New spin 0 physics from TeV to THz

Phenomenology Symposium 2021
University of Pittsburgh (Online)
25 May 2021

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University of Chicago

THE UNIVERSITY OF CHICAGO

EXPECTATION

THEORETICAL UBIQUITY

Chameleon
Relaxion
Galileon
Inflaton
Dilaton
Axion
Moduli
Sgluon
Squarks
Sleptons
Sneutrino
Dark Higgs
Light Higgs
Heavy Higgs
…

"Simplest consistent Lagrangian: why wouldn't Nature realize them?"

REALITY

EXPERIMENTAL RARITY

Spin 0

σ_{LHC} (s = 0) ~ 50 pb

Only few million Higgs bosons ever created in lab (fewer detected)

Spin ½ and 1

σ_{LHC} (s ≠ 0) ≫ mb

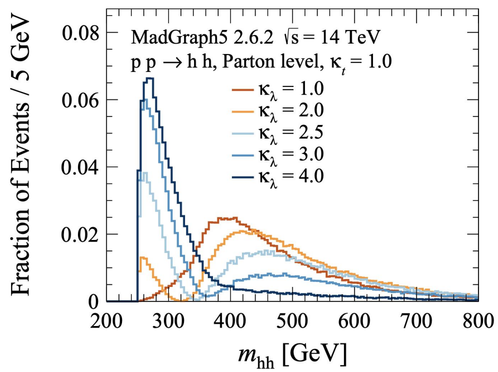
Create so many quarks & gluons we throw most away (trigger)

"Where are they all hiding or are there deeper reasons Nature avoids them?"

Today: a tale of two interferometers

Part 1: TeV Interferometry

SCALAR



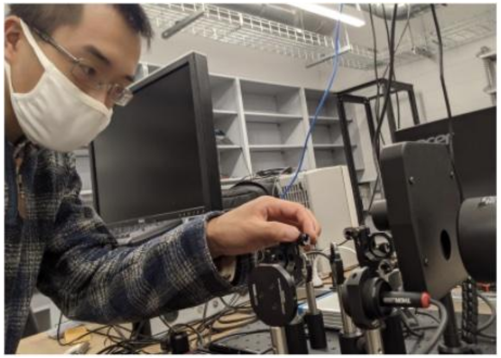
Higgs self-coupling

HL-LHC hh → bbbb

Amacker,... JL et al [2004.04240]

Part 2: THz Interferometry

PSEUDOSCALAR



Axion detection

Broadband haloscope

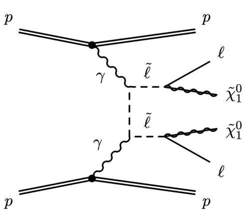
Dona, JL et al [2104.07157]

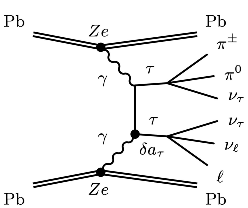
Fascinating but skipping today for brevity:

Sleptons

Beresford & JL

[1811.06465]





Tau g – 2

Beresford & JL

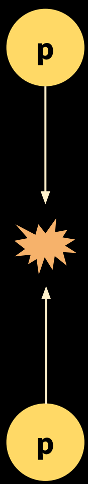
[1908.05180]

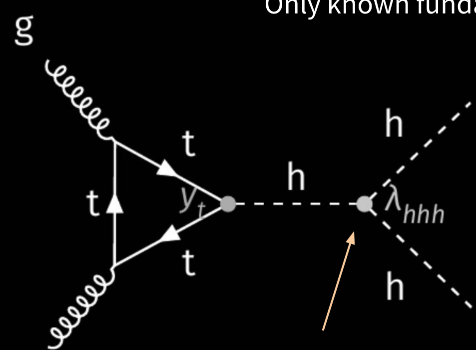
Please see my seminars at Cornell (recording) or Pittsburgh (slides) for overviews

PART 1

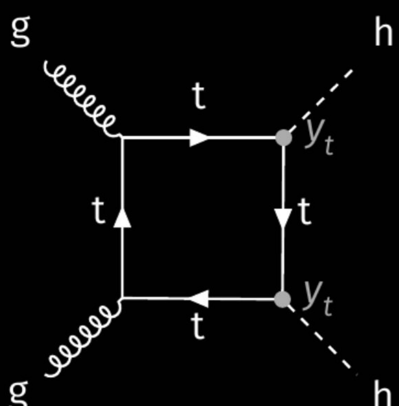
Higgs Boson Interferometry

Only known fundamental scalar remains empirically enigmatic

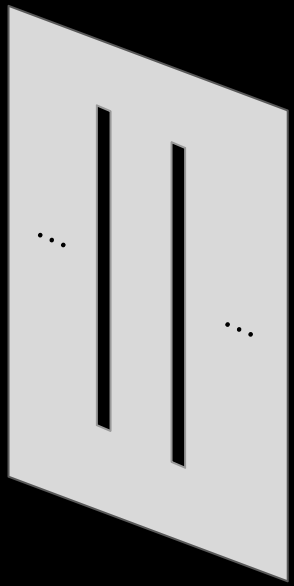




SELF-COUPLING: What we want to measure

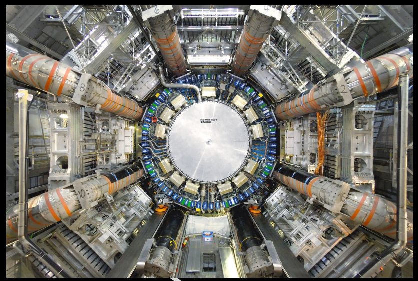


↓ QFT ~ “double slit in continuum limit”



