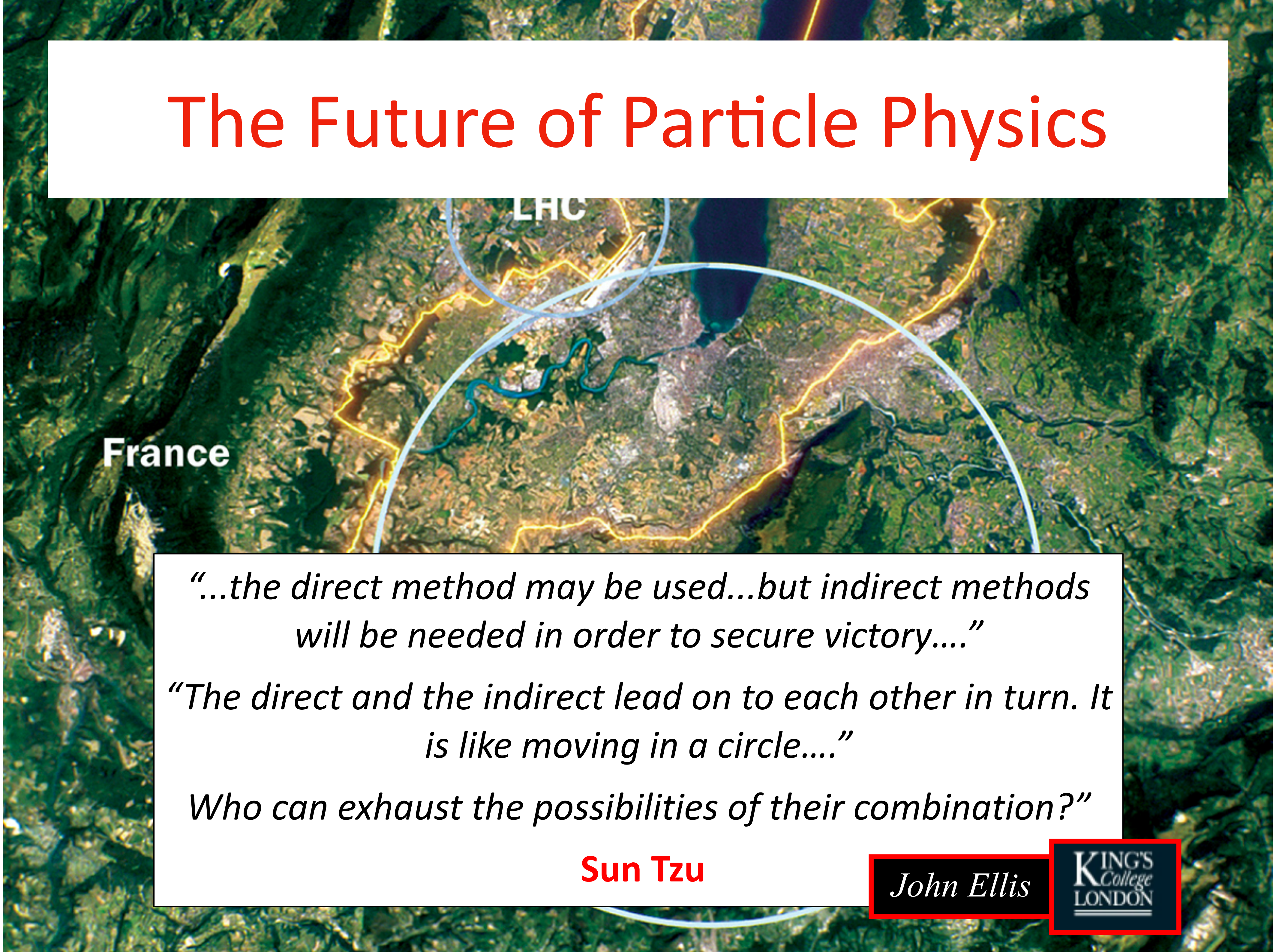
The Future of Particle Physics



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

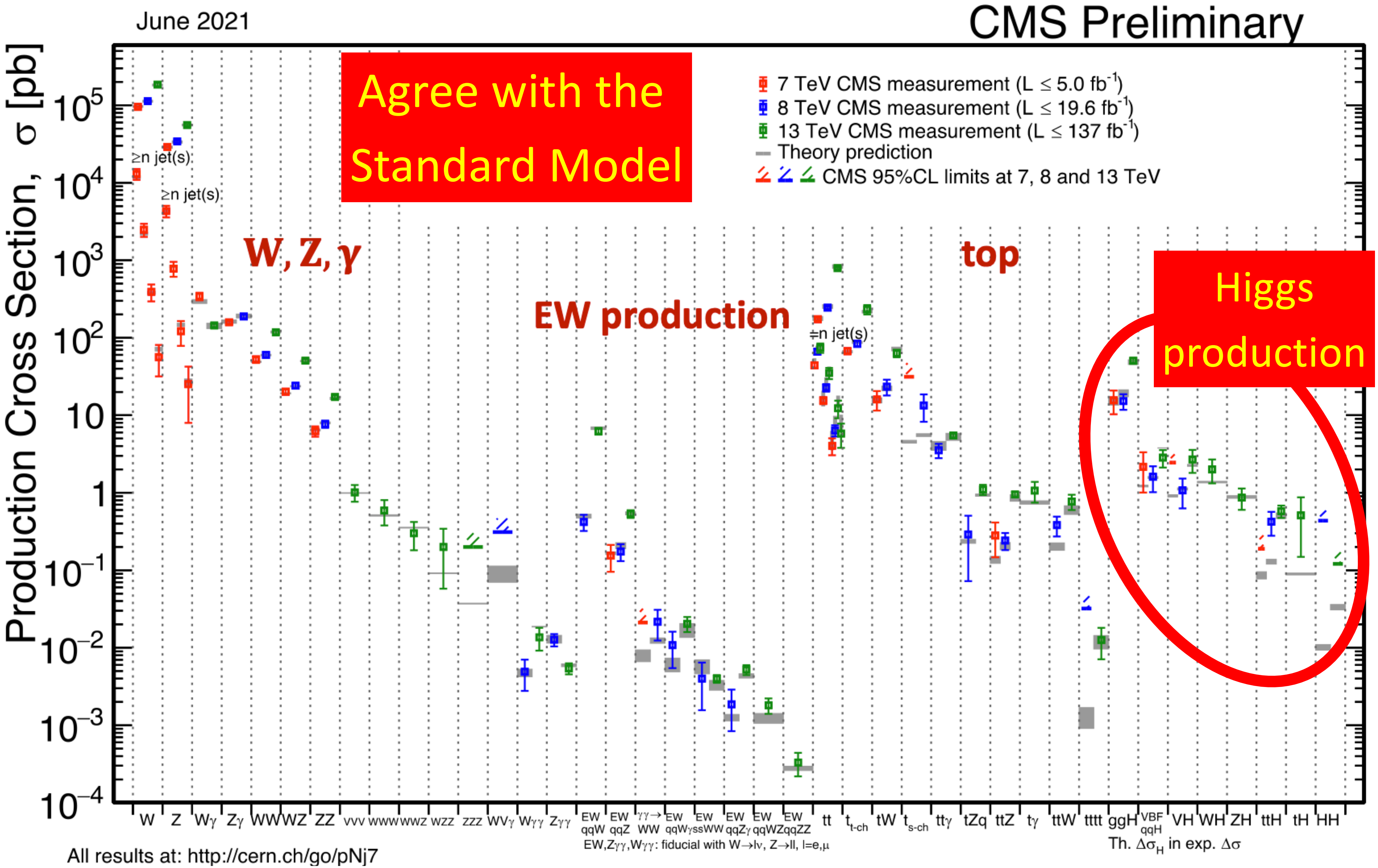
"The direct and the indirect lead on to each other in turn. It is like moving in a circle...."

Who can exhaust the possibilities of their combination?"

Sun Tzu

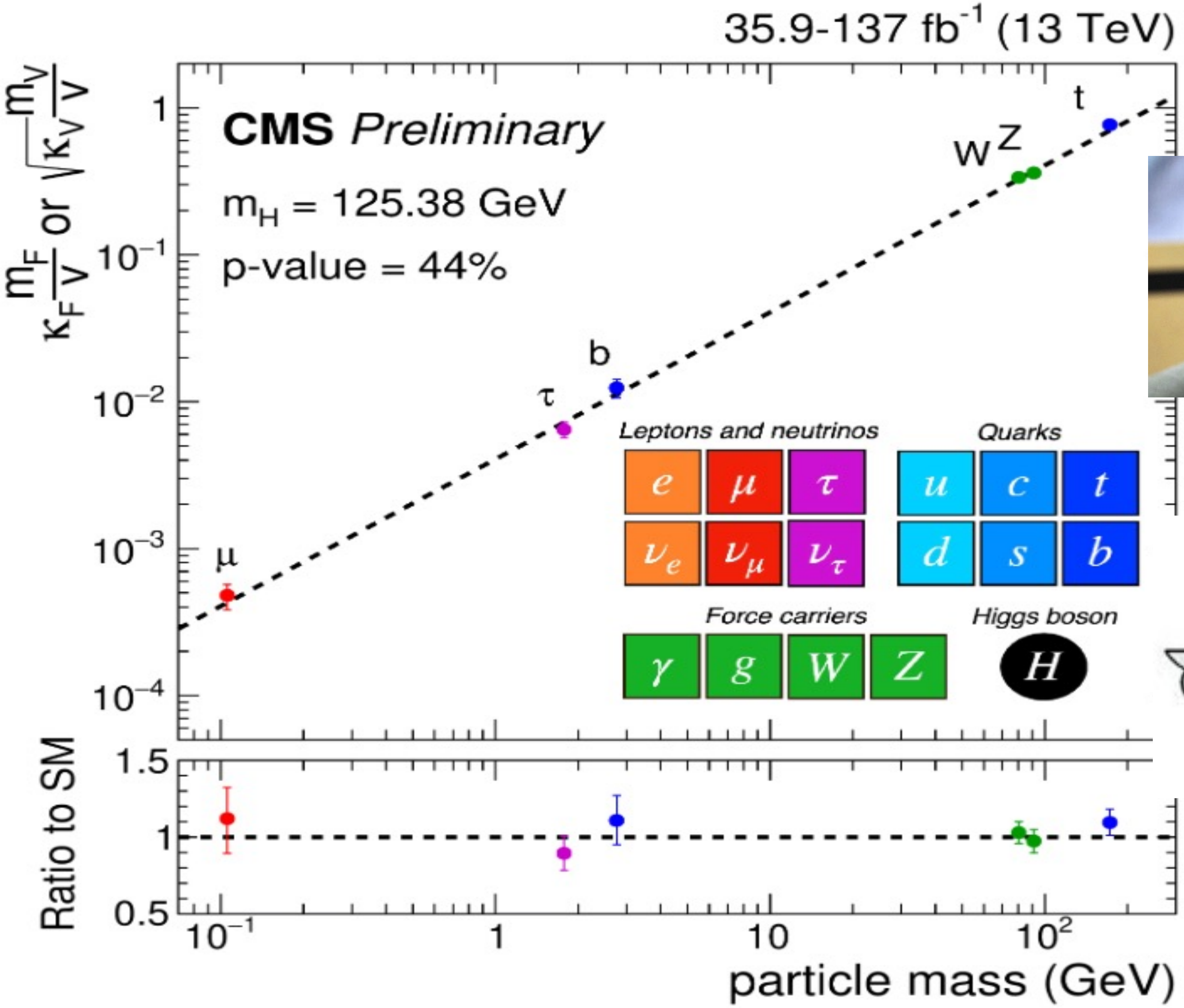
John Ellis
King's College London

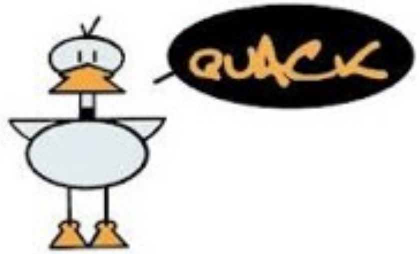
LHC Measurements

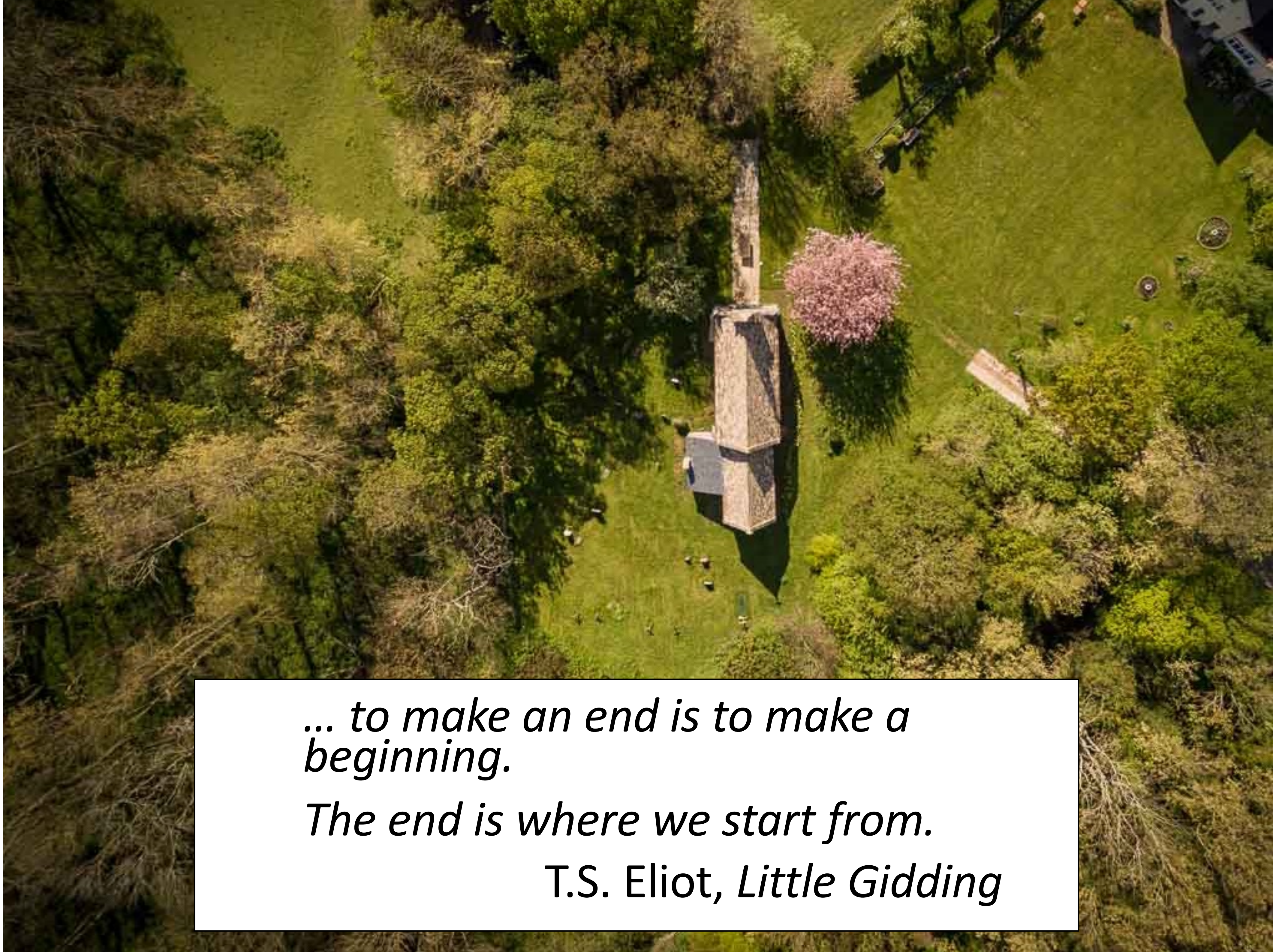


It Walks and Quacks like a Higgs

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







… to make an end is to make a beginning.

The end is where we start from.

T.S. Eliot, *Little Gidding*


ALBERT R. BROCCOLI'S EON PRODUCTIONS PRESENTS
PIERCE BROSNAN AS IAN FLEMING'S JAMES BOND 007
The World Is Not Enough
12
007
ALBERT R. BROCCOLI'S EON PRODUCTIONS PIERCE BROSNAN AS IAN FLEMING'S JAMES BOND 007
"THE WORLD IS NOT ENOUGH" SOPHIE MARCEAU ROBERT CARLYLE DENISE RICHARDS ROBBIE COLTRANE AND JUDI DENCH
LINDY HEMMING DAVID ARNOLD JIM CLARK ADRIAN BIDDLE PETER LAMONT
ANTHONY WAYE NEAL PURVIS & ROBERT WADE NEAL PURVIS & ROBERT WADE AND BRUCE FEIRSTEIN
MICHAEL G. WILSON AND BARBARA BROCCOLI MICHAEL APTED
GARBAGE

• « Empty » space is unsta
• Dark matter
• Origin of matter
• Sizes of masses
• Masses of neutrinos
• Inflation
• Quantum gravity
• …
LHC
LHC
LHC
LHC
The Standard Model
Is Not Enough
007

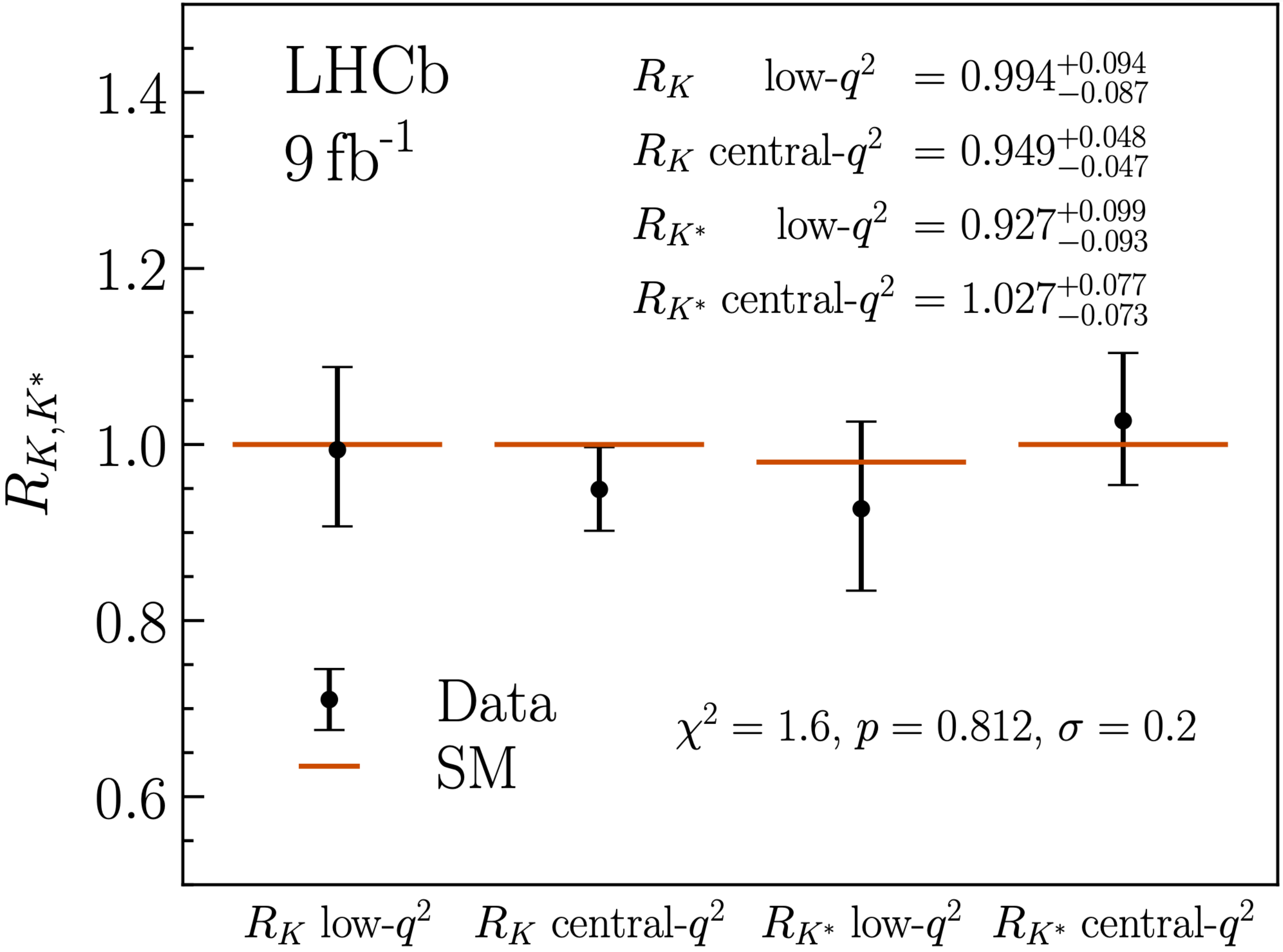
Everything about Higgs is Puzzling

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

- 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?

