Diphoton production in the ADD model to NLO+PS accuracy

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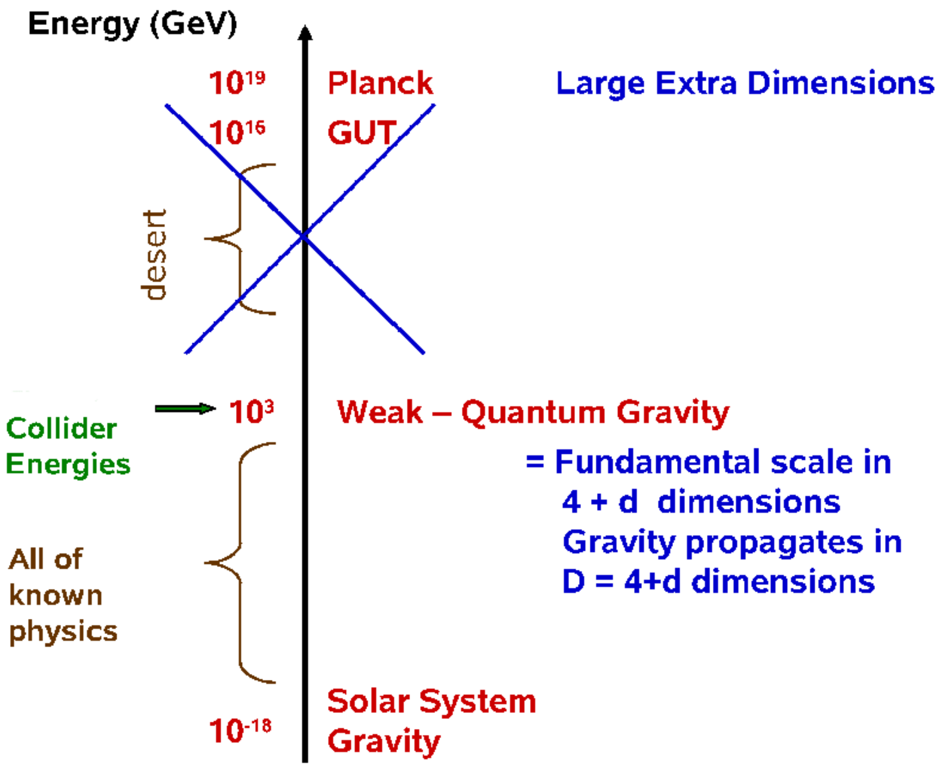
- **TeV scale gravity models**
- **Diphoton process to NLO-QCD**
- **Matching NLO corrections with PS effects using aMC@NLO**
- **Results**

with *R. Frederix, M.K. Mandal, V. Ravindran, S. Seth, P. Torrielli, M. Zaro*

RADCOR 2013

Some non SUSY avenues beyond the SM

Large extra dimension model (ADD) provides an alternate view of the hierarchy between the EW (~ 1 TeV) and the Planck scale (10^{16} TeV)— additional structure in the gravity sector in contrast to previous approaches which introduced new structure in the particle physics sector



Geometry of extra spacial dimensions is responsible for the Hierarchy. These theories should have a viable mechanism (Brane world scenarios) to hide the extra spatial dim such that space time is effectively four consistent with known physics

Brane world scenarios

Hierarchy problem has been one of the main motivation for physics beyond the SM

- **Apparent weakness of gravity accounted for by**
  - **Large extra dimensions (ADD)**
  - **Warped extra dimension (RS1)**
- **Only gravity allowed to propagate the compact extra spacial dimensions, SM is constrained on a 3-brane**
- **For ADD and RS models, the KK spectrum and their effective interactions with SM particles in 4-dim are very distinct**
- **Interaction of the KK tower with SM fields on the 3-brane**

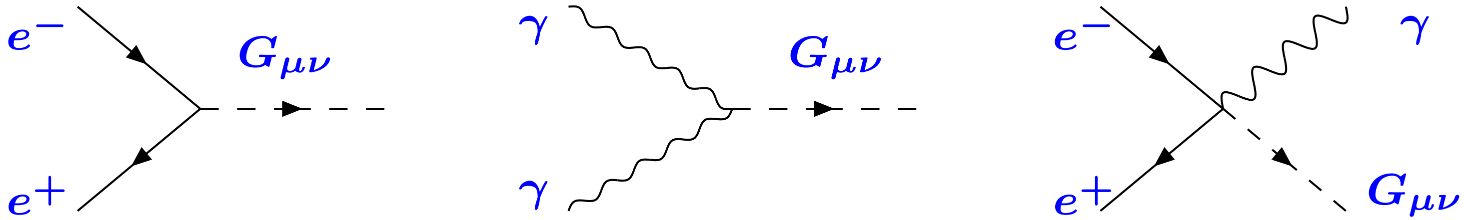
ADD $$\mathcal{L} \sim -\frac{1}{M_P} T^{\mu\nu}\, G^{(0)}_{\mu\nu} - \frac{1}{M_P} T^{\mu\nu}\, \sum_{n=1}^{\infty} G^{(n)}_{\mu\nu}$$

RS $$\mathcal{L} \sim -\frac{1}{M_P} T^{\mu\nu}\, G^{(0)}_{\mu\nu} - \frac{1}{\Lambda_\pi}\, T^{\mu\nu}\, \sum_{n=1}^{\infty} G^{(n)}_{\mu\nu}$$

