Diphoton + 2jets production at NLO

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on behalf of the BlackHat Collaboration

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$\gamma\gamma$+2j @ NLO

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

Born matrix element and real emission corrections known since '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)
  BH collaboration: to appear

NLO calculations with BlackHat+Sherpa

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

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

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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BlackHat used to compute the virtual (one-loop) contribution

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

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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	

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.

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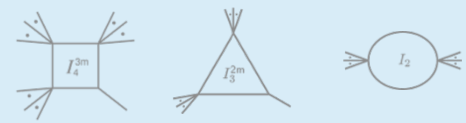

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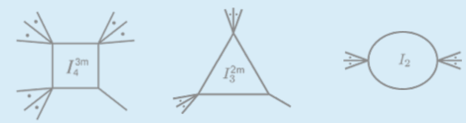

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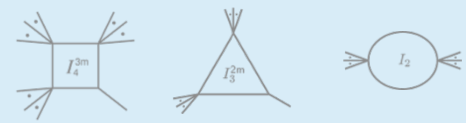

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c_j → Unitarity in D=4 : rational functions of spinors.

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

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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

Must isolate photons from surrounding hadronic radiation.
We use Frixione cone: radially-dependent E_T limit

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

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

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$\gamma\gamma$ + 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)

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

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

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

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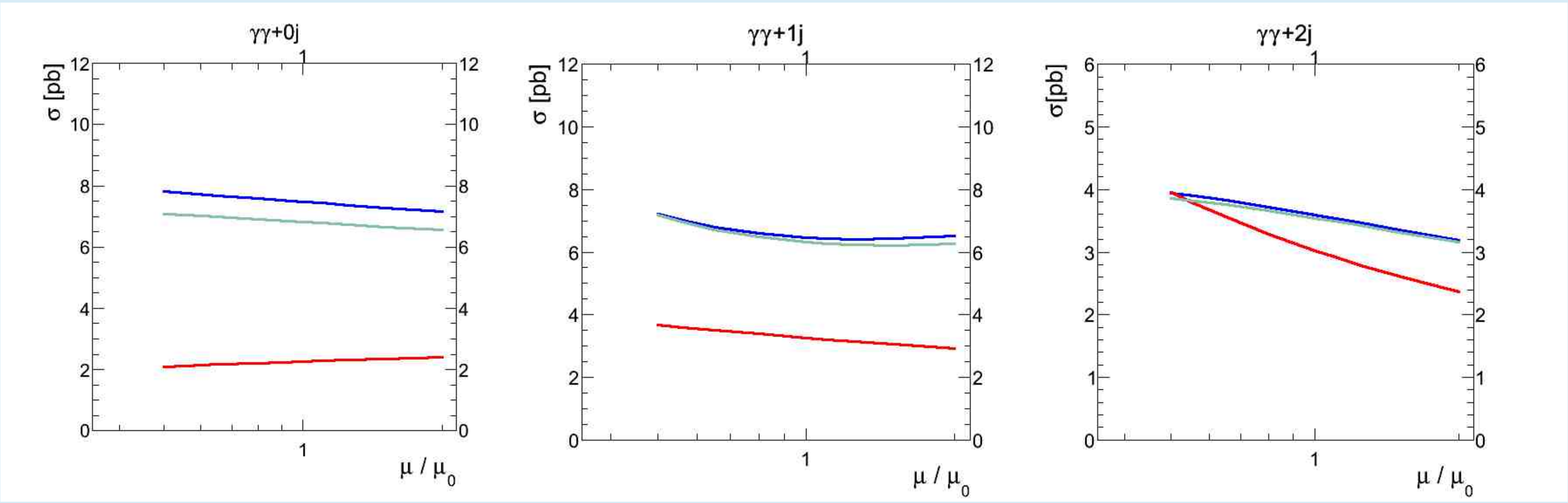

LO, NLO, NLO+(*gg*→γγ+n *g*)

γγ+2jet production: modest NLO correction

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

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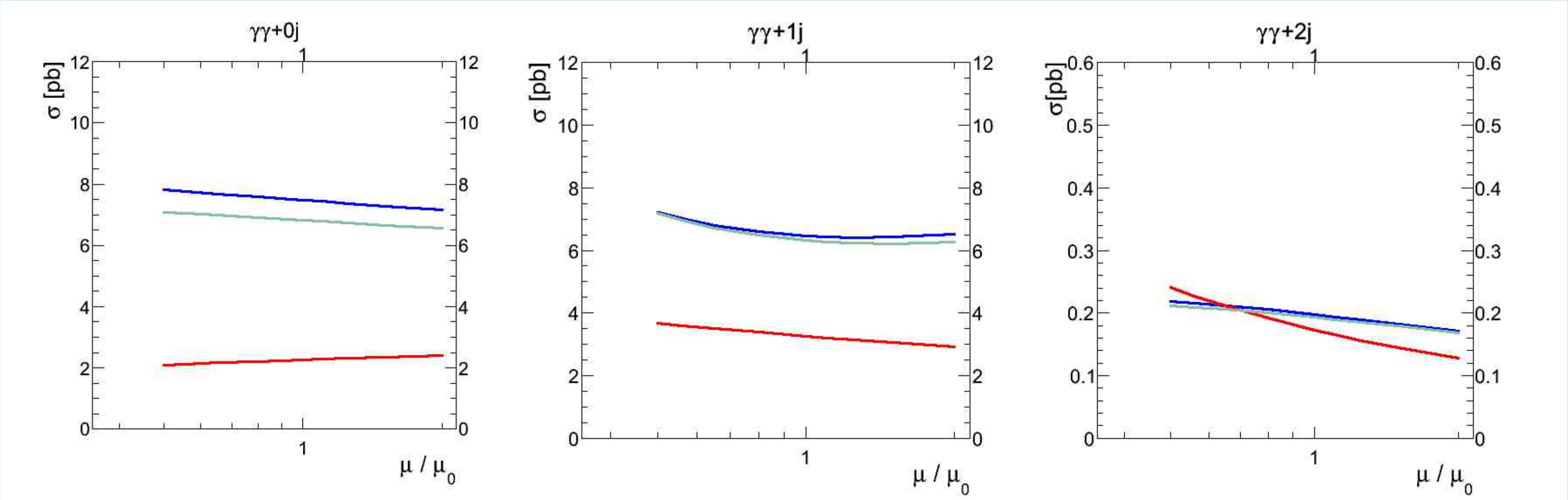

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Leading Jet's p_T-distribution

