Searching beyond the SM

"...the direct method may be used...but indirect methods will be needed in order to secure victory."

"...there are not more than two methods of attack – the direct and the indirect, ... who can exhaust the possibilities of their combination?"

Sun Tzu, *The Art of War*

John Ellis

KING'S College LONDON

Where are we?

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L , \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L , \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},-1)$
E_R	$e^-_R , \mu^-_R , \tau^-_R$	$(\mathbf{1},\mathbf{1},-2)$
Q_L	$\begin{pmatrix}u\\ d\end{pmatrix}_L , \begin{pmatrix}c\\ s\end{pmatrix}_L , \begin{pmatrix}t\\ b\end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	u_R , c_R , t_R	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	d_R , s_R , b_R	$(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

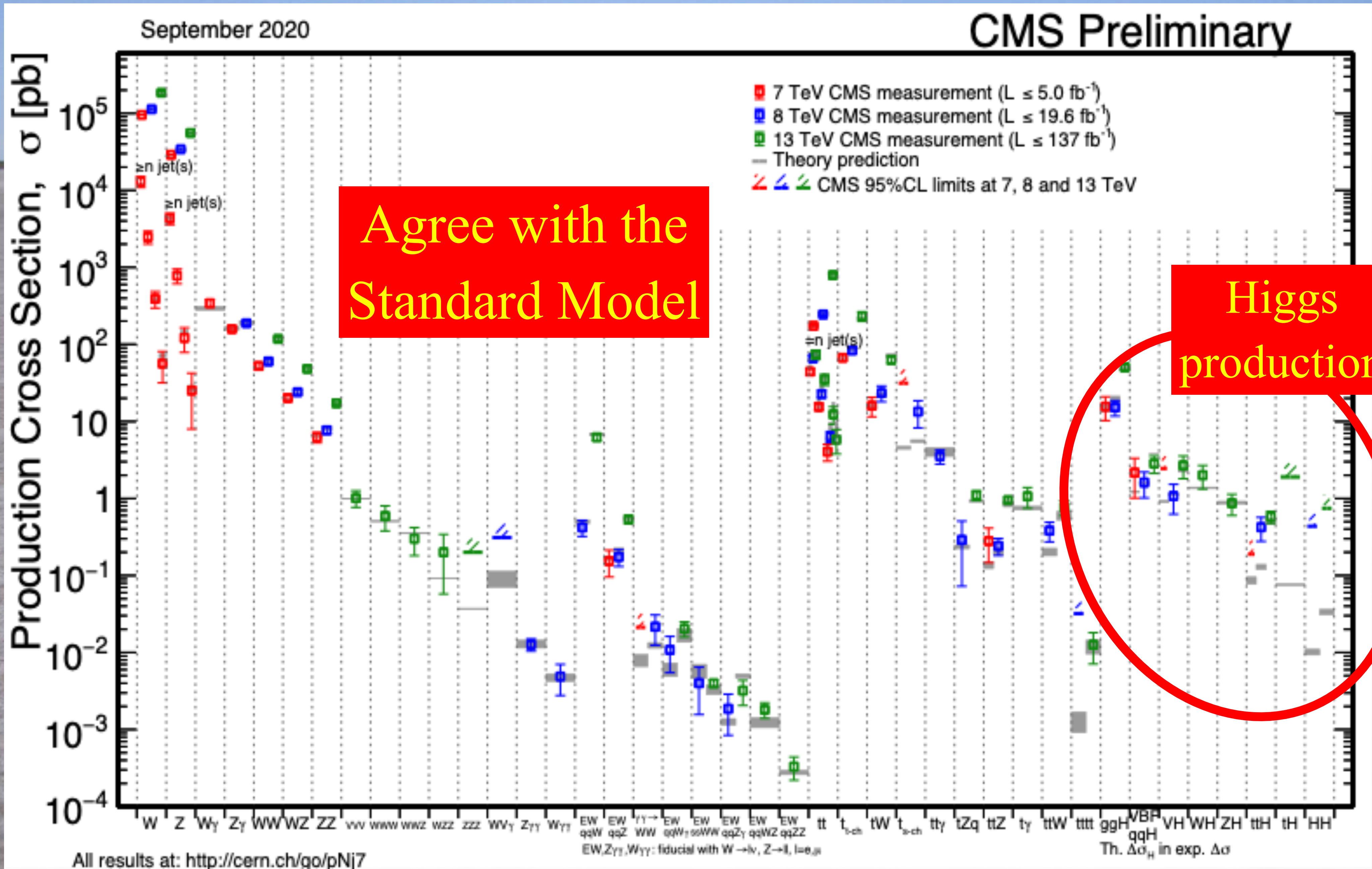
$$\begin{aligned}\mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} && \text{gauge interactions}\\ &+ i\bar{\psi}\, \not{D}\psi + h.c. && \text{matter fermions}\\ &+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions}\\ &+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential}\end{aligned}$$

Tested < 0.1% before LHC

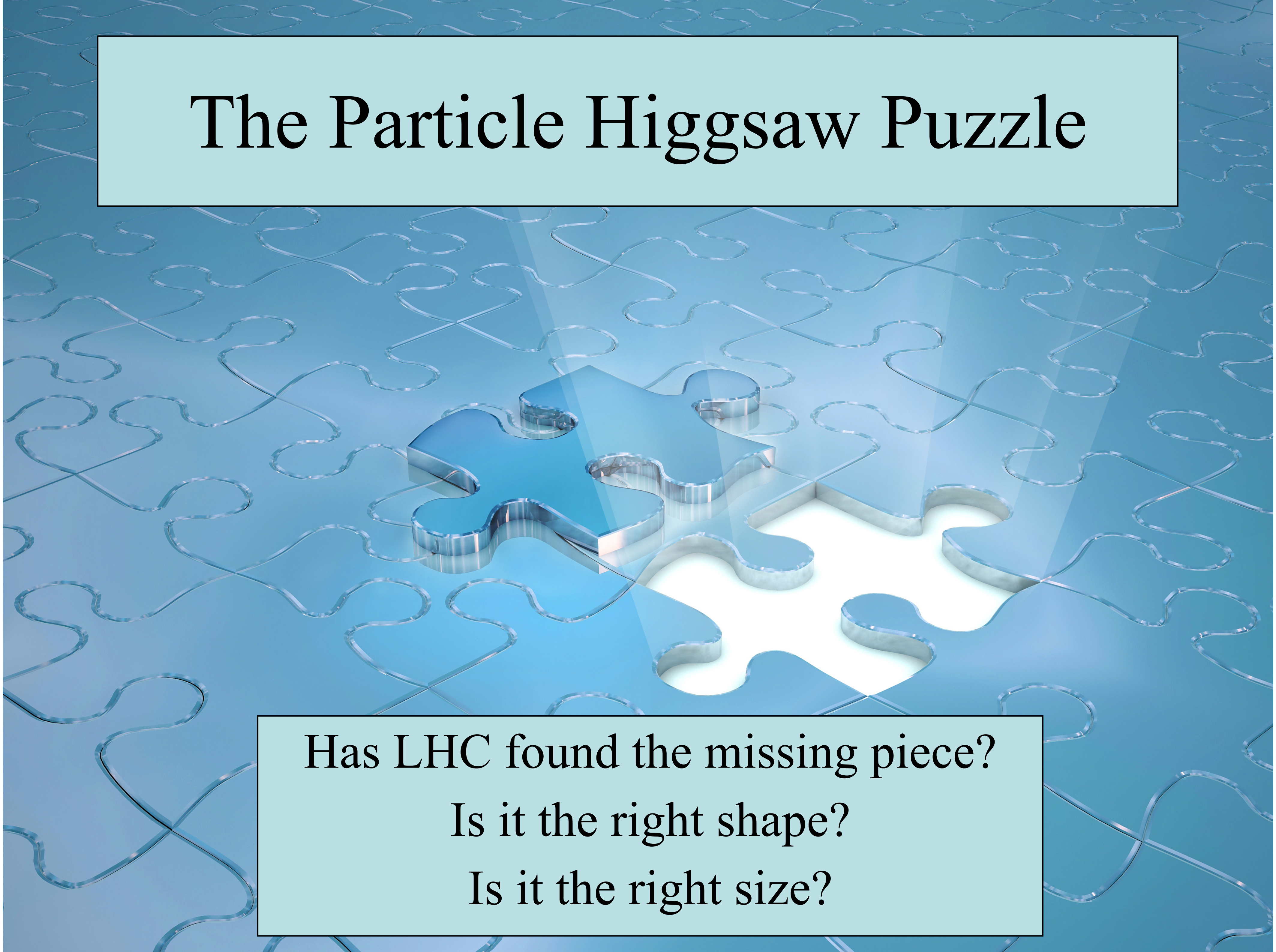
Testing now in progress

What lies beyond?

LHC Measurements



The Particle Higgsaw Puzzle



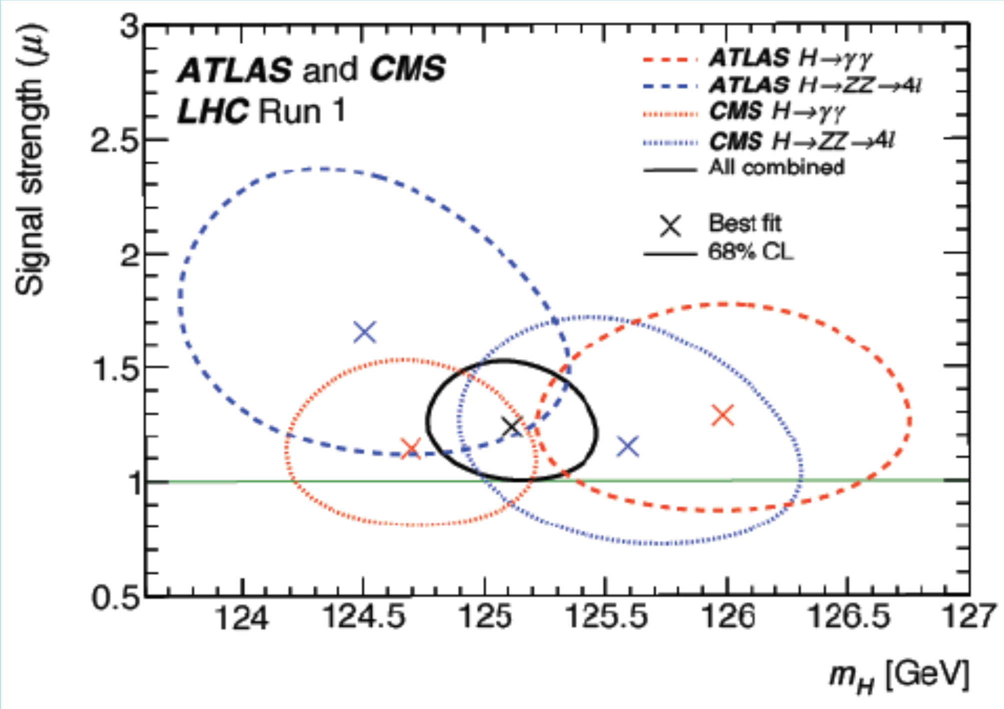
Has LHC found the missing piece?

Is it the right shape?

Is it the right size?

Higgs Mass Measurements

- ATLAS + CMS ZZ* and γγ final states



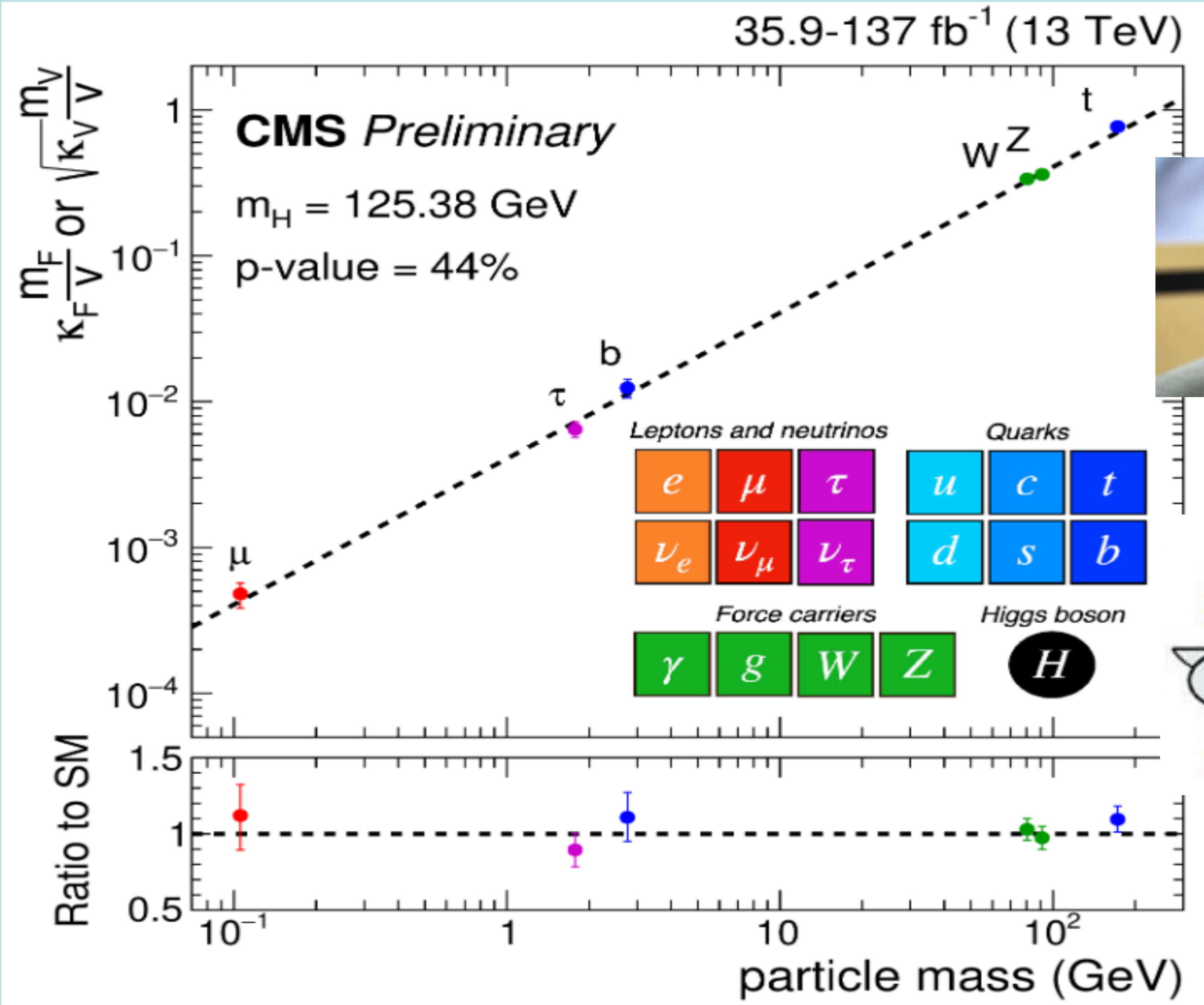
Crucial for stability of electroweak vacuum

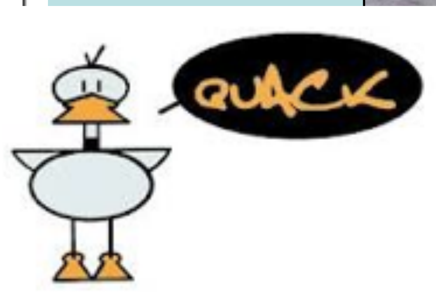
- Run 1: 125.09 ± 0.21 (stat) ± 0.11 (syst)
- ATLAS Run 2: 124.97 ± 0.24 GeV
- CMS Run 2: 125.35 ± 0.15 GeV

0.1% accuracy!

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?





