SEARCHES FOR EXOTIC BSM PHYSICS WITH ATLAS AND CMS : HIGHLIGHTS AND PROSPECTS

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On behalf of the CMS and ATLAS collaborations

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

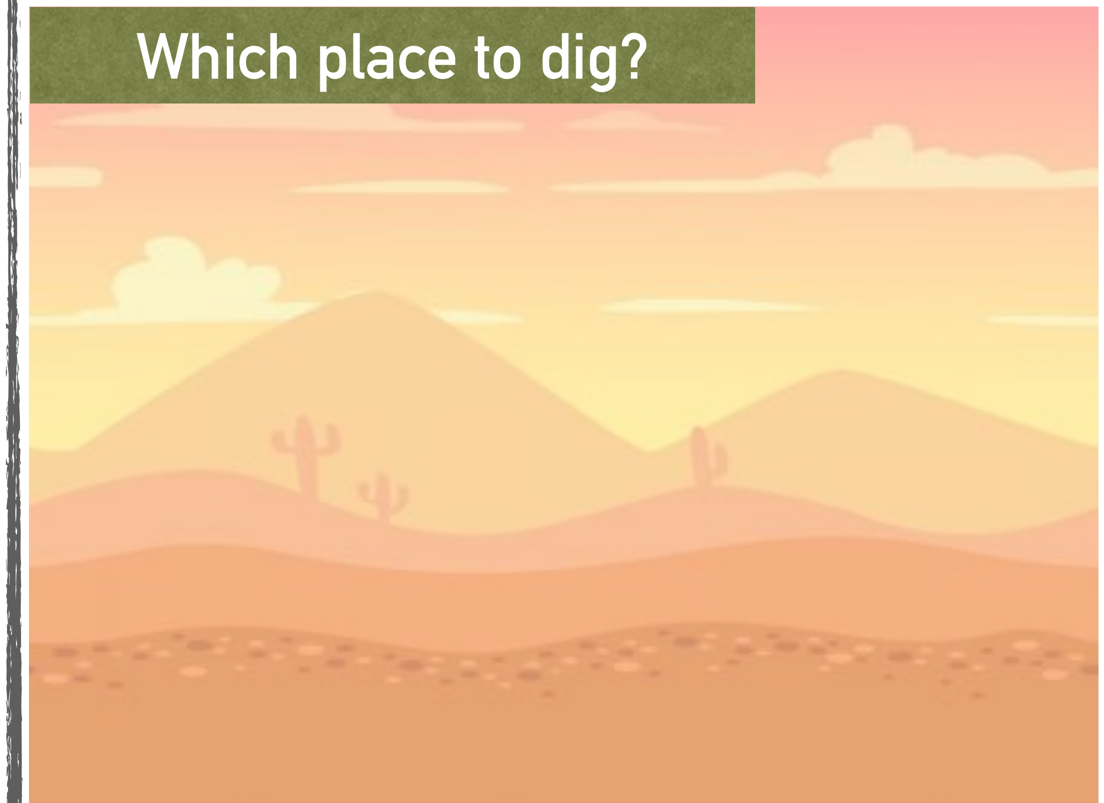
34th Rencontres de Blois, May14-19, 2023

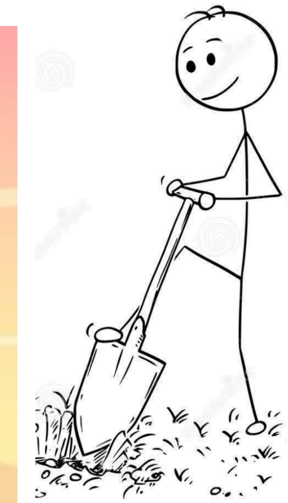
Archeologists excavating hidden gems

Let's start with our archeologist friend..

..who has no clue where to dig..

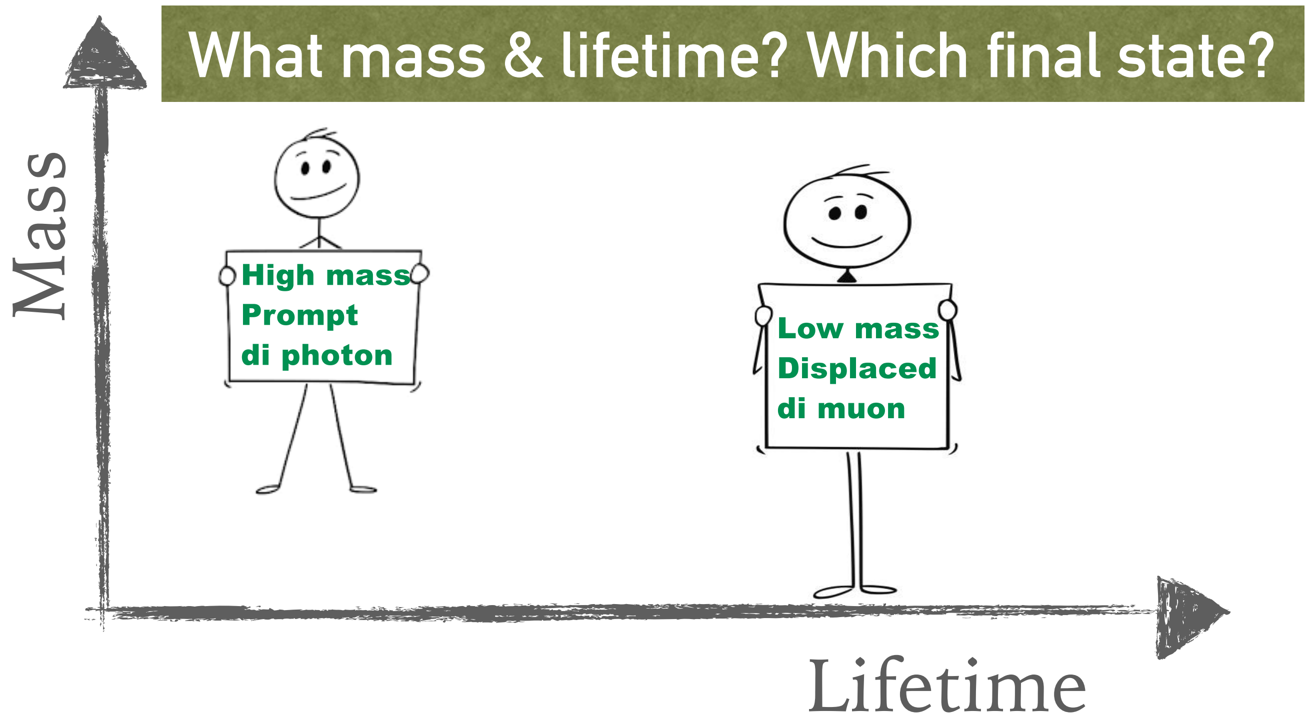
..to find the hidden gem!

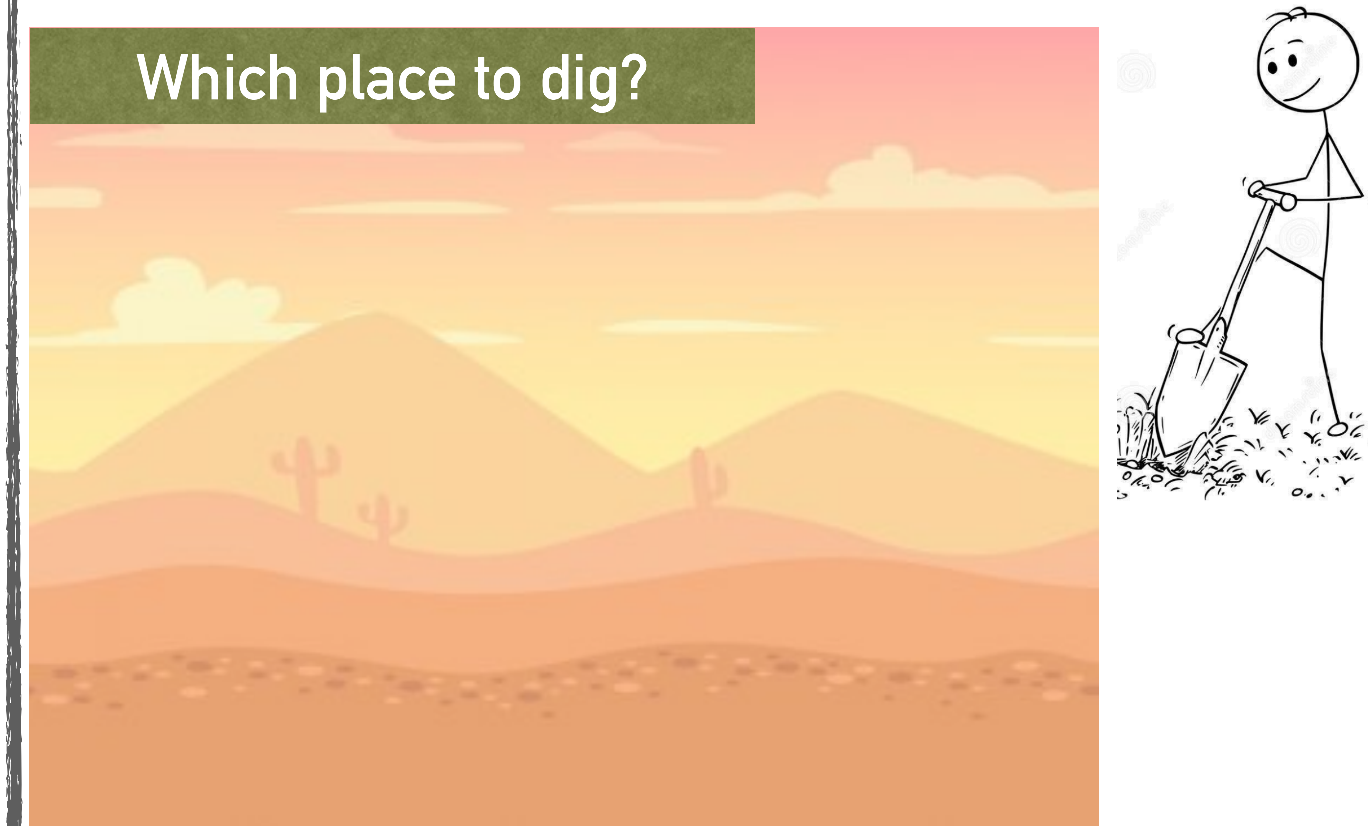




Particle physicists searching new physics

Archeologists excavating hidden gems





Our archeologist friend found the spot!

But still does not know how deep down to go!

How deep to dig?

Particle physicists searching new physics

Archeologists excavating hidden gems

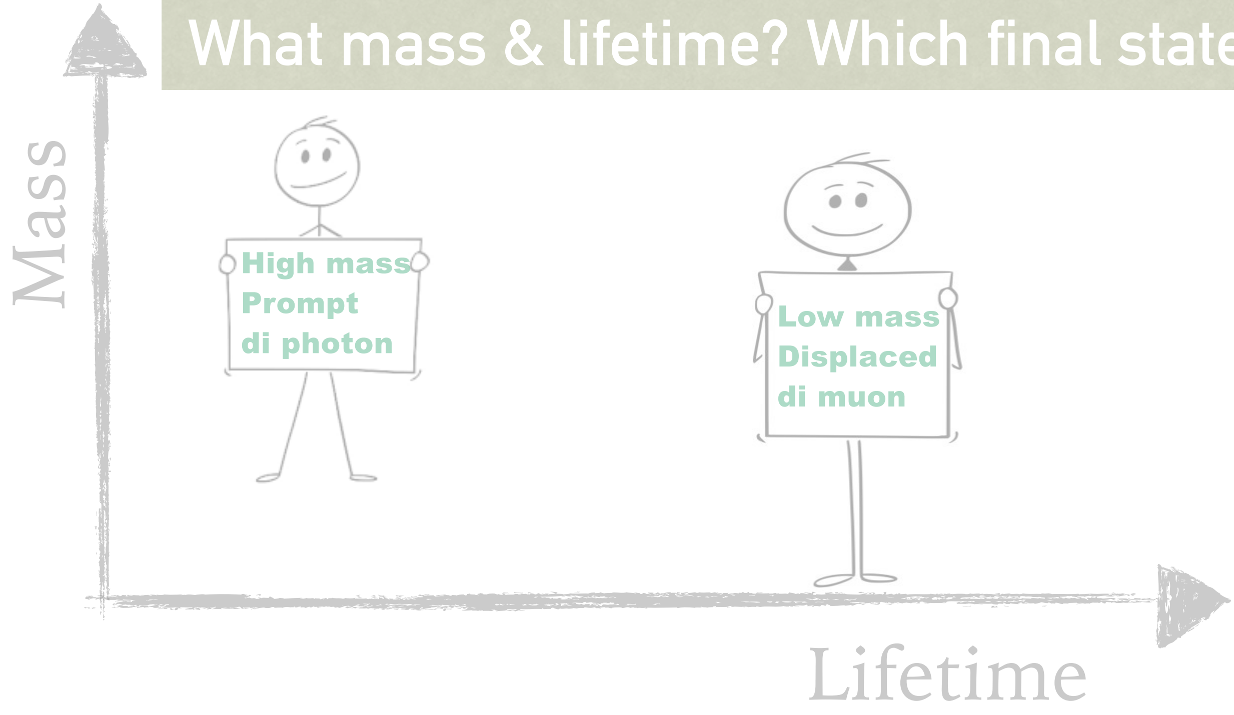
How much data we need?

i.e, how small is the cross-section of the new particle?

How deep to dig?

Particle physicists searching new physics | **Archeologists excavating hidden gems**

What mass & lifetime? Which final state?



Which place to dig?

How much data we need?

i.e, how small is the cross-section of the new particle?

How deep to dig?

Collect more data!

Search everywhere!

Dig as deep as possible!

Dig everywhere 🤔

WE ARE INDEED SEARCHING EVERYWHERE

We will hear more in

Other CMS/ATLAS plenaries

Status of searches in the long-lived particle and dark sectors	*Marianna Liberatore*
Gaston d'Orléans	11:00 - 11:30
Searches for supersymmetry and additional Higgses	*Sarah Louise Williams*
Gaston d'Orléans	11:30 - 12:00
Top quark rare or BSM interactions and the studies at new energy at CMS	*Laurids Jeppe*
Gaston d'Orléans	10:00 - 10:30

And parallels

Searches for new physics in the Higgs sector at ATLAS 15:50-	*Imma Riu*
Gaston d'Orléans	15:30 - 15:50
Searches for new physics in CMS in events with jets, leptons and photons in the final state	*Devin Mahon*
Gaston d'Orléans	15:50 - 16:10
Searches for leptoquarks with the ATLAS detector	*Volker Andreas Austrup*
Gaston d'Orléans	16:10 - 16:30
Search for new physics with long-lived and unconventional signatures in CMS	*Soham Bhattacharya*
Gaston d'Orléans	16:30 - 16:50
Searches for BSM resonances in ATLAS	*Elise Maria Le Boulicaut*
Gaston d'Orléans	16:50 - 17:20

Exotic BSM search program of ATLAS/CMS is a broad and diverse topic.

Only selected glimpses in this talk.

More details in other plenary+parallel talks during this week.

PLETHORA OF NEW EXOTIC BSM RESULTS IN 2023

ATLAS results

Leptoquark pair production (3rd generation)

Leptoquark single production (3rd generation)

Clockwork gravity search

Right-handed neutrino (resolved and boosted)

Axion-Like Particles with AFP

ttZ' to 4 tops

High-mass resonances in photon+MET

Excited taus

Vector-Like taus

Vector-Like Quarks

Multi-charged particles

Low-mass Z' search in the 4mu channel

This is not an exhaustive list

CMS results

Long-lived heavy neutral leptons

Dark matter particles decaying to WW

Search for inelastic dark matter in events with displaced muons

Search for GeV scale resonance decaying to a pair of muons

Search for W' bosons decaying to a top and a bottom quark

PLETHORA OF NEW EXOTIC BSM RESULTS IN 2023

ATLAS results

- Leptoquark pair production (3rd generation)
- Leptoquark single production (3rd generation)
- Clockwork gravity search
- Right-handed neutrino (resolved and boosted)
- Axion-Like Particles with AFP
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- High-mass resonances in photon+MET
- Excited taus
- Vector-Like taus
- Vector-Like Quarks
- Multi-charged particles
- Low mass Z’ search in the 4mu channel

I will show a subset of these results

This is not an exhaustive list

CMS results

- Long-lived heavy neutral leptons
- Dark matter particles decaying to WW
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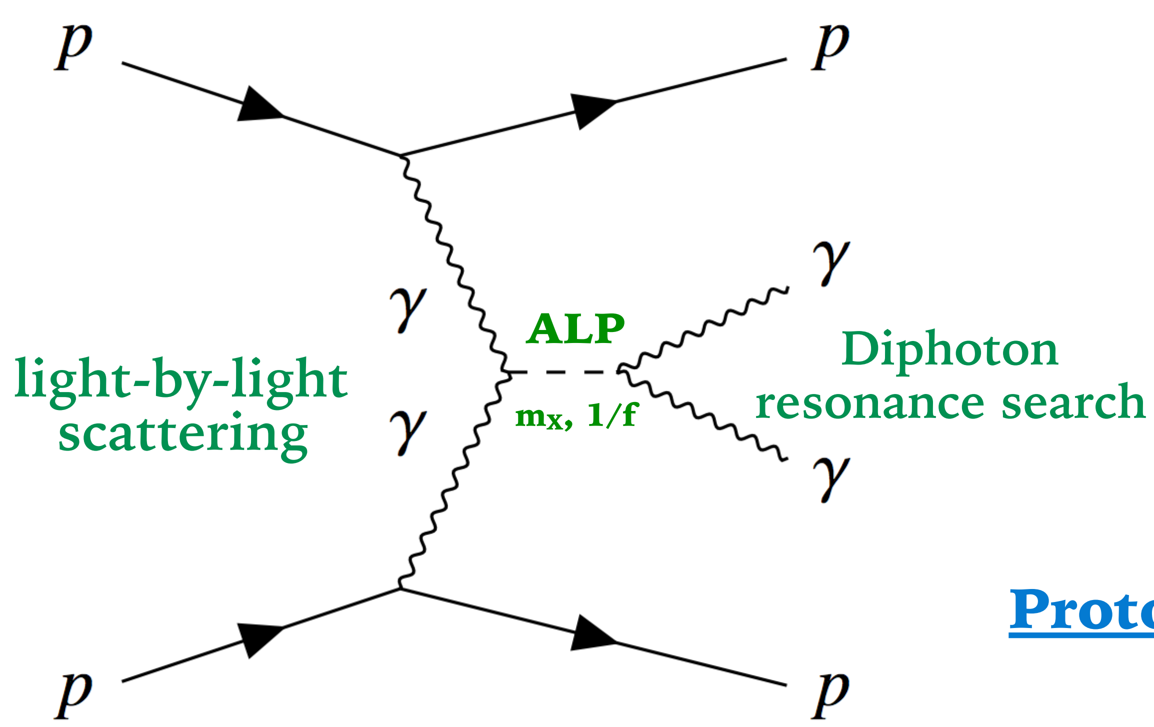
AXION LIKE PARTICLE (ALP)

https://arxiv.org/pdf/2304.10953.pdf



$$\mathcal{L} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2} m_X^2 a^2 - \frac{1}{f} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

ALP mass | ALP field | Coupling with photon

Use LHC as a γγ collider!

