Clockwork/Linear Dilaton: Structure and Phenomenology

Moriond EW 2018 - 16 Mar 2018

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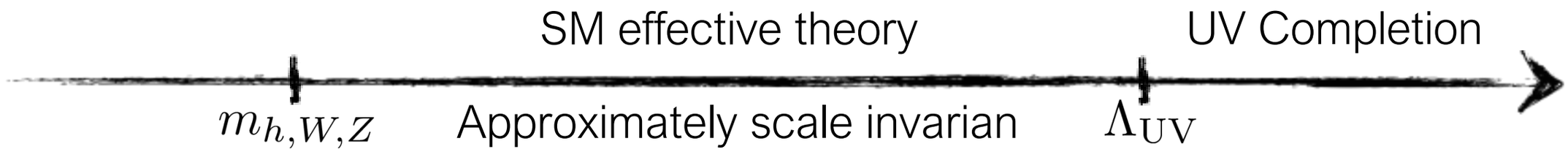
based on 1711.08437 in collaboration with G. Giudice, Y. Katz, M. McCullough and A. Urbano

Why $G_F \gg G_N$?



$$\Delta\mathcal{L}^{\rm rel}_{\rm SM} = c\Lambda^2_{\rm UV} H^\dagger H$$
$$m_h^2 = c\Lambda^2_{\rm UV} + \delta m_h^2$$

The coefficient is fixed by "scale invariance", that is NDA

- If $\Lambda_{\rm UV} \gg m_W$ one needs an incredible amount of tuning on c (Hierarchy Problem)
- To avoid tuning one needs to lower the $\Lambda_{\rm UV}$ to which the Higgs is sensitive and forbid the Higgs mass operator (or make it irrelevant/marginal) above that scale
- Extra dimensions can realize this in two different ways

Warped Extra-dimensions

$$M_P^2 = \frac{e^{2\pi k R} - 1}{k} M_5^3$$

Gravitational redshift

Large Extra-dimensions

$$M_P^2 = V_n M_D^{2+n}$$

Dilution of gravity

- If the Standard Model is confined on a 4D hypersurface (brane) where the effect of gravity is weak then m_W is of the order of the fundamental scale M_D, while M_P is an "illusion" due to the dynamics of gravity in 5D

Solving the Hierarchy Problem

- Generally these are not solutions, just offer a different perspective
- Tuning is always necessary to get 4D Poincare invariance (vanishing 4D CC)

Warped Extra-dimensions

$$M_P^2 = \frac{e^{2\pi k R} - 1}{k} M_5^3$$

Gravitational redshift

The tuning of the EW scale is traded for the tuning of a vanishing radion potential

Radion potential can be naturally stabilized through a “spectator” bulk field (Goldberger-Wise)

Randall, Sundrum, hep-ph/9905221
Goldberger, Wise, hep-ph/9907447

Large Extra-dimensions

$$M_P^2 = V_n M_D^{2+n}$$

Dilution of gravity

The tuning of the EW scale is traded for the tuning of a large volume (vanishing 5D CC)

The problem here is more severe and one generally need SUSY in the bulk

Arkani-Hamed, Dimopoulos, Dvali, hep-ph/9803315
Antoniadis, Arkani-Hamed, Dimopoulos, Dvali, hep-ph/9804398
Arkani-Hamed, Dimopoulos, Dvali, hep-ph/98007344

The Linear Dilaton setup

- We consider (4+1)D space-time where the extra dimension is a circle: $-\pi R \leq y \leq \pi R$
- The SM lives on a (TeV) brane at $y = y_{\rm T} = 0$ and there is a (Planck) brane at $y = y_{\rm P} = \pi R$
- A Z_2 orbifold symmetry identifies $y \leftrightarrow -y$
- 5D Einstein equations and dilaton equations of motion are solved by

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

- 4D Planck Mass is given by

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

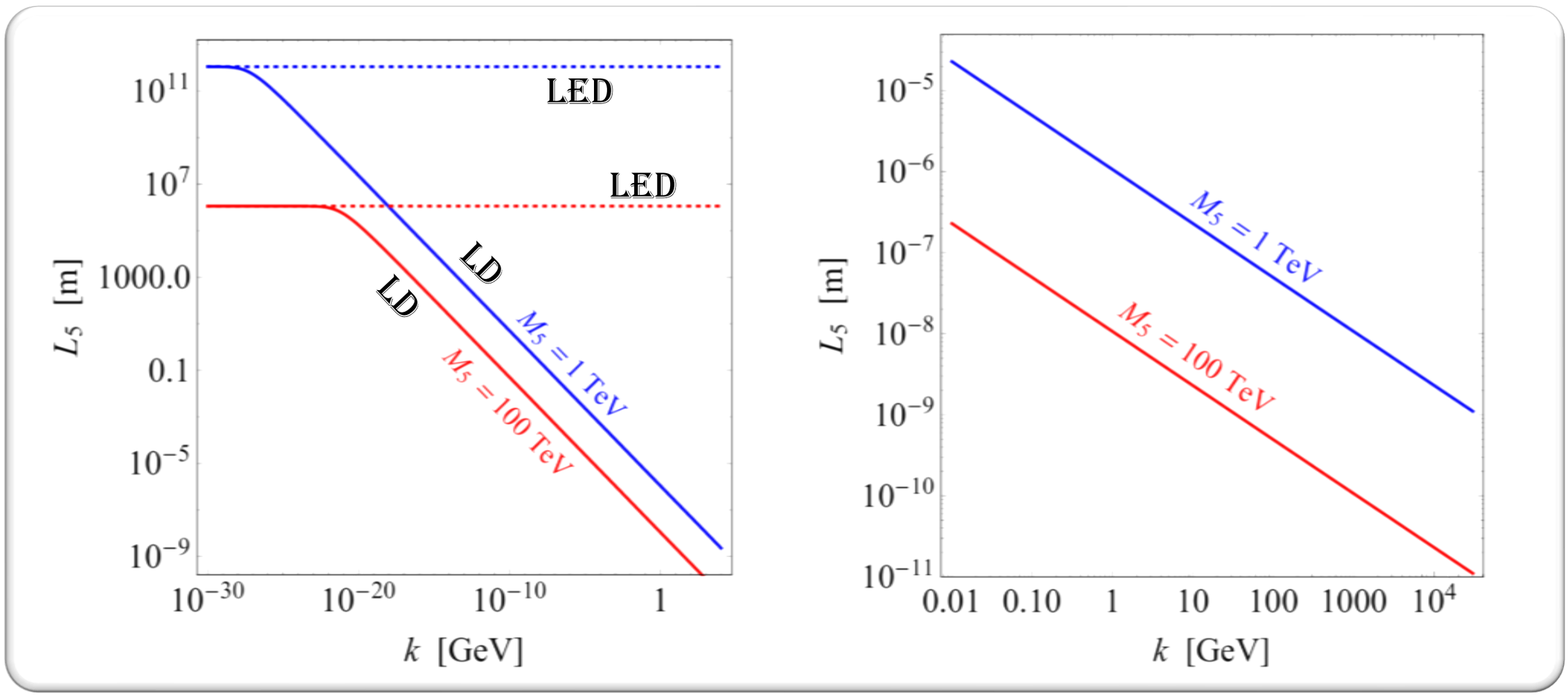
- The fundamental 5D scale M_5 is taken to be TeV scale and the required hierarchy is guaranteed by a moderate value of kR (similar to RS)

$$\boxed{kR \simeq \frac{1}{\pi}\ln\left(\frac{M_P}{M_5}\sqrt{\frac{k}{M_5}}\right) \approx 10 + \frac{1}{2\pi}\ln\left(\frac{k}{\rm TeV}\right) - \frac{3}{2\pi}\ln\left(\frac{M_5}{10\ {\rm TeV}}\right)}$$

- While kR is similar to RS, in RS $2\pi R$ is the proper length of the extra dimension, while in the LD the proper length is exponentially bigger than $2\pi R$