RULE OF THUMB: ATTACH A GRAVITON TO ANY SM LEG OR VERTEX

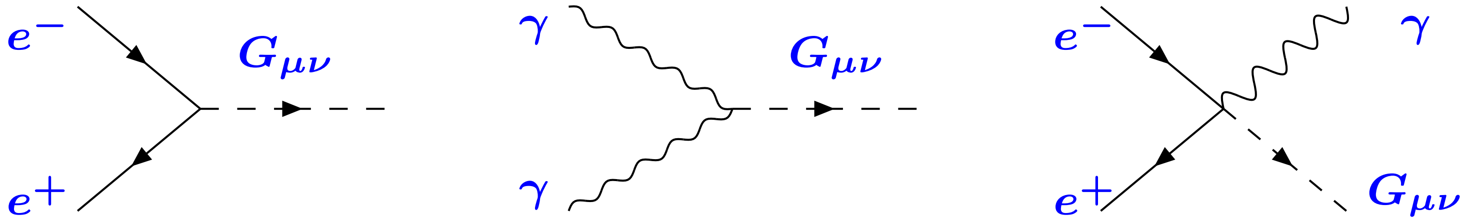
Feynman Rules

- QED

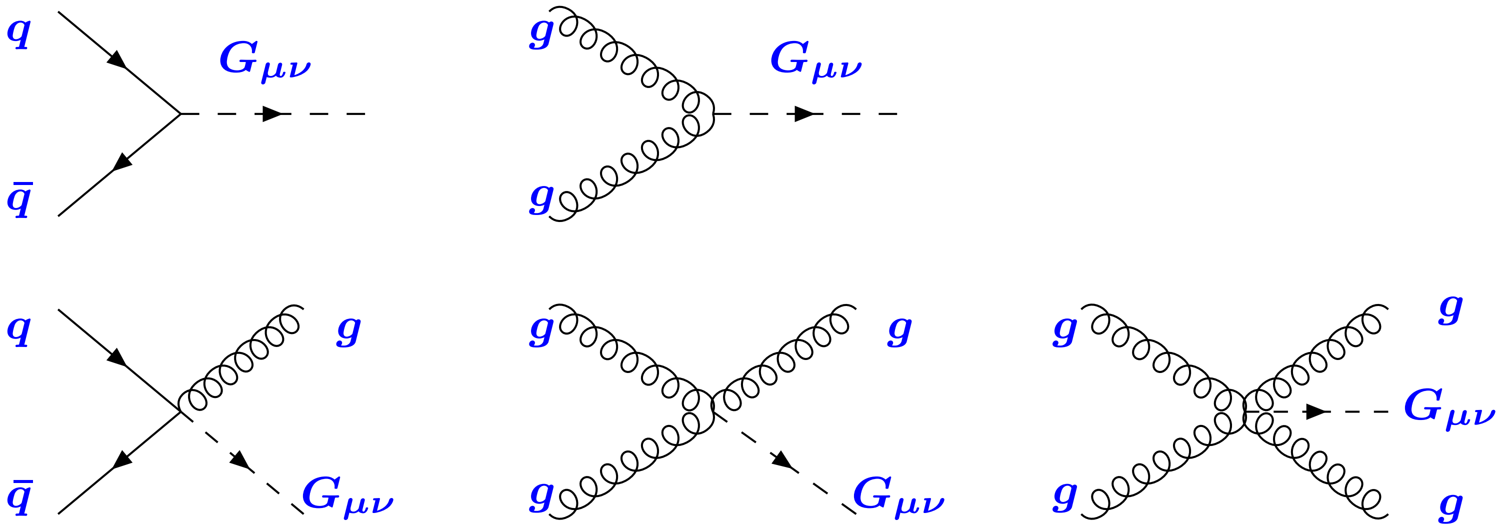


Feynman Rules

- QED



- QCD



Han, Lykken, Zhang hep-ph/9811350

Feynman Rules

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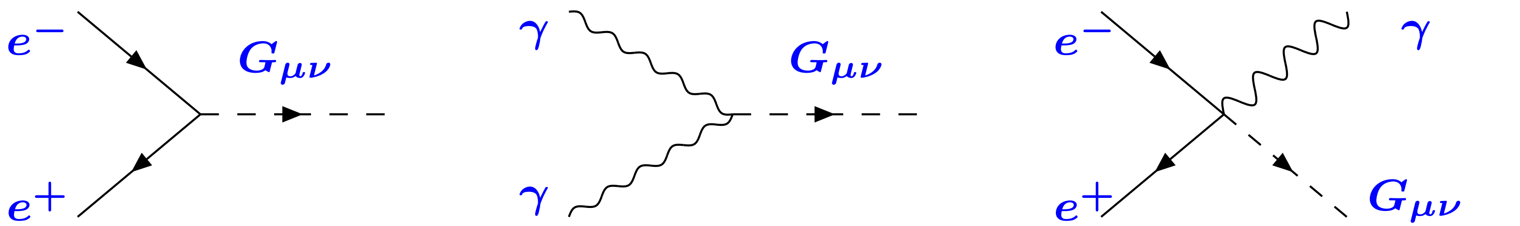
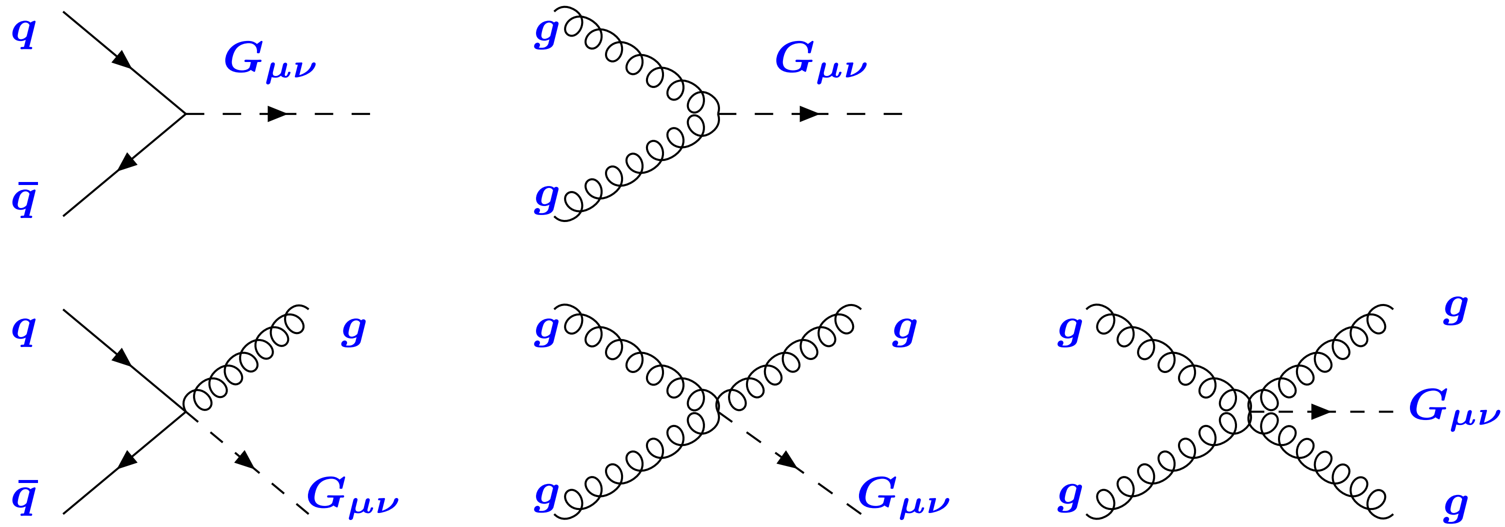


- QCD



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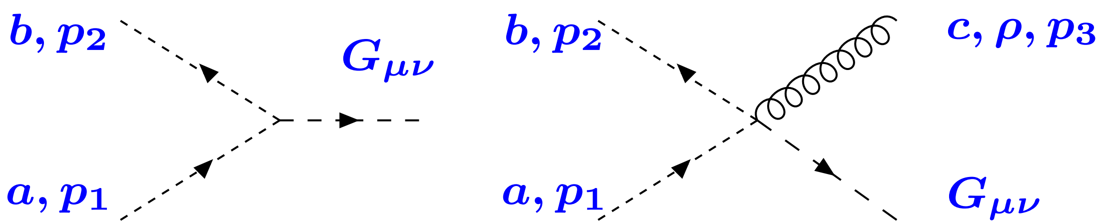
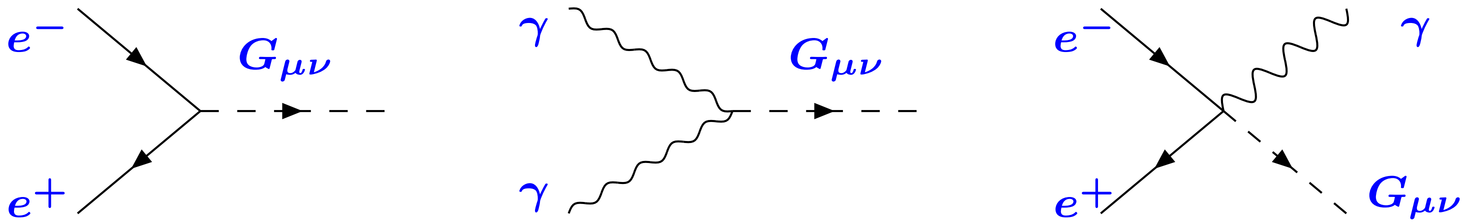


