Phenomenology of the clockwork solution to the hierarchy problem

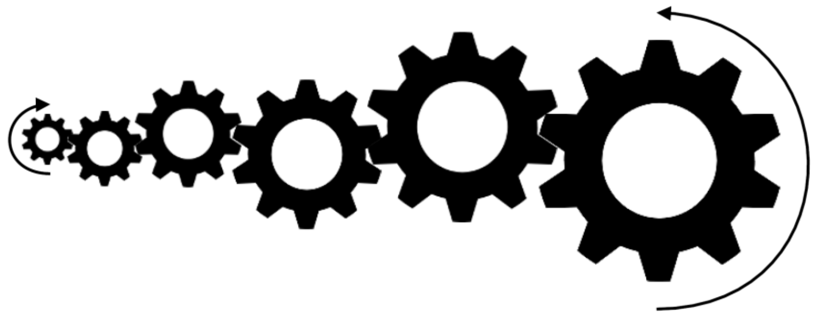
Yevgeny Kats

אוניברסיטת בן-גוריון בנגב
Ben-Gurion University of the Negev
جامعة بن غوريون في النقب

Based primarily on **arXiv:1711.08437**

w/Gian Giudice, Matthew McCullough, Riccardo Torre, Alfredo Urbano

The clockwork mechanism



A generator of tiny couplings.

First proposed to generate a tiny coupling to a **scalar** in inflation and relaxion contexts. Choi, Kim, Yun [1404.6209]; Choi, Im [1511.00132]
Kaplan, Rattazzi [1511.01827]

Later,

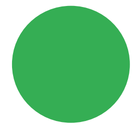
- ❑ Generalized to **fermions, gauge bosons, gravitons.**
- ❑ Obtained from deconstruction of an **extra dimension**.
- ❑ Applied to the **electroweak-Planck hierarchy** directly.

Giudice, McCullough [1610.07962]

Further discussion: Craig, Garcia Garcia, Sutherland [1704.07831]
Giudice, McCullough [1705.10162]

The clockwork mechanism

Imagine a particle P kept massless by a symmetry S.

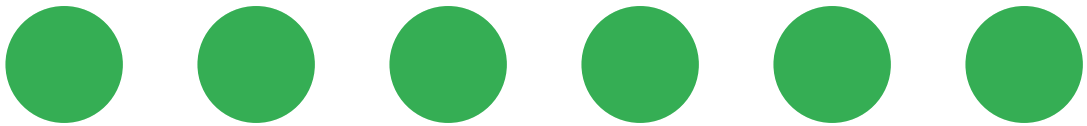


For example:

- Shift symmetry for a spin-0 particle
- Chiral symmetry for a spin-1/2 particle
- Gauge symmetry for a spin-1 particle
- Diffeomorphism invariance for a spin-2 particle

The clockwork mechanism

- Consider $N + 1$ such particles P_i $(i = 0, \dots, N)$ kept massless by symmetries S_i .



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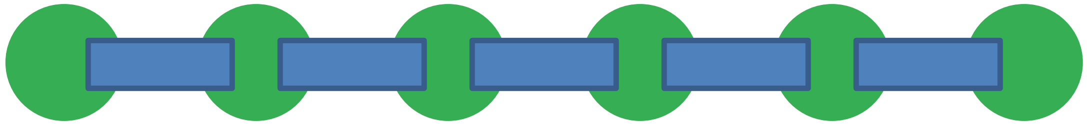

- Break the symmetries by nearest-neighbor mass mixings. One combination

$$\mathcal{P} = \sum c_i P_i$$

remains massless.

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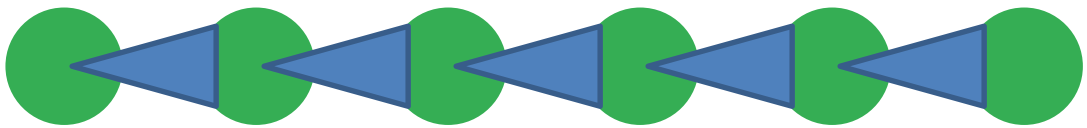

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- If the breaking is asymmetric, c_i vary with i exponentially.

The clockwork mechanism

Example: for scalar fields

$$V(\phi) = \frac{1}{2}\, m^2 \sum_{i=0}^{N-1} (\phi_i - q\phi_{i+1})^2$$

The clockwork mechanism

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$$V(\phi) = \tfrac{1}{2}\, m^2 \sum_{i=0}^{N-1} (\phi_i - q\phi_{i+1})^2 \equiv \tfrac{1}{2} \sum_{i,j=0}^{N} \phi_i\, M_{ij}^2 \phi_j$$

$$M^2 = m^2 \begin{pmatrix} 1 & -q & 0 & & & 0 \\ -q & 1+q^2 & -q & \cdots & & 0 \\ 0 & -q & 1+q^2 & & & 0 \\ & \vdots & & \ddots & & \vdots \\ & & & & 1+q^2 & -q \\ 0 & 0 & 0 & \cdots & -q & q^2 \end{pmatrix}$$

$$\Longrightarrow \qquad c_i = \frac{N(q)}{q^i}$$

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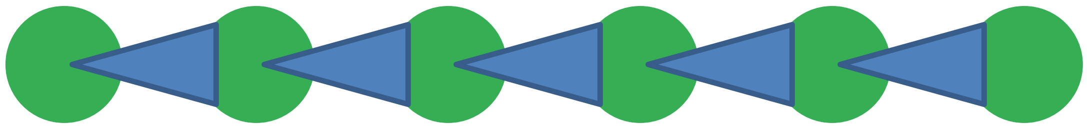

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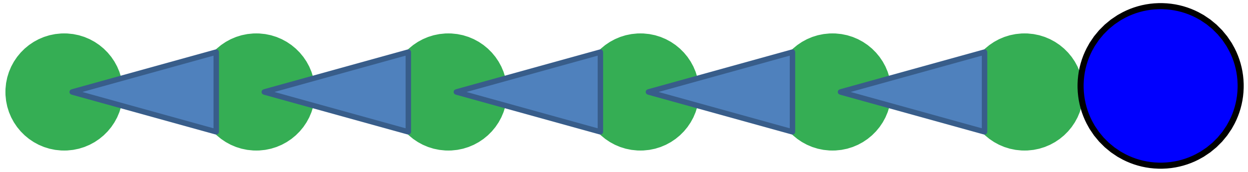

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- If the breaking is asymmetric, c_i vary with i exponentially.

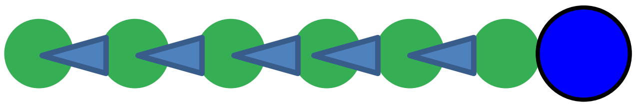
- Coupling external fields to P_N will result in their
  exponentially suppressed coupling to $\mathcal{P}$.

Continuum limit: linear dilaton scenario

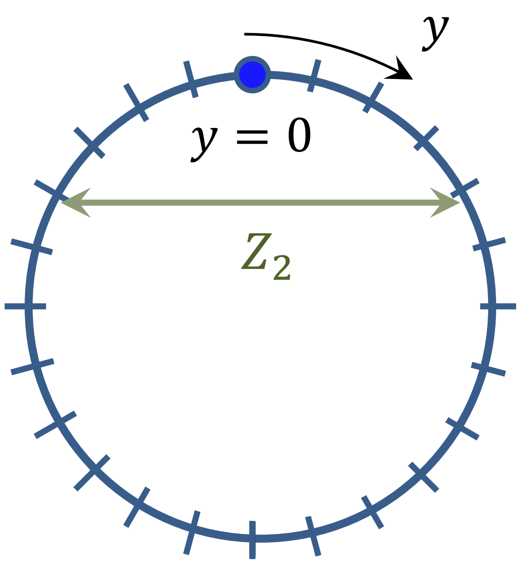
$N \to \infty$ clockwork: site i ➡ spatial coordinate y

Giudice, McCullough

$$ds^2 = e^{\frac{4}{3}k|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right)$$



k: a free parameter (mass scale)



Continuum limit: linear dilaton scenario

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$$ds^2 = e^{\frac{4}{3}k|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right)$$

scalar S (dilaton)

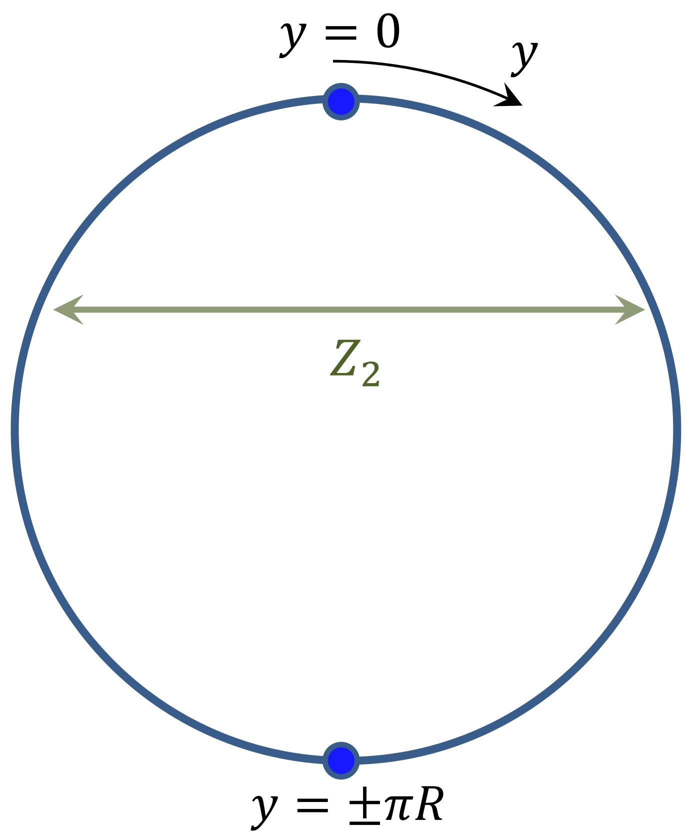
with a linear profile

$$S(y) = 2k|y|$$

due to $V(S) = -4k^2 e^{-2S/3}$

graviton

with Planck scale M_5



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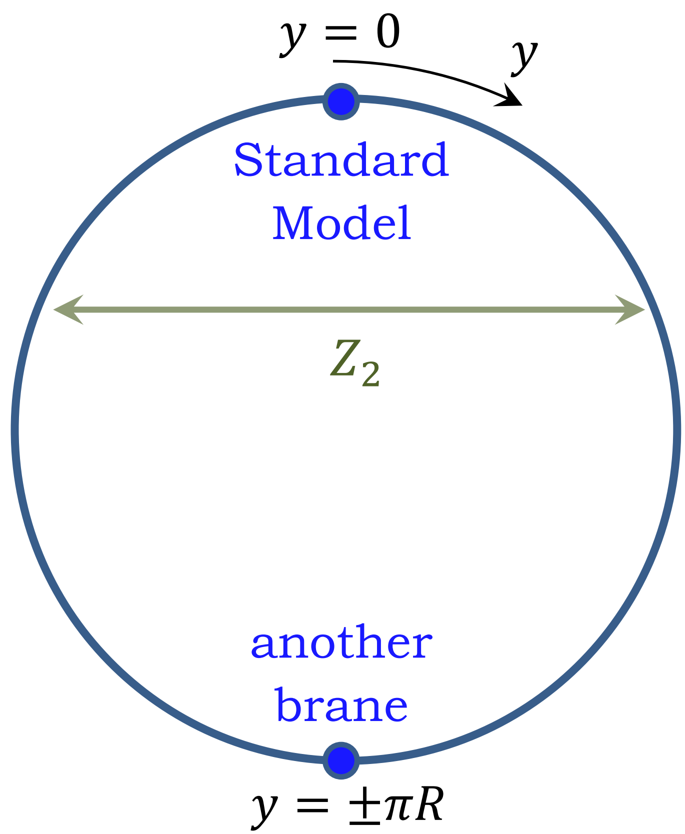
graviton

with Planck scale $M_5 \sim 10$ TeV

Electroweak-Planck hierarchy

$$M_P^2 = \frac{M_5^3}{k}\left(e^{2\pi kR} - 1\right), \qquad kR \approx 10$$



Same scenario from the Little String Theory

Stack of D3 branes

→ *4d* strongly coupled SCFT

→ dual to gravitational theory on $AdS_5 \times S^5$ Maldacena [hep-th/9711200]

→ **Randall-Sundrum** setup with two branes to explain the TeV-Planck hierarchy Randall, Sundrum [hep-ph/9905221]

Stack of NS5 branes

→ *6d* strongly coupled non-local theory: Little String Theory (LST)

Berkooz, Rozali, Seiberg [hep-th/9704089]; Seiberg [hep-th/9705221]

→ dual to *7d* gravitational theory w/linearly varying dilaton

Aharony, Berkooz, Kutasov, Seiberg [hep-th/9808149]

Giveon, Kutasov [hep-th/9909110]

→ **LST at a TeV (linear dilaton)** setup with two branes to explain the TeV-Planck hierarchy Antoniadis, Dimopoulos, Giveon [hep-th/0103033]

Phenomenology studies
Antoniadis, Arvanitaki, Dimopoulos, Giveon [1102.4043]
Baryakhtar [1202.6674]; Cox, Gherghetta [1203.5870]

Comparison with other scenarios

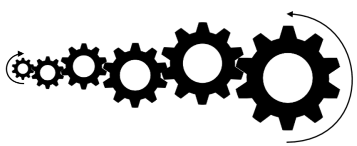
LED $ds^2 = \eta_{\mu\nu}\, dx^\mu dx^\nu + dy^2$ $M_P^2 = L_5 M_5^3$

The hierarchy is due to the extra-dimensional **volume**.

RS $ds^2 = e^{2ky}\, \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$ $M_P^2 \simeq e^{2k\pi R}\, \frac{M_5^3}{k}$

The hierarchy is due to the **warp factor**.

CW/LD $ds^2 = e^{\frac{4}{3}ky}\left(\eta_{\mu\nu} dx^\mu dx^\nu + dy^2\right)$ $M_P^2 \simeq L_5\; e^{\frac{4}{3}k\pi R}\, \frac{M_5^3}{3}$



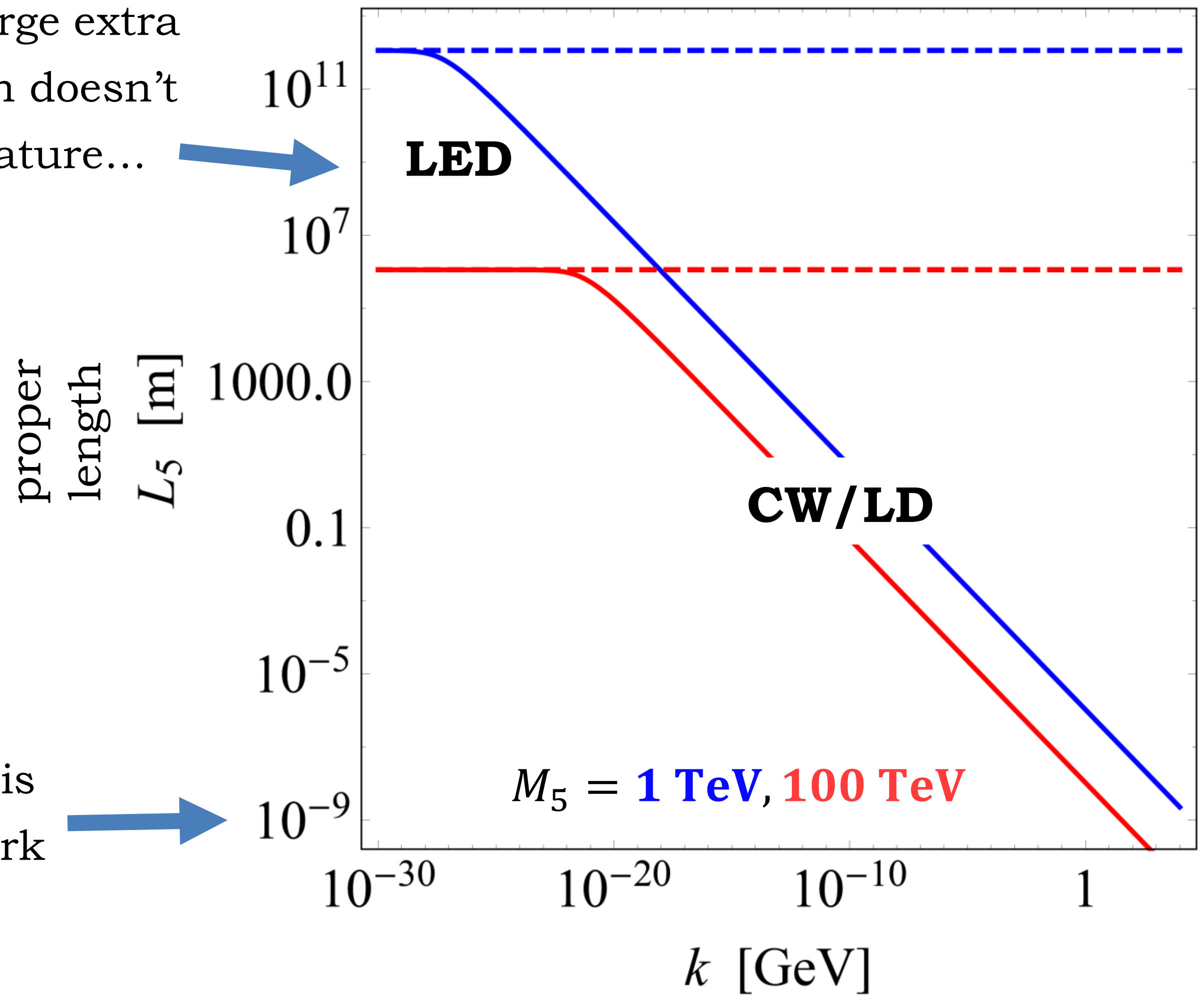
with $L_5 \simeq e^{\frac{2}{3}k\pi R}\, \frac{3}{k}$

The hierarchy is due to a combination of the **volume** and the **warp factor**.