Self-coupling directly probes Higgs potential shape

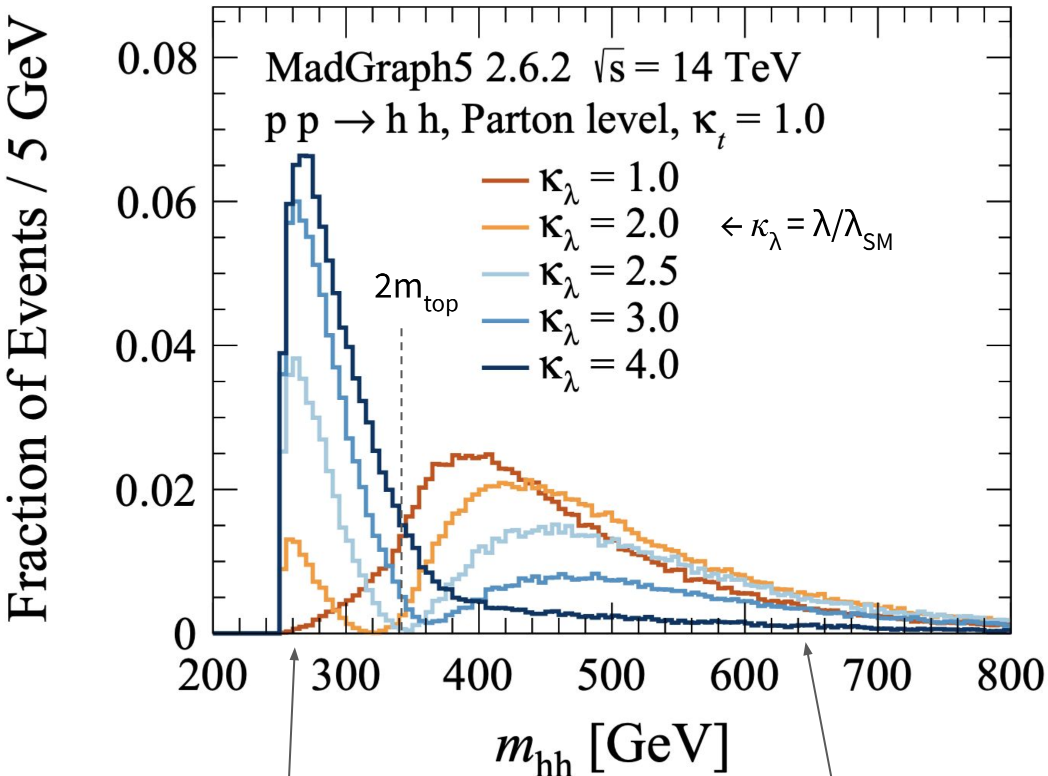
Photo: ATLAS



↑ DATA: What we actually measure

pp → hh a flagship (HL-)LHC target: see Tulika Bose and Laura Jeanty’s plenary talks earlier today

Di-Higgs quantum interference pattern



Higgs self-coupling measurements using deep learning in the $b\bar{b}b\bar{b}$ final state 2004.04240

Jacob Amacker,[a] William Balunas,[a] Lydia Beresford,[a] Daniela Bortoletto,[a] James Frost,[a] Cigdem Issever,[a,b,c] Jesse Liu,[d] James McKee,[a] Alessandro Micheli,[a] Santiago Paredes Saenz,[a] Michael Spannowsky,[e] and Beojan Stanislaus[a]

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Conventional wisdom

BSM enhances high mass m_{hh}

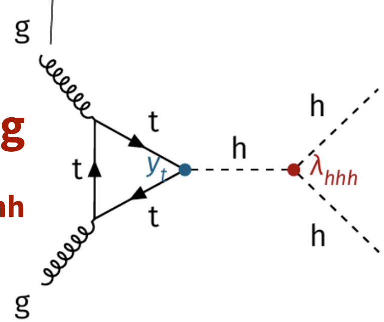
Self-coupling exception

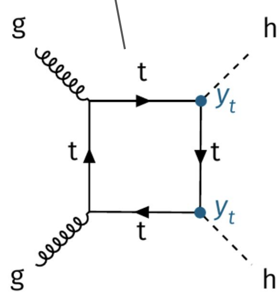
BSM appears near hh threshold at low m_{hh}

Why this is important

Need low p_T multi(b-)jet triggers

→ Self-coupling affects low m_{hh}





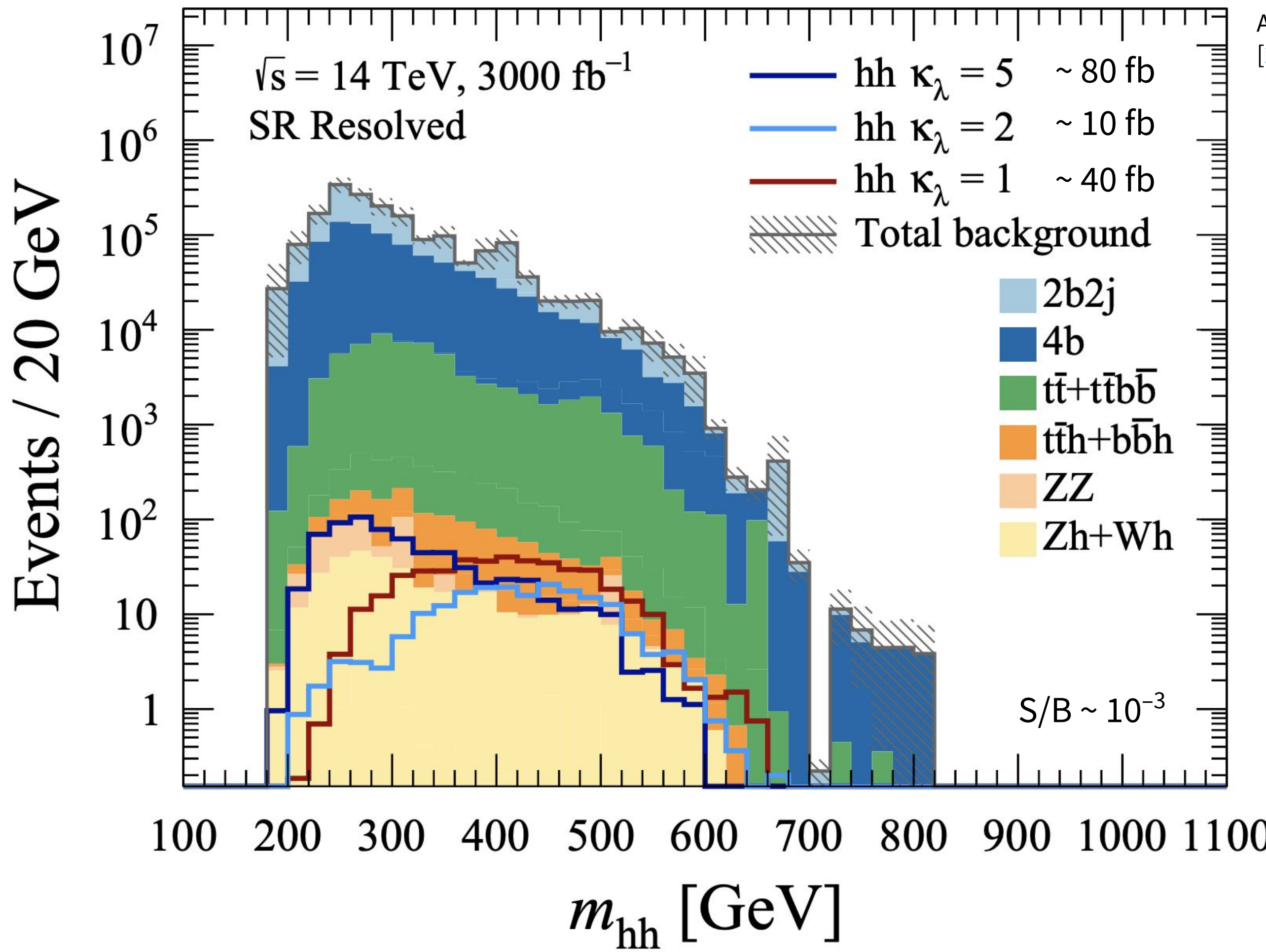
Destructive interference for $\kappa > 0$

