The clckwork paradigm and multi-ALPs at hadron colliders

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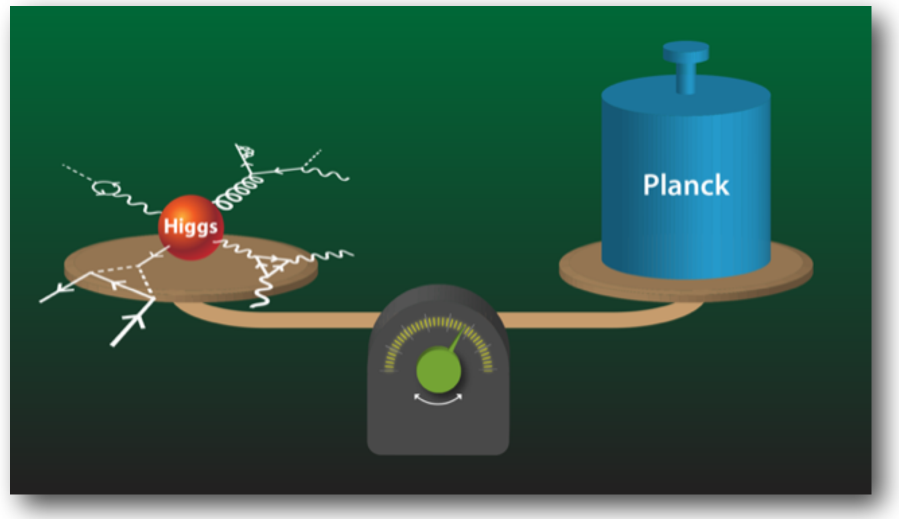
Based on PRD 112 (2025) 5, 055030 (2409.05983)
with
S. Bhattacharya (U. Witwatersrand), D. Choudhury (U. Delhi), T. Srivastava (CCNU, Wuhan)

Scalars 2025
Warsaw, September 24

Hierarchies in Particle Physics

Gauge hierarchy



APS/Alan Stonebraker

Fermion masses

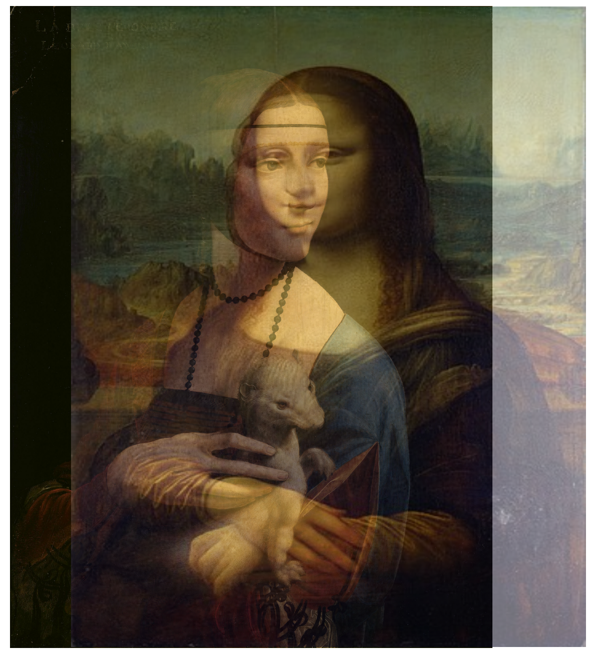
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

John Jarnestad/The Royal Swedish Academy of Sciences

Axion/ALPs

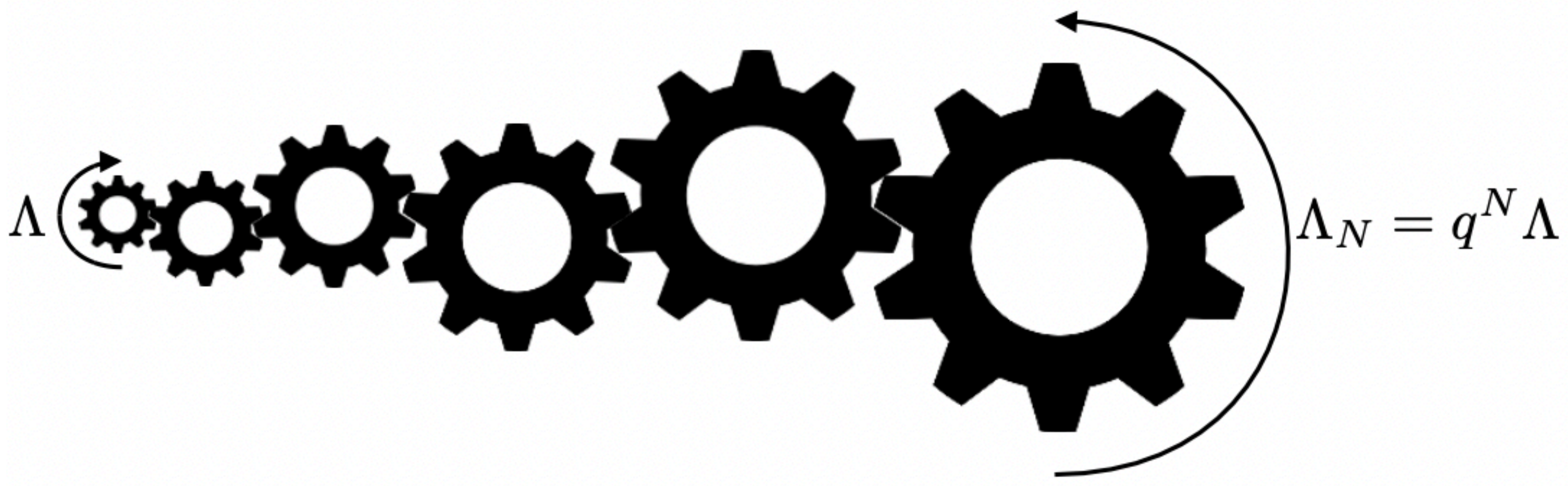
Wikipedia

Any new particle mixing with SM (e.g. dark photons)



Internet

What is clockwork?



Giudice, McCullough (2016)

A mechanism to generate large hierarchies in mass scales or couplings from a theory containing no small parameters…

Origins?

I. Natural Inflation

Freese et. al. (1990), Adams et. al. (1993)

A pNGB/axion inflaton naturally provides a flat direction: Shift symmetry $\pi \to \pi + c$ broken softly by a potential:

$$V = \Lambda^4 \left[1 - \cos\left(\frac{\pi}{f}\right)\right]$$

Nature Phys **12**, 374 (2016)

f : SSB scale / axion decay constant
Λ : Soft breaking scale

A plausible scenario requires: Freese et. al. (2004)

$$f \gtrsim M_{Planck}$$

↓

Super-Planckian decay constant ! — questionable theoretical validity ?

II. Relaxion

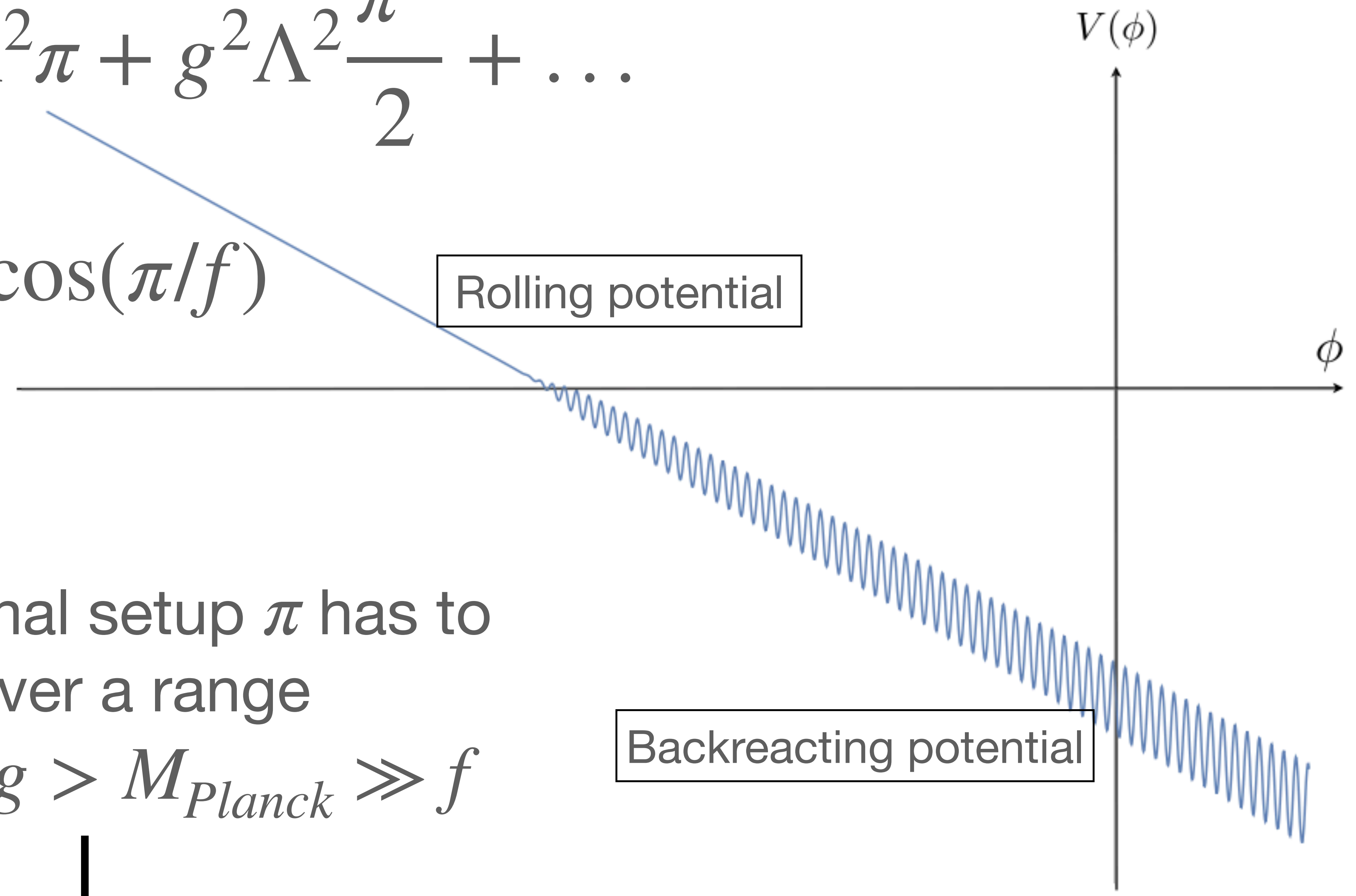
Graham et. al. PRL 115, 221801 (2015)

The weak scale is selected by dynamical evolution of a pNGB

$$V(H,\pi) = \left(-\Lambda^2 + g\Lambda\pi\right)|H|^2 + V_{roll} + V_{br}$$

$$V_{roll} = g\Lambda^2\pi + g^2\Lambda^2\frac{\pi^2}{2} + \dots$$

$$V_{br} = \Lambda^4\cos(\pi/f)$$



In the minimal setup π has to roll over a range
$\Delta\pi \sim \Lambda/g > M_{Planck} \gg f$

↓

Super-Planckian excursions again !

A PROPOSED REMEDY FOR BOTH —MULTI-AXION POTENTIALS

$$V = \sum_{i=0}^{N-1} \Lambda_i^4 \left[1 - \cos\left(\frac{\pi_i}{f} - q\frac{\pi_{i+1}}{f}\right)\right] \qquad q > 1$$

Kim, Nilles, Peloso JCAP 0501 (2005) 005

Choi, Kim, Yun PRD 90, 023545 (2014)

Choi, Im; JHEP01(2016)149

SHIFT SYMMETRY $\pi_i \to \pi_i + q^{-i} c \implies$ A flat direction

PERIODICITY $\Delta\pi_{flat} = 2\pi\sqrt{1 + q^2 + q^4 + \cdots + q^{2N}} f \sim 2\pi q^N f$

$$\implies f_{\text{eff}} \sim q^N f \gg f$$

f can in principle be sub-Planckian

Localization on theory space —The clockwork way

Consider a theory of multiple copies of a complex scalar Φ with nearest neighbour interactions —

Kaplan, Rattazzi (PRD 93, 085007 (2016))
Giudice, McCullough (JHEP02(2017)036)

$$V = -\sum_{j=0}^{N}\left[\lambda\left(\Phi_j^\dagger\Phi_j - f^2\right)^2\right] - \lambda'\Lambda^{3-q}\sum_{j=0}^{N-1}\Phi_j^\dagger\Phi_{j+1}^q + \text{h.c.} \qquad (\lambda' \ll \lambda, \quad \Lambda \ll f)$$

$U(1)^{N+1}$ symmetric, spontaneously broken at a scale f

Breaks $U(1)^{N+1} \to U(1)_{CW} = \sum_j q^{-j}$

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$U(1)^{N+1}$ symmetric, spontaneously broken at a scale f

Breaks $U(1)^{N+1} \to U(1)_{CW} = \sum_j q^{-j}$

Theory of pNGBs below the SSB scale f : $\Phi_j \to U_j \equiv \frac{1}{\sqrt{2}} f e^{i\pi_j/f}$

$$V_\pi = -\frac{m^2 f^2}{2}\left[\sum_{j=0}^{N-1} U_j^\dagger U_{j+1}^q\right] + \text{h.c.} \qquad \left[m^2 \equiv 2^{(1-q)/2}\lambda'\Lambda^{3-q}f^{q-1}\right]$$

$$= -\frac{1}{2}m^2 f^2 \sum_{j=0}^{N-1}\cos\frac{\pi_j - q\pi_{j+1}}{f}$$

Our good old periodic potential !

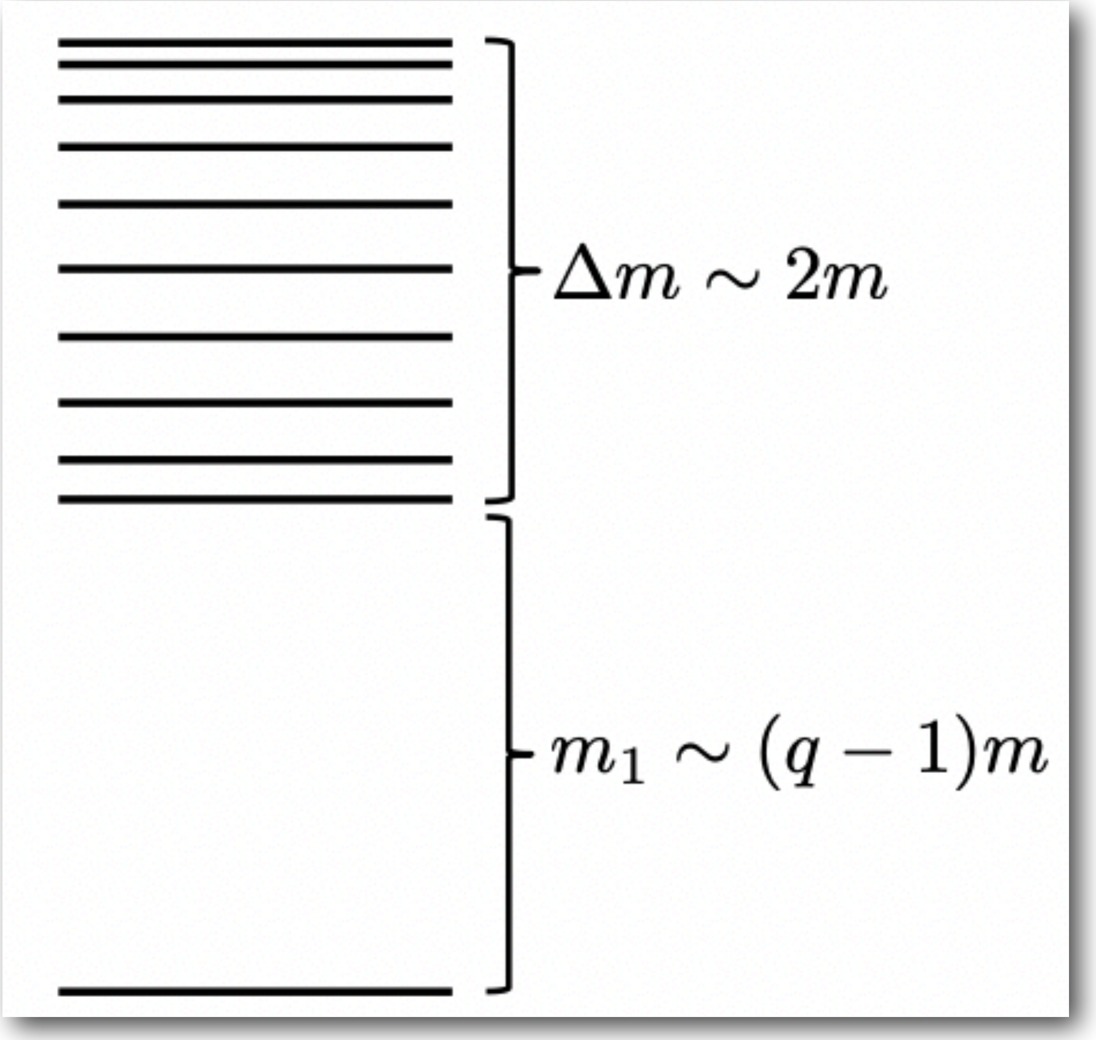
Has a flat direction due to $U(1)_{CW}$

Closer look at the quadratic terms—

$$V_\pi^{(2)} = \frac{m^2}{2} \sum_{j=0}^{N-1} (\pi_j - q\pi_{j+1})^2$$

pNGB mass matrix

$$m^2 \begin{pmatrix} -1 & -q & 0 & 0 & \dots & 0 & 0 \\ -q & q^2+1 & -q & 0 & \dots & 0 & 0 \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & -q & q^2+1 & -q & 0 & \dots & 0 \\ 0 & \dots & -q & q^2+1 & -q & \dots & 0 \\ 0 & 0 & \dots & -q & q^2+1 & -q & \dots \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ -q & 0 & 0 & 0 & \dots & -q & q^2 \end{pmatrix}_{(N+1)\times(N+1)}$$