Proton tagging Forward scattered protons are detected in the ATLAS Forward Proton (**AFP**) spectrometer

Proton energy loss fraction measured from diphoton ($\xi_{\gamma\gamma}$)

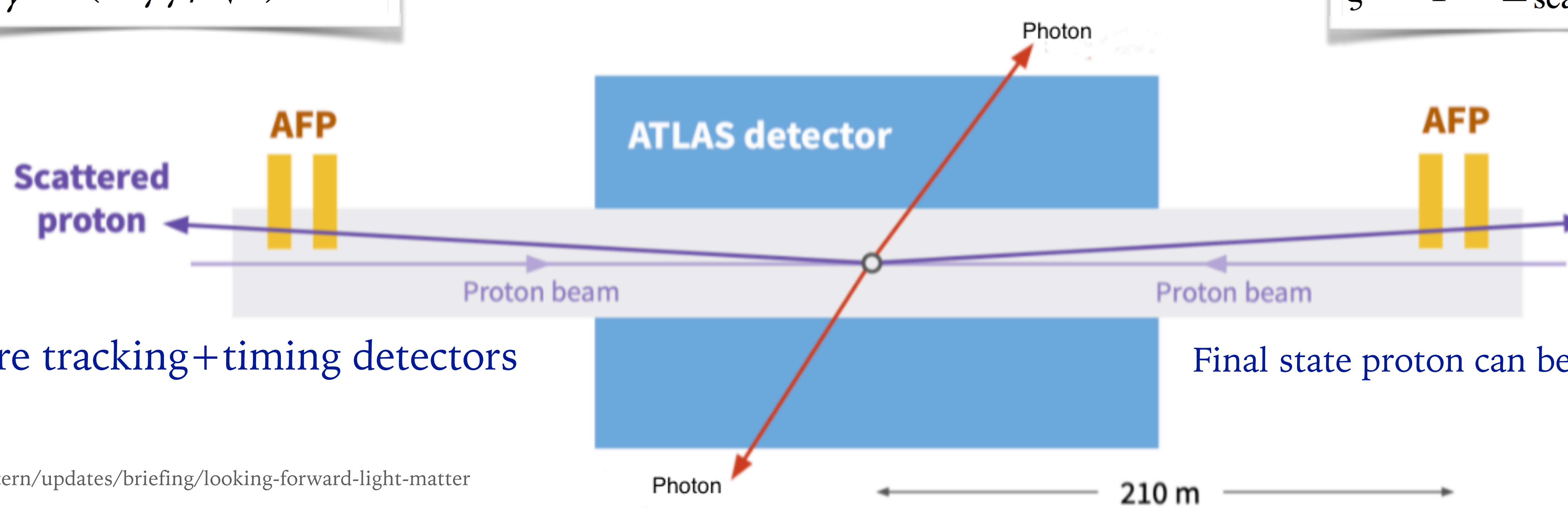
$$\xi^{\pm}_{\gamma\gamma} = (m_{\gamma\gamma}/\sqrt{s})\, e^{\pm y_{\gamma\gamma}}$$

Matching

Select events where $\xi_{\gamma\gamma}$ is close to ξ_{AFP}

Proton energy loss fraction measured in AFP(ξ_{AFP})

$$\xi = 1 - E_{scattered}/E_{beam}$$



AFPs are tracking+timing detectors

Final state proton can be intact or dissociated

https://atlas.cern/updates/briefing/looking-forward-light-matter

AXION LIKE PARTICLE (ALP)

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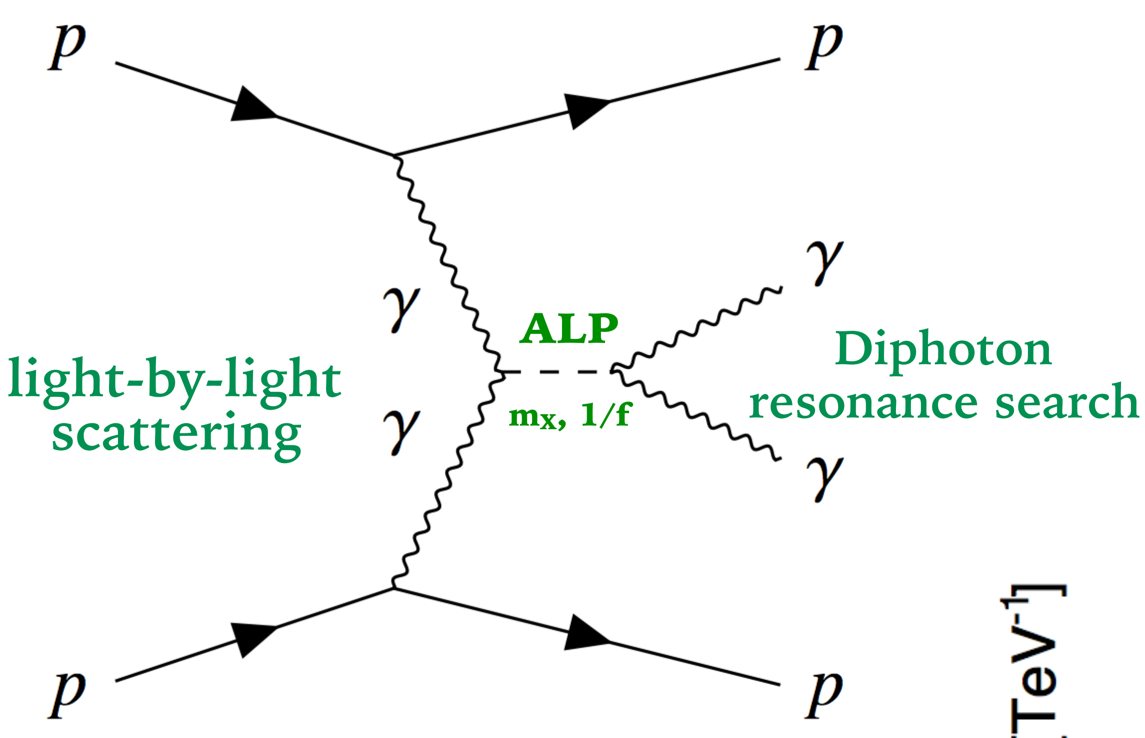


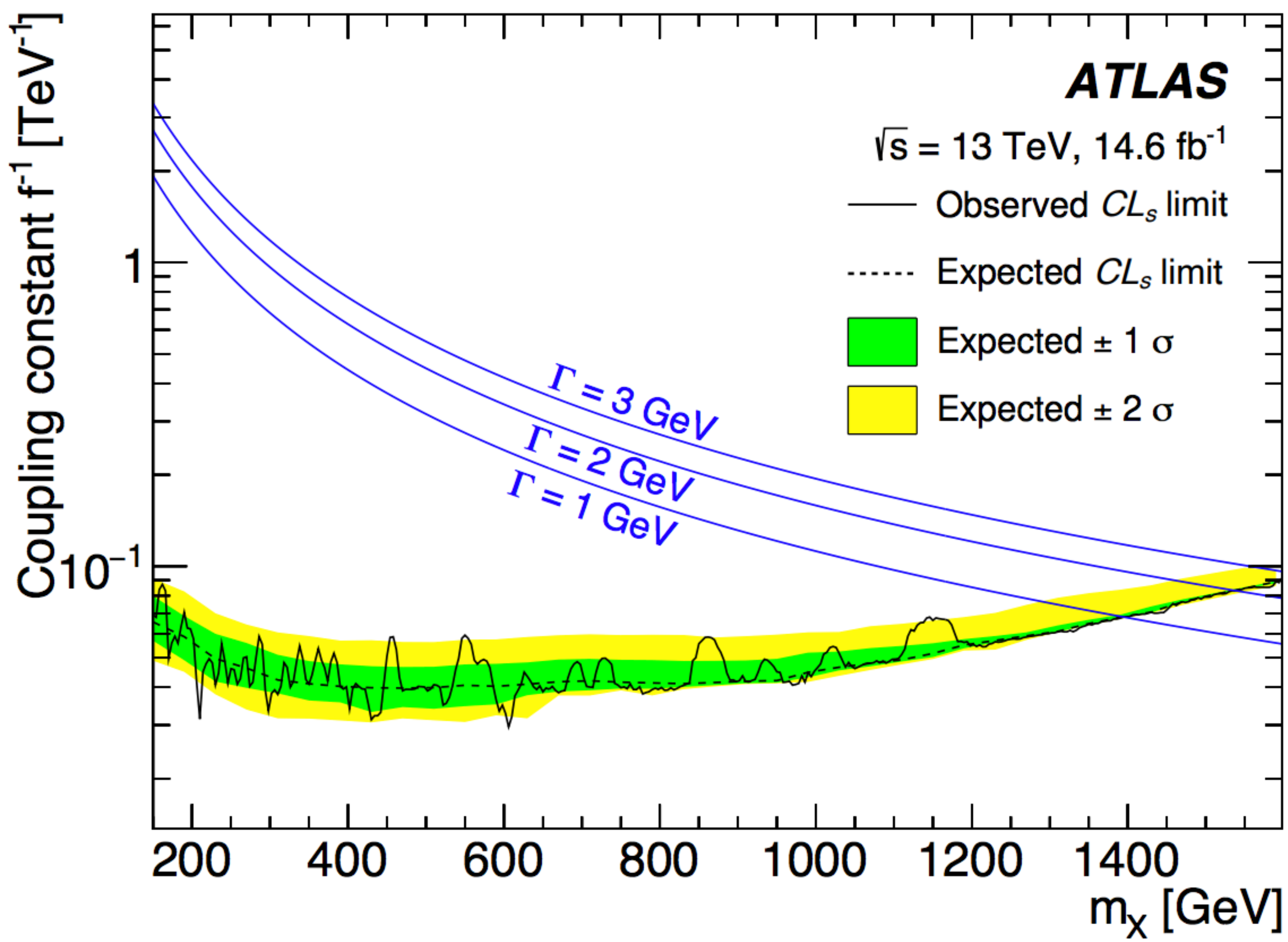
$$\mathcal{L} = \frac{1}{2}\partial^{\mu}a\partial_{\mu}a - \frac{1}{2}m_X^2 a^2 - \frac{1}{f}aF^{\mu\nu}\tilde{F}_{\mu\nu}$$

ALP mass

ALP field

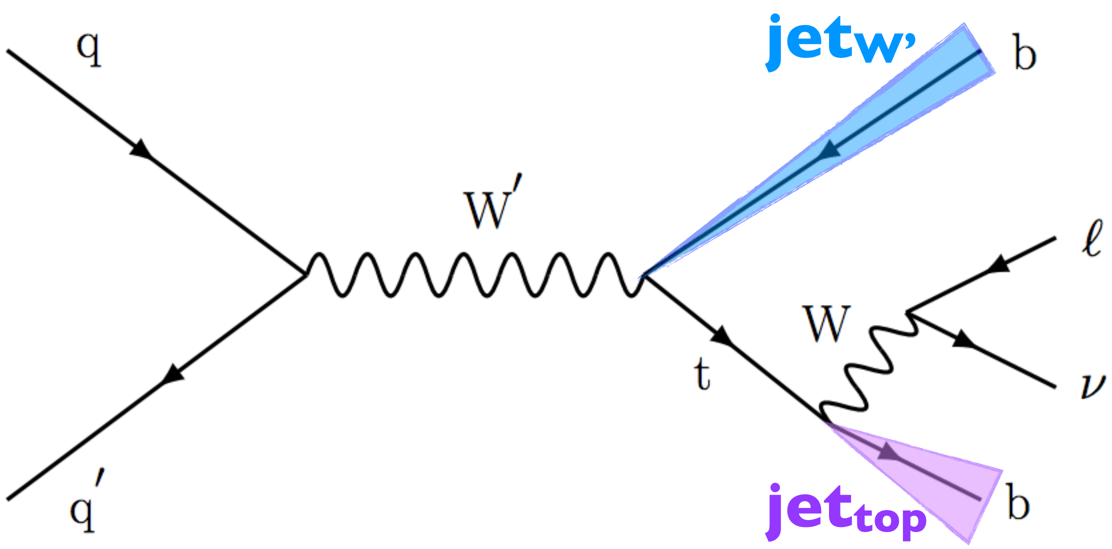
Coupling with photon

- Signal MC generated using SuperChic generator.
- Coupling f^{-1} set to 0.05 TeV^{-1}
- Narrow-width approximation.
  $$\Gamma = m_X^3/4\pi f^2$$
- Most significant excess
  - at m_X = 454 GeV
  - local significance = 2.51



WPRIME TO TOP & BOTTOM QUARK

https://cds.cern.ch/record/2853340/files/B2G-20-012-pas.pdf



- Reconstruct W and top from event kinematics
- Use those to reconstruct W' mass

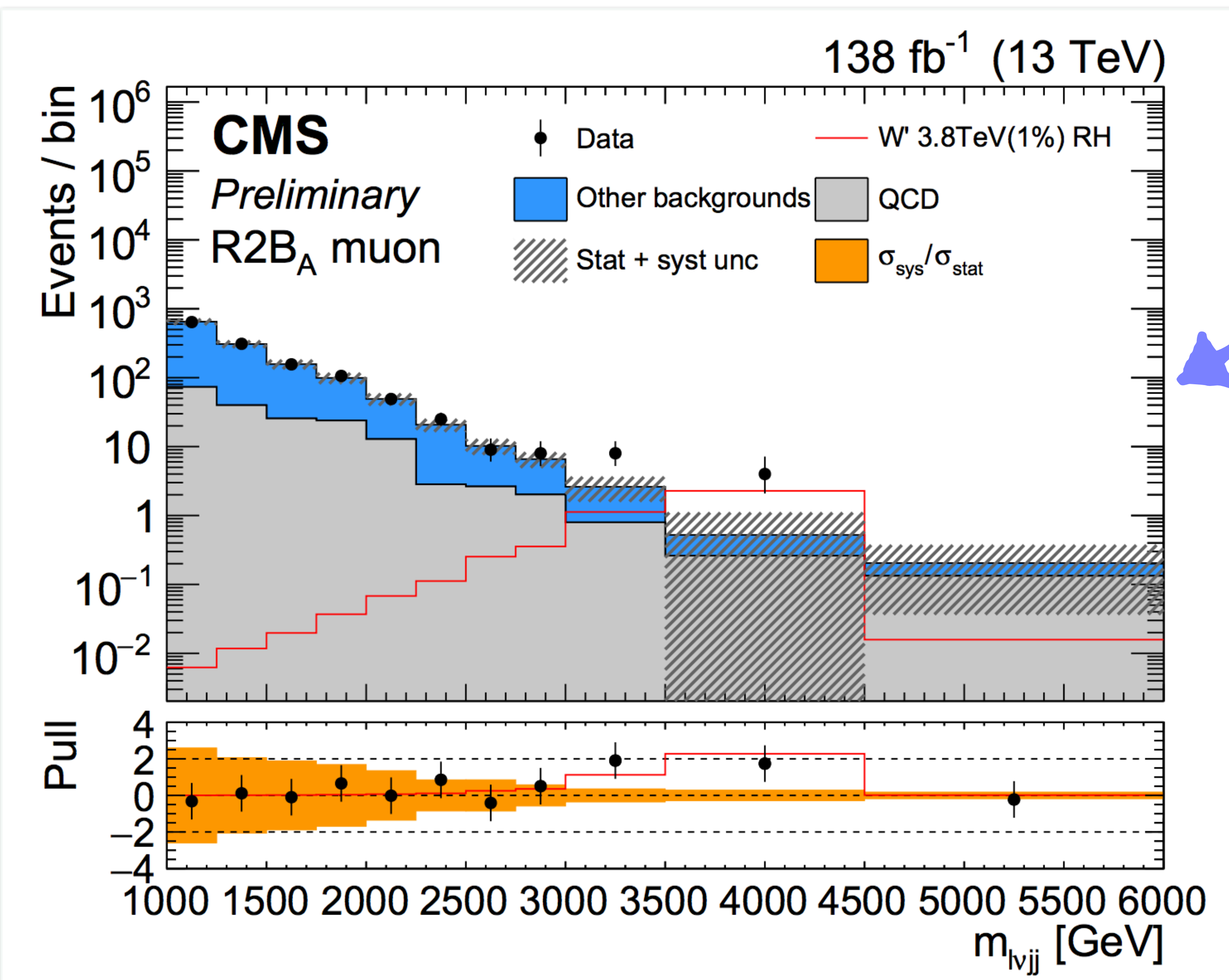
  3 signal regions

  - Only $\mathrm{jet}_{W'}$ is b-tagged
  - Only jet_{top} is b-tagged
  - Both $\mathrm{jet}_{W'}$ and jet_{top} are b-tagged

  1 control region

  - No b-tagged jet

- Backgrounds: $t\bar{t}$, single top, W+jets, QCD
- Background estimation via mass sidebands in data



WPRIME TO TOP & BOTTOM QUARK

https://cds.cern.ch/record/2853340/files/B2G-20-012-pas.pdf

$$\mathcal{L}^{\text{eff}} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_{W'} \bar{f}_i \gamma_\mu [\alpha_R^{f_i f_j}(1+\gamma^5) + \alpha_L^{f_i f_j}(1-\gamma^5)] W'^{\mu} f_j + h.c.,$$

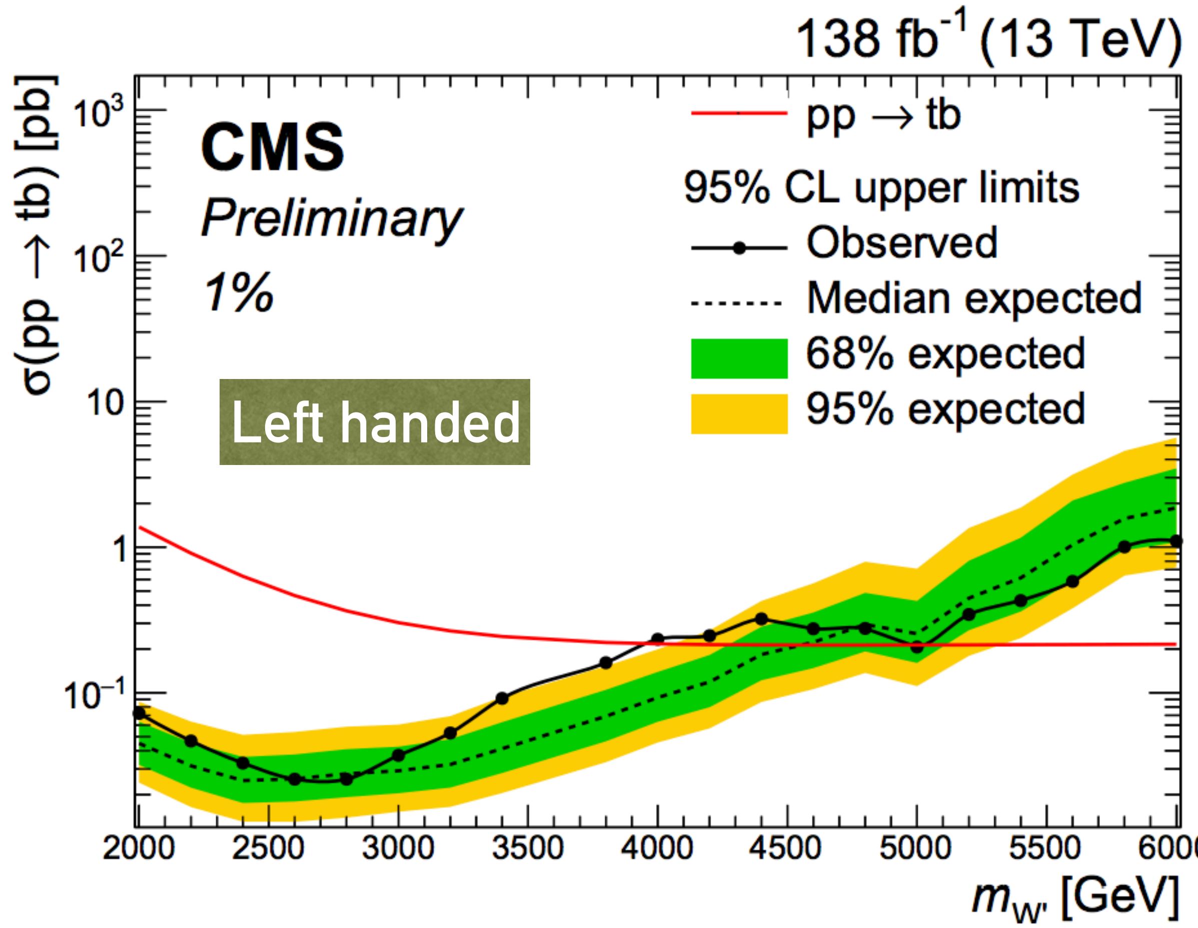
W'$q_i q_j$ interaction

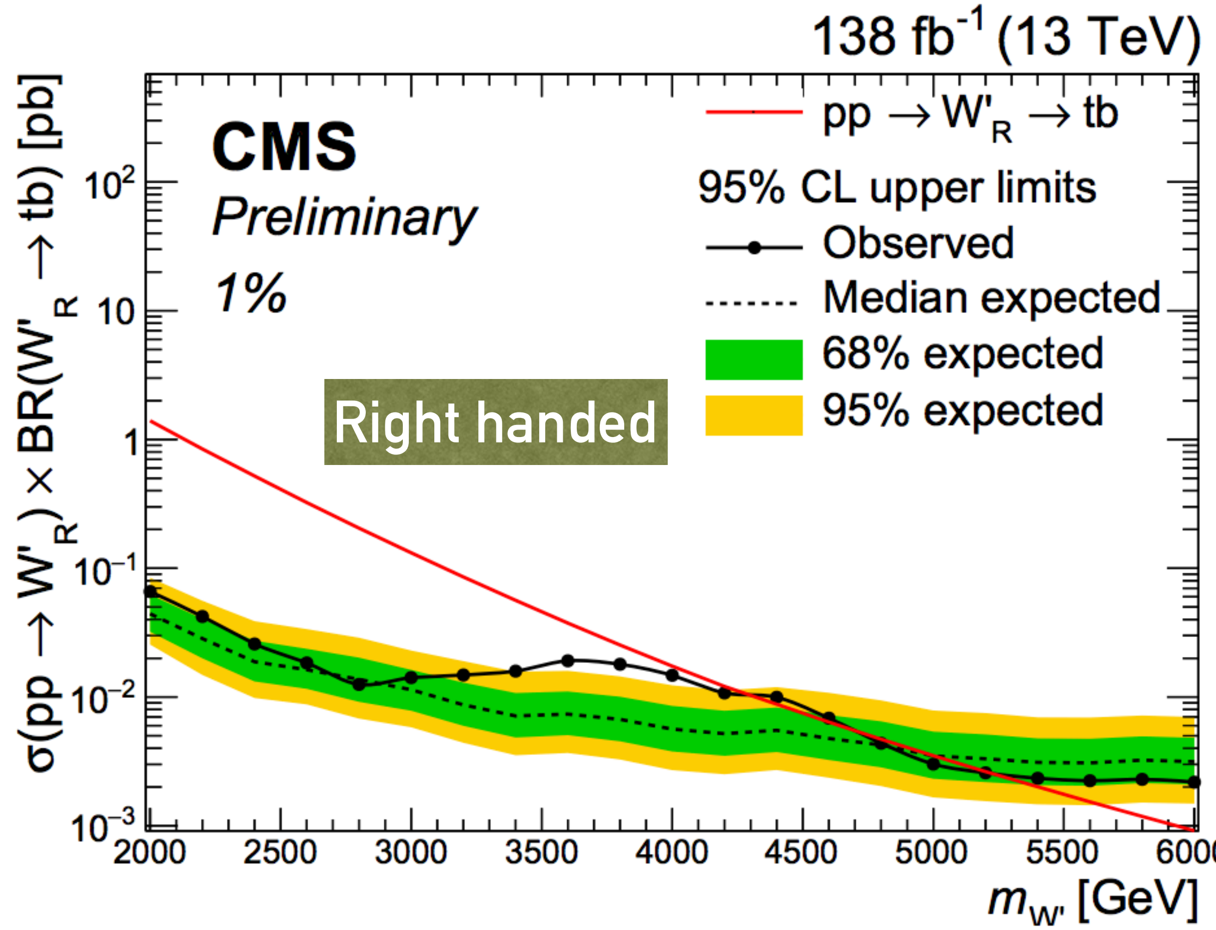
CKM for quarks

Regulate chirality fractions of W' (left-handed or right-handed)

Interference with SM W-boson taken into account when α_L is non-zero

- Different width (1, 10, 20, 30%) and chirality assumptions.
- Small excess at 3.4-4.4 TeV in muon channel. Local: 2.6σ. Global: 2.0σ.





