

Overview of BSM Searches at CMS, ATLAS, & LHCb

QCD@LHC 2024

Brendan Regnery on behalf of the CMS, ATLAS, and LHCb experiments





Last BSM overview
QCD@LHC was **2020!**

Focus on results since
ICHEP 2024

Run 2

LS 2

Run 3

2016

2017

2018

2019

2020

2021

2022

2023

2024

2025

HL-LHC


We are here



QCD@LHC2024

7 – 11 October 2024, Freiburg / Germany

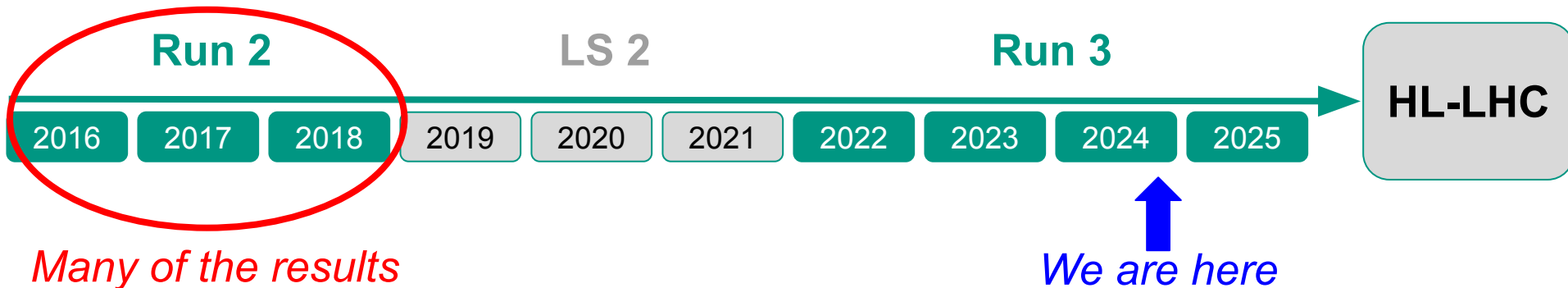
- Perturbative and resummed predictions
- Parton showers and event generators
- Parton distribution functions
- Soft interactions, non-perturbative QCD
- Higgs, electroweak and BSM physics
- Heavy quarks (including top and flavour physics)

International Advisory Committee

- Sergey Alekhin (DESY)
- Johannes Blümlein (DESY)
- Claude Duhr (Bonn)
- Kaith Ellis (Durham)
- Thomas Gehrmann (Zürich)
- Nigel Glover (Durham)
- Joey Huston (Michigan State)
- Judith Katzy (DESY)
- Frank Krauss (Durham)

Last BSM overview
QCD@LHC was **2020!**

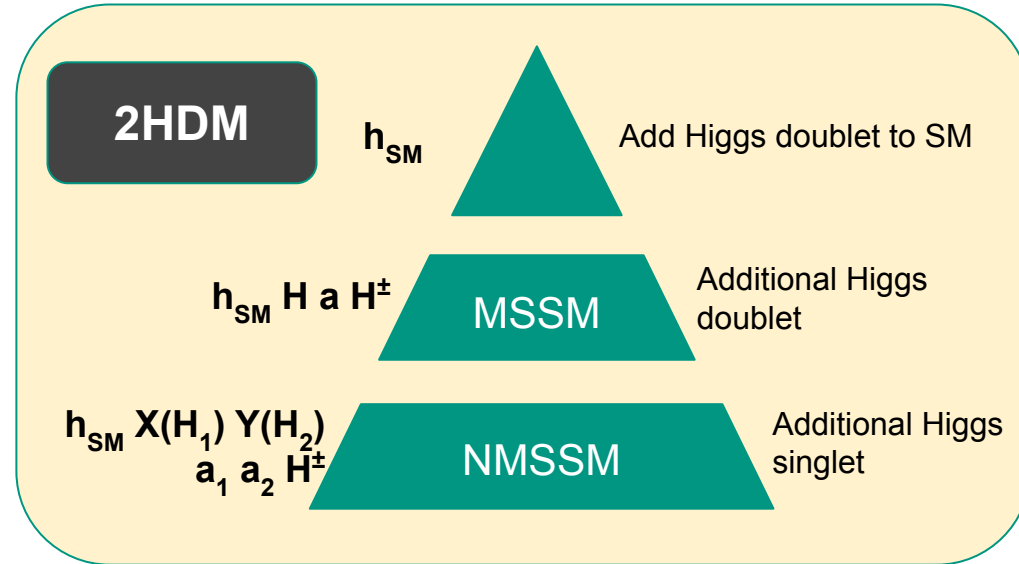
Focus on results since
ICHEP 2024



Latest Higgs BSM Searches

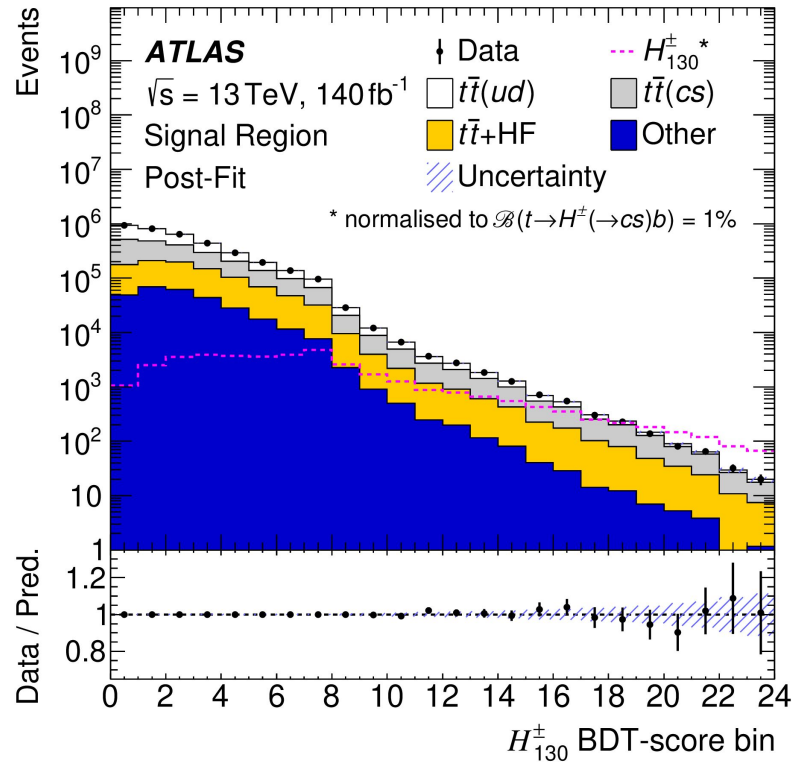
The Higgs: A tool for probing *beyond*

- It's been 12 years since the Higgs discovery and there is still so much to learn
 - Are there also charged higgs? Or light pseudo-scalars?
 - Link to dark matter? to extra dimensions?
- 2 Higgs Doublet - an answer to the matter/antimatter asymmetry
 - Increased interest from slight excesses
 - Supersymmetry?



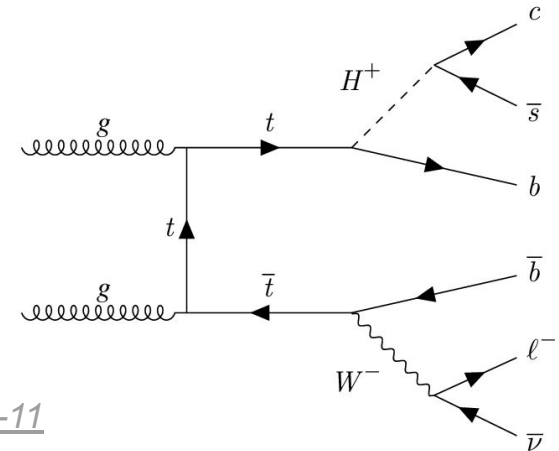
Warped extra dimensions?
(Graviton, Radion)

ATLAS Light Charged Higgs (1/2)



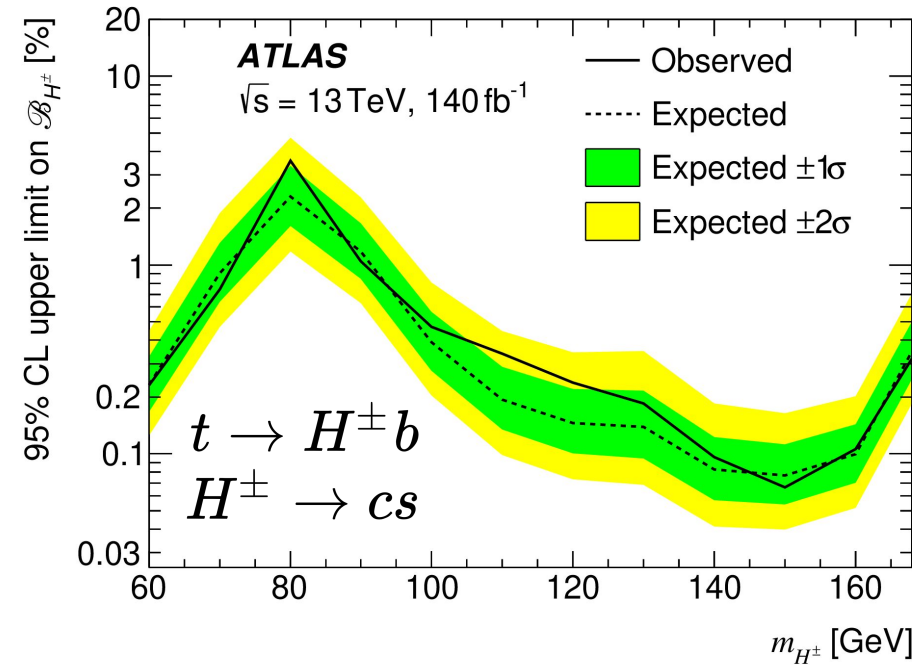
- BDT based search
 - 26 input features
 - Different BDT for each mass point
- Maximum likelihood fit to BDT score distribution