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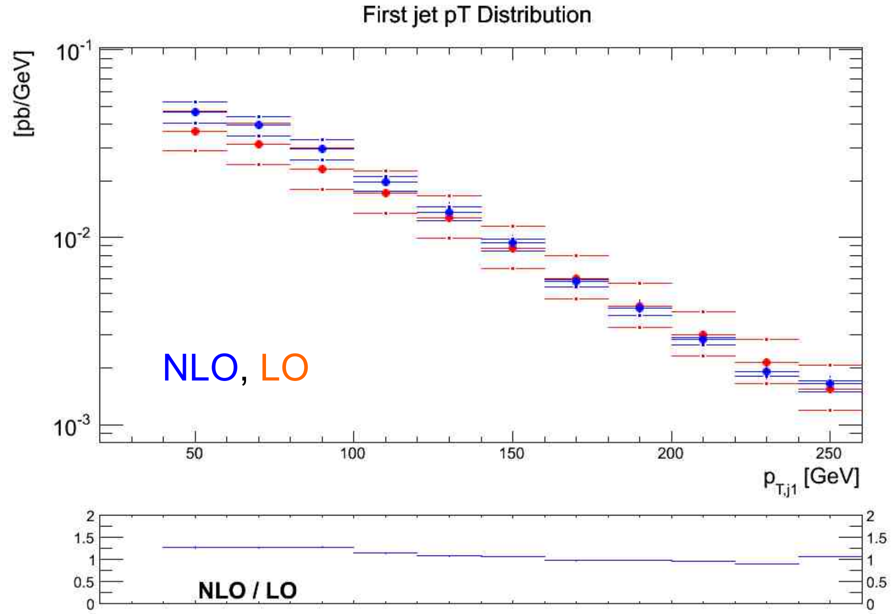
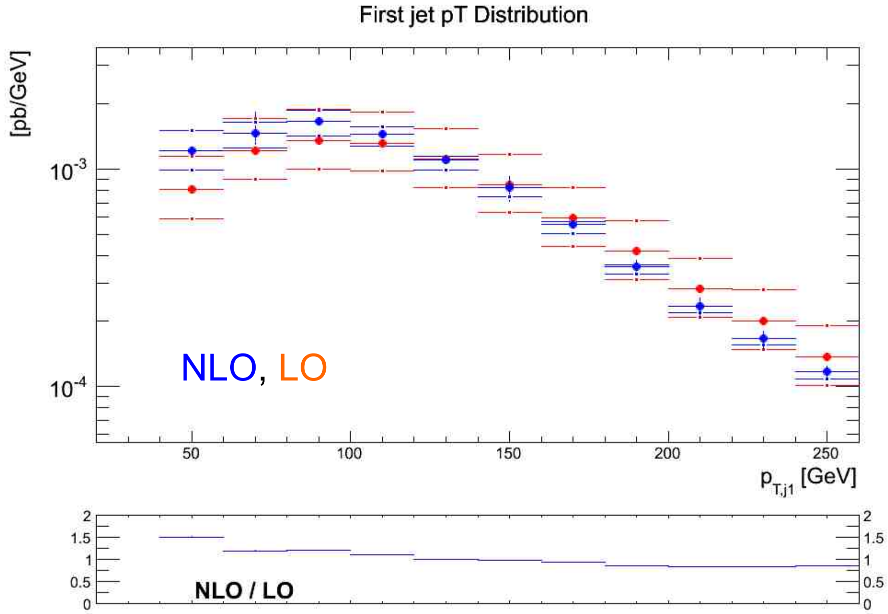
Without VBF cuts

With VBF cuts





Dijet invariant mass distributions

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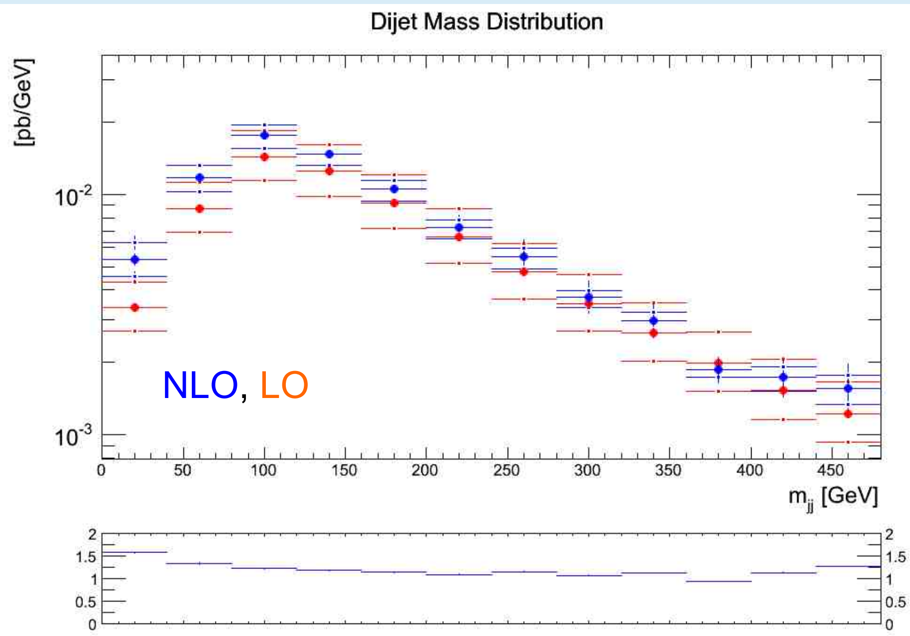

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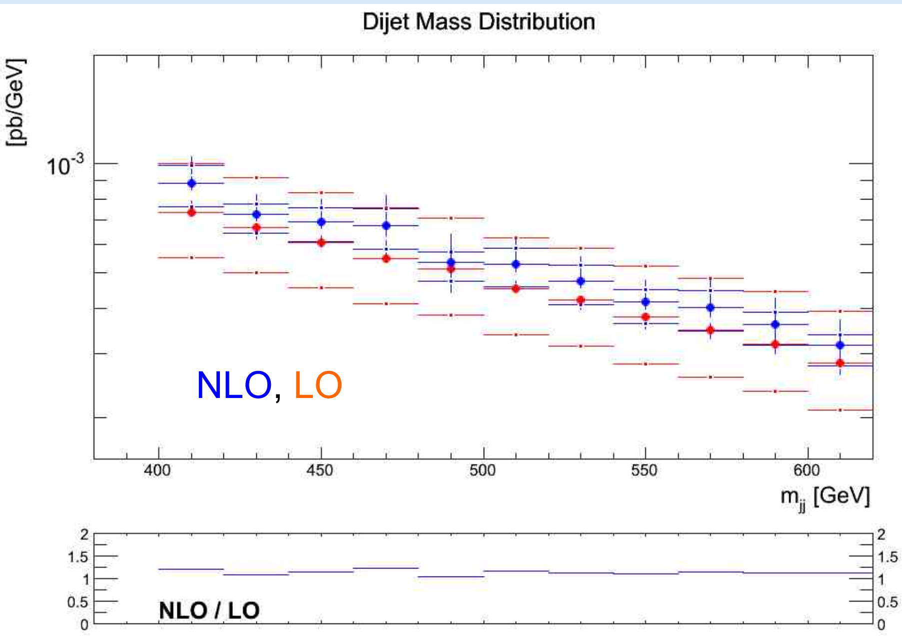