Comparison with other scenarios

Such a large extra dimension doesn't exist in nature…

… but this could work



5d effective action

$$S = \int dy d^4x \sqrt{-g}\, \frac{M_5^3}{2} e^S (R + (\nabla S)^2 + 4k^2) + \sum_{i=\mathrm{SM,h}} e^{S(y_i)} \int d^4x \sqrt{-g}\, (\mathcal{L}_i - \Lambda_i)$$

Going to Einstein frame ($g_{MN} \to e^{-2S/3} g_{MN}$):

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where $V(S) = -4k^2 e^{-2S/3}$.

One obtains the desired solution

$$ds^2 = e^{\frac{4}{3}k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu + dy^2) \qquad\qquad S(y) = 2k|y|$$

if the cosmological constants (CCs) are $\Lambda_5 = 0,\ \Lambda_\mathrm{h} = -\Lambda_\mathrm{SM} = 4M_5^3 k$.

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Question from the EFT point of view

The symmetry $S \to S + \alpha$ (with k as a spurion) forbids additional interactions, but nothing forbids the CCs!

(May dismiss only one of them as the usual CC tuning.)

Impact of cosmological constants

Suppose there is a CC of natural size, or maybe accidentally a few orders of magnitude smaller.

Does it significantly change the solution?

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Solving the EOM perturbatively in the CC:

- Spectrum corrections due to bulk CC

$$\frac{\Lambda_5}{M_5^5} \exp\left(\frac{4}{3}\pi k R\right) \sim 10^{18} \frac{\Lambda_5}{M_5^5}$$

i.e. even a tiny bulk CC converts CW/LD into RS or dS.

↪ **Must have SUSY in the bulk to avoid CC.**

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- Spectrum corrections due to SM-brane CC are governed by

$$\frac{\Lambda_{\mathrm{SM}}}{kM_5^3}$$

  ↪ **It can be OK for SUSY to be broken in the SM sector unless $k \ll M_5$.**

Possible UV completion for the bulk

From string theory textbooks:

To get a non-anomalous superstring theory, the target space must have $D = 10$ dimensions (if the background fields are flat).

$$\mathcal{S} = \frac{1}{2\alpha'} \int d^2\sigma \sqrt{-h} \left(g_{MN}(X) \partial_\alpha X^M \partial_\beta X^N h^{\alpha\beta} + \frac{\alpha'}{4\pi} S(X) \mathcal{R}^{(2)} + \dots \right)$$

$$\beta_{MN}(g) = \alpha' \mathcal{R}_{MN} - 2\alpha' \nabla_M \nabla_N S + \dots + \mathcal{O}(\alpha'^2)$$

$$\beta(S) = \boxed{\frac{10 - D}{3}} + \frac{\alpha'}{2} \nabla^2 S + \alpha' \nabla_M S \nabla^M S + \dots + \mathcal{O}(\alpha'^2)$$

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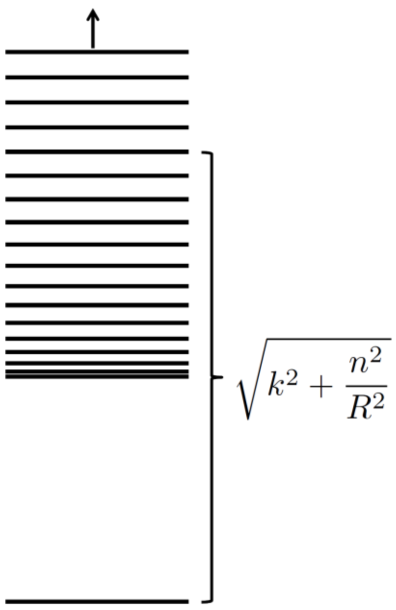
However, any $D \neq 10$ is possible for a background with
a linear dilaton profile with an appropriate slope!
This works to all orders in α' and is known as
non-critical string theory.

KK modes

KK graviton masses

$$m_0^2 = 0 \qquad m_n^2 = k^2 + \frac{n^2}{R^2} \qquad n = 1, 2, 3, \dots$$



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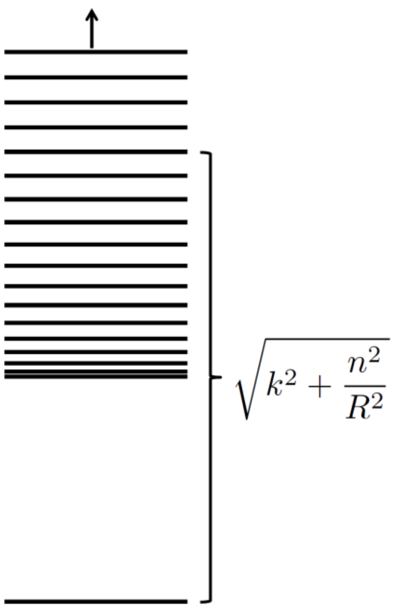
$$\mathcal{L} \supset -\frac{1}{\Lambda_n} h_{\mu\nu}^{(n)} T^{\mu\nu}$$

$$\Lambda_0^2 = M_P^2 \qquad \Lambda_n^2 = M_5^3 \pi R \left(1 + \left(\frac{kR}{n}\right)^2\right)$$



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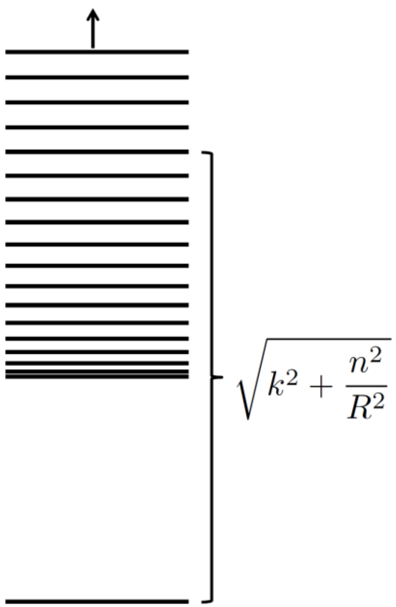

Production via $T_{\mu\nu}$ from gg and $q\bar{q}$.

Decays (1) To SM particle pairs via $T_{\mu\nu}$

(2) To pairs of lighter KK modes via 5D gravity self-interactions. Long cascades are possible.

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KK dilaton / radion masses and couplings

$$m_0^2 = \frac{8}{9} k^2 \qquad m_n^2 = k^2 + \frac{n^2}{R^2} \qquad n = 1, 2, 3, \dots$$

$$\mathcal{L} \supset -\frac{1}{\Lambda_n} \phi^{(n)} T_\mu^\mu \qquad \Lambda_0^2 \simeq \frac{18 M_5^3}{k} \qquad \Lambda_n^2 = \frac{3}{4} M_5^3 \pi R \left(10 + \left(\frac{kR}{n}\right)^2 + 9\left(\frac{n}{kR}\right)^2\right)$$

Model dependence in the case of non-rigid stabilization or Higgs-curvature coupling.

Kofman, Martin, Peloso [hep-ph/0401189]
Cox, Gherghetta [1203.5870]

KK modes of superpartners etc. are ignored only for simplicity.

KK mode mass splittings

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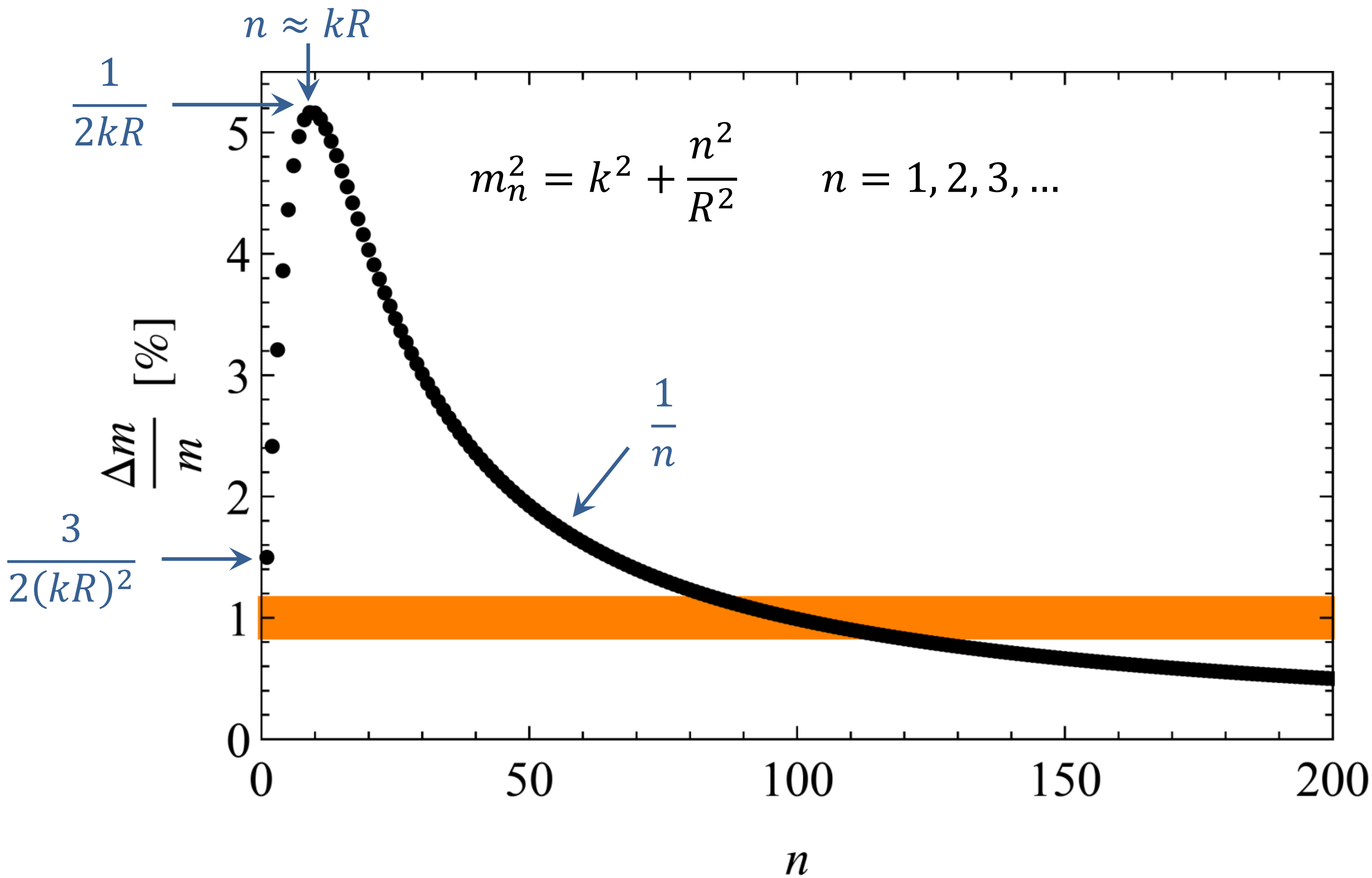
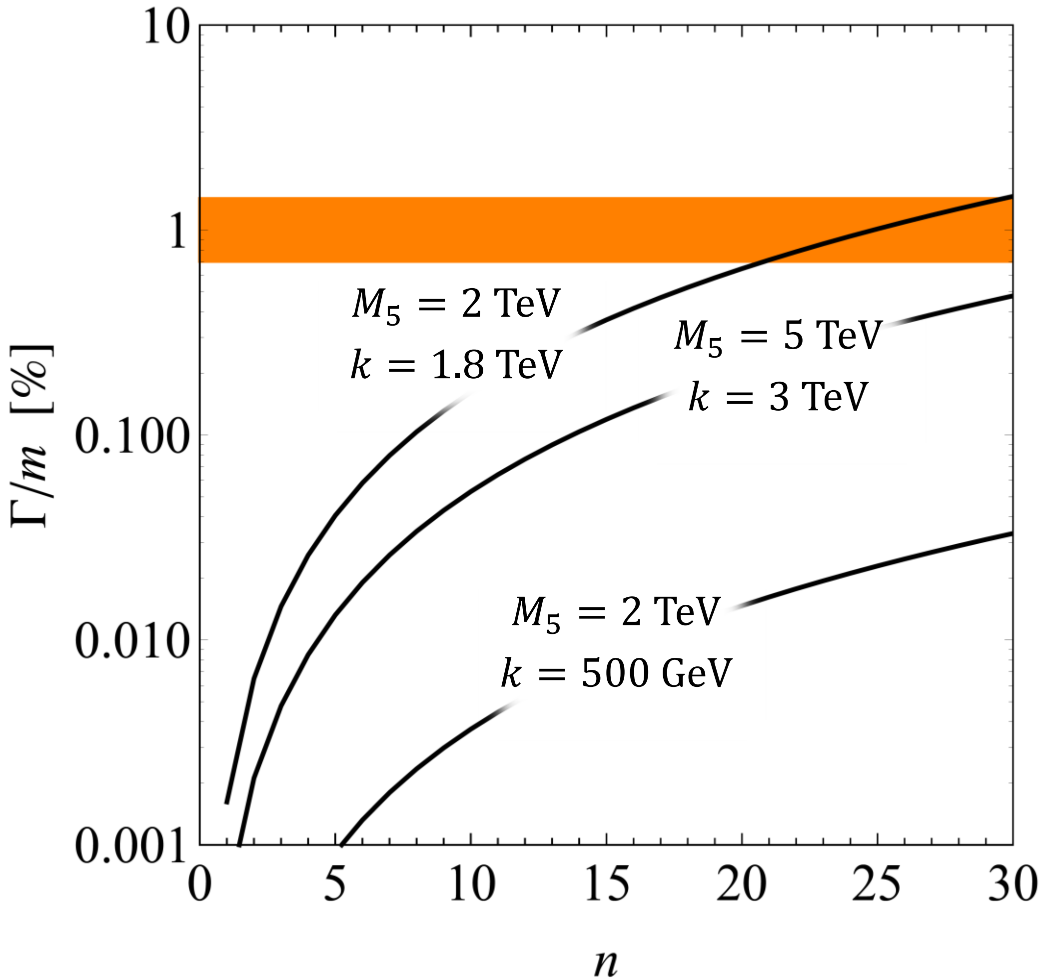
KK mode mass splittings



For $n \lesssim 100$, i.e. $k \lesssim m_n \lesssim 10k$, the individual modes can be resolved in the $\boldsymbol{\gamma\gamma}$ and $\boldsymbol{e^+e^-}$ channels in ATLAS and CMS!

KK mode mass splittings

The intrinsic widths of at least the first ~30 modes are below the resolution in the relevant range of parameters.