*BDTs ...
power in simplicity*



ATLAS HDBS-2020-11

ATLAS Light Charged Higgs (2/2)

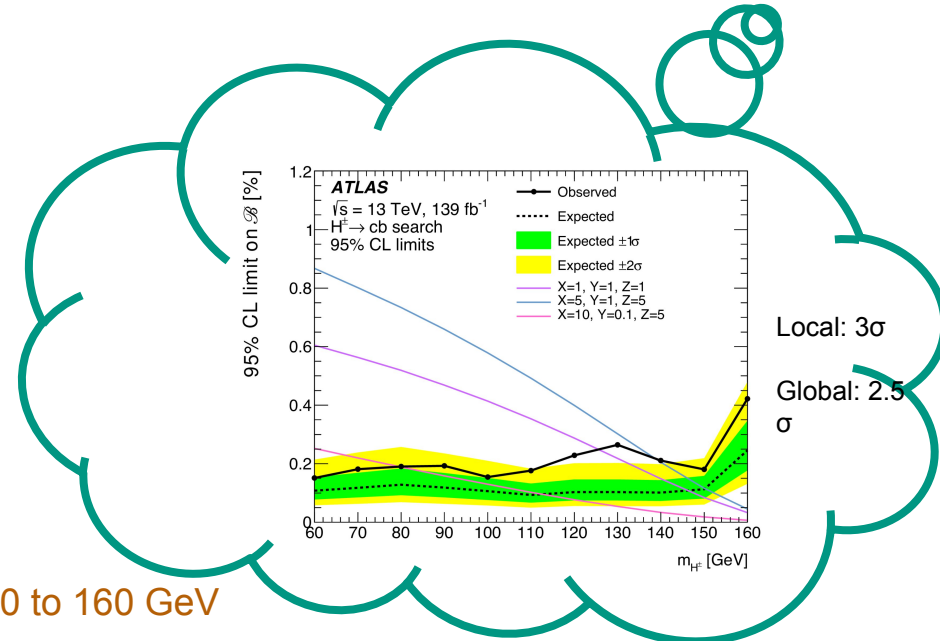


ATLAS HDBS-2020-11

First limits for $t \rightarrow H^\pm b, H^\pm \rightarrow cs$

Most stringent for masses 120 to 160 GeV

- Motivated by a previous intriguing result... ATLAS HDBS-2019-24



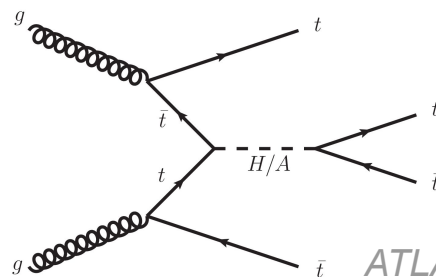
ATLAS Heavy Higgs

NOT OFF THE PRESS!

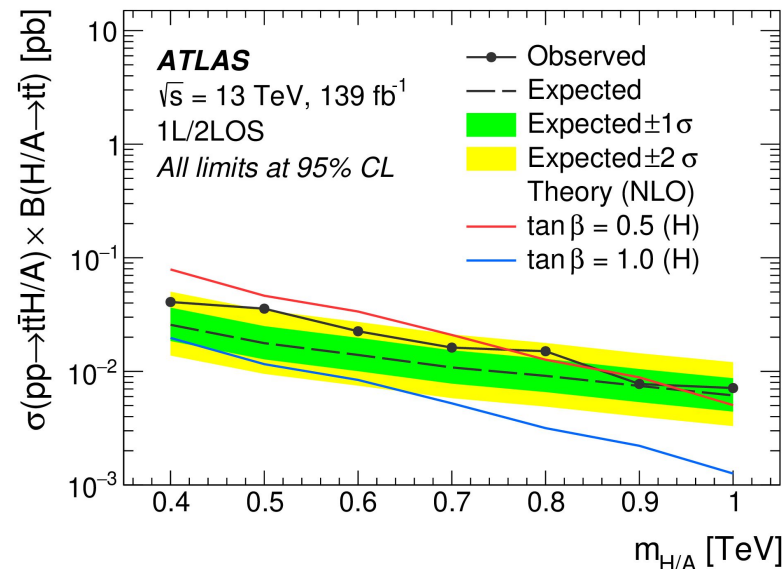
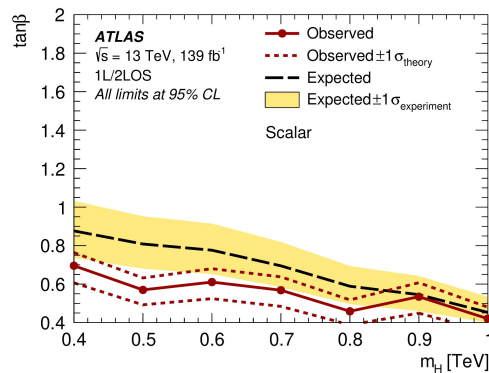
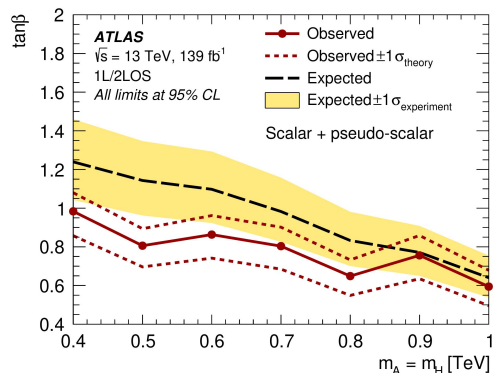


- Combined with multilepton channel
- One or two opposite sign electrons/muons
- Search conducted using GNN scores in bins based on jet multiplicity
- Limits on $\tan(\beta)$ for different mass hypotheses

$$\tan(\beta) = \frac{v_u}{v_d}$$



ATLAS-EXOT-2022-013



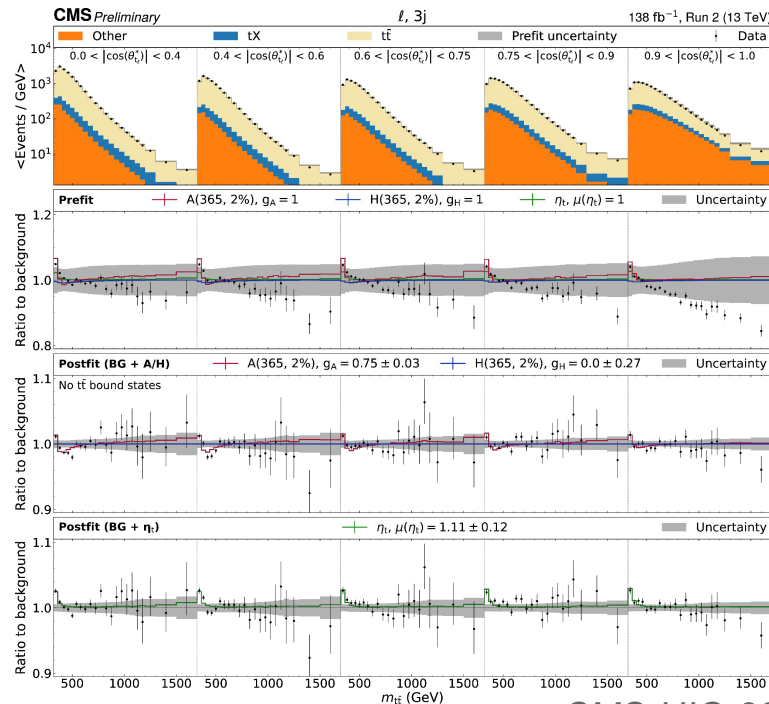
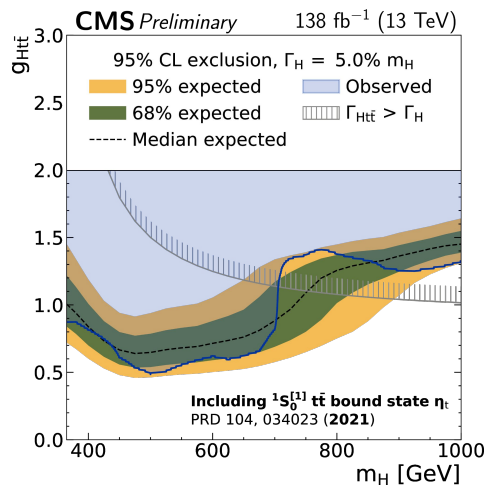
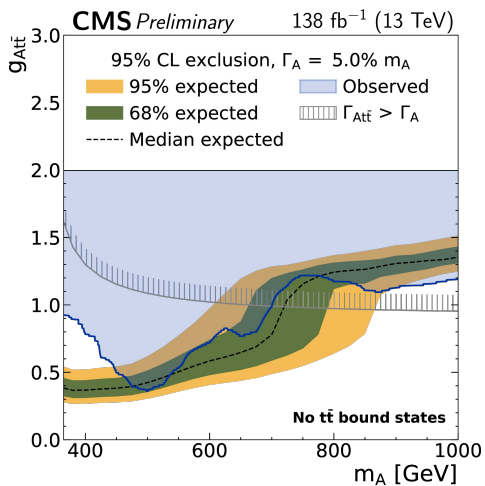
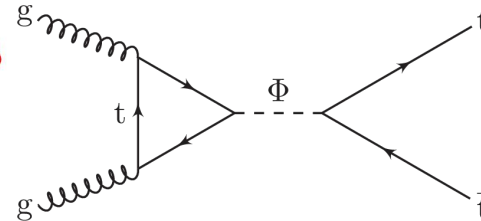
Described more in [this talk](#)

CMS Heavy Higgs

NOT OFF THE PRESS!