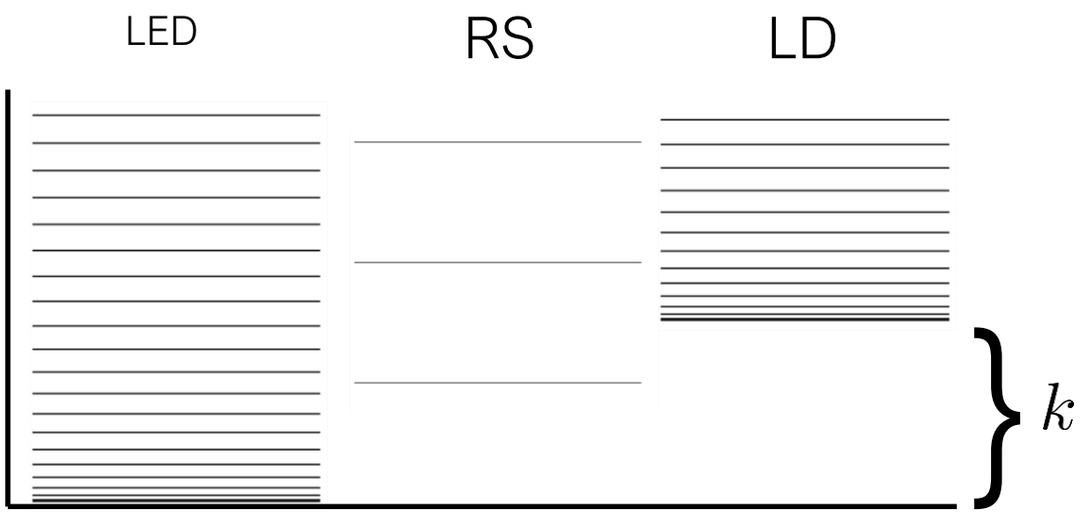
Proper size

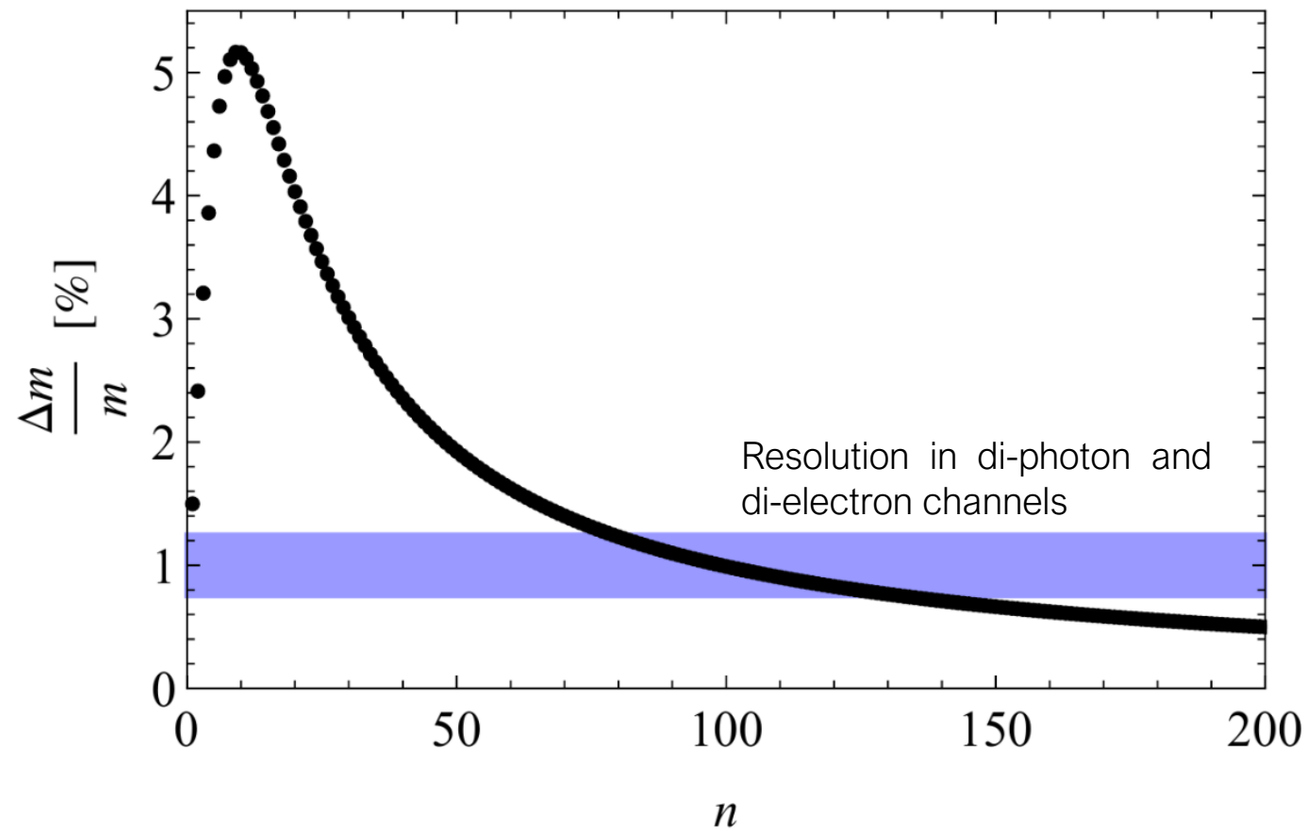
- In the LD the extra-dimension is much bigger than in RS and much smaller than in LED
- In the limit $k \to 0$ the LD reduces to LED
- LD is an interesting benchmark for a single ED with low curvature
- Fixing M_P to its physical value one obtains



Phenomenology of KK gravitons

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





$$\mathcal{L} \supset -\frac{1}{\Lambda_G^{(n)}}\, \tilde{h}_{\mu\nu}^{(n)}\, T^{\mu\nu}$$

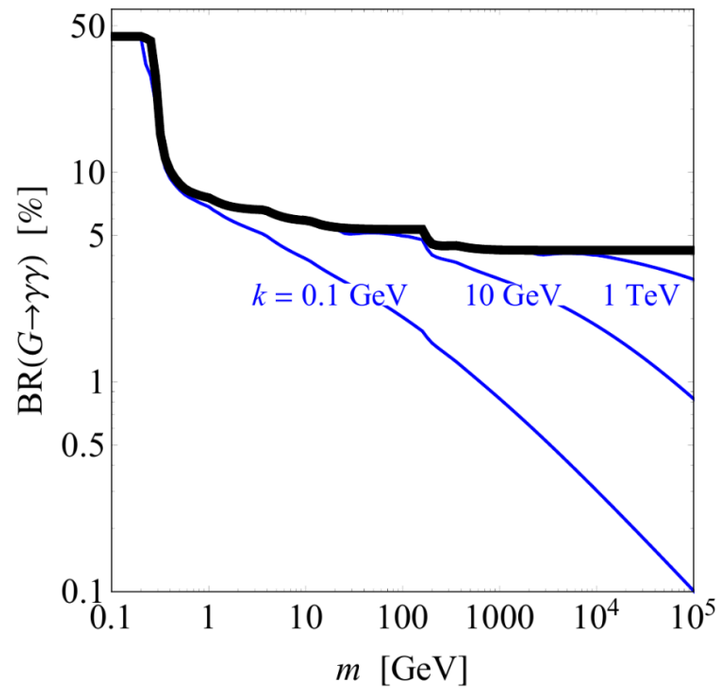
$$\Lambda_G^{(0)2} = M_P^2 \qquad \Lambda_G^{(n)2} = M_5^3 \pi R \left(1 + \frac{k^2 R^2}{n^2}\right) = M_5^3 \pi R \left(1 - \frac{k^2}{m_n^2}\right)^{-1}$$

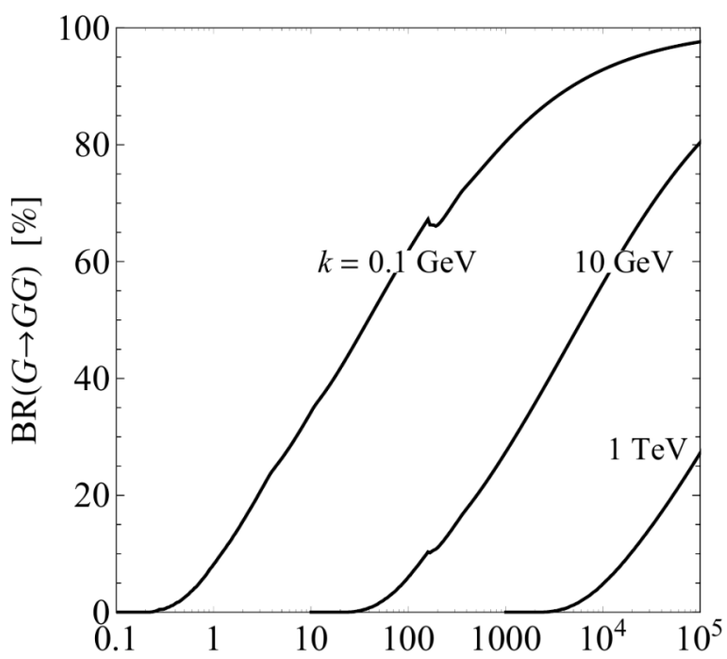
gg	$\sum_i q_i \bar{q}_i$	W^+W^-	ZZ	hh	$\gamma\gamma$	$\sum_i \ell_i^+ \ell_i^-$	$\sum_i \nu_i \bar{\nu}_i$
34%	38%	9.2%	4.6%	0.35%	4.2%	6.4%	3.2%

KK gravitons: cascade & displaced

Cascade decays

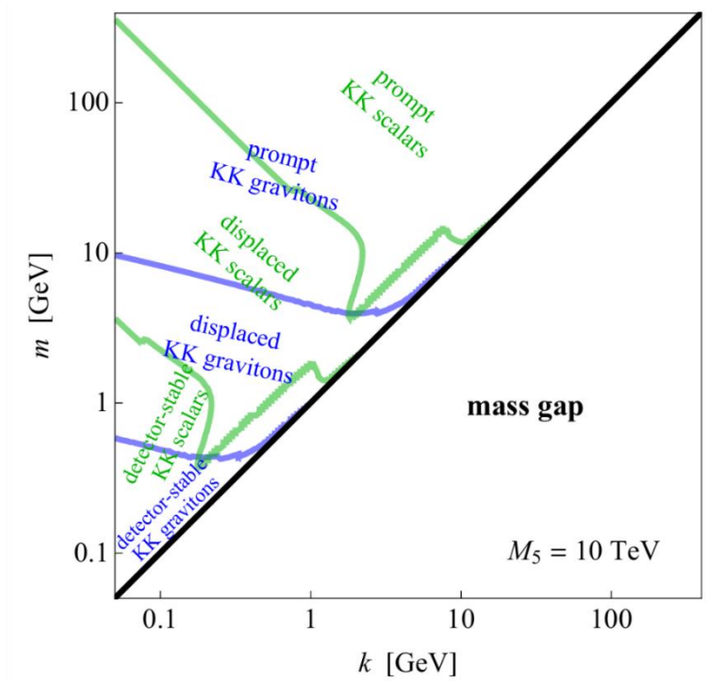
$$\frac{\Gamma_{G_n \to \sum G_\ell G_m}}{\Gamma_{G_n \to \mathrm{SM}}} \approx 4.1 \times 10^{-2} \sqrt{\frac{m_n}{k}}$$