Everything about Higgs is Puzzling

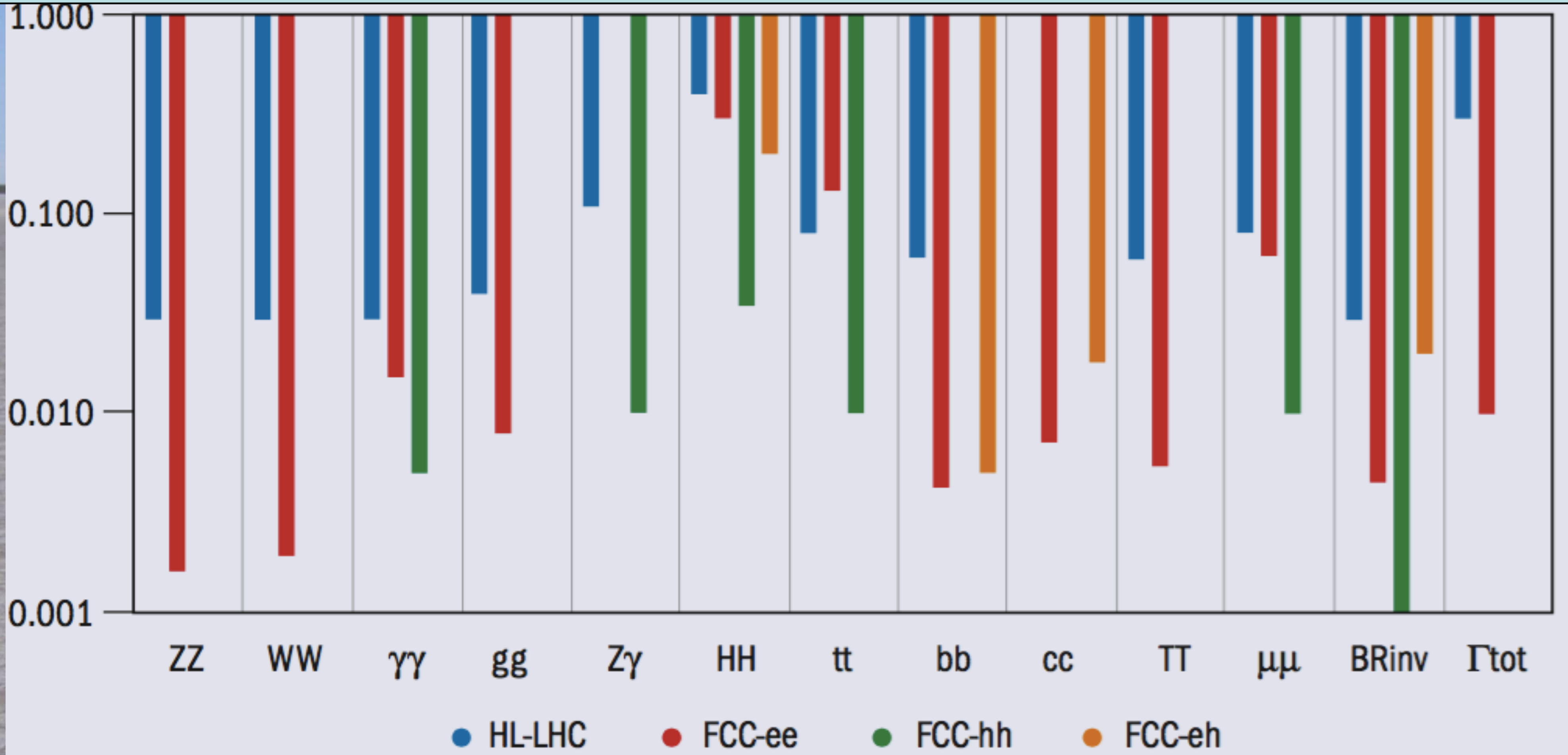
$$\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0$$ + ...

- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term V_0:
  - **Dark energy**

Higher-dimensional interactions?

FCC CDR

Possible Future Higgs Measurements



- Need to reduce theoretical uncertainties to match experimental errors
  - Needed for BSM interpretation

High precision at FCC-ee/CEPC
Big statistics at FCC-hh/SppC

Numbers of Diagrams to be Calculated

Blondel et al, arXiv:1809.01830

$Z \to b\bar{b}$

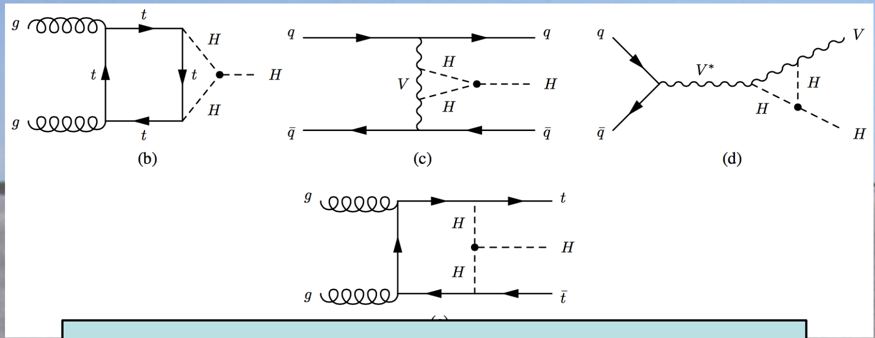
	1 loop	2 loops	3 loops
Number of topologies	1	$14 \overset{(A)}{\to} 7 \overset{(B)}{\to} 5$	$211 \overset{(A)}{\to} 84 \overset{(B)}{\to} 51$
Number of diagrams	15	$2383 \overset{(A,B)}{\to} 1074$	$490387 \overset{(A,B)}{\to} 120472$
Fermionic loops	0	150	17580
Bosonic loops	15	924	102892
Planar / Non-planar	15 / 0	981/133	84059/36413
QCD / EW	1 / 14	98 / 1016	10386/110086

$Z \to e^+e^-, \ldots$

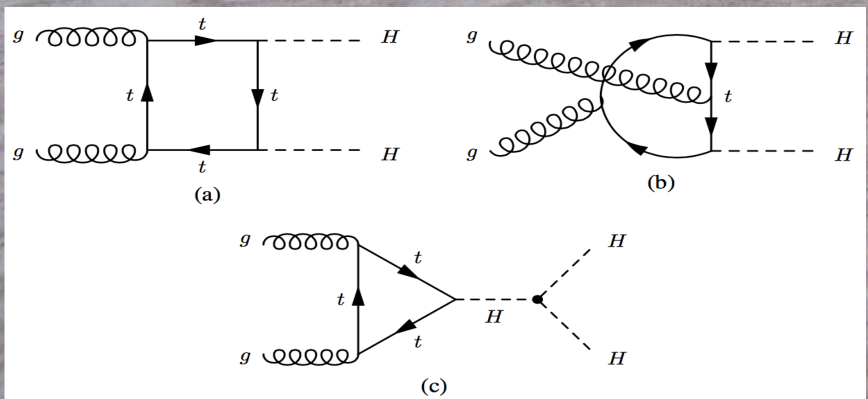
	1 loop	2 loops	3 loops
Number of topologies	1	$14 \overset{(A)}{\to} 7 \overset{(B)}{\to} 5$	$211 \overset{(A)}{\to} 84 \overset{(B)}{\to} 51$
Number of diagrams	14	$2012 \overset{(A,B)}{\to} 880$	$397690 \overset{(A,B)}{\to} 91472$
Fermionic loops	0	114	13104
Bosonic loops	14	766	78368
Planar / Non-planar	14 / 0	782/98	65487/25985
QCD / EW	0 / 14	0 / 880	144/91328

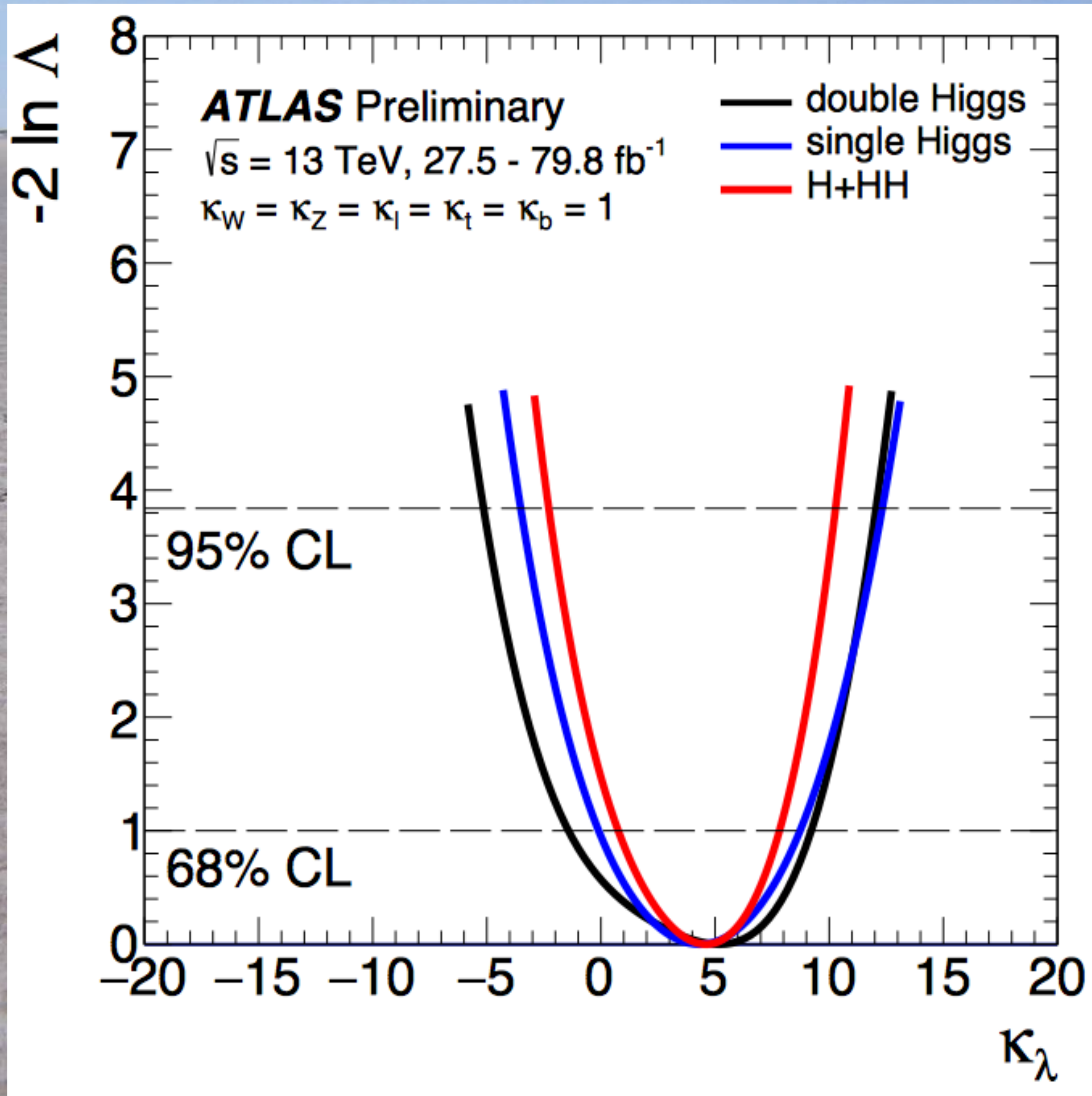
A lot of work for theorists, but feasible!

Sensitivity to HHH Coupling



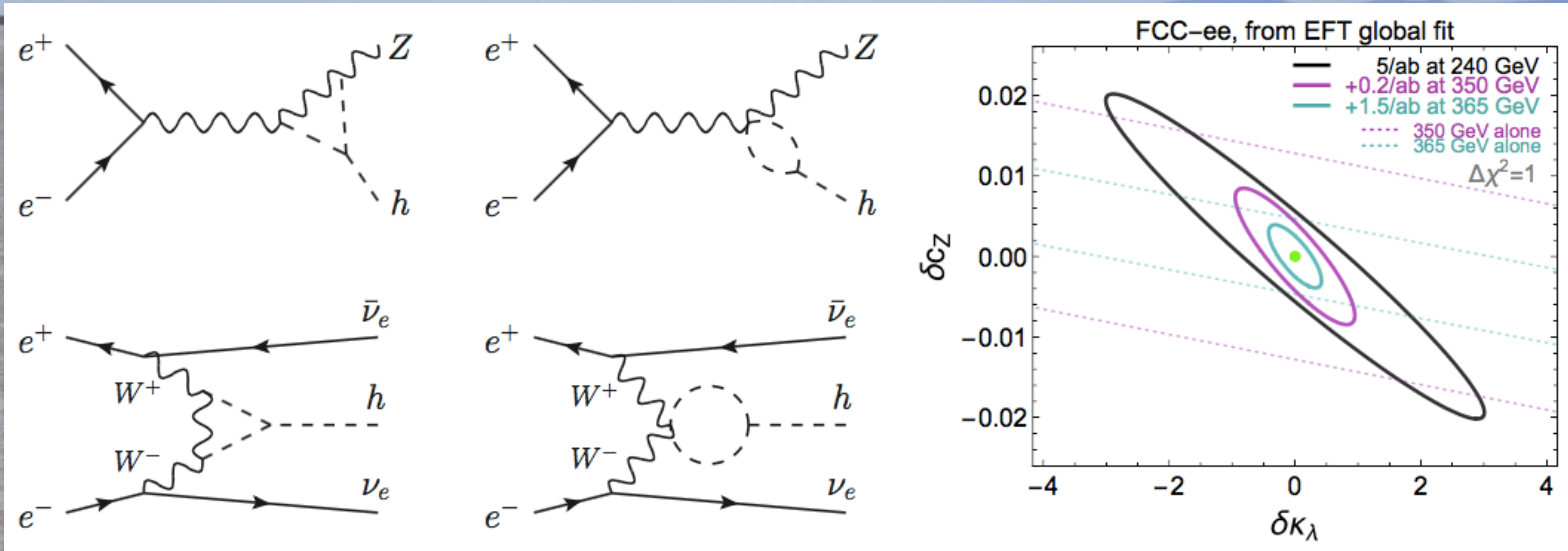
Similar sensitivities from single and double Higgs production – but still a long way to go!