Ghost Couplings

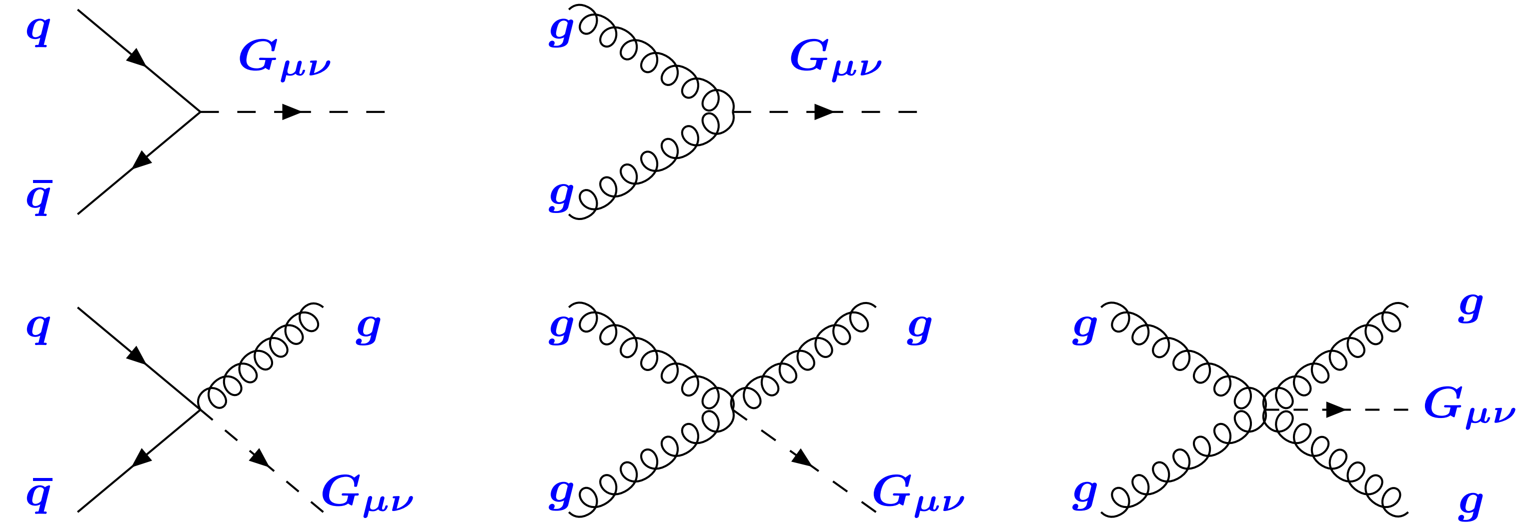
with V Ravindran et. al. JHEP 0408 (2004) 048

Feynman Rules: Implemented in FeynRules

- QED



- QCD



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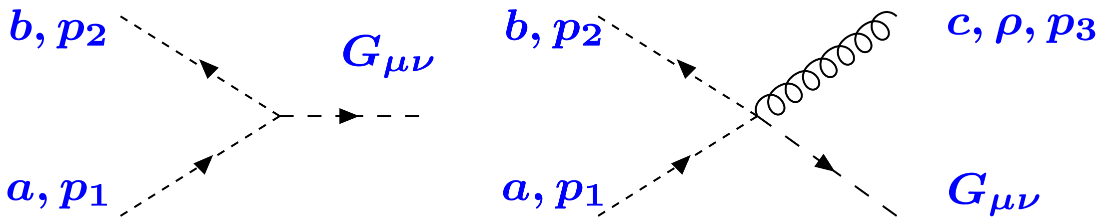

Ghost Couplings

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Probe Extra dimensions @ Colliders— ADD

- Massless graviton and KK modes couple with SM fields with coupling M_P^{-1}
- Effects of KK modes
  - Real KK modes emission
  - Virtual KK modes exchange
- Have to sum over the tower of KK modes to get observable effect
  - Real case $\Rightarrow$ Inclusive production cross section of KK mode

    Phase space enhancement compensates M_P^{-1} suppression for production of a single KK mode. All states up to $m_n = \sqrt{s}$ can be emitted— integral cut off by kinematics

  - Virtual case $\Rightarrow$ contact interaction

    In contrast to real KK emission the summation of virtual KK modes depends on the UV cutoff

Virtual Exchange

- Being virtual all states in fact contribute, not kinematically bound— but bounded by the validity of the effective theory
- KK density of state

$$\rho(m_{\vec{n}}) = \frac{R^d m_{\vec{n}}^{d-2}}{(4\pi)^{d/2}\Gamma(d/2)}$$

- Sum over KK mode propagator

$$\kappa^2 \sum_{\vec{n}} \frac{1}{s - m_{\vec{n}}^2 + i\epsilon} = \kappa^2 \int_0^\infty dm_{\vec{n}}^2 \, \rho(m_{\vec{n}}) \, \frac{1}{s - m_{\vec{n}}^2 + i\epsilon}$$

$$\kappa = \sqrt{16\pi}/M_P$$

- Dominated by UV contribution:

$d = 1$	$d = 2$	$d > 2$
convergent	$\ln(\frac{s}{\Lambda_c^2})$	$\frac{1}{M_S^4}\left(\frac{\Lambda_c}{M_S}\right)^{d-2} \Rightarrow \frac{1}{M_S^4}$

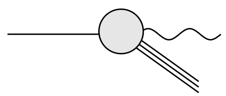
Modifying spin-2 propagator, summation over KK modes incorporated

Di-photon Process

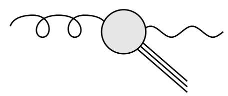
- Prompt photon can be produced as a result of (a) hard subprocess (direct photons) and (b) fragmentation subprocess of partons (fragmentation photons)

- Fragmentation functions of the photon are needed to compute the fragmentation subprocess— additional non-perturbative inputs which are poorly known

$D_{\frac{\gamma}{q}}(z)$



$D_{\frac{\gamma}{g}}(z)$



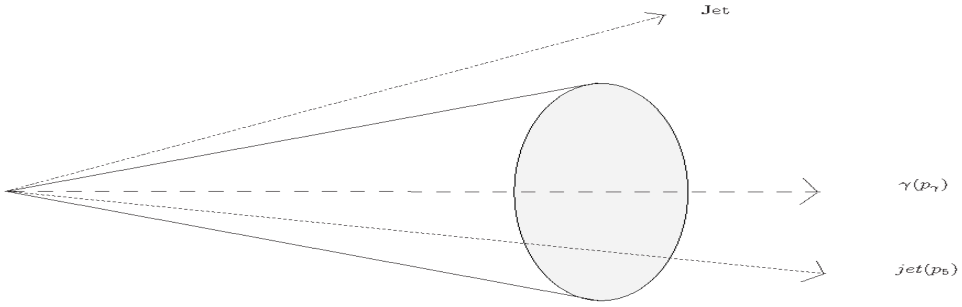
- In the subprocess $gq \to q\gamma\gamma$, final state quark-photon collinear singularity appears. These singularities can be factorised and absorbed into the fragmentation functions $D_{\gamma/a}(z, \mu_F)$

