New particle searches at LHC (non-SUSY)

DISCRETE 2024 in Ljubljana
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on behalf of ATLAS, CMS and LHCb collaborations

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Ministero dell'Università e della Ricerca

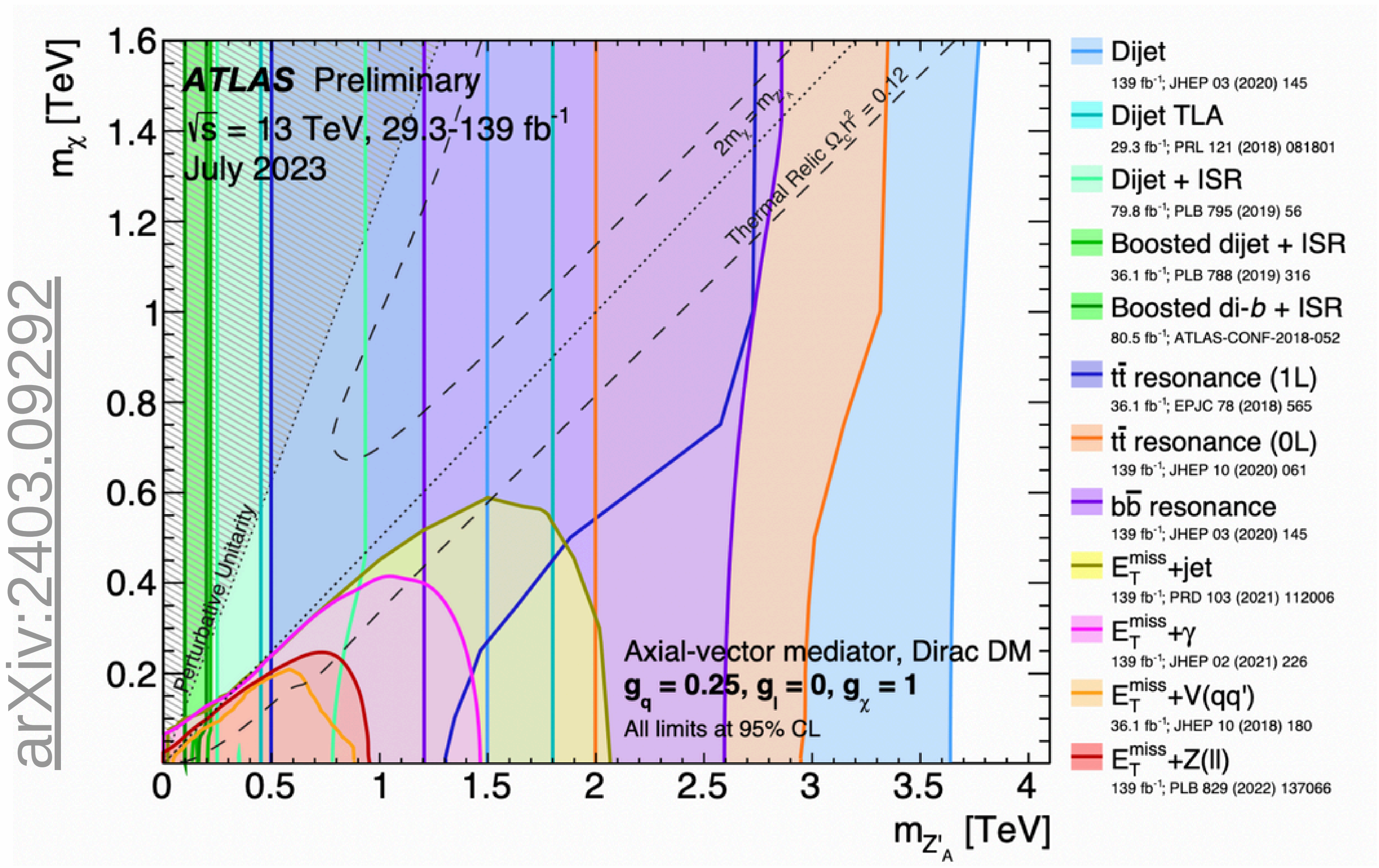
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

A Comprehensive review of BSM searches at LHC

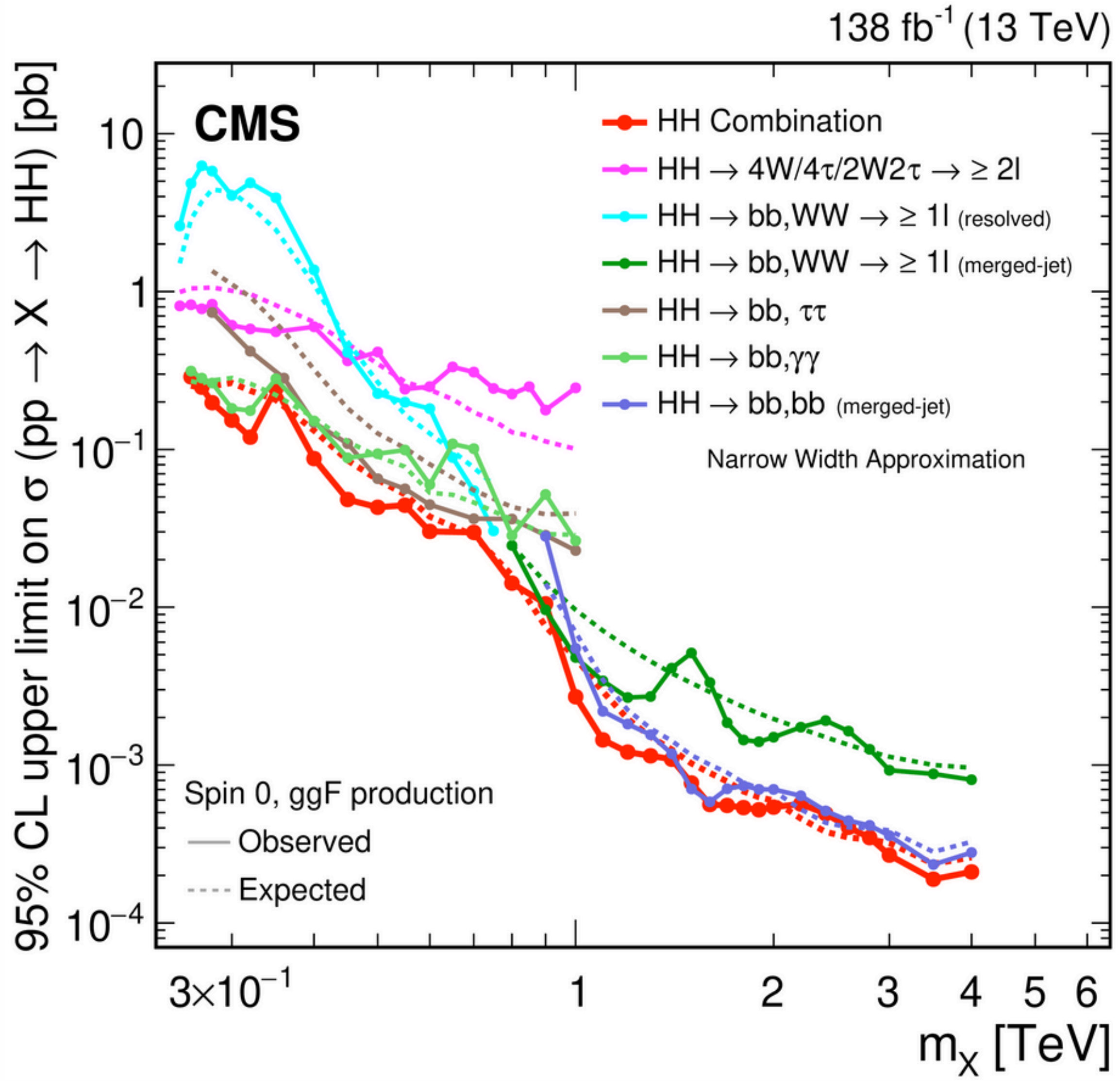
Many **Physics Reports about BSM Run 2 physics @LHC** submitted: state-of-the-art of a broad set of physics results and techniques in many areas of LHC BSM physics. Two examples:

All 2024 Physics Reports from ATLAS

arXiv:2403.09292



Dark Matter @ Colliders: wide range of phase space explored w/ **complementary signatures**



Search for X to HH/G to HH: **different analyses techniques** optimized in dedicated final states

arXiv:2403.16926

All 2024 Physics Reports from CMS

BSM searches since summer 2024

Reference	Topic	Experiment	Model	Explored energy range (0, 300, 600, 900, 1200, 1500, 1800, 2100, 2400, 2700, 3000 [GeV])
HDBS-2021-07	$H \to aa \to bb\tau\tau$	ATLAS	Extended Higgs Sector	
HDBS-2020-11 and HDBS-2024-45	$H^{\pm} \to cs$ and $H^{+} \to Wh$	ATLAS		
HDBS-2023-19	Combination of charged Higgs searches	ATLAS		
HDBS-2021-08	$A \to \tau\tau$	ATLAS 🔔		
EXOT-2022-13	$t\bar{t}A \to t\bar{t}t\bar{t}$	ATLAS		
HIG-24-002	$H \to ZZ \to 4l$	CMS		
HIG-22-004	$A \to Zh(\tau\tau)$	CMS		
SUS-24-001	$\phi \to bb$	CMS		
HIG-20-012	$X \to YH \to 4b$	CMS 🔔		
HIG-22-013	$A \to tt$	CMS 🔔		
EXOT-2018-55	Prompt Lepton-Jets	ATLAS	Dark Sector	
EXOT-2022-04	Long Lived Particles in the hadronic calorim.	ATLAS		- displaced
HDBS-2021-09	$H \to Za \to llj$	ATLAS 🔔		
SUS-23-004	$\mathrm{mono}-t$	CMS		
SUS-23-012	$\mathrm{mono}-h(\tau\tau)$	CMS		
SUS-23-018	$H \to Za \to ll\chi\chi$	CMS		
SUS-24-004	pMSSM	CMS	Supersymmetry	
SUS-23-003	Compressed Supersymmetry	CMS		
ATLAS-CONF-2024-011	Run3 displaced leptons	ATLAS		- displaced
SUS-23-002	Supersymmetry w/ charged leptons and missing	CMS		
ATLAS-CONF-2024-008	Vector Like Leptons (VLL) 4321 model (tau	ATLAS	Heavy Fermions	
EXOT-2021-31	VLL (1st and 2nd gen)	ATLAS 🔔		
EXOT-2021-02	Combination of VLQ	ATLAS		
EXOT-2022-43	VLQ Wb (0L)	ATLAS 🔔		
TOPQ-2019-31	t-HNL	ATLAS 🔔		
EXO-23-015	$\mathrm{VLL} \to \tau a(\gamma\gamma)$	CMS		- displaced
B2G-22-005	$t^{*} \to tg$	CMS		
EXO-23-010	$ll + \mathrm{b-jets, non-resonant}$	CMS	EFT	
EXOT-2022-33	Low mass dijet + ISR gamma	ATLAS	New Mediators	
EXOT-2020-26	Dark Higgs via Z'	ATLAS		
HDBS-2021-13	S into four leptons	ATLAS 🔔		
EXO-24-007	Low mass dijet+ISR	CMS		
EXO-22-006	$Z' \to \mu\mu + \mathrm{b-jets, resonant}$	CMS		
EXO-22-013	t-channel scalar and vector leptoquark	CMS	Leptoquarks	

🔔 == New w.r.t. ICHEP2024 | Shown today

Beyond

Standard

Model

Strategies

Signatures

Tools

Beyond **S**tandard **M**odel

- *Extended Higgs Sector(2HDM)*
- *Supersymmetry (see I. Vivarelli's talk)*
- *Heavy fermions*

Strategies

Signatures

Tools

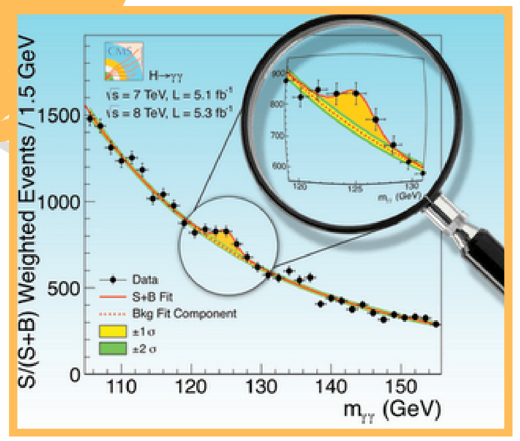
Extended Higgs Sector: Two Higgs doublet model (2HDM).

$H^{\pm}$

A

H

h



[link]

Already observed Higgs Boson

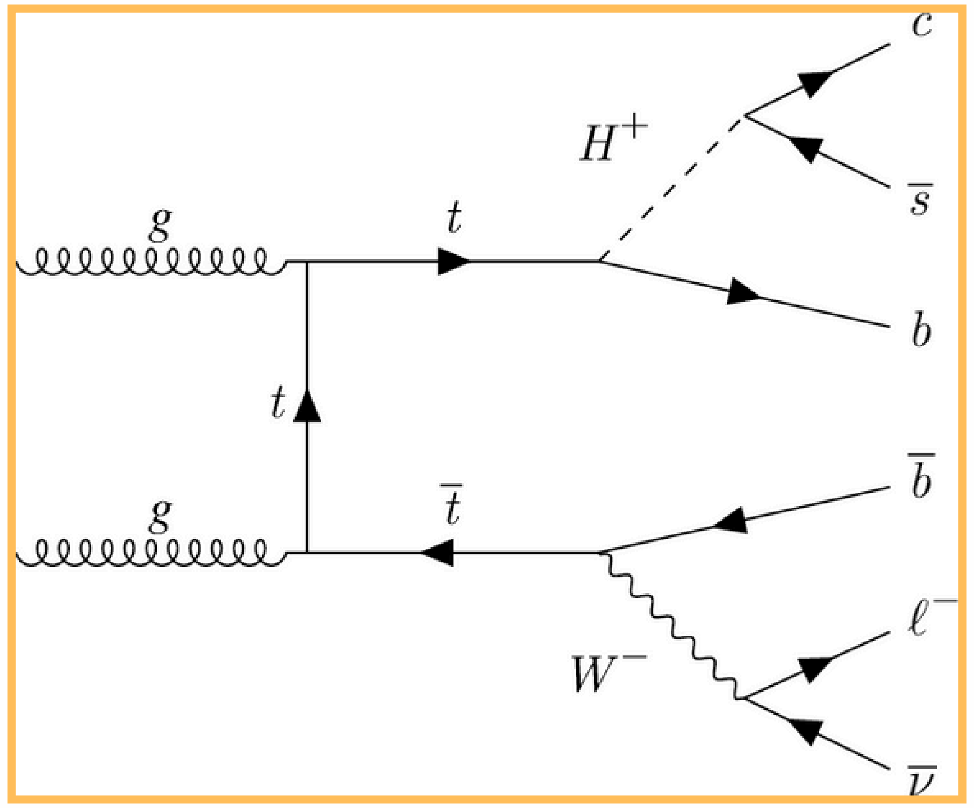
arXiv:2203.07244

Two Higgs doublet model (2HDM): $H^{\pm}$, A, H, h

ATLAS EXPERIMENT

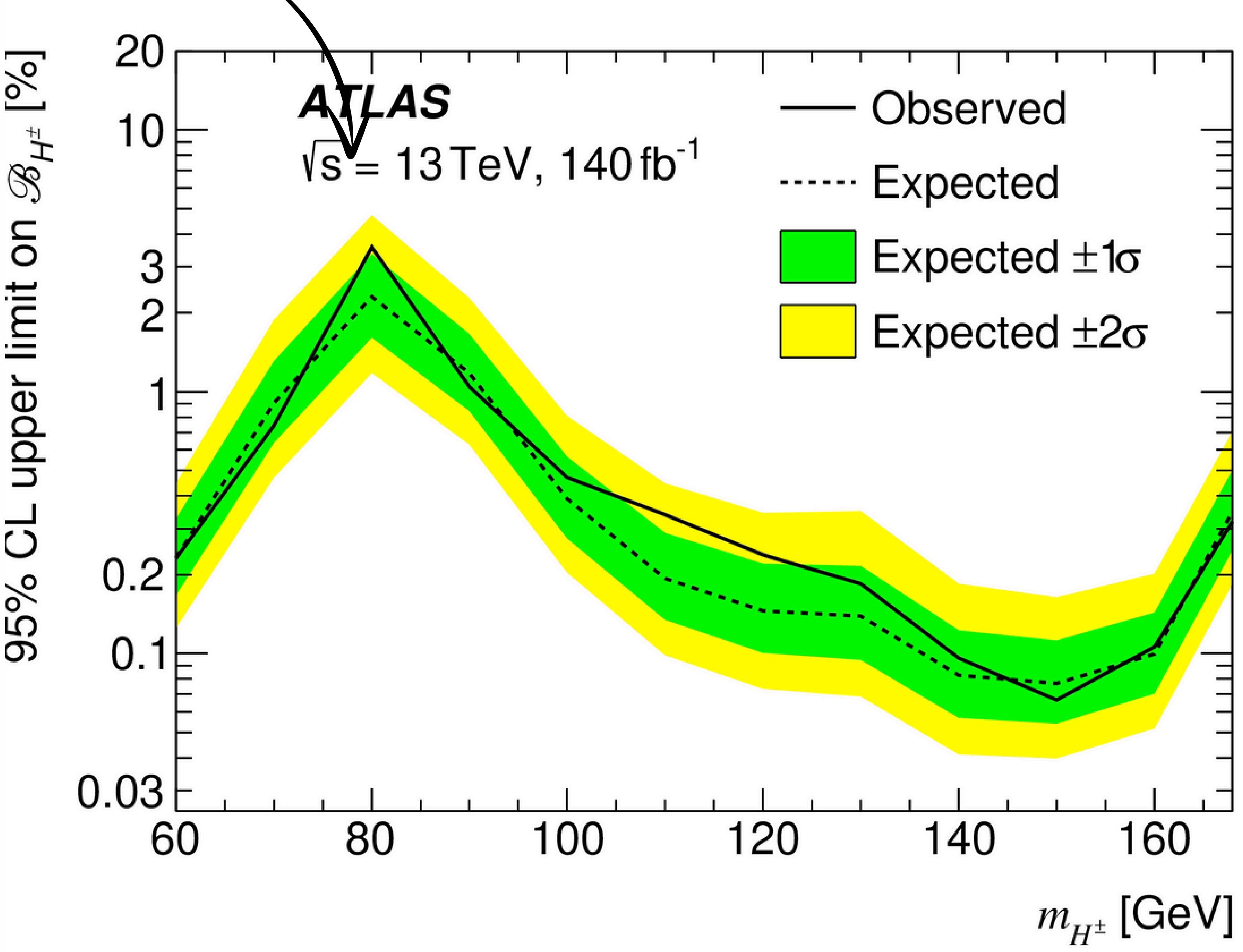
Search for $t \to H^{\pm}b$ with $H^{\pm} \to cs$

$H^{\pm} \to cb$ moderate **excess around 130 GeV from ATLAS**, with global significance of 2.5 σ [link]



Dedicated flavour-tagging scheme: **simultaneous tagging of b- and c-jets.**

Least stringent at ~80 GeV about 2.3%, as signal mass closest to W-boson



Limits worsen as the acceptance decreases

arXiv:2407.10096

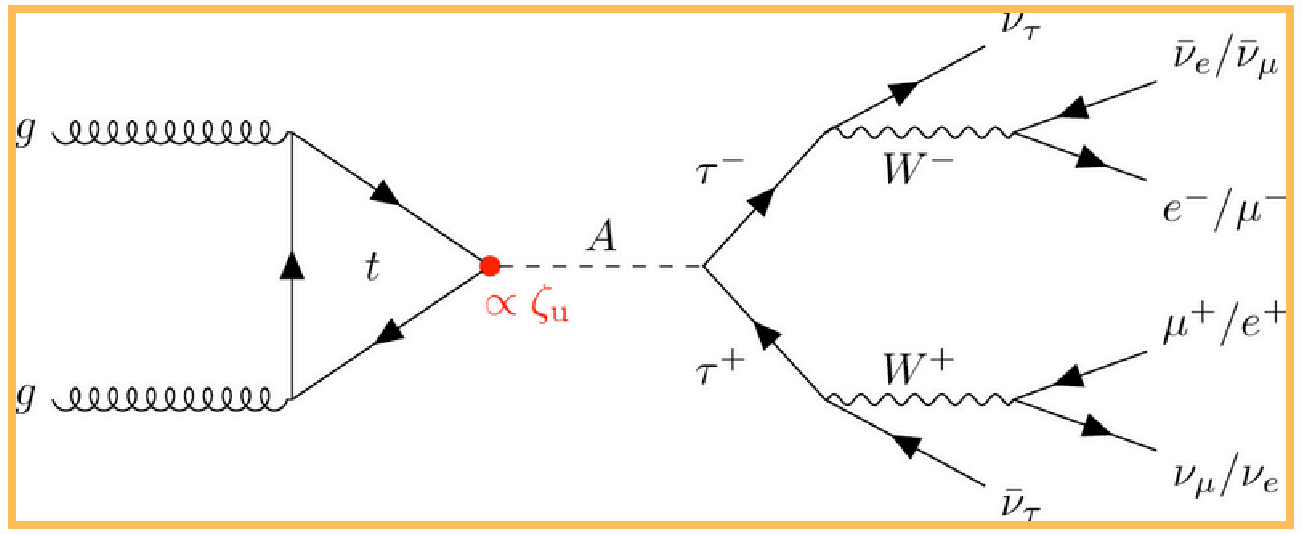
Backup

Two Higgs doublet model (2HDM): $H^{\pm}$, A, H, h

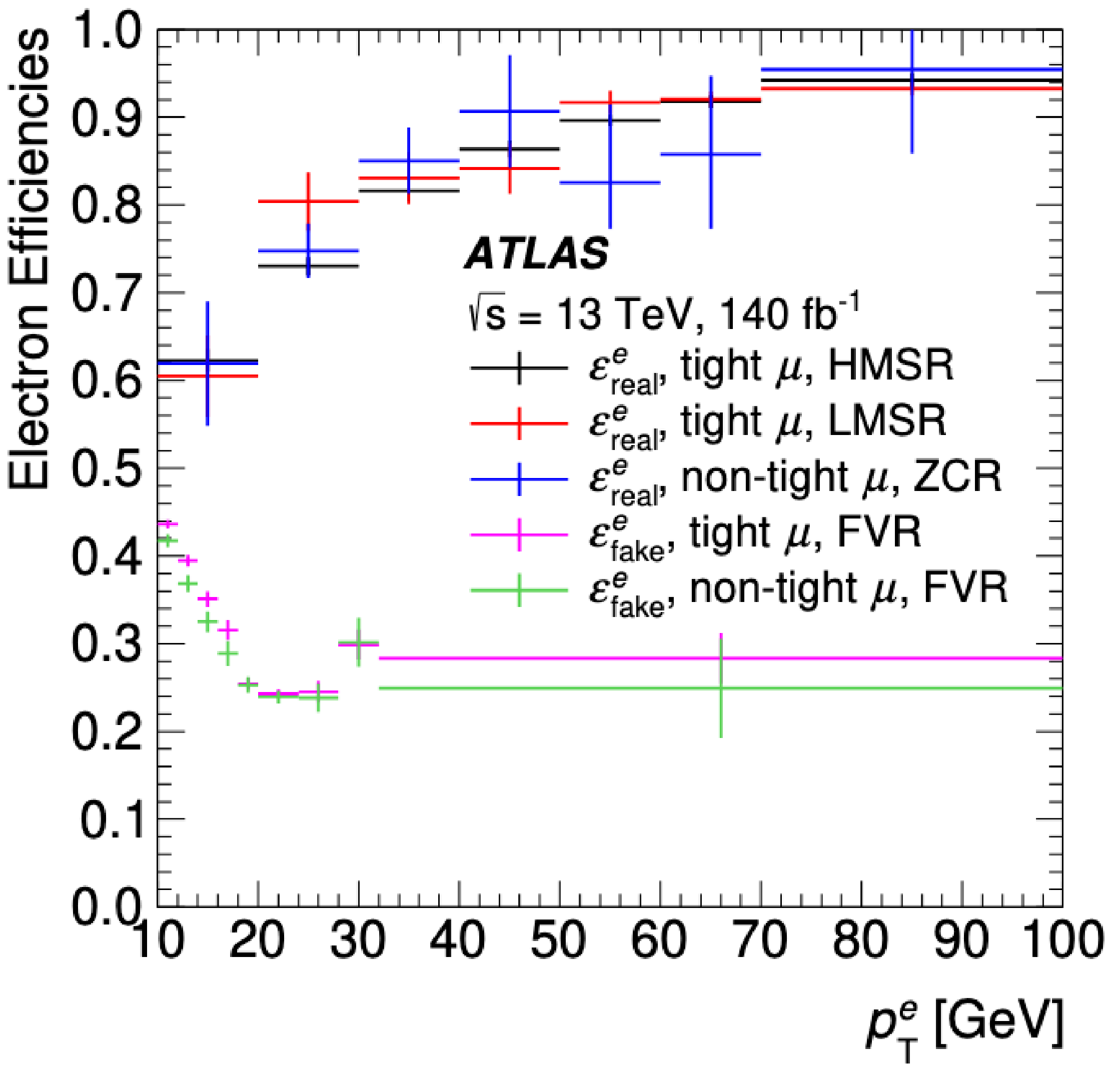
Search for a **light CP-odd scalar resonance** with a mass of 20 GeV to 90 GeV

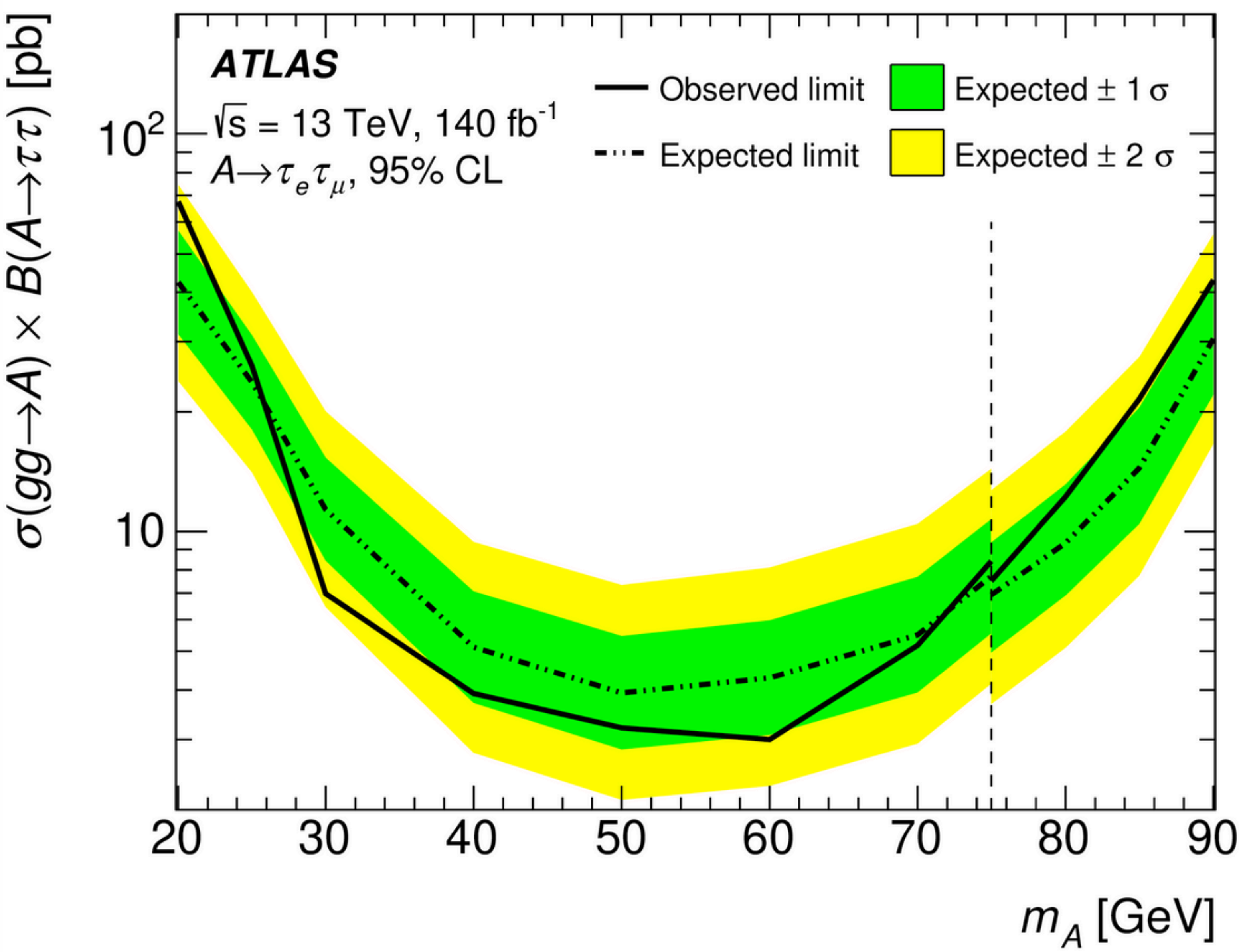
Motivated by anomalies such as muon **g−2 discrepancy**.

Fully leptonic final states (e+μ) from ττ decays to bypass trigger limitations for low energy τ



Excellent **understanding of low-energy** electrons (and muons)



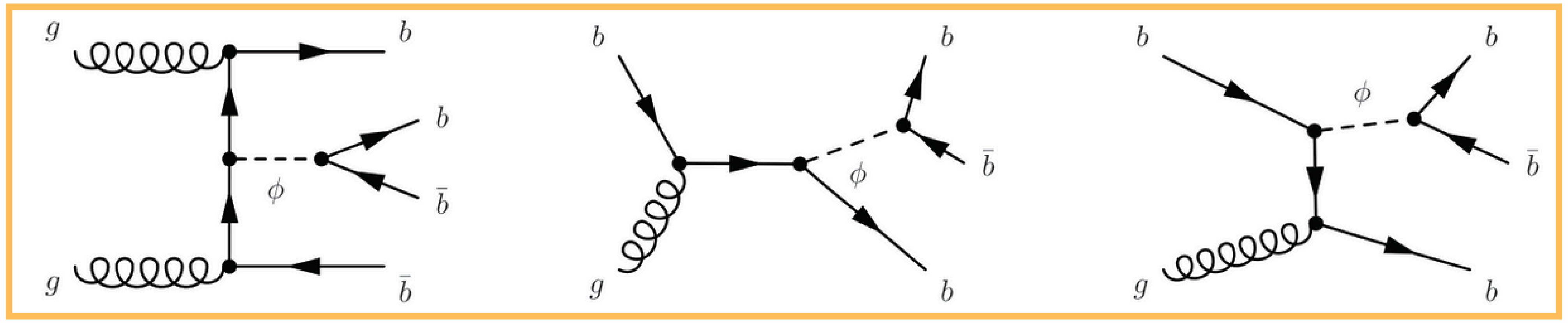


arXiv:2409.20381

Backup

Two Higgs doublet model (2HDM): $H^{\pm}$, A, H, h

Search for bosons of an extended Higgs sector in b quark final states



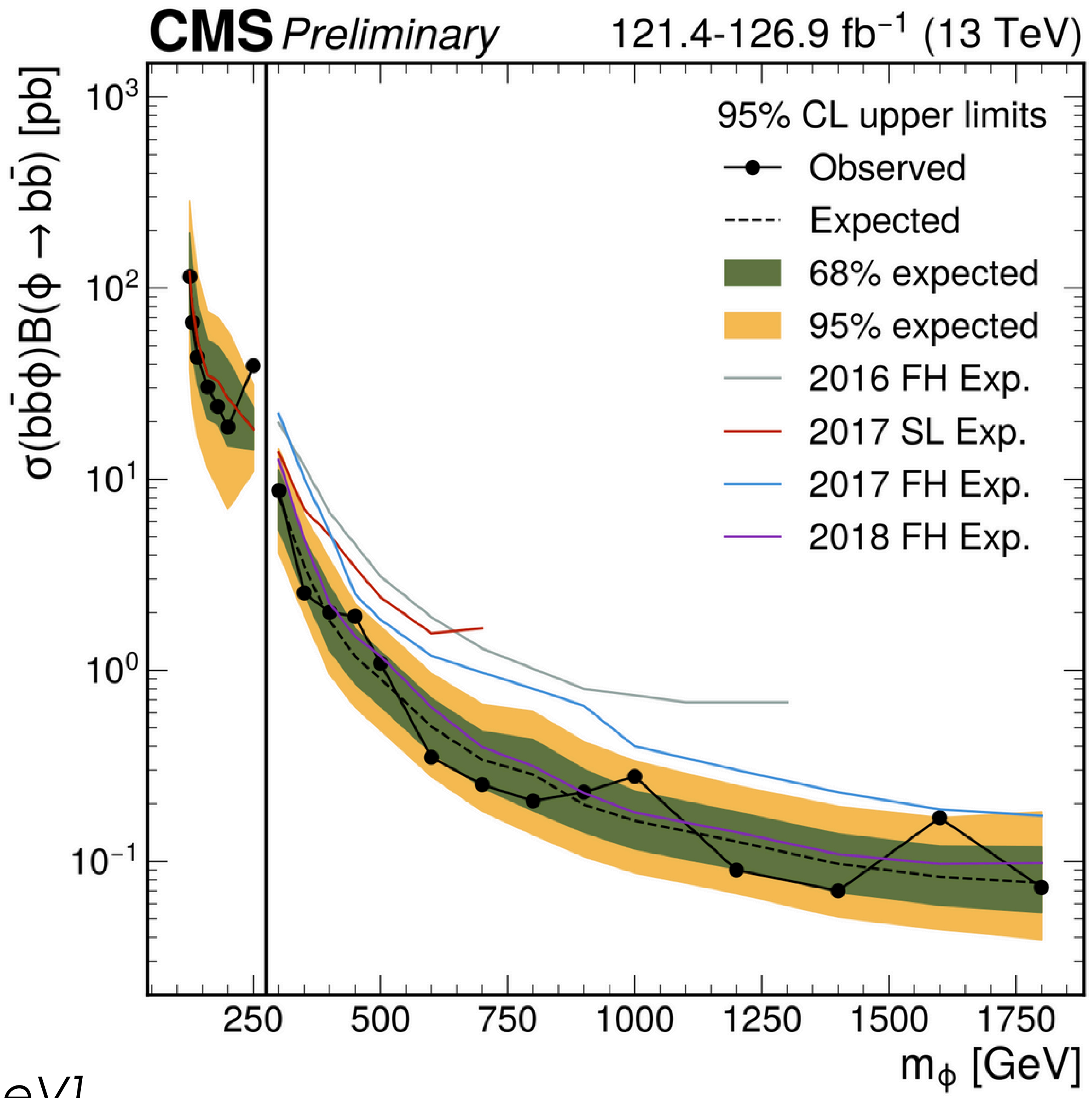
Searching for a **peak in the invariant mass distribution**, of the two b jets with the highest p_T values

Two different signatures explored to maximize sensitivity over a wide mass range

Semi Leptonic (SL) **Fully Hadronic (FH)**

125 700 1800

m [GeV]

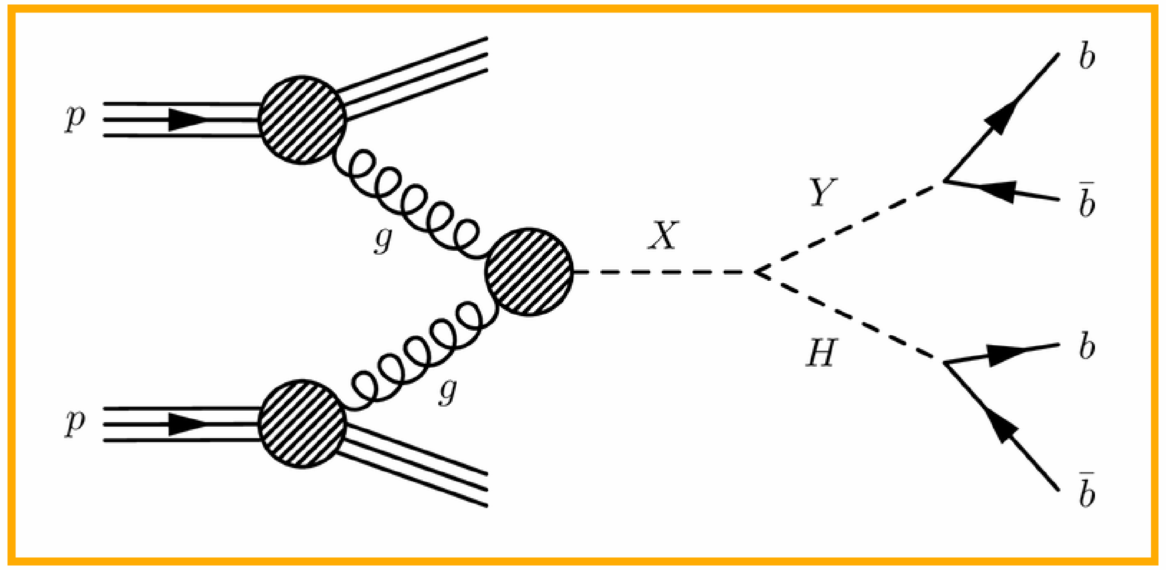


CMS-PAS-SUS-24-001

Backup

Two Higgs doublet model (2HDM): $H^{\pm}$, A, H, h

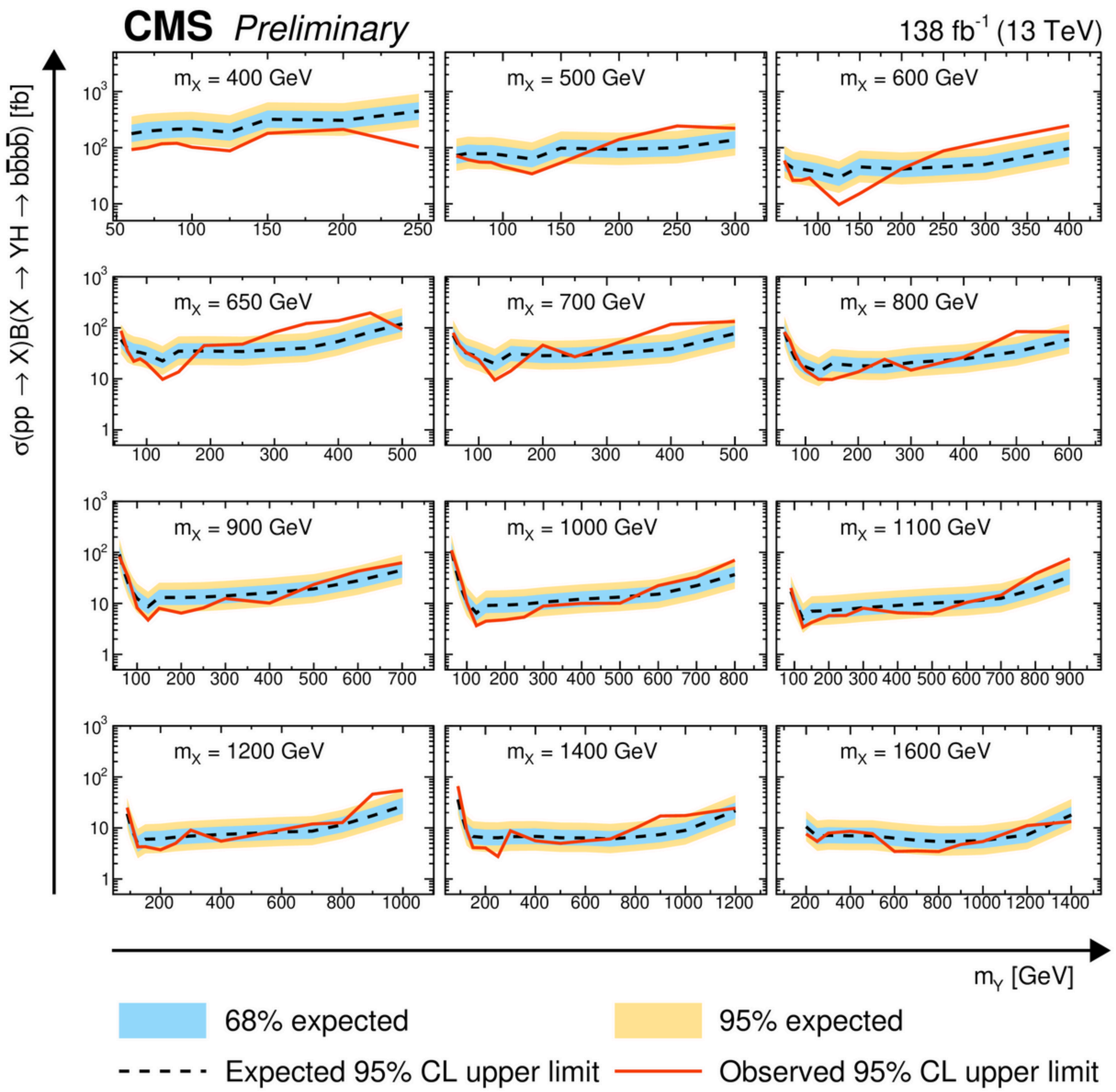
Search for $X \to YH \to 4b$



Probes mass ranges: mX=400–1600 GeV and mY=60–1400 GeV

Model-independent approach with **two-dimensional fit in reconstructed masses** and data-driven background model with different b-tagging criteria

Largest excess for **mX=700 GeV and mY=400 GeV**, with a **local significance of 4.1 standard deviations**, reduced to 2.8 after accounting for the global significance.

