# Collider constraints on massive gravitons coupling to photons

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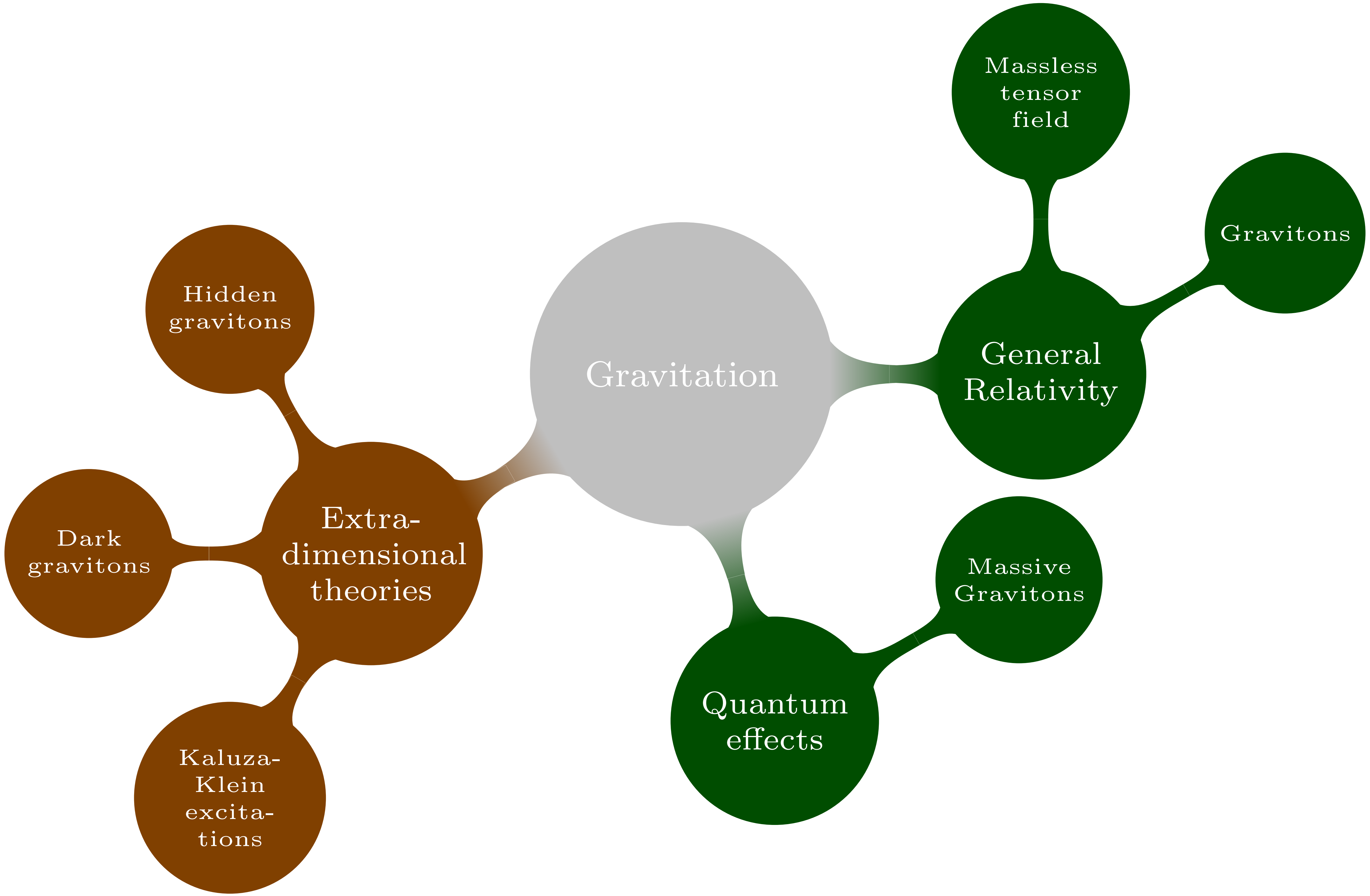
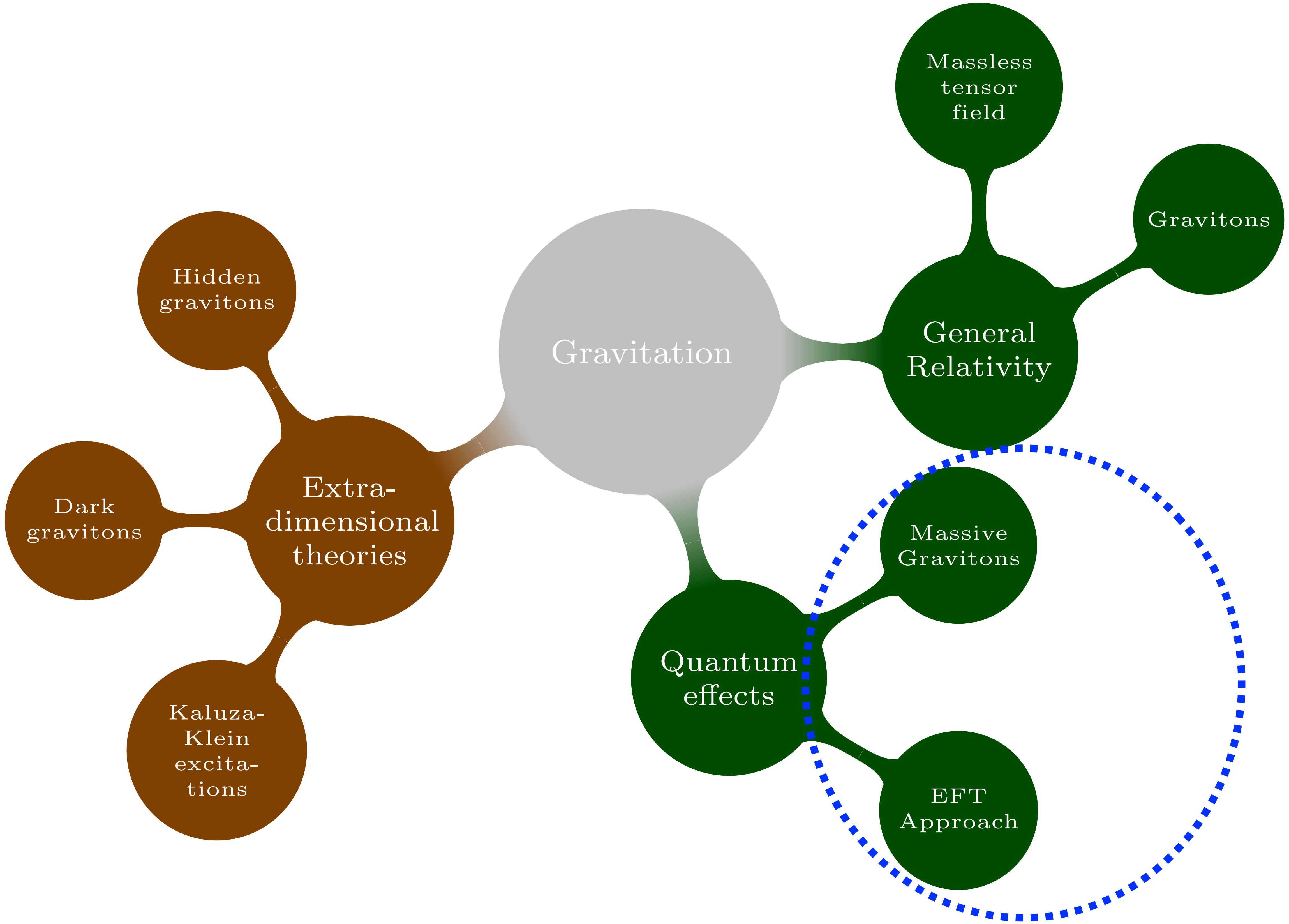
# INTRODUCTION



