# Highlights of BSM & Exotic Searches

35th Rencontres de

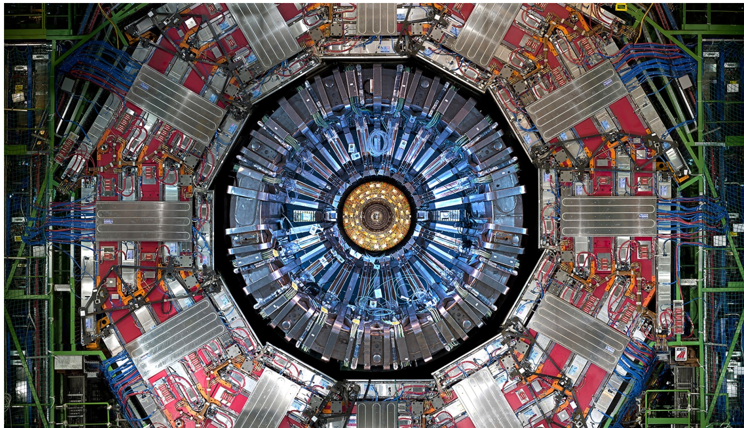
# Blois

2024

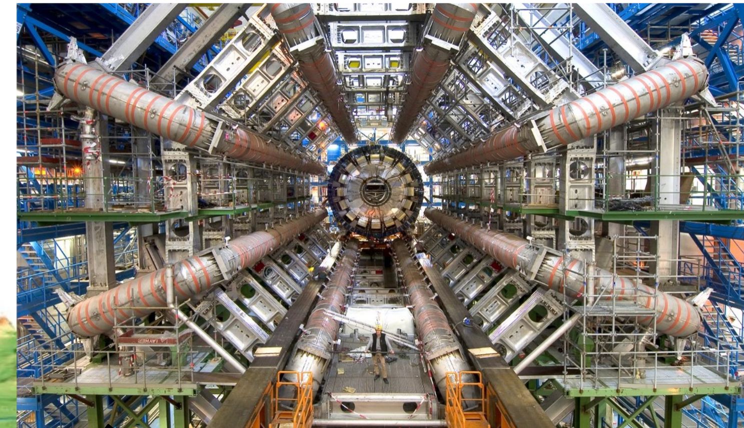
Ben Hooberman • University of Illinois
on behalf of ATLAS and CMS

# CMS & ATLAS at the Large Hadron Collider

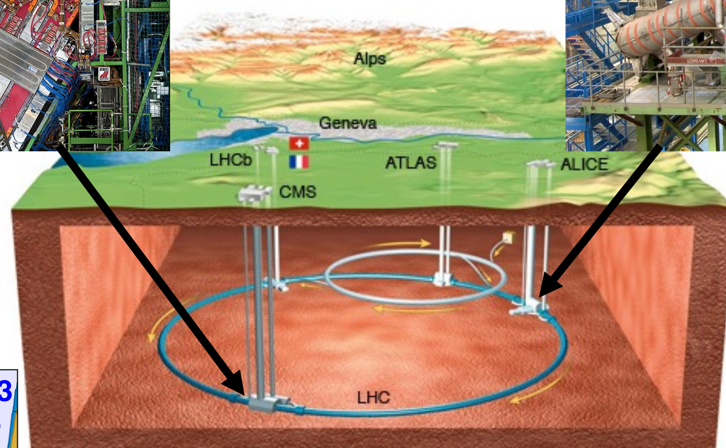
**CMS**



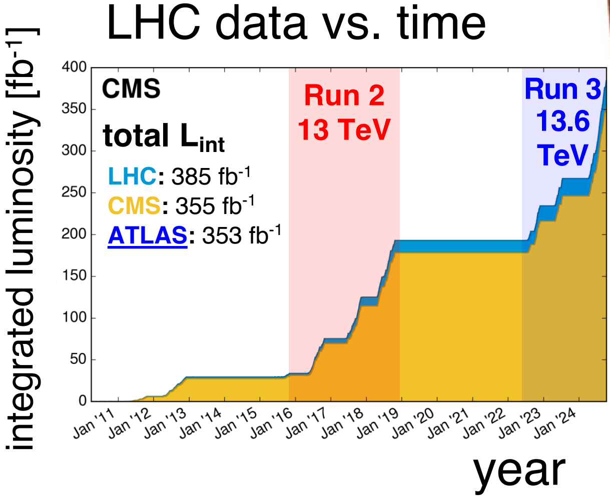
**ATLAS**



**LHC**



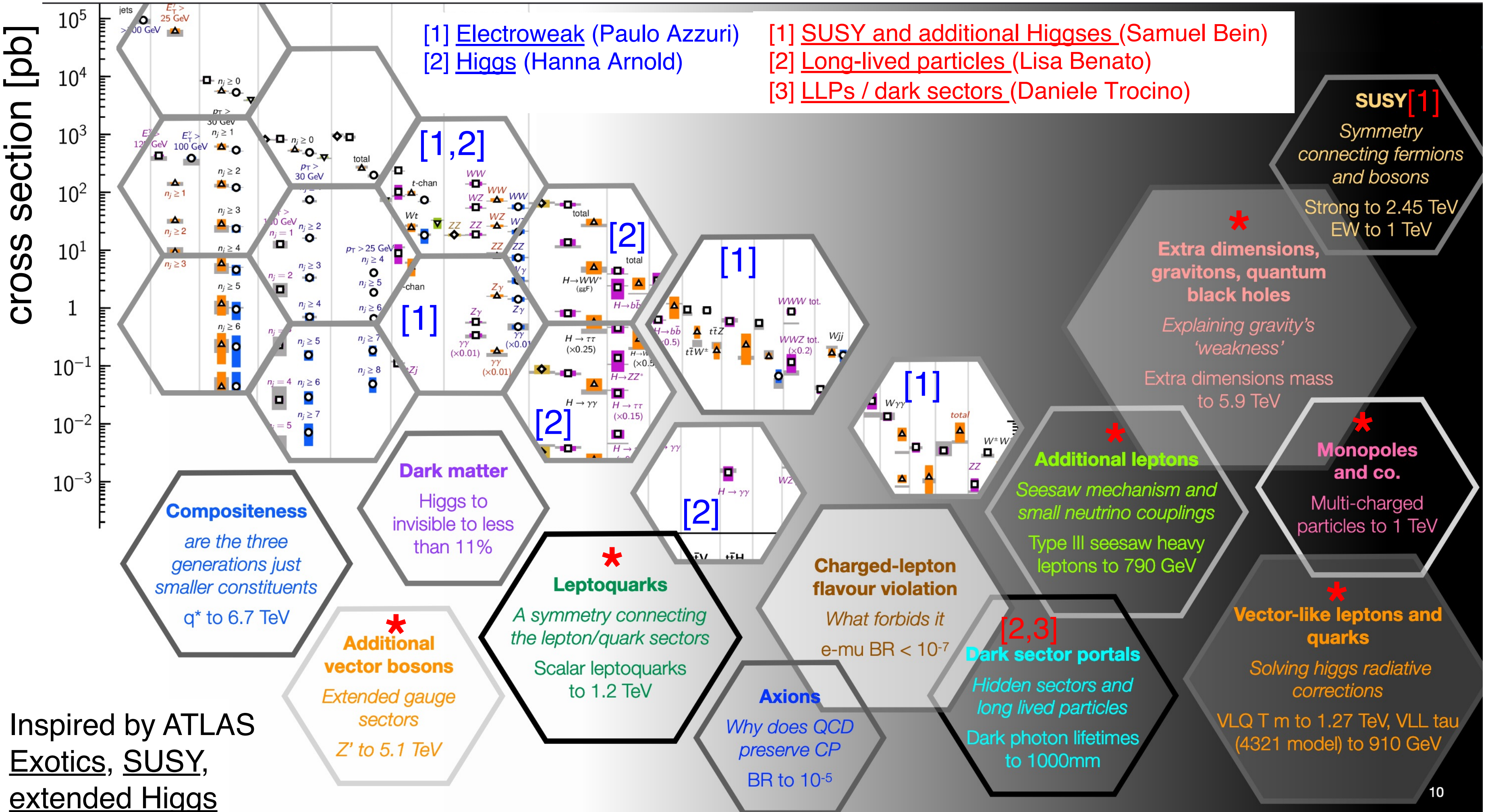

LHC data vs. time




- Higgs discovery  completed the Standard Model (SM) → **what lies *beyond* the SM** (BSM)?
- Showing some highlights from recent **Run 2** and **Run 3** LHC **direct searches for BSM physics**

# Probe BSM physics with **direct searches** and **measurements**

additional Blois24 plenary talks:




Inspired by ATLAS Exotics, SUSY, extended Higgs physics reports

Monica Dunford ICHEP24 talk

***this talk**

**“toponium”**
HIG-22-013

# Search for Bosons Decaying to Top Quark Pairs

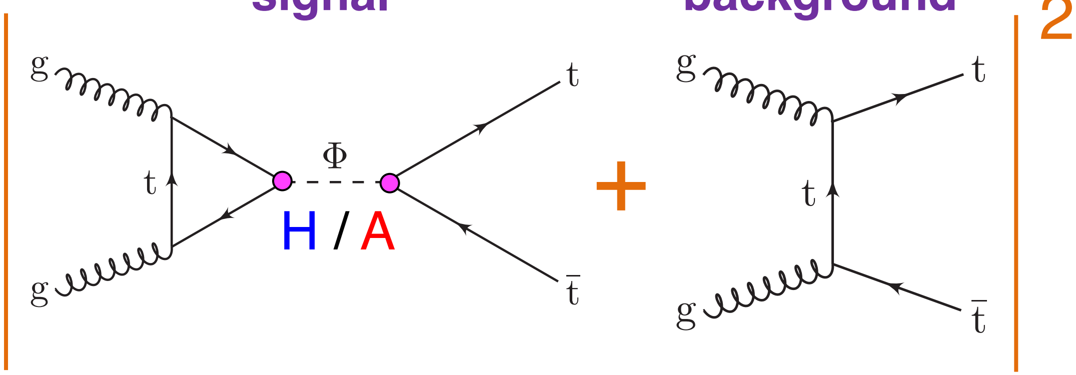
**see dedicated talks by:**
Sam Baxter, Higgs Hunting 2024
Laurids Jeppe, TOP 2024

- Search for extended Higgs sector (2HDM) introducing a **scalar** / **pseudo-scalar** Higgs boson decaying to top quark pairs
- At threshold, non-perturbative QCD effects become important, including a possible $t\bar{t}$ bound state
- Model effect as pseudo-scalar with $m_{\eta t}$ = 343 GeV, $\sigma_{\eta t}$ = 6.3 pb [PRD 104 (2021) 3, 034023]
- Search in **3 channels**:
  - **1$\ell$** (e/$\mu$), ≥2 b-jets, **3j** / **≥4j**
    - Exploit $|\cos\theta^*_{t_\ell}|$ (angle btw leptonic top and $t\bar{t}$ )
  - **2$\ell$** (ee/$\mu\mu$/e$\mu$), ≥1 b-jet, ≥2j
    - Exploit $c_{hel}$ and $c_{han}$ spin correlation variables

$$\mathcal{L}_H = -g_{\mathrm{Ht\bar{t}}}\frac{m_\mathrm{t}}{v}\bar{\mathrm{t}}\mathrm{t}\mathrm{H},$$

$$\mathcal{L}_A = ig_{\mathrm{At\bar{t}}}\frac{m_\mathrm{t}}{v}\bar{\mathrm{t}}\gamma_5\mathrm{t}\mathrm{A}$$

**signal** **background**




signal model includes interference effects

# $2\ell$ Results*

similar excesses observed in $1\ell$ (backup)

138 fb$^{-1}$, Run 2 (13 TeV)

bins of $c_{hel}$ and $c_{han}$

$\frac{1}{3} < c_{han} < 1$
$\frac{1}{3} < c_{hel} < 1$

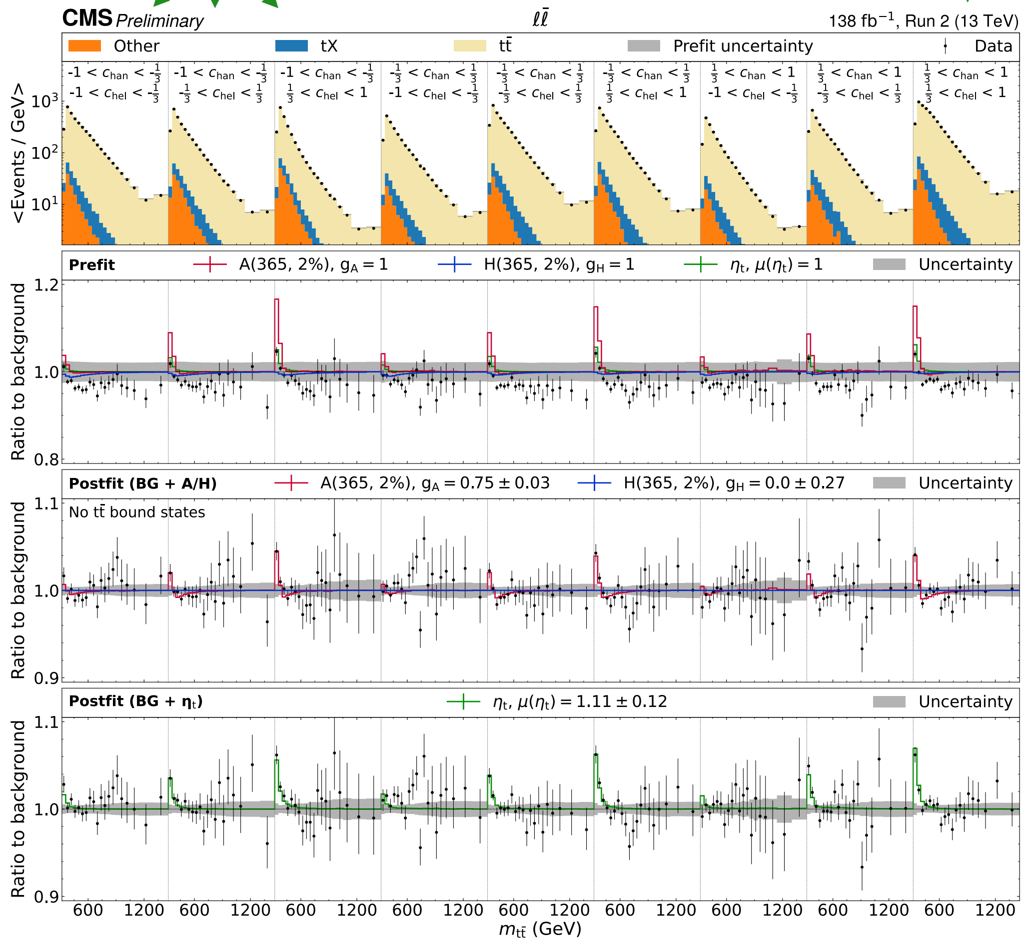
**data vs. background:**

**ratio of data to background:**

pre-fit

post-fit including **H** / **A** signal

post-fit including $\eta_t$ signal




$m_{t\bar{t}}$ [GeV]

# $2\ell$ Results

**>5σ excess**

near $m_{t\bar{t}} \sim 2m_t$ threshold

138 fb$^{-1}$, Run 2 (13 TeV)