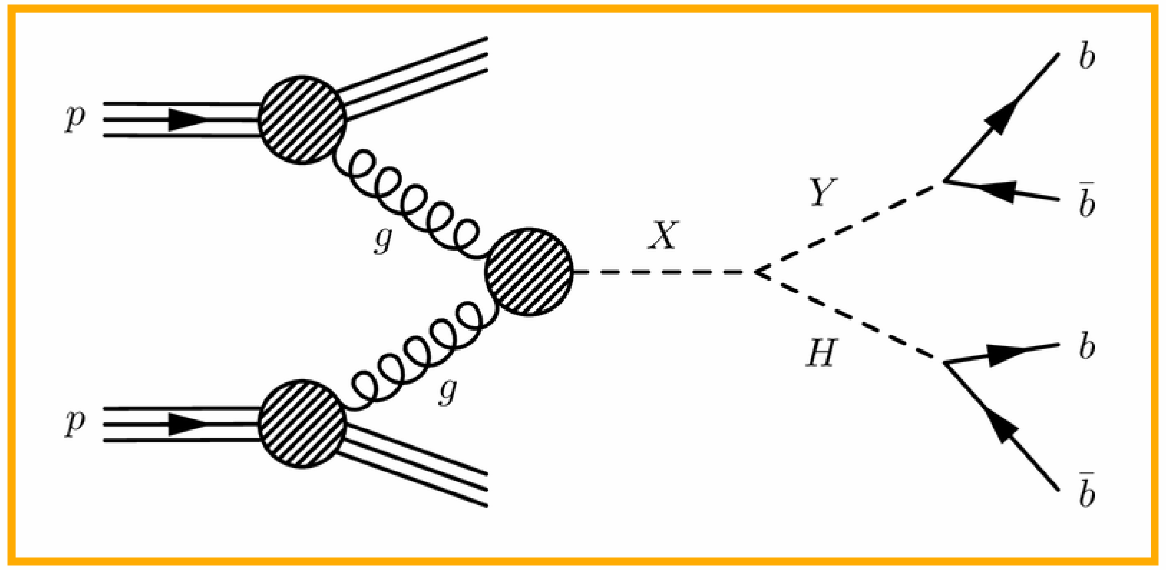


CMS-PAS-HIG-20-012

Backup

Two Higgs doublet model (2HDM): $H^{\pm}$, A, H, h

Search for $X \to YH \to 4b$



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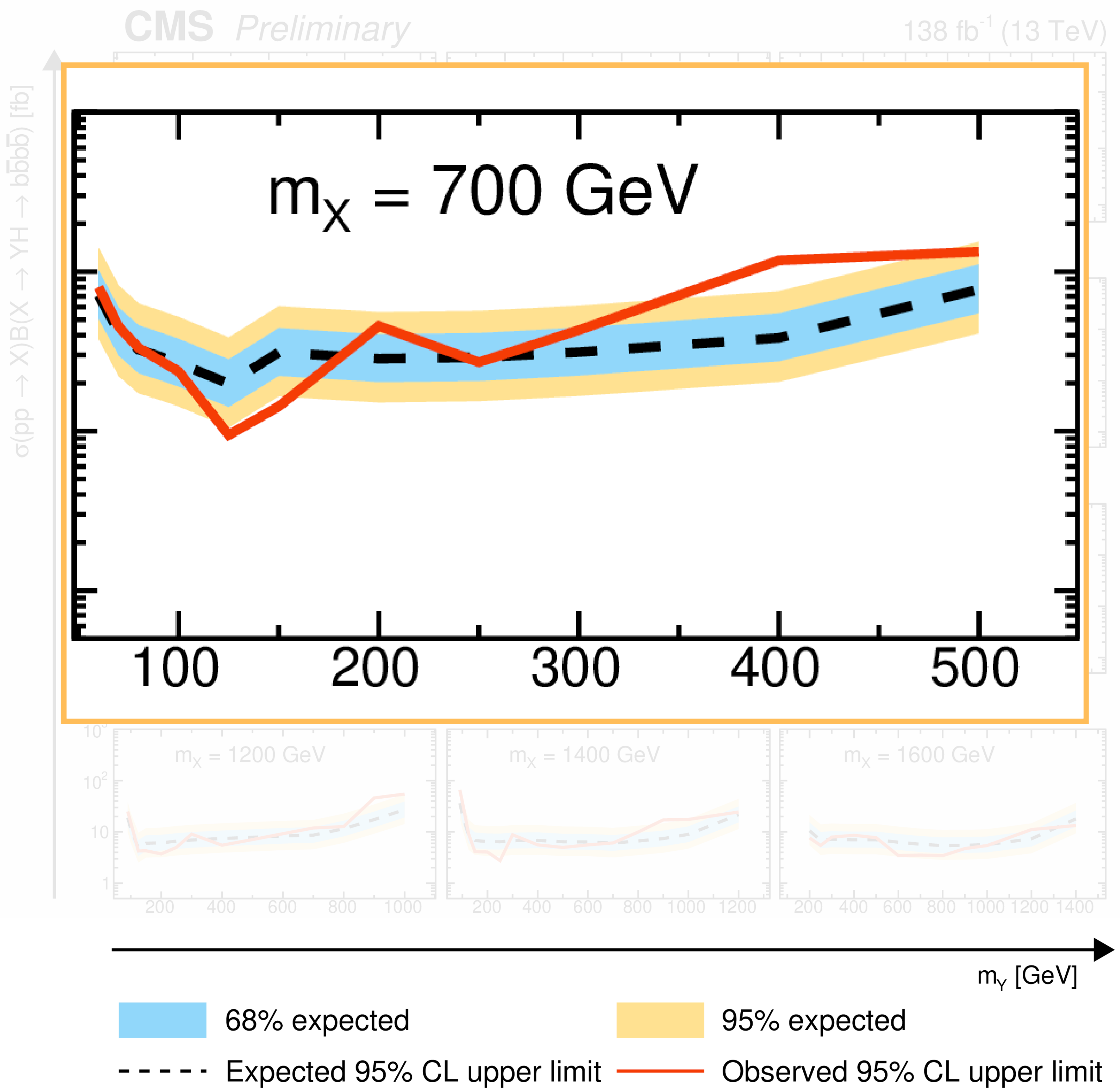


CMS-PAS-HIG-20-012

Backup

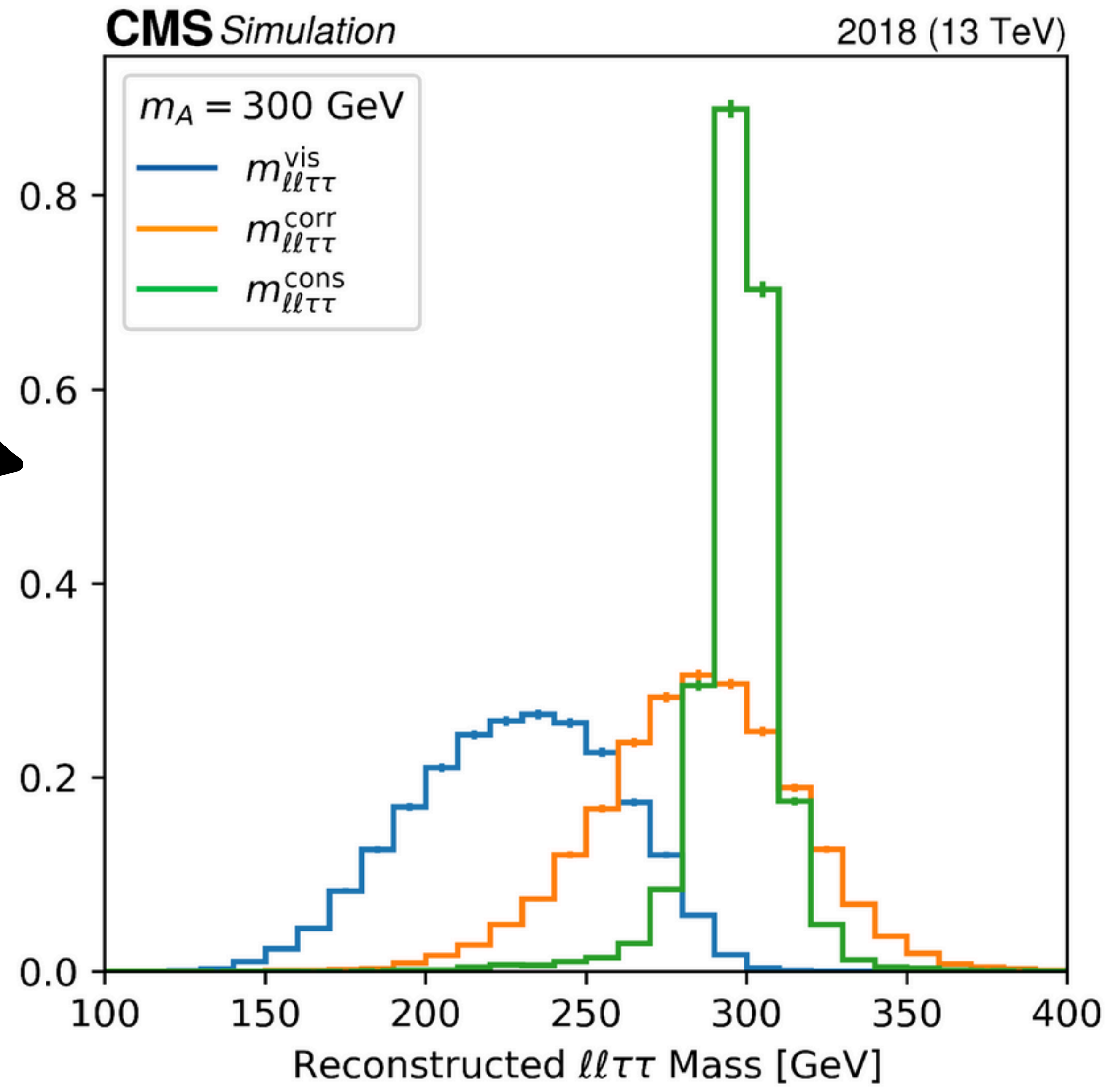
+ interesting excesses in bb-gg final state in Run 2:

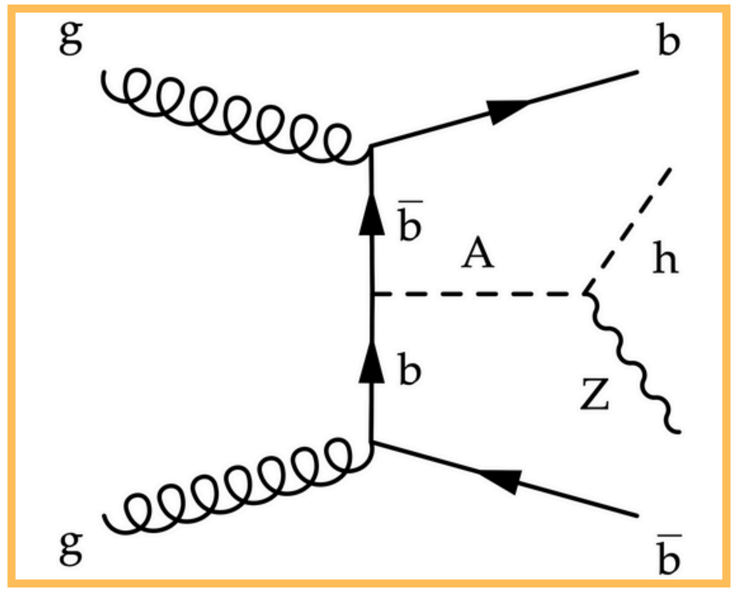
CMS: (mX, mS) = (650, 90) GeV, local (global) significance of 3.8σ (2.8σ)
ATLAS: (mX, mS) = (575, 200) GeV, local (global) significance of 3.5σ (2.0σ)

Two Higgs doublet model (2HDM): $H^{\pm}$, A, H, h

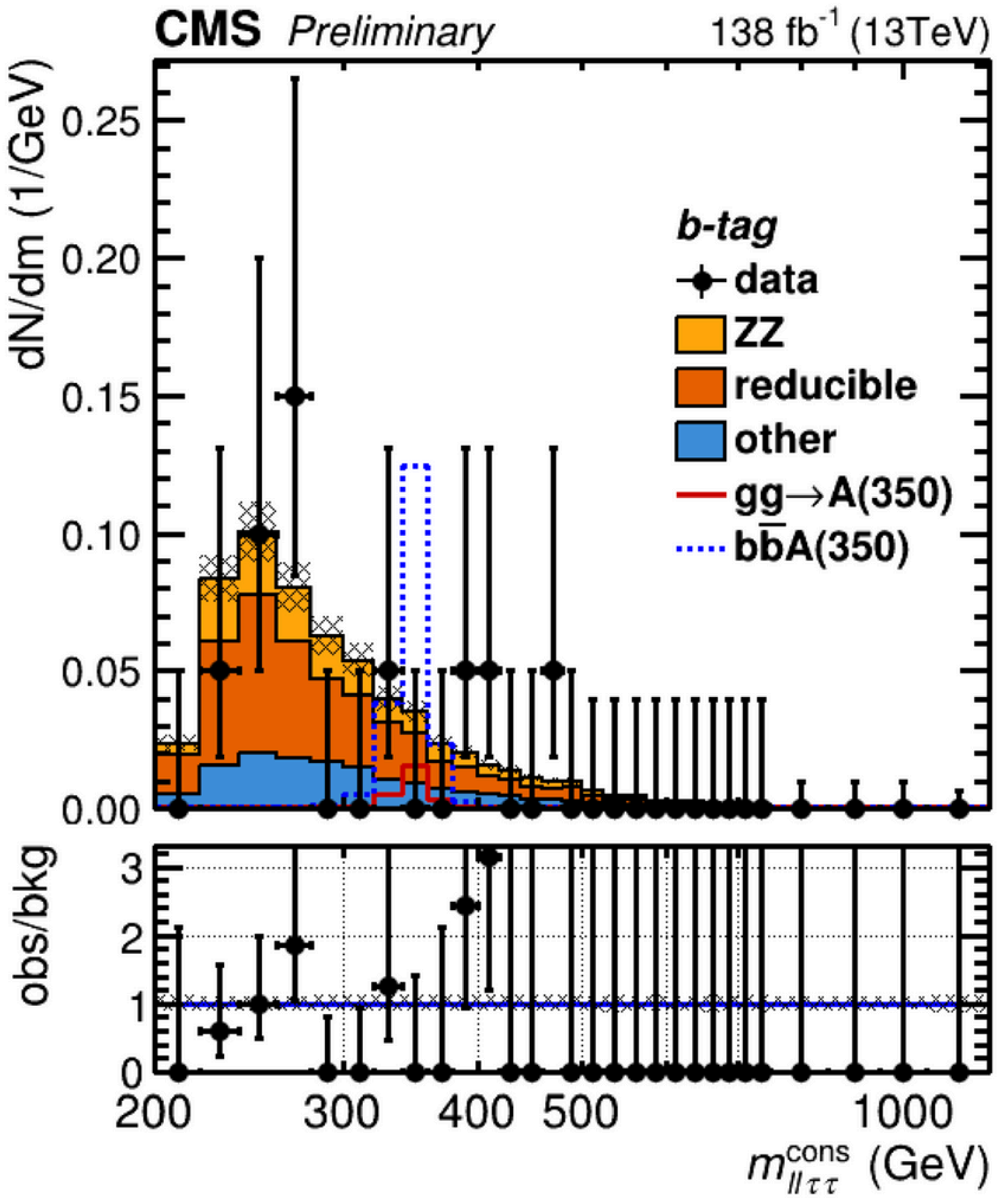
Search for $A \rightarrow Zh(h \rightarrow \tau\tau)$

Dedicated mass estimator corrects for missing momentum from neutrinos while constraining h mass to 125 GeV: **best mass resolution of 5-7%**





Category w/ b-jets designed to bbF production mode

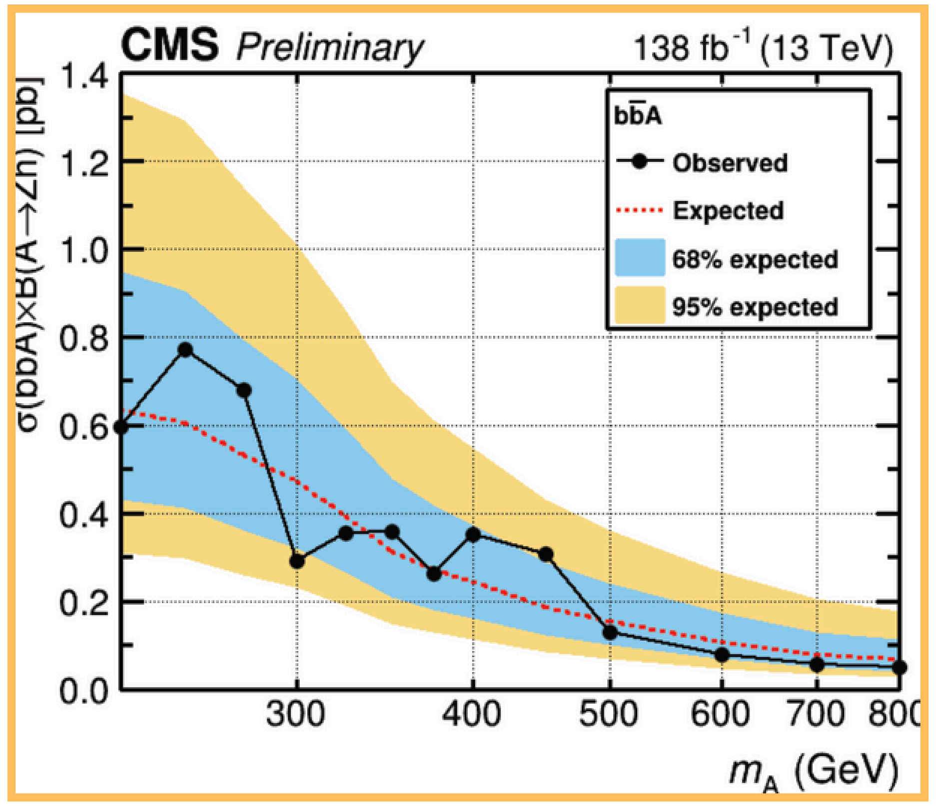


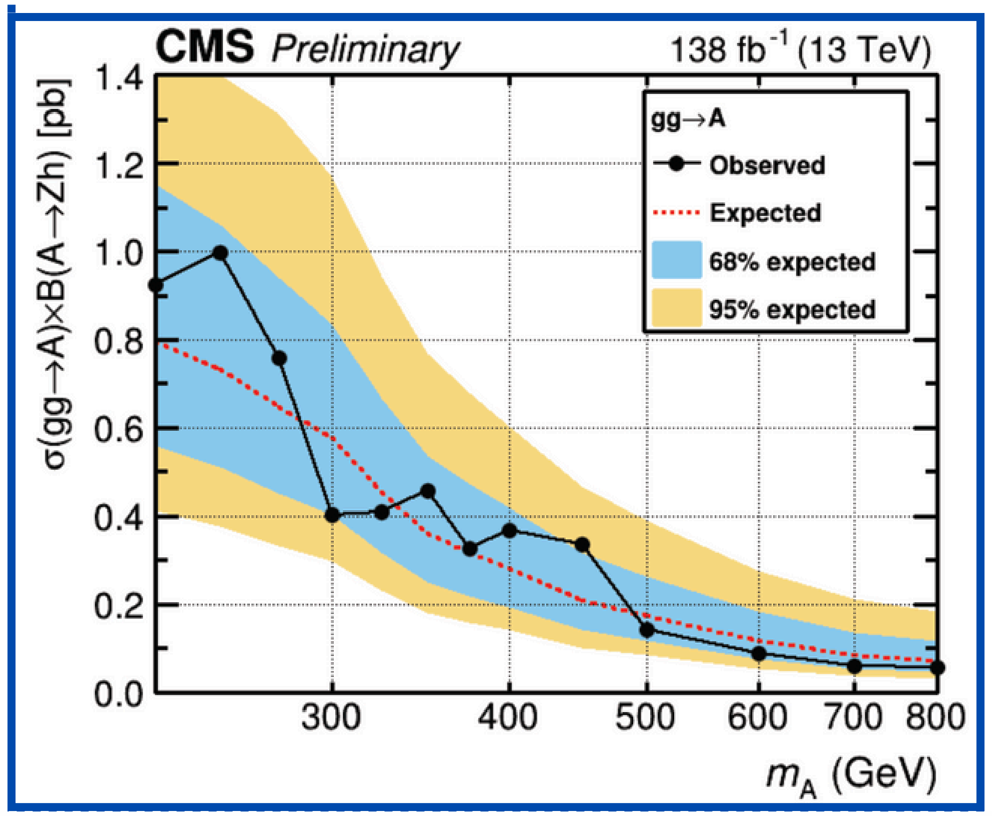
CMS-PAS-HIG-22-004

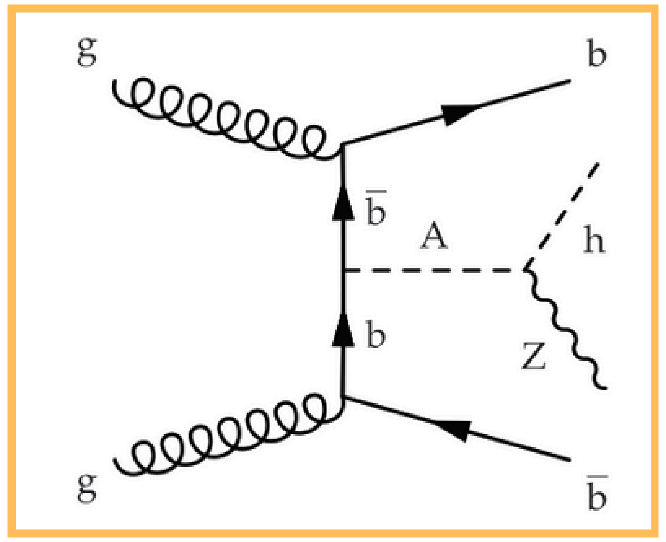
Backup

Two Higgs doublet model (2HDM): $H^{\pm}$, A, H, h

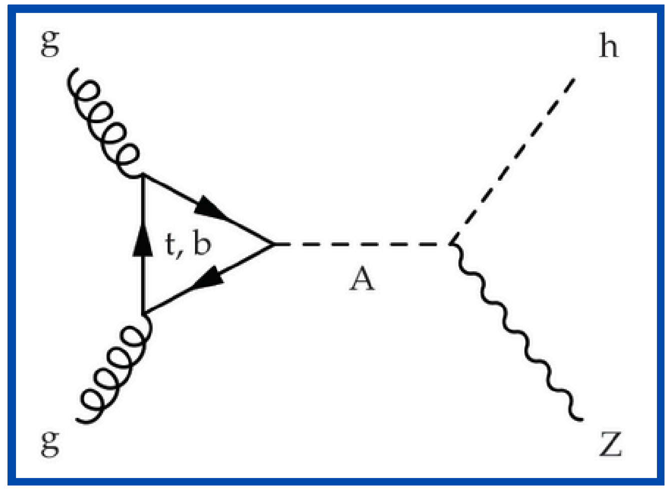
Search for $A \rightarrow Zh(h \rightarrow \tau\tau)$





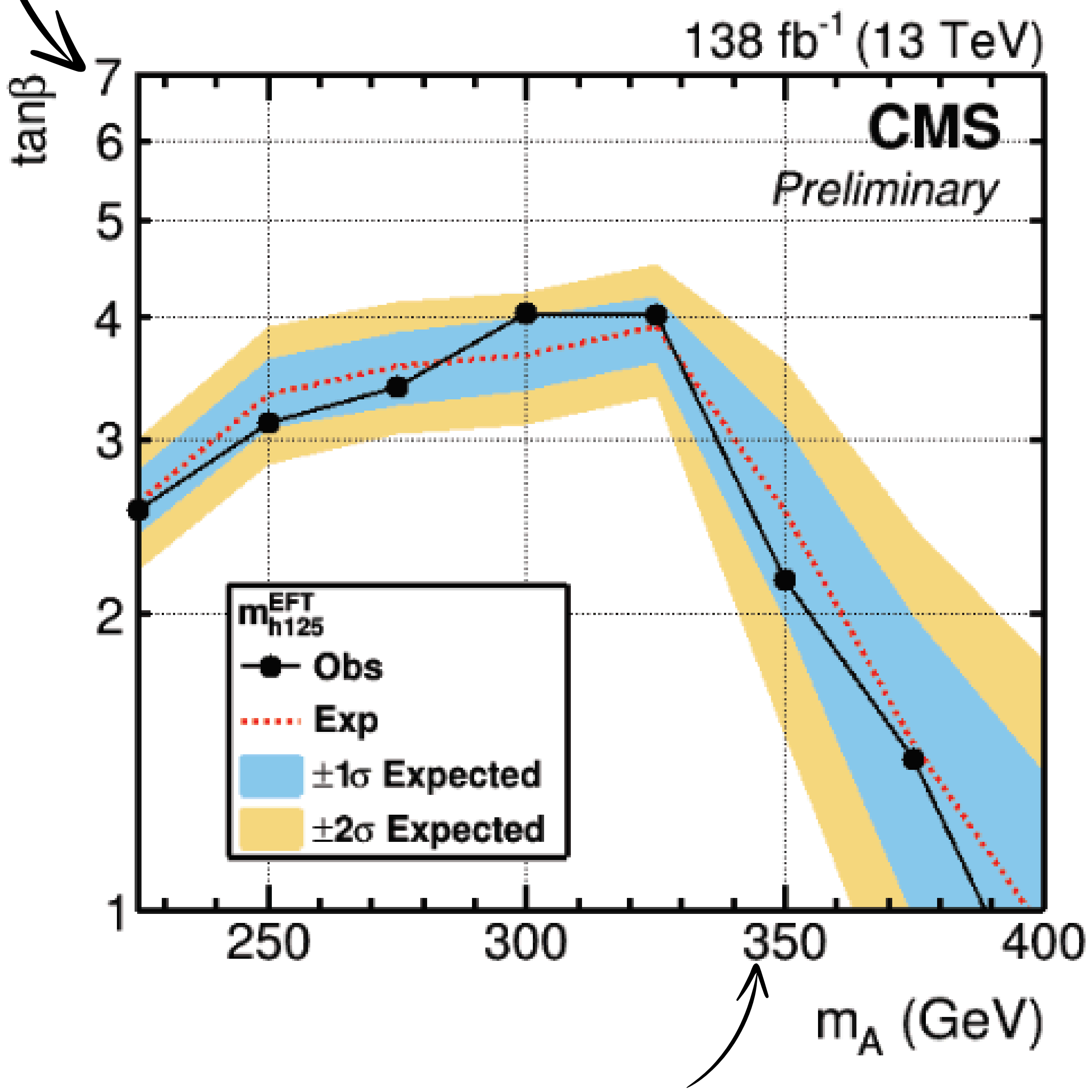


bbF



ggF

At high tan β values associated production w/ b-quarks takes over



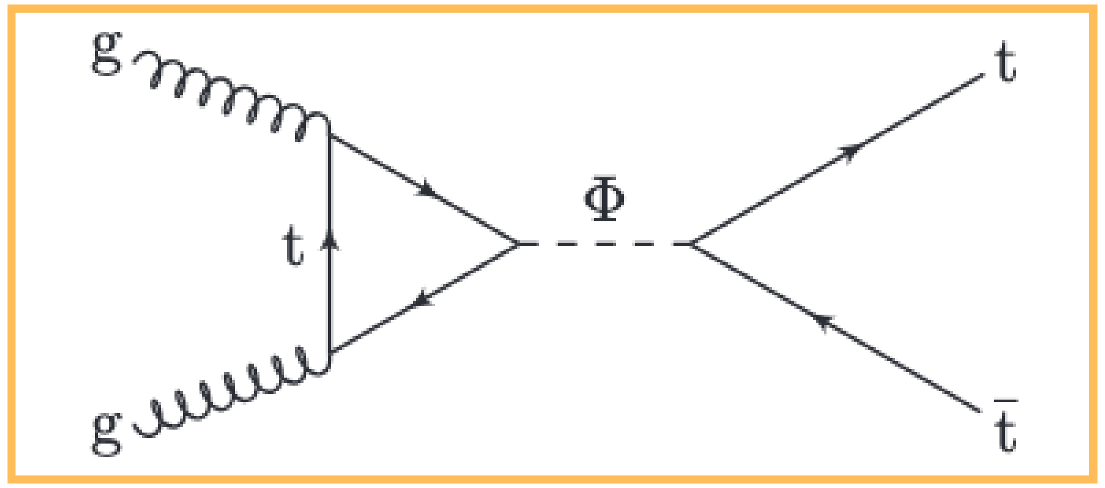
Opening of the tt channel

CMS-PAS-HIG-22-004

Backup

Two Higgs doublet model (2HDM): $H^{\pm}$, A, H, h

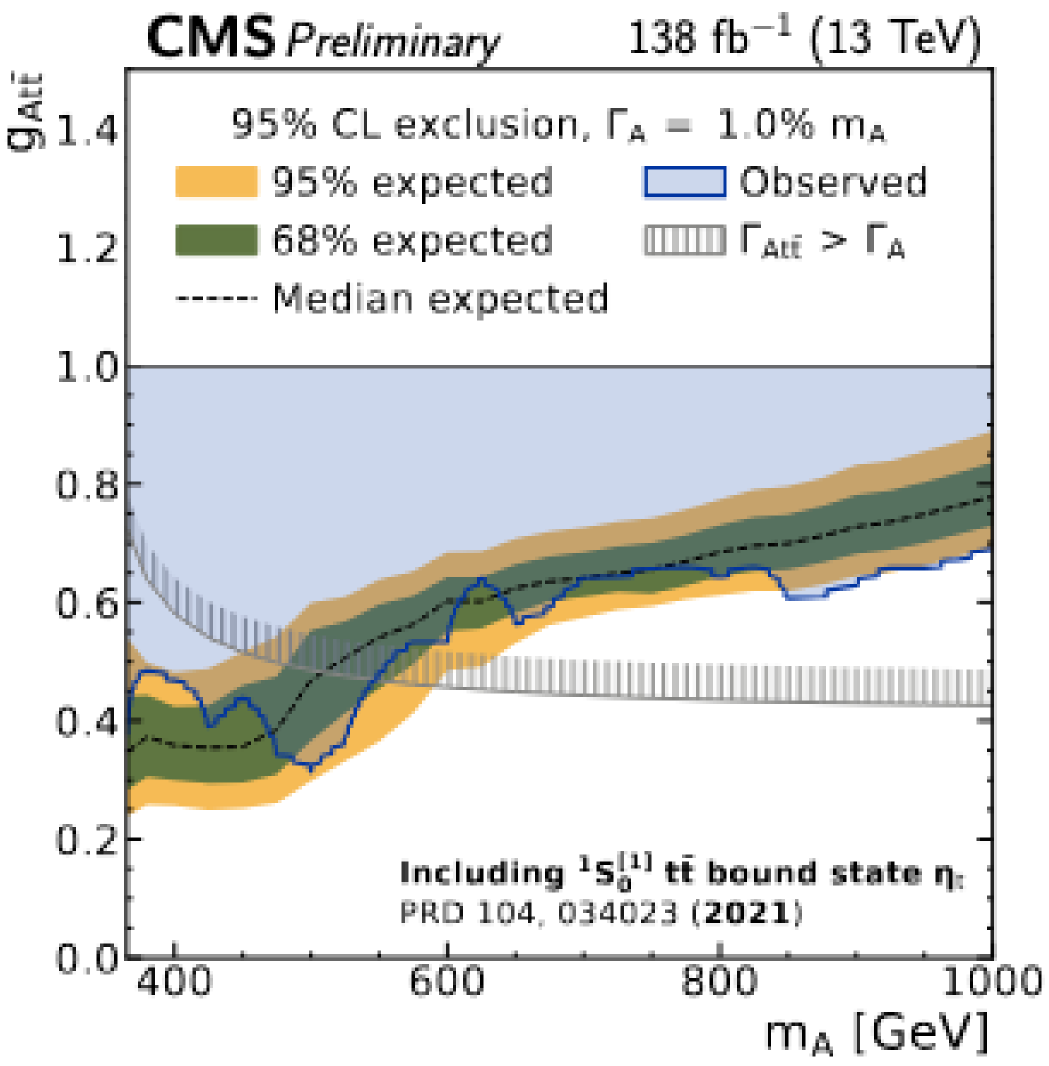
Search for $A \rightarrow t\bar{t}$

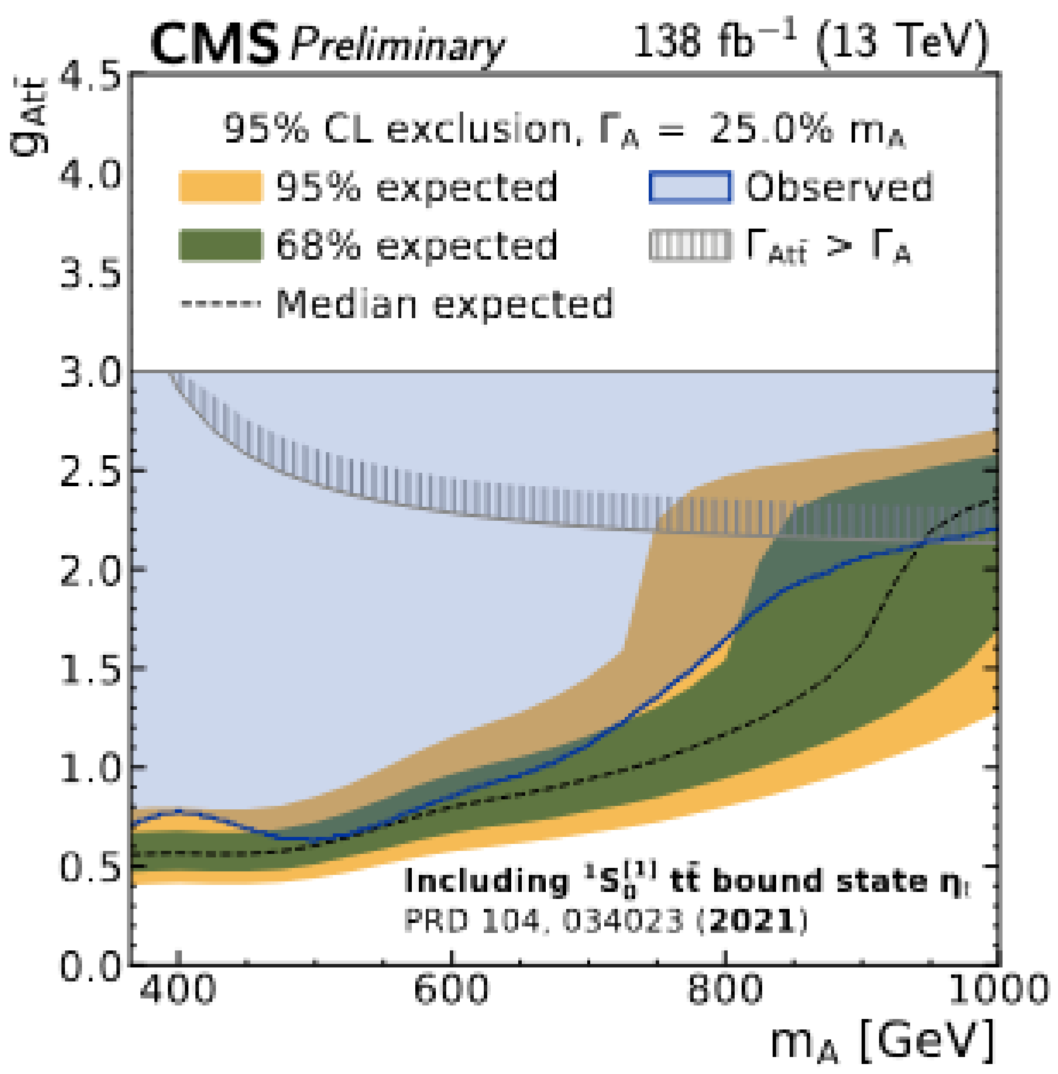


Probes masses in the range of **365–1000 GeV** and relative **widths of 0.5–25%**. Constraints placed on coupling strength to top quarks.

Excess observed near the tt production threshold (> 5 σ)

Bound State Evidence: consistent with a tt bound state, predicted by nonrelativistic QCD, with a σ of 7.1 pb ± 11%.





CMS-PAS-HIG-22-013

Backup

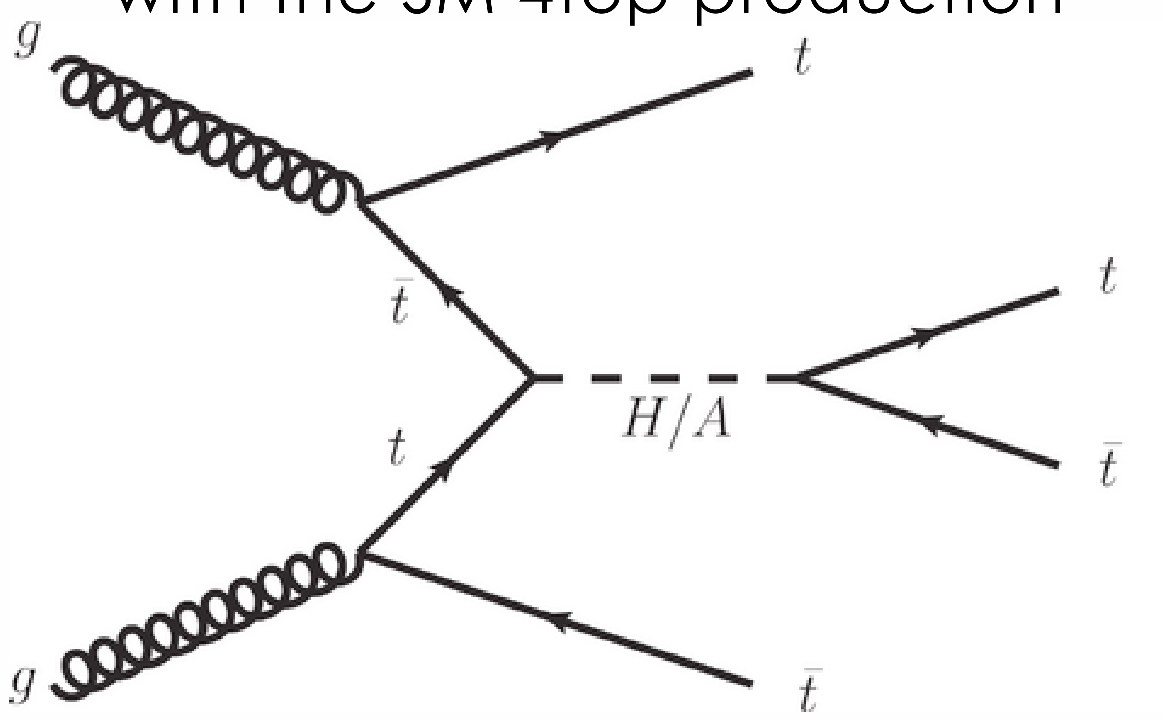
Highlights the importance of **modeling tt bound states in searches for heavy bosons**.