KK graviton decays

Decays to SM particles

gg	$\sum_i q_i\bar{q}_i$	W^+W^-	ZZ	hh	$\gamma\gamma$	$\sum_i \ell_i^+\ell_i^-$	$\sum_i \nu_i\bar{\nu}_i$
34%	38%	9.2%	4.6%	0.35%	4.2%	6.4%	3.2%

*when phase space suppressions are negligible

Easiest decays to see: $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$

Total rate to SM particles (for $n \gg kR,\ m_n \gg m_t$):

$$\Gamma_{n\to\mathrm{SM}} \simeq \frac{283}{960\pi^2}\frac{m_n^3}{RM_5^3}$$

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Decays to pairs of lighter KK gravitons

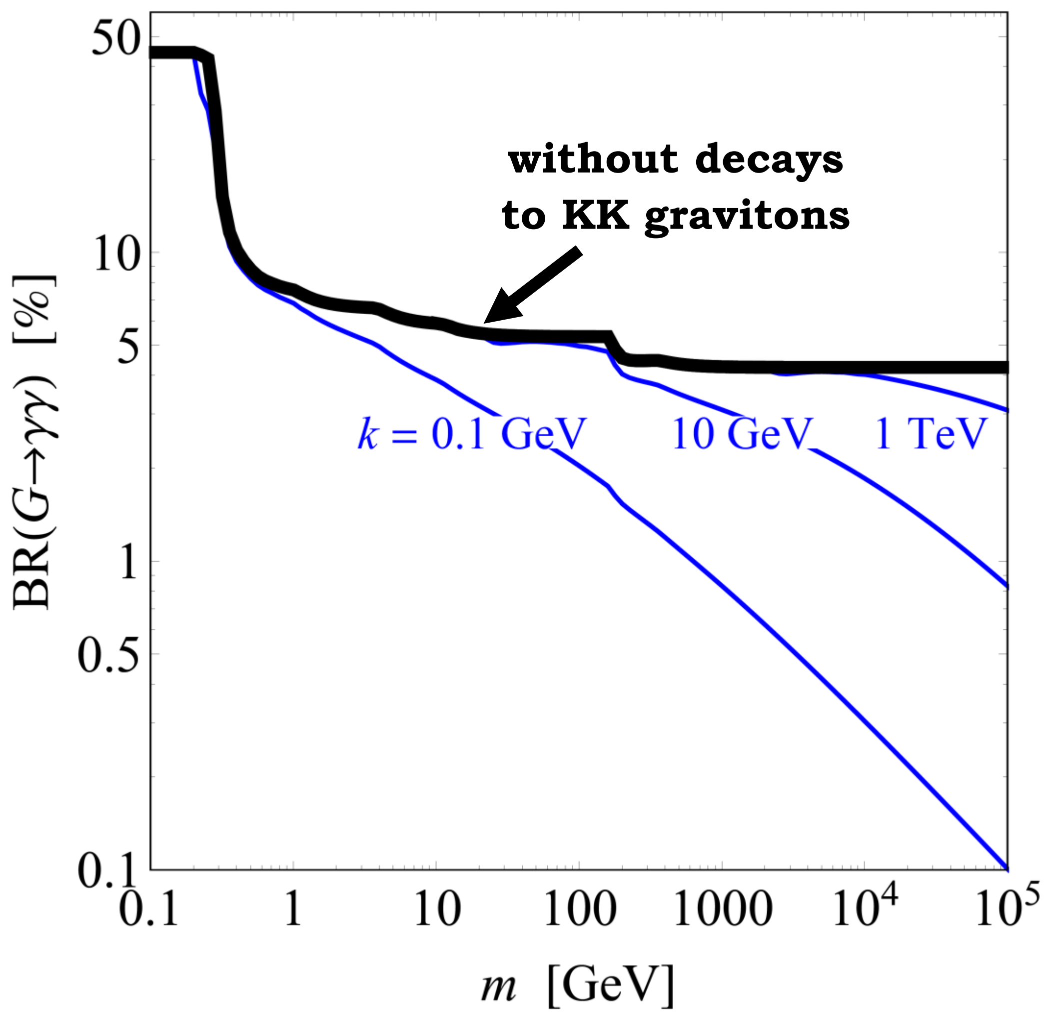
For $n \gg kR \gg 1$:

$$\Gamma_{n\to\mathrm{KK}} \simeq \frac{5\cdot 7\cdot 17}{3\cdot 2^{14}\pi^2}\frac{\sqrt{km_n}\,m_n^3}{kRM_5^3} \quad \Rightarrow \quad \frac{\Gamma_{n\to\mathrm{KK}}}{\Gamma_{n\to\mathrm{SM}}} \approx 0.04\sqrt{\frac{m_n}{k}}$$

A very large effect for low k.

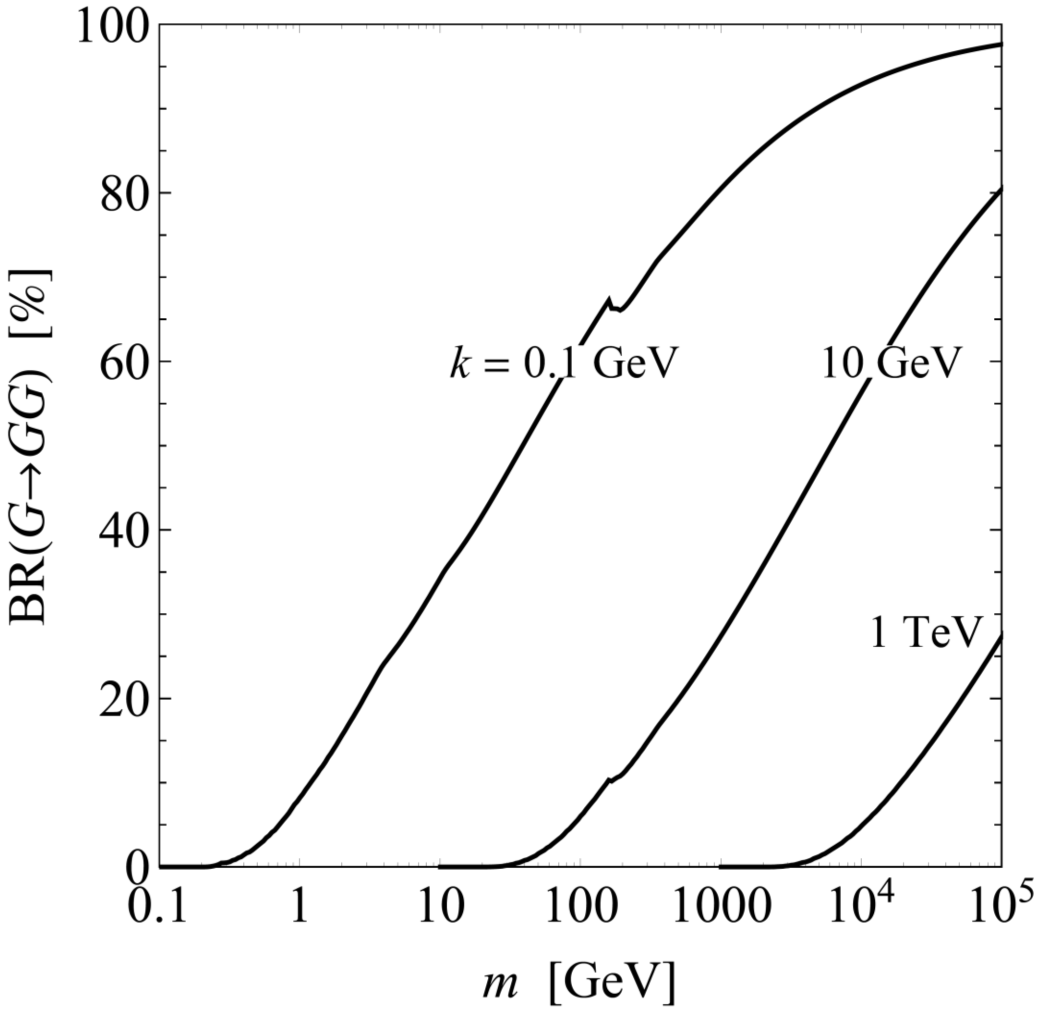
KK graviton decays

Effect on the diphoton branching fraction



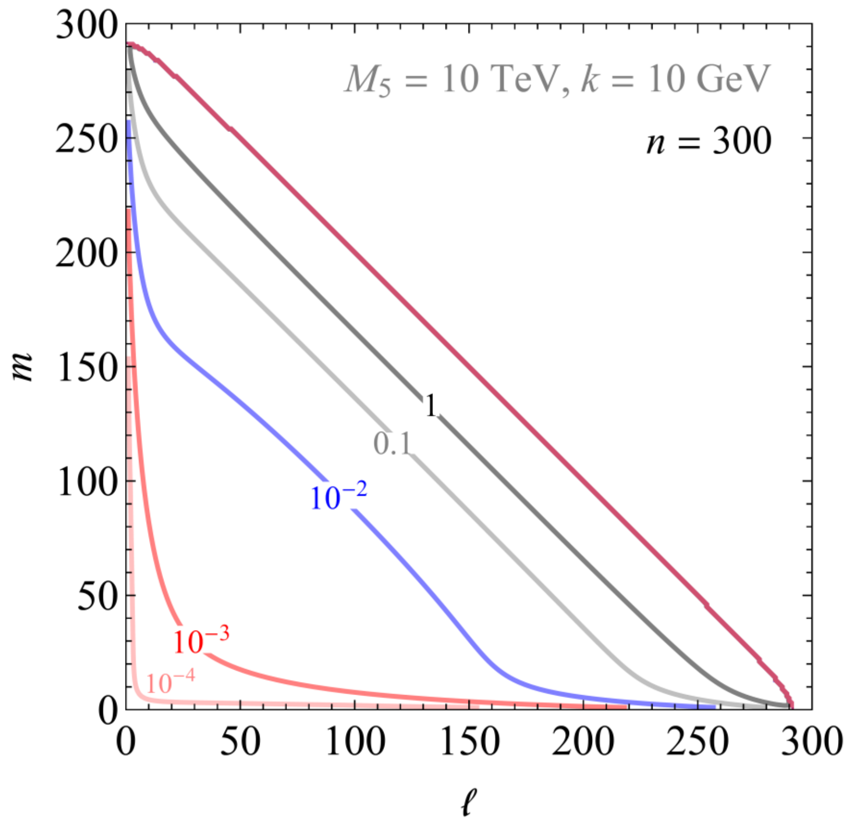
KK graviton decays

Branching fraction of the KK cascades



KK graviton decays

Preferred phase space region for the cascade decay products



Mode n decays primarily to modes ℓ and m satisfying $n \approx \ell + m$.

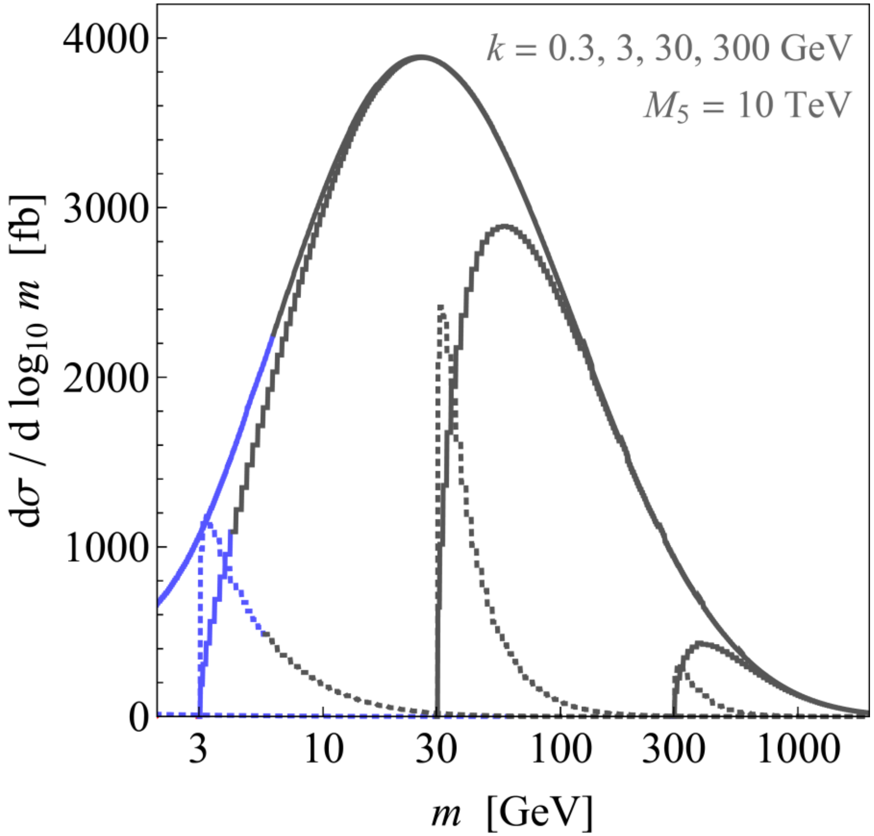
➡ Potential for multi-step cascades.

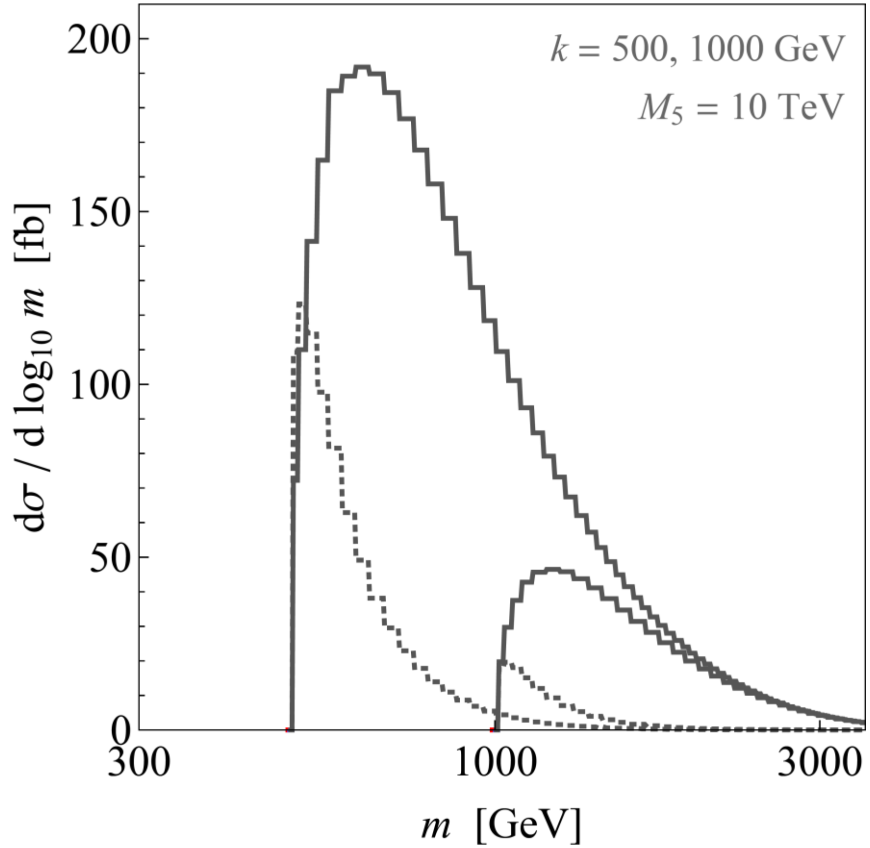
Production cross sections and lifetimes

KK graviton and KK scalar (× 500, dashed)