Diphoton invariant mass distributions

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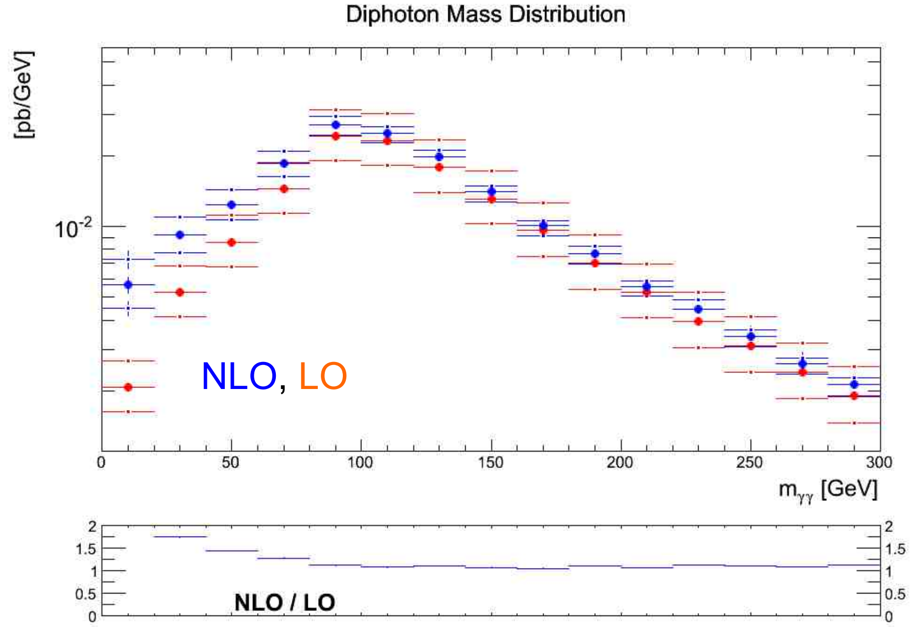

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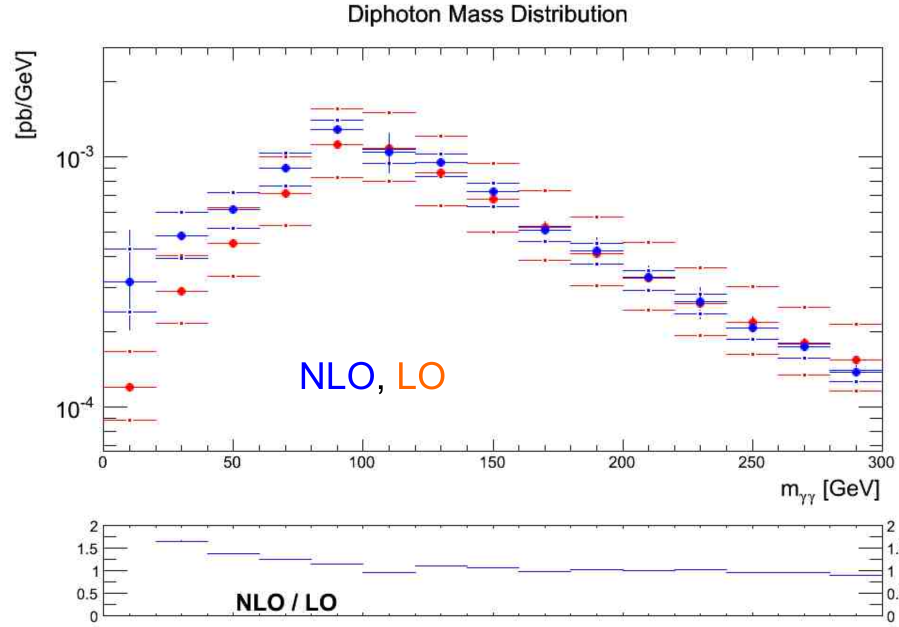

Large NLO correction for low values of diphoton mass.

Diphoton Rapidity distribution – altern. cuts

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$$p_T^{\gamma_1} > 0.35\,m_{\gamma\gamma}, \qquad p_T^{\gamma_2} > 0.25\,m_{\gamma\gamma}, \qquad |\eta^\gamma| < 2.37, \qquad |\eta^{\text{jet}}| < 4.4,$$
$$p_T^{\text{jets}} > 30\text{ GeV}, \qquad 122 \leq m_{\gamma\gamma} \leq 130\text{ GeV}, \qquad \left(M_{jj} > 400\text{ GeV}, \qquad \Delta\,\eta_{jj} > 2.8\right)$$

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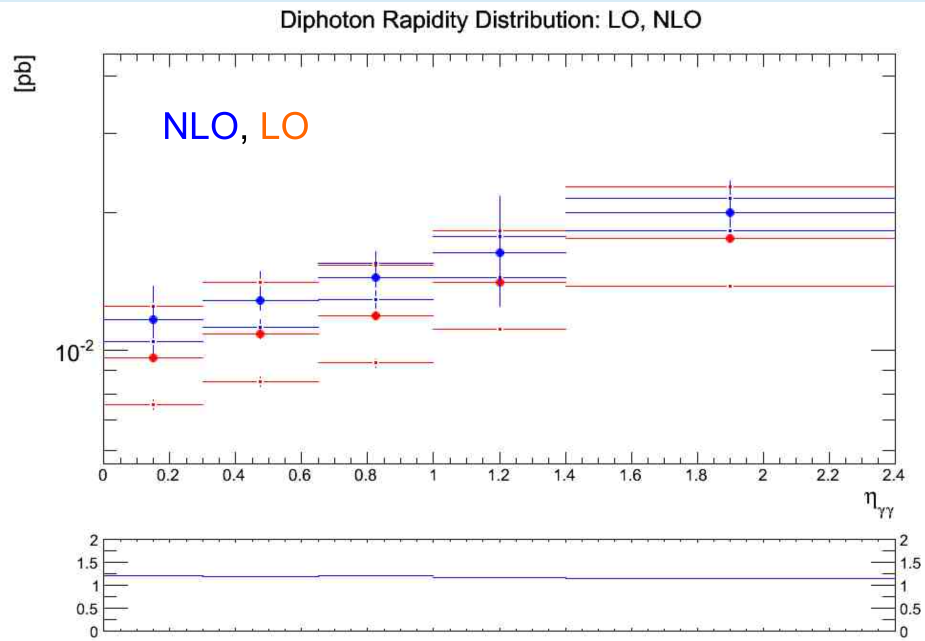