Sic Transit Gloria R_K Anomaliae



Is Empty Space Unstable?

- Dependence of instability scale on masses of Higgs boson and top quark, and strong coupling:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 10.5 - 1.3\left(\frac{m_t}{\mathrm{GeV}} - 172.6\right) + 1.1\left(\frac{m_H}{\mathrm{GeV}} - 125.1)\right) + 0.6\left(\frac{\alpha_s(m_Z) - 0.1179}{0.0009}\right)$$

Buttazzo et al, arXiv:1307.3536; Franceschini et al, 2203.17197

- New CMS value of m_t : CMS Collaboration, April 2022

$$m_t = 171.77 \pm 0.38\,\mathrm{GeV}$$

- Particle Data Group values:

$$m_H = 125.25 \pm 0.17\,\mathrm{GeV}, \quad \alpha_s(m_Z) = 0.1179 \pm 0.0009$$

- Instability scale:

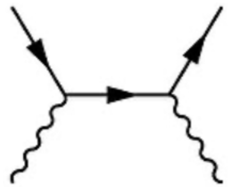
$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 11.7 \pm 0.8$$

- Dominant uncertainties those in α_s and m_t

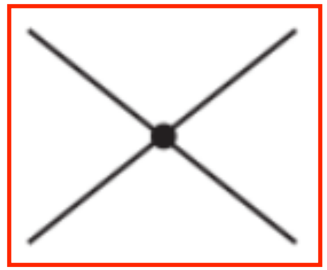
Effective Field Theories (EFTs)

a long and glorious History

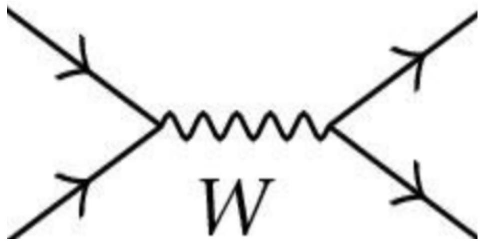
- 1930's: "Standard Model" of QED had d=4



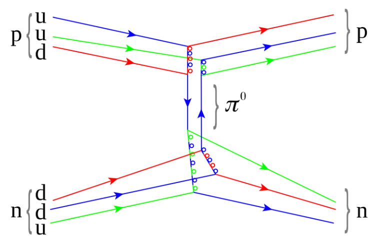
- **Fermi's four-fermion theory of the weak force**



- 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: (∂π∂π)ππ clue ➔ QCD

Standard Model Effective Field Theory

a more powerful way to analyze the data

- Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
- Look for additional interactions between SM particles due to exchanges of heavier particles
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other experiments
- **Model-independent way to look for physics beyond the Standard Model (BSM)**

Dimension-6 SMEFT Operators

- Including 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate SU(3)^5 symmetry
- Important when including top observables

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

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

Anomalous magnetic moments

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

Flavour anomalies

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

Baryon decay

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

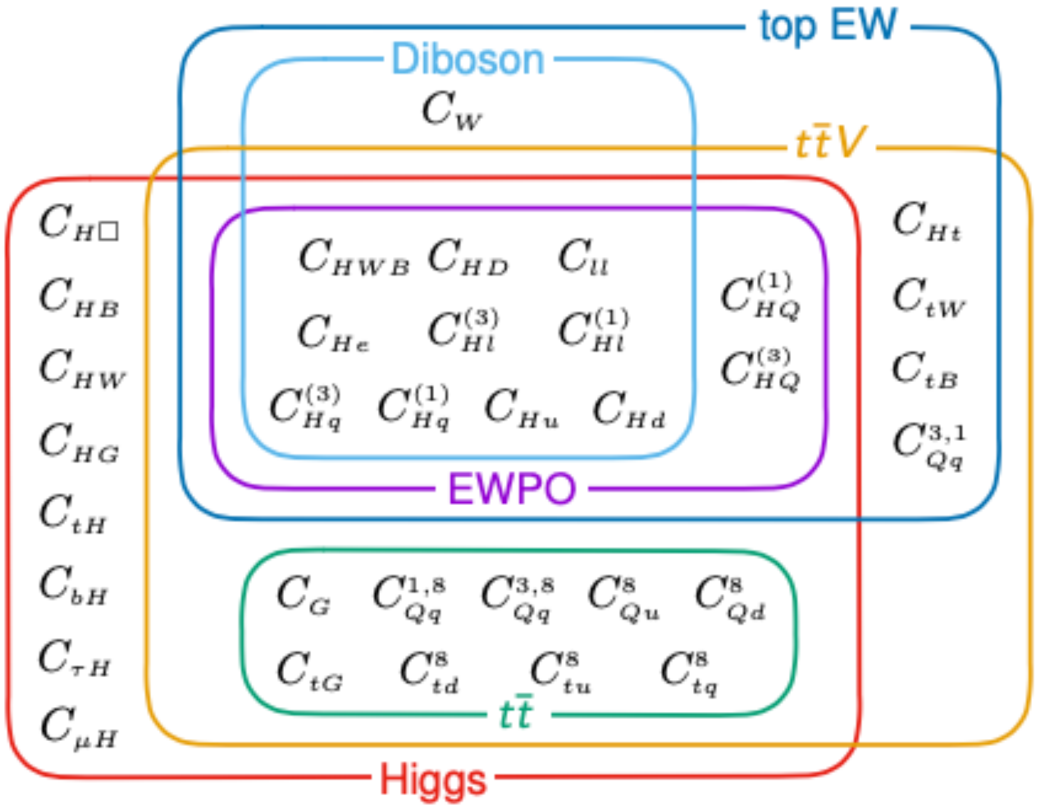
Global SMEFT Fit

to Top, Higgs, Diboson, Electroweak Data

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

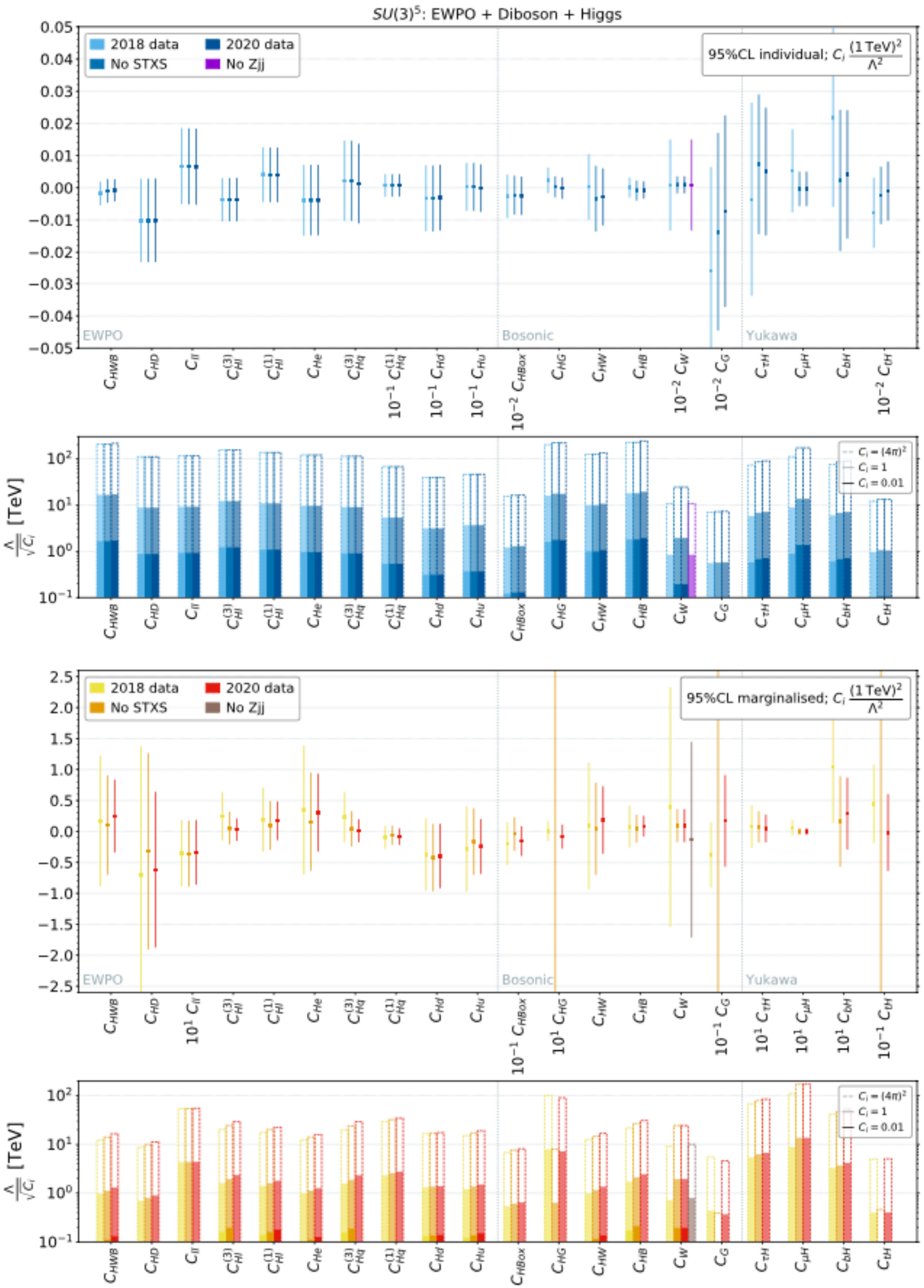
- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level

341 measurements included in global analysis



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

- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

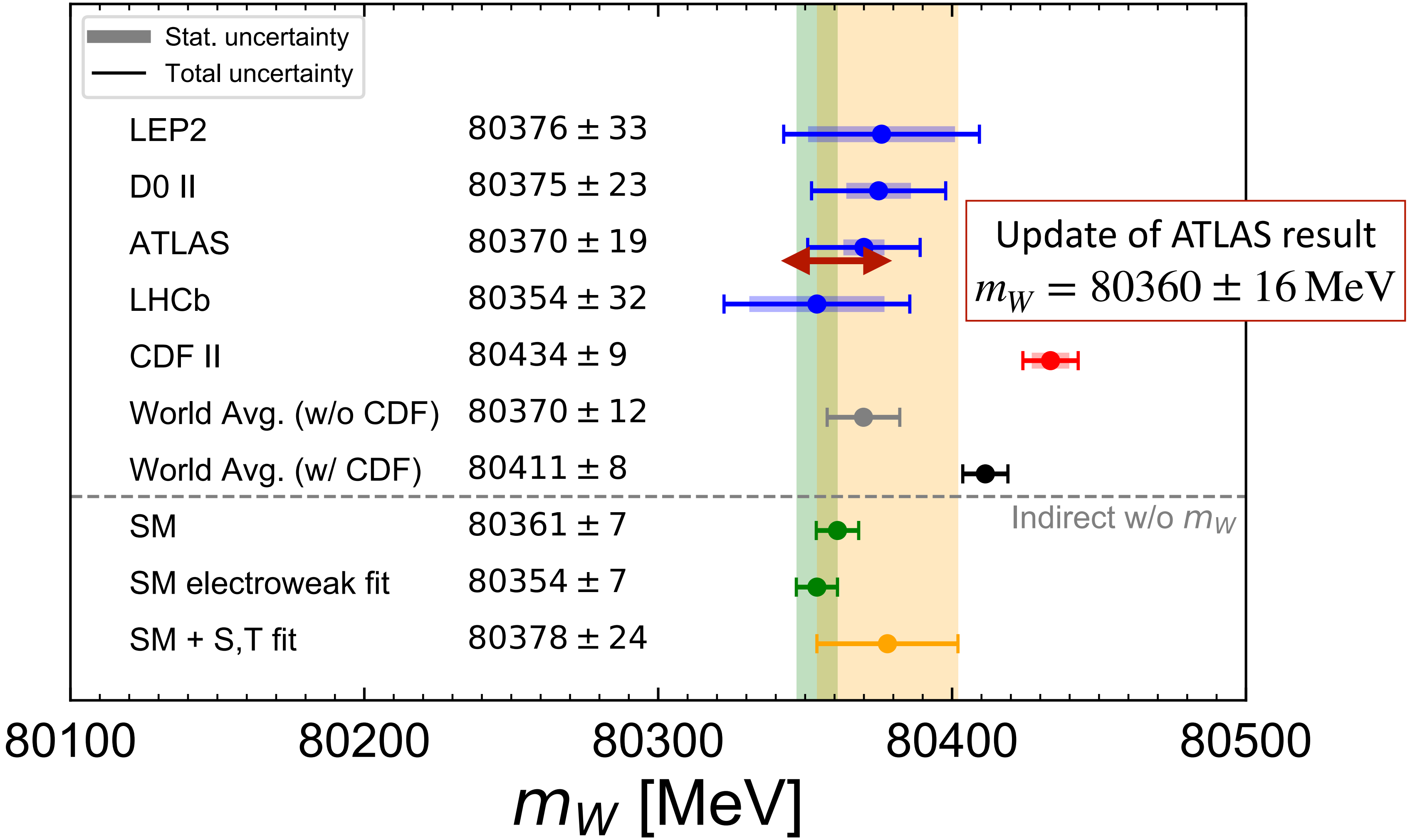


No significant deviations from SM

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

CDF Measurement of m_W

compared with other measurements



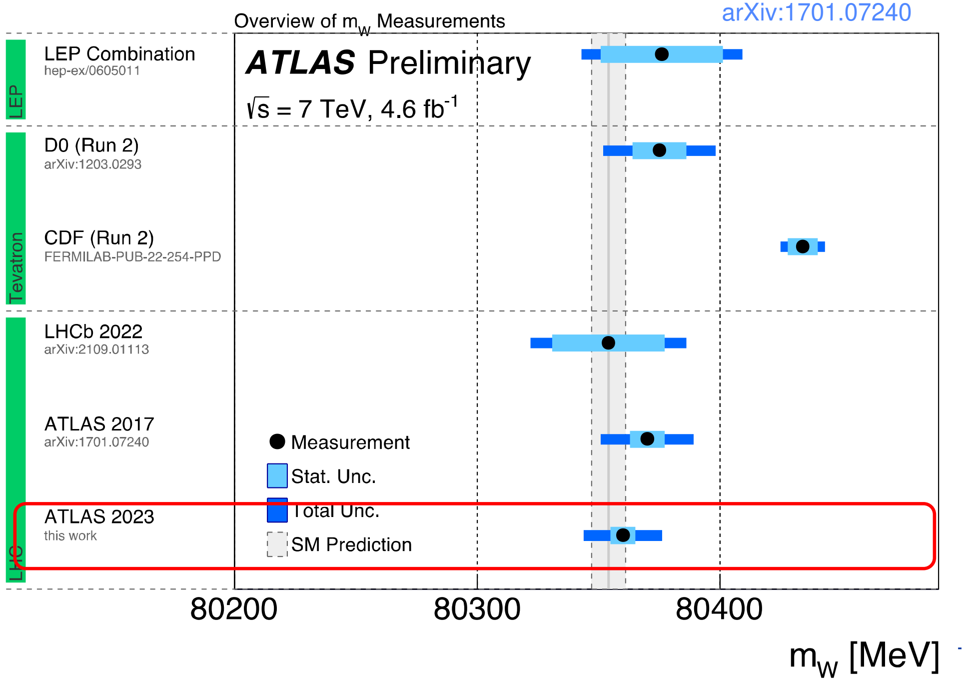
Tension: 7-σ discrepancy with Standard Model?

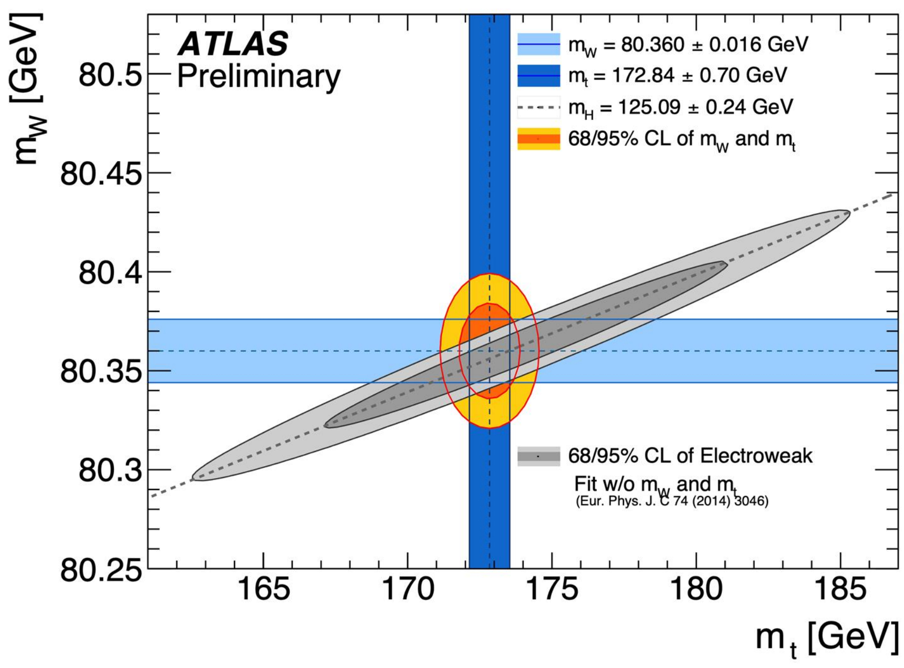
Last Week's News

ATLAS: Improved Measurement of the W Mass

Re-analysis of 7 TeV data with improved precision: $\mathbf{m_W = 80360 \pm 16}$ **MeV** (previous ATLAS results: 80370 ± 19 MeV)

- ❑ Based on sample of 5.9 million $W \to e\nu$ and 7.8 million $W \to \mu\nu$ events
- ❑ More recent PDF, constrained profile likelihood fit, verification of p_T,W modelling with dedicated Run 2 low-pileup data
- ❑ Agreement with SM





ATLAS Collaboration, ATLAS-CONF-2023-004

SMEFT Operators that can Contribute to W Mass

- Relevant SMEFT operators

$$\mathcal{O}_{HWB} \equiv H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_{HD} \equiv \left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$$

$$\mathcal{O}_{\ell\ell} \equiv \left(\bar{\ell}_p \gamma_\mu \ell_r\right)\left(\bar{\ell}_s \gamma^\mu \ell_t\right), \quad \mathcal{O}^{(3)}_{H\ell} \equiv \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{\ell}_p \tau^I \gamma^\mu \ell_r\right)$$

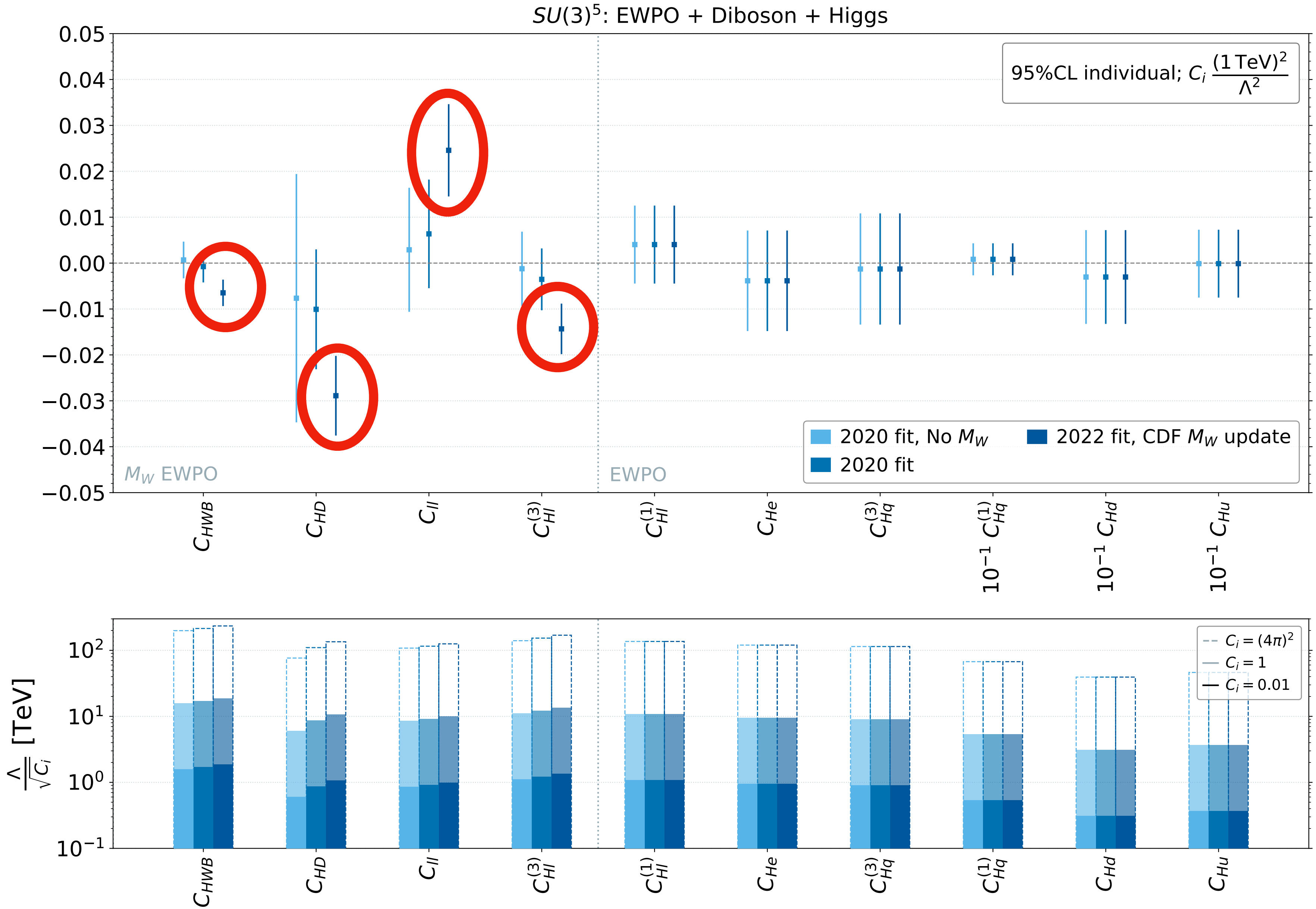
- Contributions to W mass

$$\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w}\frac{v^2}{4\Lambda^2}\left(\frac{\cos\theta_w}{\sin\theta_w}C_{HD} + \frac{\sin\theta_w}{\cos\theta_w}\left(4C^{(3)}_{Hl} - 2C_{ll}\right) + 4C_{HWB}\right)$$