prompt **displaced** **detector-stable**

$\sqrt{s} = 13$ TeV





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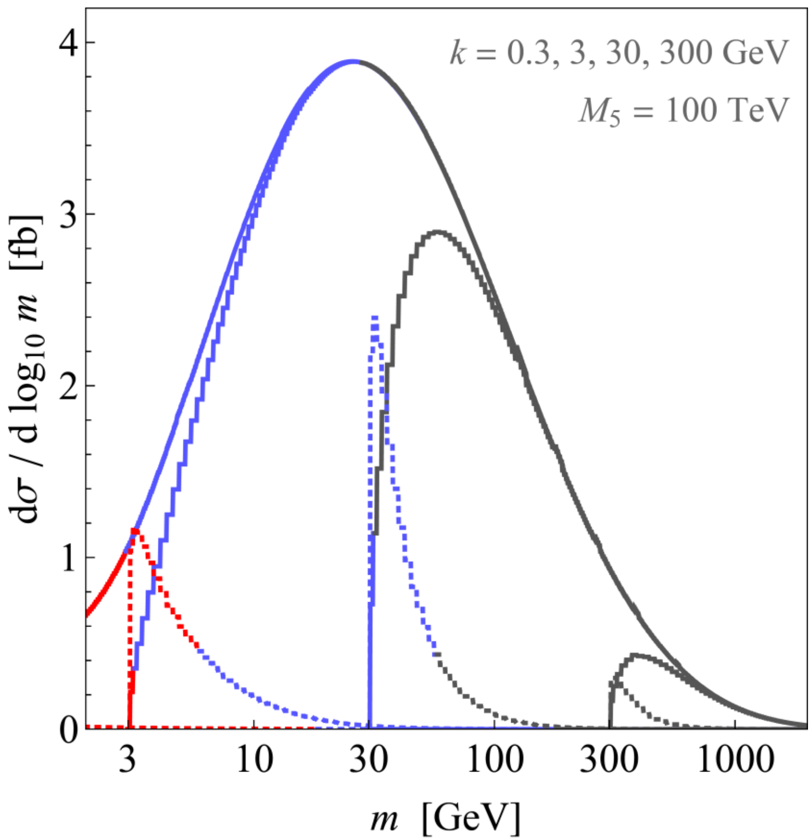
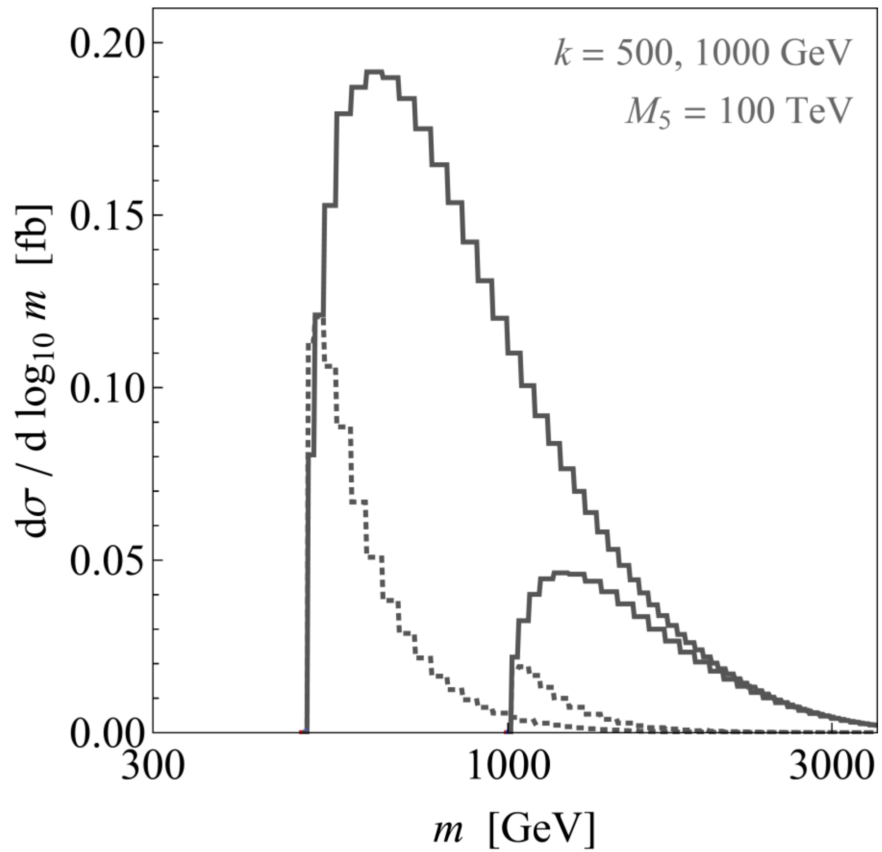
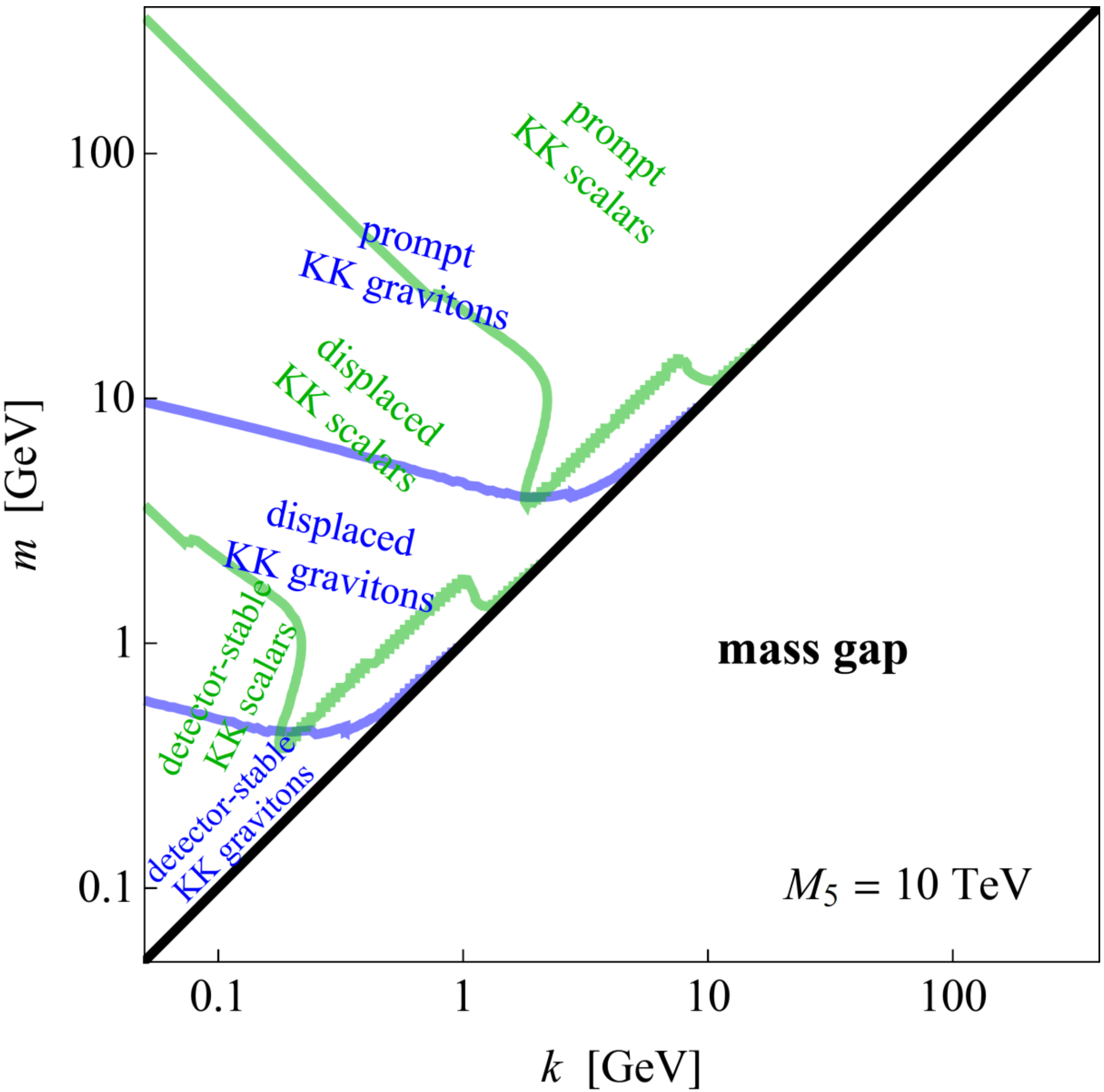




Lifetimes



prompt KK scalars
prompt KK gravitons
displaced KK scalars
displaced KK gravitons
detector-stable KK scalars
detector-stable KK gravitons
mass gap
$M_5 = 10$ TeV
100
10
1
0.1
m [GeV]
0.1
1
10
100
k [GeV]

Signatures in ATLAS / CMS

Standard signatures

- Enhancement of the $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$ spectra at high mass.

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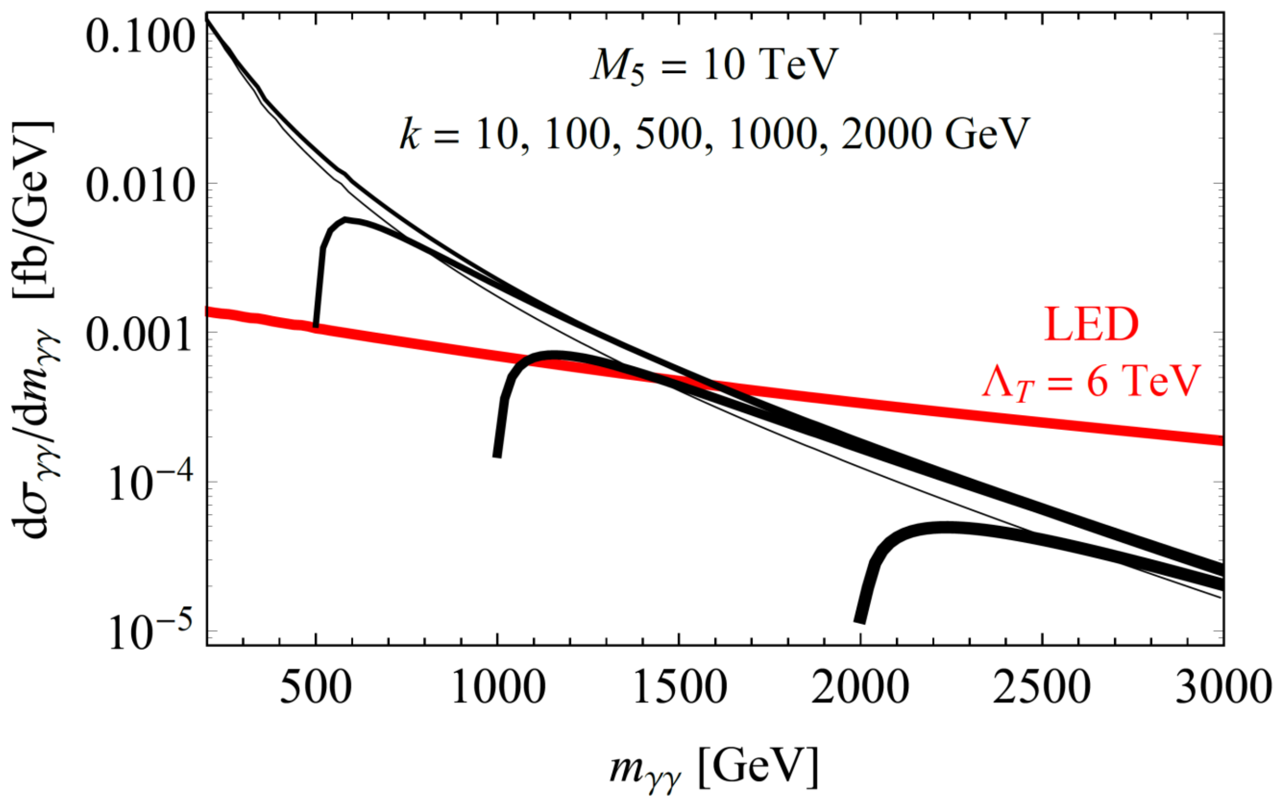

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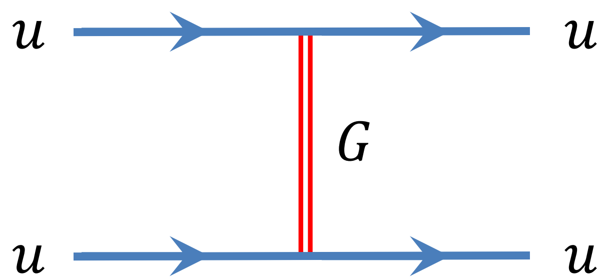

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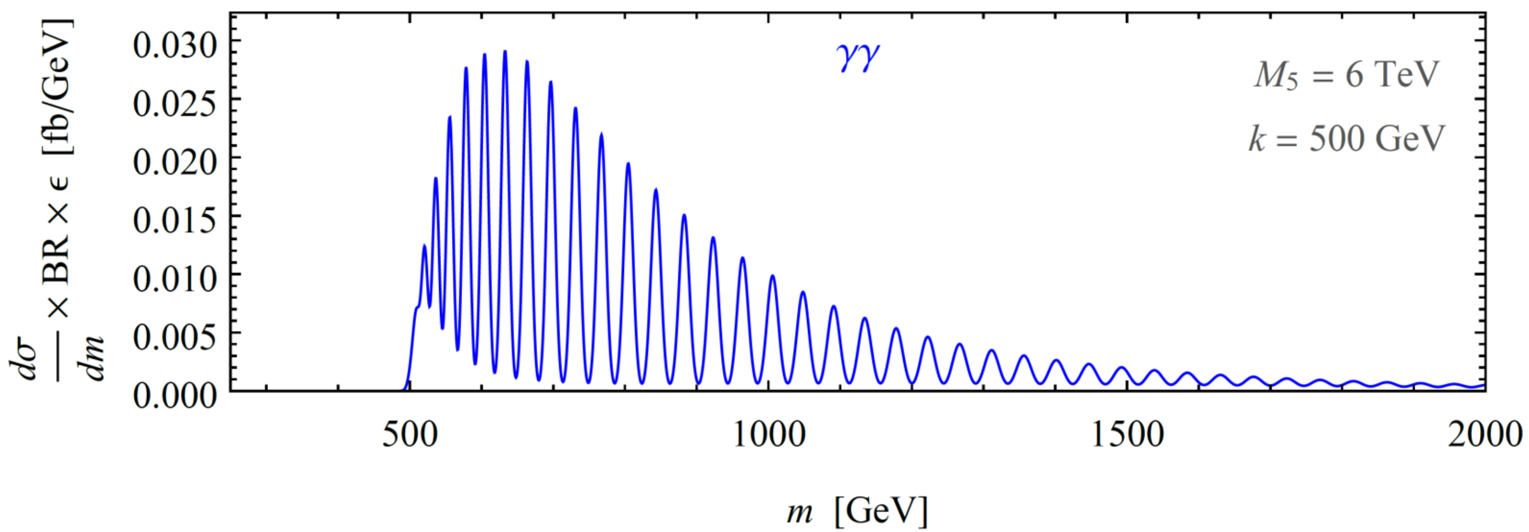
  However, how are resonance searches affected by nearby peaks?



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  However, how are resonance searches affected by nearby peaks?

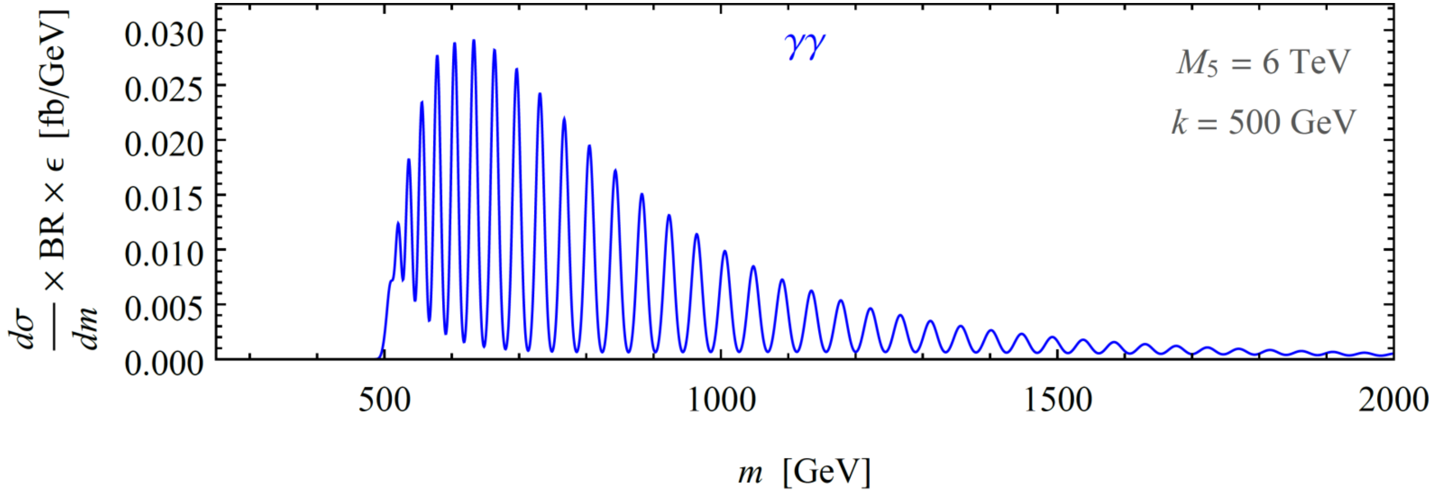
- Strong gravity signatures (black holes etc.) around $m \sim M_5$.

  As in other scenarios, unknown and model dependent.

Signatures in ATLAS / CMS

Novel signatures

- Periodic peaks in $\gamma\gamma$ and e^+e^- spectra, i.e. a peak in **Fourier space**.



Signatures in ATLAS / CMS

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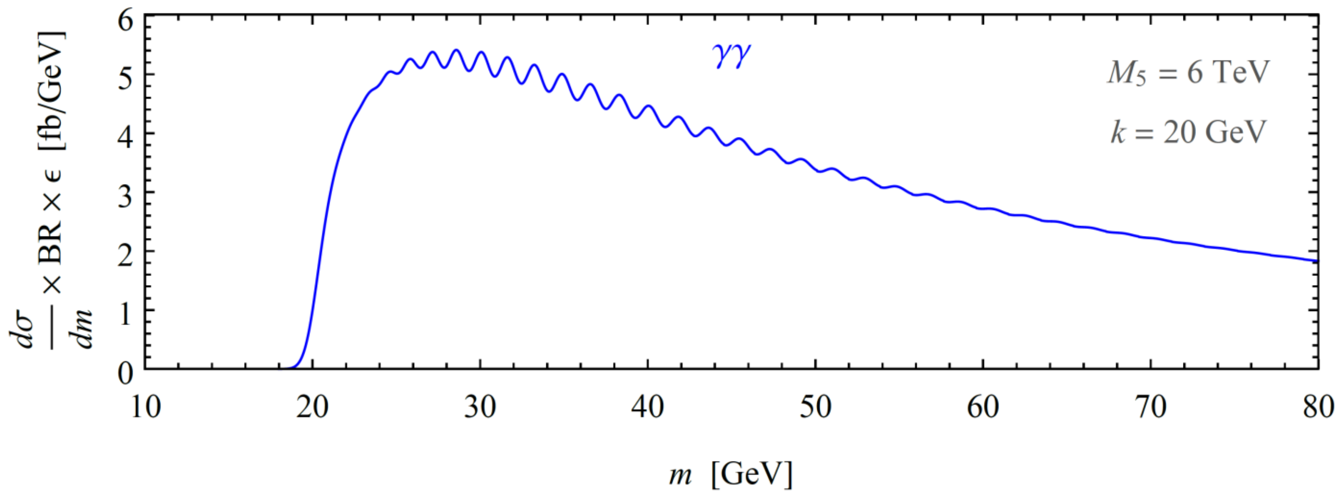

Requires triggering on ISR, or doing data scouting / trigger-level analysis.