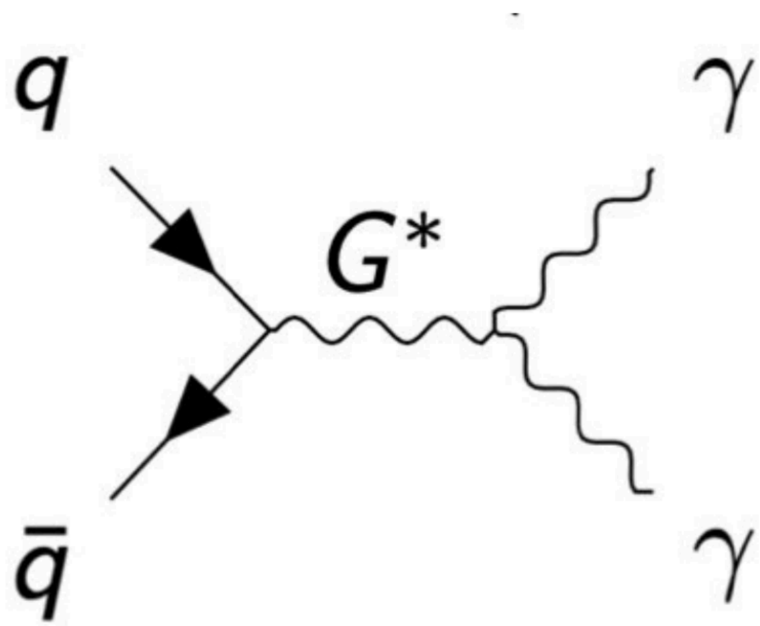
ATLAS-CONF-2023-010

PERIODIC SIGNALS

Clockwork/Linear Dilaton (CW/LD) model

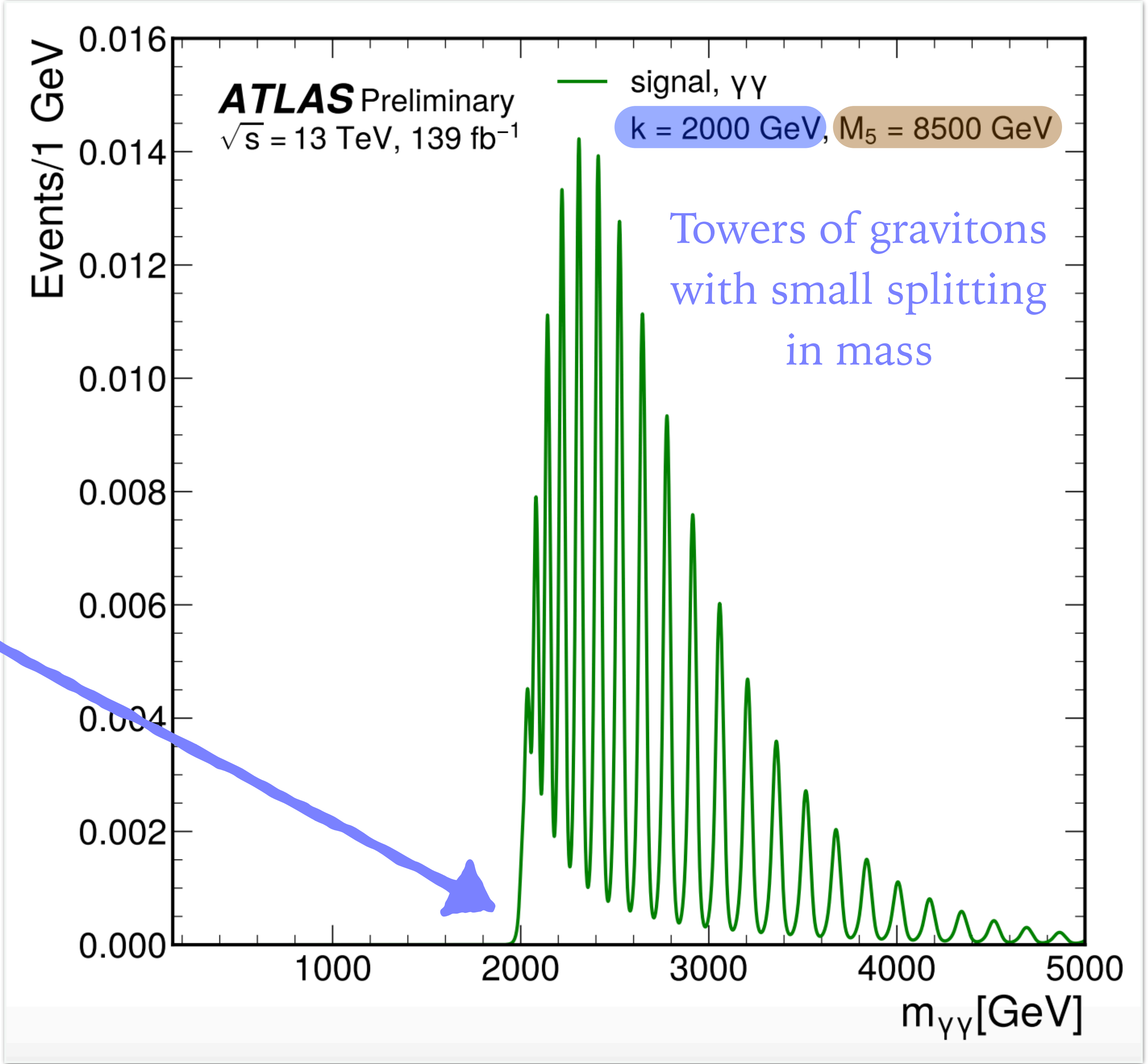
Associated with quantum gravity

Predicts narrowly-spaced spectrum of resonances in mass



Two important parameters

- k: mass parameter that determines the onset of the KK graviton spectrum
- M_5: 5D reduced Planck mass



Challenging signature due to low signal cross-sections

scales inversely with $(M_5)^3$

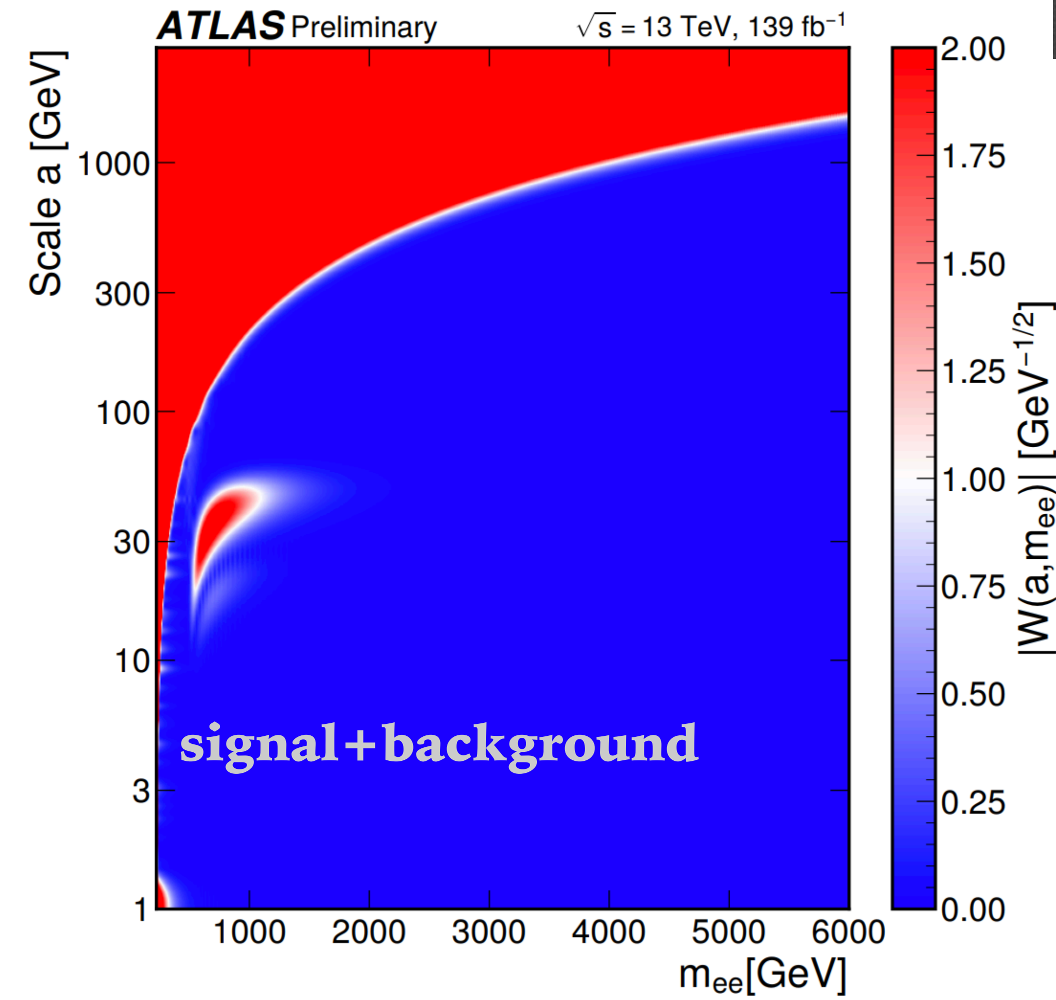
PERIODIC SIGNALS

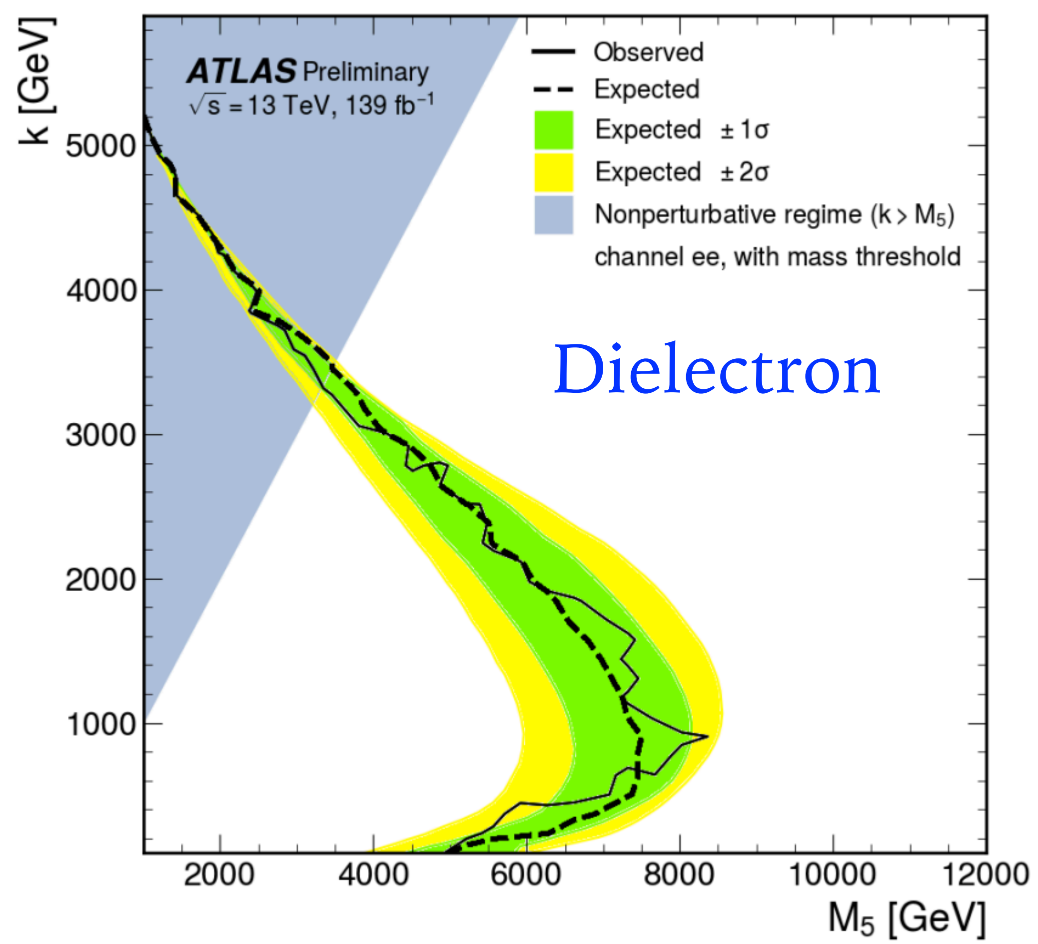
Search uses continuous wavelet transform (**CWT**) to analyse mass spectra in frequency domain.

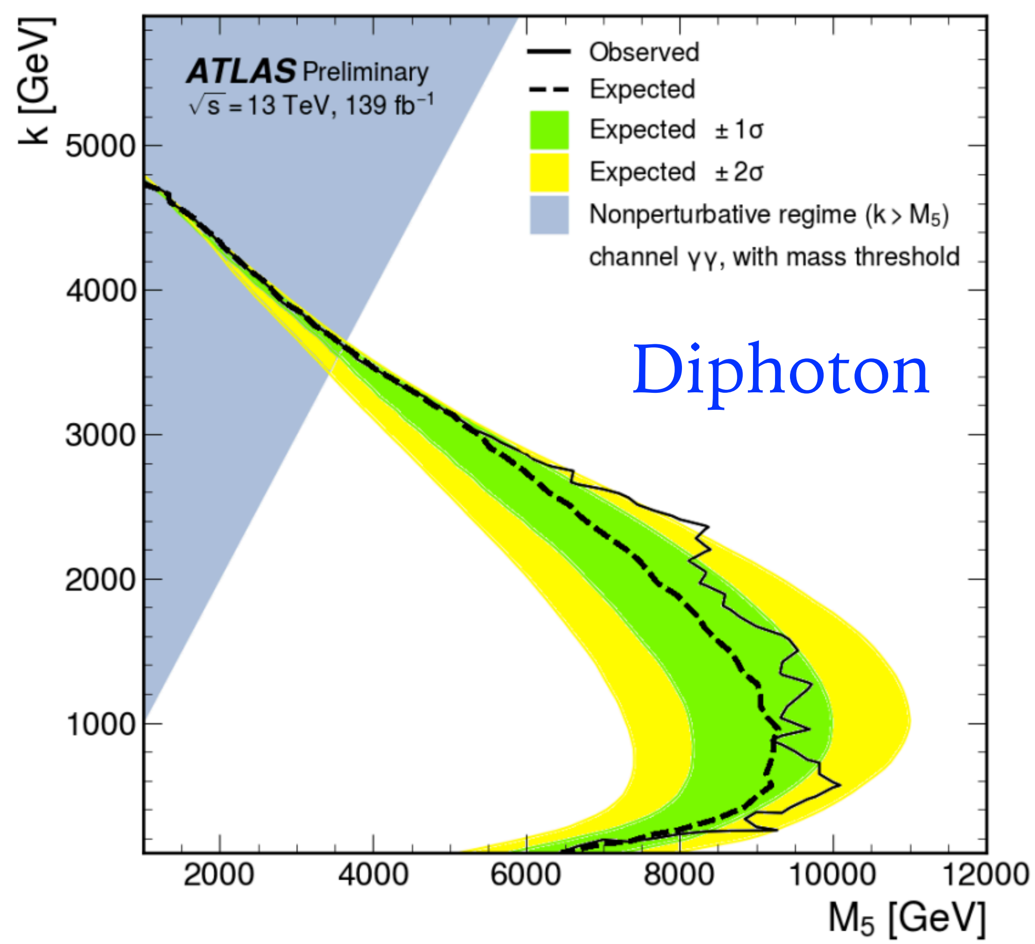
Output of the CWT is 2D image. Periodicity of signal can be revealed as a local "**blob**"

ATLAS-CONF-2023-010

Excludes values of M_5 in the range 11 TeV to 1 TeV for values of k in the range 100 GeV to 5 TeV.



