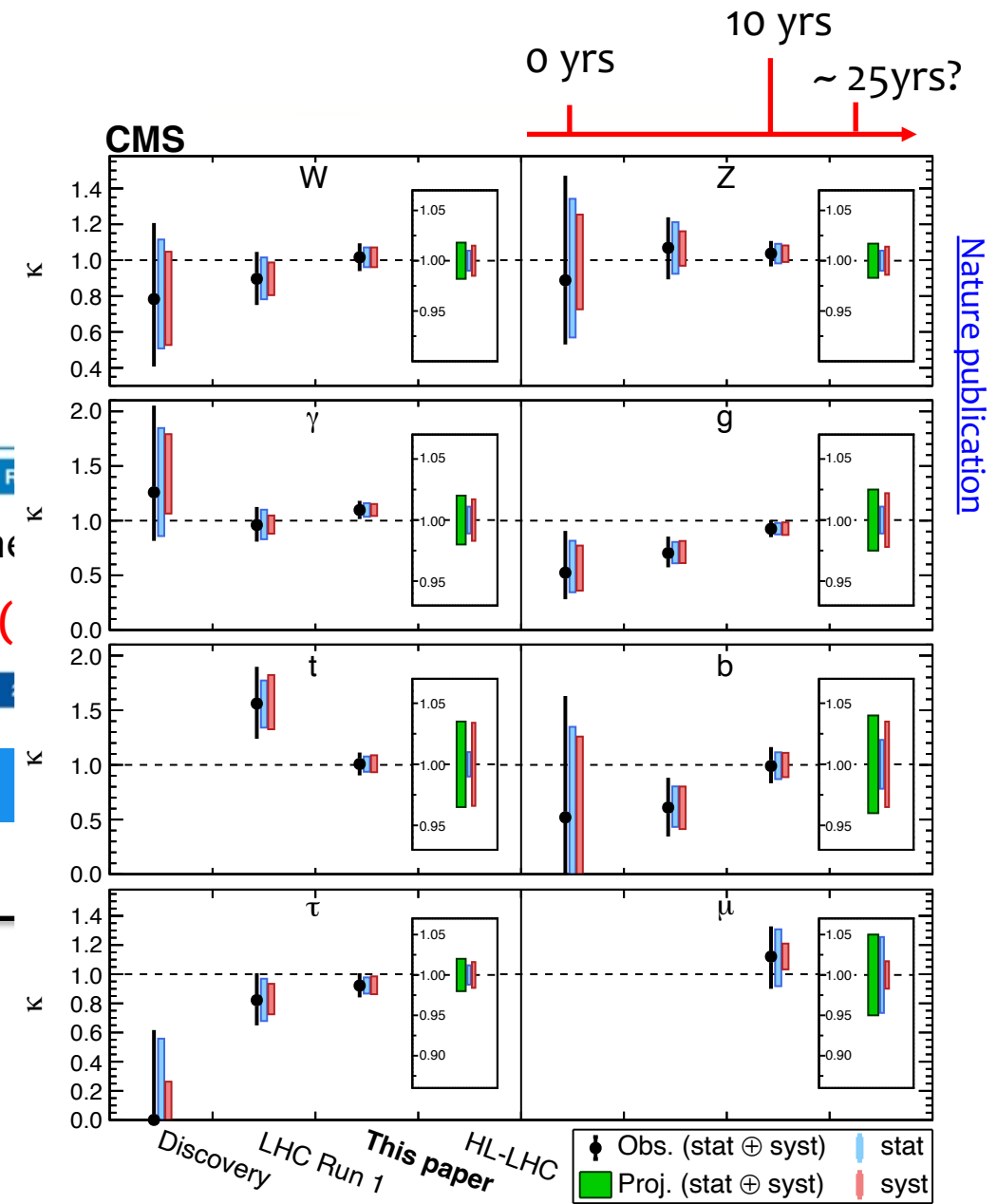
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Precision Measurements for Discovery

Examples from the past have taught us that precision measurements can lead to *revolutionary discoveries...*

Herschel 1781



Uranus discovery
“as a planet” (1781)

Le Verrier, Galle, d'Arrest 1846



Neptune discovered with 1°
of predicted position (1846)



Precise measurements of position
revealed deviations from expected orbit
→ new planet predicted (1845/46)

Measurements of Mercury's orbit reveals
43 arcseconds/century anomaly
→ new planet (or body) predicted (1859)

Slide shamelessly stolen from excellent Jesse Liu (Cambridge) seminar

Precision Measurements for Discovery

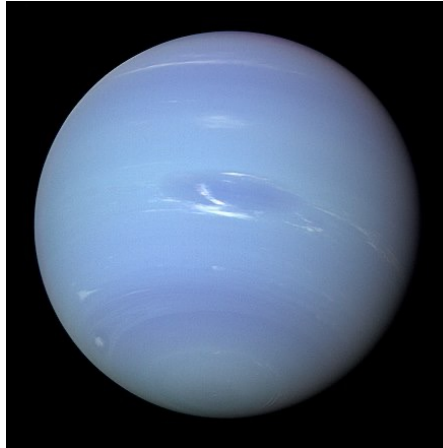
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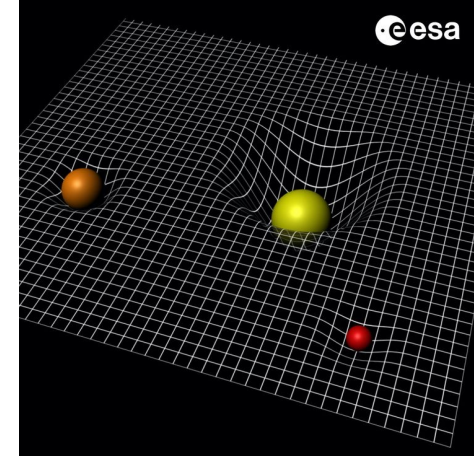


Uranus discovery
“as a planet” (1781)

Le Verrier, Galle, d'Arrest 1846



Neptune discovered with 1°
of predicted position (1846)



General relativity solves
anomaly and changes view
of space & time (1915)

Precise measurements of position
revealed deviations from expected orbit
→ new planet predicted (1845/46)

Measurements of Mercury's orbit reveals
43 arcseconds/century anomaly
→ new planet (or body) predicted (1859)

