Massive gravitons exchange in light by light scattering in Pb Pb, simulations in ATLAS

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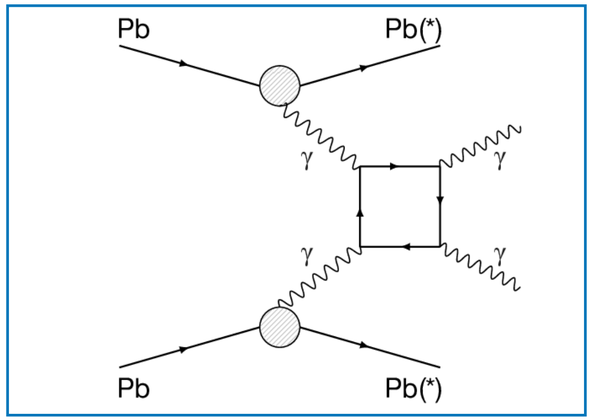
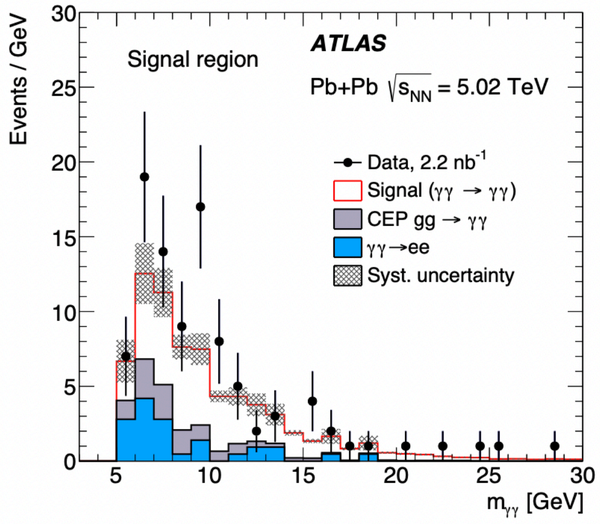
LHC Forward Physics meeting

Introduction

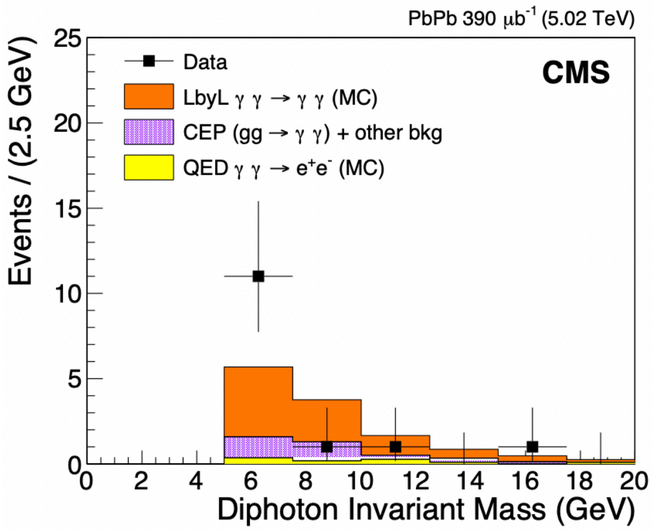
- Elastic two-photon collision-> fundamental quantum mechanical process

Experimentally observed at the LHC





arXiv:2008.05355



arXiv:1810.04602

- Interpretations (and perspectives) based on the recent ATLAS LbyL results
  - Our goal is to describe the exchange of an intermediate massive gravitons in light-by-light

Theoretical framework : graviton model

- We use the effective filed theory of a massive spin-2 graviton interacting with SM fields:

https://arxiv.org/abs/2207.03012, JHEP 09 (2022) 248

- The massive spin-2 graviton G is described by a symmetric tensor $h_{\mu\nu}$ and the interaction with the EM field is

Effective graviton-photon coupling

Energy-momentum tensor of the EM field

symmetric tensor

$$\mathcal{L}_{G\gamma} = \frac{k_\gamma}{\lambda} T^{\gamma}_{\mu\nu} h^{\mu\nu}$$

$$\mathcal{L}_{G\gamma} = \frac{k_\gamma}{\lambda} T^{\gamma}_{\mu\nu} h^{\mu\nu} = \frac{k_\gamma}{\lambda}(-F_{\mu\rho}F^{\rho}_{\nu} + \frac{1}{4}\eta_{\mu\nu}(F_{\rho\sigma})^2)h^{\mu\nu}$$

$$T^{\gamma}_{\mu\nu} = -F_{\mu\rho}F^{\rho}_{\nu} + \frac{1}{4}\eta_{\mu\nu}(F_{\rho\sigma})^2$$