← Top quark box dominates high m_{hh}

↓ Sensitive to sign

$$\sigma_{\text{triangle}} \sim \lambda_{hhh}^2 y_t^2, \quad \sigma_{\text{box}} \sim y_t^4, \quad \sigma_{\text{interference}} \sim -\lambda_{hhh} y_t^3$$

hh → 4b: experimentally challenging at HL-LHC



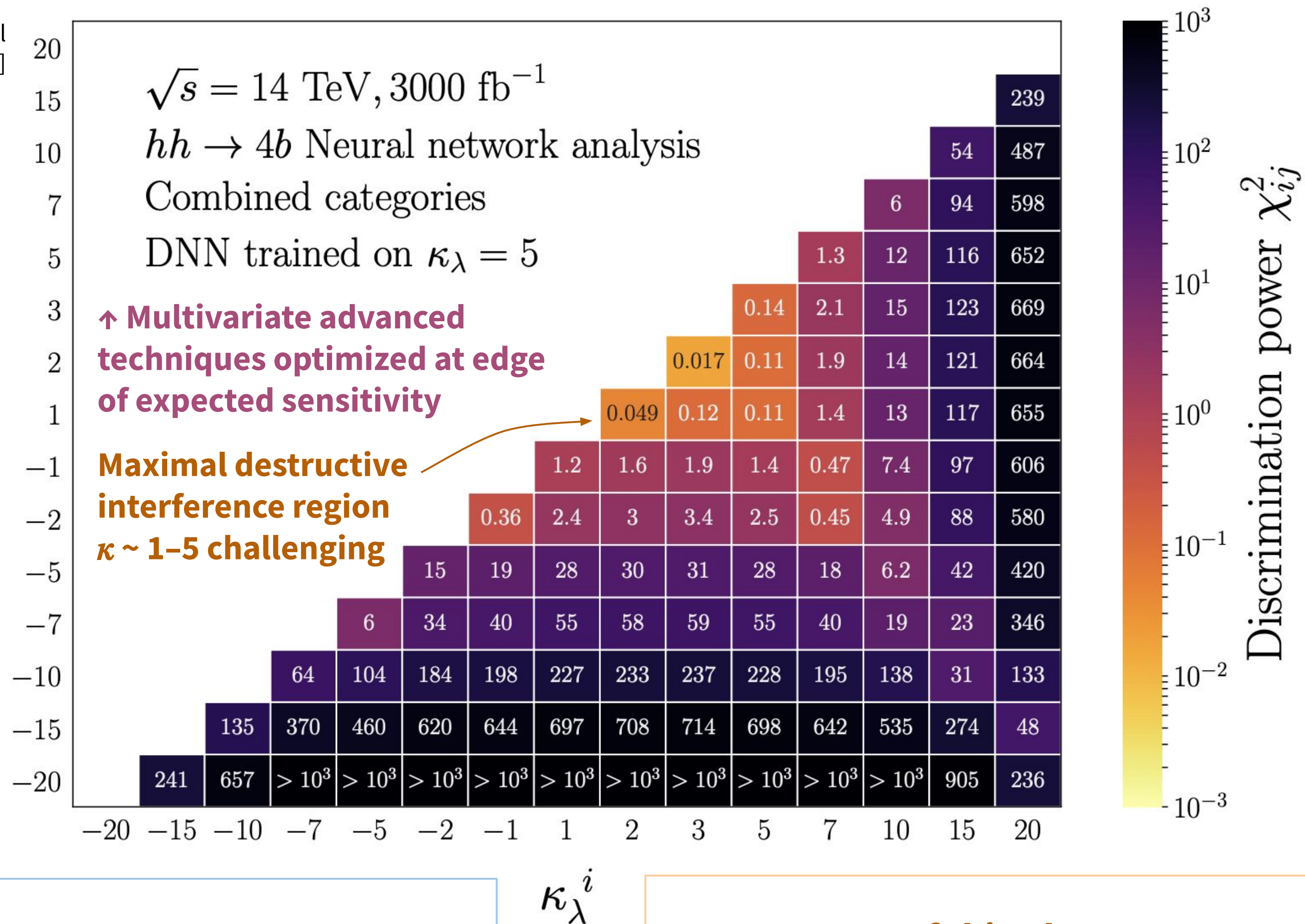
Amacker,…JL et al [2004.04240]

Probing interference desires signal statistics
hh → 4b profits from high BR(h → bb) ~ 58%

Formidable multijet backgrounds
Demands %-level systematics control

How well can we tell BSM scenarios apart?

Amacker,…JL et al [2004.04240]



Many 1D limits* show BSM vs SM

E.g. κ = 1 row/column of this plot ↑

Importance of this plot: BSM vs BSM

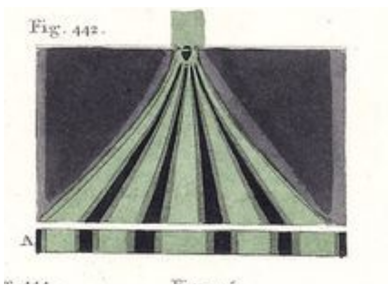
κ constraints change if Nature is BSM

*e.g. ATL-PHYS-PUB-2018-053

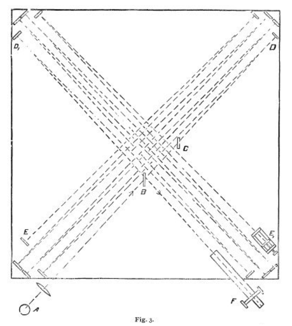
Not just new particles: new transformative paradigms

Spin 1 Interferometry

1800s: Young 1807, Michelson & Morley 1887



BBVA



Am J Sci (1887) 3 34 333-345

New paradigm

Light is a wave

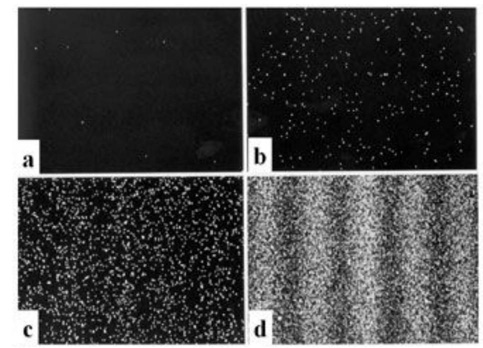
Foundational to

Michelson–Morley experiment for

Special Relativity

Spin ½ Interferometry

1900s: Thomson & Reid, Davisson & Germer 1927



Physics World

New paradigm

Matter is a wave

Foundational to

de Broglie hypothesis for

Quantum Theory

2000s: What new paradigms could Higgs Spin 0 Interferometry reveal?