JHEP02(2017)036

Mass eigenvalues:

$$m_n^2 = m^2 \begin{cases} 0, & n = 0 \\ 1 + q^2 - 2q\cos\left(\frac{n\pi}{N+1}\right), & \text{otherwise} \end{cases}$$

$n = 0$ ⟶ 1 massless pseudoscalar a_0

otherwise ⟶ N massive pseudoscalars $a_n - m_n \sim mq$

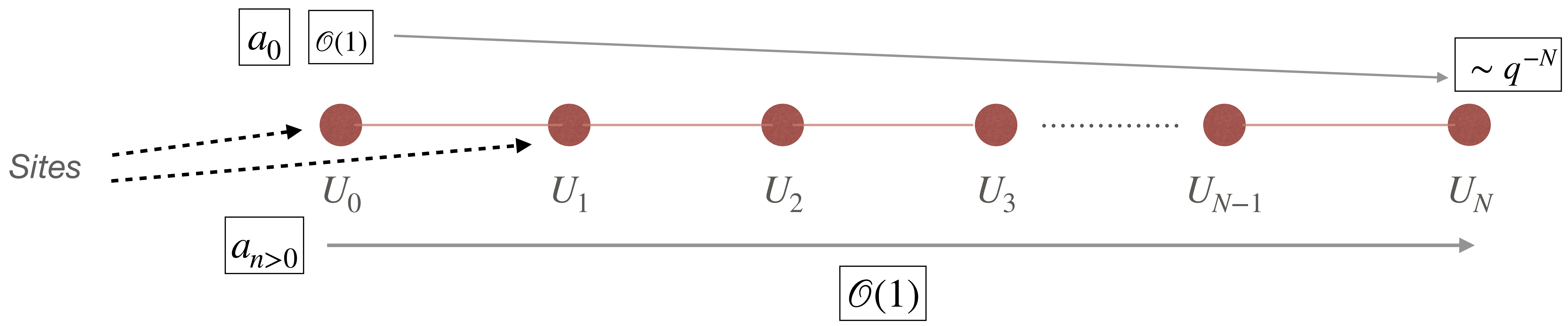
With the basis transformation, $a_n = \sum_j C_{nj}\pi_j$, the eigenvectors are:

$$\langle a_0 | \pi_j \rangle \equiv C_{0j} = \frac{\mathcal{N}_0}{q^j}, \qquad \langle a_{n>0} | \pi_j \rangle \equiv C_{nj} = \mathcal{N}_n \left[q \sin \frac{jn\pi}{N+1} - \sin \frac{(j+1)n\pi}{N+1} \right] \qquad j = 0 \ldots N, \quad n = 1 \ldots N$$

Zero mode has exponentially small overlap with π_N with an effective decay constant $f_{\text{eff}} = q^N f \gg f$

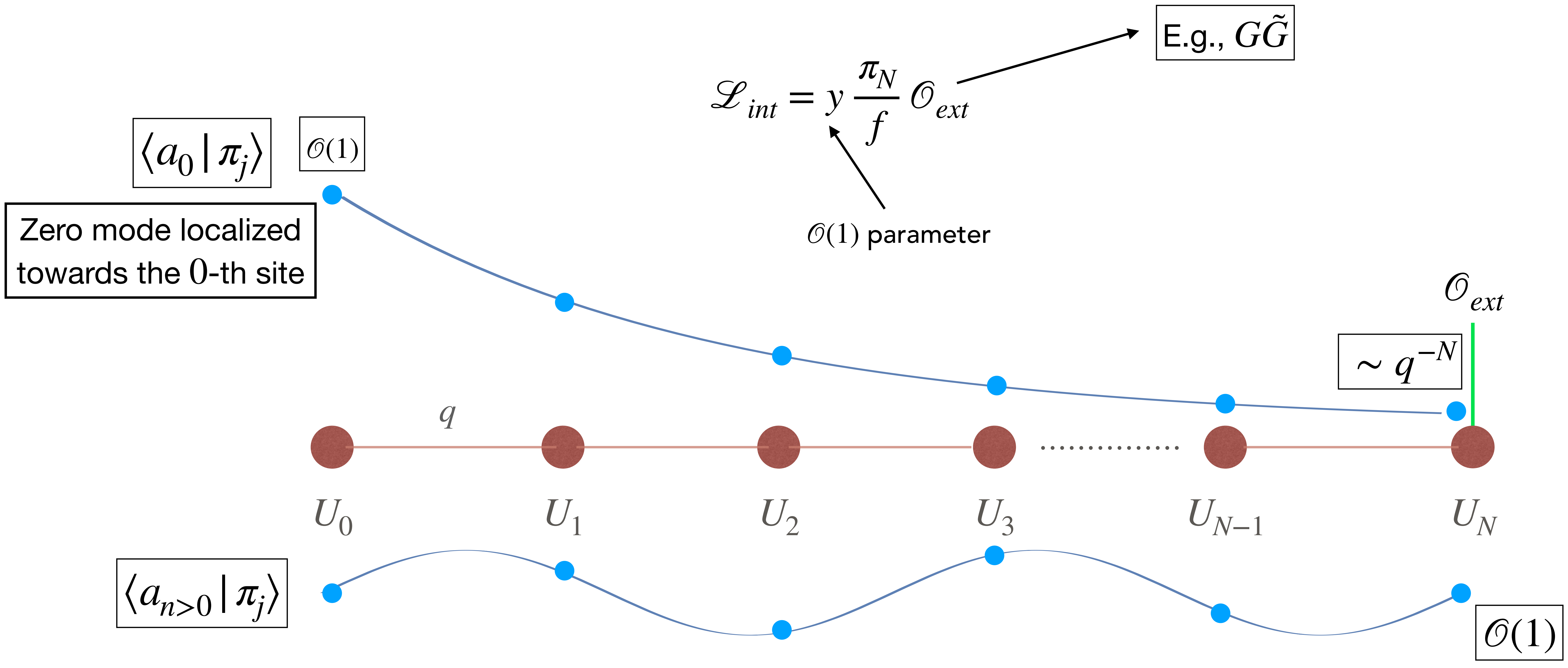
Massive modes have nearly similar overlaps with all $\pi' s$ with an effective decay constant $f_{\text{eff}}^{(n)} \sim f$

Theory space lattice –



Couplings with an external sector:

Suppose the CW sector couples to an external operator at the N-th site.



In the mass basis this results in: $\mathscr{L}_{int} = y \left[\frac{\mathcal{N}_0}{q^N} \frac{a_0}{f} \mathcal{O}_{ext} + \sum_{n=1}^{N} \mathcal{N}_n q (-1)^n \sin \frac{n\pi}{N+1} \frac{a_n}{f} \mathcal{O}_{ext} \right]$

$f_{\text{eff}}^{(0)} = q^N f \gg f$

$f_{\text{eff}}^{(n)} \sim f$

What is Clockwork ?

- A mechanism to generate large hierarchies through **localization** in a theory space of **multiple** fields.

- Basic requirement— near-neighbour interacting fields with mass terms of the form: $$\left(\pi_j - q\pi_{j+1}\right)^2$$

  — Leads to a correspondence with a 5D linear dilaton theory of gravity.

- Can be generalized to fermions, vector bosons and gravitons.

Clockwork QCD Axion

M. Farina et. al., (2017);
S. Bhattacharya, D. Choudhury, SM, T. Srivastava, hep-ph 2409.05983

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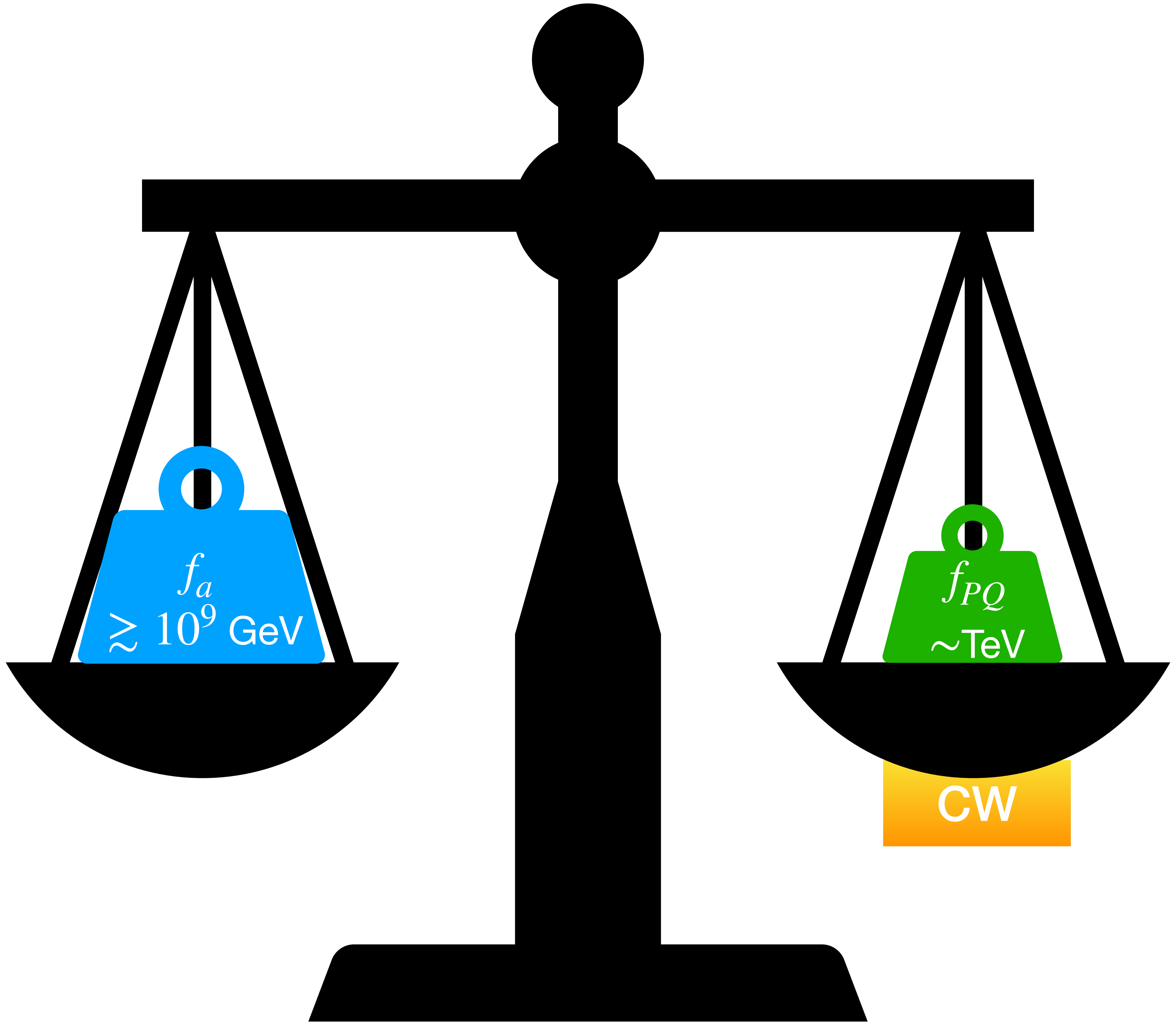
Goal: To have a low-scale PQ breaking



Introduce a CW sector:

$N + 1$ copies of a complex scalar Φ – $N + 1$ copies of $U(1)_{PQ}$ symmetry

$$\mathscr{L}_{CW} = \sum_{j=0}^{N} \left[\partial_\mu \Phi_j \partial^\mu \Phi_j - \lambda \left(\Phi_j^\dagger \Phi_j - f^2/2 \right)^2 \right] + \lambda' \Lambda^{3-q} \sum_{j=0}^{N-1} \Phi_j^\dagger \Phi_{j+1}^q + \text{h.c.}$$

SSB at scale $f_{PQ} \equiv f \quad \longrightarrow \quad \Phi_j = \frac{1}{\sqrt{2}} (\phi_j + f) e^{i\pi_j/f}$

Introduce a CW sector:

$N+1$ copies of a complex scalar Φ — $N+1$ copies of $U(1)_{PQ}$ symmetry

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SSB at scale $f_{PQ} \equiv f \quad \longrightarrow \quad \Phi_j = \frac{1}{\sqrt{2}}(\phi_j + f) e^{i\pi_j/f}$

The usual PQ axion with decay constant $f_0 \gg f$ (TeV)

Couple it to the color anomaly at the N-th site:

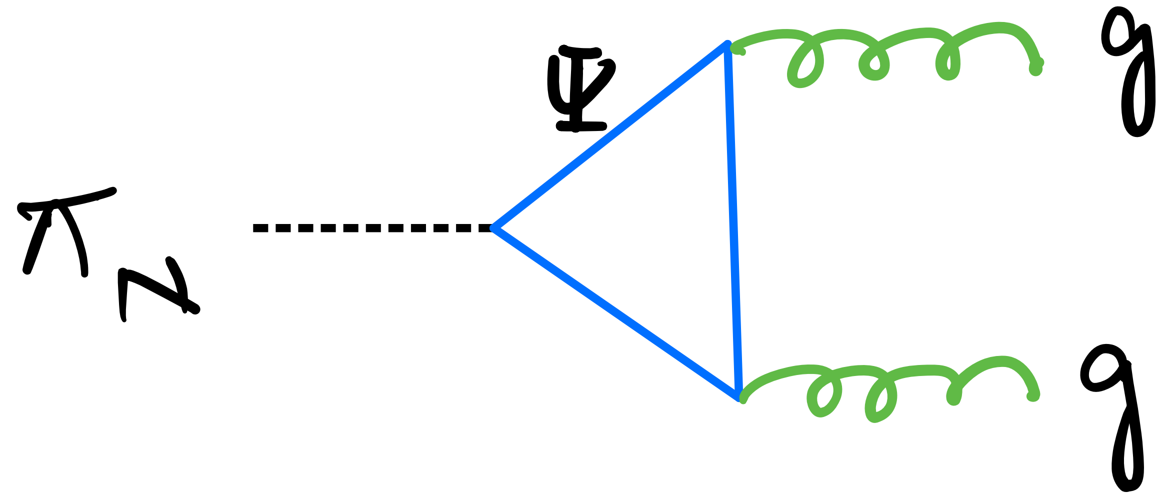
$$-\frac{\pi_N}{f} G^{A\mu\nu} \tilde{G}^A_{\mu\nu} \longrightarrow -\frac{a_0}{q^N f} G^{A\mu\nu} \tilde{G}^A_{\mu\nu}$$

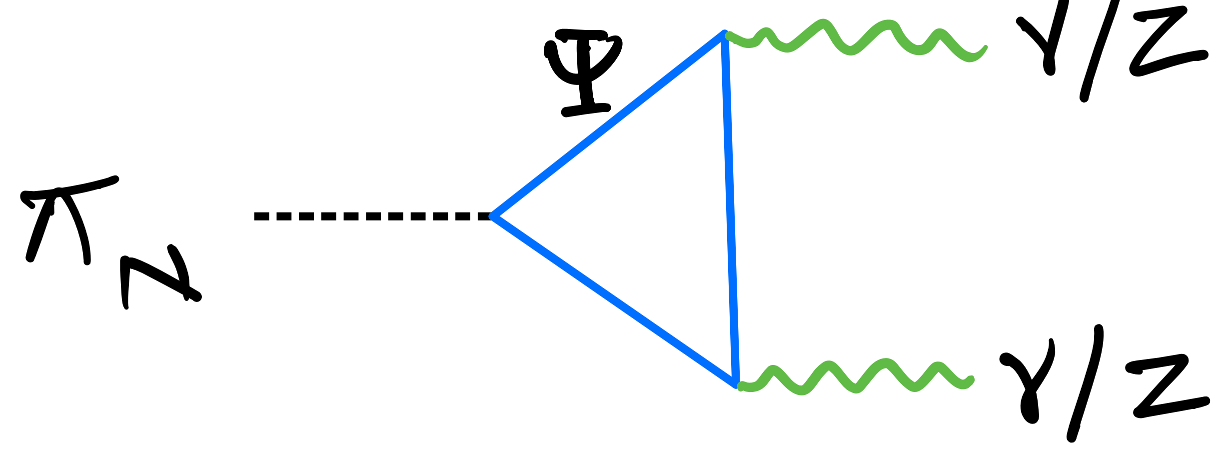
How do you get the color anomaly ? → Introduce a set of new coloured fermions $\Psi_{L,R}$ (à la KSVZ)