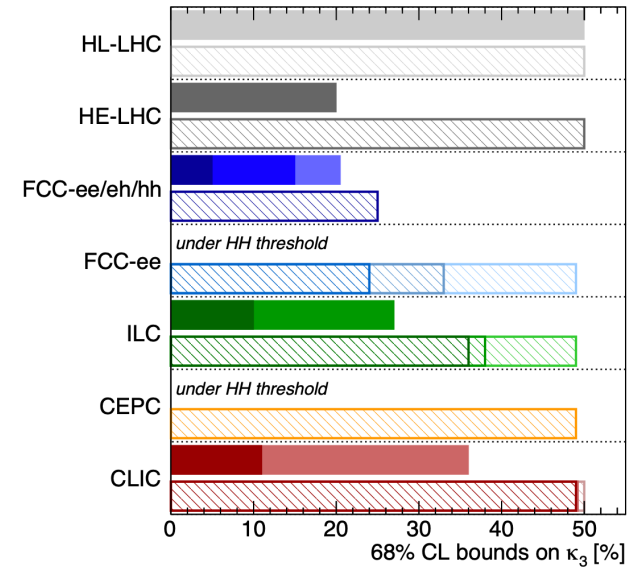
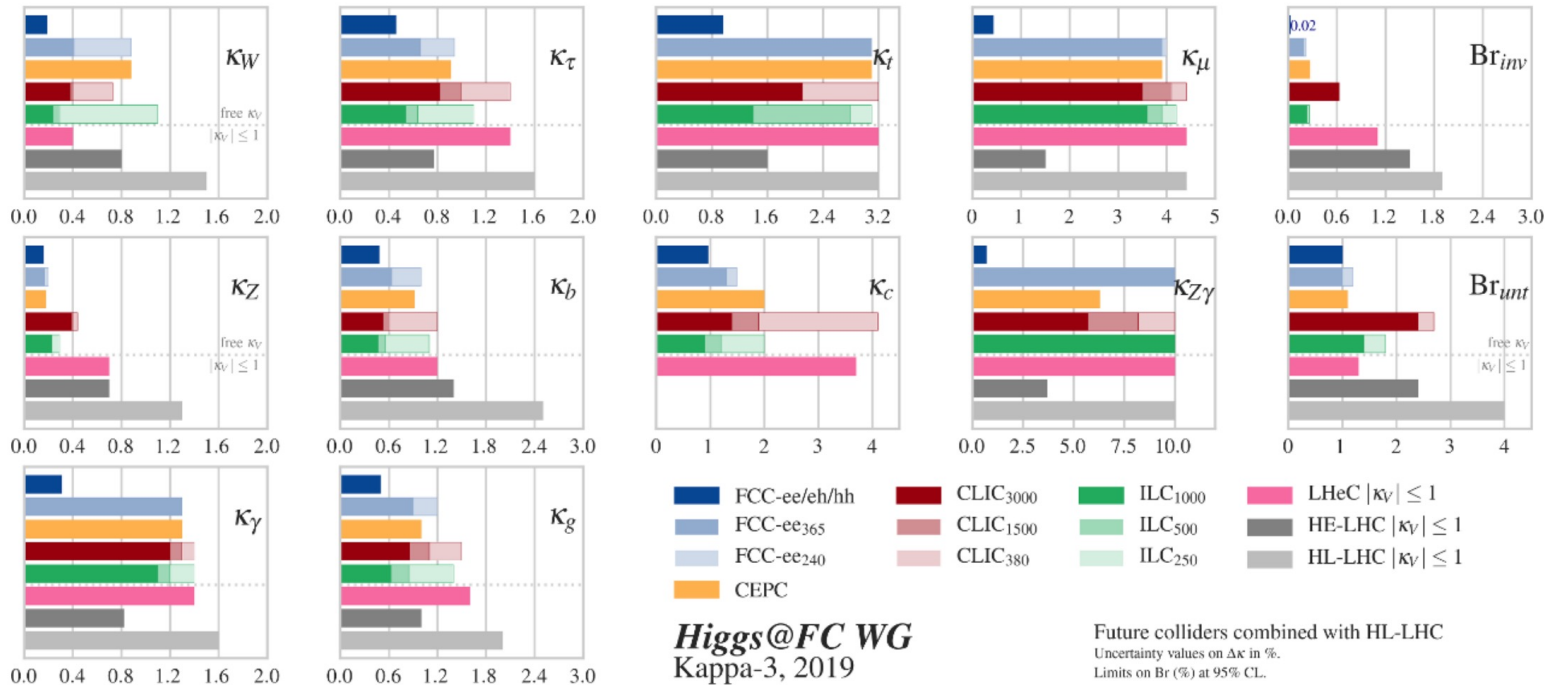
Slide shamelessly stolen from excellent Jesse Liu (Cambridge) seminar

... History has a habit of repeating itself 🙌 ...

FCC reach (there's more than just Higgs but...)

Many potential options but all lead to high precision (O(%) level) characterization of the Higgs boson couplings

Higgs boson self-coupling requires high energy (O(100)TeV) machine for % level measurement



Higgs@FC WG September 2019

di-Higgs		single-Higgs	
HL-LHC 50%	HL-LHC 50% (47%)	HL-LHC 50% (47%)	HL-LHC 50% (47%)
HE-LHC [10-20]%	HE-LHC 50% (40%)	HE-LHC 50% (40%)	HE-LHC 50% (40%)
FCC-ee/eh/hh 5%	FCC-ee/eh/hh 25% (18%)	FCC-ee ³⁵⁵ 24% (14%)	FCC-ee ³⁵⁵ 24% (14%)
LE-FCC 15%	LE-FCC n.a.	FCC-ee ³⁰⁰ 33% (19%)	FCC-ee ³⁰⁰ 33% (19%)
FCC-eh ³⁵⁰⁰ -17+24%	FCC-eh ³⁵⁰⁰ n.a.	FCC-ee ²⁴⁰ 49% (19%)	FCC-ee ²⁴⁰ 49% (19%)
		ILC ¹⁰⁰⁰ 10%	ILC ¹⁰⁰⁰ 36% (25%)
		ILC ⁵⁰⁰ 27%	ILC ⁵⁰⁰ 38% (27%)
		ILC ²⁵⁰	ILC ²⁵⁰ 49% (29%)
		CEPC	CEPC 49% (17%)
		CLIC ³⁰⁰⁰ -7%+11%	CLIC ³⁰⁰⁰ 49% (35%)
		CLIC ¹⁵⁰⁰	CLIC ¹⁵⁰⁰ 49% (41%)
		CLIC ⁵⁰⁰	CLIC ⁵⁰⁰ 49% (41%)
		CLIC ³⁰⁰	CLIC ³⁰⁰ 50% (46%)

All future colliders combined with HL-LHC

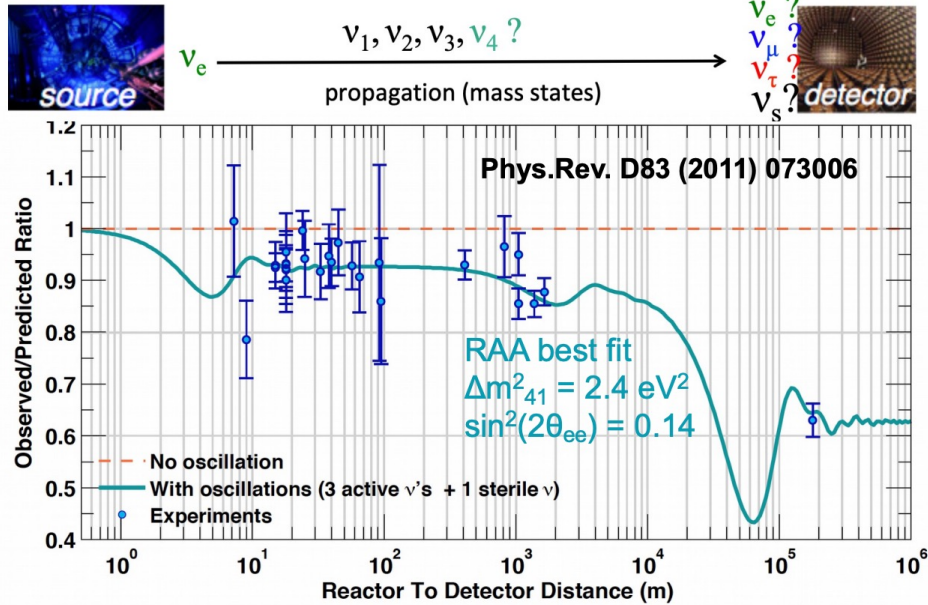
JHEP 139 (2020)

No Summary – time for discussion!