Two Higgs doublet model (2HDM): $H^{\pm}$, A, H, h

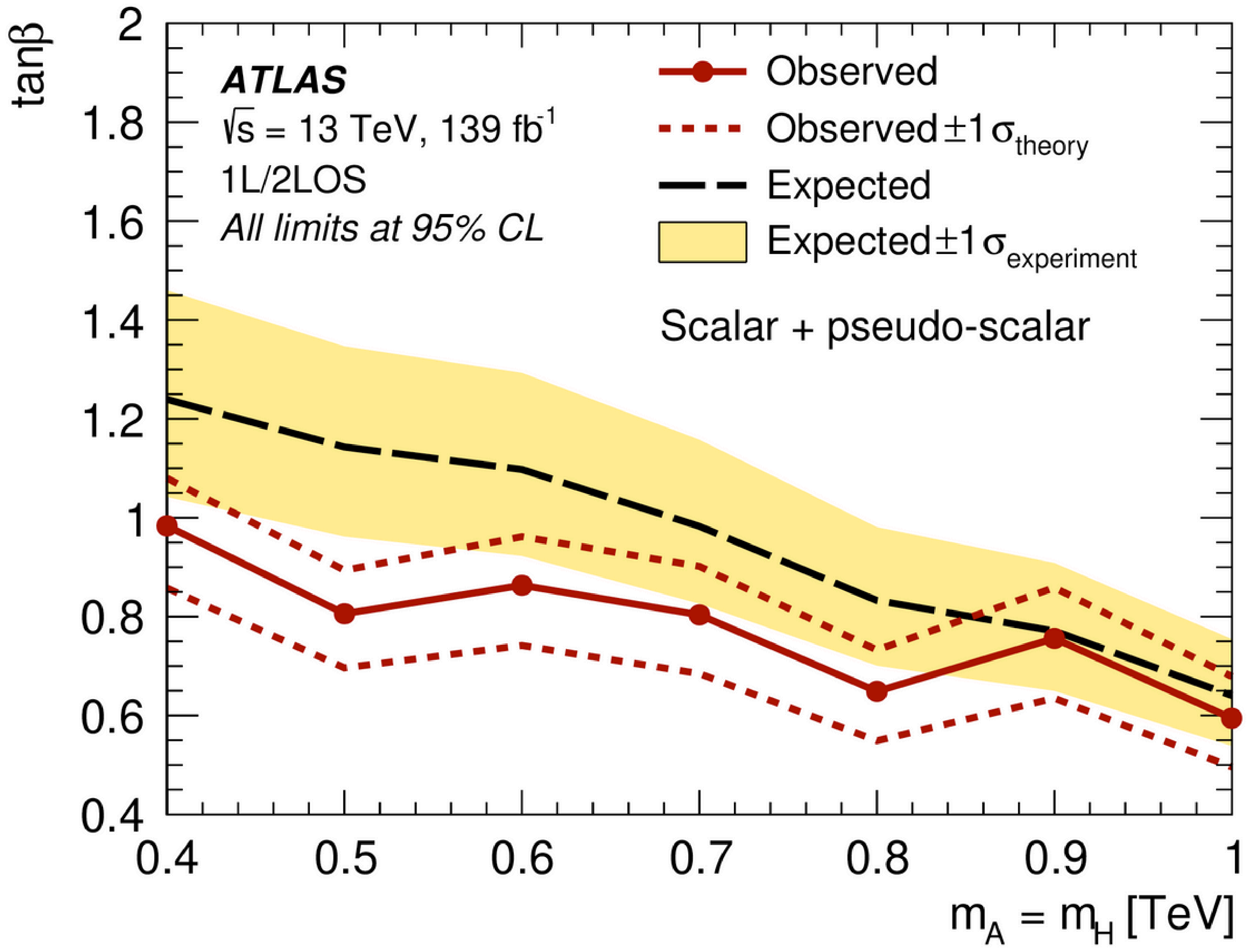
Search for $t\bar{t}A/H \to t\bar{t}t\bar{t}$

Data-driven technique applied to improve modelling of the **tt+jets bkg in regime with high (b-)jet multiplicities**

H/A production in **association with a tt pair**, much less susceptible to interference effects with the SM 4top production



Exactly one lepton (electron or muon) or two leptons with opposite electric charge (1L/2LOS)



arXiv:2408.17164

The search in the 1L/2LOS final states **combined with that in the multilepton final states (+19%)**

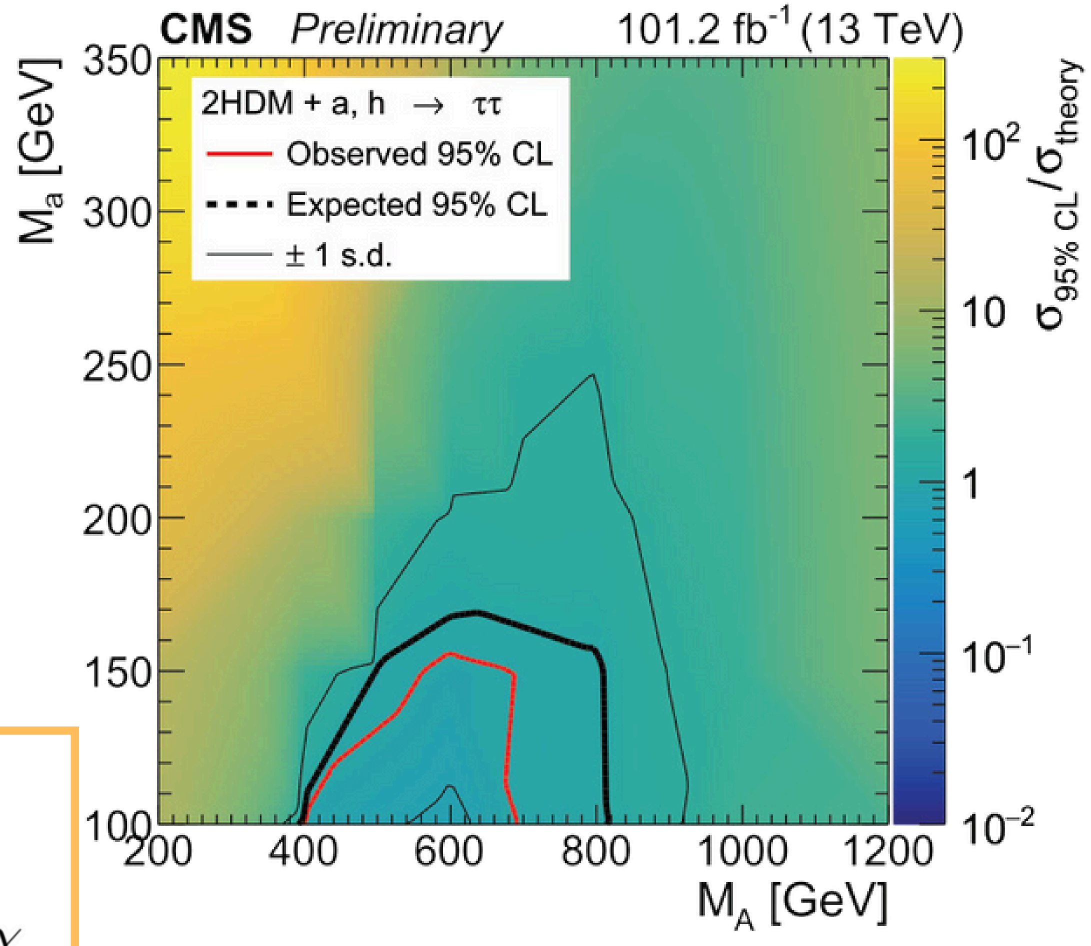
Backup

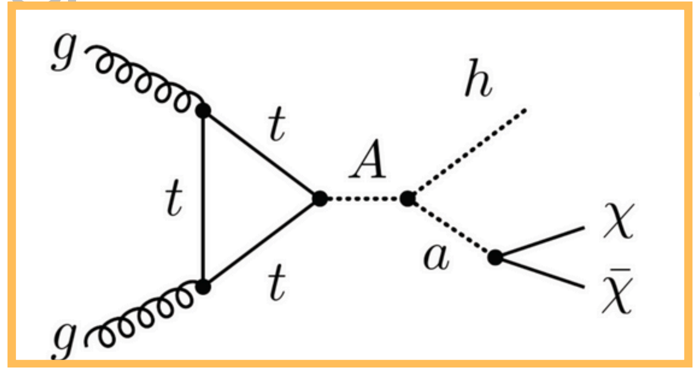
Two Higgs doublet model (2HDM+a): $H^{\pm}$, A, H, h,a

2HDM+a: extension of the Standard Model that includes two Higgs doublets and **an additional pseudoscalar particle (a)**

CMS-PAS-SUS-23-012

Search for ***dark matter produced with a Higgs boson*** *decaying to* $\tau\tau$





Search for ***dark matter with b-quarks and lepton pairs***

CMS-PAS-SUS-23-018

Impacts the masses and couplings of the Higgs bosons

tan β

b-quark fusion

first time at the LHC

Backup

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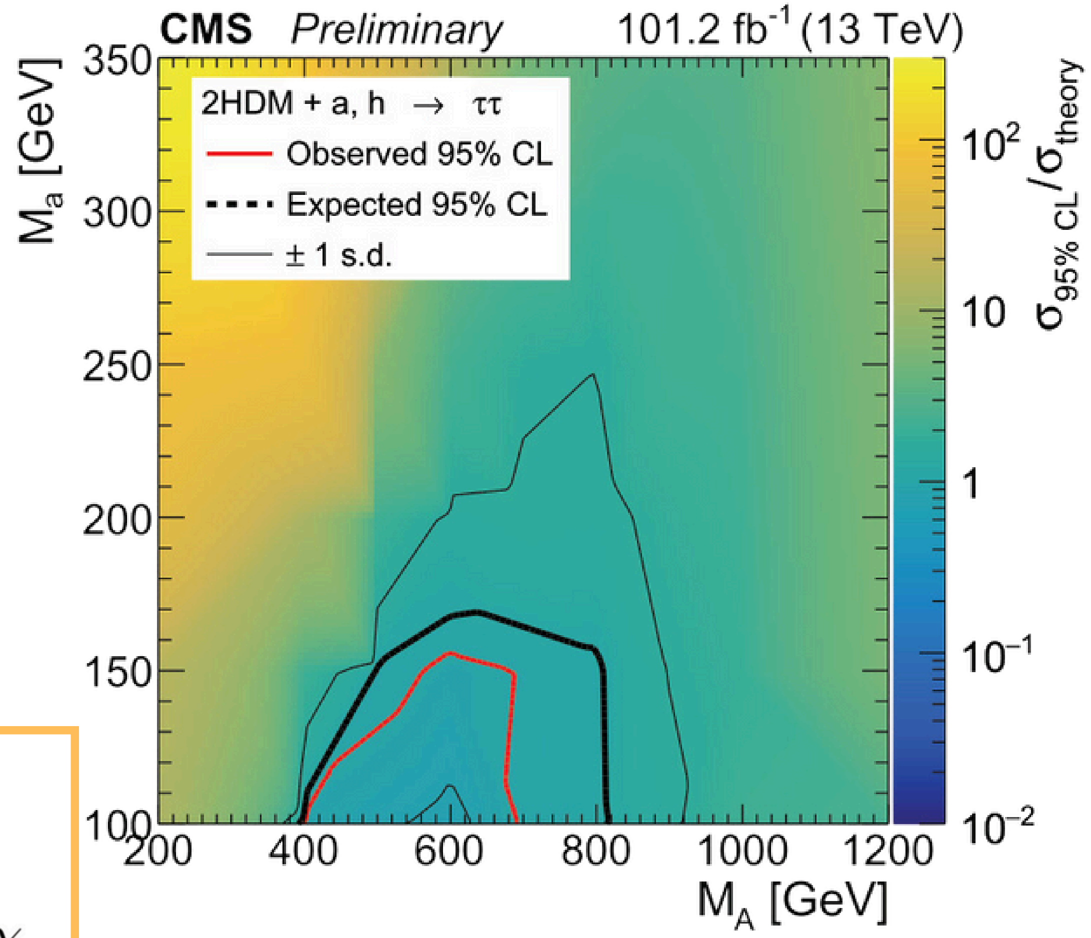

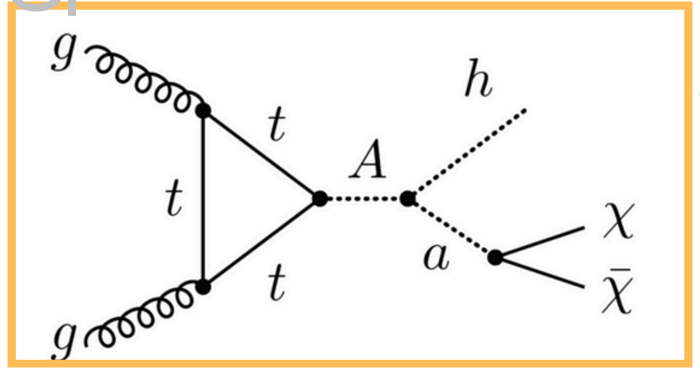

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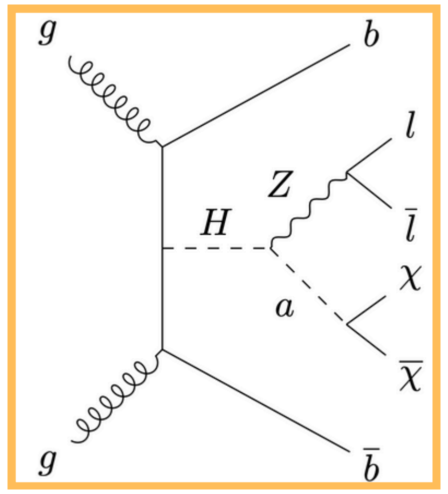
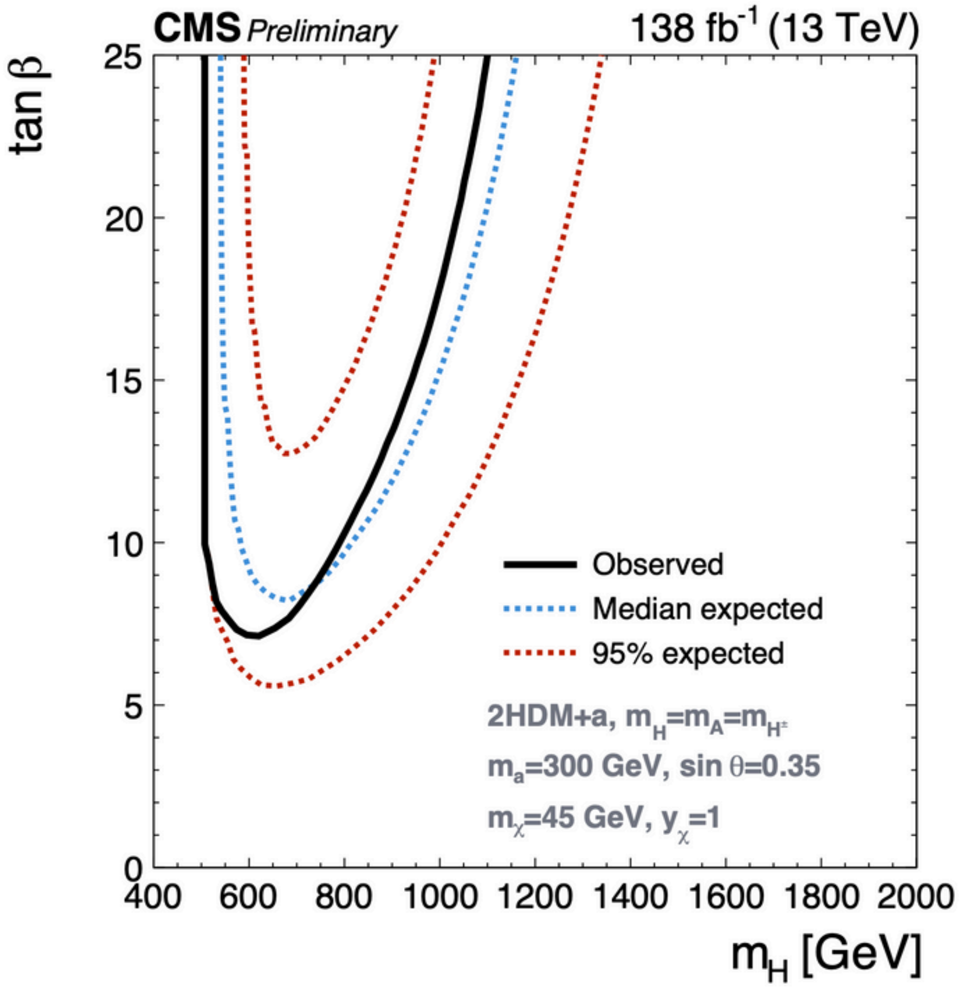




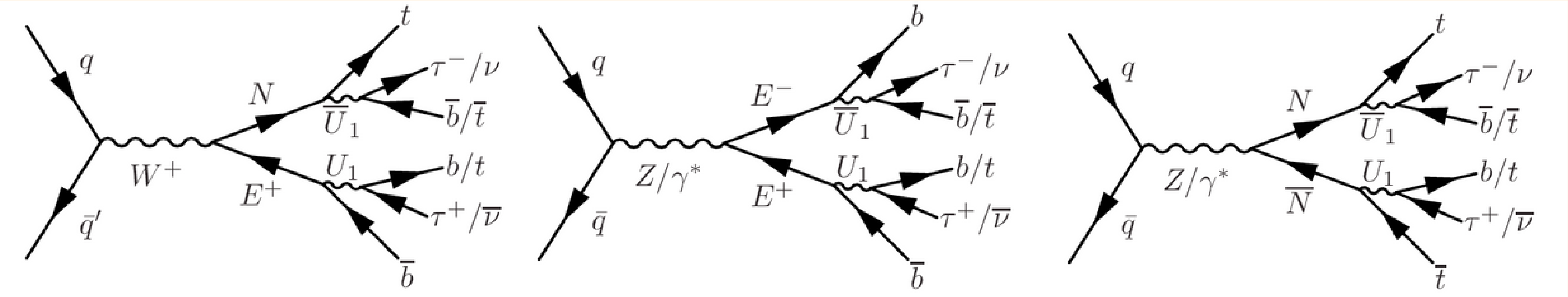
first time at the LHC

CMS-PAS-SUS-23-018

Backup

Heavy Fermions

Vector Like Leptons

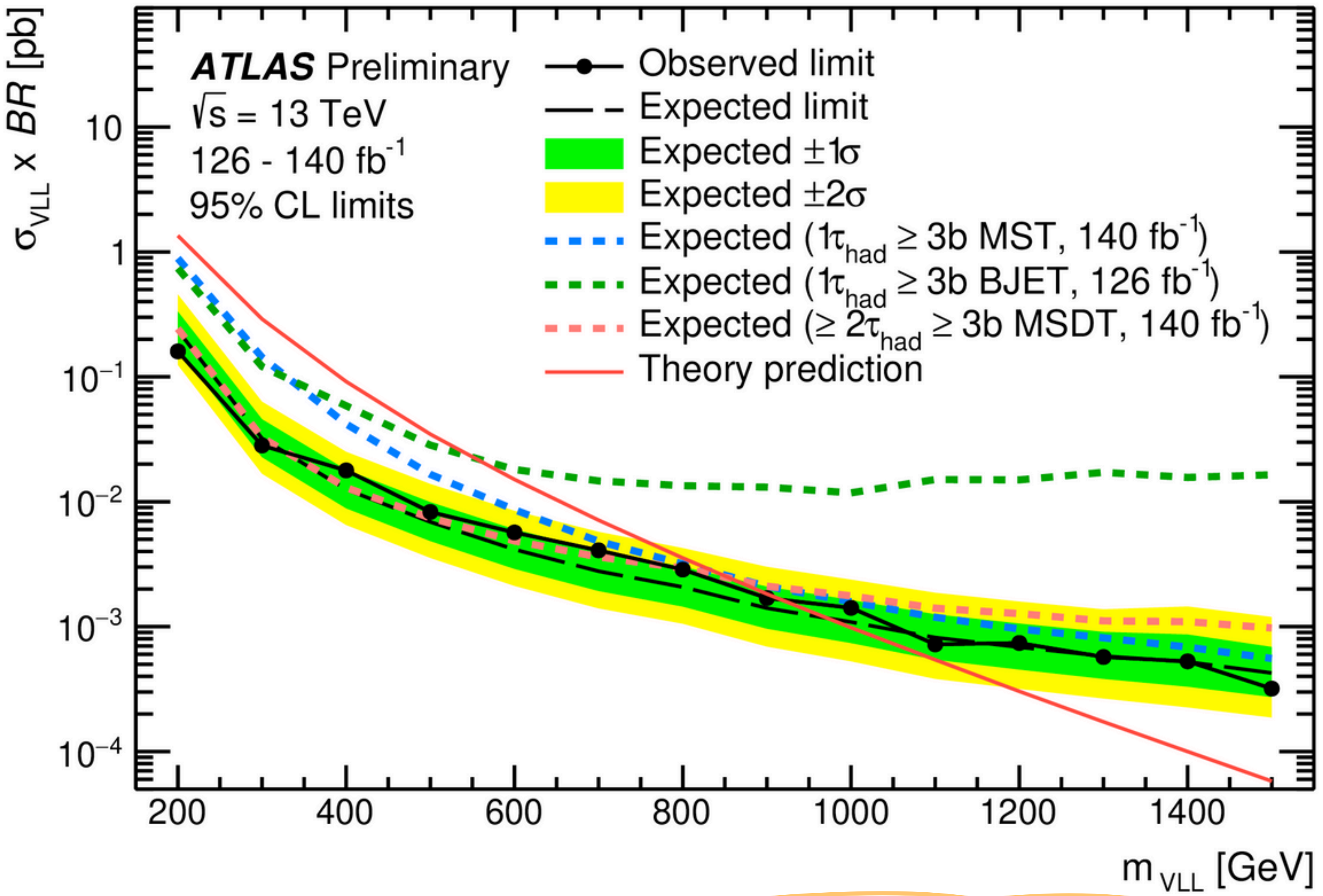


3rd gen

"4321 model" explored

Signature: large # jets, b-jets, and multiple τ_h

ATLAS-CONF-2024-008



Existing result from CMS w/ local 2.8σ **excess at mass of 600 GeV** disfavoured

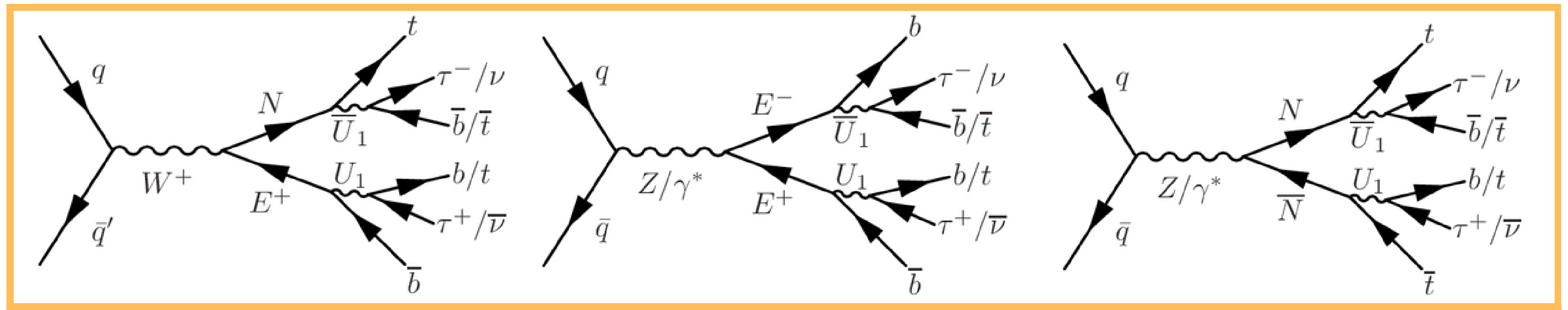
1st-2nd gen

Categorization: flavor, # leptons, missing energy

Stringent mass exclusion limits (**up to 1270 GeV**) in doublet and singlet scenarios

Backup

Vector Like Leptons at ATLAS



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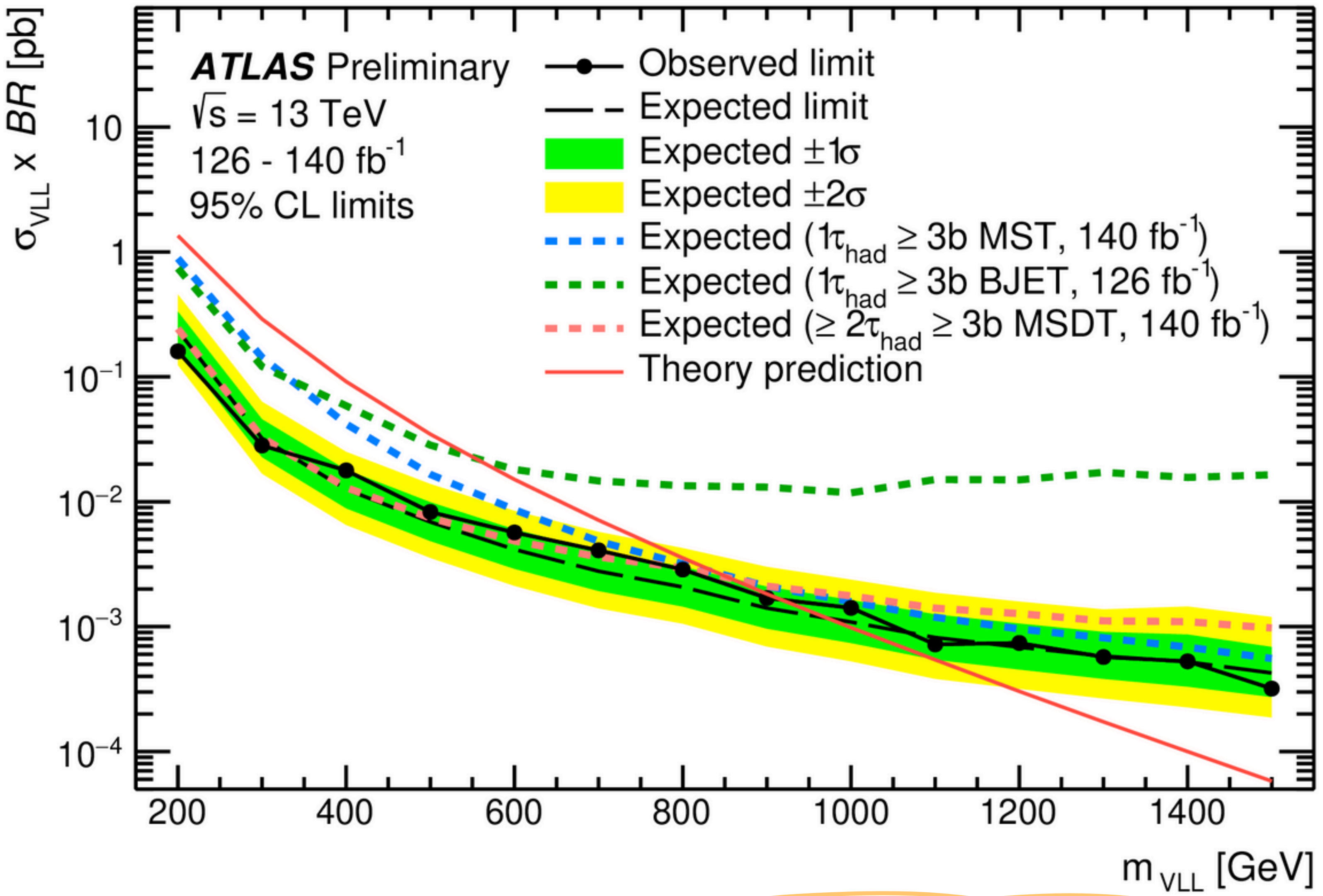

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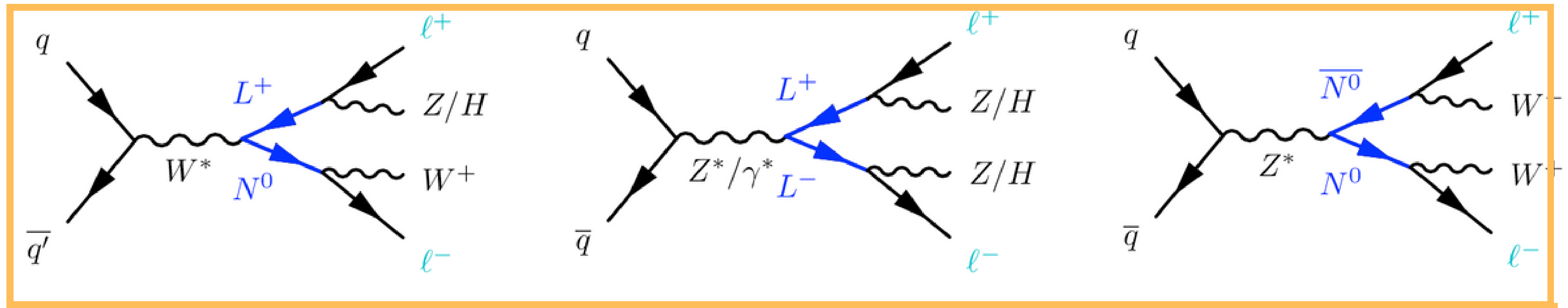

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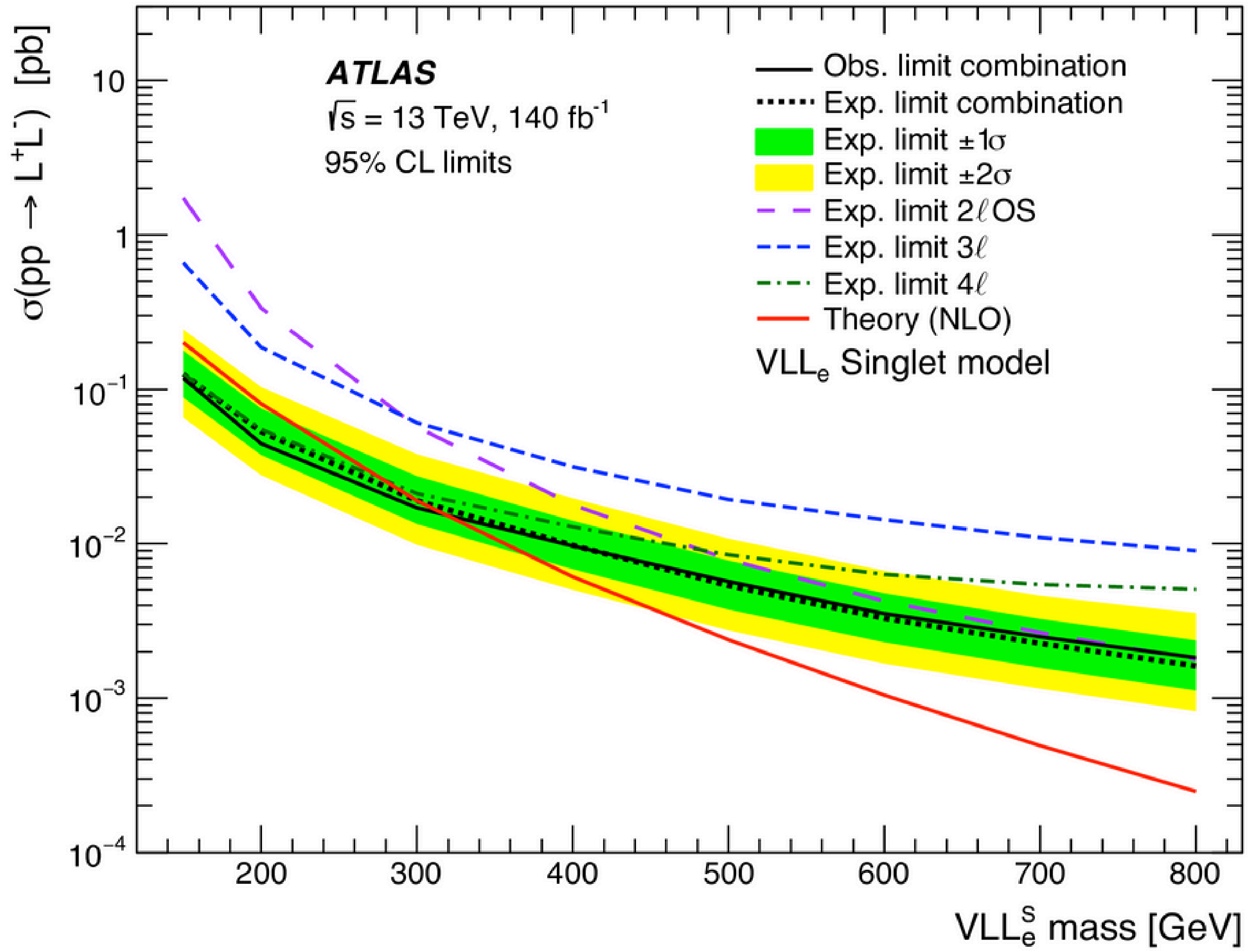


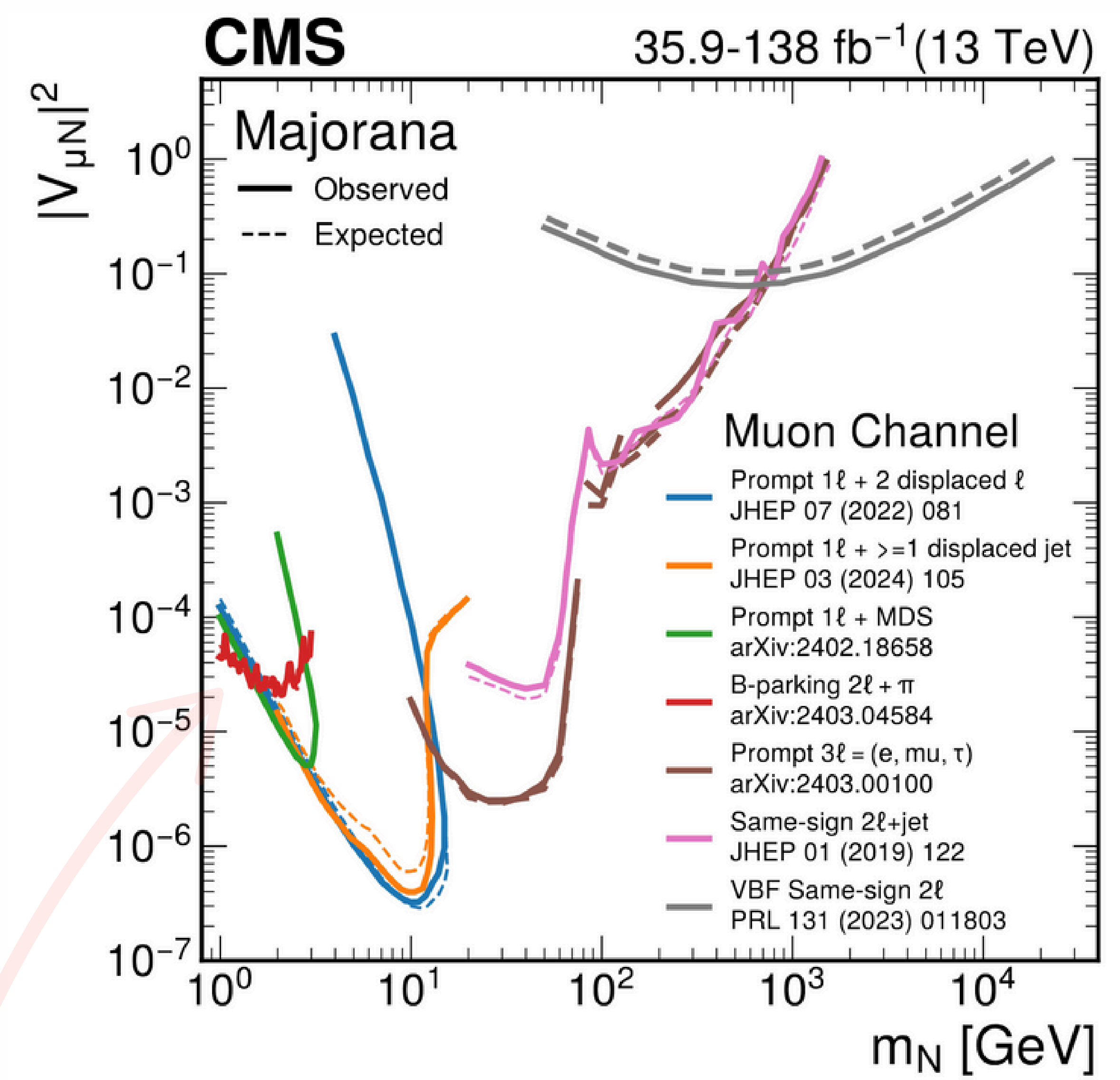
arXiv:2411.07143

Stringent mass exclusion limits (**up to 1270 GeV**) in different scenarios

Backup

Heavy Neutral Leptons at LHC

arXiv:2405.17605



Different analyses techniques optimized in dedicated mass ranges

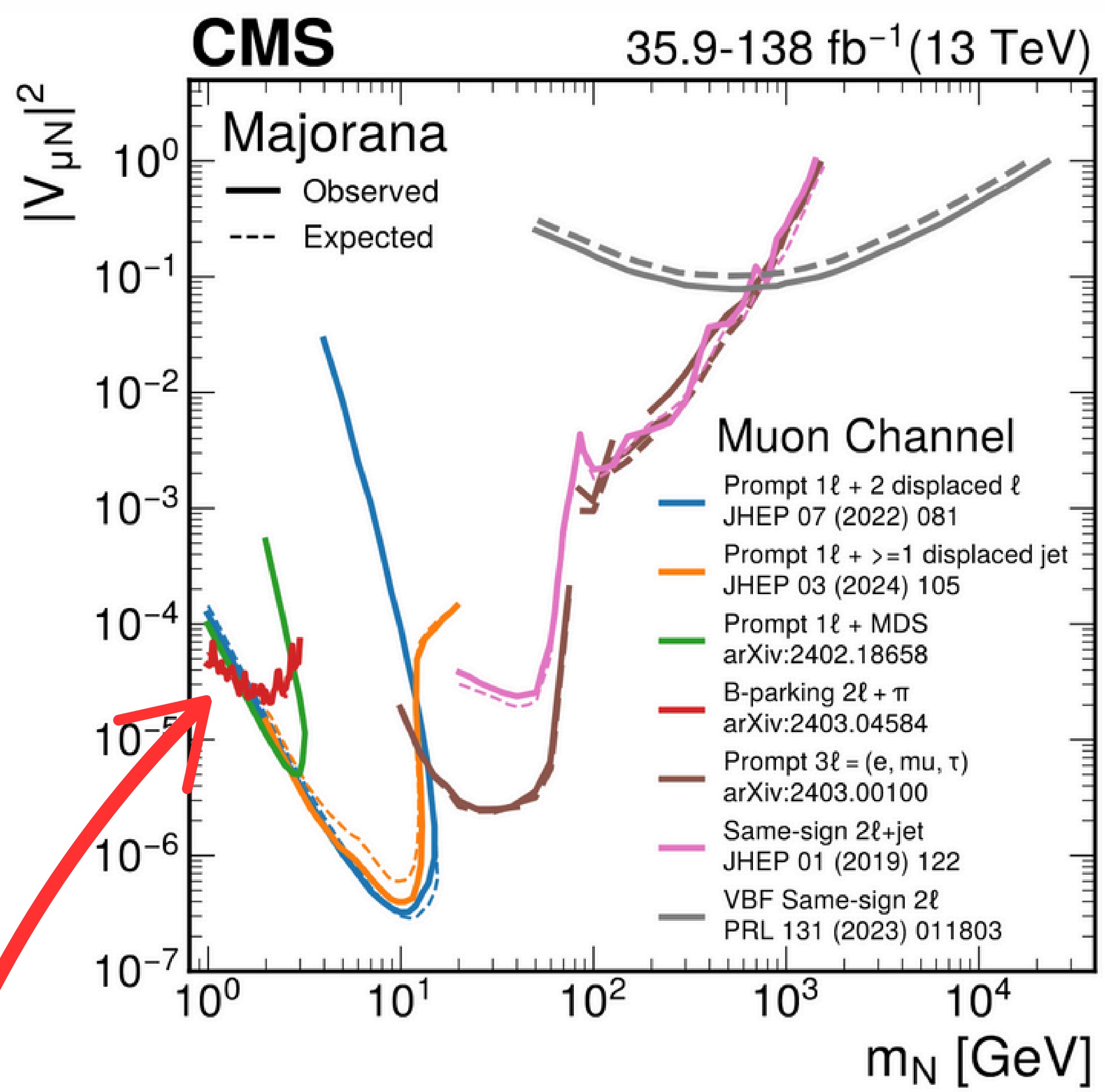
arXiv:2408.05000

Unique top-quark decay channels, enhancing sensitivity to specific HNL scenarios while utilizing **advanced b-tagging** and multivariate analysis techniques.