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_N$
Φ_N	1	1	0	ξ
Ψ_L	3	1	Y_Ψ	ξ
Ψ_R	3	1	Y_Ψ	0

→ Localized PQ charge

Leads to couplings with γ and Z as well





$$\mathscr{L}_{\pi vv} = -\, g_{\pi gg}\, \pi_N G^{A\mu\nu}\tilde{G}^A_{\mu\nu} - g_{\pi\gamma\gamma}\, \pi_N F^{\mu\nu}\tilde{F}_{\mu\nu} - g_{\pi\gamma Z}\, \pi_N F^{\mu\nu}\tilde{Z}_{\mu\nu} - g_{\pi ZZ}\, \pi_N Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

$$g_{\pi gg} = \frac{\alpha_s \xi}{8\pi f}, \quad g_{\pi\gamma\gamma} = \frac{2N_c \alpha_{EM} \xi Y_\Psi^2}{8\pi f}, \quad g_{\pi\gamma Z} = \frac{-4N_c s_w^2 \alpha_{EM} \xi Y_\Psi^2}{8\pi f s_w c_w}, \quad g_{\pi ZZ} = \frac{2N_c s_w^4 \alpha_{EM} \xi Y_\Psi^2}{8\pi f s_w^2 c_w^2}$$

What's more? → The ALPs

$$\mathcal{L}_{\pi vv} = -\, g_{\pi gg}\, \pi_N G^{A\mu\nu}\tilde{G}^A_{\mu\nu} - g_{\pi\gamma\gamma}\, \pi_N F^{\mu\nu}\tilde{F}_{\mu\nu} - g_{\pi\gamma Z}\, \pi_N F^{\mu\nu}\tilde{Z}_{\mu\nu} - g_{\pi ZZ}\, \pi_N Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

Expand π_N in the physical basis — the ALPs can couple to gluons, photons and Z with relatively **small decay constant** $f_n \sim f$

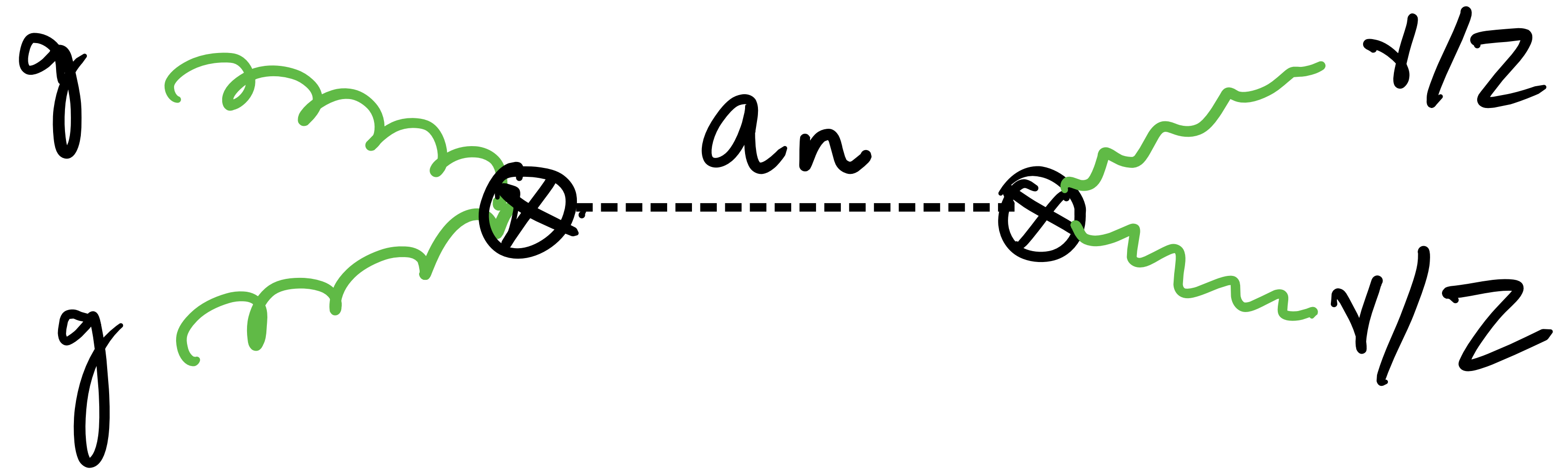
$$g_{\pi XX} \propto \langle a_n | \pi_N \rangle$$

Possibility of resonant production at hadron colliders ?

$$p\,p \to a_n(+X) \to \gamma\,\gamma$$

$$p\,p \to a_n(+X) \to Z\gamma$$

$$p\,p \to a_n(+X) \to ZZ$$



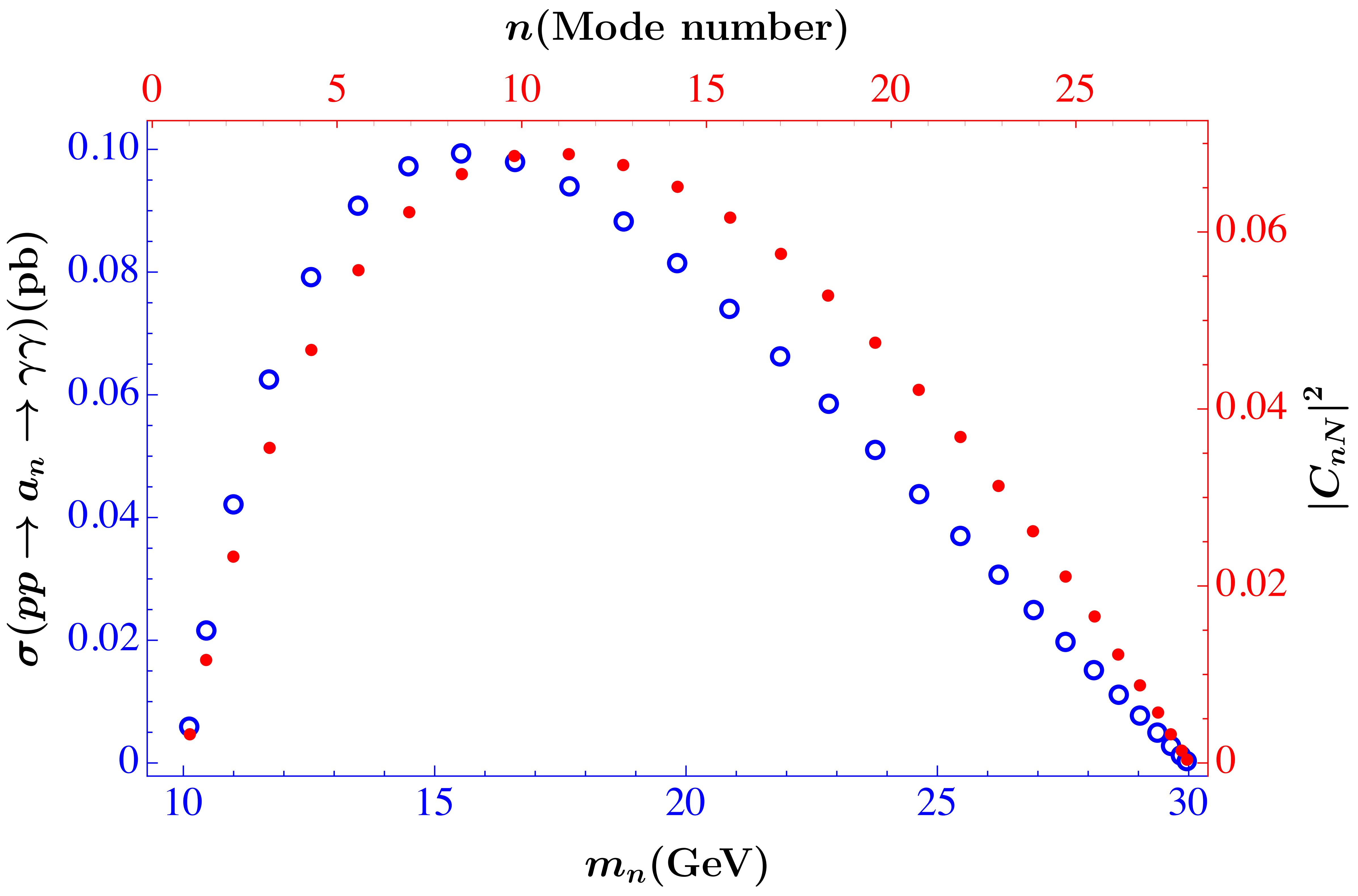
Signatures

S. Bhattacharya, D. Choudhury, SM, T. Srivastava, hep-ph 2409.05983

- **Benchmark I - light ALPs**

QCD axion can be DM via misalignment

For $m = 10$ GeV, $q = 2$, $f = 1$ TeV, $N = 28$, $\xi = 3$, $Y_\Psi = 2/3$



Masses, couplings and diphoton cross-sections over the full phase space for individual resonances $\left(\sqrt{s} = 13\text{ TeV}\right)$.

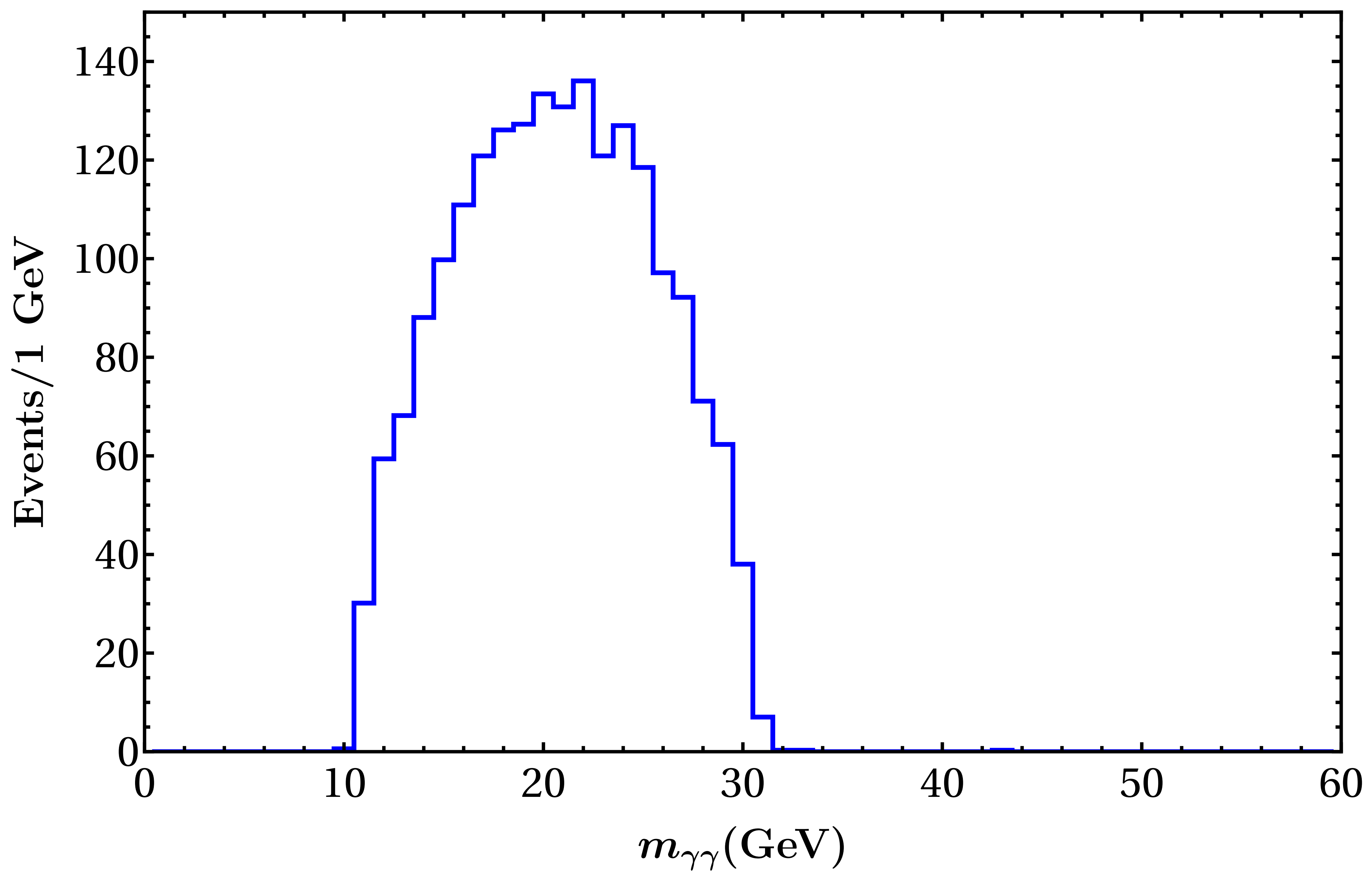
Small mass splittings

$\Delta m \sim 2m/N \lesssim 1$ GeV

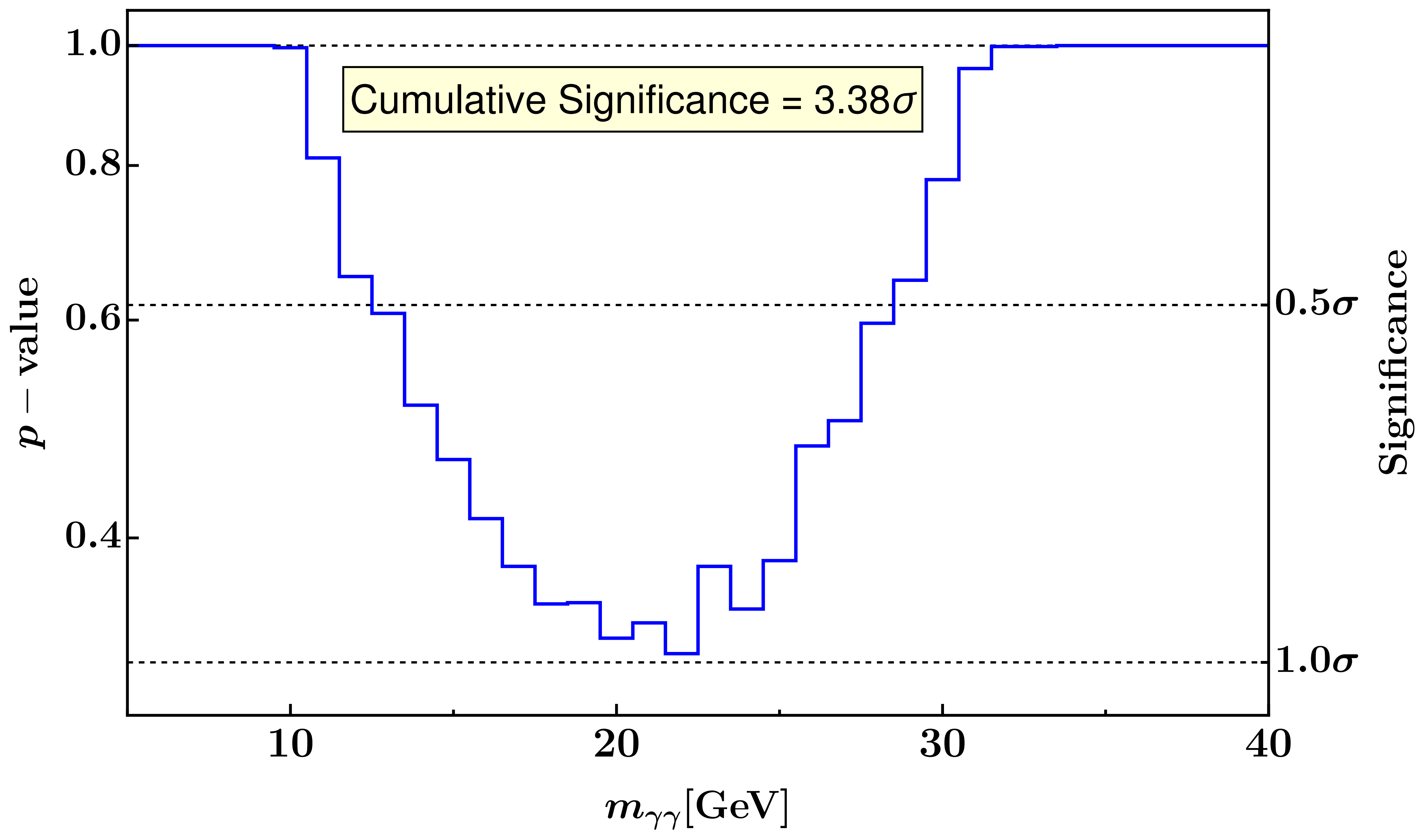
Scenario at the $\sqrt{s} = 13$ TeV and $\mathscr{L} = 138$ fb^{-1} LHC :

Channel	Event Selection Criteria
$pp \to a_n + 0/1/2\,\text{jets}$ $a_n \to \gamma\gamma$	$N_\gamma = 2,\ 1 \le N_j \le 2,$ $\lvert\eta_\gamma\rvert < 2.37$ $E_T(\gamma) > 22$ GeV, $p_T^{\gamma\gamma} > 50$ GeV

Kinematic cuts and background profile adopted from the ATLAS diphoton analysis 2211.04172