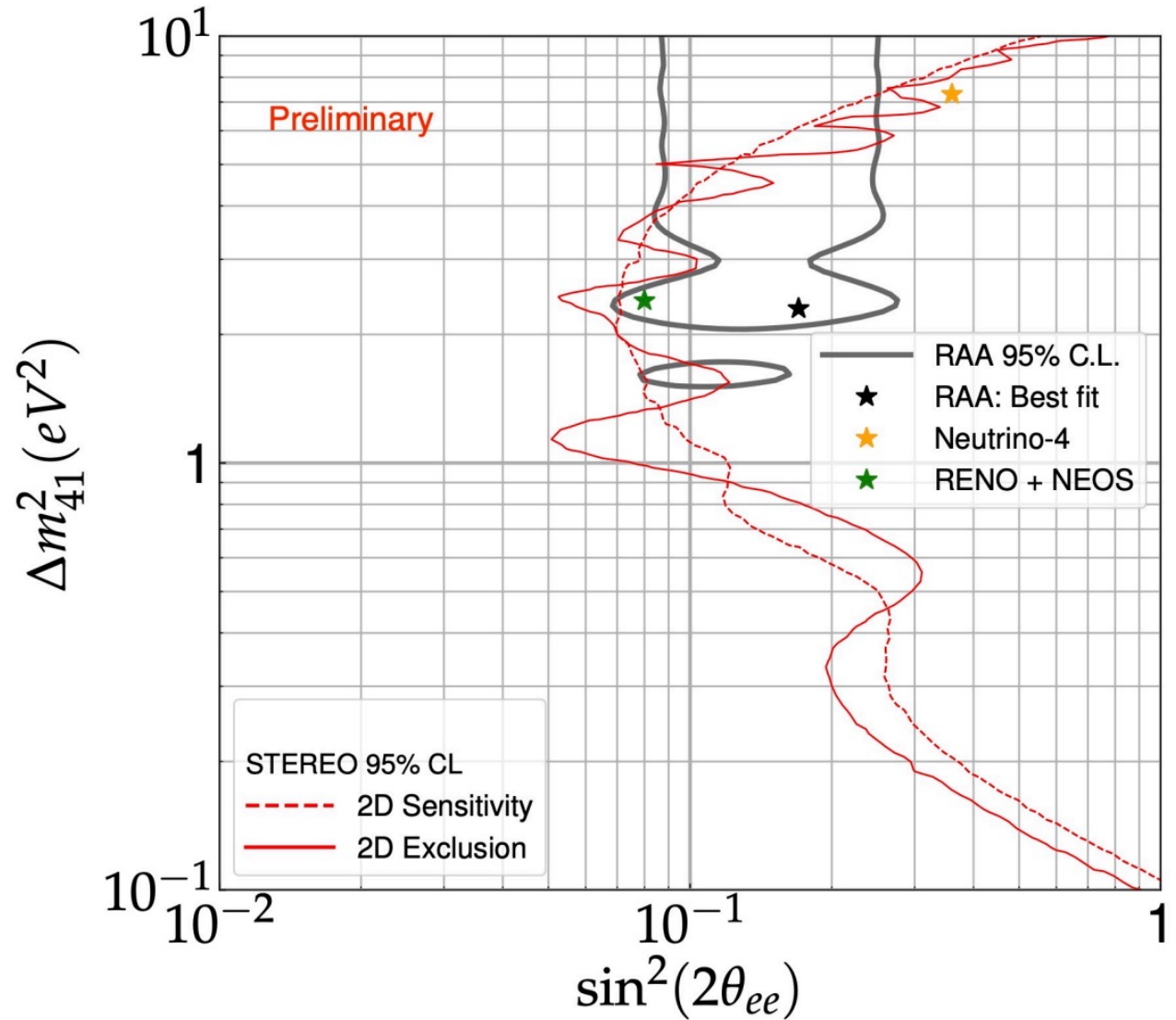


Backup Slides

Reactor Anomaly (STEREO)



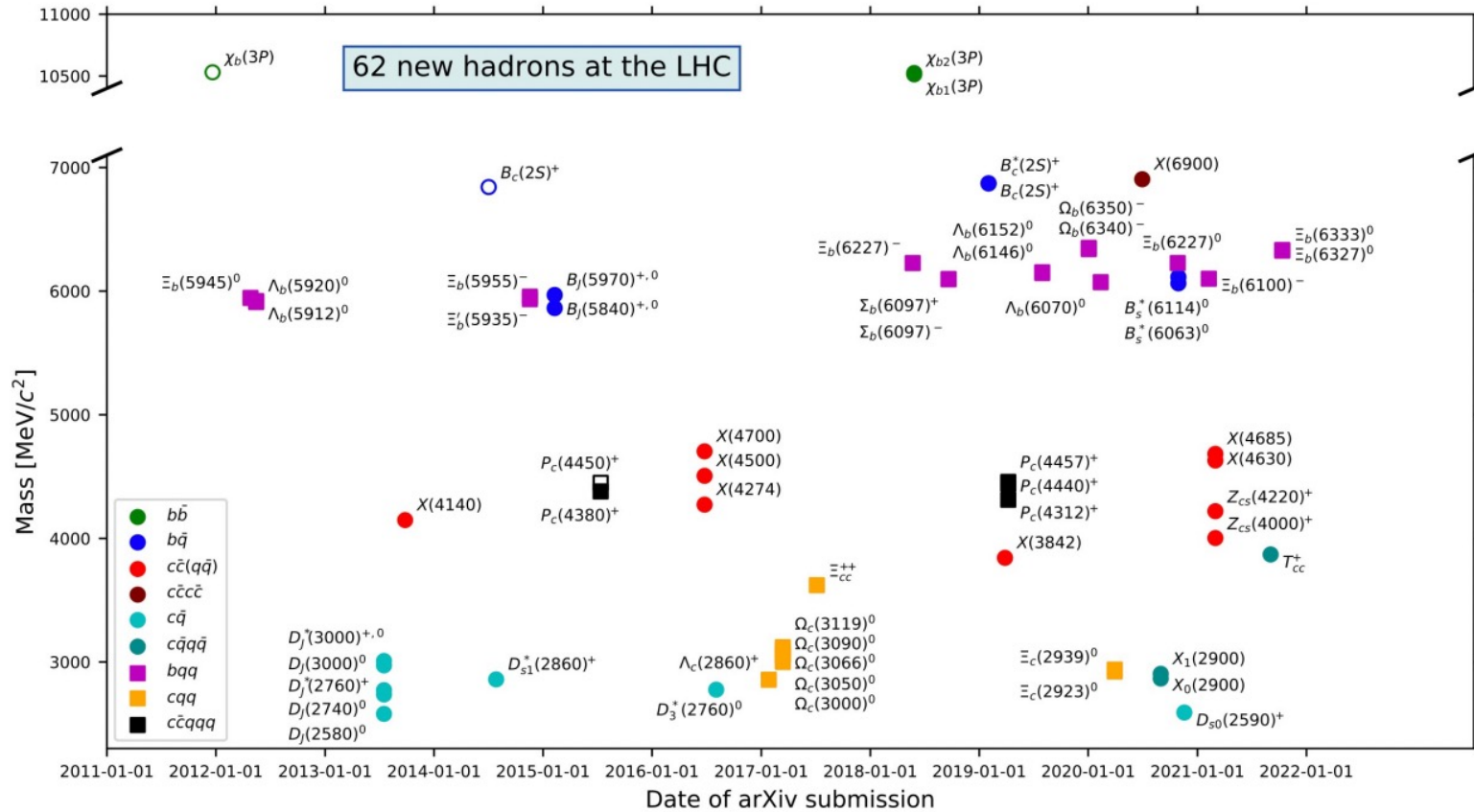
RAA : Reactor Antineutrino Anomaly (deficit in anti-neutrino flux from reactor)