Explores lepton number violation via **same-charge same-flavor leptons**

Heavy Neutral Leptons at LHC

arXiv:2405.17605



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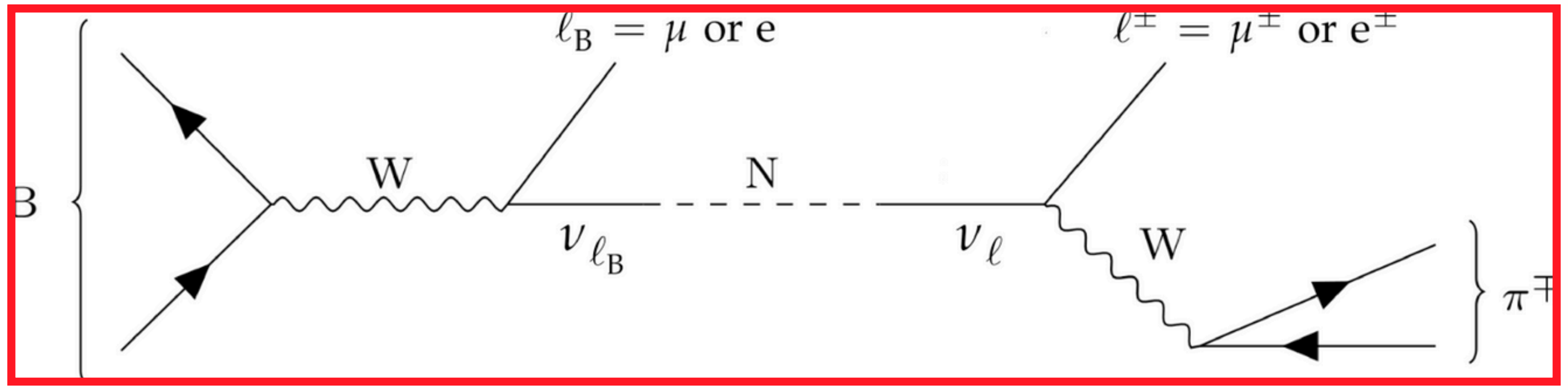

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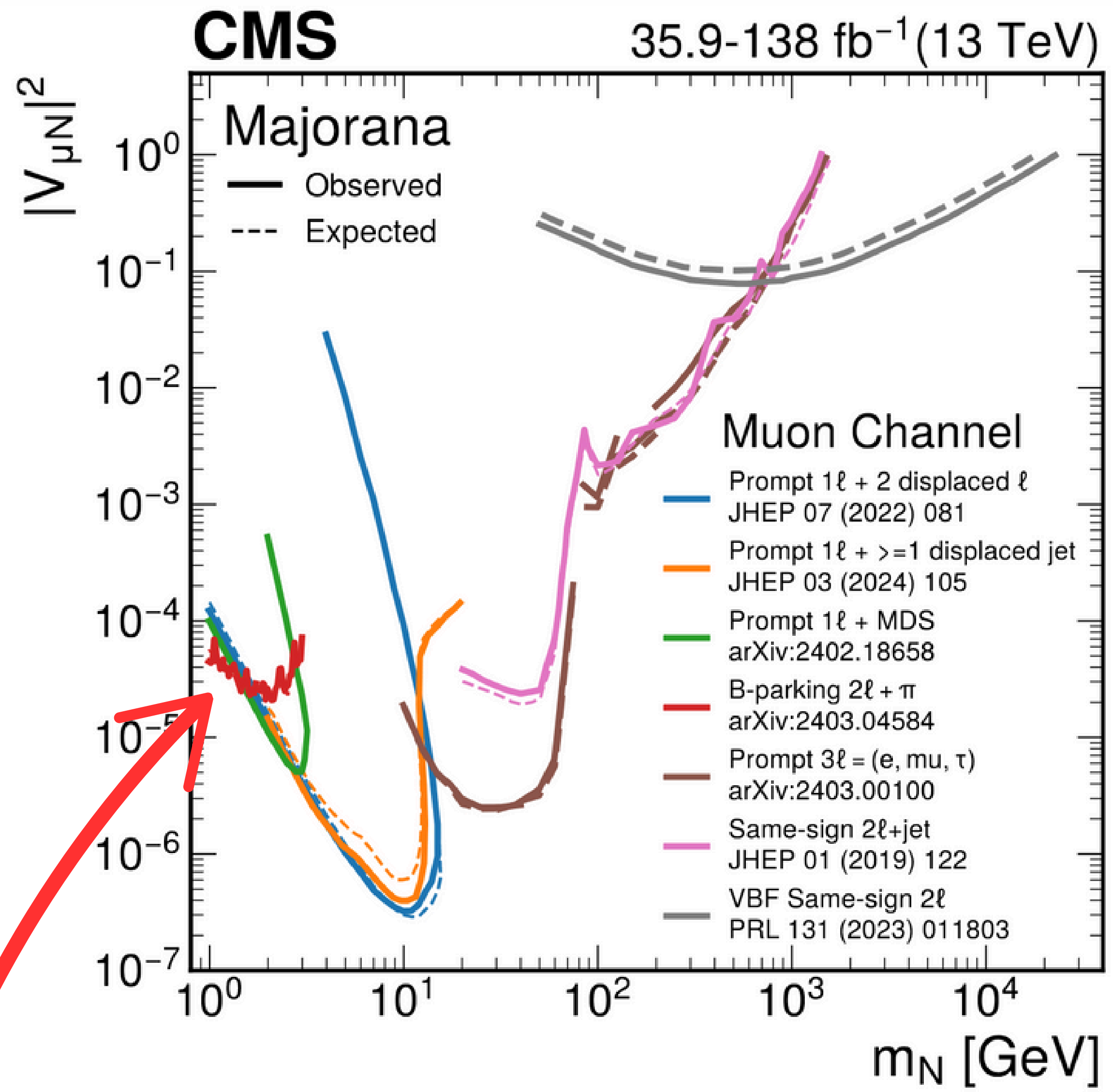

Identifying one of the top quarks through its decay according to the SM, while **utilizing the decay of the other top quark to search for HNLs**.

Unique top-quark decay channels, enhancing sensitivity to specific HNL scenarios while utilizing **advanced b-tagging** and multivariate analysis techniques.

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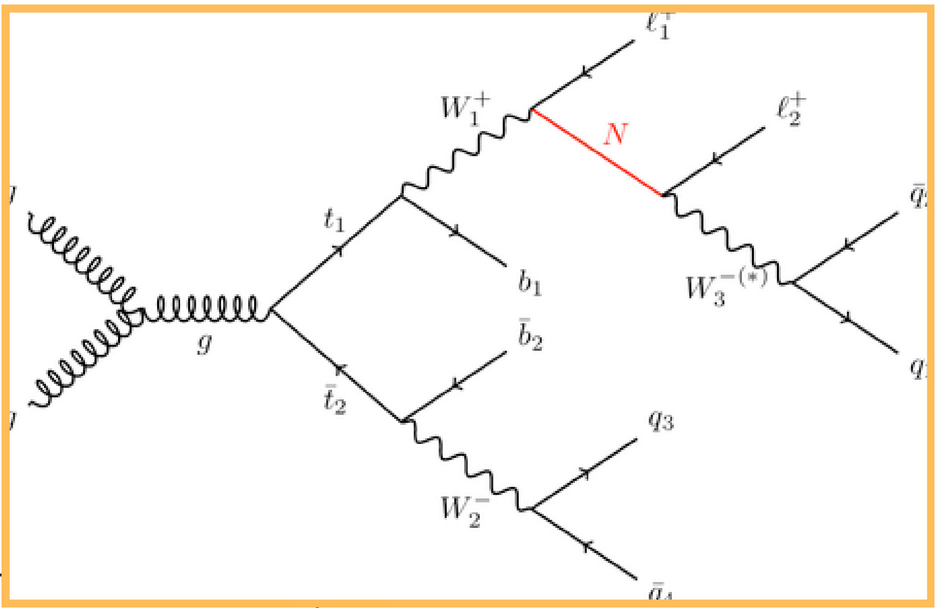
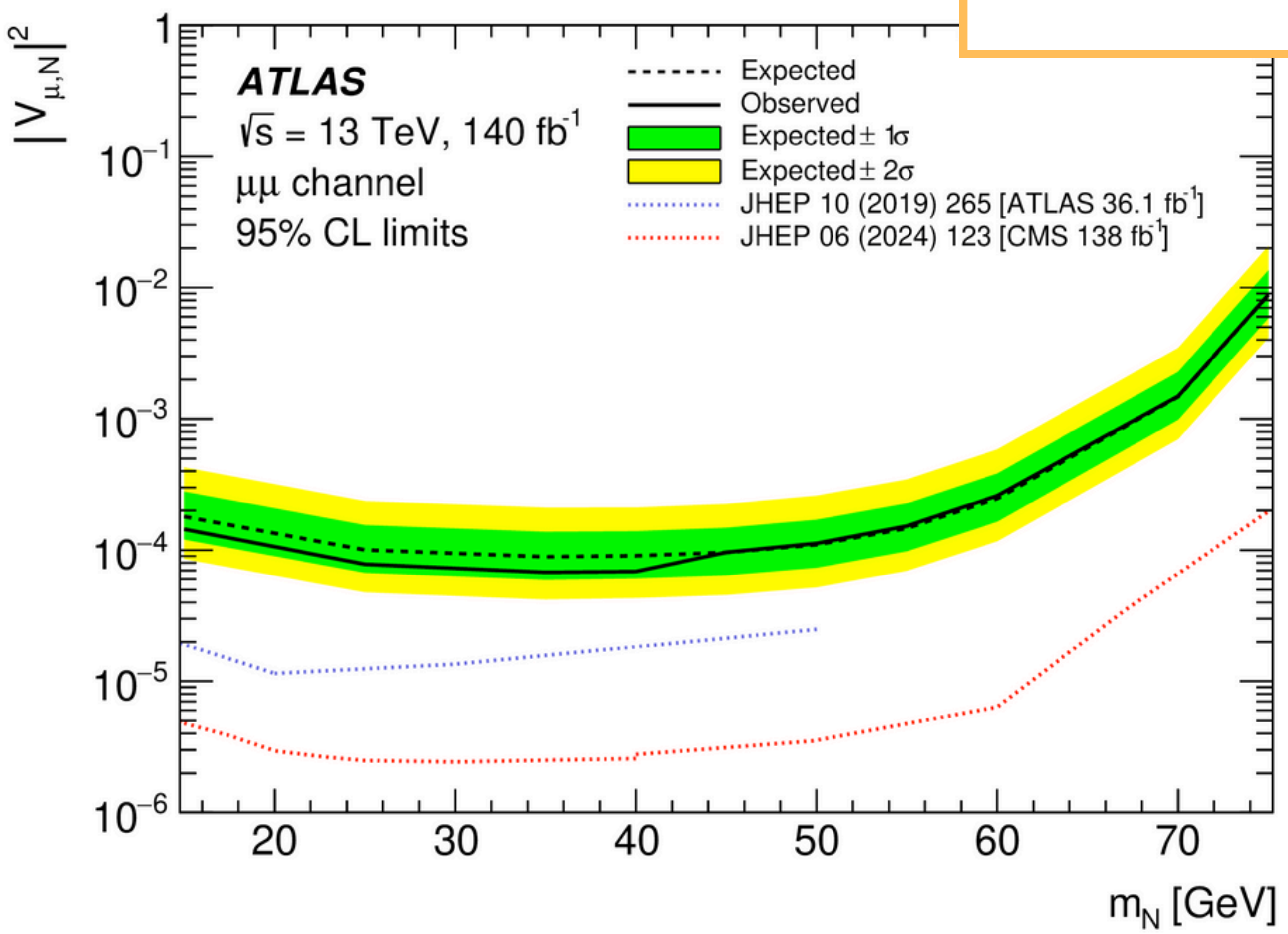
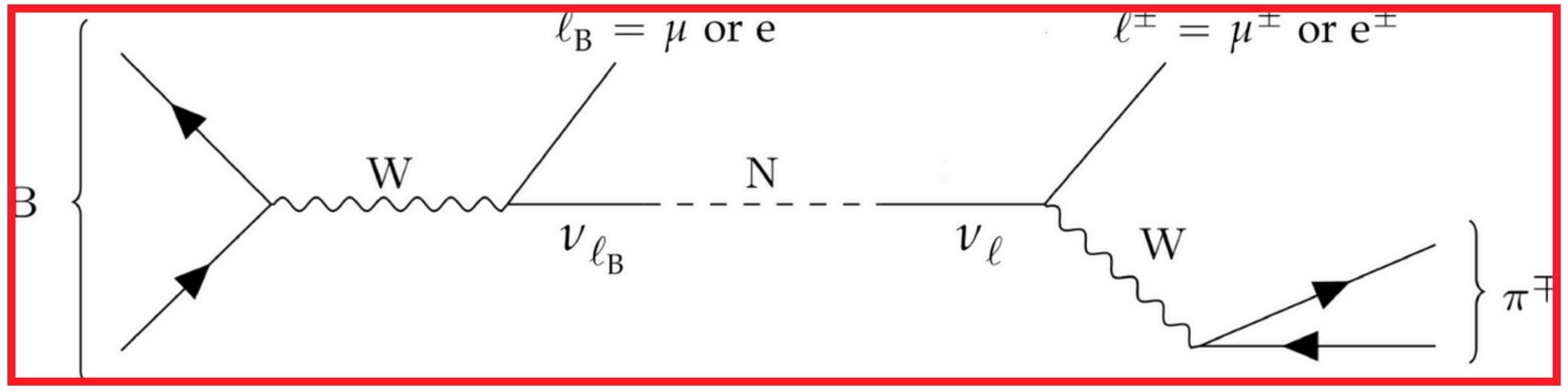
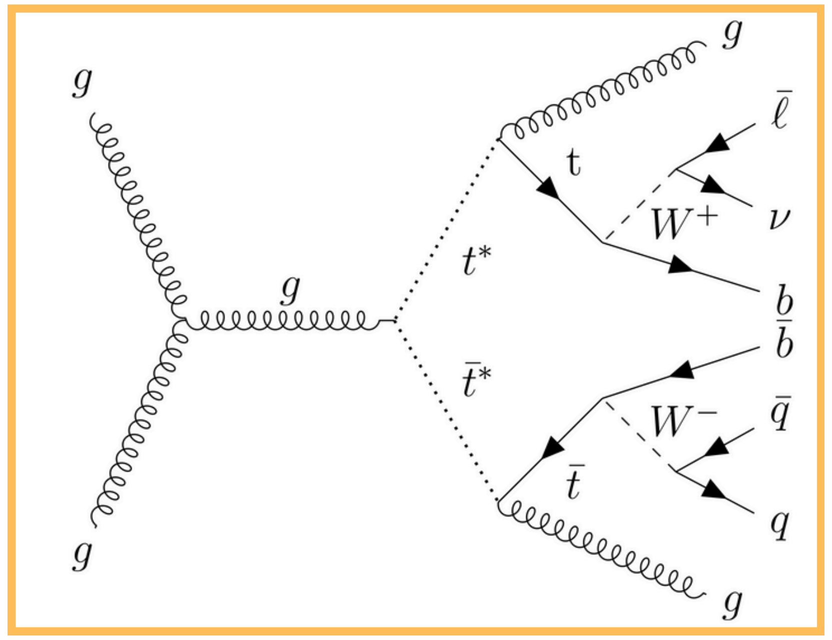




Different analyses techniques optimized in dedicated mass ranges

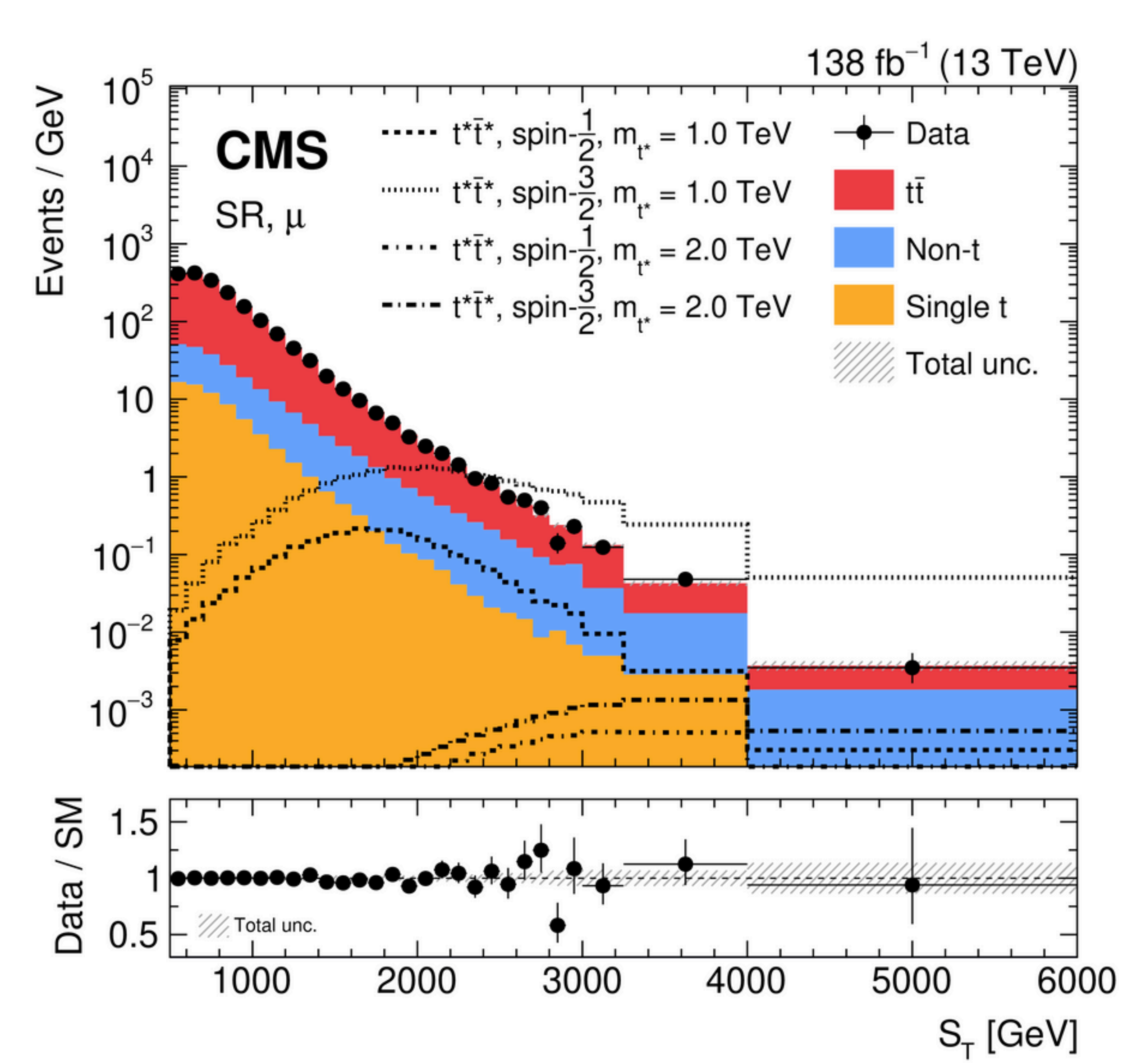


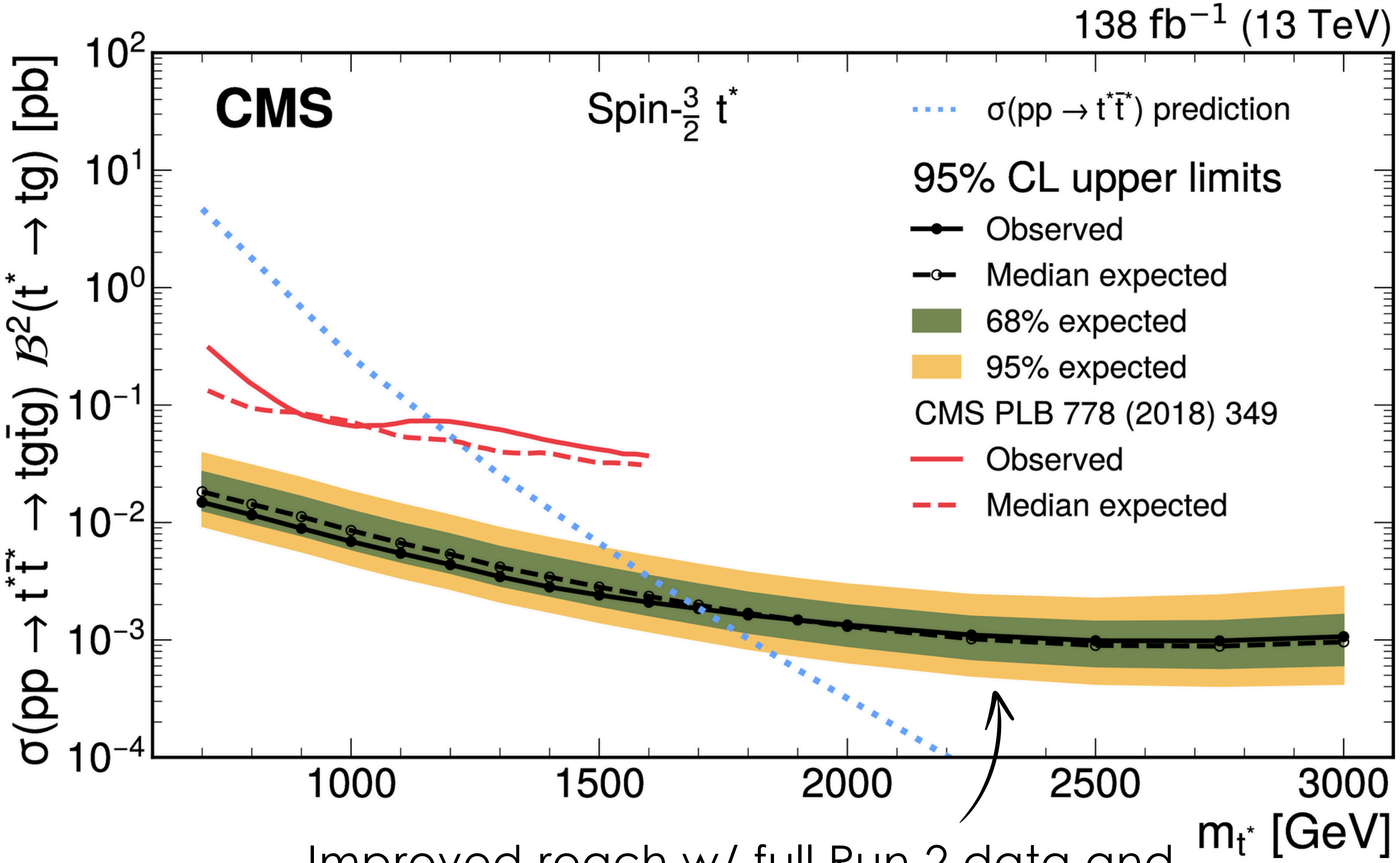
Pair production of excited top (t*)



$$S_T = p_T^{\ell} + p_T^{\text{miss}} + \sum_i p_{T,i}^{\text{jet}}$$

Quarks as non fundamental particles can have substructure and could exist in excited states





Improved reach w/ full Run 2 data and doubled mass range explored

arXiv:2410.20601

Backup

Beyond Standard

Model

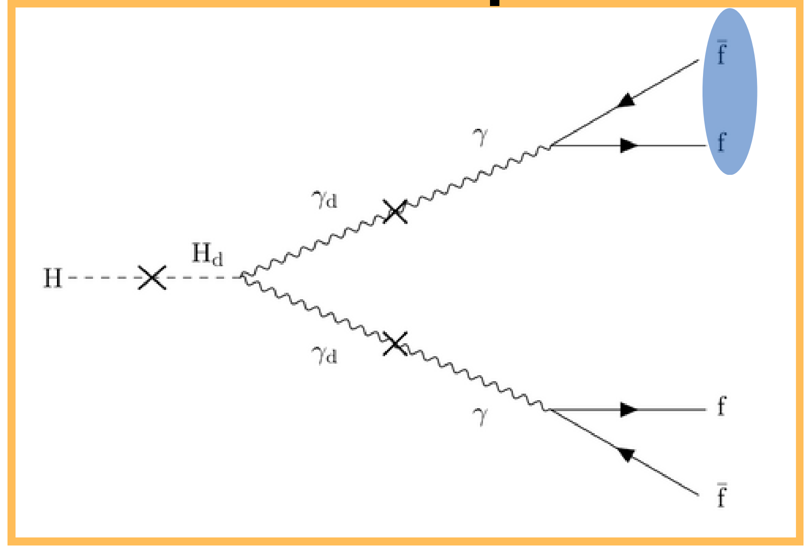
Strategies

- *Identifying merged objects*
- *Accessing low energies*

Signatures

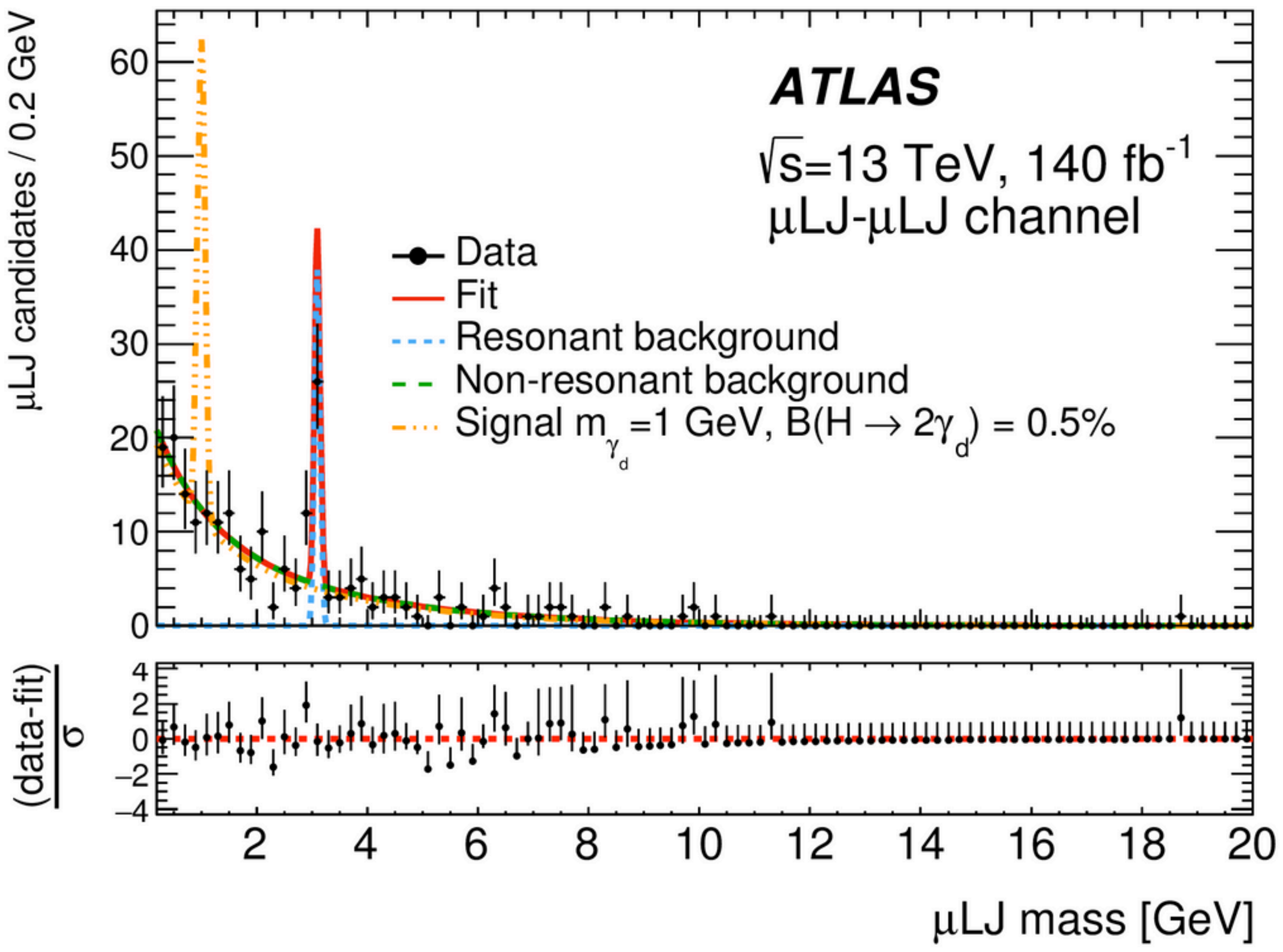
Tools

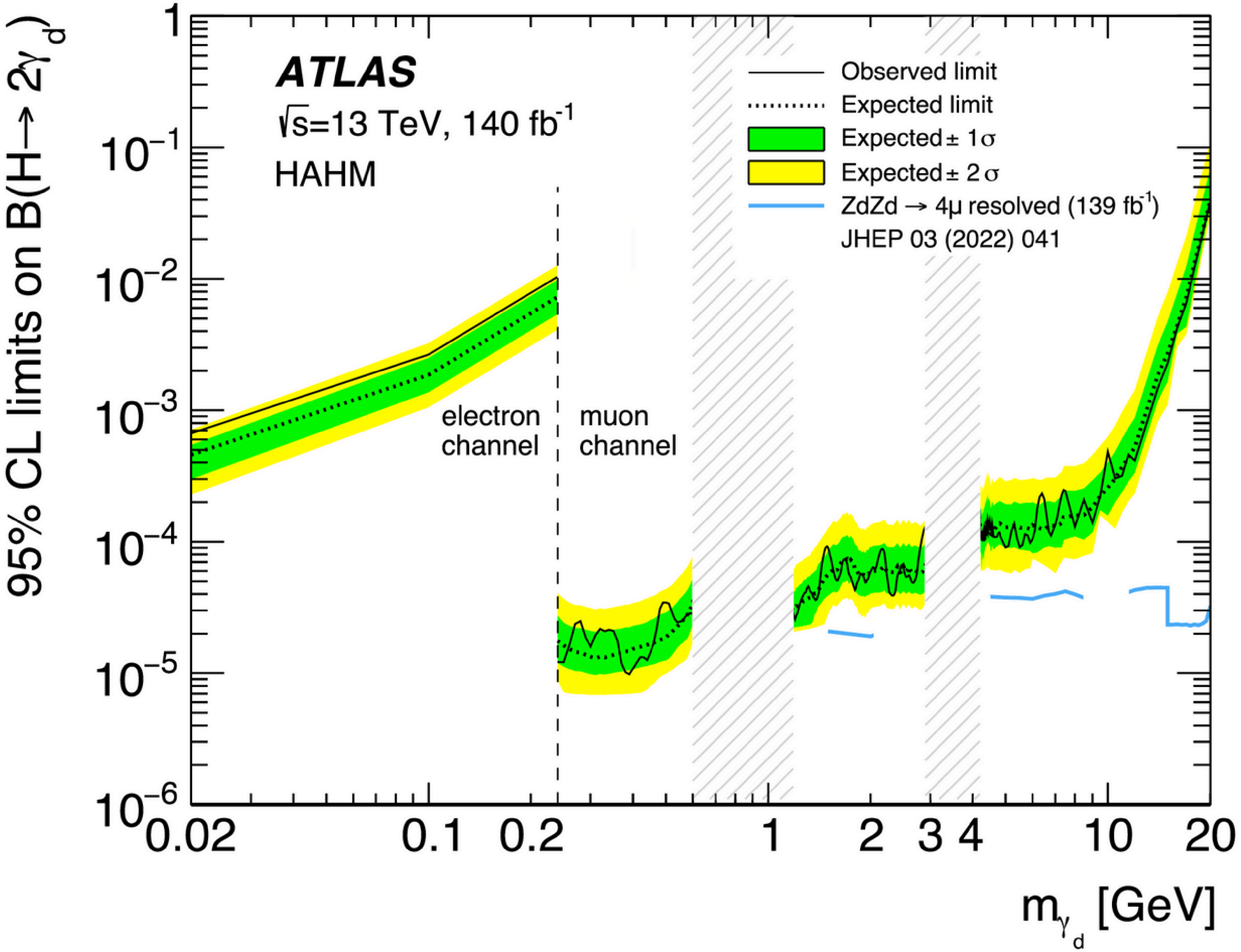
Search for neutral particles decaying promptly to collimated pairs of leptons



LeptonJets (LJs): highly collimated pairs of electrons or muons from light neutral particles decay

Dedicated reconstruction and ID of merged dilepton pairs



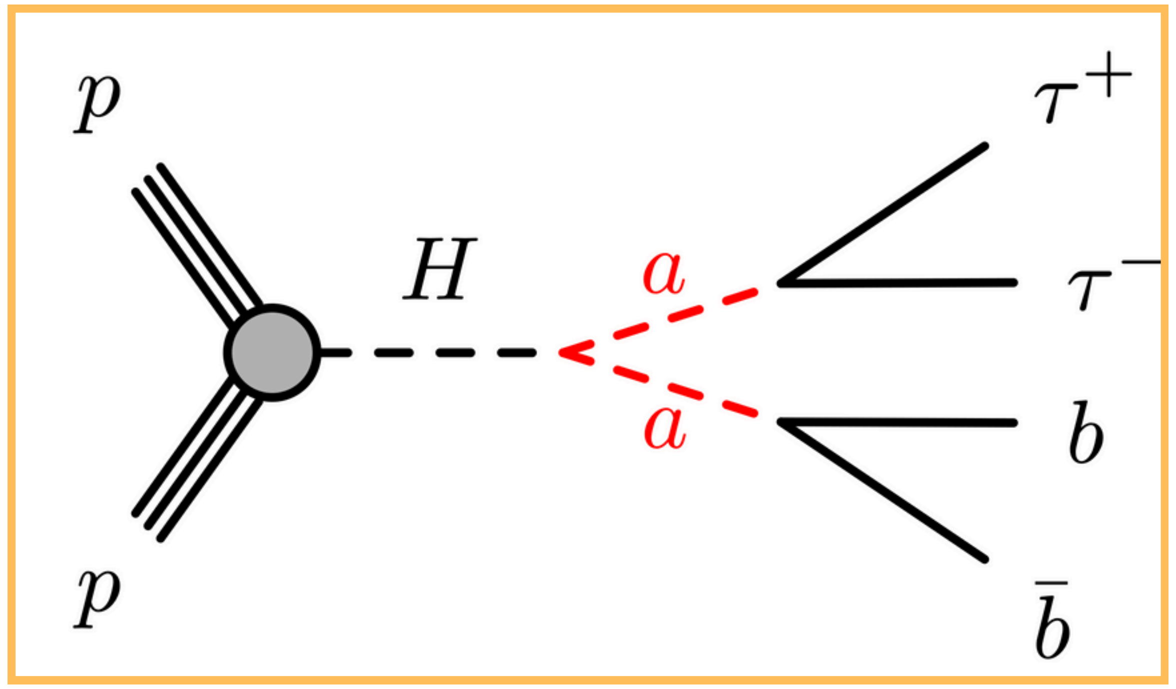


arXiv:2407.09168

Backup

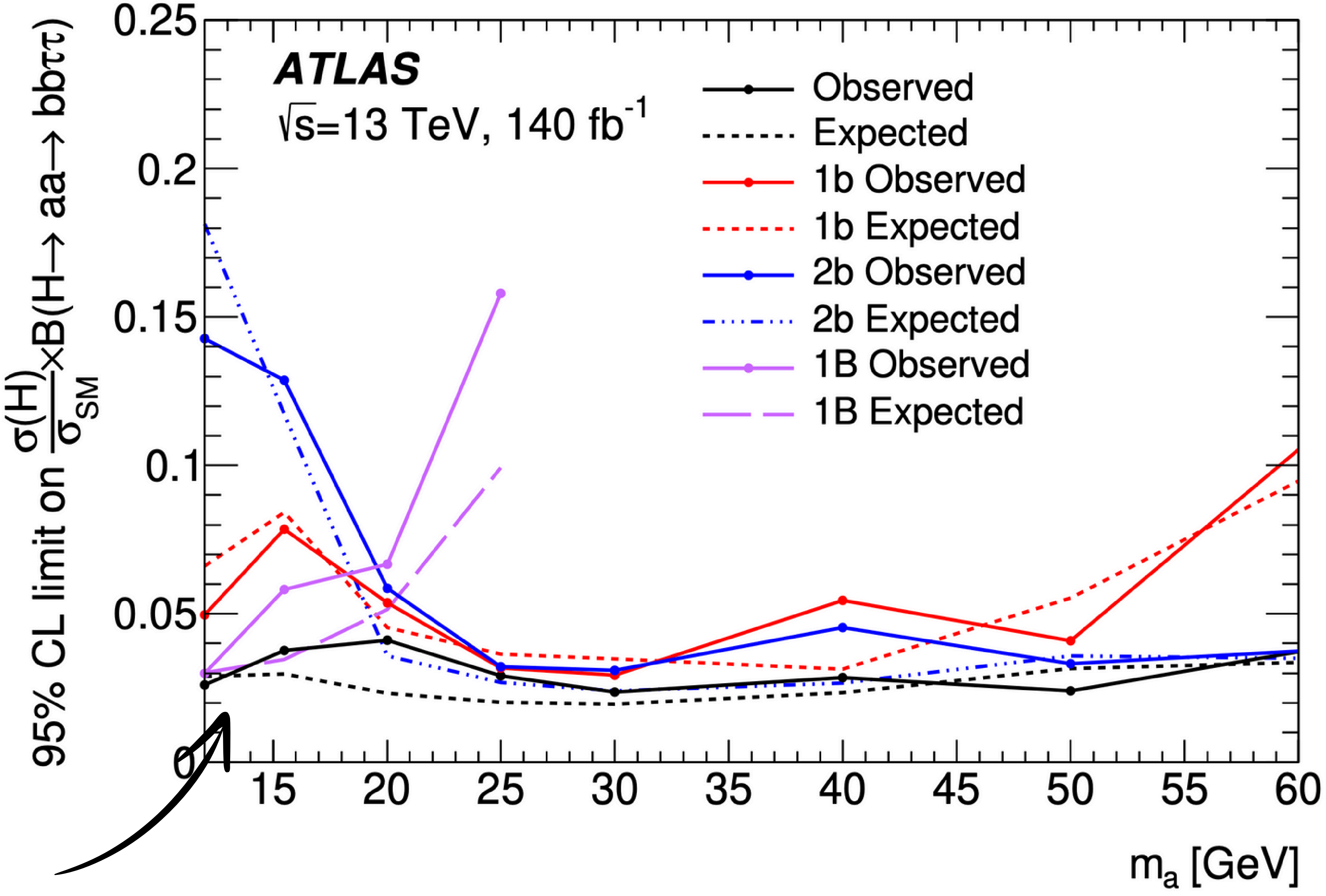
Exotic decays of the SM Higgs boson

Search for decays of the Higgs boson into a pair of pseudoscalar particles decaying into $b\bar{b}\tau\tau$