Simulated diphoton invariant mass distribution of the signal



Bin-wise significance estimate from a naive χ^2 analysis

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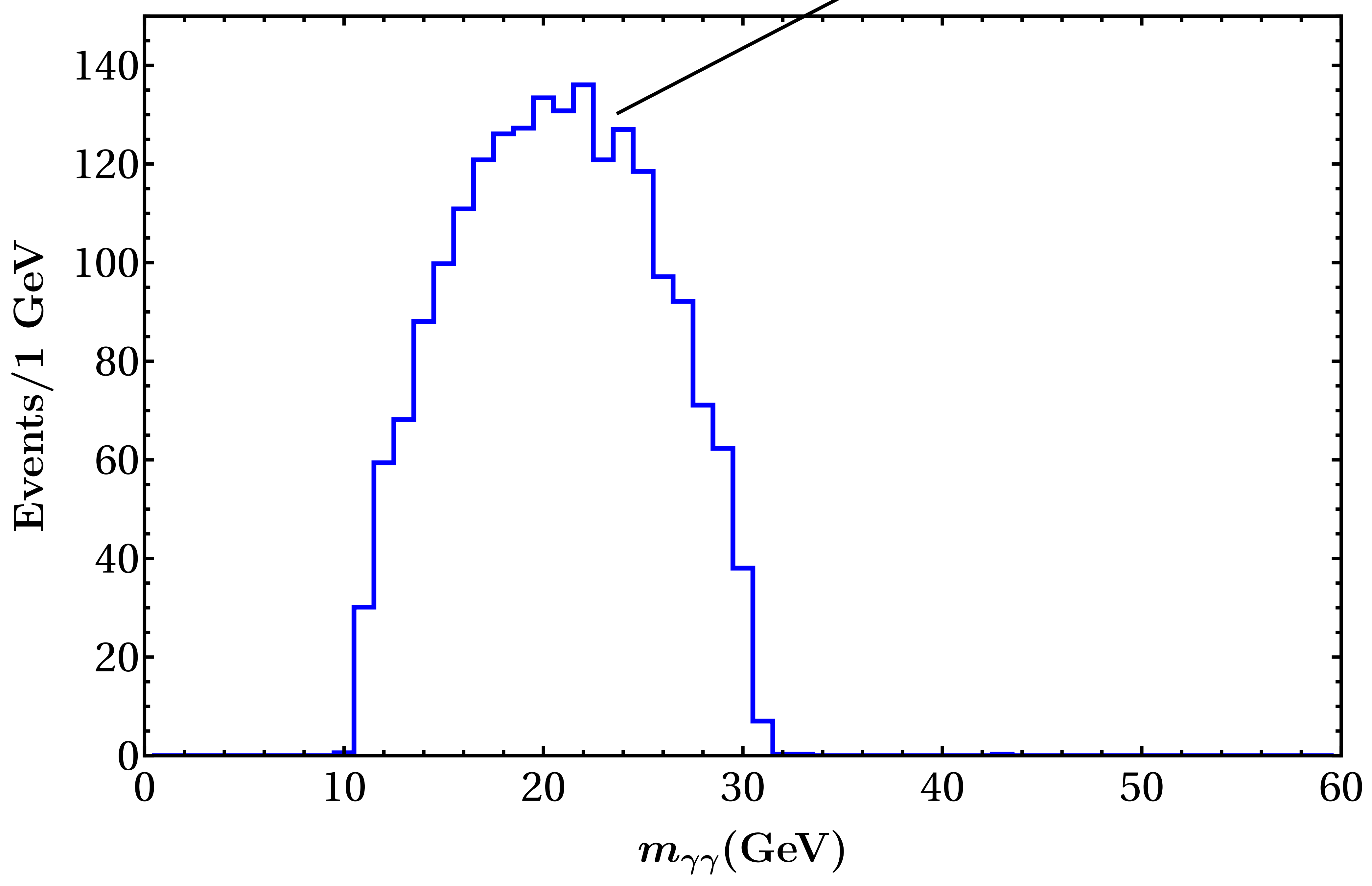
A **broad resonance** — An *axion iceberg*



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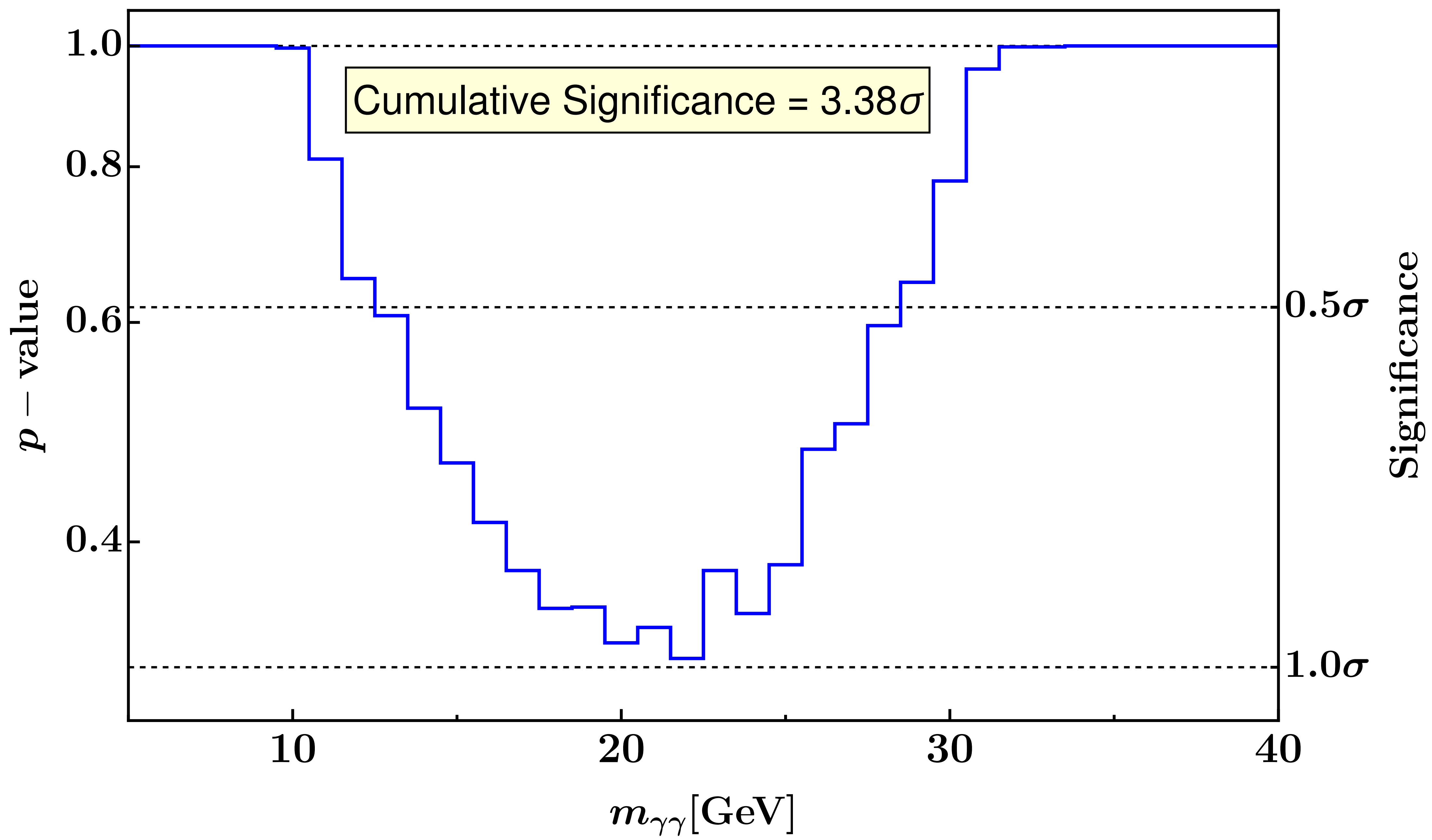
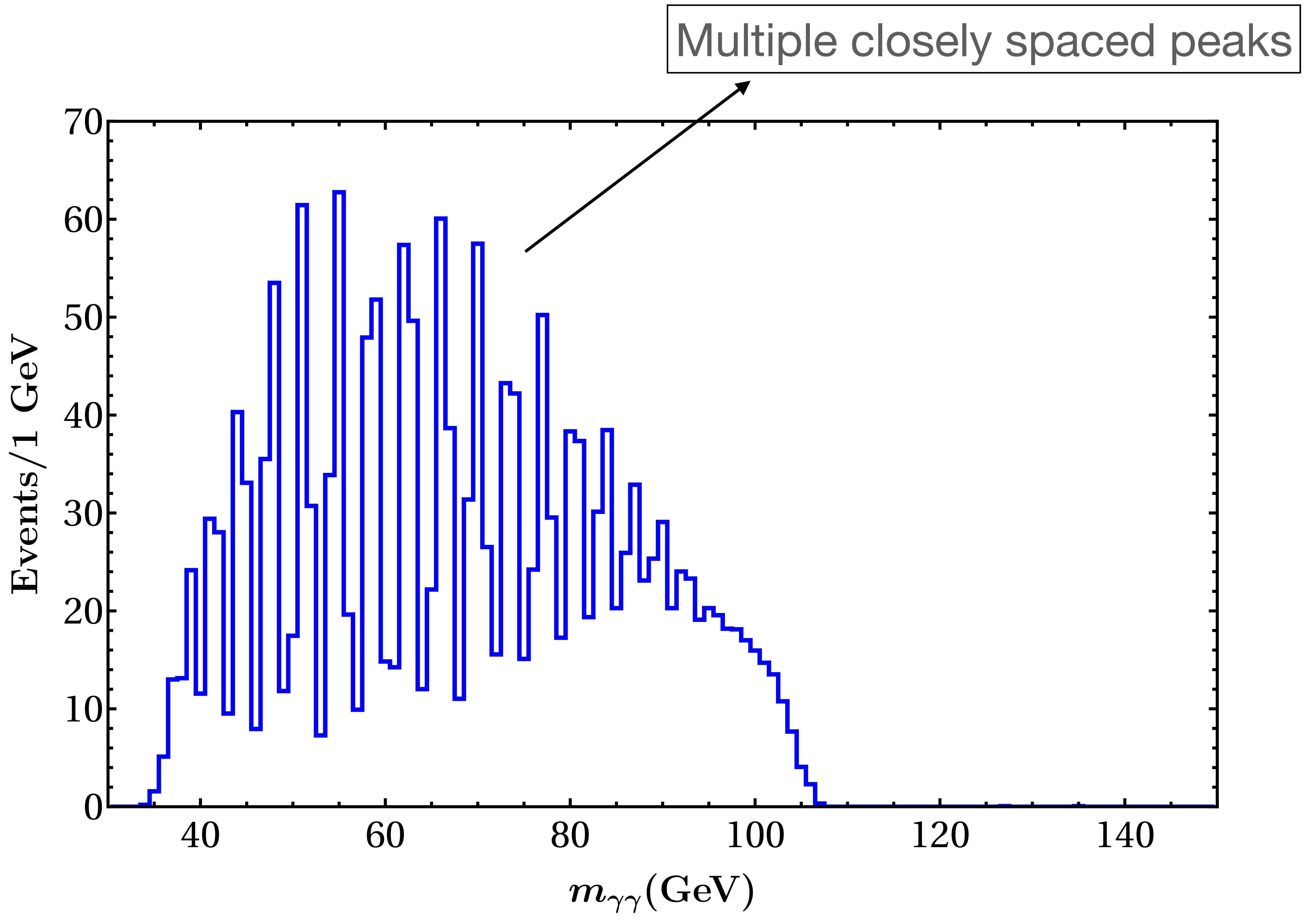


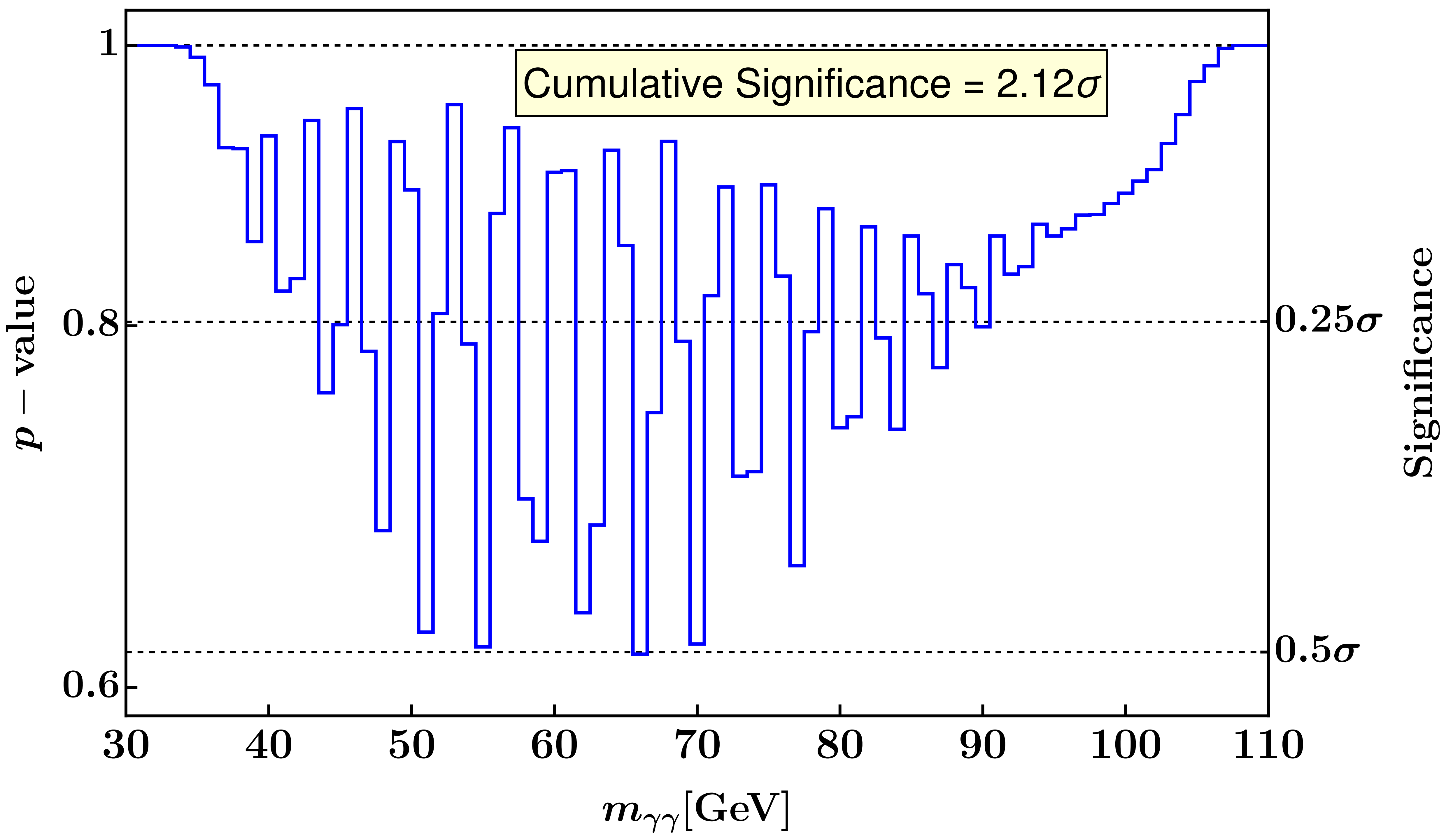
Bin-wise significance estimate from a naive χ^2 analysis

- **Benchmark II :** For $m = 35$ GeV, $q = 2$, $f = 1$ TeV, $N = 28$, $\xi = 3$, $Y_\Psi = 2/3$

Relatively larger mass splittings $\Delta m \lesssim 2.5$ GeV



Signal profile for $\sqrt{s} = 13$ TeV and $\mathscr{L} = 138$ fb^{-1} LHC.



Bin-wise significance

Takeaways

The good:

- Clockwork is a neat hierarchy generating mechanism via localization .
- Works for scalars, fermions, vector fields as well as gravitons.
- Many interesting applications - Axions, Dark Matter, flavour hierarchies, neutrino masses, baryogenesis, inflationary cosmology etc.
- Most notable application — realization of a QCD axion with a small PQ breaking scale. The associated ALPs could be potentially probed at the LHC, HL-LHC and beyond through signatures like broad resonances and multiple closely packed peaks.