# INTRODUCTION



# Massive Gravitons in EFT

- In the EFT framework, the interaction of the gravitons with SM field is given by the following **Fierz-Pauli Lagrangian density**:

Energy-Momentum tensor

The strength of the coupling

The spin-2 quantum field

$$\mathscr{L}_{V,f}^{\mathrm{G}} = \frac{k_{V,f}}{\Lambda} T_{\mu\nu}^{V,f} G^{\mu\nu}$$

Energy scale

- For gravitons coupling to photons:

$$\mathscr{L}_{\gamma}^{\mathrm{G}} = g_{\mathrm{G}\gamma} \left( -F_{\mu\rho} F_{\nu}^{\rho} + \frac{1}{4} \eta_{\mu\nu} (F_{\rho\sigma})^2 \right) G^{\mu\nu}$$

Graviton-Photon coupling

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Graviton-Photon coupling → **The Goal of this work is to derive constraints on this coupling**

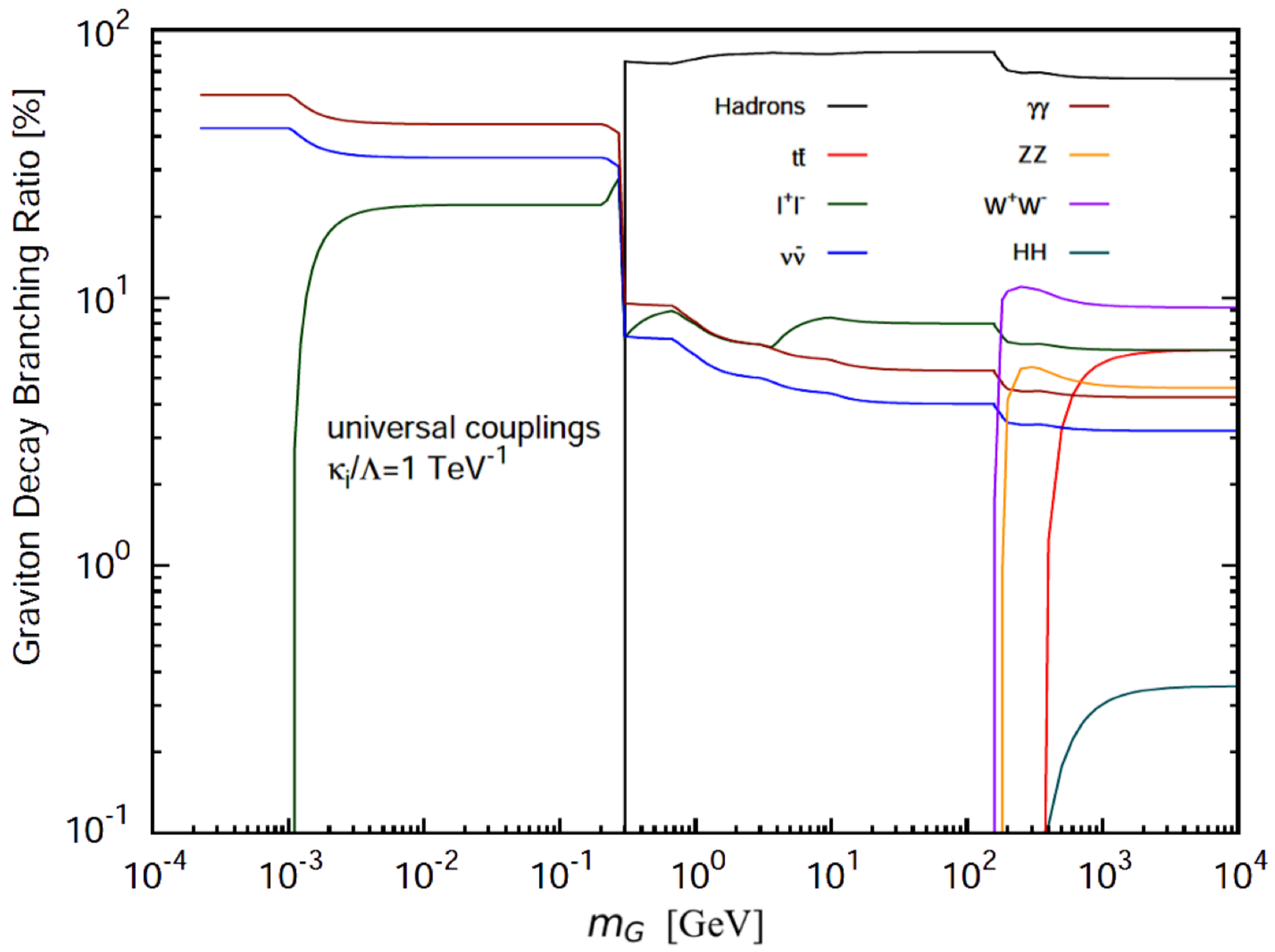
# Graviton couplings

- Graviton without universal coupling , the simplified approach **Br($G \rightarrow \gamma\gamma$ ) = 1**