- The full Lagrangian of the system(graviton and photon) is then given by adding the kinetic terms

Theoretical framework : graviton model

- The kinetic term for the graviton (Fierz-Pauli Lagrangian

$$\mathscr{L}_{\mathscr{G}} = -\frac{1}{2}(\partial_\rho h_{\mu\nu})^2 + \partial_\mu h_{\nu\rho}\partial^\nu h^{\mu\rho} - \partial_\mu h^{\mu\nu}\partial_\nu h + \frac{1}{2}(\partial_\rho h)^2 - \frac{1}{2}m^2((h_{\mu\nu})^2 - h^2)$$

- The kinetic term for the EM field

$$\mathscr{L}_\gamma = -\frac{1}{4}(F_{\mu\nu})^2$$

- The Lagrangian for our problem of the form

$$\mathscr{L} = \mathscr{L}_{\mathscr{G}} + \mathscr{L}_\gamma + \mathscr{L}_{\mathscr{G}\gamma}$$

Theoretical framework : graviton model

- The idea is to show that the graviton (of mass m) created by a source point of mass M really acts as a graviton

$$\mathscr{L} = -\frac{1}{2}(\partial_\rho h_{\mu\nu})^2 + \partial_\mu h_{\nu\rho}\partial^\nu h^{\mu\rho} - \partial_\mu h^{\mu\nu}\partial_\nu h + \frac{1}{2}(\partial_\rho h)^2 - \frac{1}{2}m^2((h_{\mu\nu})^2 - h^2) - kT^{\mu\nu}h_{\mu\nu}$$

$$T^{\mu\nu}(x) = M\delta_0^\mu\delta_0^\nu\delta(x)$$

- This problem can be resolved using Euler-Lagrange equation, the value of $h_{\mu\nu}$ found is

$$h_{\mu\nu} = kMe^{-mr}/r$$

Gamma-UPC MC event generator

- gamma-UPC is a library for calculating the photon fluxes in the exclusive photon-photon processes in ultra peripheral proton and nuclear collisions(UPCs): **David d'Enterria, Hua-Sheng Shao**
- The library has been integrated into both **HELAC-Onia** and **MadGraph5_aMC@NLO**

Process	Physics motivation
$\gamma\gamma \to e^+e^-, \mu^+\mu^-$	"Standard candles" for proton/nucleus γ fluxes, EPA calculations, and higher-order QED corrections
$\gamma\gamma \to \tau^+\tau^-$	Anomalous τ lepton e.m. moments [29–32]
$\gamma\gamma \to \gamma\gamma$	aQGC [25], ALPs [27], BI QED [28], noncommut. interactions [36], extra dims. [37],...
$\gamma\gamma \to \mathcal{T}_0$	Ditauonium properties (heaviest QED bound state) [38, 39]
$\gamma\gamma \to (c\bar{c})_{0,2}, (b\bar{b})_{0,2}$	Properties of scalar and tensor charmonia and bottomonia [40, 41]
$\gamma\gamma \to$ XYZ	Properties of spin-even XYZ heavy-quark exotic states [42]
$\gamma\gamma \to$ VM VM	(with VM = ρ, ω, ϕ, J/ψ, Υ): BFKL-Pomeron dynamics [43–46]
$\gamma\gamma \to W^+W^-$, ZZ, Z$\gamma, \cdots$	anomalous quartic gauge couplings [11, 26, 47, 48]
$\gamma\gamma \to$ H	Higgs-γ coupling, total H width [49, 50]
$\gamma\gamma \to$ HH	Higgs potential [51], quartic $\gamma\gamma$HH coupling
$\gamma\gamma \to t\bar{t}$	anomalous top-quark e.m. couplings [11, 49]
$\gamma\gamma \to \tilde{\ell}\tilde{\ell}$, $\tilde{\chi}^+\tilde{\chi}^-$, $H^{++}H^{--}$	SUSY pairs: slepton [11, 52, 53], chargino [11, 54], doubly-charged Higgs bosons [11, 55].
$\gamma\gamma \to a, \phi, \mathcal{MM}, G$	ALPs [27, 56], radions [57], monopoles [58–61], gravitons [62–64],...