- Contributions to *S* and *T* oblique parameters

$$\frac{v^2}{\Lambda^2}C_{HWB} = \frac{g_1 g_2}{16\pi}S \quad , \quad \frac{v^2}{\Lambda^2}C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)}T$$

SMEFT Fit with the Mass of the W Boson



Non-zero coefficients for any of four operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Extensions of the Standard Model

Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
W_1	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$

Spin zero

Vector

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

Single-Field Models that can Contribute to W Mass

Model	C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S_1		X							
Σ			X	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			X	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	X					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
B	-2						$-y_\tau$	$-y_t$	$-y_b$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	X					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

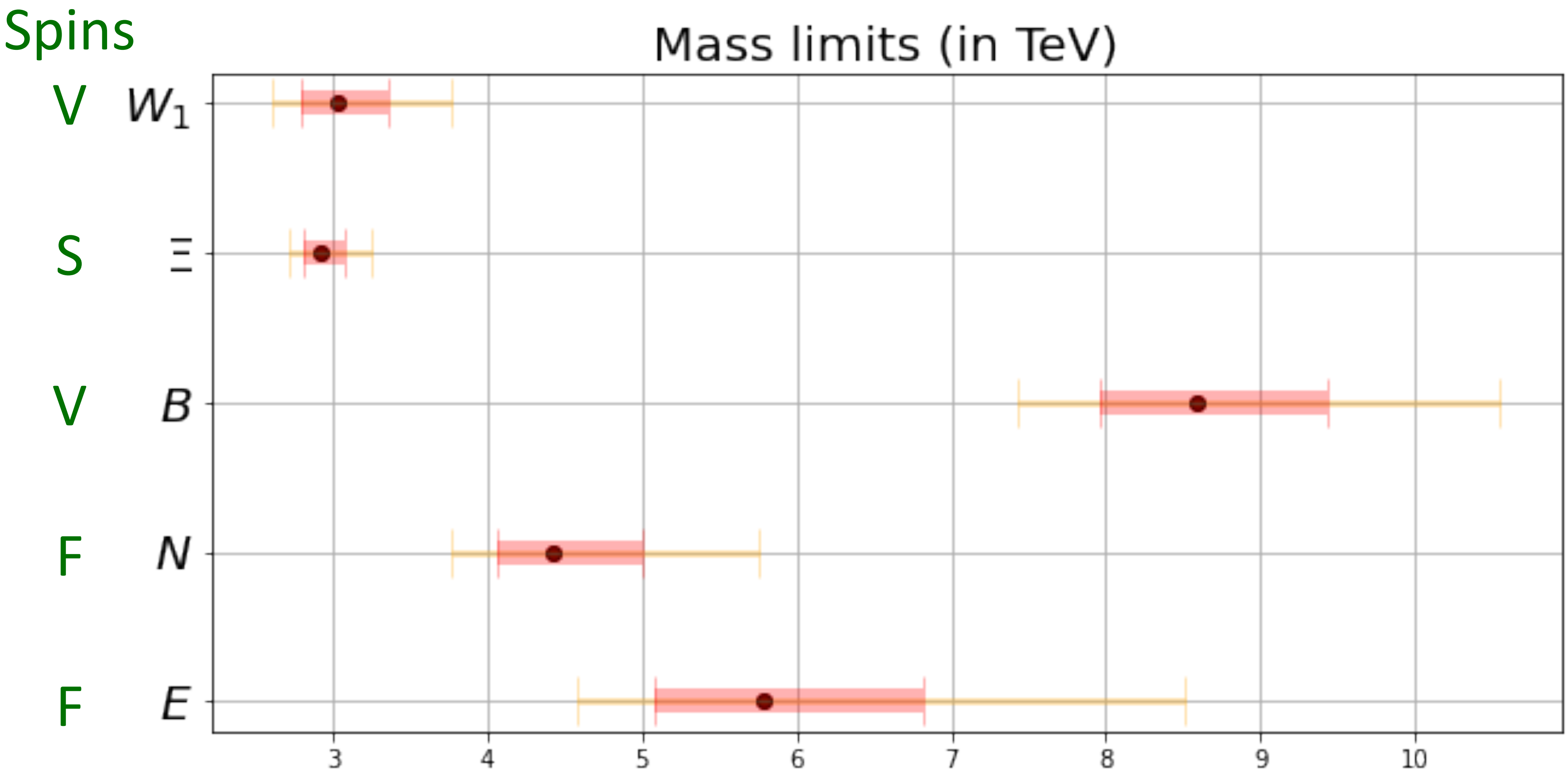
Wrong sign

Right sign

Operators contributing to m_W

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Models Fitting the Mass of the W Boson



68 and 95% CL ranges of masses assuming unit couplings, mass range proportional to coupling

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Quo Vadis m_W?

- The jury is still out concerning the experimental measurement
    - Tension with SM, previous measurements

“Extraordinary claims require extraordinary evidence”

- Nevertheless, much theoretical speculation (> 90 papers!)
- 4 SMEFT operators can increase m_W
- 3 SMEFT operators generated by single field extensions of the SM at tree level
    - Vector bosons W or B, scalar boson Ξ, fermions N, E
- Prospects for the LHC?

$g_\mu - 2$:
from Dirac and Schwinger to Fermilab and Beyond

Hadronic Vacuum Polarization

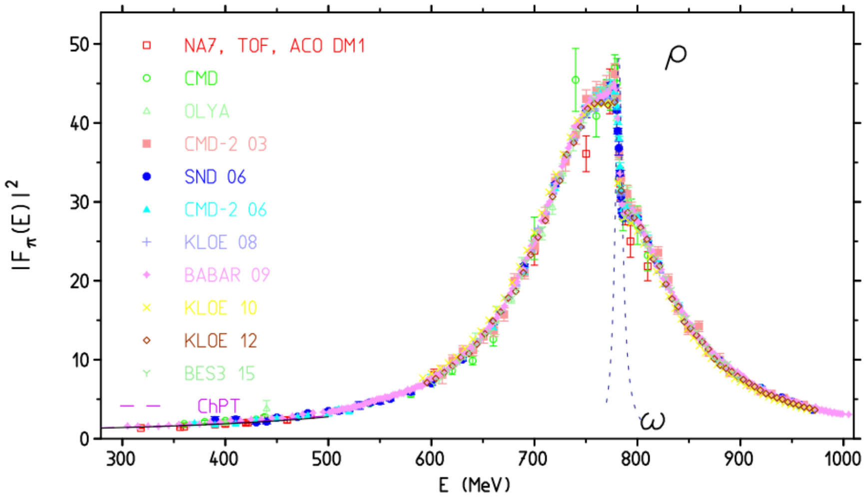
- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by ρ and ω peaks, taking account of interference effects

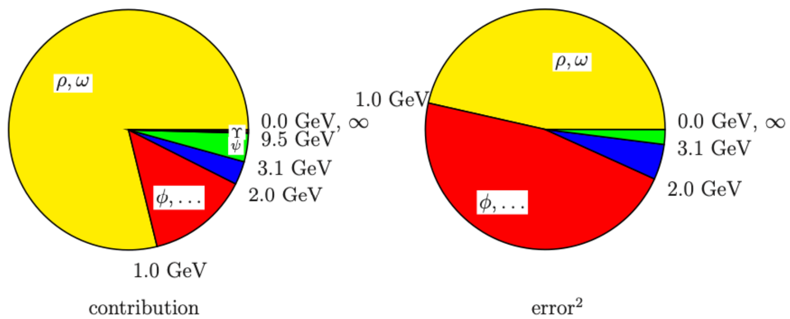
- Uncertainties dominated by ρ and ω region, and by region between 1 and 2 GeV (ϕ, etc.)

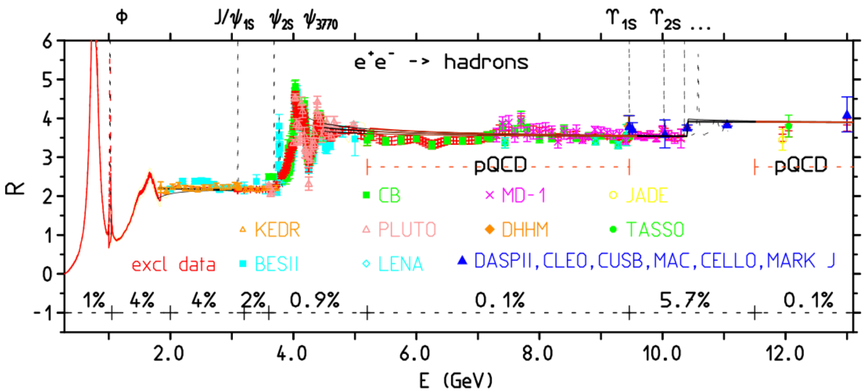
- High energies under good control from perturbative QCD

$$a_\mu^{\text{HVP, LO}} = 693.1(2.8)_{\text{exp}}(2.8)_{\text{sys}}(0.7)_{\text{DV+QCD}} \times 10^{-10}$$
$$= 693.1(4.0) \times 10^{-10}\,.$$

Aoyama et al, arXiv:2006.04822





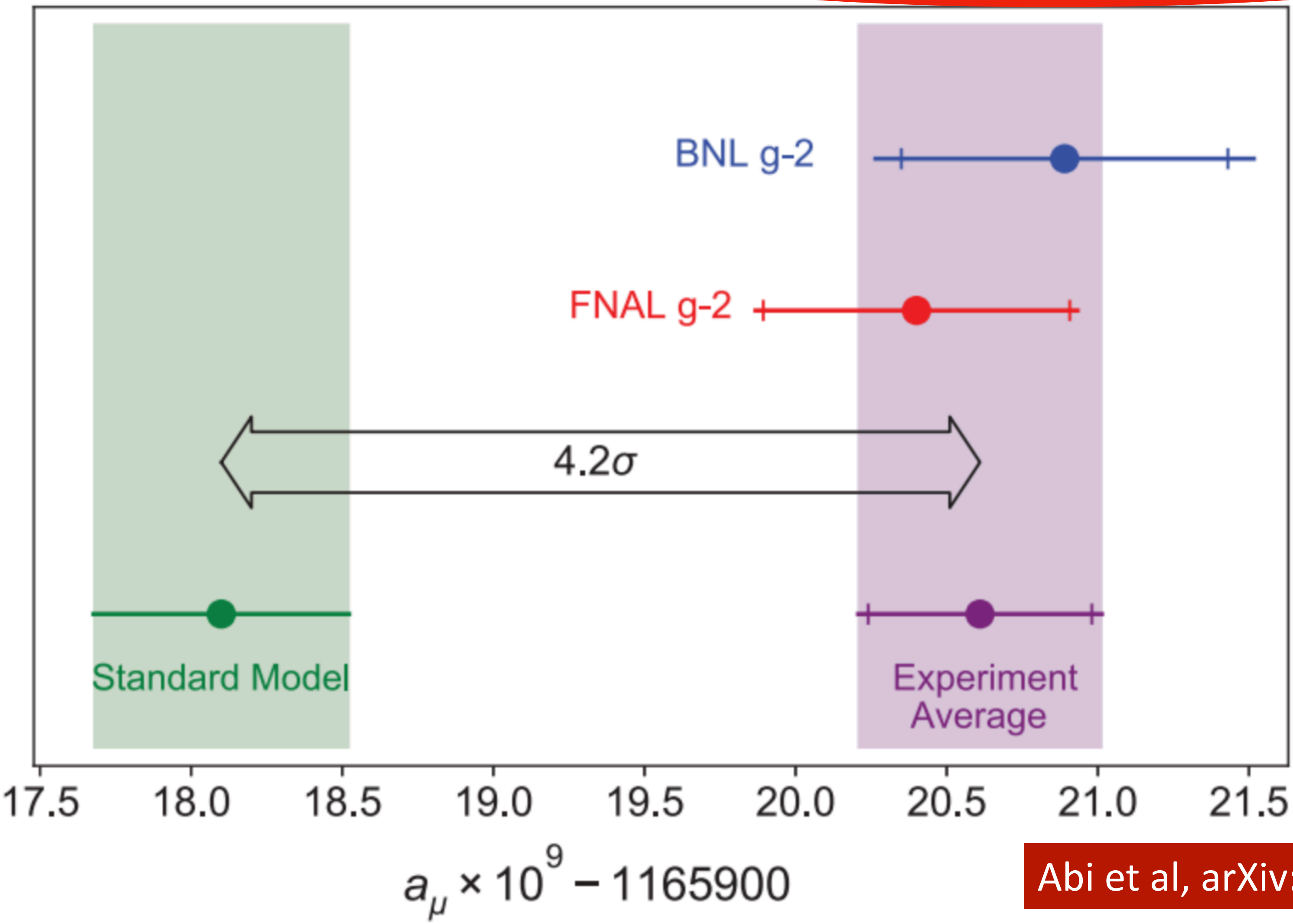


Fermilab Measurement

FNAL result: $a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11}$ $(0.46\,\mathrm{ppm})$

Combined result: $a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11}$ $(0.35\,\mathrm{ppm})$

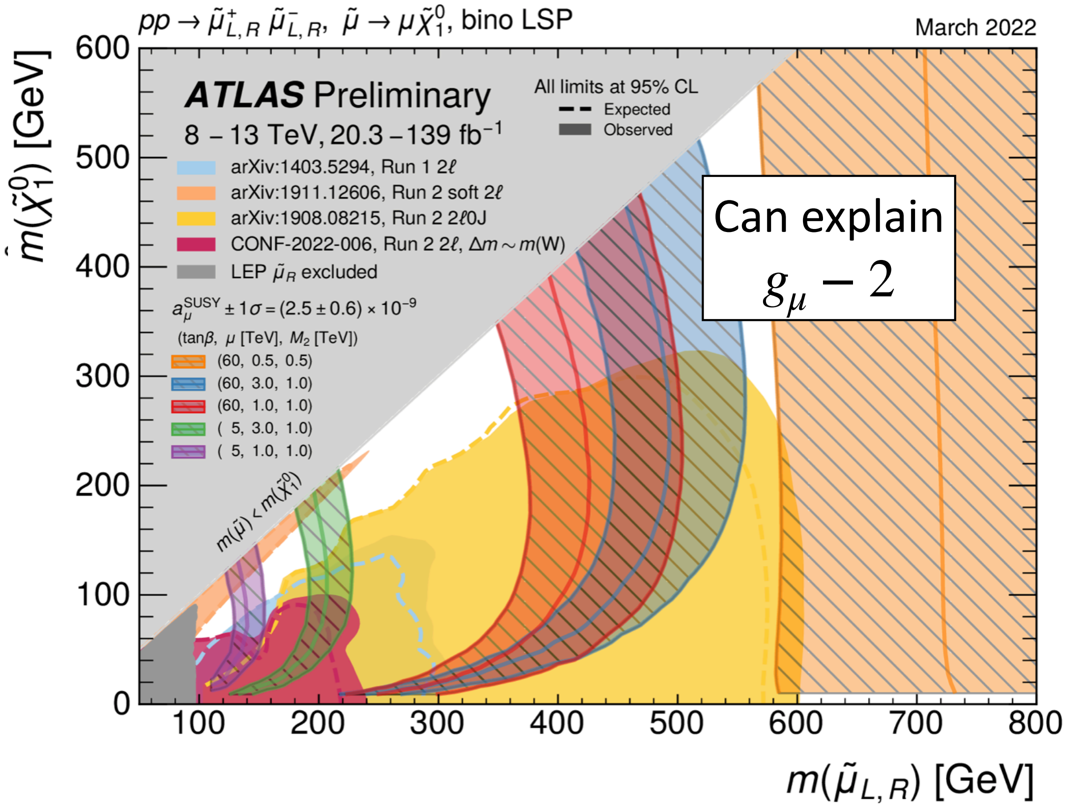
Difference from Standard Model: $a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$

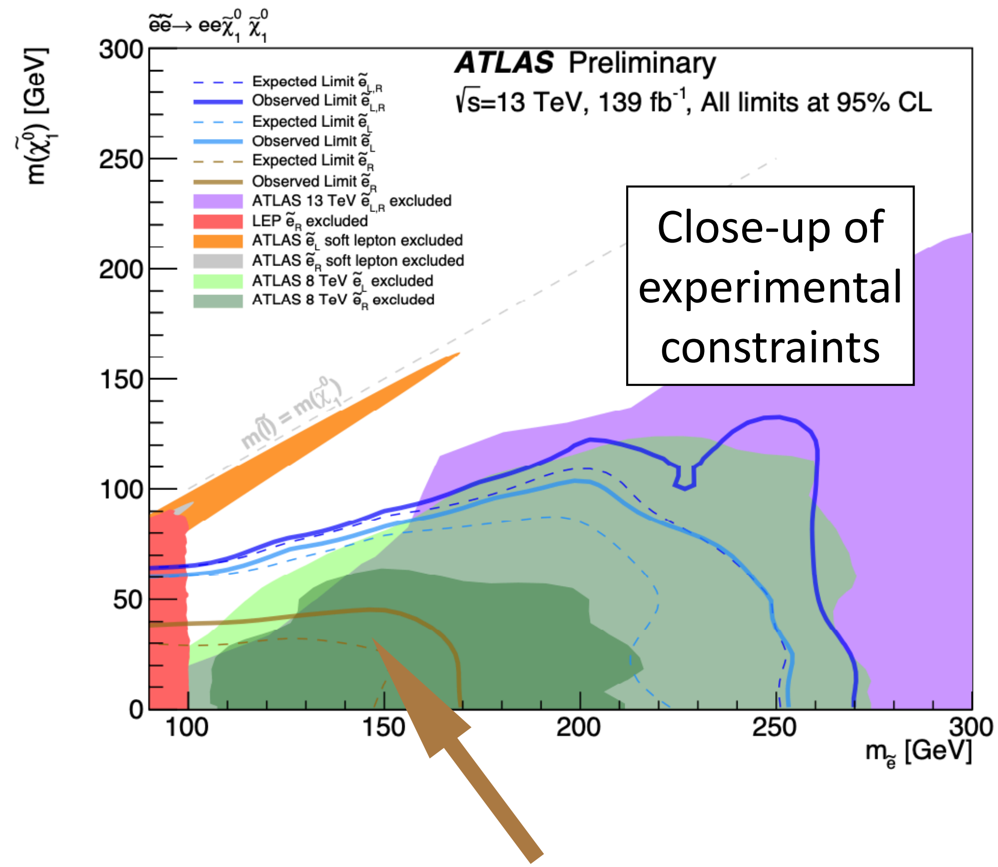


Abi et al, arXiv:2104.03281

LHC vs Supersymmetry

- LHC favours squarks & gluinos > 2 TeV (but loopholes)
- Does not exclude lighter electroweakly-interacting particles, e.g., sleptons