Signatures in ATLAS / CMS

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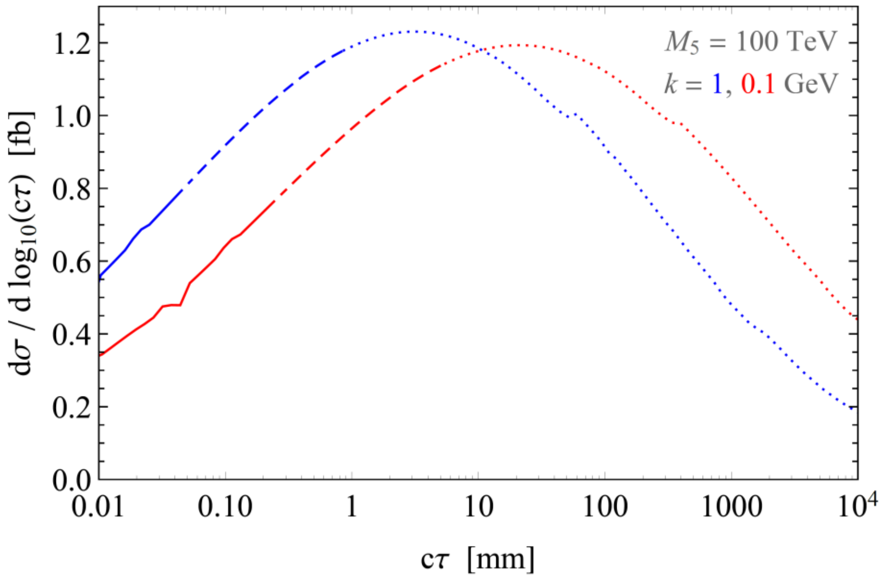
- Resonant production of somewhat long-lived (although not very boosted) light KK gravitons.



dotted: $m < 40$ GeV

dashed: $40 < m < 100$ GeV

solid: $m > 100$ GeV

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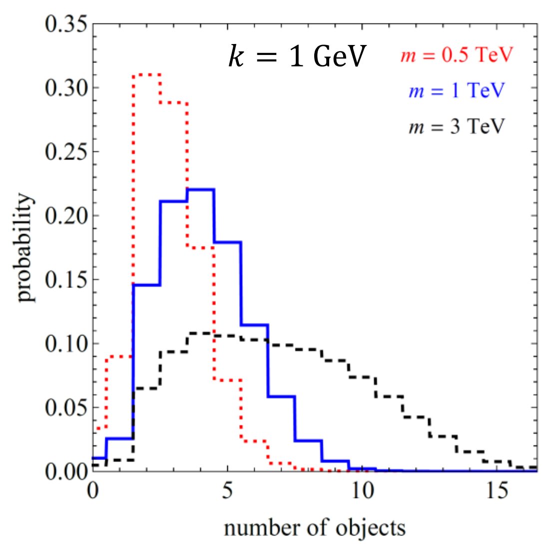

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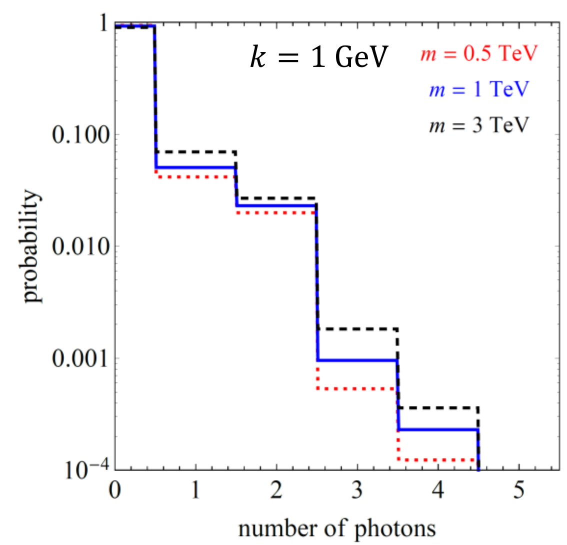

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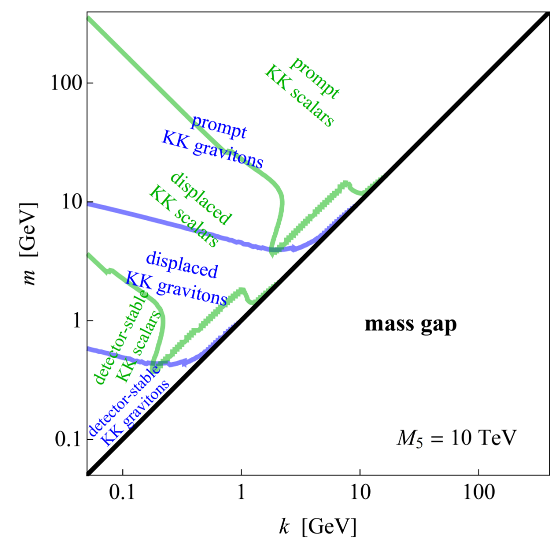
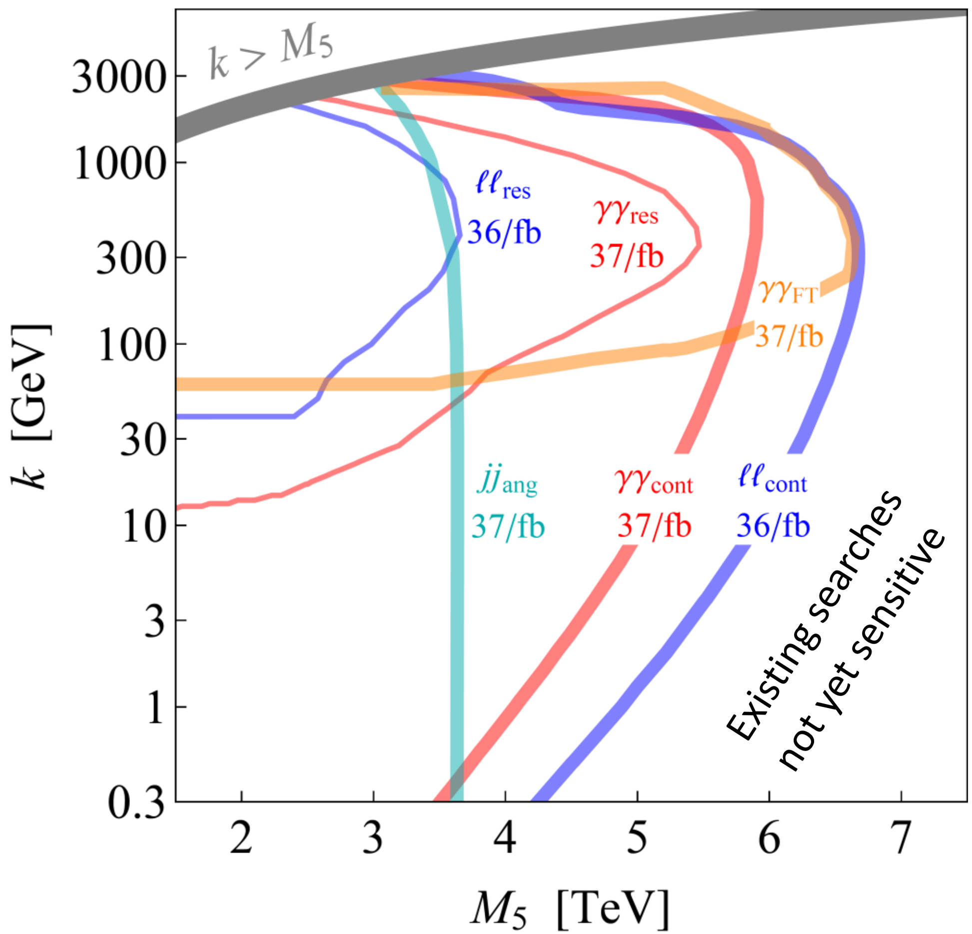
- Cascades within the KK graviton and KK scalar towers.
  - High object multiplicity.
  - High multiplicity of special objects, such as leptons, photons, b jets.
  - Displaced objects along with prompt objects.



Sensitivity of some of the channels



- Reasonably natural parameter values are still allowed.
- Limits on M_5 from continuum searches weaken at low k because KK tower cascades dilute the SM BRs.
- Fourier space search is competitive with the other methods.

Summary

- The "clockwork" is a tool for generating hierarchies.
- For the electroweak-Planck hierarchy, it suggests the "linear dilaton" setup in an extra dimension.
- The bulk must be supersymmetric, while SUSY breaking on the SM brane does not need to ruin the setup.
- Novel LHC signatures
  - ※ Effects on high-mass $\gamma\gamma$ and $\ell^+\ell^-$ spectra quite different from LED benchmark models.
  - ※ Motivation for searches in Fourier space.
  - ※ Motivation for low-mass resonance / turn-on searches.
  - ※ Benchmark models for high-multiplicity final states.
  - ※ Benchmark models for displaced decays.

Thank You!

Supplementary Slides

Production cross sections

Single KK graviton:

$$\sigma_n = \frac{\pi}{48\Lambda_n^2}\left(3\mathcal{L}_{gg}(m_n^2) + 4\sum_q \mathcal{L}_{q\bar{q}}(m_n^2)\right)$$

KK graviton tower approximated by a continuum:

$$\frac{d\sigma}{dm} \simeq \frac{\pi}{48M_5^3}\sqrt{1-\frac{k^2}{m^2}}\left(3\mathcal{L}_{gg}(m^2) + 4\sum_q \mathcal{L}_{q\bar{q}}(m^2)\right)$$

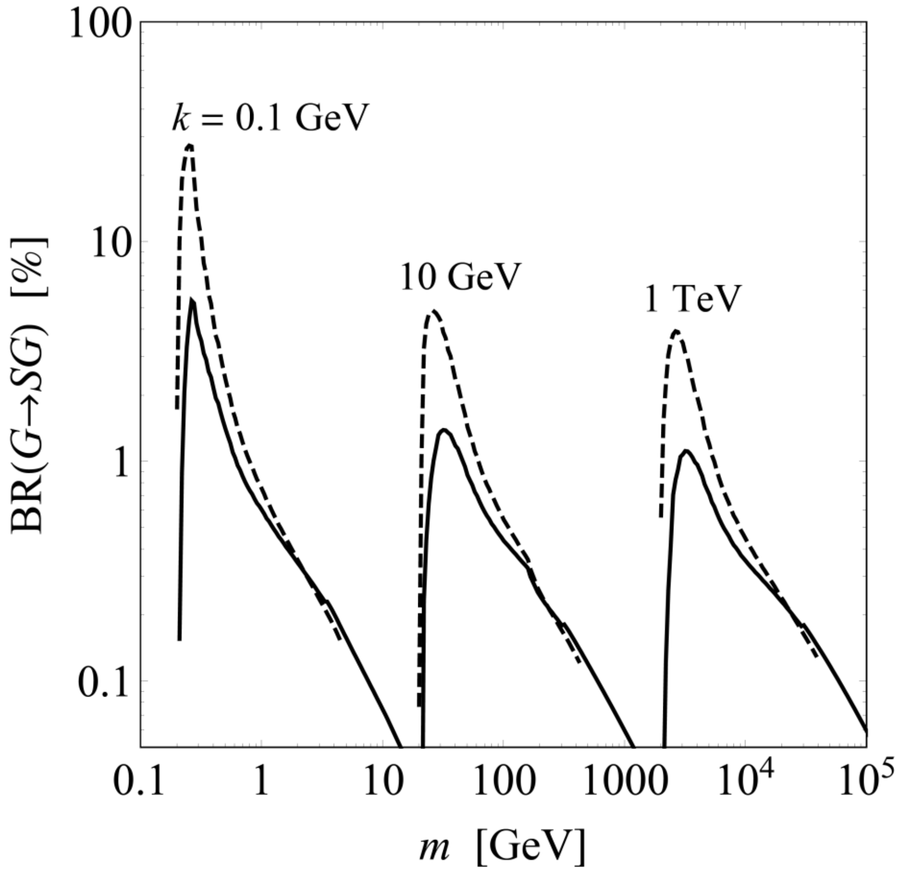
Independent of k for $m \gg k$.

KK scalar tower:

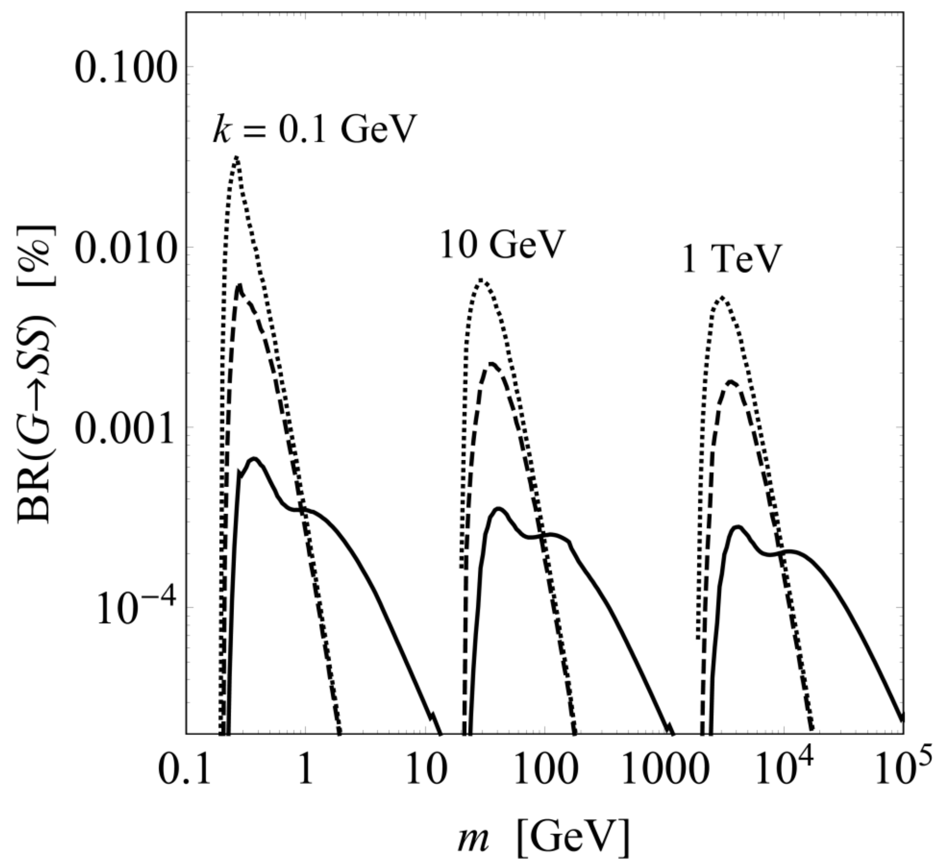
$$\frac{d\sigma}{dm} \simeq \frac{49\alpha_s^2}{864\pi^2 M_5^3}\sqrt{1-\frac{k^2}{m^2}}\left(1-\frac{8}{9}\frac{k^2}{m^2}\right)^{-1}\frac{k^2}{m^2}\,\mathcal{L}_{gg}(m^2)$$