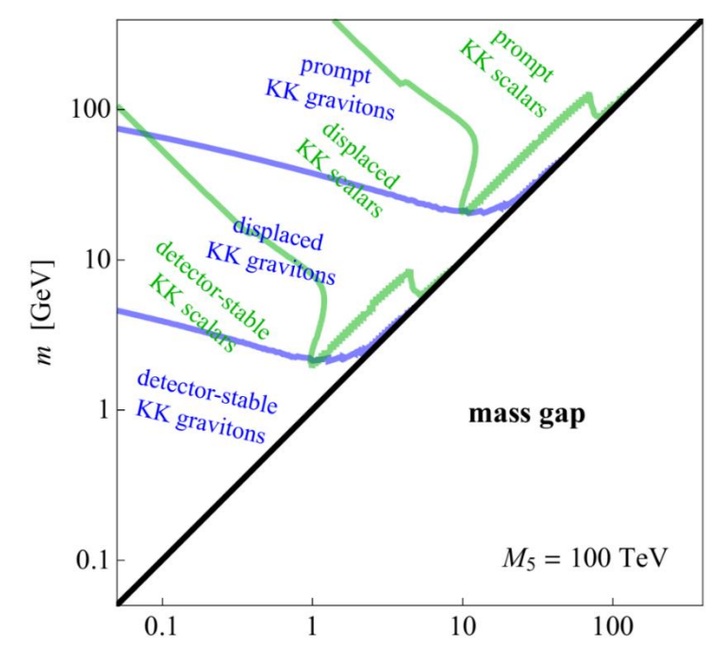




Displaced decays

$$c\tau_n \approx 6.6 \times 10^{-8}\,\mathrm{m} \left(\frac{M_5}{10\ \mathrm{TeV}}\right)^3 \left(\frac{1\ \mathrm{GeV}}{k}\right) \left(\frac{100\ \mathrm{GeV}}{m_n}\right)^3 \left(\frac{kR}{10}\right) \left(1 - \frac{k^2}{m_n^2}\right)^{-1}$$





KK modes are usually prompt

$$c\tau \lesssim 1\ \mathrm{mm}$$

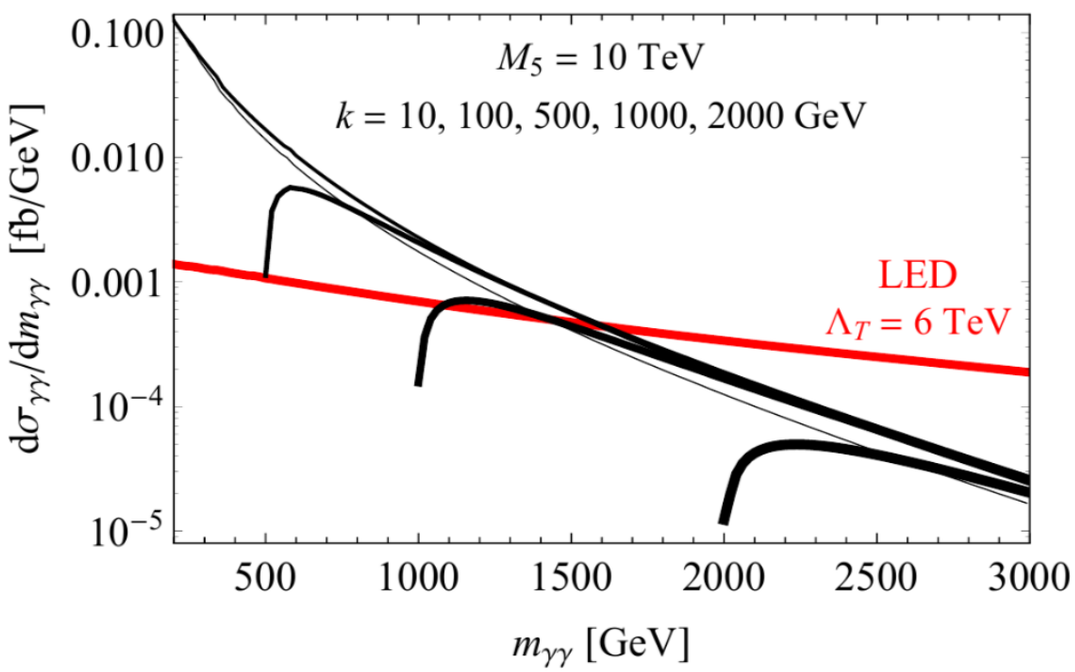
but there are regions of parameters space where they can be displaced, or even collider stable

$$c\tau \gtrsim 10\ \mathrm{m}$$

KK gravitons: tails & resonances

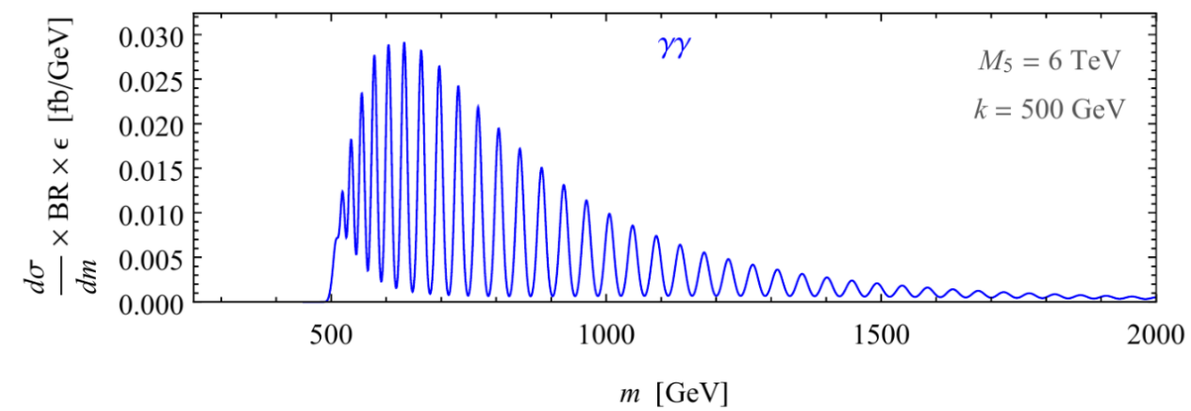
- KK-gravitons contribute both resonantly and non-resonantly to di-photon, di-lepton, di-jet events
- Different than LED with >1 ED and fully calculable

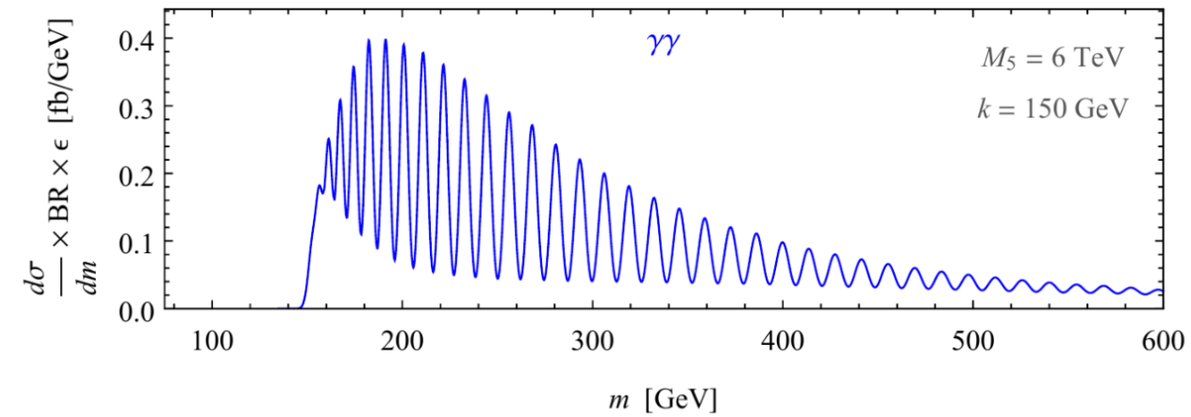
Tails



- s-channel relevant for searches in tails of invariant mass distributions (di-leptons/di-photons)

Resonances





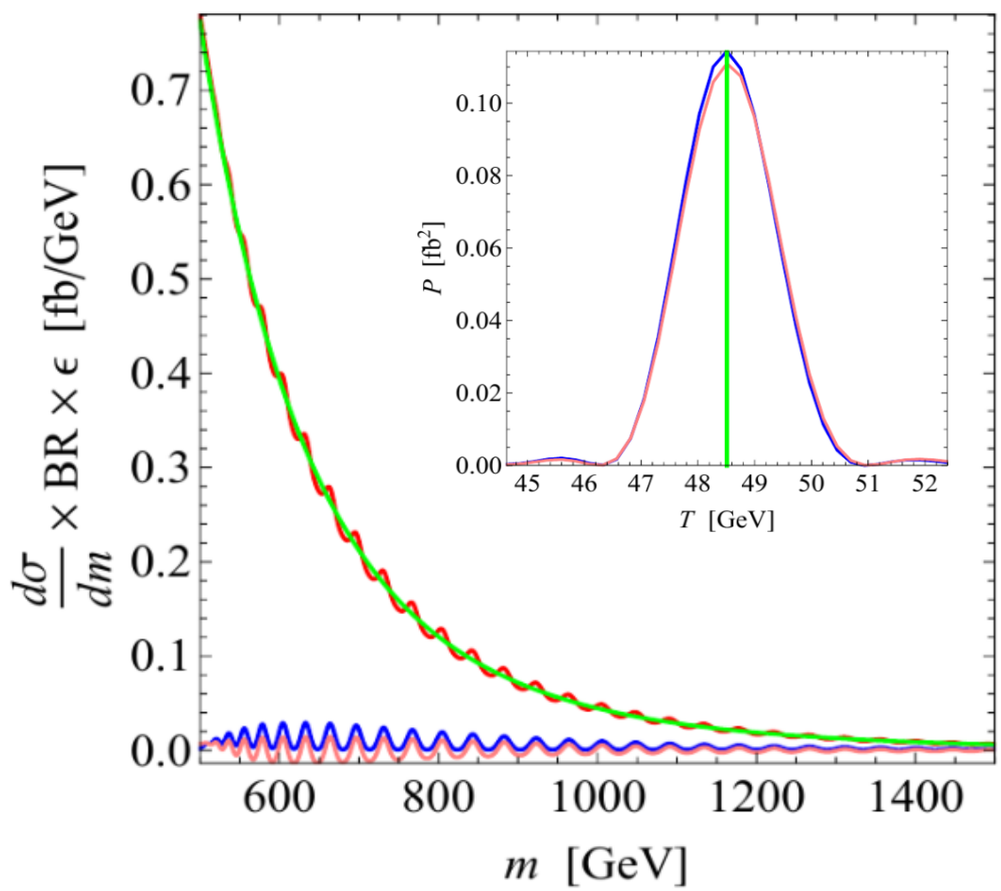
- The model contains a large number of resonances that in some cases can be resolved given the resolution in di-electron and di-photon channels
- However, bump-hunt searches are not suited, since they do not take into account the presence of all other resonances

