Diphoton + 2jets production at NLO

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On behalf of the BlackHat Collaboration

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Harald Ita, David A. Kosower, A. L., Daniel Maître

arxiv:1402.4127 [hep-ph]

LHCphenonet meeting
4th June 2014

γγ+2j @ NLO

Higgs boson decays into a photon pair through massive-quark loop

With two jets:
Background to the production of the Higgs boson via Vector Boson Fusion (VBF)

NLO needed to reduce the large dependence on scales
and have the first quantitative prediction.

- $pp \to \gamma\gamma + 0j$
  DIPHOX (Binoth, Guillet,Pilon,Werlen)
  2gammaMC (Bern,Dixon,Schmidt)
  MCFM (Campbel,Ellis,Williams)
  Catani, Cieri, de Florian, Ferrera, Grazzini (2011) (NNLO)

- $pp \to \gamma\gamma + 1j$
  Del Duca, Maltoni, Nagy, Trocsanyi (2003)
  Gehrmann, Greiner, Heinrich (2013)

- $pp \to \gamma\gamma + 2j$
  Gehrmann, Greiner, Heinrich (2013)
  Badger, Guffanti, Yundin (2014)
  BH collaboration

NLO calculations with BlackHat+Sherpa

$$\sigma_n^{\rm NLO} = \int_n \sigma_n^{\rm born} + \int_n \sigma_n^{{\rm virt},f} + \int_{n+1} \left(\sigma_{n+1}^{\rm real} - \sigma_{n+1}^{\rm subtr}\right) + \int_n \Sigma_n^{\rm subtr}$$

Catani-Seymour dipole subtraction scheme.

COMIX package (Gleisberg,Höche) used to compute Born and real-emission matrix elements, along with the Catani–Seymour dipole subtraction terms.

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Numerical implementation of on-shell methods for one-loop amplitudes

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Used previously for			
$W,\ Z/\gamma^* + 3j$,	$W,\ Z/\gamma^* + 4j$,	W+5j ,	4 Jet ,
high-p_T W polarization ,		$\gamma + n$-jet / $Z + n$-jet ratios	

BlackHat

Numerical implementation of On-Shell Methods

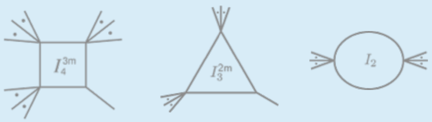
Britto et al. (BCFW, 2005), Bern,Dixon,Dunbar,Kosower (1994), Bern,Dixon,Kosower (1998,2006), Brandhuber,McNamara,Spence,Travaglini (2005), Anastasiou,Britto,Feng,Kunszt,Mastrolia (2007); Ellis,Giele,Kunszt,Melnikov, Zanderighi(2008) , Ossola,Papadopoulos,Pittau (2007), … and many others.

BlackHat

Numerical implementation of On-Shell Methods

$$\text{Ampl} \;=\; \sum_{j\in\text{Basis}} c_j\,\text{Int}_j \;+\; \text{Rational}$$

Int_j $\rightarrow$ Known integral basis (Passarino-Veltman):



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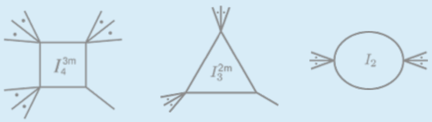

c_j → Unitarity in D=4 : rational functions of spinors

BH computes them using contour integral at ∞ [D. Forde ('07)]

Rational → BH uses D-dim unitarity via massive integral basis [S. Badger ('09)]

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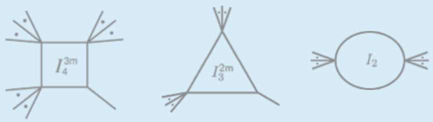

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Required tree amplitudes computed numerically (on-shell recursion relations).

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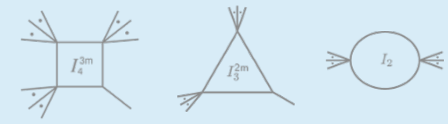

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Coefficients reduce to products of trees.
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BH sums the loop-tree interference terms over the colour configurations.

BlackHat-Sherpa *n*-tuples

In order to have small statistical uncertainty we need to compute hard matrix elements in million of different phase-space points.
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BH-Sherpa n-tuple branches
id, nparticle, px, py, pz, E, x1, x2, x1p, x2p, id1, id2, kf alpha_power, alpha_s, fac_scale, ren_scale, weight, weight2, me_wgt, me_wgt2, nuwgt, usr_wgts, part

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Sufficient information can be stored
to re-evaluate cross sections and distributions
without the need of re-computing the hard matrix elements