Novel, **dedicated algorithm** to identify low mass merged, **“double b-quark” jets (B)** from $a \to b\bar{b}$

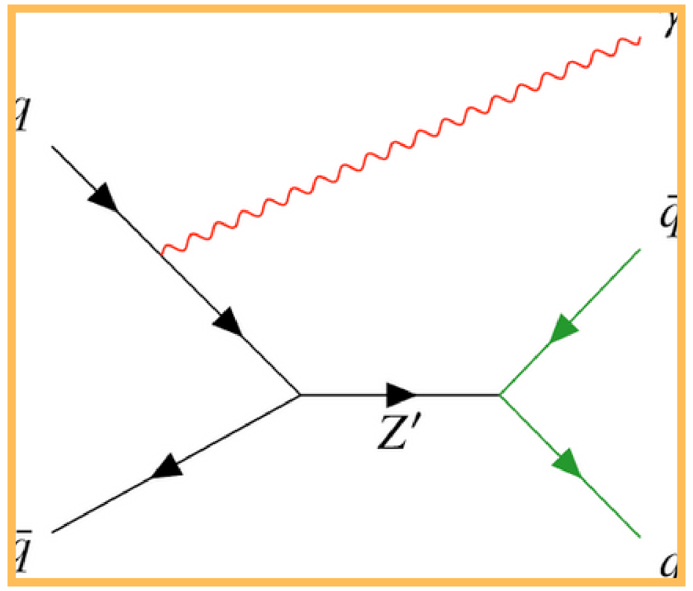
B categories sensitive at low-mass



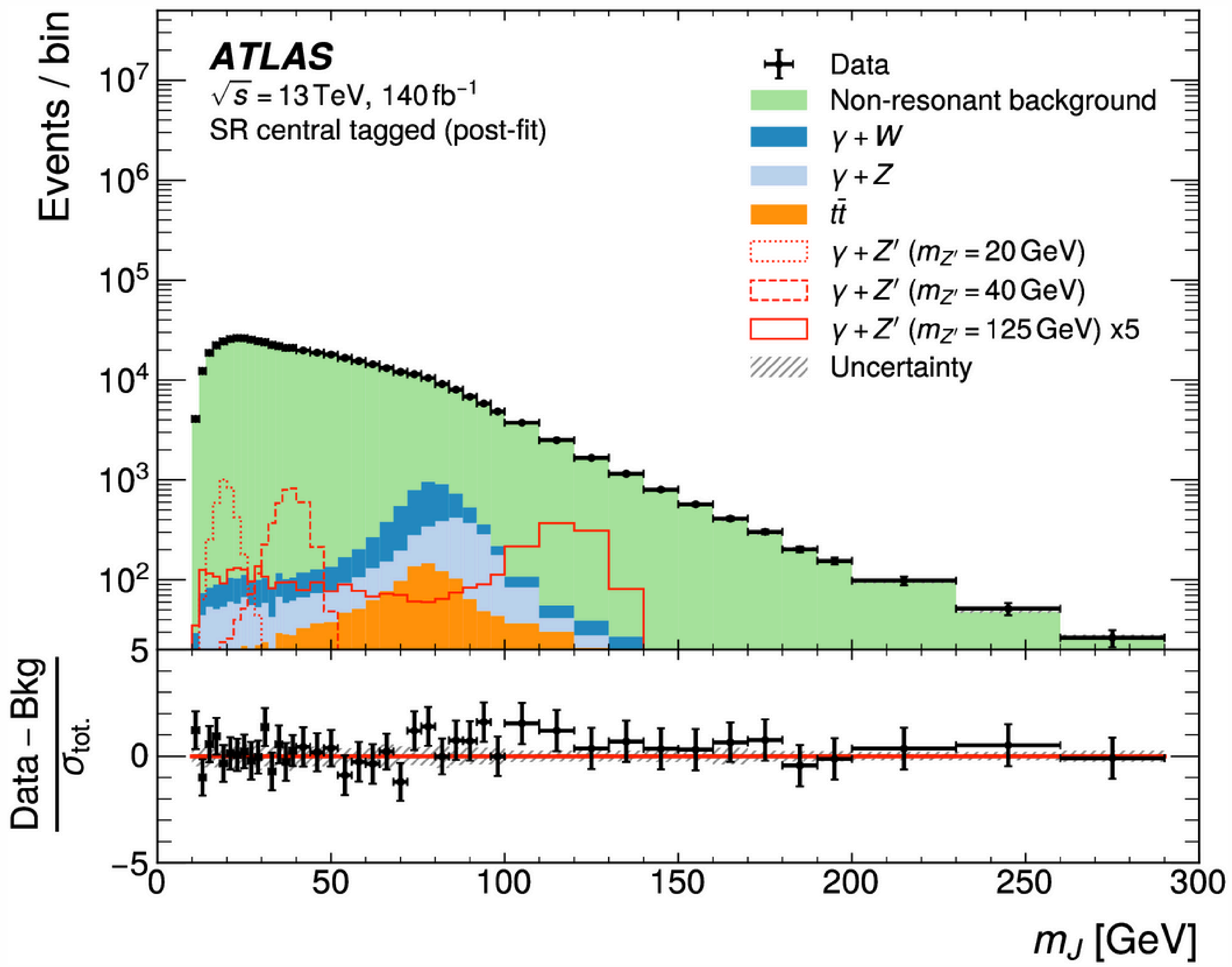
arXiv:2407.01335

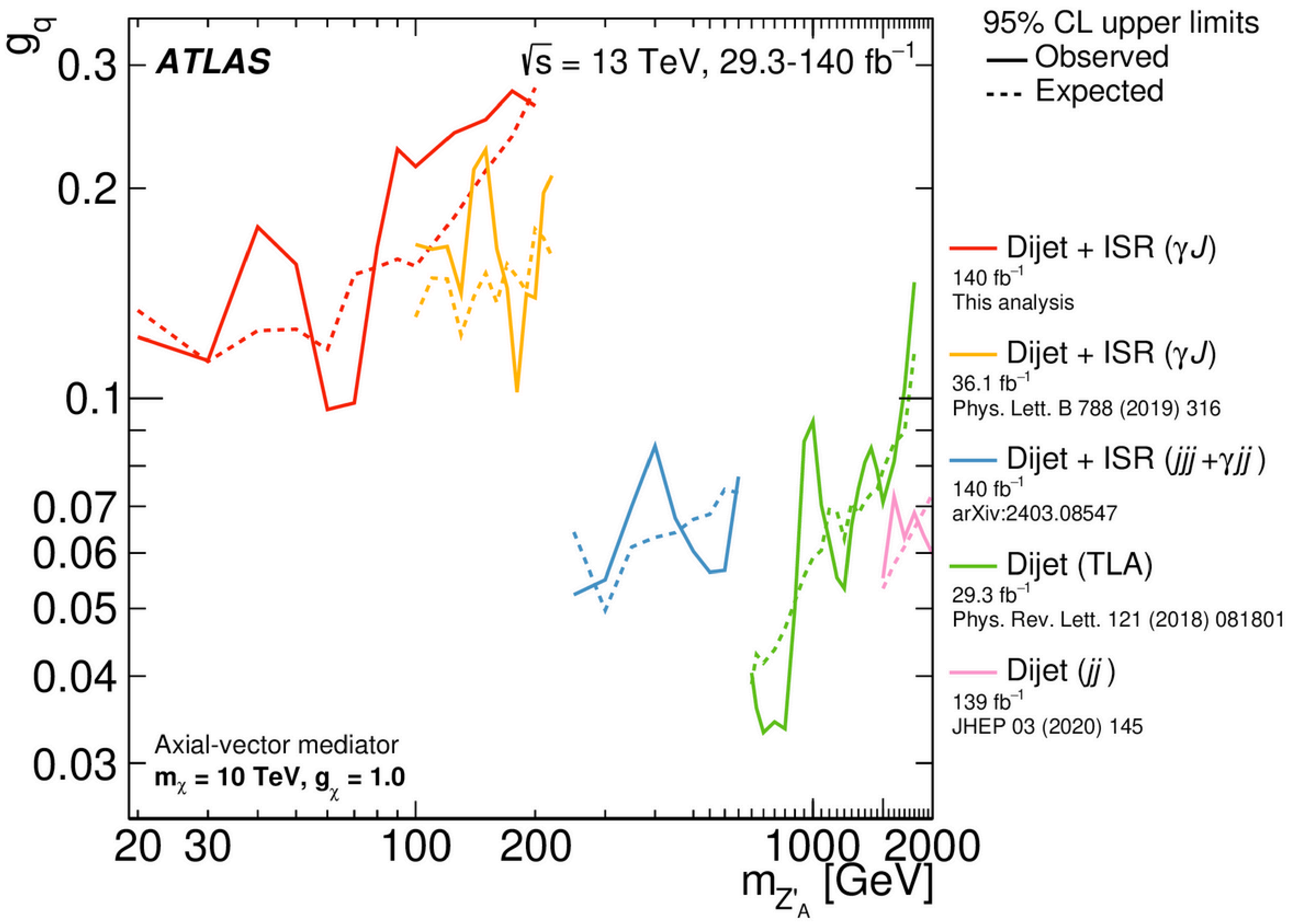
Backup

Search for low-mass resonances into hadrons + ISR photon



Photon from initial state radiation, which is **used as a trigger** to circumvent limitations on the maximum data recording rate.

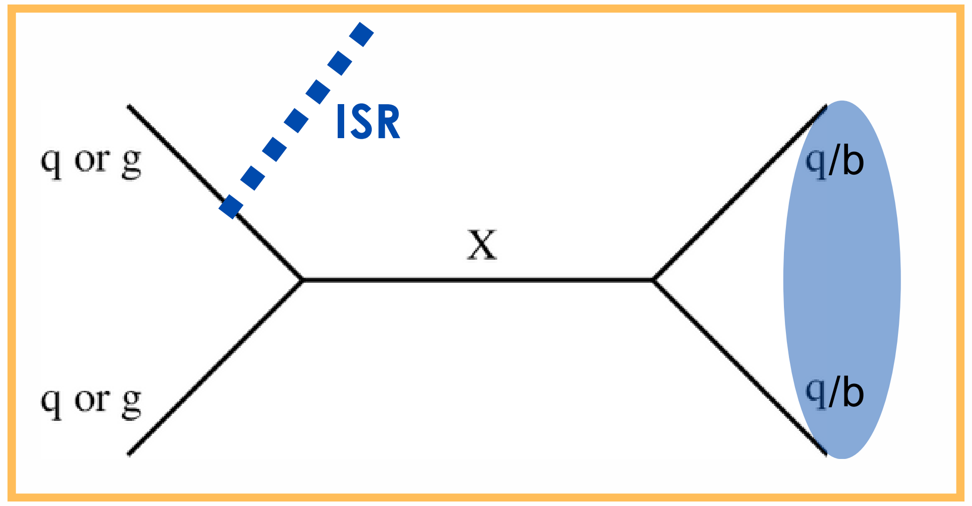




arXiv:2408.00049

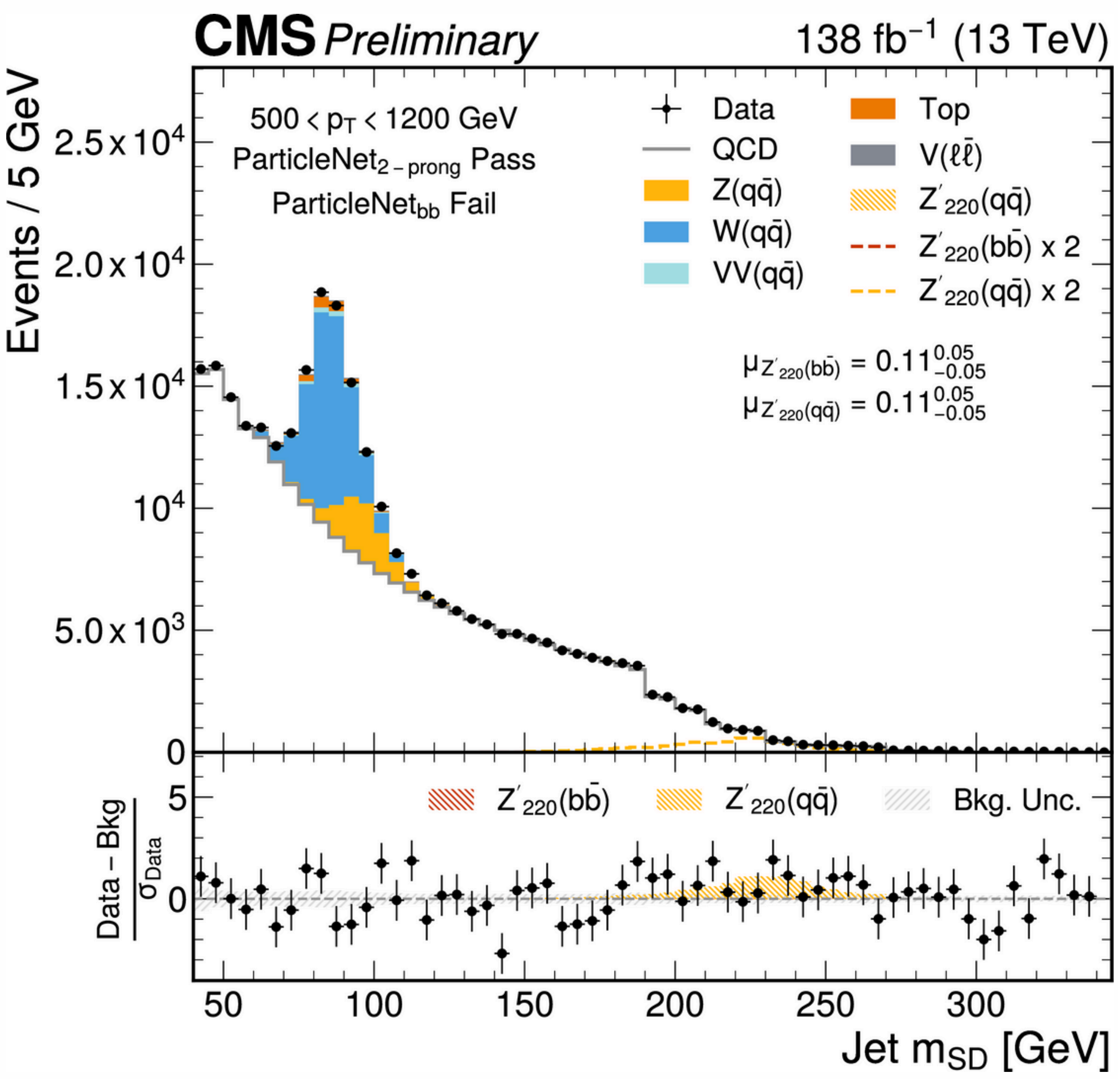
Backup

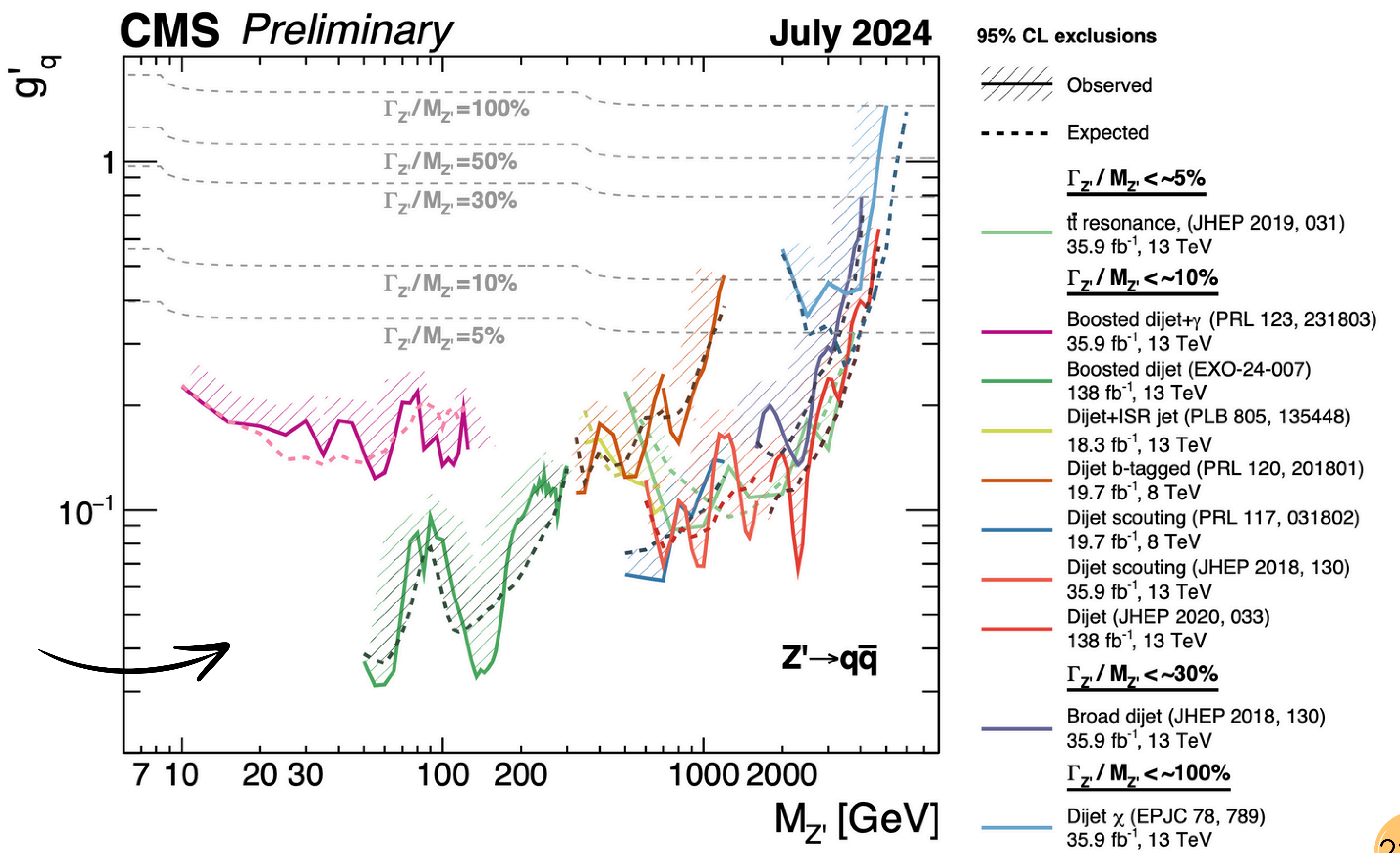
Search for low-mass resonances into hadrons + ISR



ParticleNet algorithm reconstructs **Large Radius Jet w/ 2 pronged substructure**

CMS-PAS-EXO-24-007





CMS-EXO-Summary -Plots

Backup

Beyond Standard Model

Strategies

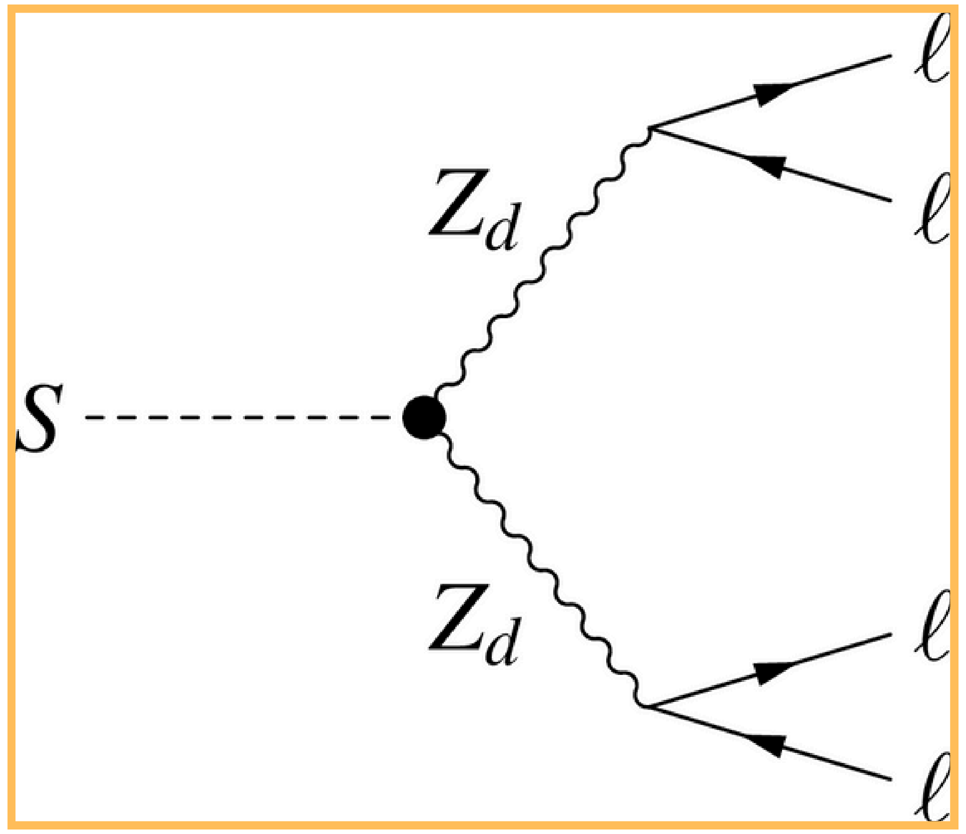
Signatures

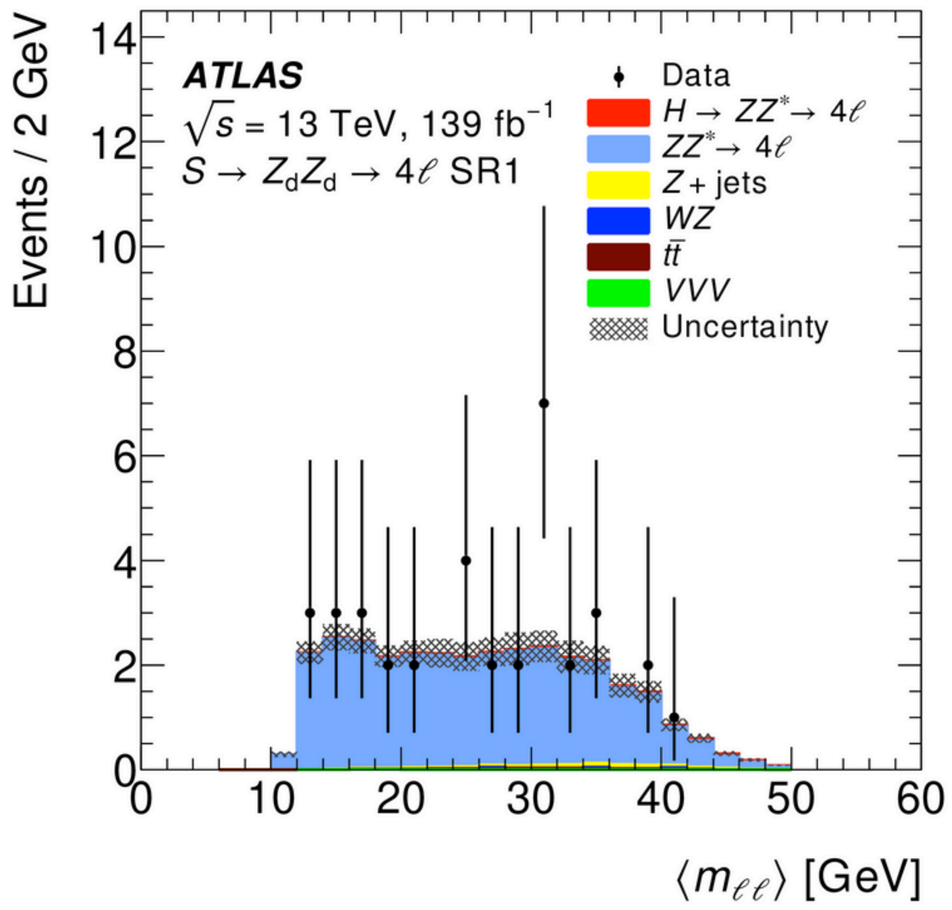
- *Di-objects searches*
- *Long-lived particles*
- *Innovative usage of the detector*

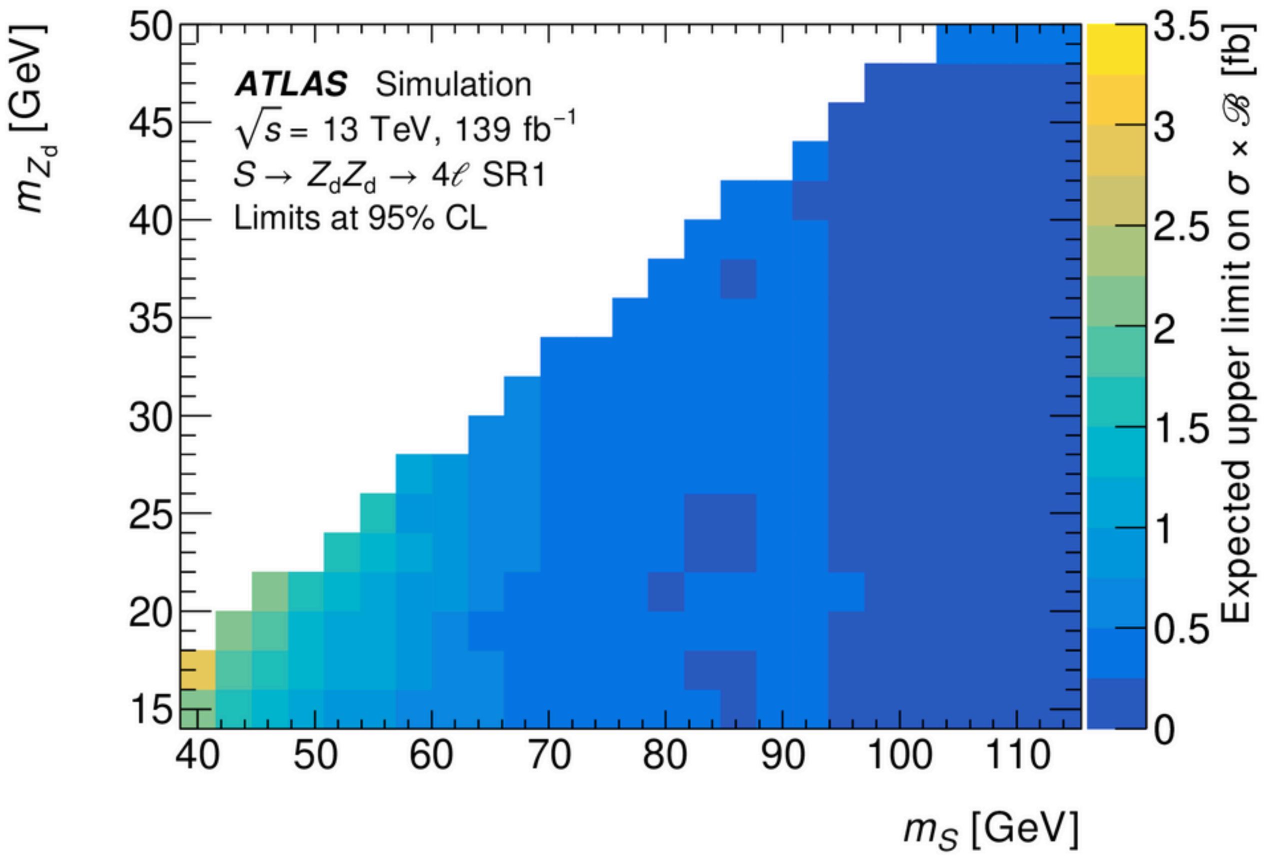
Tools

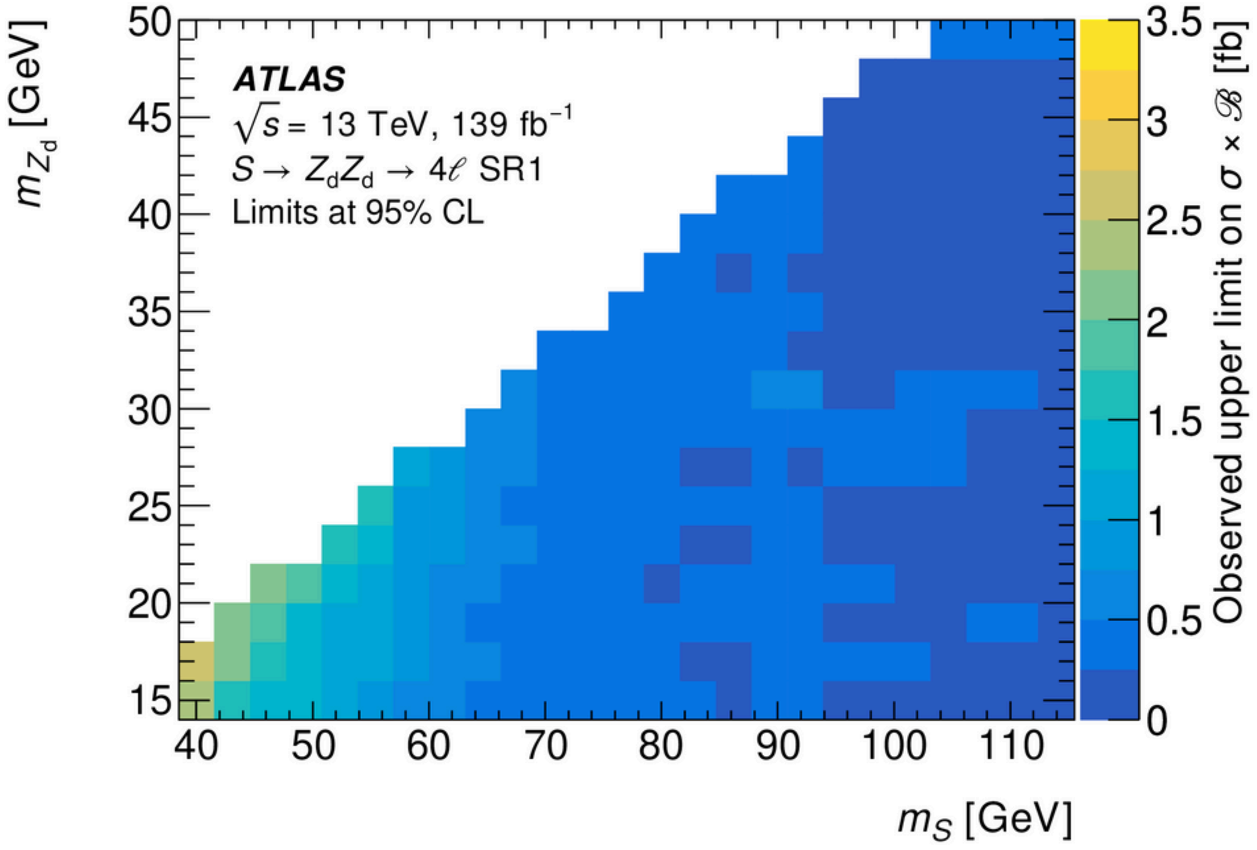
Search for a new scalar decaying into four-lepton final states

Zd mass between 15 and 300 GeV, and the S mass between either 30 and 115 GeV or 130 and 800 GeV









arXiv:2410.16781

Extends previous searches, **covering a broader mass range** w/ upper limits (σ·B) from:

0.14 fb to 3.1 fb for mS<115 GeV
0.05 fb to 0.60 fb for mS>130 GeV

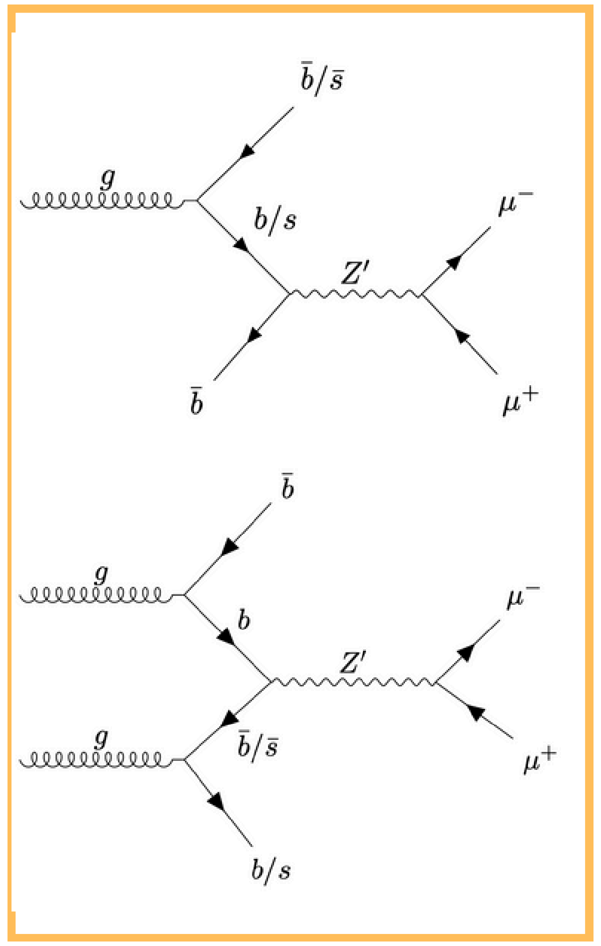
Searches for energetic dileptons w/ b-jets

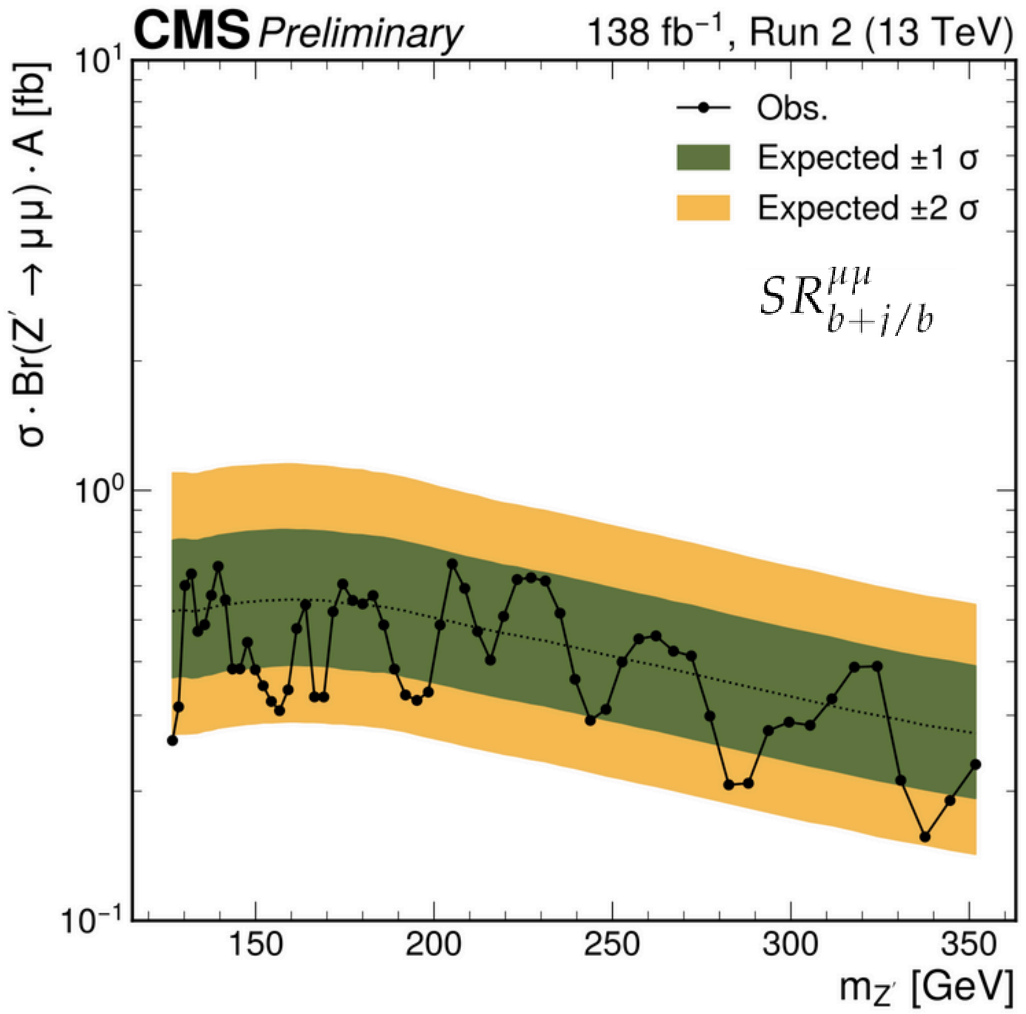
Less conventional dilepton searches beyond inclusiveness in number of jets

Resonant Z' *in dimuon decay + b-jets*

Complementary **result at high mass** (up to 2 TeV) already published

CMS-PAS-EXO-22-006





Backup

Non-resonant dilepton *+ b-jets*

Lepton flavor universality tested by comparing dimuon and dielectron mass vs # b-jets.