Fourier analysis

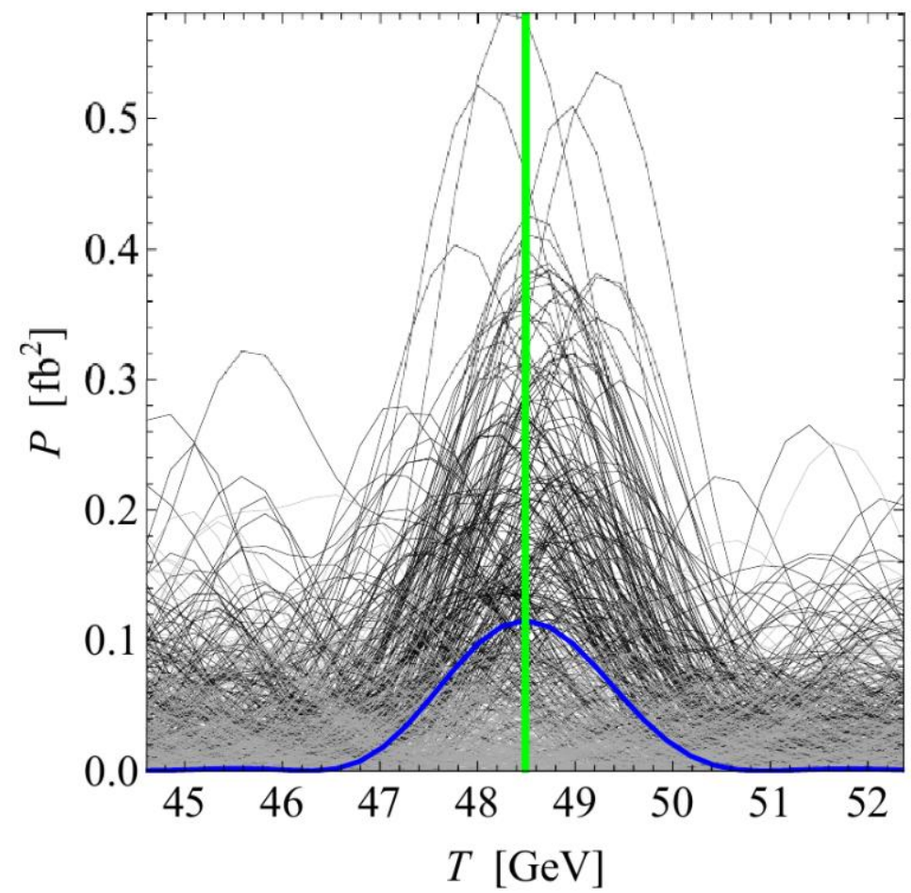
- Given the periodic nature of the signal one can try and employ a Fourier analysis to extract the power spectrum (analogous to what is done in astrophysics)

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

- This power spectrum assumes periodicity in $\sqrt{m^2 - k^2}$ for a given signal hypothesis on k
- The function $P(T)$ is expected to produce a peak centered near $T \sim 1/R$



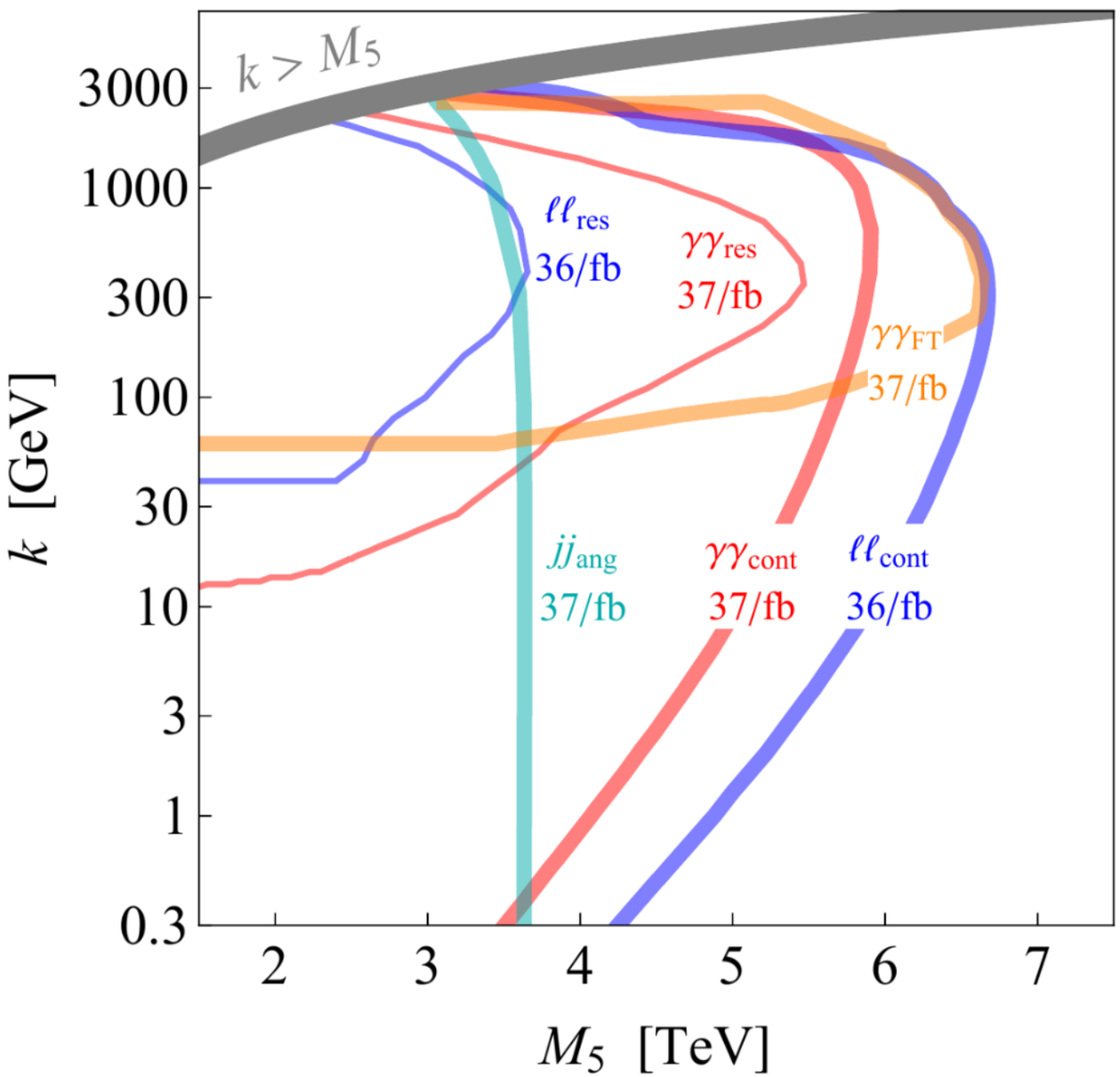
- Even adding background (assuming BG shape is known) the situation is good



- Even adding bin-by-bin Poisson smearing the signal could still emerge

Summary

- Putting together all recasted existing searches (resonant, non-resonant, angular, continuum) and our proposed Fourier analysis we get the summary plot



- Rather natural regions still allowed
- Limits from continuum worsen due to cascade decays
- Fourier transform does not overperform the other methods, but improvement is possible
- Single resonant searches and angular searches subject to caveats, but usually less sensitive that continuum searches
- High-multiplicity, displaced decays, spectrum turn-on not yet included

Conclusions

- LD also provides an interesting framework for a single ED with low curvature
- The phenomenology is radically new and interpolates between LED and RS
- We studied several standard signatures
- We proposed a Fourier analysis that is novel for collider searches
- In the future may be interesting to extend the Fourier analysis to be sensitive to other geometries, and maybe, to extract information on the geometry itself directly from SM distributions

THANK YOU

BACKUP SLIDES

The Linear Dilaton setup

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- The SM lives on a (TeV) brane at $y = y_{\rm T} = 0$ and there is a (Planck) brane at $y = y_{\rm P} = \pi R$
- A Z_2 orbifold symmetry identifies $y \leftrightarrow -y$

Antoniadis, Dimopoulos, Giveon, hep-ph/0103033
Antoniadis, Arvanitaki, Dimopoulos,
Giveon, hep-ph/1102.4043 [hep-ph]
Baryakhtar, 1202.6674
Cox, Gherghetta, 1203.5870

$$\boxed{\mathcal{S} = \mathcal{S}_{\rm bulk} + \mathcal{S}_{\mathcal{B}} + \mathcal{S}_{\rm GHY} + \mathcal{S}_{\rm SM}}$$

$$\mathcal{S}_{\rm bulk} = M_5^3 \int d^4x \int_0^{\pi R} dy \sqrt{-g} \left[\mathcal{R} - \frac{1}{3} g^{MN} \partial_M S \partial_N S - V(S) \right]$$

$$\mathcal{S}_{\mathcal{B}} = -2 \sum_{i={\rm T,P}} \int d^4x \int_0^{\pi R} dy \sqrt{-\gamma}\, \delta(y - y_i) \lambda_i(S)$$

$$\mathcal{S}_{\rm GHY} = 2 M_5^3 \int d^4x \int_0^{\pi R} dy\, \partial_y \left(\frac{1}{\sqrt{g_{55}}} \partial_y \sqrt{-\gamma} \right)$$

$$\mathcal{S}_{\rm SM} = 2 \int d^4x \int_0^{\pi R} dy \sqrt{-\gamma}\, e^{-S/3} \mathcal{L}_{\rm SM} \delta(y - y_{\rm T})$$

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

$$\lambda_{\rm T}(S) = e^{-\frac{S}{3}} M_5^3 \left[-4k + \frac{\mu_{\rm T}}{2} (S - S_{\rm T})^2 \right]$$

$$\lambda_{\rm P}(S) = e^{-\frac{S}{3}} M_5^3 \left[+4k + \frac{\mu_{\rm P}}{2} (S - S_{\rm P})^2 \right]$$