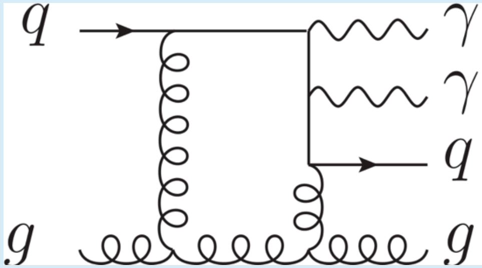
γγ+2j with BlackHat

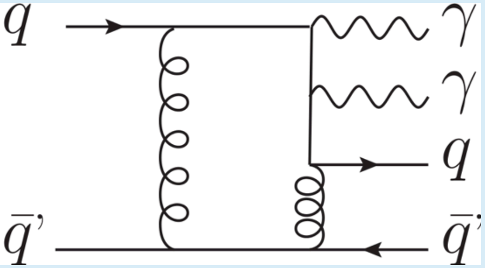
Approximations: No top-contributions,
The five lighter quarks treated as massless

γγ + 0-jet:
confirmed HELAC (PS points) and MCFM (PS points & after integration)

γγ + 1-jet: confirmed GoSam (PS points & after integration)
γγqqg also confirmed against previous analytic calculation (L. Dixon)

γγ + 2-jet: confirmed GoSam (PS points) and after integration
confirmed Njet after integration





Example of loop diagrams for the processes $qg \rightarrow \gamma\gamma q'g$ and $qq' \rightarrow \gamma\gamma qq'$.

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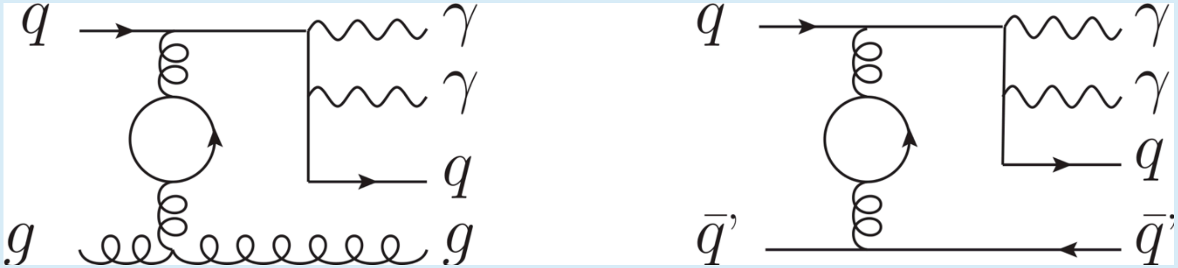

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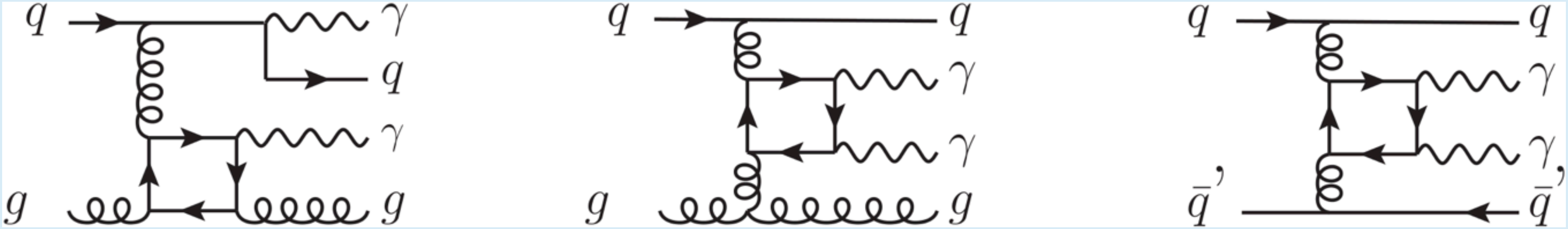

Example of loop diagrams for the processes *qg* → *γγq'g* and *qq'* → *γγqq'* .

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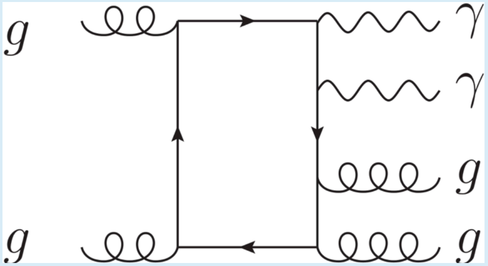