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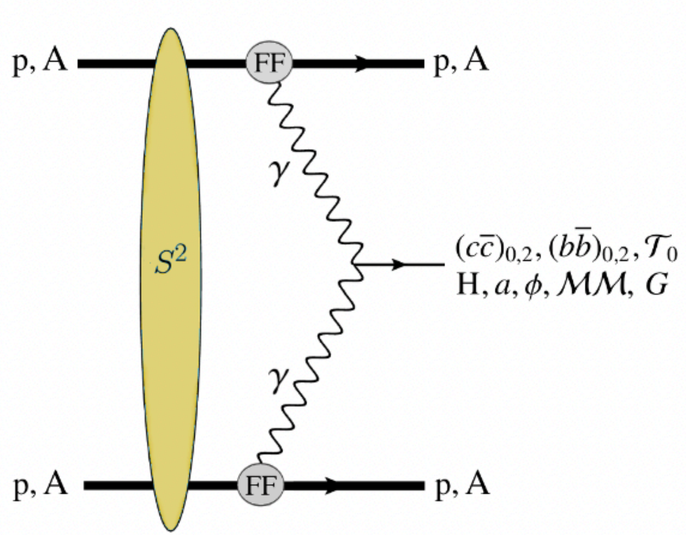
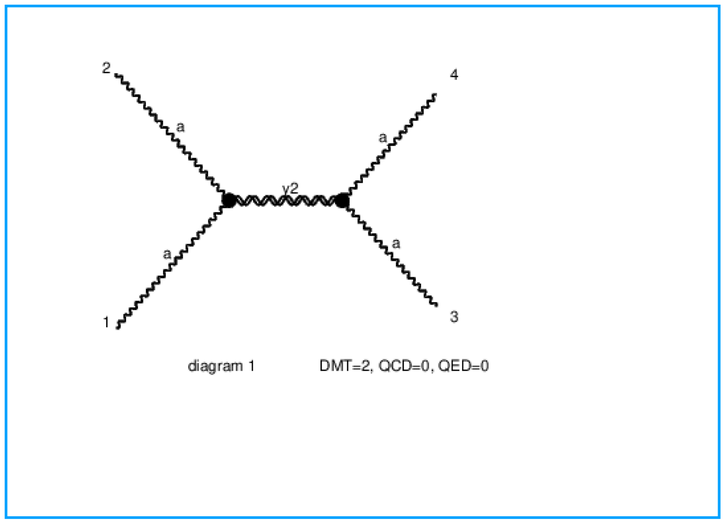


More details in the David's Talk: Link

Usage in Madgraph5_aMC@NLO

- Request the standalone version of MadGraph5_aMC@NLO with gamma-UPC from **Shao Hua-Sheng**

Our Goal: Simulate the graviton exchange in light by light scattering




```
MG5_aMC>import model DMspin2-full
INFO: Change particles name to pass to MG5 convention
Pass the definition of 'j' and 'p' to 5 flavour scheme.
Kept definitions of multiparticles l+ / l- / vl / vl~ unchanged
Defined multiparticle all = g ghg ghg~ u c d s b u~ c~ d~ s~ b~ a gha gha~ ve vm
 vt e- mu- ta- ve~ vm~ vt~ e+ mu+ ta+ t t~ z w+ ghz ghwp ghwm h y2 w- ghz~ ghwp~
 ghwm~ xd xd~
MG5_aMC>generate a a > y2 > a a

MG5_aMC>output test
INFO: initialize a new directory: test
INFO: remove old information in test
perl: warning: Setting locale failed.
perl: warning: Please check that your locale settings:
        LANGUAGE = (unset),
        LC_ALL = (unset),
        LC_CTYPE = "UTF-8",
        LANG = "en_US.UTF-8"
    are supported and installed on your system.
perl: warning: Falling back to the standard locale ("C").
INFO: Organizing processes into subprocess groups
INFO: Generating Helas calls for process: a a > y2 > a a DMT<=2 WEIGHTED<=4 @1
INFO: Processing color information for process: a a > y2 > a a DMT<=2 @1
INFO: Creating files in directory P1_aa_aa
INFO: Generating Feynman diagrams for Process: a a > y2 > a a DMT<=2 WEIGHTED<=4
 @1
INFO: Finding symmetric diagrams for subprocess group aa_aa
Generated helas calls for 1 subprocesses (1 diagrams) in 0.006 s
Wrote files for 6 helas calls in 1.242 s
ALOHA: aloha starts to compute helicity amplitudes
ALOHA: aloha creates VVT5 routines
```

Madgraph5_aMC@NLO simulation

- Once the process is generated , the parameters for the run are stored in various cards (files)