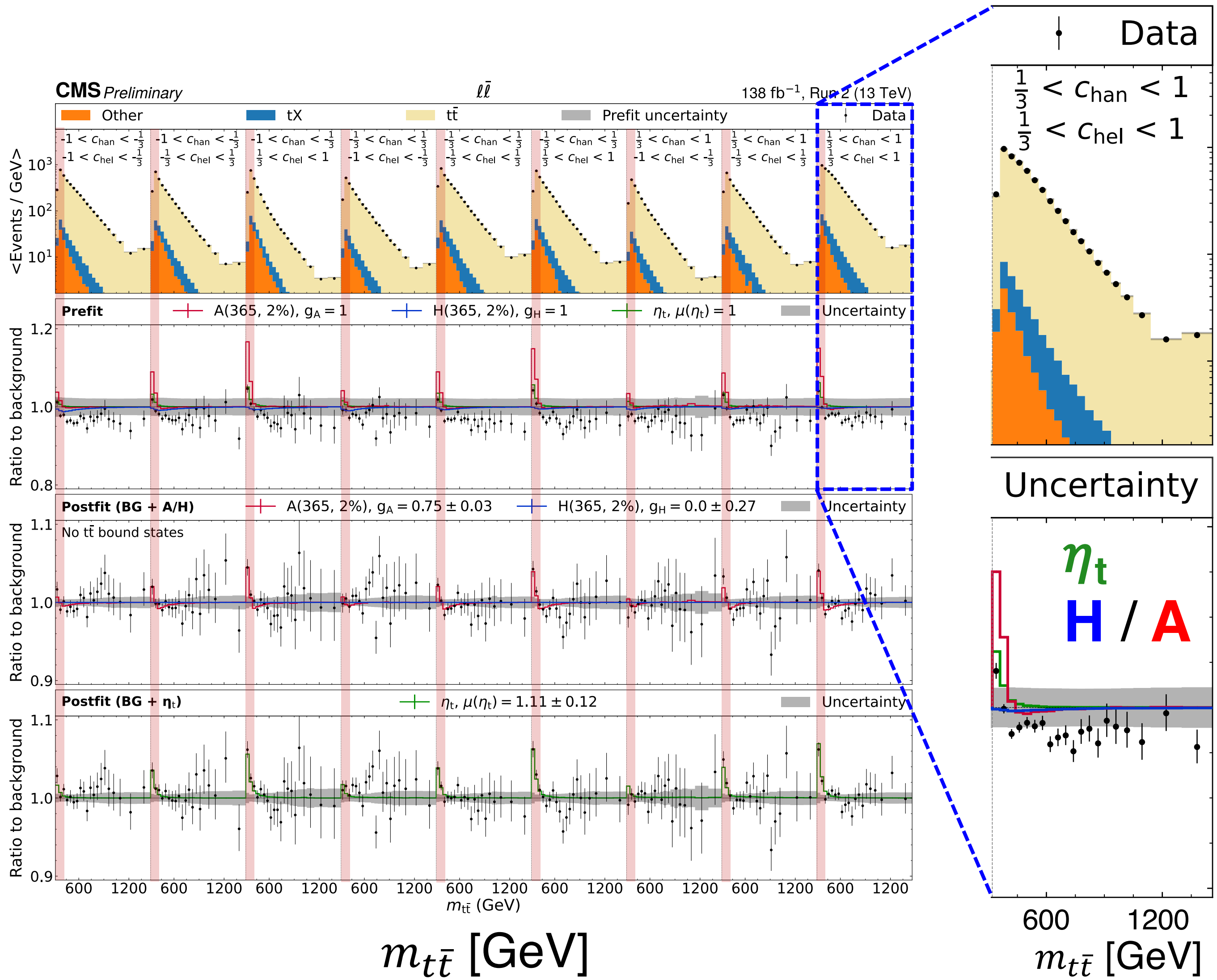
**data vs. background:**

**ratio of data to background:**

pre-fit

post-fit including **H** / **A** signal

post-fit including $\eta_t$ signal

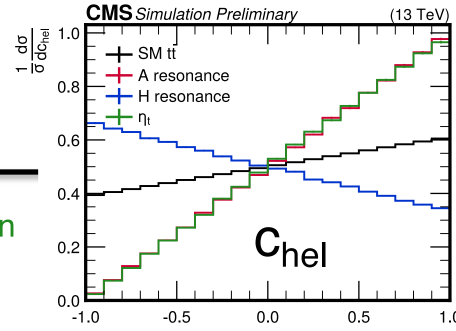


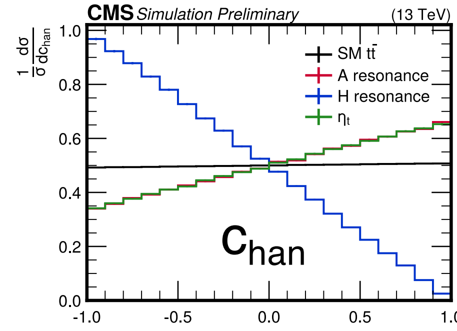
# toponium
[HIG-22-013](HIG-22-013)

# $2\ell$ Results

138 fb$^{-1}$, Run 2 (13 TeV)

bins of $c_{hel}$ and $c_{han}$




**data vs. background:**

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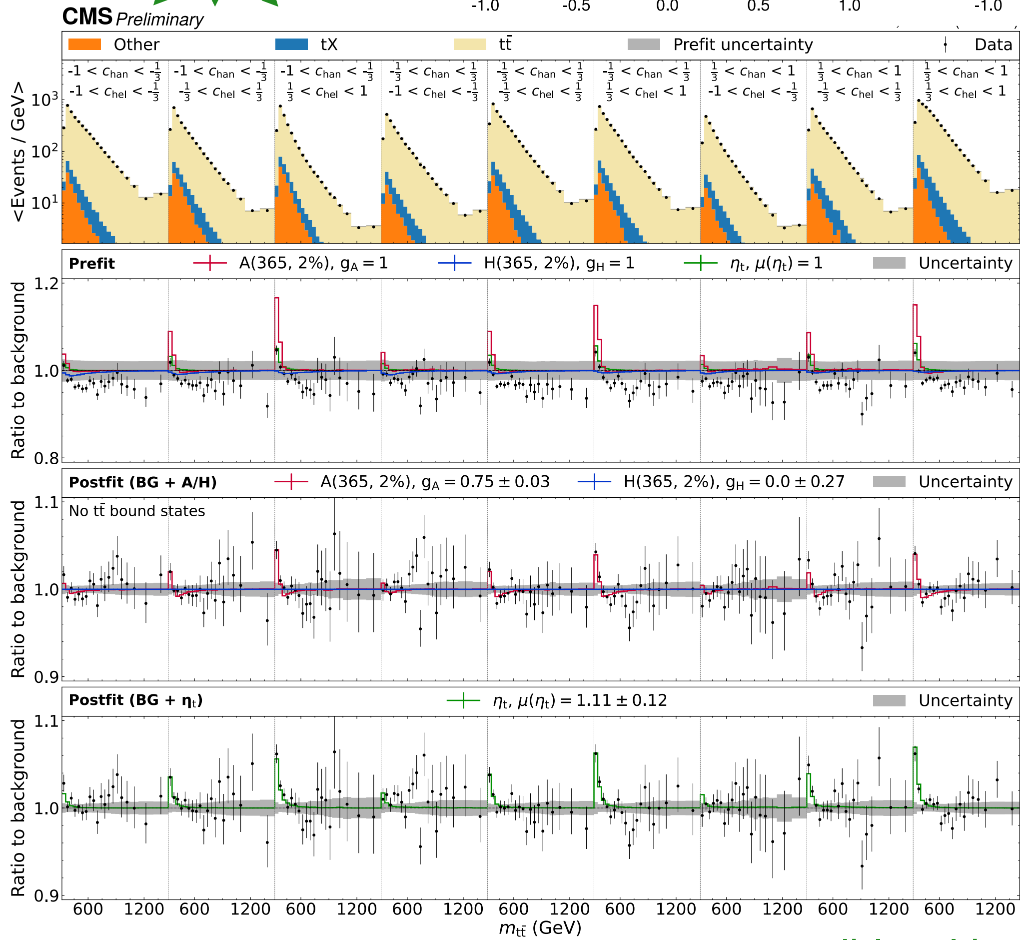



$m_{t\bar{t}}$ [GeV]

**pseudo-scalar** favored over **scalar**

A (365 GeV, 2%)
$g_A = 0.75 \pm 0.03$

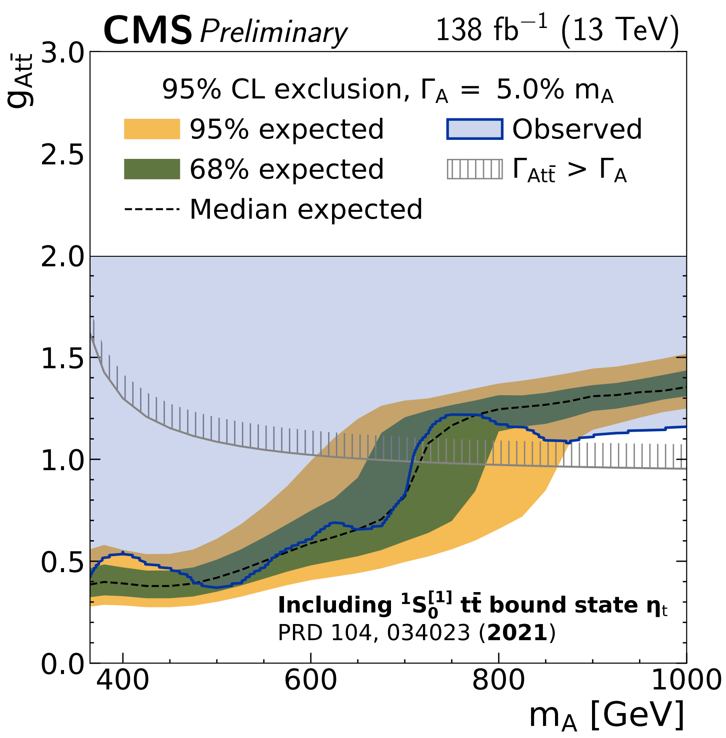
H (365 GeV, 2%)
$g_H = 0.0 \pm 0.27$

$\sigma = 7.1 \pm 0.7$ pb
$\mu = 1.11 \pm 0.12$

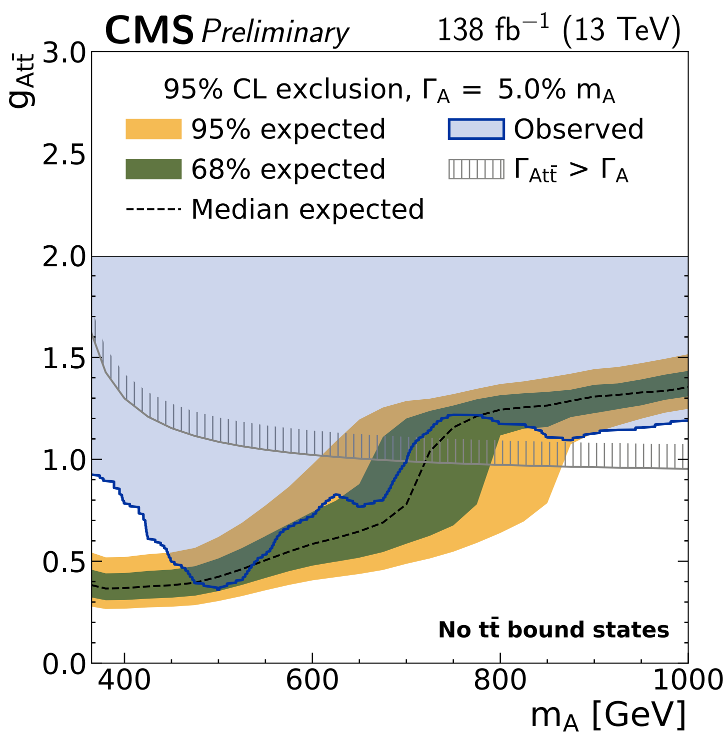
compatible with $\eta_t$ from a simplified [model](model) of non-relativistic QCD

# 2HDM Constraints

## with $t\bar{t}$ bound states




## no $t\bar{t}$ bound states



“toponium”
HIG-22-013

# Discussion and Summary

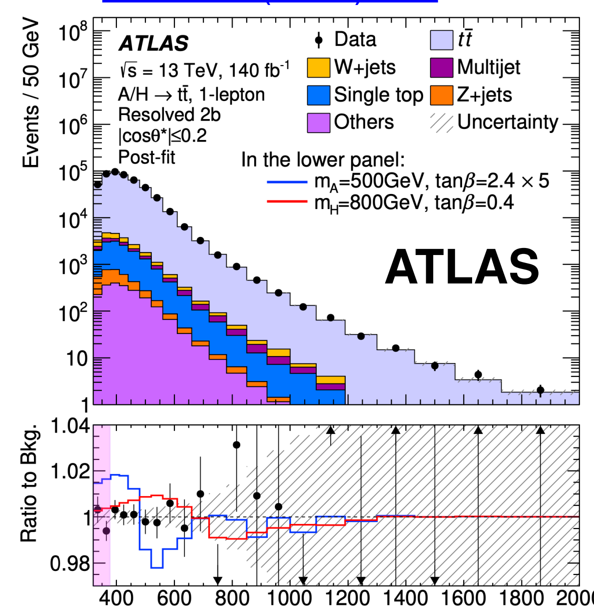
Sam Baxter
Higgs Hunting 2024

- **Summary of CMS observations**
  - **A full Run 2 CMS search for a (pseudo-)scalar boson has been performed** in the $2\ell$ and $\ell$+jets final states of $t\bar{t}$ using $m_{t\bar{t}}$ and angular and spin observables
  - **A >5σ local excess at low $m_{t\bar{t}}$ has been observed,** which fits better the **pseudoscalar** than scalar hypotheses
    - Excess also fits best to a model of **the $t\bar{t}$ bound state $\eta_t$**, with a fitted cross section of 7.1 ± 0.7 pb
    - **Stringent limits have been set** on the scalar and pseudoscalar signal models, with a floating normalization
- **Summary of ATLAS observations**
  - **No excess** observed in similar kinematic region at **low $m_{t\bar{t}}$**
    - Optimized for higher H/A masses
    - Search probes down to $m_{t\bar{t}} > 320$ GeV but limits are set only for $m_{t\bar{t}} > 400$ GeV region
    - Slightly different background modeling (e.g. ATLAS $m_{top}$ = 173.3 GeV vs. CMS $m_{top}$ = 172.5 GeV)

see CERN HEP seminar from Benjamin Fuks

and potential 2HDM explanation from Lu et al.

JHEP 08 (2024) 013




$m_{t\bar{t}}$ [GeV]

# Maxwell's Laws in Vacuum

**Gauss's Law for E**

$$\nabla \cdot \vec{E} = 0$$

**Gauss's Law for B**

$$\nabla \cdot \vec{B} = 0$$

**Ampere's Law**

$$\frac{1}{c^2}\frac{d\vec{E}}{dt} - \nabla\times\vec{B} = 0$$

**Faraday's Law**

$$\frac{d\vec{B}}{dt} + \nabla\times\vec{E} = 0$$

**symmetry** between E and B in vacuum

# Adding Electric Charge & Current

**Gauss's Law for E**

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

**Gauss's Law for B**

$$\nabla \cdot \vec{B} = 0$$

**Ampere's Law**

$$\frac{1}{c^2}\frac{d\vec{E}}{dt} - \nabla \times \vec{B} = -\mu_0 \vec{J}$$

**Faraday's Law**

$$\frac{d\vec{B}}{dt} + \nabla \times \vec{E} = 0$$

symmetry is **broken** by electric **charge** and **current**

# Adding Magnetic Charge & Current (?)

**Gauss's Law for E**

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

**Gauss's Law for B**

$$\nabla \cdot \vec{B} = \mu_0 \rho_M$$

**Ampere's Law**

$$\frac{1}{c^2}\frac{d\vec{E}}{dt} - \nabla \times \vec{B} = -\mu_0 \vec{J}$$

**Faraday's Law**

$$\frac{d\vec{B}}{dt} + \nabla \times \vec{E} = -\mu_0 \vec{J}_M$$

- Symmetry could be restored by magnetic **charges** and **currents** ⟶ not forbidden by *classical* E&M
- Dirac 1931: magnetic monopoles are consistent with quantum mechanics *iff* their charge is quantized: $g = \frac{2\pi\hbar}{\mu_0 e} n$
  - Force between 2 magnetic monopoles is **4700 times** larger than Coulomb force between 2 electrons!

# The Valentine's Day Monopole

- Search for **magnetic monopoles** passing through a **loop with 8 turns**
- **Valentine's Day 1982**: Blas Cabrera observed an event with precisely the **right magnitude of flux** expected for a monopole!