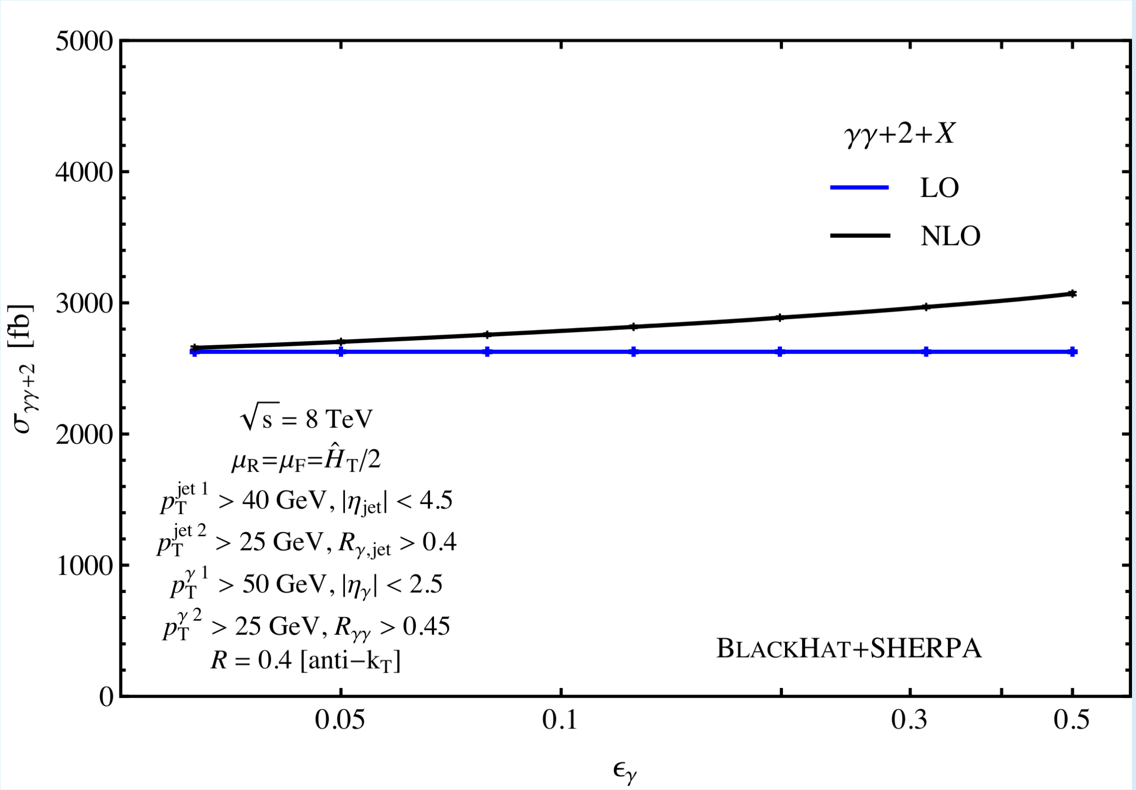
Light-by-light scattering contribution:
have no corresponding tree-level amplitudes and are finite.

Photon isolation criterion – ε dependence

Frixione isolation: radially-dependent E_T limit [Frixione, 1998]

$$\sum_p E_{Tp}\theta(\delta - R_{p\gamma}) \leq E(\delta) \qquad \text{with} \qquad E(\delta) = E_T^\gamma\,\epsilon\left(\frac{1-\cos\delta}{1-\cos\delta_0}\right)^n$$

($\delta_0 = 0.4$, $n = 1$)

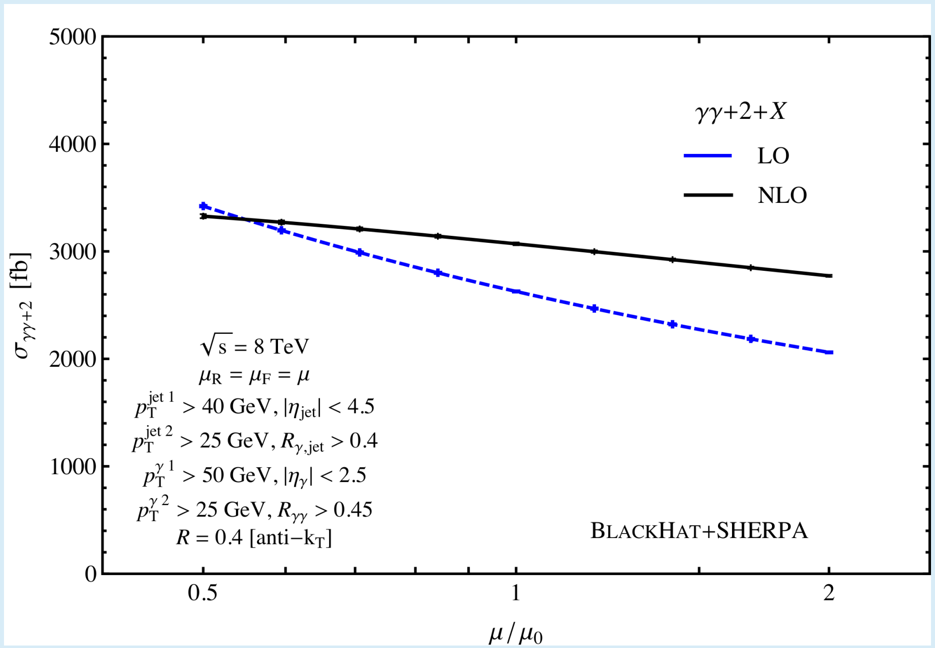


γγ+2 jets: total xsec scale dependence

$$\text{PDF} = \text{MSTW(2008)}\,, \qquad \mu_0 = \frac{1}{2}\left(p_T^{\gamma_1} + p_T^{\gamma_2} + \sum_m p_T^m\right), \qquad \sqrt{s} = 8\,\text{TeV}$$

$$p_T^{\gamma_1} > 50\text{ GeV}\,, \quad p_T^{\gamma_2} > 25\text{ GeV}\,, \quad |\eta^\gamma| < 2.5\,, \quad |\eta^{\text{jet}}| < 4.5\,, \quad R_{\gamma,jet} > 0.4\,,$$

$$p_T^{\text{jet}_1} > 40\text{ GeV}\,, \quad p_T^{\text{jet}_2} > 25\text{ GeV}\,, \quad \left(M_{jj} > 400\text{ GeV}\,, \quad \Delta\eta_{jj} > 2.8\right), \quad \Delta R_{\gamma\gamma} > 0.45$$