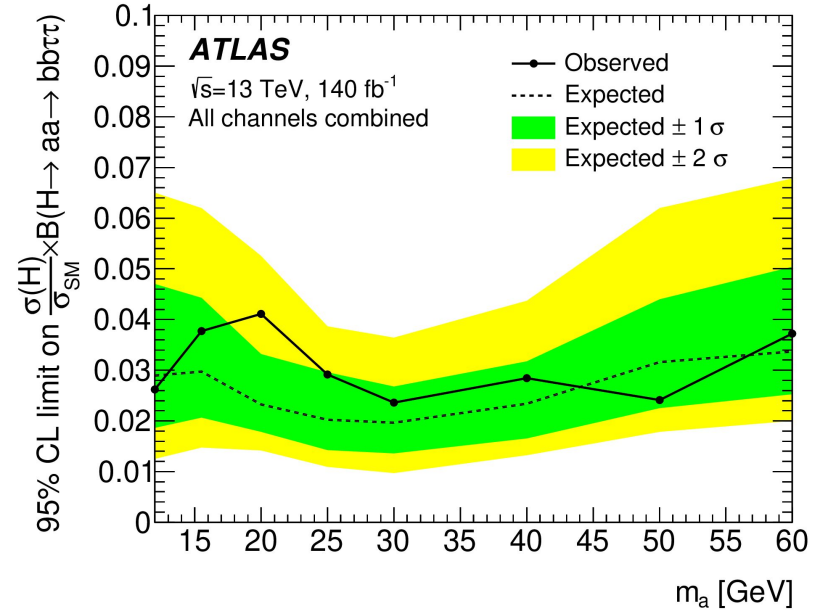
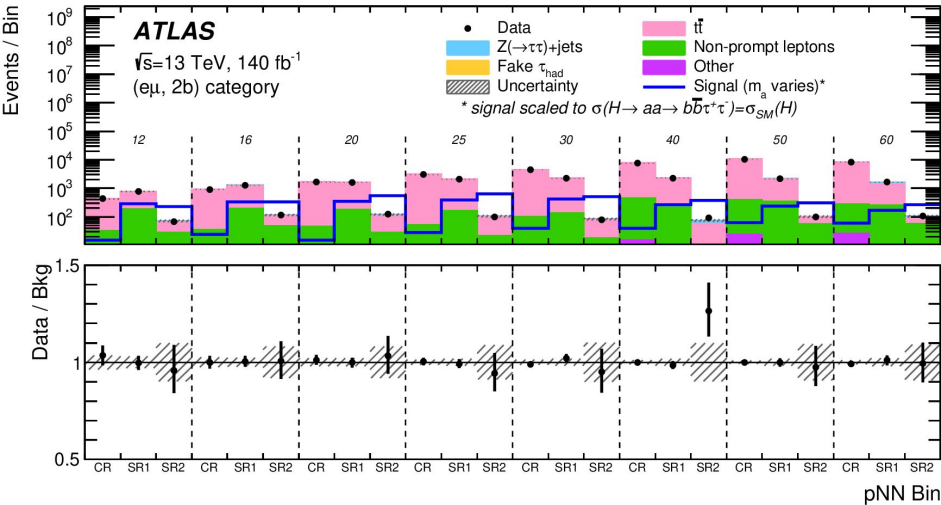
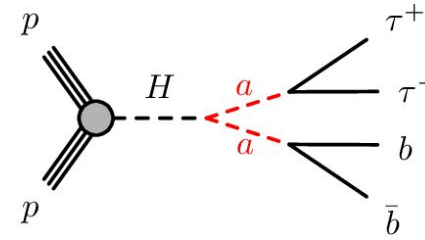
- Single and dilepton channels
- Excess observed in low m_{tt}
- Compatible with heavy pseudoscalar or top bound state (singlet)



CMS-HIG-22-013

ATLAS Light pseudoscalar

- Appears in extensions of the Higgs sector, dark matter models, hidden sector models, ...
- Each optimized with NN parameterized as a function of m_a



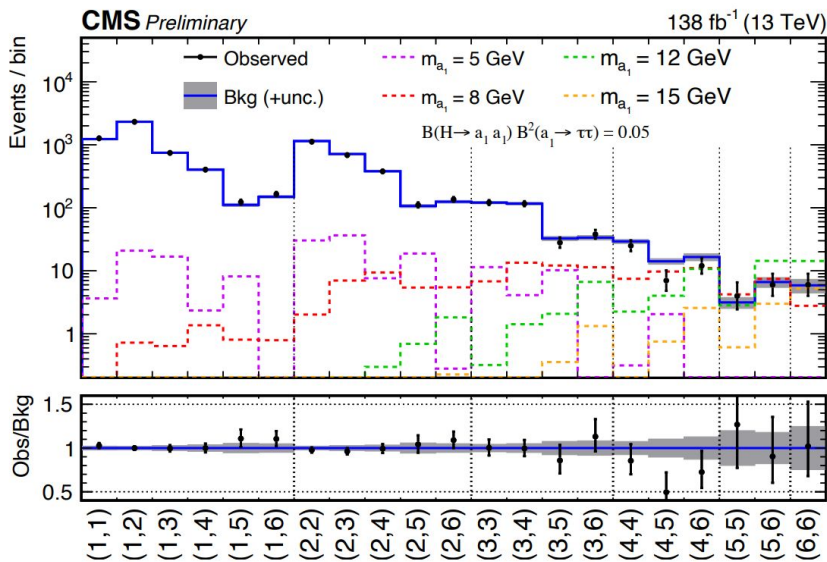
9 search categories (based on decays)
 3 bins in $pNN(m_a)$ based on S/B ratio

ATLAS-HDBS-2021-07

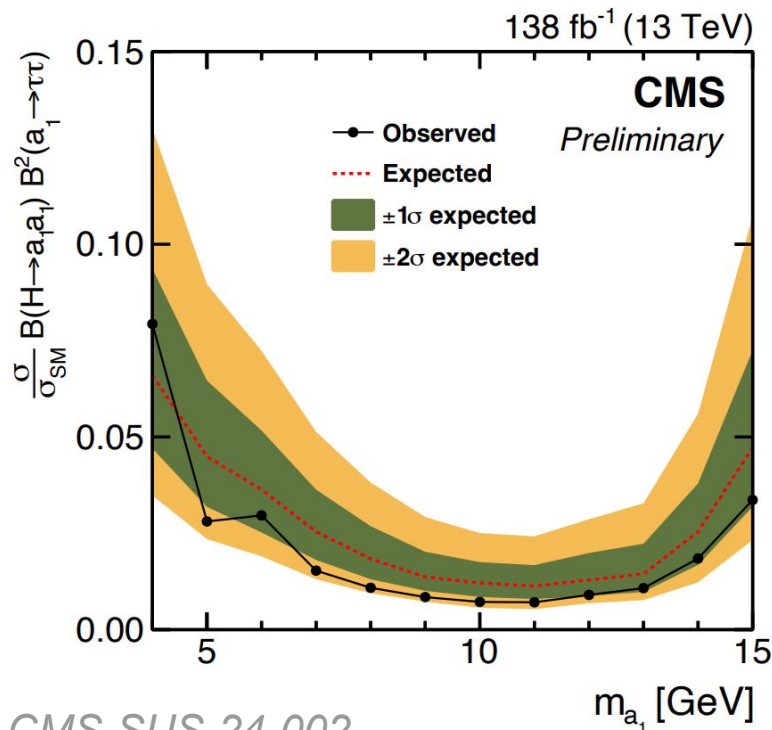
CMS Light pseudoscalar

- $H \rightarrow aa \rightarrow \tau\tau\tau\tau$ and $\rightarrow \mu\mu\tau\tau$
- 2 dimensional fit in bins of reconstructed 'a' mass

Strong exclusion on type-II 2HDM+S between 4 and 9 GeV



NOT OFF THE PRESS!