Definition of the radius

- In conformally flat coordinates: $ds^2 = e^{2\sigma(y)}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right)$

$$\sigma_{\rm LED}(y) = 0 \qquad \sigma_{\rm RS}(y) = -\ln(1 - k_{\rm RS}|y|) \qquad \sigma_{\rm LD}(y) = \frac{2}{3}k|y|$$

$$0 \le y \le \pi R_{\rm LED} \qquad 0 \le y \le \frac{1-e^{\pi k_{\rm RS} R_{\rm RS}}}{k_{\rm RS}} \qquad 0 \le y \le \pi R_{\rm LD}$$

Defined in conformally flat coordinates
(mass splitting between KK scales as $1/R_{\rm LD}$)

- In "proper" coordinates ($g_{55} = 1$): $ds^2 = e^{2\hat{\sigma}(z)}\eta_{\mu\nu}dx^\mu dx^\nu + dz^2$

$$\sigma_{\rm LED}(z) = 0 \qquad \sigma_{\rm RS}(z) = k_{\rm RS}|z| \qquad \sigma_{\rm LD}(z) = \log(1 + \frac{2k_{\rm LD}z}{3})$$

$$0 \le z \le \pi R_{\rm LED} \qquad 0 \le z \le \pi R_{\rm RS} \qquad 0 \le z \le \frac{3}{2k_{\rm LD}}\left(e^{2/3\pi k_{\rm LD} R_{\rm LD}} - 1\right)$$

Defined in "proper" coordinates (mass splitting between KK scales as $1/R_{\rm RS}$)

Proper size

- We can define a proper length of the extra dimension and a "warp factor" (redshift) as

$$L_5 \equiv \int_{-\pi R}^{\pi R} dy\, \sqrt{g_{55}} \qquad\qquad w \equiv \left[\frac{\int d^5x\, \sqrt{-g}\, \delta(y-\pi R)/\sqrt{g_{55}}}{\int d^5x\, \sqrt{-g}\, \delta(y-0)/\sqrt{g_{55}}} \right]^{1/4}$$

- These quantities and the Planck masse, are given, for LED, RS and LD by

$$L_5 = 2\pi R_{\rm LED} \qquad w = 1 \qquad M_P^2 = L_5\, M_5^3$$

$$L_5 = 2\pi R_{\rm RS} \qquad w = e^{k_{\rm RS}\pi R_{\rm RS}} \qquad M_P^2 = \frac{w^2-1}{\ln w^2}\, L_5\, M_5^3$$

$$L_5 = \frac{3\left(e^{\frac{2}{3}k_{\rm LD}\pi R_{\rm LD}}-1\right)}{k_{\rm LD}} \qquad w = e^{\frac{2}{3}k_{\rm LD}\pi R_{\rm LD}} \qquad M_P^2 = \frac{w^2+w+1}{3}\, L_5\, M_5^3$$

- The hierarchy is generated only by volume (dilution) in LED, only by warping (redshift) in RS and by an interplay of the two in LD

Production cross sections

- For KK-gravitons one gets

$$\sigma_n = \frac{\pi}{48\Lambda_G^{(n)2}} \left[3\,\mathcal{L}_{gg}(m_n^2) + 4\sum_q \mathcal{L}_{q\bar{q}}(m_n^2) \right] \qquad \mathcal{L}_{ij}(\hat{s}) = \frac{\hat{s}}{s}\int_{\hat{s}/s}^1 \frac{dx}{x}\, f_i(x)\, f_j\left(\frac{\hat{s}}{xs}\right)$$

- Approximating with a continuum the invariant mass spectrum can be written as

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

- For KK-scalars one gets ($b_{\rm QCD} = 7$ for $m_n \gg m_t$)

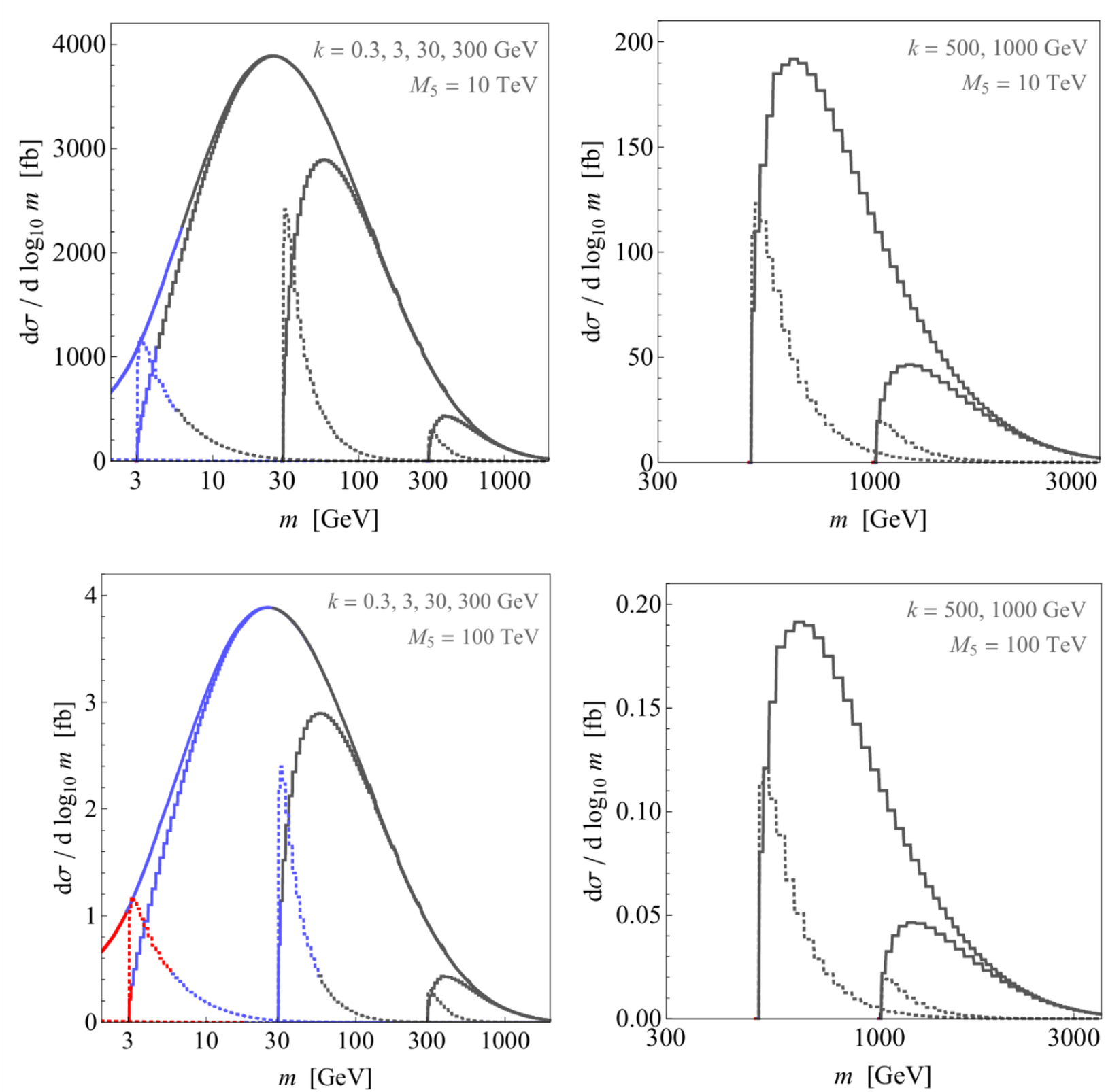
$$\sigma_n = \frac{b_{\rm QCD}^2\alpha_s^2}{256\pi\Lambda_\Phi^{(n)2}}\,\mathcal{L}_{gg}(m_n^2) \qquad \mathcal{L}_{ij}(\hat{s}) = \frac{\hat{s}}{s}\int_{\hat{s}/s}^1 \frac{dx}{x}\, f_i(x)\, f_j\left(\frac{\hat{s}}{xs}\right)$$

- Approximating with a continuum the invariant mass spectrum can be written as

$$\frac{d\sigma}{dm} \simeq \theta(m-k)\,\frac{b_{\rm QCD}^2\alpha_s^2}{1728\pi^2 M_5^3}\sqrt{1-\frac{k^2}{m^2}}\left(1-\frac{8k^2}{9m^2}\right)^{-1}\frac{k^2}{m^2}\,\mathcal{L}_{gg}(m^2)$$

- Production of KK-scalars generally suppressed compared to KK-gravitons
- Main source of KK-scalars production is through cascade decays of KK-gravitons

