Diphoton + 2jets production at NLO

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on behalf of the BlackHat Collaboration

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Max-Planck-Institut für Physik – Munich, Germany
10 January 2014

$\gamma\gamma$+2j @ NLO

Diphoton production is a very interesting process at the LHC

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

Prompt diphoton production: background for SM precision measurements

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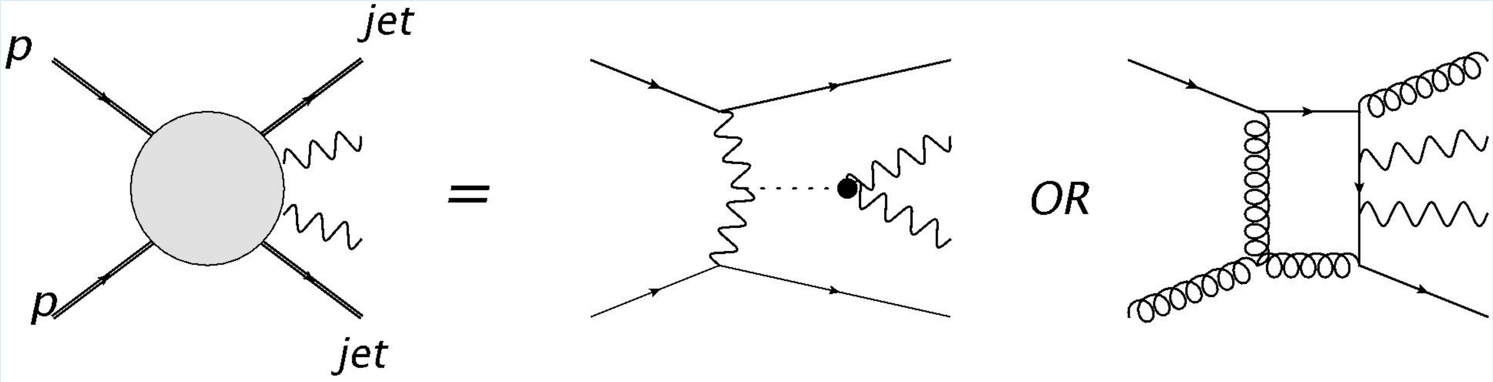
With two jets:

Background to the production of the Higgs boson via Vector Boson Fusion (VBF)



$\gamma\gamma$+2j @ NLO

Born matrix elements known since the '90s

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 (2013) (also $\gamma\gamma + 3j$)

  BH collaboration:
  presented at RADCOR2013 , arXiv:1312.0592[hep-ph] , paper to appear

NLO calculations with BlackHat+SHERPA

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

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

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BlackHat used to compute the virtual (one-loop) contribution
Numerical implementation of on-shell methods for one-loop amplitudes

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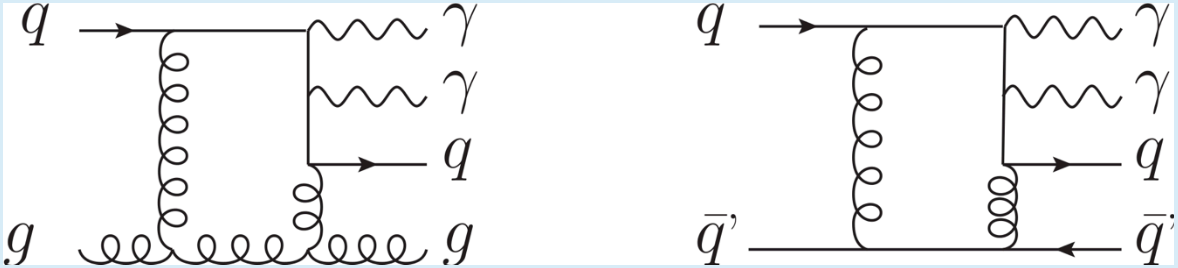

Examples of diagrams for the processes $qg \to \gamma\gamma q'g$ and $qq' \to \gamma\gamma qq'$.

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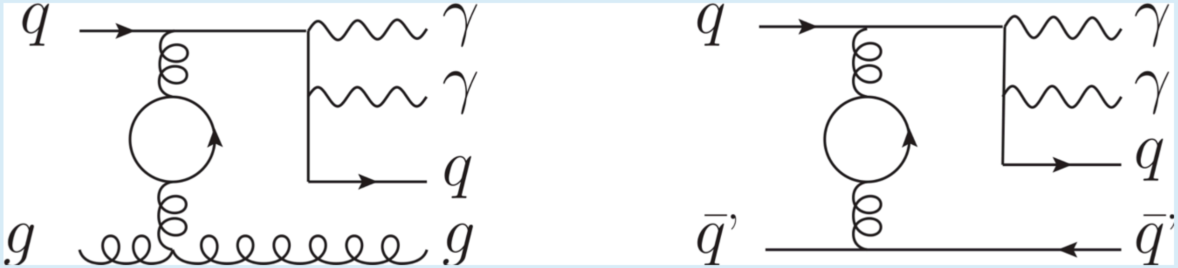

nf-term loop diagram:
closed fermion loop, but photons do not couple directly to it.

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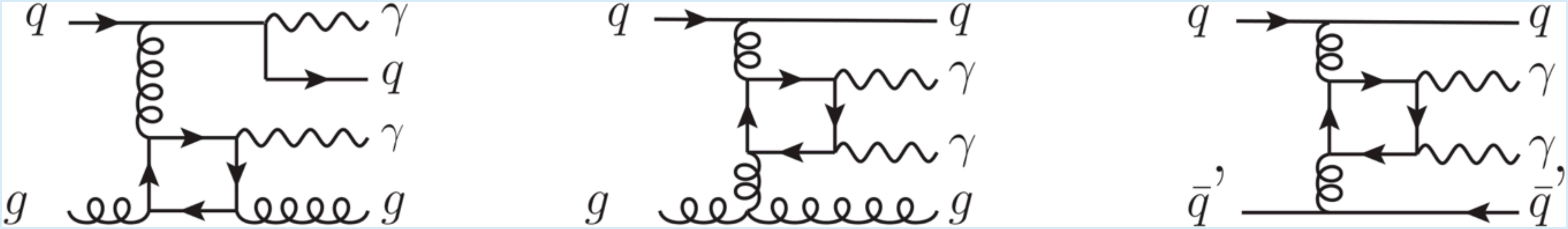

Charge-weighted fermion loop pieces:
closed fermion loop, at least one photon couples directly to it.

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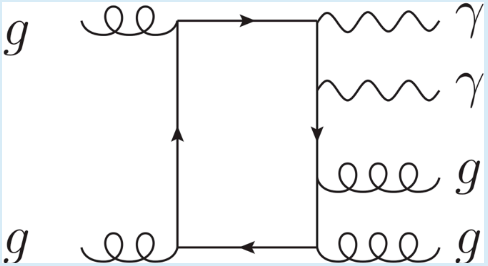

Light-by-light scattering contribution:
have no corresponding tree-level amplitudes and are finite.

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BlackHat used to compute the virtual (one-loop) contribution
Numerical implementation of on-shell methods for one-loop amplitudes

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	

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SHERPA (Höche,Krauss,Schönherr,Schumann,Siegert,Winter,Zapp)
used to manage the partonic subprocesses and to integrate over phase space.

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.

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

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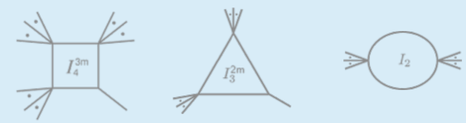

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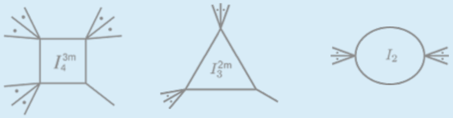

Integrals universal and well tabulated → Aim of the calculation is to compute coefficients and rational terms

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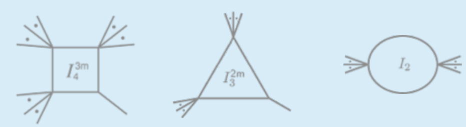

Integrals universal and well tabulated → Aim of the calculation is to compute coefficients and rational terms

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

$\mathrm{Rational}$ → On-shell Recursion; D-dimensional unitarity

BlackHat

1) BH computes *primitive amplitudes*:

Integrals given by analytic formulae.