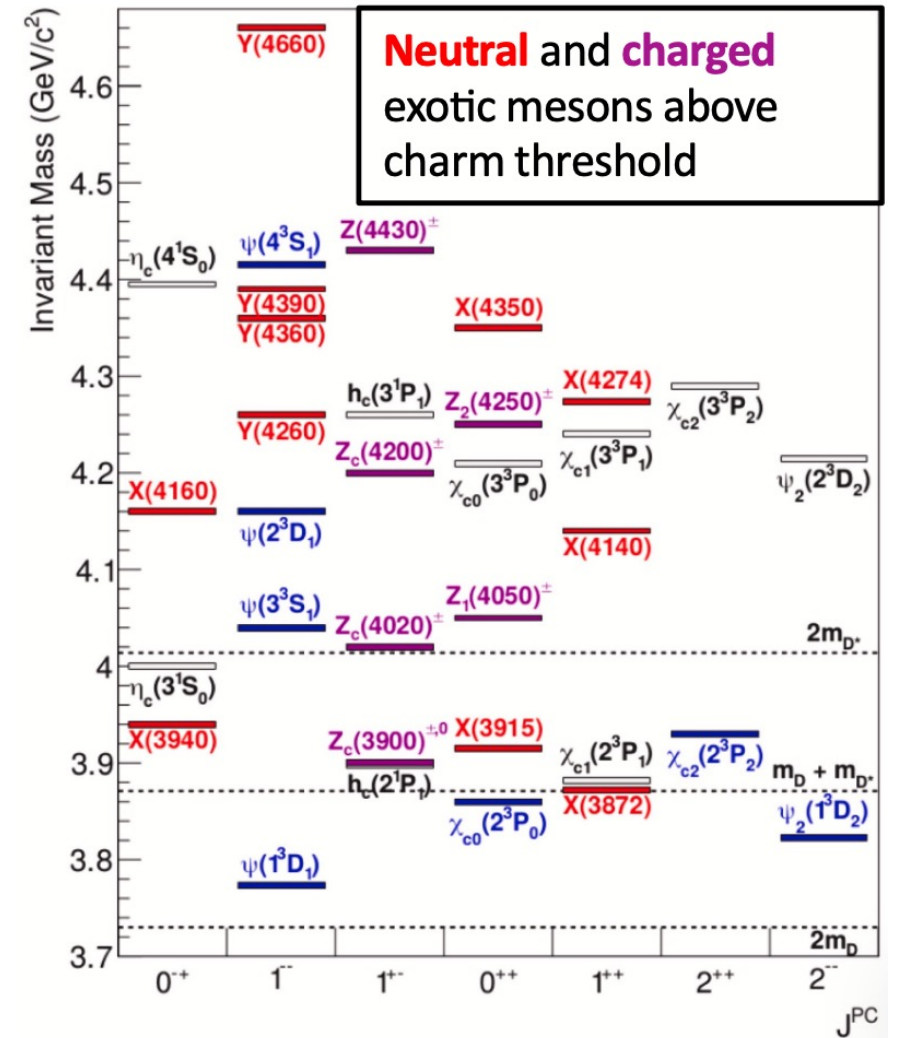
P. Del Amo Sanchez – ICHEP22

Spectroscopy

Many “new” states observed at the LHC & e^+e^- colliders



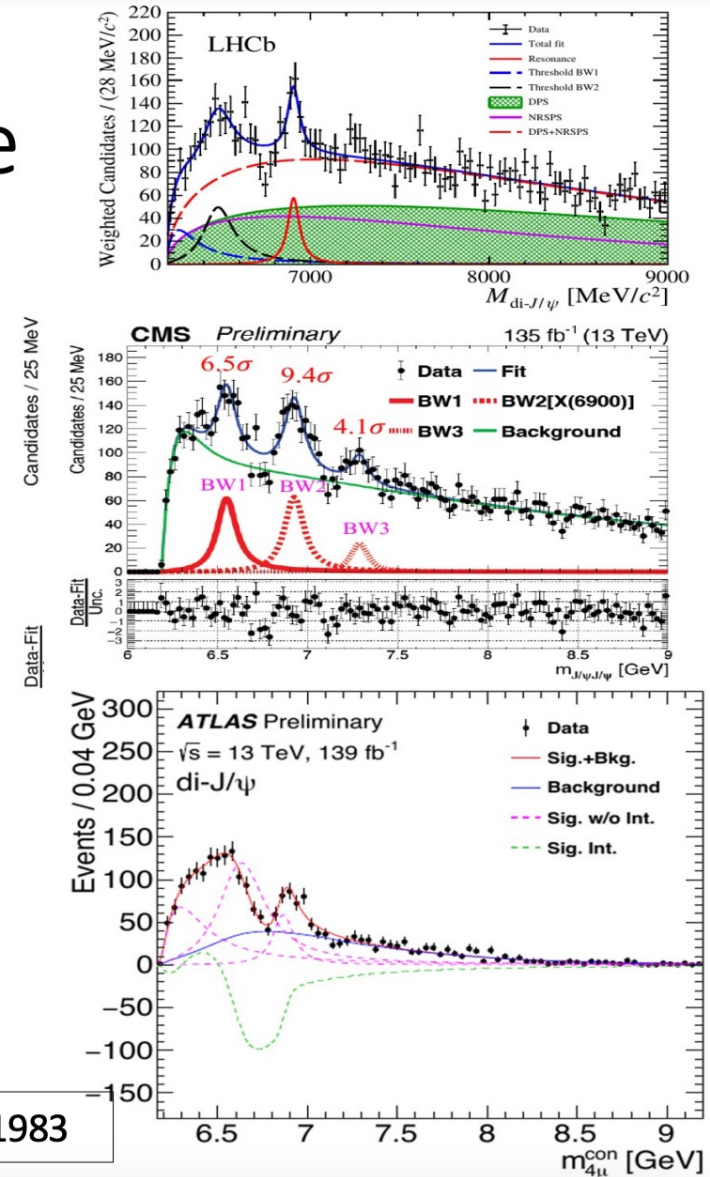
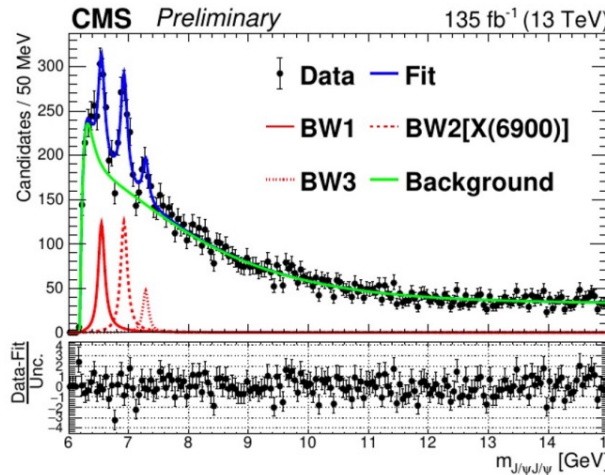
Includes e^+e^- , e.g. BES III, Belle