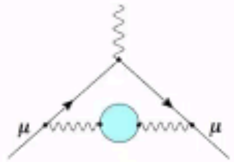




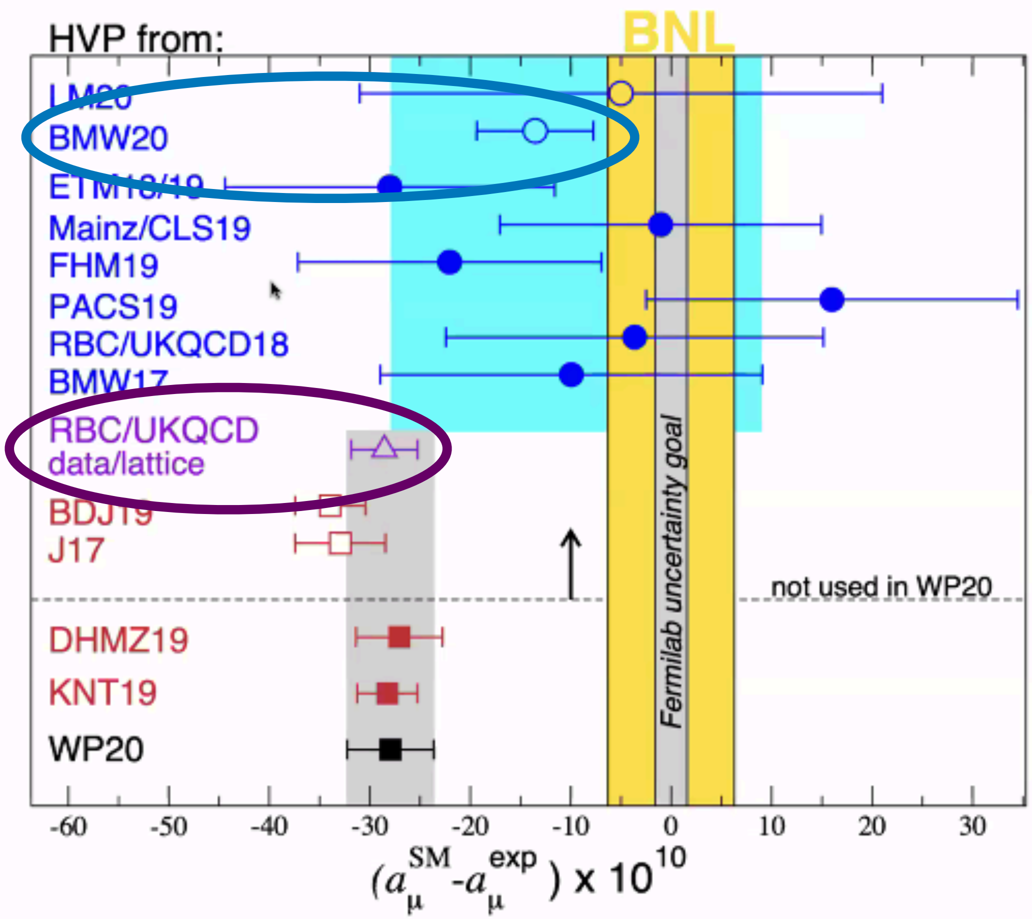
- Most models have $m_{\tilde{\mu}_L} > m_{\tilde{\mu}_R}$ but $m_{\tilde{\mu}_R} \simeq m_{\tilde{e}_R}$: **relevant constraint**

ATLAS Collaboration

Lattice Calculations of Hadronic Vacuum Polarization

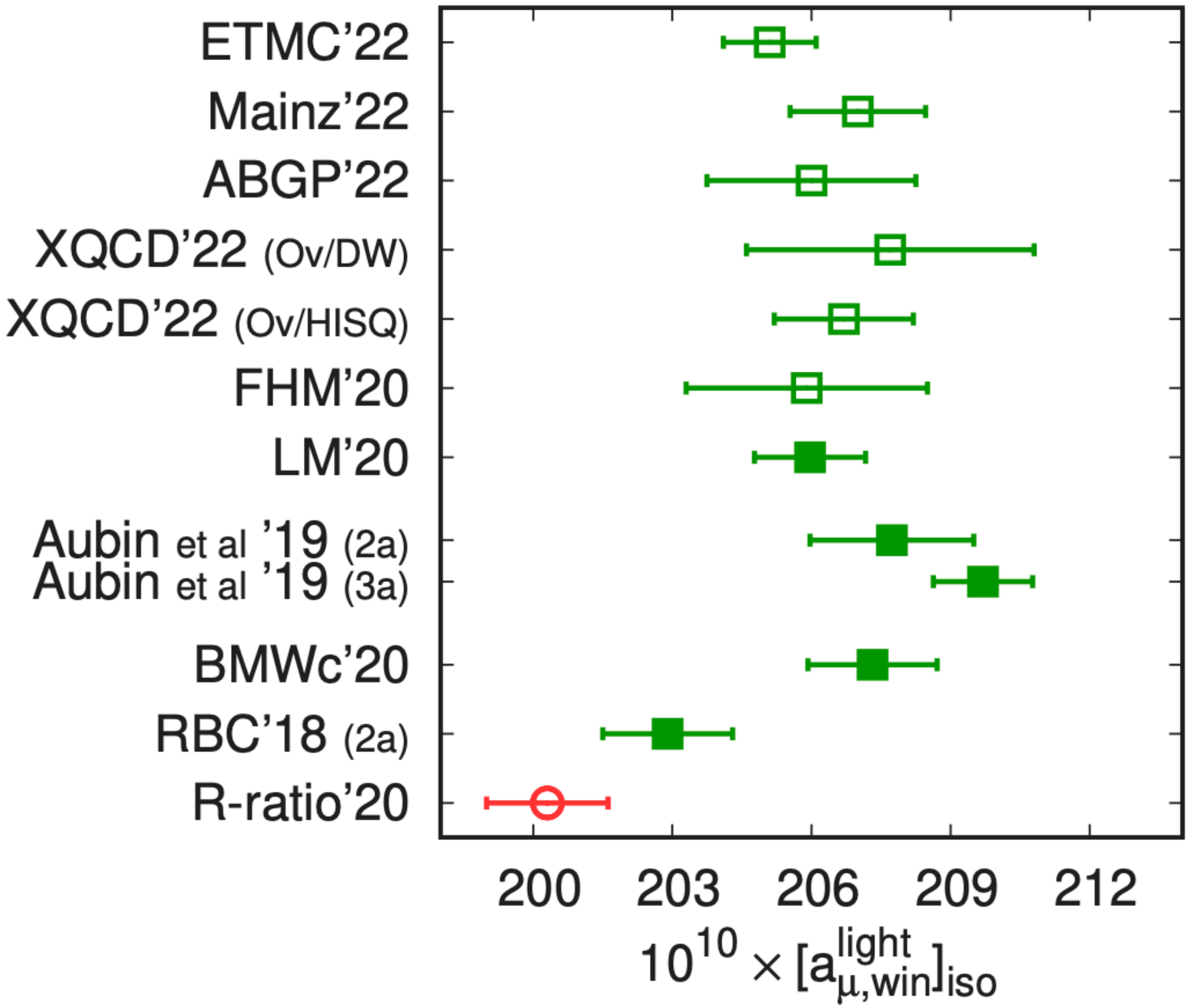


$$a_\mu^{\rm HVP} + \left[a_\mu^{\rm QED} + a_\mu^{\rm Weak} + a_\mu^{\rm HLbL}\right] \rangle \; a_\mu^{\rm SM}$$



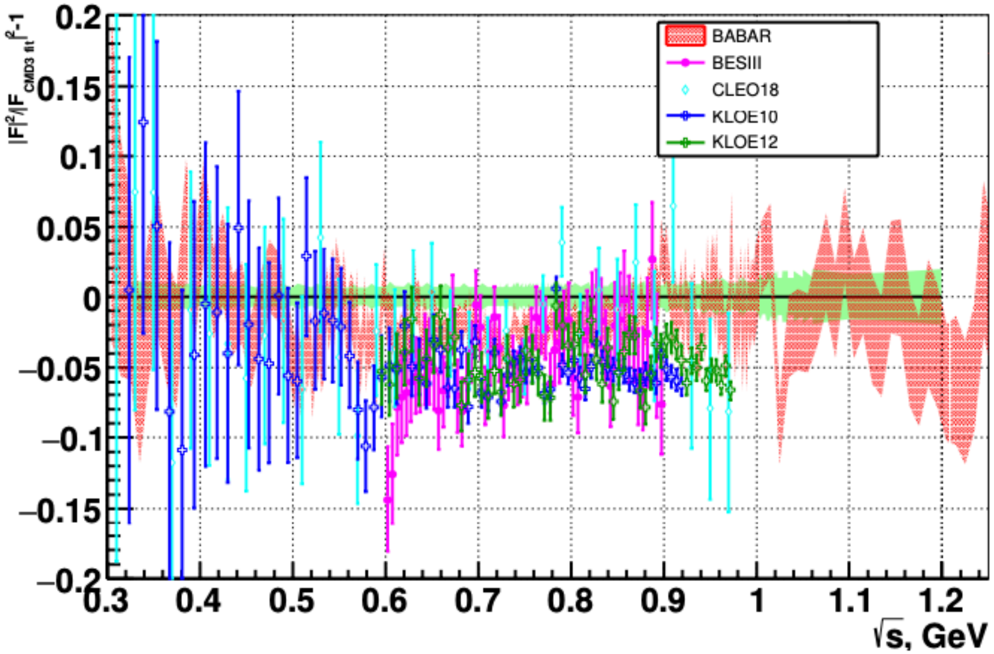
Aoyama et al, arXiv:2006.04822

Recent Lattice Calculations

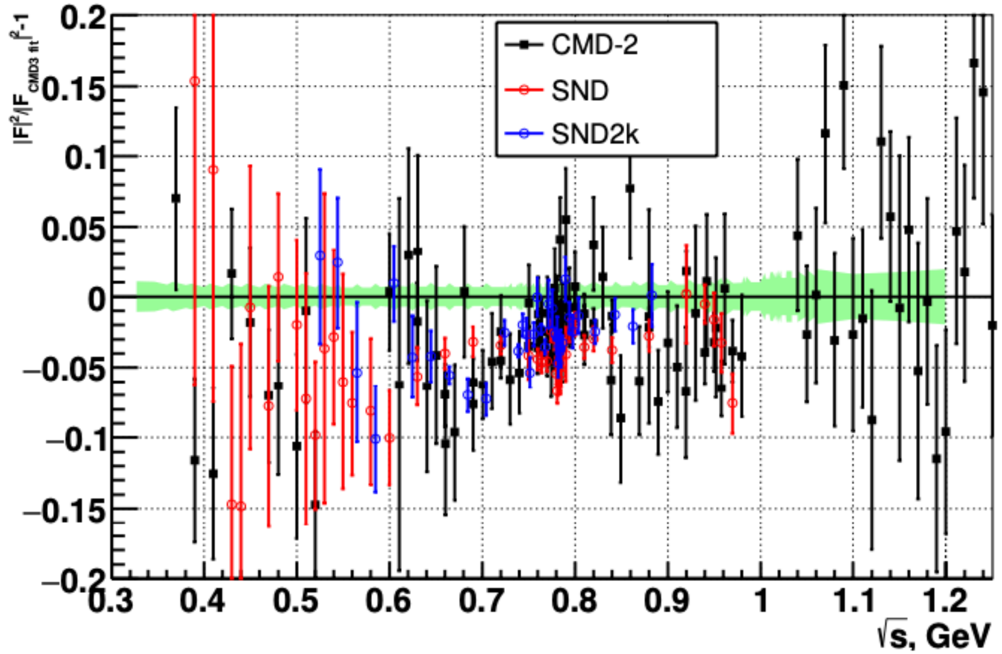


New CMD-3 Measurement of HVP

Comparison with radiative return (ISR) measurements



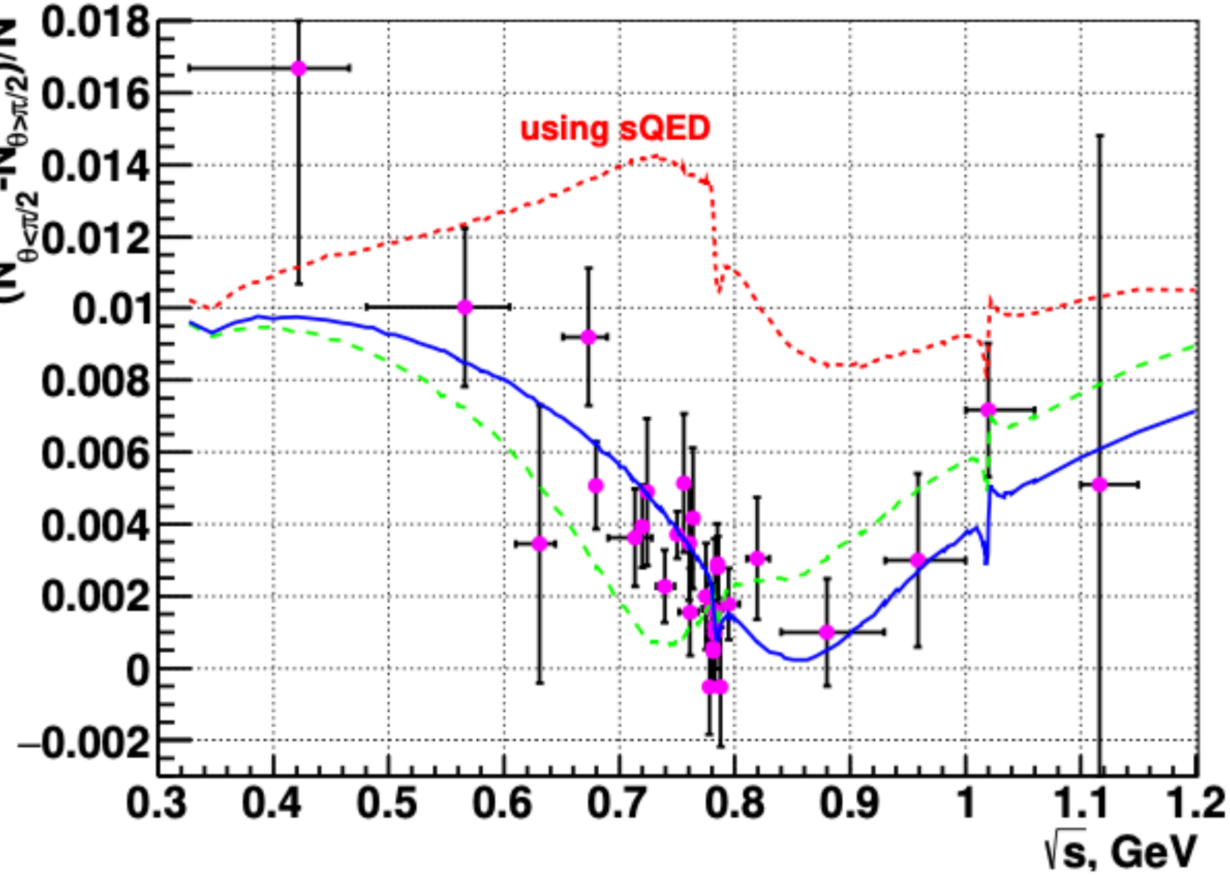
Comparison with previous energy scan measurementss



A task here for Belle II?

CMD-3 Collaboration, arXiv:2302.08834

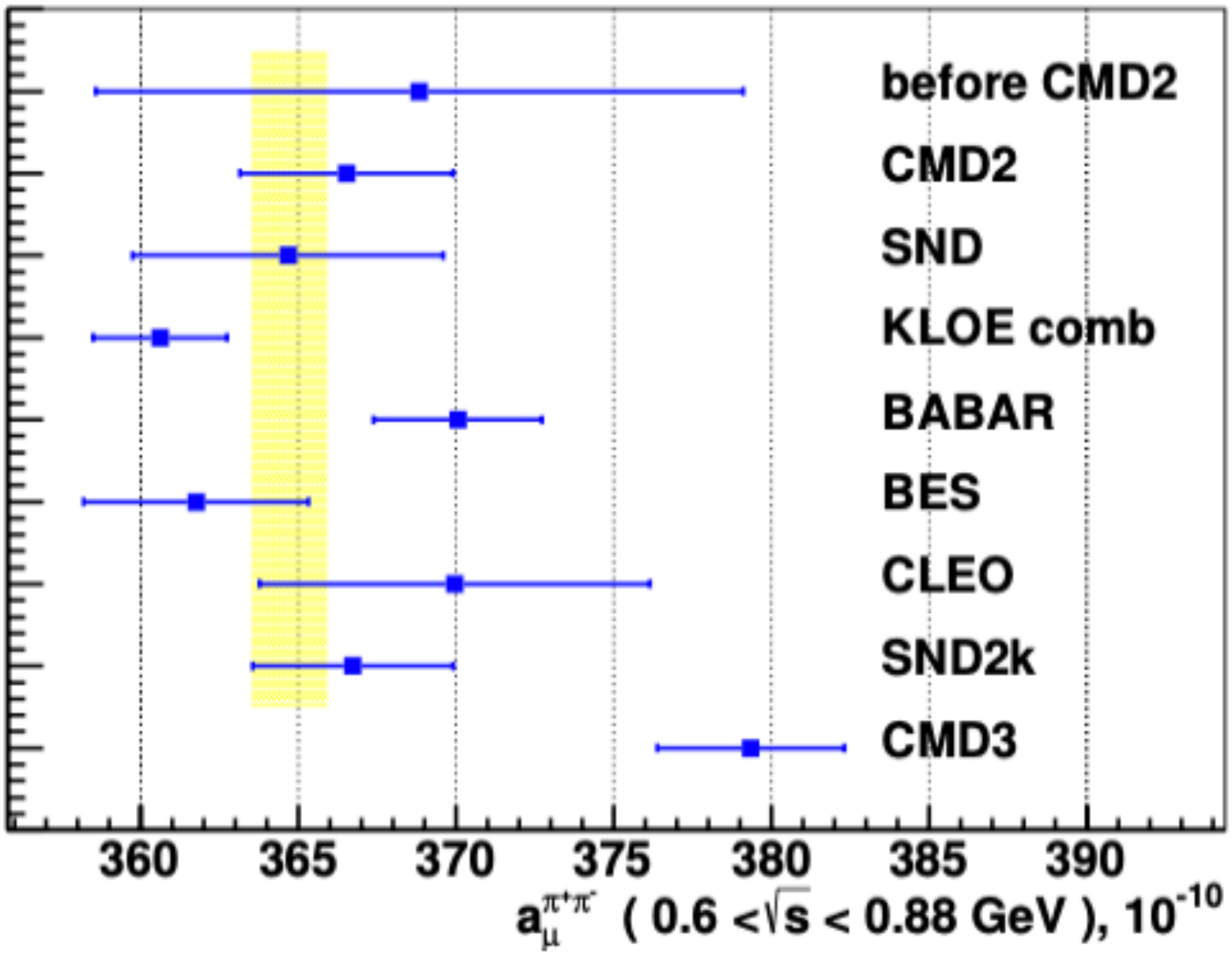
Discrepancy with Calculation of Radiative Corrections



Measured forward-backward asymmetry in $e^+e^- \to \pi^+\pi^-$ disagrees with standard sQED code