- Graviton with universal coupling to all standard Model particles, it can decay with different modes, the Br(G-> XX) depends on the graviton mass $m_G$

- The graviton coupling to di-photons is dominant only <u>at low masess</u>

- <u>Above a few GeV</u>, $Br(G \rightarrow \gamma\gamma)$≈**0.05**



# Motivation

- Photon-Photon collisions (Light-by-Light scattering: LbL) provide a clean environment to search for BSM particles ( Axion-Like-Particle , spin0) and ( gravitons, spin2)

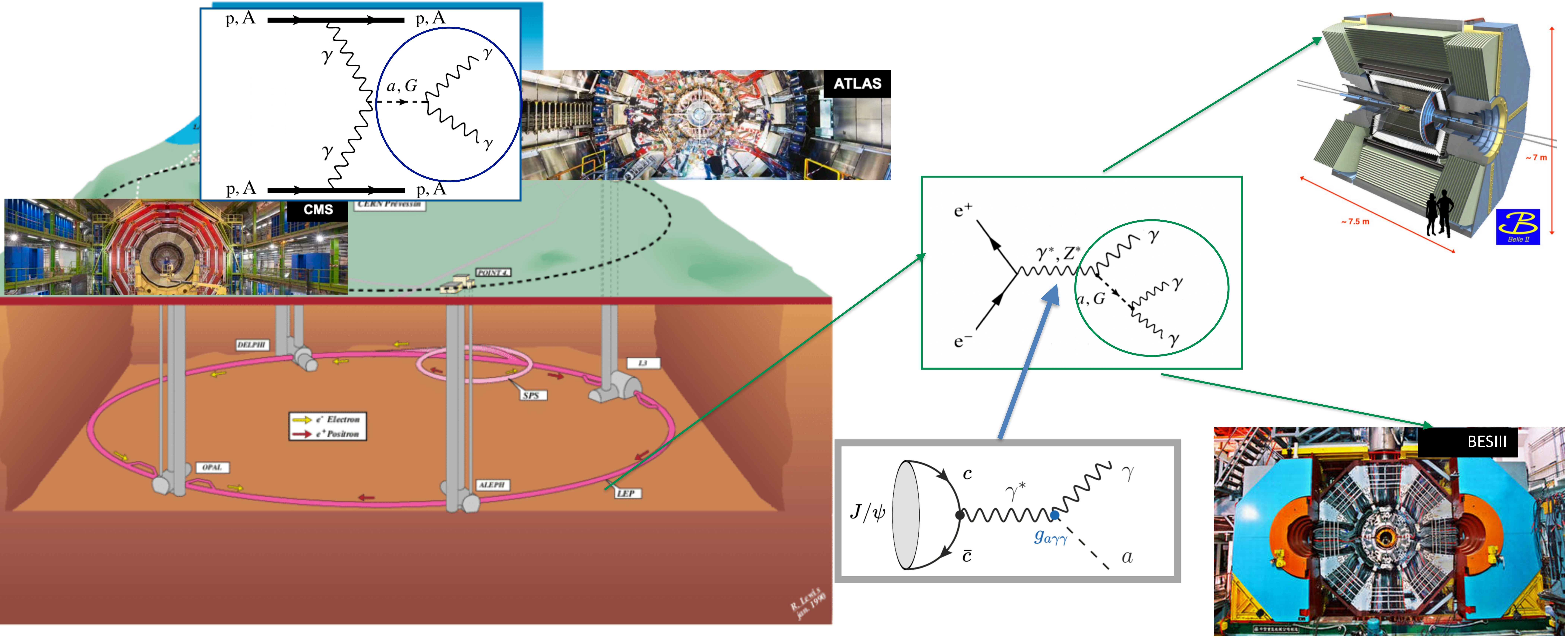
- Recent searches for exclusive diphotons resonances produced in LbL at the **LHC** have allowed placing the most stringent constraints on **ALPs** over $m_a \approx 5 - 100$ GeV in PbPb UPCs **ATLAS, CMS**
  And $m_a \approx 0.5 - 2$ TeV in pp collisions **ATLAS, CMS**
- There are also constraints from $e^+e^-$ colliders : **BelleII**, **BESIII**, **LEP**

- The Goal of this work is **extracting new bounds on photon-graviton coupling by recasting the existing ALP constraints**

- Considering two cases for massive gravitons:

  - Without universal coupling: **Br($G \to \gamma\gamma$ ) = 1**
  - With universal coupling : **Br( $G \to \gamma\gamma$ ) < 1**