Sensitivity to HHH Coupling

Sensitivity through radiative corrections

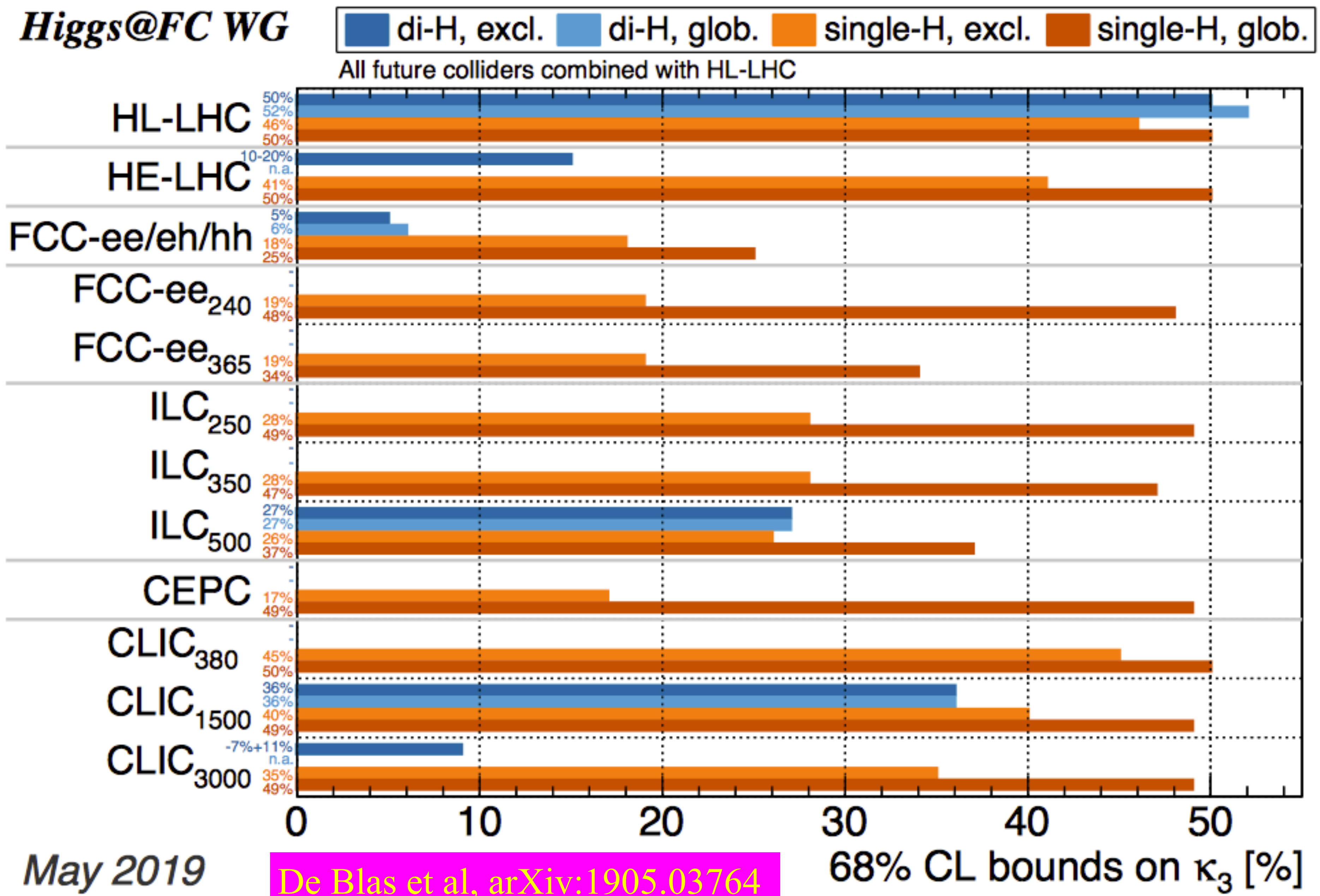


Combining all FCC-ee centre-of-mass energies: precision in κ_λ of ±40%

Improved to ±35% in combination with HL-LHC

Further improved to ±25% when c_Z fixed to SM value.

Triple-Higgs Coupling Analyses

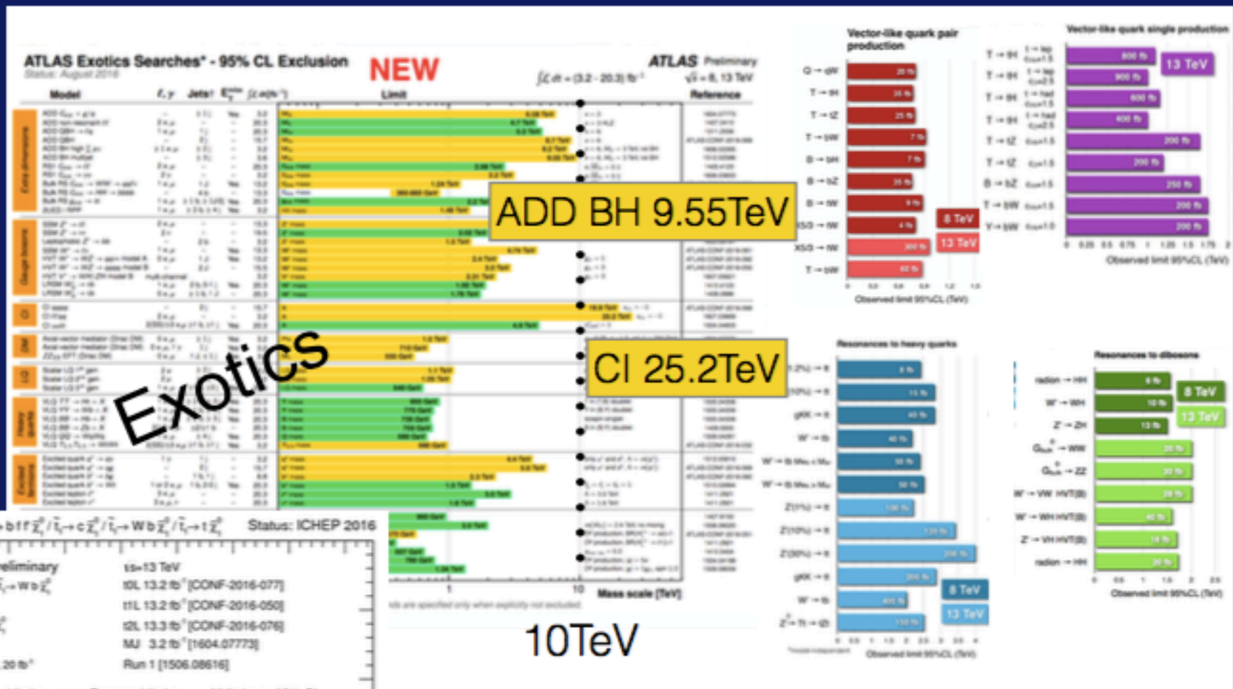


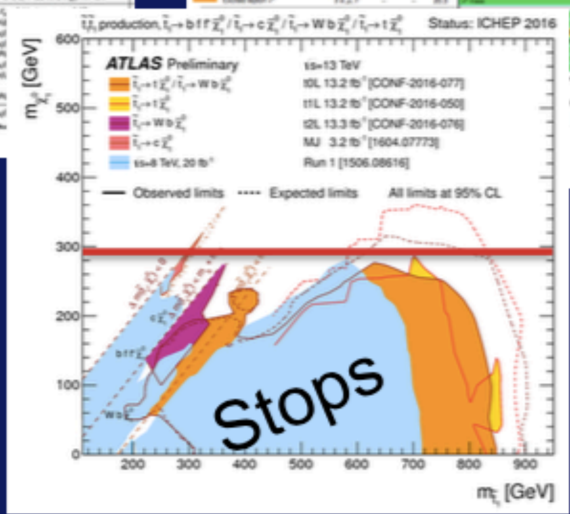
De Blas et al, arXiv:1905.03764

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either





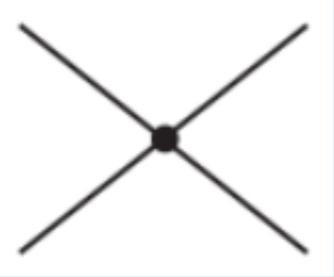
Unexplored nooks?

Novel signatures?

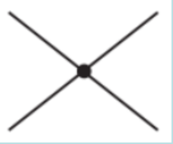
Look indirectly?

Effective Field Theories (EFTs)
a long and glorious History

- 1930's: "Standard Model" of QED had d=4
- Fermi's four-fermion theory of the weak force



- Dimension-6 operators: form = S, P, V, A, T?
  - Due to exchanges of massive particles?
- V-A ➔ massive vector bosons ➔ gauge theory
- Yukawa's meson theory of the strong N-N force



  - Due to exchanges of mesons? ➔ pions
- Chiral dynamics of pions: $(\partial\pi\partial\pi)\pi\pi$ clue ➔ QCD

One way to look for BSM physics

Standard Model Effective Field Theory

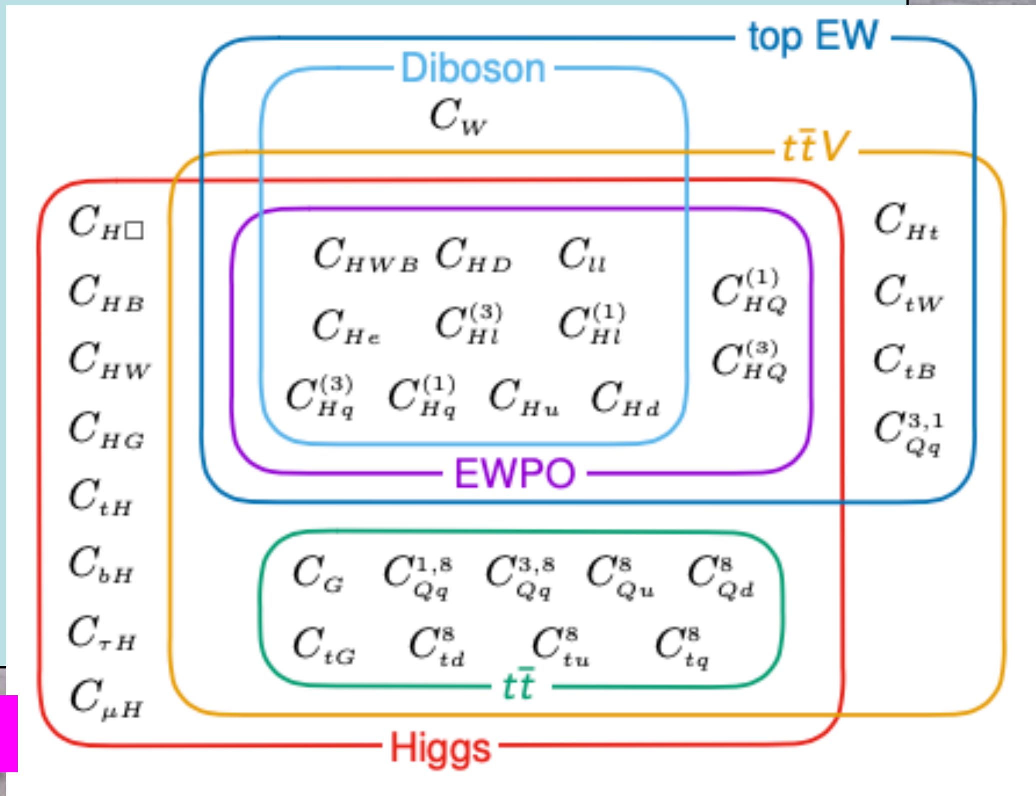
- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6:

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

- Operators constrained by SU(2) × U(1) symmetry, assuming conventional representation assignments for SM particles
- Constrain coefficients with top, EW, Higgs, diboson data
- Non-zero coefficient(s) could indicate what BSM
  - Masses, spins, quantum numbers of new particles?
  - Derivative interactions characteristic of new strong dynamics?

Global SMEFT Fit
to Top, Higgs, Diboson, Electroweak Data

- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1 and 2
- Constraints on BSM
  - At tree level
  - At loop level
- Any indications?



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Dimension-6 Operators in Detail

- Including 2- and 4-fermion operators
- Grey cells violate SU(3)^5 symmetry
- Use when including top observables

Cosmological phase transition

Derivative interaction

X^3		H^6 and H^4D^2			
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar l_p e_r H)$
$\mathcal{O}_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\square}$	$(H^\dagger H)\square(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar q_p d_r H)$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH			
$\mathcal{O}_{HG}$	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G_{\mu\nu}^A$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W_{\mu\nu}^I$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

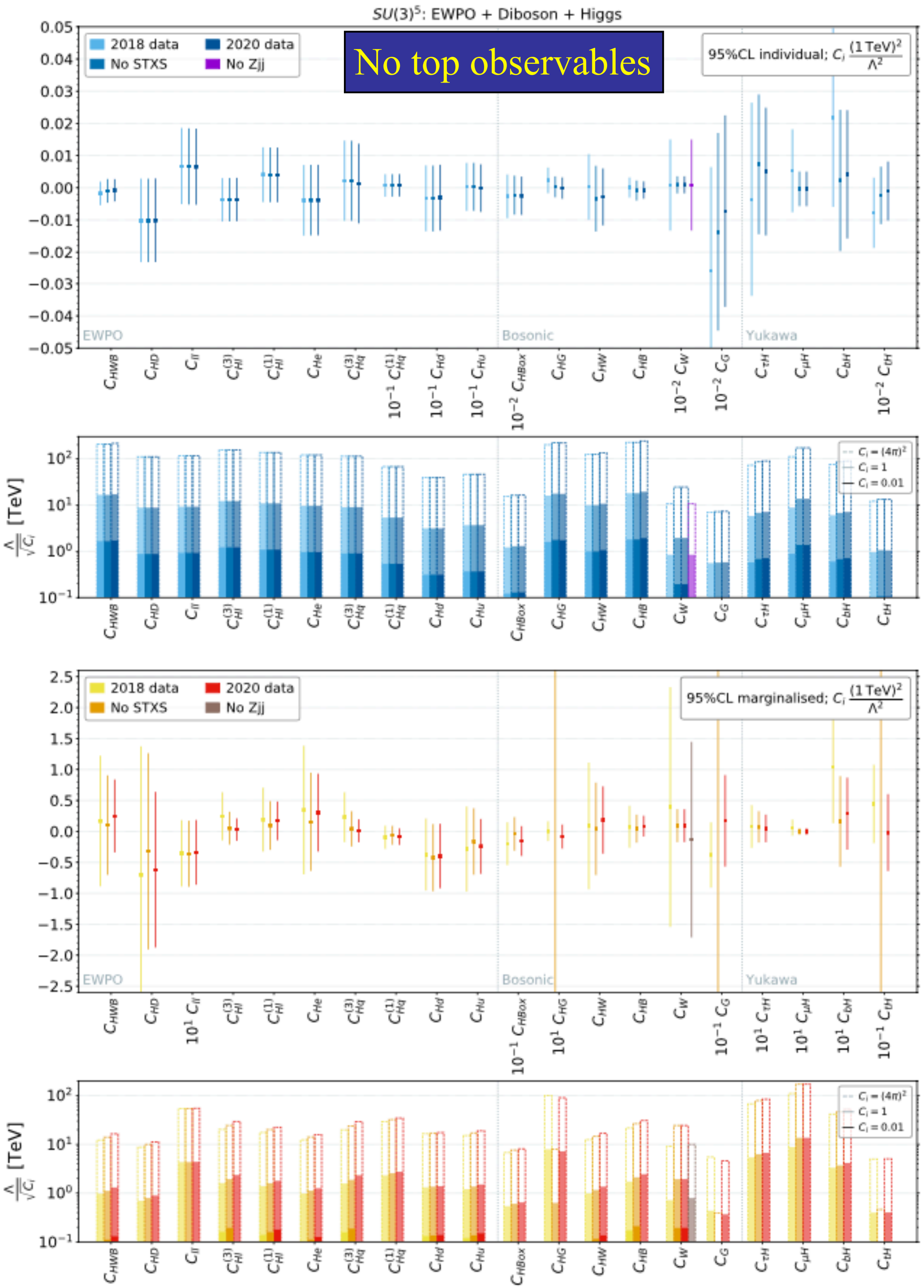
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$\mathcal{O}_{ll}$	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$		

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Dimension-6 Constraints with SU(3)^5 Symmetry

- Individual operator coefficients
- Marginalised over other operator coefficients