CMD-3 Collaboration, arXiv:2302.08834

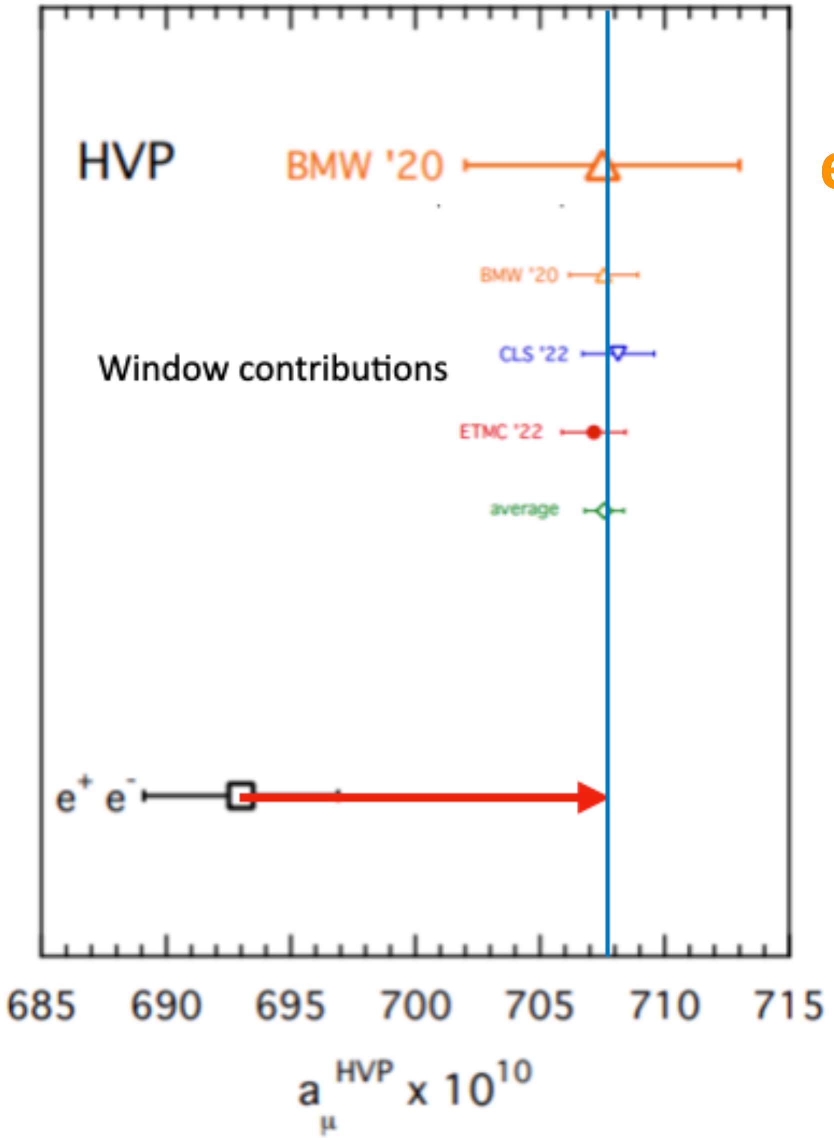
New CMD-3 Measurement of HVP



Discrepancy $\Delta a_\mu \sim 15 \times 10^{-10}$

CMD-3 Collaboration, arXiv:2302.08834

Update on Hadronic Vacuum Polarization



BMW including "window" + extrapolations to small/large distances

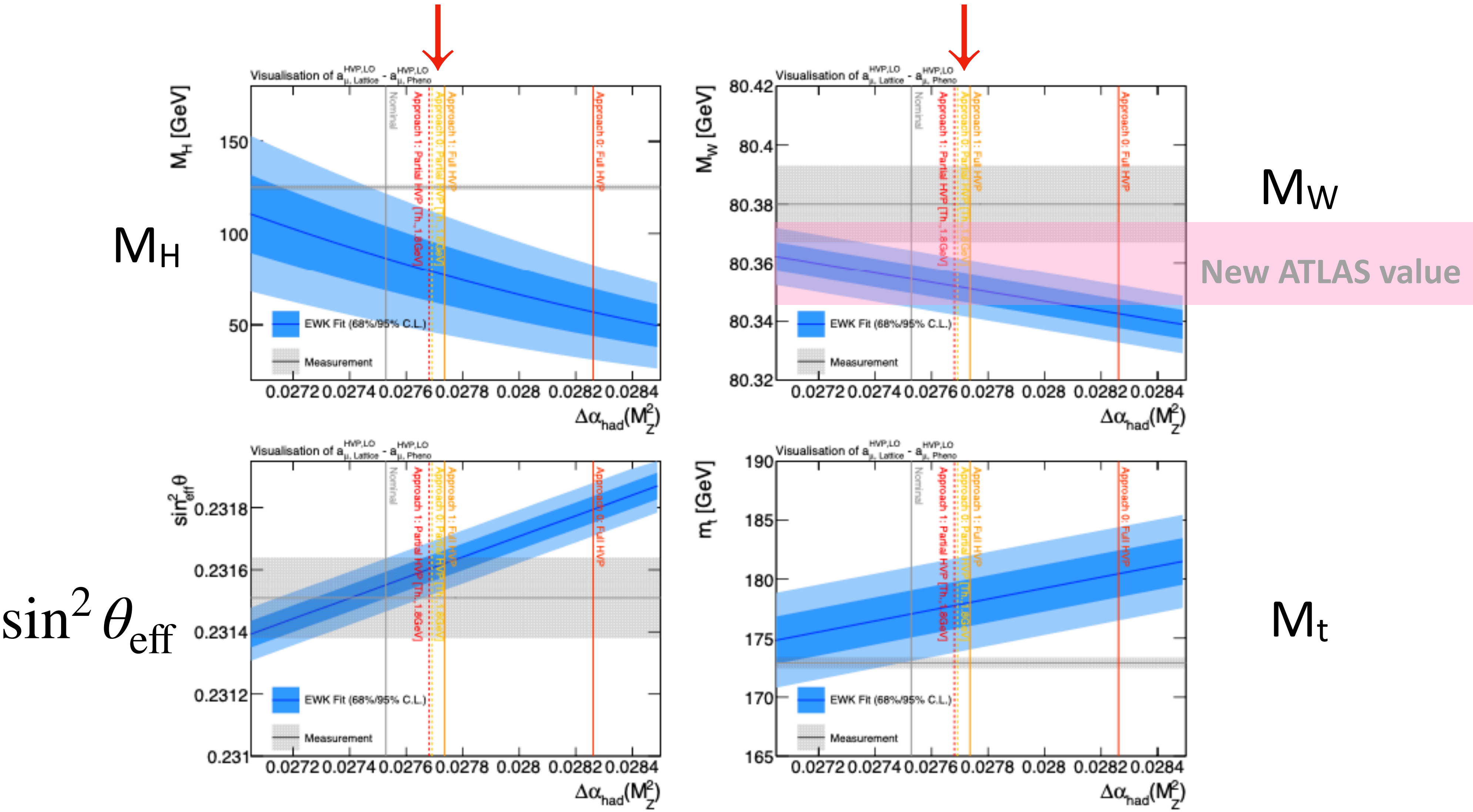
New lattice values of "window" contribution
from intermediate scales

Previous HVP world average

Difference between CMD-3 and previous data

Effects on Electroweak Observables

Dashed lines = rescaling of low-energy HVP data to match BMW et al



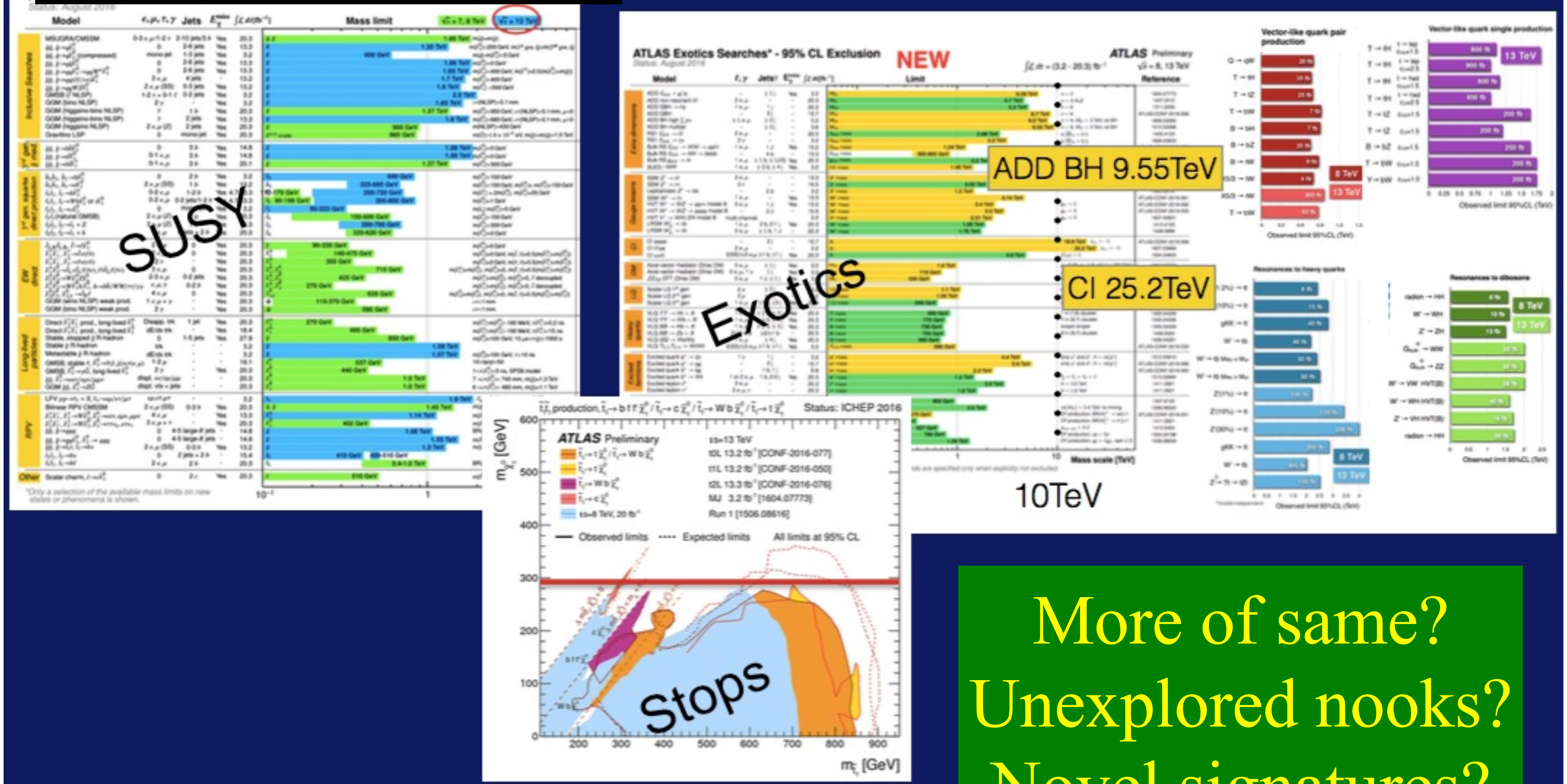
Small changes in Standard Model predictions

Malaescu & Schott, arXiv:2008.08107

Nothing (yet) at the LHC

No supersymmetry

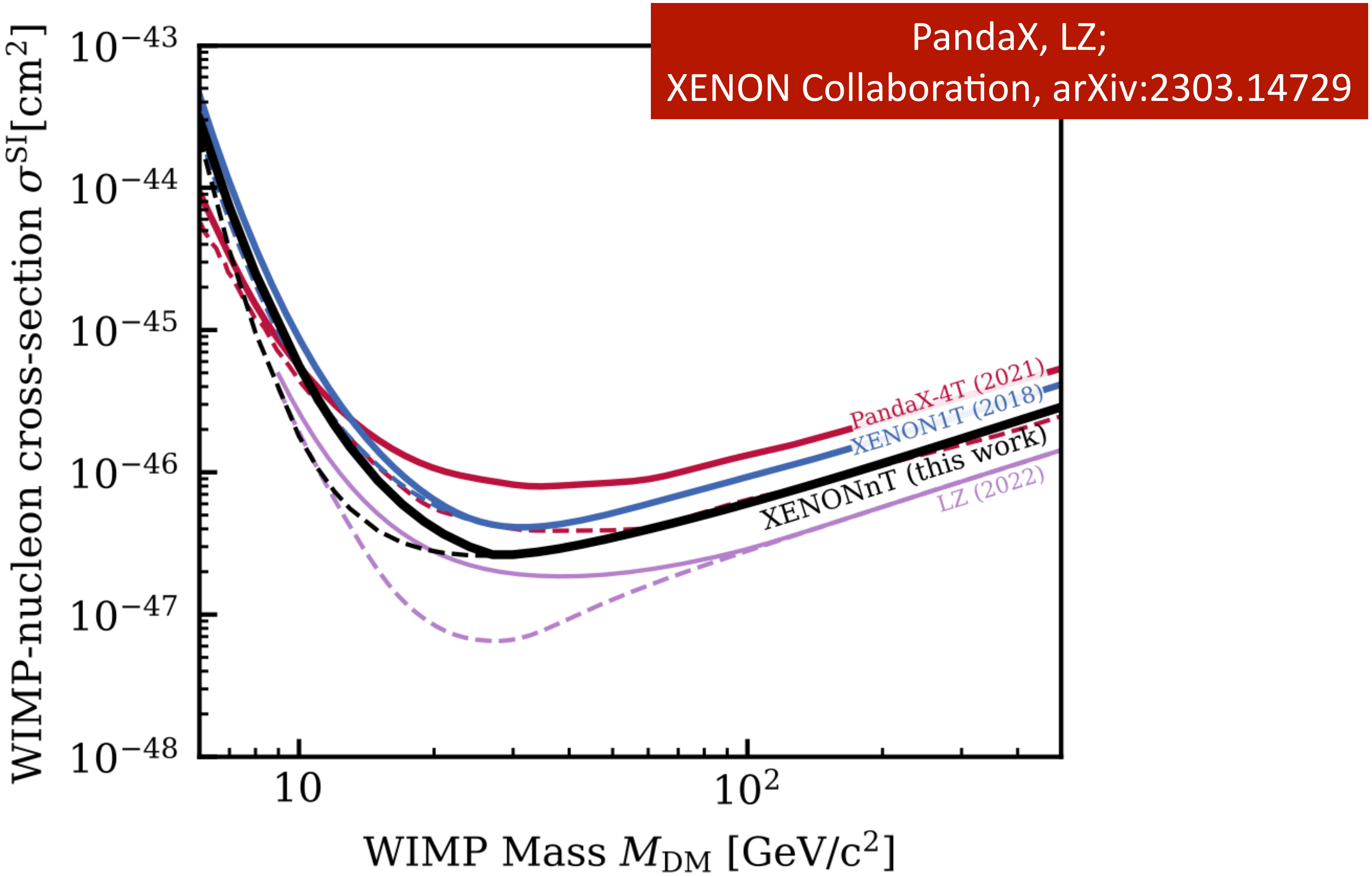
Nothing else, either



More of same?
Unexplored nooks?
Novel signatures?

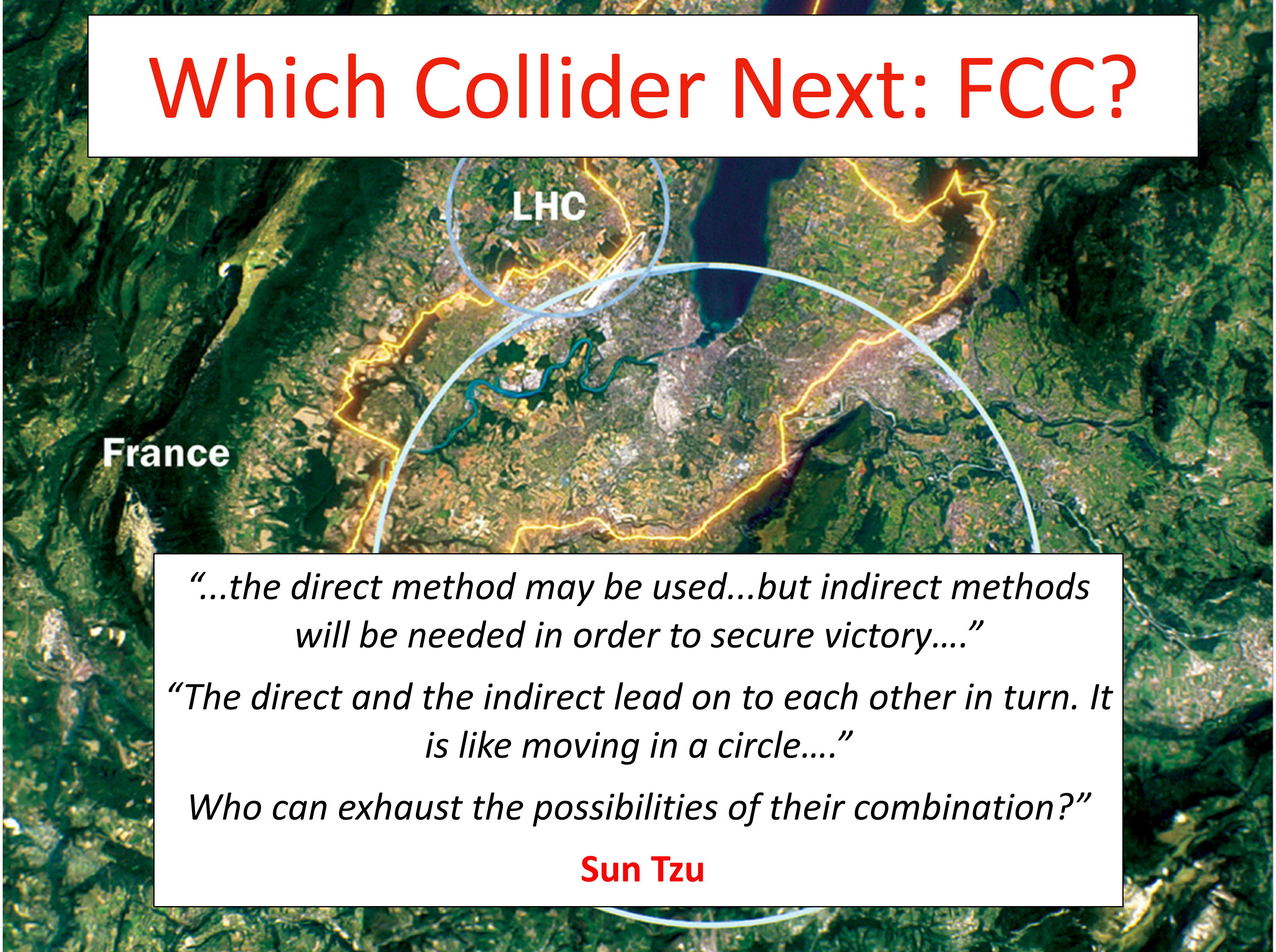
Direct Dark Matter Searches

- Latest experimental results



Next step: international xenon collaboration
to reach into the neutrino "fog"?

Which Collider Next: FCC?



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

"The direct and the indirect lead on to each other in turn. It is like moving in a circle…."

Who can exhaust the possibilities of their combination?"