Parameter	Value
Graviton mass[GeV]	[20,30,40,50,60,70,80,90,100]
Coupling factor	$1TeV^{-1}$
Width	Calculated by the formula(1)
Beam	5.02 TeV
Gamma-UPC model	EDFF
Number of events	10000

$$\frac{k_\gamma m_G^3}{80\pi\lambda^2} \quad \textbf{(1)}$$

param_card.dat

```
## INFORMATION FOR MASS
###################################
BLOCK MASS #
      6 1.720000e+02 # mt
      23 9.118760e+01 # mz
      25 1.250000e+02 # mh
      52 1.000000e+01 # mxd
      56 scan:[20,30,40,50,60,70,80,90,100] # my2

#       PDG        Width
DECAY  24   2.085000e+00
#
#       PDG        Width
DECAY  25   4.070000e-03
#
#       PDG        Width
DECAY  52   0.000000e+00
#
#       PDG        Width
DECAY  56   7.460388e-05
```

run_card.dat

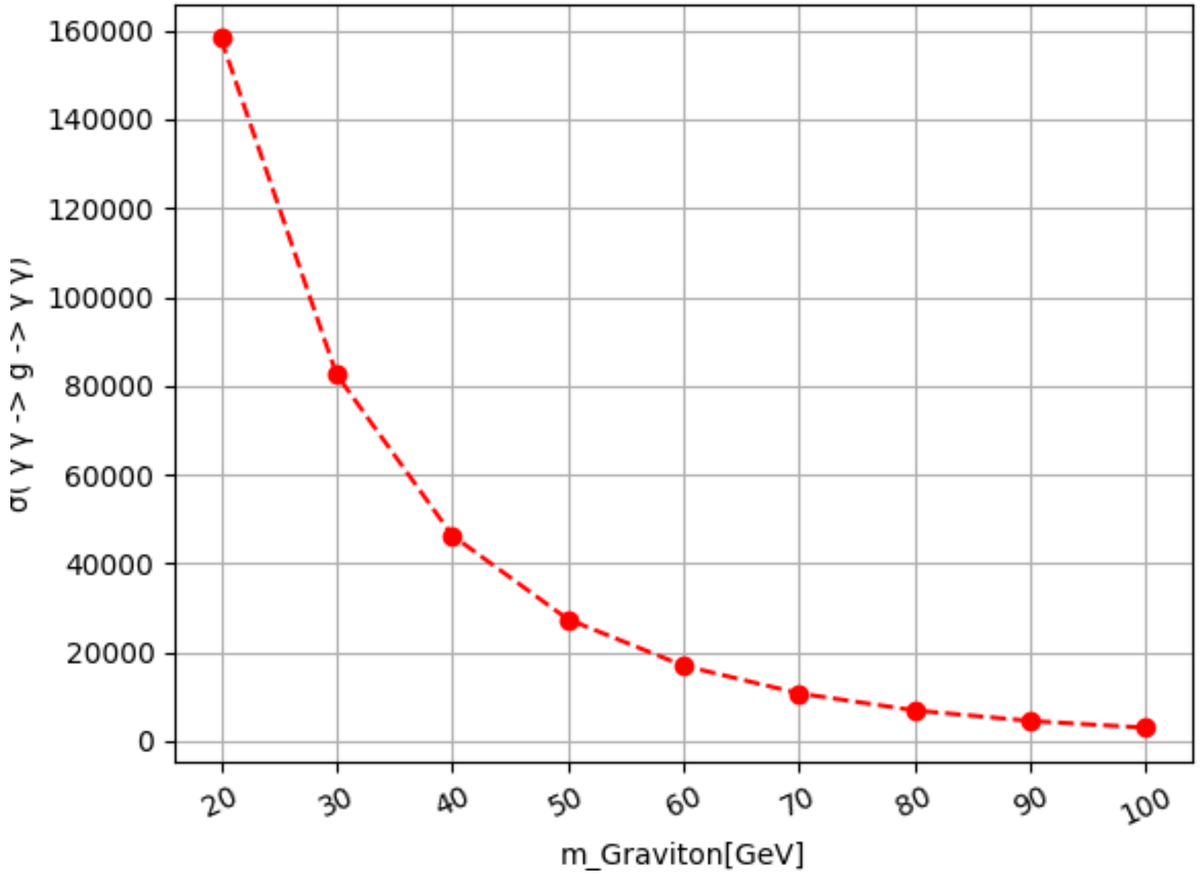
```
#*********************************************************************
  2     = lpp1 ! beam 1 type
  2     = lpp2 ! beam 2 type
  522080.0      = ebeam1 ! beam 1 total energy in GeV
  522080.0      = ebeam2 ! beam 2 total energy in GeV
# To see polarised beam options: type "update beam_pol"

#*********************************************************************
# PDF CHOICE: this automatically fixes alpha_s and its evol.         *
# pdlabel: lhapdf=LHAPDF (installation needed) [1412.7420]           *
#          iww=Improved Weizsaecker-Williams Approx.[hep-ph/9310350] *
#          eva=Effective W/Z/A Approx.       [2111.02442]            *
#          edff=EDFF in gamma-UPC            [22yy.zzzzz]            *
#          chff=ChFF in gamma-UPC            [22yy.zzzzz]            *
#          none=No PDF, same as lhapdf with lppx=0                   *
#*********************************************************************
  edff  = pdlabel ! PDF set
  230000        = lhaid ! if pdlabel=lhapdf, this is the lhapdf number
```