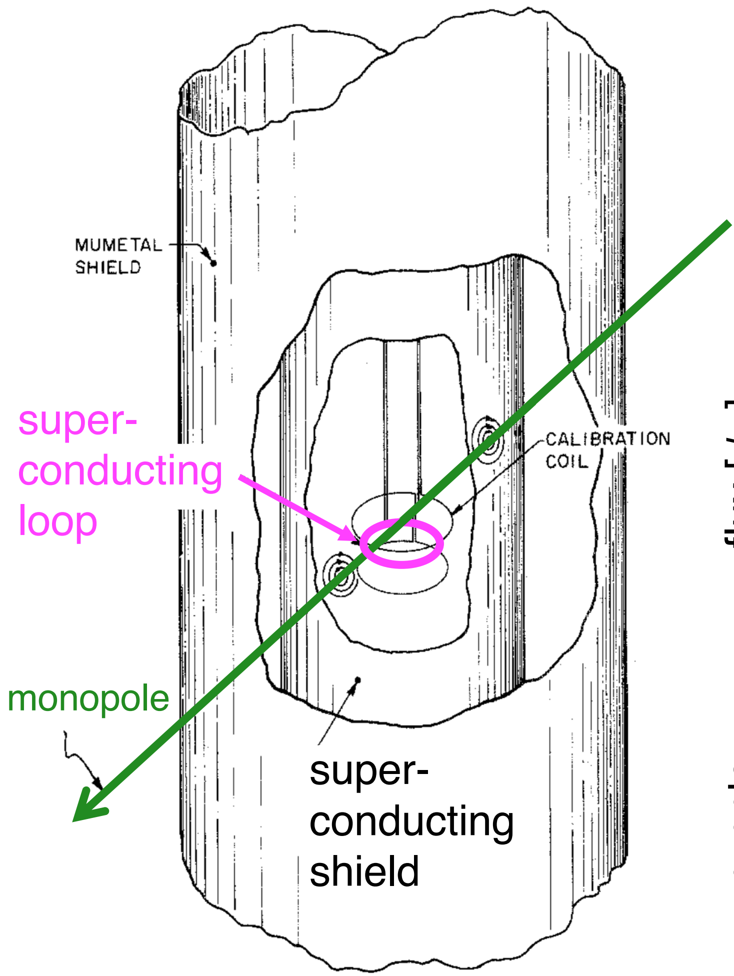
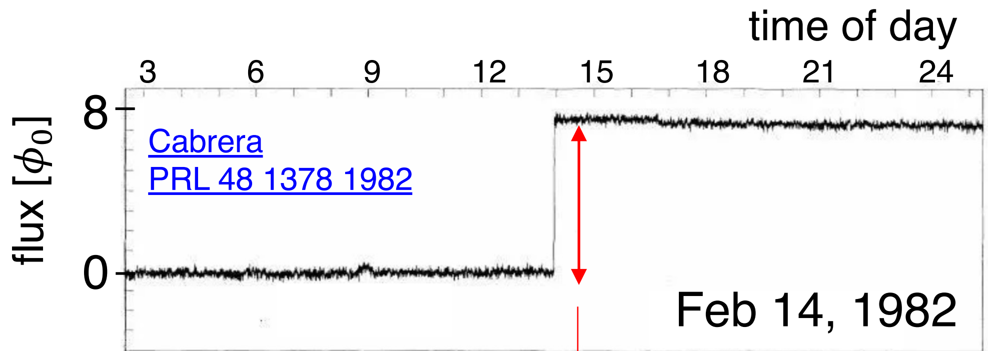
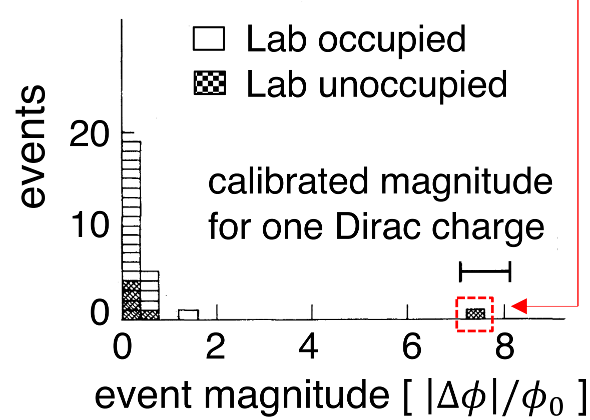



Fig. 3. Schematic of the dynamic monopole detector.

Cabrera and Trower



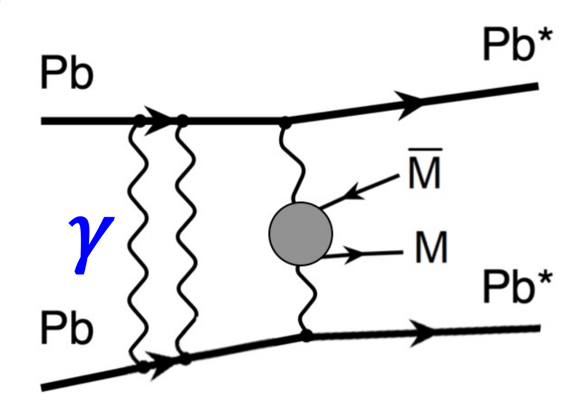




*Roses are red, violets are blue,*
*It's time for monopole number 2!*

- Steven Weinberg
Valentine's Day 1983

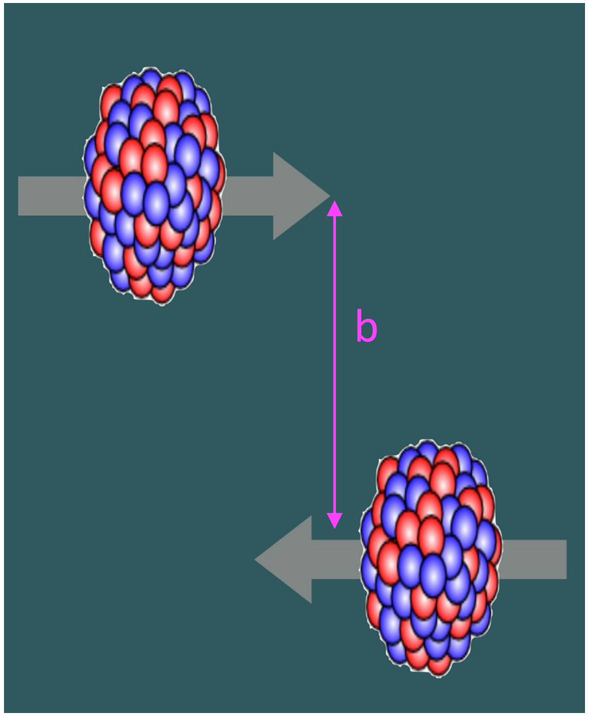
***Search for more monopoles in ATLAS!***

# Magnetic Monopole Search Strategy



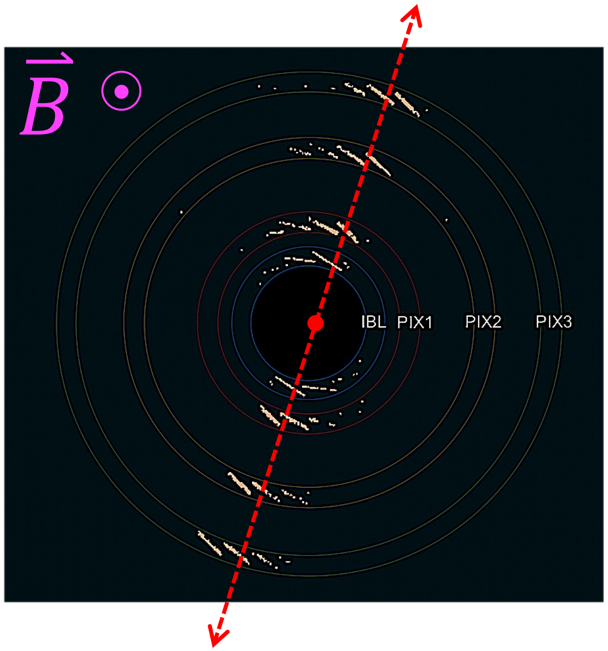

- Magnetic monopoles are produced by EM interactions ⟶ enhanced by $Z^4$ = $82^4$ ~ 45 million in **Pb-Pb collisions**

- Central collisions (small impact parameter, b) are dominated by strong processes ⟶ search in **ultra-peripheral collisions (UPC)**

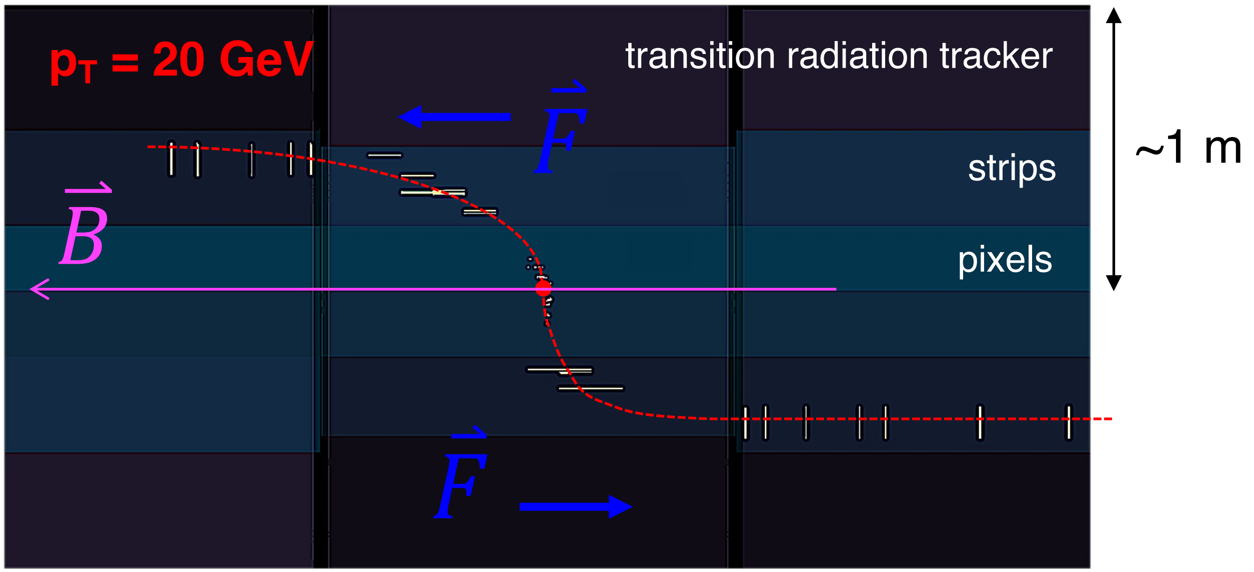


# Magnetic Monopoles in ATLAS

$r\phi$ view




$rz$ view




- $F_{r\phi} = 0$ → no bending in the $r - \phi$ plane

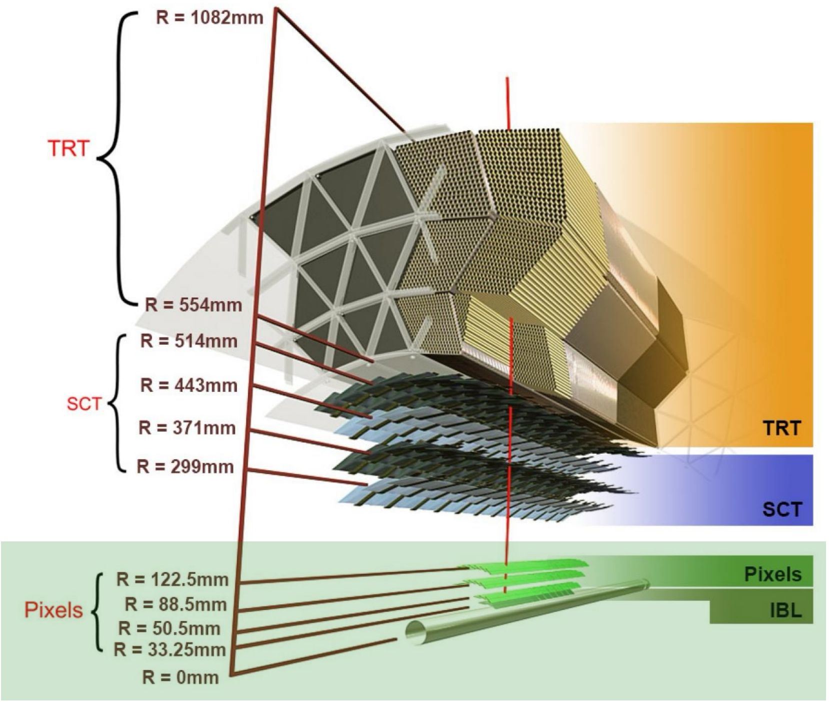
$$\vec{F} = q_M\left(\vec{B} - \frac{1}{c^2}\vec{v}\times\vec{E}\right) = q_M\vec{B}$$

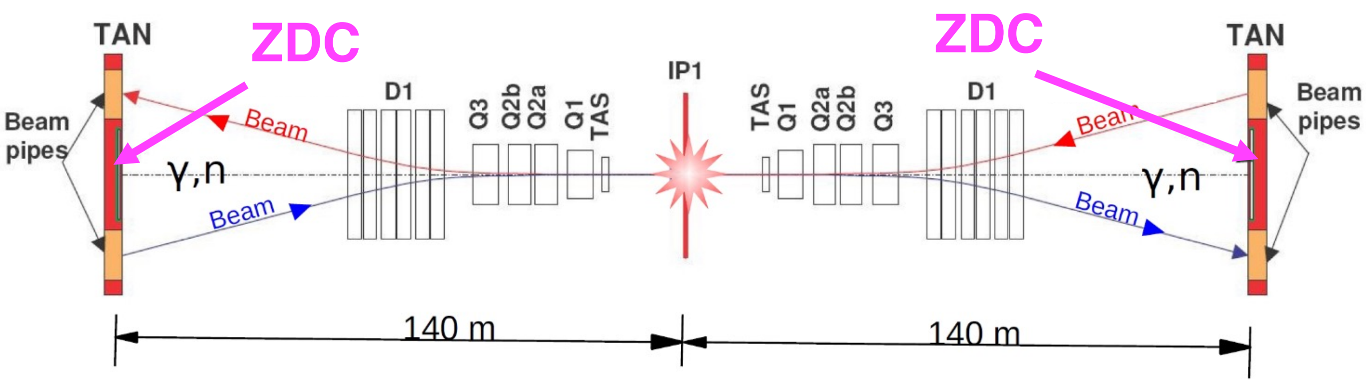
- $\vec{F} = q_M B\hat{z}$ → parabolic $r - z$ trajectory (like a projectile)
- Strong bending → main focus on **pixel activity**

# Magnetic Monopole Selections

- Large activity in **pixels / IBL**
- Significant activity in far-forward Zero Degree Calorimeter (ZDC) due to *spectator* neutrons
- Define signal region with high "transverse thrust" *T > 0.95:*

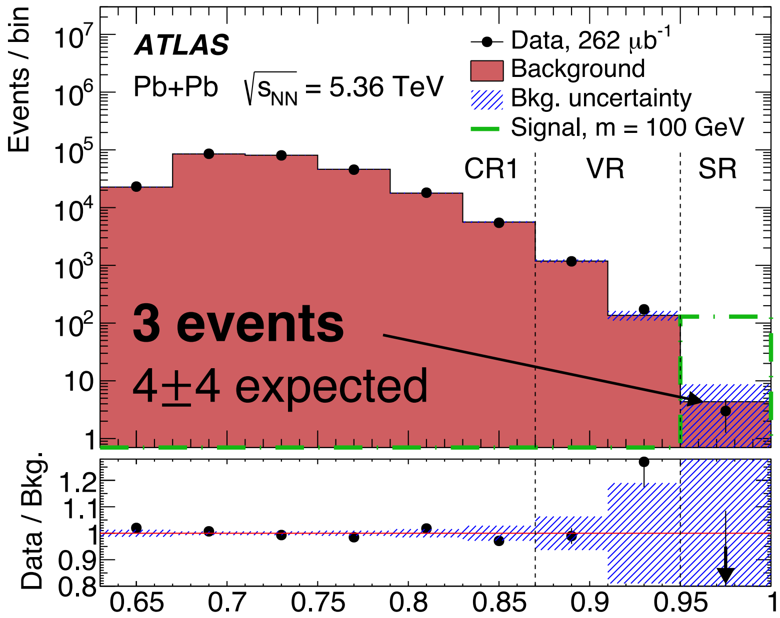
$$T = (1/n_{\text{PixCl}}) \sum_{i=1}^{n_{\text{PixCl}}} |\hat{r}_i \cdot \hat{n}|$$