KK graviton decays
with KK scalars in the final state

KK graviton + KK scalar



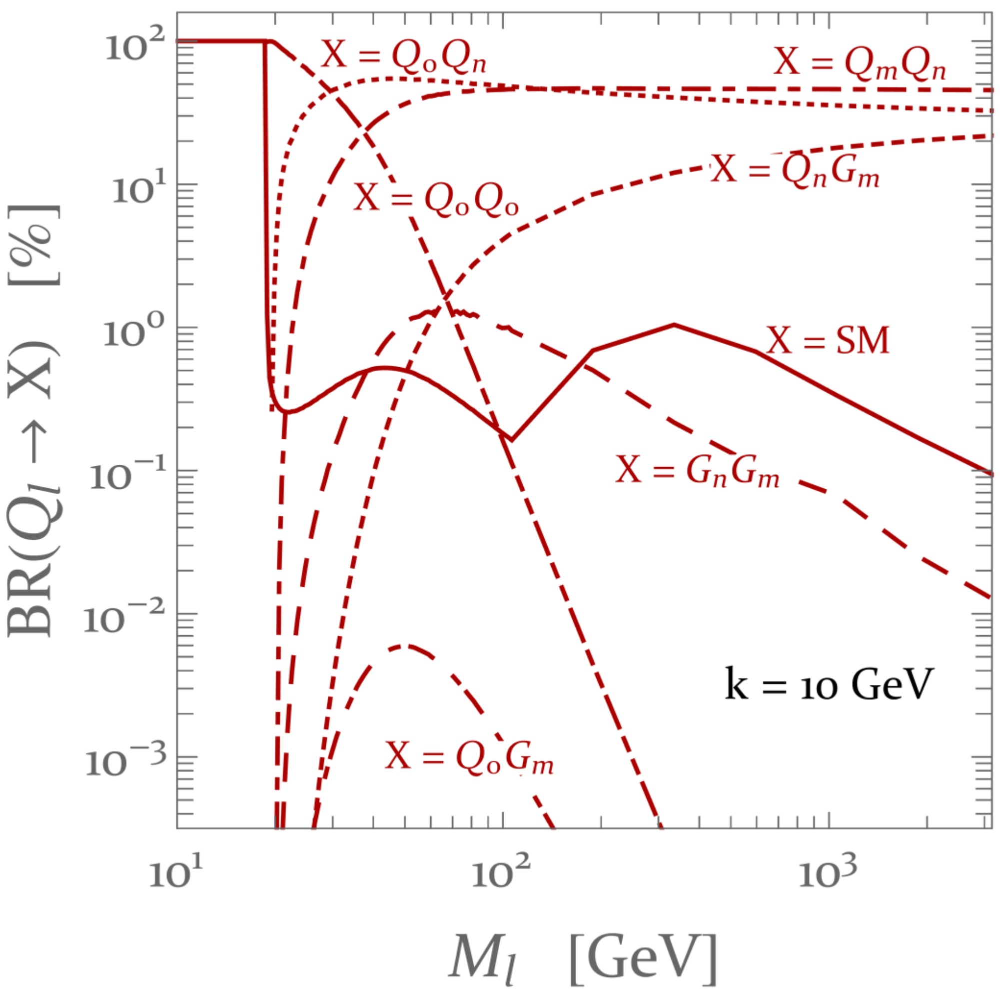
Pair of KK scalars



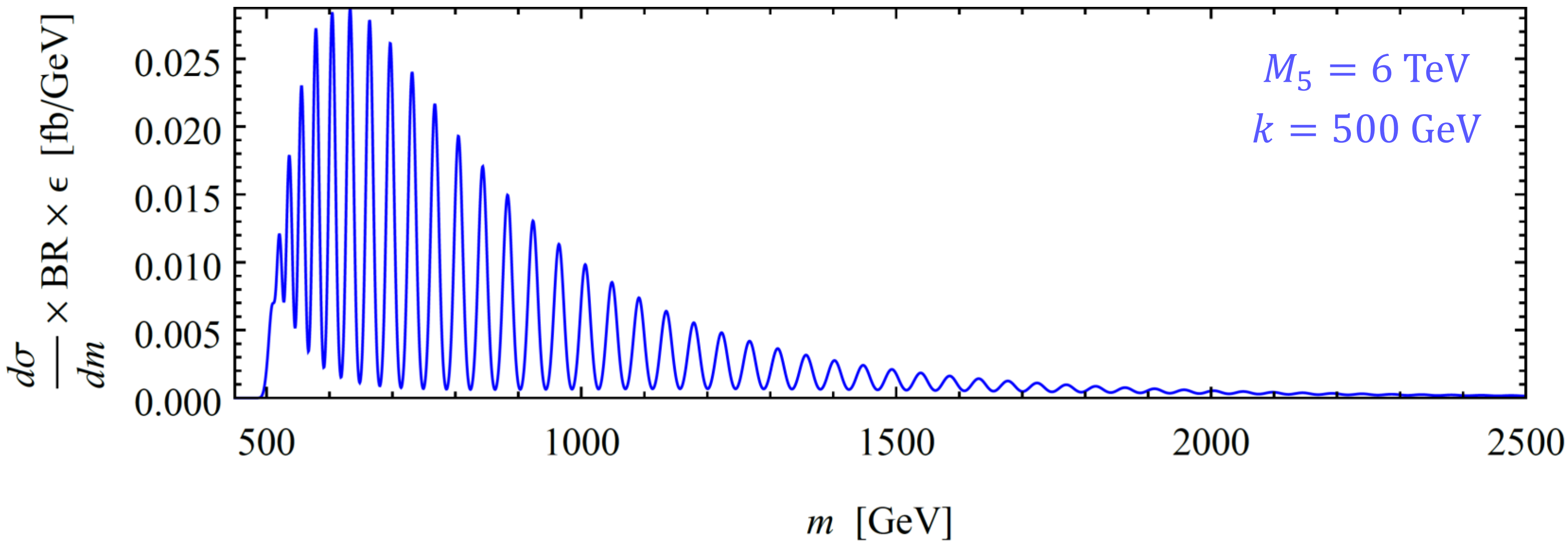
# of scalar zero modes in the final state: 0 (solid), 1 (dashed), 2 (dotted)

KK scalar decays

Except for the few lowest modes, KK cascades typically dominate over the SM decays of the KK scalars.



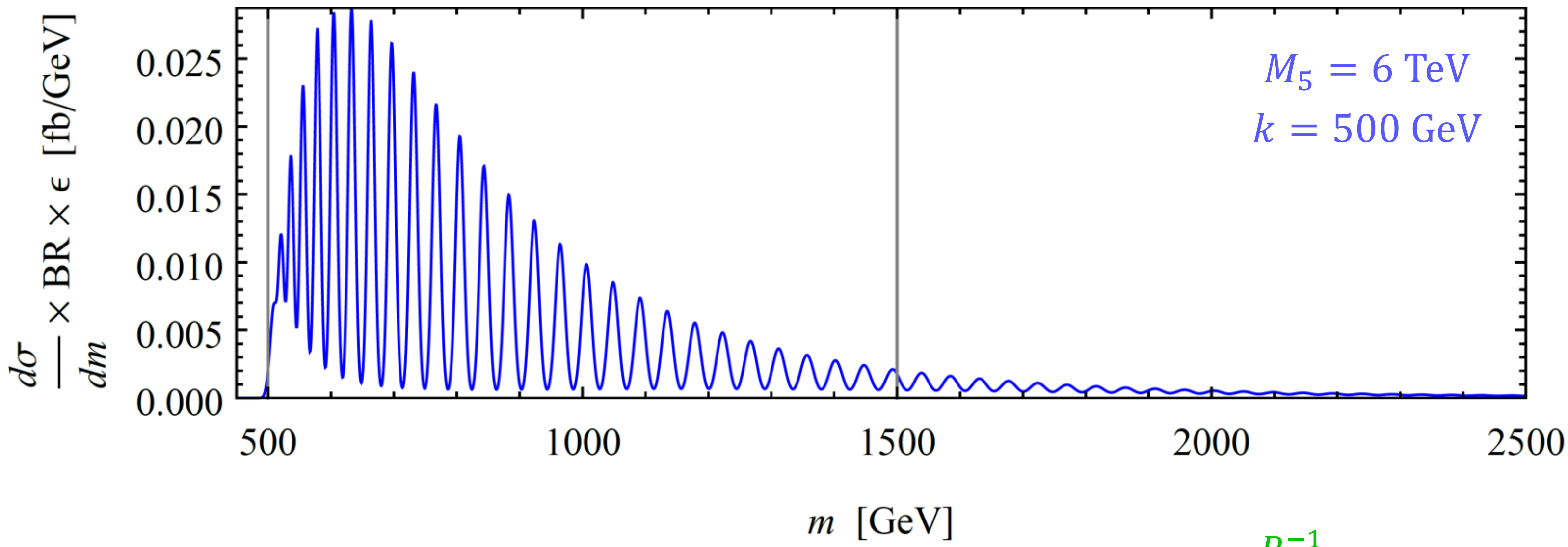
Fourier analysis of the $\gamma\gamma$ spectrum

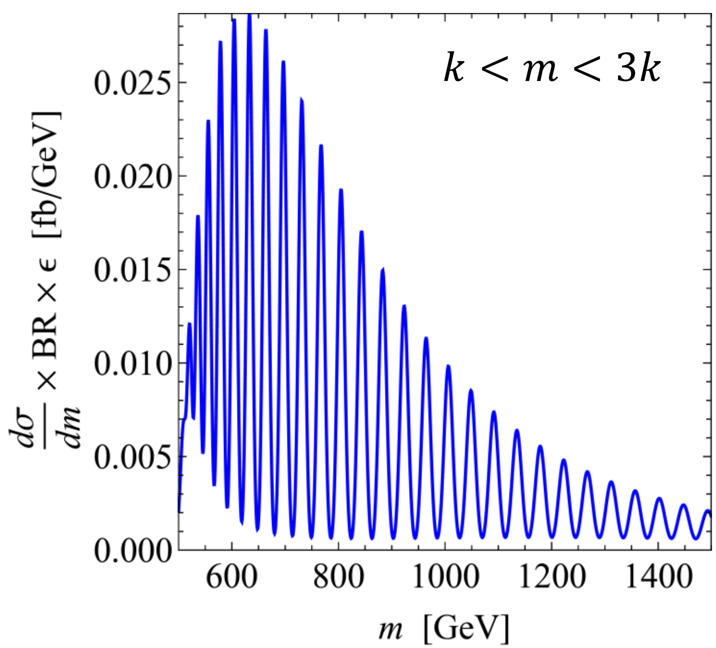


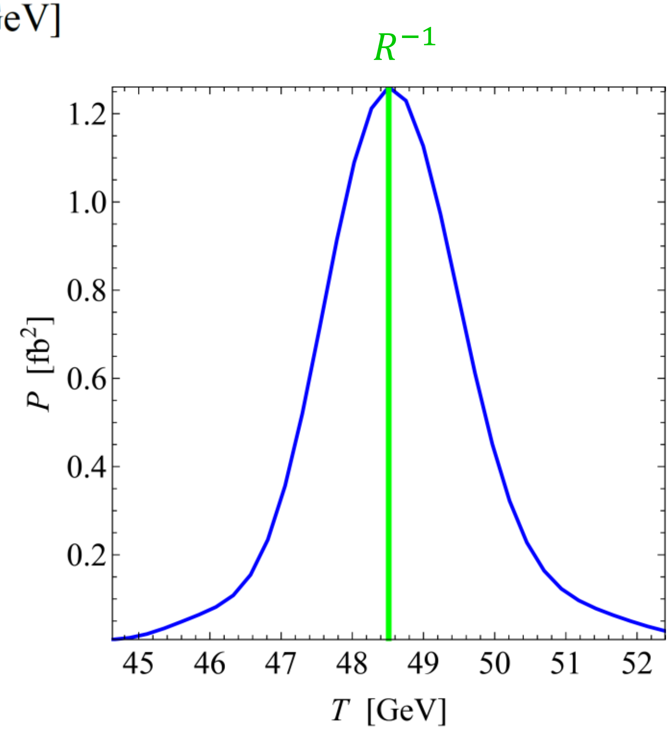
Is it possible to detect the periodic structure by analyzing the $\gamma\gamma$ spectrum in Fourier space?

$$P(T) \equiv \left| \frac{1}{\sqrt{2\pi}} \int_{m_{\min}}^{m_{\max}} dm \, \frac{d\sigma}{dm} \exp\left(i \, \frac{2\pi\sqrt{m^2 - k^2}}{T} \right) \right|^2$$

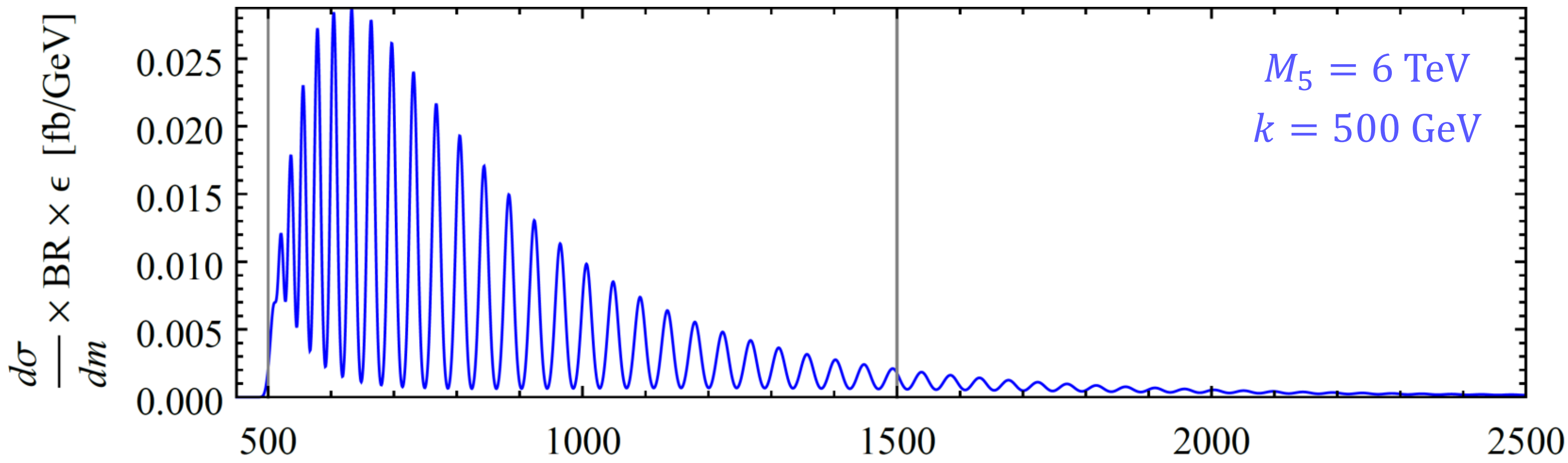
Fourier analysis of the $\gamma\gamma$ spectrum