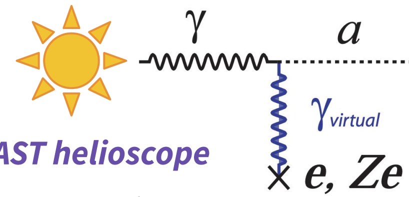
PART 2

Axions and THz Interferometry

↑ Symmetry Magazine

Axion search landscape

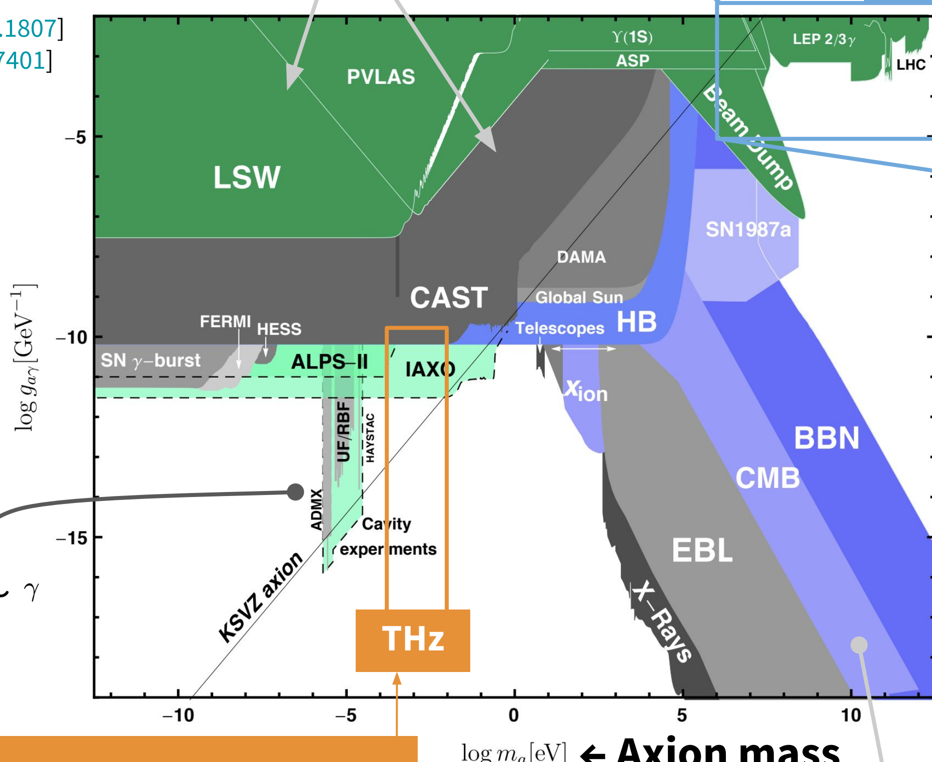
Primakoff Production

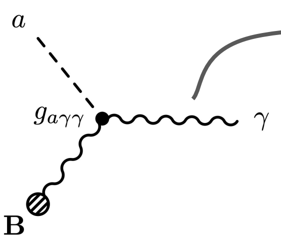


Light shining through wall, CAST helioscope

Ziotus et al [0903.1807]
MADMAX [1901.07401]

→ Axion photon coupling

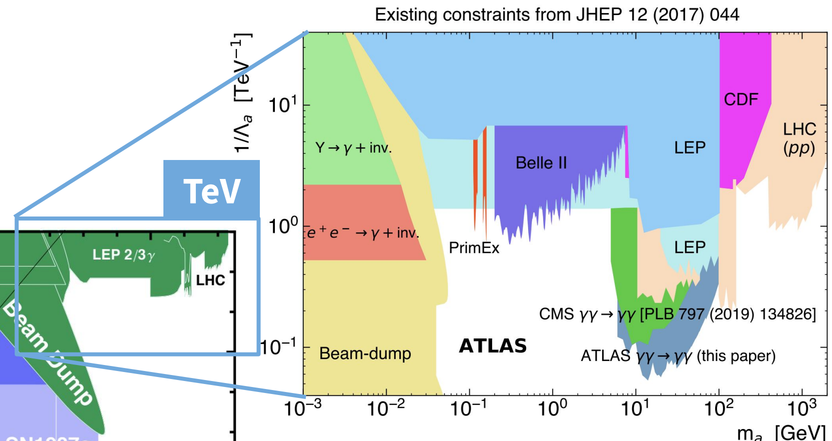




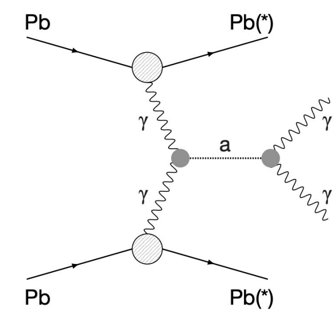
← Axion mass

Haloscope Detection (today's focus)

Axion dark matter direct detection



Knapen et al [1607.06083], Bauer et al [1708.00443]
CMS [1810.04602], ATLAS [2008.05355]



Collider Production

Di-/tri-photon resonances, Z-strahlung

Astrophysics and cosmology

Problem: high frequency obstructions

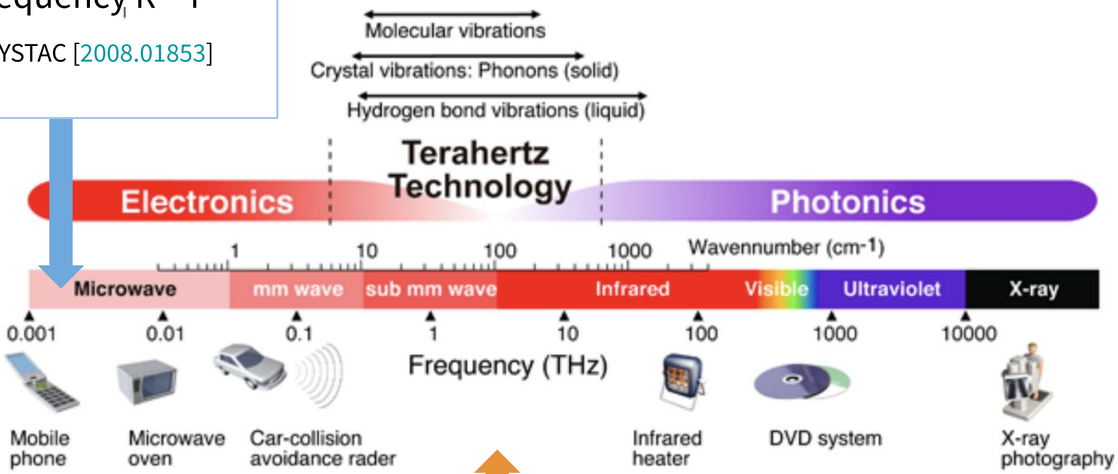
Problem 1
Resonant ⇒ narrowband

ADMX cavity haloscope scan rates scale poorly with frequency $R \sim f^{-14/3}$

ADMX [1804.05750], HAYSTAC [2008.01853]

Longstanding confluence of obstructions

Stalled high frequency axion discovery progress



1 THz = 4 meV

Problem 2
Terahertz technology gap

Historically bright THz sources neither cheap nor commercially mature

Dhillon et al [J. Phys. D 50 (2017) 043001]
Fukunaga et al [doi.org/10.1117/12.827452]

New proposed solution: BREAD

BREAD COLLABORATION

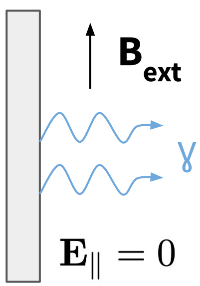
Broadband Reflector Experiment for Axion Detection

See e.g. Andrew Sonnenschein's CPAD 2021 talk or Snowmass LoI for further details

Argonne National Laboratory | Fermilab | The University of Chicago | NASA Goddard Space Flight Center | Illinois Tech | NIST | Lawrence Livermore National Laboratory

STEP 1: CONVERSION

Induce axion–photon conversion via conducting surface in B-field



$\mathbf{E}_{||} = 0$

Axion dark matter modifies Ampère–Maxwell dynamics

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\mathbf{B}_{\rm ext}\cos(m_a t)$$

$$\frac{P_a}{10^{-21}\ \mathrm{W}} = 3.1 \cdot \frac{\rho_{\rm CDM}}{0.3\ \mathrm{GeV\ cm^{-3}}} \frac{A}{10\ \mathrm{m}^2} \left(\frac{B}{10\ \mathrm{T}}\right)^2 \times \left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \mathrm{GeV}^{-1}} \frac{1\ \mathrm{meV}}{m_a}\right)^2.$$