Spectroscopy

News about the X(6900) structure

CMS observed three $J/\psi J/\psi$ resonances compatible with predictions of **ccc tetraquarks** states around the **X(6900)** observed by LHCb
 ATLAS confirmed structure in the same region



	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

ATLAS-CONF-2022-040

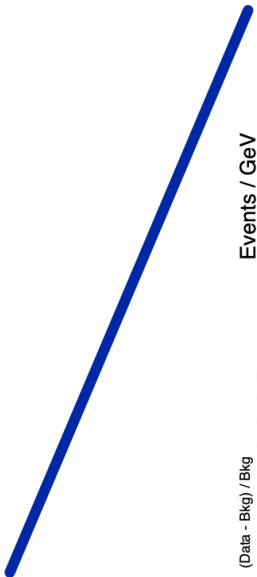
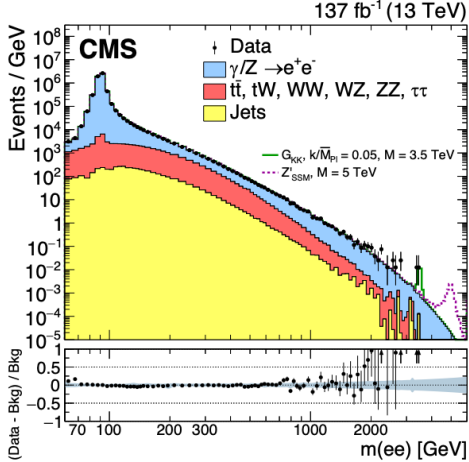
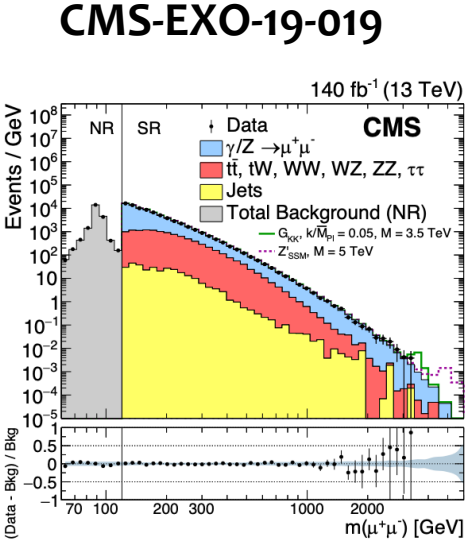
CMS-PAS-BPH-021-003

LHCb Science Bulletin 65 (2020) 1983

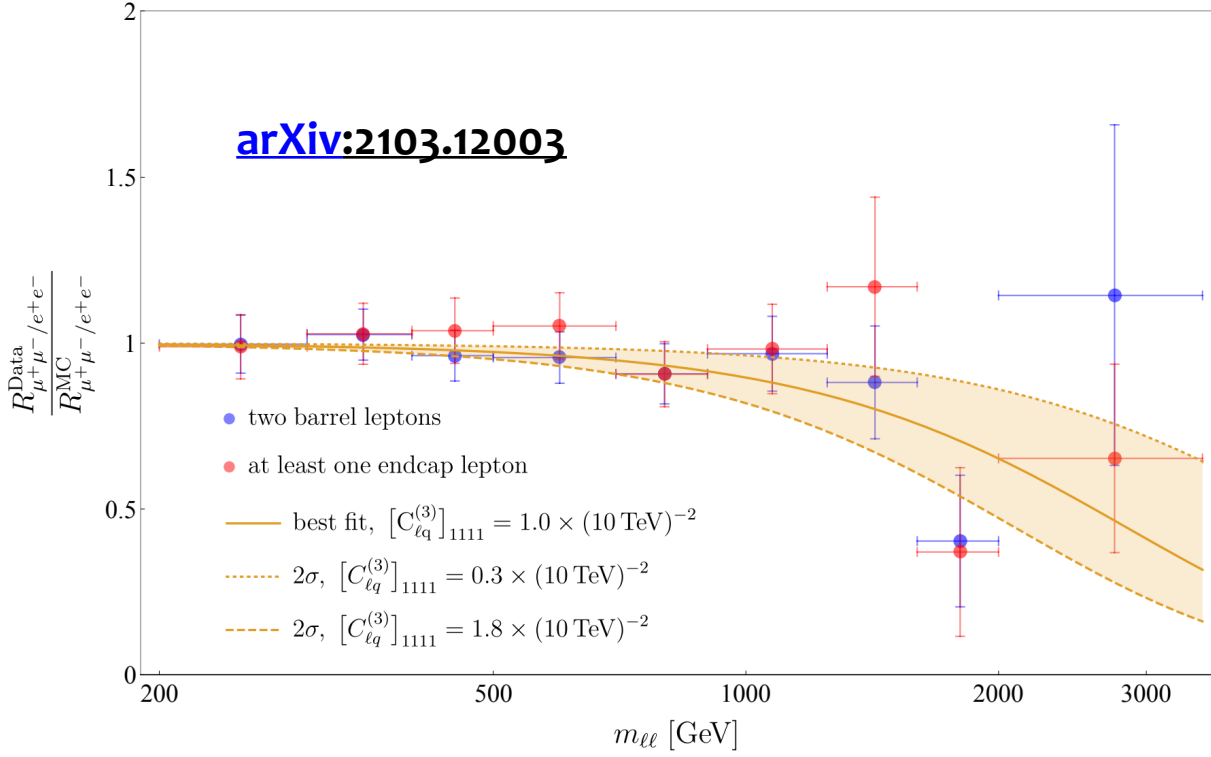
LFU test at TeV scale

Ration of searches for high mass dilepton resonances → Tests of LFU at the TeV scale

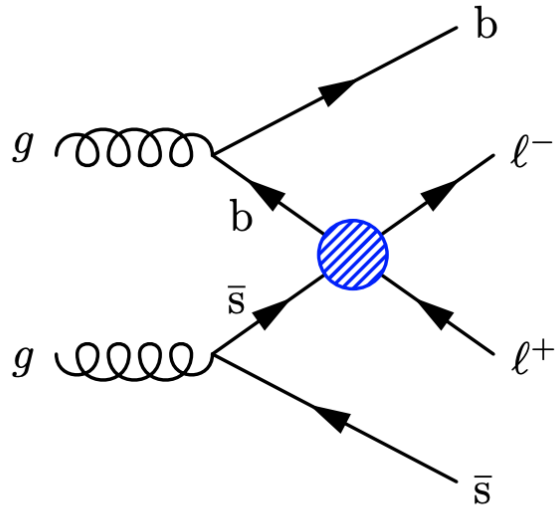
“combined preference for the new physics hypothesis of 4.5σ”