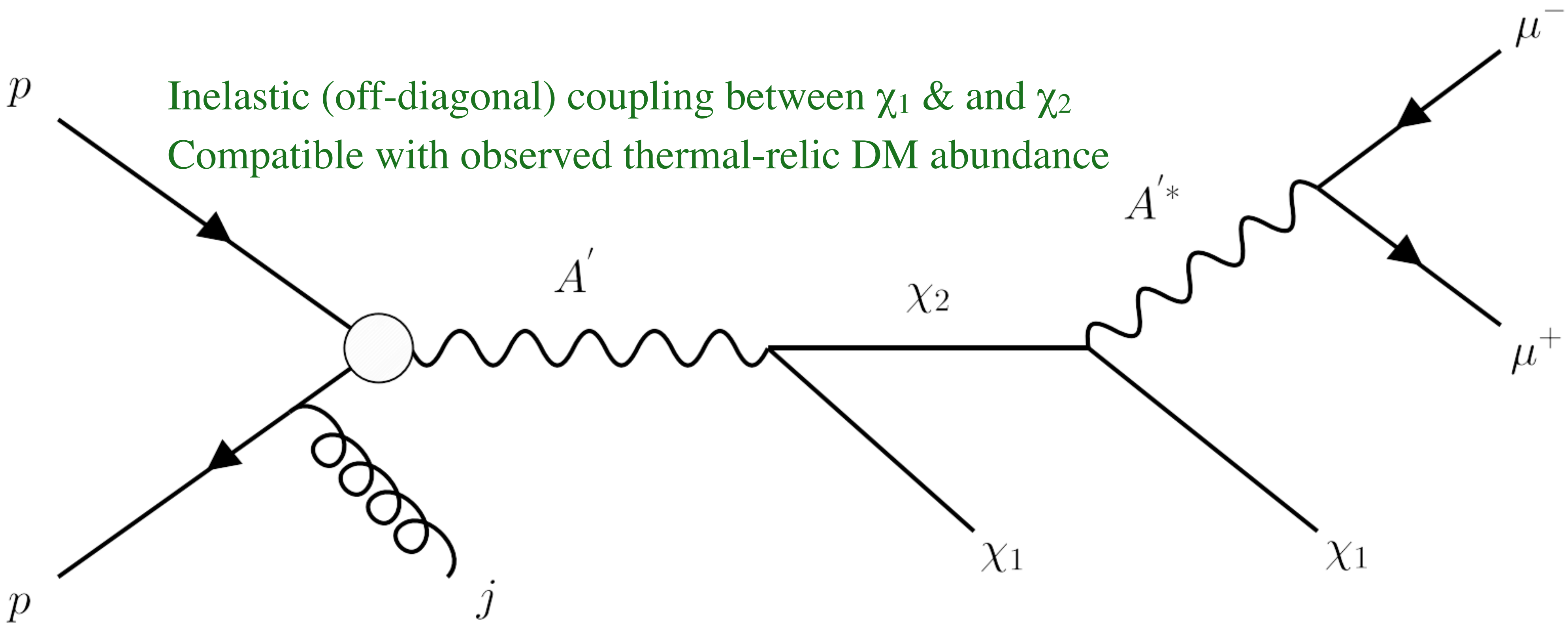




INELASTIC DARK MATTER

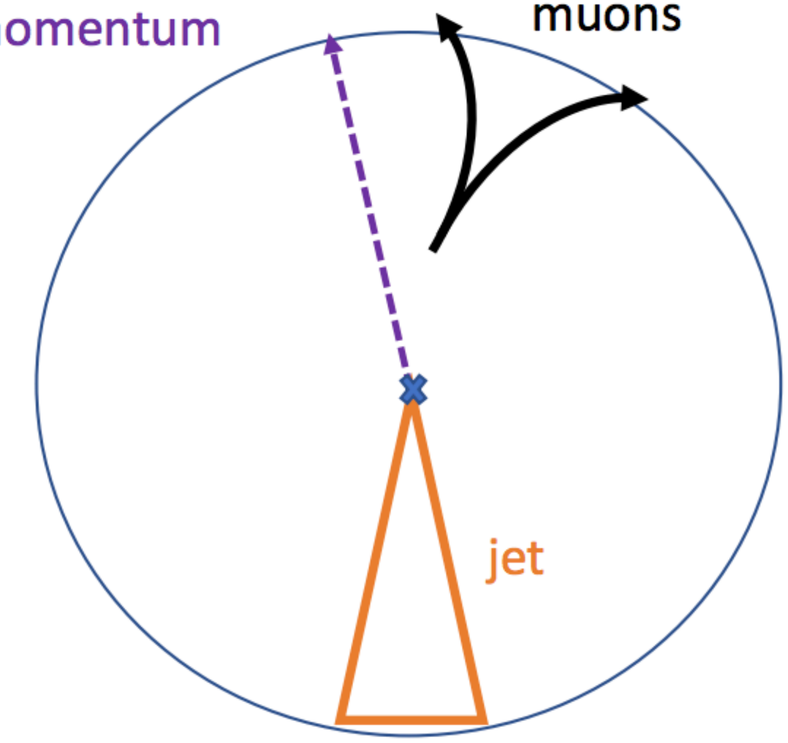
CMS-EXO-20-010

Inelastic (off-diagonal) coupling between χ_1 & and χ_2
Compatible with observed thermal-relic DM abundance



- Inelastic dark matter model (iDM)
  - Predicts at least two inelastically coupled dark matter states accompanied by a dark photon
- iDM production cross sections can be large
  - up to a few femtobarns for high-mass and displaced signals.
- Dark photon decaying to **nearly mass-degenerate** dark matter states
- Mass splitting $m(\chi_2-\chi_1)$ small
- Heavier state χ_2 can be long-lived
- Soft & displaced muons in final state

$$c\tau \propto \frac{(m_{A'})^4}{(\Delta m_{DM})^5}$$



INELASTIC DARK MATTER

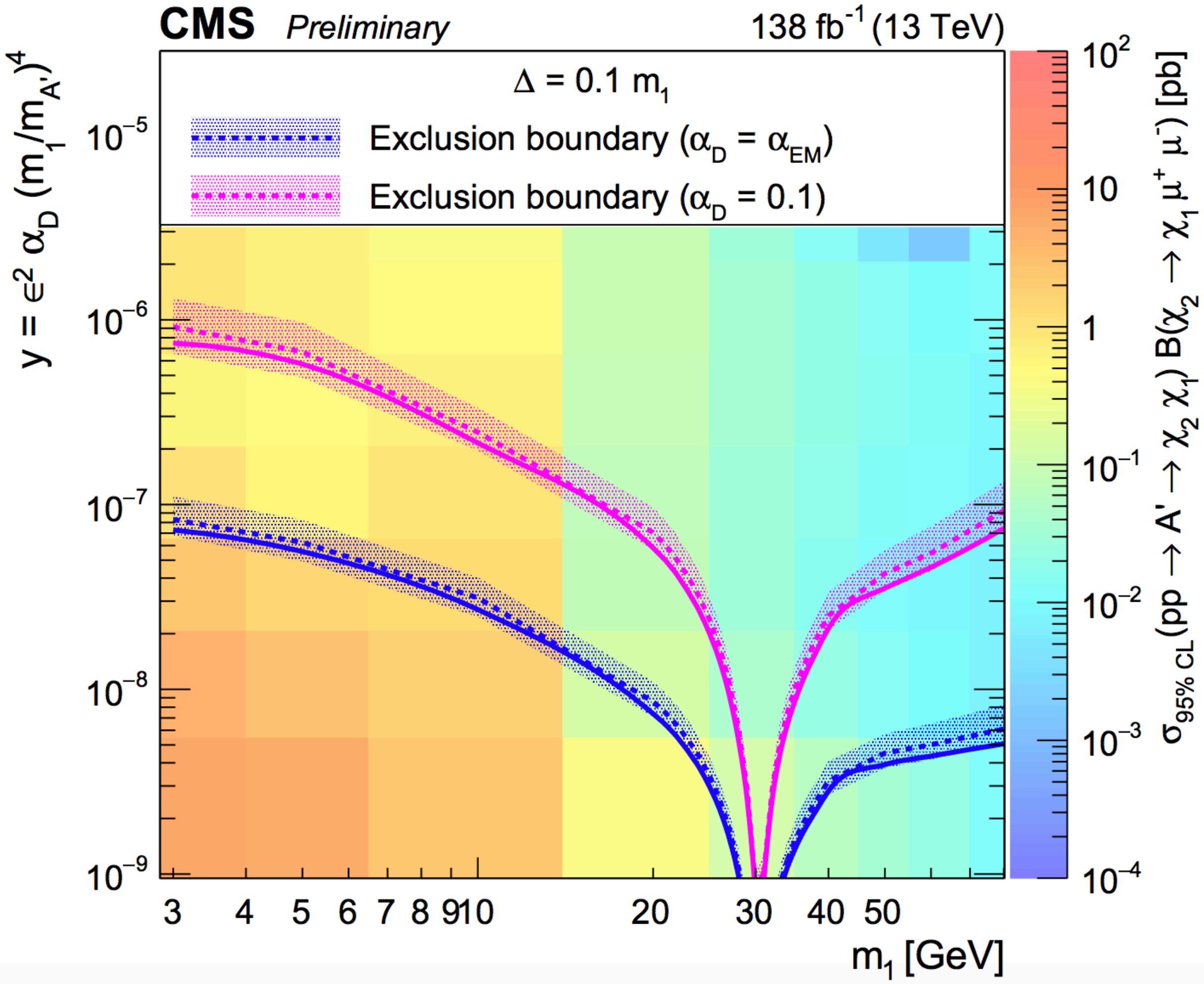
CMS-EXO-20-010

Interaction strength

$$y \equiv \epsilon^2 \alpha_D (m_1/m_{A'})^4$$

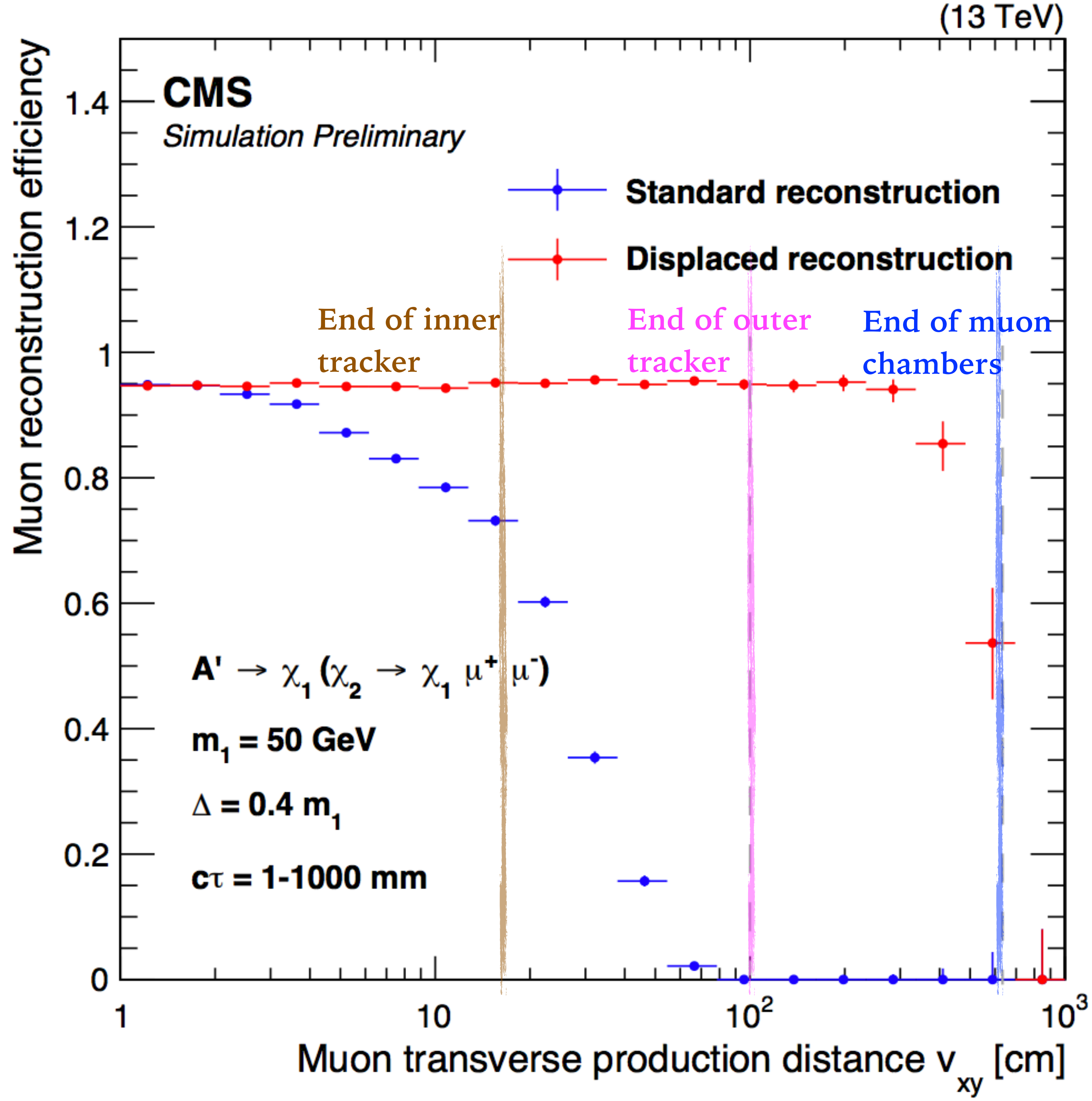
Kinetic mixing between dark photon and SM photon

coupling strength of $U(1)_D$ in dark sector

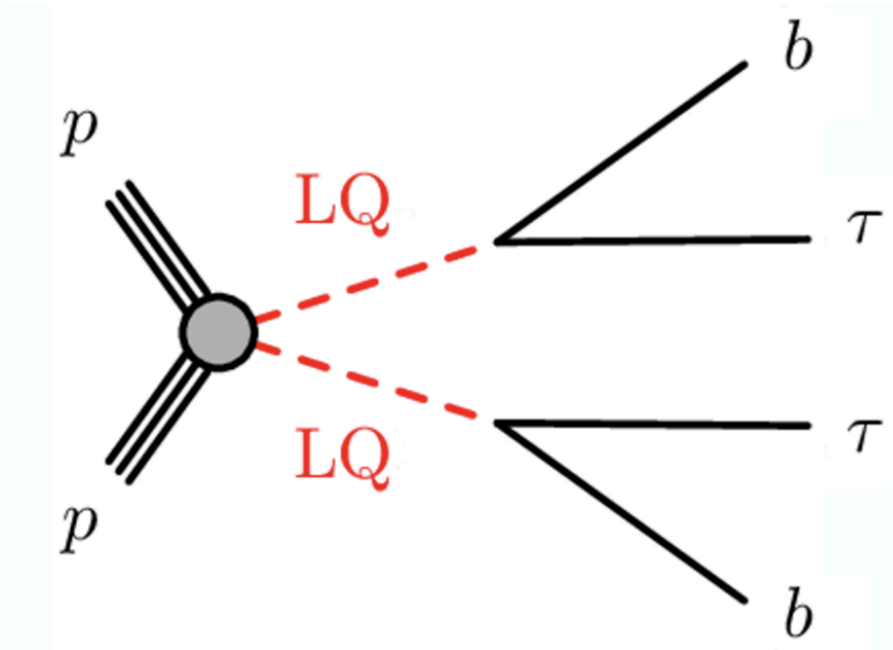


Dedicated displaced muon reconstruction

Target 1 mm to 1 meter displacement range



PAIR PRODUCTION OF 3RD GENERATION LEPTOQUARK



Leptoquark (carrying both lepton and baryon number)

Many degrees of freedom! Rich phenomenology.

- Mass, electrical charge, scalar/vector type, Yukawa couplings
- Can be produced in pairs, singly, off-shell, s/t-channel
- β parameter: Determines branching fraction of LQ into charge lepton or neutrino

https://arxiv.org/pdf/2303.01294.pdf

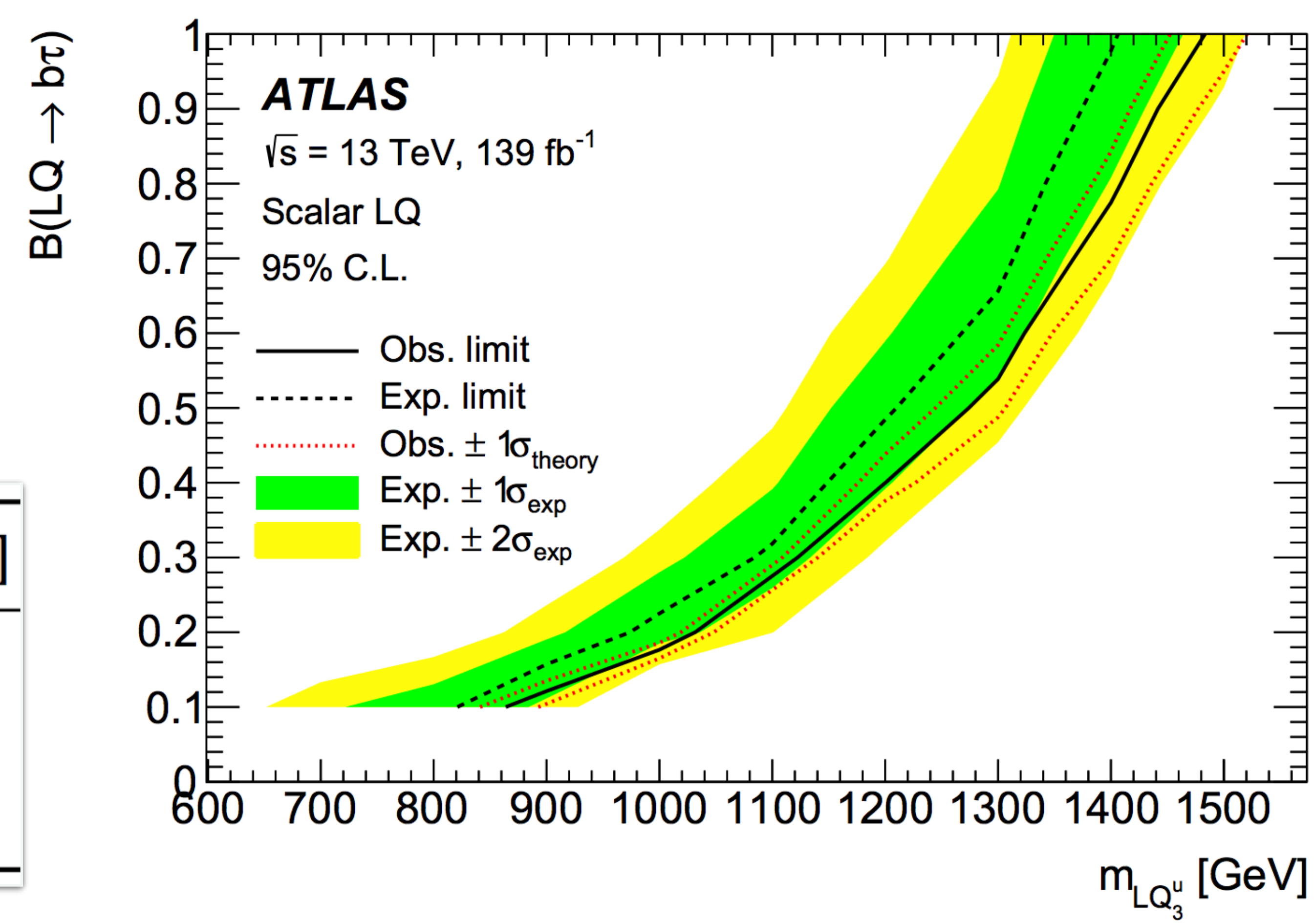
Analysis performed in $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels

Parameterised neural network (**PNN**) used for signal extraction.

Parameterised in terms of generated LQ mass.

PNN consists of three hidden layers, each with 32 nodes.

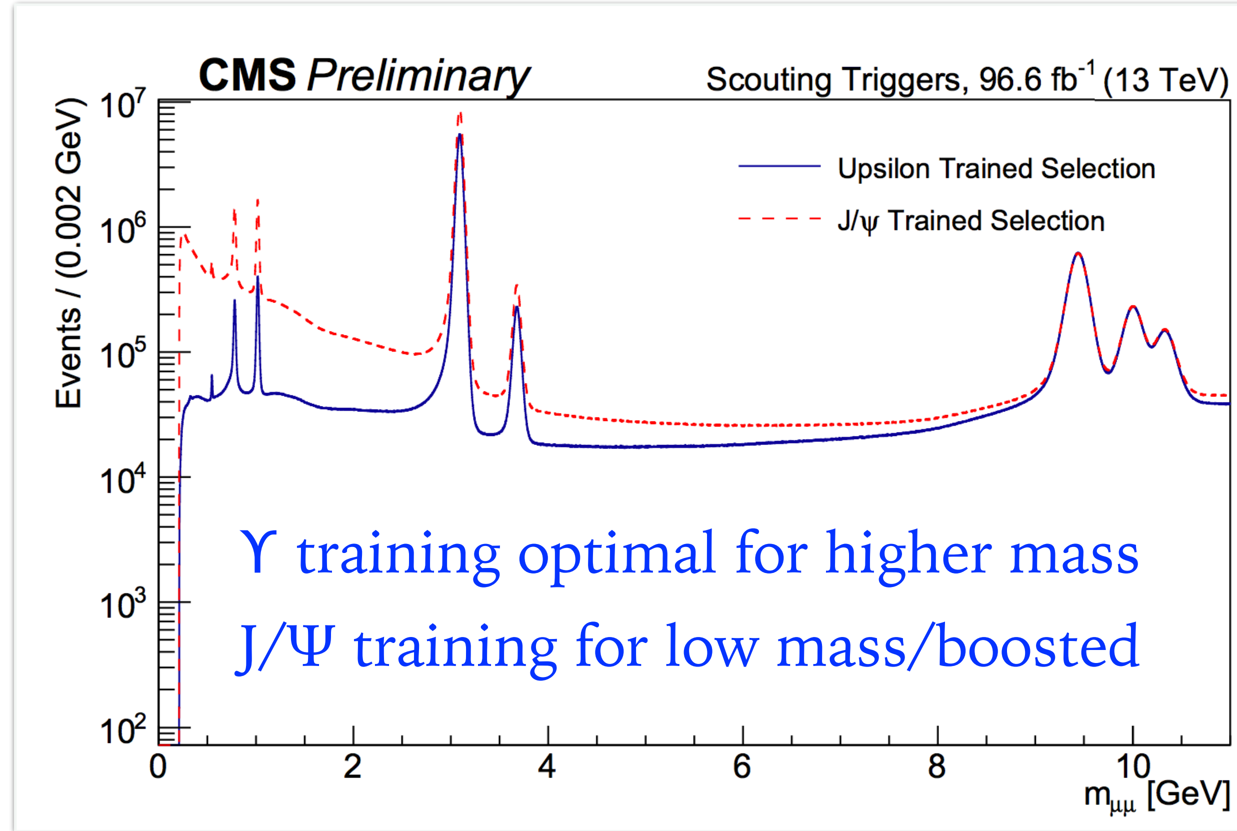
	Obs. limit [GeV]
Scalar LQ	1490
Vector LQ (minimal-coupling)	1690
Vector LQ (Yang–Mills)	1960