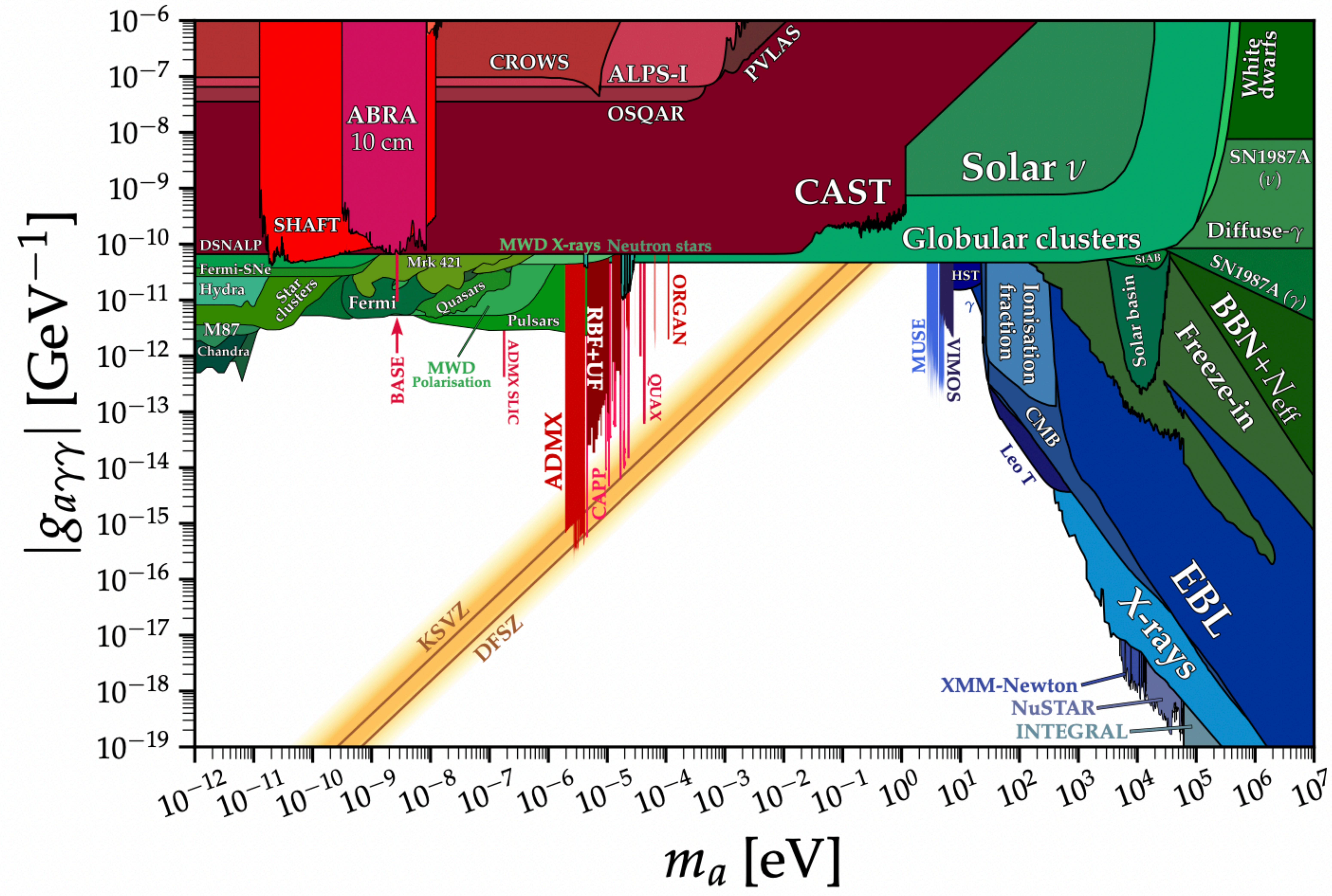
The bad and the ugly —- motivates future work:

- Reliance (largely) on global symmetries —better understanding of possible UV completions needed.
- Incompatibility with non-Abelian gauge theories.
- The CW-LD correspondence is a nice feature but not very well explored, needs careful inspection.
- Difficult to derive robust conclusions on the evolution of topological defects for high multiplicity axion models [see Long (2018), Higaki et. al.(2016), Lee et. al. (2025)]

Dziękuję !

Backup

Identifying benchmark points ⟶ $m, \quad q, \quad f$ of the CW sector are free parameters



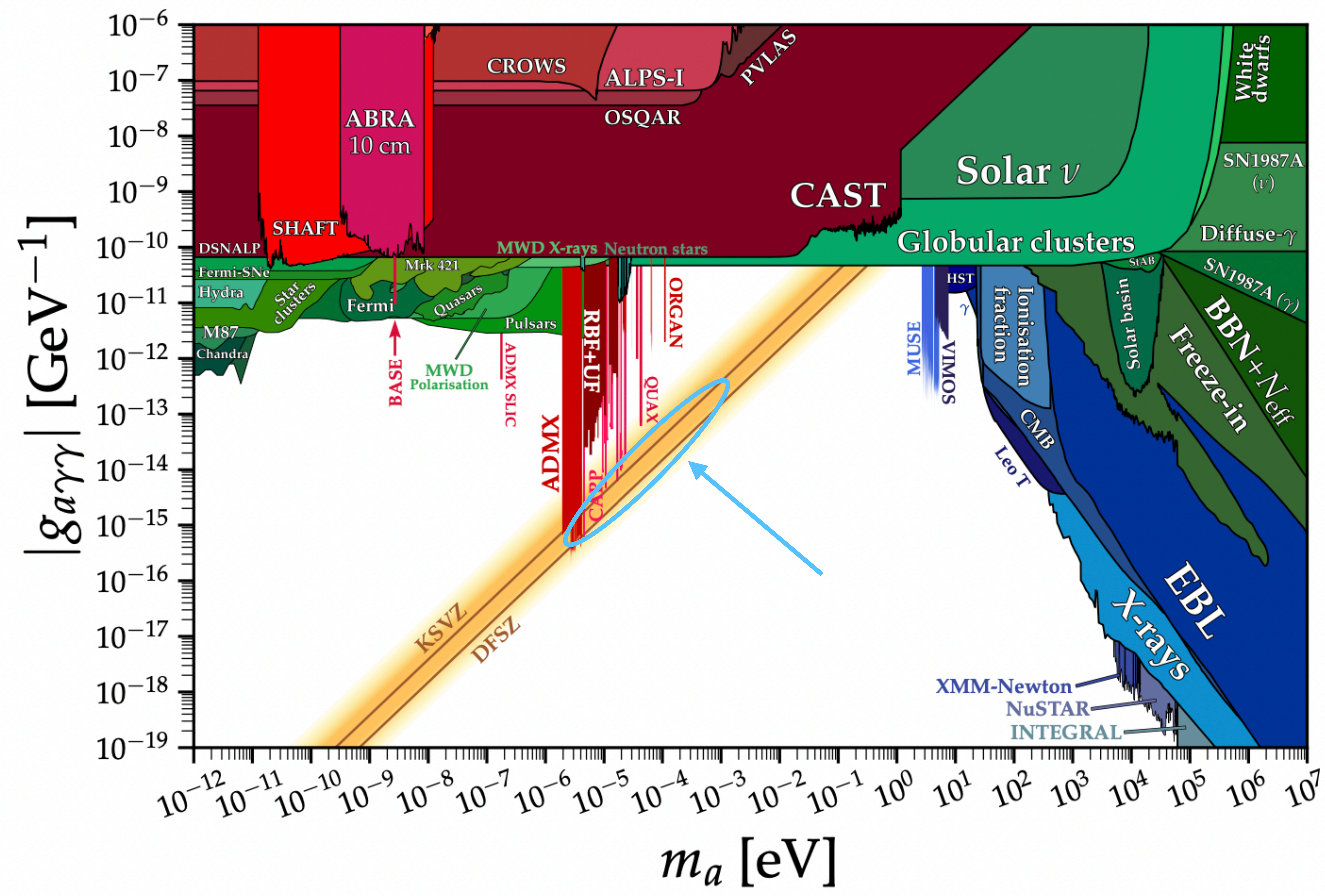
PDG (2023)

Lower limit from experimental and astro-cosmo observations

$$10^9\,\text{GeV} \lesssim \frac{q^N f}{\xi} \lesssim 10^{11}\,\text{GeV}$$

Upper limit from acceptable axion abundance in Universe

PDG (2023)



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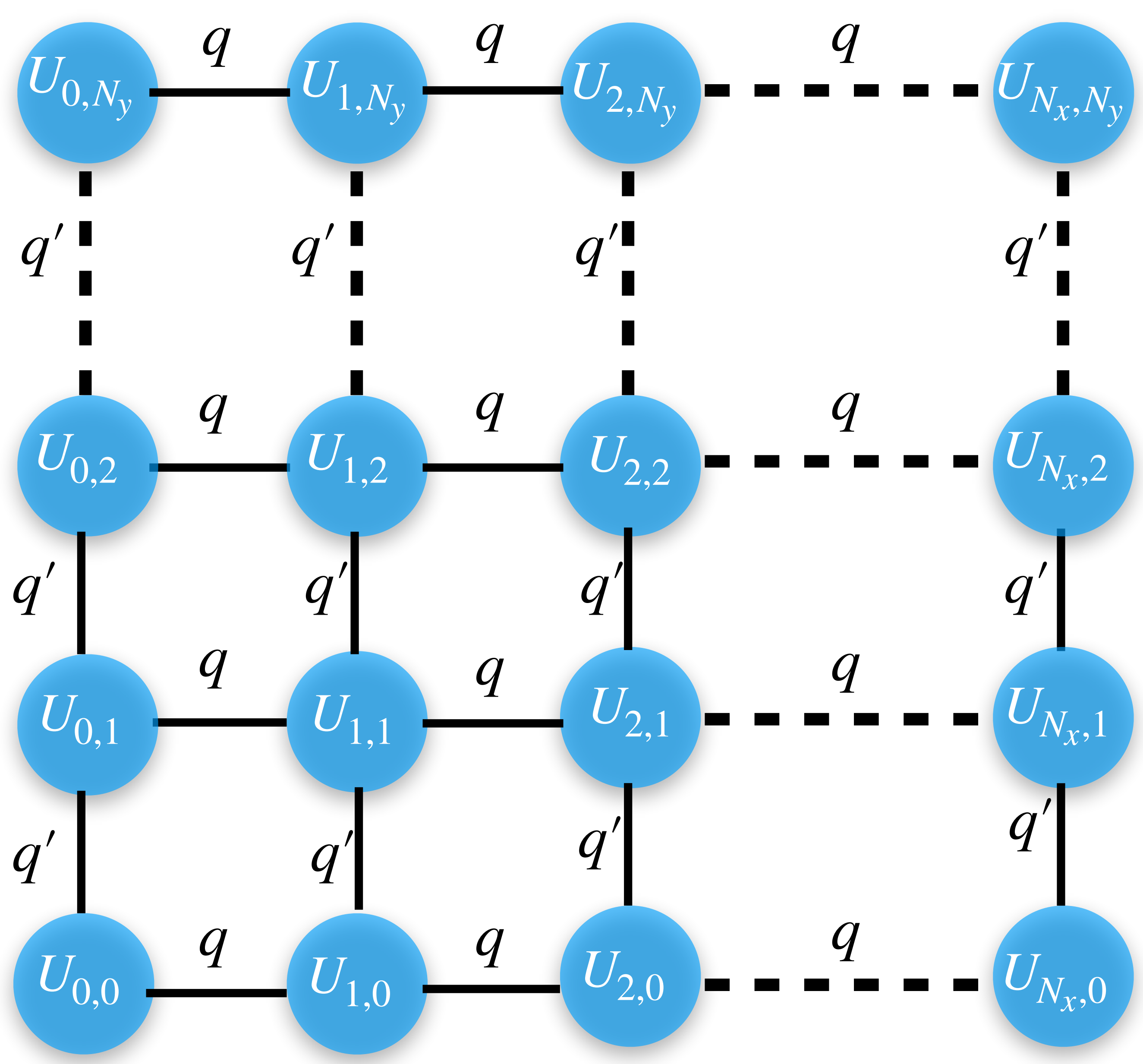
Axions from a 2D Clockwork

D. Choudhury, SM, T. Srivastava, *In preparation*



$$\mathscr{L}_{CW} = -\frac{f^2}{2}\sum_{x,y=0}^{N_x,N_y} \partial_\mu U^\dagger_{x,y}\partial^\mu U_{x,y} + \frac{m^2 f^2}{2}\sum_{x,y=0}^{N_x-1,N_y-1}\left[U^\dagger_{x,y}U^q_{x+1,y} + U^\dagger_{x,y}U^{q'}_{x,y+1}\right] + \text{h.c.}$$

$$\longrightarrow -\frac{1}{2}\sum_{x,y=0}^{N_x,N_y}\partial^\mu\pi_{x,y}\partial_\mu\pi_{x,y} + \frac{m^2}{2}\sum_{x,y=0}^{N_x-1,N_y-1}\left[(\pi_{x,y} - q\pi_{x+1,y})^2 + (\pi_{x,y} - q'\pi_{x,y+1})^2\right] + \mathcal{O}\left(\pi^4\right)$$

- Consider a similar KSVZ-type model, now with a 2D clockwork sector

$$\mathscr{L}_{\pi VV} = -\, g_{\pi GG}\, \pi_{N_x,N_y} G^{A\mu\nu} \tilde{G}^{A}_{\mu\nu} - g_{\pi BB}\, \pi_{N_x,N_y} B^{\mu\nu} \tilde{B}_{\mu\nu}$$

$$m^2_{n_x,n_y} = m^2 \begin{cases} 0 & n_x = 0, n_y = 0\ , \\ \left(1 + q^2 - 2q\cos\frac{n_x\pi}{N+1}\right) & n_x > 0, n_y = 0 \\ \left(1 + q'^2 - 2q'\cos\frac{n_y\pi}{N'+1}\right) & n_x = 0, n_y > 0 \\ 2\left[1 + \frac{1}{2}\left(q^2 + q'^2\right) - q\cos\frac{n_x\pi}{N+1} - q'\cos\frac{n_y\pi}{N'+1}\right] & n_x, n_y \neq 0\,. \end{cases}$$

$n_x = 0, n_y = 0$ → The QCD axion

$n_x > 0, n_y = 0$ and $n_x = 0, n_y > 0$ → Two bands of ALPs with suppressed couplings to gluons and photons—**(Long-lived ALPs)** l**-ALPs**

$n_x, n_y \neq 0$ → Band of ALPs with unsuppressed couplings similar to the 1D case—**(Short-lived ALPs)** s**-ALPs**

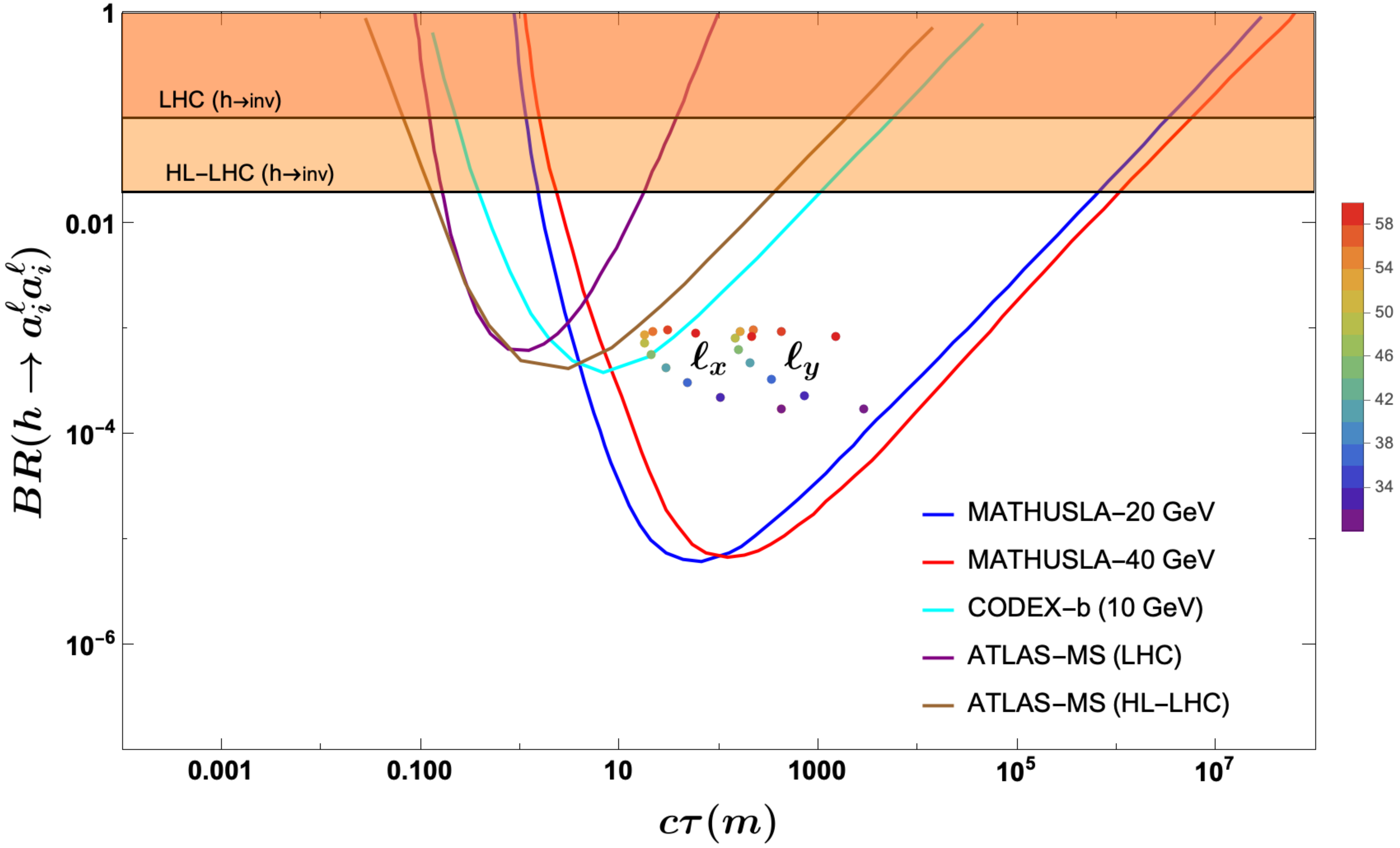
- Phenomenology of the s-ALPs is qualitatively similar to that in the 1D model.
- What's new is the presence of the long-lived ALPs. The dominant production channel would be hadron colliders is $h \to a_{LLP}\, a_{LLP}$ enabled by the $H - \Phi_{x,y}$ mixing terms—

$$\mathscr{L}_{\Phi H} = -\lambda_{\Phi H} \sum_{x,y=0}^{N_x,N_y} \Phi^{\dagger}_{x,y} \Phi_{x,y} H^{\dagger} H$$

- Long-lived ALPs are likely to decay beyond the LHC's main apparatus. However, they could be sensitive to displaced-vertex detectors such as the upcoming MATHUSLA experiment.