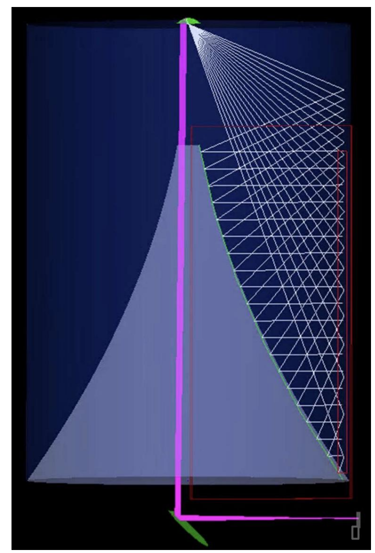
Dish antenna ⇒ inherently broadband

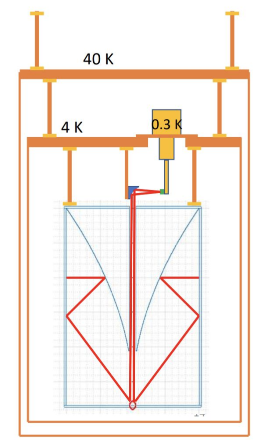
Tradeoff: replace resonant amplification with $P \propto A$

Horns et al [1212.2970]

STEP 2: COLLECTION

Focus signal photons onto sensor using parabolic reflector





Challenge: detect tiny signal above noise

Need broadband spectral analyzer ⇒ motivated us to build interferometer

Design & build Michelson interferometer at UChicago

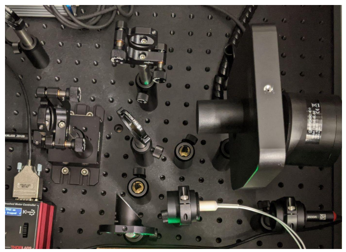
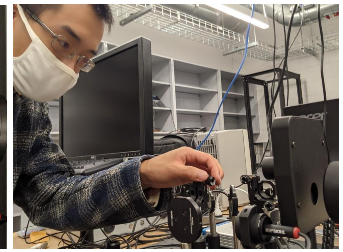
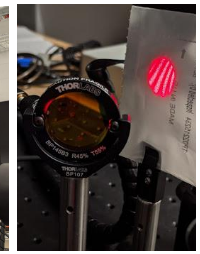
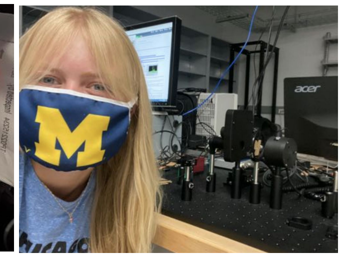
JANUARY 2020
Hardware arrival & assembly

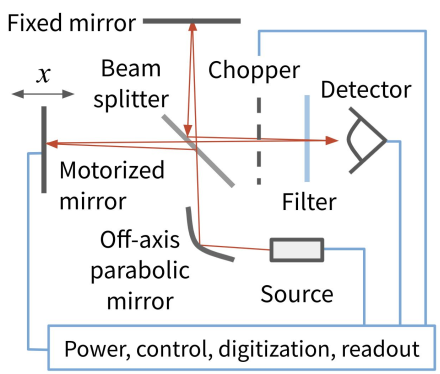
AUGUST
First laser fringes

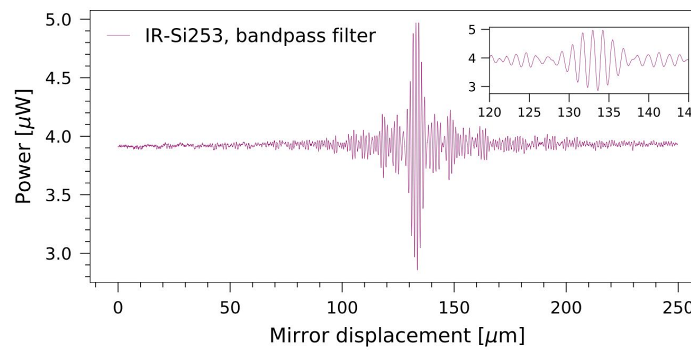
OCTOBER
Begin measurements

APRIL 2021
Dona, JL et al
[2104.07157]







Design and performance of a multi-terahertz Fourier transform spectrometer for axion dark matter experiments

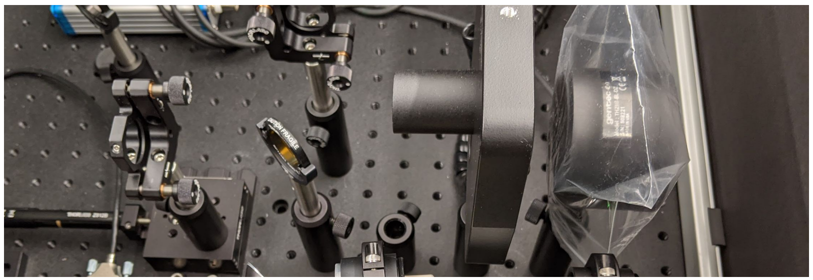
Kristin Dona,[1,*] Jesse Liu,[1,†] Noah Kurinsky,[2,3,‡] David Miller,[1,§]
Pete Barry,[2,4] Clarence Chang,[2,4] and Andrew Sonnenschein[3,¶]
[1] *Department of Physics, University of Chicago, Chicago IL 60637, USA*
[2] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago IL 60637, USA*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[4] *Argonne National Laboratory, Lemont, IL 60439, USA*

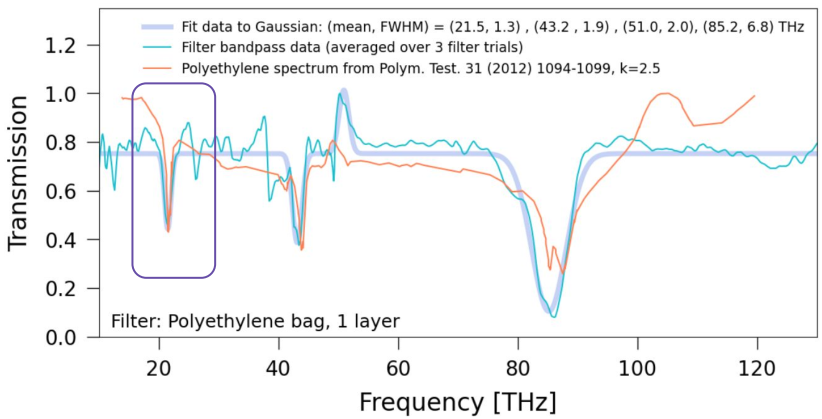
Funded by DOE HEP-QIS QuantISED grant with FNAL and Argonne collaborators

First tests & performance characterization

Polyethylene plastic bag

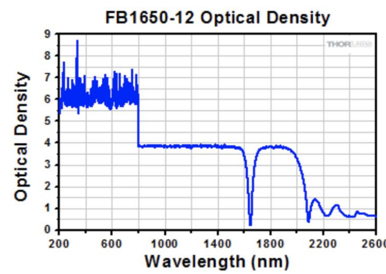
Surprisingly clear far/mid-IR spectral features at low cost