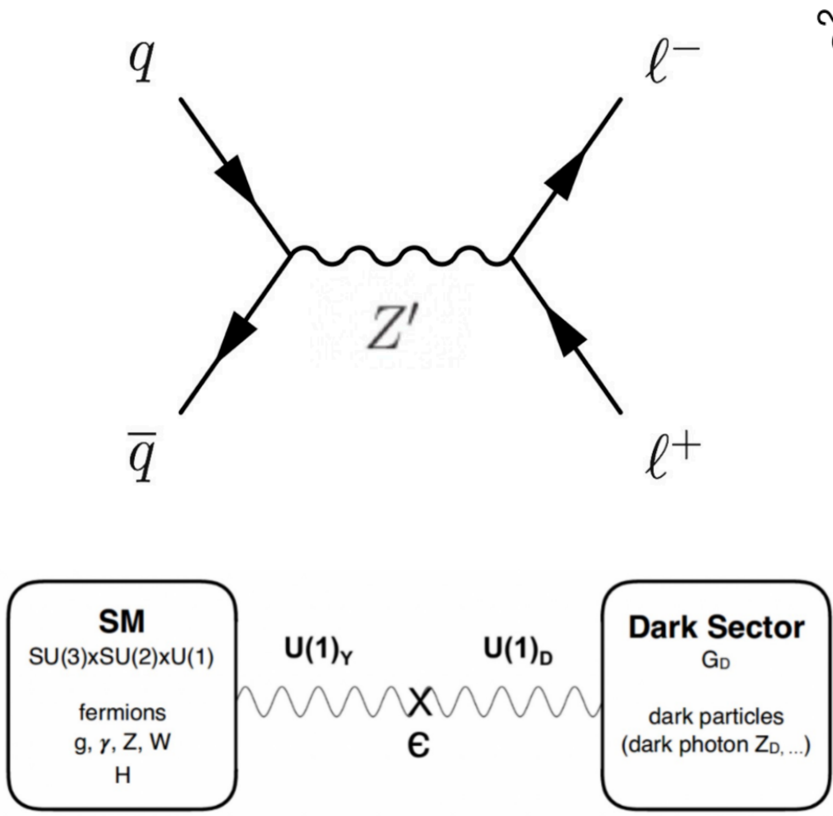


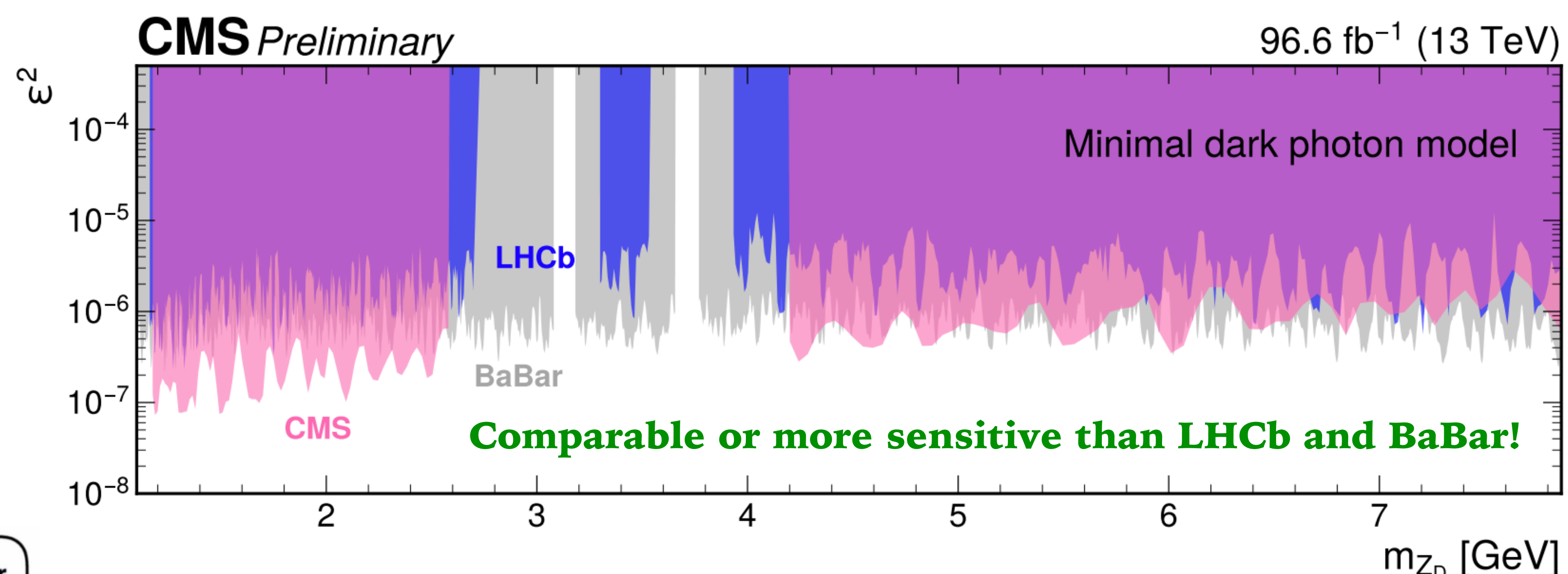
GEV SCALE RESONANCE DECAYING TO MUONS

EXO-21-005

- Search for ultra low mass dimuon resonances
  - Mass range: 1.1-2.6 GeV and 4.2-7.9 GeV
- Data collected by dedicated **scouting** muon trigger.
  - Muons reconstructed at high-level trigger used in analysis.
- Muons required to pass a MVA discriminant
  - Two MVAs based on J/ψ and ϒ(1S)
- Results interpreted in context of dark photon and pseudoscalar (2HDM+S)





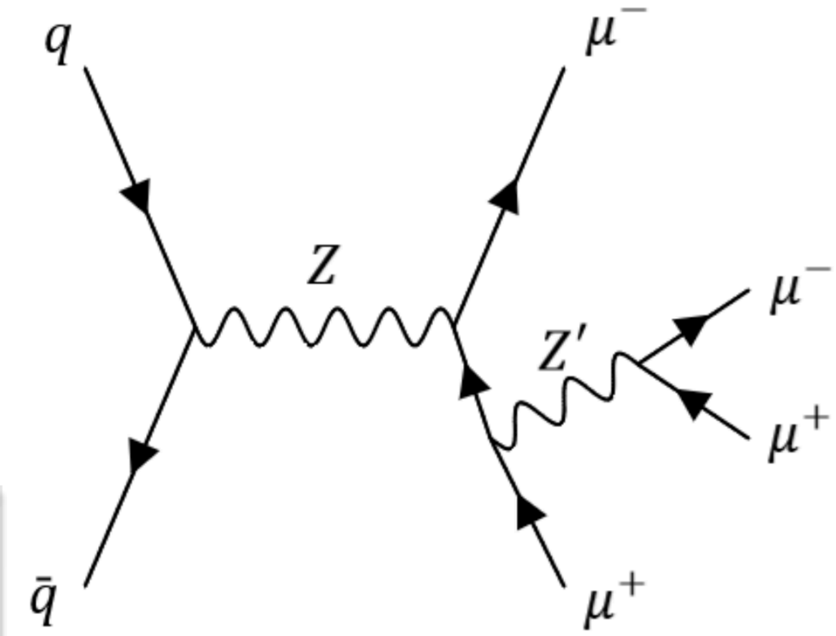


Model independent limits on σ×B×Acceptance also provided for the inclusive and boosted selections.

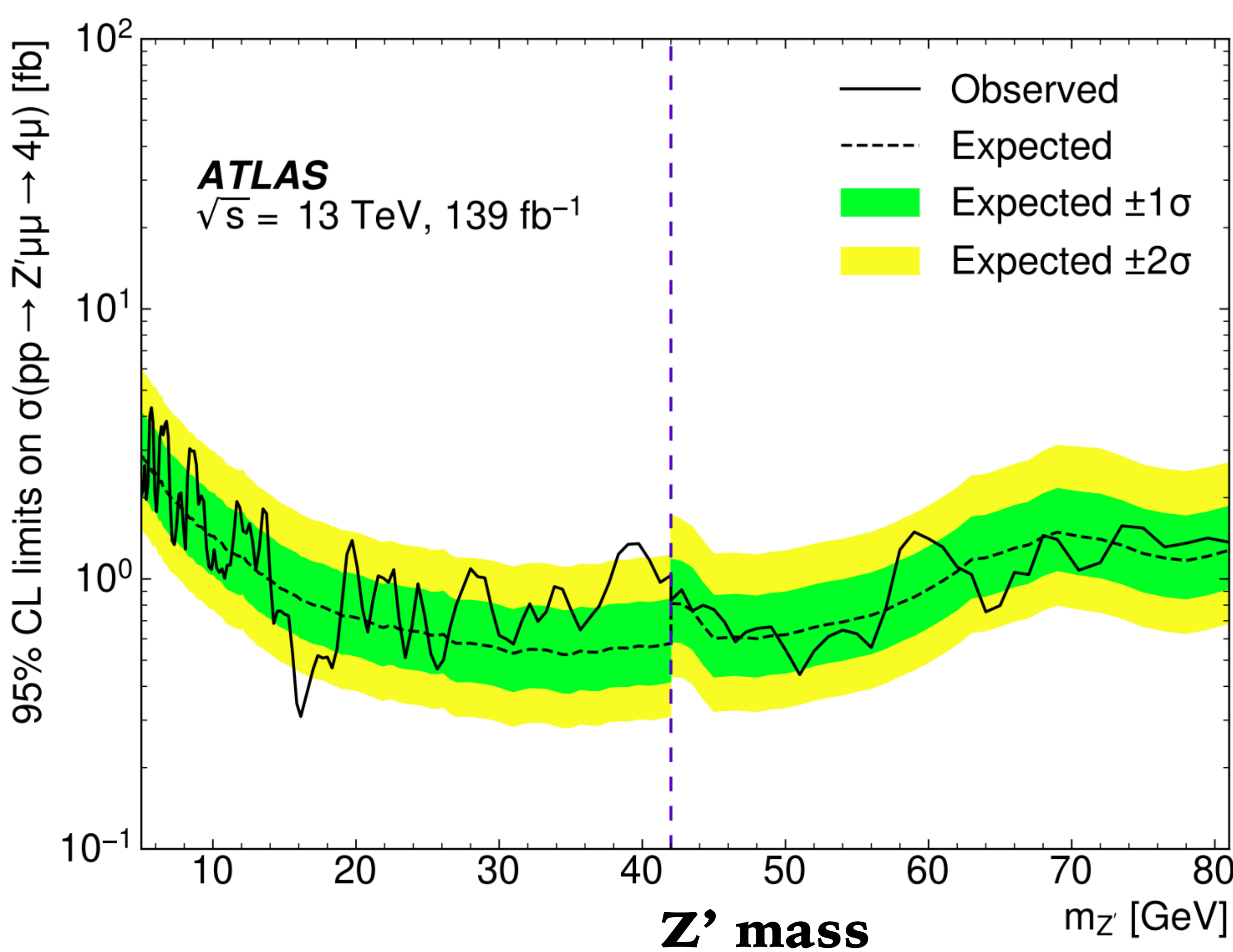
SEARCH FOR ZPRIME IN 4 MUON CHANNEL

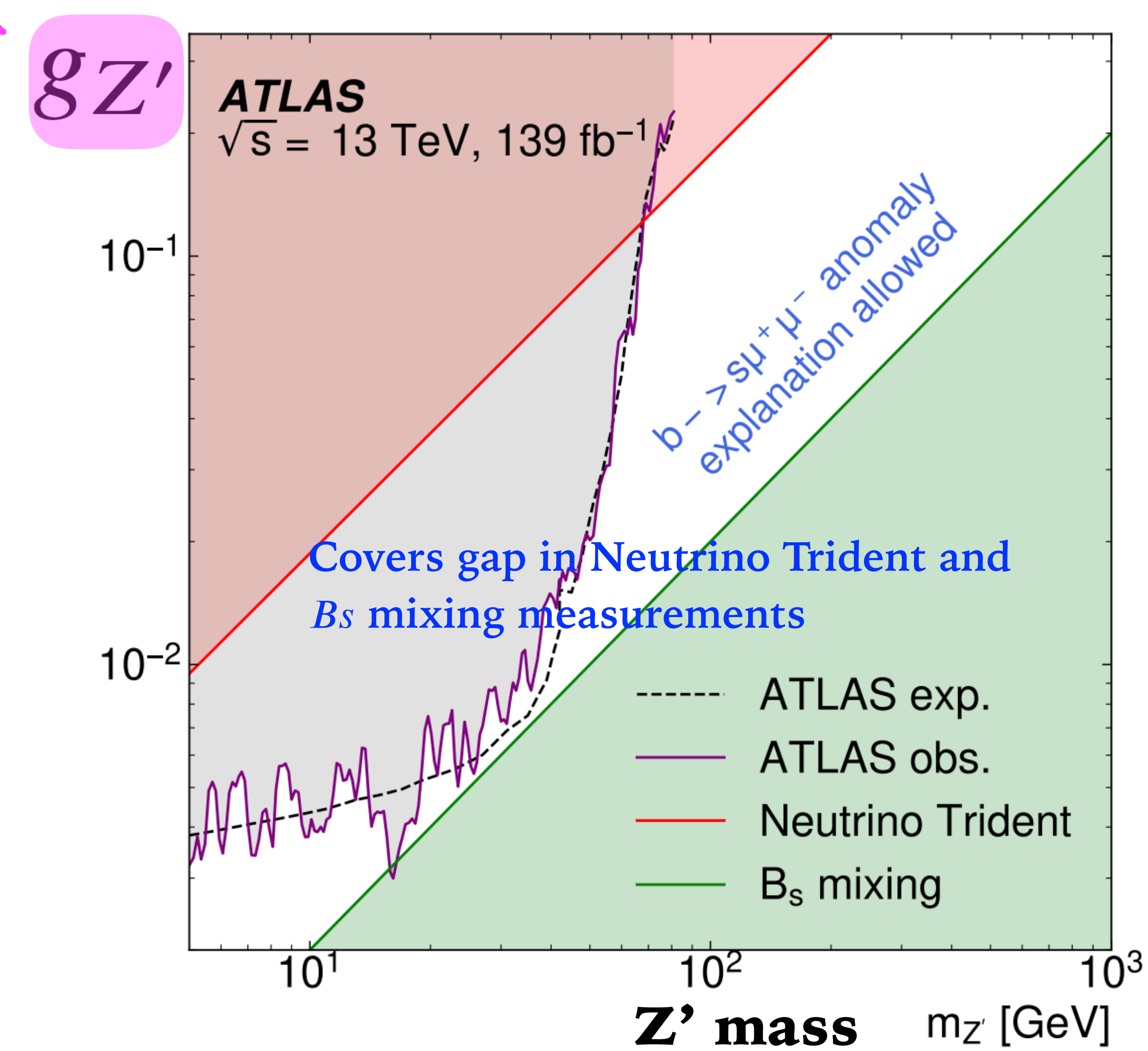
https://arxiv.org/pdf/2301.09342.pdf

- Search for low mass Z' predicted by *Lμ-L***τ** model
  - Z' only couples to muons and taus.
  - **Not directly produced** in pp (or ee) collision.
- Search ranges from 5 to 81 GeV



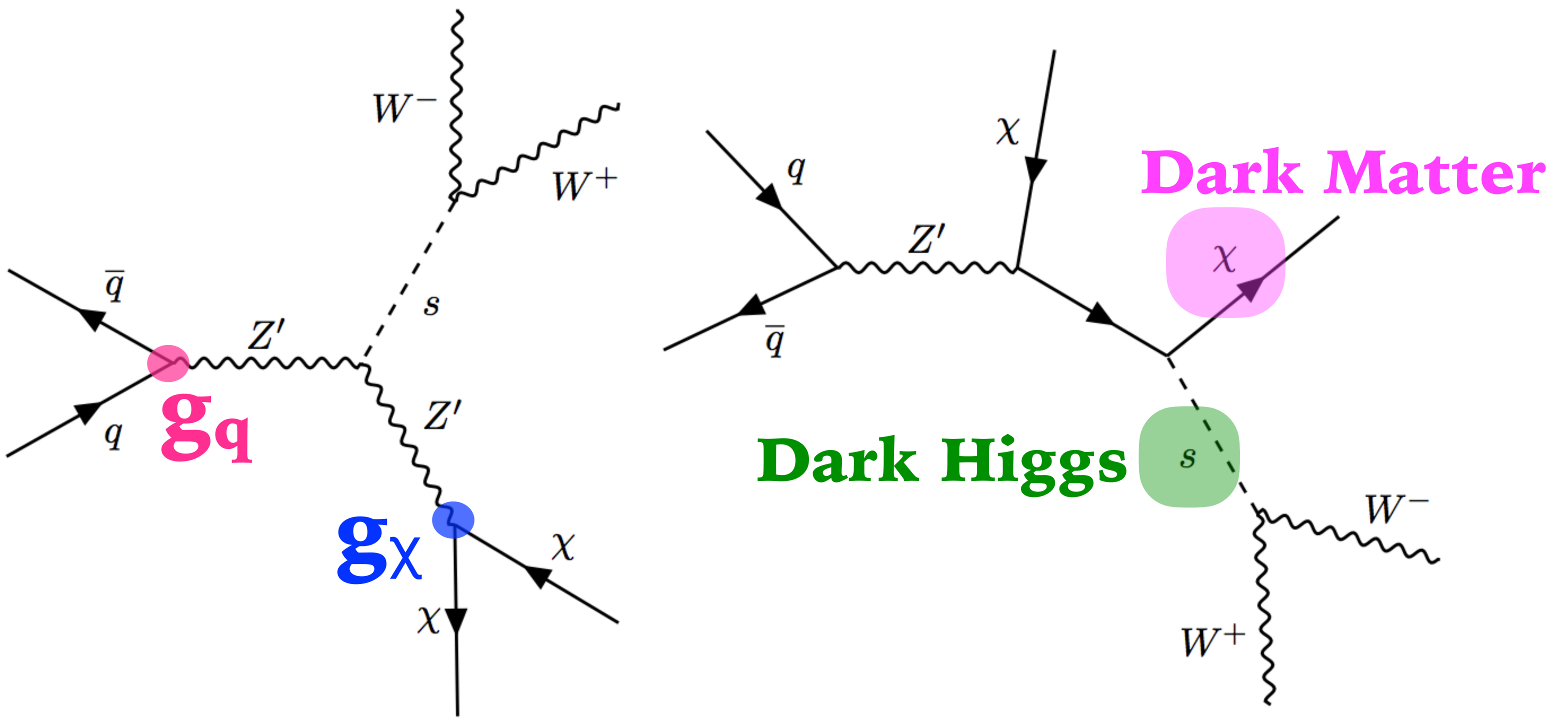
$$L_{Z'} = -\frac{1}{4}F_{\alpha\beta}F^{\alpha\beta} + \frac{1}{2}M_{Z'}^2 Z'^{\alpha}Z'_{\alpha} - g_{Z'}Z'_{\alpha}(\bar{\ell}_2\gamma^{\alpha}\ell_2 + \bar{\mu}\gamma^{\alpha}\mu - \bar{\ell}_3\gamma^{\alpha}\ell_3 - \bar{\tau}\gamma^{\alpha}\tau)$$