For $m = 15$ GeV, $q = q' = 3$, $f = 1$ TeV, $N_x = 10$, $N_y = 11$, $\xi = 3$, $Y_\Psi = 2/3$, $\lambda_{H\Phi} = 0.03$

Branching fractions of the SM Higgs decaying to two l-ALPs



Masses in GeV

Proper decay length of the l-ALP. The dominant decay mode is $a_{LLP} \to gg$.

Origins?…

Large decay constant from aligned axions

- The two axion Kim-Nilles-Peloso model –

JCAP 0501 (2005) 005

$$V = \Lambda_1^4 \left[1 - \cos\left(a_1 \frac{\pi_1}{f} + a_2 \frac{\pi_2}{f} \right) \right] + \Lambda_2^4 \left[1 - \cos\left(b_1 \frac{\pi_1}{f} + b_2 \frac{\pi_2}{f} \right) \right]$$

Only **one combination** appears in the potential when

$$\frac{a_1}{a_2} = \frac{b_1}{b_2}$$

Alignment condition

Standard axion potential

$$\Lambda^4 \left[1 - \cos\left(c\frac{\pi}{f}\right)\right]$$

Dynamically generated from ⟷

Axion coupling with the topological term of some confining sector

$$\frac{c}{32\pi^2}\frac{\pi(x)}{f}F\tilde{F}$$

Anomaly coefficient

Standard axion potential

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KNP potential

$$\Lambda^4 \left[1 - \cos\left(\frac{\pi_1}{f} + n\frac{\pi_2}{f}\right)\right]$$

⟷

$$\frac{1}{32\pi^2}\left(\frac{\pi_1}{f} + n\frac{\pi_2}{f}\right)F\tilde{F}$$

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Dynamically generated from

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Anomaly coefficient

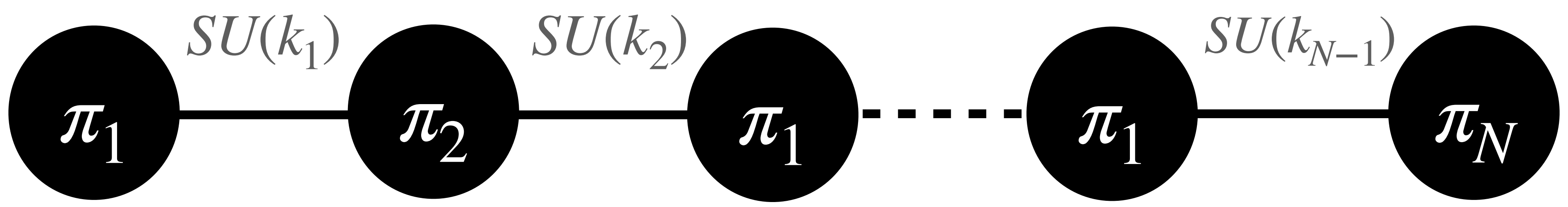
KNP potential

$$\Lambda^4\left[1-\cos\left(\frac{\pi_1}{f}+n\frac{\pi_2}{f}\right)\right]$$

$$\frac{1}{32\pi^2}\left(\frac{\pi_1}{f}+n\frac{\pi_2}{f}\right)F\tilde{F}$$

$$\sum_{i=1}^{N-1}\Lambda_i^4\left[1-\cos\left(\frac{\pi_i}{f}+n\frac{\pi_{i+1}}{f}\right)\right]$$

Multiple confining sectors



Clockwork as a deconstruction

Giudice, McCullough (JHEP02(2017)036)

Posit a warped five dimensional geometry of the form:

$$ds^2 = e^{-\frac{4}{3}kz}(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2) \qquad \eta_{\mu\nu} = \{-1,1,1,1\}$$

5D theory of a massless scalar $\phi(x,z)$:

$$\mathcal{S} = \int d^4x \int_0^{\pi R} dz \sqrt{-g} \left[-\frac{1}{2} g^{MN} \partial_M \phi(x,z)\, \partial_N \phi(x,z)\right]$$

Discretise (fifth)z-dimension of size πR into a lattice of $N+1$ sites with spacing $a = \dfrac{\pi R}{N}$

$$\phi(x,z) \to \phi_j(x)$$

$$\mathcal{S} = -\frac{1}{2}\int d^4x \sum_{j=0}^{N-1} \left\{(\partial_\mu \phi_j)^2 + \frac{N^2}{\pi^2 R^2}\left(\phi_j - e^{\frac{k\pi R}{N}}\phi_{j+1}\right)^2\right\}$$

The derivative is now a difference

CW Lagrangian with $m^2 \equiv \dfrac{N^2}{\pi^2 R^2}, \quad q \equiv e^{\frac{k\pi R}{N}}$

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The metric can be obtained from a Linear Dilaton Theory of Gravity

[Antionadis et. al. PRL (2012); Cox, Gherghetta JHEP (2012)]

5D theory of gravity with a linear dilaton generates the required geometry:

$$\mathcal{S}_{Bulk} = \int d^4x\, dz \sqrt{-g} \left\{ 2M_5^3 \left(\frac{1}{4}\mathcal{R} - \frac{1}{12} g^{MN} \partial_M S \partial_N S - V(S) \right) \right\}$$

$$\mathcal{S}_{Brane} = - \int d^4x\, dz \frac{\sqrt{-g}}{\sqrt{g_{55}}} \sum_\alpha \lambda_\alpha(S) \delta(z - z_\alpha) \quad \alpha = 1,2; z_\alpha = 0, \pi R$$

$\lambda_\alpha(S)$: Dilaton potentials on the branes

$$V(S) = -\, e^{-2S/3} k^2$$

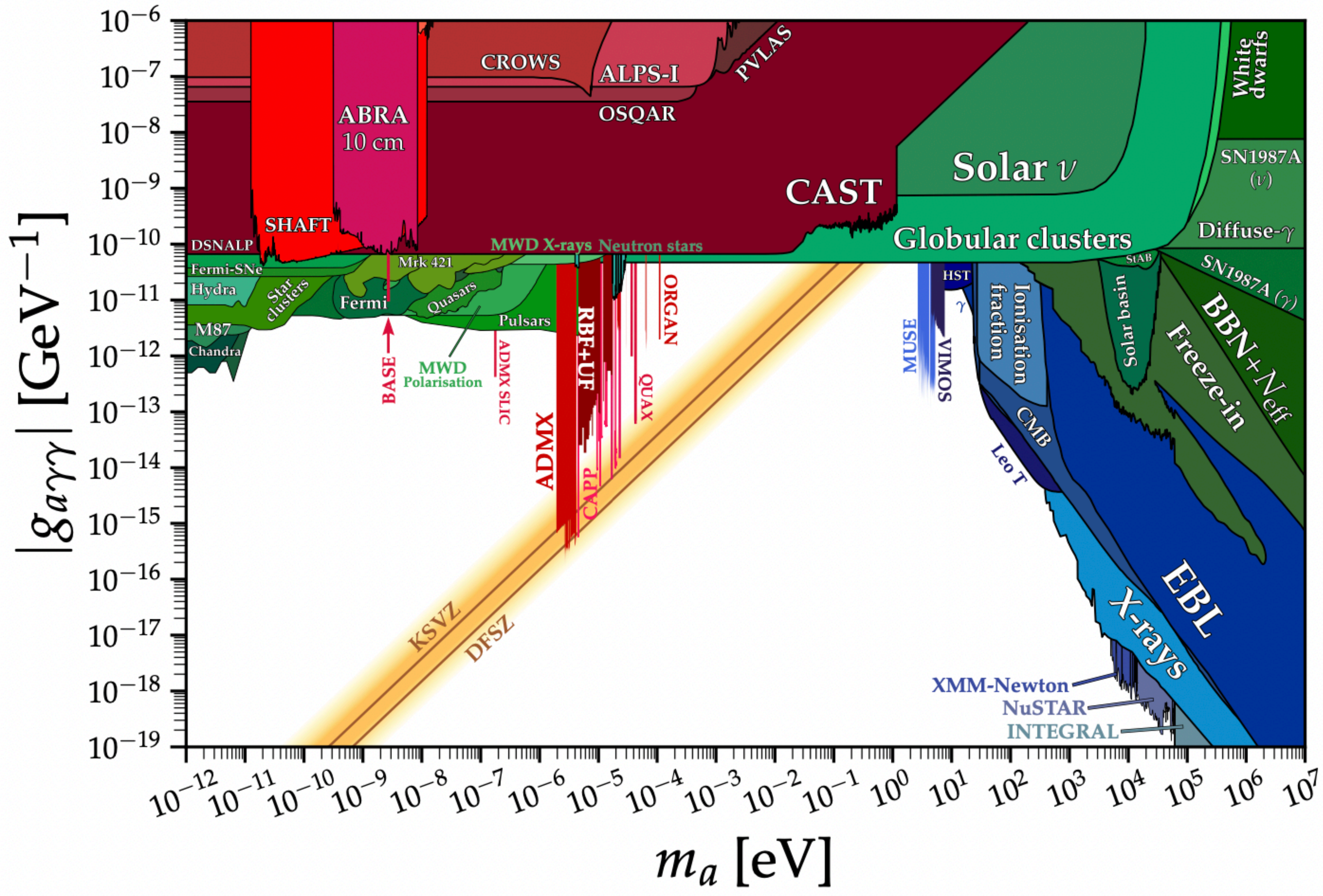
$$\lambda_\alpha(S) = e^{-S/3} \Lambda_\alpha,$$

k: A bulk mass parameter

Λ_α: Brane tensions

A fifth spatial dimension on an $S^1/\mathbb{Z}_2$ orbifold, essentially an interval of size πR.

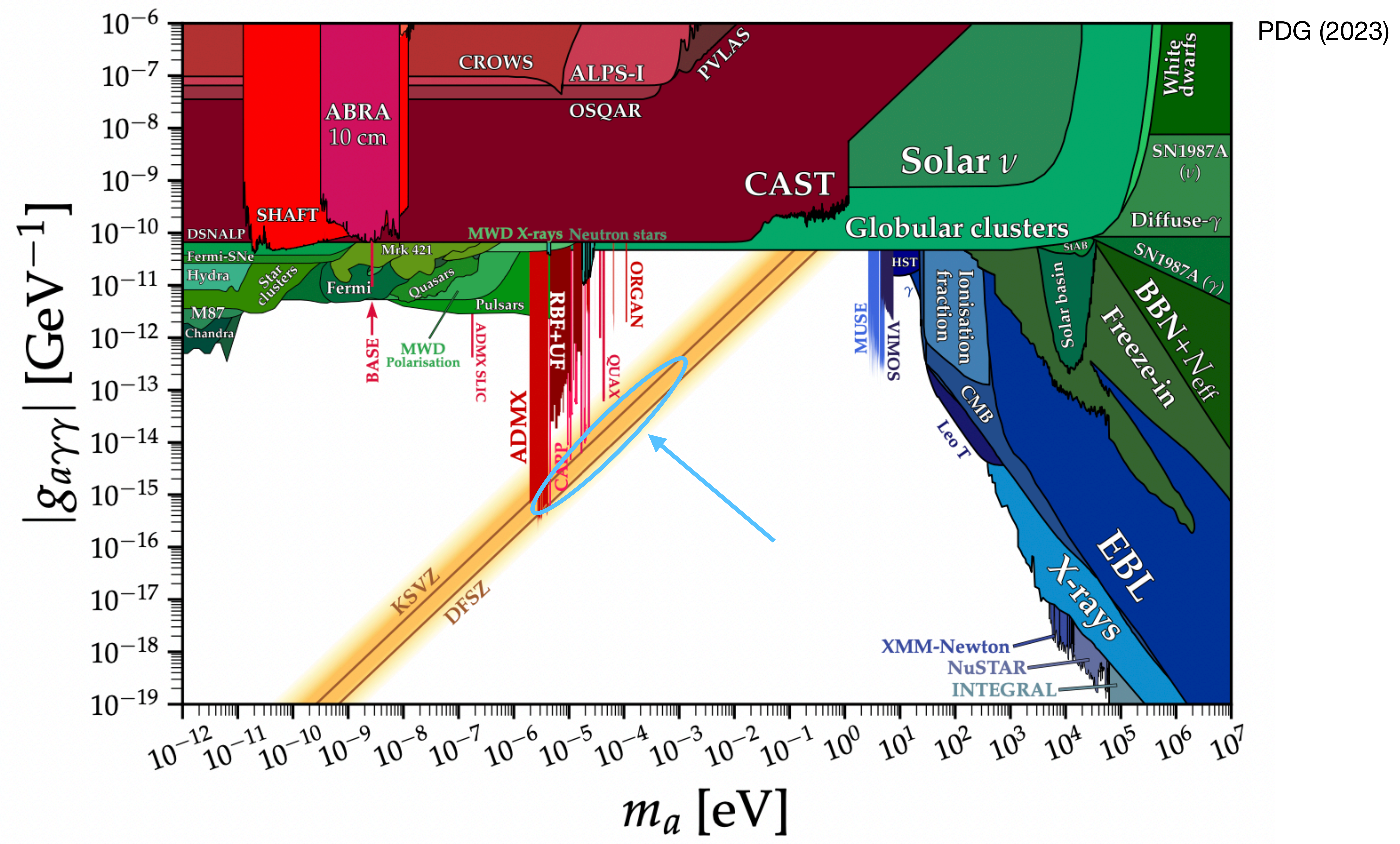
$$\boxed{ds^2 = e^{-\frac{4}{3}k\,z}(\eta_{\mu\nu} dx^\mu dx^\nu + dz^2)}$$



Lower limit from experimental and astro-cosmo observations

$$10^9\,\text{GeV} \lesssim \frac{q^N f}{\xi} \lesssim 10^{11}\,\text{GeV}$$

Upper limit from acceptable axion abundance in Universe



Lower limit from experimental and astro-cosmo observations

$$10^9\,\text{GeV} \lesssim \frac{q^N f}{\xi} \lesssim 10^{11}\,\text{GeV}$$

Upper limit from acceptable axion abundance in Universe

Benchmark III: Heavy ALPs

Channel	Event selection criteria
$pp \to a_n$	$N_\gamma = 2$, $N_j \leq 2$ $\lvert\eta_\gamma\rvert < 2.37$ (excluding barrel-to-endcap region $1.37 < \lvert\eta_\gamma\rvert < 1.52$),
$a_n \to \gamma\gamma$	$E_T(\gamma_1) > 0.3 m_{\gamma\gamma}$, $E_T(\gamma_2) > 0.25 m_{\gamma\gamma}$ $p_T^j > 20$ GeV, $\lvert\eta_j\rvert < 2.5$

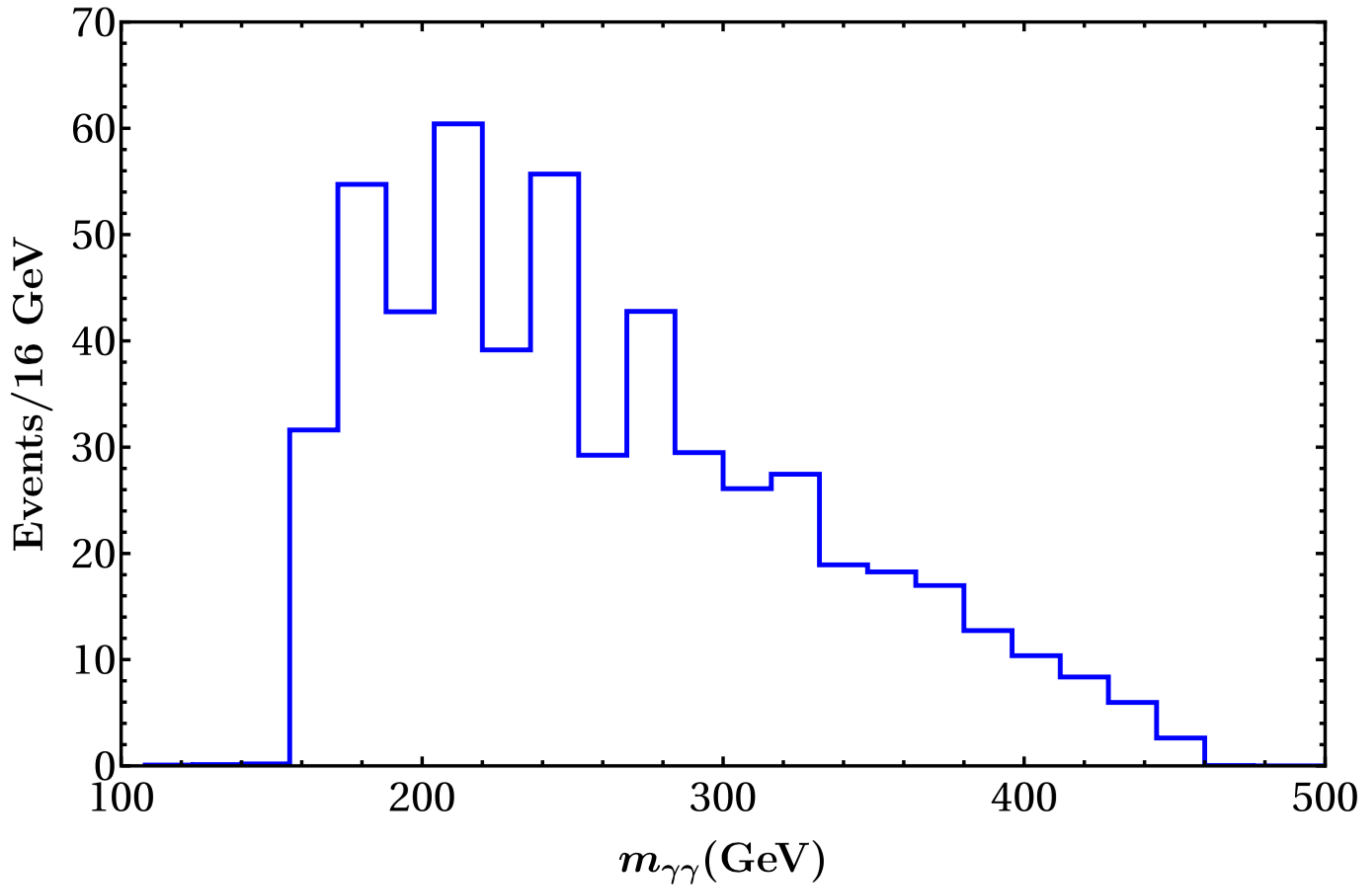


FIG. 16. BP-III: diphoton invariant mass distribution after applying selection cuts.