- Coefficients: computed using contour integral at ∞ [D. Forde ('07)]
  The contour integrals are computed numerically
  by using a discrete Fourier sum

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

Coefficients reduce to products of trees.
Required tree amplitudes computed numerically (on-shell recursion relations).

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3) Sum of the loop-tree interference over colours (leading/subleading)

BlackHat-SHERPA *n*-tuples

One needs to be able to re-evaluate cross section and distributions with different choices of

- observables
- cuts
- jet algorithms
- PDF
- renormalization and factorization scales
- …

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In order to have small statistical uncertainty we need to compute hard matrix elements in million of different phase-space points.
This calculation is computationally very demanding.

SHERPA is used to create weighted events,
which are stored in ROOT n-tuples.

BlackHat-SHERPA *n*-tuples

BH-SHERPA n-tuple branches
id,
nparticle,
px, py, pz, E,
x1, x2,
x1p, x2p,
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fac_scale,
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me_wgt,
me_wgt2,
nuwgt,
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part

Changing the scale: Virtual contribution

$$
\begin{aligned}
w &= m \cdot f_1(\mathbf{id1}, \mathbf{x1}, \mu_F)\, f_2(\mathbf{id2}, \mathbf{x2}, \mu_F)\, \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} \\
m &= \mathbf{me\_wgt2} + l\, \mathbf{usr\_wgts}[0] + \frac{l^2}{2} \mathbf{usr\_wgts}[1] \\
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\end{aligned}
$$

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

Photon isolation criterion

We are interested in photons which originated in the hard interaction.

Must isolate photons from surrounding hadronic radiation.

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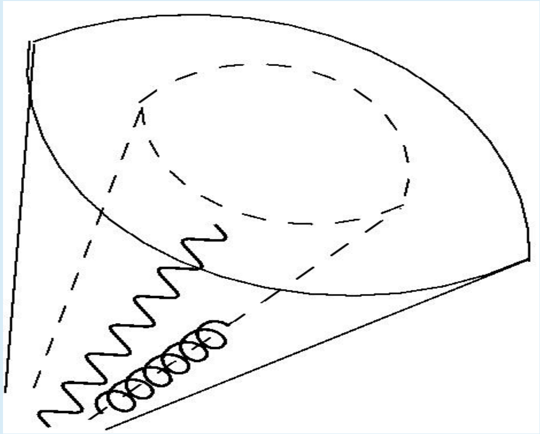
We use Frixione isolation: radially-dependent E_T limit [Frixione, 1998]

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

($\epsilon = 0.5$, $\delta_0 = 0.4$, $n = 1$)

The dependence on the parameters n and ϵ typically weak.



$\gamma\gamma$+2j with BlackHat

Approximations: No top-contributions,
the other five quarks treated as massless

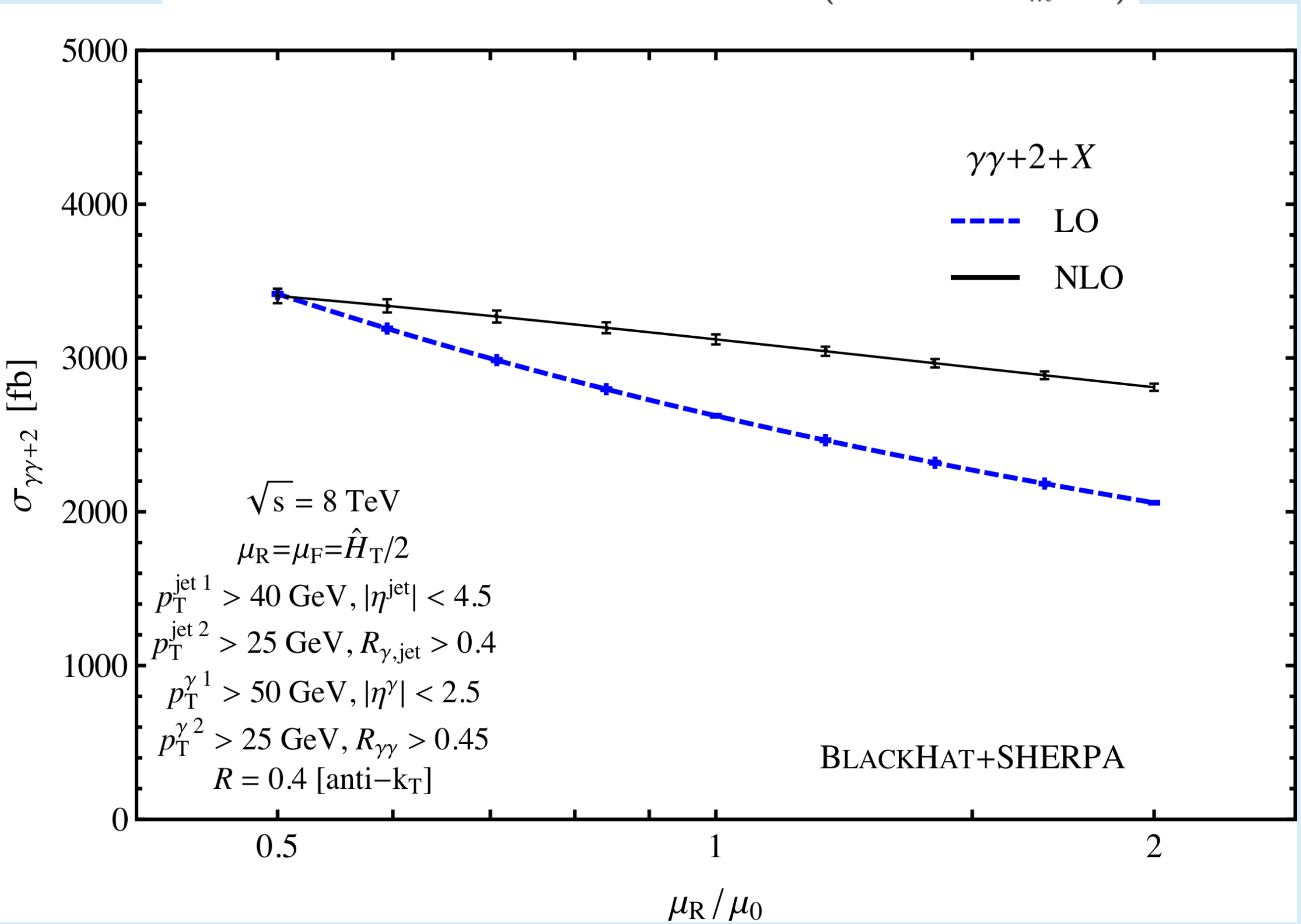
$\gamma\gamma$ + 0-jet:
confirmed HELAC (PS points) and MCFM (PS points & after integration)

$\gamma\gamma$ + 1-jet: confirmed GoSam (PS points & after integration)
$\gamma\gamma$qqg also confirmed against previous analytic calculation (L. Dixon)

$\gamma\gamma$ + 2-jet: confirmed GoSam (PS points)
total cross section confirmed against Gehrmann, Greiner, Heinrich