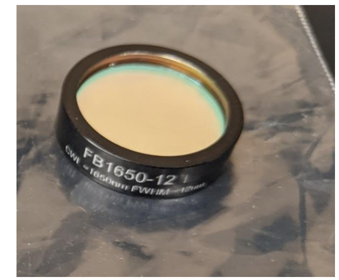


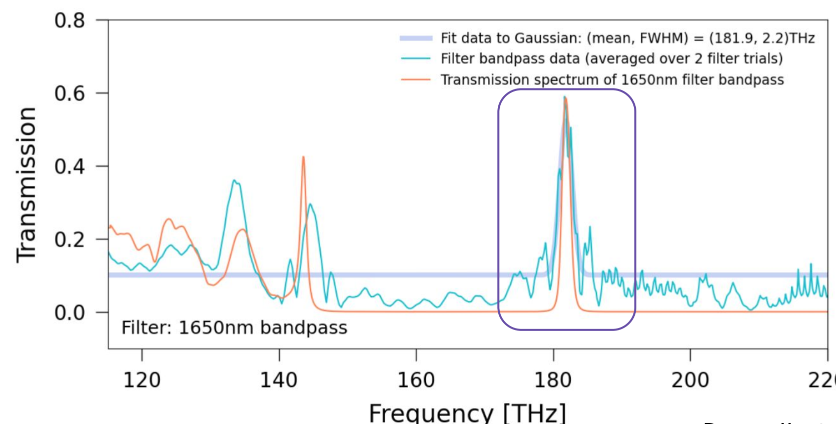


Thorlabs near-IR bandpass

FB1650-12: f = 1650 ± 2.4 nm, FWHM = 12 ± 2.4 nm







Dona, JL et al [2104.07157]

Measured vs expectation across an order of magnitude

Good resolution σ_f / f ~ % (shape + width of narrow peaks)

Axion dark matter would appear as **localized peak** $f = m_{DM}$

Use instrument to test optics – future work to see if feasible in real-world axion search

SUMMARY

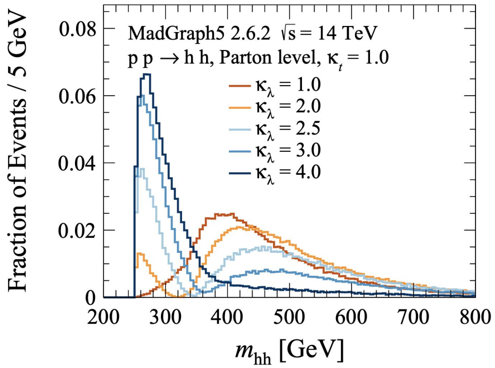
A TALE OF TWO INTERFEROMETERS

Spin 0: theoretical ubiquity yet experimental rarity ⇒ discoveries soon?

Motivates new ideas to probe only fundamental scalar & search for new ones

TeV Interferometry

SCALAR



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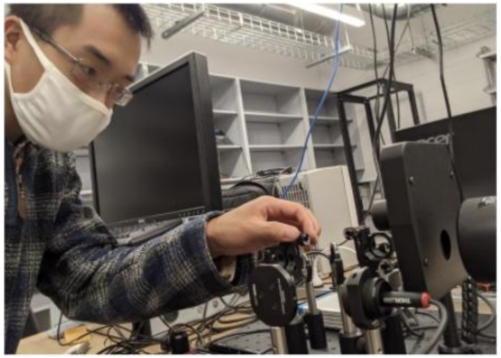
Amacker, ..., JL et al [2004.04240]

THz Interferometry

PSEUDOSCALAR



Axion detection

Broadband haloscope

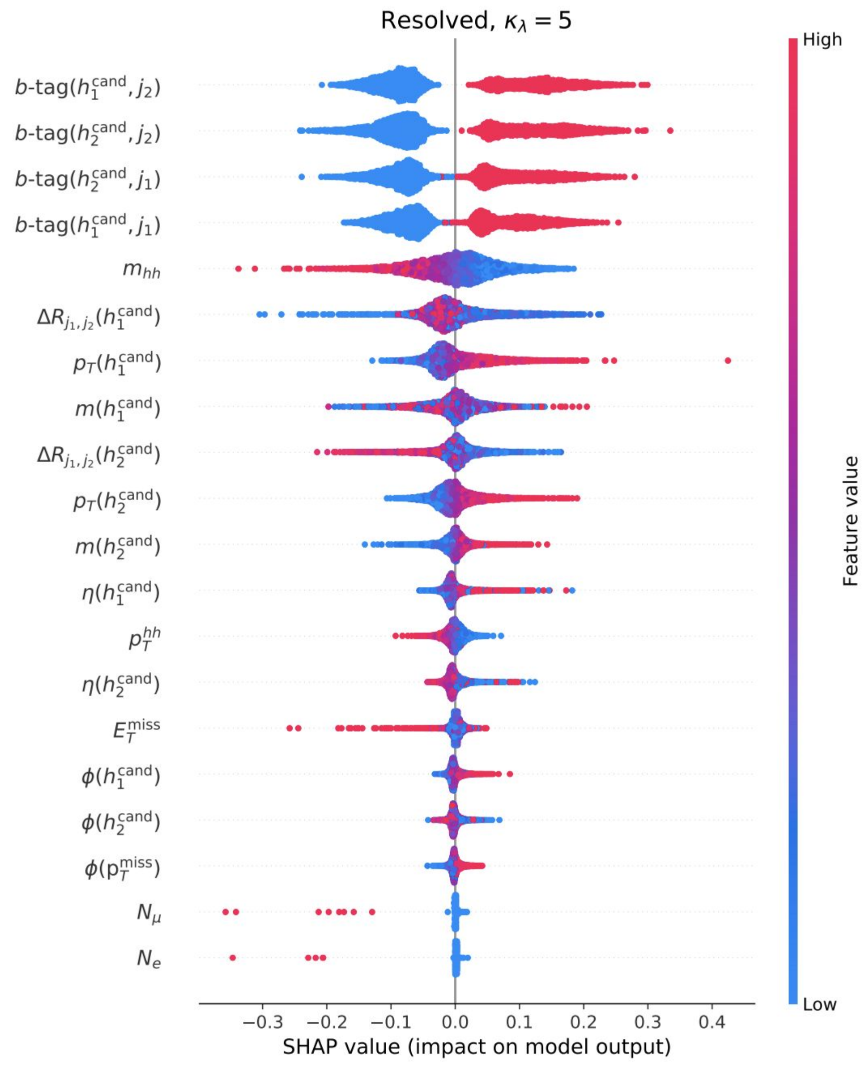
Dona, JL et al [2104.07157]

Today just a taster – happy to chat about further details or other science :)