- Fragmentation photon will be accompanied by hadronic activity in its vicinity

- Hadronic jets can be misidentified as photons when their leading hadron is a π^0 or η. Rejected by photon isolation criteria

Isolation criterion used by collider experiments:

- Define a cone of radius R in the rapidity (η), azimuthal angle (ϕ) plane around the photon direction



- Amount of deposited hadronic transverse energy $\sum E_T^{\text{had}}$ in the cone is less then some value E_T^{iso} (chosen by the experiment)

$$\sum E_T^{\text{had}} \leq E_T^{iso} \quad \text{inside} \quad (\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2) \leq R^2$$

- Standard cone isolation criterion in addition to rejecting background of secondary photons, also reduces the fragmentation contribution
- A tight isolation cut, though gets rid of fragmentation effects, it also forbids region of available phase space to gluons— not IR safe

Frixione photon isolation

- Fragmentation mechanism is a collinear phenomenon, to eliminate its contribution— sufficient to veto **only** collinear configurations $D_{\frac{\gamma}{q,g}}(z)\Big|_{z=1} = 0$

- Frixione smooth cone isolation is a modification of the standard cone isolation

$$\sum E_T^{\text{had}} \leq E_T^{iso}\, H(r) \quad \text{inside any} \quad r^2 = (\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2) \leq R^2$$

◦ $H(r) \to 0,\, r \to 0$ Restricts hadronic activity closer to the photon
◦ $H(R) \to 1,\, r \to R$ Coincides with standard cone isolation for outer cone

$$H(r) = \left(\frac{1 - \cos(r)}{1 - \cos(R)}\right)^n \qquad 0 \leq H(r) \leq 1 \quad \text{for} \quad 0 \leq r \leq R$$

- Fragmentation contribution is entirely suppressed, at the same time no region of phase space is forbidden to radiation— IR safe observable

- $\Rightarrow$ Cross section $\sigma^{\text{Frix}} \leq \sigma^{\text{Stand}}$ for same isolation parameters (E_T^{iso}, R), but there are experimental issues regarding implementation of the smooth cone isolation due to finite granularity of the detector

- Activity in experimental implementation of discretized version Frixione isolation

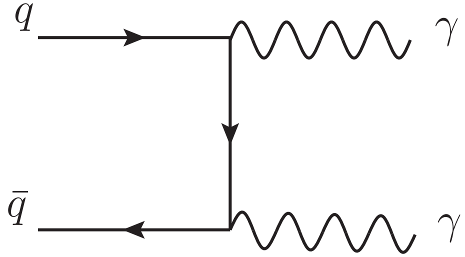
Wielers, ATL-PHYS-2002-004

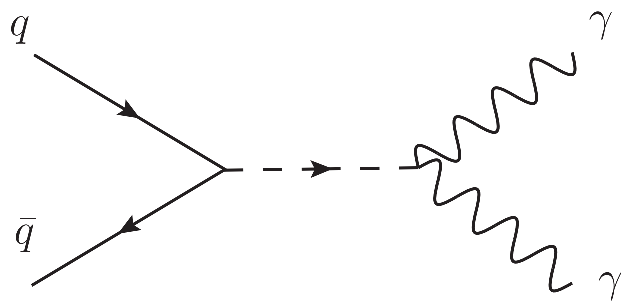
Di-photon Process to LO

$$P_1(p_1) + P_2(p_2) \to \gamma(k_1) + \gamma(k_2) + X$$

- $q\,\bar{q} \to \gamma\,\gamma$

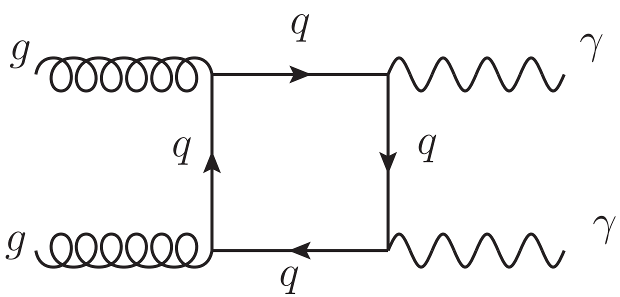
SM $\mathcal{O}(e_q^2)$ BSM $\mathcal{O}(\kappa^2)$

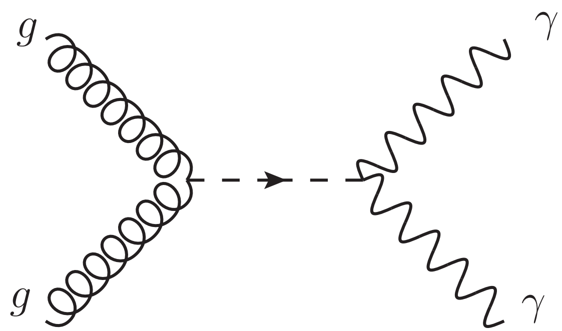




- $g\,\bar{g} \to \gamma\,\gamma$

$\kappa = \sqrt{16\pi}/M_P$





SM $\mathcal{O}(g_s^2 \epsilon_q^2)$ BSM $\mathcal{O}(\kappa^2)$

Dashed line denotes the graviton KK mode G

Theoretical Uncertainties

- **As a result of new interactions in BSM models, additional subprocess contribute at LO**

- **K-factor for diphoton final state in extra dimension scenarios are large hence NLO essential for extra dimension searches at the LHC**

Phys. Lett. B 672, 45; Nucl. Phys. B 818, 28 with M C Kumar, V Ravindran & A Tripathi

- **Physical observables should be independent of μ_F and μ_R, but scale dependence to a fixed order is an artifact of perturbation theory. Including higher orders, reduces scale dependence and hence theoretical uncertainties— improves predictions**

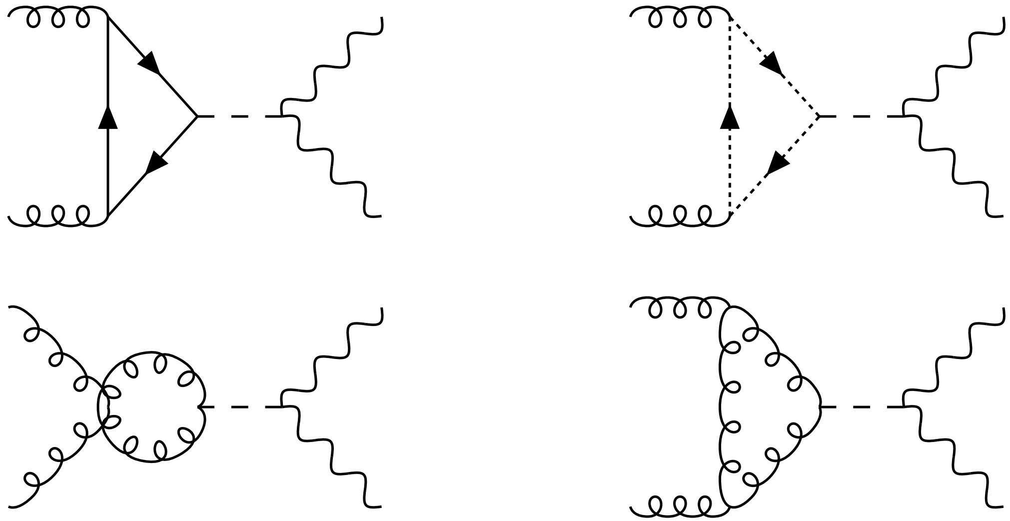
Virtual Contributions $q\,\bar{q} \to \gamma\,\gamma$