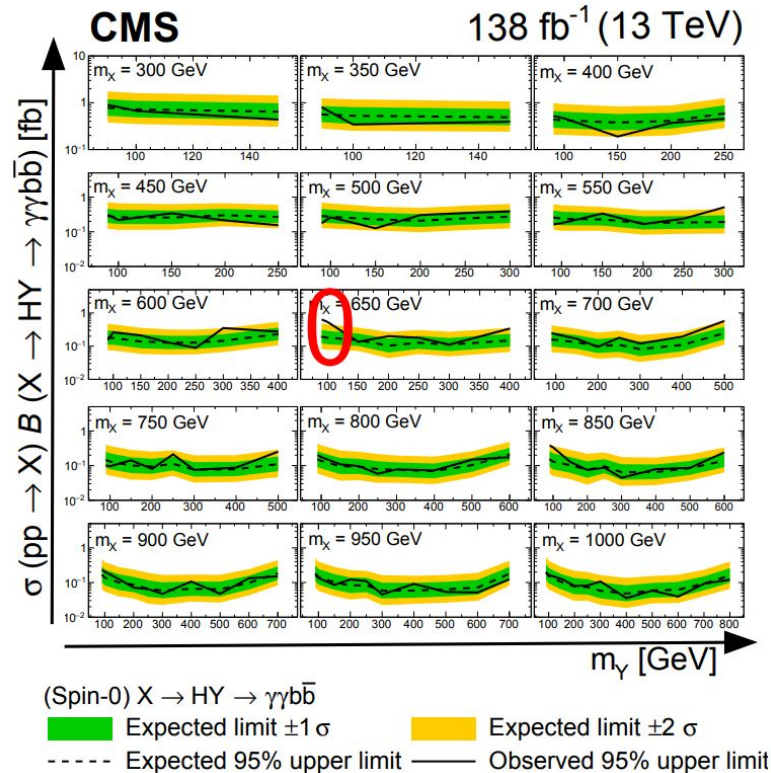
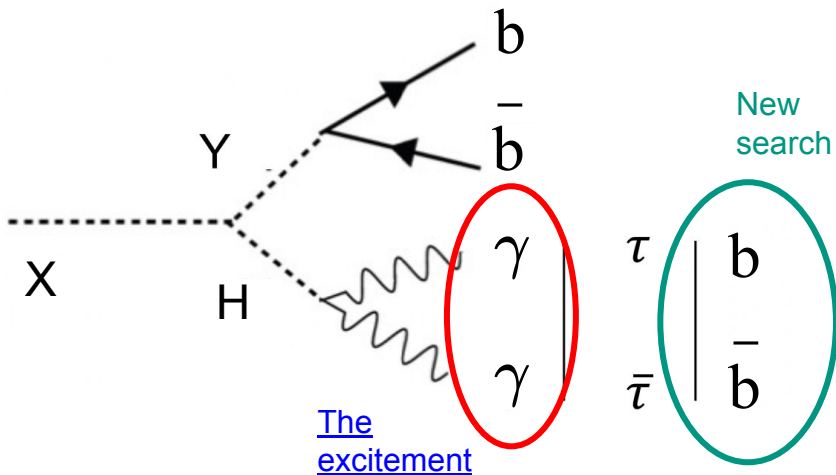
CMS-SUS-24-002

CMS Higgs + Y Resonance (1/2)

- Excitement triggered by previous 2.8 global excess (3.8 local) at $X=650$ GeV $Y=90$ GeV

- $X \rightarrow HY \rightarrow (H \rightarrow \gamma\gamma)(Y \rightarrow b\bar{b})$

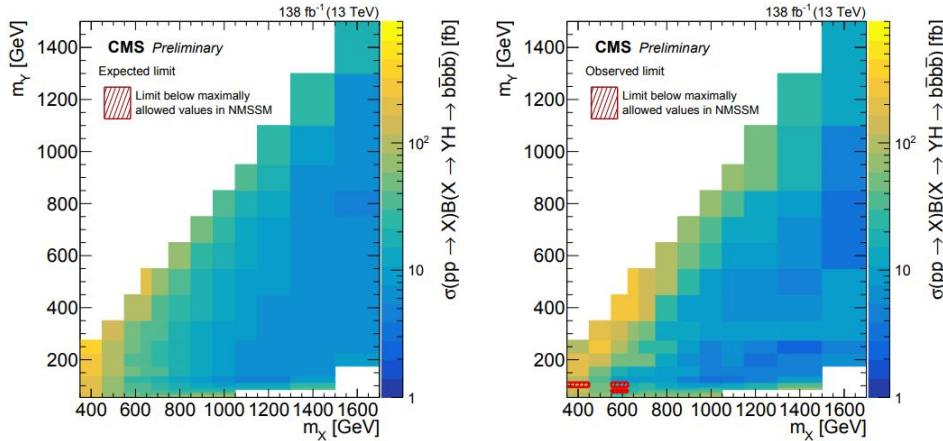
- Search for $X \rightarrow HY \rightarrow b\bar{b}b\bar{b}$



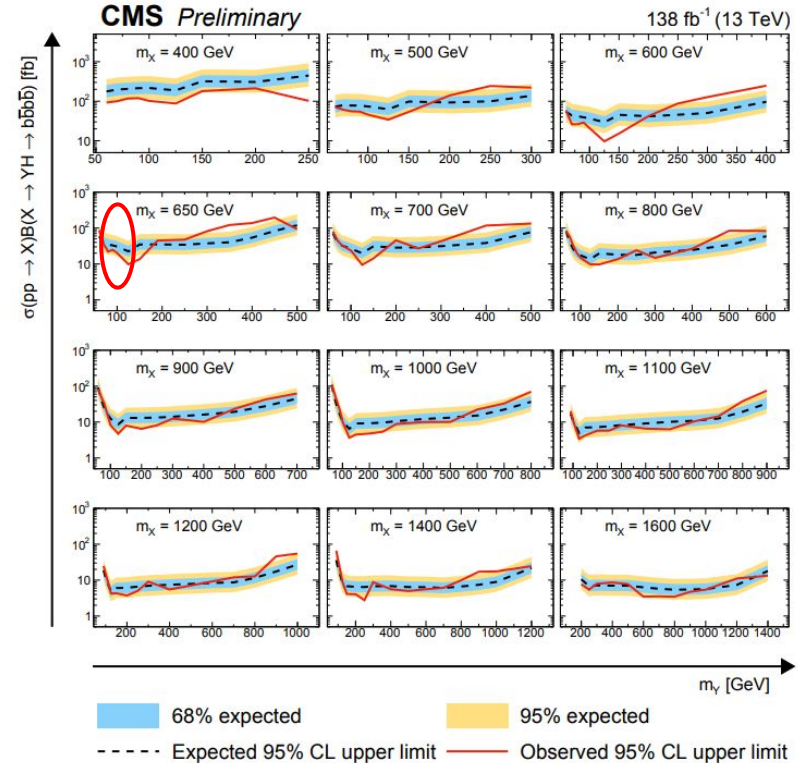
CMS Higgs + Y Resonance (2/2)

NOT OFF THE PRESS!

- No significant excesses observed
 - 650 GeV bin does not show the same excess
- Expected and observed limits (with comparison to maximally allowed values in NMSSM)



CMS-HIG-20-012

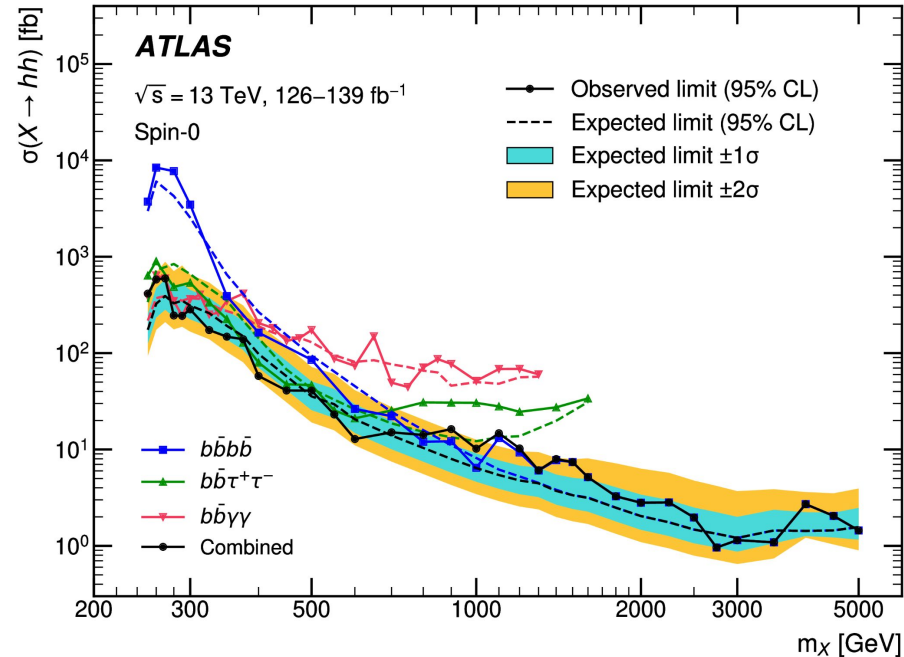


Latest Higgs BSM Summaries

ATLAS Resonant Di-Higgs Summary

- **Combination** of full run 2 resonant di-higgs search results
- No excess observed after combination
- Can be used to constrain:
 - Type-I 2 Higgs doublet model
 - Minimal supersymmetric standard model
 - (see paper for constraints)