Production cross sections



LHC

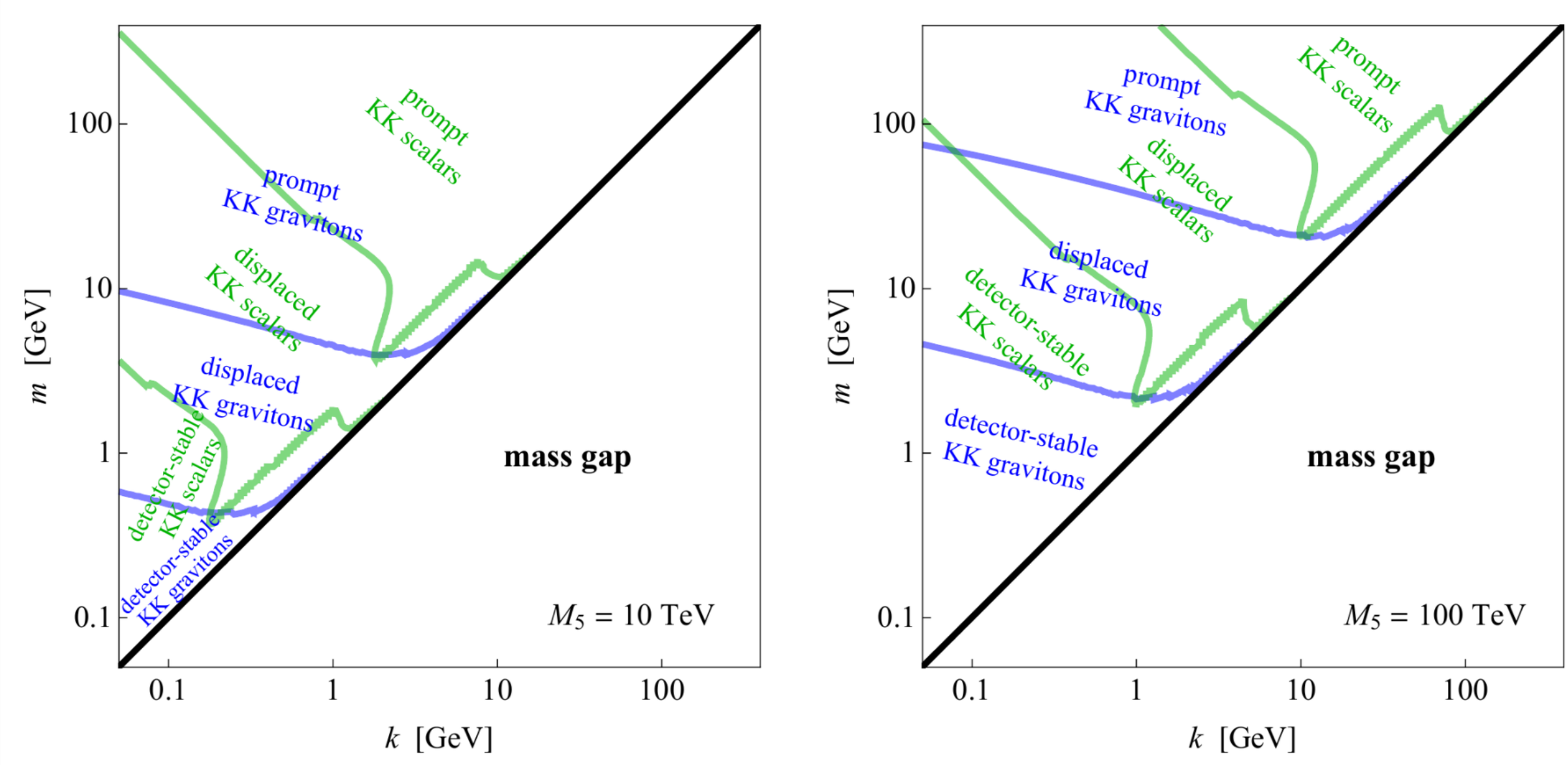
Solid: KK-gravitons

Dashed: KK-scalars

FCC

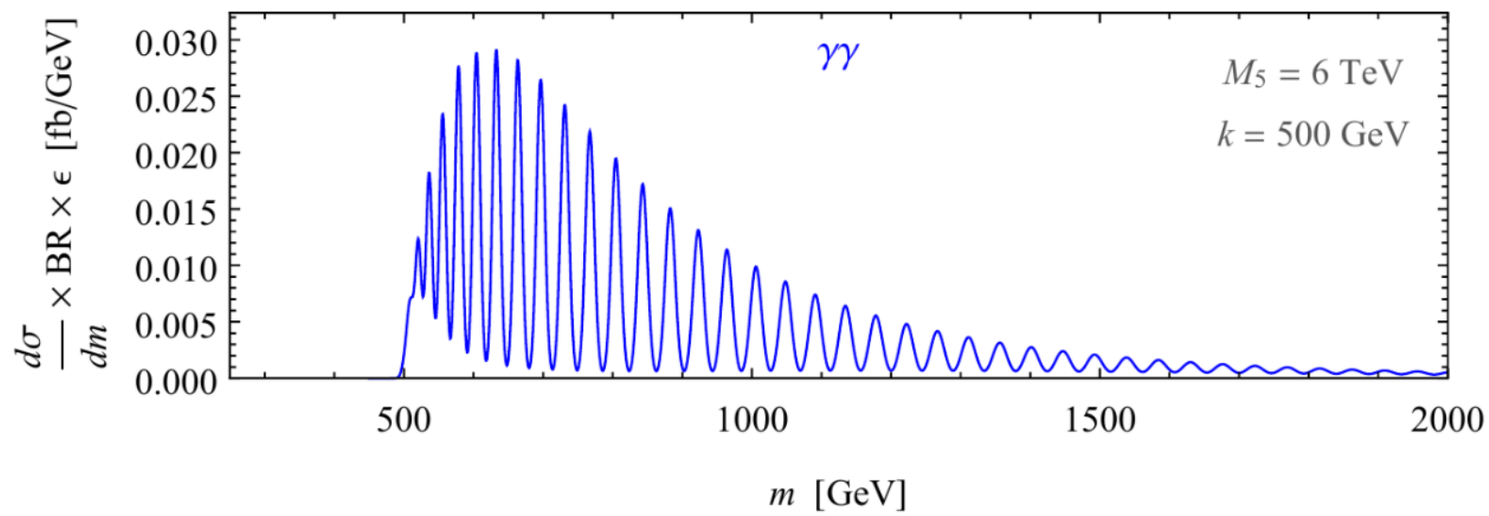
Lifetime summary

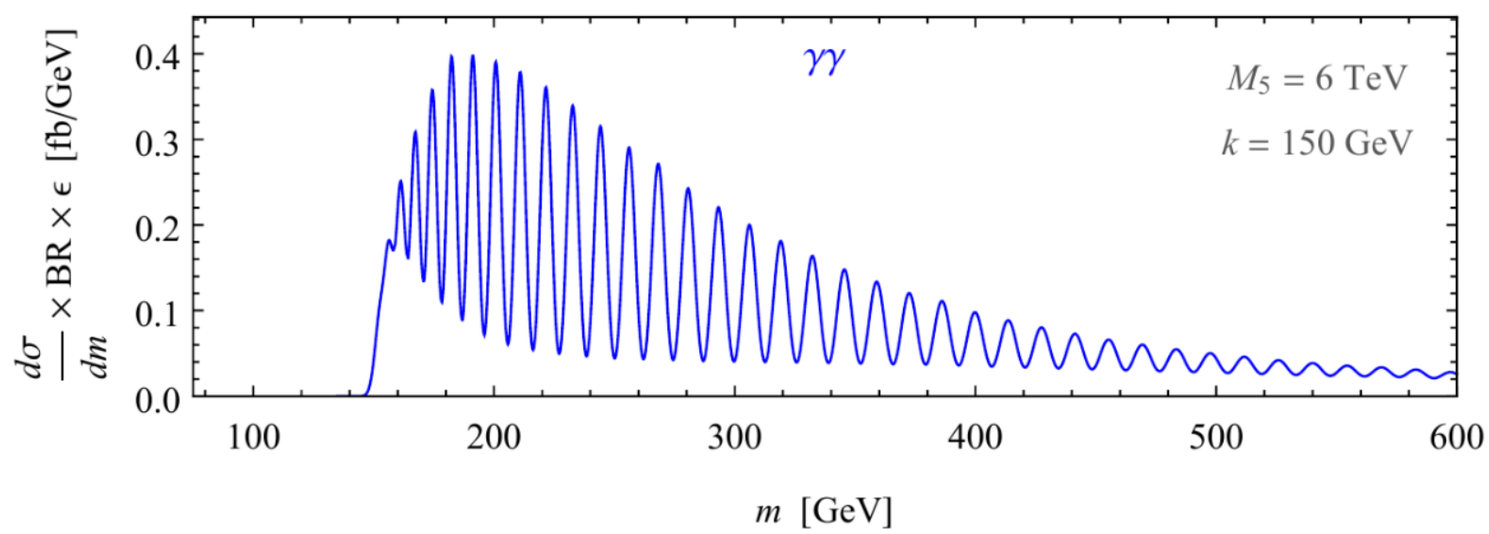
- One of the peculiar features of the model is that for any given choice of the parameters it contains detector-stable, displaced and prompt KK decays depending on their masses



Signatures: single resonance

- The model contains a large number of resonances that in some cases can be resolved given the resolution in di-electron and di-photon channels
- However, bump-hunt searches are not suited, since they do not take into account the presence of all other resonances