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

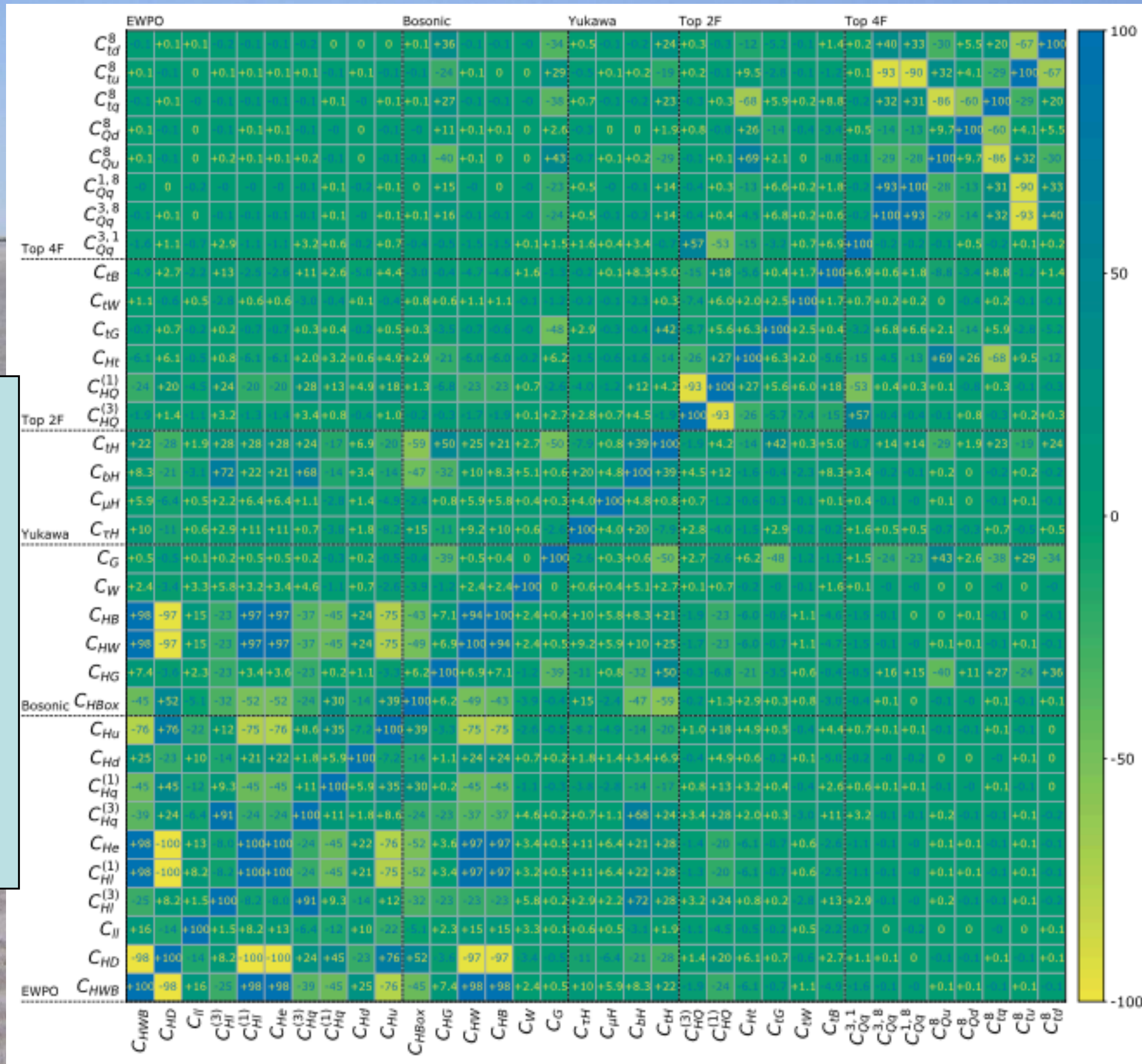
Dimension-6 Constraints with SU(2)^2 x SU(3)^3

- Individual operator coefficients
- Marginalised over other operator coefficients

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Correlation Analysis

- Main correlations within sectors
- Also significant correlations of top with other sectors



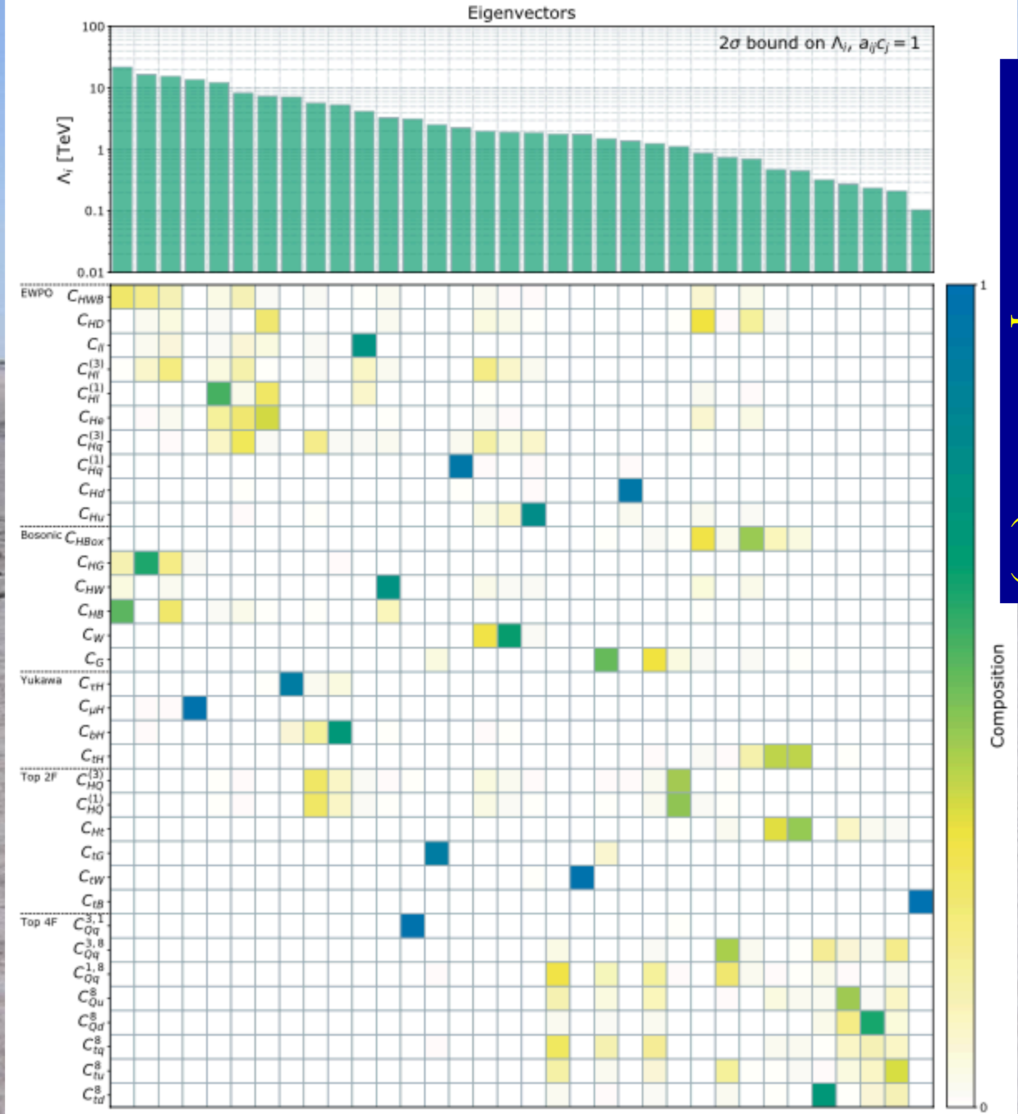
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Principal Component Analysis

- Diagonalise correlation matrix
- Analyze eigenvectors and eigenvalues
- Scales from 20 TeV to 100 GeV
- Strongest constraints from EW, H, STXS

Less constrained operator combinations ➔

Relative importance (%)



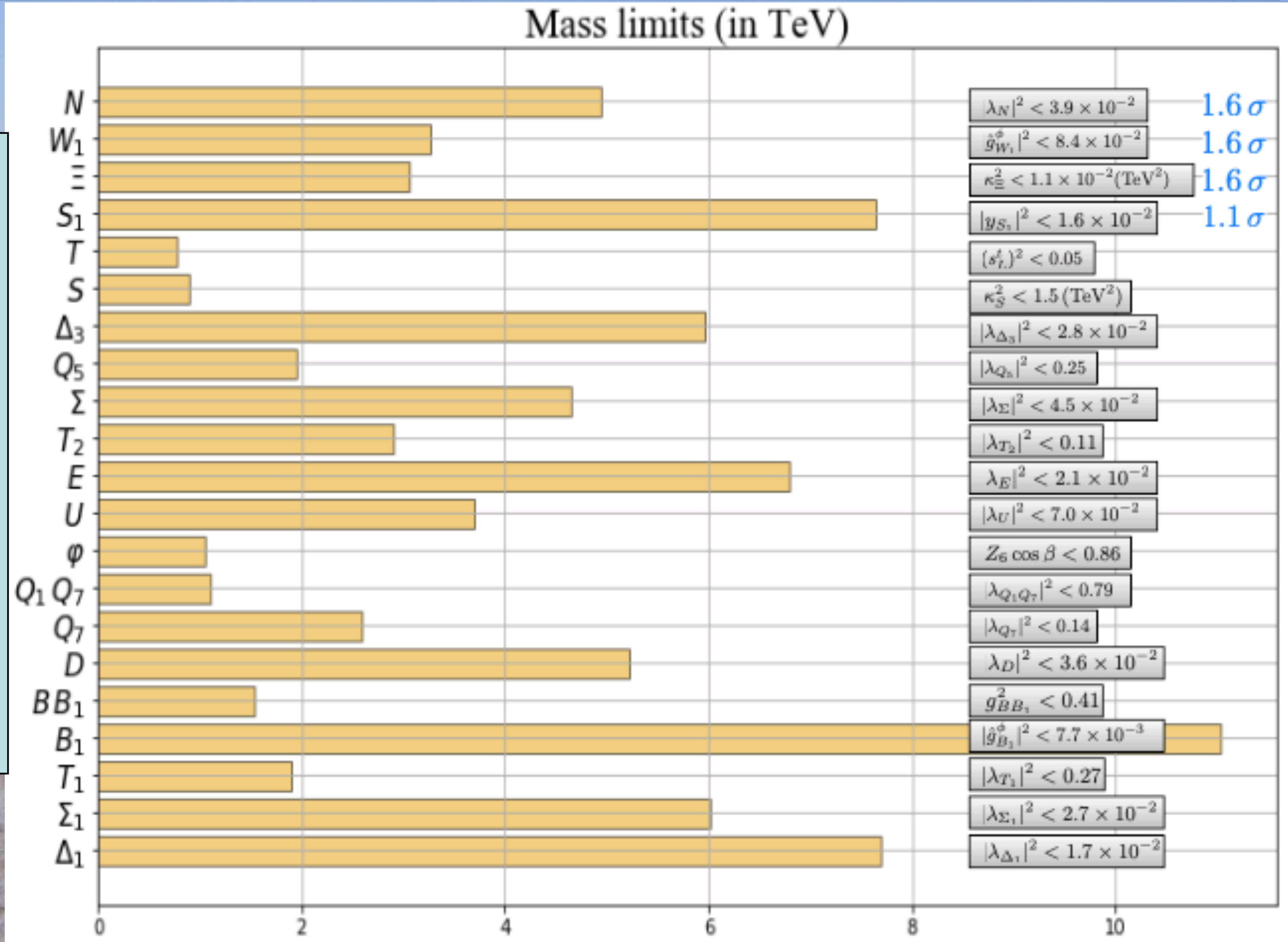
EWPO	6	35	59	–	99	97	99	–	73	25	75	–	–	–	91	8	8	60	–	–	–	90	–	–	3	–	3	1	–	–	–	–	–	–
LEP WW	–	–	–	–	–	–	–	–	–	–	24	–	–	–	2	9	3	8	–	–	–	6	–	–	5	–	4	–	–	–	–	–	–	–
Run 1, μ_H	15	13	7	5	–	–	–	21	2	7	–	6	–	1	1	6	3	3	–	–	–	–	1	–	25	–	12	10	6	–	–	–	–	–
Run 2, μ_H	29	28	16	94	–	–	–	45	5	17	–	90	–	14	2	14	6	5	–	–	8	–	11	2	37	2	30	26	17	–	–	–	–	–
STXS	50	23	18	1	–	–	–	33	19	50	–	2	–	6	3	24	11	17	–	–	4	1	4	–	12	–	19	12	8	–	–	–	–	–
LHC WW	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	1	3	–	–	–	–	–	–	9	–	4	–	–	–	–	–	–	–
LHC Zjj	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	30	66	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$t\bar{t}$	–	–	–	–	–	–	–	–	–	–	–	–	–	71	–	1	–	–	99	84	72	–	72	10	7	12	19	11	27	97	98	100	99	1
single top	–	–	–	–	–	–	–	–	–	–	–	–	100	–	–	2	1	–	–	14	–	1	2	76	1	6	–	6	8	–	–	–	–	96
$t\bar{t}V$	–	–	–	–	–	–	–	–	–	–	–	–	–	8	–	–	–	–	–	–	15	–	9	10	–	79	8	31	33	3	–	–	–	–

Relative constraining power (%)

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

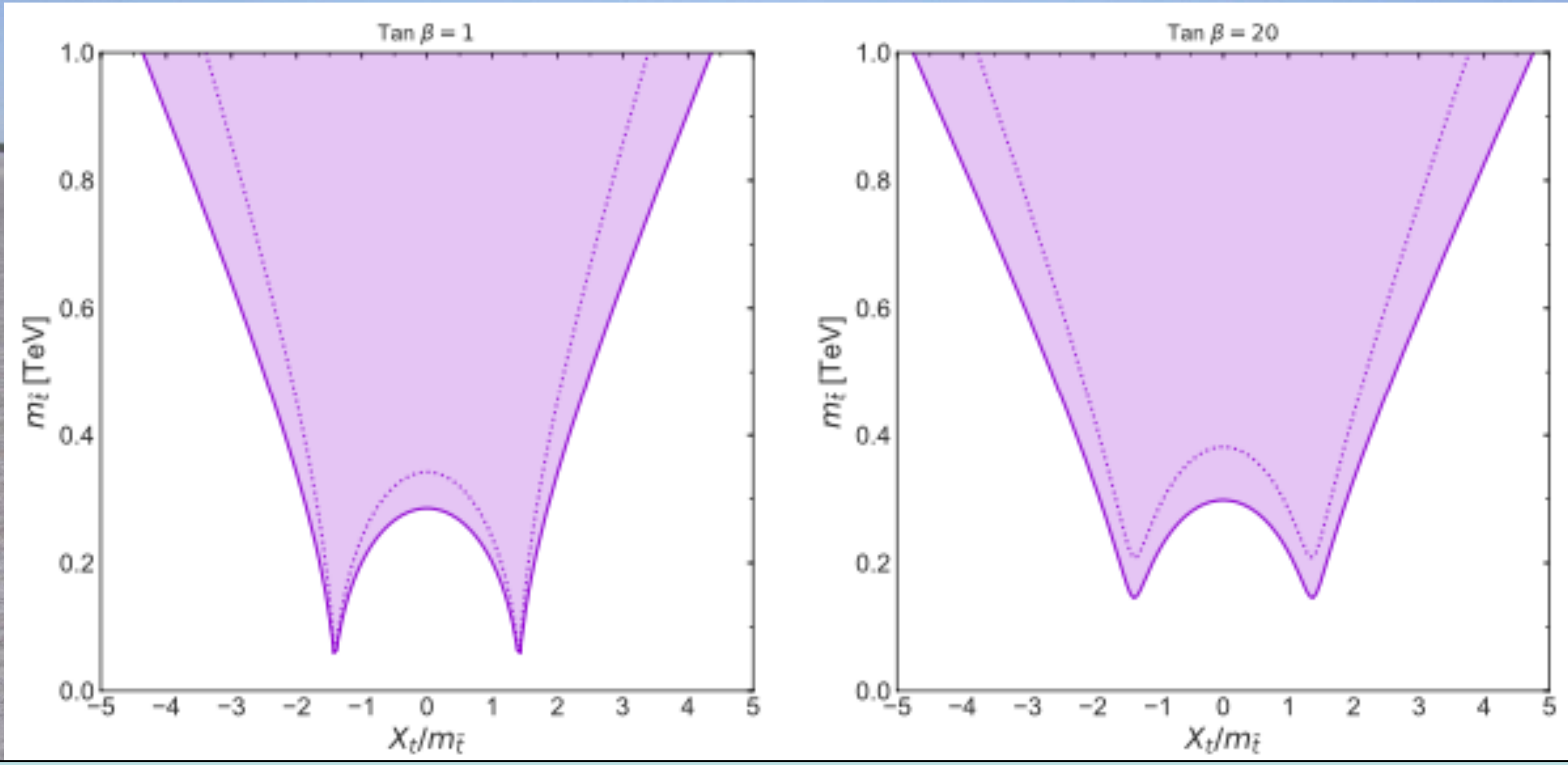
Constraints on Single-Field BSM Scenarios

- No significant pulls away from SM
- Any single-field extension of SM must have mass scale > 400 GeV if coupling = 1