$\mathcal{O}(\alpha_s)$ **virtual corrections comes from the interference between the virtual graphs of the (SM + BSM) and the (SM + BSM) Born graphs**

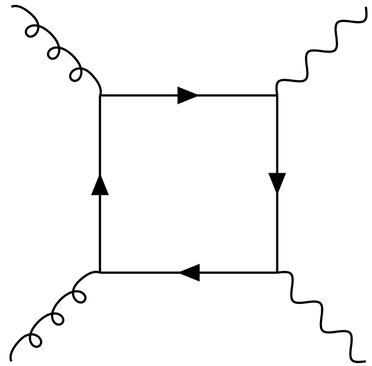
- $\mathcal{O}\Big(g_s^2(e_q^4 + e_q^2\kappa^2 + \kappa^4)\Big)$

Virtual contributions $g\, g \to \gamma\, \gamma$

- $\mathcal{O}\left(g_s^2\ \kappa^4\right)$



- **SM gluon fusion via quark loop** $\mathcal{O}\left(g_s^2 e_q^2 \kappa^2\right)$



Virtual Corrections

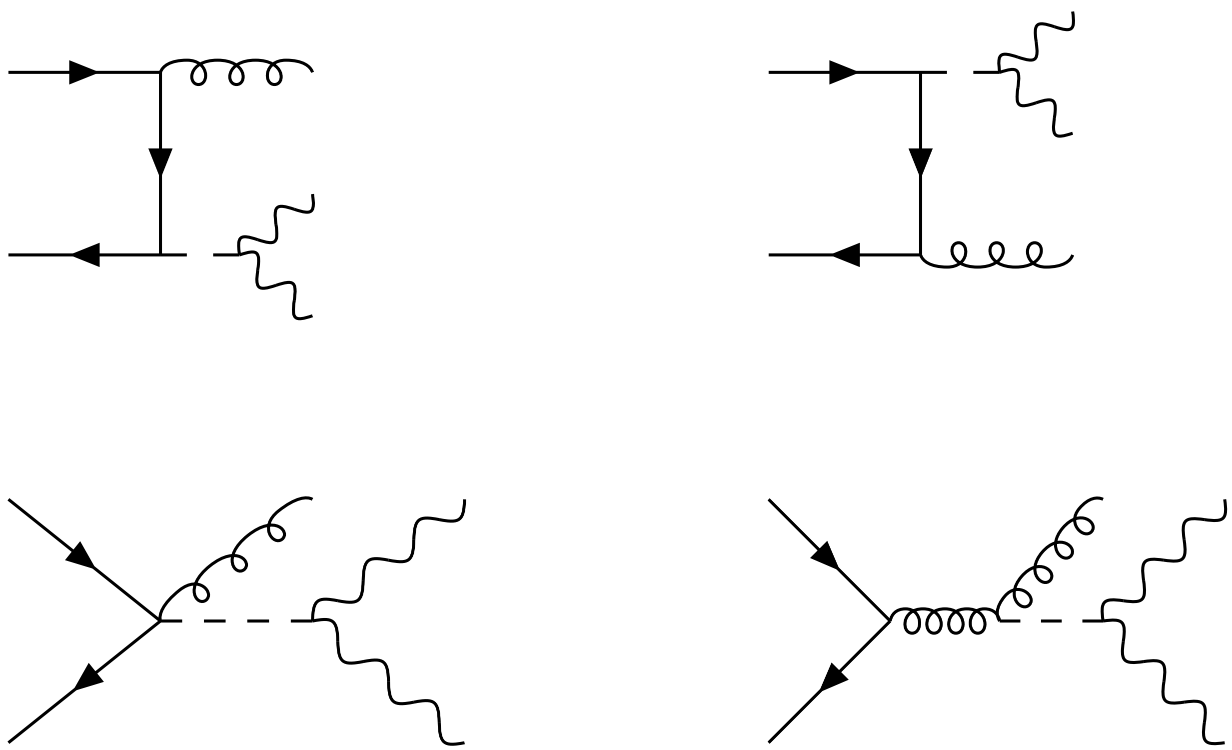
- For diphoton production including gravity there are no UV singularities—
  - KK modes couple to SM energy momentum tensor which is a conserved quantity
- Performing the loop integrals the virtual contributions

$$
\begin{aligned}
d\sigma^V \;=\; & a_s(\mu_R^2)\, dx_1\, dx_2\, \mathcal{K}(\epsilon, \mu_R^2, s) \\
& \Big\{ C_F \Big[\Big(-\frac{16}{\epsilon^2} + \frac{12}{\epsilon} \Big)\, d\sigma^0_{q\bar{q}}(\epsilon) + d\sigma^{fin}_{q\bar{q}} \Big] \Phi_{q\bar{q}}(x_1, x_2) \\
& + C_A \Big[\Big\{ -\frac{16}{\epsilon^2} + \frac{4}{\epsilon} \frac{1}{C_A} \Big(\frac{11}{3} C_A - \frac{4}{3} n_f T_F \Big) \Big\}\, d\sigma^0_{gg}(\epsilon) + d\sigma^{fin}_{gg} \Big] \Phi_{gg}(x_1, x_2) \Big\}
\end{aligned}
$$

$$
\mathcal{K} = \frac{\Gamma(1+\frac{\epsilon}{2})}{\Gamma(1+\epsilon)} \left(\frac{s}{4\pi\mu_R^2} \right)^{\frac{\epsilon}{2}} \qquad a_s(\mu_R^2) = \frac{\alpha_s(\mu_R^2)}{4\pi}
$$