Cuts	
Parameter	**Value**
Minimum of outgoing photon	3
Maximum of photons	100
Minimum pseudo rapidity	-2.4
Maximum pseudo rapidity	2.4
Minimum invariant mass	6.00
Maximum invariant mass	100

Cross section measurements@Madgraph

- Total cross section for the process $\gamma\gamma -> G -> \gamma\gamma$
- The cross cross section for the model is shown as a function of the graviton mass

Graviton mass[GeV]	Cross section(pb)
20	1.583×10^5
30	8.259×10^4
40	4.634×10^4
50	2.746×10^4
60	1.699×10^4
70	1.075×10^4
80	6.922×10^4
90	4.546×10^4
100	3.021×10^4



Cross-check: Total cross section

- Reproducing the result of the paper to validate our simulation : gamma-UPC paper
- Based on the following cross section formula:

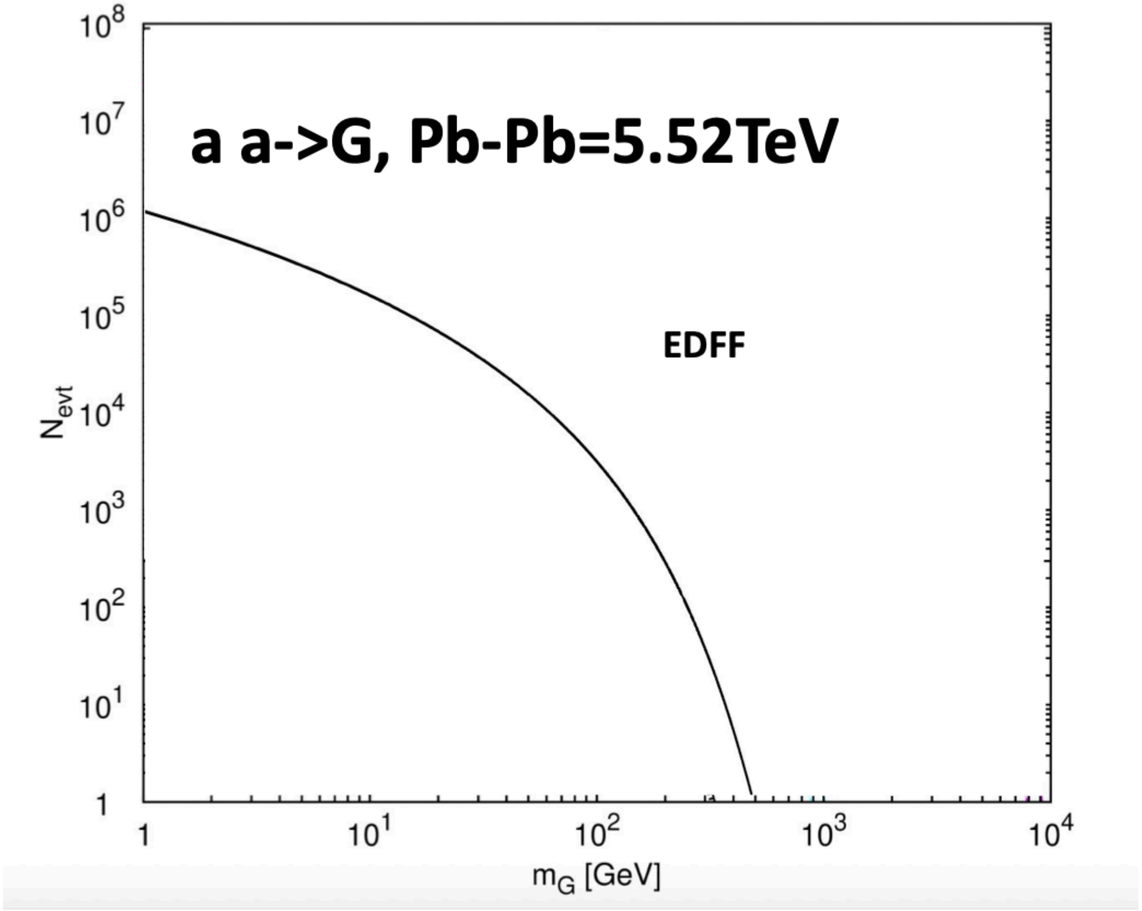
$$\sigma(AB \xrightarrow{\gamma\gamma} AXB) = 4\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}(X)}{m_X^2}\frac{d\mathscr{L}_{\gamma\gamma}^{(AB)}}{dW_{\gamma\gamma}}\Big|_{W_{\gamma\gamma}=m_X}$$