γγ+jets (incl.) @ LO&NLO : cross sections

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



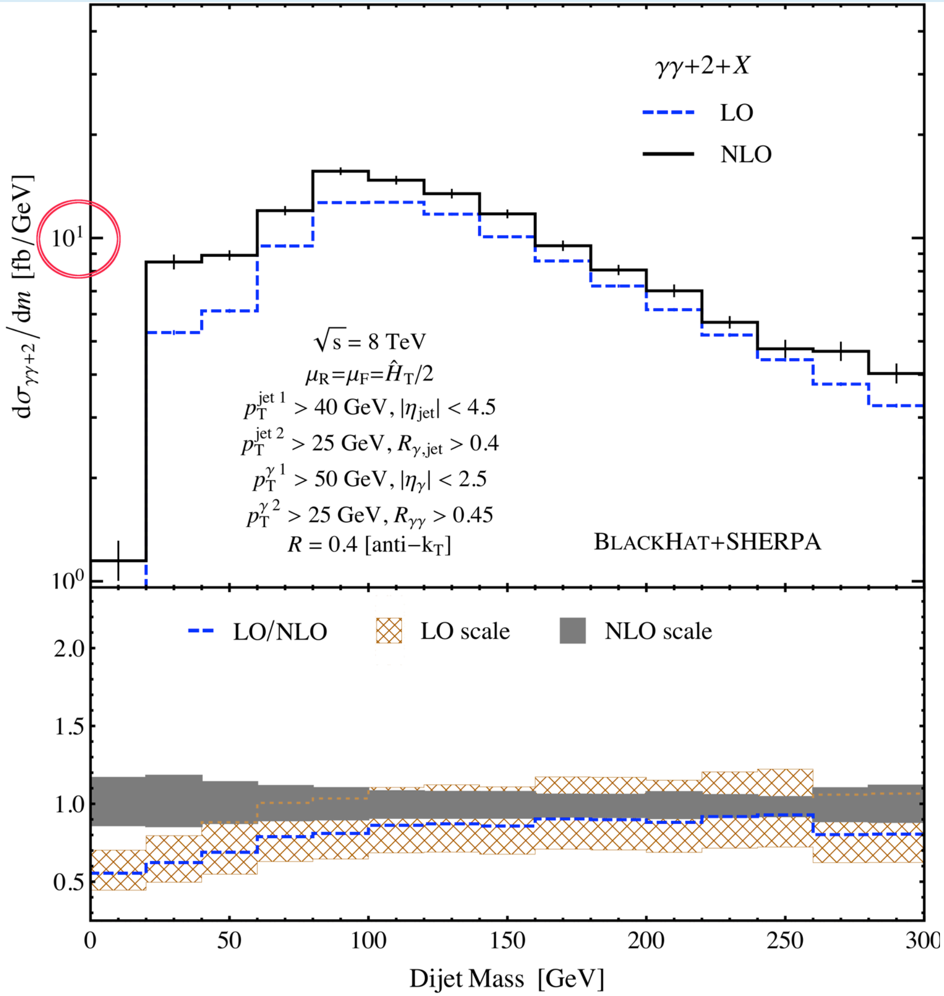
γγ+2jet production: modest NLO correction

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

Dijet invariant mass distributions

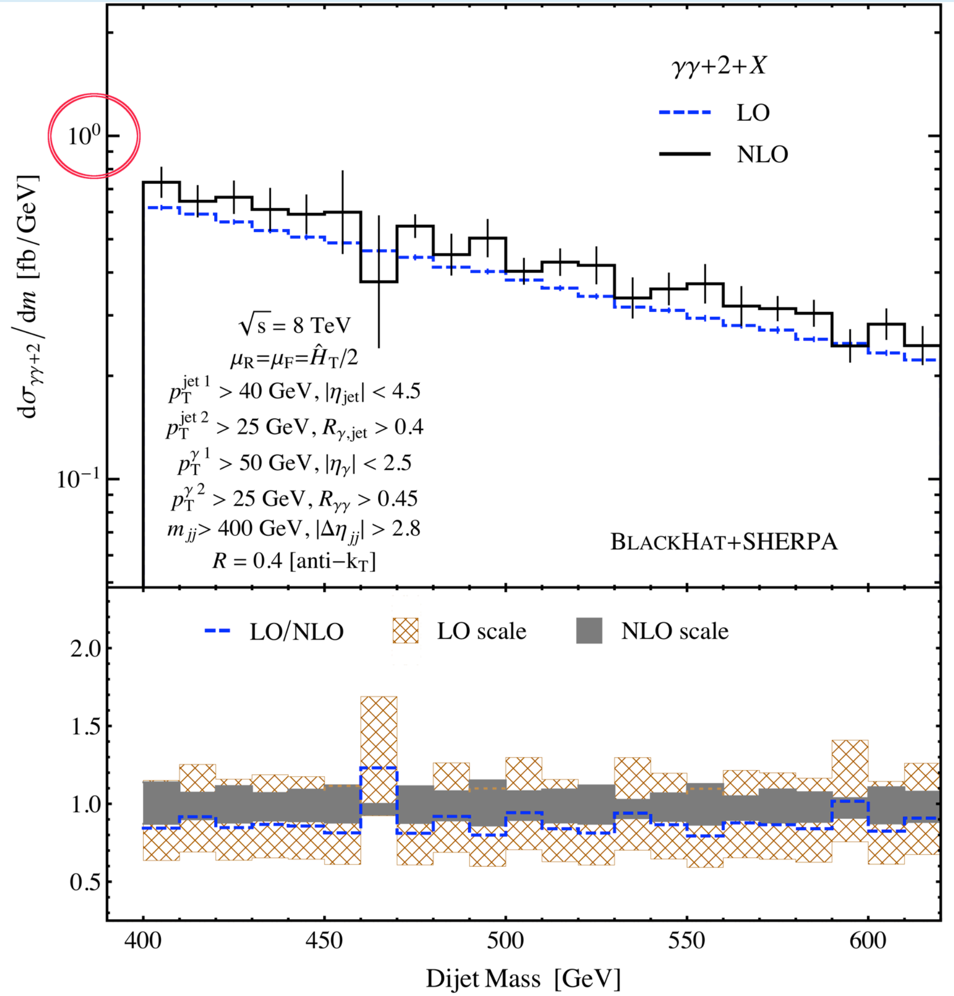
$$\mathrm{PDF} = \mathrm{MSTW}(2008)\,, \qquad \mu_0 = \frac{1}{2}\left(p_T^{\gamma_1} + p_T^{\gamma_2} + \sum_m p_T^m\right)$$

Without VBF cuts



With VBF cuts

$$\left(M_{jj} > 400\ \mathrm{GeV}\,, \qquad \Delta\eta_{jj} > 2.8\right)$$



Diphoton Rapidity distribution – ATLAS cuts

$$\mathrm{PDF} = \mathrm{MSTW(2008)}\,, \qquad \mu_0 = \frac{1}{2}\left(p_T^{\gamma_1} + p_T^{\gamma_2} + \sum_m p_T^m\right)\,, \qquad 122 \le m_{\gamma\gamma} \le 130 \;\; \mathrm{GeV},$$

Without VBF cuts

With VBF cuts

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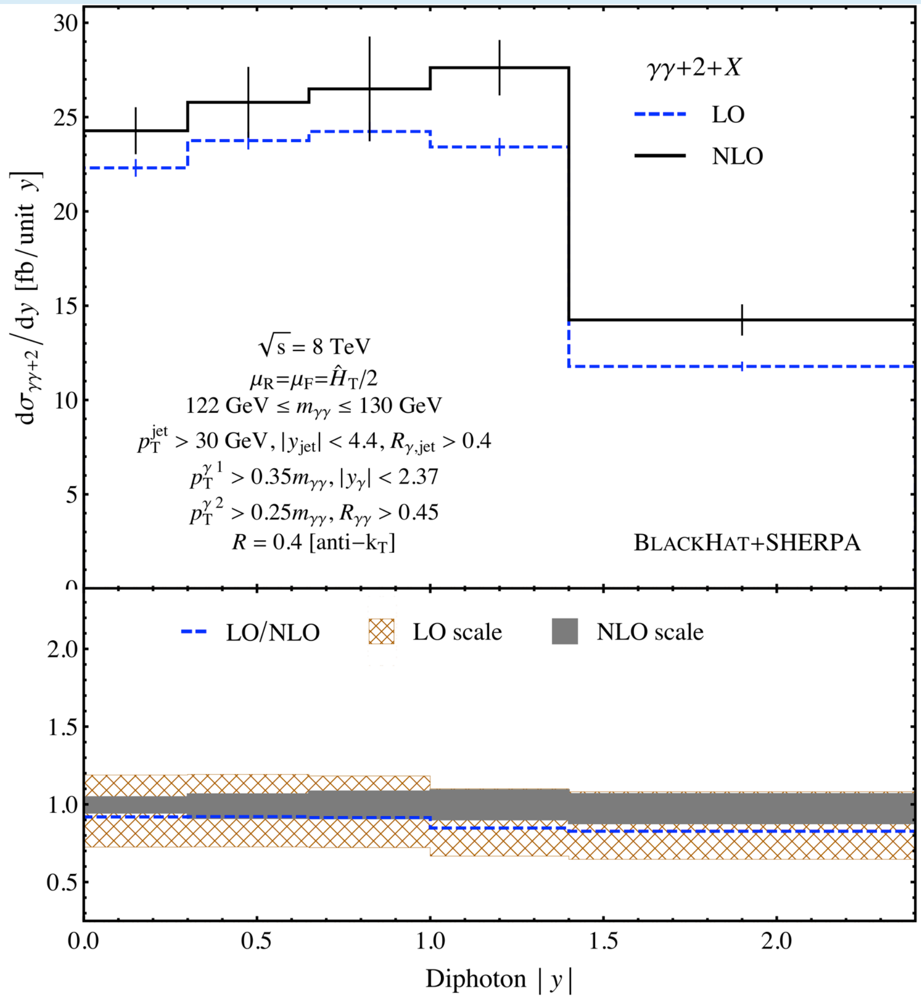