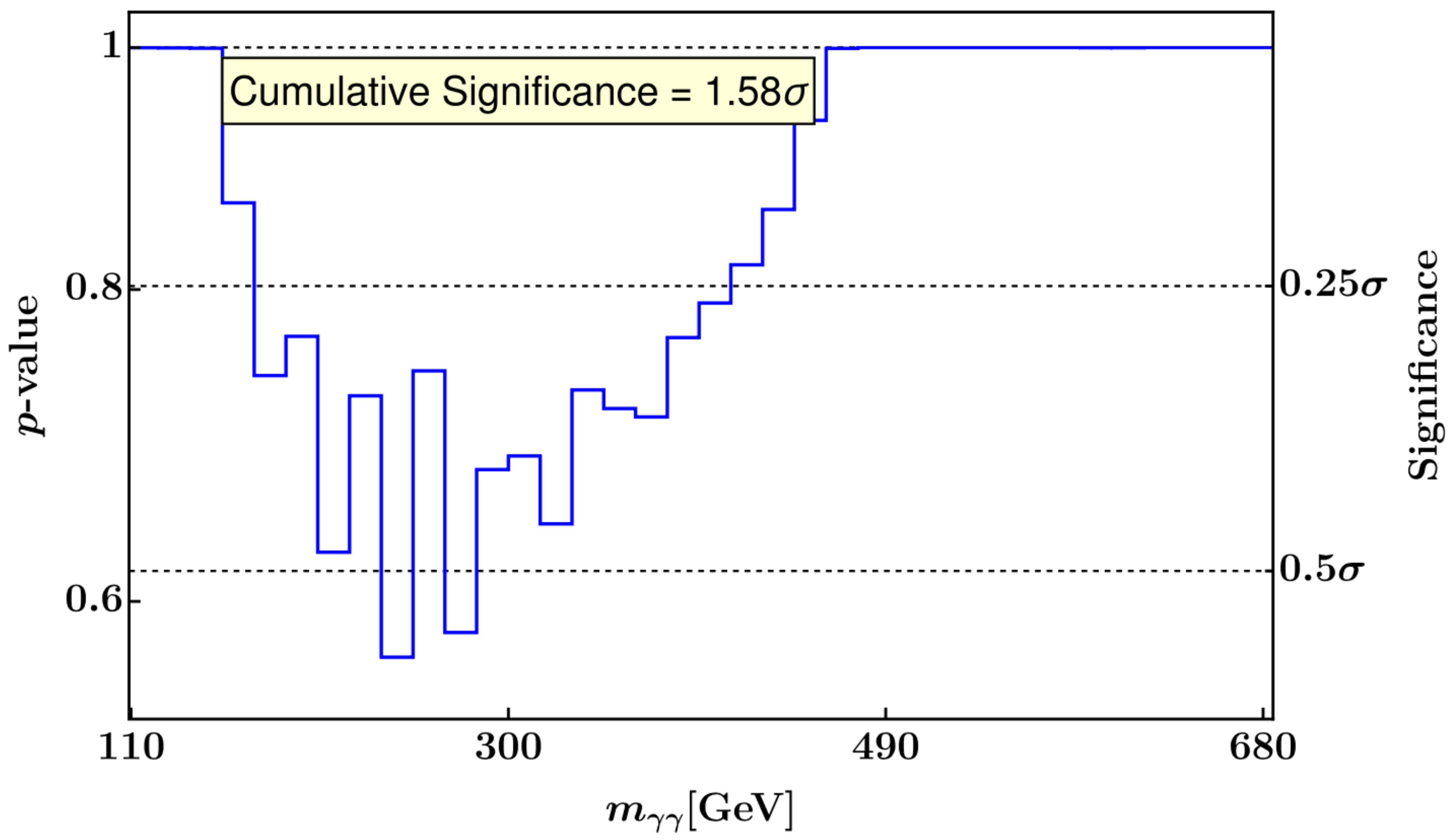
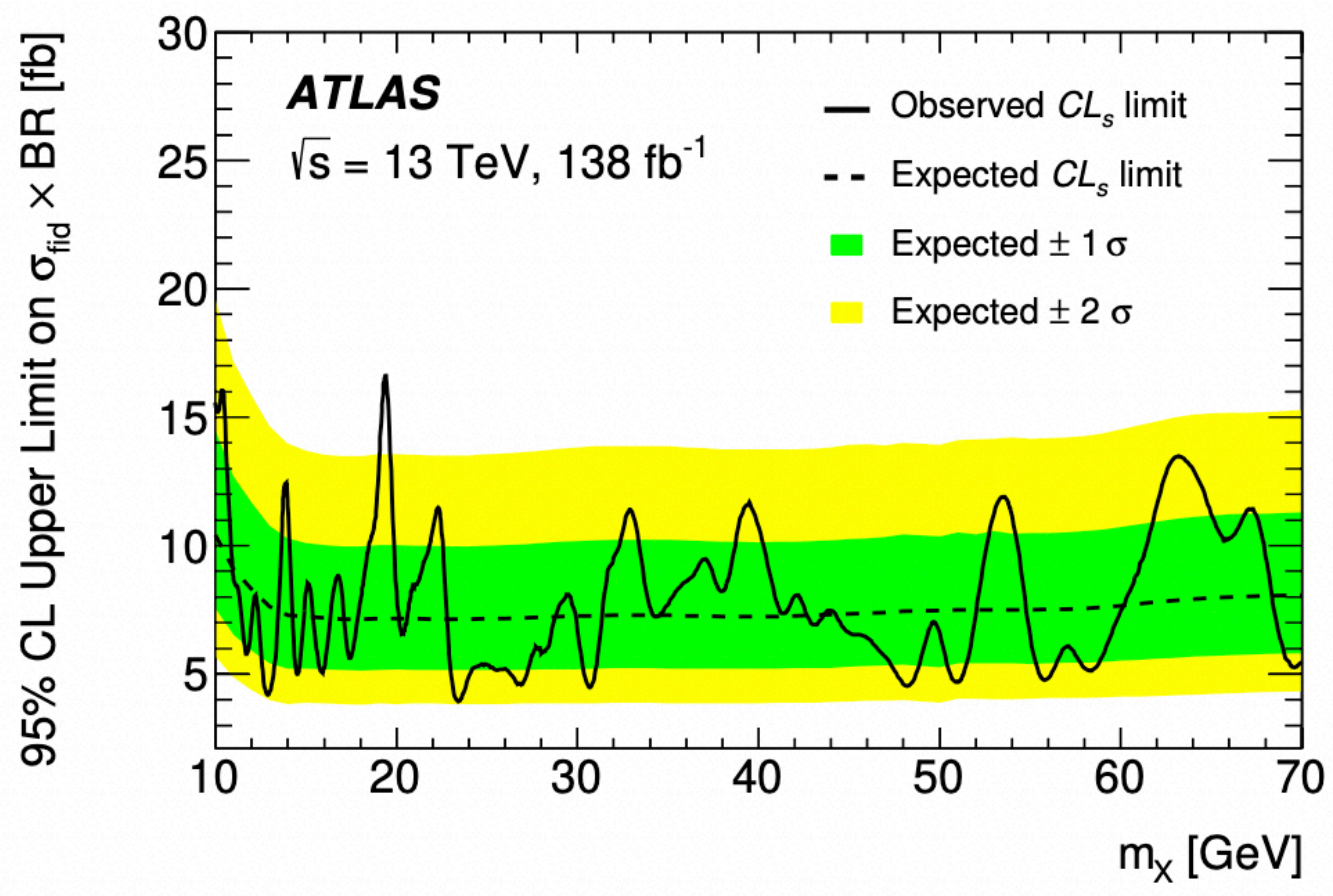


FIG. 17. Bin-wise significance for benchmark III at the LHC for $\mathcal{L} = 138$ fb^{-1}.

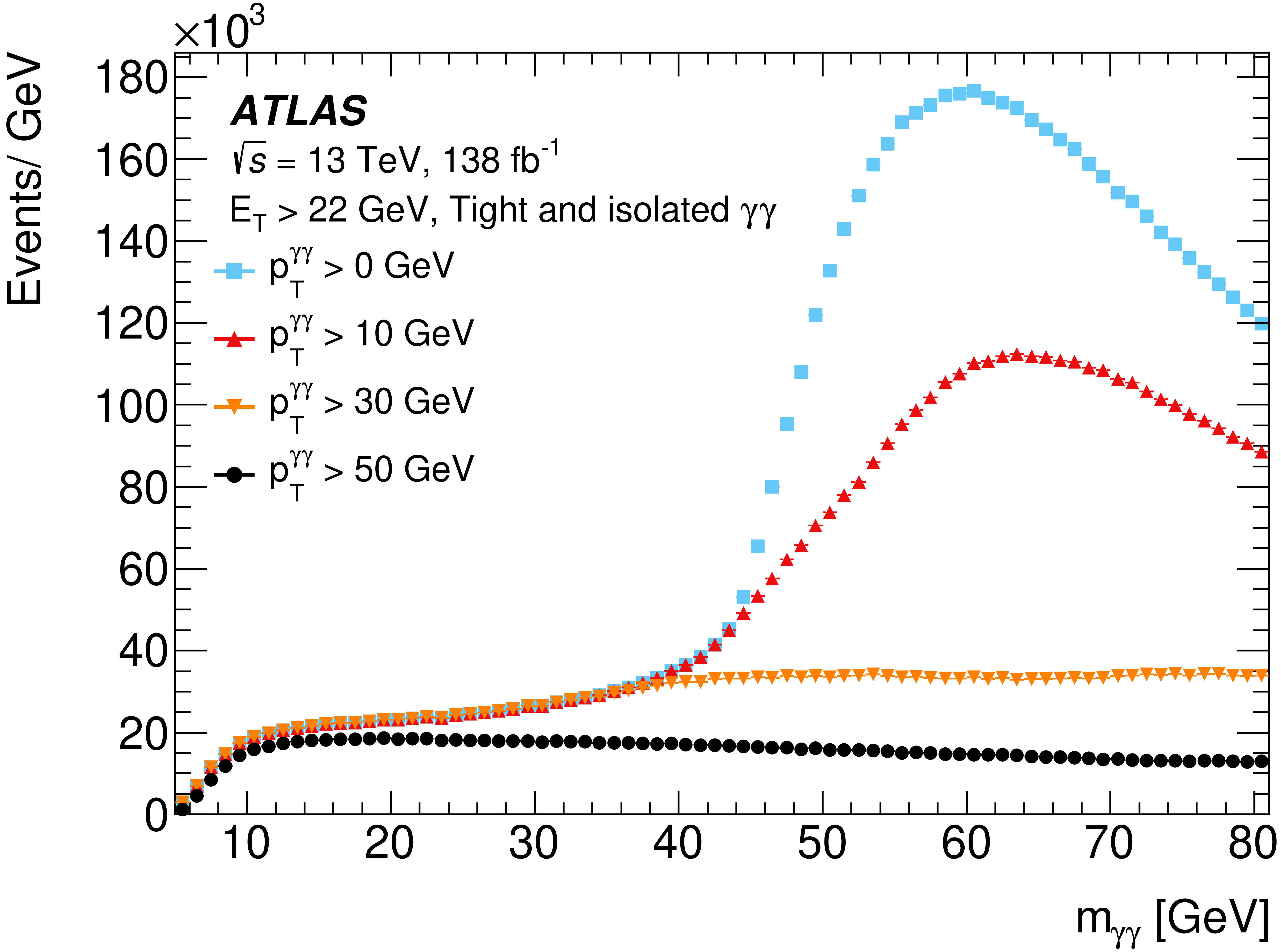
Can we get close to the current LHC sensitivities? $\rightarrow$ Motivates $f \sim \mathcal{O}(\text{TeV})$

Simplest and cleanest channel : $p\,p \rightarrow a_n(+X) \rightarrow \gamma\,\gamma$



Low mass diphoton resonance search: 2211.04172

Low mass $\gamma\gamma$ resonance search background



$pp \to \gamma\gamma$

$pp \to \gamma j$

$pp \to jj$

2211.04172

Back

VLQs and Heavy Scalars

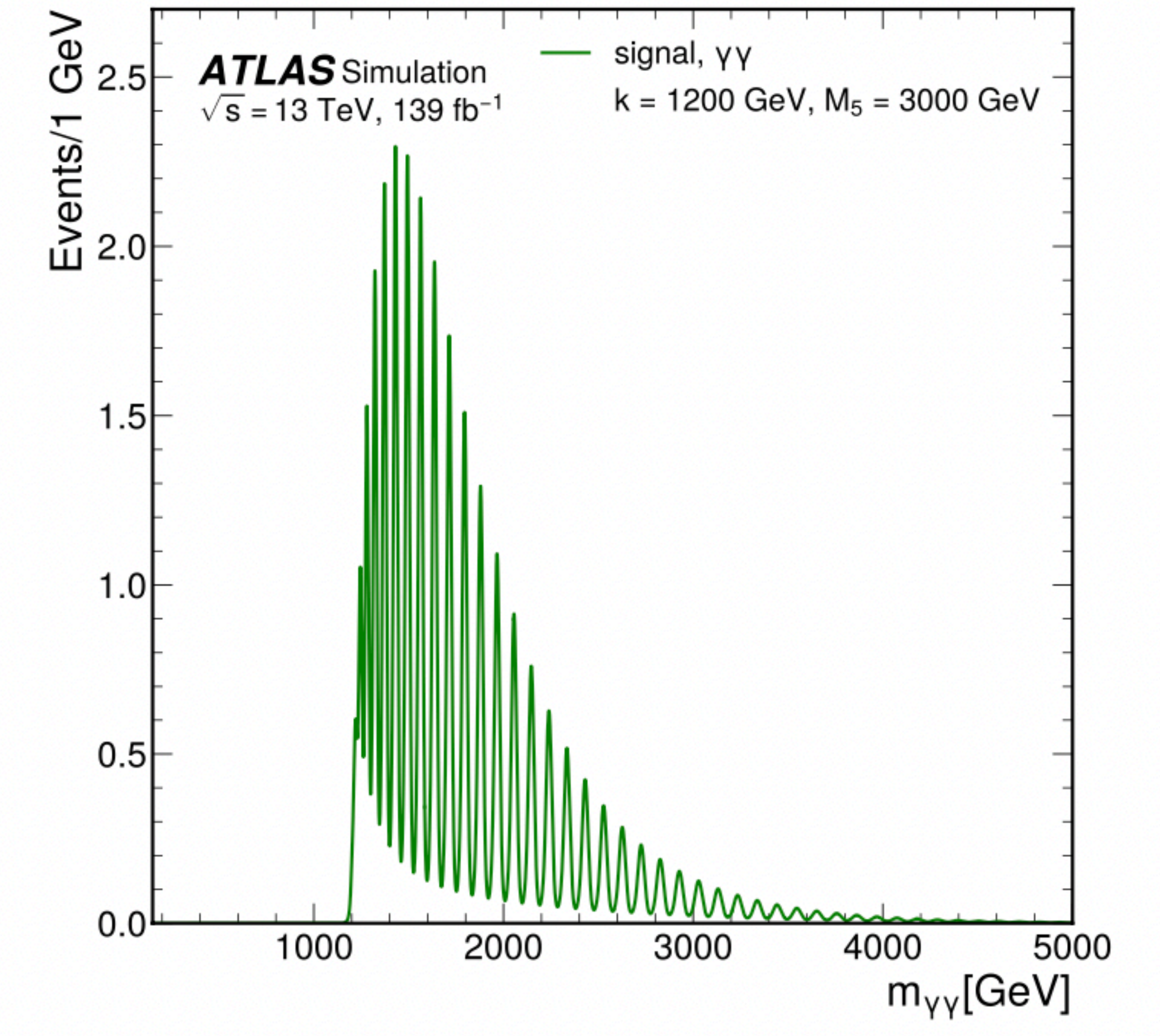
$$m_\Psi = \frac{1}{\sqrt{2}}\lambda_\Psi f, \quad m_\phi = \sqrt{2\lambda} f$$