Sun Tzu

Examples of FCC Physics

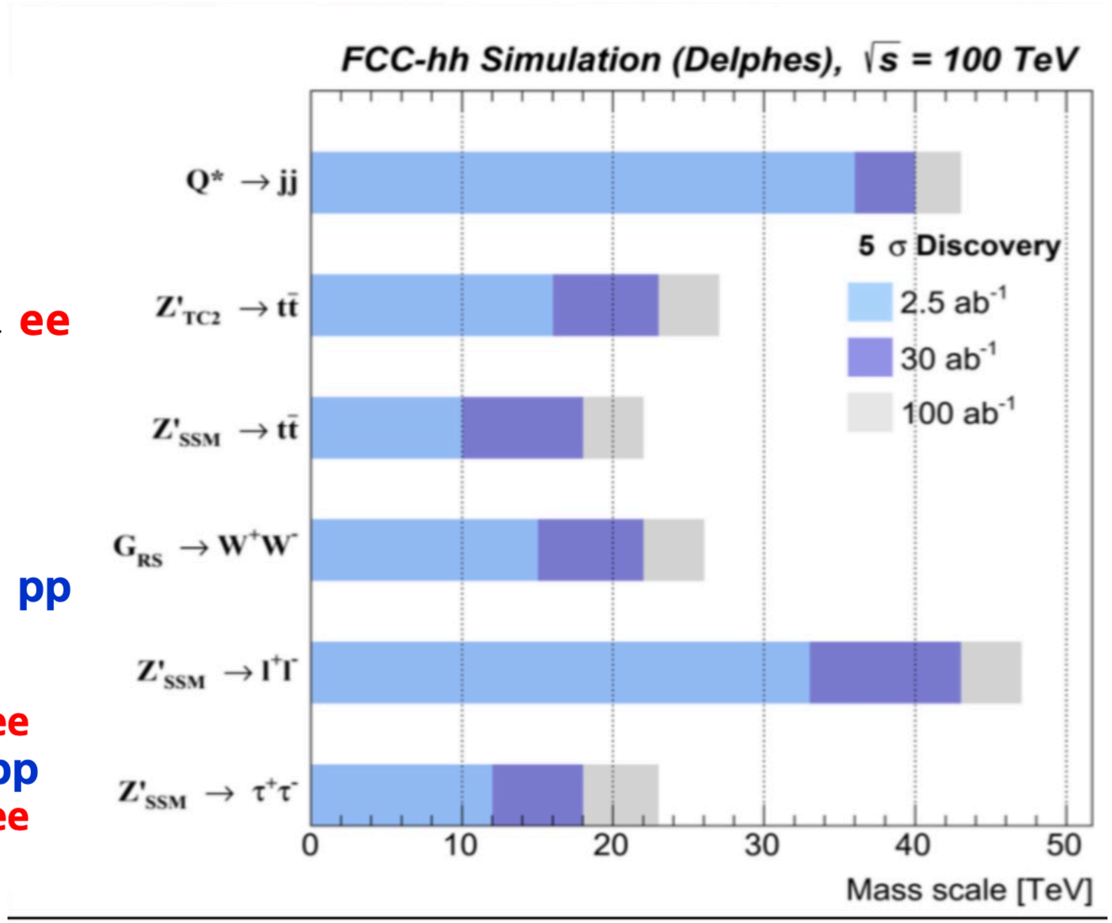
The indirect …

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95
g_{HHH} (%)	50.	44./33. 27./24.	3-5
Γ_H (%)	SM	1.1	0.91
BR_{inv} (%)	1.9	0.19	0.024
BR_{EXO} (%)	SM (0.0)	1.1	1

ee (rows g_{HZZ} – $g_{H\tau\tau}$)
pp (rows $g_{H\mu\mu}$ – g_{HHH})
ee (Γ_H)
pp (BR_{inv})
ee (BR_{EXO})

* g_{HWW} includes also ep

and the direct

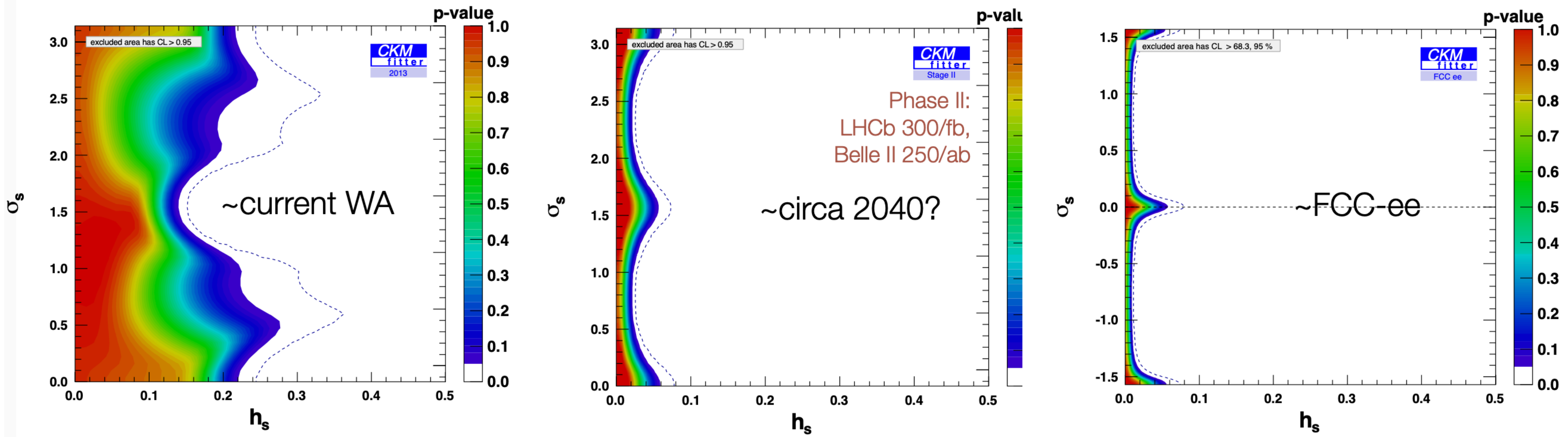


… and gluinos up to 20 TeV and stops up to 10 TeV ….

A project for the 21st century

FCC Flavour Physics

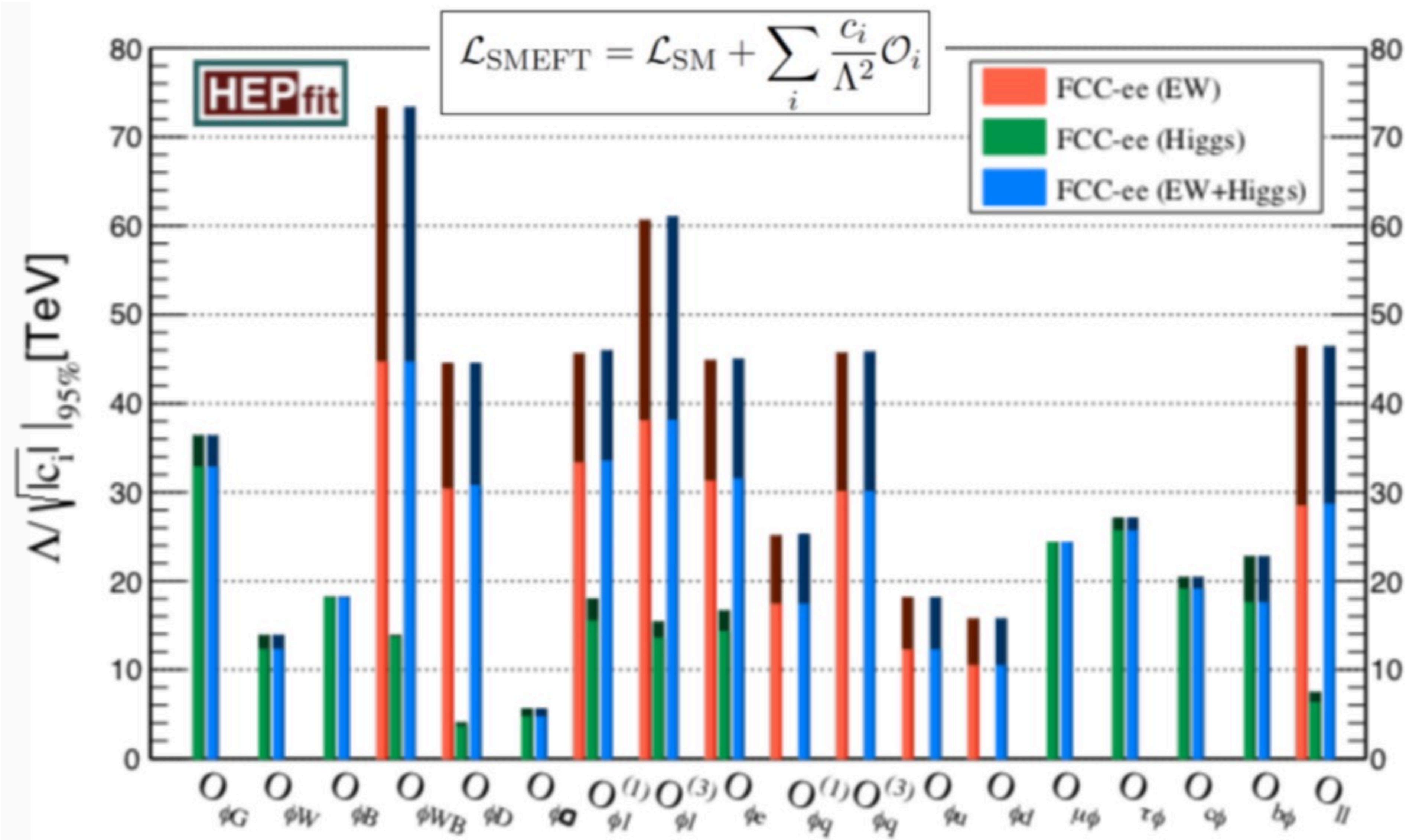
$$\langle B_q|\mathcal{H}^{\mathrm{SM+NP}}_{\Delta B=2}|\bar{B}_q\rangle = \langle B_q|\mathcal{H}^{\mathrm{SM}}_{\Delta B=2}|\bar{B}_q\rangle\left(1+h_q e^{i\sigma_q}\right)$$



FCC-ee: sensitivity of scale of new physics (with MVF structure) > 20 TeV

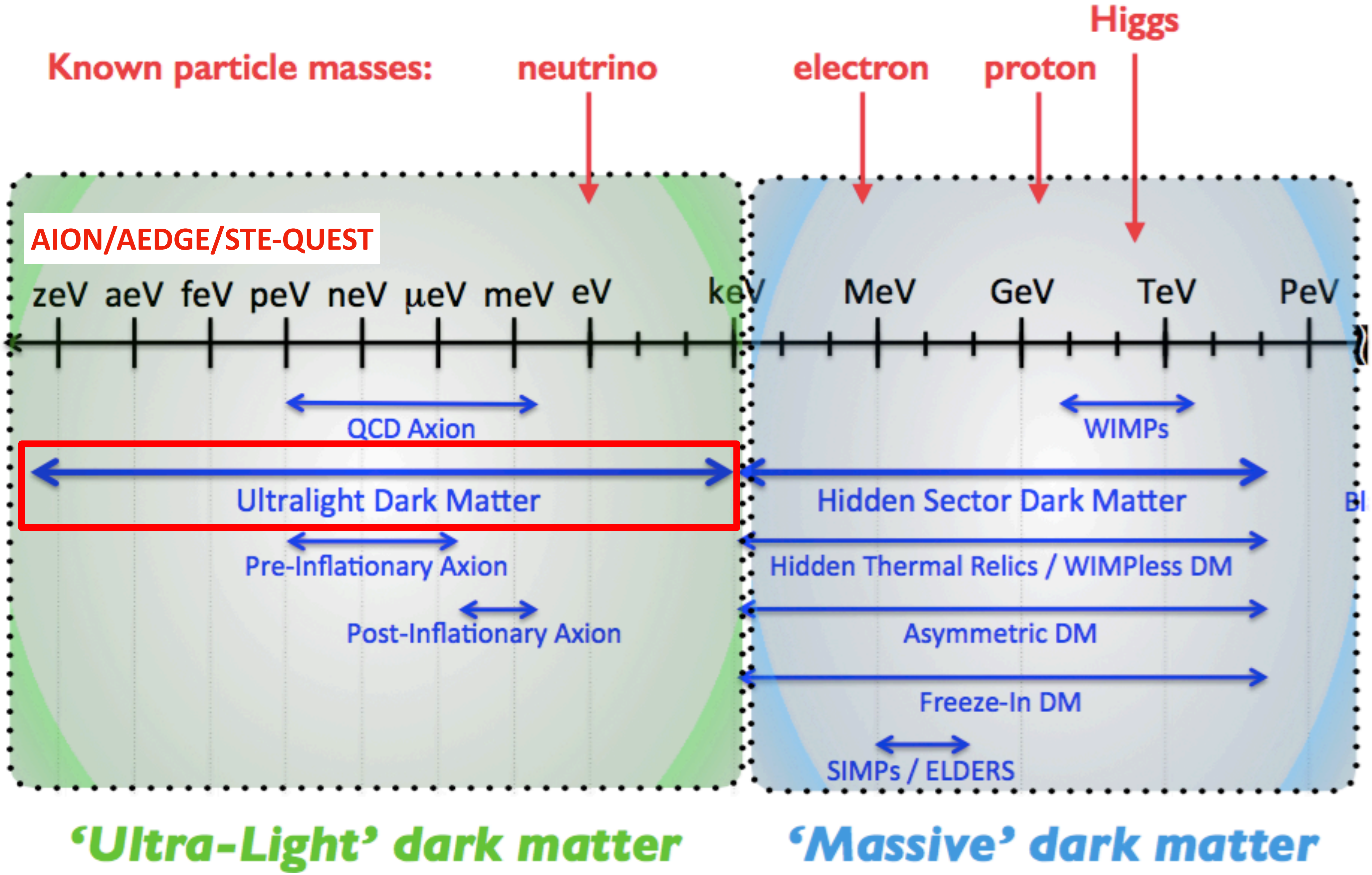
A project for the 21st century

Indirect FCC Physics



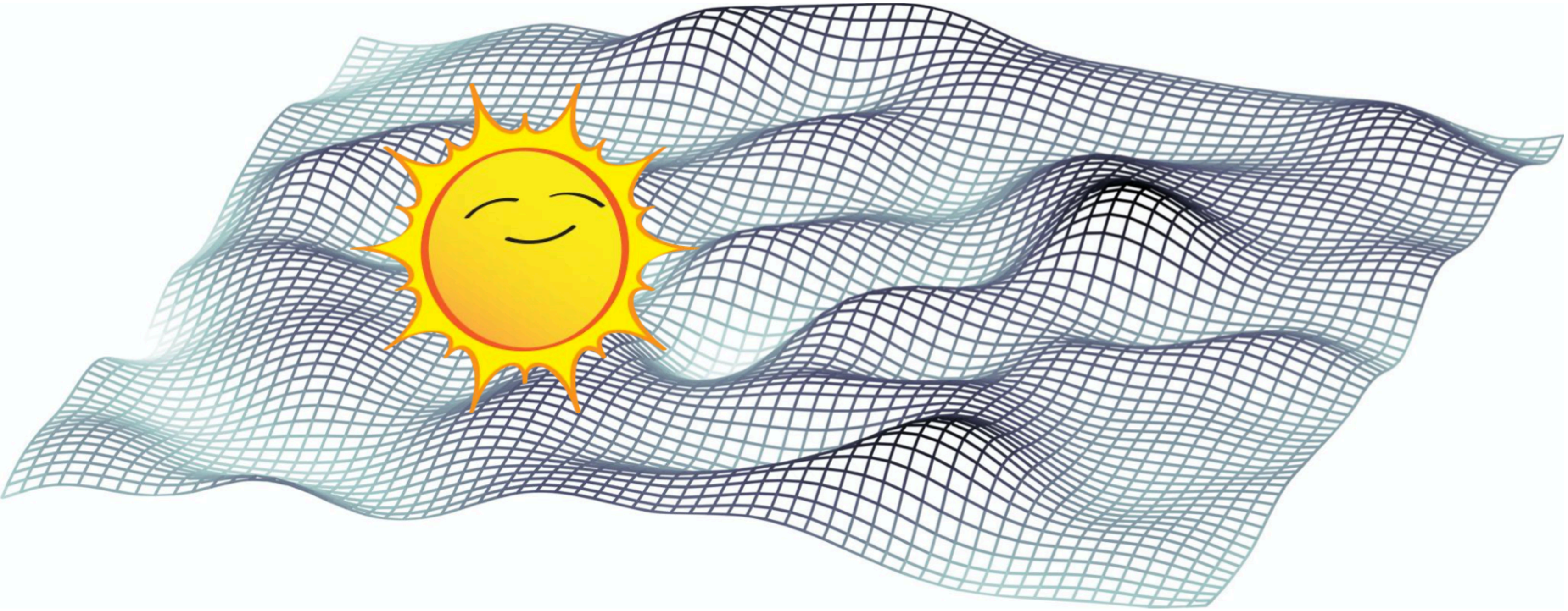
A project for the 21st century

Search for Ultralight Dark Matter



Ultralight Dark Matter

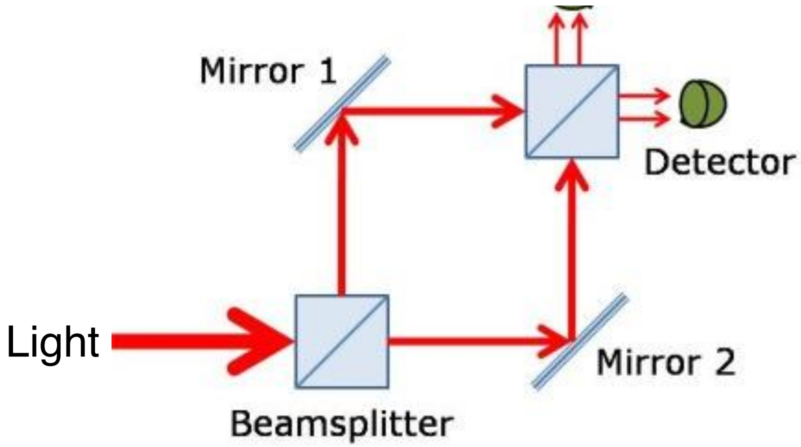
A scalar ULDM $\phi(\mathbf{x}, t)$ field would be present throughout the Solar System

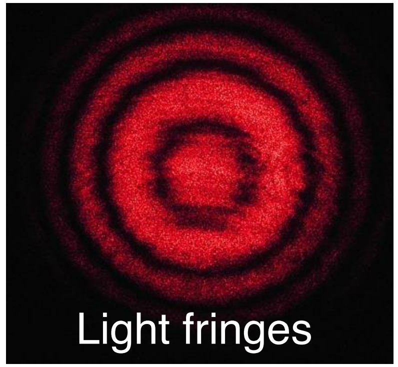


The wavelength depends on the ULDM mass: $\lambda \sim 10^8\,\mathrm{km}\left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)$

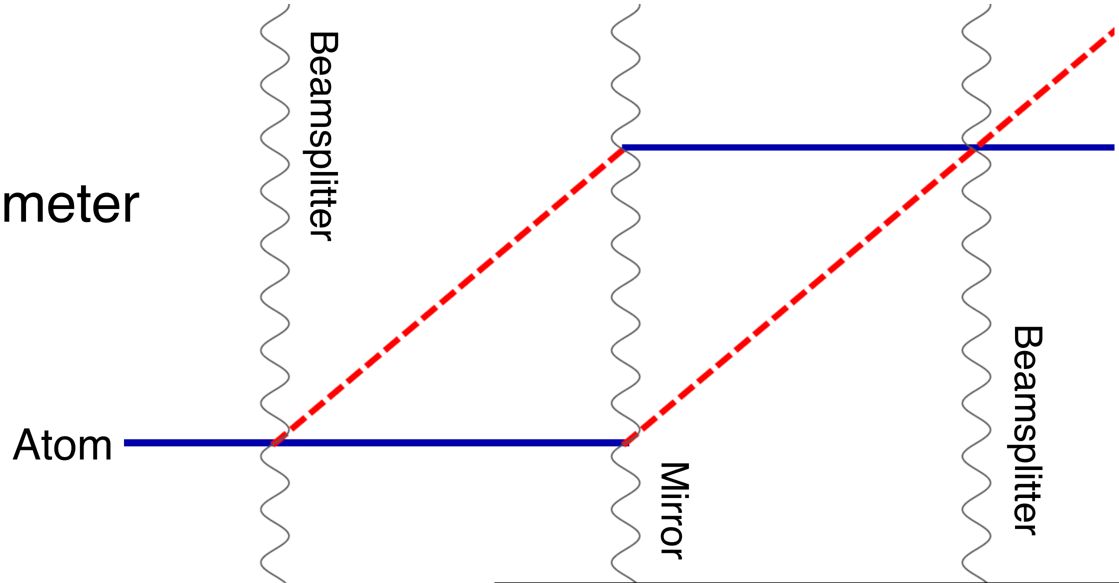
Principle of Atom Interferometry

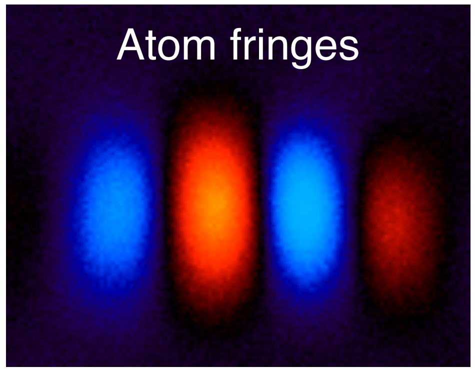
Light interferometer





Atom interferometer





Laser pulses act as beamsplitters and mirrors

AION Collaboration

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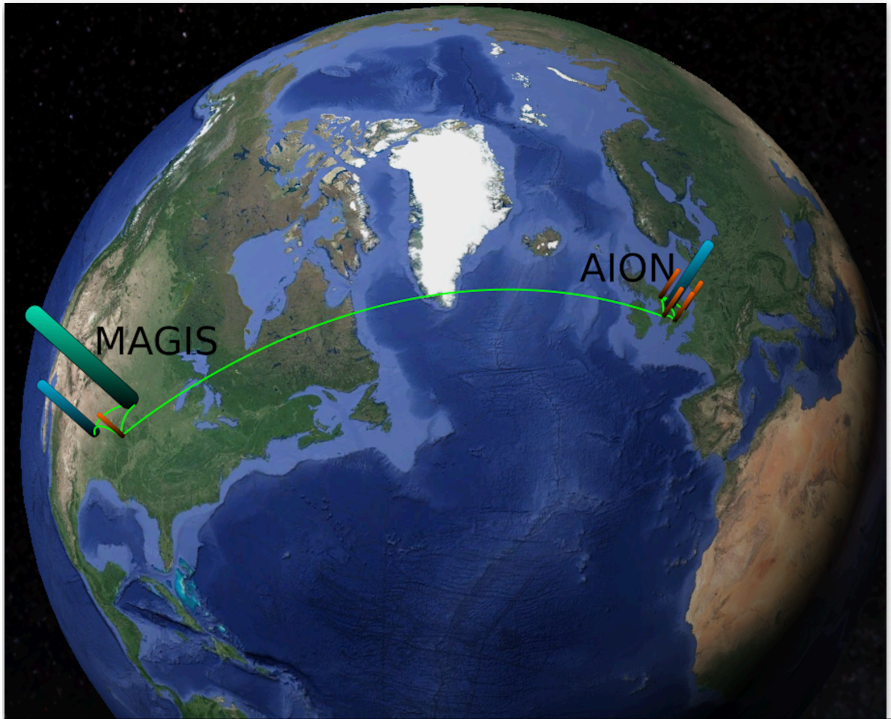
[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge