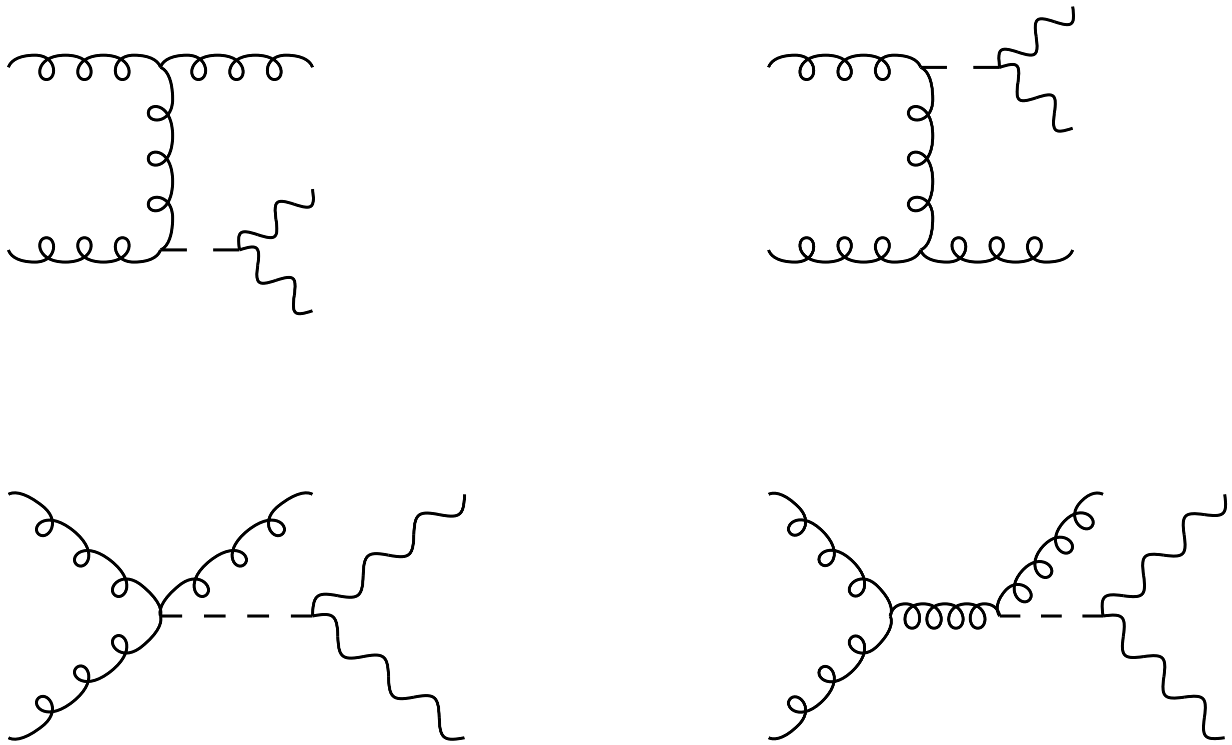
- SM gluon fusion diagram via quark loop would interfere with the LO gravity mediated diagram, but this is a finite contribution (LO)
- SM gluon fusion contribution, though at $\mathcal{O}(\alpha_s^2)$ is comparable to LO for small diphoton invariant mass, but falls off rapidly for larger invariant mass

Real Contributions $q\,\bar{q} \to \gamma\,\gamma\,g$



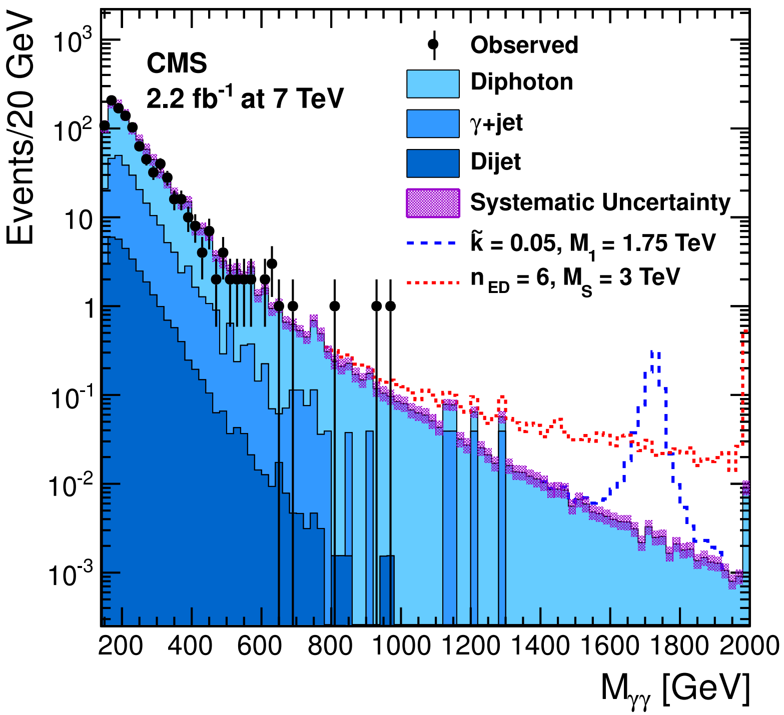
- **Real emission correction compute by MadFKS within MADGraph5**

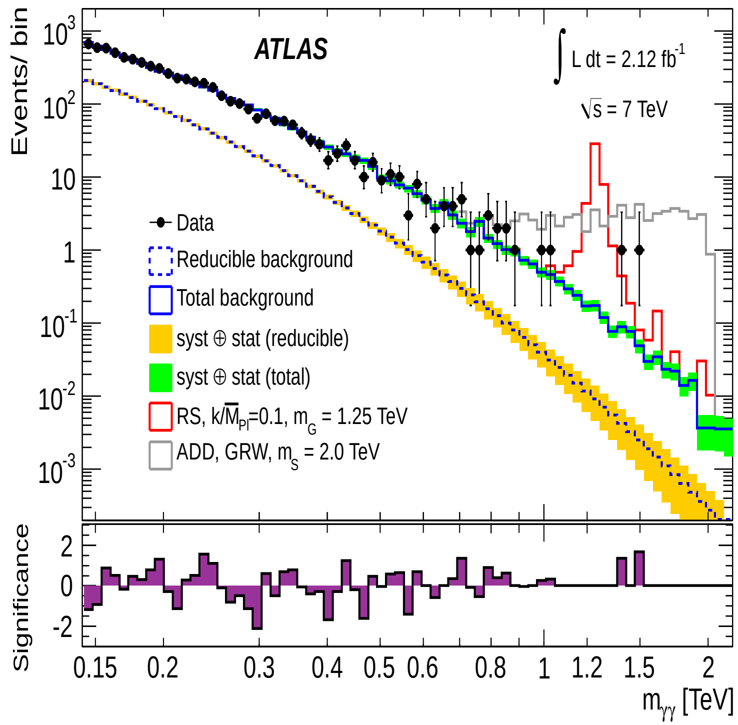
Real Contributions $g\,g \to g\,\gamma\,\gamma$



- Virtual corrections are incorporate, using the our analytical results
- Numerical cancellation of double and single poles coming from real and virtual checked

Extra dimension searches @LHC (Diphoton)





CMS arXiv:1112.0688 **ATLAS arXiv:1112.2194**

- **ADD** $M_s < 2.7(d = 6) - 3.7(d = 2)$ **TeV, excluded at 95 % CL,** $K = 1.6$

Phys. Lett. B 672, 45; Nucl. Phys. B 818, 28 with M C Kumar, V Ravindran & A Tripathi