Often use a radion or graviton from warped extra dimensional theories



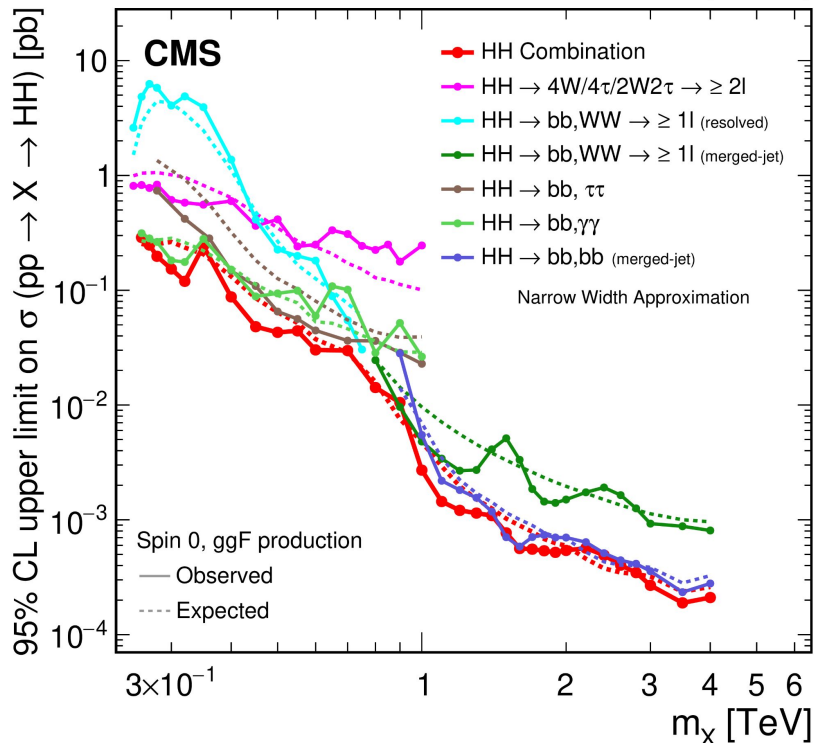
Comprehensive review

ATLAS-HDBS-2023-17

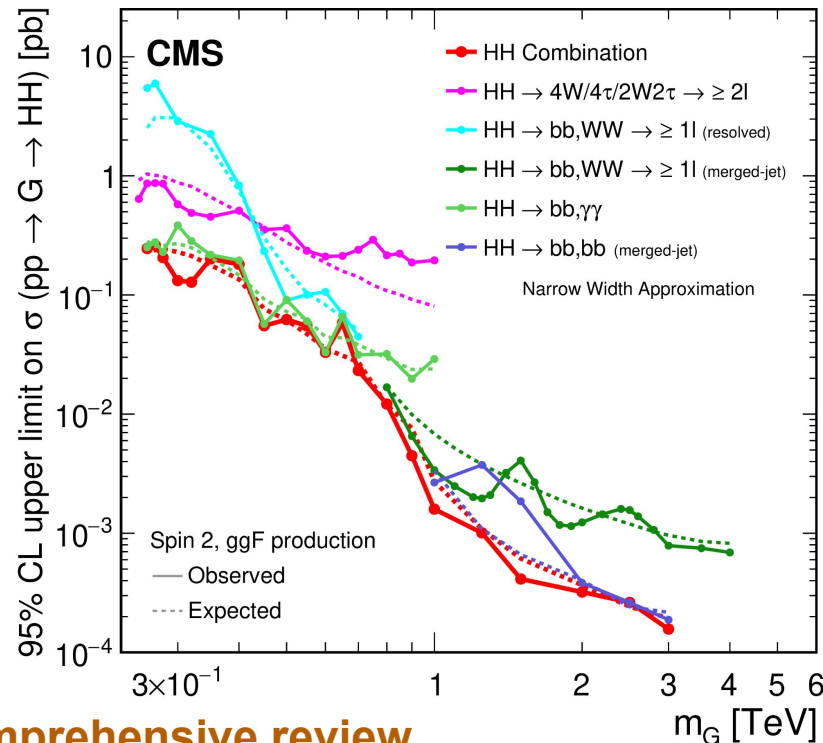
CMS Resonant Di-Higgs Summary

CMS-B2G-23-002

138 fb⁻¹ (13 TeV)

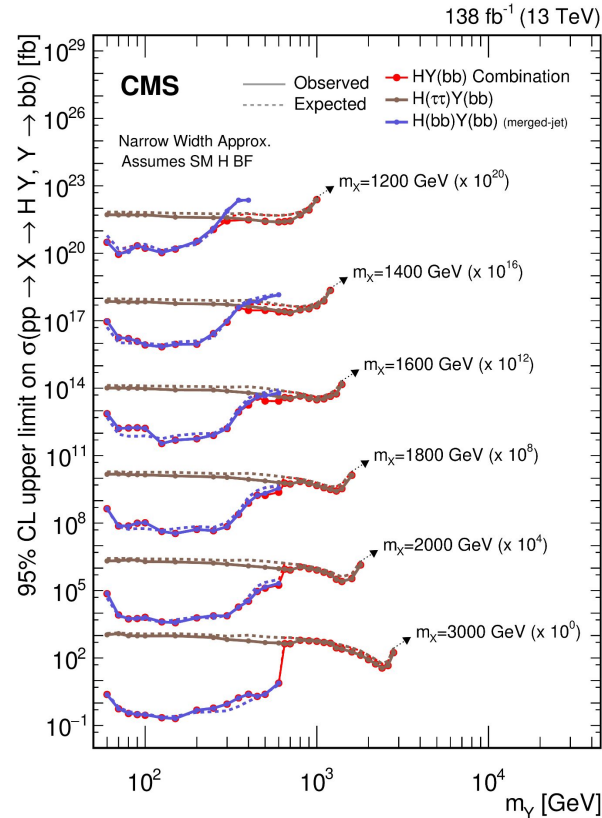
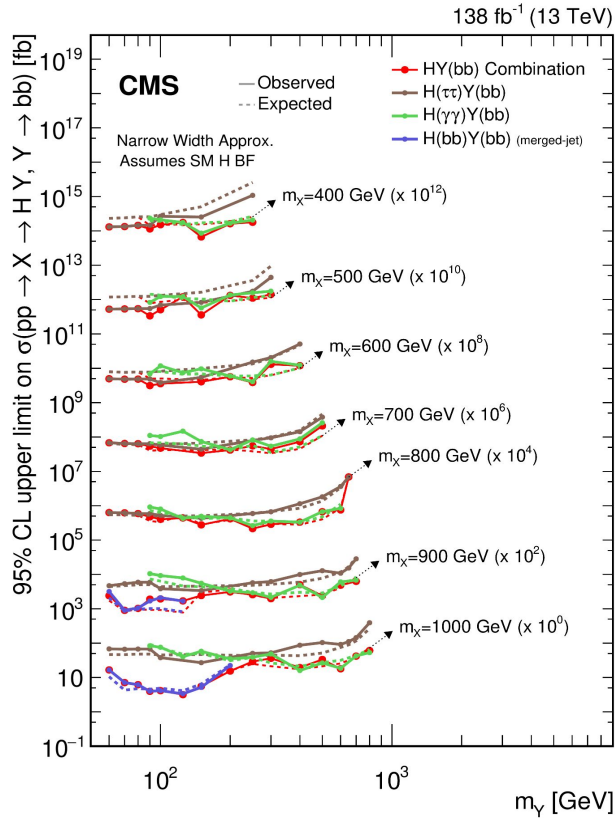


138 fb⁻¹ (13 TeV)



Comprehensive review

CMS Higgs + Y Resonance Summary

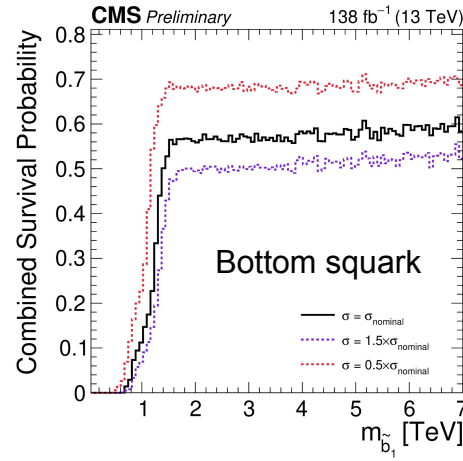
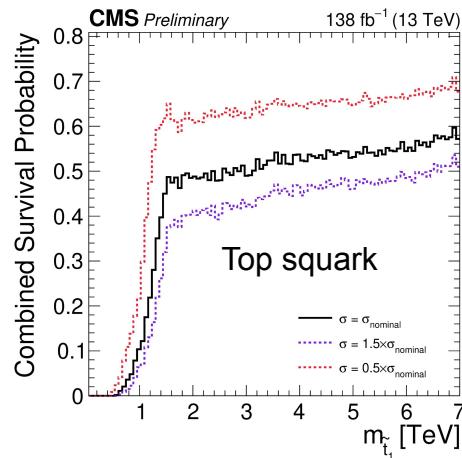
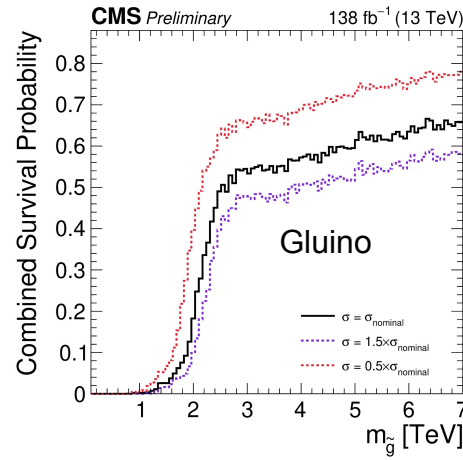
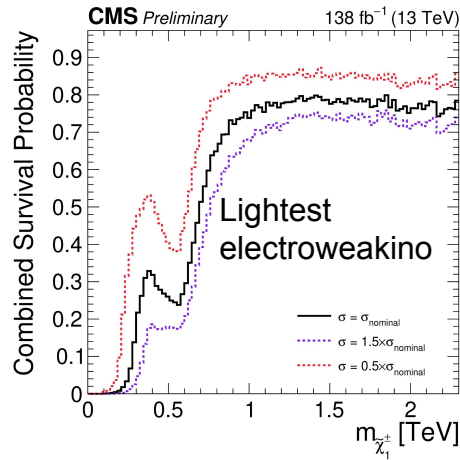


CMS-B2G-23-002

- No excesses observed after combination
- Combination filled with many interpretations
- NMSSM, 2HDM, etc.