γγ+2jet production: modest NLO correction

small gg→γγgg contribution (~2% of total cross section)

Leading Jet's p_T-distribution

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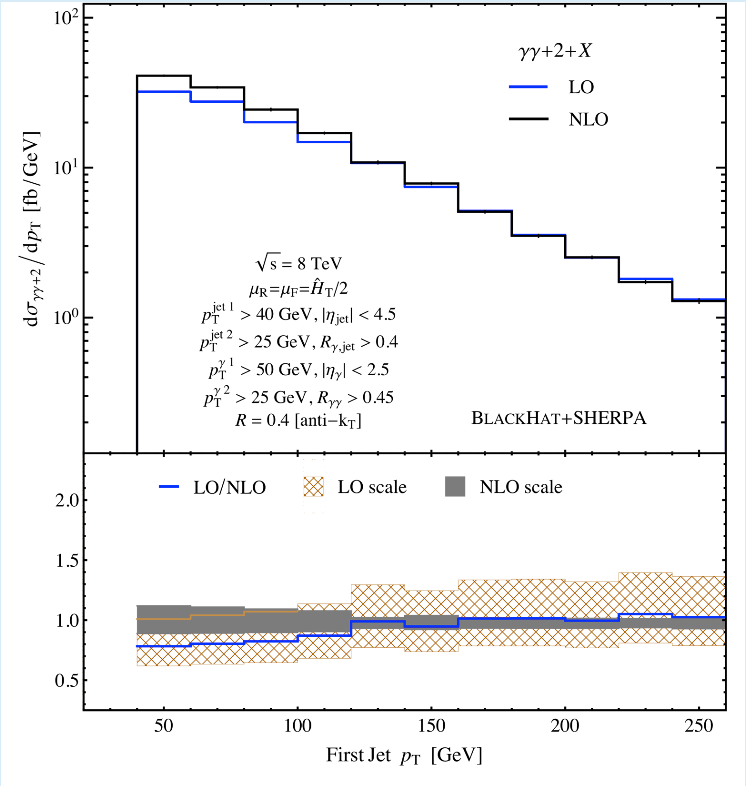
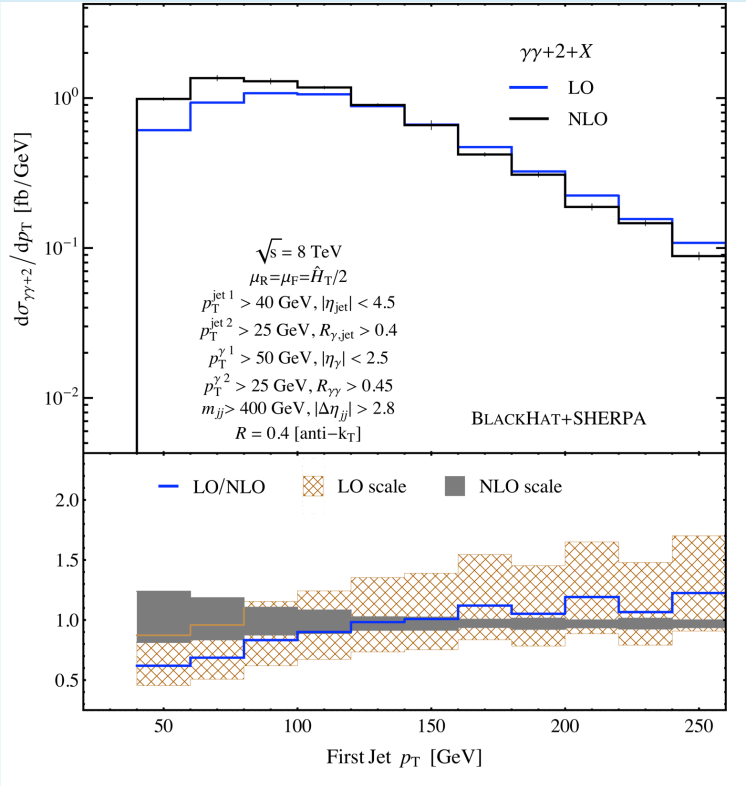
Without VBF cuts



With VBF cuts



Dijet invariant mass distributions

$$\mathrm{PDF} = \mathrm{MSTW(2008)}\,, \qquad \mu_0 = \frac{1}{2}\left(p_T^{\gamma_1} + p_T^{\gamma_2} + \sum_m p_T^m\right)\,, \qquad \sqrt{s} = 8\,\mathrm{TeV}$$