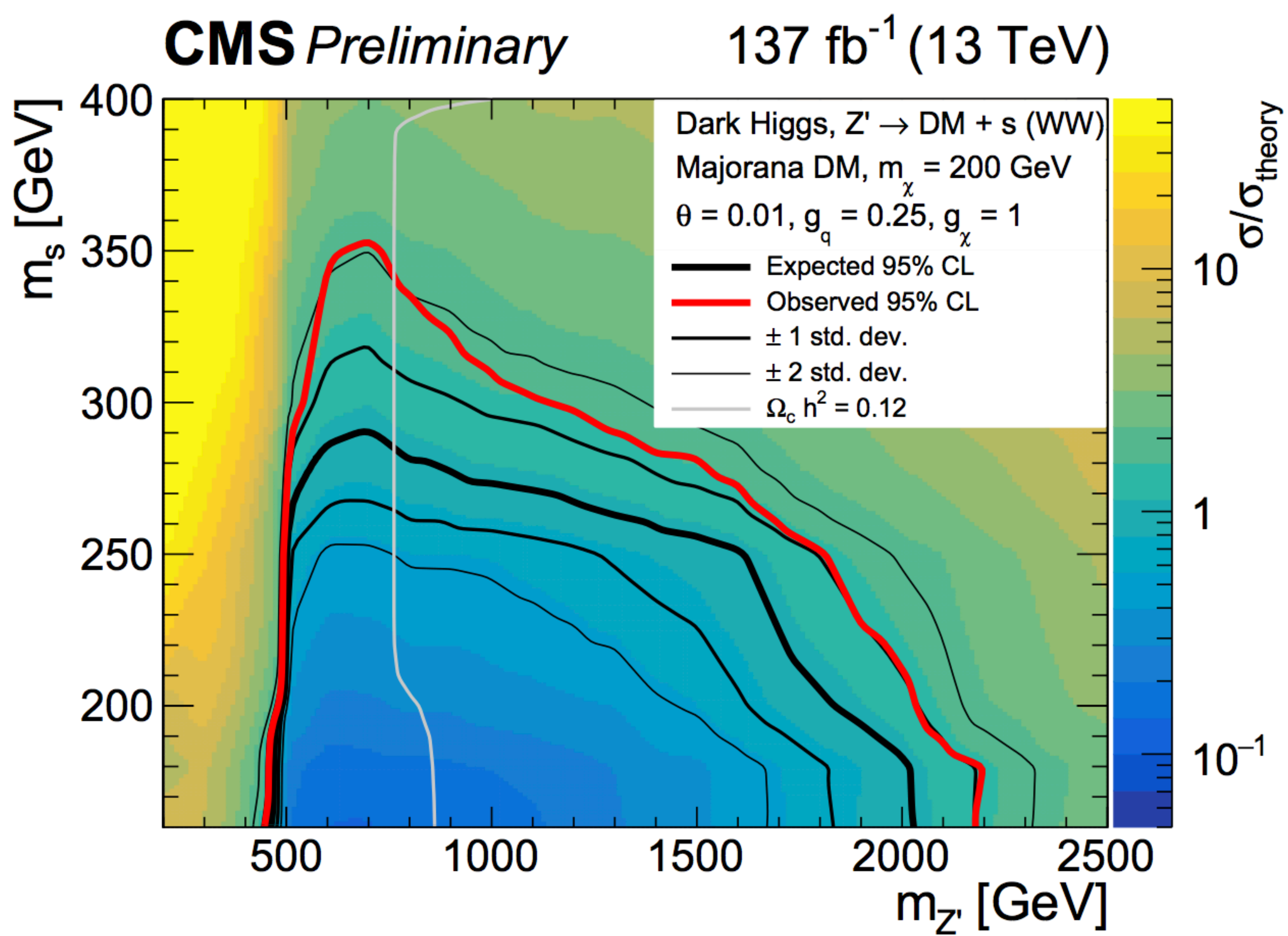
SEARCH FOR DARK MATTER IN WW EVENTS

CMS-EXO-21-012

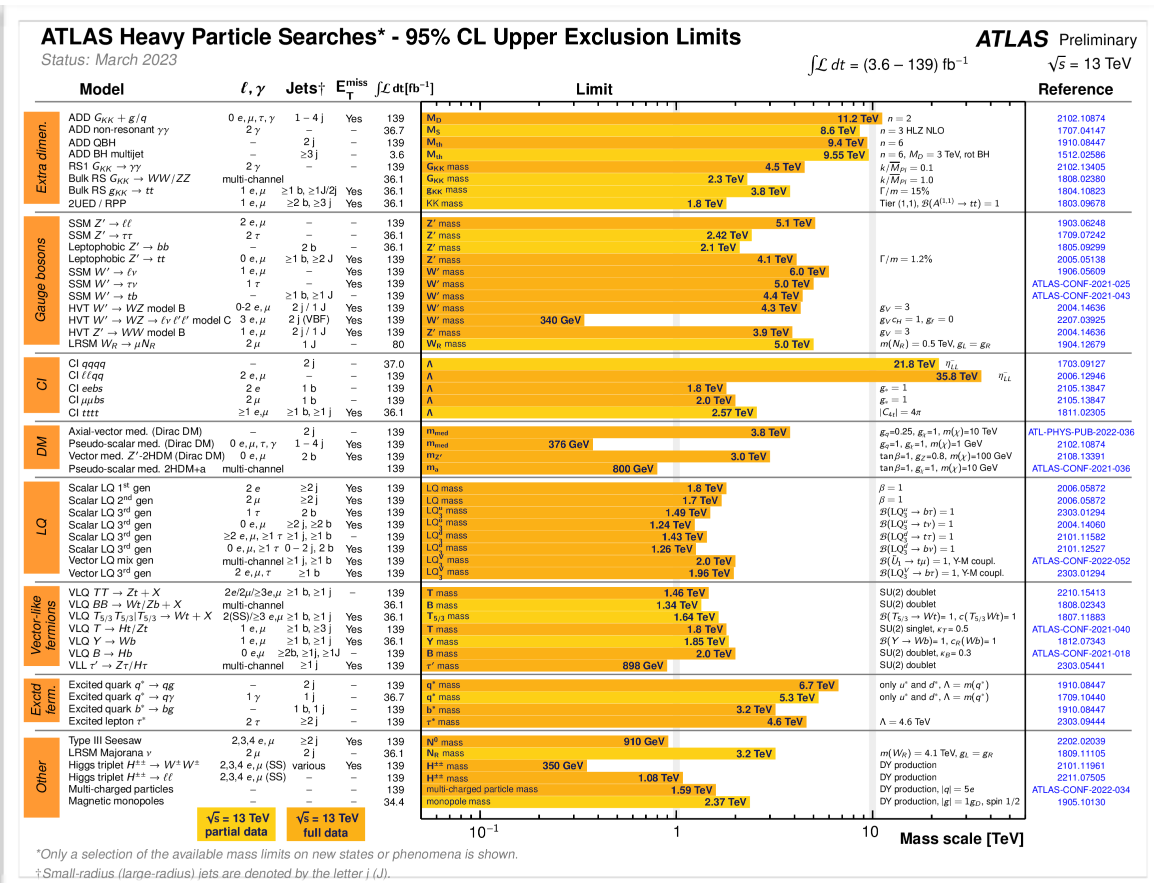


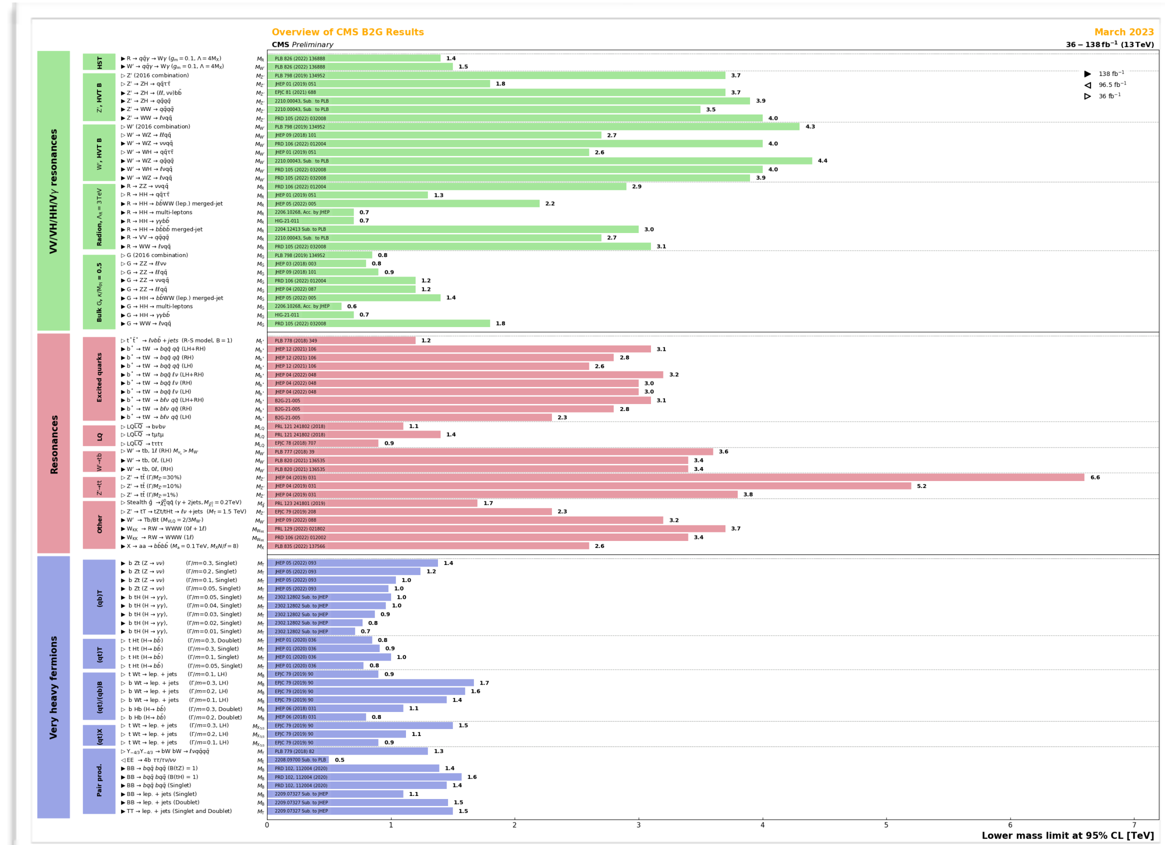
- Dark Matter particle acquires mass through its interaction with dark Higgs (s)
- Dark Higgs(s) lighter than dark matter.
- sinθ = mixing angle between SM Higgs and dark Higgs.

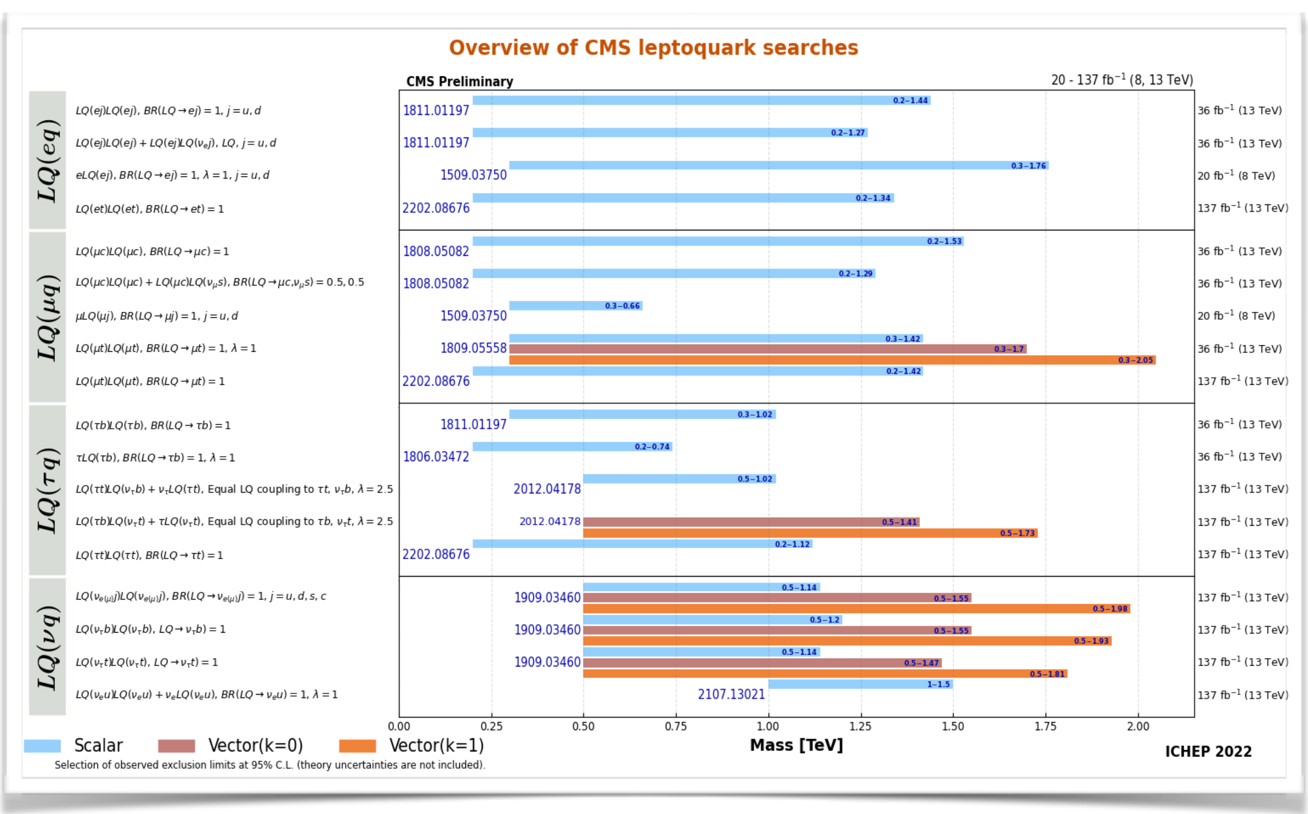
- Search performed in 2 channels:
  - di-leptonic: main variable is transverse mass of the trailing lepton and MET
  - semi-leptonic: main variable is BDT score (BDT trained on 13 input variables)
- Backgrounds: WW, $Z \rightarrow \mu\mu$, W+jets, tW, tt
- Limits derived in (m_s vs. $m_{Z'}$) plane, for different m_χ assumptions,

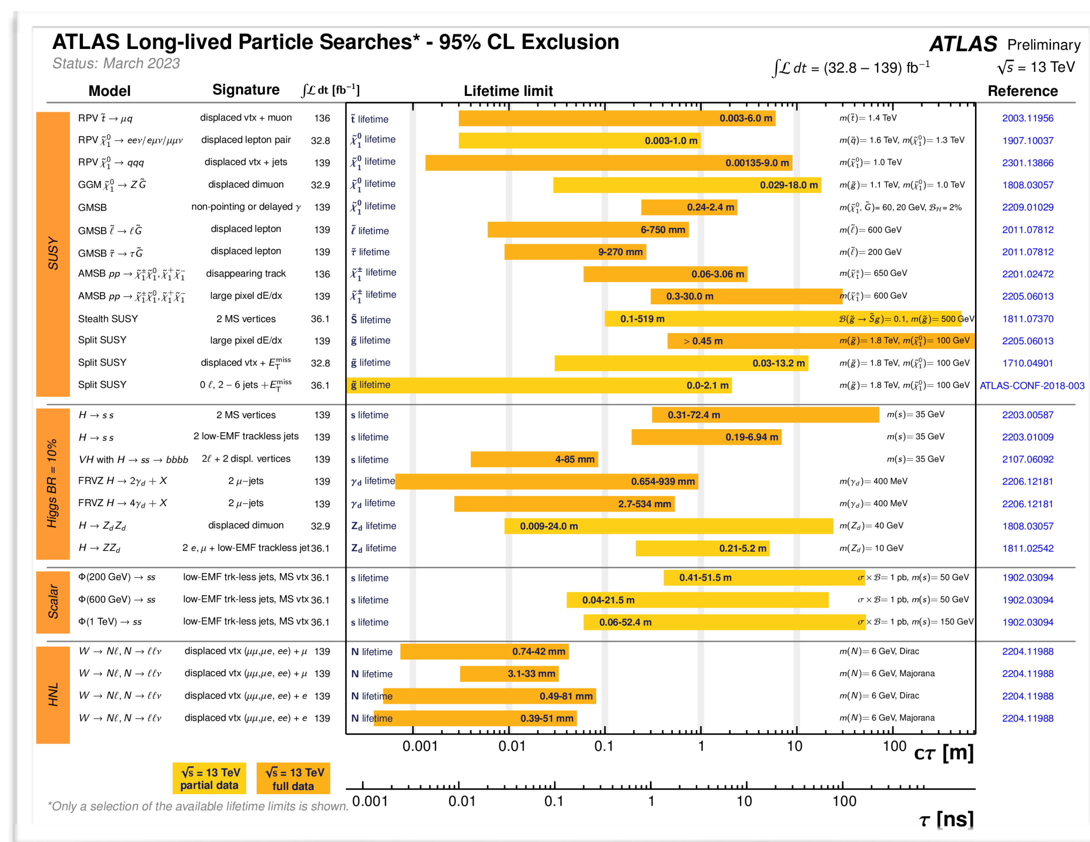


TO REITERATE, WE ARE SEARCHING EVERYWHERE!







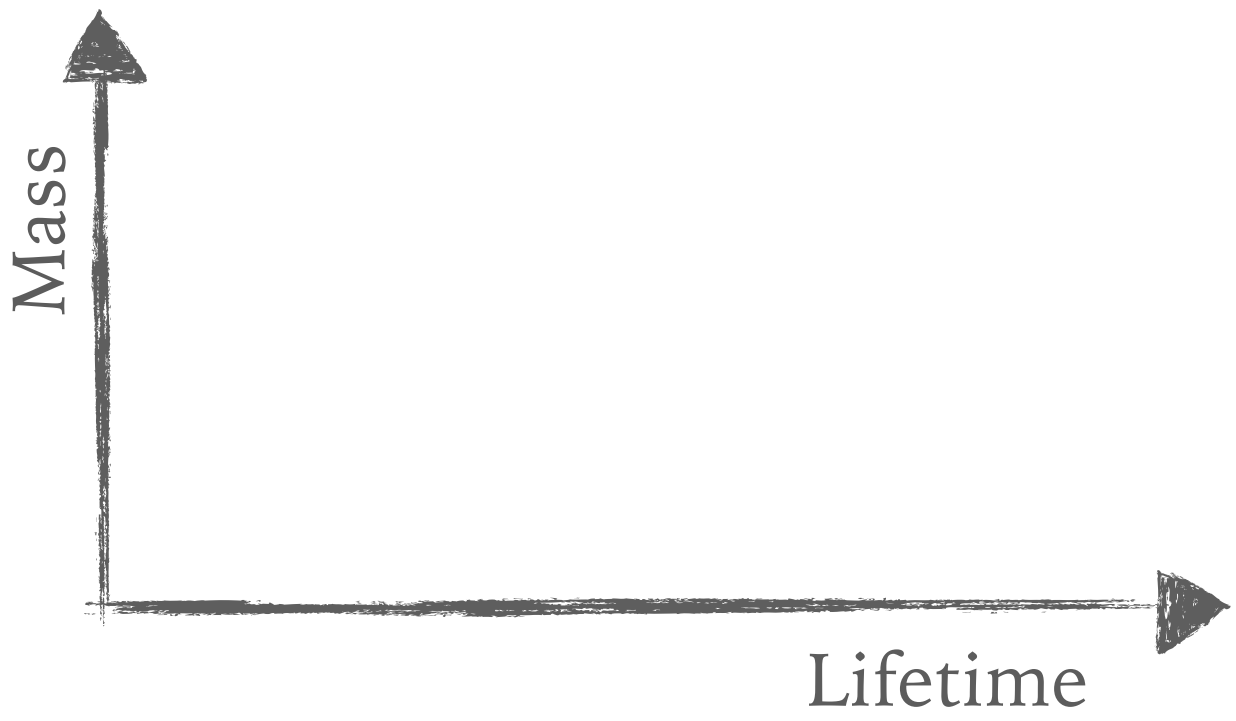


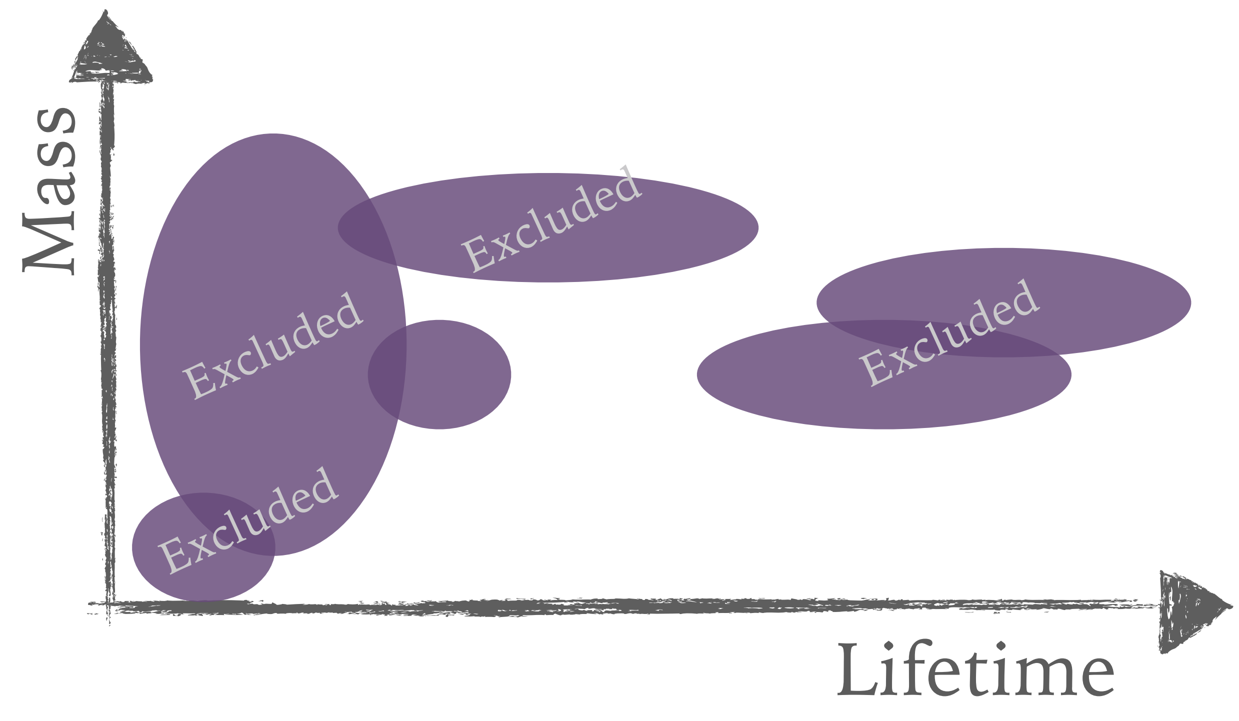
WRAPPING UP

What is there to look forward to?