# Processes & Colliders



# Methodology

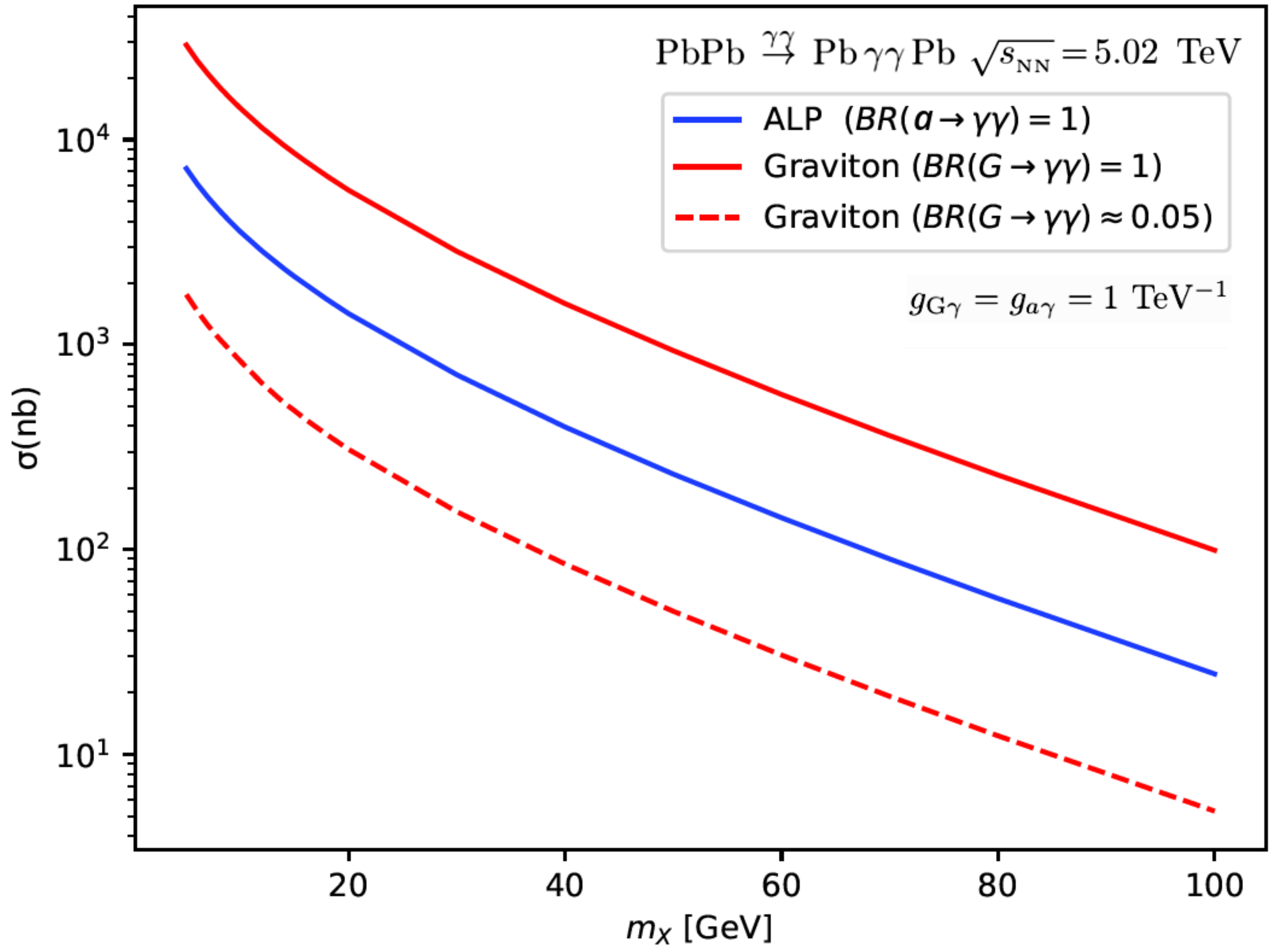
- We generated the production of both ALP and Graviton using gamma-UPC code, in different processes and considering different colliders systems, for the same coupling factors $g_{a\gamma}^{Gen} = g_{G\gamma}^{Gen} = 1TeV^{-1}$

| Process | Colliding system | Energy | Mass Range |
|---|---|---|---|
| $\gamma\gamma \to a, G \to \gamma\gamma$ | PbPb | 5.02 TeV | 5–100 GeV |
| $\gamma\gamma \to a, G \to \gamma\gamma$ | pp | 14 TeV | 0.15–2 TeV |
| $a, G\gamma \to \gamma\gamma\gamma$ | $e^+e^-$ | 3–11 GeV | 0.16–10 GeV |

- We computed the total cross section of production in function of $m_{a,G}$

**Case 1:** **Br( $G \to \gamma\gamma$ )= 1** $\sigma_G \approx 5\sigma_a$

**Case 2:** **Br( $G \to \gamma\gamma$ ) $\approx$ 0.05** $\sigma_G \approx \frac{1}{4}\sigma_a$




- The factor $\frac{\sigma_a}{\sigma_G}$ will play a role in the extraction of $g_{G\gamma}$

# Methodology

- Based on the simulated samples and by applying the following event selection criteria

- We calculated the difference of detector acceptance between ALP and graviton: $\frac{A_G}{A_a}$

- In this case, **Br( $G \rightarrow \gamma\gamma$ )=1**, the formula (1) is used

$$g_{G\gamma} = g_{a\gamma} \times \sqrt{\frac{\sigma_a}{\sigma_G}} \times \frac{A_G}{A_a} \quad (1)$$

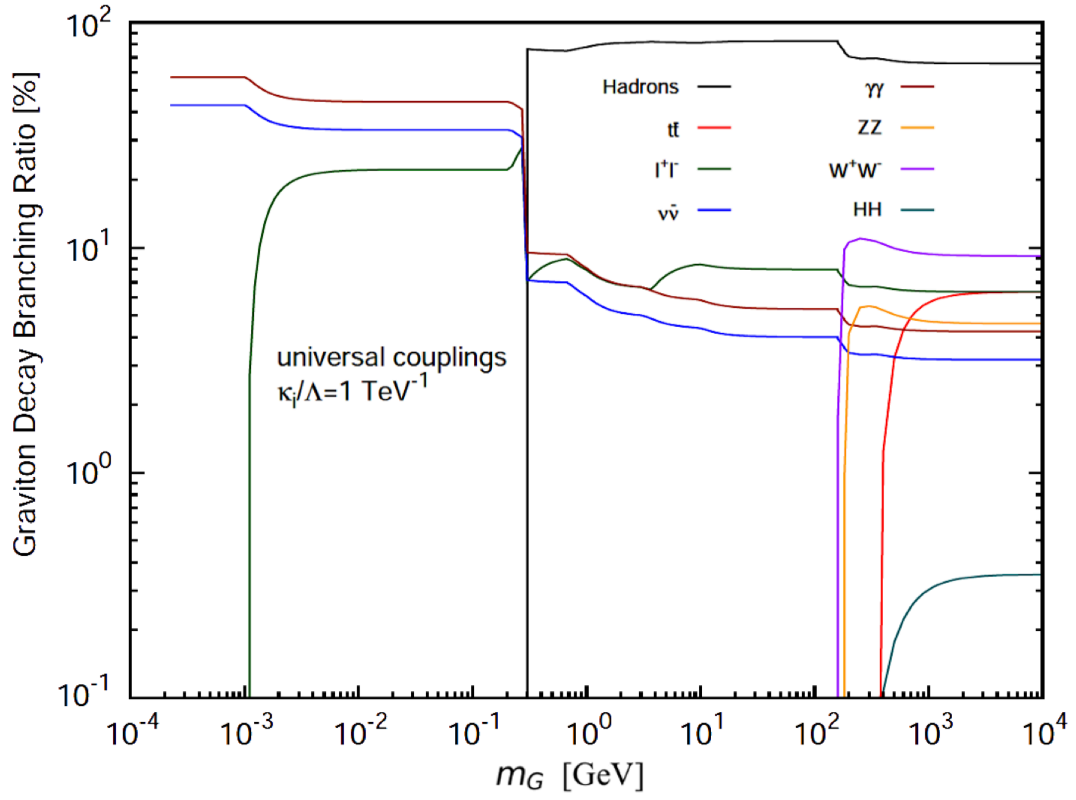
**Selection criteria for ATLAS and CMS**