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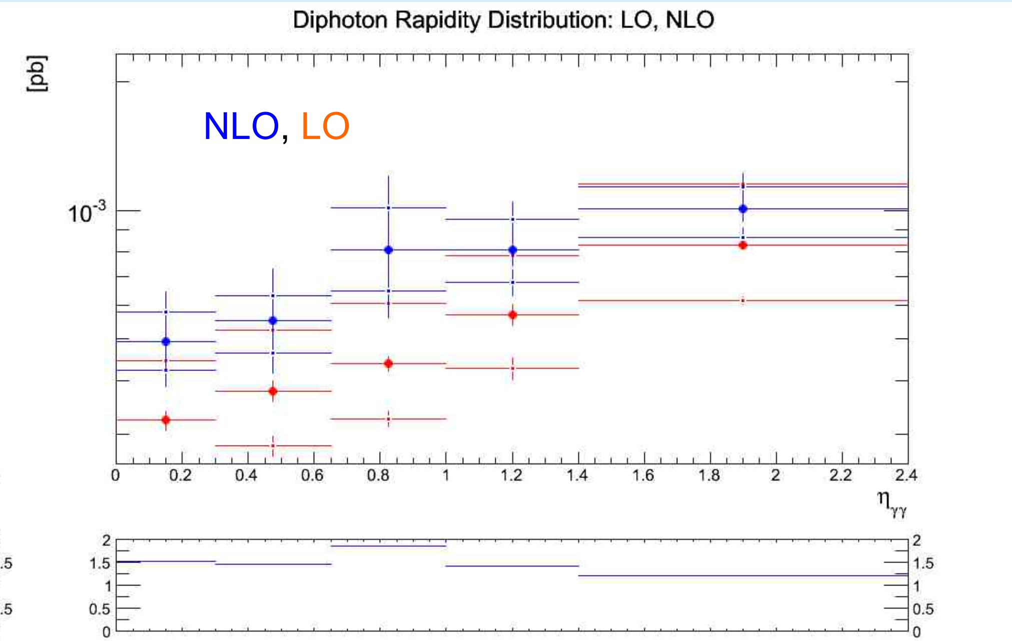

Large NLO correction for small values of η, especially after VBF cuts

$|\Delta\phi_{jj}|$ distribution – altern. cuts

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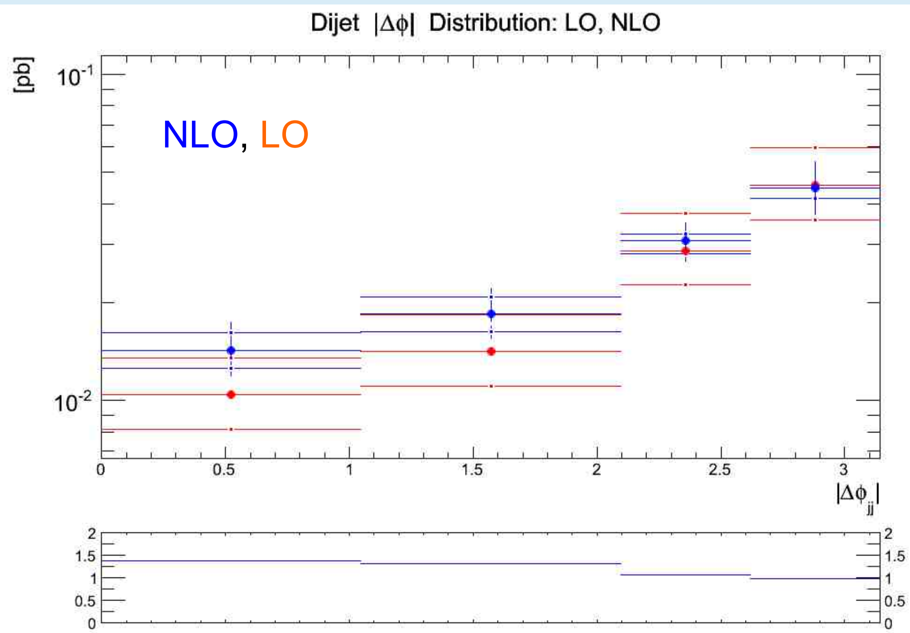

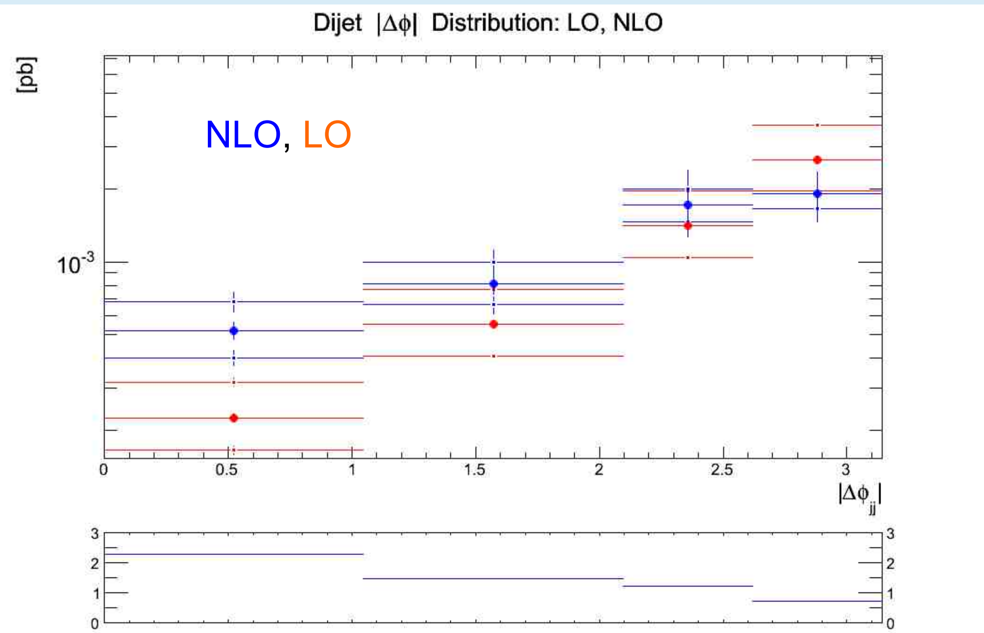

Large NLO correction for small values of $\Delta\phi$, especially after VBF cuts

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

Outlook:
- dependence on Frixione cone's parameters (or other isolation criteria)
- estimate effect of including top-quark loops
- …