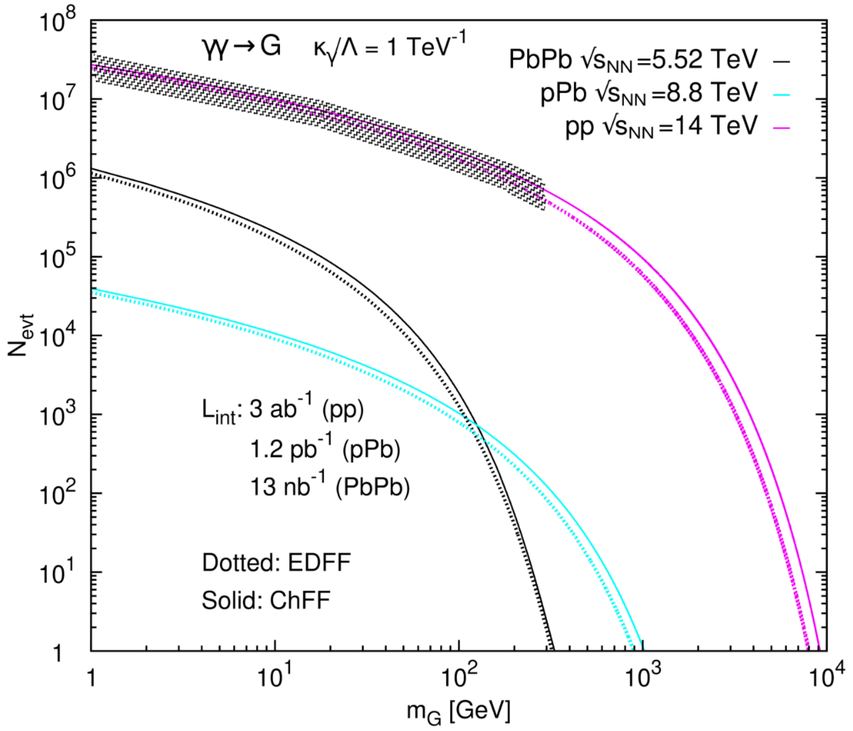
- Using **HELAC-ONIA** MC generator
  - Process $\gamma\gamma \rightarrow G$
  - Graviton mass range in GeV:$[1, 10^4]$
  - Gamma-UPC model: EDFF
  - Beam: Pb-Pb with E=5.52TeV
  - Integrated luminosity : $13nb^{-1}$
  - Coupling factor: K_γ/Λ= $1GeV^{-1}$

```
! for graviton mass scan
!OPEN(UNIT=20344,FILE="/eos/user/m/maittaml/PbPb5.5TeV_GravitonXS_M_CFF.dat")
OPEN(UNIT=20344,FILE="/eos/m/maittaml/PbPb5.5TeV_GravitonXS_M.dat")
J1=2
br1=1d0
gagam=1d-3 ! in unit of GeV-1 (this is kappa/Lambda)
dM=1d0
DO I=1,10000
! for others
!DO I=1,2000
   mass1=dM*DBLE(I)
   width1=gagam**2*mass1**3/(80d0*pipipi)
   ! PbPb, XeXe, KrKr, ArAr, CaCa, OO
   flux1=dLgammagammadW_UPC(mass1,3,1)
   ! pPb
   !flux1=dLgammagammadW_UPC(mass1,2,1)
   ! pp
   !flux1=dLgammagammadW_UPC(mass1,1,1)
   flux1=FOURPI2*DBLE(2*J1+1)*br1**2*width1/mass1**2*convfac*flux1
   WRITE(20344,*)mass1,flux1
ENDDO
CLOSE(UNIT=20344)

RETURN
```

Cross-check: Total cross section

- The total number graviton events expected via $\gamma\gamma \rightarrow G$ a function of graviton mass