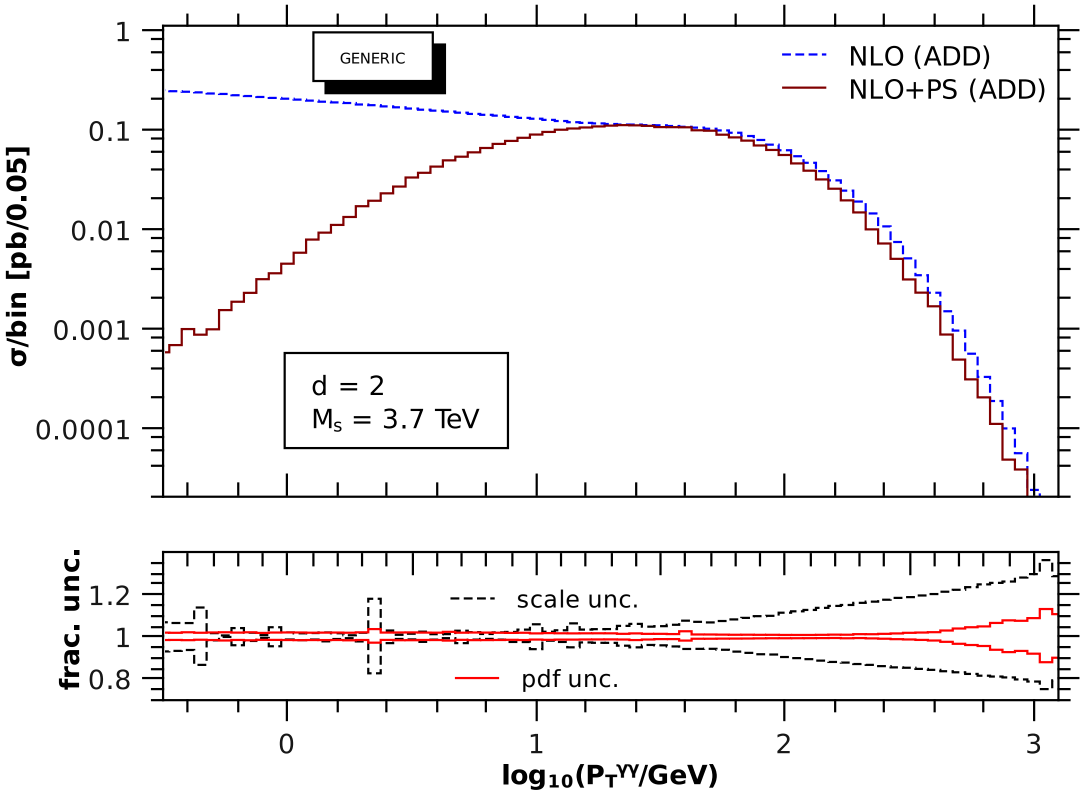
Numerical Results

- **Photon isolation criteria:**

$E_T^{iso} = E_T^{\gamma}, \qquad n = 2, \qquad R = 0.4$

- **Parton Distribution Functions:**
  - LO MSTW2008LO68cl
  - NLO MSTW2008NLO68cl
  - $n_f = 5$ light quark flavours
  - $\mu_F = \mu_R = M_{\gamma\gamma}$ (140 GeV $< M_{\gamma\gamma} < M_S$)
- **Kinematical cuts:**
  - $p_T^{\gamma_1} > 40$ GeV and $p_T^{\gamma_2} > 25$ GeV
  - $|\eta_\gamma| < 2.5$ for each photon
  - $r_{\gamma\gamma} = 0.4$ minimum separation between two photons
- **Use lose cuts at the event generation level and at the time of showering the above cuts are used**

$p_T^{\gamma\gamma}$ distribution of the diphoton fixed order NLO and NLO+PS



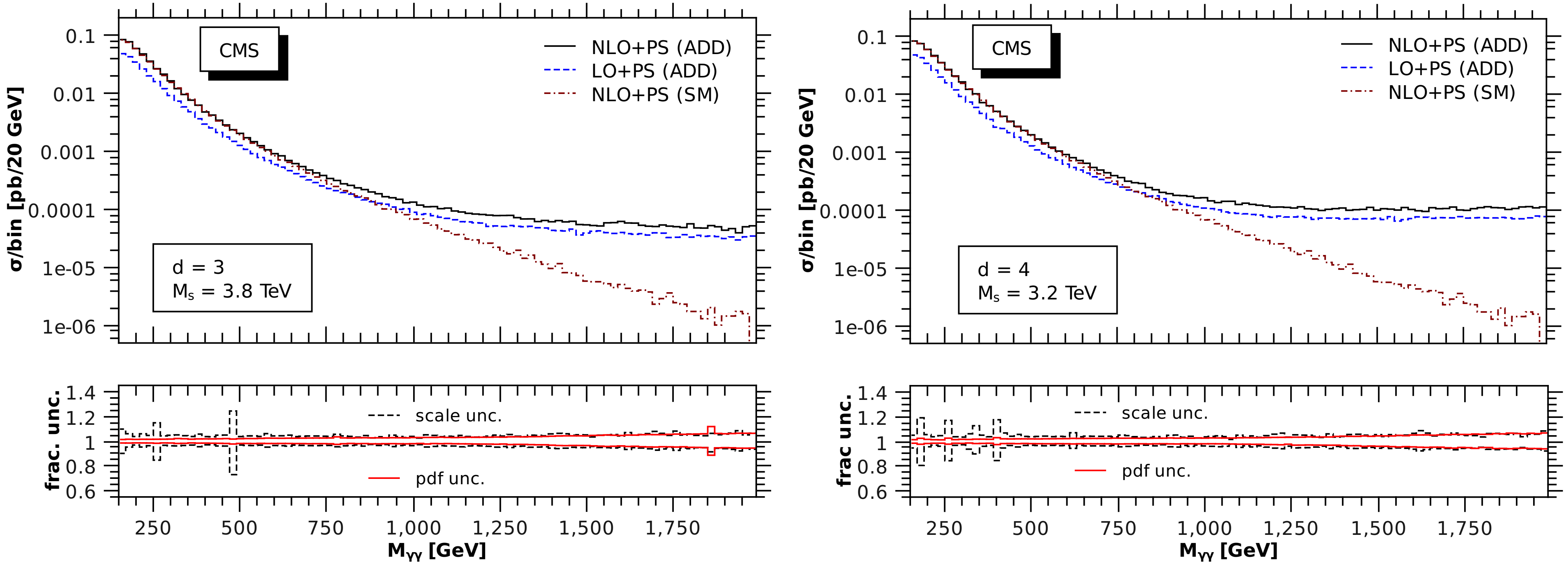
● Effects of parton shower ensures correct resummation of the Sudakov logarithms in the collinear region, leading to a suppression of the cross section in the low $p_T^{\gamma\gamma}$ region

● No significant deviation in the high $p_T^{\gamma\gamma}$ region

● Lower inset displays the scale and PDF, fractional uncertainties for NLO+PS results

● FO $p_T^{\gamma\gamma}$ distribution is only LO— sensitive to scale. In the low $p_T^{\gamma\gamma}$, PS includes higher order effects there by reducing scale dependence in that region