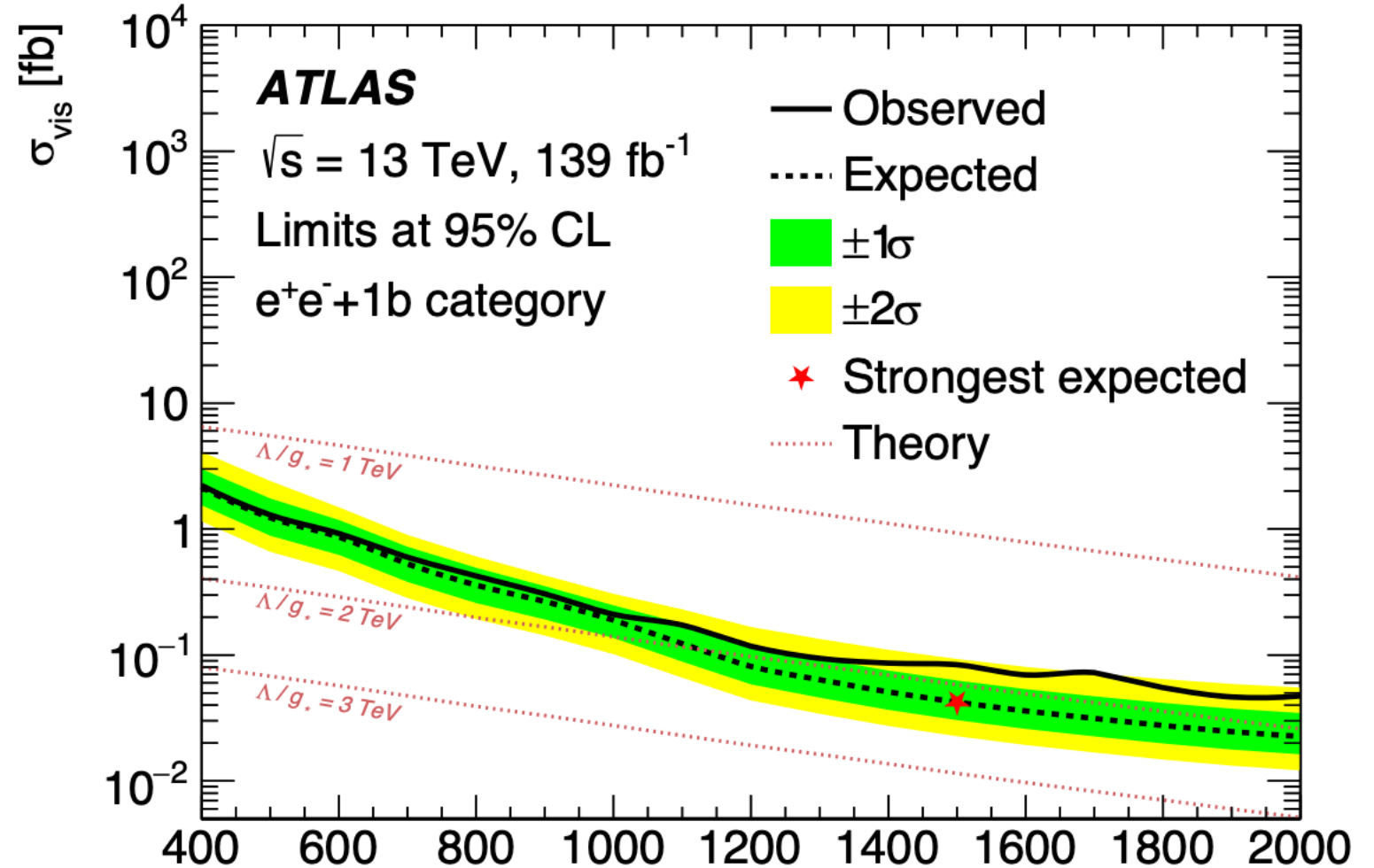
$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \rightarrow \mu^+\mu^-) / dm_{\ell\ell}}{d\sigma(q\bar{q} \rightarrow e^+e^-) / dm_{\ell\ell}}$$



ATLAS 1st Gen LQ



ATLAS-EXOT-2018-16



cfr. B anomalies favor $\Lambda/g_* \sim 30 \text{ TeV}$ $m_{ee}^{\min} [\text{GeV}]$

Further 600-something evidence?

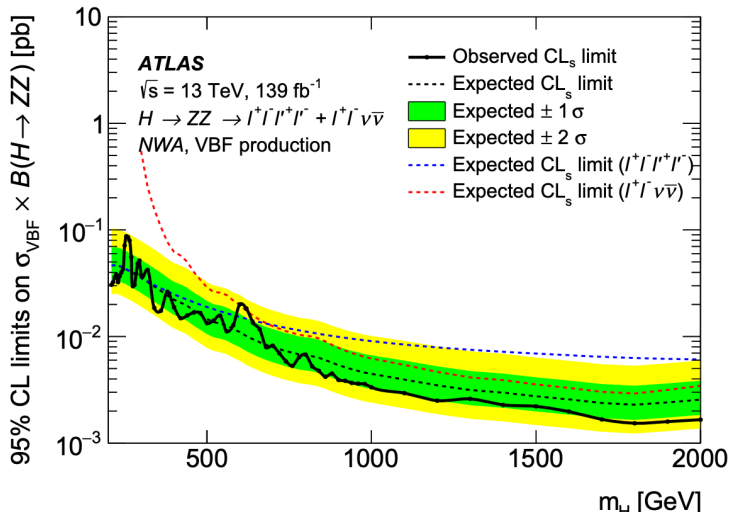
<https://arxiv.org/abs/2111.08962> (acc by IJMP A)

Maurizio Consoli & Leonardo Cosmai

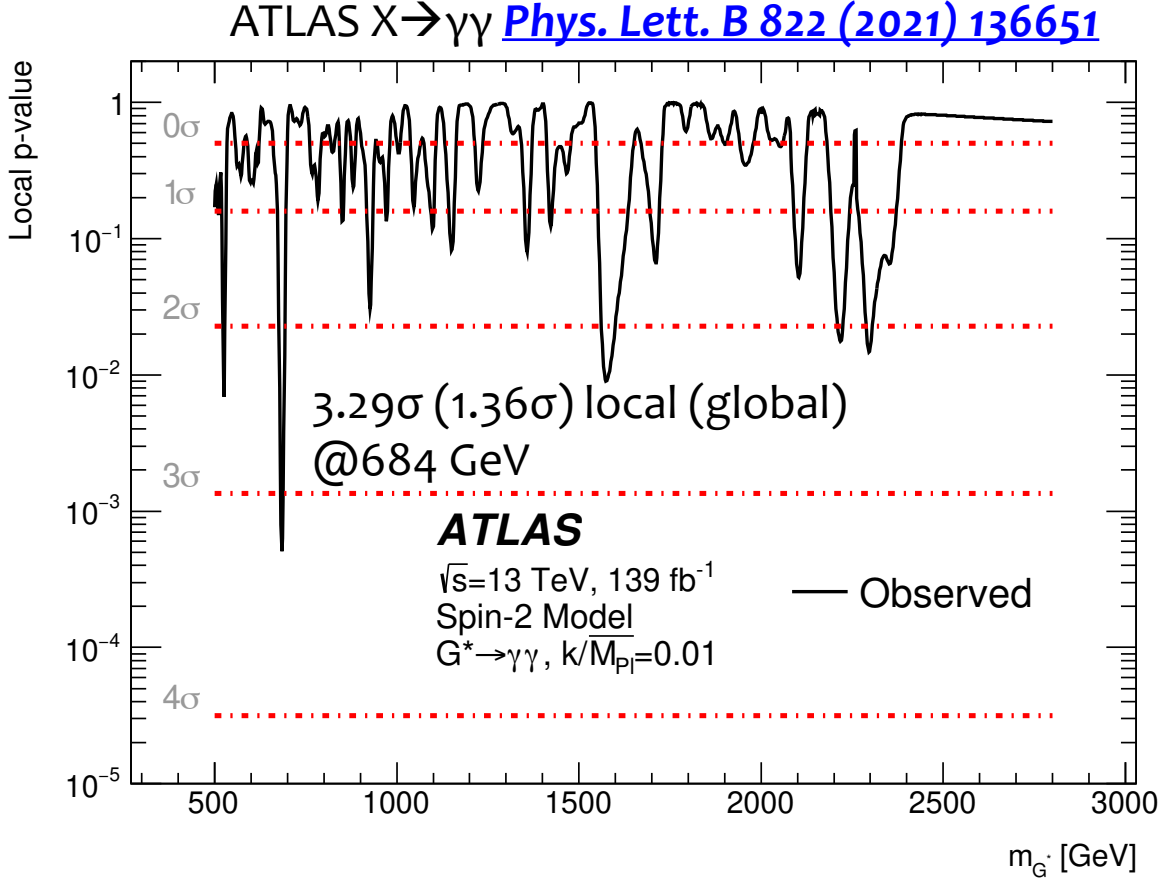
In the region of invariant mass $620 \div 740$ GeV, we have analyzed the ATLAS sample of 4-lepton events that could indicate a new scalar resonance produced mainly via gluon-gluon fusion. These data suggest the existence of a new heavy state H whose mass $660 \div 680$ GeV would fit well with the theoretical range $M_H = 690 \pm 10$ (stat) ± 20 (sys) GeV for the hypothetical second resonance of the Higgs field that has been recently proposed and which would couple to longitudinal W's with the same typical strength of the low-mass state at 125 GeV. Since the total width Γ_H is very poorly determined, to sharpen