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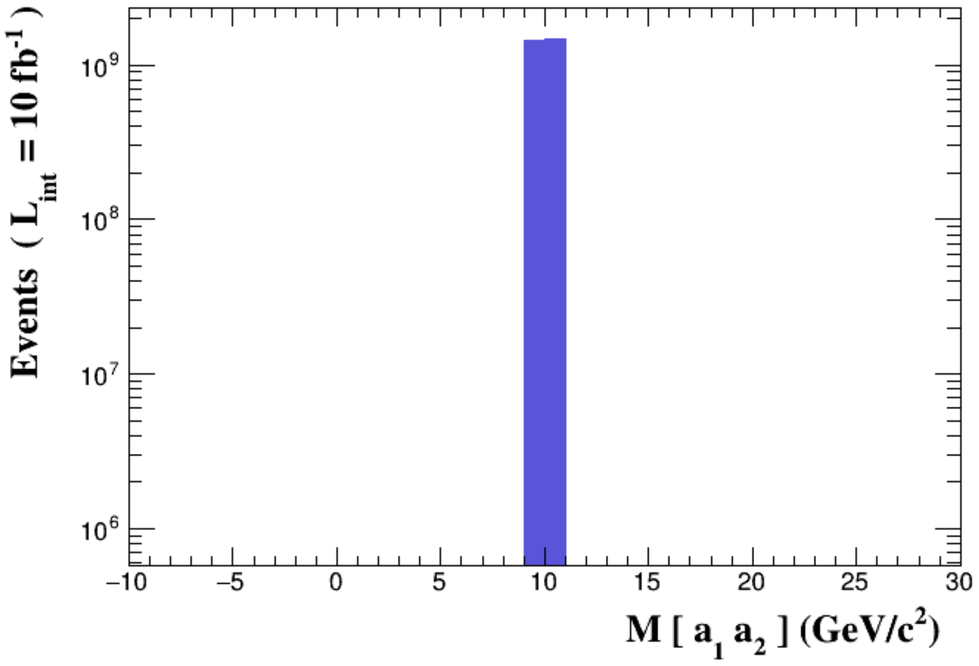
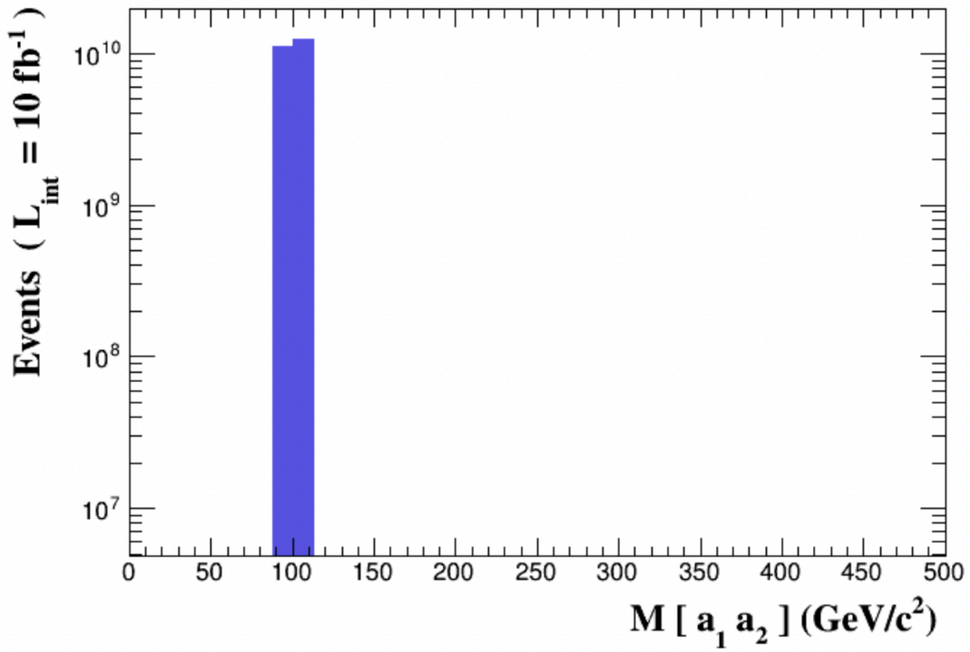
Di-photons invariant mass distribution

- Invariant mass for the two outgoing photons at parton level **(Madevent output)**