Latest Supersymmetry Constraints

CMS pMSSM



- First CMS SUSY combination with full run 2 results
- Searches at CMS interpreted to constrain 19 parameter phenomenological MSSM
- “Survival probability” = fraction of masses that have not been excluded for a mass bin

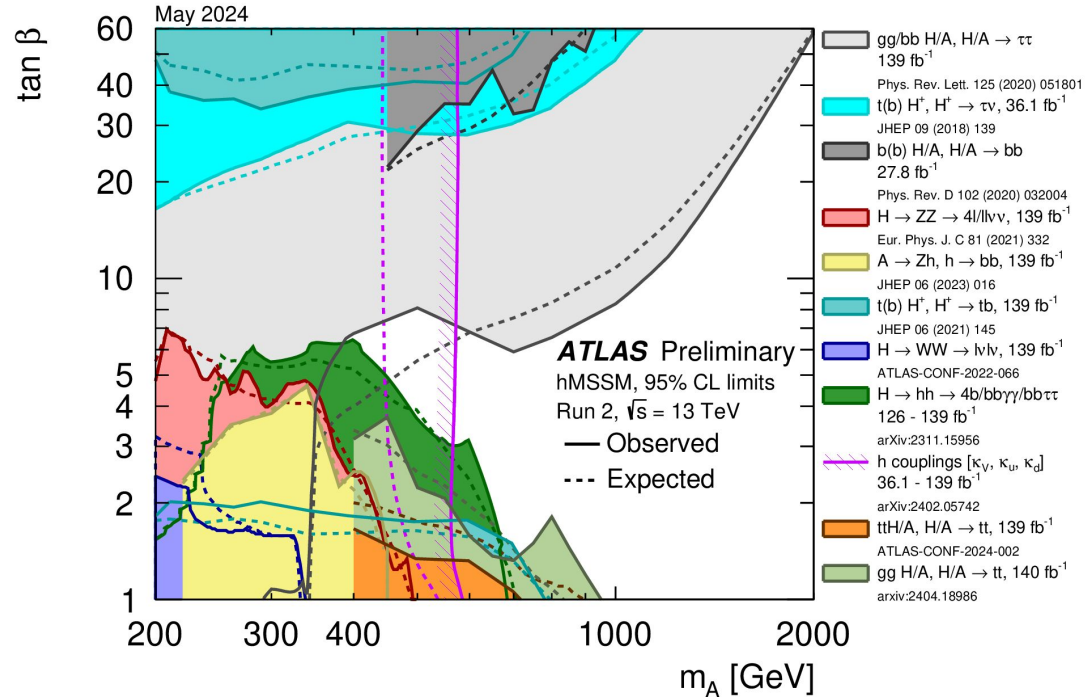
CMS-SUS-24-004

ATLAS hMSSM

Described more in [this talk](#)

- Constraining the supersymmetric Higgs sector using:
 - Higgs branching ratio constraints
 - Heavy Higgs results
- Many more detailed plots included in the interpretation

$$\tan(\beta) = \frac{v_u}{v_d}$$

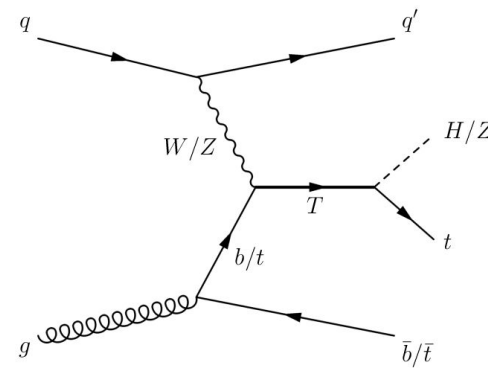


ATLAS-PHYS-PUB-2024-008

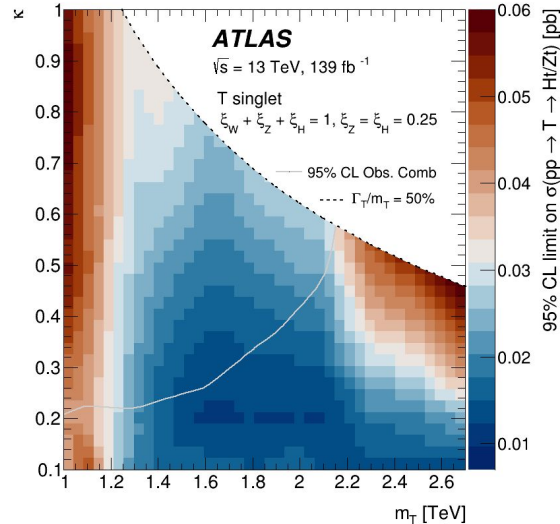
And a fourth generation? (or sort of)

ATLAS Vector-like Quarks

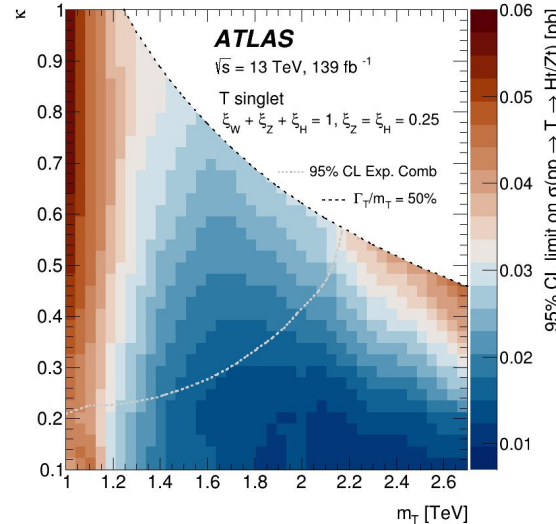
Most restrictive limits to date



VLQ	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} B \\ T \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ T \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
Isospin	0	0	1/2	1/2	1/2	1	1
Hypercharge	+2/3	-1/3	+1/6	+7/6	-5/6	+2/3	-1/3



Observed

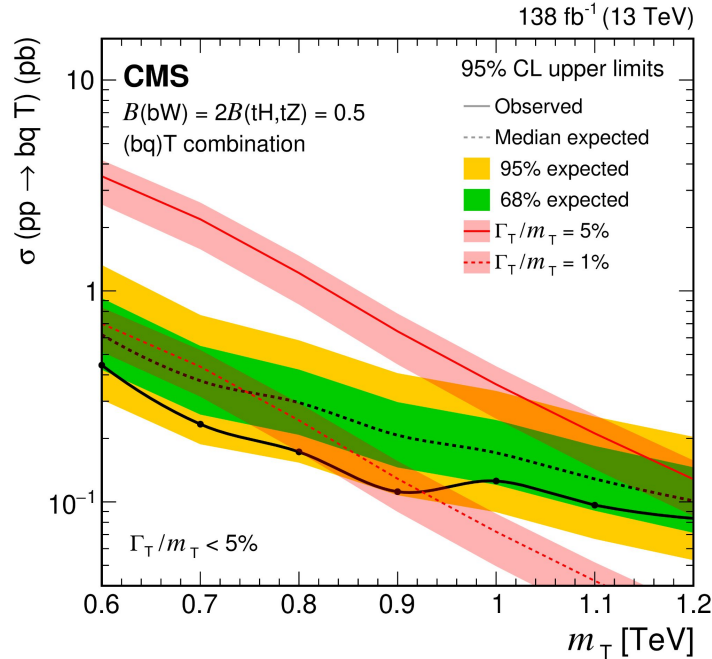


Expected

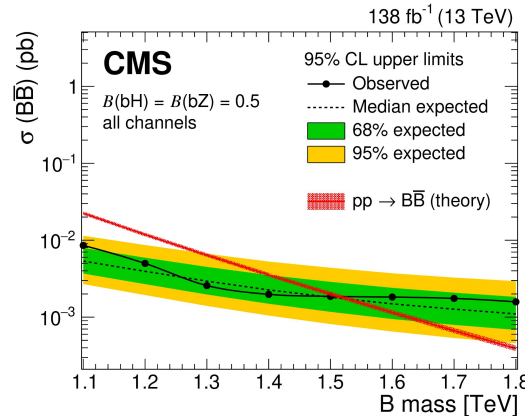
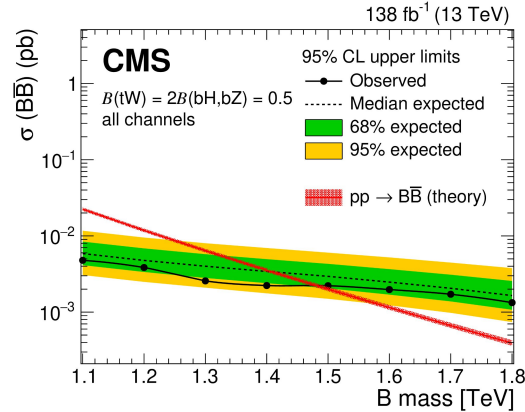
- Combination of **single** VLQ production
- No significant excess observed
- Limits set for singlets (left) **and** doublets
 - Set on coupling constant κ

ATLAS-EXOT-2021-02

CMS Vector-like Quarks (Combination)



Probing many **unexplored** regions of parameter space



- Combination of T' single production
- Combination of BB pair production
 - Singlet (top)
 - Doublet (bottom)
- Review complete with current CMS run 2 VLQ searches

CMS-EXO-23-006

CMS Vector-like Quarks

Overview of CMS B2G Results

June 2024

36 – 138 fb⁻¹ (13 TeV)