| Variable | PbPb $\gamma\gamma\rightarrow$ Pb$\gamma\gamma$Pb ATLAS | CMS | pp $\gamma\gamma\rightarrow$ p$\gamma\gamma$p ATLAS | CMS |
|---|---|---|---|---|
| $\sqrt{s_{\rm NN}}$ energy (TeV) | 5.02 | 5.02 | 13.0 | 13.0 |
| Integrated luminosity $\mathcal{L}$ | $2.2\,\mathrm{nb}^{-1}$ | $0.4\,\mathrm{nb}^{-1}$ | $14.6\,\mathrm{fb}^{-1}$ | $9.4\,\mathrm{fb}^{-1}$ |
| Exclusive number of photons | 2 | 2 | 2 | 2 |
| Single photon $^{\gamma}$ (GeV) | $> 2.5$ | $> 2$ | $> 40$ | $> 100$ |
| Single photon $\lvert\eta^{\gamma}\rvert$ | $< 2.37$ | $< 2.4$ | $< 2.37$ | $< 2.5$ |
| Pair $^{\gamma\gamma}$ (GeV) | $< 1$ | $< 1$ | $< 1$ | $< 1$ |
| Pair $m_{\gamma\gamma}$ (GeV) | $> 5$ | $> 5$ | $> 150$ | $> 200$ |
| Pair acoplanarity $A_{\phi}^{\gamma\gamma}$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ |
| Rapidity gap range $\lvert\eta^{\rm gap}\rvert$ | $< 5$ | $< 5$ | – | – |
| Proton tagging | – | – | single | double |
| Proton energy loss $\xi$ | – | – | [0.035–0.08] | [0.02–0.2] |

# Methodology

- In this case, **Br( $G \rightarrow \gamma\gamma$ ) < 1** , the formula (2) is used

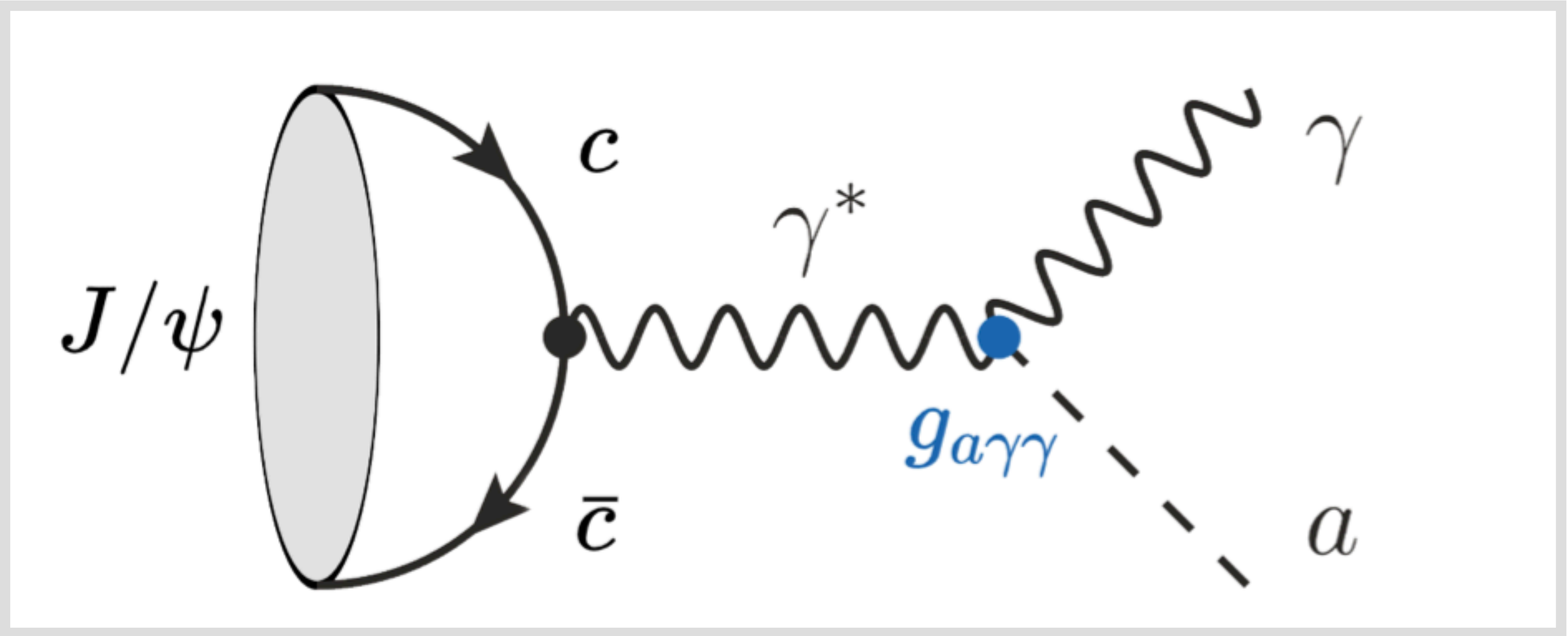
$$g_{G\gamma} = g_{a\gamma} \times \sqrt{\frac{\sigma_a}{\sigma_G}} \times \frac{A_G}{A_a} \times Br(G -> \gamma\gamma)$$




- We used this formula for both Pb-Pb, pp ( ATLAS, CMS) and $e^+e^-$ ( LEP and BELLEII)

- For BES-III experiment , we use the following formula:

$$g_{G\gamma} = g_{a\gamma} \times \frac{m_{J/\Psi}^2 - m_G^2}{\sqrt{(4m_G^4 + 2m_G^2 m_{J/\Psi}^2 + \frac{2}{3}m_{J/\Psi}^4)B_{G\rightarrow\gamma\gamma}}}$$