EXTRAS

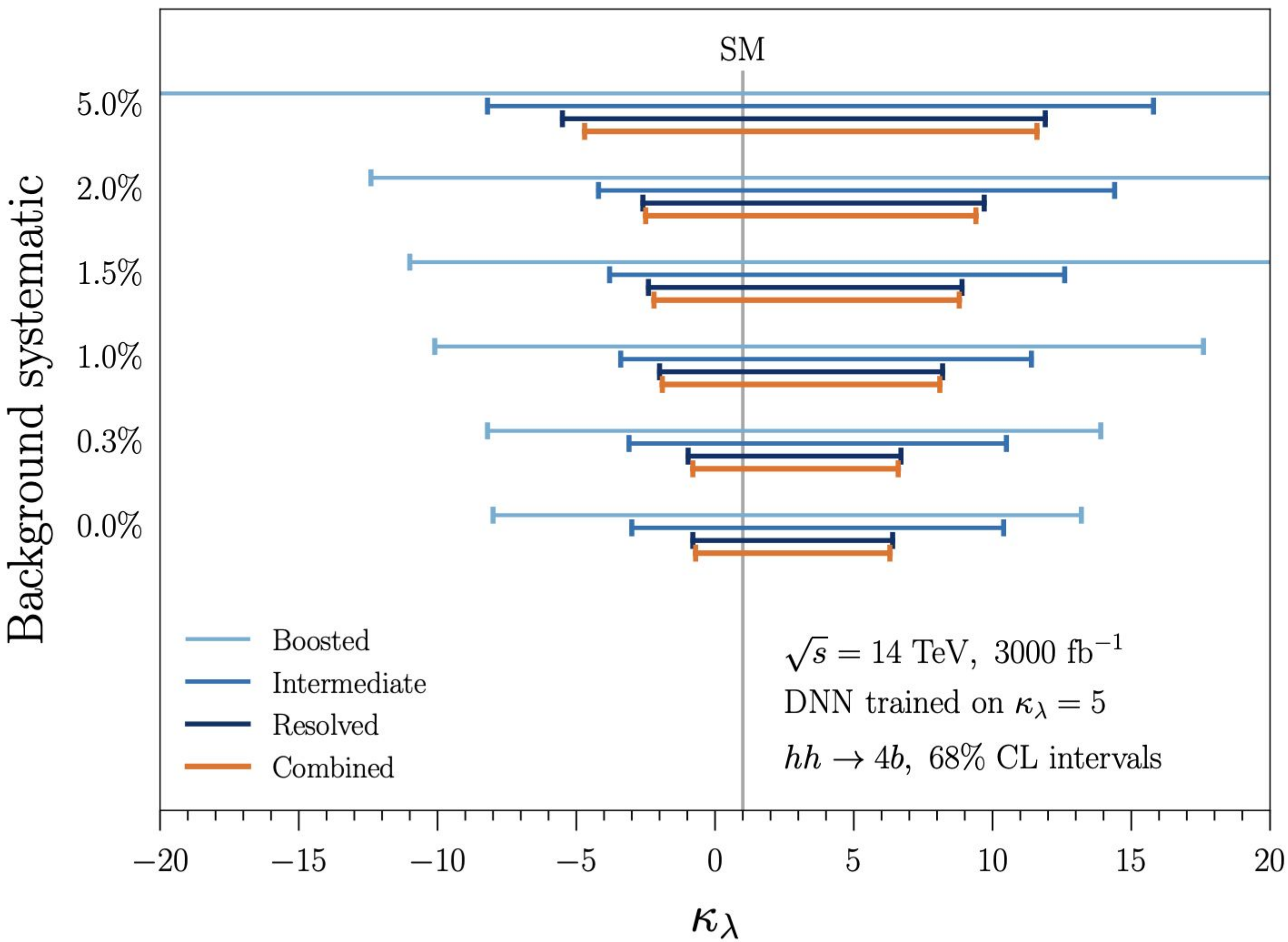
hh → 4b event selection and variable importance

Observable	Preselection		
Large jet j_L	$R = 1.0, p_{\mathrm{T}} > 250$ GeV, $\lvert\eta\rvert < 2.0$		
Small jet j_S	$R = 0.4, p_{\mathrm{T}} > 40$ GeV, $\lvert\eta\rvert < 2.5$		
Track jet j_T	$R = 0.2, p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.5$		
$j_T \in j_L$	$\Delta R(j_T, j_L) < 1.0$		
	Resolved	Intermediate	Boosted
$N(j_L)$	$= 0$	$= 1$	$= 2$
$N(j_S)$	≥ 4	≥ 2	≥ 0
h_1^{cand}	$j_S^{(i)}$ pair	j_L	$j_L^{(1)}$
h_2^{cand}	$j_S^{(i)}$ pair	$j_S^{(i)}$ pair, $\Delta R(j_S^{(i)}, j_L) > 1.2$	$j_L^{(2)}$
ΔR_{jj}	See Eqs. 3.2, 3.3	—	—
	Signal region		
$j_T \in h_1^{\mathrm{cand}}$	—	≥ 2	≥ 2
$j_T \in h_2^{\mathrm{cand}}$	—	—	≥ 2
b-tagging	Two b-tags for each h_i^{cand}		
$\lvert\Delta\eta(h_1, h_2)\rvert$	< 1.5		
$E_{\mathrm{T}}^{\mathrm{miss}}$	< 150 GeV		
$p_{\mathrm{T}}^{\ell}, \lvert\eta_\ell\rvert$	> 10 GeV, < 2.5		
N_ℓ	$= 0$		
$p_{\mathrm{signal}}^{\mathrm{DNN}}$	> 0.75 (*neural network analysis* only)		
	Resolved	Intermediate	Boosted
$m(h_1)$ [GeV]	[90, 140]	[90, 140]	[90, 140]
$m(h_2)$ [GeV]	[90, 140]	[90, 140]	[90, 140]
	Lower bin edges for m_{hh} binning [GeV]		
Resolved	$[200, 250, 300, 350, 400, 500]$		
Intermediate	$[200, 500, 600]$		
Boosted	$[500, 800]$		



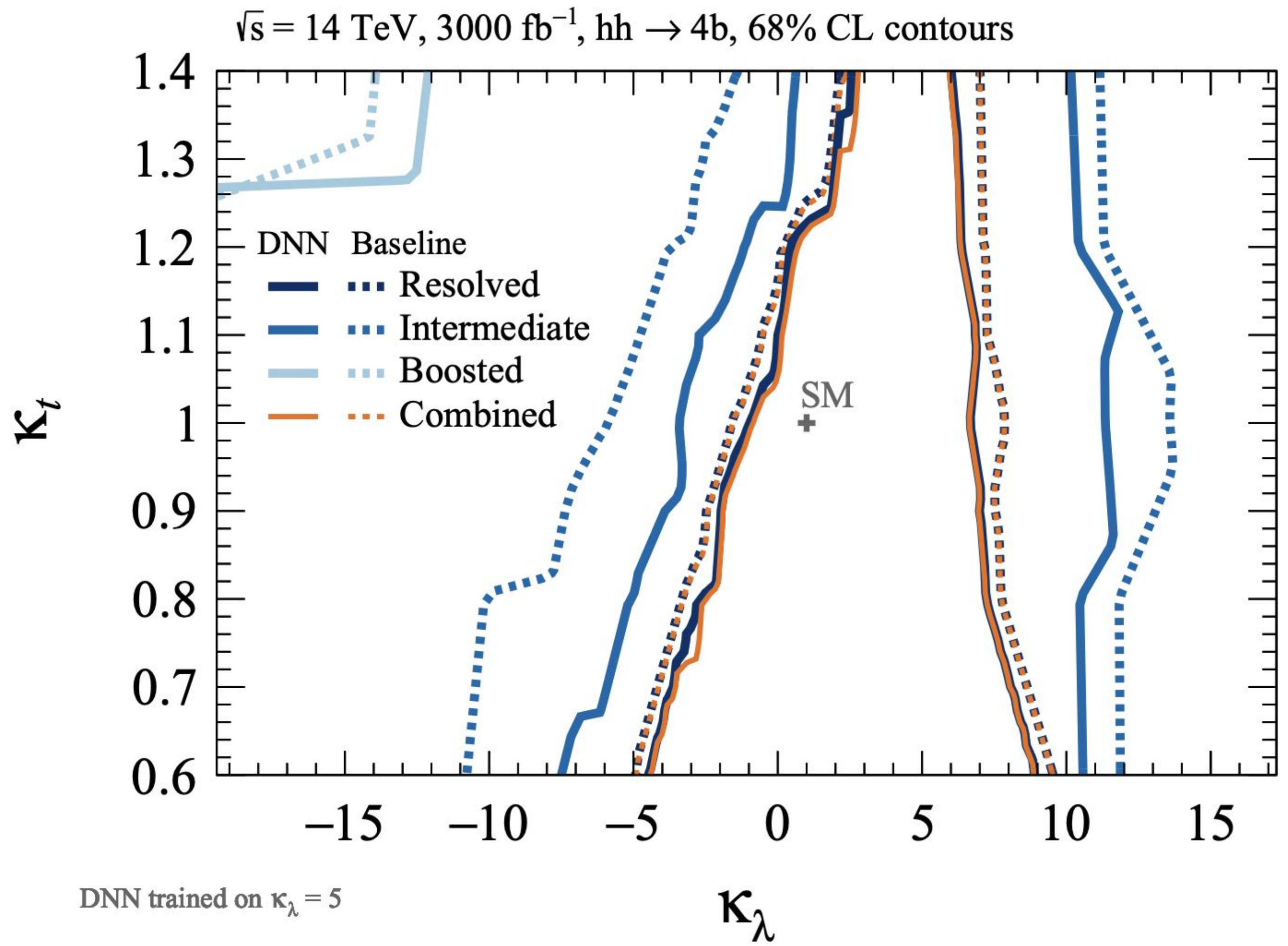
Amacker,… JL et al [2004.04240]