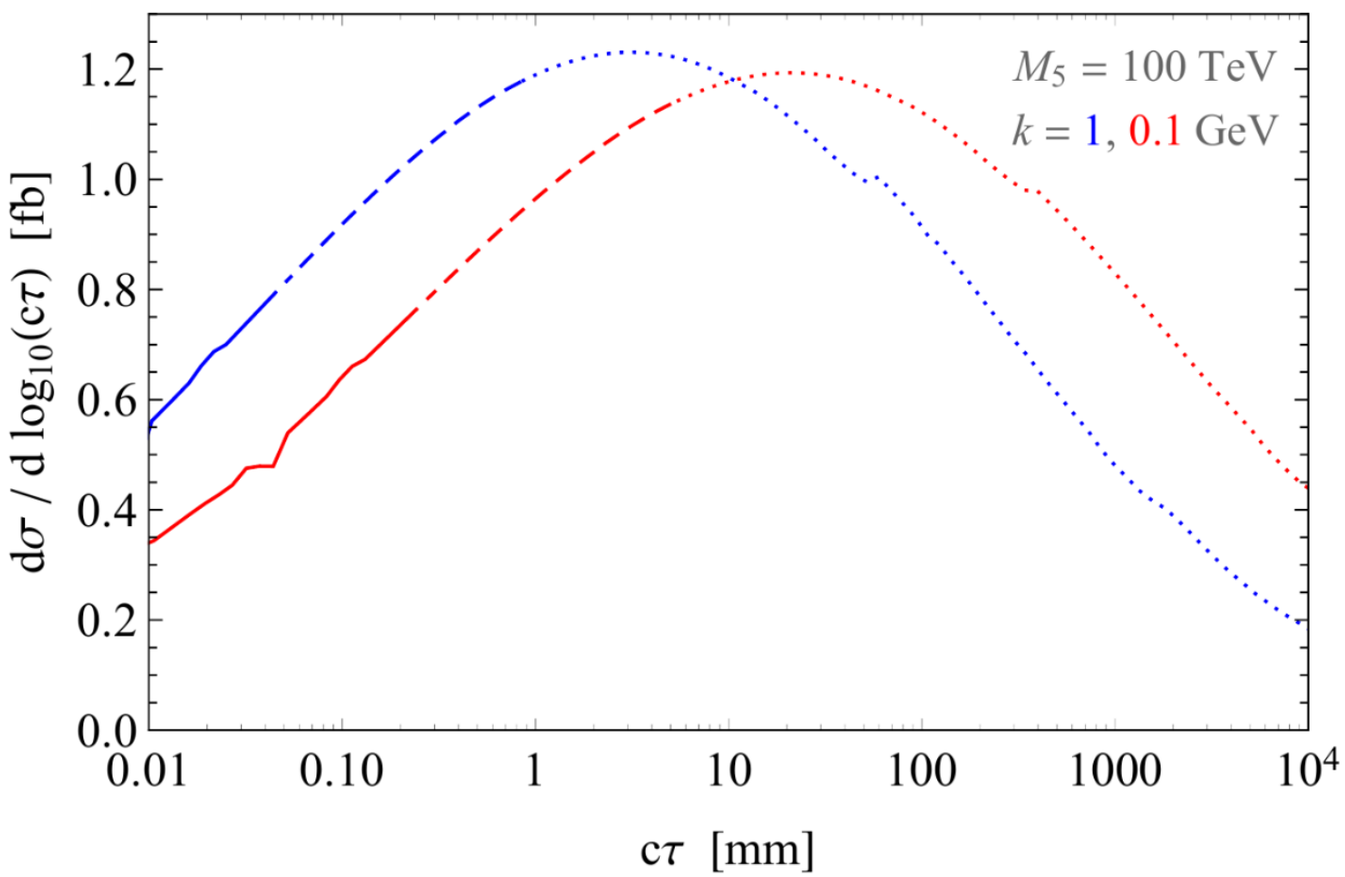




- Instead of looking for a single or multi resonances, it would be better to profit by the periodic structure of the signal and the particular shape of the turn-on of the spectrum

Signatures: displaced

- Usually sizeable production leads to prompt decay
- Difficult to think of a particle sizeably produced that has long lifetime
- However for the LD may happen that each KK-mode production is small, but the sum is large enough to lead to observable displaced decays
- Can lead to interesting novel signatures



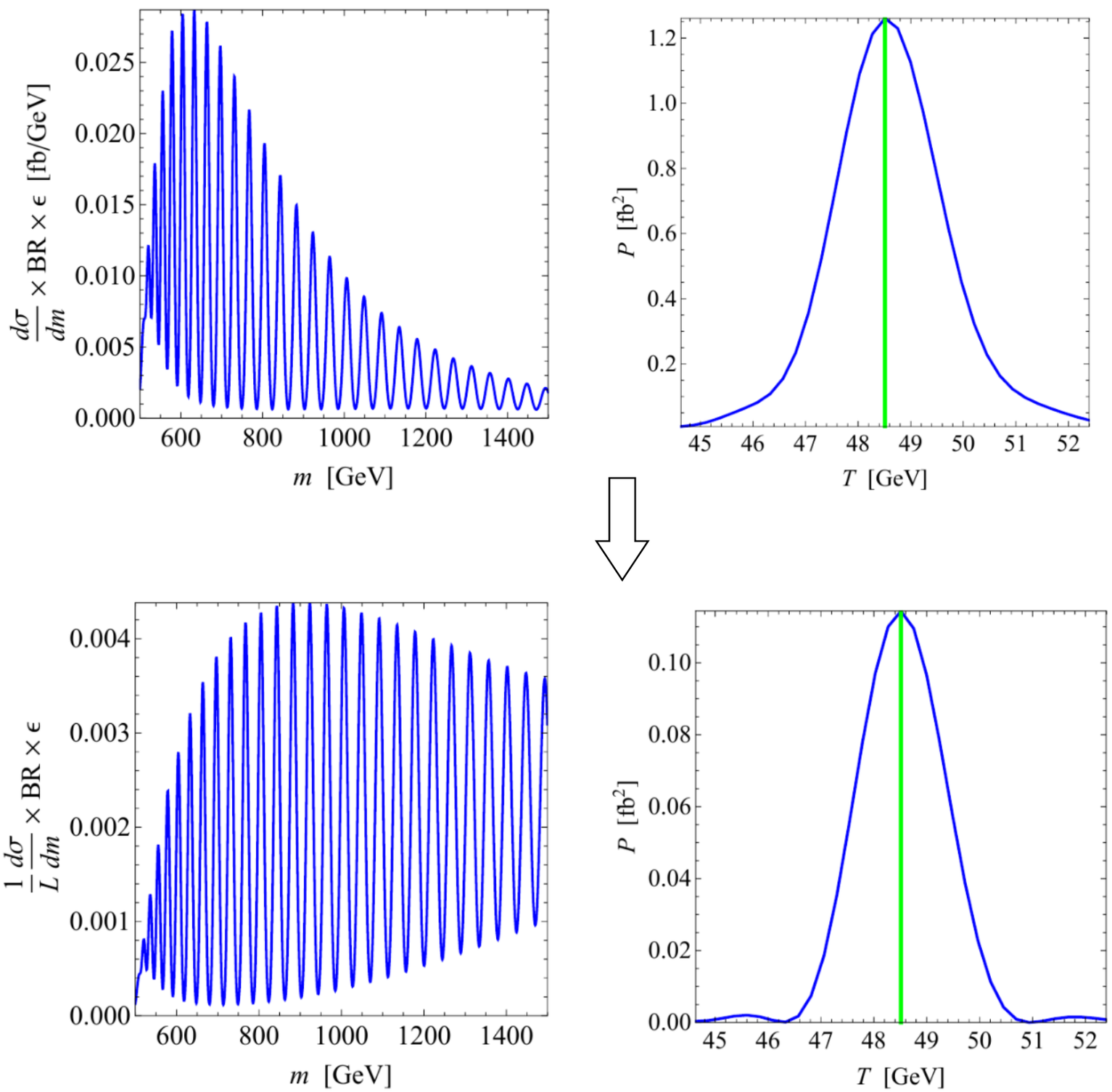
Dotted: $m < 40$ GeV

Dashed: $40 < m < 100$ GeV

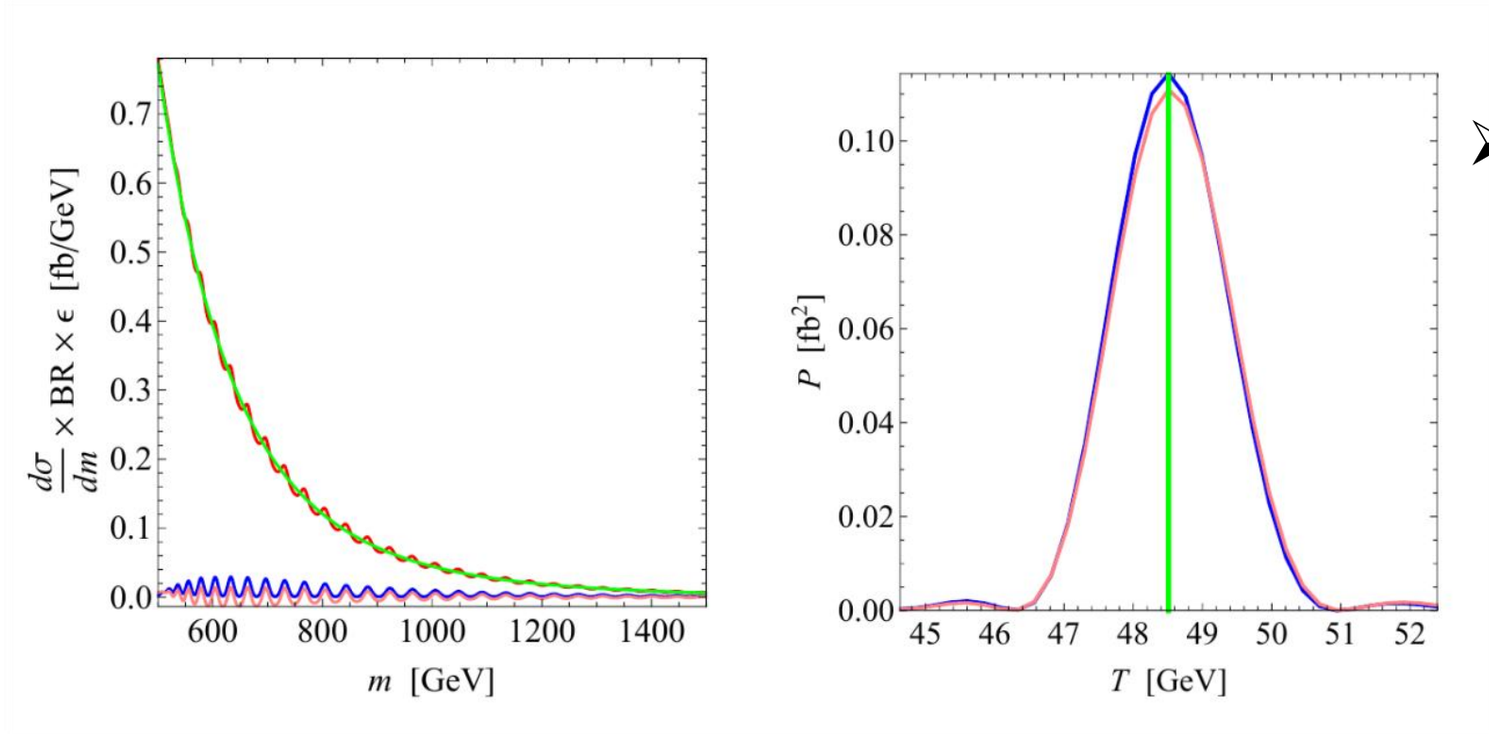
Solid: $m > 100$ GeV

Signatures: Fourier analysis

- Even better sensitivity is obtained dividing the rate by the parton luminosities