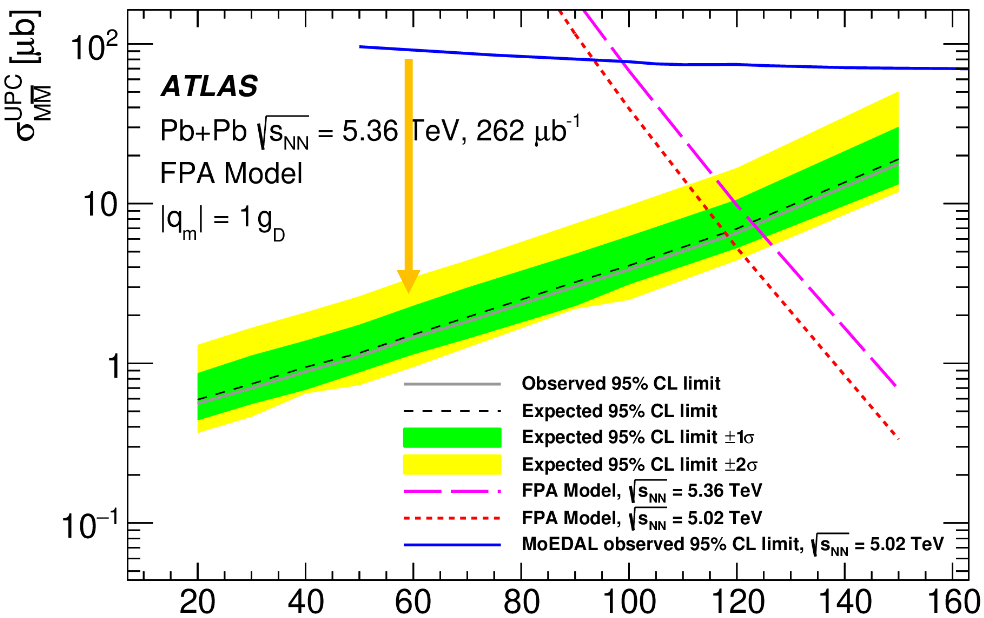


# Magnetic Monopole Results

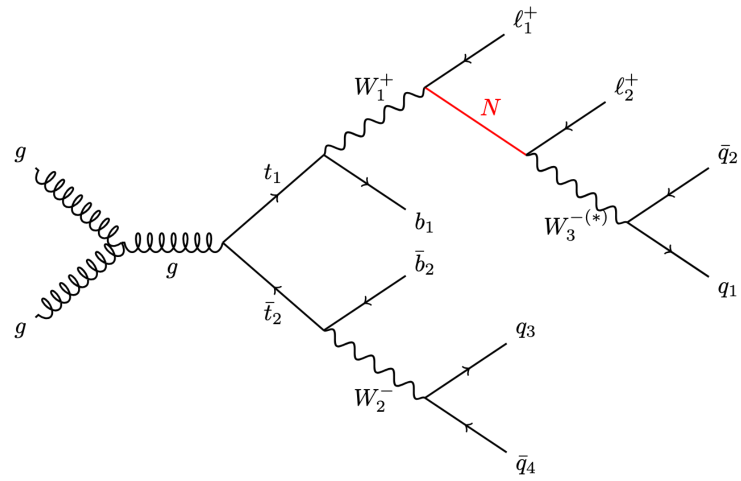
- **No excess** observed in signal region
- Exclude **monopoles below 120 GeV** in FPA model and improve $\sigma_{UL}$ from prior MoEDAL constraints by up to ~100×

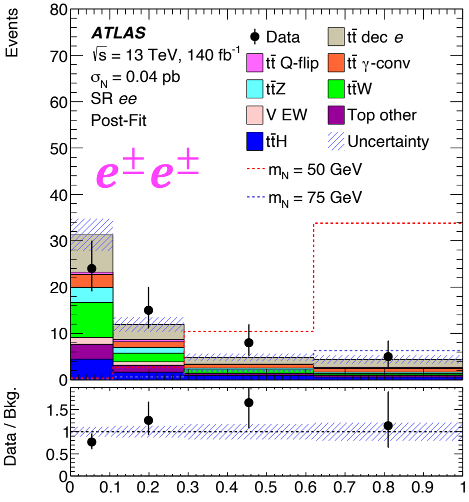


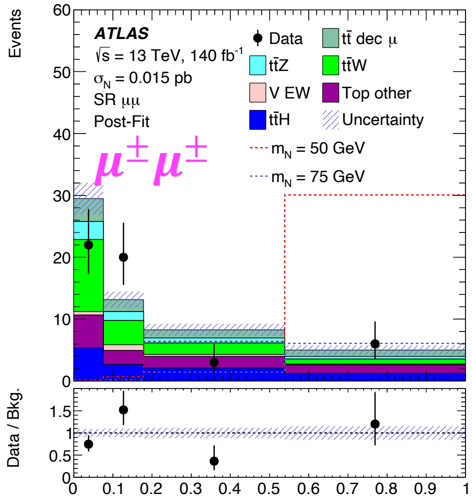
# Heavy Neutral Leptons Search

- Neutrino masses could be explained by Type 1 Seesaw with **3 Heavy Neutral Lepton (HNL)** Majorana neutrinos, which violate lepton conservation ($|\Delta L = 2|$)
- Perform first search for 15-75 GeV HNLs in $t\bar{t}$ **events**
- Require semi-leptonic decays yielding a pair of **same-charge same-flavor leptons**
- Enhance sensitivity with multi-variate Boosted Decision Tree
- No excess in either flavor channel






High mass BDT output



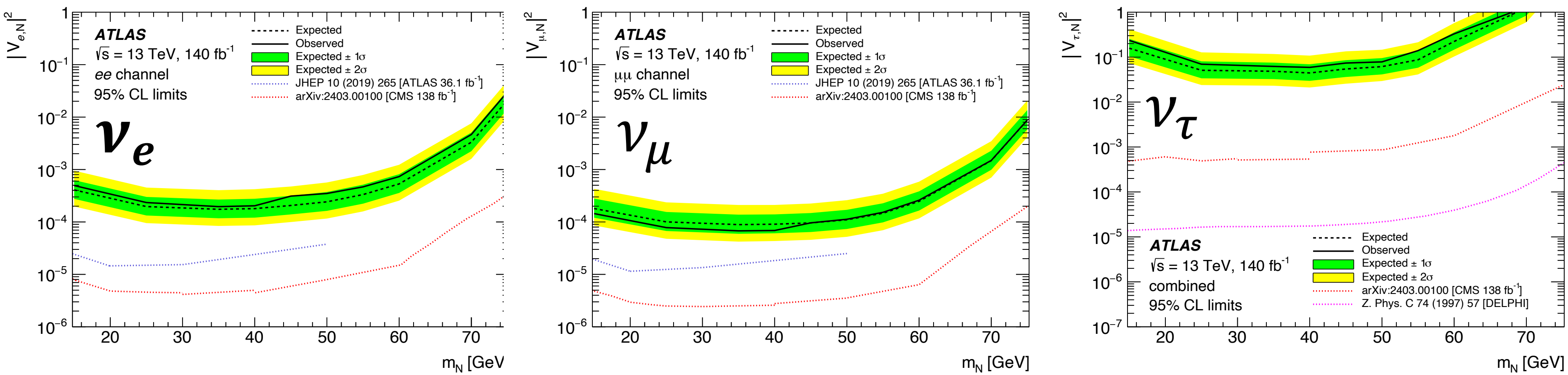

High mass BDT output

# Constraints on Heavy Neutral Leptons

- Benchmark model has single HNL candidate $N$ coupling either to $\nu_e$, $\nu_\mu$, or $\nu_\tau$ via mixing matrix:

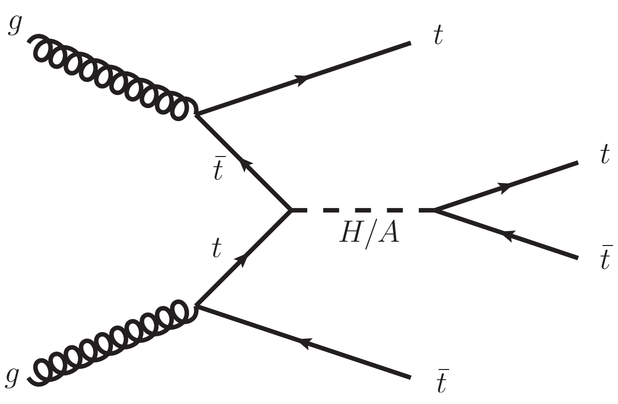
$$V_{\ell,N} = \begin{pmatrix} V_{e,N} & 0 & 0 \\ 0 & V_{\mu,N} & 0 \\ 0 & 0 & V_{\tau,N} \end{pmatrix}$$

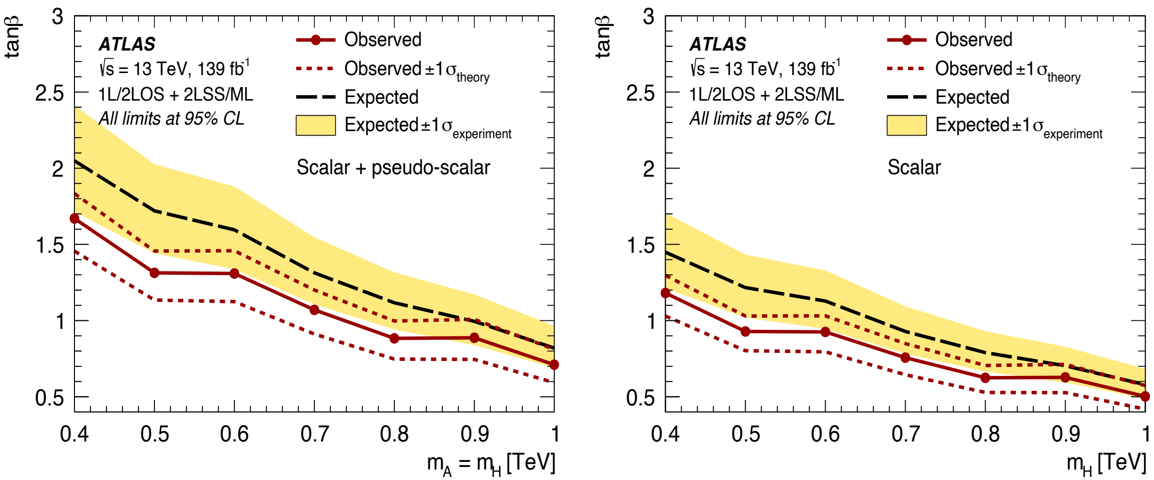
- Set constraints on squared couplings $|V_{\ell,N}|^2$ for $15 < m_N < 75$ GeV



# tt(H/A) ⟶tttt Search

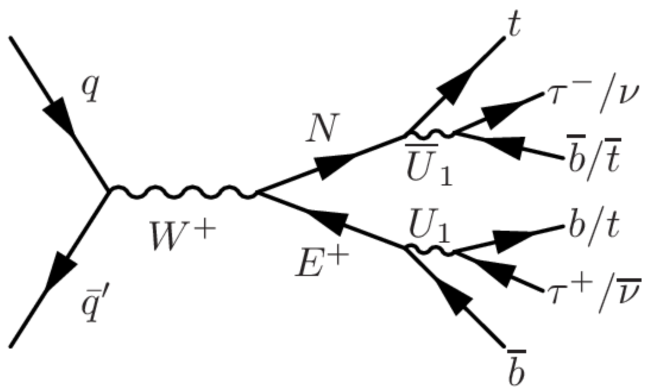
- SM Higgs is a complex doublet
  ⟶ 4 d.o.f. ⟶ 3 d.o.f. are "eaten" by
  $W^+$, $W^-$, and $Z^0$ ⟶ **1 physical Higgs**
- Many BSM scenarios introduce
  2nd Higgs doublet ⟶ 8 d.o.f.
  ⟶ 3 d.o.f. are "eaten" by $W^+$, $W^-$, and $Z^0$
  ⟶ **4 extra physical Higgs bosons:**
  - 2 neutral: H, A ← search for these
  - 2 charged: $H^+$ $H^-$
- Results exclude
  $\tan\beta < 1.7$ ($m_{H/A} = 400$ GeV),
  $\tan\beta < 0.7$ ($m_{H/A} = 1000$ GeV)

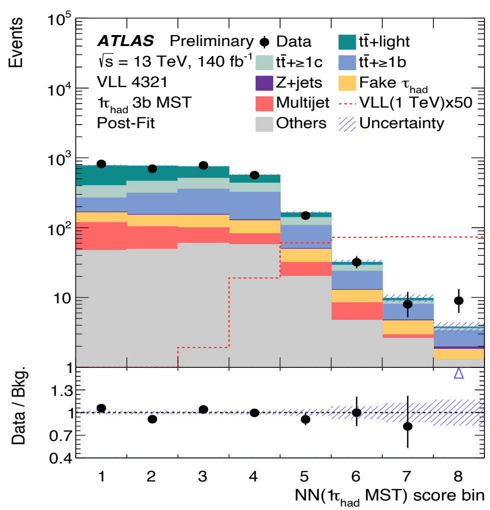


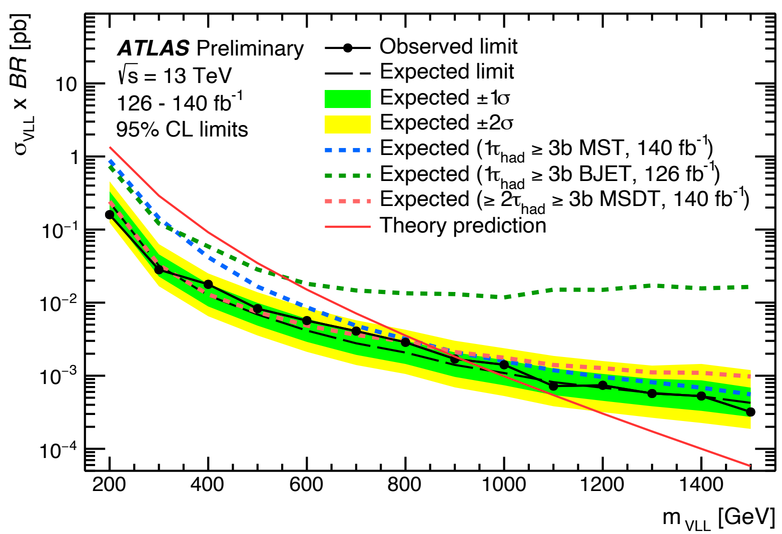



# Vector-Like Leptons with Taus

- Search for **vector-like leptons** (VLL) decaying to leptoquark ($U_1$) and 3[rd] gen quarks (4321 model) decaying to tau leptons
- Enhance sensitivity with multi-variate Neural Network discriminant
- No excess → **exclude $m_{VLL}$ < 910 GeV**

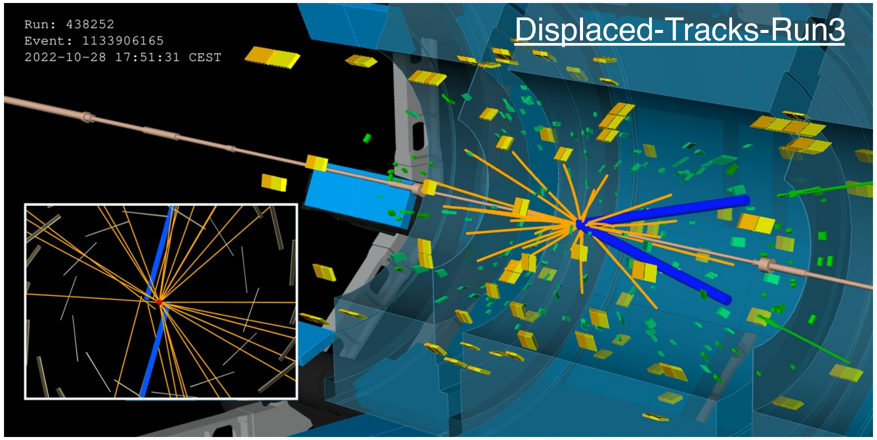


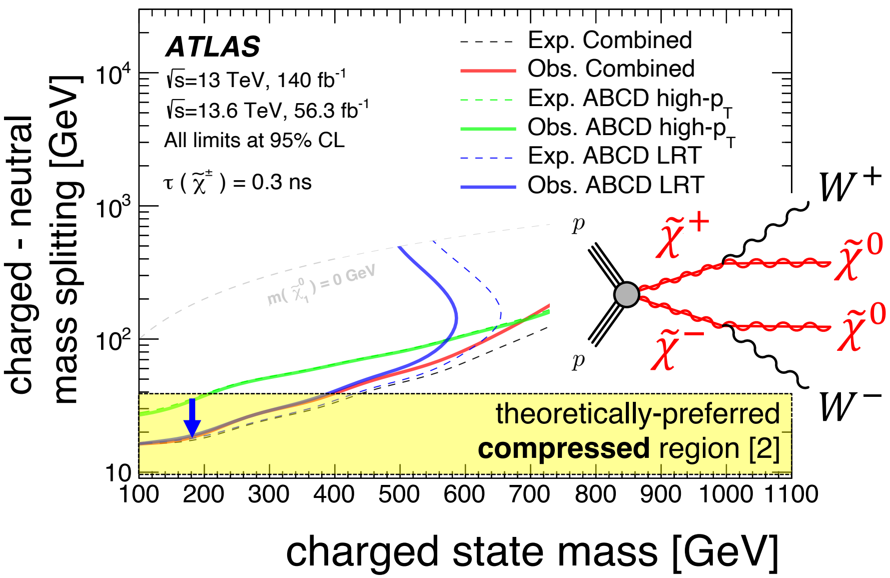
**displaced leptons**
CERN-EP-2024-257
[1] Filimonova and Westhoff
[2] Blekman, Desai, Filimonova, Sahasransu, Westhoff

# Displaced Leptons

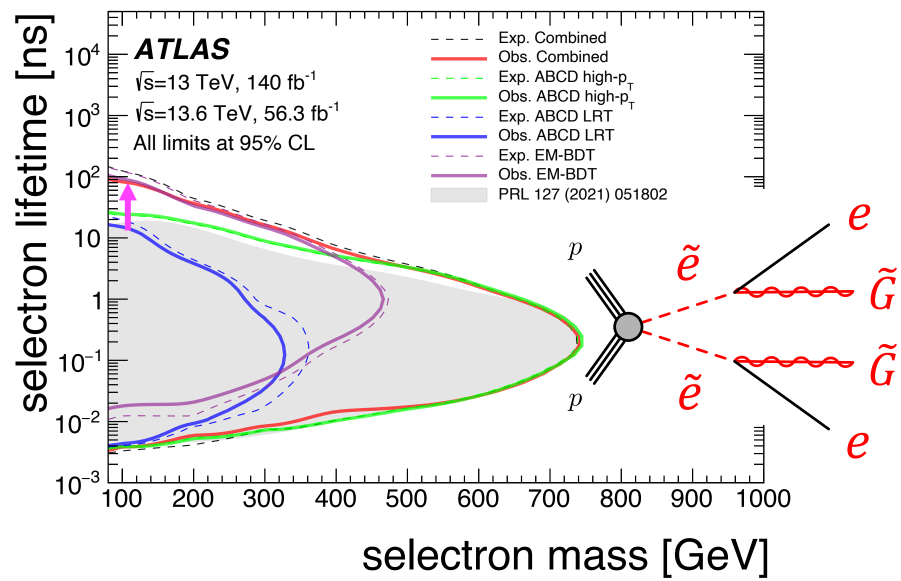



- **First ATLAS 13.6 TeV BSM search!**
- New **Large Radius Tracking** triggers enhance sensitivity to **low $p_T$ leptons**
  - First constraints on a compressed dark sector Higgs portal model! [1,2]
- New **e/γ Boosted Decision Tree** enhances sensitivity to **long-lived selectrons**

[1] Long live the Higgs portal!