Backup slides

Leading photon's pT-distributions

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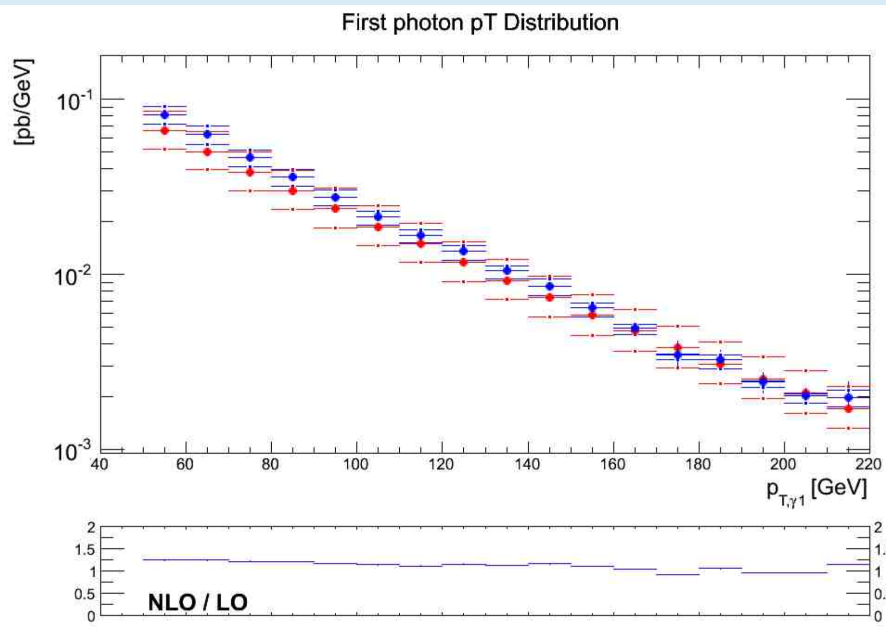

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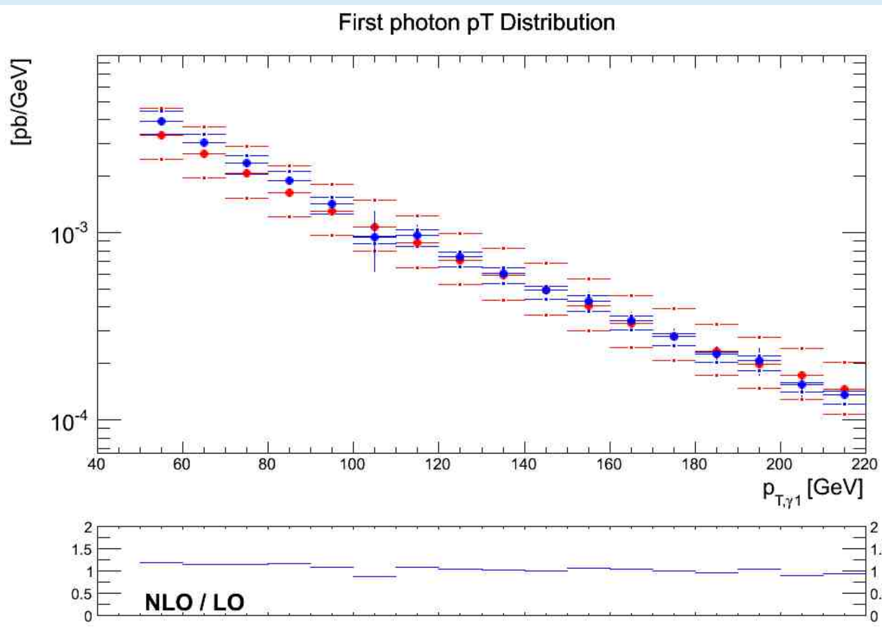

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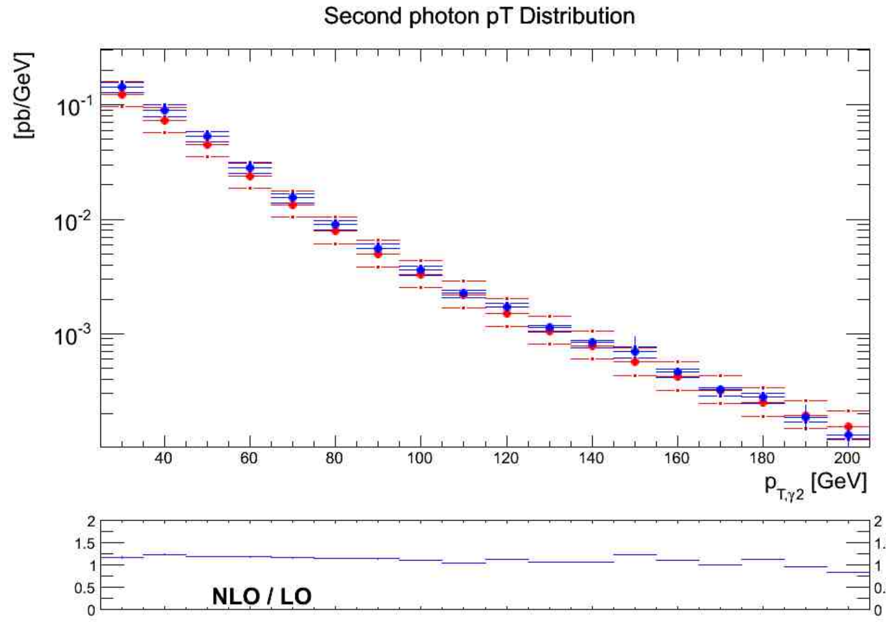