NULL RESULT ≠ DISAPPOINTMENT

NULL RESULT ≠ DISAPPOINTMENT





Before we began the hunt for new physics

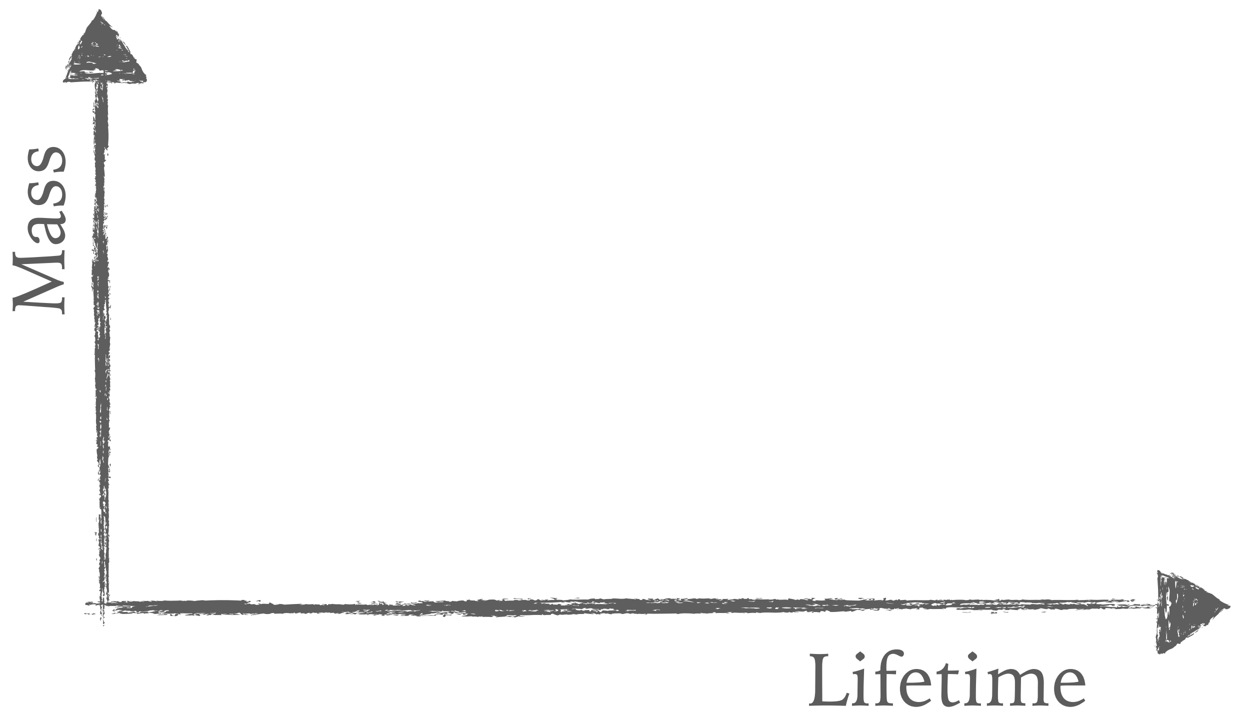
Where to look?

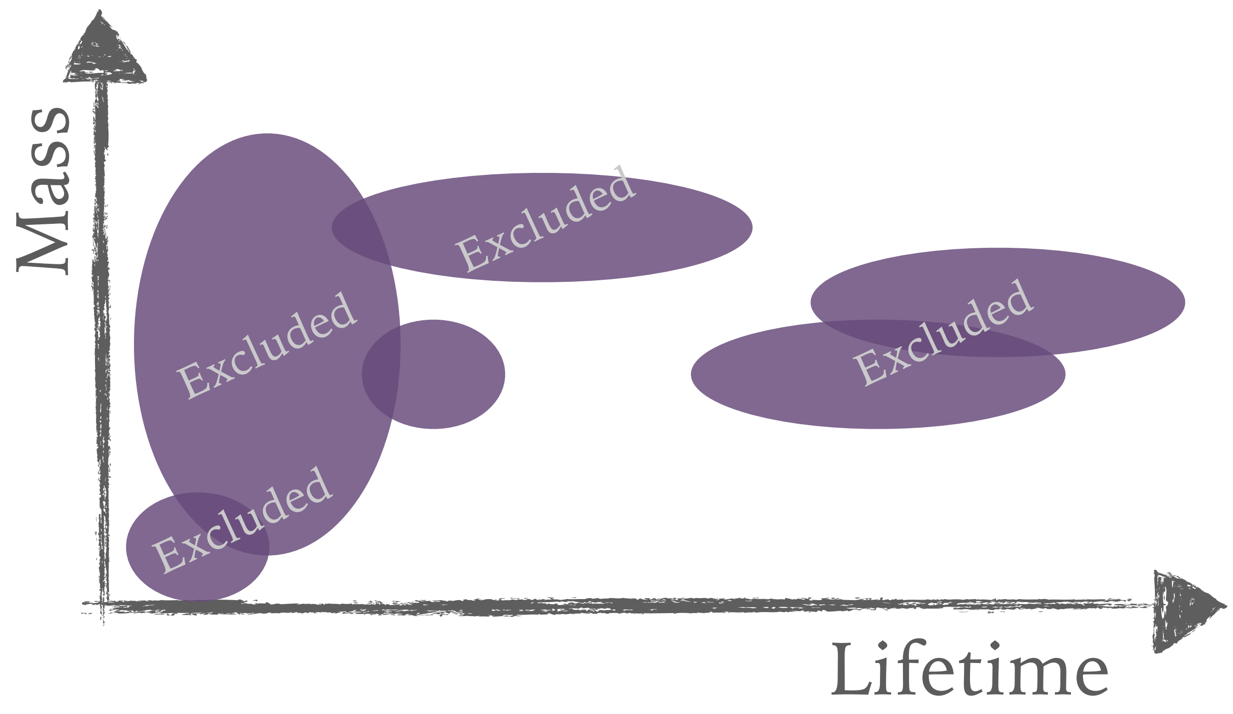
Everywhere!

Now

We have better idea where to look. We can plan analysis/make triggers accordingly

NULL RESULT ≠ DISAPPOINTMENT





Before we began the hunt for new physics

Where to look?

Everywhere!

Now

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NULL RESULT = INSIGHT

IMPROVEMENTS IN RUN3

- Used long shutdown (2019-21) time to make needed improvements/adjustments in
  - detector-hardware / electronics
  - object reconstruction software
  - calibration strategy
- **Improved** triggers for Run3. Usage of **GPUs** allow us to run more complicated algorithms at trigger level.
- Improvements in Data scouting (Trigger-level-analysis) and data-parking strategy.
- More computing resource allocated to collect and process more data in Run3.
- New triggers for long-lived particle searches.
- Ability to trigger on **displaced muon** at hardware trigger.
- **Increased usage of ML** in software-based triggers, object reconstruction, calibration and in physics analyses.
- Utilise **timing capability** and **longitudinal depths** of different sub-detectors in trigger-level and analysis-level.
- And many more …

ALL SET & ALREADY STARTED TO EXPLORE RUN3 DATA

Search in **new final states** that were never searched before

Use **innovative analysis techniques** that can boost the reach of an analysis significantly

Keep an eye on **existing anomalies**

13.6 TeV center-of-mass energy

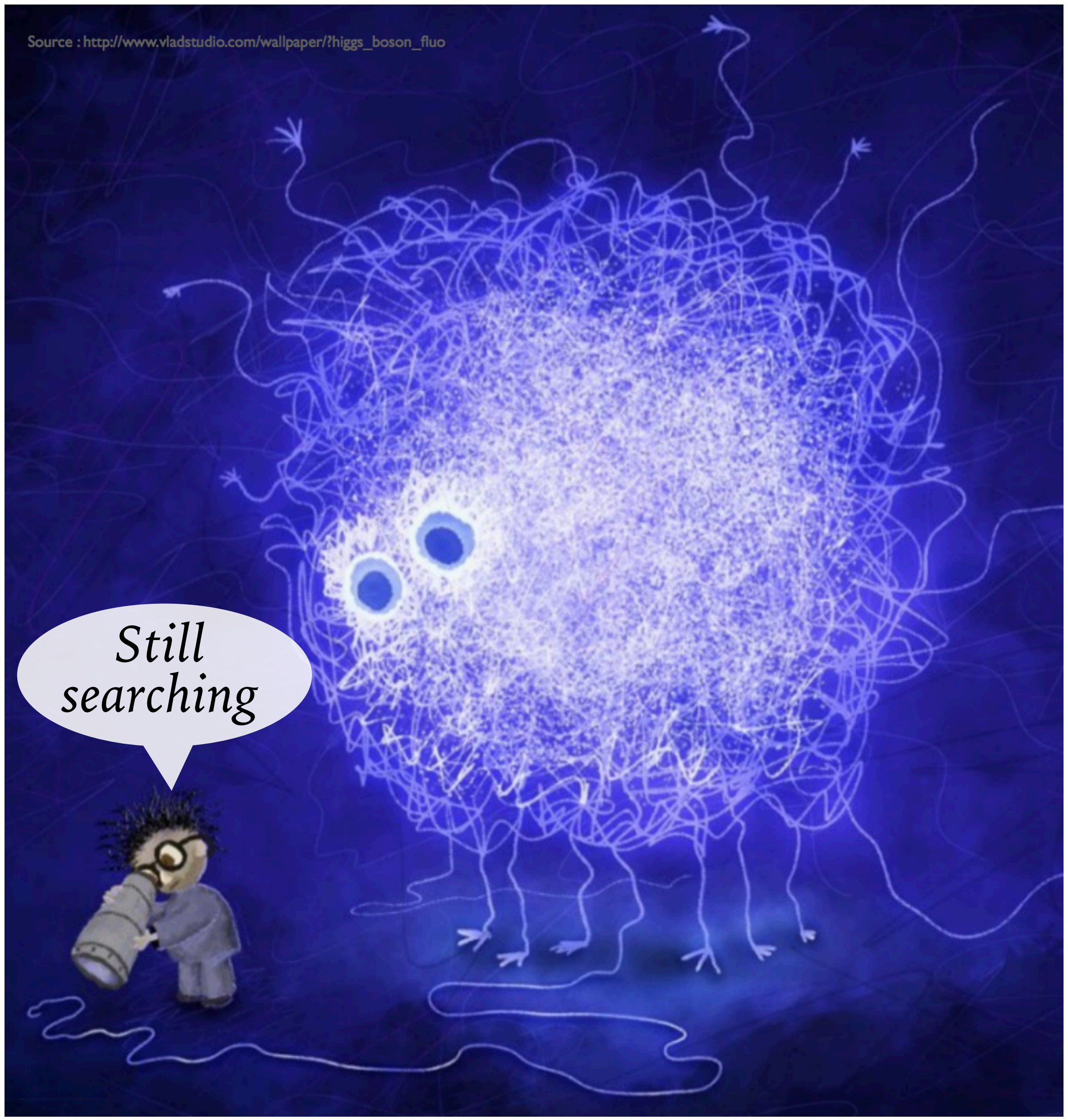
More integrated luminosity expected compared to Run2

The hunt for exotic BSM is on!

LHC data is valuable and finite.

Our main aim is to make the most of it.

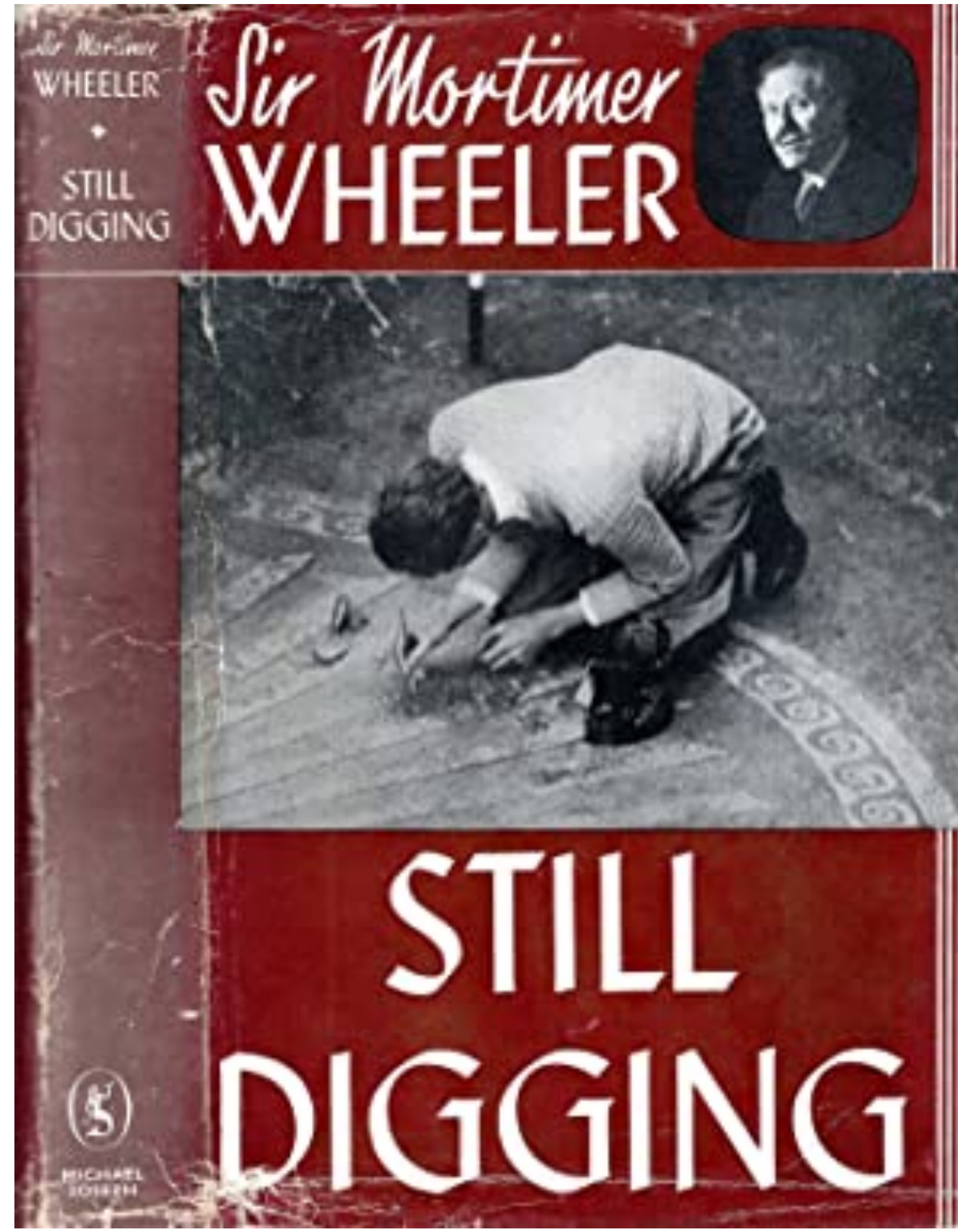
Particle physicists searching new physics



AN EXCITING FUTURE AWAITS...

STICK WITH US!

Archeologists excavating hidden gems



autobiography of an archeologist

QUESTIONS ?

EXTRA SLIDES

CWT calculates measure of similarity, between wavelet and signal at different scales and positions. The result is a two-dimensional representation that shows how the frequency content of the signal changes over time.

Signal

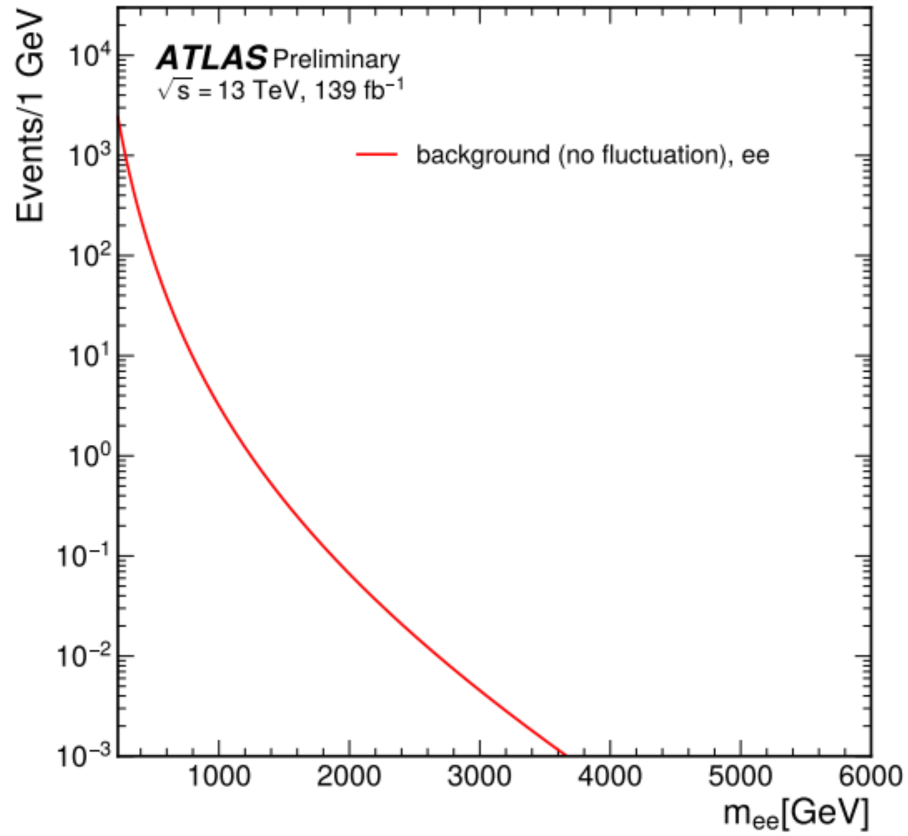
$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(m)\, \psi^* \left(\frac{m-b}{a} \right) dm$$

wavelet (Morlet wavelet)

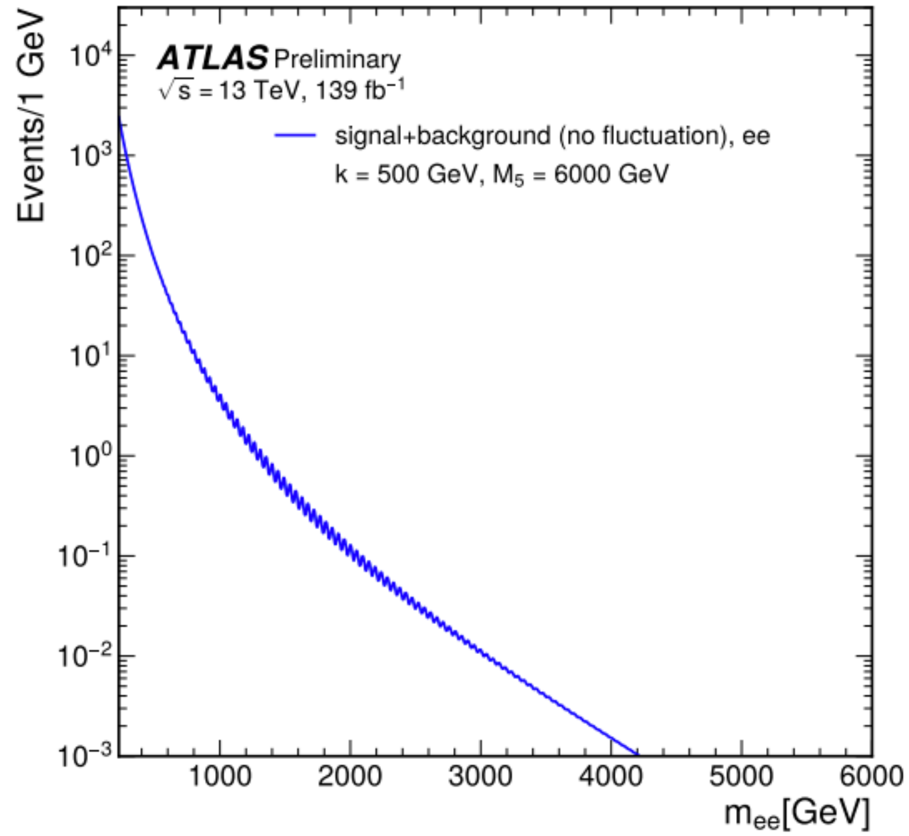
$$\psi(x) \equiv \frac{1}{\sqrt{B\pi}} e^{-x^2/B} \left(e^{i2\pi Cx} - e^{-\pi^2 BC^2} \right),$$

A 2D picture can be produced by taking the norm of the coefficient $W(a, b)$ for all values of a and b.