**long-lived GMSB selectrons**



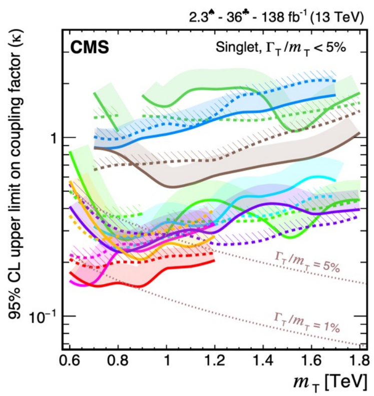


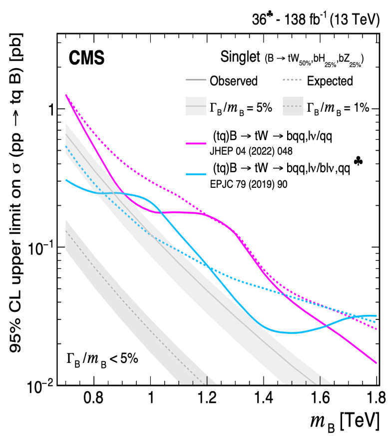
**see more in Ian's BSM parallel talk Wed evening!**

# Review of VLQ / VLL / HNL Searches

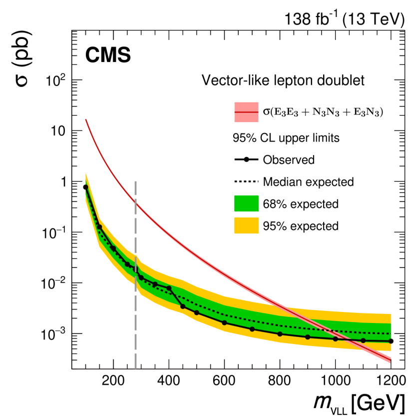
- Comprehensive program of searches in wide variety of signatures provides stringent constraints on several scenarios!

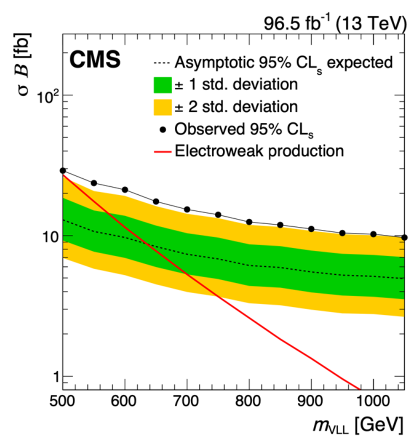
## Vector-like quarks



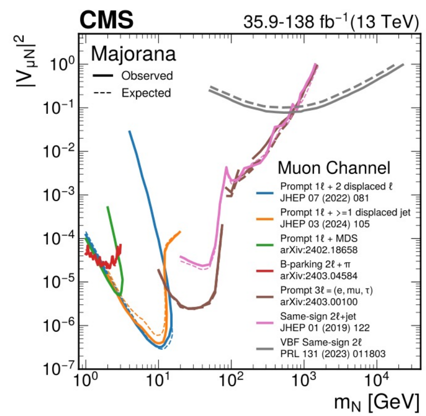



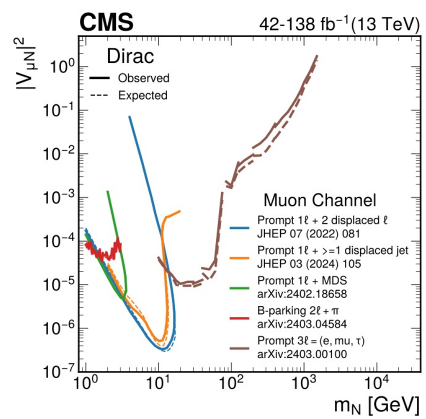

## Vector-like leptons



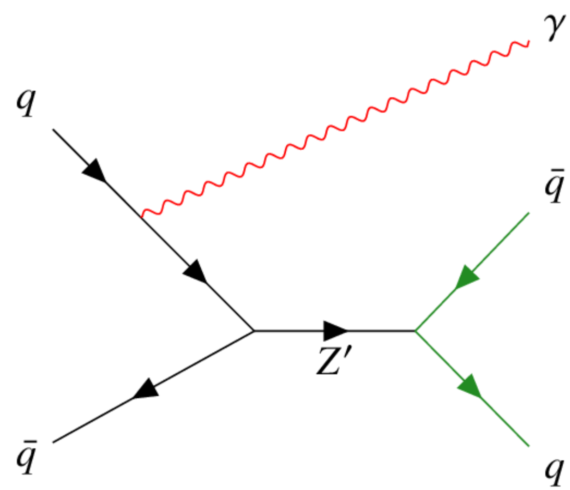

## Heavy neutral leptons

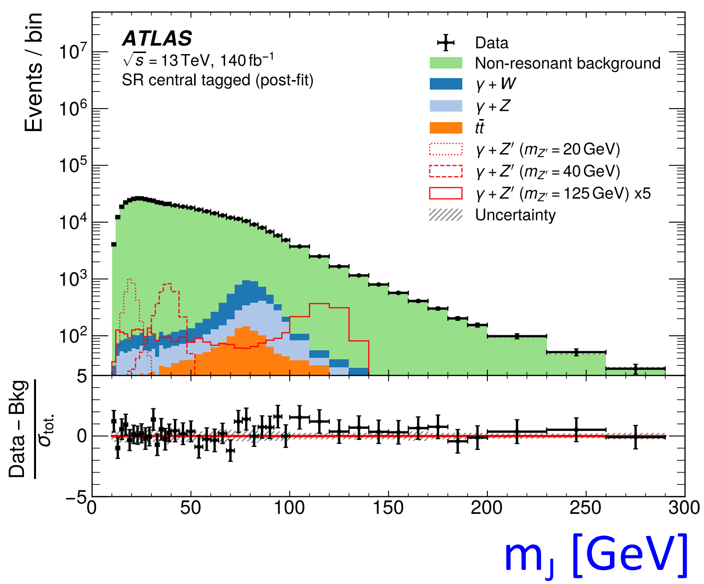


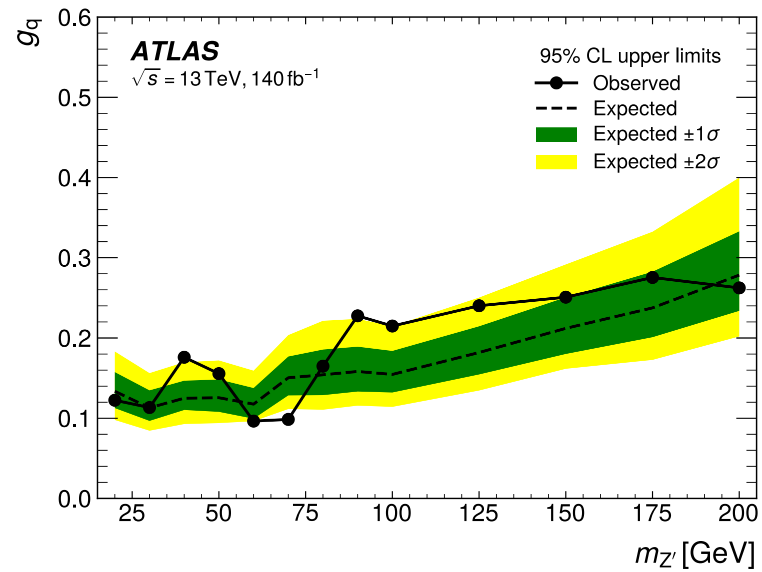



# ISR photon + boosted dijet Search

- Search for low-mass boosted hadronically-decaying resonances
- Trigger on **photon** due to high hadronic rates
- Search for bumps in the **fat jet invariant mass distribution** tagging 2-pronged jet substructure
- Set constraints on Z' couplings for 20-200 GeV → **first ATLAS sensitivity to $m_{Z'}$ < 100 GeV!**

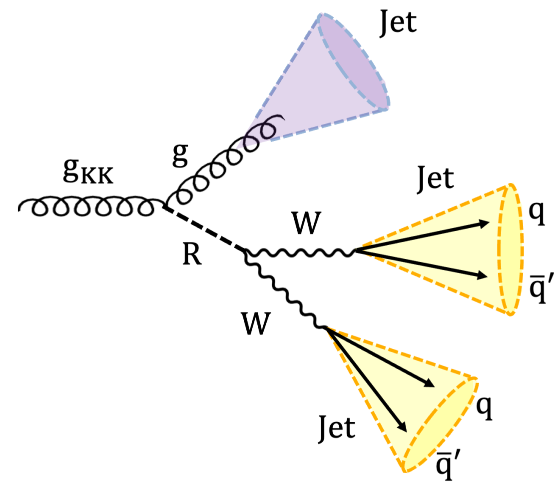


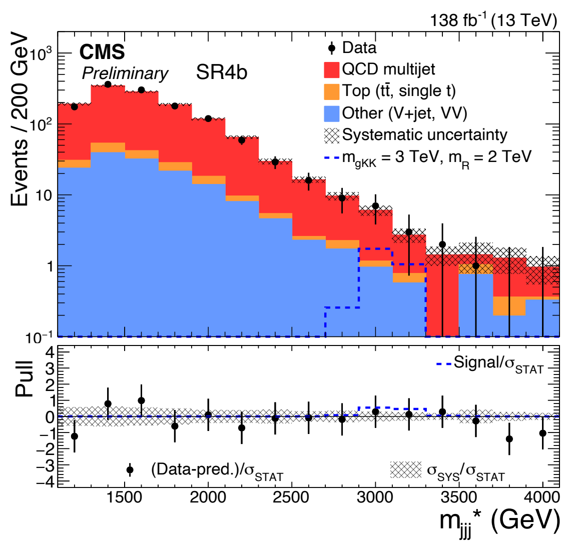



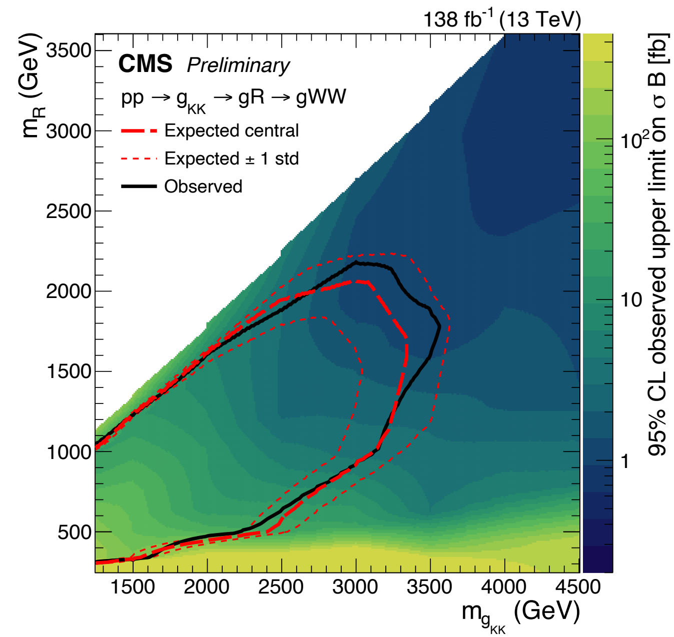



# Kaluza Klein Gluon Resonances

- Search for KK gluon resonance $g_{KK}$ decaying to gluon + radion R, R decays 2 X $W \rightarrow q\bar{q}'$
- Define signal regions based on ratio of masses of dijet (R) / trijet ($g_{KK}$) and ParticleNet tagger score based on *particle clouds*
- Search for signal in trijet mass $m_{jjj^*}$
- No excess → probe $g_{KK}$ masses up to 3.5 TeV

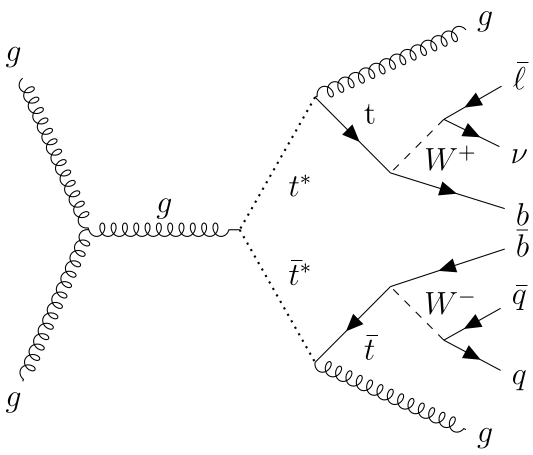


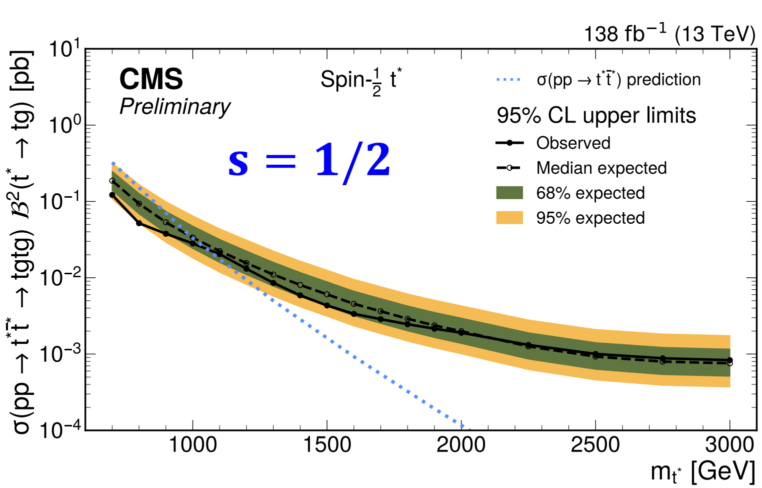



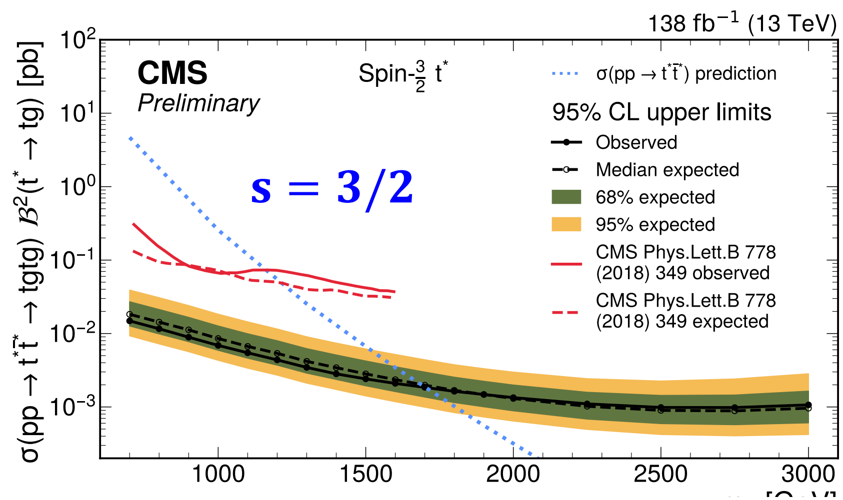



# Heavy Resonances → top + gluon

- Search for pair production of new heavy resonances decaying to top + gluon in 1ℓ final state
- Select events with e/μ + jets + $E_t^{miss}$ and search for excess at high scalar sum of transverse momentum ($S_T$)
- No excess → exclude t* masses up to 1050 GeV ($s = 1/2$) and 1700 GeV for ($s = 3/2$)