CMS Preliminary

Very heavy fermions

(qb)T

- ▷ b (tH + tZ) (H/Z → bb), (Γ/m=0.05, Singlet) M_T
- ▶ b (tH + tZ) (H/Z → bb̄), (Γ/m=0.05, Singlet) M_T
- ▶ b Zt (Z → νν) (Γ/m=0.3, Singlet) M_T
- ▶ b Zt (Z → νν) (Γ/m=0.2, Singlet) M_T
- ▶ b Zt (Z → νν) (Γ/m=0.1, Singlet) M_T
- ▶ b Zt (Z → νν) (Γ/m=0.05, Singlet) M_T
- ▷ b Zt (Z → ll) (Γ/m=0.05, Singlet) M_T
- ▶ b tH (H → γγ), (Γ/m=0.05, Singlet) M_T
- ▶ b tH (H → γγ), (Γ/m=0.04, Singlet) M_T
- ▶ b tH (H → γγ), (Γ/m=0.03, Singlet) M_T
- ▶ b tH (H → γγ), (Γ/m=0.02, Singlet) M_T
- ▶ b tH (H → γγ), (Γ/m=0.01, Singlet) M_T
- ▶ (qb)T Comb. (Γ/m=0.05, Singlet) M_T

(qt)/(qb)B

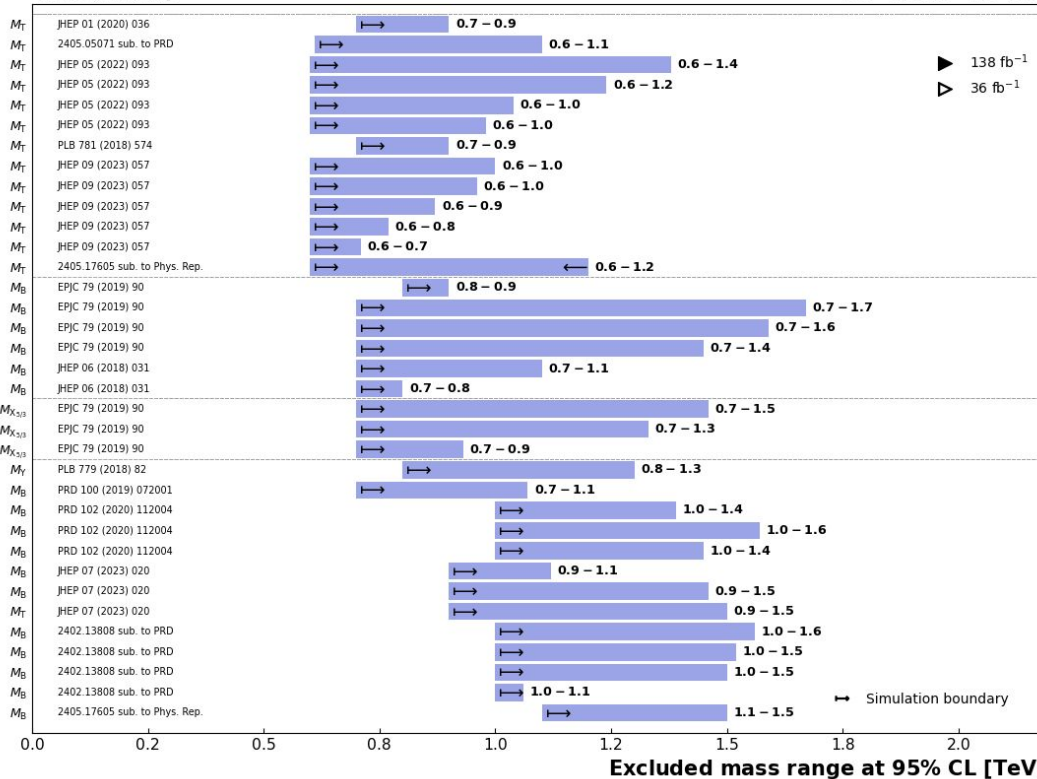
- ▷ t Wt → lep. + jets (Γ/m=0.1, LH) M_B
- ▷ b Wt → lep. + jets (Γ/m=0.3, LH) M_B
- ▷ b Wt → lep. + jets (Γ/m=0.2, LH) M_B
- ▷ b Wt → lep. + jets (Γ/m=0.1, LH) M_B
- ▷ b Hb (H → bb̄) (Γ/m=0.3, Doublet) M_B
- ▷ b Hb (H → bb̄) (Γ/m=0.2, Doublet) M_B

(qt)X

- ▷ t Wt → lep. + jets (Γ/m=0.3, LH) M_{K₃₃}
- ▷ t Wt → lep. + jets (Γ/m=0.2, LH) M_{K₃₃}
- ▷ t Wt → lep. + jets (Γ/m=0.1, LH) M_{K₃₃}

Pair prod.

- ▷ Y_{-4/3}Y_{-4/3} → bW bW → lνq̄q̄q̄ M_T
- ▷ BB → tZ tZ → bq̄q̄ bq̄q̄ M_B
- ▶ BB → bq̄q̄ bq̄q̄ (B(bZ) = 1) M_B
- ▶ BB → bq̄q̄ bq̄q̄ (B(bH) = 1) M_B
- ▶ BB → bq̄q̄ bq̄q̄ (Singlet) M_B
- ▶ BB → lep. + jets (Doublet) M_B
- ▶ BB → lep. + jets (Singlet) M_B
- ▶ TT → lep. + jets (Singlet and Doublet) M_T
- ▶ BB → lep. + jets (B(bH) = 1) M_B
- ▶ BB → lep. + jets (B(bZ) = 1) M_B
- ▶ BB → lep. + jets (Doublet) M_B
- ▶ BB → lep. + jets (Singlet) M_B
- ▶ BB Comb. (Singlet and Doublet) M_B



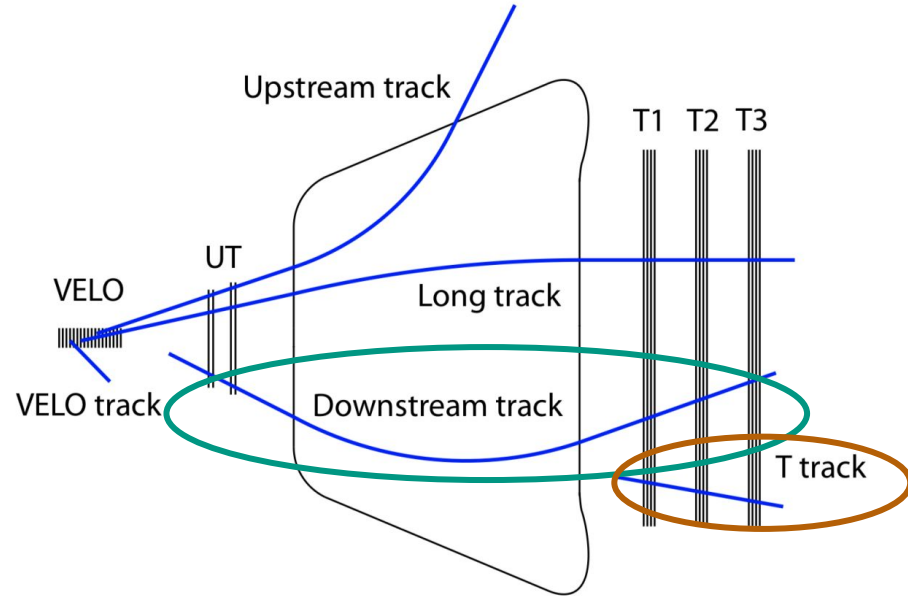
Summary of current CMS VLQ results (LHCP 2024)

Single and pair production

Looking to Run 3 (and Beyond)

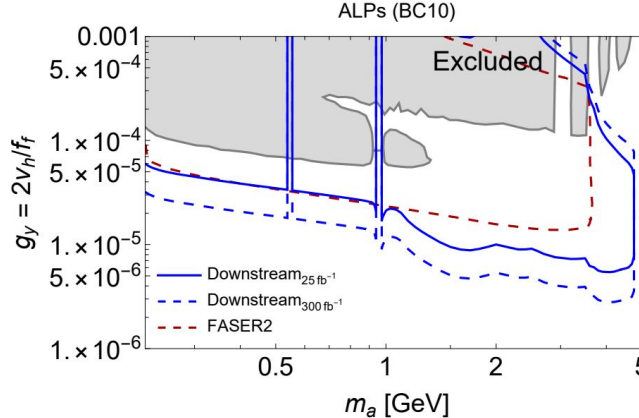
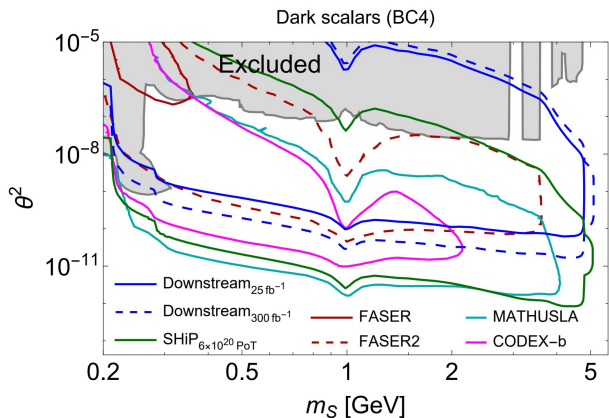
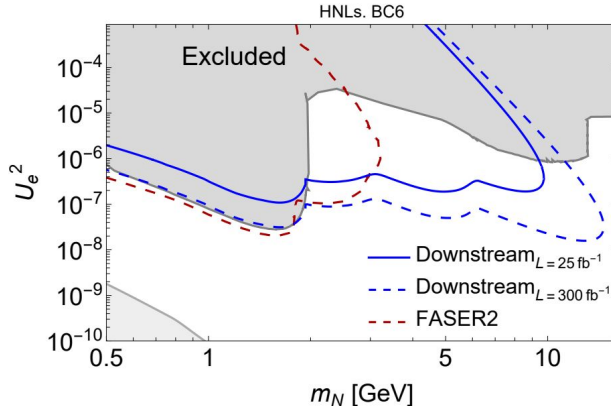
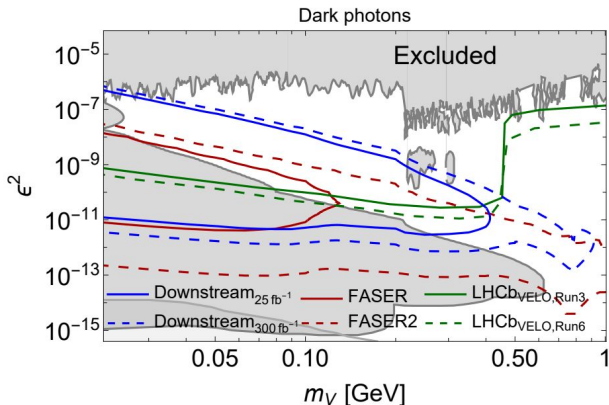
LHCb Triggers for Long Lived Particles (1/2)