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

SMEFT Constraints on Light Stops

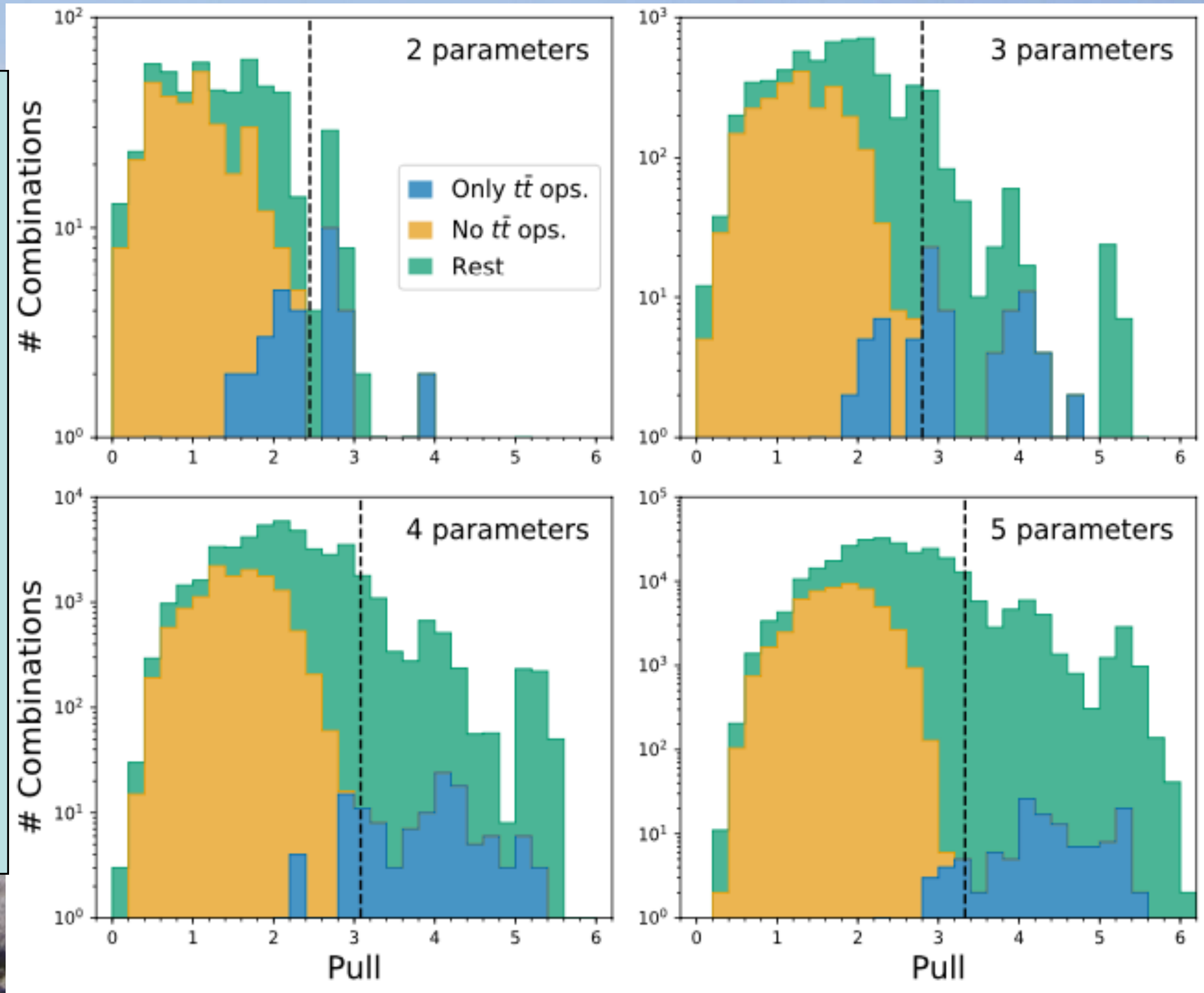


- Stops contribute to 4 SMEFT operators
- Must weigh > 300 GeV, except for mixing parameter $X_t \sim 1.5\ m_{stop}$

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

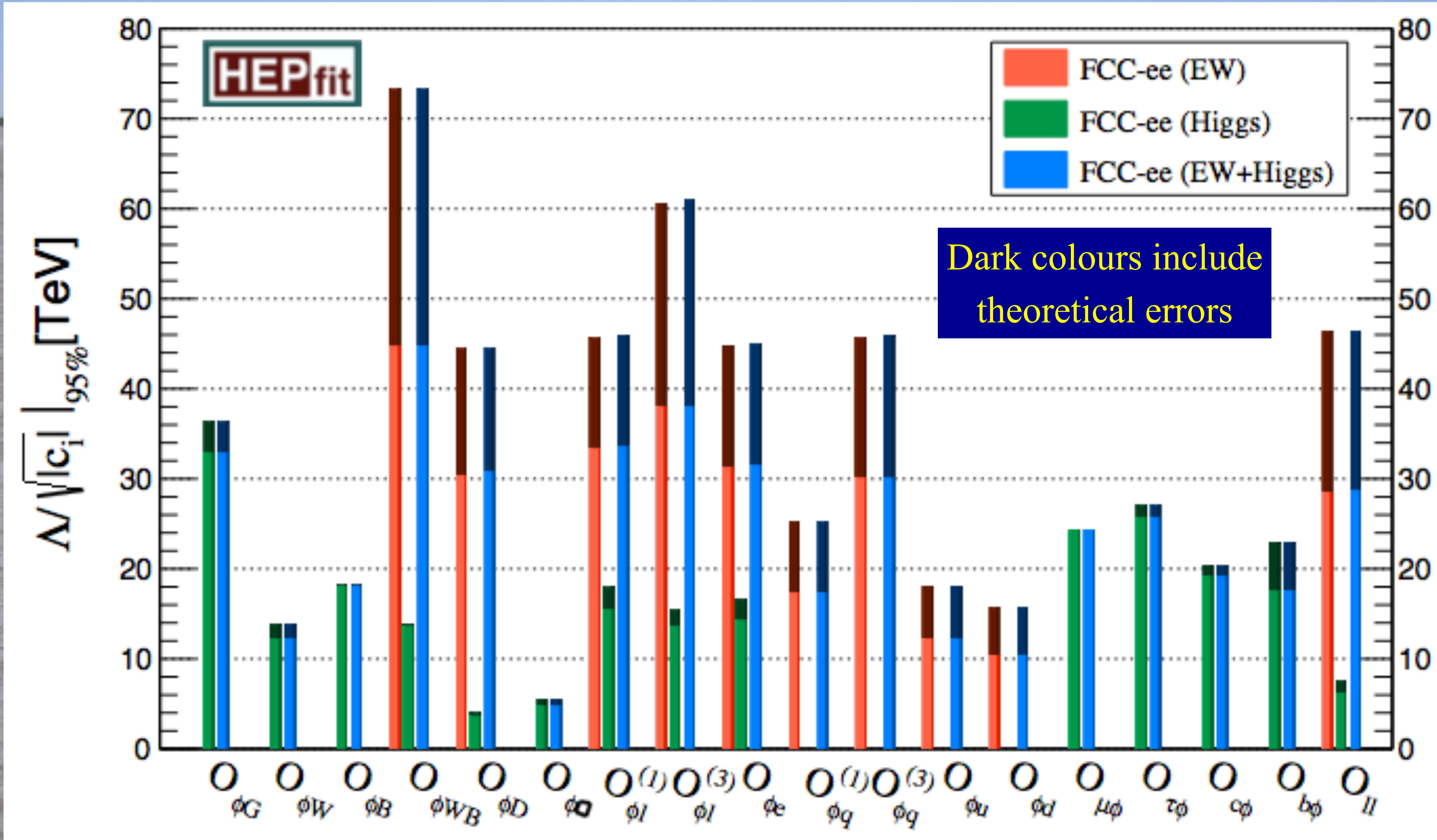
Model-Independent BSM Survey

- Top-less sector fits SM very well
- Top sector does not fit so well
- Overall, pulls not excessive
- No hint of BSM

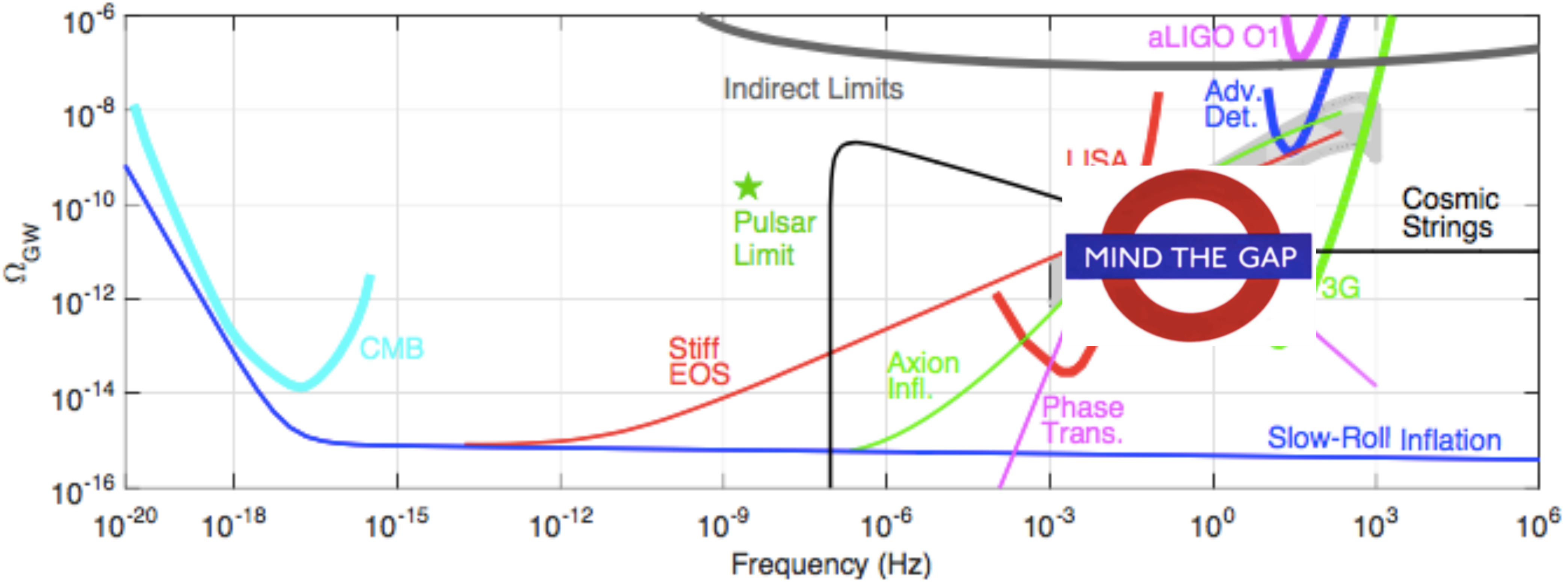


JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Future EFT Constraints from Higgs and Electroweak Measurements



Gravitational Wave Spectrum

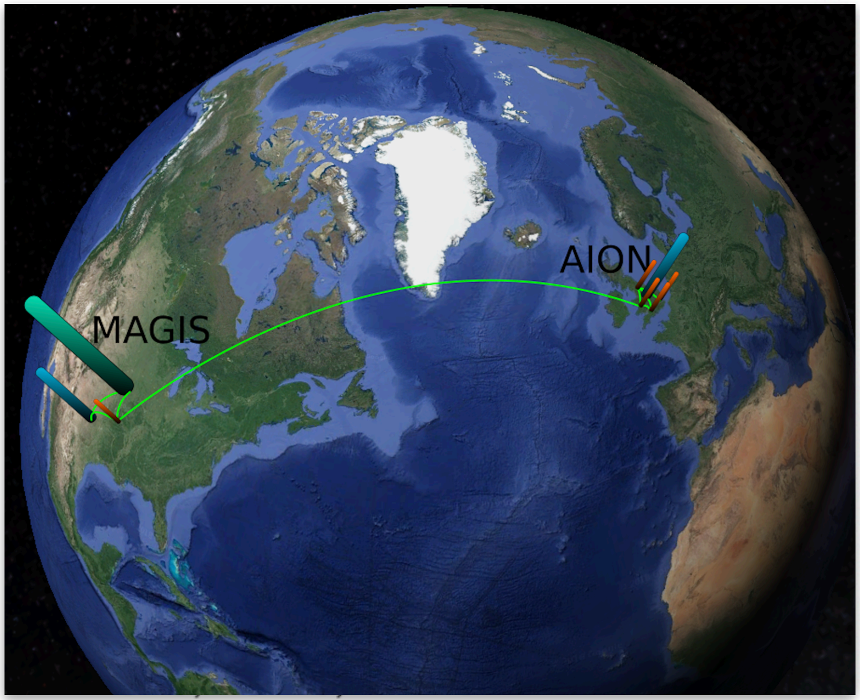


- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Electroweak phase transition? Cosmic strings?
- Gap between LISA & pulsar timing arrays (PTAs)

AION Atom Interferometer Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], G. Elertas, J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski, A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7], P. Majewski[2], S. Malik[6], J. March-Russell[3], C. McCabe[1], D. Newbold[2], R. Preece[3], B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh[4], M. Tarbutt[6], M. A. Uchida[7], T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7], J. Zielinska[6]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge



AION – Staged Programme

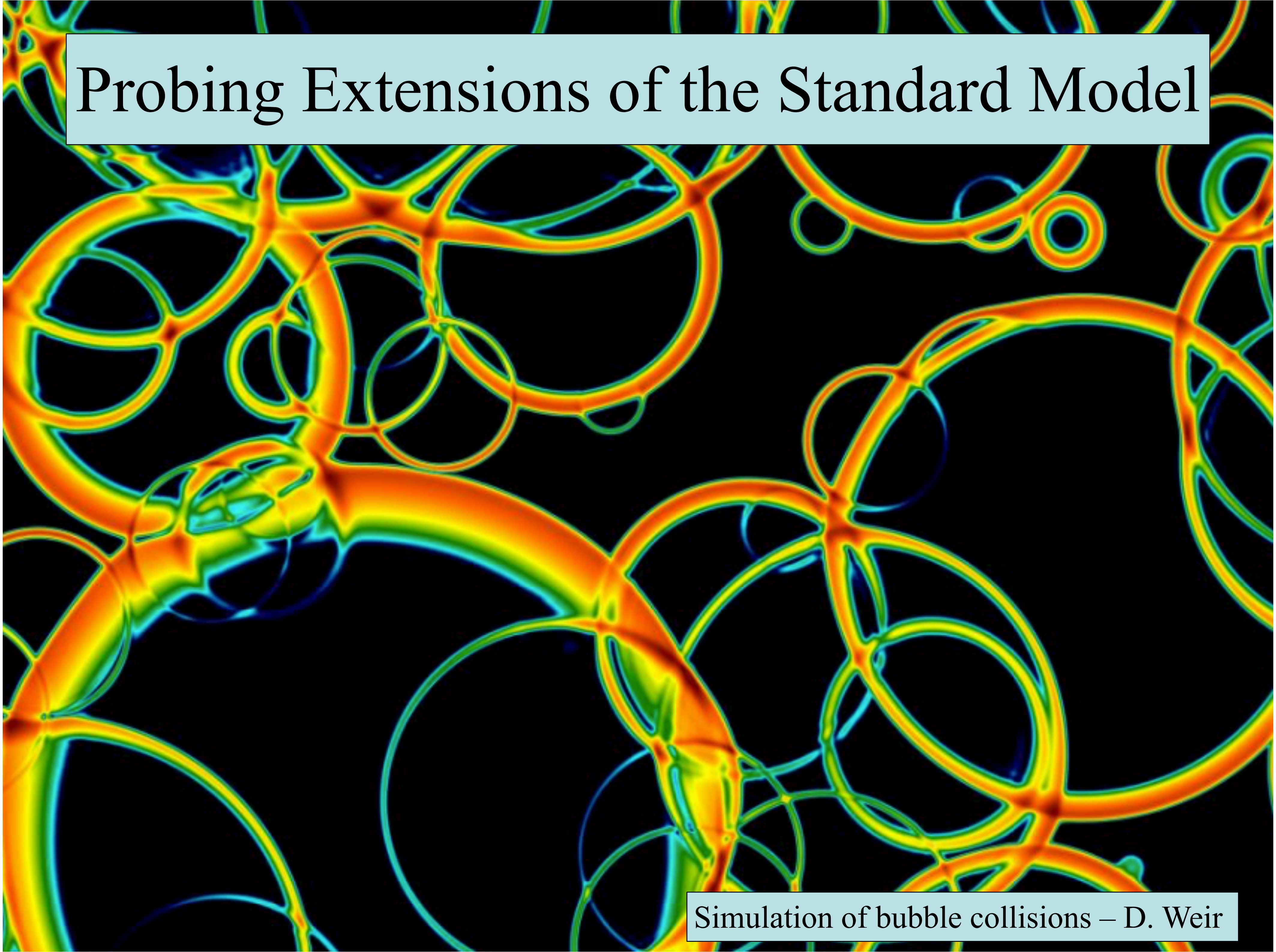
- AION-10: Stage 1 [year 1 to 3]
  - Strontium labs, 10 m interferometer & studies for 100m Baseline