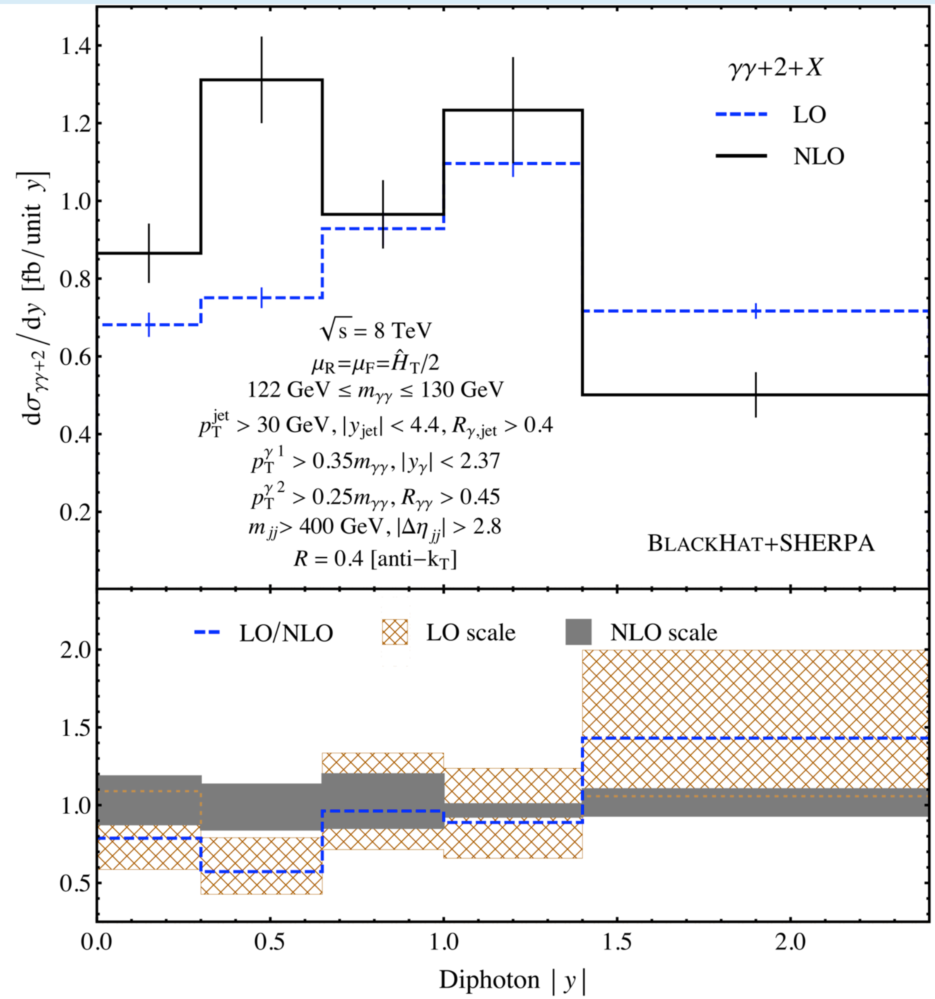

$|\Delta\phi_{jj}|$ distribution – ATLAS cuts

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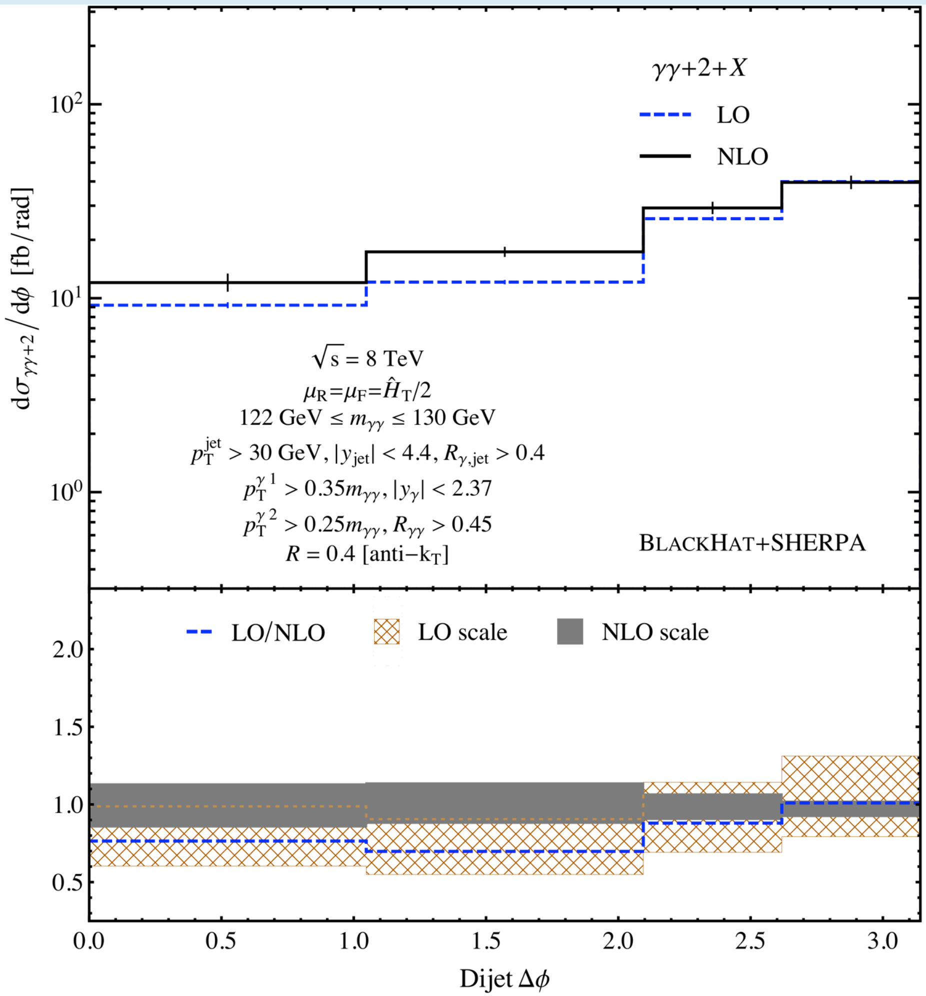