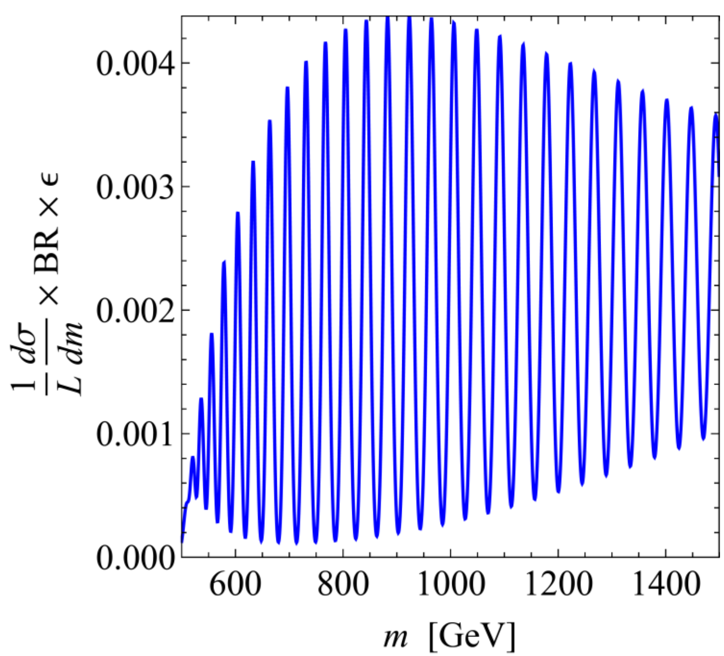


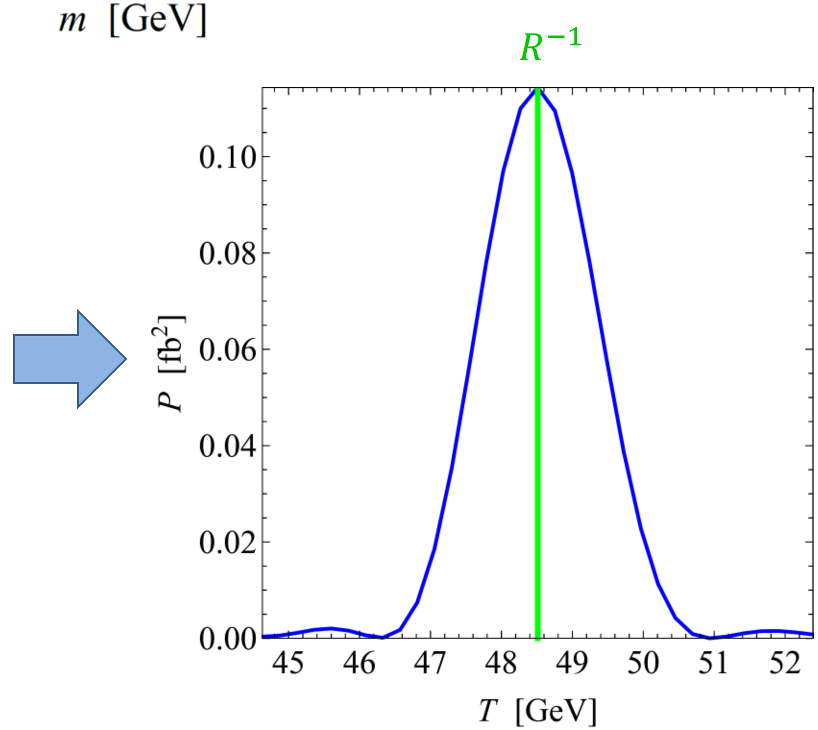


Fourier analysis of the $\gamma\gamma$ spectrum



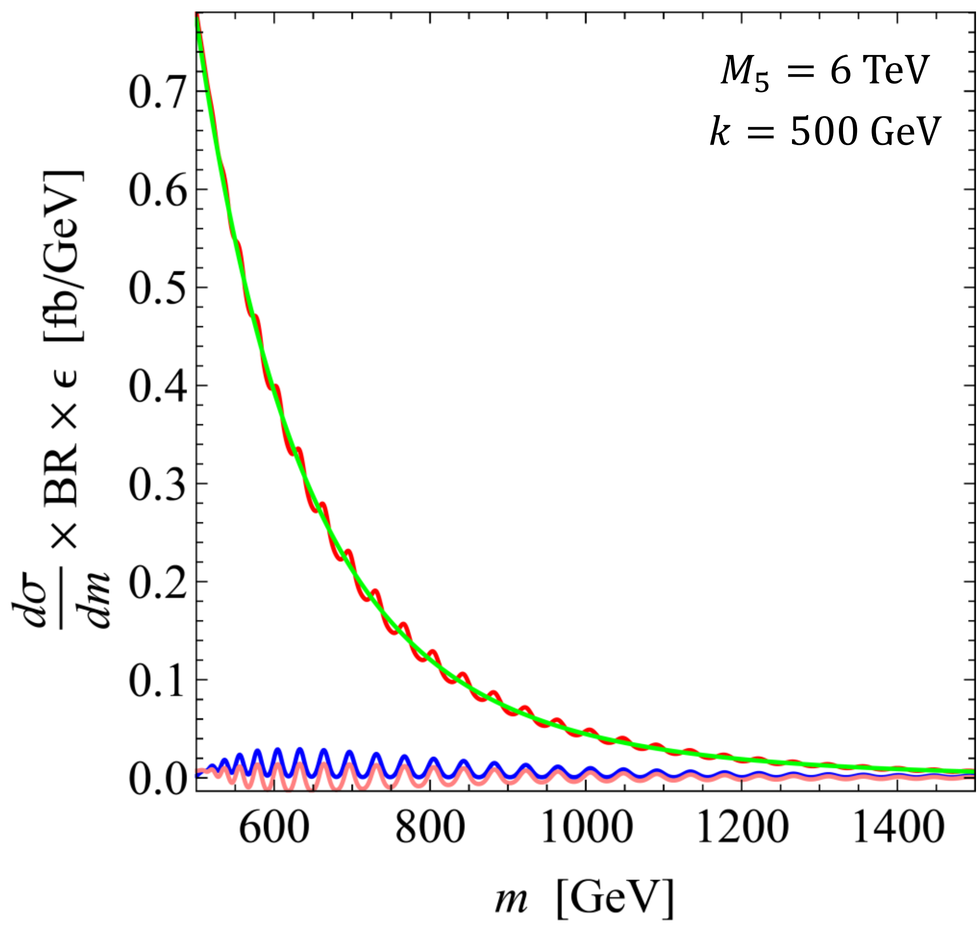
Also divide out the parton luminosity:





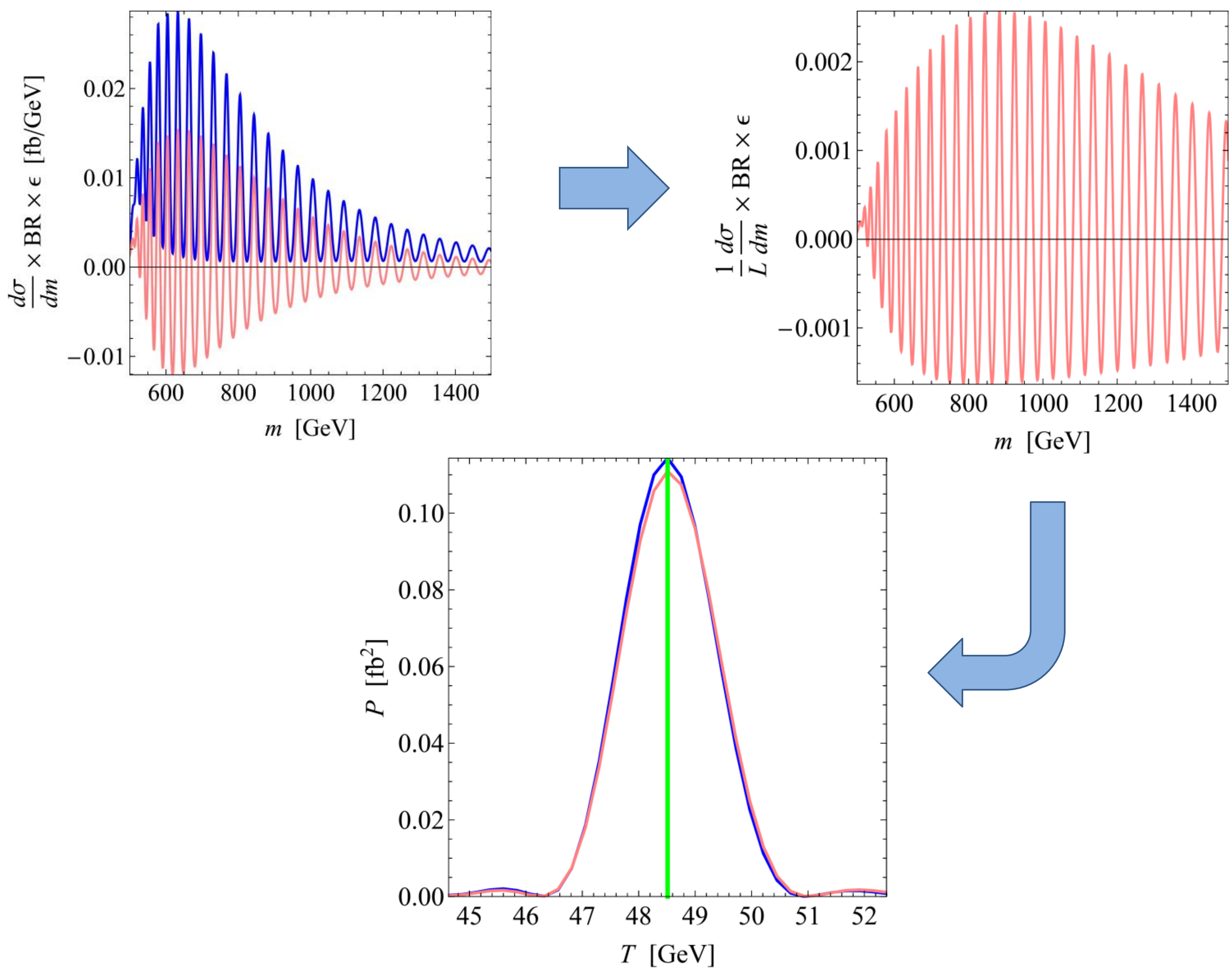
Fourier analysis of the $\gamma\gamma$ spectrum

Adding background and subtracting
a fit to a smooth function.



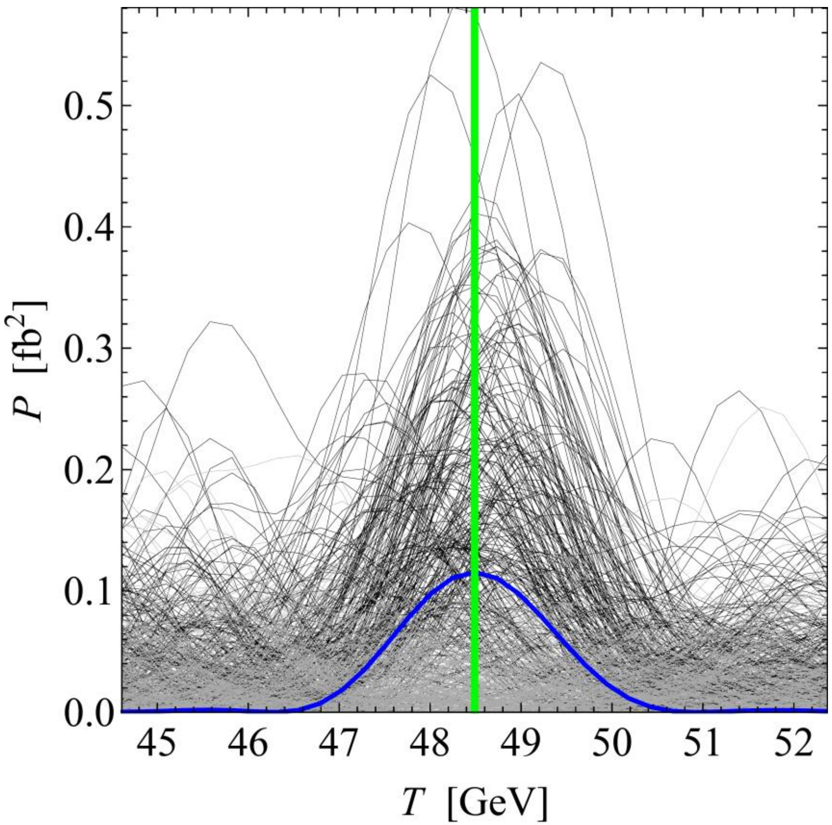
Fourier analysis of the $\gamma\gamma$ spectrum

Dividing out the parton luminosity and Fourier transforming.

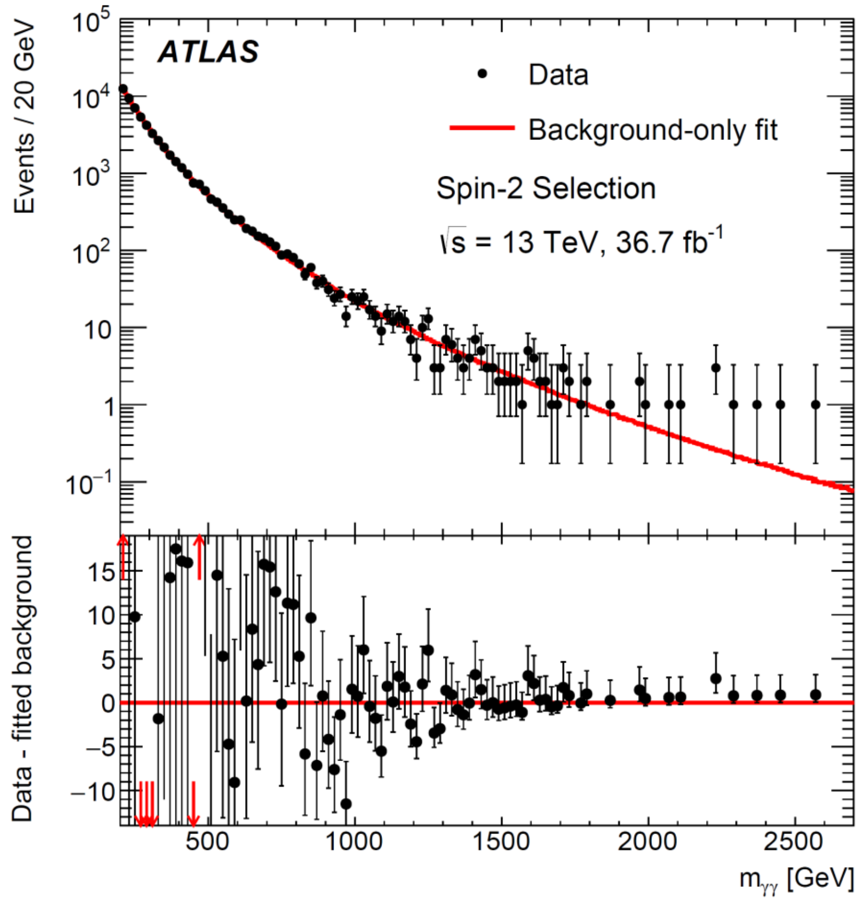


Fourier analysis of the $\gamma\gamma$ spectrum

Generating multiple realizations of signal+background (black) and background alone (gray) to quantify significance.



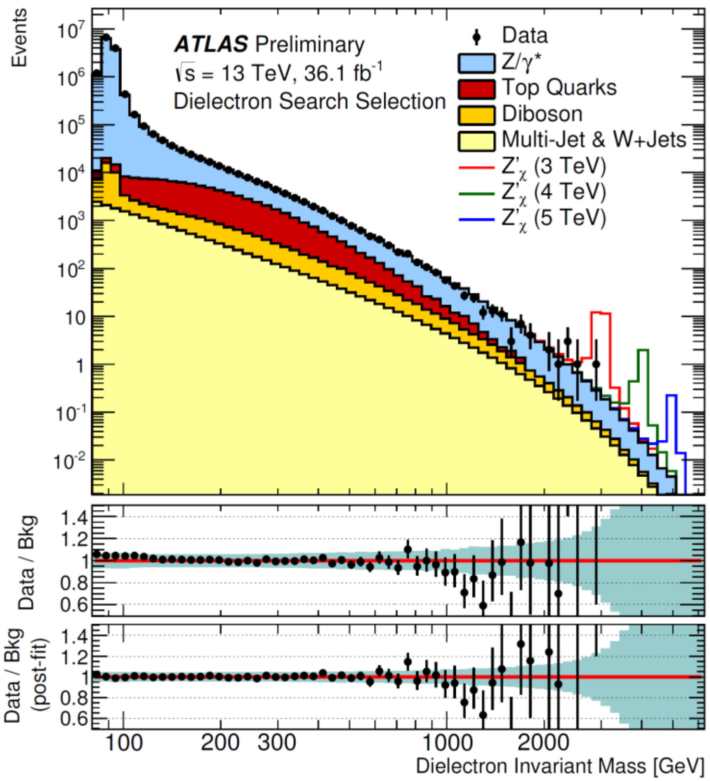
Searches in high-mass $\gamma\gamma$ continuum



arXiv:1707.04147

Unfortunately, uses just a single search region, $m_{\gamma\gamma} > 2240$ GeV.
Optimized for LED, suboptimal for CW/LD.