Initial funding from UK STFC

- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & Commissioning
- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AEDGE (AION-SPACE): Stage 4 [after AION-KM]
  - Space-based version

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

Probing Extensions of the Standard Model



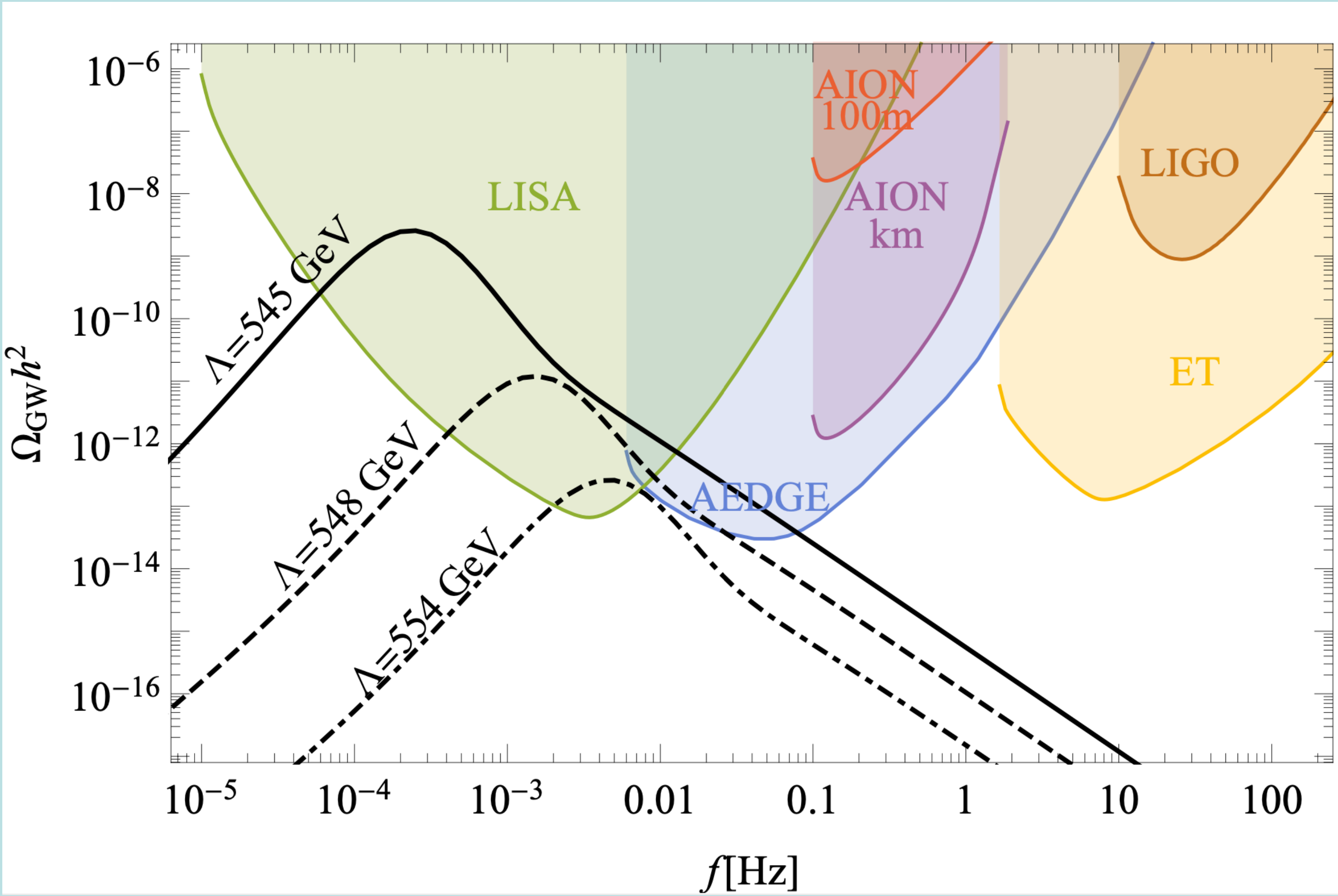
Simulation of bubble collisions – D. Weir

GWs from First-Order Phase Transition

- Transition by percolation of bubbles of new vacuum
- Bubbles grow and collide
- Possible sources of GWs:
  - Bubble collisions
  - Turbulence and sound waves in plasma
- Models studied:
  - Standard Model + H^6/Λ^2 interaction
  - Standard Model + $U(1)_{B-L}$ Z'
- These also have prospective collider signatures

GW Signal in H^6 Model

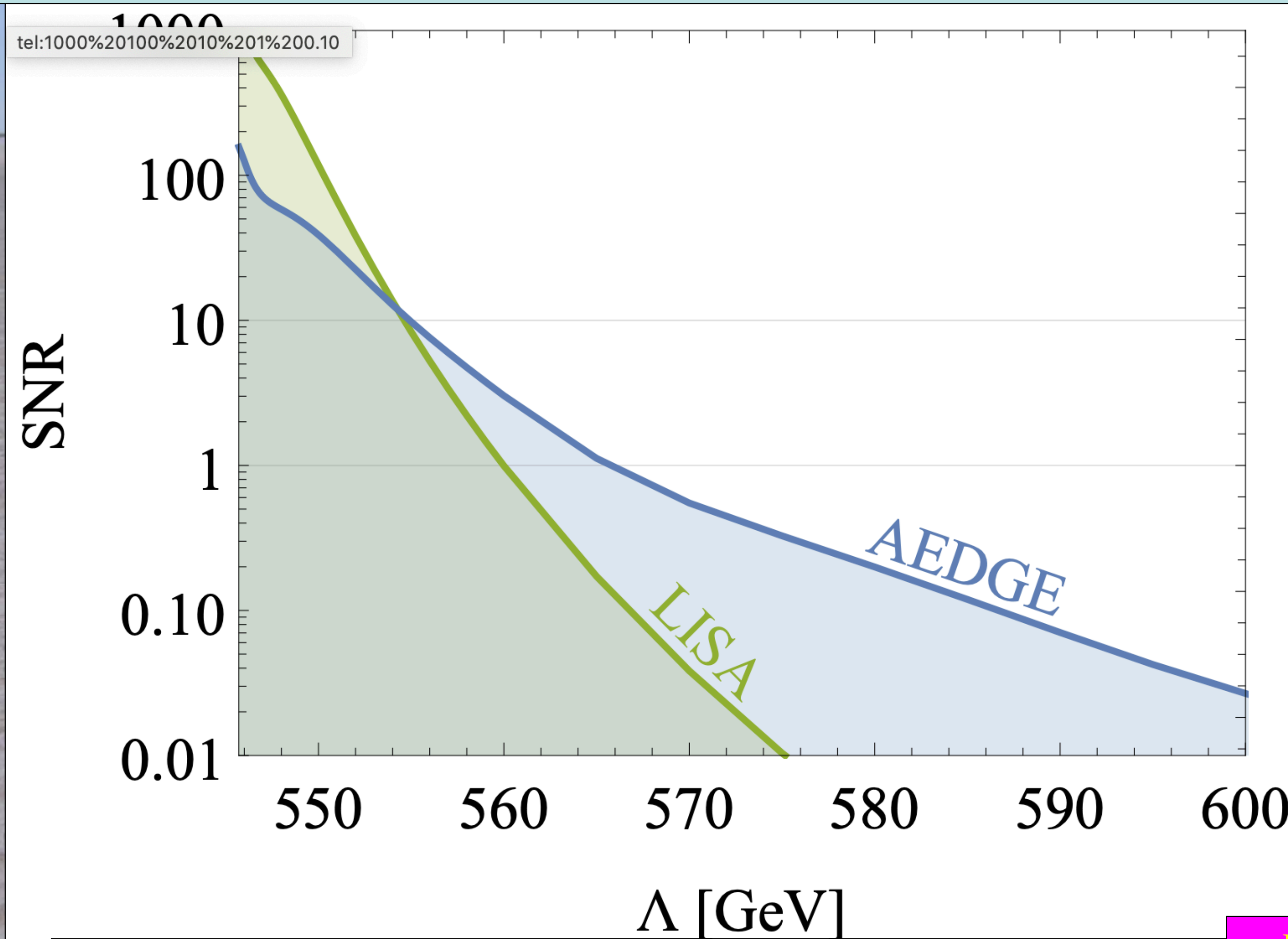
- Strongest signal for which percolation is assured



- AEDGE and LISA SNR = 8 sensitivities very similar

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

Gravitational Wave Sensitivity to Scale of H^6 Interaction

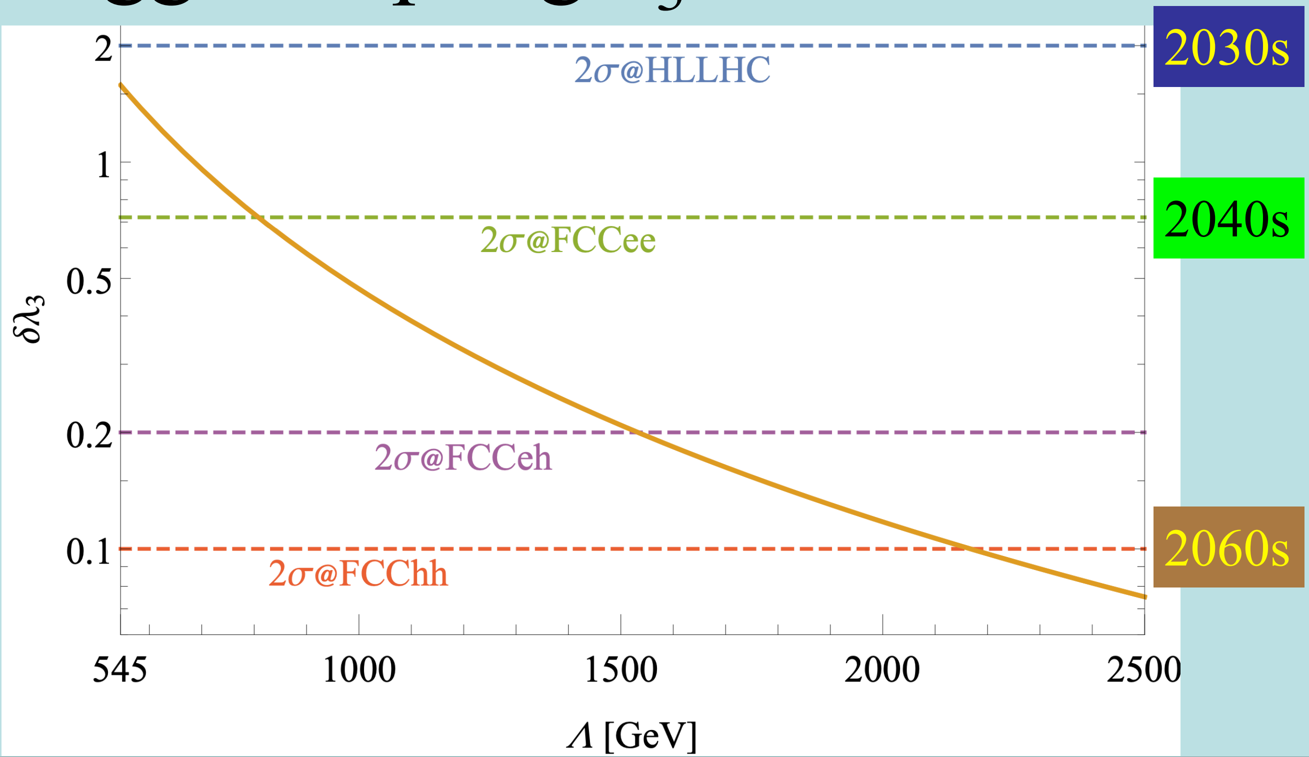


Gravitational wave sensitivity to Λ

Updated from
JE, Lewicki & No,
arXiv:1809.08242

Modification of Triple-H Coupling

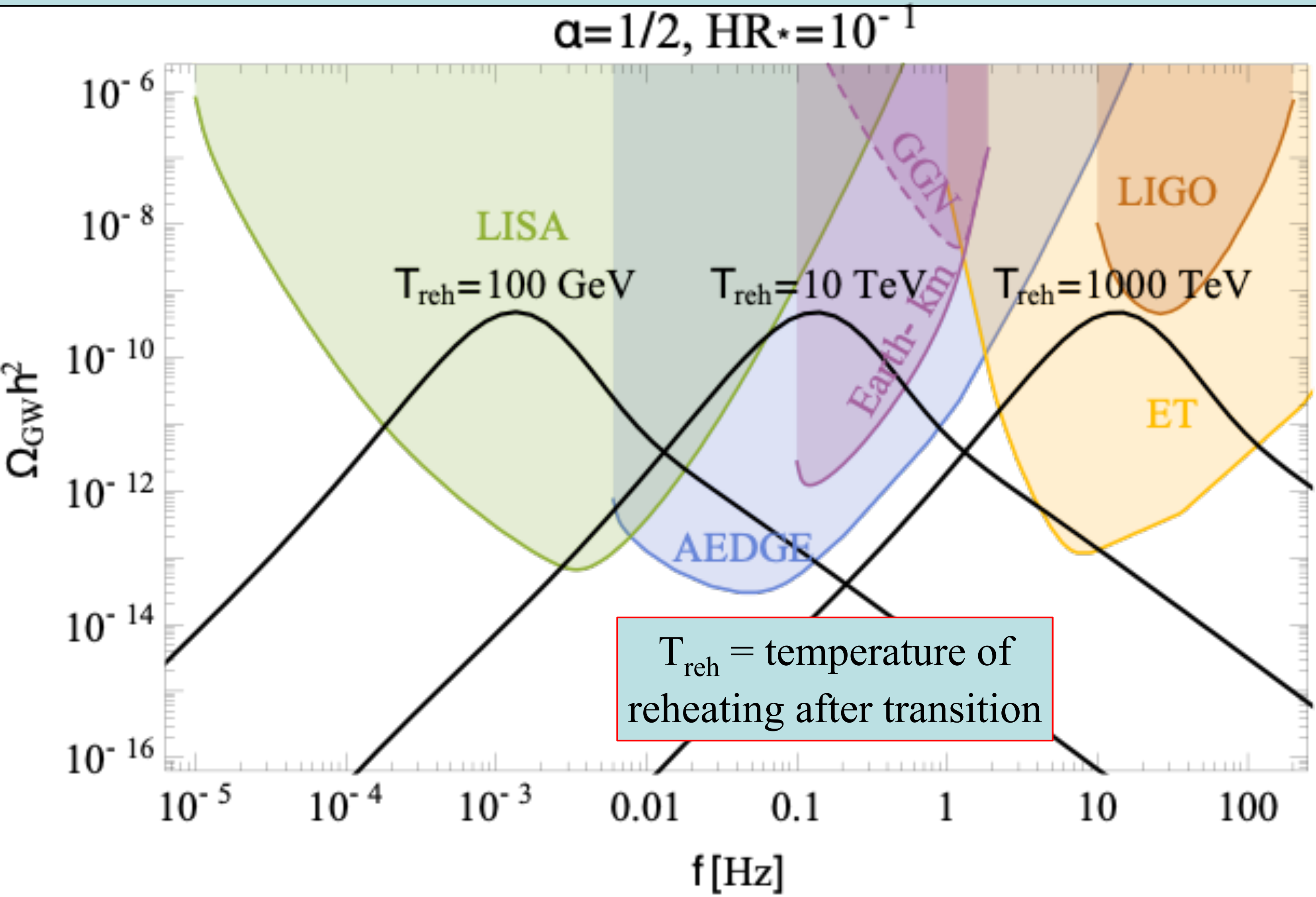
- Current LHC data insensitive to H^6/Λ^2 coupling
- Future collider sensitivity via modification of triple-Higgs coupling λ_3