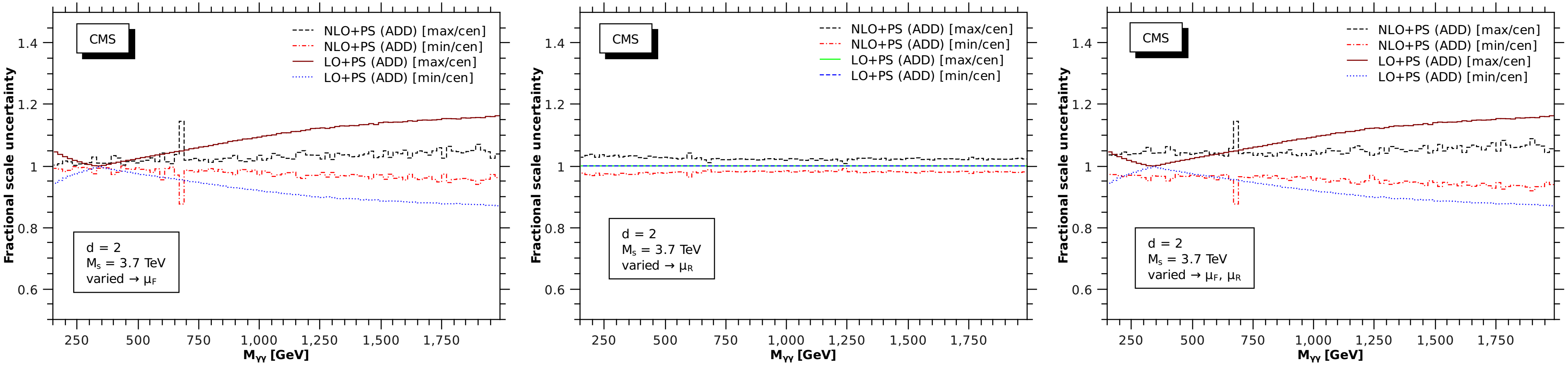
Invariant mass distribution of the diphoton to NLO+PS accuracy



- Lower insets gives corresponding scale (varying both μ_F and μ_R) & PDF, fractional uncertainties for NLO+PS (ADD)

- Scale dependence goes down from about 25% at LO to 10% at NLO

Factorisation & renormalisation scale dependence



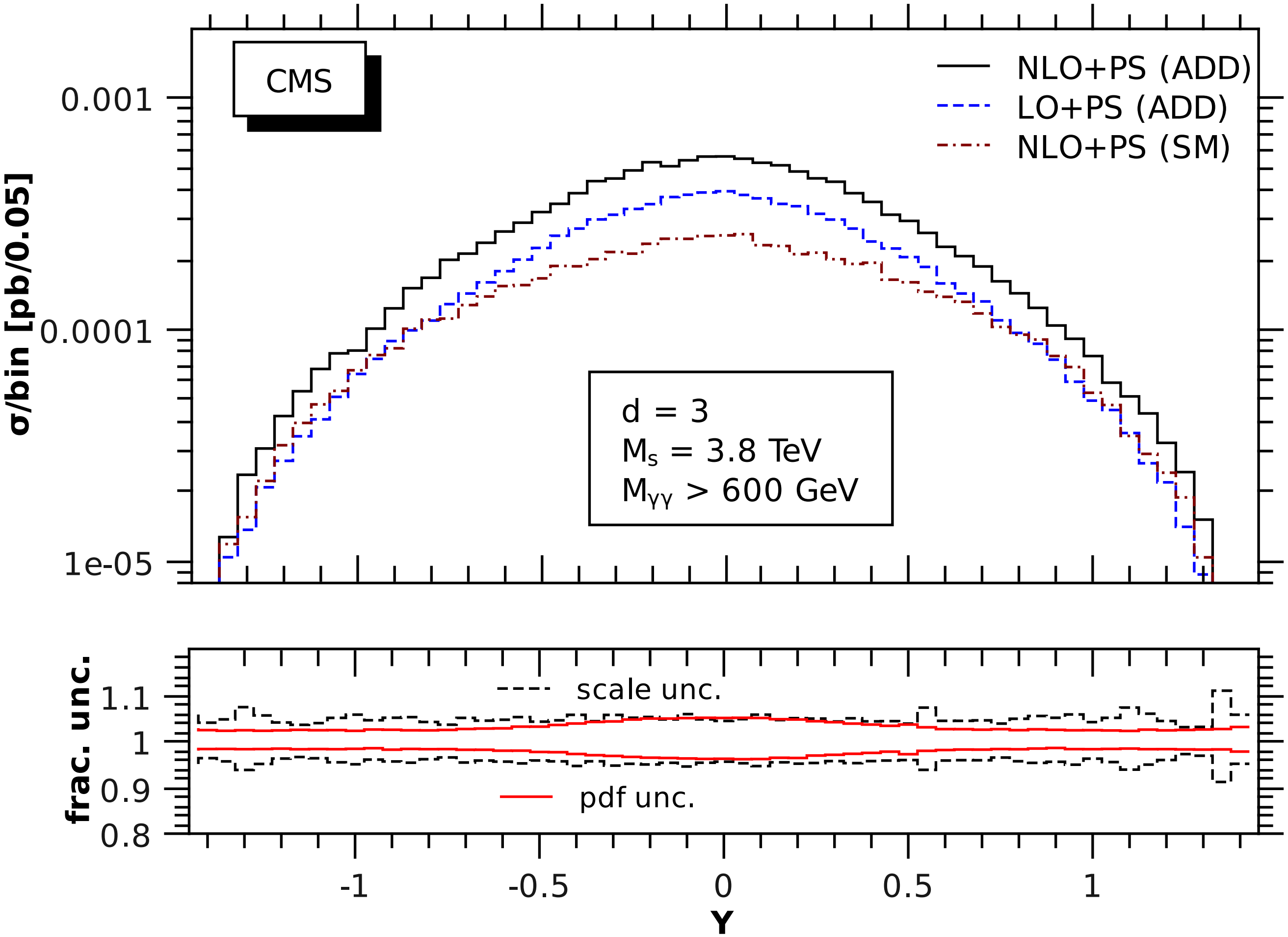
- Fractional uncertainties as a result of μ_F variation (left), μ_R variation (central) and $\mu_F,\ \mu_R$ variation (right), for the invariant mass distribution

- As expected inclusion of NLO corrections reduces the μ_F dependence from about 25% to 5% in the high invariant mass region but at low invariant mass region this variation is much smaller

- μ_R dependence enter only at NLO level and will get reduced when NNLO corrections are included. The μ_R dependence is about 5% and is fairly constant

- On varying both μ_F and μ_R simultaneously, at the low invariant mass region as the μ_F variation is smaller the NLO μ_R variation is larger and hence explains the NLO+PS variation which is in excess of the LO+PS

Rapidity distribution of the diphoton to NLO+PS accuracy



- **Rapidity distribution of diphoton pair for SM and ADD. Lower inset displays corresponding fractional scale and PDF uncertainties of NLO+PS (ADD) results**
- **We choose the region where the ADD model dominates ($M_{\gamma\gamma} > 600$ GeV). Scale uncertainties reduces for 20% to 10% when NLO+PS corrections are included**

Summary

- Diphoton final state in the ADD model to NLO in QCD and matching to parton shower is implemented using the aMC@NLO framework
- Substantial enhancement of the various distribution due to the inclusion of NLO correction
- Significant decrease in theoretical uncertainties NLO corrections are included
- Stand alone codes are now available at http://amcatnlo.cern.ch for most di-final state processes in ADD model