- For run 3 and beyond, LHCb now has a fully software trigger
 - 2 stages: HLT1 and HLT2
- Long and upstream tracks have tracks in the VELO
- Downstream tracks are reconstructed outside the VELO
 - Potential LLP decays
- T tracks also being used!
 - Motivated by CMS and ATLAS



LHCb Dark Photons
LHCb LLP Sensitivity

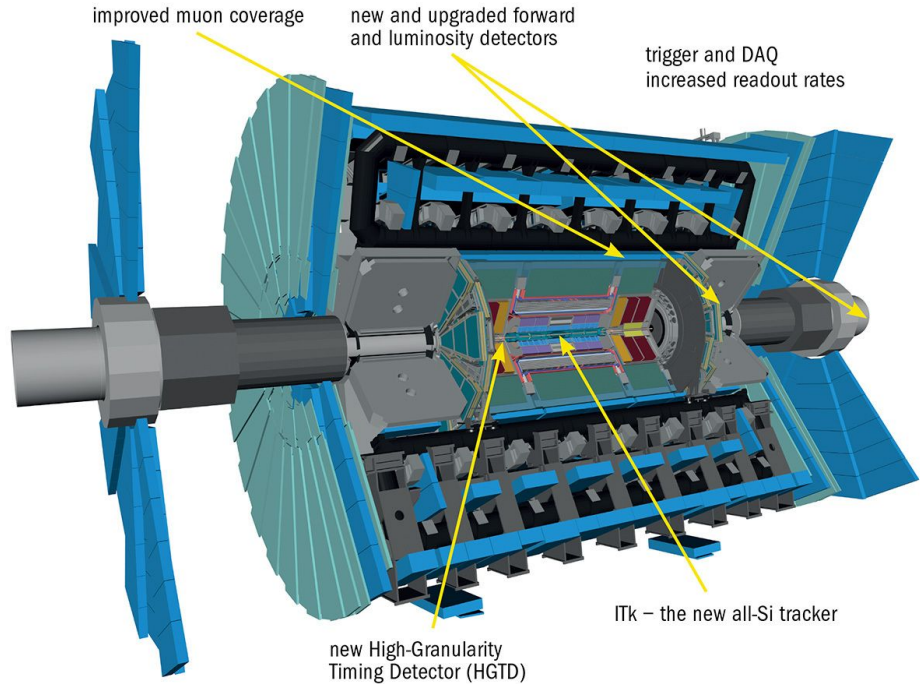
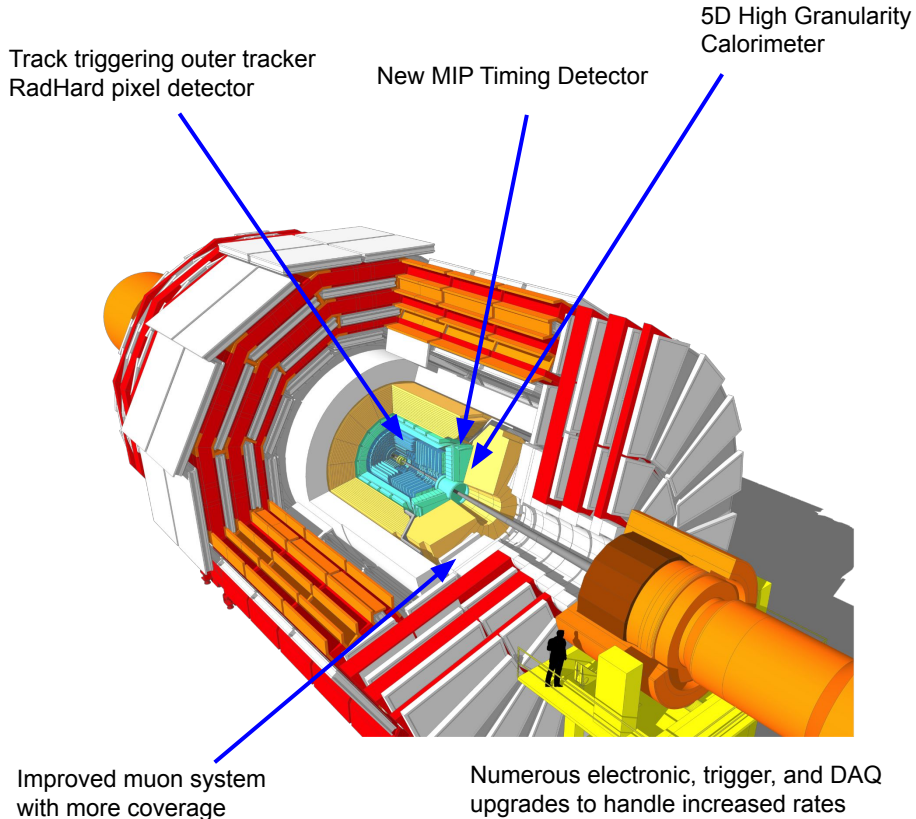
LHCb Triggers for Long Lived Particles (2/2)



- Triggers competitive with LLP specific experiments
- HNLs coupling exclusively to ν_e
- ALPs coupled to fermions
- **All projected limits!**
- More in the paper!

LHCb Dark Photons
LHCb LLP Sensitivity

The Upgrades



Many more results

- [ATLAS-EXOT-2020-26](#)
- [ATLAS-EXOT-2022-04](#)
- [ATLAS-EXOT-2018-55](#)
- [ATLAS-EXOT-2022-33](#)
- [ATLAS-HDBS-2023-19](#)
- [ATLAS-HDBS-2019-19](#)
- [ATLAS-HDBS-2021-03](#)

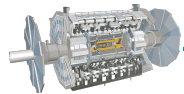
- [CMS-SUS-23-003](#)
- [CMS-B2G-22-005](#)
- [CMS-B2G-23-004](#)
- [CMS-EXO-22-013](#)
- [CMS-EXO-23-010](#)
- [CMS-EXO-23-015](#)
- [CMS-EXO-24-007](#)

More BSM in QCD@LHC

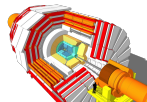
**Talk on EFT before
mine**

[More Higgs BSM](#)

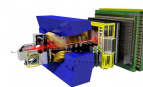
[Ultra-peripheral heavy
ion collisions](#)



[Recent ATLAS Results](#)



[Recent CMS Results](#)



[Recent LHCb Results](#)

Did we find BSM physics???

Did we find BSM physics???



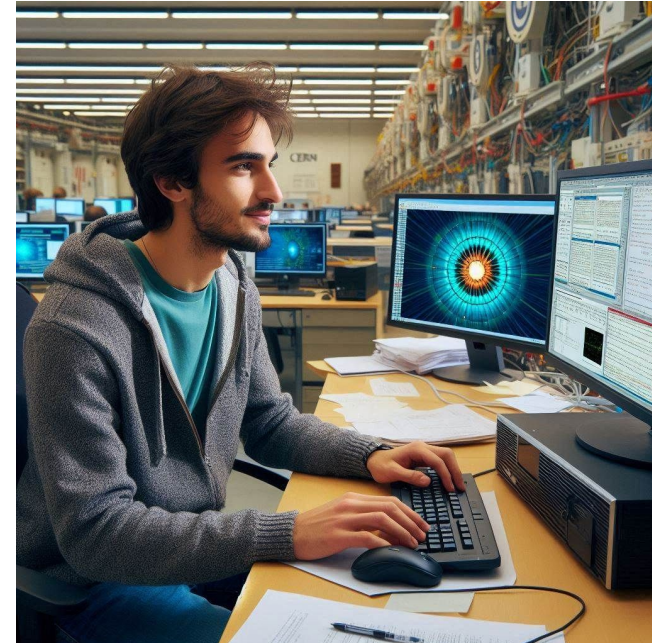
No

But there is a lot of data to go through in run 3

And we are about to have new experiments capable of observing collisions like never before

“A particle physics graduate student working on a computer in an office at CERN”

- computer generated with Bing image creator



Back Up