M_G =10GeV



M_G =100GeV

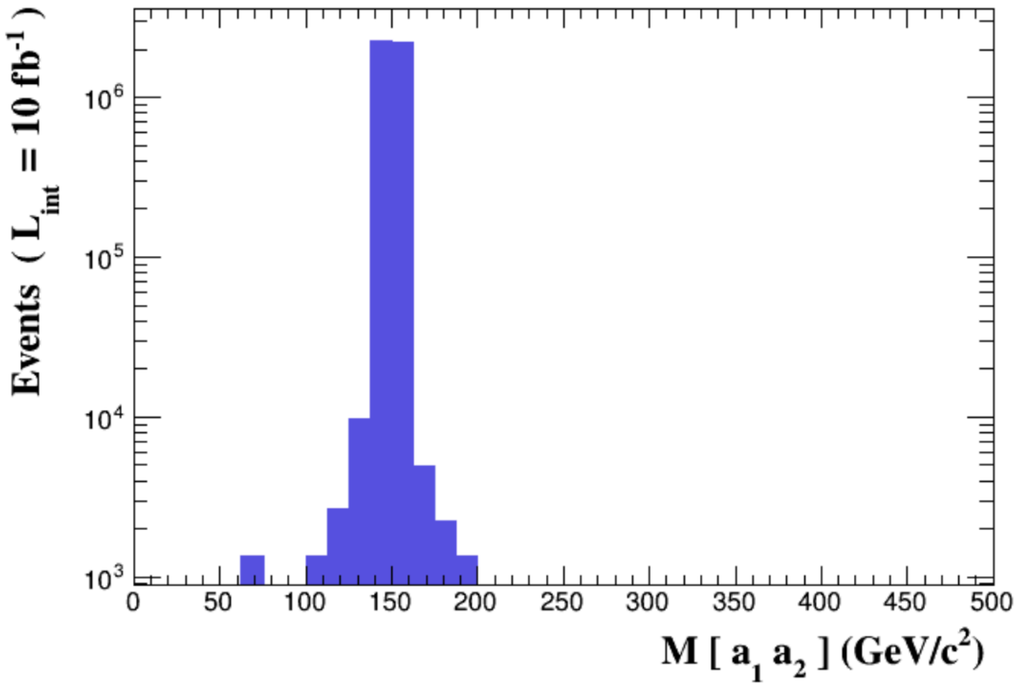


- The theoretical width is very small, below 1GeV
- The width is determined by the detector resolution

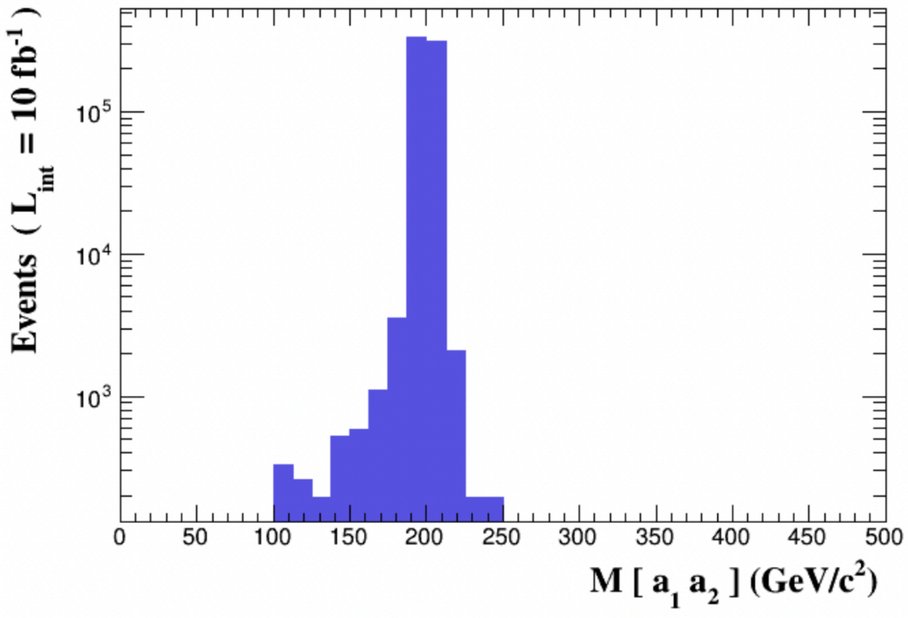
Di-photons invariant mass distribution

- Increasing the graviton mass

M_G =150GeV



M_G = 200GeV



Conclusion

- The graviton exchange in photon-photon scattering is not implemented in any of the exiting MC generators(Starlight, Superchic …)

- **gamma-UPC** is a new MC generator for any $\gamma\gamma$ process, helpful tool for our model of interest: spin-2 massive graviton
- Ongoing work:
  - Implementation of the graviton model in the **SuperChic** MC generator, following the Axion-Like Particle model already exists
  - Calculation of the theoretical amplitude for the graviton production in lbyl

THANK YOU FOR YOUR ATTENTION