AION



Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

AION – Staged Programme

AION

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & site investigation for 100m baseline

Initial funding from UK STFC

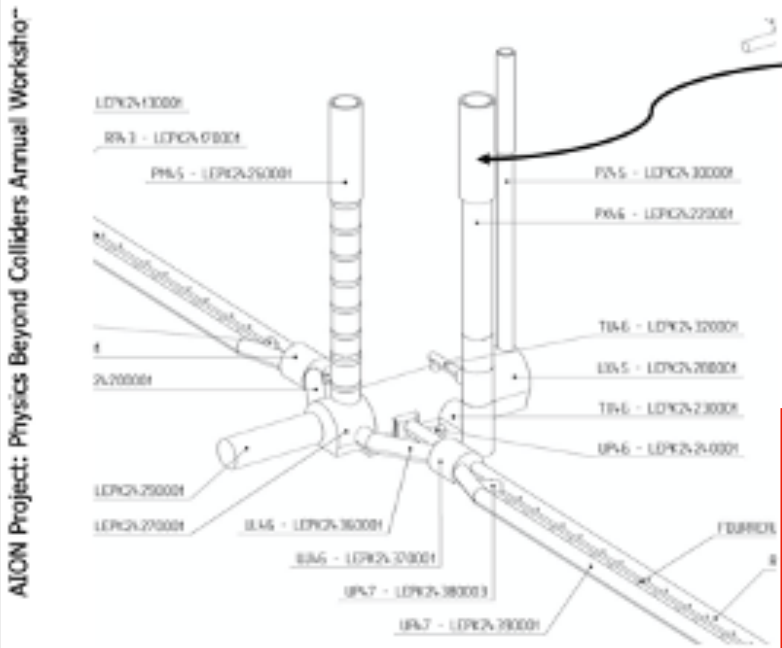
- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning
- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

Workshop @ CERN, March 13/14, 2023

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

AION

Possible CERN Location of AION-100m



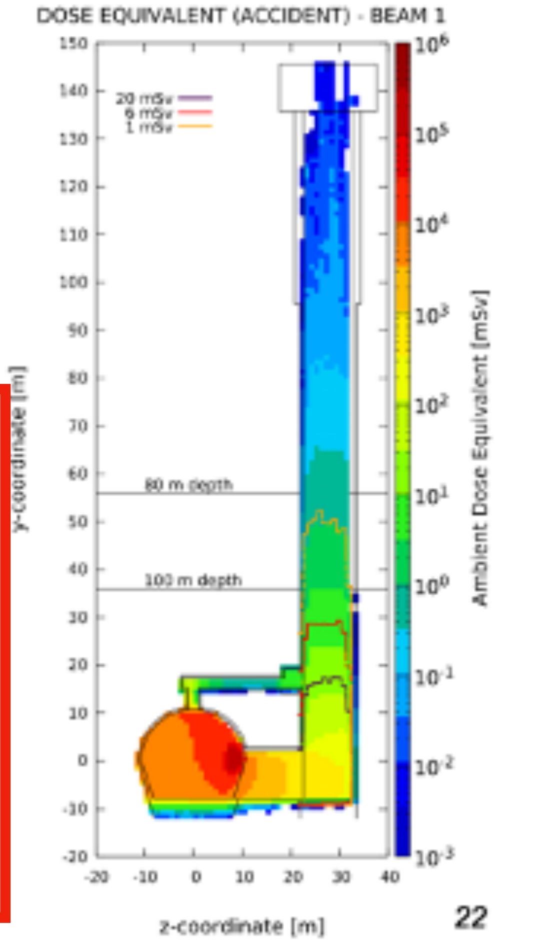
PX46 – P4 Support shaft

Lengths 143m

D = 10.10m

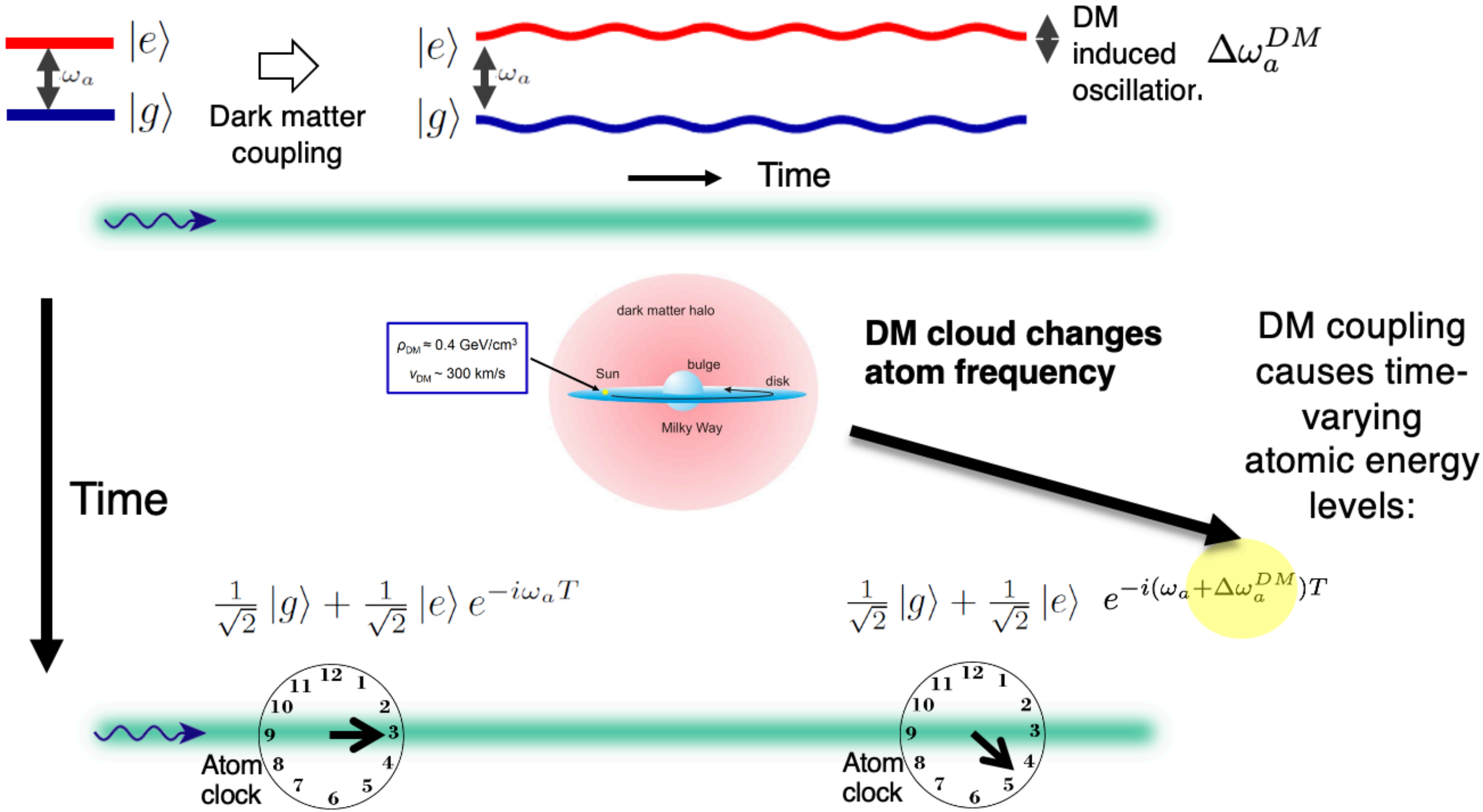
➢ **Ideal basic parameters for AION100**

Supported by CERN PBC Team
(Gianluigi Arduini, Sergio Calatroni …)
on feasibility study:
Seismology
Temperature
Ventilation
Radiation protection
Electromagnetic interference
Access & safety



Also studying possible site at STFC Boulby Laboratory in UK

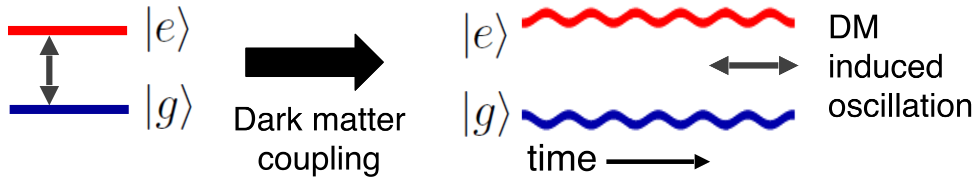
Effect of Dark Matter on Atom Interferometer

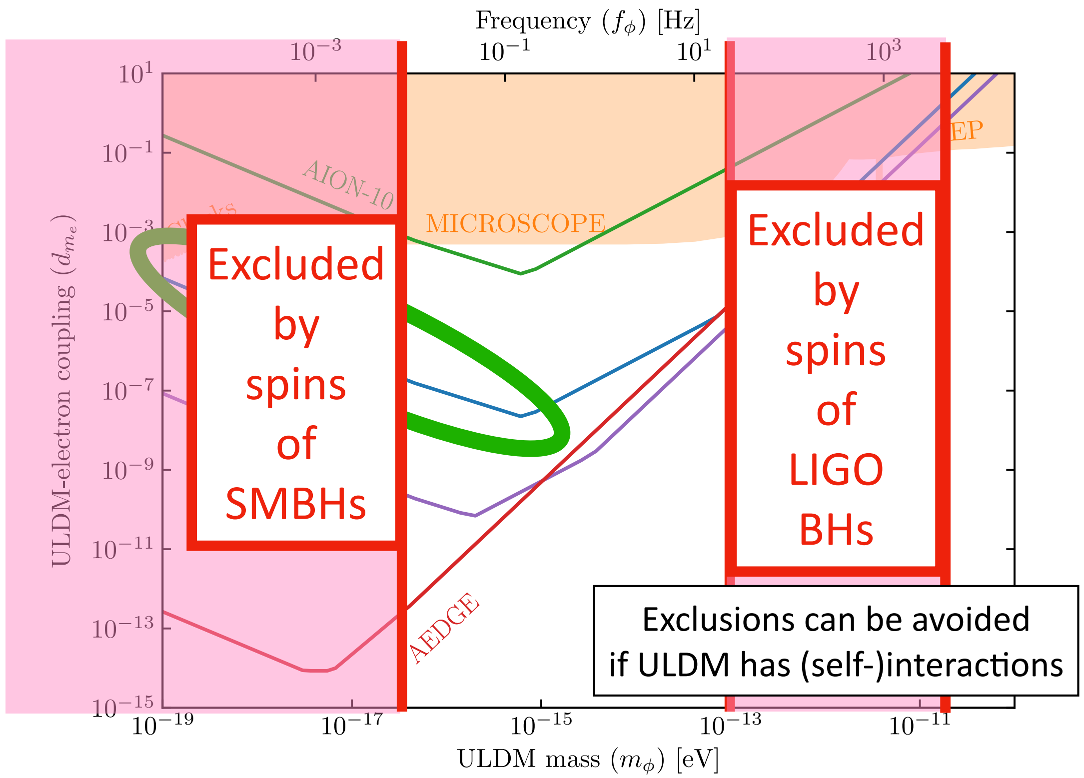


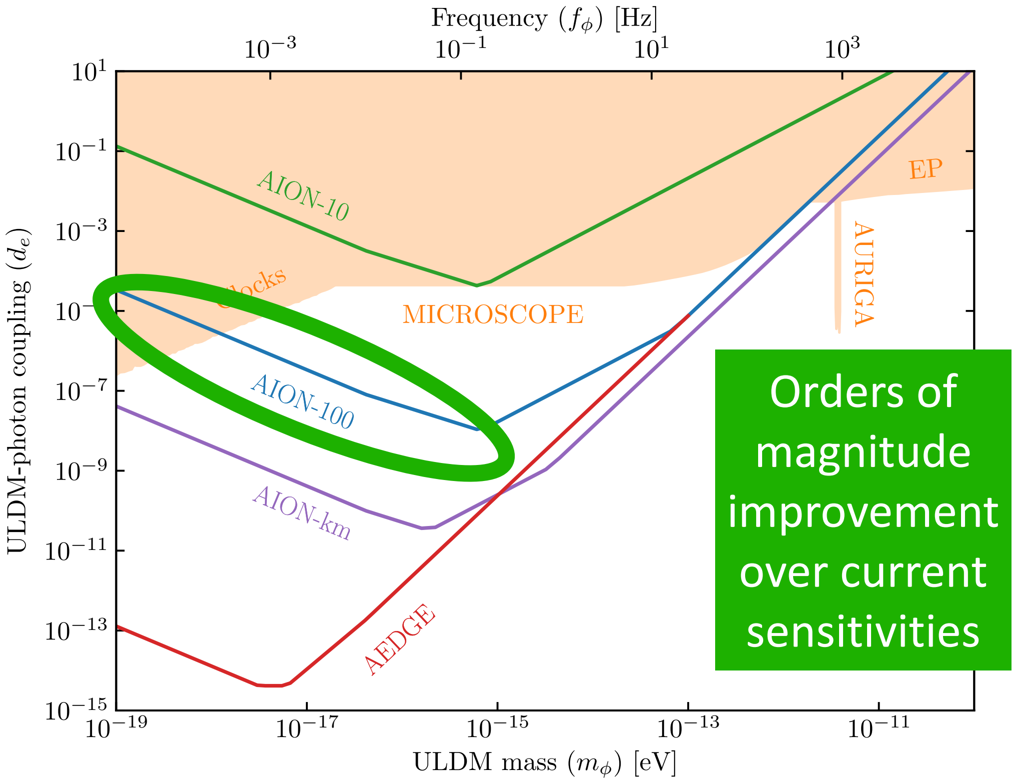
Searches for Light Dark Matter

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\text{int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

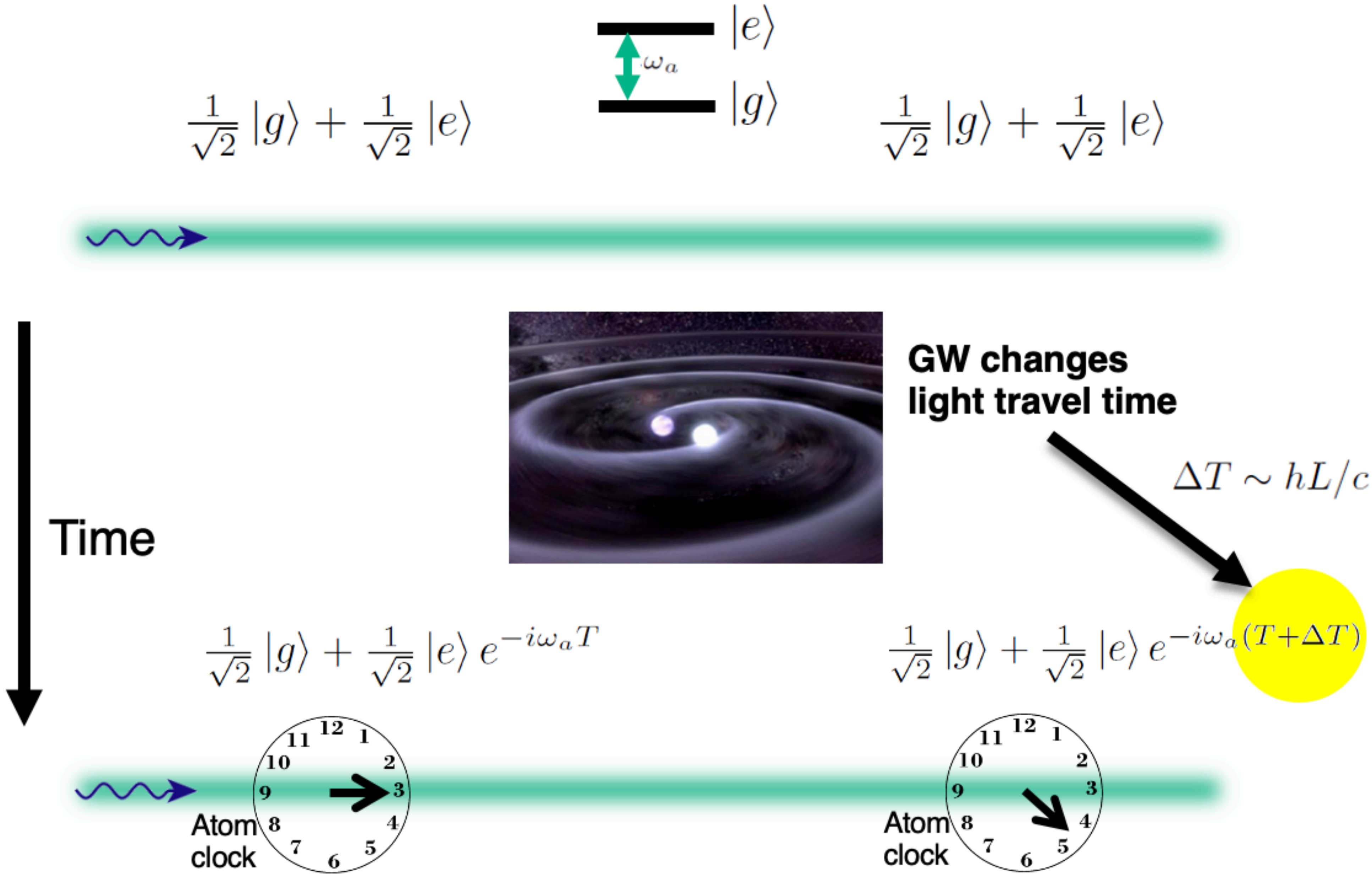




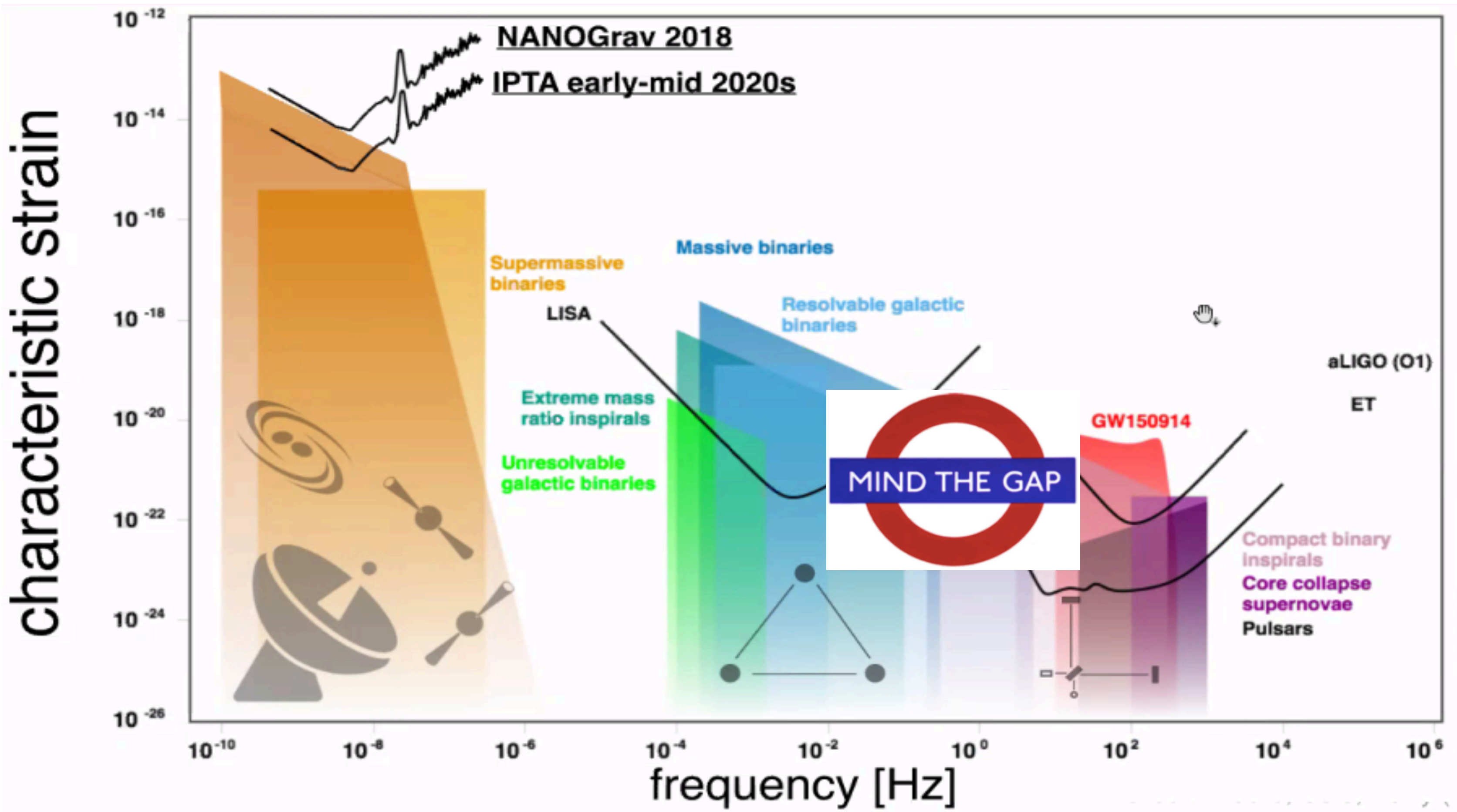


AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Effect of Gravitational Wave on Atom Interferometer