Searches in high-mass $\ell^+\ell^-$ continuum



m_{ee} [GeV]	80–120	120–250	250–400	400–500	500–700
Drell-Yan	11800000 ± 700000	216000 ± 11000	17230 ± 1000	2640 ± 180	1620 ± 120
Top Quarks	28600 ± 1800	44600 ± 2900	8300 ± 600	1130 ± 80	560 ± 40
Dibosons	31400 ± 3300	7000 ± 700	1300 ± 140	228 ± 25	146 ± 16
Multi-jet & W+jets	11000 ± 9000	5600 ± 2000	780 ± 80	151 ± 21	113 ± 17
Total SM	11900000 ± 700000	273000 ± 12000	27600 ± 1100	4150 ± 200	2440 ± 130
Data	12415434	275711	27538	4140	2390
Z'_χ (4 TeV)	0.00635 ± 0.00021	0.0390 ± 0.0015	0.0564 ± 0.0025	0.0334 ± 0.0027	0.064 ± 0.004
Z'_χ (5 TeV)	0.00305 ± 0.00012	0.0165 ± 0.0006	0.0225 ± 0.0010	0.0139 ± 0.0007	0.0275 ± 0.0015

m_{ee} [GeV]	700–900	900–1200	1200–1800	1800–3000	3000–6000
Drell-Yan	421 ± 34	176 ± 17	62 ± 7	8.7 ± 1.3	0.34 ± 0.07
Top Quarks	94 ± 8	27.9 ± 2.8	5.1 ± 0.7	< 0.001	< 0.001
Dibosons	39 ± 4	16.9 ± 2.1	5.8 ± 0.8	0.74 ± 0.11	0.028 ± 0.004
Multi-jet & W+jets	39 ± 6	16.1 ± 2.0	7.9 ± 2.3	1.6 ± 1.2	0.08 ± 0.27
Total SM	590 ± 40	237 ± 17	81 ± 7	11.0 ± 1.8	0.45 ± 0.28
Data	589	209	61	10	0
Z'_χ (4 TeV)	0.0585 ± 0.0035	0.074 ± 0.005	0.121 ± 0.011	0.172 ± 0.017	2.57 ± 0.27
Z'_χ (5 TeV)	0.0218 ± 0.0013	0.0295 ± 0.0021	0.040 ± 0.004	0.040 ± 0.004	0.280 ± 0.030

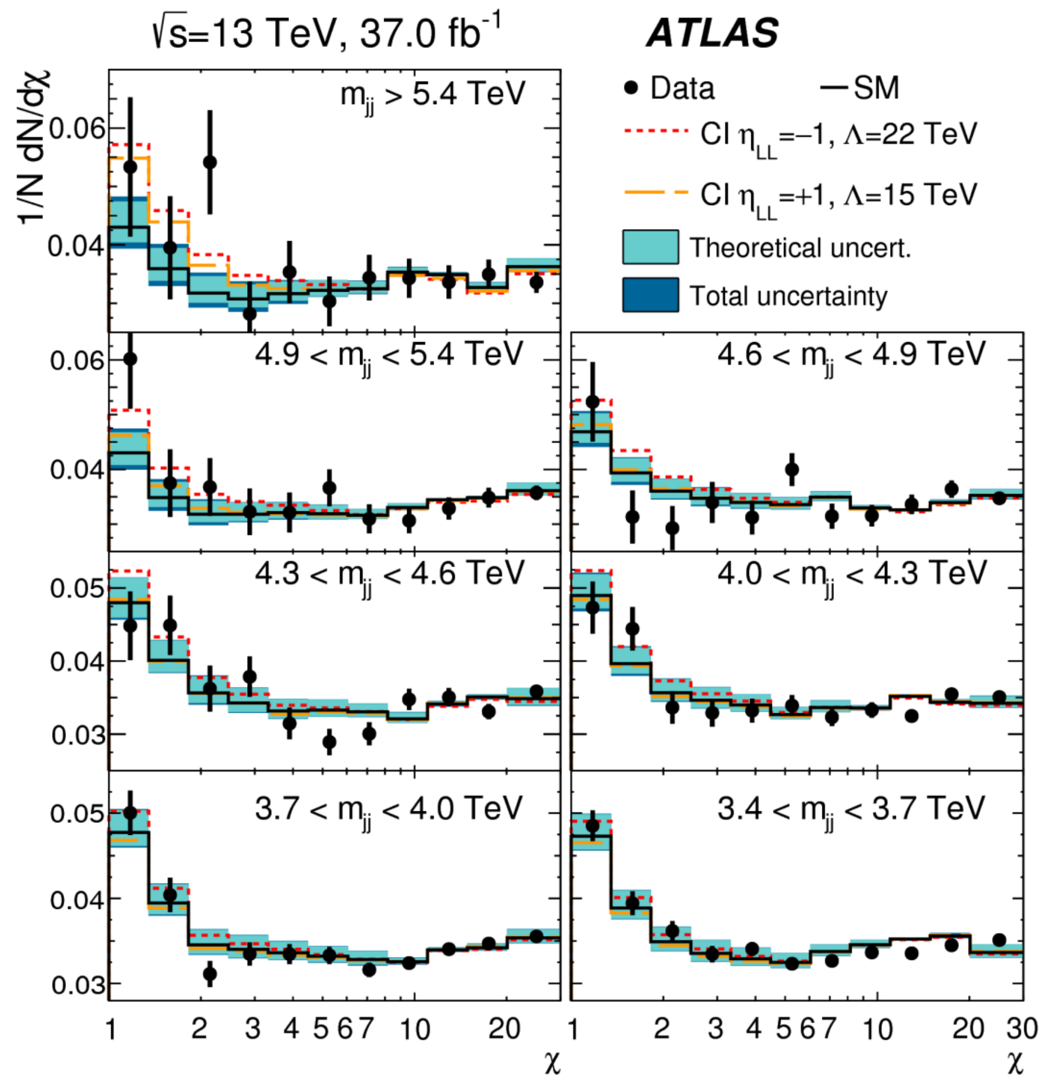
… and analogously for muons.

ATLAS-CONF-2017-027

Searches in dijet angular distributions

Searches look at angular distributions in m_{jj} bins, using the variable

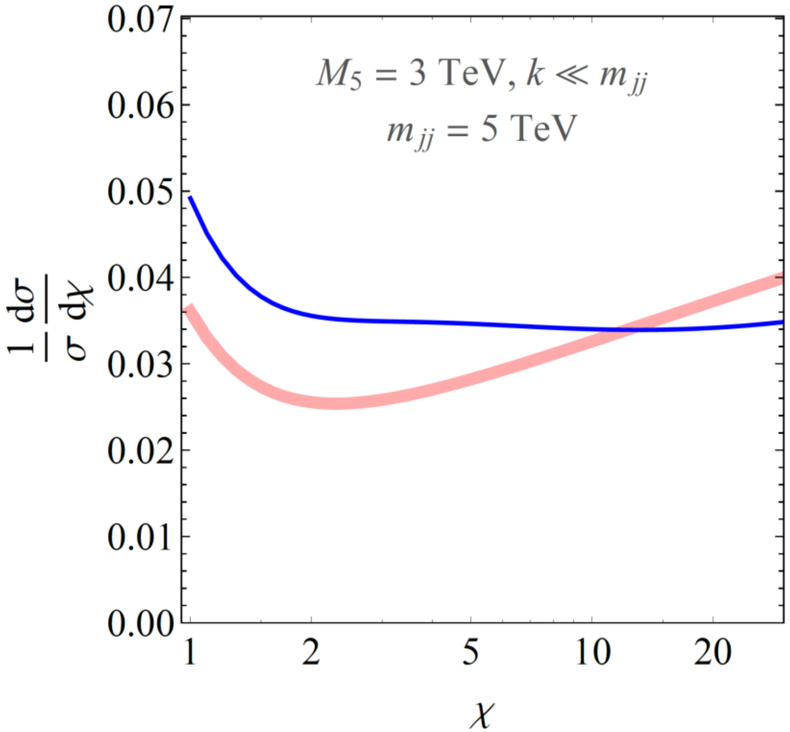
$$\chi = \exp(|y_1 - y_2|)$$

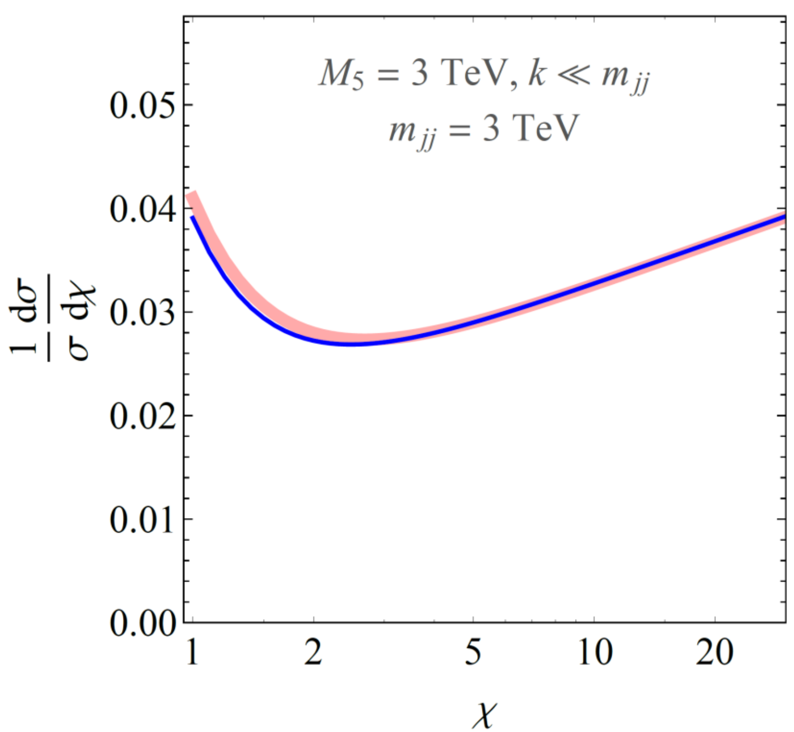


arXiv:1703.09127

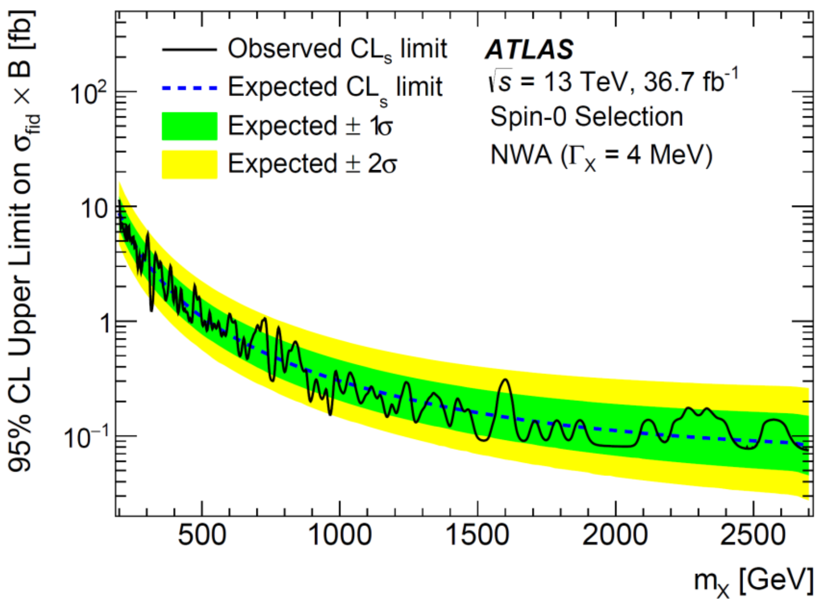
Searches in dijet angular distributions

Unfortunately, limits can only be set by relying on masses $> M_5$ (where the validity of the theory is questionable), so the interpretation in terms of the model parameters is uncertain.



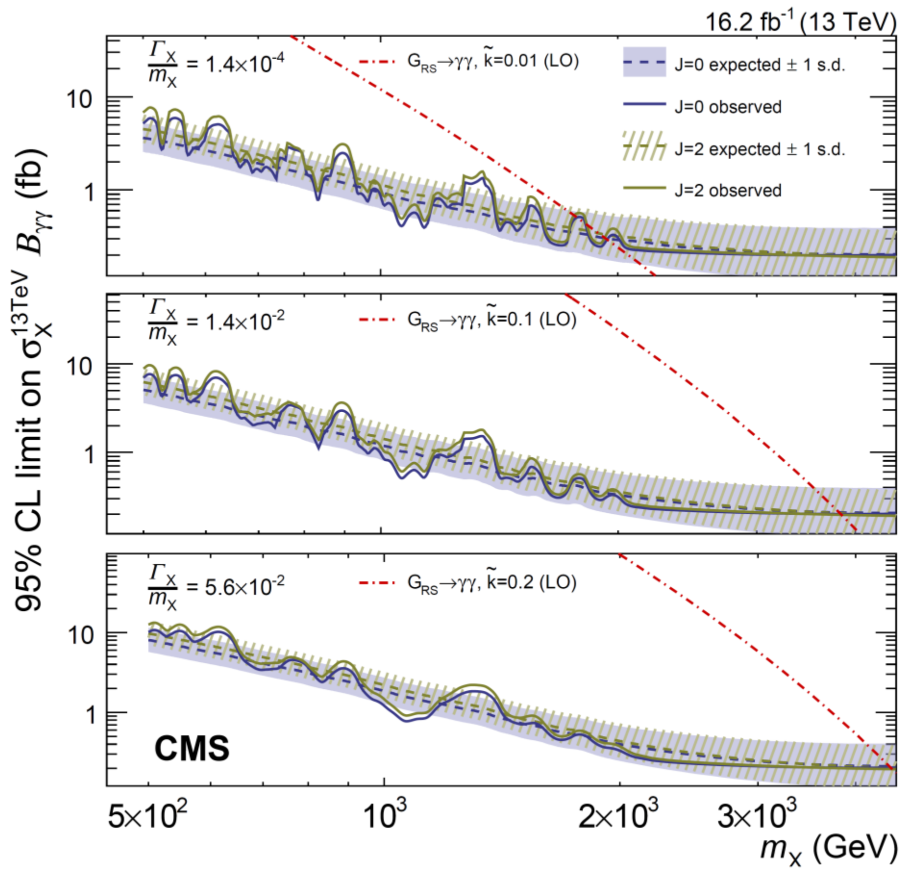


$\gamma\gamma$ resonance searches



arXiv:1707.04147

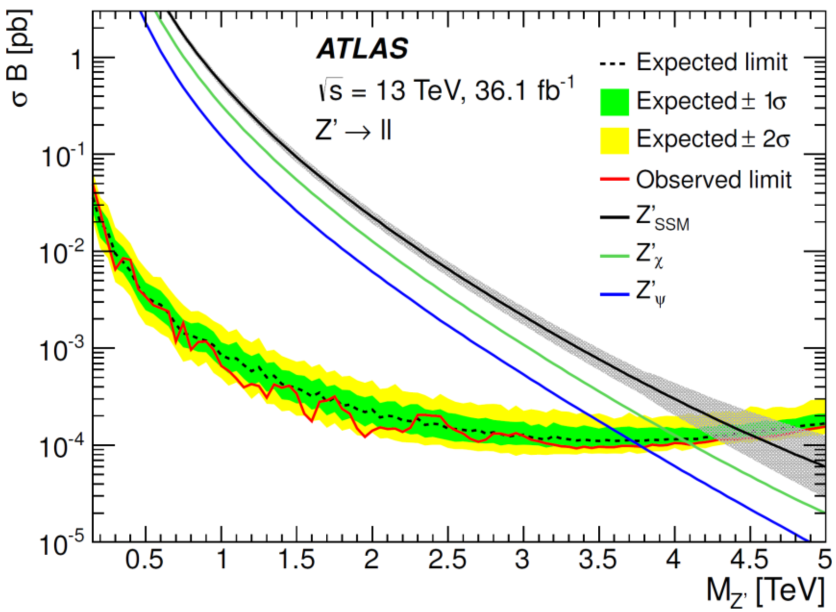
* We use the results of the "spin-0 selection" because the "spin-2 selection" results are not presented for low masses.

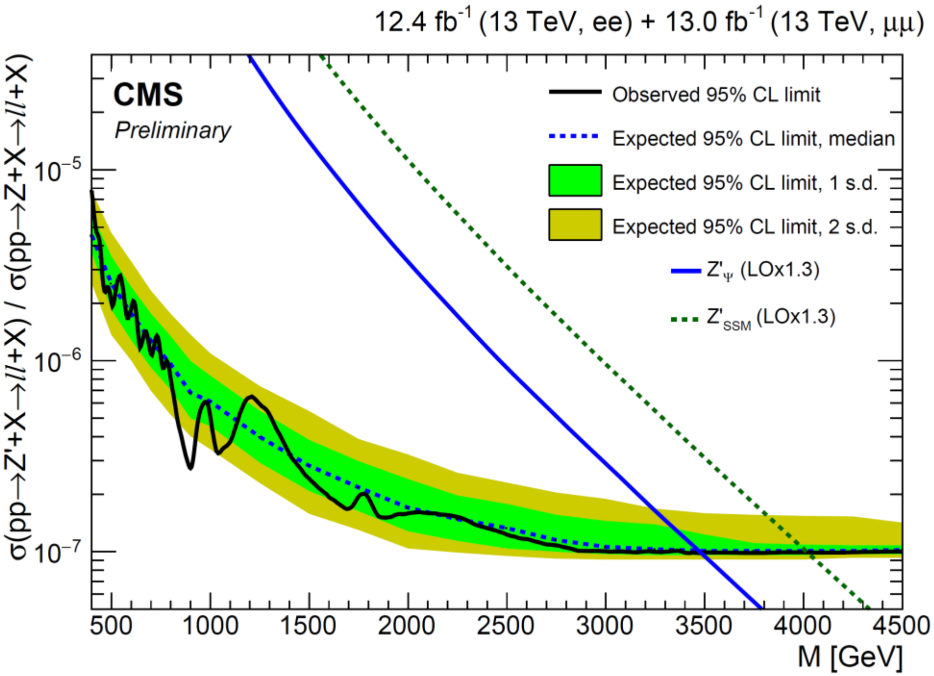


arXiv:1609.02507

Caveats:
1. We use a single (best) signal peak for limit setting.
2. Intrinsic background due to the rest of the KK tower is not taken into account.
3. In practice, nearby peaks might confuse the "bump hunter".

$\ell^+\ell^-$ resonance searches





arXiv:1707.02424 **CMS-PAS-EXO-16-031**

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2. Intrinsic background due to the rest of the KK tower is not taken into account.
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