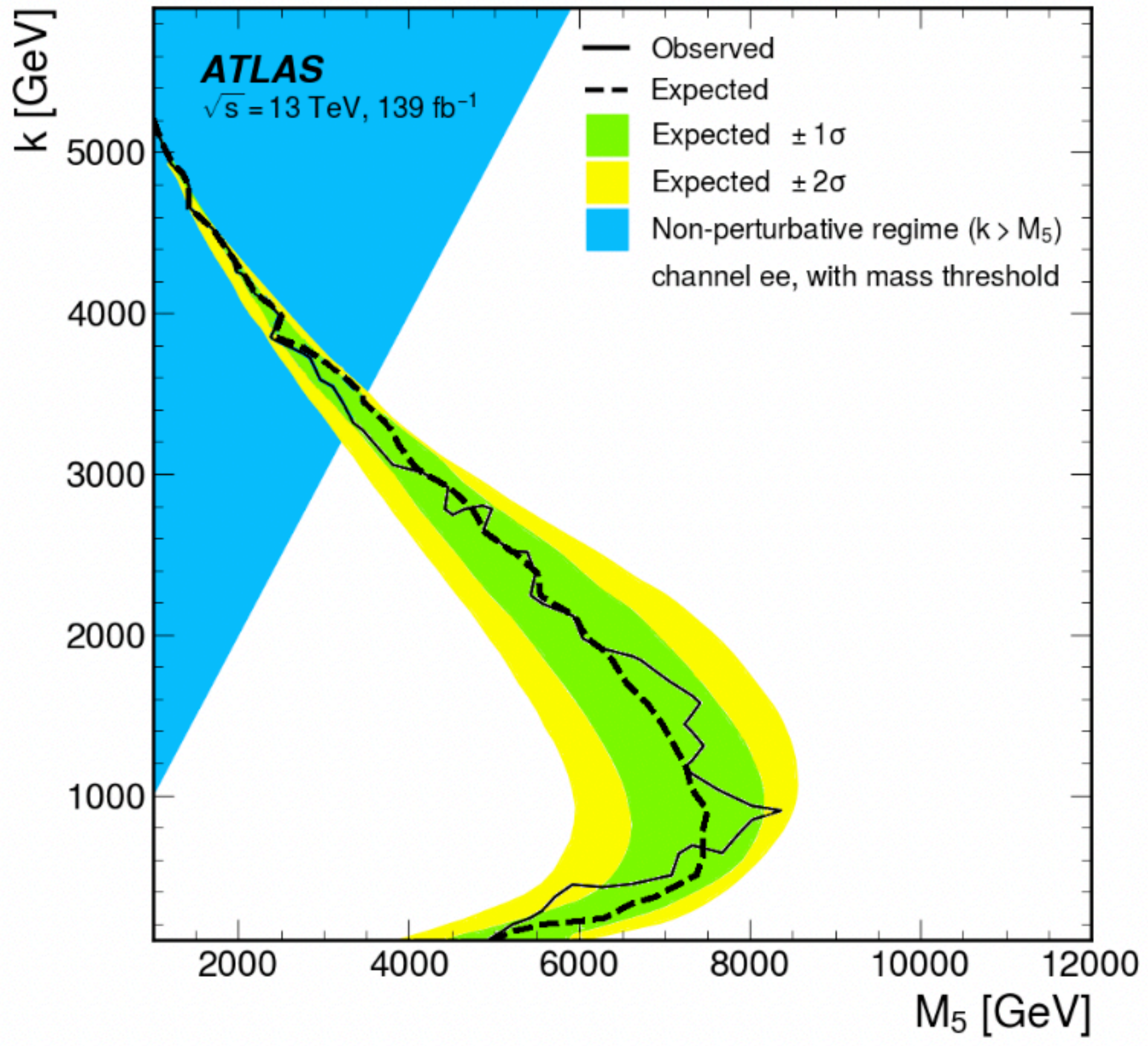
$$\lambda_\Psi = 2.2,\ y_\Psi = \epsilon y'_\Psi,\ \lambda = 1.8 \text{ and } y'_\Psi \lesssim 0.1 \text{ with } \epsilon = 0.1$$

Channel	**Branching Ratios**		
	SM	BP-I & II	BP-III
$T \to b\,W$	0.5	0.44	0.47
$T \to t\,Z$	0.25	0.21	0.23
$T \to t\,h$	0.25	0.23	0.25
$T \to t\,a_{(\text{all})}$	—	0.12	0.05
m_T **lower limit**	1540 GeV [105, 106]	1500 GeV	$\approx$ 1540 GeV

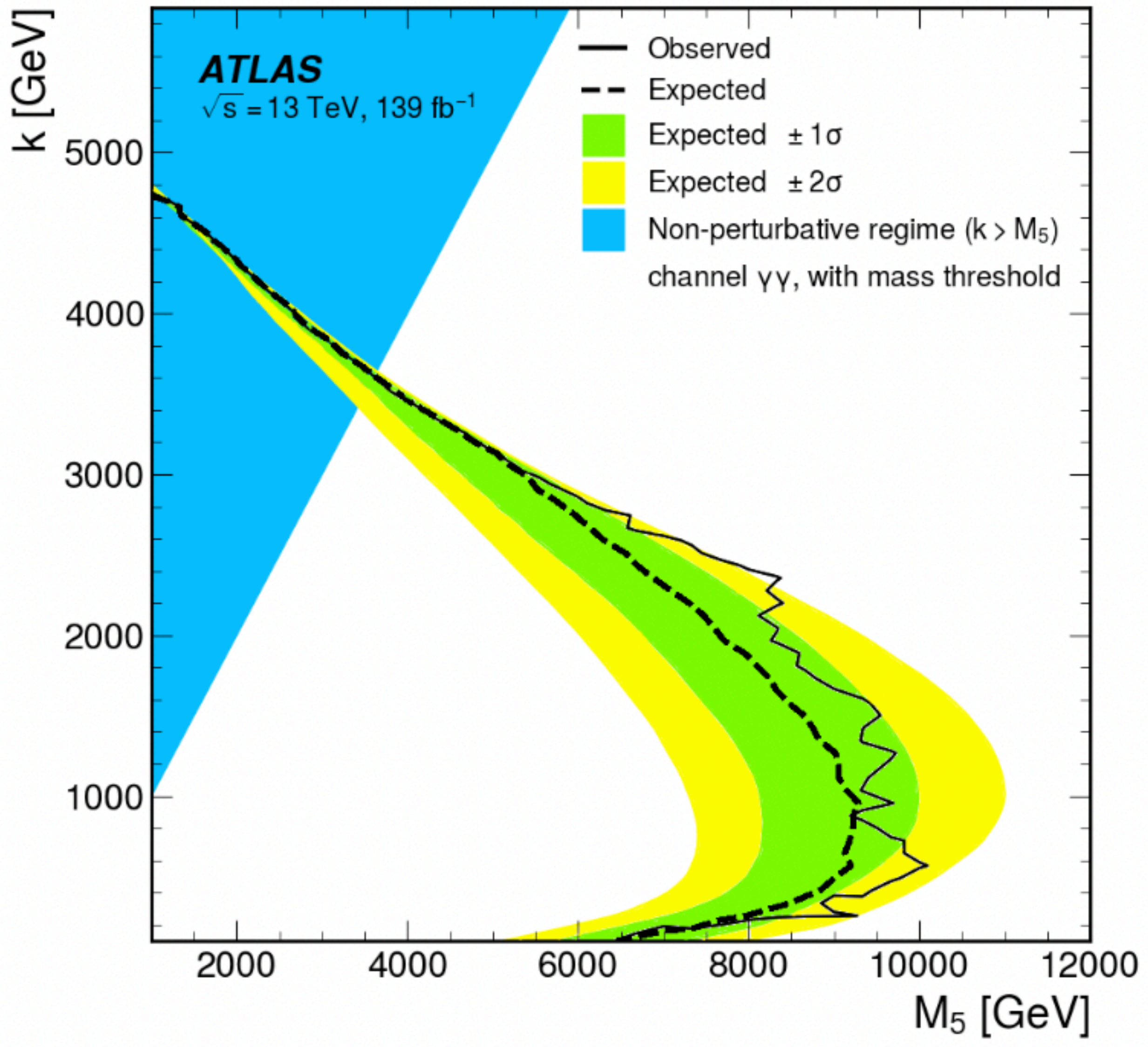
Linear Dilaton Gravity-Search for periodic signals

2305.10894

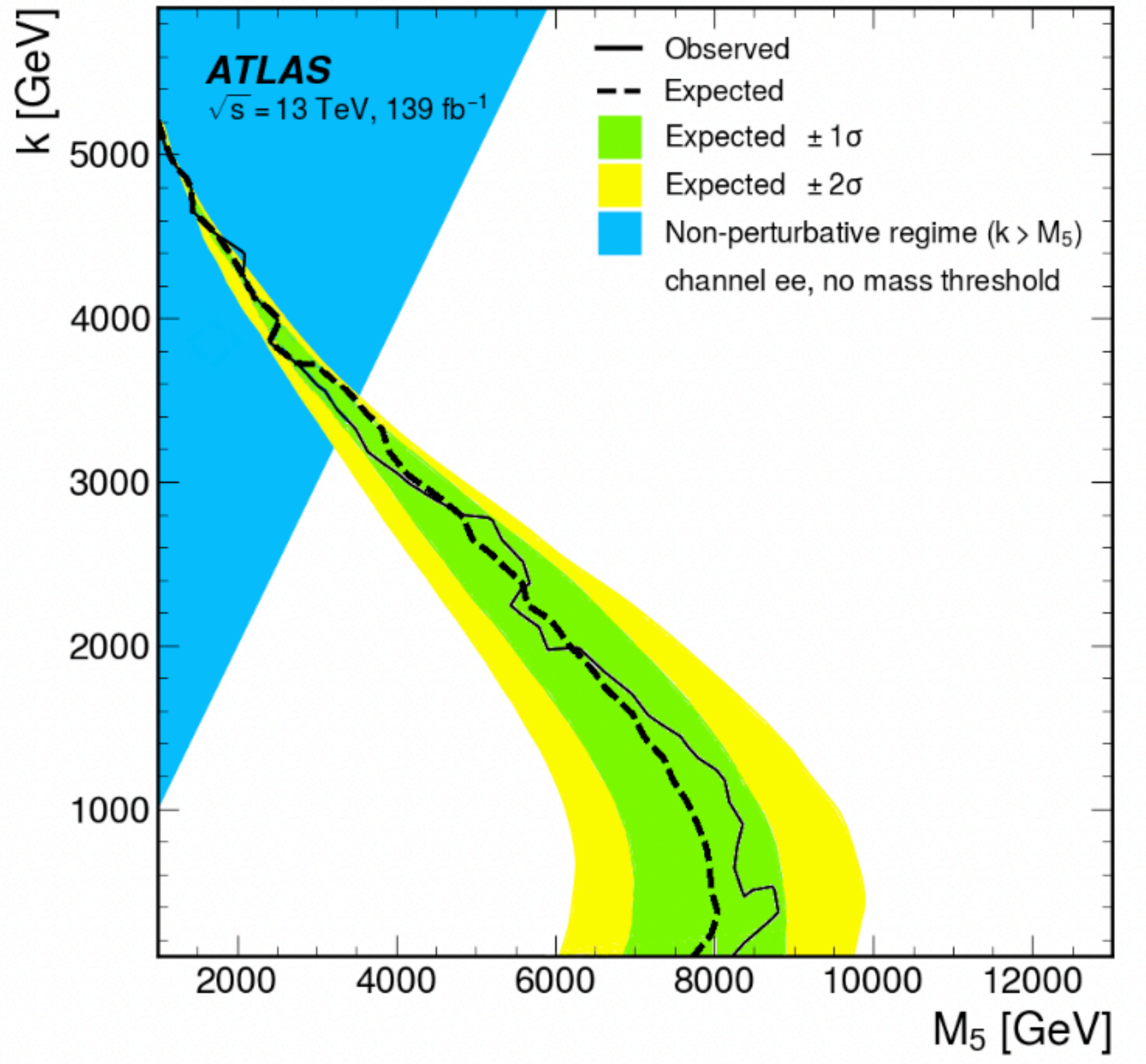




(a)



(b)



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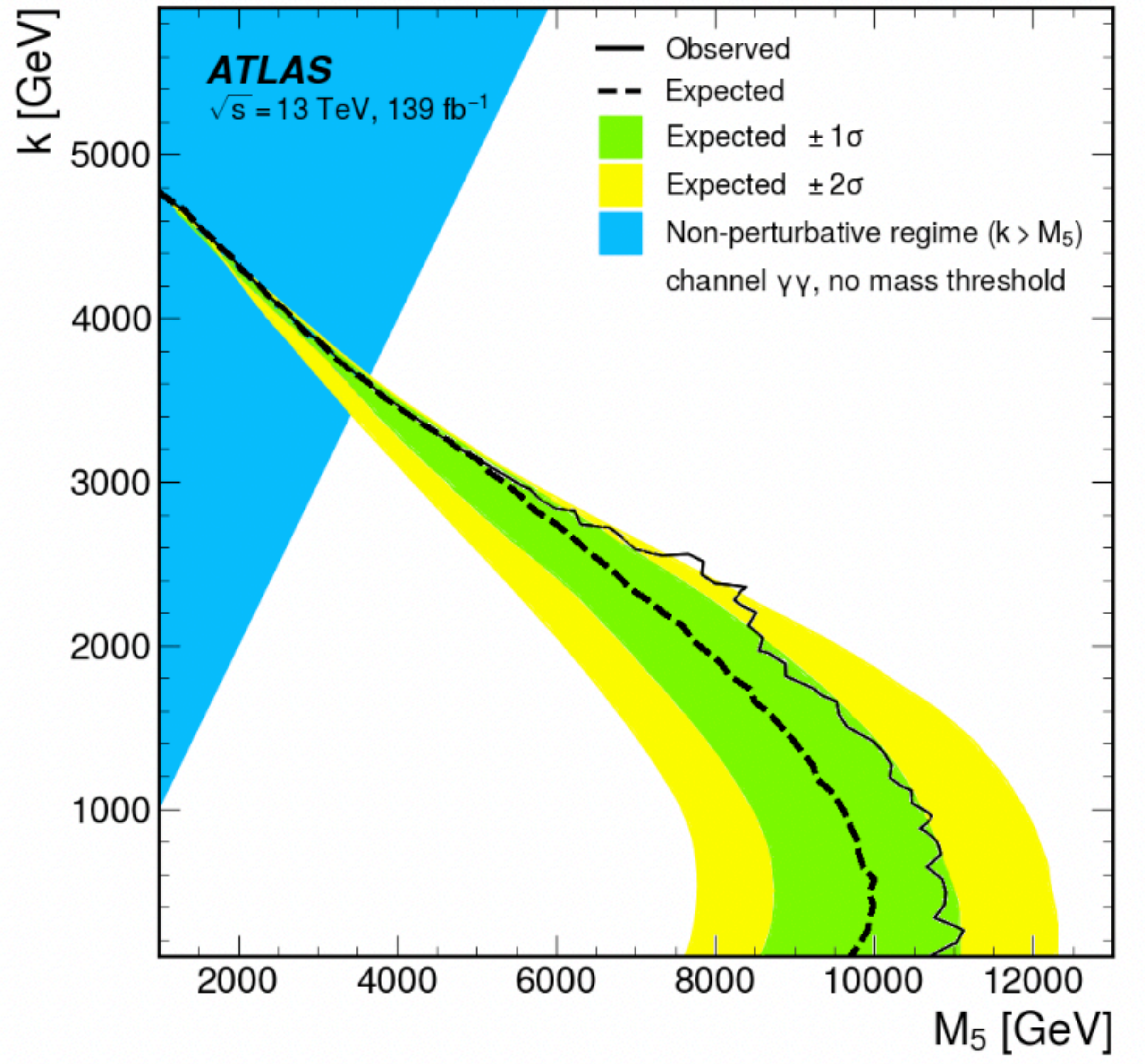

(b)