$m_{J/\Psi}$: The mass of $J/\Psi$ meson

$m_G$: The mass of the graviton

# Results: $\text{Br}(G \to \gamma\gamma) = 1$

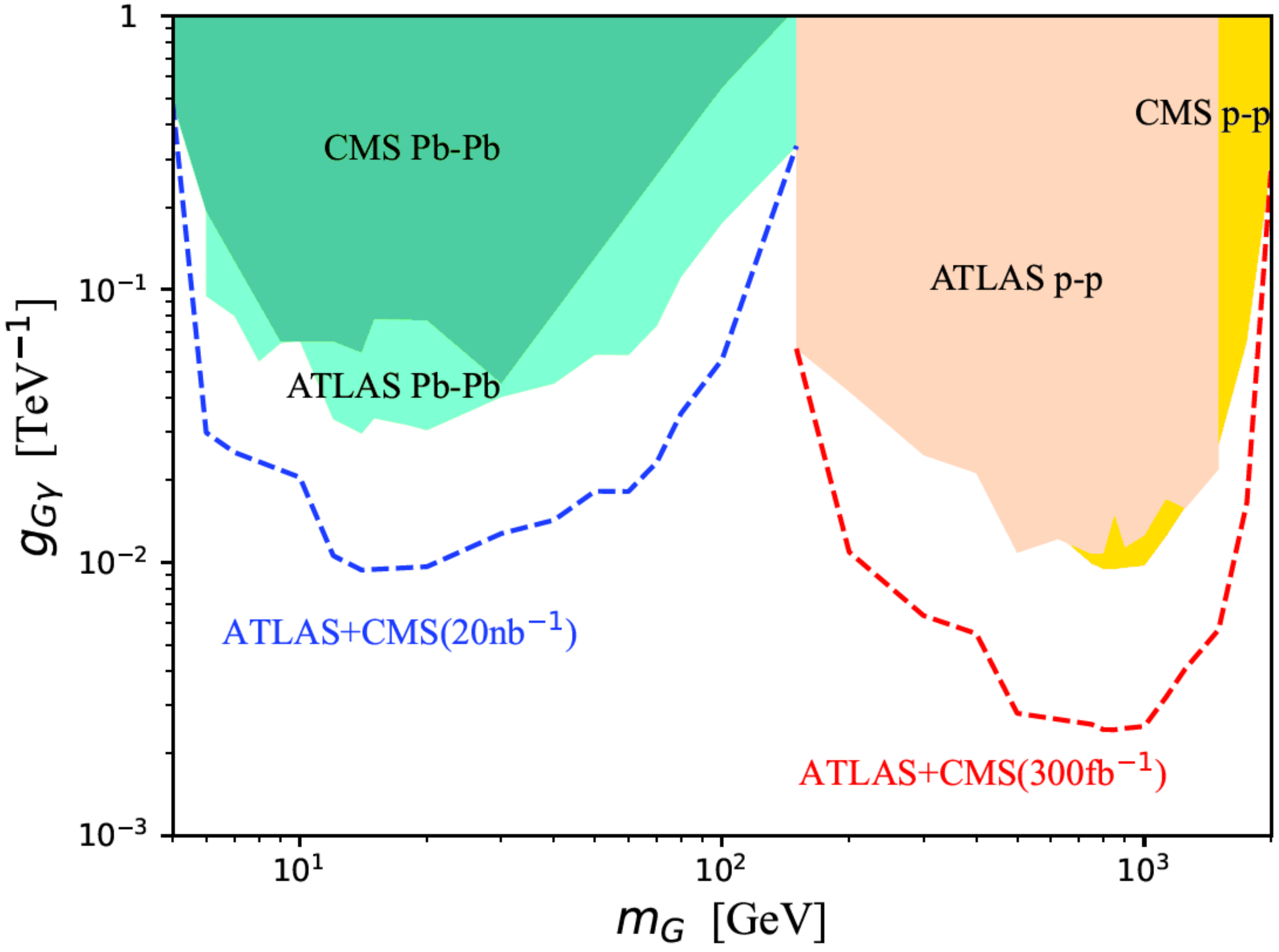
- In Pb-Pb , For $m_G$=5 GeV-100 GeV

$$g_{G\gamma} \approx 1 - 0.01\ TeV^{-1}$$

- In p-p, For $m_G$= 150GeV- 2TeV

$$g_{G\gamma} \approx 0.5 - 0.002\ TeV^{-1}$$

- The dashed curves are obtained by extrapolating the results to the integrated luminosity of HL-LHC
  - The constraints on $g_{G\gamma}$ can be enhanced by **factor 4**