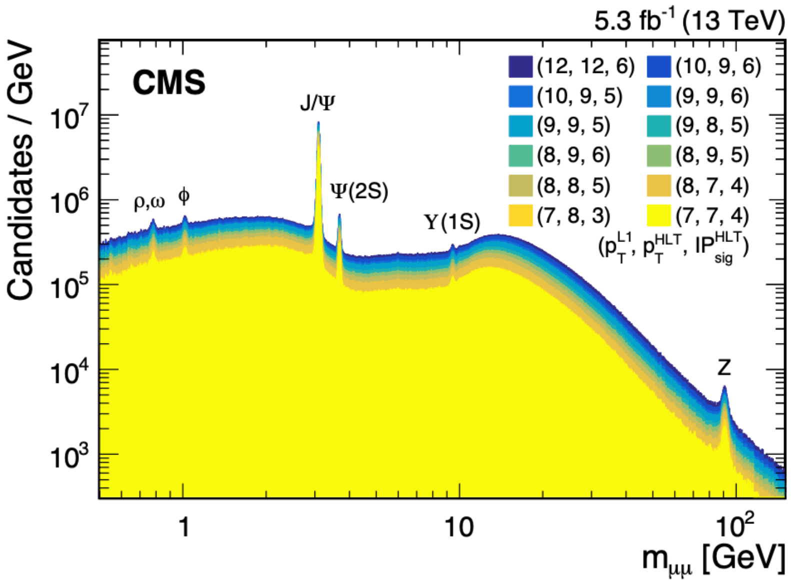


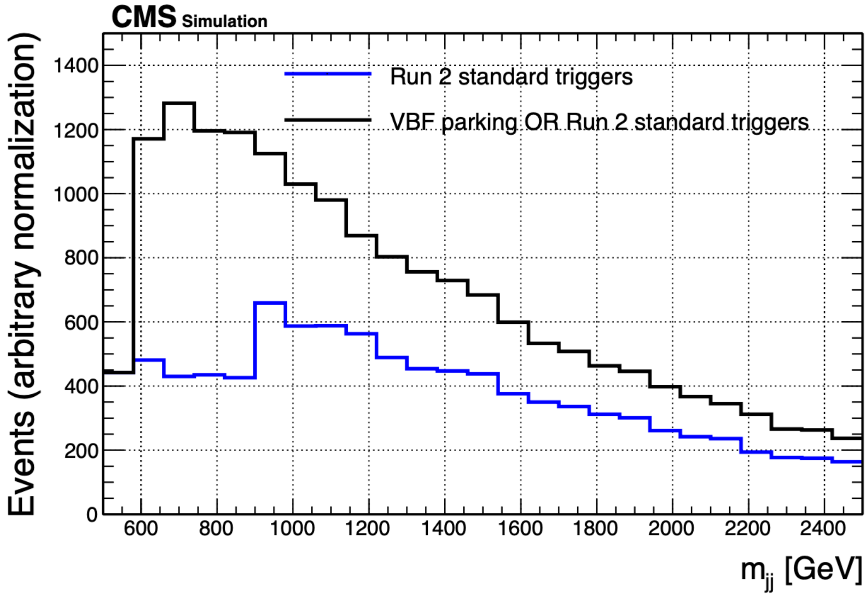
# Data Parking & Scouting

- Event rate stored for offline analysis is limited by offline reconstruction and data storage constraints
- 2 methods circumvent constraints to allow for reduced thresholds
  - **Data scouting**: ***no offline reco***, store High-Level Trigger objects (since Run 2)
  - **Data parking**: ***delay offline reco*** (developed substantially for Run 3)

vertexed dimuons
Run 2 parked data




$m_{jj}$ for VBF H ⟶ invisible
Run 3 simulation



# Recent ATLAS Exotics Results

| Subgroup | Search | Reference |
|---|---|---|
| UEH | magnetic monopoles | 2408.11035 briefing ★ |
| UEH | displaced jets | 2407.09183 Lisa |
| UEH | lepton jets | 2407.09168 |
| HQT | VLQ T/Y→Wb | 2409.20273 |
| HQT | tt H/A → tttt | 2408.17164 |
| HQT / TOPQ | Heavy neutrinos search in $t\bar{t}$ | 2408.05000 ★ |
| HQT | VLQ combination | 2408.08789 Adrian |
| LPX | vector-like leptons | CONF-2024-08 ★ |
| JDM | mono S(bb) | 2407.10549 Sam |
| JDM | boosted ISR dijet | 2408.00049 ★ |

ExoticsPublicResults

UEH = Unconventional Signatures & Exotic Higgs

HQT = Heavy Quarks, Top and Composite Higgs

LPX = Leptons, Z’, W’, and LFV

JDM = Jets and Dark Matter

CMS

# Recent CMS B2G / SUS / EXO Results

| Group | Search | Reference |
|---|---|---|
| B2G | Higgs bosons from heavy resonances | 2403.16926 Sam |
| B2G | $t^*t^* \rightarrow$ tg tg ($1\ell$) | B2G-22-005 |
| B2G | $g_{KK} \rightarrow$ g R, R→WW | B2G-23-004 |
| B2G | A → ZH → $\ell\ell$ ttbar ($0\ell$) | B2G-23-006 Sam |
| B2G | Z' → $Z(\ell\ell)$H(qq / cc) | B2G-23-008 |
| SUS | phenomenological MSSM | SUS-24-004 Sam |
| SUS | $H \rightarrow a_1 a_1 \rightarrow 4\tau$ / $2\tau 2\mu$ | SUS-24-002 Sam |
| EXO | Review of dark sectors | 2405.13778 Daniele |
| EXO | Long-lived vector-like leptons | EXO-23-015 Lisa |
| EXO | Displaced jets | 2409.10806 Daniele |
| EXO | Data parking / scouting | 2403.16134 |
| EXO | Long-lived dimuons | JHEP 05 (2024) 047 Lisa |
| EXO | Vector-like quarks & leptons and heavy neutral leptons | 2405.17605 |

B2G = Searches for BSM particles decaying to top quarks and Higgs and Gauge bosons

SUS = Searches for new physics in final states with Unbalanced $p_T$ and Standard objects

EXO = Searches for Exotica

# A Lesson From History (?)

1864

**“Maxwell’s” Laws**

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon} \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt} \qquad \vec{\nabla} \times \vec{B} = \epsilon_0 \mu_0 \frac{d\vec{E}}{dt}$$

# A Lesson From History (?)

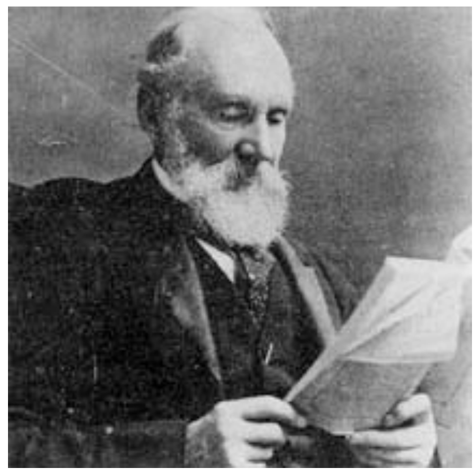
1864 — 1900

**“Maxwell’s” Laws**

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\epsilon} \qquad \vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{d\vec{B}}{dt} \qquad \vec{\nabla}\times\vec{B} = \epsilon_0\mu_0\frac{d\vec{E}}{dt}$$

**wrapping up?**



“There is nothing new to be discovered in physics now.
All that remains is more and more precise measurement.”

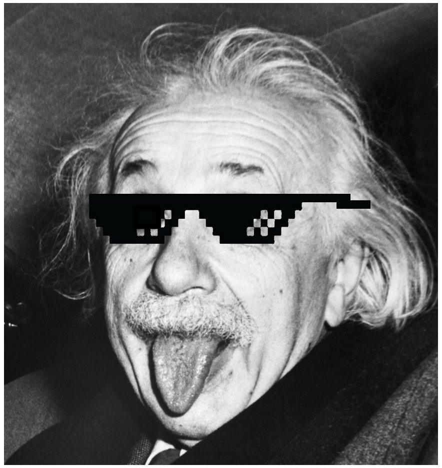
- Lord William Thomson Kelvin

# A Lesson From History (?)

| 1864 | 1900 | 1905 |
|---|---|---|
| **“Maxwell’s” Laws** | **wrapping up?** | ***spacetime is <u>relative</u>!!!*** |

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon} \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt} \qquad \vec{\nabla} \times \vec{B} = \epsilon_0 \mu_0 \frac{d\vec{E}}{dt}$$



3. *Zur Elektrodynamik bewegter Körper;*
*von A. Einstein.*

# A Lesson From History (?)

1864 — "Maxwell's" Laws

1900 — **wrapping up?**

1905 — ***spacetime is relative!!!***

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\epsilon} \qquad \vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{d\vec{B}}{dt} \qquad \vec{\nabla}\times\vec{B} = \epsilon_0\mu_0\frac{d\vec{E}}{dt}$$

take curl of both sides

$$\vec{\nabla}\times\vec{\nabla}\times\vec{E} = -\frac{d}{dt}\vec{\nabla}\times\vec{B}$$

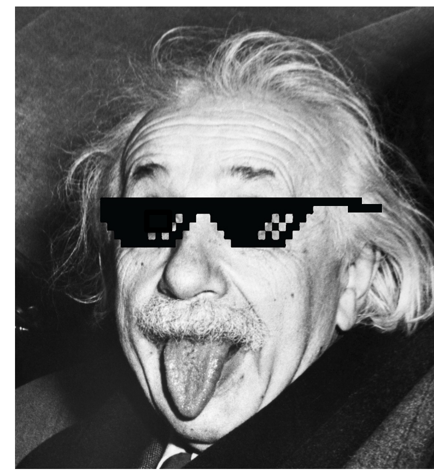
vector identity

$= \rho/\varepsilon_0 =$ 0 in vacuum

$$\vec{\nabla}(\vec{\nabla}\cdot\vec{E}) - \vec{\nabla}^2\vec{E} = -\frac{d}{dt}\epsilon_0\mu_0\frac{d\vec{E}}{dt}$$

$$\vec{\nabla}^2\vec{E} = \epsilon_0\mu_0\frac{d^2\vec{E}}{dt^2}$$

let there be ***light*** !



3. ***Zur Elektrodynamik bewegter Körper;***
***von A. Einstein.***

# A Lesson From History (?)

1864 — 1900 — 1905

**"Maxwell's" Laws**

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\epsilon} \qquad \vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{d\vec{B}}{dt} \qquad \vec{\nabla}\times\vec{B} = \epsilon_0\mu_0\frac{d\vec{E}}{dt}$$

take curl of both sides

$$\vec{\nabla}\times\vec{\nabla}\times\vec{E} = -\frac{d}{dt}\vec{\nabla}\times\vec{B}$$

vector identity

$= \rho/\varepsilon_0 =$ 0 in vacuum

$$\vec{\nabla}(\vec{\nabla}\cdot\vec{E}) - \vec{\nabla}^2\vec{E} = -\frac{d}{dt}\epsilon_0\mu_0\frac{d\vec{E}}{dt}$$

$$\vec{\nabla}^2\vec{E} = \epsilon_0\mu_0\frac{d^2\vec{E}}{dt^2}$$

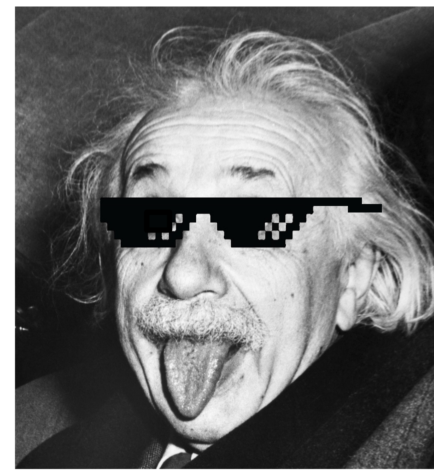
let there be ***light*** !

$$c = \frac{1}{\sqrt{\epsilon_0\mu_0}}$$

… propagating at a fixed ***constant*** speed!!!