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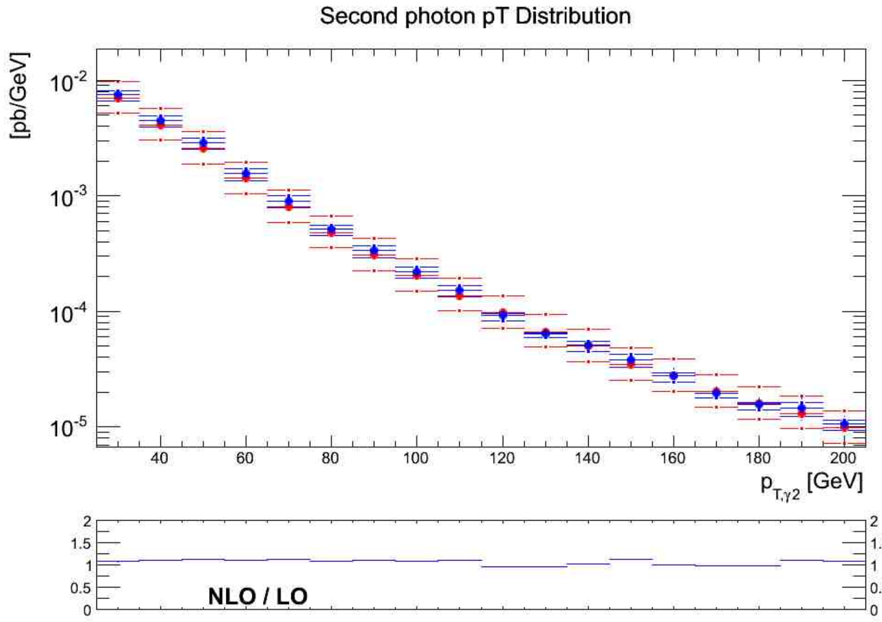

Alternative cuts

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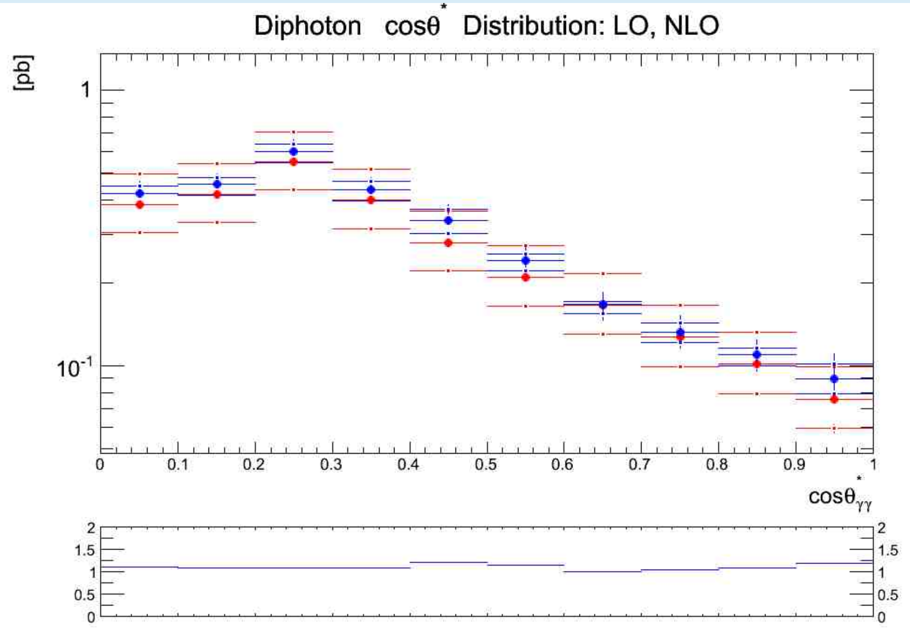
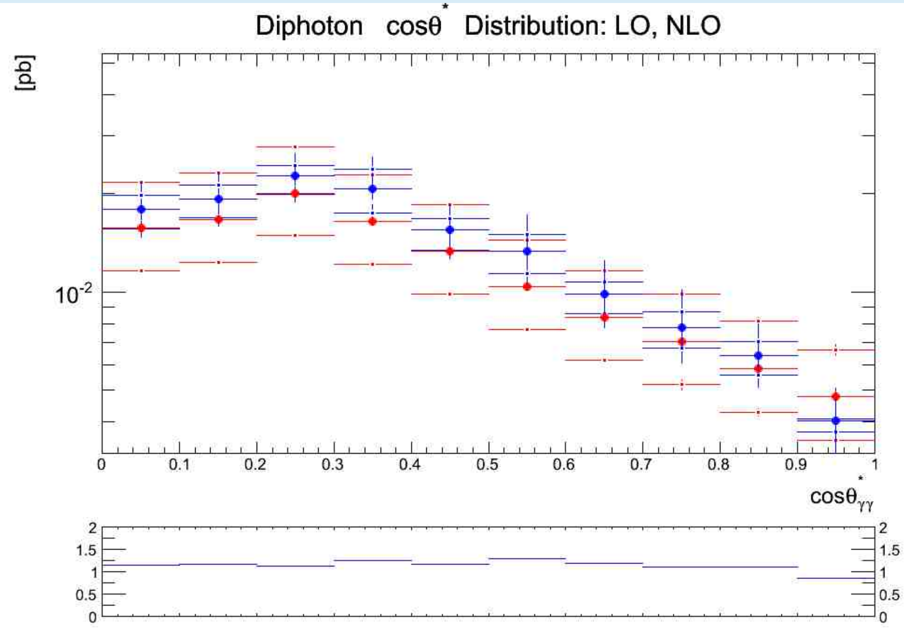
With VBF cuts