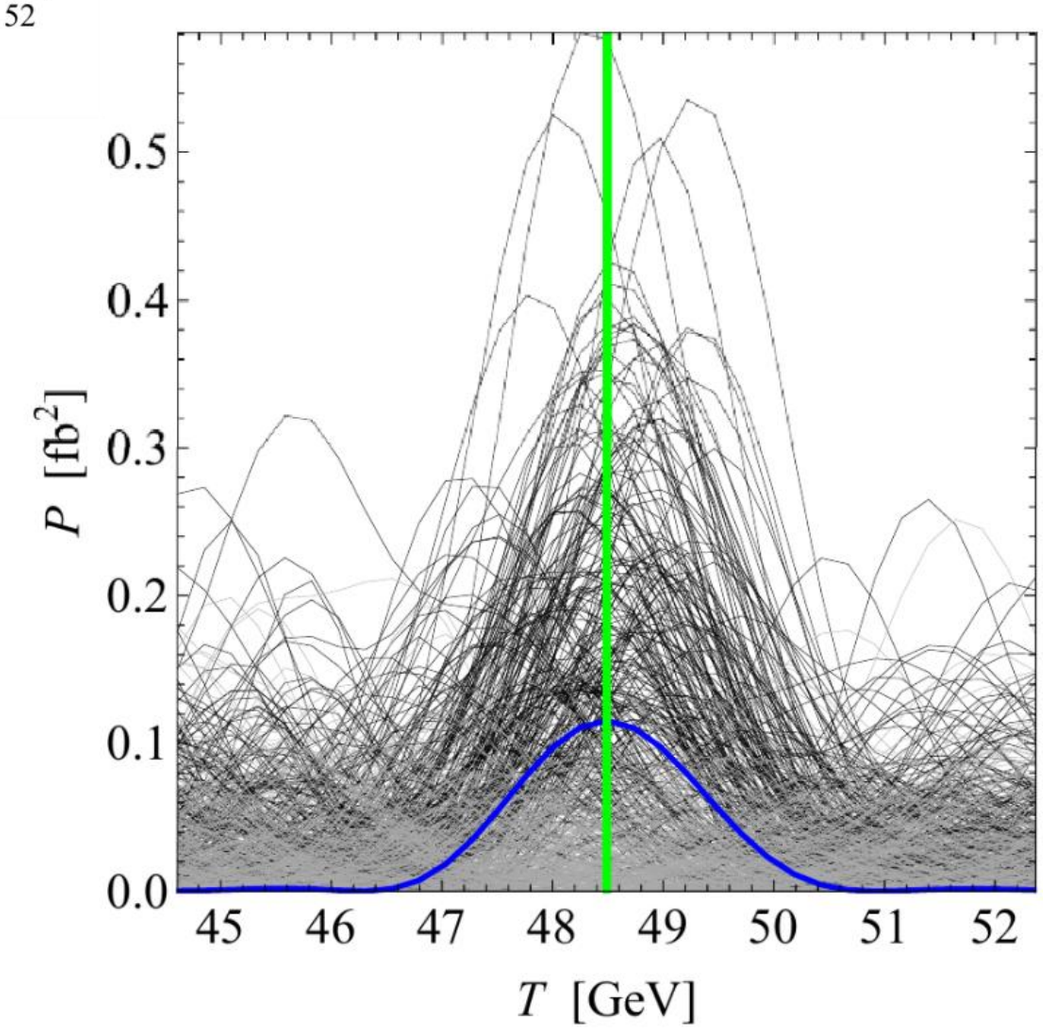


Signatures: Fourier analysis

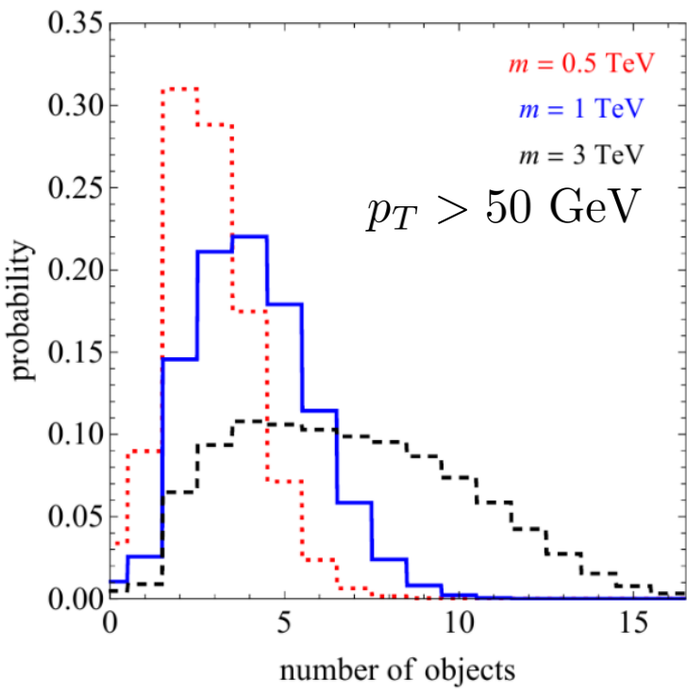


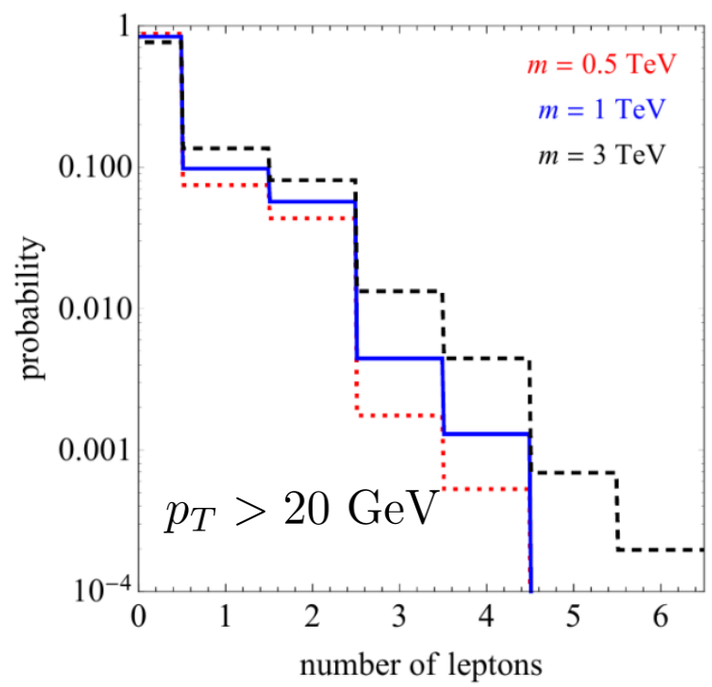
- Even adding background (assuming BG shape is known) the situation is good

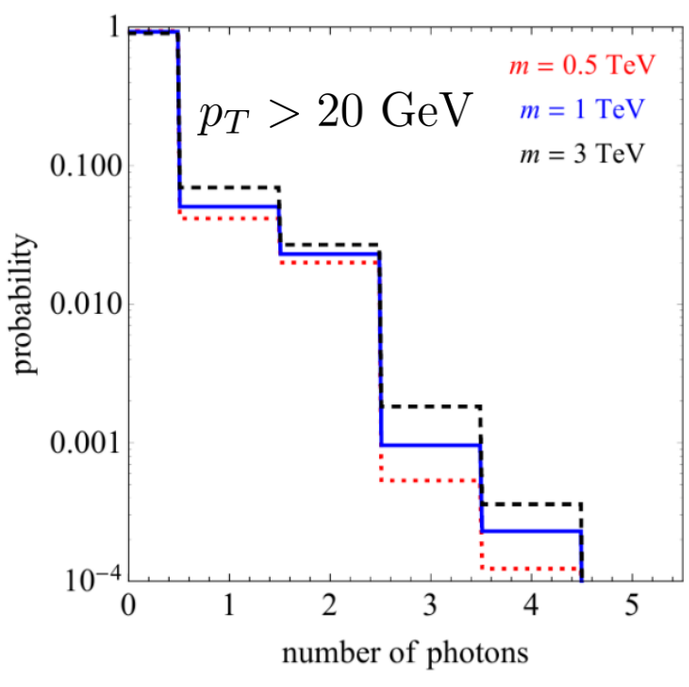
- To allow for statistical fluctuations we allow for bin-by-bin Poisson smearing
- Signal defined as the integrated power spectrum within one width around the peak (signal assumption)
- Significance computed by dividing the average signal-induced excess on top of the average background by the background uncertainty

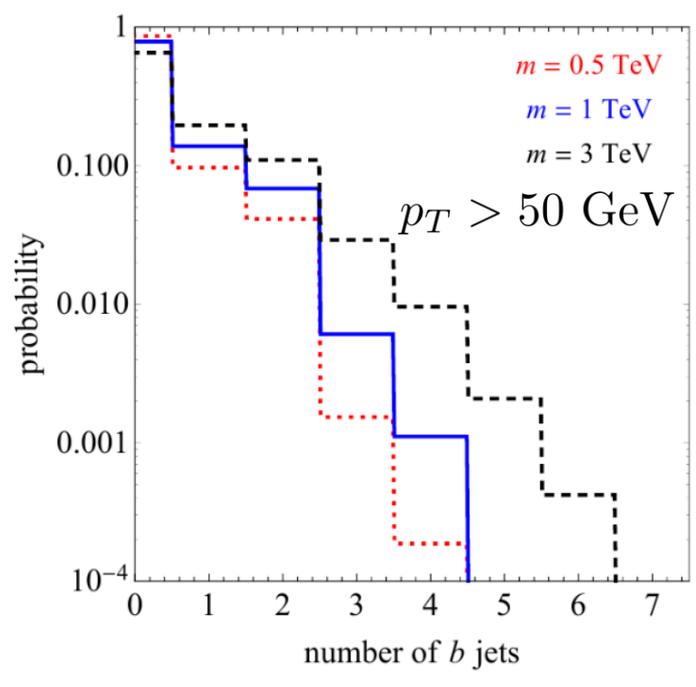


KK gravitons: cascade decays









- For small k cascade decays of KK-gravitons are important
- They tend to saturate the allowed phase space
- Multiple cascades are therefore present leading to high-multiplicity final states

$$M_5 = 10 \text{ TeV}$$

$$k = 1 \text{ GeV}$$

$$|\eta| < 2.5$$