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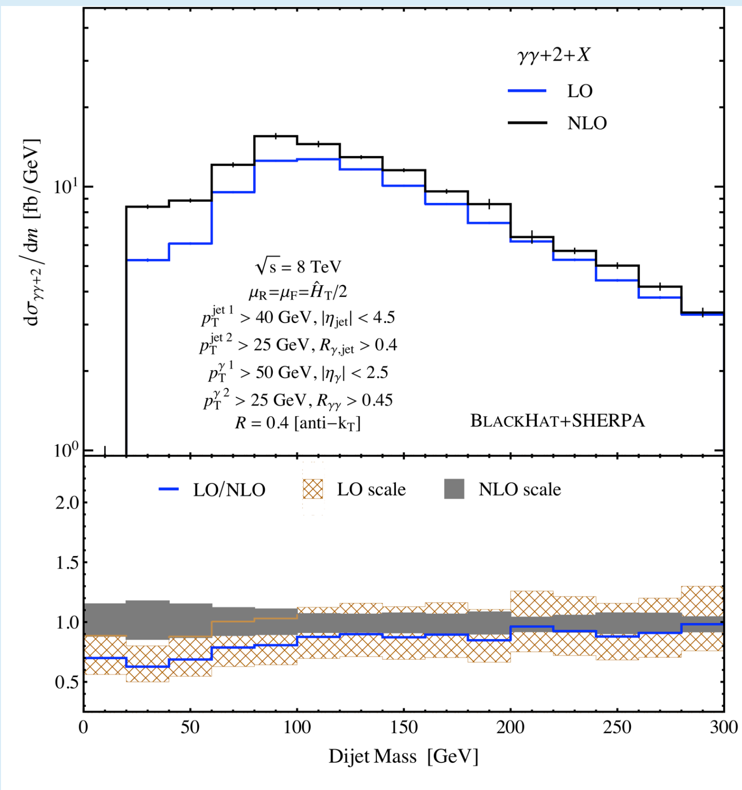
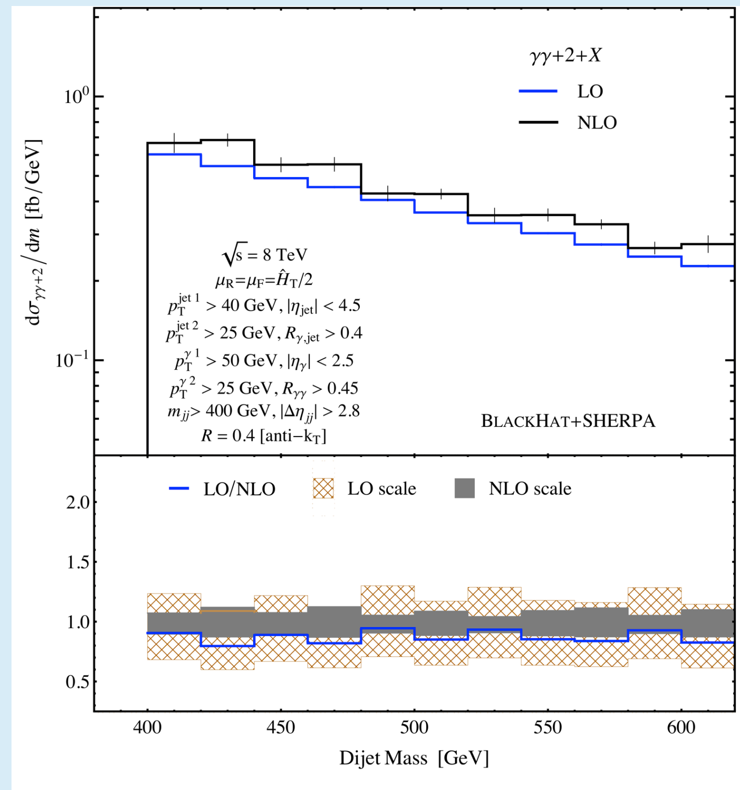


With VBF cuts



Diphoton invariant mass distributions

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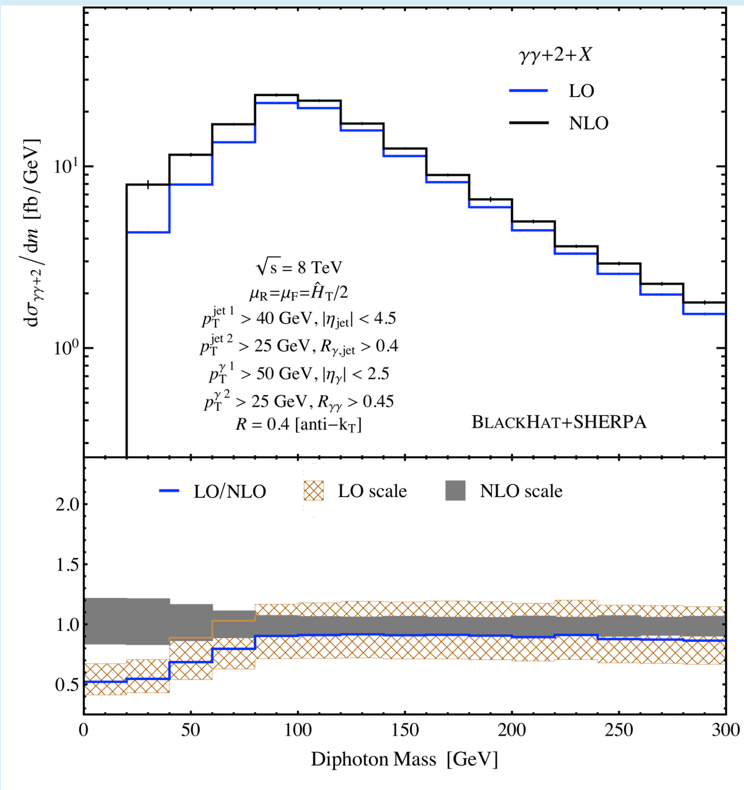