Backup

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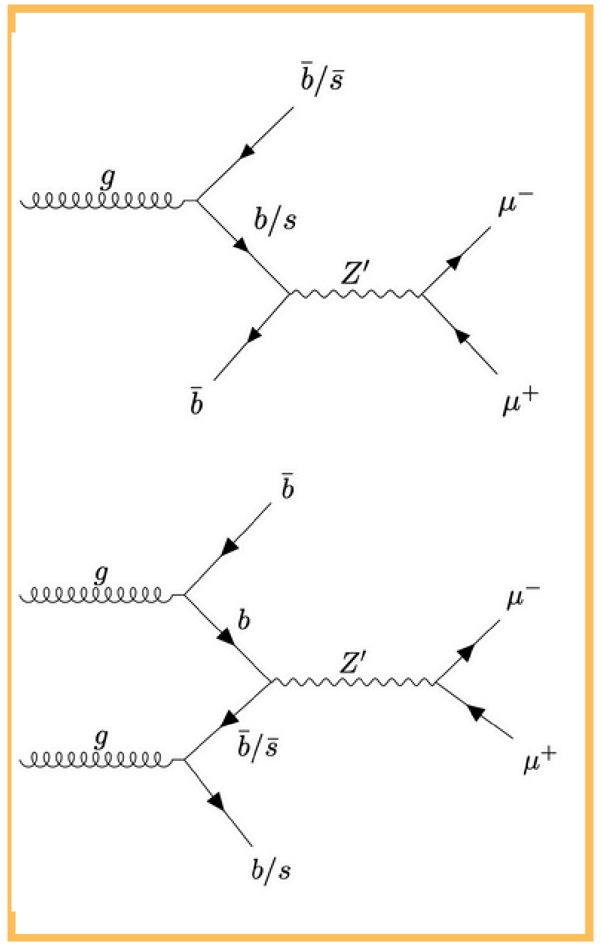
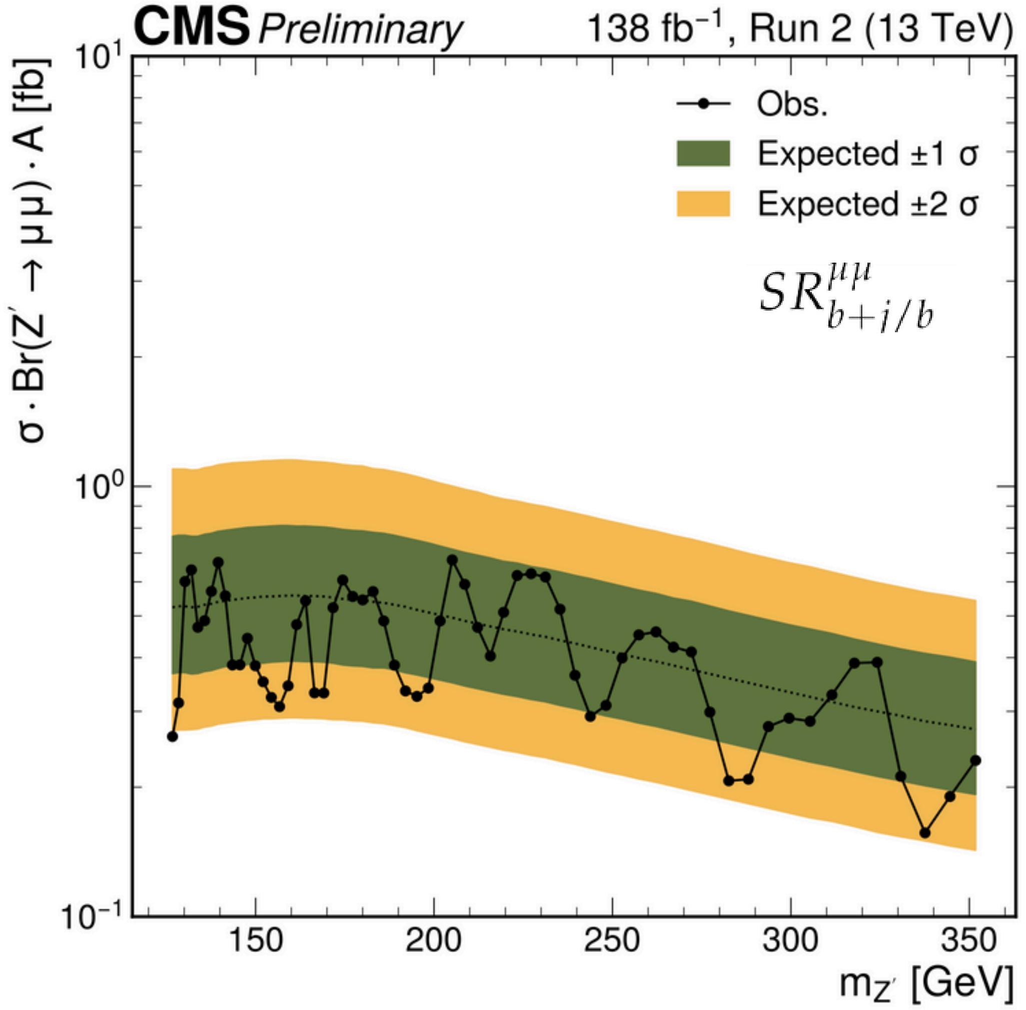
CMS-PAS-EXO-22-006





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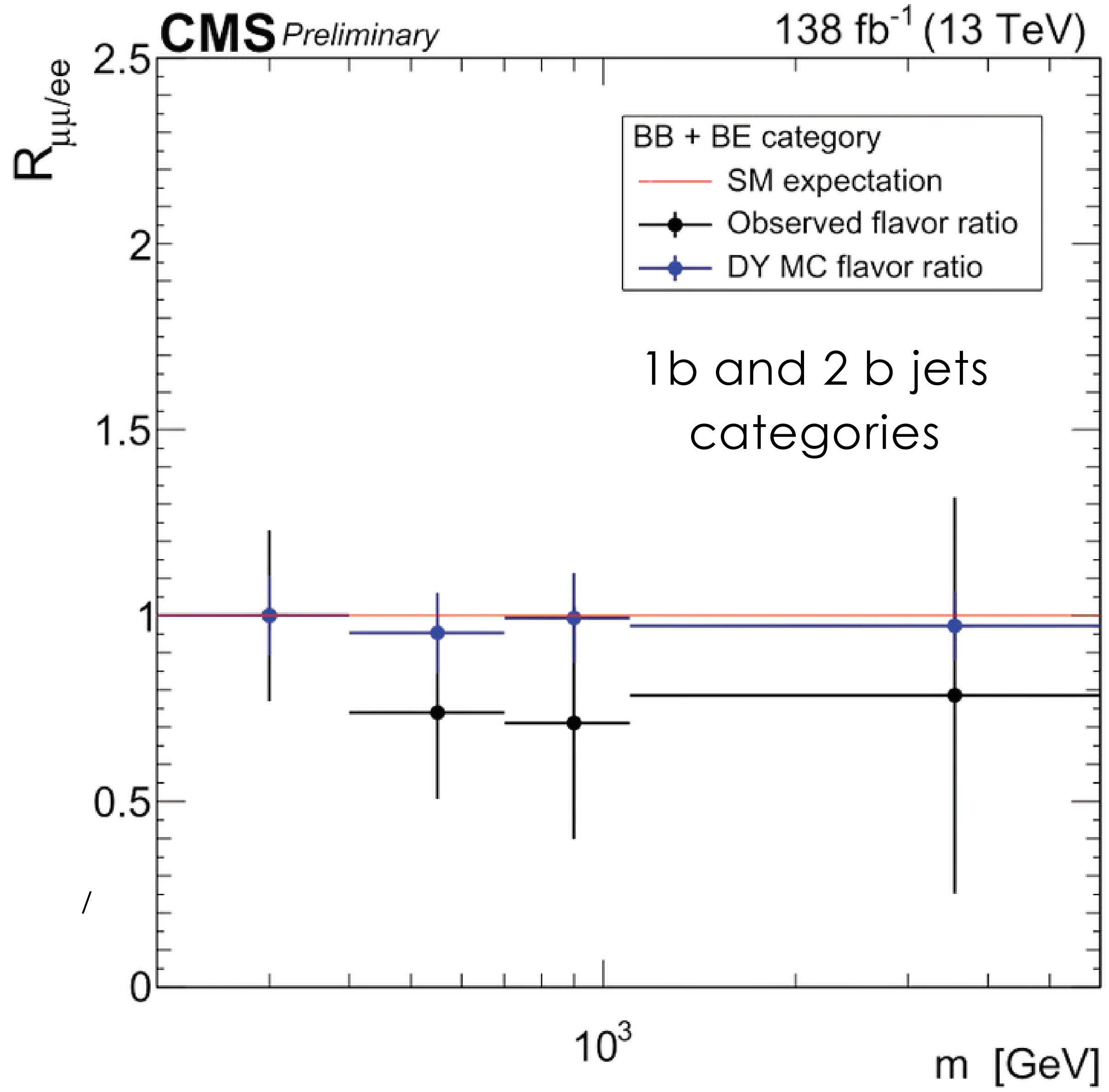
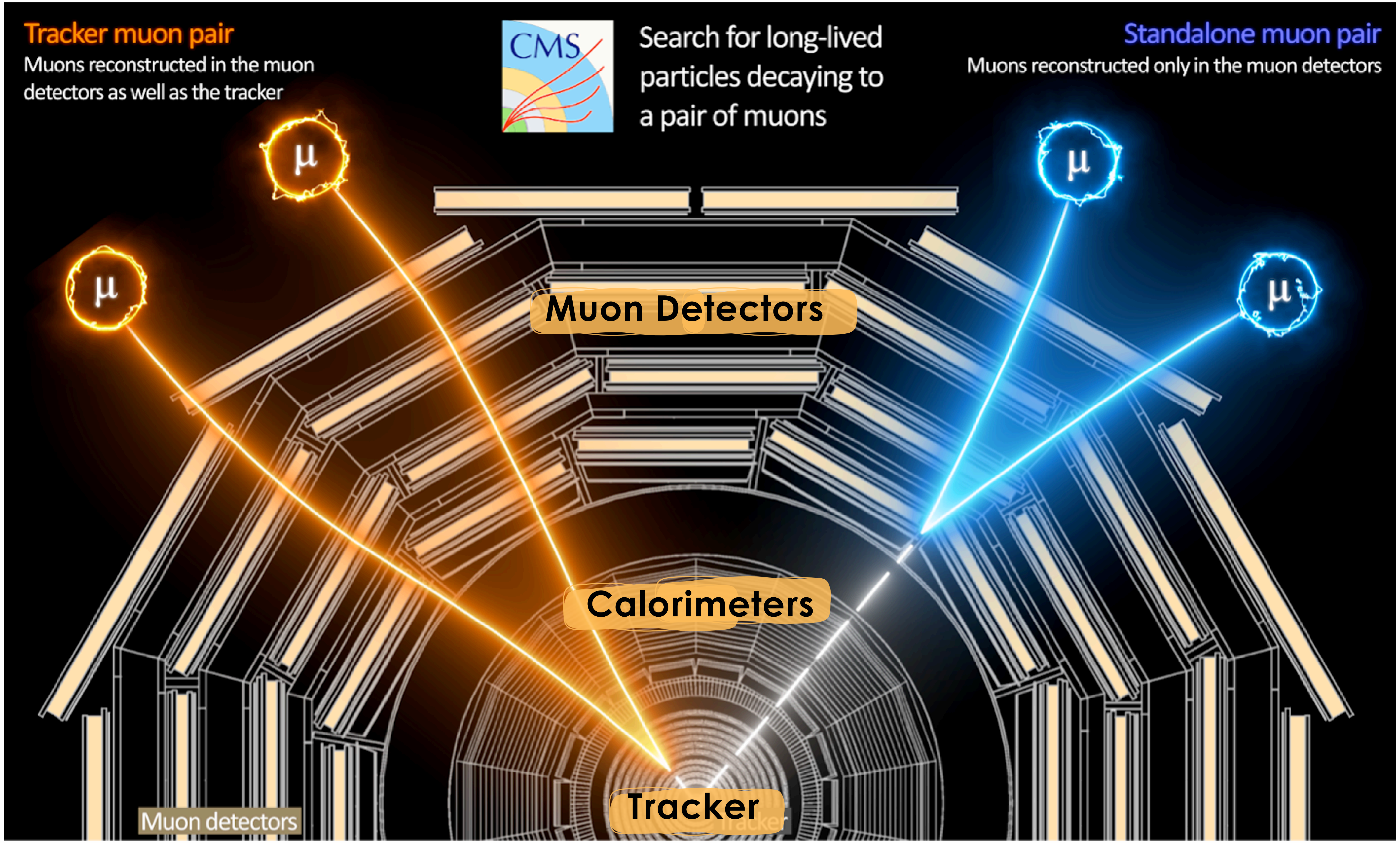


Backup

CMS-PAS-EXO-23-010

Searches for Long Lived Particles: Decays in Tracker, Calorimeters and Muon Detectors



[link]

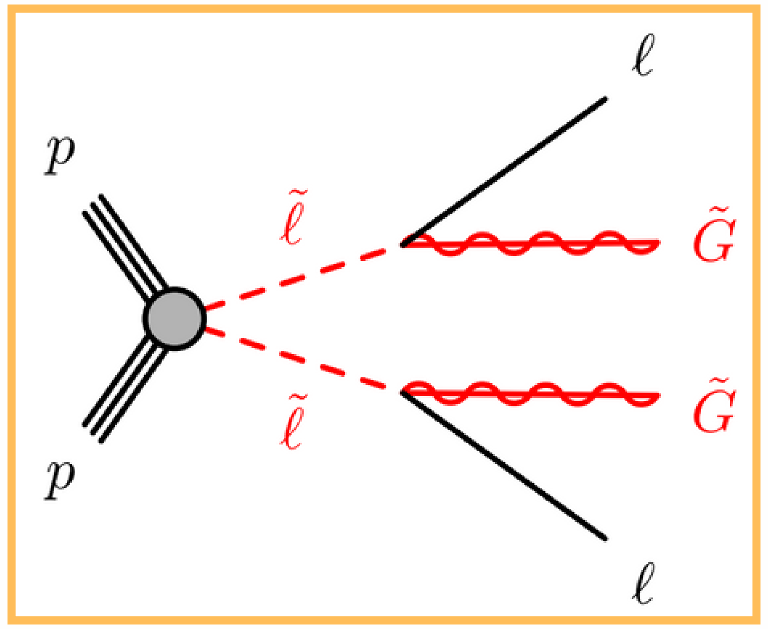
Searches for Long Lived Particles: Decays in Tracker, Calorimeters and Muon Detectors

ATLAS EXPERIMENT

Search for displaced leptons in 13 TeV and 13.6 TeV

Large Radius Tracking: designed to increase efficiency for decay products of LLPs.

LRT run in the HLT for the first time at Run 3



Enhanced discovery reach beyond prior searches through several **novel additions.**

95% CL exclusion contours for **long-lived selectrons (smuons** and **staus**, see backup)

arXiv:2410.16835

Backup

Searches for Long Lived Particles: Decays in Tracker, Calorimeters and Muon Detectors

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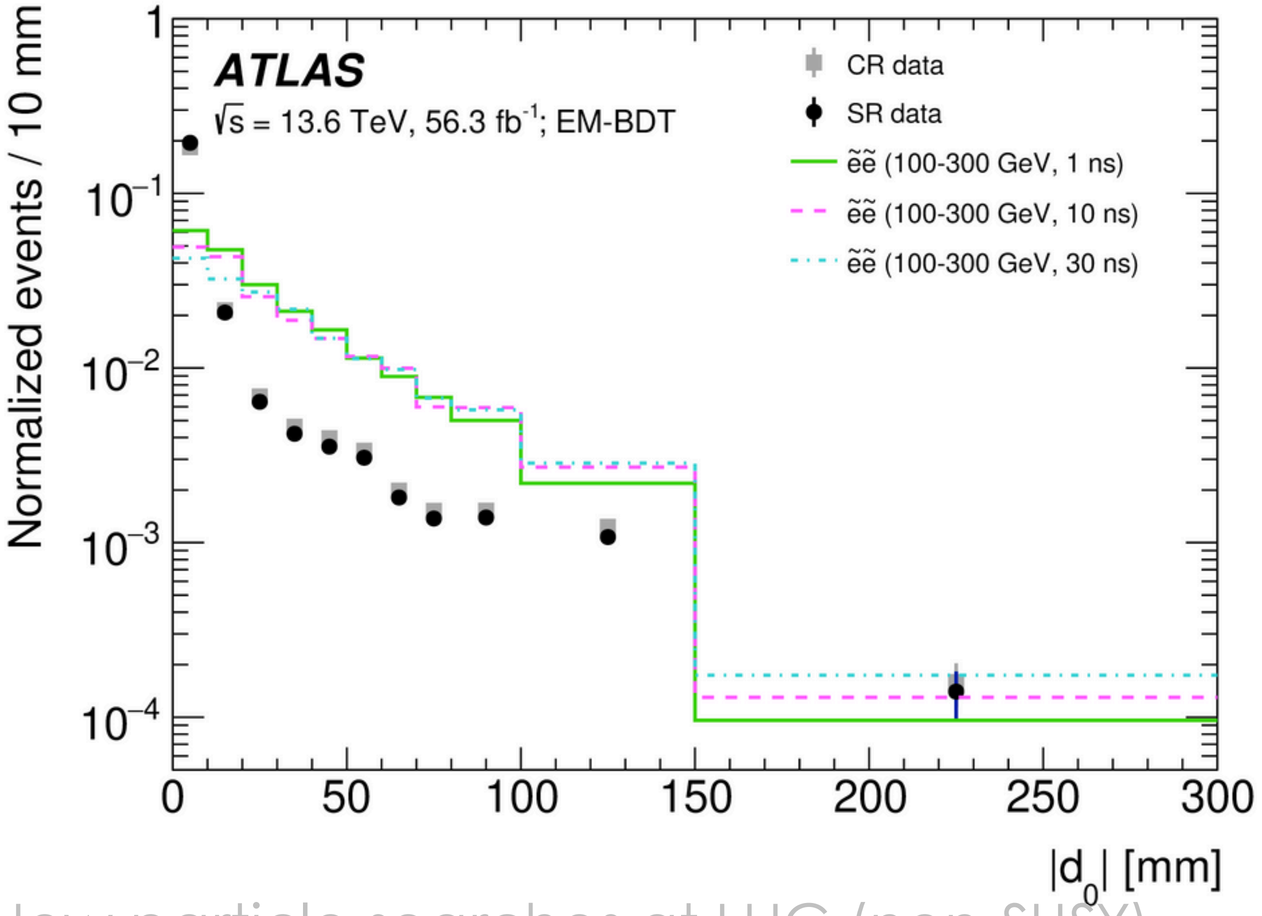

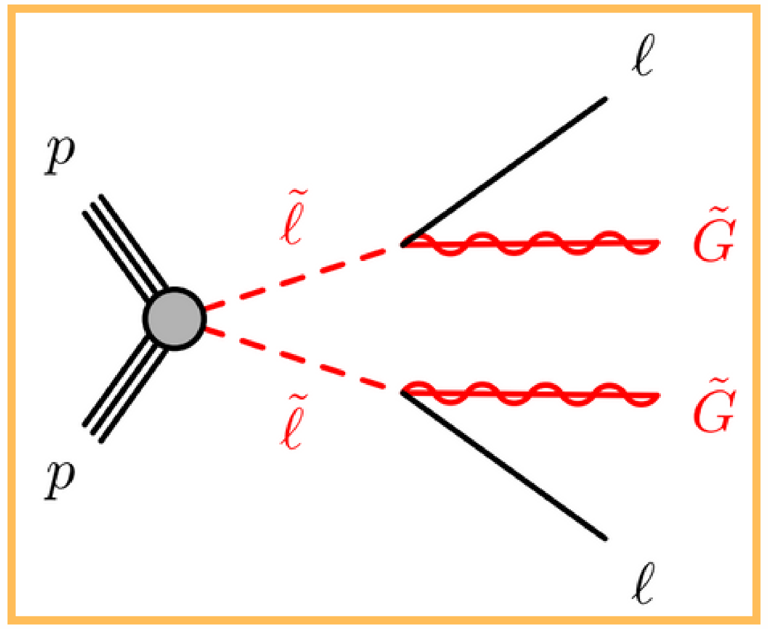

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Backup

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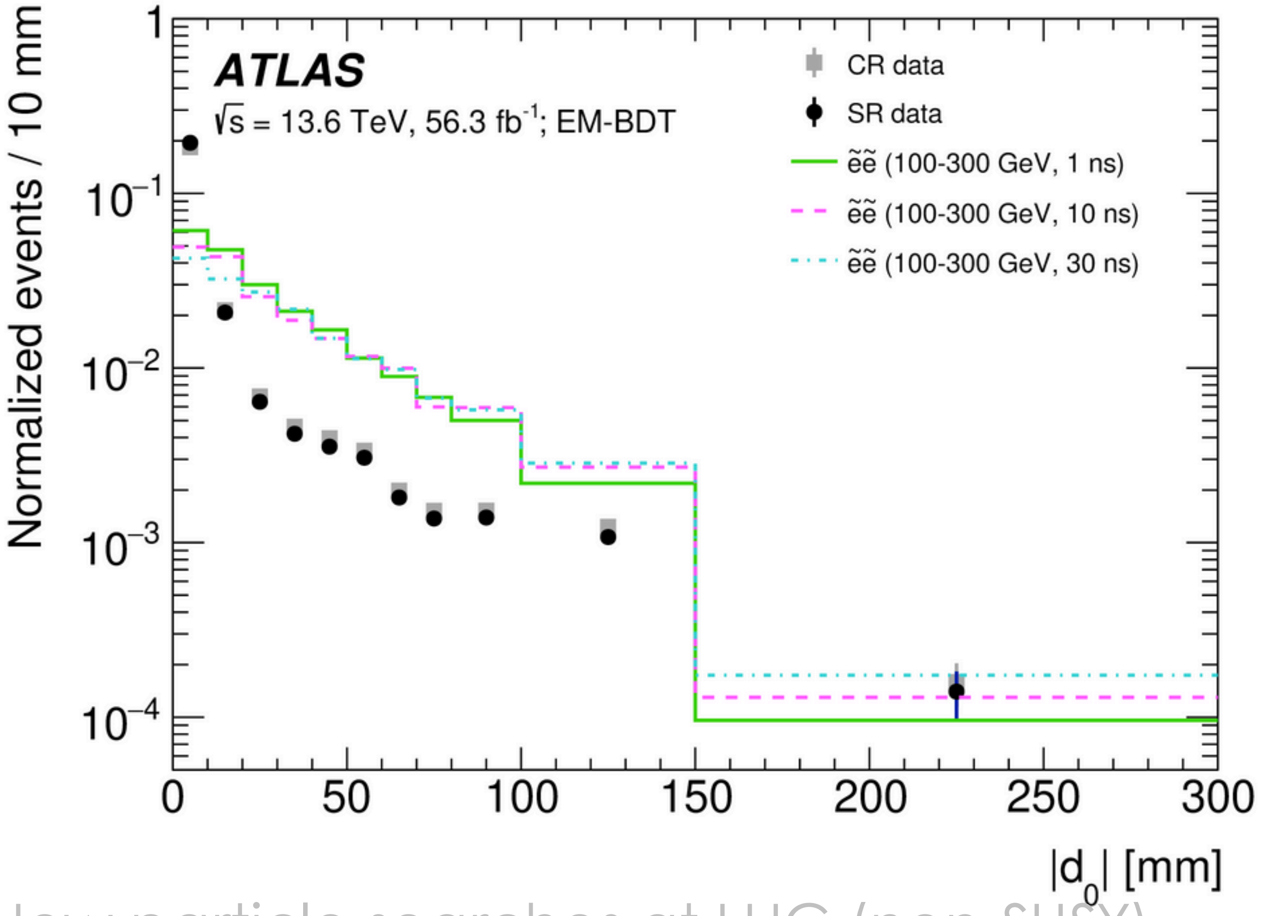

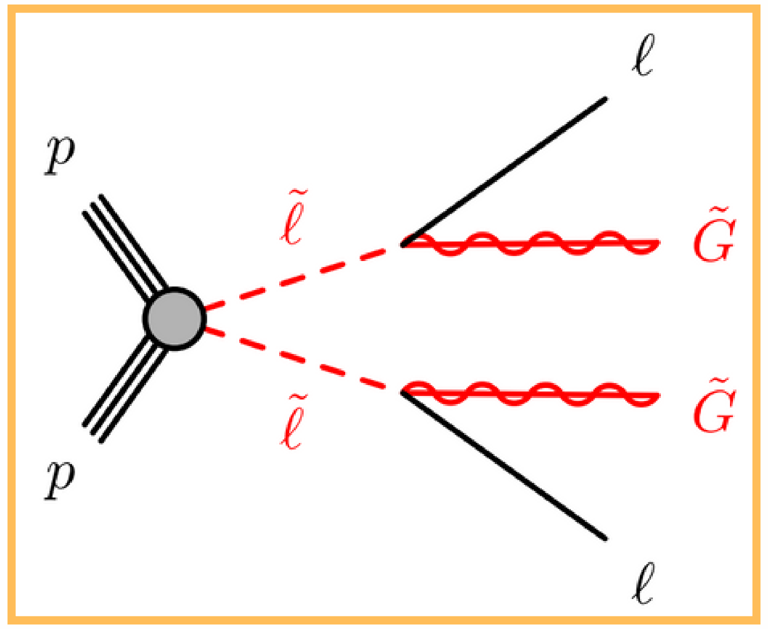

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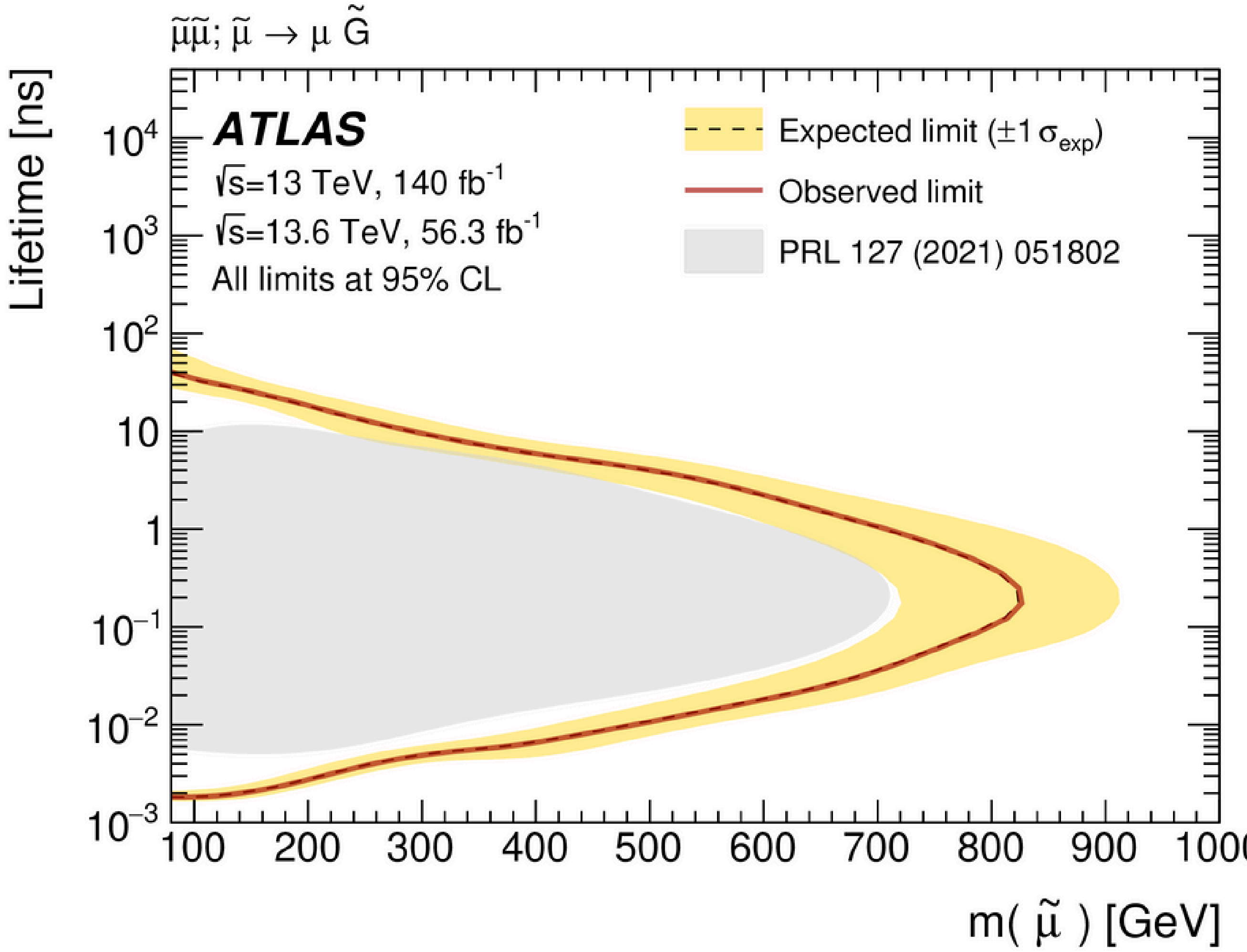
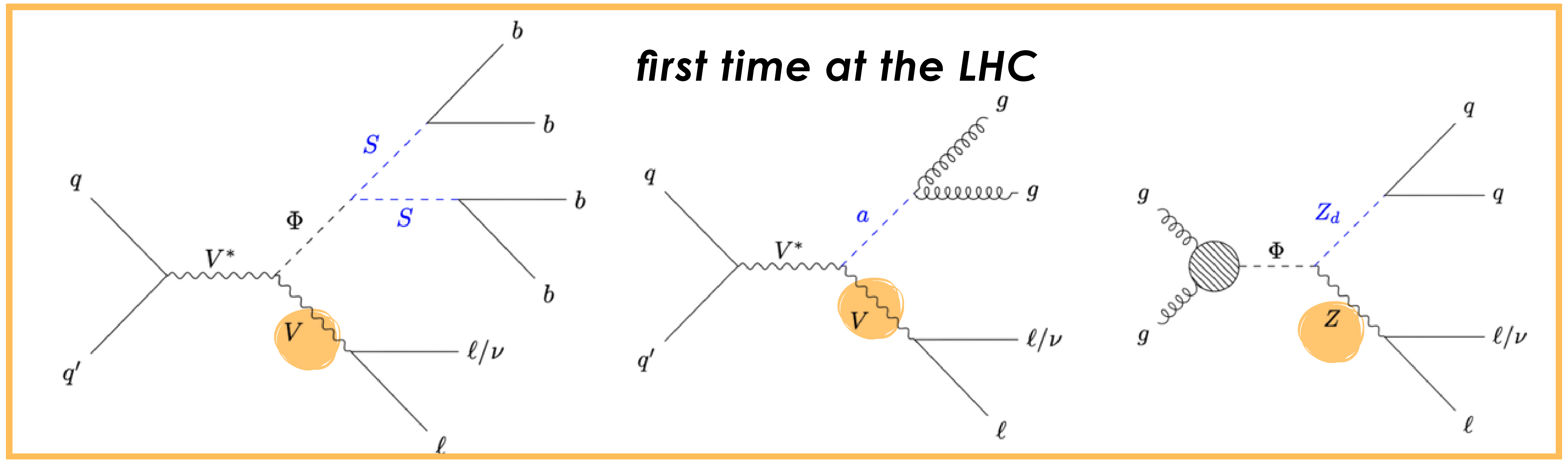


arXiv:2410.16835

Backup

Searches for Long Lived Particles: Decays in Tracker, Calorimeters and Muon Detectors

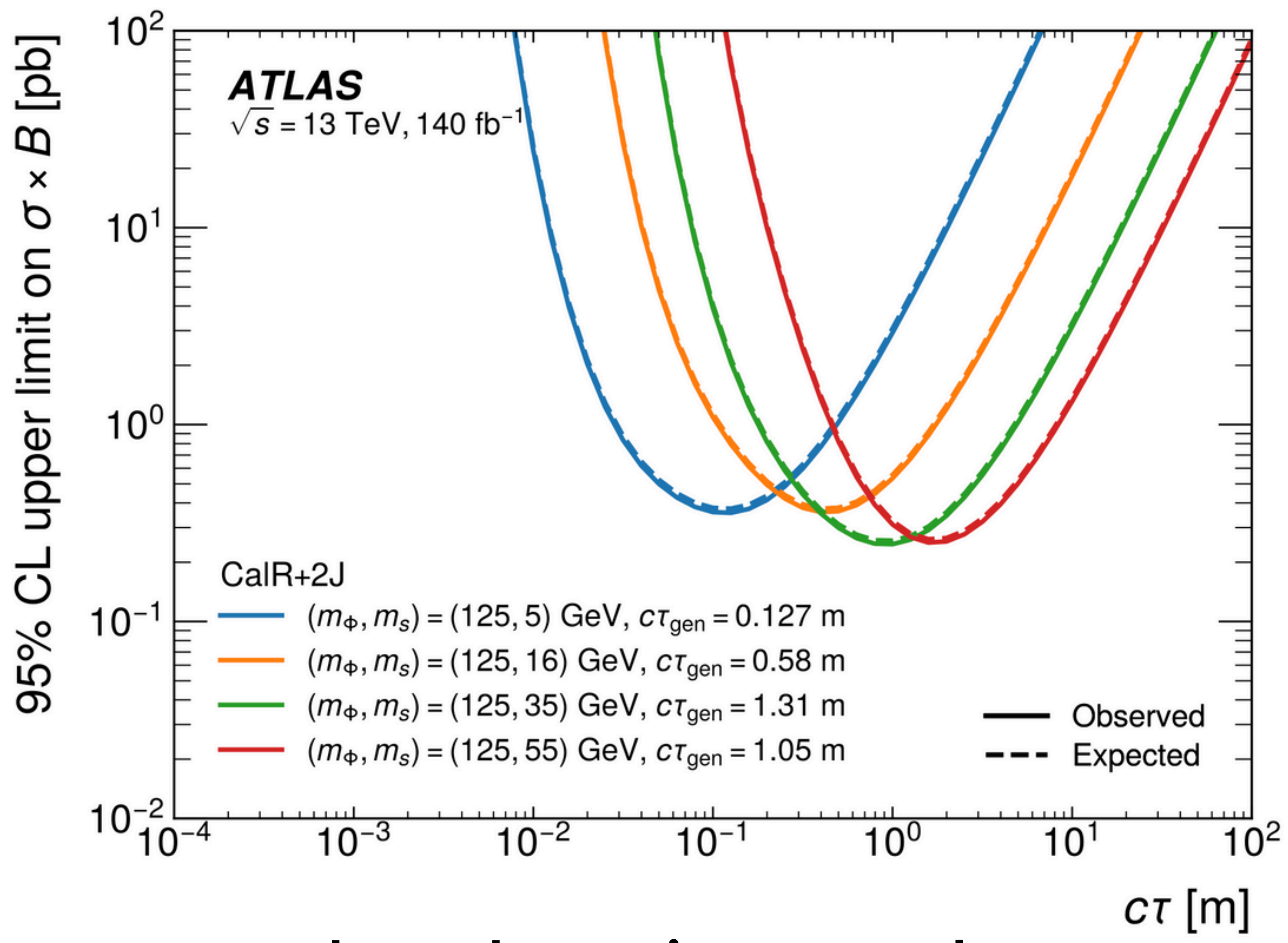
Search for neutral long-lived particles that decay into displaced jets in the calorimeter w/ leptons or jets



== **additional object to trigger** the event + access low-mass/boost regions (enhance sensitivity)

CalRatio: LLPs that decay after the electromagnetic calorimeter have very low electromagnetic component

few cm -- tens of m



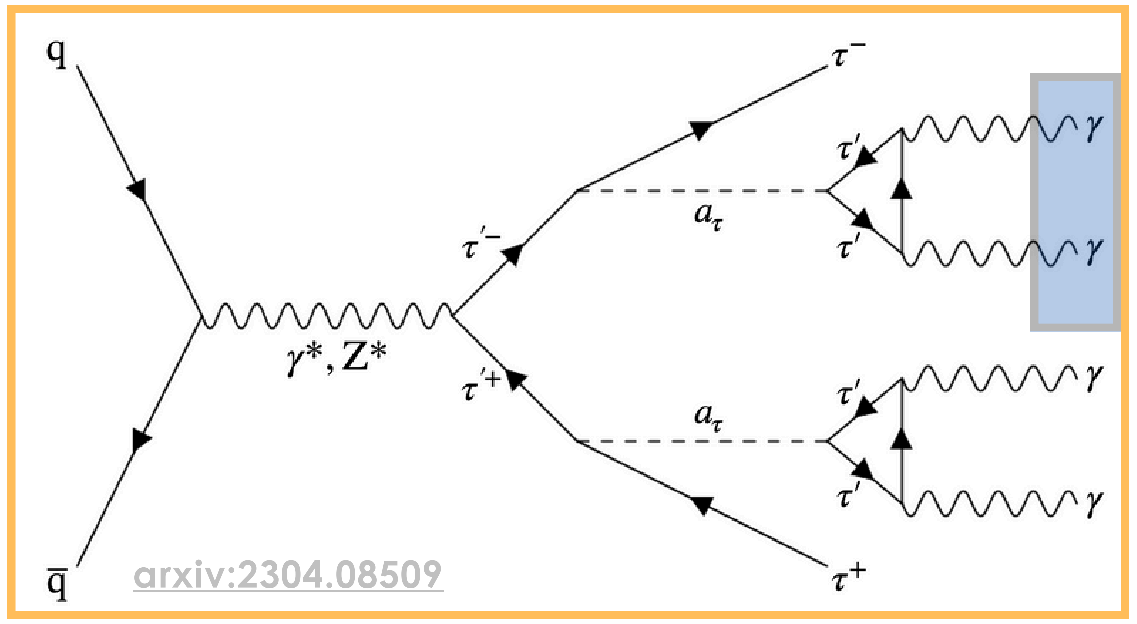
x3 improvements w.r.t. previous searches

arXiv:2407.09183

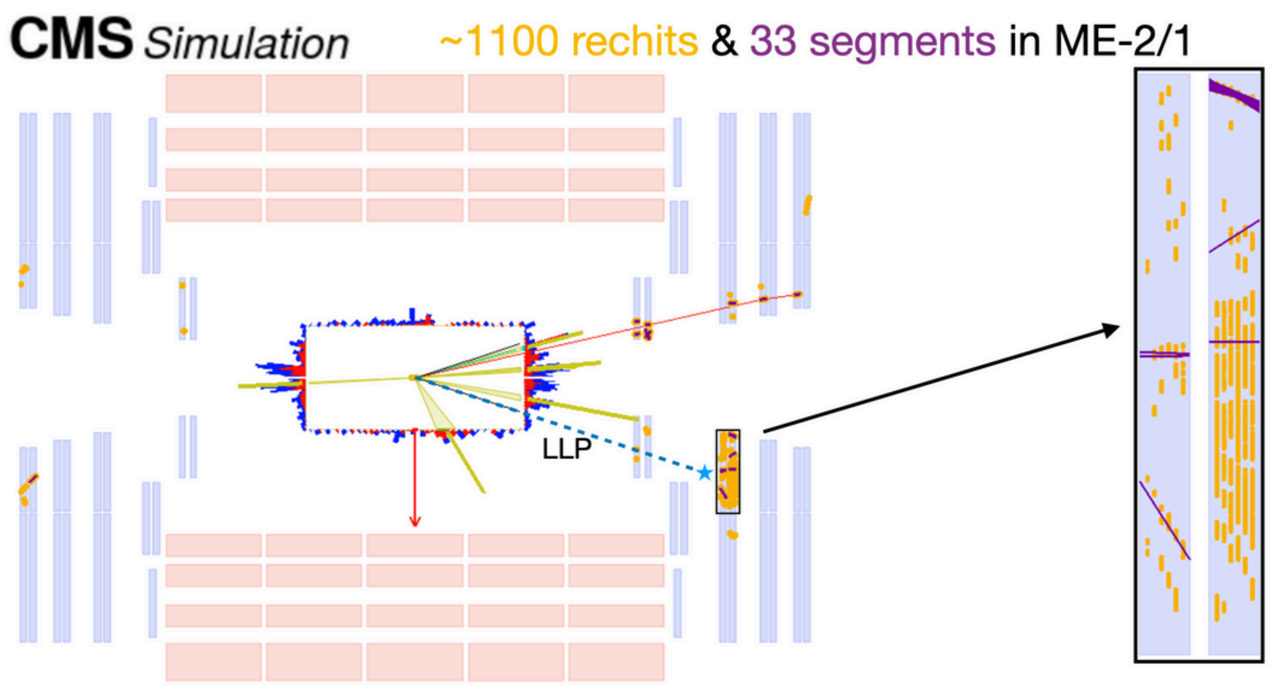
Backup

Searches for Long Lived Particles: Decays in Tracker, Calorimeters and Muon Detectors

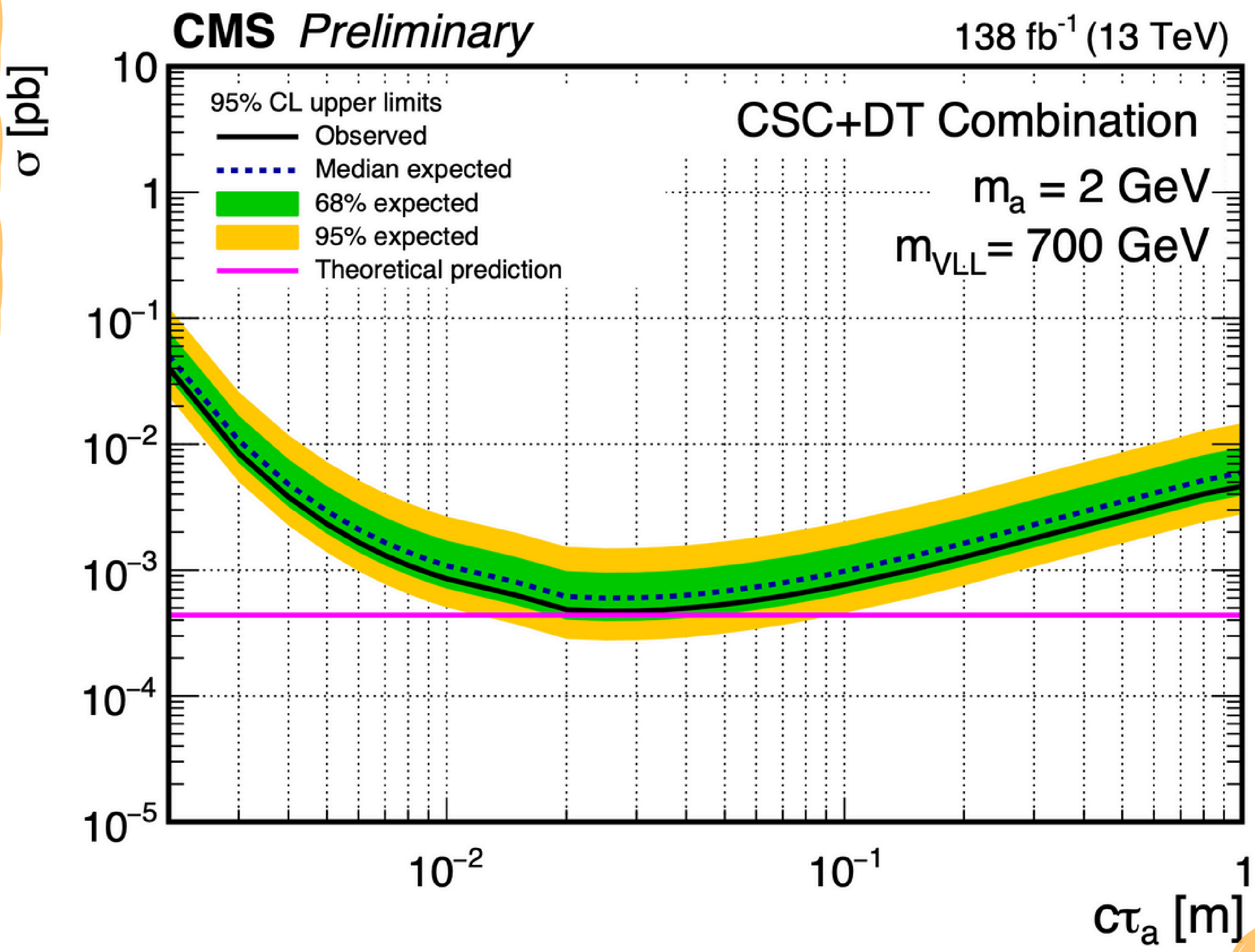
Vector Like Leptons via LLP decays in the muon system