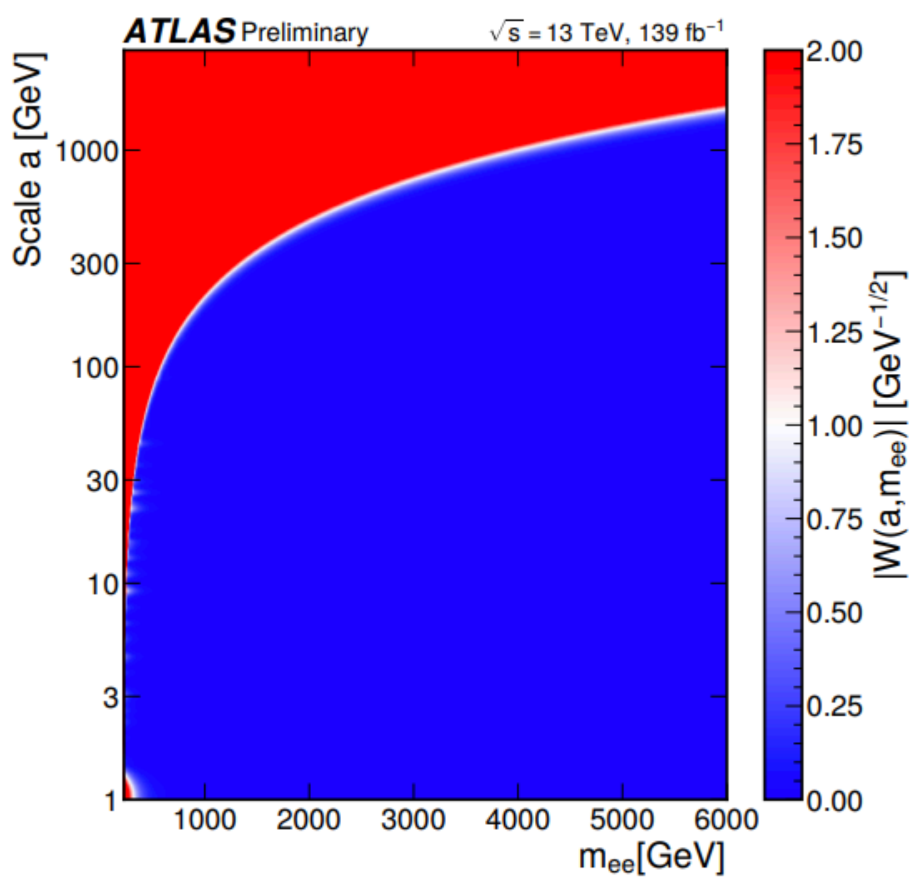
CWT in this analysis defines how much of a certain frequency is present in the signal at a given invariant mass bin.


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
background (no fluctuation), ee
Events/1 GeV
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
1000
2000
3000
4000
5000
6000
m_{ee}[GeV]

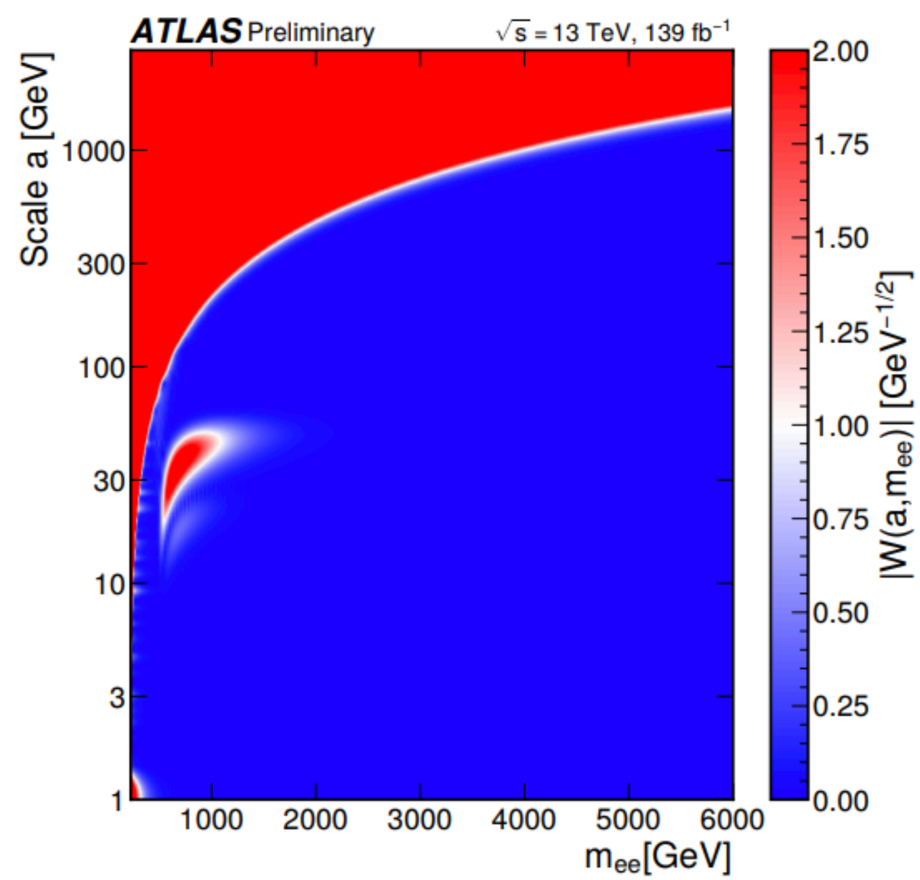
(a)


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
signal+background (no fluctuation), ee
k = 500 GeV, M_5 = 6000 GeV
Events/1 GeV
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
1000
2000
3000
4000
5000
6000
m_{ee}[GeV]

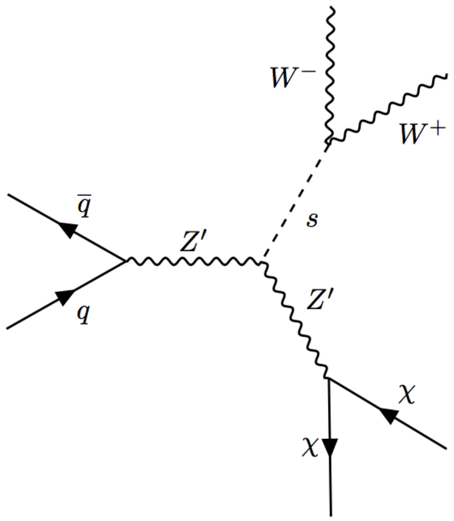
(b)

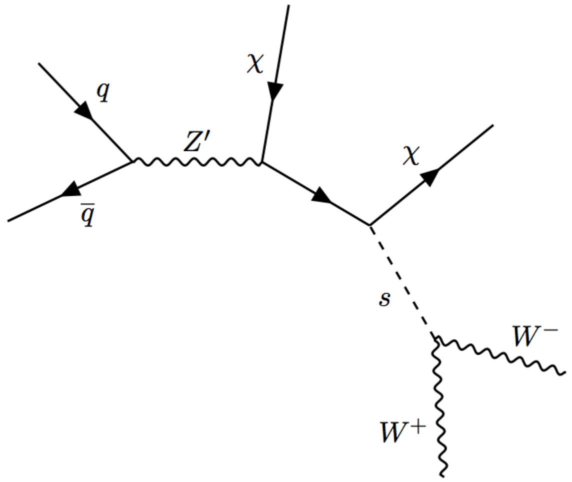

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Scale a [GeV]
1000
300
100
30
10
3
1
1000
2000
3000
4000
5000
6000
m_{ee}[GeV]
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
$|W(a,m_{ee})|$ [GeV$^{-1/2}$]

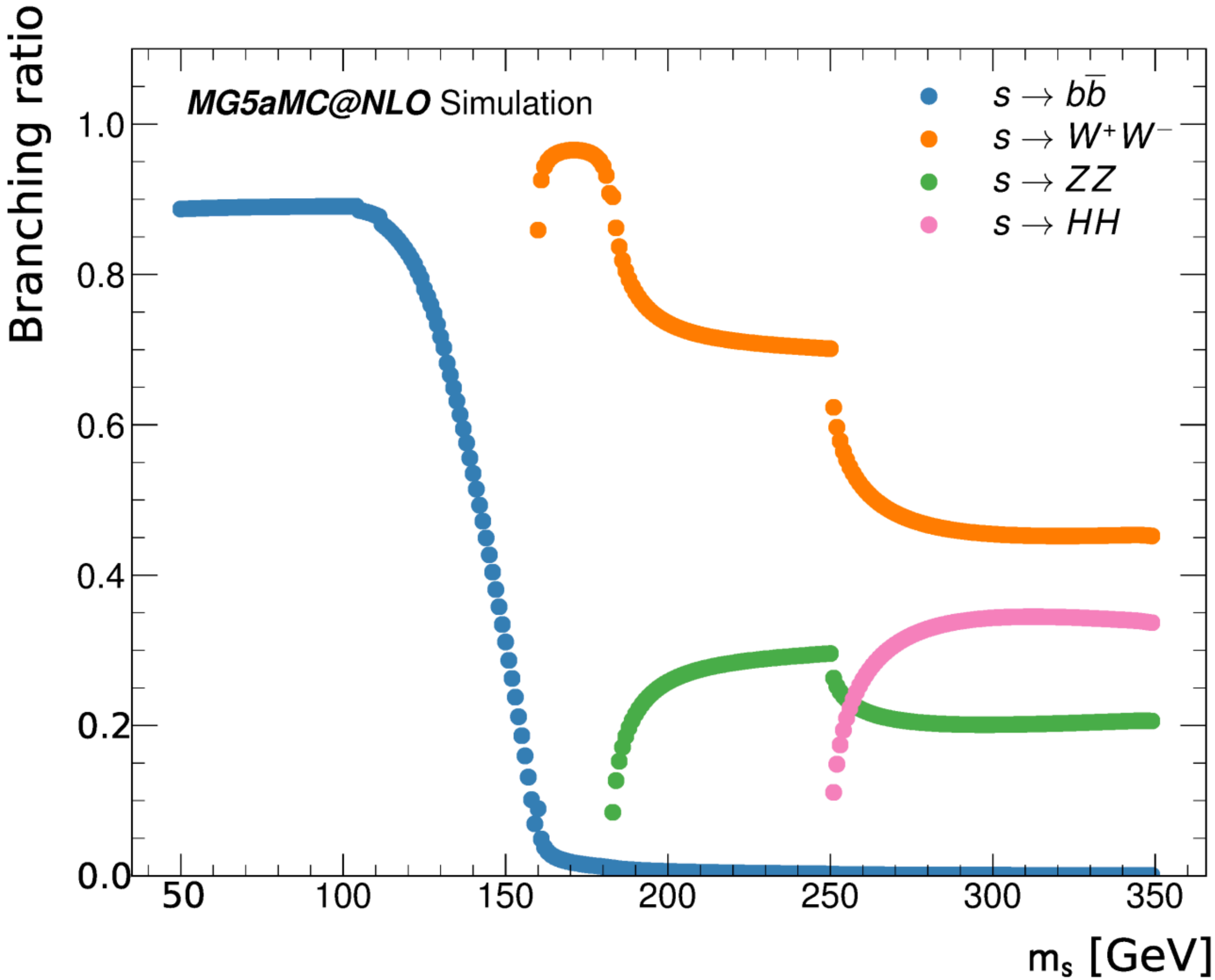
(c)


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Scale a [GeV]
1000
300
100
30
10
3
1
1000
2000
3000
4000
5000
6000
m_{ee}[GeV]
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
$|W(a,m_{ee})|$ [GeV$^{-1/2}$]

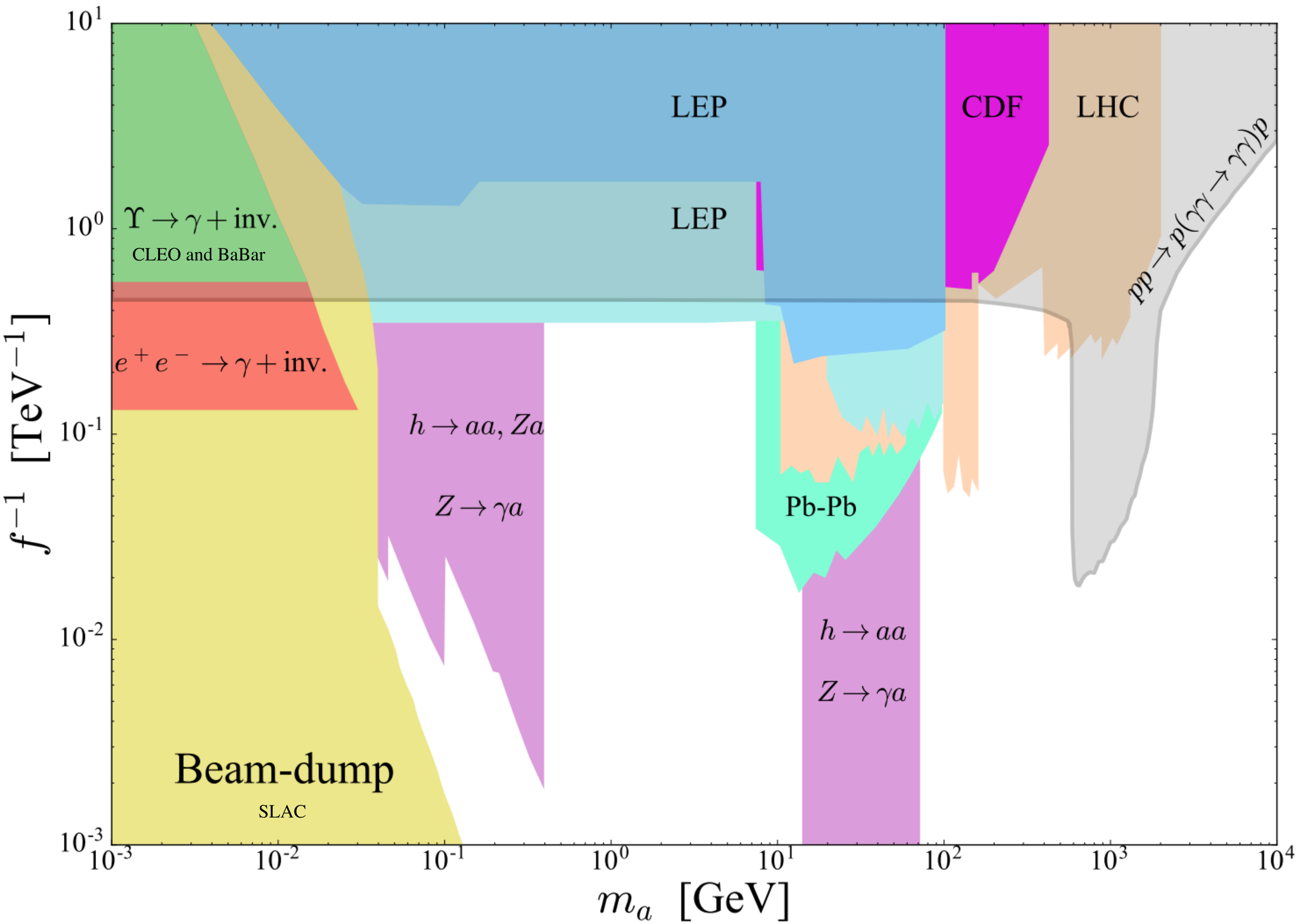
(d)


W⁻
W⁺
$\bar{q}$
q
Z′
s
Z′
χ
χ


q
$\bar{q}$
Z′
χ
χ
s
W⁻
W⁺

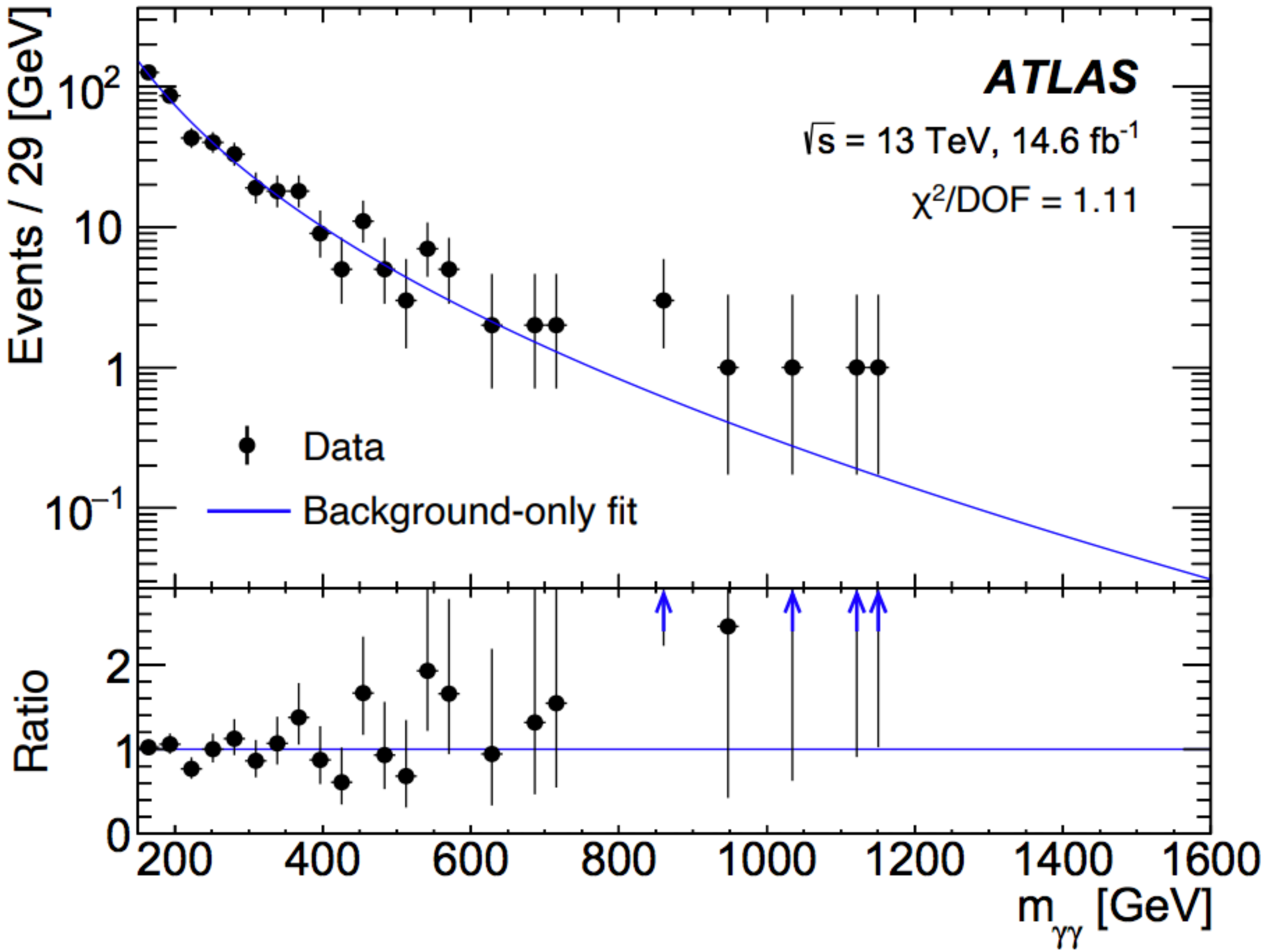

MG5aMC@NLO Simulation
$s \to b\bar{b}$
$s \to W^+W^-$
$s \to ZZ$
$s \to HH$
Branching ratio
0.0
0.2
0.4
0.6
0.8
1.0
50
100
150
200
250
300
350
m_s [GeV]

ALP



LEP
CDF
LHC
LEP
$pp \to p(\gamma\gamma \to \gamma\gamma)p$
$\Upsilon \to \gamma + \text{inv.}$
CLEO and BaBar
$e^+e^- \to \gamma + \text{inv.}$
$h \to aa, Za$
$Z \to \gamma a$
Pb-Pb
$h \to aa$
$Z \to \gamma a$
Beam-dump
SLAC
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
f^{-1} [TeV^{-1}]
m_a [GeV]

ALP


ATLAS
√s = 13 TeV, 14.6 fb⁻¹
χ²/DOF = 1.11
Data
Background-only fit
Events / 29 [GeV]
Ratio
m_γγ [GeV]
10²
10
1
10⁻¹
2
1
0
200
400
600
800
1000
1200
1400
1600