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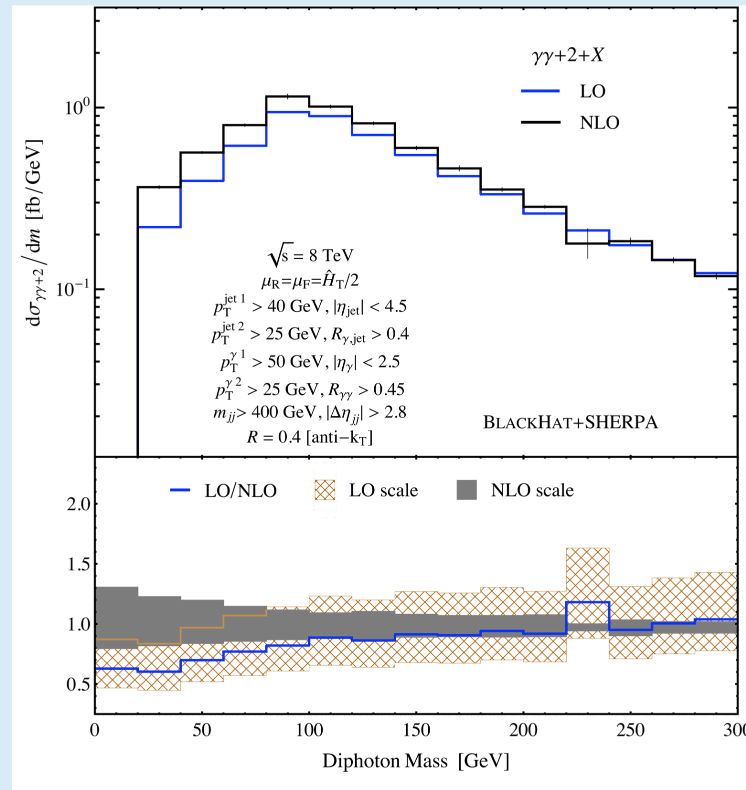

Diphoton Rapidity distribution – ATLAS cuts

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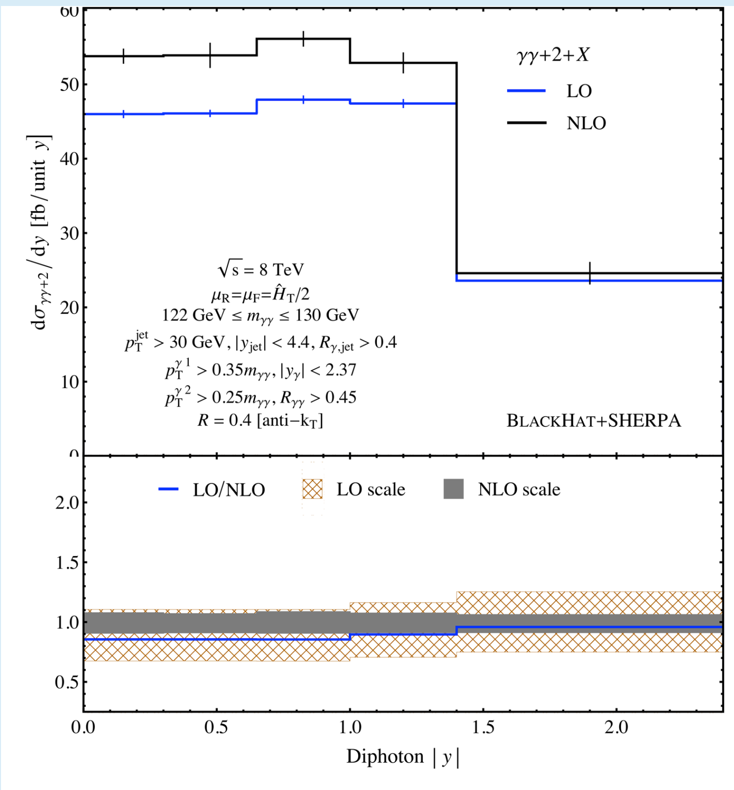
$$p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}\,, \qquad p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}\,, \qquad |\eta^{\gamma}| < 2.37\,, \qquad |\eta^{\mathrm{jet}}| < 4.4\,,$$

$$p_T^{\mathrm{jets}} > 30\ \mathrm{GeV}\,, \qquad 122 \le m_{\gamma\gamma} \le 130\ \ \mathrm{GeV}, \qquad \left(M_{jj} > 400\ \mathrm{GeV}\,, \qquad \Delta\,\eta_{jj} > 2.8\right)$$