No collider sensitivity now, will eventually be > gravitational waves

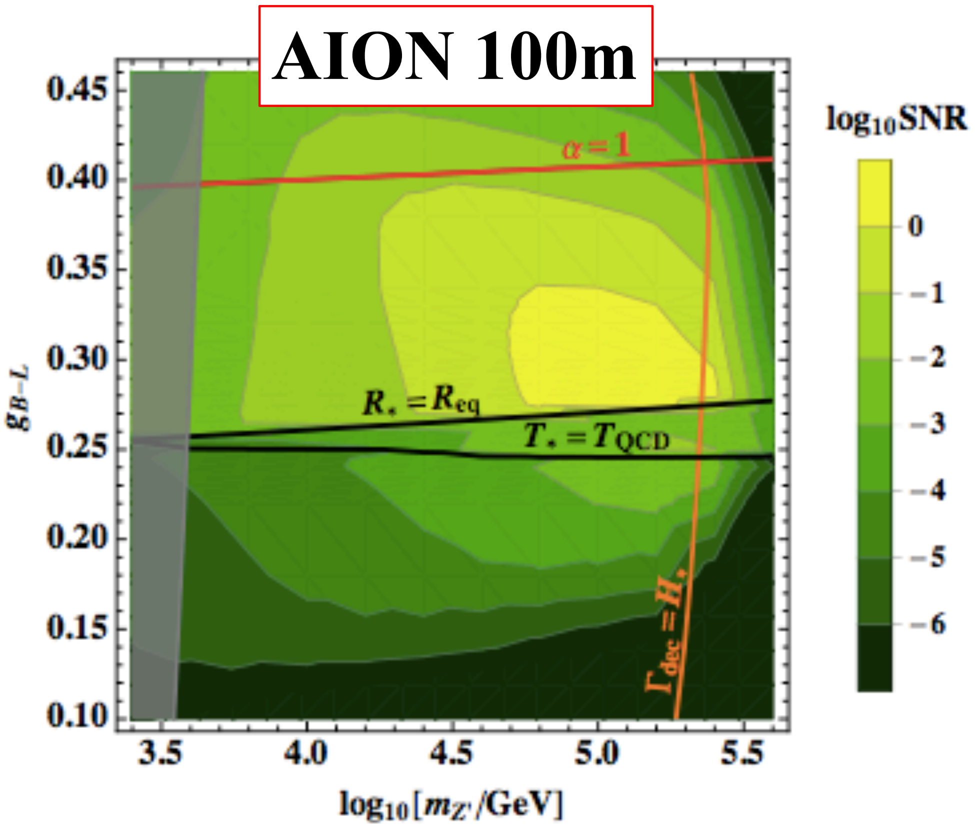
Updated from JE, Lewicki & No, arXiv:1809.08242

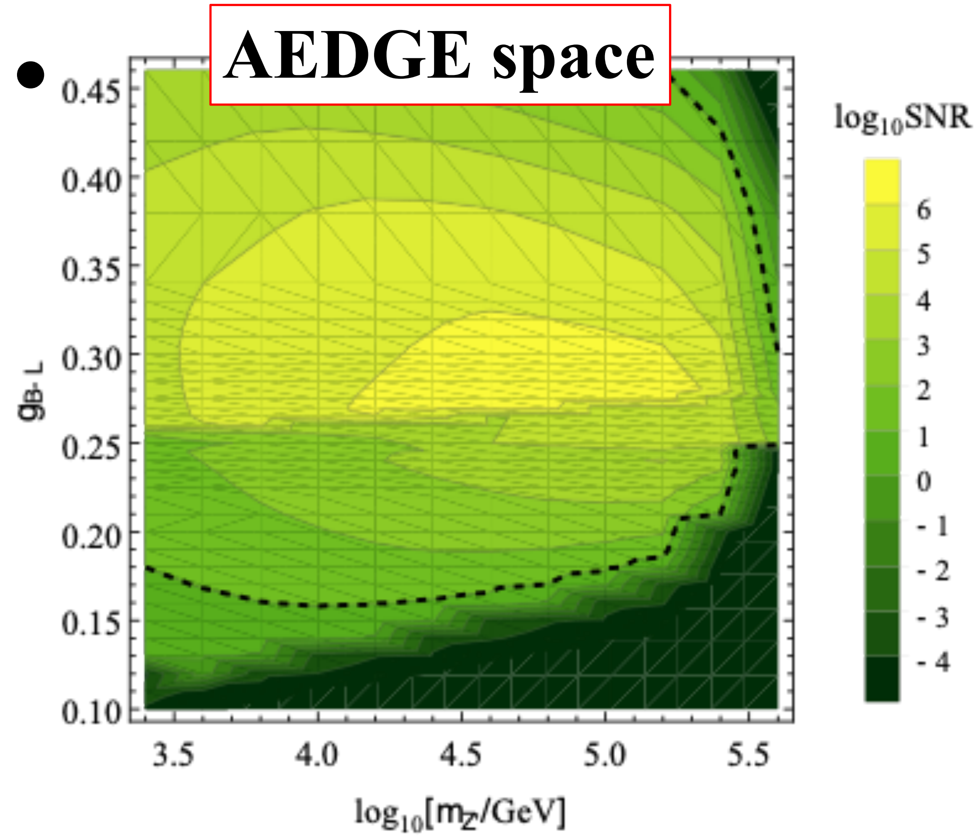
Gravitational Waves from $U(1)_{B-L}$ Phase Transition



AEDGE: Bertoldi, …, JE et al: arXiv:1908.00802

AION GW SNR in Z' Model





Discovery of GW possible with AION 1km

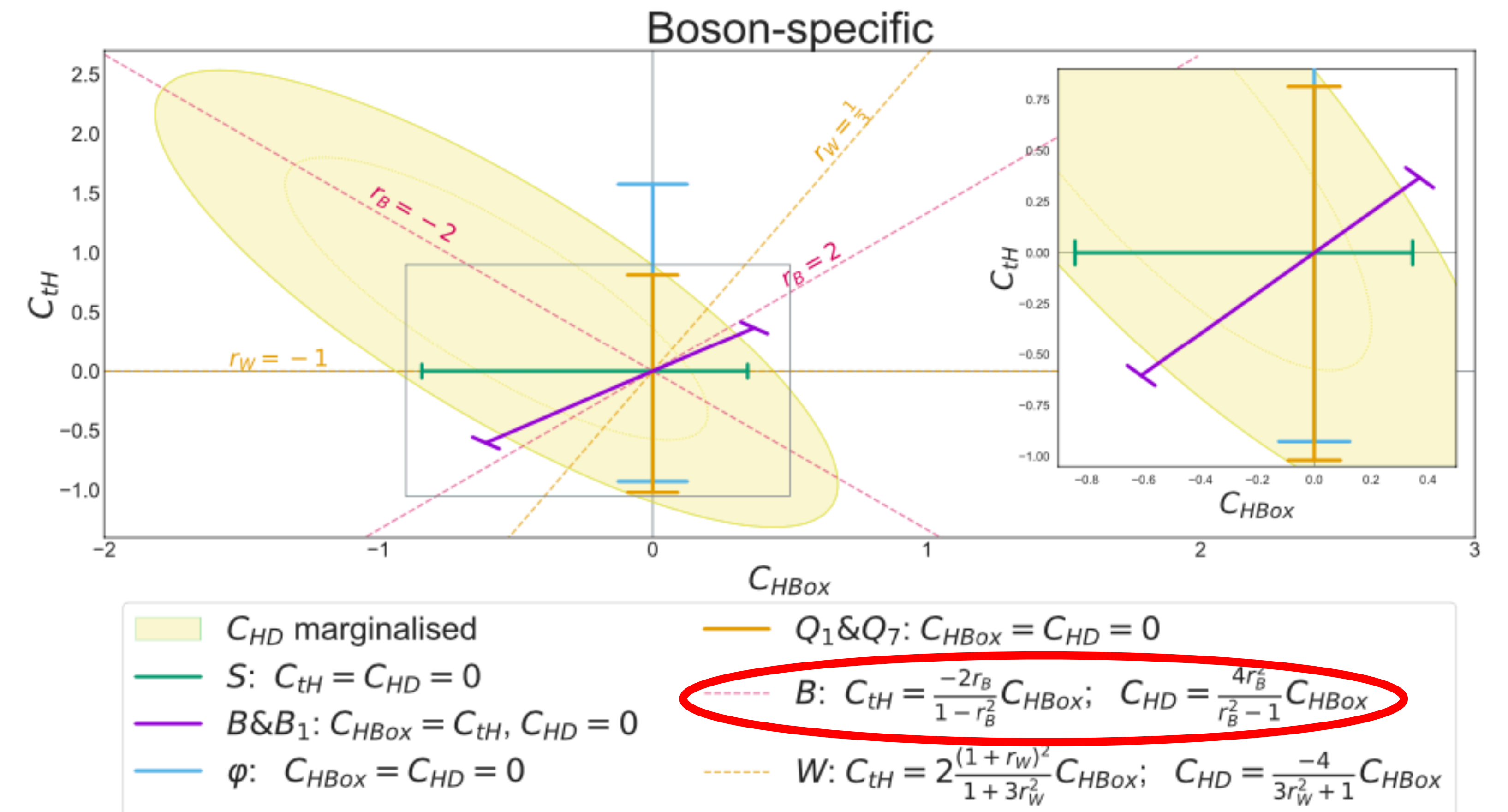
Mass reach beyond LHC, FCC, SppC

Above red line: transition before vacuum energy dominates
Right of orange line: period of matter domination

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

Collider Sensitivities to Z' Models

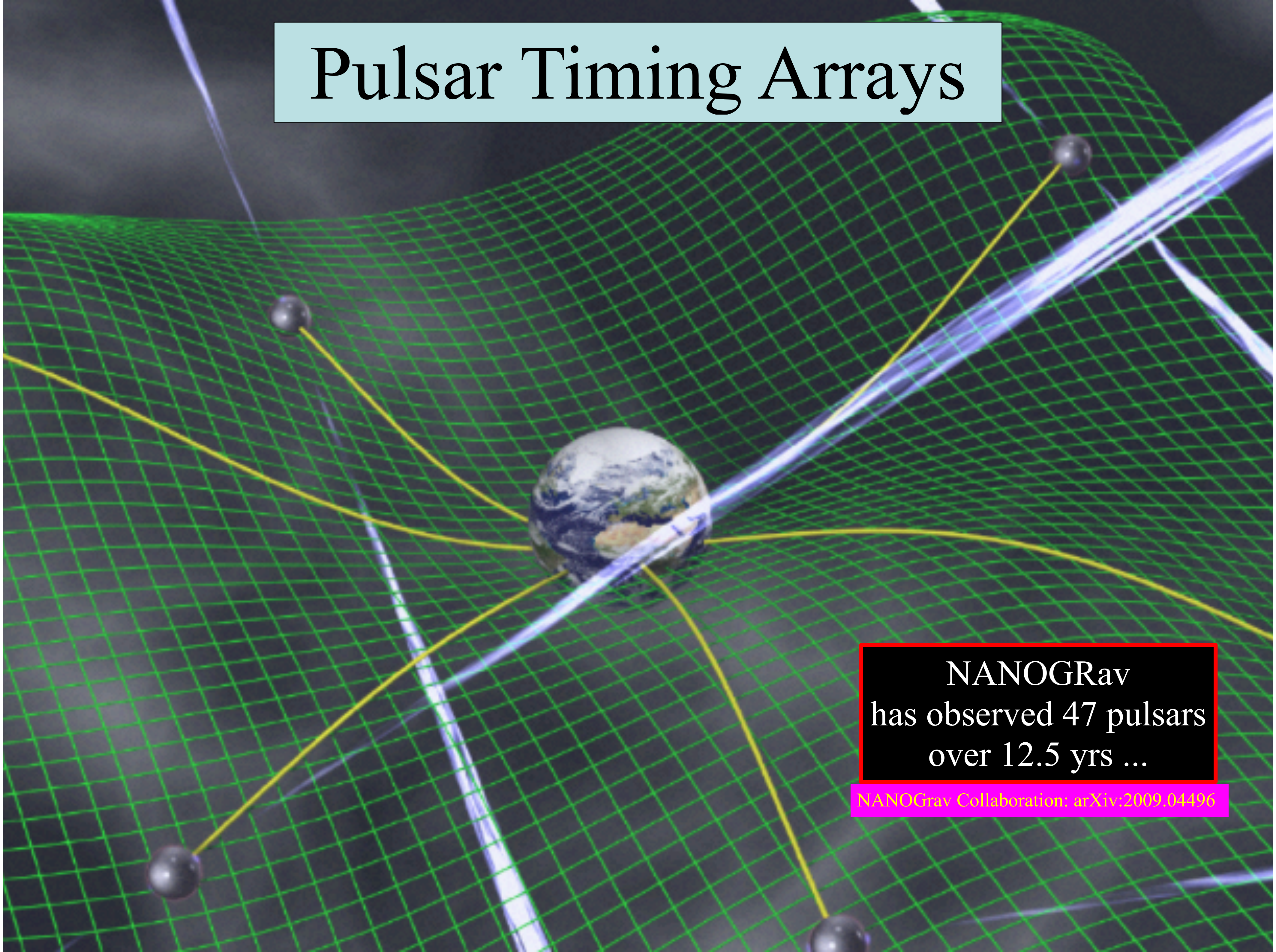
- Direct limit > 3.5 TeV
- Indirect limit > 1 TeV for couplings O(1)



Collider sensitivity will be < gravitational waves

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Pulsar Timing Arrays



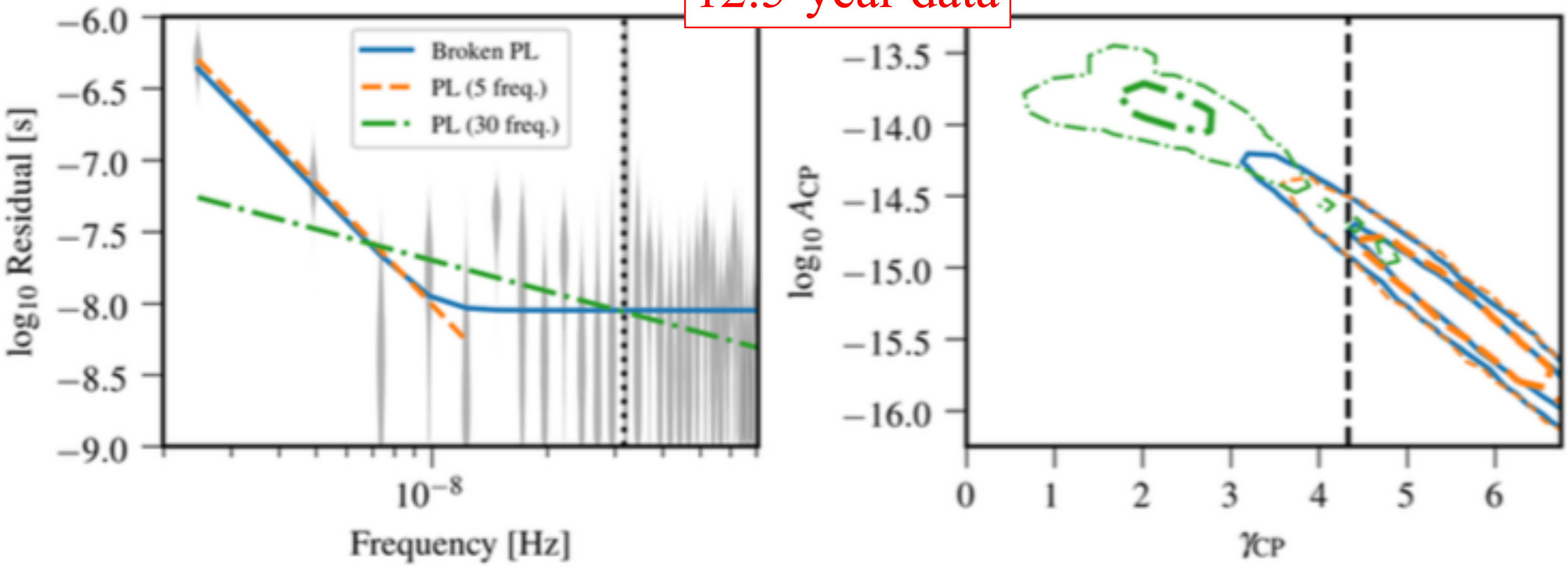
NANOGRav
has observed 47 pulsars
over 12.5 yrs ...