Background systematics impact on self-coupling



Amacker,... JL et al [2004.04240]

Constraints on top Yukawa and self-coupling

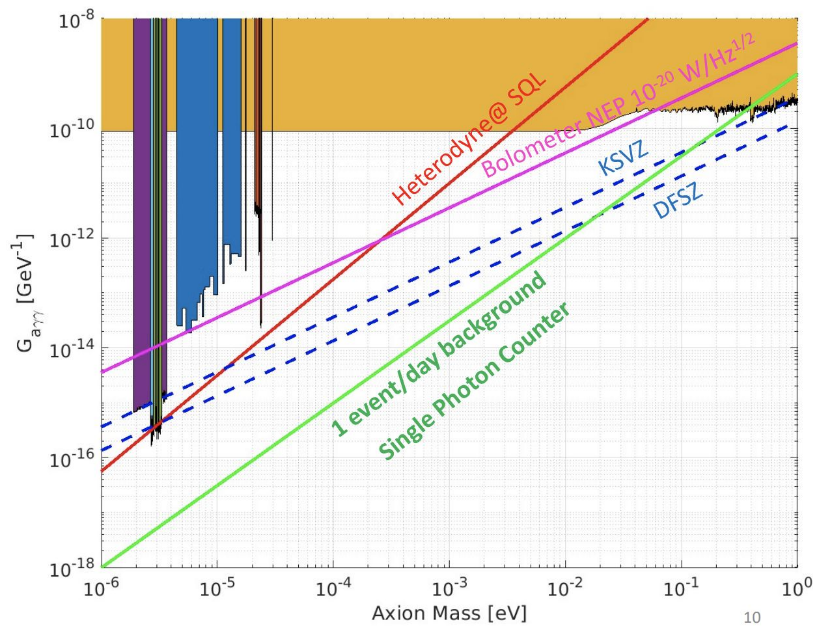


Amacker,... JL et al [2004.04240]

Axion-induced photon detection strategies

10 m^2 x (10 T)^2 radiator

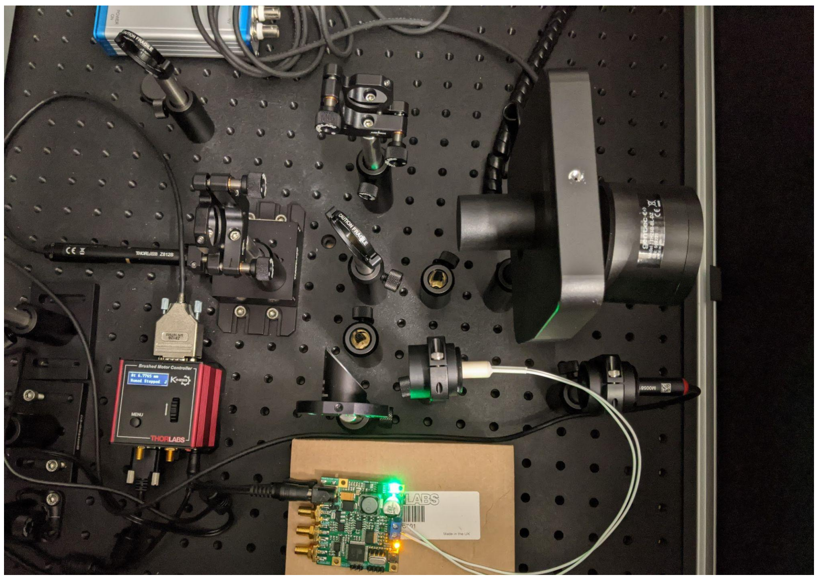
100-day integration time



	Microwave		Mm			IR	Visible	UV
	1 GHz	**10 GHz**	**100 GHz**	**1 THz**	**10 THz**	**100 THz**	**1000 THz**	**1 PHz**
Photomultiplier						Mature single photon counting		
Photodiode, SIPM, APD						high dark counts		
HEMT	Phase sensitive and broadband							
Superconducting paramp JPA, TWPA	~quantum limited							
Photomixers SIS, HEM			Narrow band					
Semiconductor bolometer			Bolometers					
Transition Edge Sensor (TES)			NEP~10^{-18} W/$\sqrt{Hz}$			Superconducting photon		
Kinetic Inductance Detector (KID)						counters with		
Superconducting Nanowire SNSPD						low dark current		
Qubit								
Quantum Capacitance Detector			~10^{-20} W/$\sqrt{Hz}$					
Current Biased Josephson Junction		Developing single photon technologies for GHz- THz						

Andrew Sonnenschein CPAD talk

Spectrometer components



FTS component	Attribute
Beamsplitter	Thorlabs Pellicle BP145B3
R:T datasheet	[0.4, 2.5] μm
Coated for 45:55 R:T	[1, 2] μm
Mirrors	Aluminium PF10-03-G01
Design wavelengths	[0.45, 20] μm
Fixed arm length	76 mm
Motorized stage	
Model	Thorlabs MT1-Z8
Min. step size	0.05 μm
Max. travel distance	12 mm
Infrared source	
Model	IR-Si253
Emitter material	Silicon Nitride
Temperature at 9V	1200 K
Photosensor	
Model	Gentec THZ5B-BL-DA-D0
Technology	Pyroelectric
Sample rate	5 Hz
Design noise power	50 nW
Design range	[0.1, 30] THz
Chopper rate	25 Hz (model SDC-500)
Readout	T-RAD USB 12 bit ADC
Gentec filter windows	
Polyethylene (PEW)	[3, 30] μm
Silicon (SiW)	[1.1, 9], [50, 1000] μm

Interferometer signal and noise spectra