Gravitational Wave Spectrum

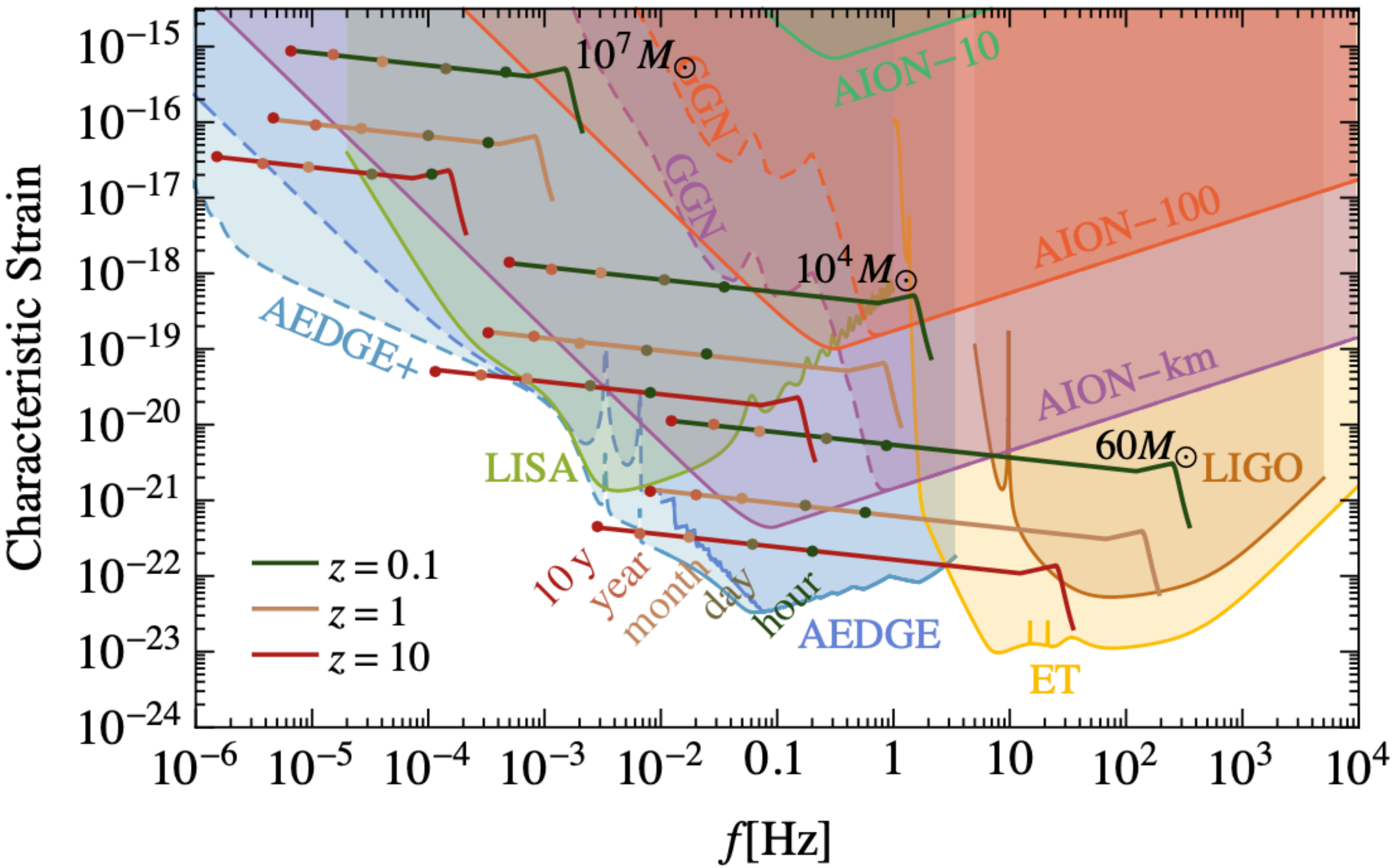


- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Supernovae? Phase transitions? …

[Gap between LISA & pulsar timing arrays (PTAs)]

Gravitational Waves from IMBH Mergers

AION

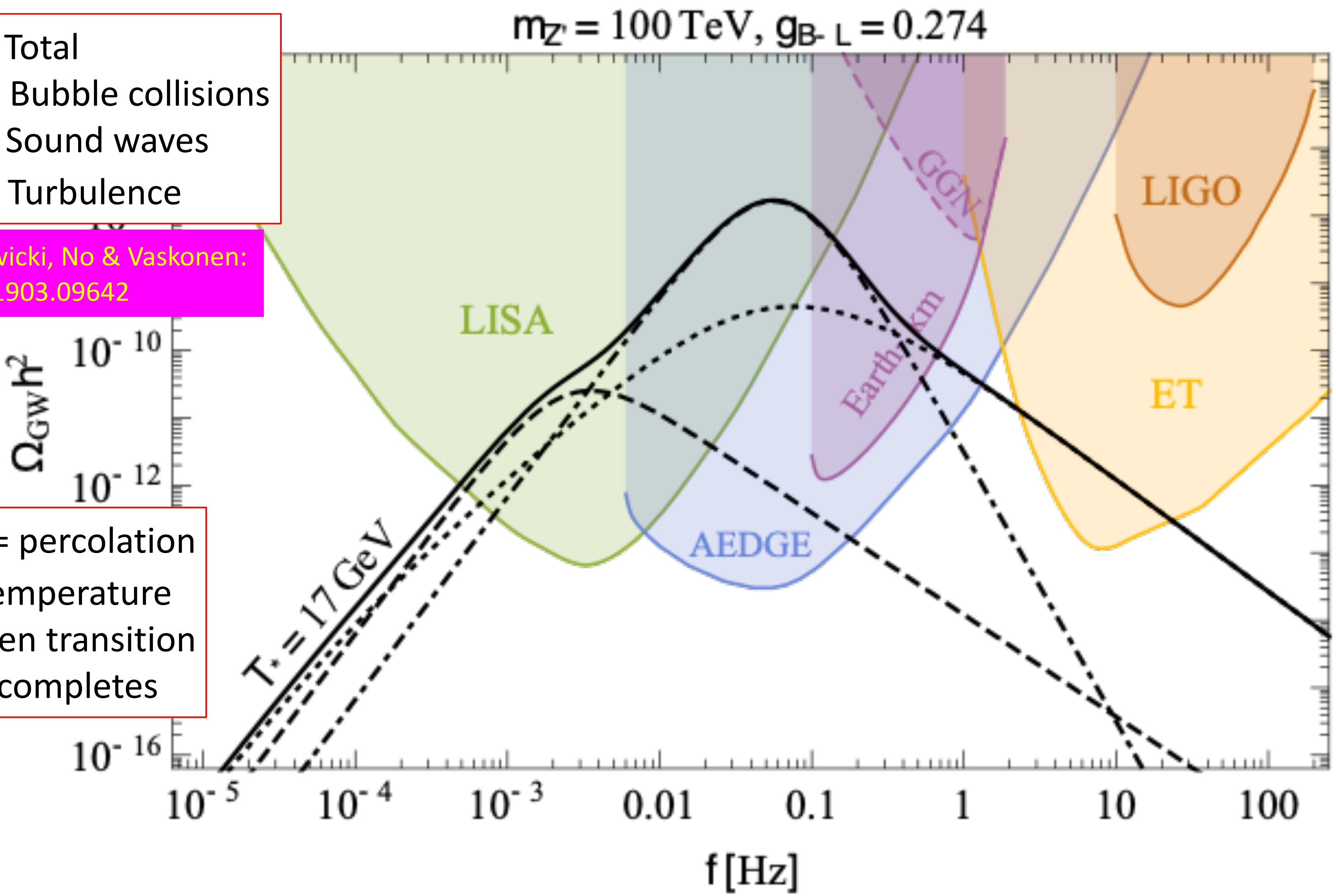


Probe formation of SMBHs

Synergies with other GW experiments (LIGO, LISA), test GR

Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

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



____ Total
- - - - Bubble collisions
_ - _ Sound waves
……. Turbulence

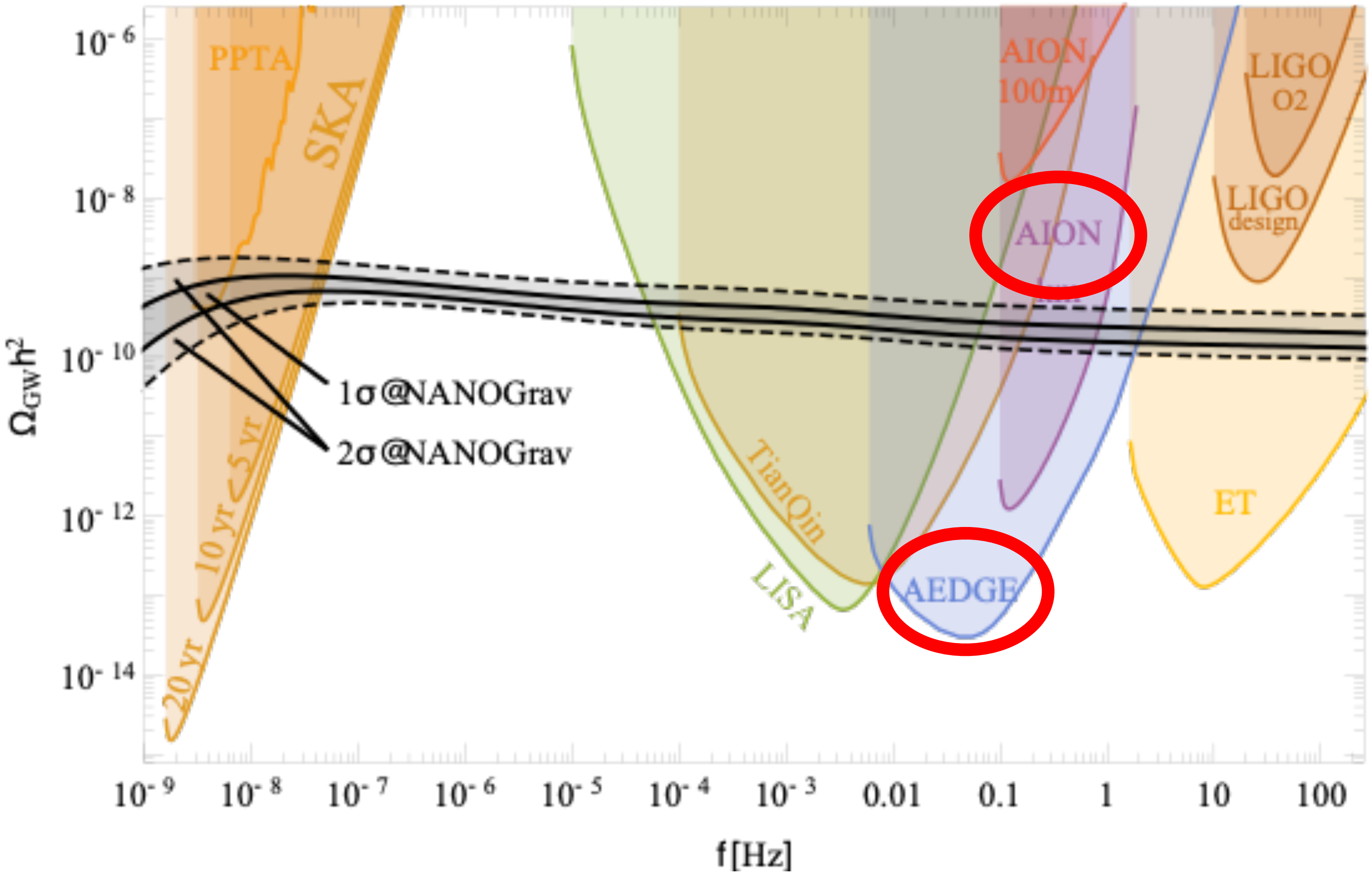
JE, Lewicki, No & Vaskonen: arXiv:1903.09642

T_* = percolation temperature when transition completes

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

JE & Lewicki: arXiv:2009.06555

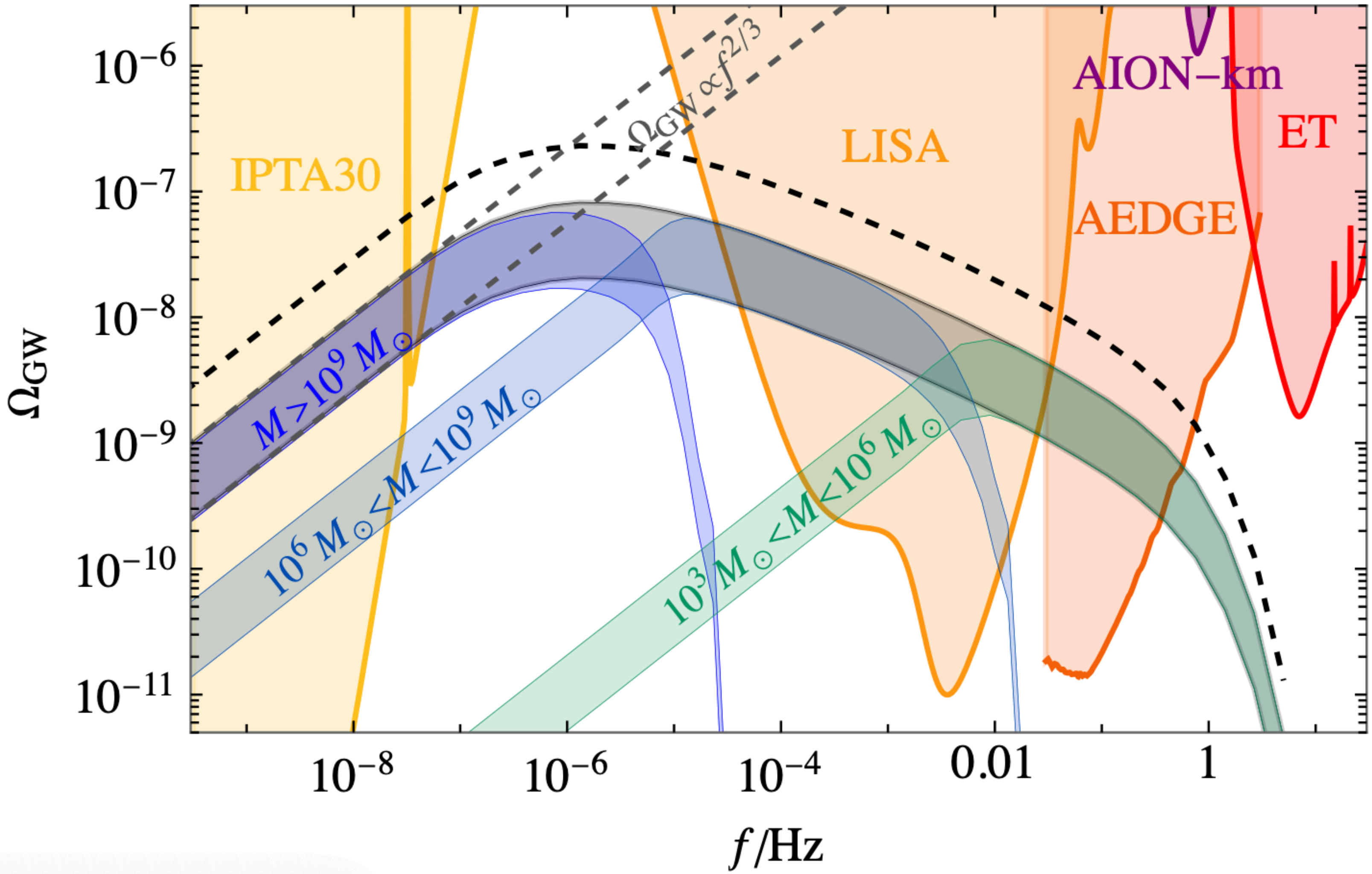
Cosmic String Interpretation of NANOGrav



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

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

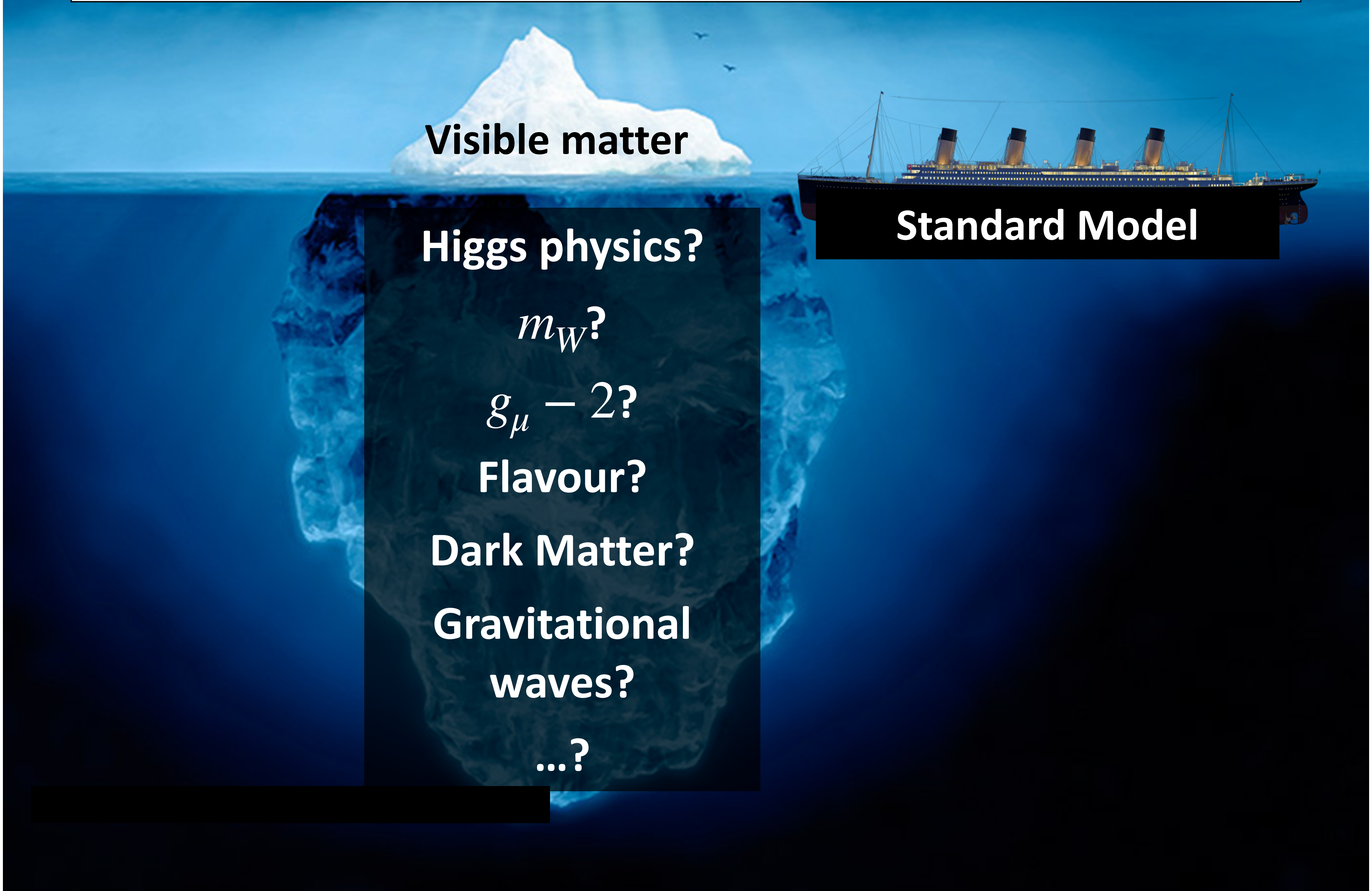
Stochastic GW Background from BH Mergers



Black dashed line is maximum possible Ω_{GW}, i.e., $p_{BH} = 1$

JE, Fairbairn, Hütsi, Raidal, Urrutia, Vaskonen & Veermäe: arXiv:2301.13854

Summary



[redacted]