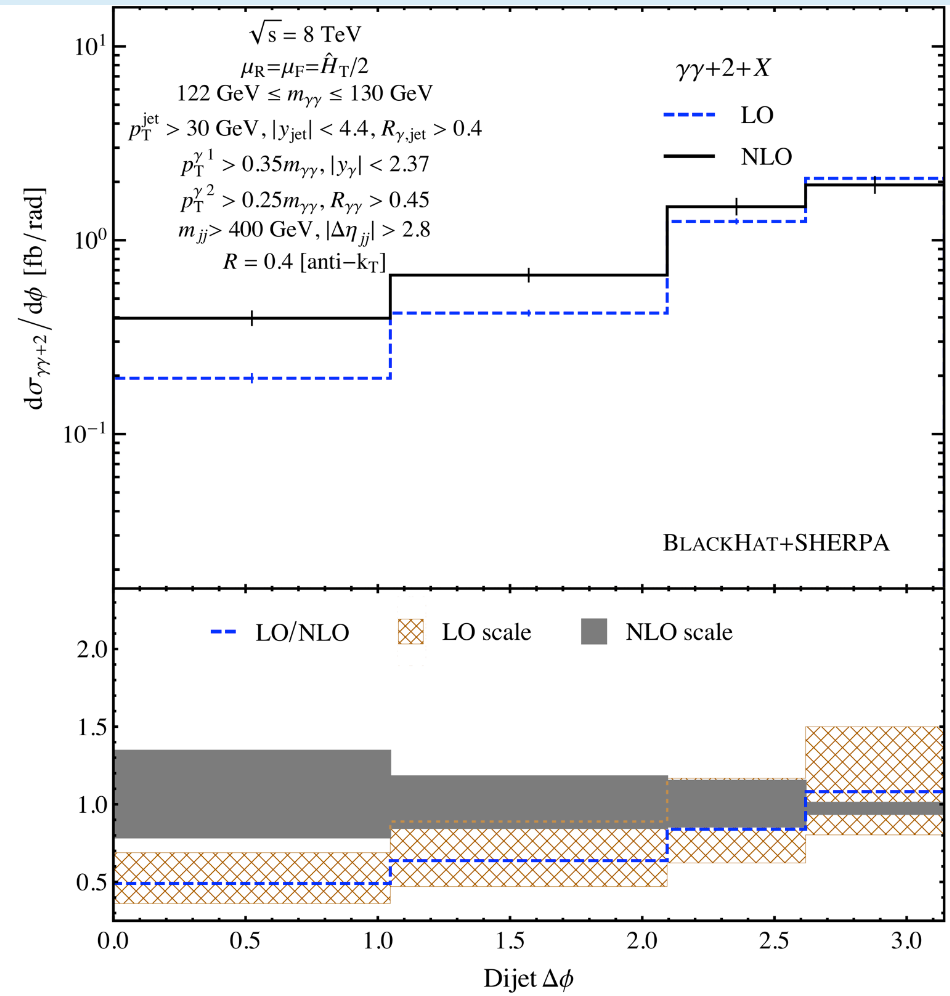

Summary

- We have presented a full NLO calculation for $pp\rightarrow\gamma\gamma+2jets$

- We have included the one loop $gg\rightarrow\gamma\gamma gg$ contribution

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

- We have considered total cross sections and distributions with and without 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!

Backup slides

BlackHat-SHERPA *n*-tuples

We split the calculation in parts B, I, RS, V (subsequently spit 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

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

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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

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Changing the scale: Born and Real contribution

$$w = \mathbf{me\_wgt2} \cdot f_1(\mathbf{id1}, \mathbf{x1}, \mu_F)\, f_2(\mathbf{id2}, \mathbf{x2}, \mu_F)\, \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n}$$

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Changing the scale: Virtual contribution

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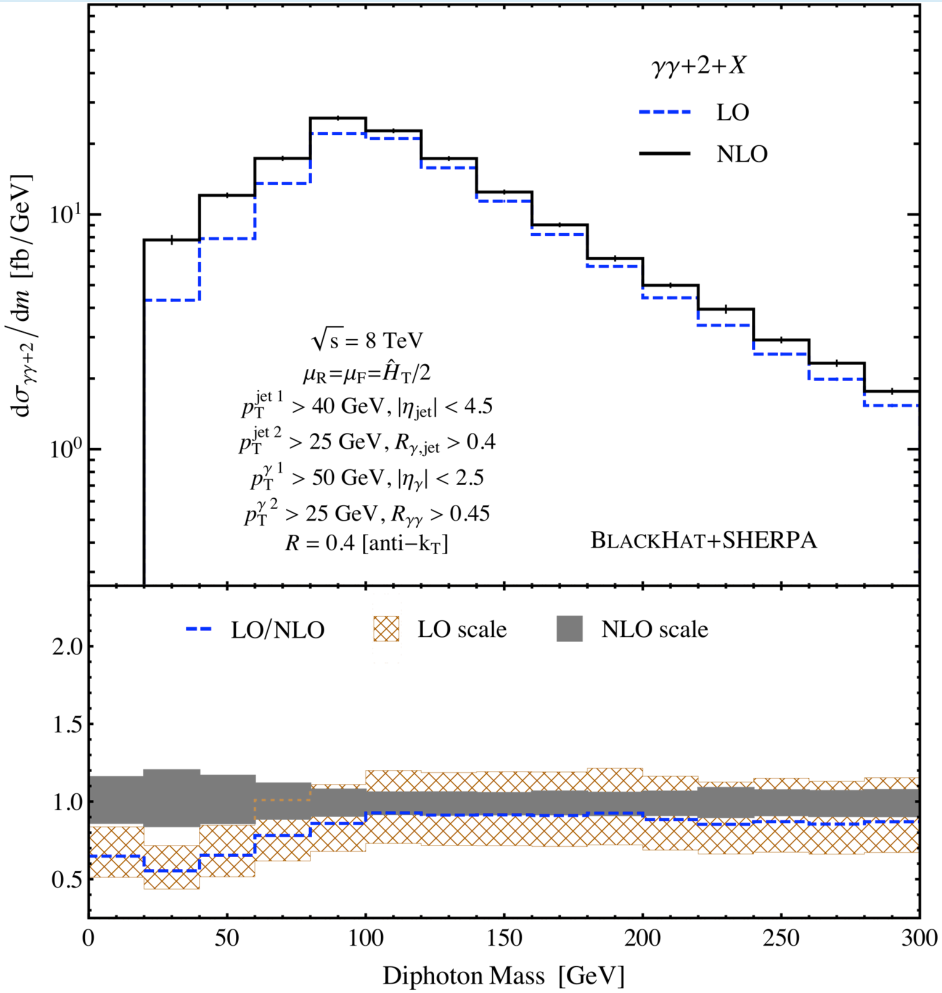
Changing the scale: Integrated subtraction contribution

$$
\begin{aligned}
w &= m \cdot \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} \\
m &= \omega_0 \cdot f_1(\mathbf{id1}, \mathbf{x1}, \mu_F)\, f_2(\mathbf{id2}, \mathbf{x2}, \mu_F) \\
&\quad + \left(f_{1,a}^1 \omega_1 + f_{1,a}^2 \omega_2 + f_{1,a}^3 \omega_3 + f_{1,a}^4 \omega_4\right) f_{2,b}(x_b) \\
&\quad + \left(f_{2,b}^5 \omega_1 + f_{2,b}^6 \omega_2 + f_{2,b}^7 \omega_3 + f_{2,b}^8 \omega_4\right) f_{1,a}(x_a) \\
\omega_0 &= \mathbf{me\_wgt2} + l\, \mathbf{usr\_wgts}[0] + \frac{l^2}{2} \mathbf{usr\_wgts}[1] \\
l &= \ln\left(\frac{\mu_R^2}{\mathbf{ren\_scale}^2}\right) \\
\omega_i &= \mathbf{usr\_wgts}[i+1] + \mathbf{usr\_wgts}[i+9] \ln\left(\frac{\mu_F^2}{\mathbf{fac\_scale}^2}\right)
\end{aligned}
$$

Diphoton invariant mass distributions

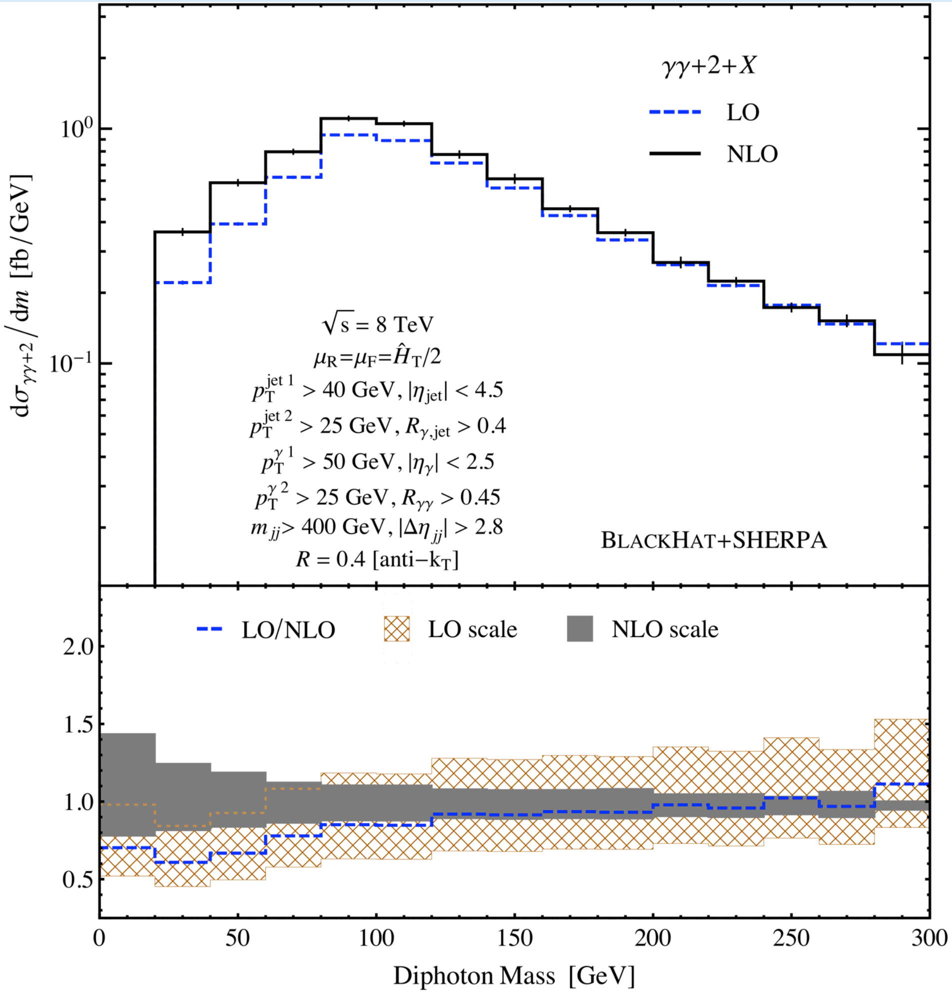
$$\mathrm{PDF} = \mathrm{MSTW(2008)}\,, \qquad \mu_0 = \frac{1}{2}\left(p_T^{\gamma_1} + p_T^{\gamma_2} + \sum_m p_T^m\right)$$