Without VBF cuts



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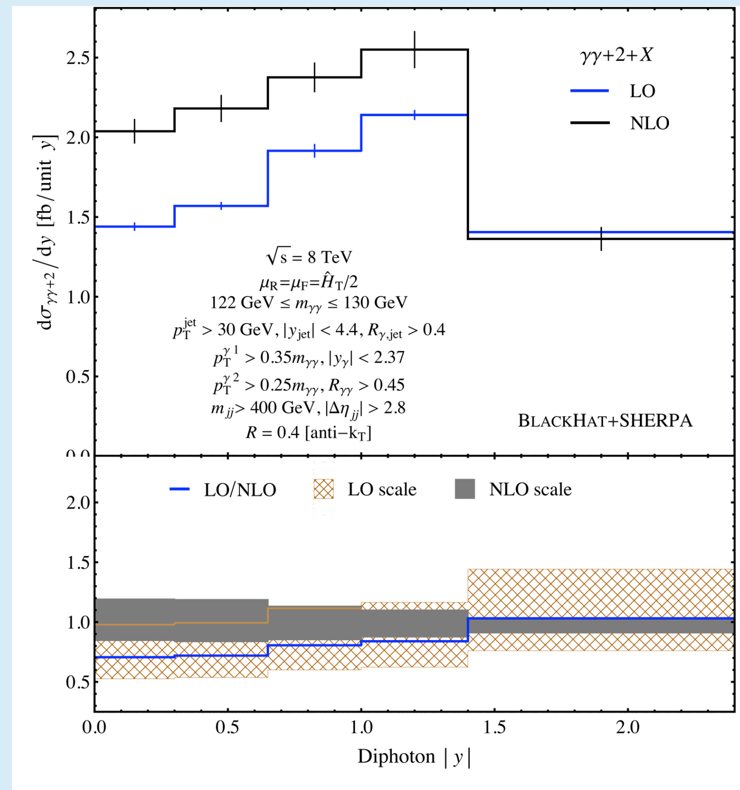

$|\Delta\phi_{jj}|$ distribution – ATLAS cuts

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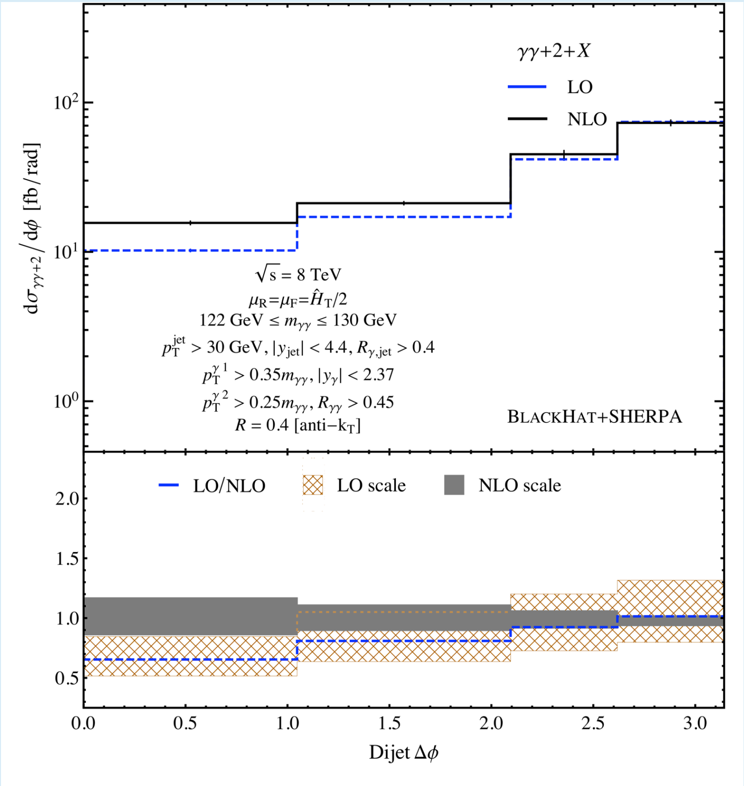