Muon Detector Shower (MDS): cascade of secondary particles produced by high energy particles crossing muon detectors



high-multiplicity MDS



CMS-PAS-EXO-23-015

CMS-DPS-2022-062

Backup

Beyond

Standard

Model

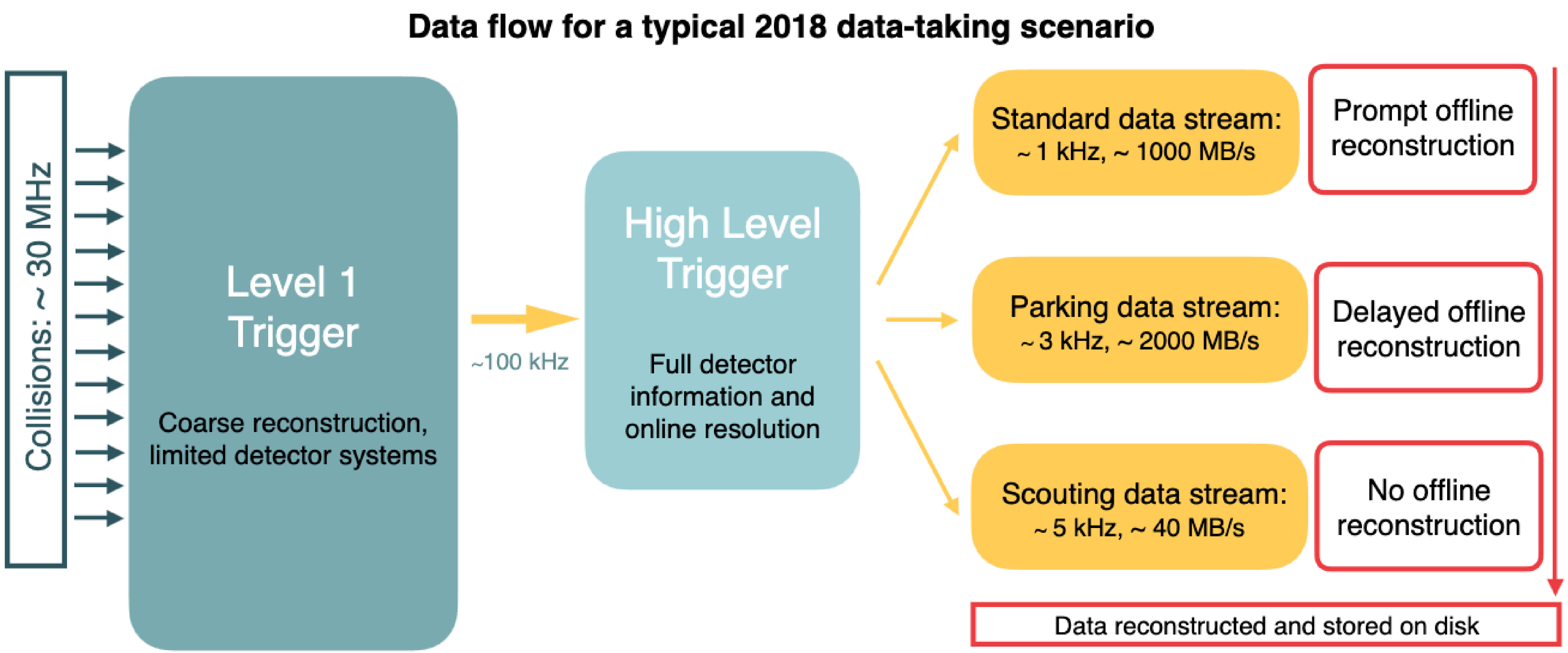
Strategies

Signatures

Tools

- *Dedicated data streams*
- *Ad-hoc triggers for LLPs at Run 3*

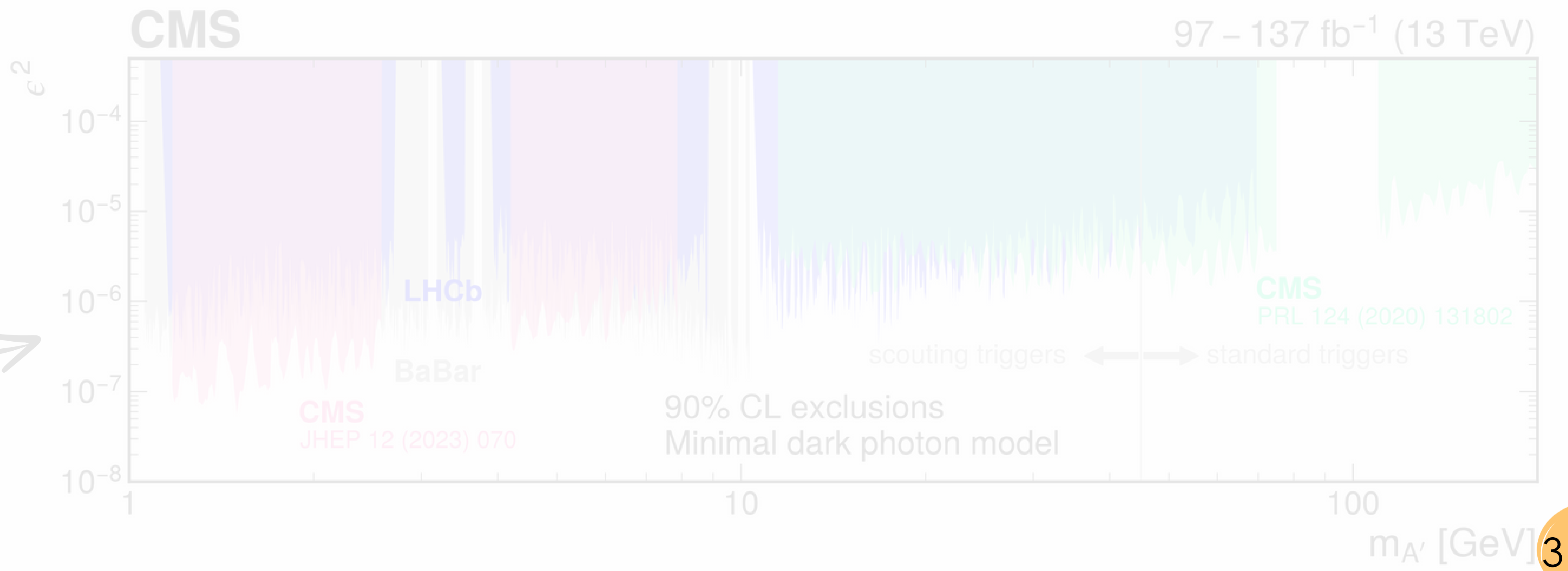
Scouting opportunities at Run 2 & 3



arXiv:2403.16134

Size ↘ Rate ↗

Scouting in Run 2 explored **simple objects**: low-mass **dimuon** spectra



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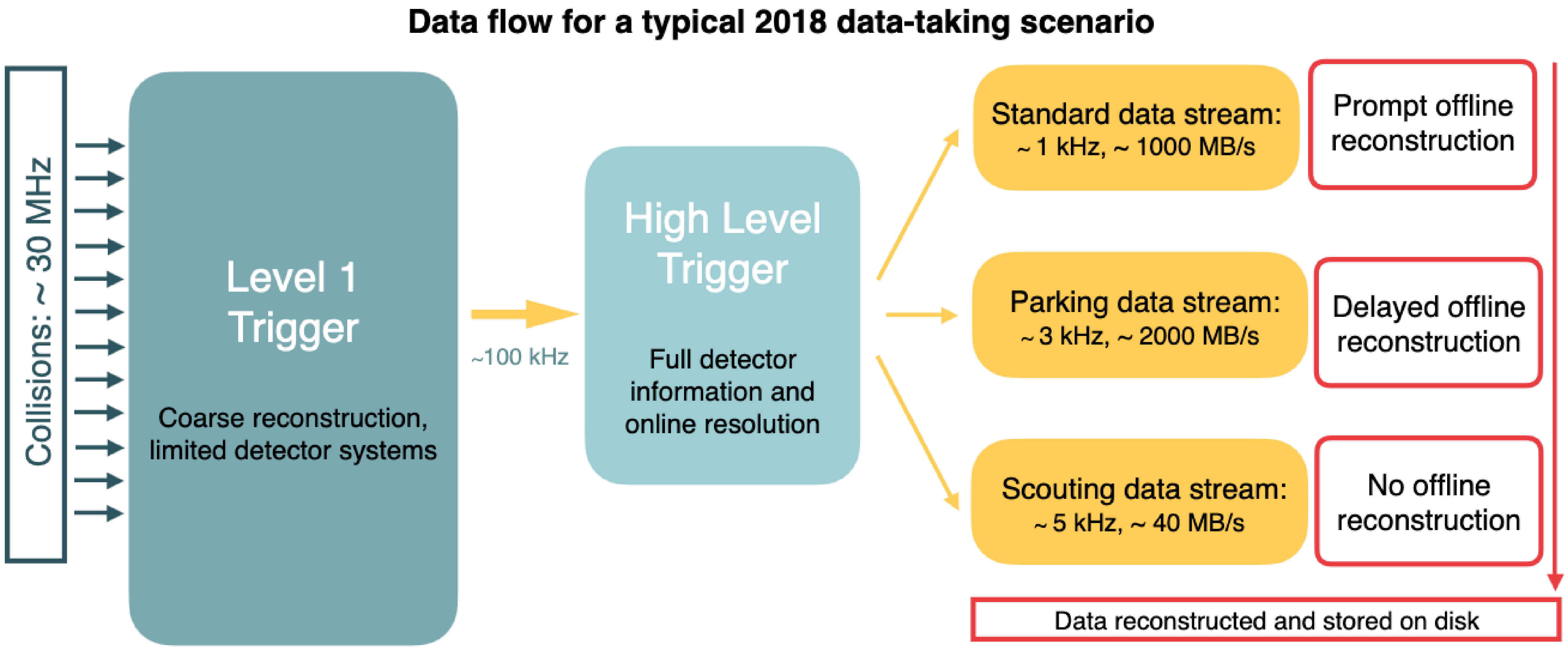

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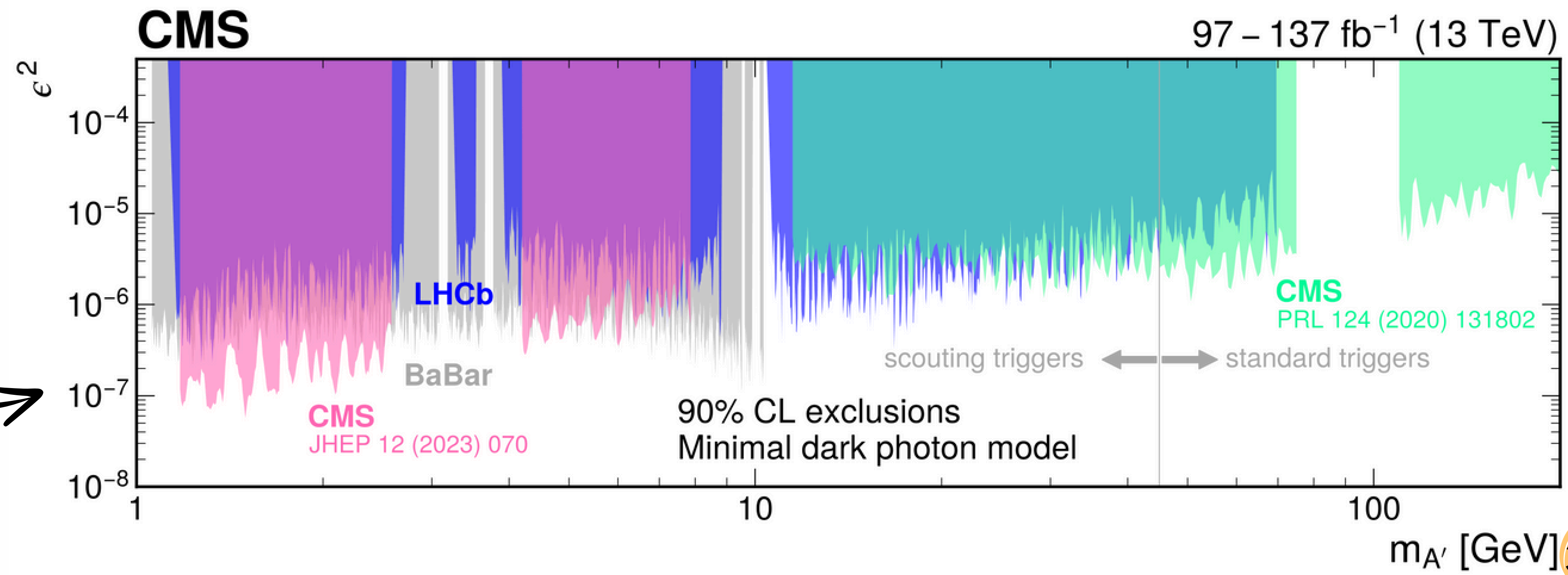
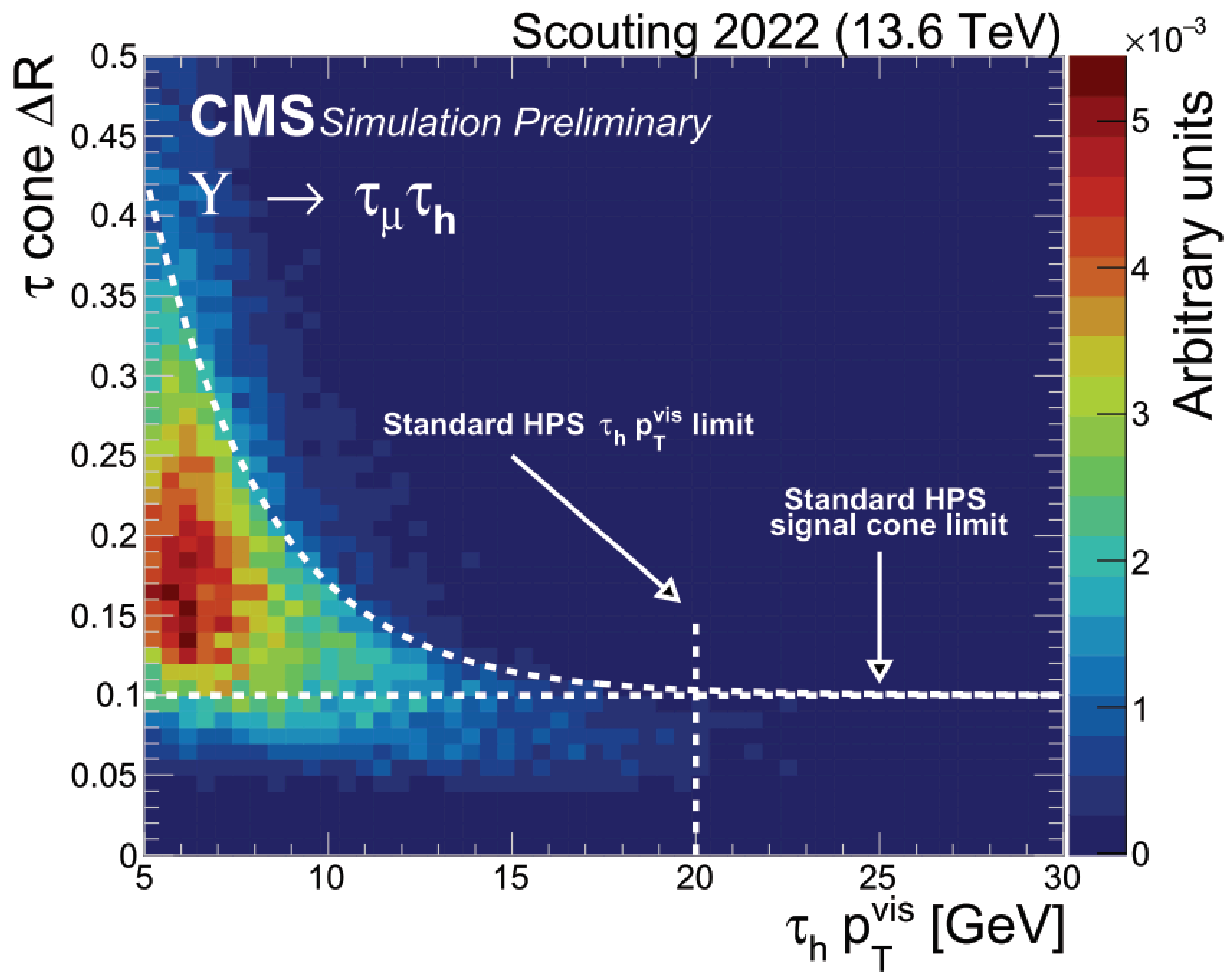


arXiv:2403.16134

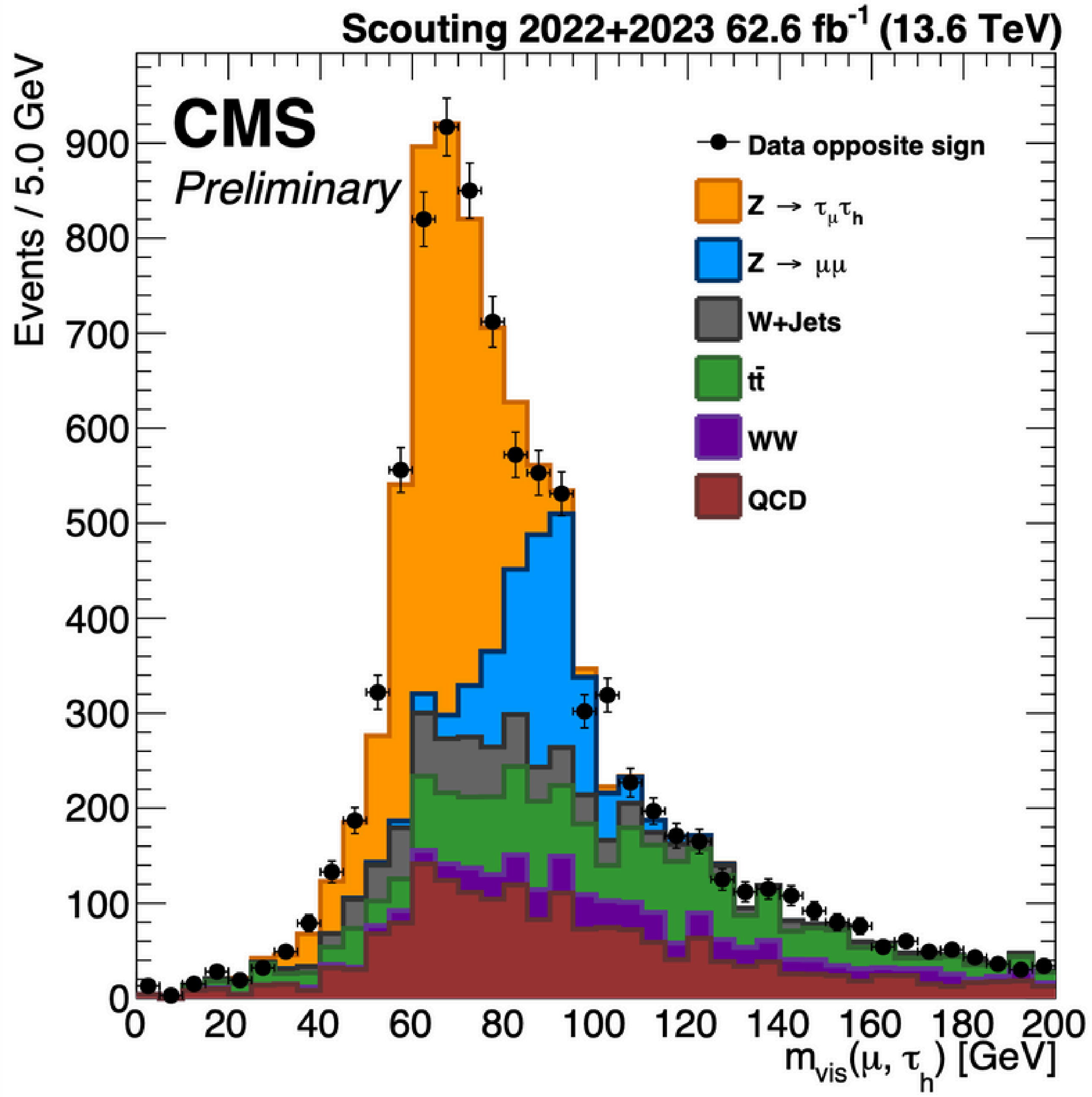
Scouting opportunities at Run 3

Scouting Run 3: more elaborated objects, tau leptons reconstruction from all info stored in scouting dataset

dynamical tau cone definition vs p_T



first time in Scouting data



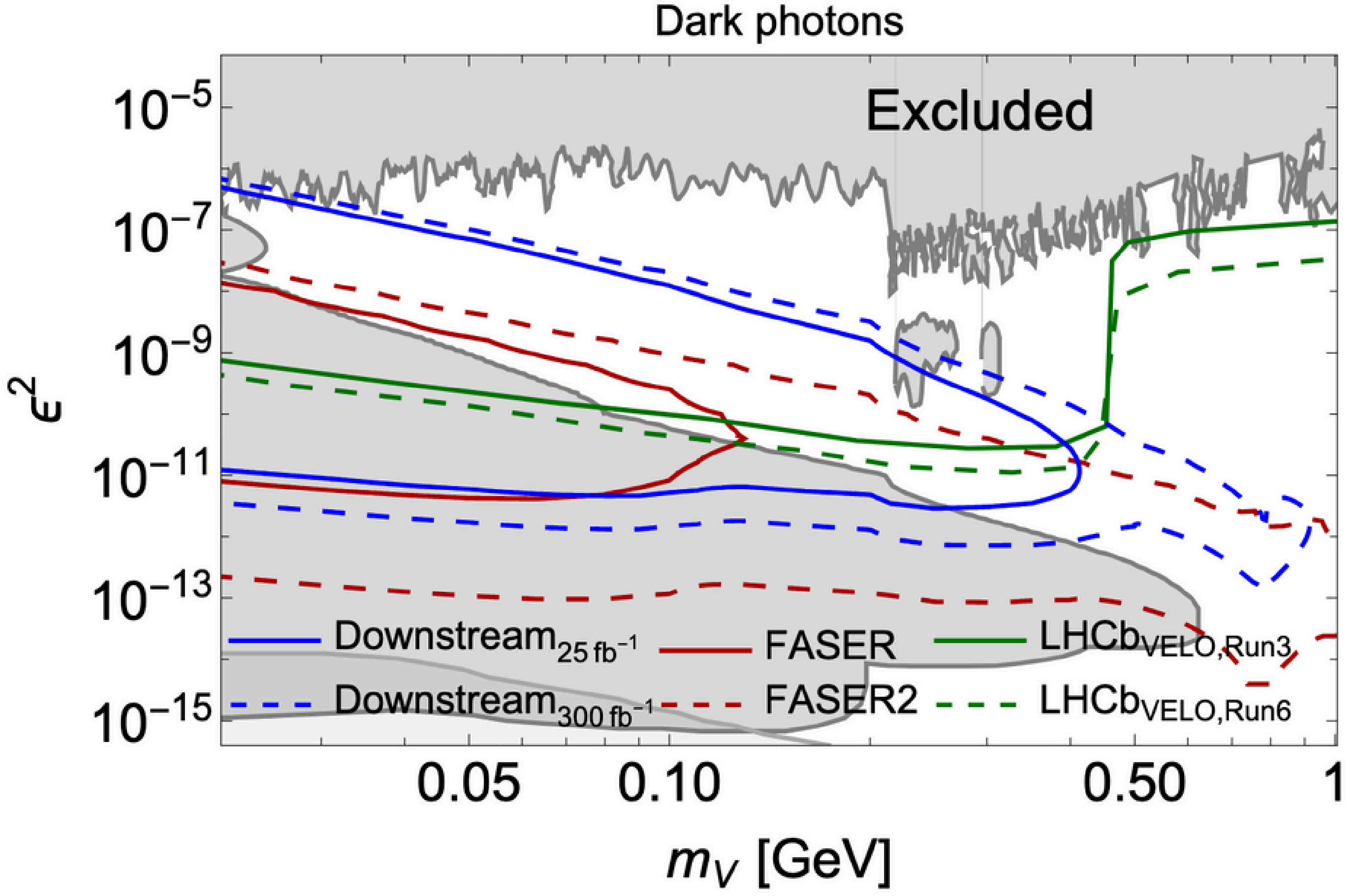
CMS NOTE-2024/006

Backup

Innovative trigger strategies at Run 3

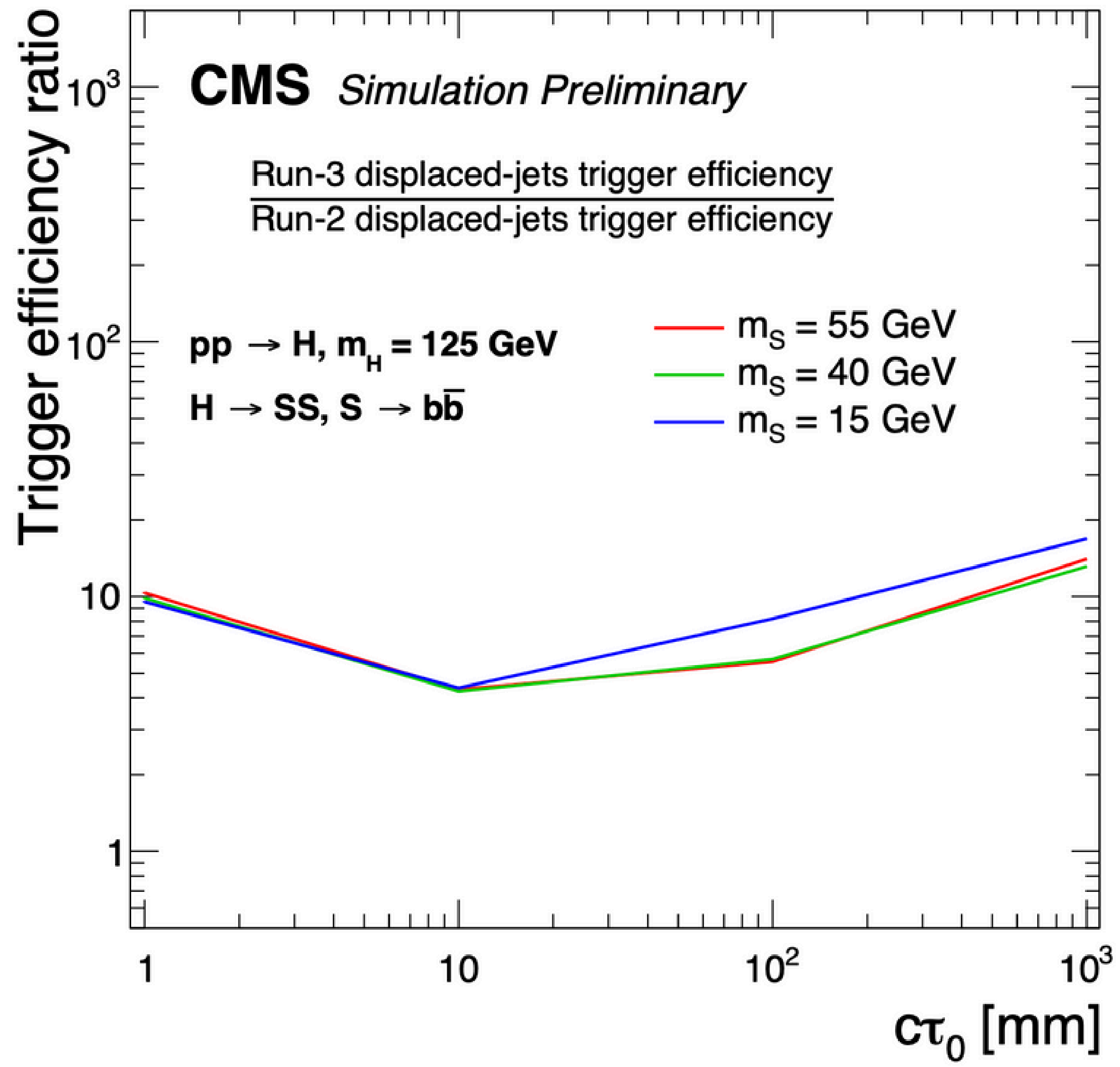
Run 3 physics program **expands the scope of searches for BSM** with addition of dedicated LLP triggers

Improved Muon ID @ LHCb and **dedicated downstream tracks reconstruction** at HLT to identify new low mass displaced particles



arXiv:2312.14016

Displaced-jets tagging in Run 3 search brings up to x10 improvements w.r.t. Run 2.



CMS-DPS-2023-043

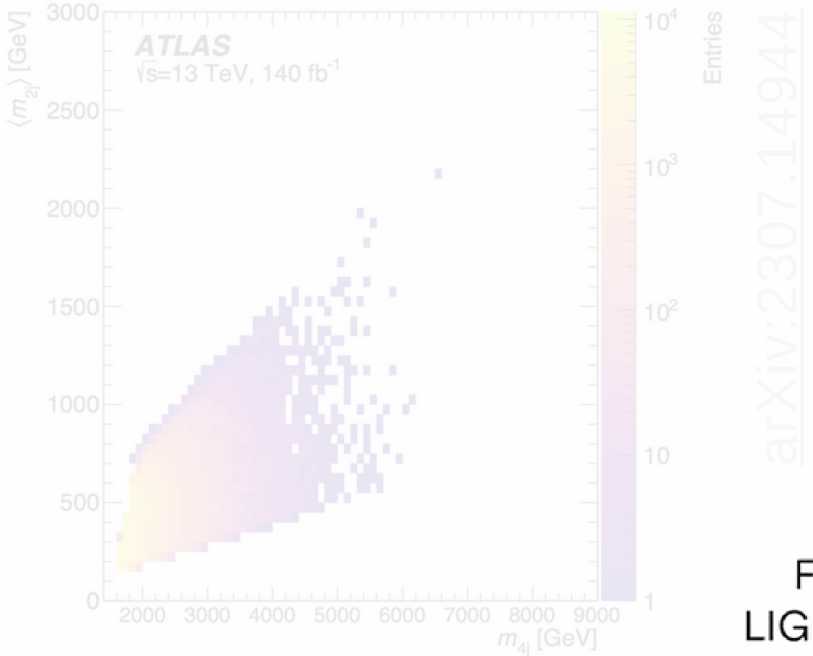
BSM searches in our light-cone

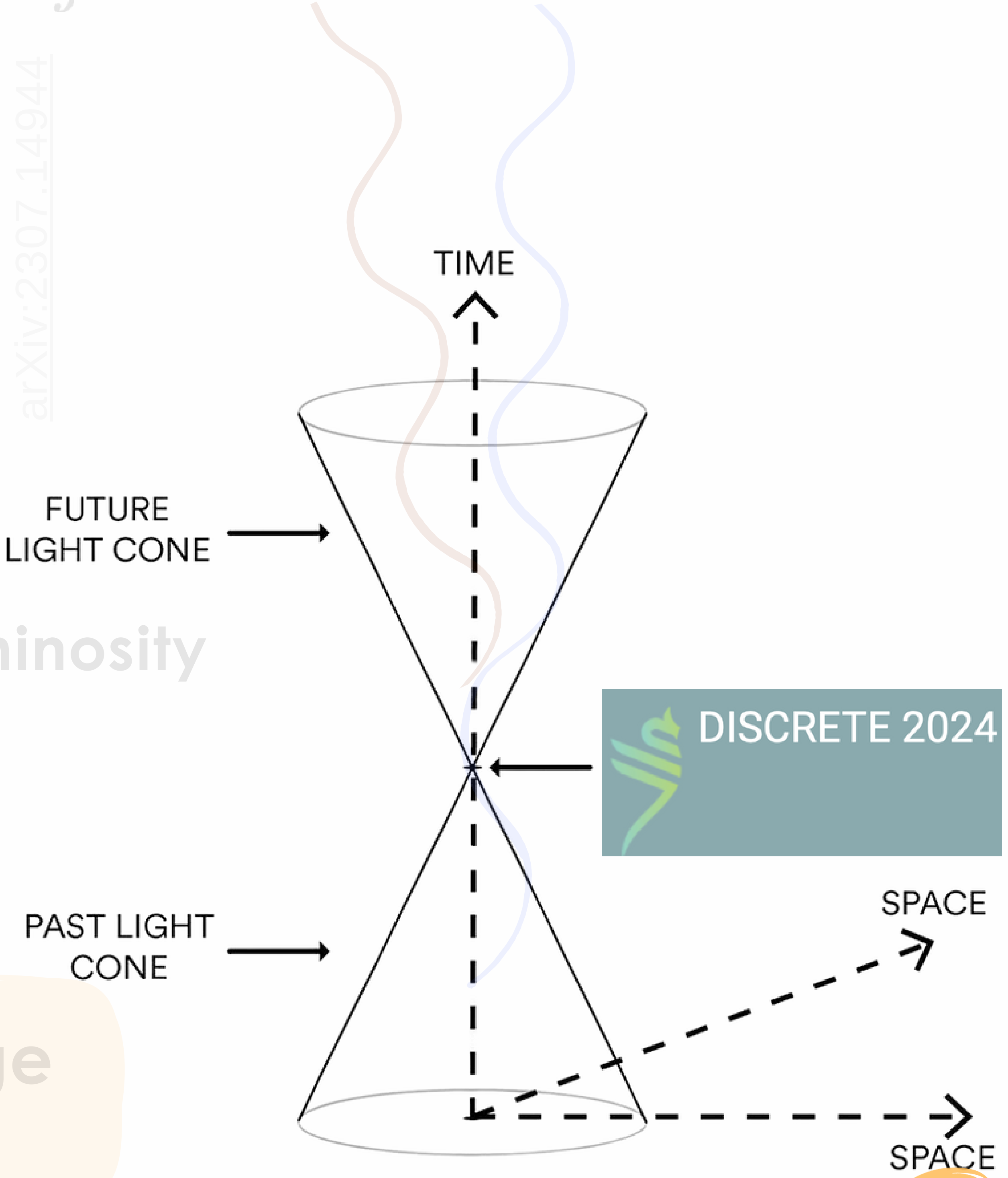
Run 3 provides a powerful platform to explore new physics through combination of **higher energy, increased luminosity, and improved experimental techniques**

Some excesses around to chase..e.g.:

Low-mass $X \to \gamma\gamma$

High-mass $Y \to XX \to 4j$





HL-LHC will significantly increase physics reachs: gains from **high luminosity and new detector capabilities**

e.g. Long Lived Particles searches and Particle ID with timing detectors

Next years will provide massive amount of new knowledge and we are expecting to exceed expectations!