Without VBF cuts



With VBF cuts

$$\left(M_{jj} > 400\ \mathrm{GeV}\,, \qquad \Delta\eta_{jj} > 2.8\right)$$



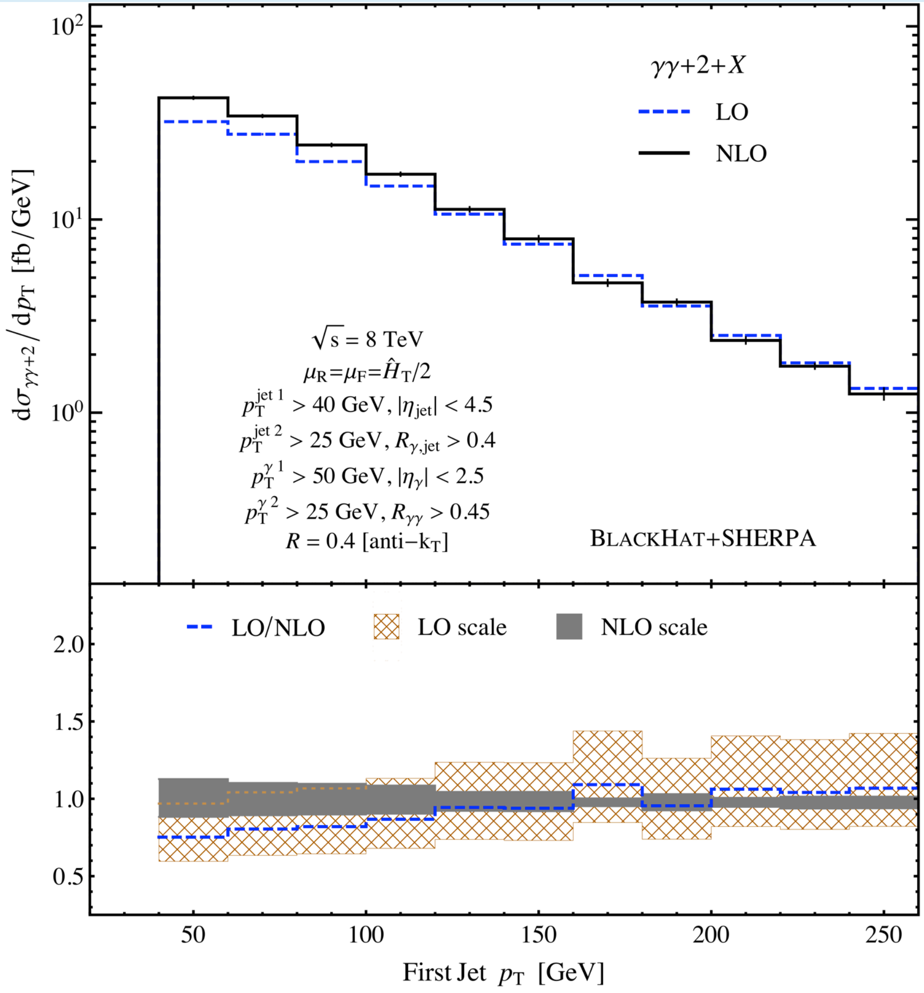
Leading jet p_{T} distributions

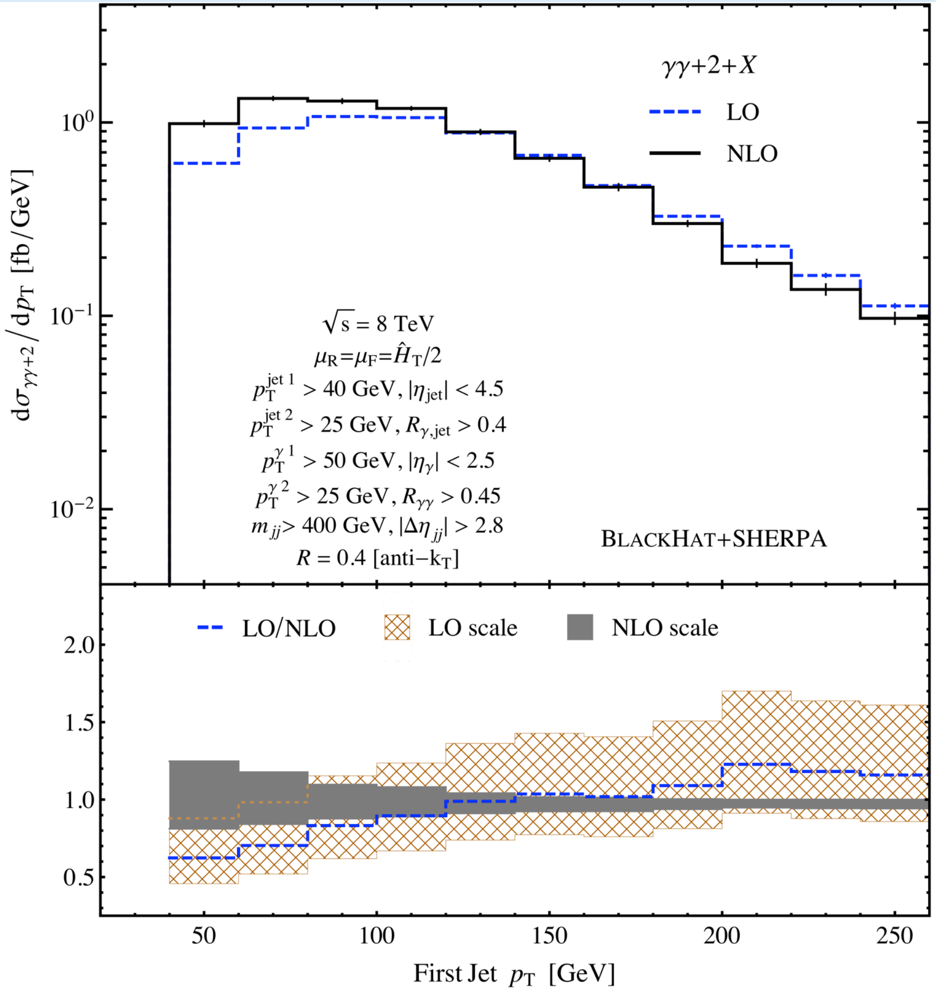
$$\mathrm{PDF} = \mathrm{MSTW}(2008)\,, \qquad \mu_0 = \frac{1}{2}\left(p_T^{\gamma_1} + p_T^{\gamma_2} + \sum_m p_T^m\right)$$