NANOGrav Collaboration: arXiv:2009.04496

NANOGrav Collaboration: arXiv:2009.04496

Pulsar Timing Data from NANOGrav

12.5-year data



NANOGrav reports
"strong evidence for a stochastic common-spectrum process"
at frequencies < 10^{-8} Hz
No dipole or quadrupole signal detected

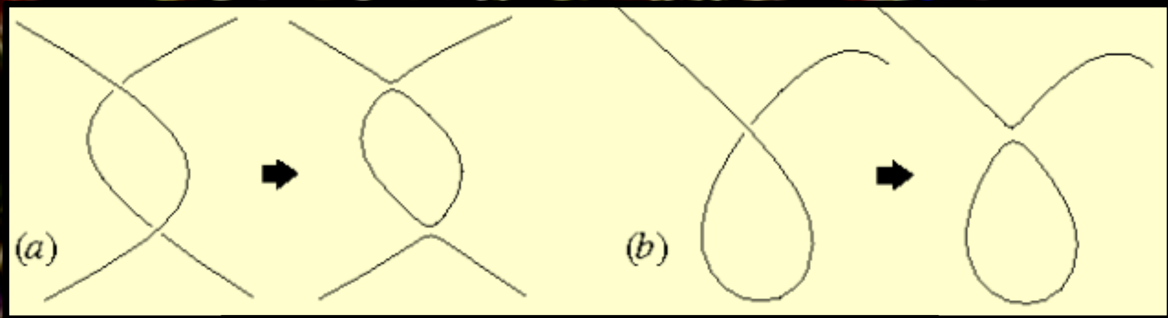
Fits to amplitude of signal
Focus on simple power law
Amplitude A ~ 10^{-15}
Slope $\gamma \sim 5$

Vertical dashed line: expected in models of mergers of supermassive BHs

Default model

Probing Cosmic Strings

Hint from the NANOGrav pulsar timing array?

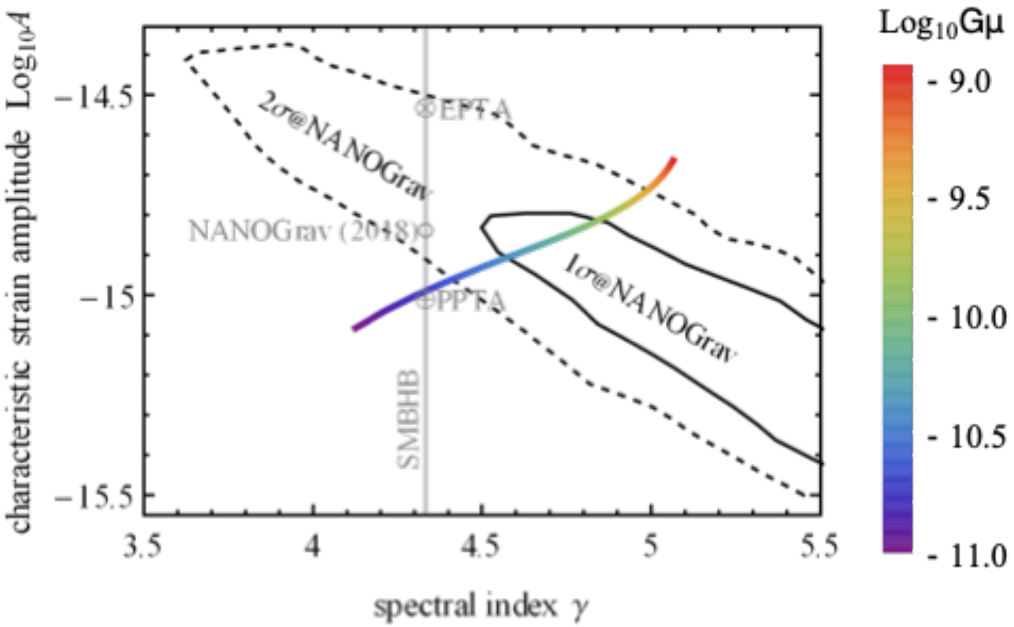


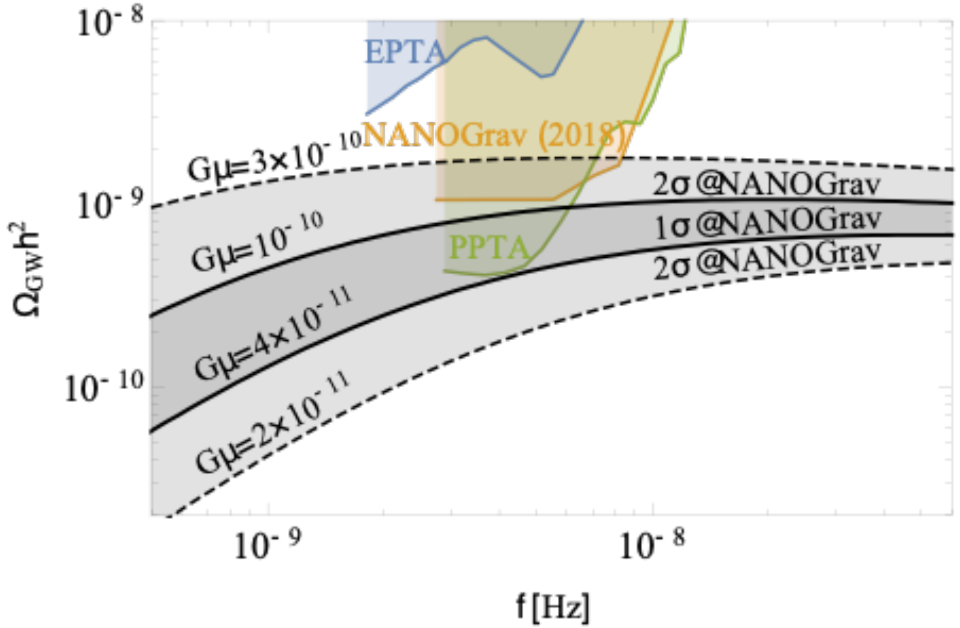
GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group

JE & Lewicki: arXiv:2009.06555

Cosmic String Interpretation of NANOGrav



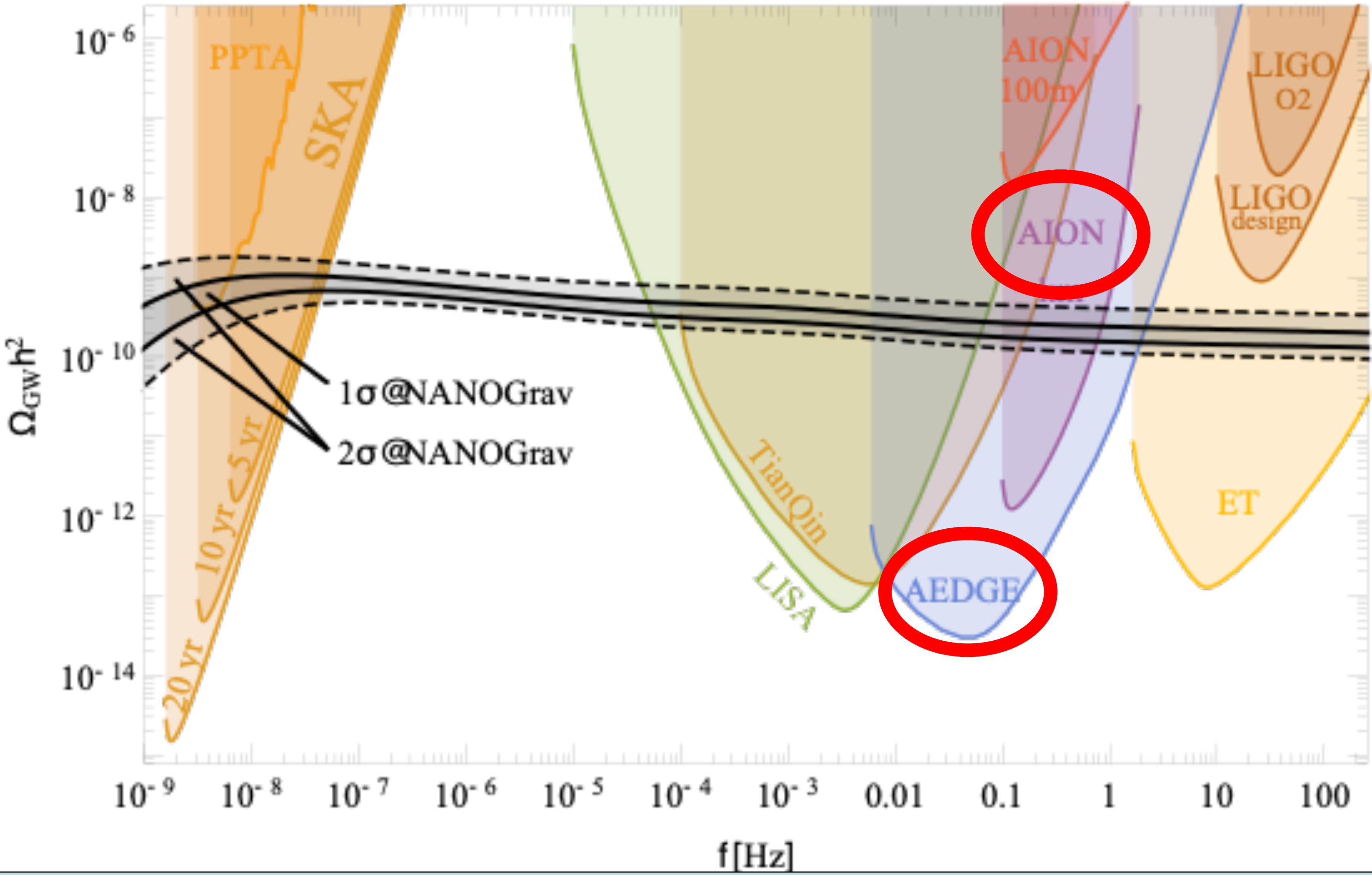


"Rainbow curve"
is cosmic string prediction as a
function of the cosmic string tension Gμ
Vertical line is naïve SMBH merger prediction
Previous PTA upper limits for
this value of γ

Fits to NANOGrav signal
at 1σ (68%), 2σ (95%) levels
Compared to previous
upper limits
(previous NANOGrav superseded)

JE & Lewicki: arXiv:2009.06555

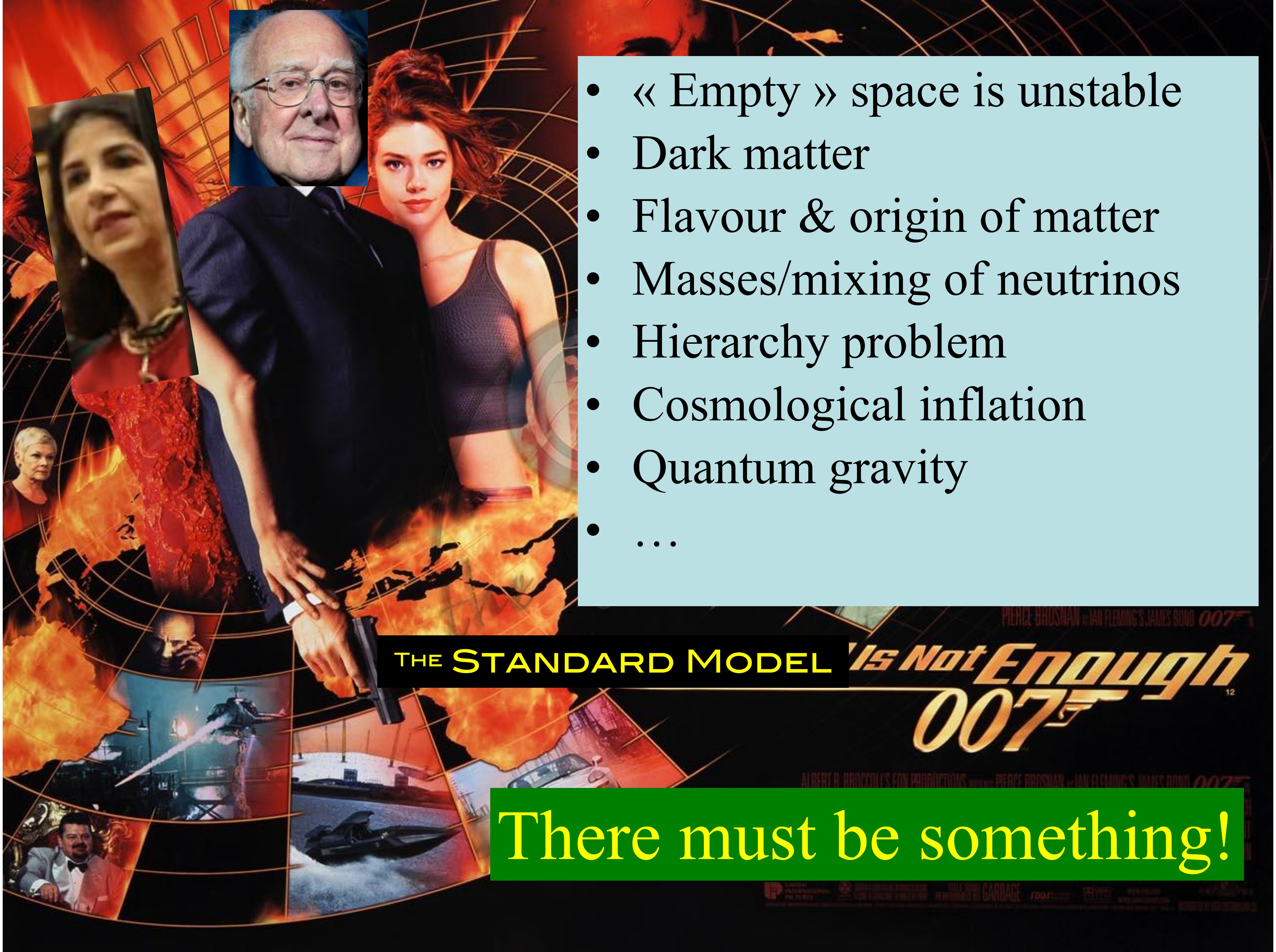
Cosmic String Interpretation of NANOGrav



Cosmic string prediction can be tested in several upcoming experiments (not LIGO)

See also Blasi, Vrdar & Schmitz: arXiv:2009.06607v2

- « Empty » space is unstable
- Dark matter
- Flavour & origin of matter
- Masses/mixing of neutrinos
- Hierarchy problem
- Cosmological inflation
- Quantum gravity
- …



There must be something!