**wrapping up?**

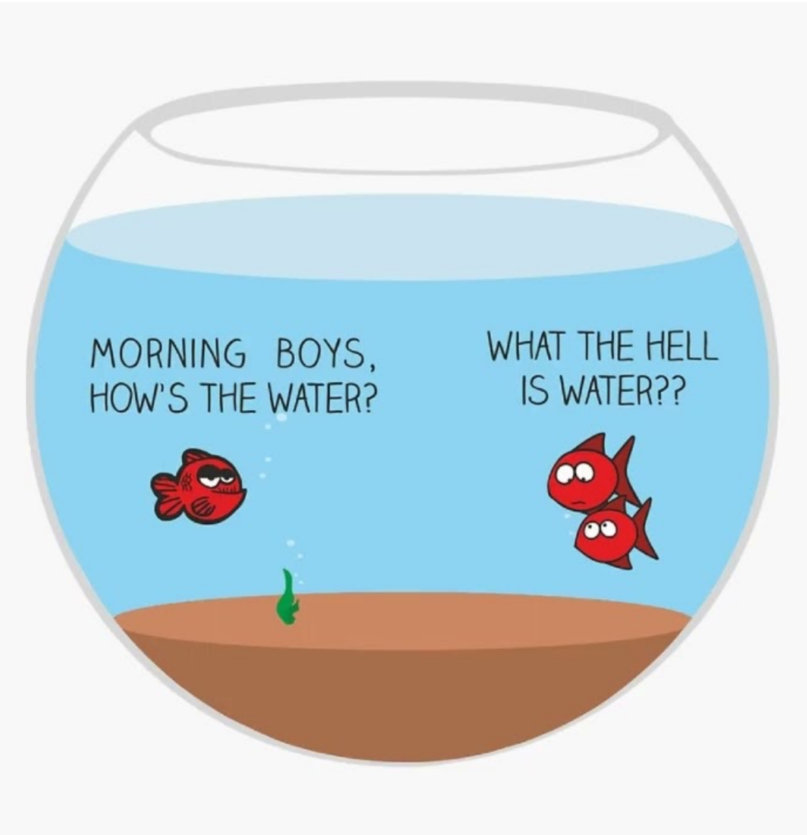
***spacetime is relative!!!***

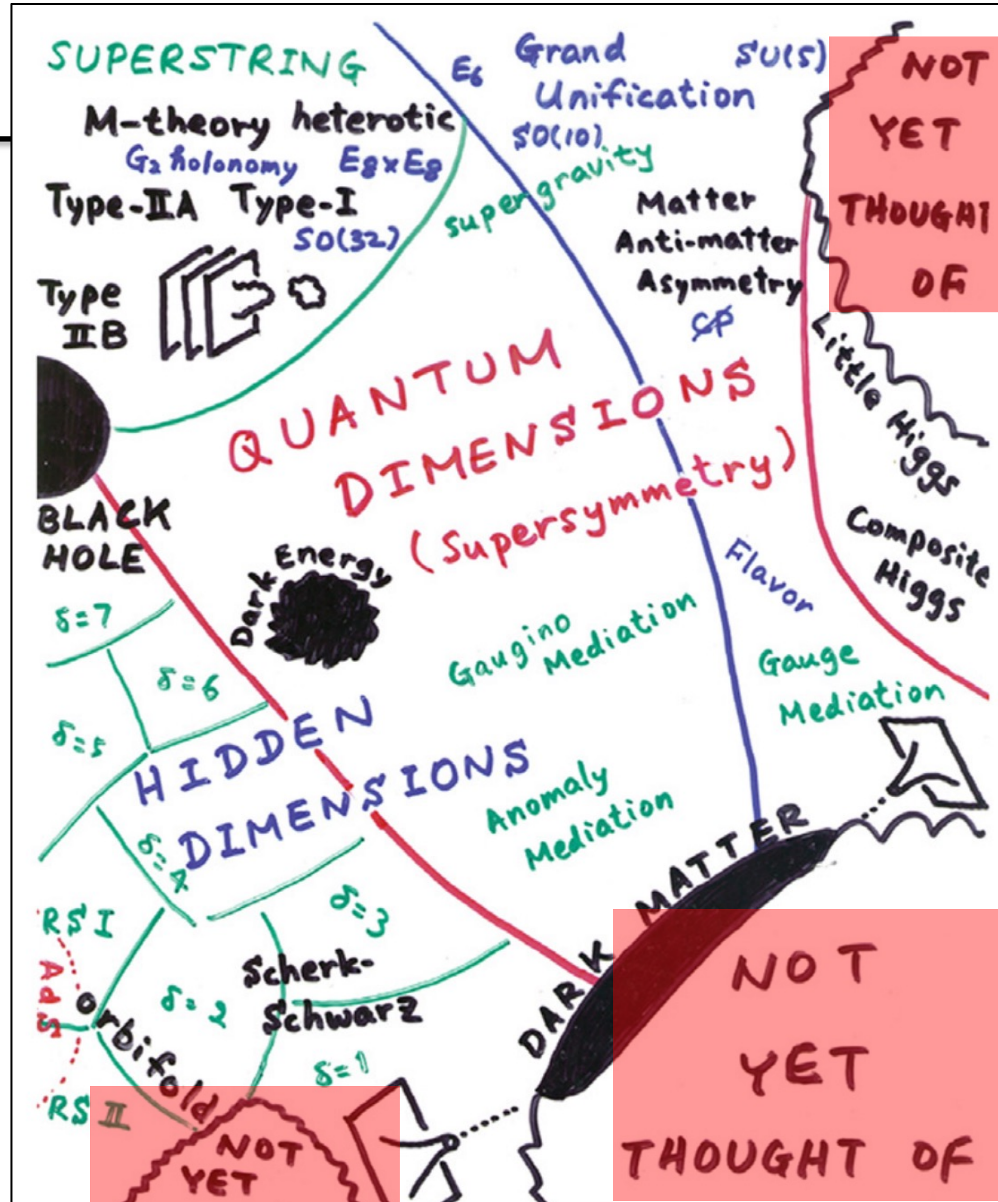


**3. Zur Elektrodynamik bewegter Körper; von A. Einstein.**

*the seeds of relativity were contained in Maxwell's Laws from half a century earlier!*

# *Fin*



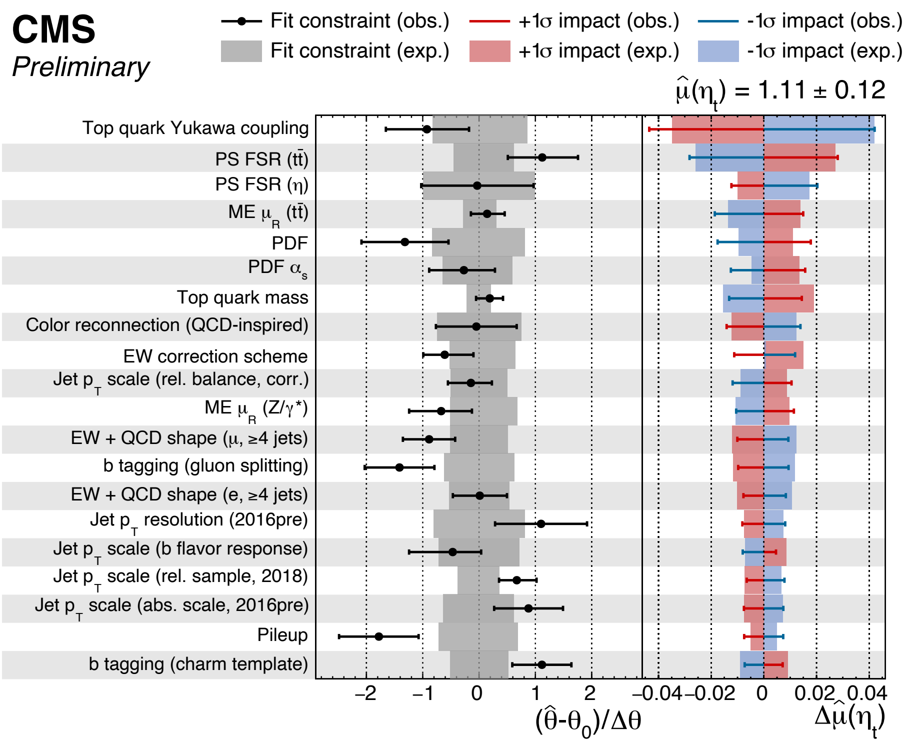



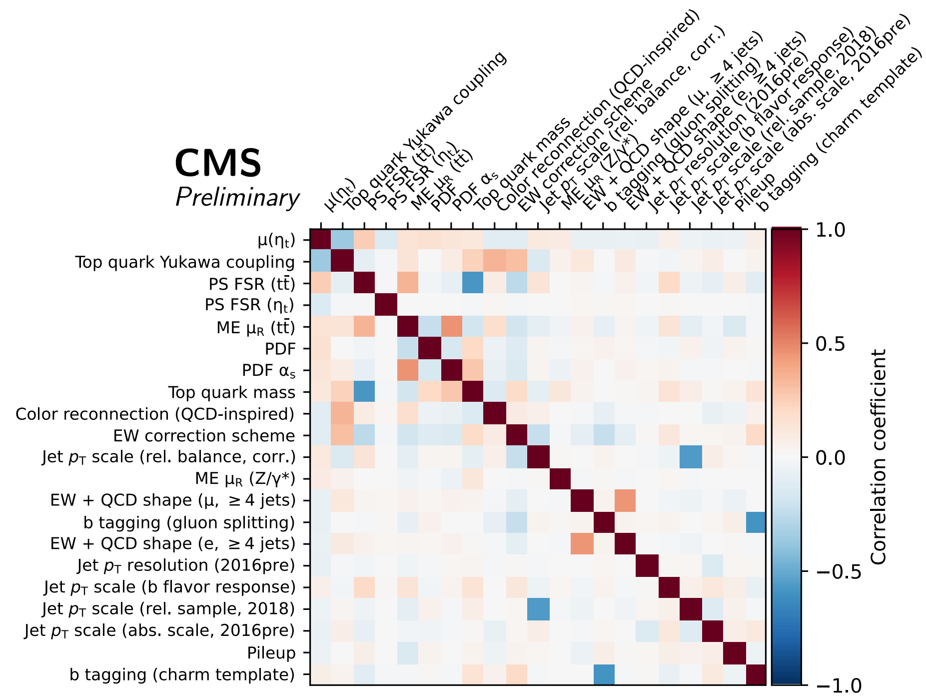

(Hitoshi Murayama)

**what might <u>we</u> be missing?**

# Additional Material

# Systematic Uncertainties



# Results ($\ell$, ≥4j channel)

bins of $|\cos\theta^*_{t_\ell}|$ ≡ angle btw leptonic top (p=0 frame) and $t\bar{t}$ system (lab)

high S / B ⟷ low S / B

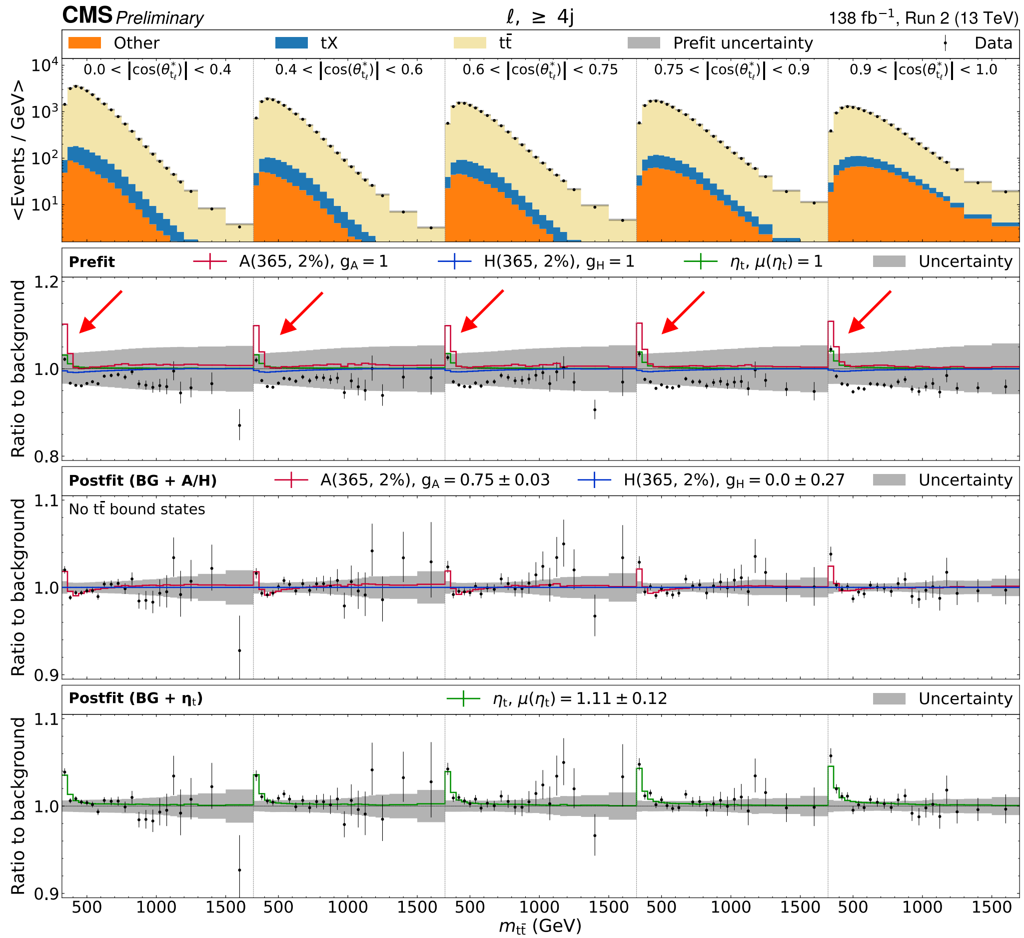
**data vs. background:**

**data / background:**

pre-fit

post-fit
including A/H signal

post-fit
including $\eta_t$ signal
$\sigma = 7.1 \pm 0.7$ pb
$\mu = 1.11 \pm 0.12$




$m_{t\bar{t}}$ [GeV]

# Results ($\ell$, 3j channel)

bins of $\left|\cos\theta^*_{t_\ell}\right|$ ≡ angle btw leptonic top (p=0 frame) and $t\bar{t}$ system (lab)

**high S / B** ⟷ **low S / B**

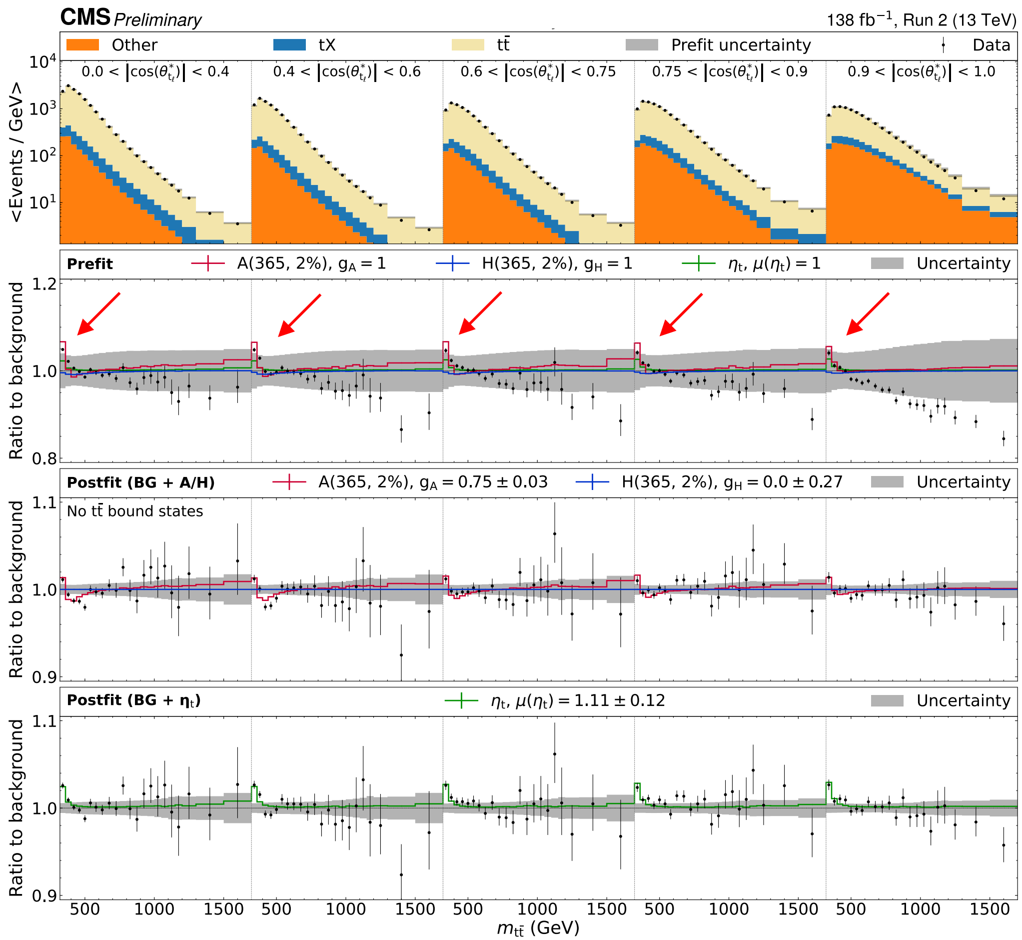
**data vs. background:**

**data / background:**

pre-fit

post-fit
including A/H signal

post-fit
including $\eta_t$ signal
$\sigma$ = 7.1 ± 0.7 pb
$\mu$ = 1.11 ± 0.12

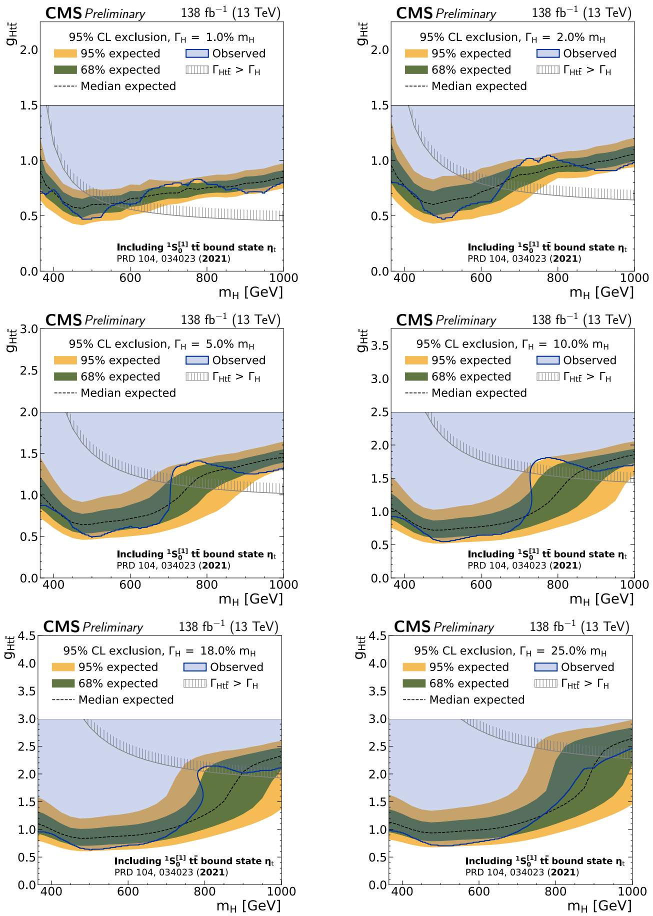



$m_{t\bar{t}}$ [GeV]