Without VBF cuts

With VBF cuts

$$\left(M_{jj} > 400\ \mathrm{GeV}\,, \qquad \Delta\,\eta_{jj} > 2.8\right)$$





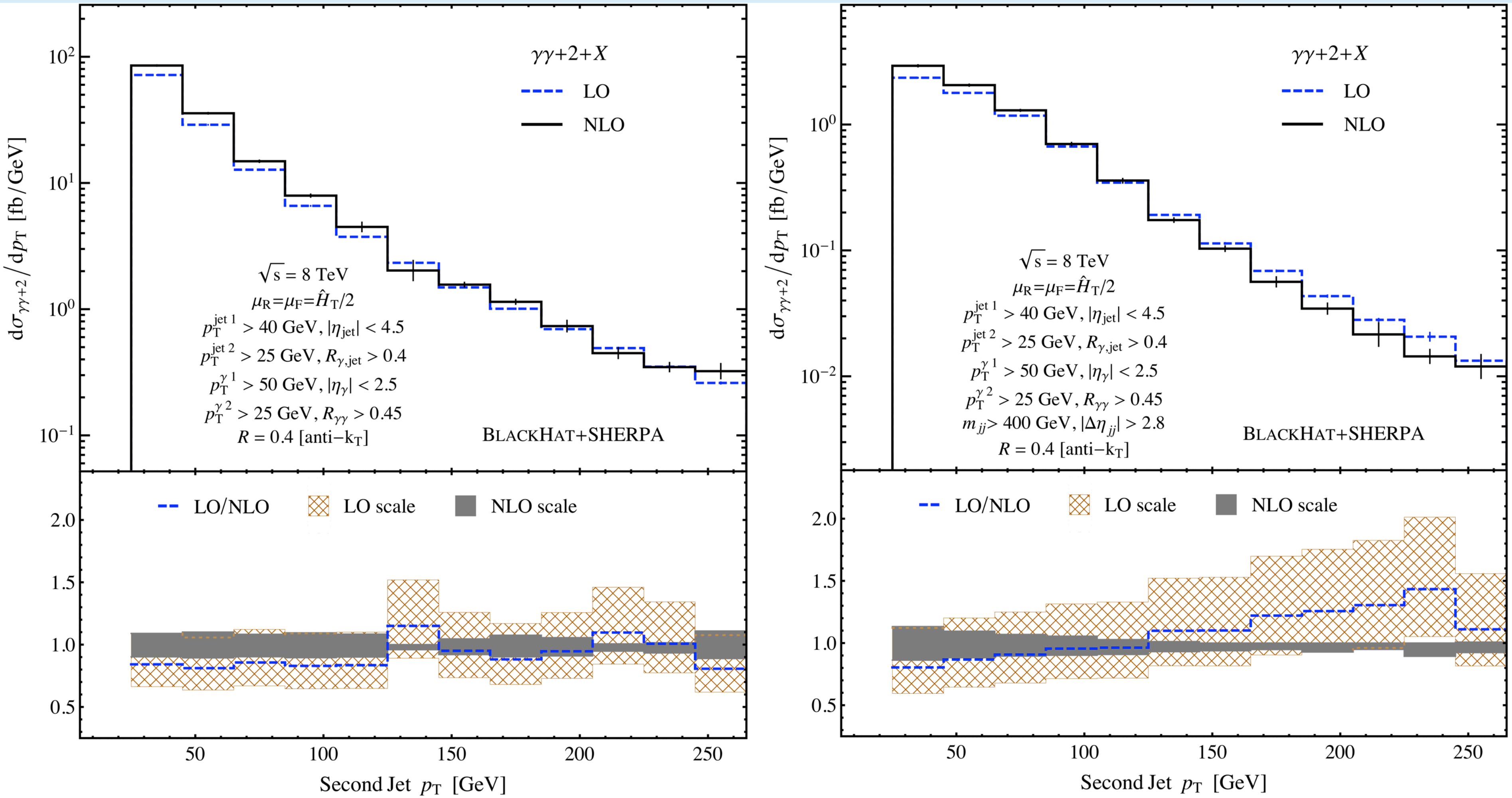
Second jet p_T distributions

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

Without VBF cuts

With VBF cuts

$$\left(M_{jj} > 400\ \mathrm{GeV}, \qquad \Delta\eta_{jj} > 2.8\right)$$



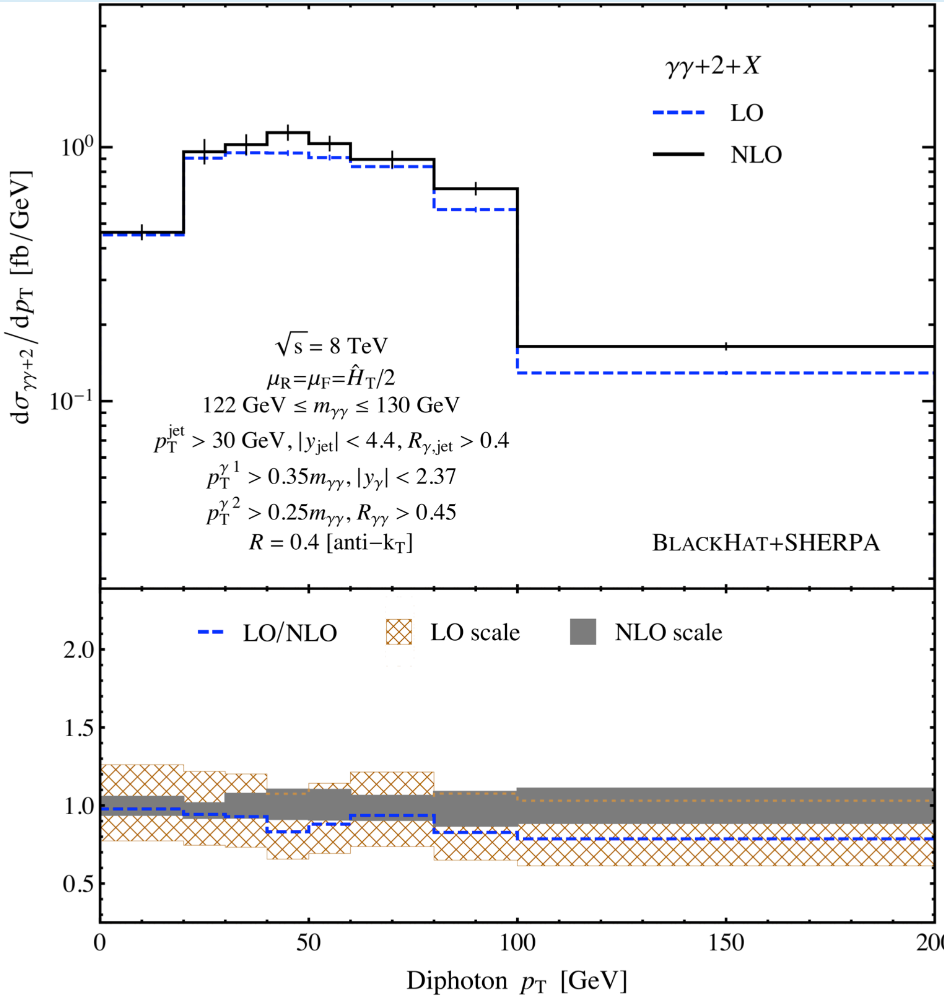
Diphoton p_T distribution – ATLAS cuts

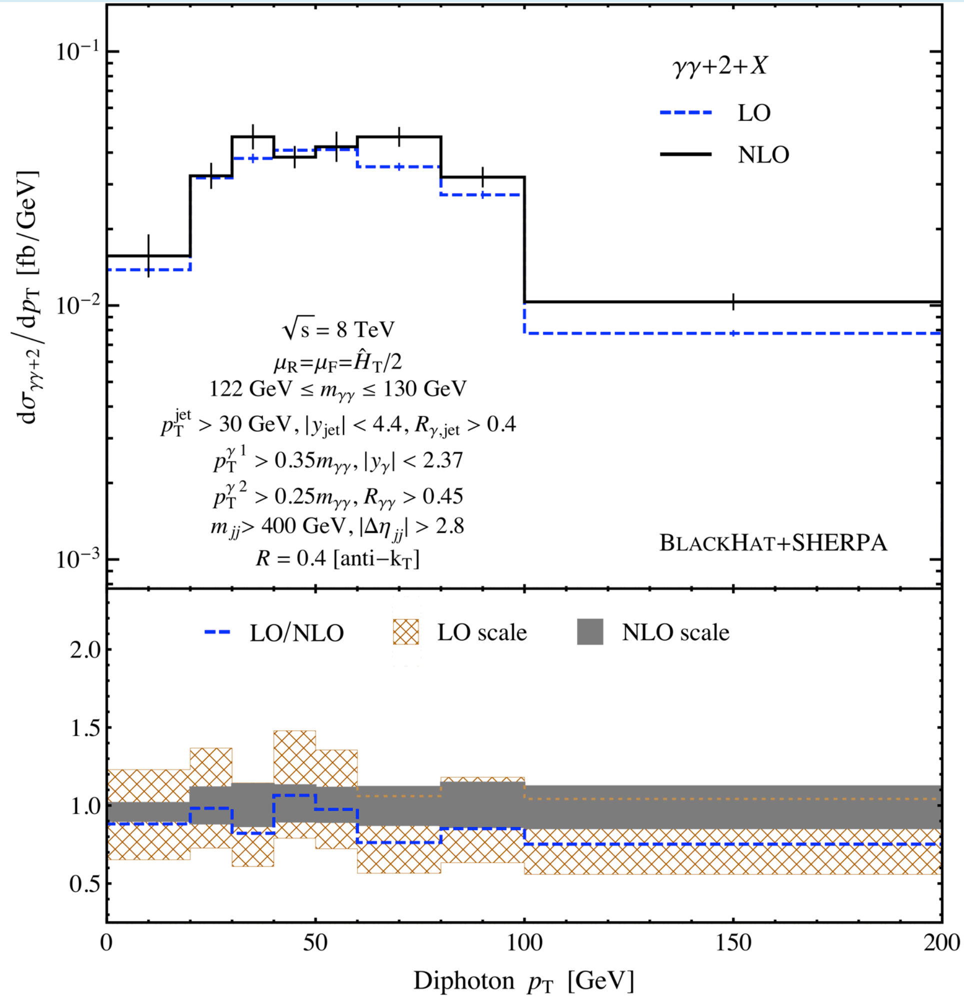
$$\text{PDF} = \text{MSTW(2008)}, \qquad \mu_0 = \frac{1}{2}\left(p_T^{\gamma_1} + p_T^{\gamma_2} + \sum_m p_T^m\right), \qquad 122 \le m_{\gamma\gamma} \le 130 \ \text{GeV},$$