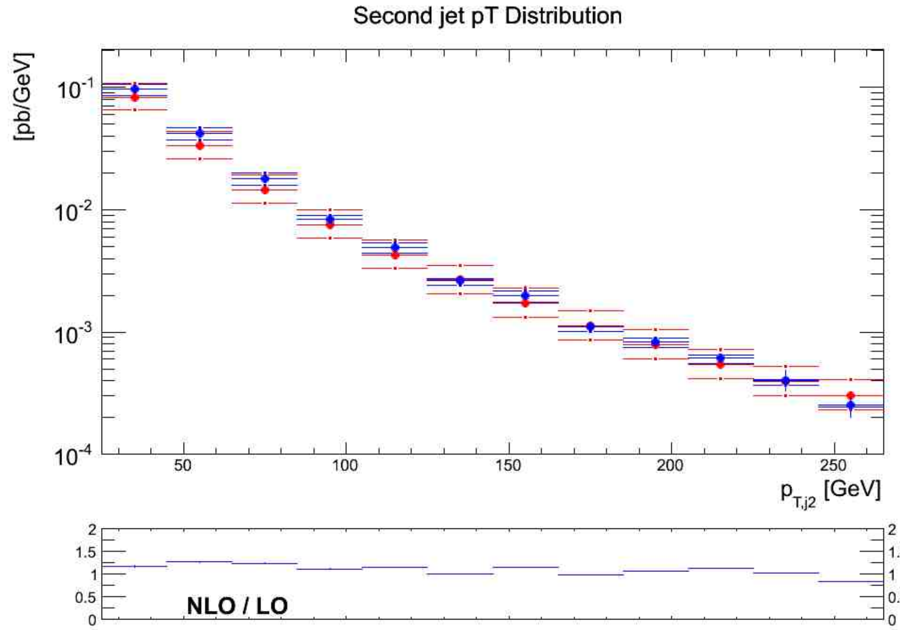
Second Jet's pT-distributions

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

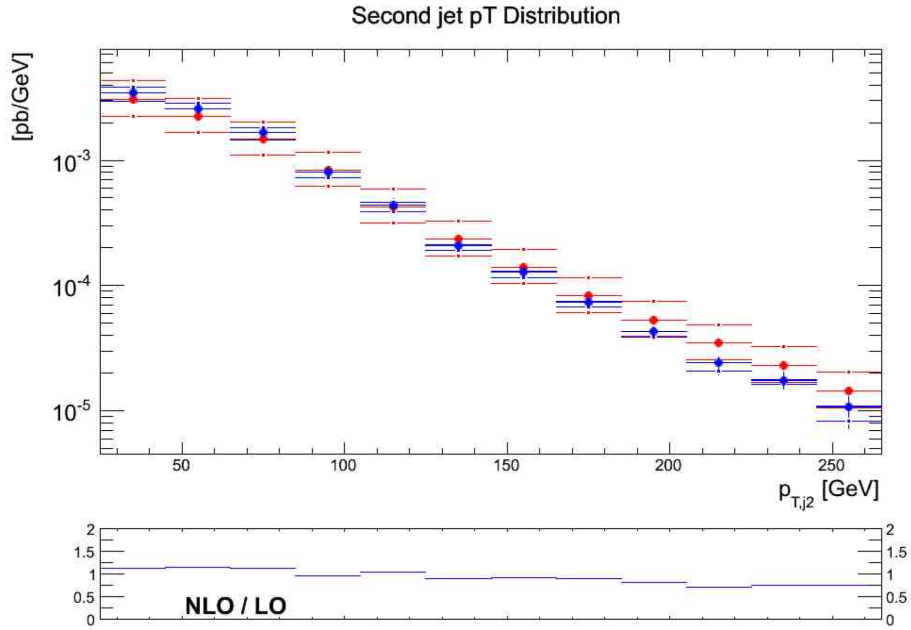
$$p_T^{\gamma_1} > 50\ \mathrm{GeV}\,, \qquad p_T^{\gamma_2} > 25\ \mathrm{GeV}\,, \qquad |\eta^\gamma| < 2.5\,, \qquad |\eta^{\mathrm{jet}}| < 4.5\,,$$

$$p_T^{\mathrm{jet}_1} > 40\ \mathrm{GeV}\,, \qquad p_T^{\mathrm{jet}_2} > 25\ \mathrm{GeV}\,, \qquad \left(M_{jj} > 400\ \mathrm{GeV}\,, \qquad \Delta\,\eta_{jj} > 2.8\right)$$

Without VBF cuts



With VBF cuts



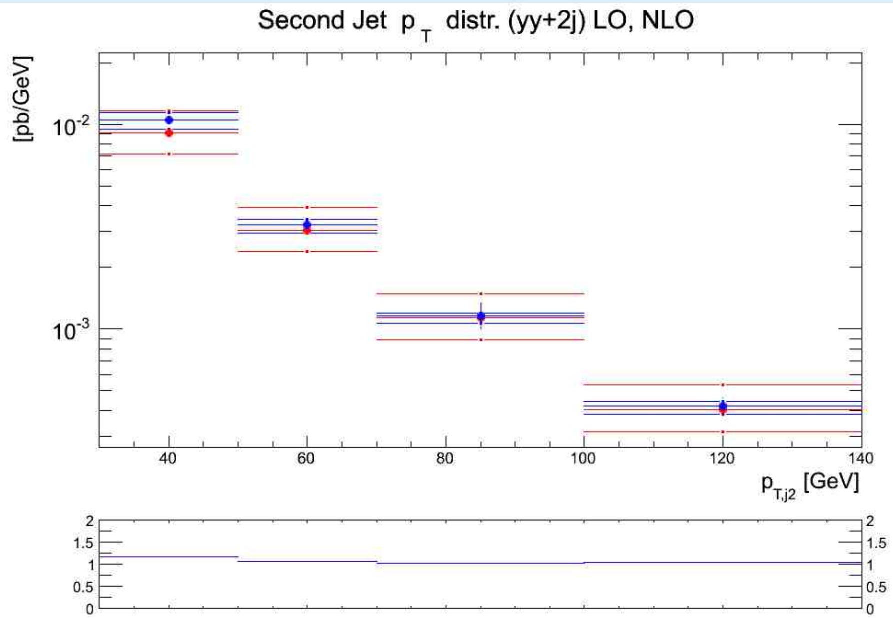
Second Jet's pT distribution with alternative cuts

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

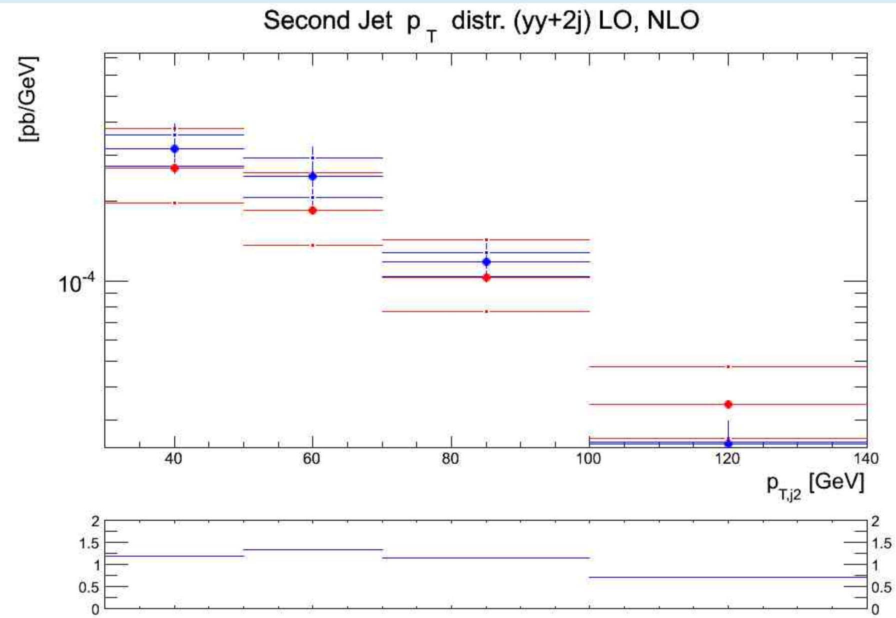
$$p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}\,, \qquad p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}\,, \qquad |\eta^{\gamma}| < 2.37\,, \qquad |\eta^{\mathrm{jet}}| < 4.4\,,$$