prediction

According to their estimate, 2.5σ local, 1.4σ global, from ATLAS $H \rightarrow ZZ$ search for $M_X = 660-680$ GeV

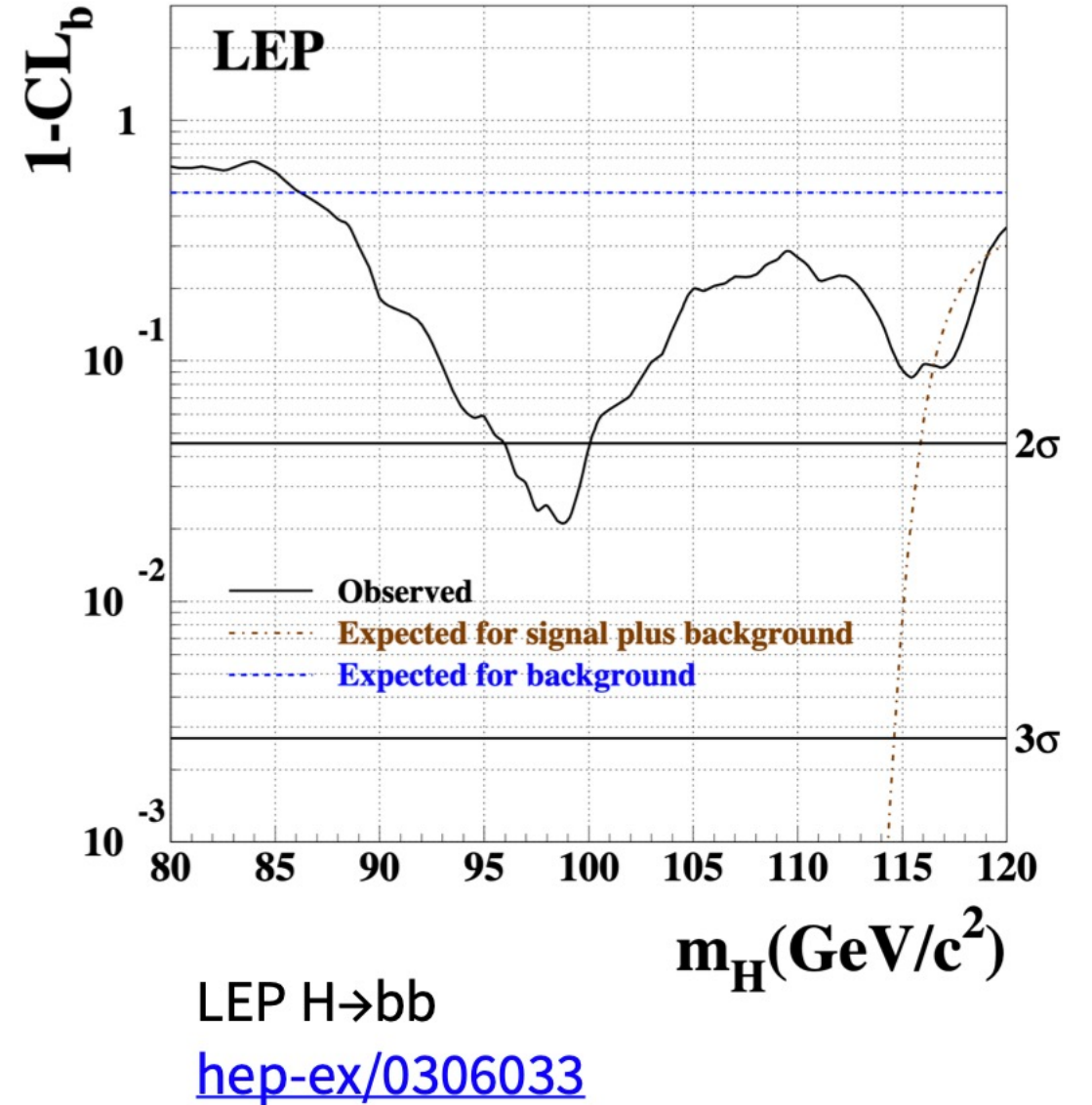
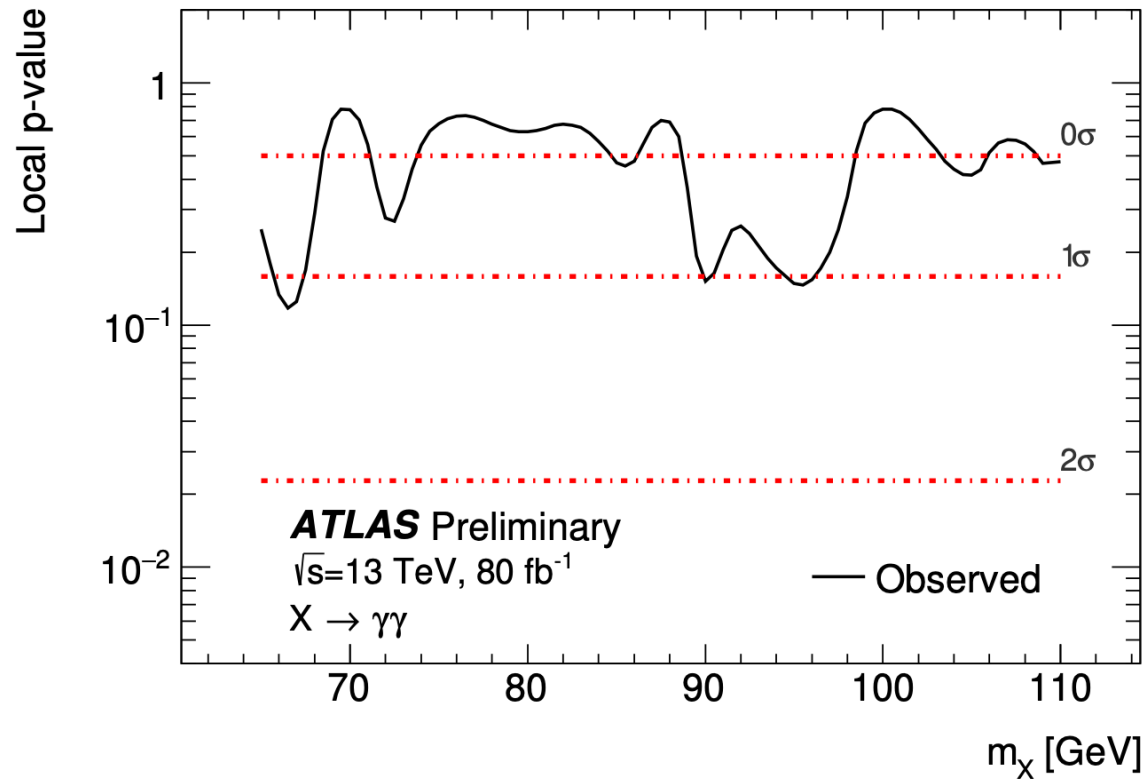