Without VBF cuts

With VBF cuts

$$\left(M_{jj} > 400 \ \text{GeV}, \qquad \Delta\eta_{jj} > 2.8\right)$$





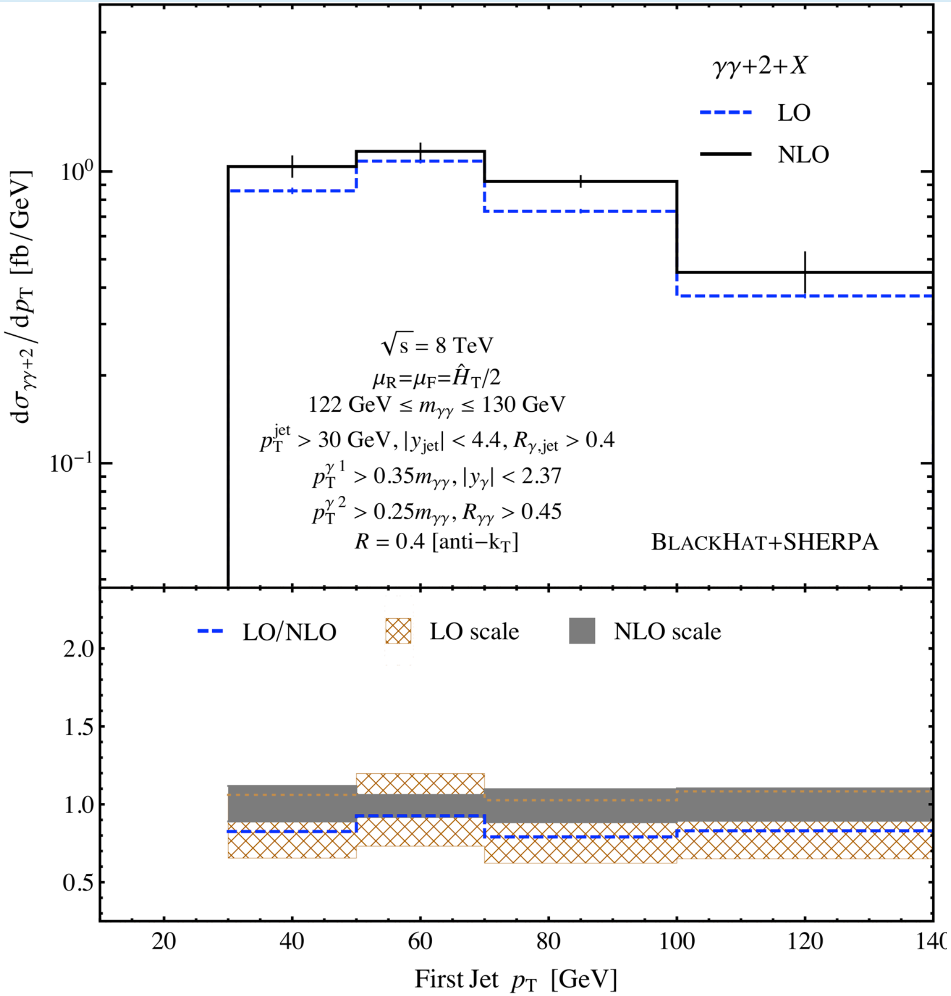
Leading jet p_T distributions – ATLAS cuts

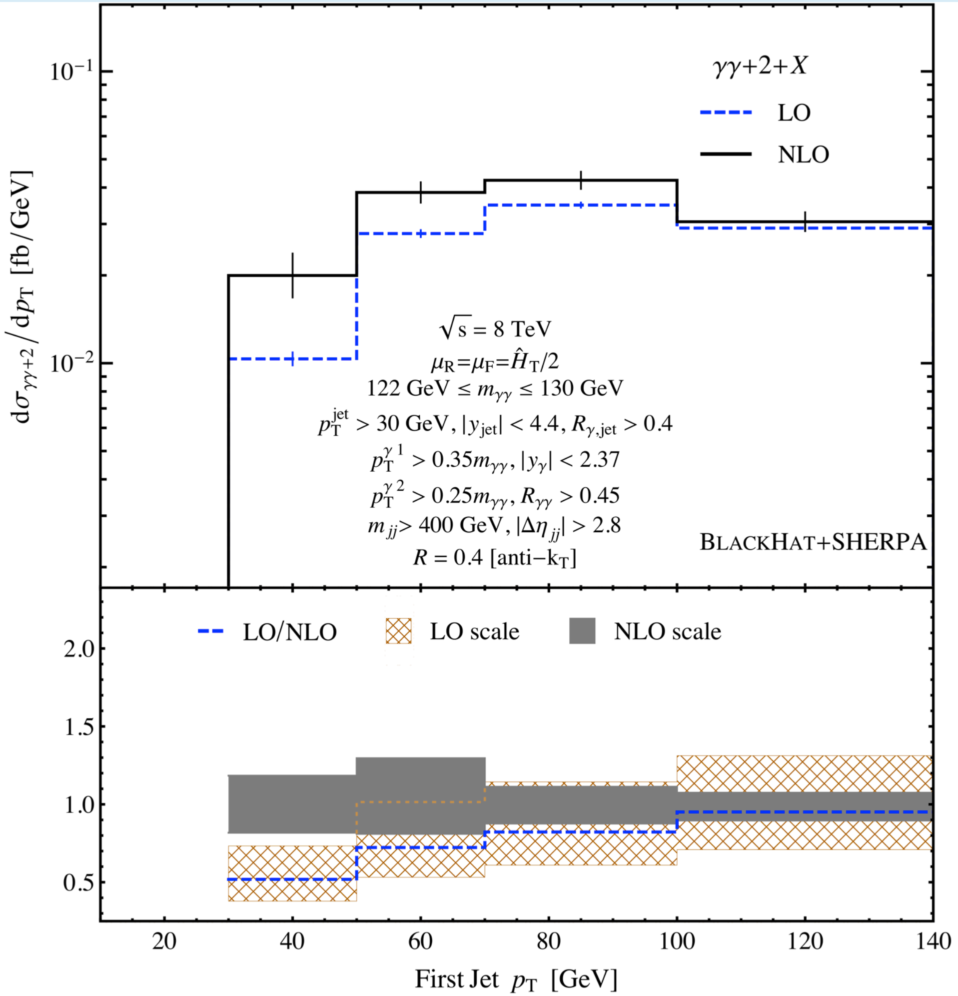
$$\text{PDF} = \text{MSTW}(2008)\,, \qquad \mu_0 = \frac{1}{2}\left(p_T^{\gamma_1} + p_T^{\gamma_2} + \sum_m p_T^m\right)\,, \qquad 122 \leq m_{\gamma\gamma} \leq 130 \;\; \text{GeV},$$

Without VBF cuts

With VBF cuts

$$\left(M_{jj} > 400 \text{ GeV}\,, \qquad \Delta\,\eta_{jj} > 2.8\right)$$





Frixione epsilon dependence

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