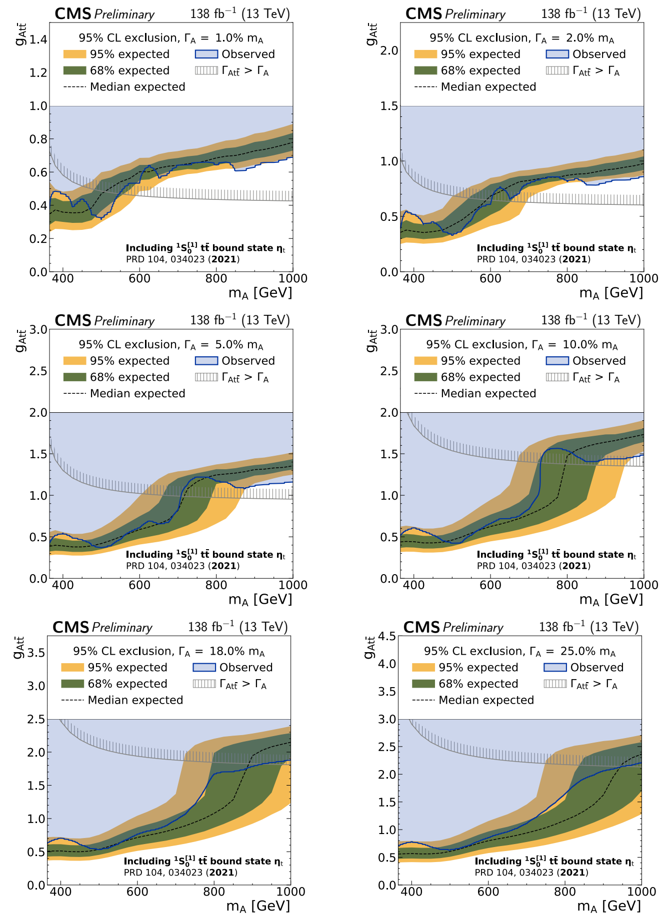
“toponium”
[HIG-22-013]

# Constraints

## H coupling vs. mass

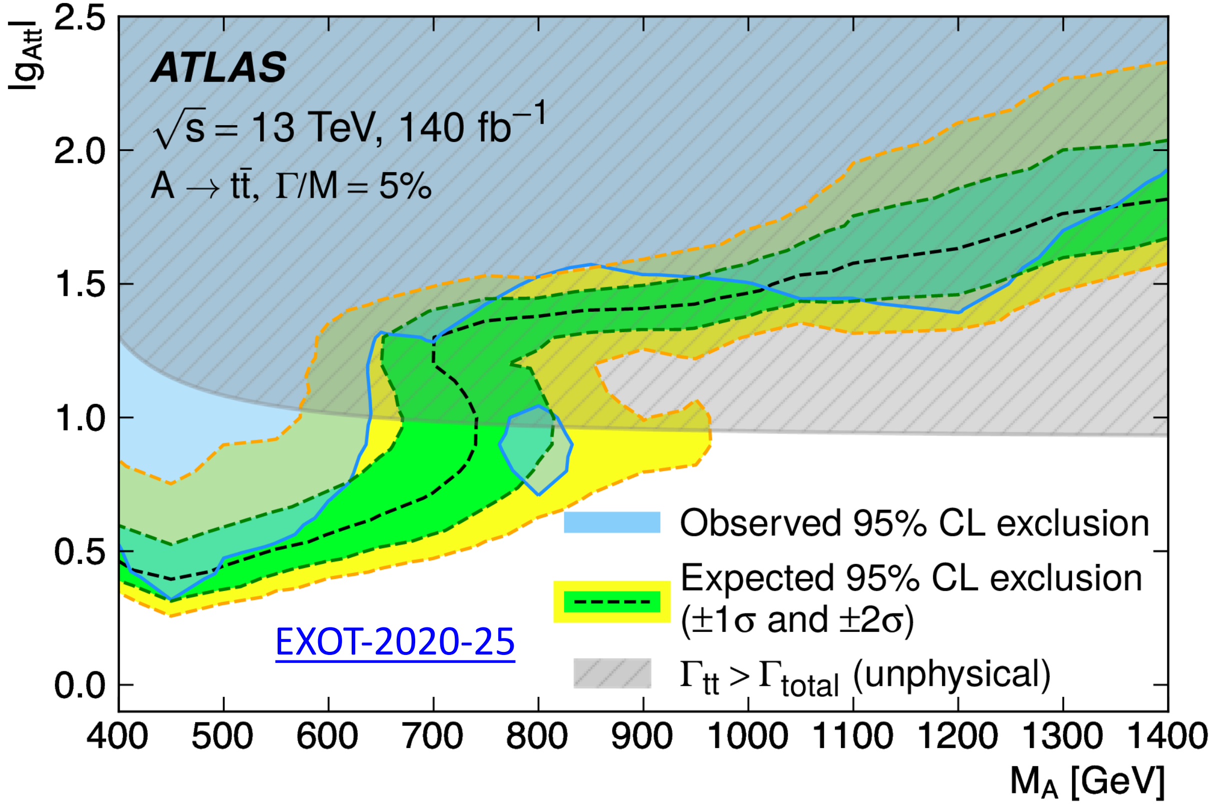



## A coupling vs. mass




- **Including $\eta_t$ in the background**, set 95% CL limits on coupling of further 365-1000 GeV (pseudo-)scalar bosons to top quarks with relative widths of 0.5–25%

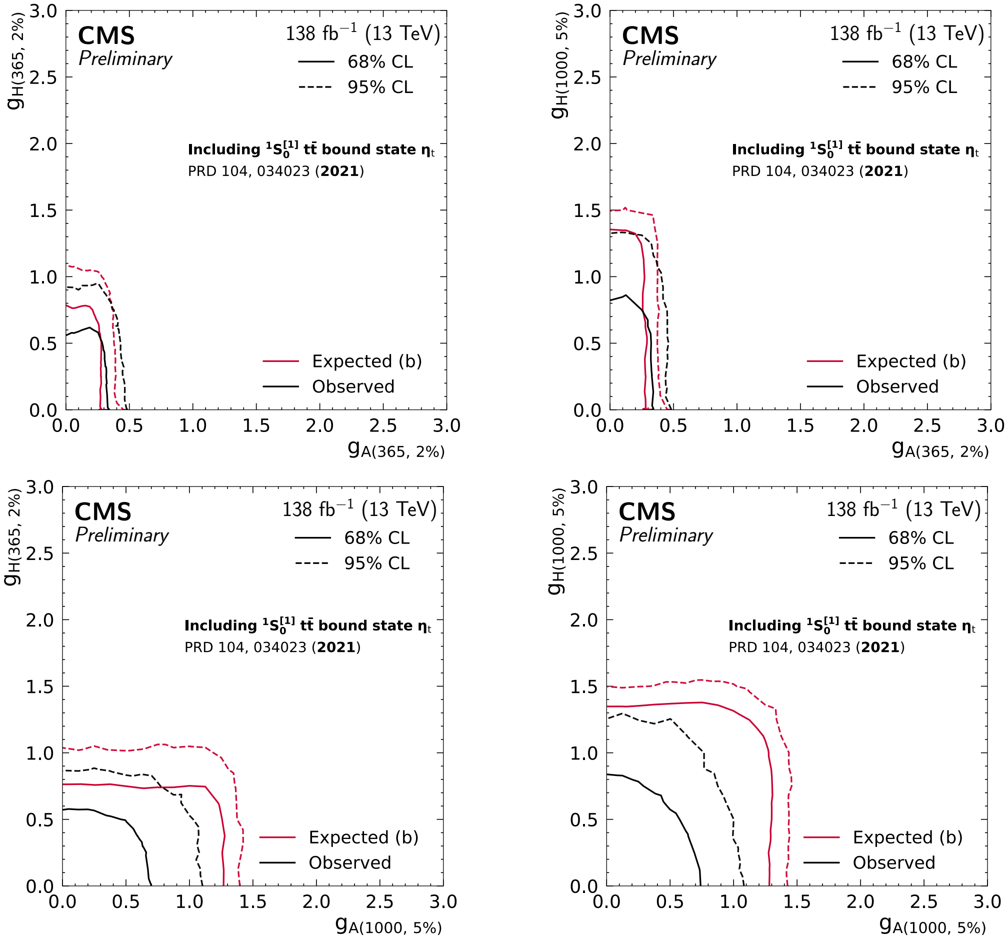
# ATLAS 2HDM Constraints

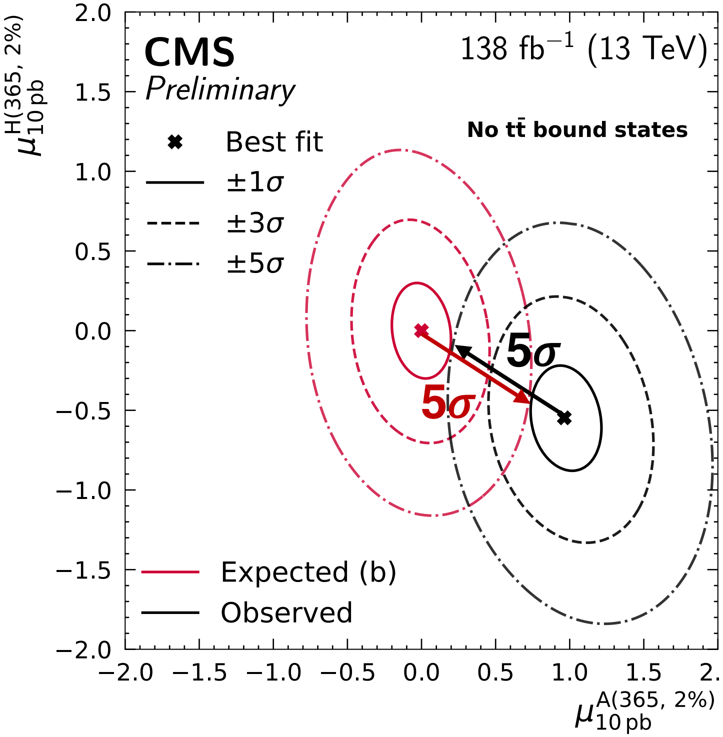



EXOT-2020-25

# “toponium” HIG-22-013

# Interpretations



# Can a pseudoscalar with a mass of 365 GeV in two-Higgs-doublet models explain the CMS $t\bar{t}$ excess?

Chih-Ting Lu,[1,*] Kingman Cheung,[2,3,4,†] Dongjoo Kim,[2,‡] Soojin Lee,[2,§] and Jeonghyeon Song[2,¶]

## V. CONCLUSIONS

The intriguing $t\bar{t}$ excess recently reported by the CMS Collaboration has generated excitement among those anticipating signs of new physics. This excess, observed in $t\bar{t}$ production at an invariant mass of around 365 GeV, has prompted our investigation into whether it can be attributed to the pseudoscalar boson of conventional Two-Higgs-Doublet Models (2HDMs). This possibility is particularly compelling given that the angular distributions of charged leptons from top-pair decay strongly point to a pseudoscalar as the source of the enhancement.

While the toponium $\eta_t$ with $m_{\eta_t} \simeq 343$ GeV shows a marginally higher $-2\ln L$ than the single pseudoscalar $A$ at 365 GeV, exploring both scenarios, along with other Beyond Standard Model (BSM) theories, remains valuable. Conventional 2HDMs, which naturally incorporate a pseudoscalar boson $A$, are among the first candidates one might consider. These models have been subjected to numerous theoretical and experimental constraints.

The best-fit parameters for the pseudoscalar boson are $m_A = 365$ GeV, $\Gamma_A/M_A = 0.02$, and $\tan\beta = 1.28$. Accounting for experimental uncertainties, we allowed a 10% variation in $\tan\beta$. With this consideration, we conducted a comprehensive scan of the allowed parameter space for Type-I and Type-II 2HDMs. Since the results of Type-I (II) are the same as Type-X (Y), our study effectively covers all four types. We systematically imposed constraints on the parameter space, including theoretical restrictions, electroweak precision data, perturbativity, Flavor-Changing Neutral Current (FCNC) constraints, and the most recent $t\bar{t}Z$ data.

Our analysis revealed that the perturbativity condition imposes relatively low upper bounds on $M_{H^\pm}$ and $M_A$ of approximately 723 GeV. Subsequently, upon applying FCNC constraints, we found that the entire parameter space for Type-II 2HDMs is ruled out, while only a small region survives for Type-I. However, even this remaining viable region in Type-I is ultimately eliminated when we consider the recent ATLAS $t\bar{t}Z$ data. This sequential application of constraints demonstrates the cumulative power of theoretical requirements and experimental observations in restricting the 2HDM parameter space.

The conclusion of our study is unequivocal: conventional 2HDMs (Types I, II, X, Y) lack viable parameter space to accommodate a pseudoscalar boson with mass $m_A = 365$ GeV and $\tan\beta \simeq 1.3$, which is necessary to explain the observed excess in the $t\bar{t}$ production threshold region.

https://arxiv.org/pdf/2410.08609

# Science and US Politics

**"The search for magnetic monopoles"**
Physics Today, Vol 69 Issue 10, 2016


## Clinton and Trump: Where do they stand on science?

*The candidates' positions on climate change and energy policy differ starkly. Comparing their views on other issues is harder.*

David Kramer

Check for updates

*Physics Today* **69** (10), 24–26 (2016);
https://doi.org/10.1063/PT.3.3324

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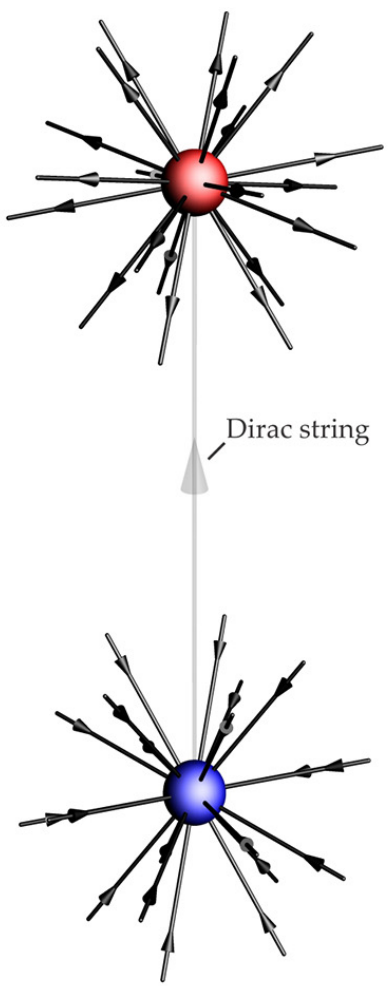
As in past elections, it's an understatement to say that science and technology (S&T) haven't been much of an issue in this presidential campaign. Apart from climate change and its close kin energy policy, S&T issues have barely been mentioned on the campaign trail by either Democratic nominee Hillary Clinton or Republican nominee Donald Trump. If Trump has positions on science policy matters, he has kept them to himself. Clinton, on the other hand, has published a considerable amount in position papers available on her campaign website.

Neither campaign responded to multiple requests from *Physics Today* for input to this article or to make their S&T advisers available for interviews. Clinton did provide answers to a list of 20 S&T questions posed by ScienceDebate.org, a coalition of 56 scientific societies, universities, and other nonprofits; Trump provided more general, terse responses to the questions.

 https://royalsocietypublishing.org/doi/10.1098/rspa.1931.0130

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Article

# Quantised singularities in the electromagnetic field,

Paul Adrien Maurice Dirac

Published: **01 September 1931** https://doi.org/10.1098/rspa.1931.0130

## Abstract

The steady progress of physics requires for its theoretical formulation a mathematics that gets continually more advanced. This is only natural and to be expected. What, however, was not expected by the scientific workers of the last century was the particular form that the line of advancement of the mathematics would take, namely, it was expected that the mathematics would get more and more complicated, but would rest on a permanent basis of axioms and definitions, while actually the modern physical developments have required a mathematics that continually shifts its foundations and gets more abstract. Non-euclidean geometry and non-commutative algebra, which were at one time considered to be purely fictions of the mind and pastimes for logical thinkers, have now been found to be very necessary for the description of general facts of the physical world. It seems likely that this process of increasing abstraction will continue in the future and that advance in physics is to be associated with a continual modification and generalisation of the axioms at the base of the mathematics rather than with a logical development of any one mathematical scheme on a fixed foundation. There are at present fundamental problems in theoretical physics awaiting solution, *e.g.*, the relativistic formulation of quantum mechanics and the nature of atomic nuclei (to be followed by more difficult ones such as the problem of life), the solution of which problems will presumably require a more drastic revision of our fundamental concepts than any that have gone before. Quite likely these changes will be so great that it will be beyond the power of human intelligence to get the necessary new ideas by direct attempts to formulate the experimental data in mathematical terms. The theoretical worker in the future will therefore have to proceed in a more indirect way. The most powerful method of advance that can be suggested at present is to employ all the resources of pure mathematics in attempts to perfect and generalise the mathematical formalism that forms the existing basis of theoretical physics, and *after* each success in this direction, to try to interpret the new mathematical features in terms of physical entities (by a process like Eddington's Principle of Identification).