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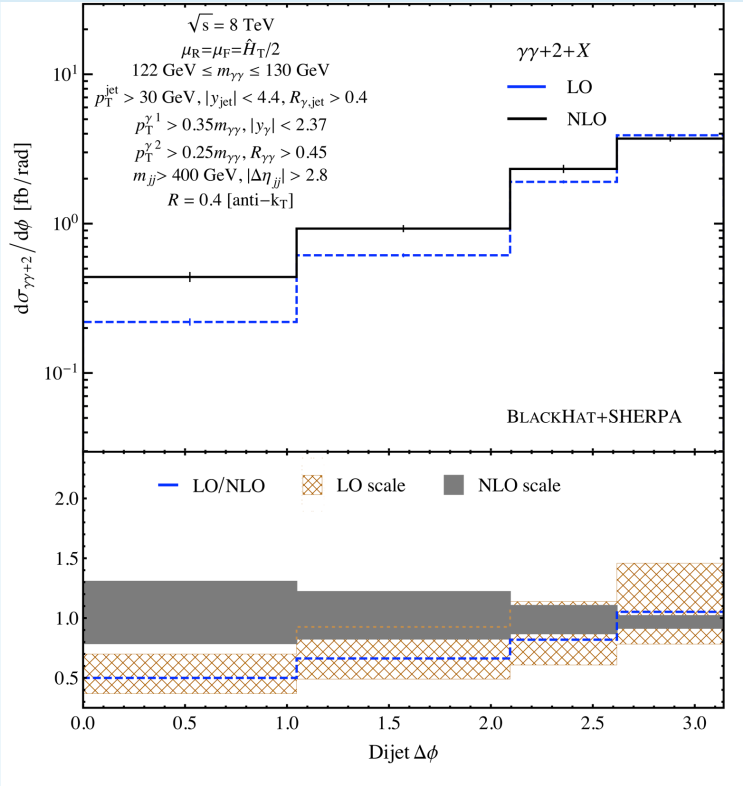

Summary

- We have presented a full NLO calculation for $pp\to\gamma\gamma$+2jets
- We have included the one loop $gg\to\gamma\gamma gg$ contribution

  It contributes to the ~2% of the total cross section

- We have considered cuts on m_{jj} and $\Delta\eta_{jj}$ to highlight kinematic region where Vector Boson Fusion (VBF) dominates
- The NLO corrections : ~20% (without VBF cuts)
  ~10% (with VBF cuts)
- Larger corrections at small leading-jet's p_T and small diphoton and dijet invariant masses

Thank you for the attention!

Back up slides

BlackHat-Sherpa *n*-tuples

We split the calculation in parts B, I, RS, V (subsequently split in sub-parts).
The physical observables (distributions, total cross sections…)
are constructed by summing the sub-parts

$$\langle \mathcal{O} \rangle = \sum_{t \in T, p \in P_t} \mathcal{O}^{(t,p)}$$

Each of these parts is calculated summing over the weighted events

$$\langle \mathcal{O}^{(t,p)} \rangle = \frac{1}{N_{t,p}} \sum_{e=1}^{N_{t,p}} w_{t,p,e}\, \mathcal{O}_{t,p,e}$$

For each part the error is calculated as

$$\epsilon_{\mathcal{O}}^{t,p} = \frac{1}{\sqrt{N_{t,p}(N_{t,p}-1)}} \left[\sum_{e=1}^{N_{t,p}} (w_{t,p,e}\mathcal{O}_{t,p,e})^2 - \frac{1}{N_{t,p}} \left(\sum_{e=1}^{N_{t,p}} w_{t,p,e}\mathcal{O}_{t,p,e} \right)^2 \right]^{1/2}$$

The errors of the different sub-parts are then summed in quadrature

BlackHat-Sherpa *n*-tuples

BH-Sherpa n-tuple branches
id,
nparticle,
px, py, pz, E,
x1, x2,
x1p, x2p,
id1, id2,
kf
alpha_power,
alpha_s,
fac_scale,
ren_scale,
weight,
weight2,
me_wgt,
me_wgt2,
nuwgt,
usr_wgts,
part

Changing the scale: Born and Real contribution

$$w = \mathbf{me\_wgt2} \cdot f(\mathbf{id1}, \mathbf{x1}, \mu_F)\, F(\mathbf{id2}, \mathbf{x2}, \mu_F)\, \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n}$$

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Changing the scale: Virtual contribution

$$w = m \cdot f(\mathbf{id1}, \mathbf{x1}, \mu_F)\, F(\mathbf{id2}, \mathbf{x2}, \mu_F)\, \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n}$$

$$m = \mathbf{me\_wgt2} + l\, \mathbf{usr\_wgts}[0] + \frac{l^2}{2} \mathbf{usr\_wgts}[1]$$

$$l = \ln\left(\frac{\mu_R^2}{\mathbf{ren\_scale}^2}\right)$$

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Changing the scale: Integrated subtraction contribution

$$
\begin{aligned}
w &= m \cdot \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} \\
m &= \omega_0 \cdot f(\mathbf{id1}, \mathbf{x1}, \mu_F)\, F(\mathbf{id2}, \mathbf{x2}, \mu_F) \\
&\quad + \left(f_a^1\omega_1 + f_a^2\omega_2 + f_a^3\omega_3 + f_a^4\omega_4\right) F_b(x_b) \\
&\quad + \left(F_b^5\omega_1 + F_b^6\omega_2 + F_b^7\omega_3 + F_b^8\omega_4\right) F_a(x_a) \\
\omega_0 &= \mathbf{me\_wgt2} + l\,\mathbf{usr\_wgts}[0] + \frac{l^2}{2}\mathbf{usr\_wgts}[1] \\
l &= \ln\left(\frac{\mu_R^2}{\mathbf{ren\_scale}^2}\right) \\
\omega_i &= \mathbf{usr\_wgts}[i+1] + \mathbf{usr\_wgts}[i+9]\ln\left(\frac{\mu_F^2}{\mathbf{fac\_scale}^2}\right)
\end{aligned}
$$