# Results: $\mathrm{Br}(G \to \gamma\gamma) < 1$

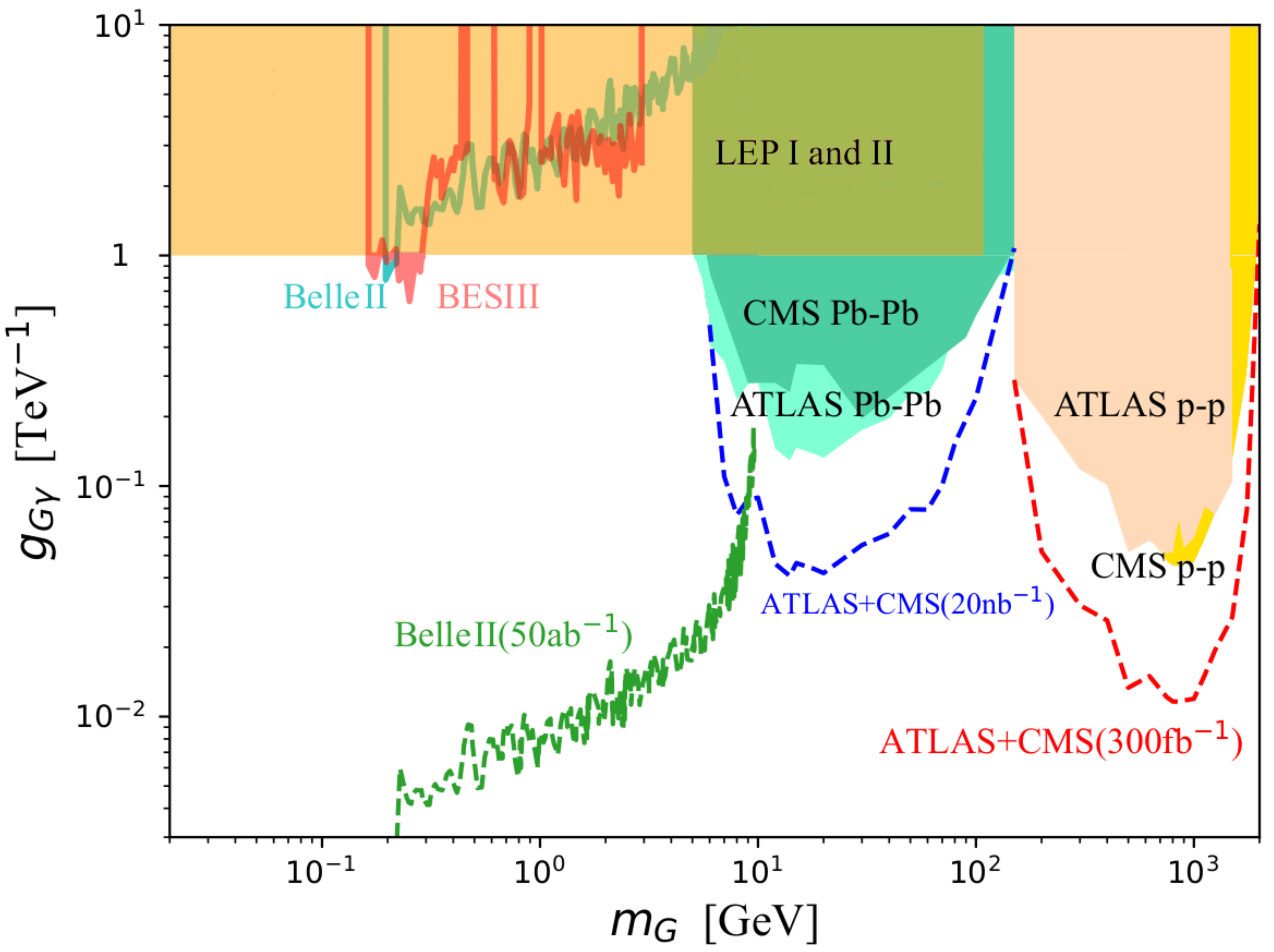
- In LHC, **For** $m_G = $ 5GeV to 1TeV

$$g_{G\gamma} \approx 1 - 0.01\ TeV^{-1}$$

- In $e^+e^-$ colliders , For $m_G$= 100MeV-10 GeV

$$g_{G\gamma} \approx 1\ TeV^{-1}$$

- For BelleII, the limit can be improved by a **<u>factor 100</u>** at low masses , for future luminosity



# Exclusive .Vs Inclusive searches

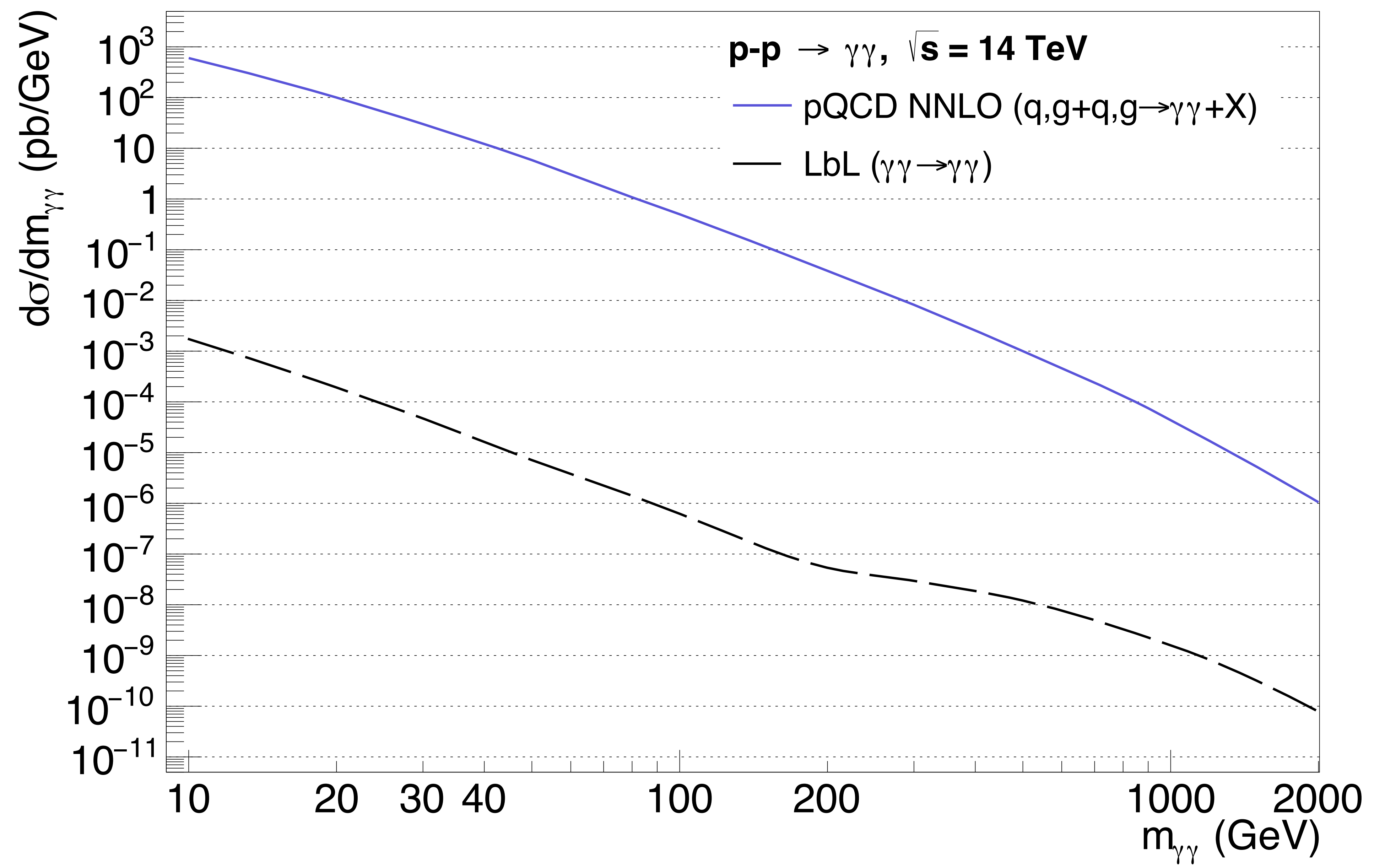
- Comparing the main backgrounds of the two searches:
  - **The exclusive LbL**

$$pp \stackrel{\gamma\gamma}{\rightarrow} p\gamma\gamma p$$

  - **The inclusive pQCD**

$$pp \rightarrow \gamma\gamma + X$$

- The cross sections for <u>inclusive γγ</u> are up to 6 orders-of-magnitude larger than the <u>exclusive γγ</u> one