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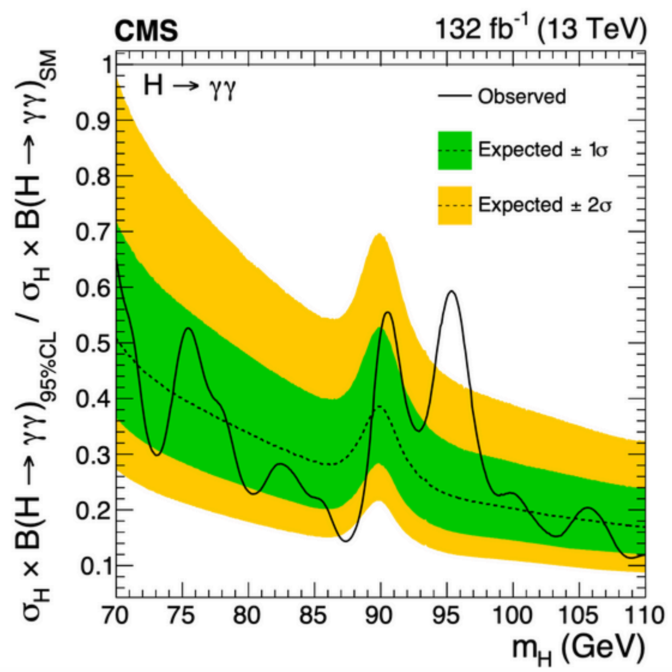

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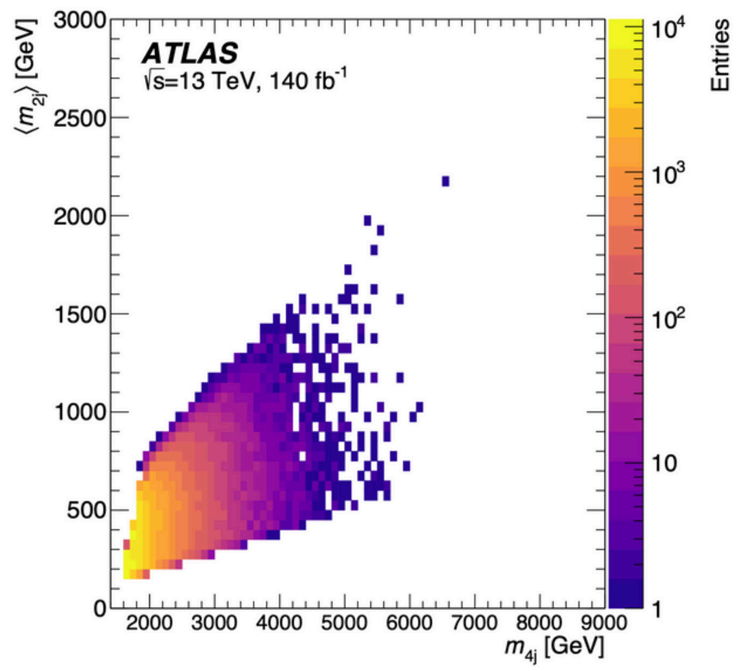

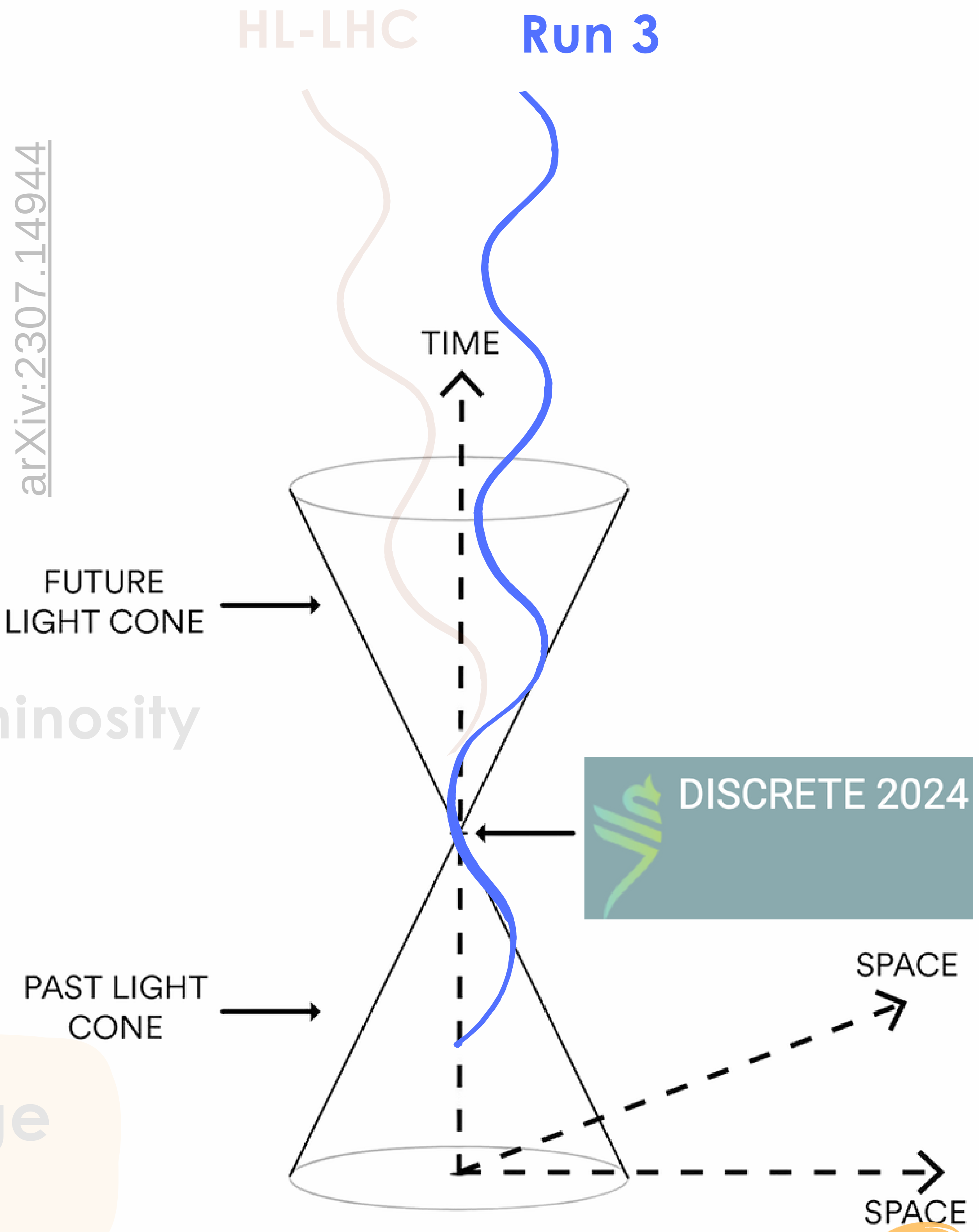

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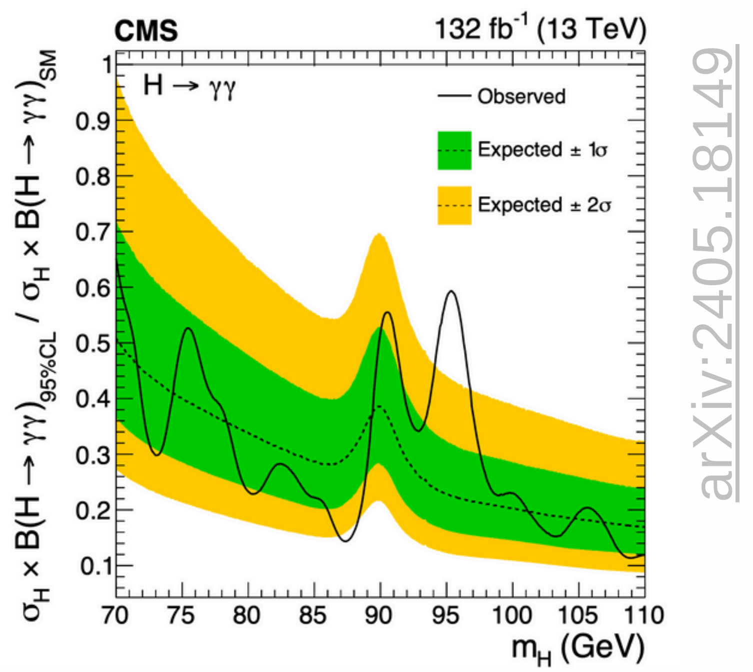

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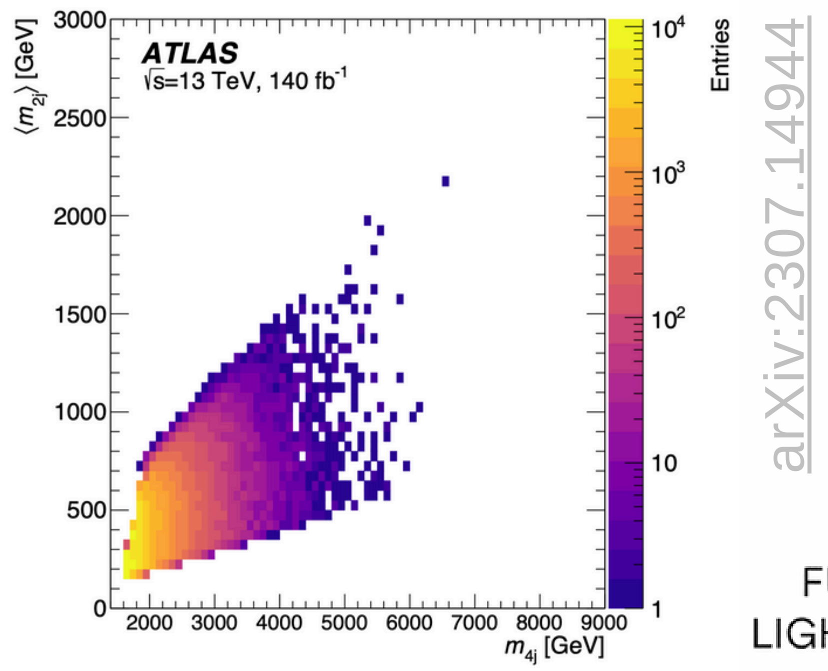

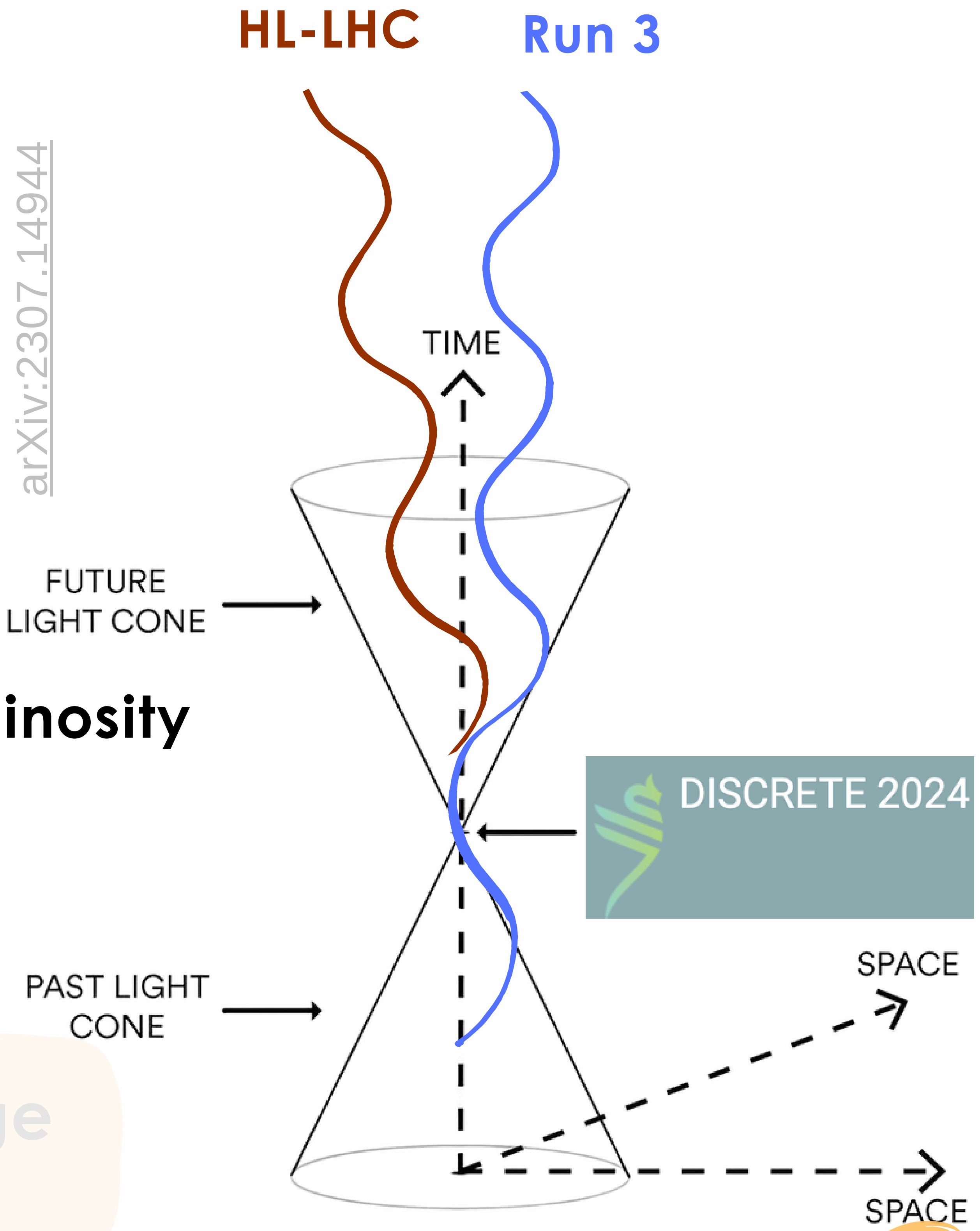

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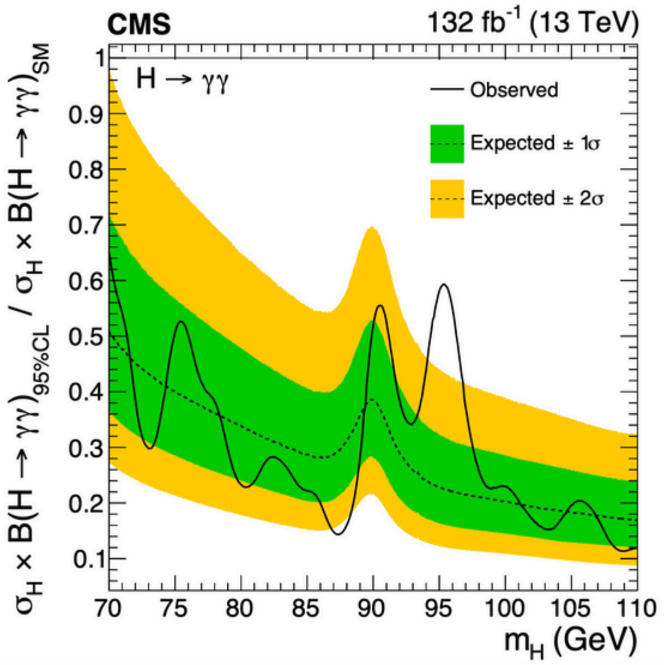
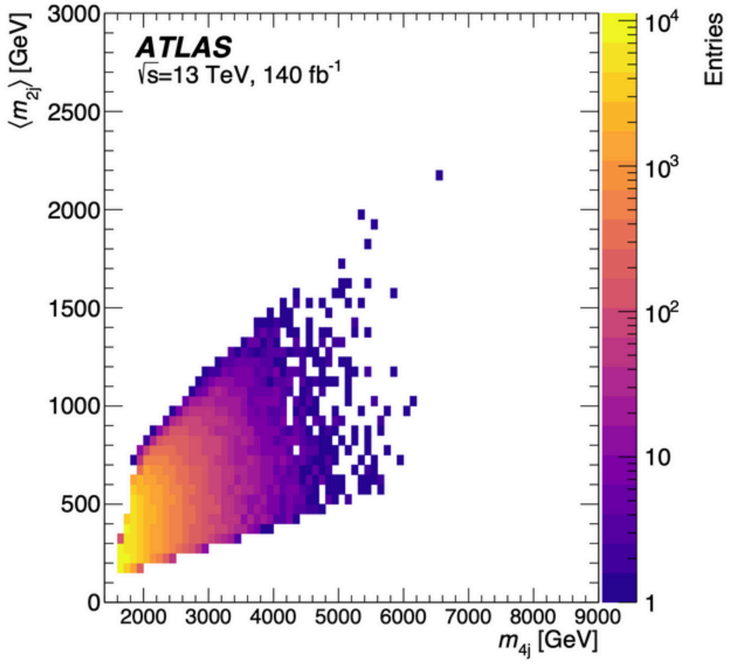
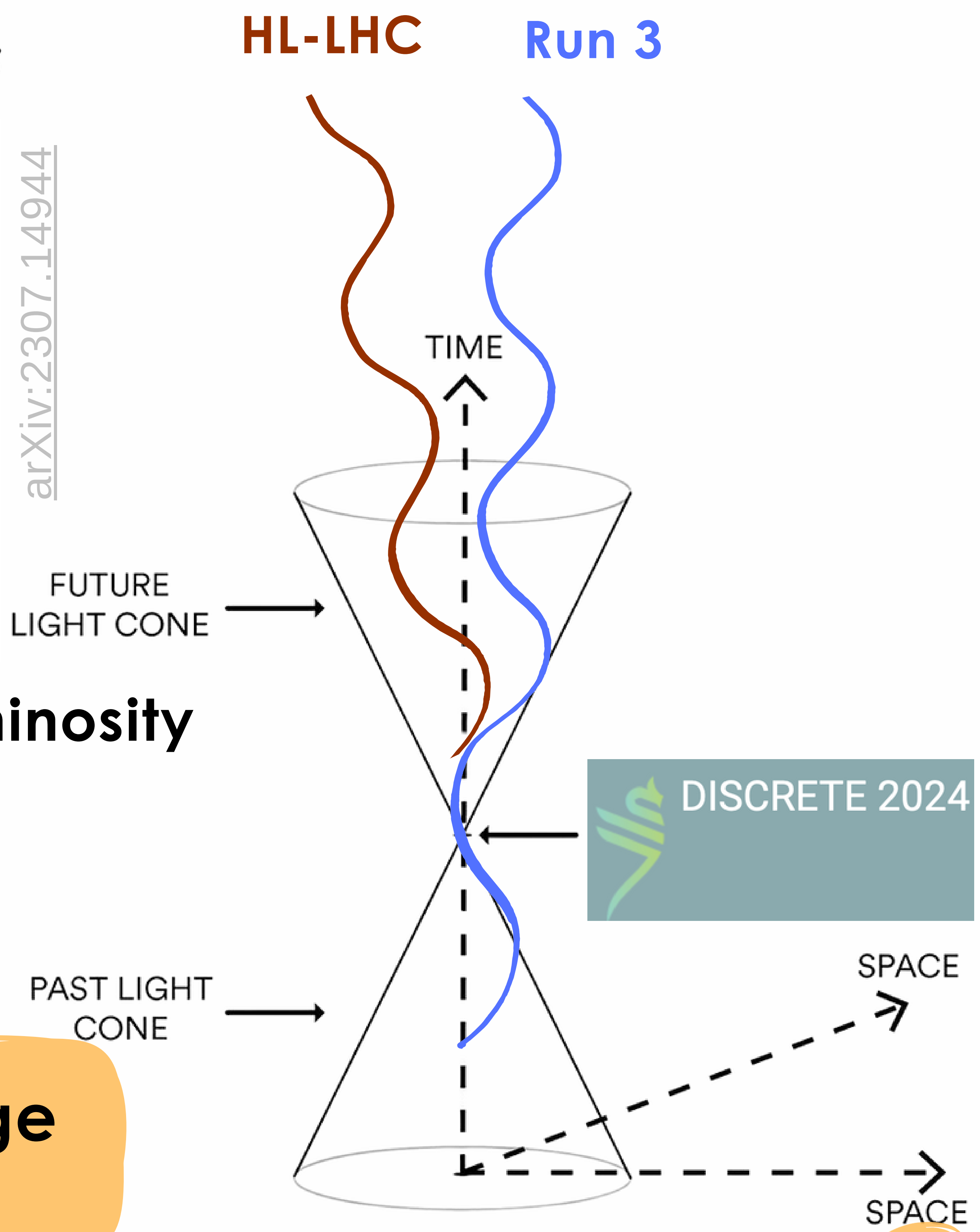


arXiv:2405.18149

High-mass $Y \to XX \to 4j$



arXiv:2307.14944



HL-LHC will significantly increase physics reach: gains from **high luminosity and new detector capabilities**

e.g. Long Lived Particles searches and Particle ID with timing detectors

Next years will provide massive amount of new knowledge and we are expecting to exceed expectations!

BSM searches in our light-cone

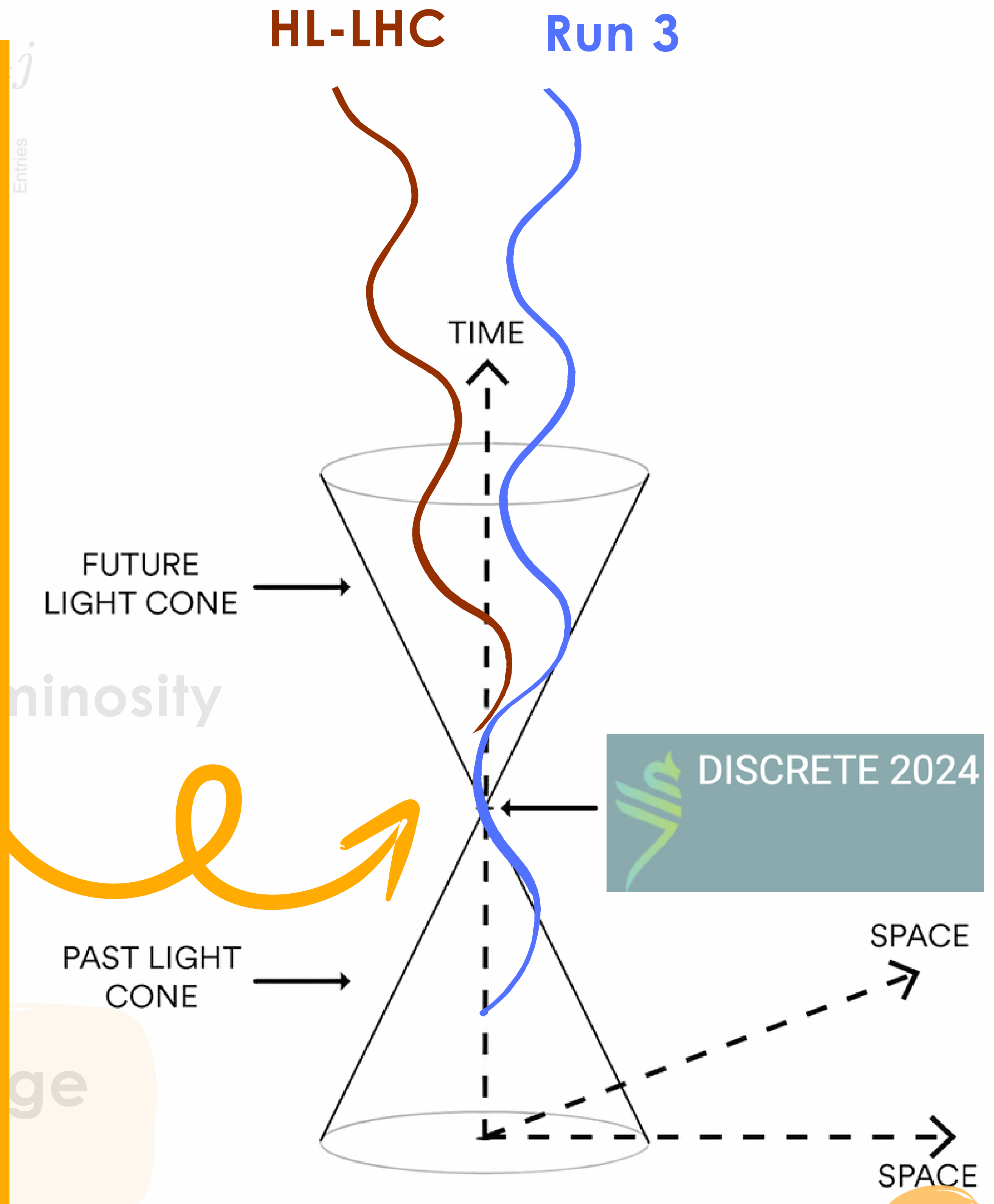
Run 3 provides a powerful platform to explore new physics through combination of **higher energy, increased luminosity, and improved experimental techniques**

2024: the newly formed **BSM LHC WG**

https://lpcc.web.cern.ch/content/lhc-bsm-wg

- will **extend the existing work of the LHC DM and LLP WGs** to other BSM scenarios, under a common structure, together with the other **LHC experiments + members of the Theory community**

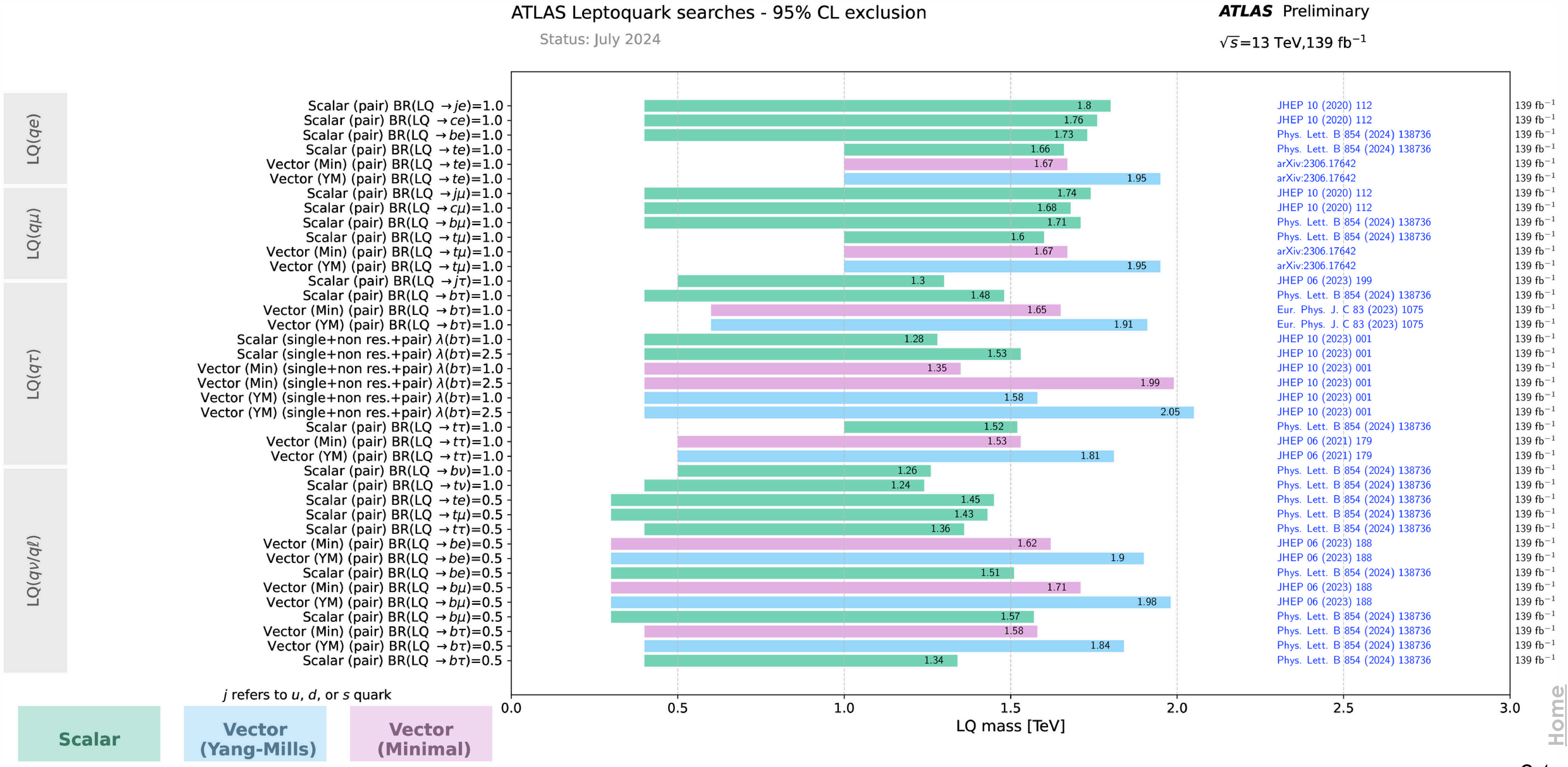
- consolidated and broad overview of **BSM LHC physics program** and of **current state of the art and plans** from LHC experiments



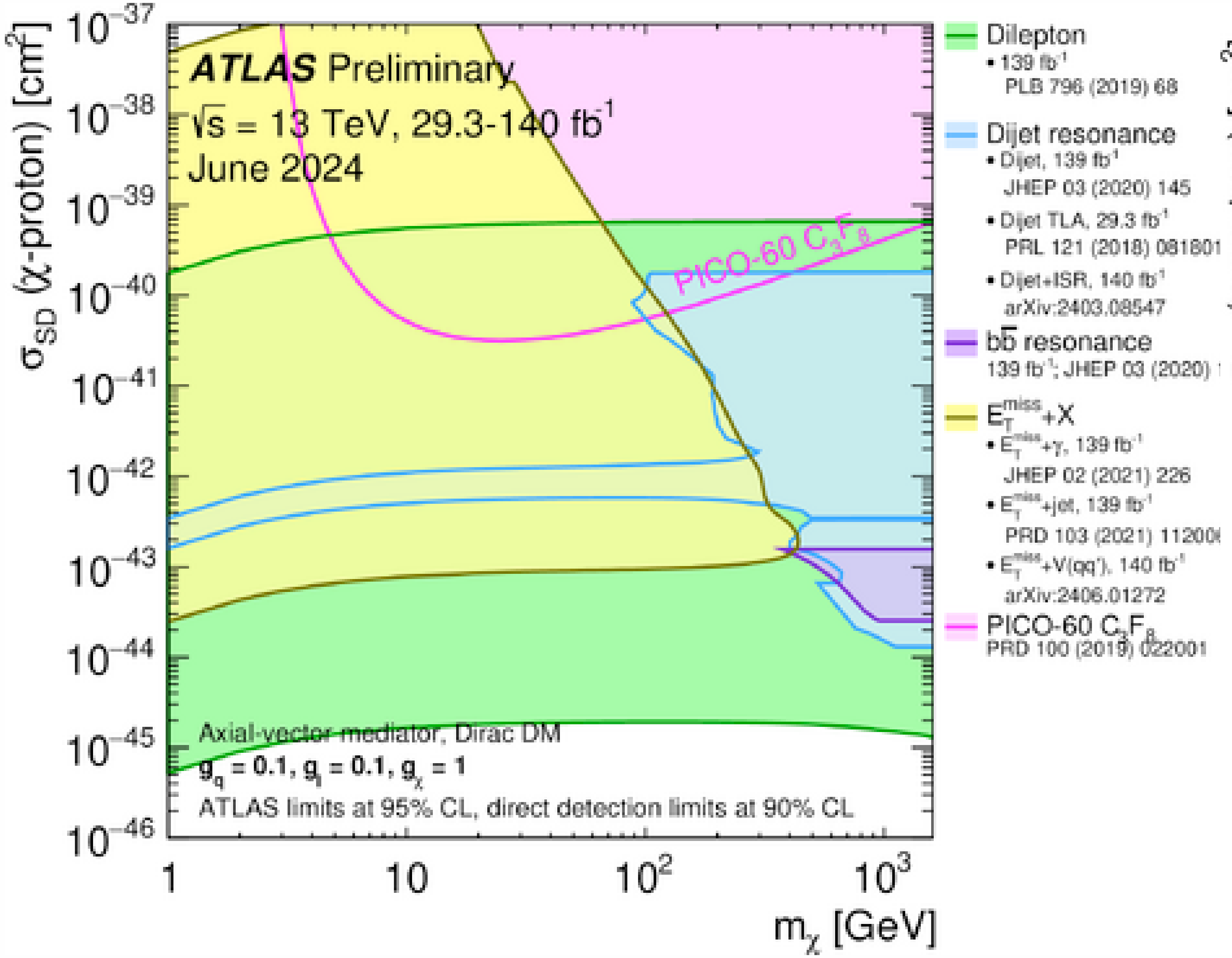
Thank you for listening!

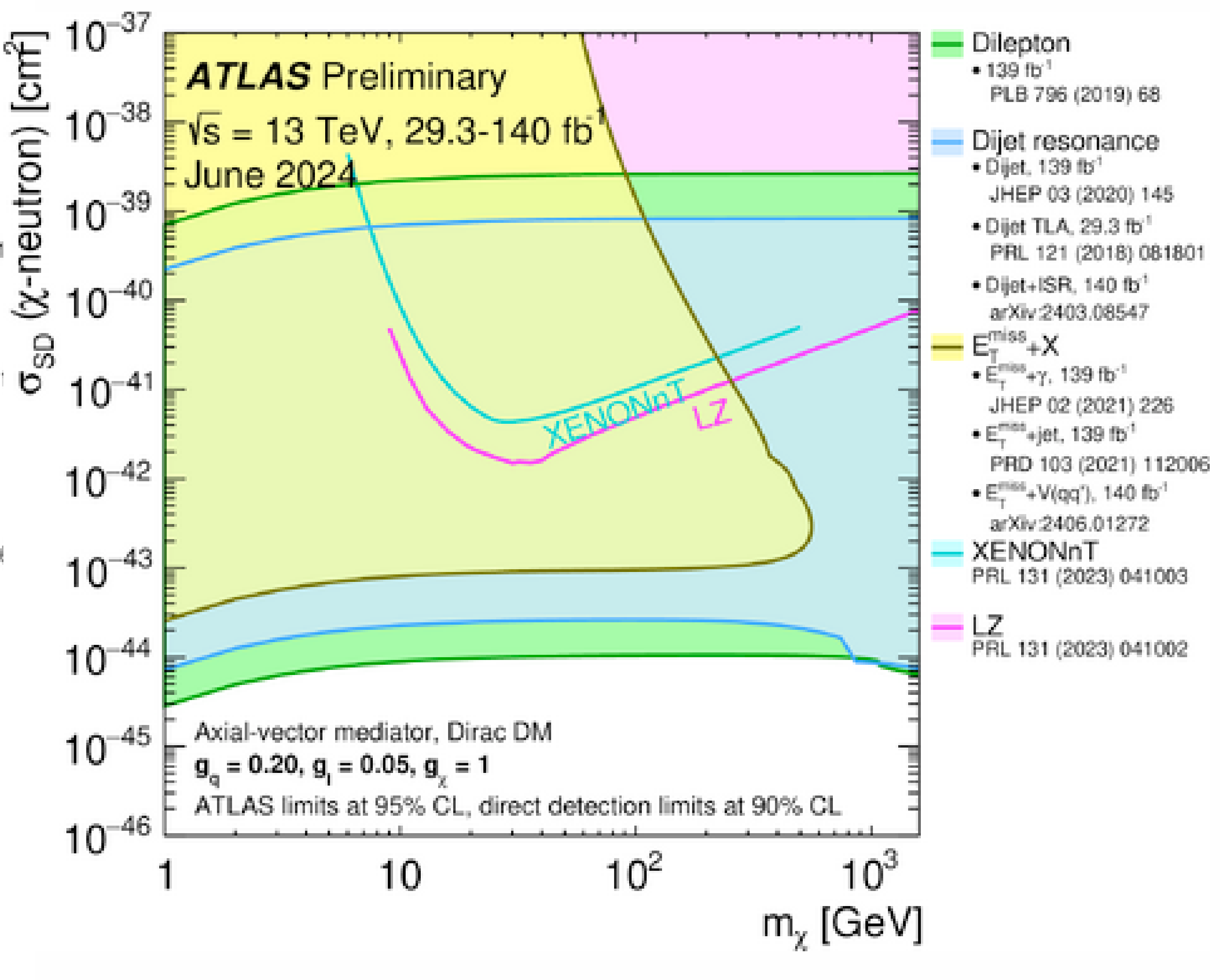
Backup

ATLAS Leptoquark summary



ATLAS Dark Matter summary





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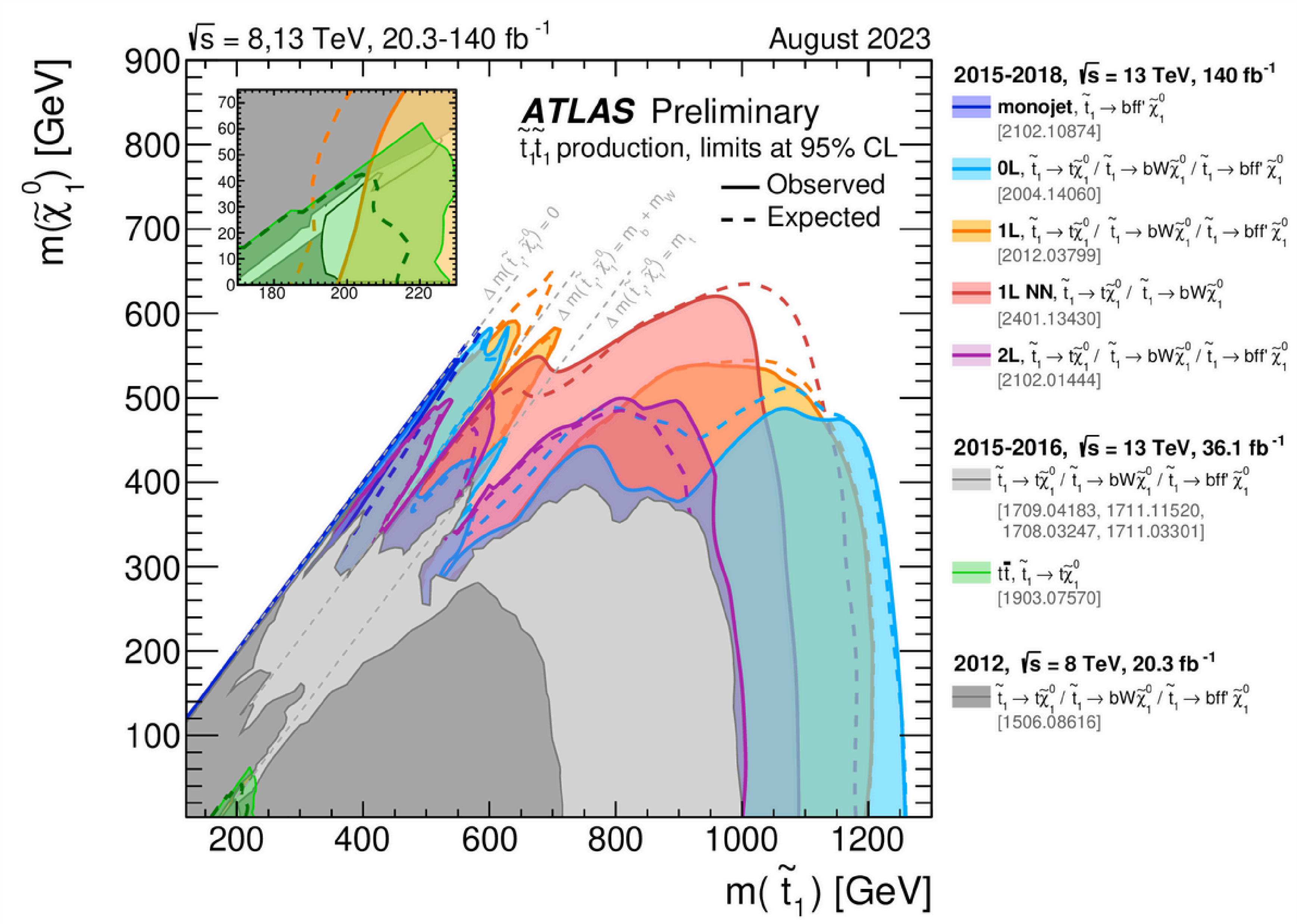
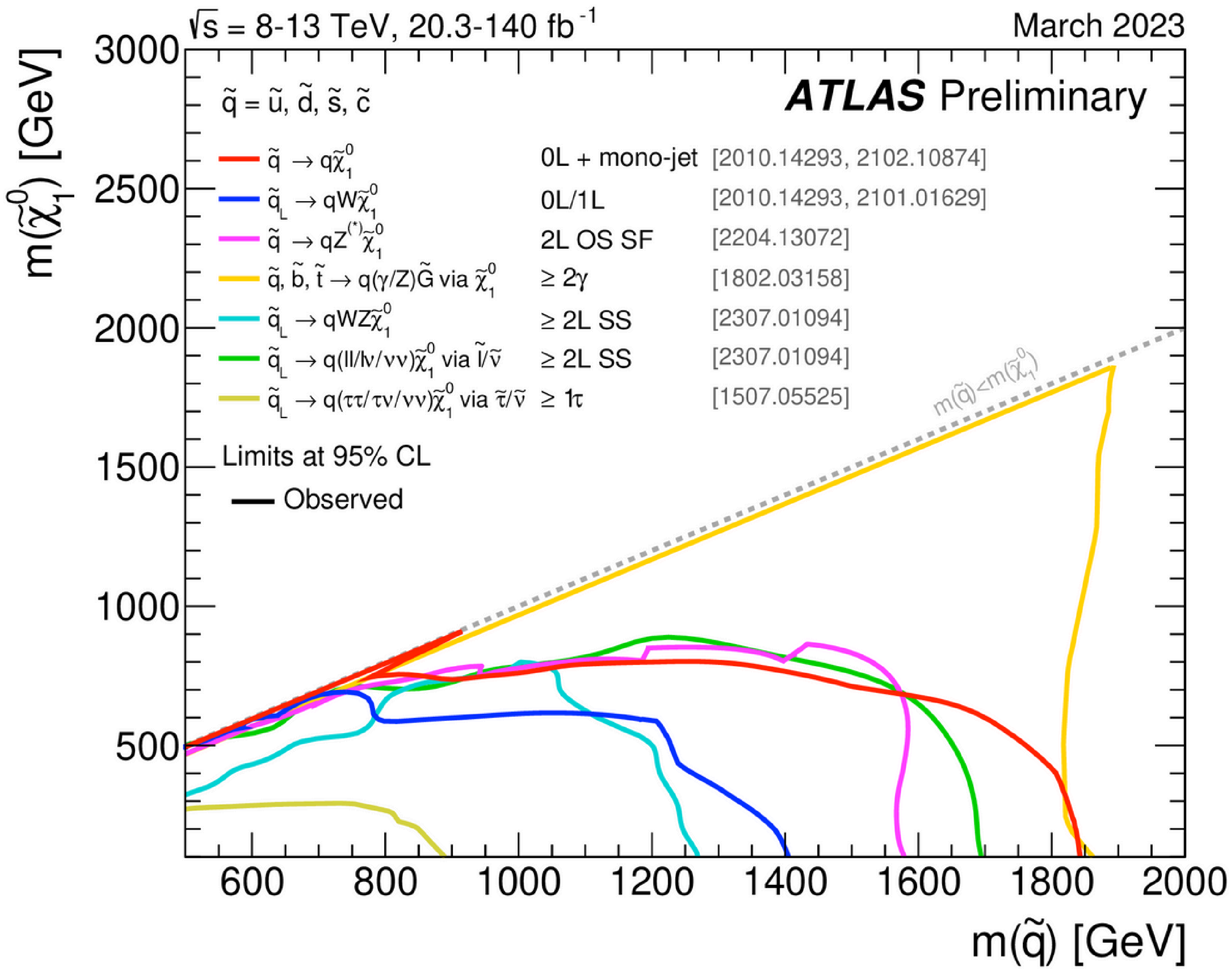
ATLAS SUSY summary





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CMS Heavy Resonances summary