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

Without VBF cuts



With VBF cuts



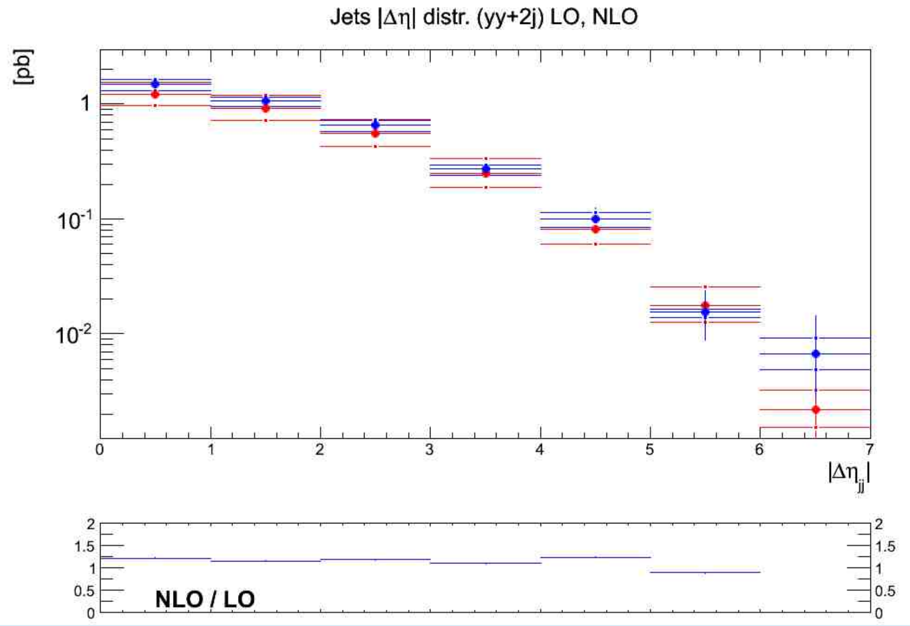
$\Delta\eta_{jj}$-distributions

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

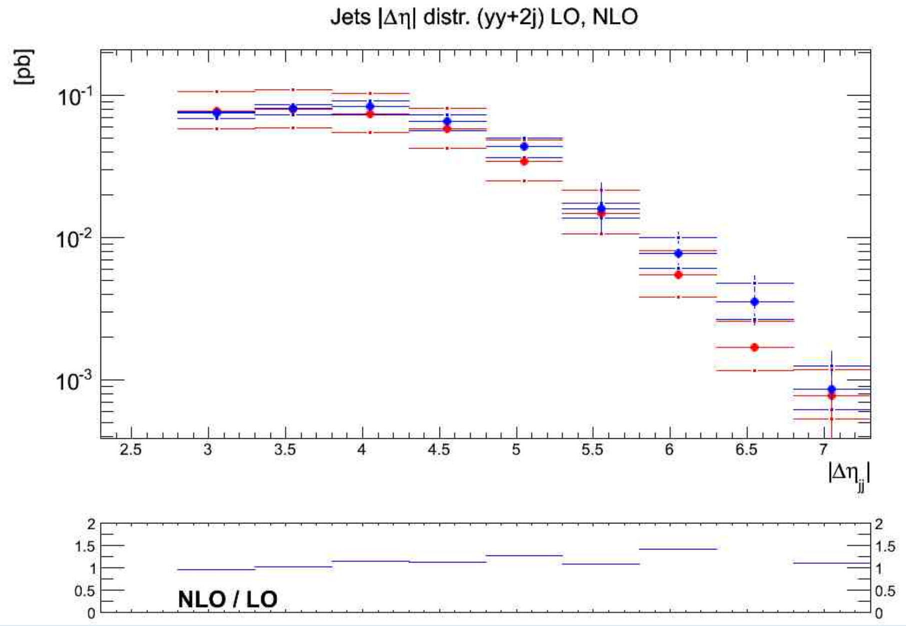
$$p_T^{\gamma_1} > 50\ \text{GeV}\,, \qquad p_T^{\gamma_2} > 25\ \text{GeV}\,, \qquad |\eta^{\gamma}| < 2.5\,, \qquad |\eta^{\text{jet}}| < 4.5\,,$$

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

Without VBF cuts



With VBF cuts



BH-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

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

BH-Sherpa n-tuples

BH-Sherpa n-tuple branches
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weight,
weight2,
me_wgt,
me_wgt2,
nuwgt,
usr_wgts,
part

Changing the scale: Virtual contribution

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

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

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

BH-Sherpa n-tuples

BH-Sherpa n-tuple branches
id,
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alpha_s,
fac_scale,
ren_scale,
weight,
weight2,
me_wgt,
me_wgt2,
nuwgt,
usr_wgts,
part

Changing the scale: Integrated subtraction contribution

$$w = m \cdot \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n}$$

$$\begin{aligned} m = {} & \omega_0 \cdot f(\mathbf{id1}, \mathbf{x1}, \mu_F)\, F(\mathbf{id2}, \mathbf{x2}, \mu_F) \\ & + \left(f_a^1 \omega_1 + f_a^2 \omega_2 + f_a^3 \omega_3 + f_a^4 \omega_4\right) F_b(x_b) \\ & + \left(F_b^5 \omega_1 + F_b^6 \omega_2 + F_b^7 \omega_3 + F_b^8 \omega_4\right) F_a(x_a) \end{aligned}$$

$$\omega_0 = \mathbf{me\_wgt2} + l\, \mathbf{usr\_wgts}[0] + \frac{l^2}{2} \mathbf{usr\_wgts}[1]$$

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

$$\omega_i = \mathbf{usr\_wgts}[i+1] + \mathbf{usr\_wgts}[i+9] \ln\left(\frac{\mu_F^2}{\mathbf{fac\_scale}^2}\right)$$

BH-Sherpa *n*-tuples

BH-Sherpa n-tuple branches
id,
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id1, id2,
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alpha_power,
alpha_s,
fac_scale,
ren_scale,
weight,
weight2,
me_wgt,
me_wgt2,
nuwgt,
usr_wgts,
part

No need to repeat the entire computation at each scale:

Possible to evaluate cross sections and distributions for different scales and PDFs !