# Summary

- Exploring the possibility of detecting massive spin-2 (graviton) particles using EFT and via :

  -Two photons processes: $PbPb(pp) \to Pb(p)G(\gamma\gamma)Pb(p)$
  - Three-photons final states: $e^+e^- \to G(\gamma\gamma)\gamma$

- The universal-coupling scenario, maintaining consistency with perturbative unitarity principles enabling consideration of a free G-$\gamma$ coupling in $e^+e^-$collisions

- The Exclusive studies showed, set G-$\gamma$ coupling constraints that are more competitive than conventional inclusive LHC searches: UPC final states gain from reduced pileup backgrounds , negligible SM irreducible backgrounds

- The work presented is published in Physics Letters B journal:

  **Phys.Lett.B 846 (2023) 138237 ([https://arxiv.org/abs/2306.15558](https://arxiv.org/abs/2306.15558))**

# THANK YOU FOR YOUR ATTENTION

# BACKUP SLIDES

# Cross section for photon-photon collisions

- The kinetic term for the graviton field of mass $m_G$ in photon-photon collisions :

$$\mathscr{L}_{\mathrm{FP}} = -\frac{1}{2}(\partial_\rho G_{\mu\nu})^2 + \partial_\mu G_{\nu\rho}\partial^\nu G^{\mu\rho} - \partial_\mu G^{\mu\nu}\partial_\nu G + \frac{1}{2}(\partial_\rho G)^2 - \frac{1}{2}m_{\mathrm{G}}^2\left((G_{\mu\nu})^2 - G^2\right)$$

- The propagator for the graviton field can be computed by

$$T^{\mu\nu\rho\sigma} = \frac{i}{p^2 - m_{\mathrm{G}}^2 + i\epsilon}\left(\frac{1}{2}(P_{\mu\rho}P_{\nu\sigma} + P_{\mu\sigma}P_{\nu\rho}) - \frac{1}{3}P_{\mu\nu}P_{\rho\sigma}\right)$$

$$P_{\mu\nu} = \eta_{\mu\nu} + p_\mu p_\nu / m_{\mathrm{G}}^2$$

# Cross section for $e^+e^-$ collisions

- The inclusive cross section for gravitons in $e^+e^-$ collisions, Br( $G \to \gamma\gamma$ )=1

$$\sigma(e^+e^- \to \mathrm{G}\gamma \to \gamma\gamma\gamma) = \frac{\alpha}{36}\left(\frac{k_\gamma}{\Lambda}\right)^2 \frac{(s-m_\mathrm{G}^2)^3}{s^3}\frac{s^2+3sm_\mathrm{G}^2+6m_\mathrm{G}^4}{m_\mathrm{G}^4}\mathcal{B}_{\mathrm{G}\to\gamma\gamma}$$

- This cross section has an asymptotic form:

$$\lim_{s\gg m_\mathrm{G}^2}\sigma(e^+e^- \to \mathrm{G}\gamma \to \gamma\gamma\gamma) = \frac{\alpha}{36}\left(\frac{k_\gamma}{\Lambda}\right)^2 \frac{s^2}{m_\mathrm{G}^4}\mathcal{B}_{\mathrm{G}\to\gamma\gamma}$$

- It is divergent in limit : $m_\mathrm{G}^2/s \to 0$

# Cross section for $e^+e^-$ collisions

- The inclusive cross section for gravitons with universal coupling in $e^+e^-$ collisions:

$$\sigma(e^+e^- \to G\gamma \to \gamma\gamma\gamma) = \frac{\alpha}{24}\left(\frac{k_U}{\Lambda}\right)^2 \frac{(s - m_G^2)^3}{s^3} \mathcal{B}_{G\to\gamma\gamma}$$

- Considering gravitons coupling only to photons and electrons: $K_U = K_e = K_\gamma$

- The asymptotic cross section for $s \gg m_G^2$: $\sigma \approx \frac{\alpha}{6}\left(\frac{k_U}{\Lambda}\right)^2 \mathcal{B}_{G\to\gamma\gamma}$

  - For $m_G << 2m_e$, $Br(G -> \gamma\gamma) = 1$
  - For $m_G >> 2m_e$, $Br(G -> \gamma\gamma) = \frac{2}{3}$

**The assumption $Br(G -> \gamma\gamma) = 1$ would be incorrect for $e^+e^-$ colliders**

# Decay widths

- **Photon-Photon collisions:**

$$\Gamma(\mathrm{G} \to \gamma\gamma) = (\frac{k_\gamma}{\Lambda})^2 \frac{m_\mathrm{G}^3}{80\pi}$$

- $e^+e^-$**collisions (BelleII , LEP I&II):**

$$\Gamma(\mathrm{G} \to e^+e^-) = (\frac{k_e}{\Lambda})^2 \frac{m_\mathrm{G}^3}{160\pi}(1 - \frac{4m_e^2}{m_\mathrm{G}^2})^{3/2}(1 + \frac{8m_e^2}{3m_\mathrm{G}^2})$$

- $e^+e^-$**collisions (BES-III):**

$$\Gamma(J/\psi \to a\gamma \to \gamma\gamma\gamma) \quad = \quad \frac{\alpha}{81} g_{a\gamma}^2 \left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^3 \langle O^{J/\psi} \rangle \, \mathcal{B}_{a\to\gamma\gamma}$$

$$\Gamma(J/\psi \to \mathrm{G}\gamma \to \gamma\gamma\gamma) \quad = \quad \frac{2\alpha}{243} \left(\frac{k_U}{\Lambda}\right)^2 \left(1 - \frac{m_\mathrm{G}^2}{m_{J/\psi}^2}\right) \left(1 + 3\frac{m_\mathrm{G}^2}{m_{J/\psi}^2} + 6\frac{m_\mathrm{G}^4}{m_{J/\psi}^4}\right) \langle O^{J/\psi} \rangle \, \mathcal{B}_{\mathrm{G}\to\gamma\gamma} (16)$$

# Statistical method

- The gravitons, could manifest as **resonances in shape** of the standard invariant mass spectrum of the two outgoing photons in **LbyL**

- An alternative statistical method could be used to extract the graviton-photon coupling :

Analyzing the distributions of the signal and backgrounds by varying $m_G$ ,and taking into account the experimental diphoton counts observed in each mass bin