ATLAS search in $H \rightarrow ZZ \rightarrow 4l/2l2\nu$
Eur. Phys. J. C 81 (2021) 332



Further 90-something evidence?

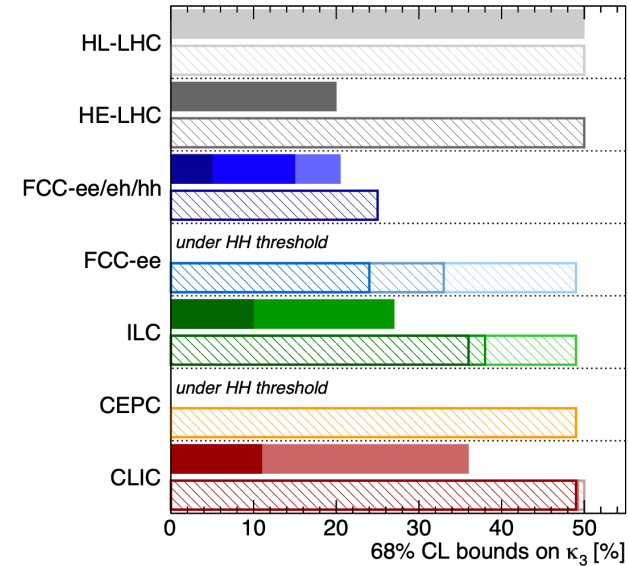
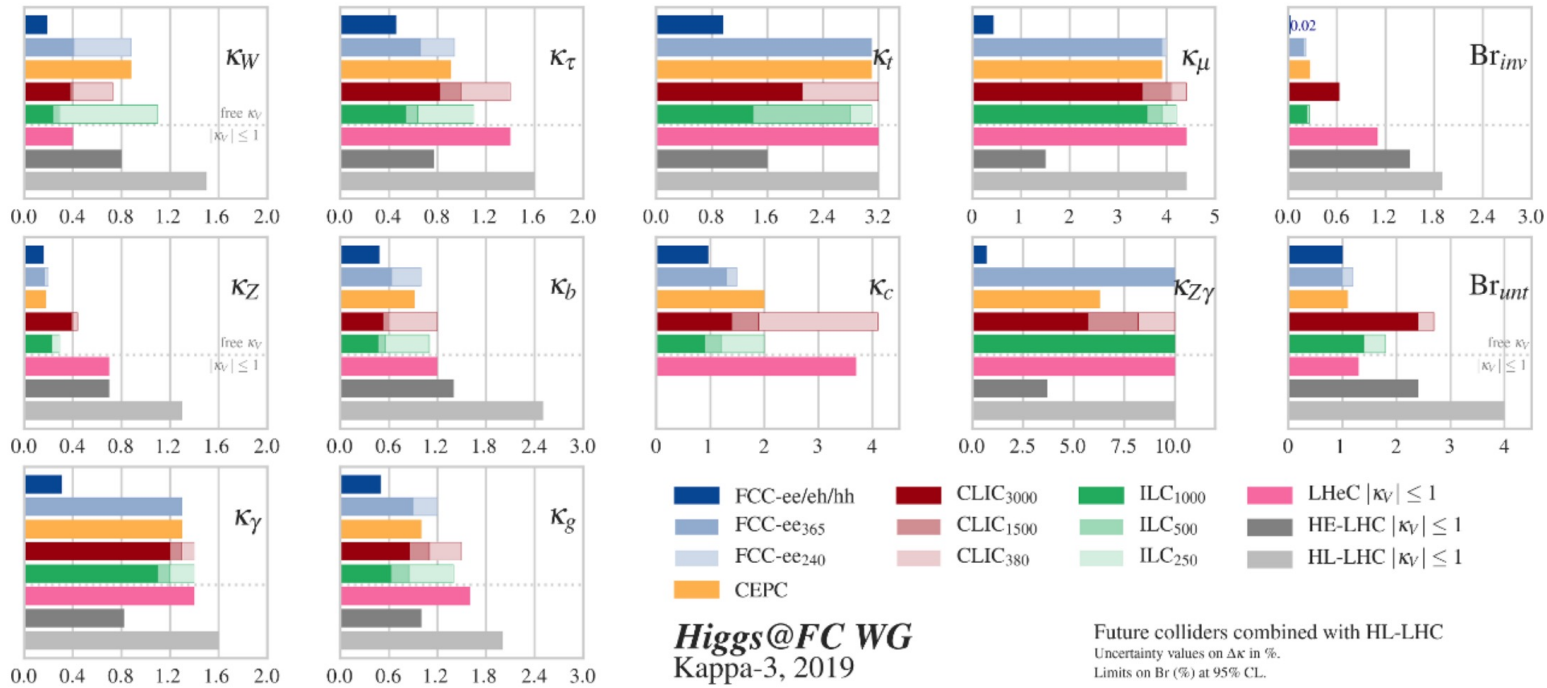
[ATLAS-CONF-2018-025](#)



Higgs boson couplings beyond the HL-LHC

The **long road ahead** for the Higgs has many potential options but all lead to high precision ($\sim\%$ level) characterization of the Higgs boson couplings

Higgs boson **self-coupling** requires **high energy machine** for $\%$ level



Higgs@FC WG September 2019

di-Higgs		single-Higgs	
HL-LHC	50%	HL-LHC	50% (47%)
HE-LHC	10-20%	HE-LHC	50% (40%)
FCC-ee/eh/hh	5%	FCC-ee/eh/hh	25% (18%)
LE-FCC	15%	LE-FCC	n.a.
FCC-eh ₃₅₀₀	-17+24%	FCC-eh ₃₅₀₀	n.a.
		FCC-ee ₃₆₅	24% (14%)
		FCC-ee ₃₀₀	33% (19%)
		FCC-ee ₂₄₀	49% (19%)
		ILC ₁₀₀₀	49% (29%)
		ILC ₁₀₀₀	36% (25%)
		ILC ₅₀₀	38% (27%)
		ILC ₂₅₀	49% (28%)
		CEPC	49% (17%)
		CLIC ₃₀₀₀	49% (35%)
		CLIC ₁₅₀₀	49% (41%)
		CLIC ₃₈₀	36%
		CLIC ₃₀₀	50% (46%)

All future colliders combined with HL-LHC

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