NNLO+PS event generator for photon pair production with MiNNLO$_{\mathrm{PS}}$

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based on AG, C. Oleari, E. Re JHEP 09 (2022) 061

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Photon pair production

We study proton-proton scattering processes with two isolated on-shell photons in the final state at the LHC ($\sqrt{S} = 13$ TeV)

$$p\,p \to \gamma\,\gamma + X$$

with the aim of **generating events** accurate up to **NNLO QCD** within the Powheg Box + MiNNLO$_{\rm PS}$ framework and combining them with the Pythia8 parton shower

- The MiNNLO$_{\rm PS}$ method to resum the transverse momentum of the first QCD emission (Monni, Nason, Re, Wiesemann, Zanderighi JHEP 05 (2020) 143)
- The Powheg method to resum the transverse momentum of the second QCD emission (Frixione, Nason, Oleari JHEP 11 (2007) 070)
- Amplitudes for configurations with 1 and 2 final-state partons from OpenLoops2 (Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller Eur.Phys.J.C 79 (2019) 10, 866)
- Analytic two-loop amplitudes (Anastasiou, Glover, Tejeda-Yeomans Nucl.Phys.B 629 (2002) 255-289)

Phase space cuts and photon isolation criterion

In order to make the **cross section well defined** both from the theoretical and experimental point of view, the analysis has to select the events where the two photons are produced in the hard scattering

- Three **phase space cuts** on the momenta of the two photons

$$p_{\mathrm{T}\gamma_1} > 25\ \mathrm{GeV} \qquad p_{\mathrm{T}\gamma_2} > 22\ \mathrm{GeV} \qquad m_{\gamma\gamma} > 25\ \mathrm{GeV}$$

- **Frixione isolation algorithm** (Frixione Phys.Lett.B 429 (1998) 369-374) : any configuration with $n_{\rm part}$ final-state partons is discarded unless, for every photon γ and every angular distance R

$$\sum_{i=1}^{n_{\rm part}} p_{\mathrm{T}i}\,\theta(R - R_{i\gamma}) < 4\ \mathrm{GeV}\left(\frac{1-\cos R}{1-\cos 0.4}\right)$$

where

$$R_{i\gamma} = \sqrt{(\eta_i - \eta_\gamma)^2 + (\phi_i - \phi_\gamma)^2}$$

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The Powheg differential cross section for $\gamma\gamma j$ production

The POWHEG differential cross section for the production of **two photons** accompanied by **one jet** is given by

$$d\sigma^{\rm PWG}_{\gamma\gamma j} = \bar{B}(\Phi_{\gamma\gamma j})\Big[\Delta(\Phi_{\gamma\gamma j}, k_{\rm T}^{\rm min})\, d\Phi_{\gamma\gamma j} + \theta(k_{\rm T} - k_{\rm T}^{\rm min})\, \frac{R(\Phi_{\gamma\gamma jj})}{B(\Phi_{\gamma\gamma j})}\, \Delta(\Phi_{\gamma\gamma j}, k_{\rm T})\, d\Phi_{\gamma\gamma jj}\Big]$$

where

$$\bar{B}(\Phi_{\gamma\gamma j}) = B(\Phi_{\gamma\gamma j}) + V(\Phi_{\gamma\gamma j}) + \int d\Phi'_{\rm rad}\, R(\Phi_{\gamma\gamma j}, \Phi'_{\rm rad})$$

and the POWHEG Sudakov form factor is given by

$$\Delta(\Phi_{\gamma\gamma j}, k_{\rm T}) = \exp\left(-\int d\Phi'_{\rm rad}\, \frac{R(\Phi_{\gamma\gamma j}, \Phi'_{\rm rad})}{B(\Phi_{\gamma\gamma j})}\, \theta(k'_{\rm T} - k_{\rm T})\right)$$

The damping function

By mean of a **damping function** F, the real amplitudes are divided into **two terms**, containing respectively only **QCD** and **QED singularities**

$$R_{\mathrm{QCD}} = F\,R \qquad\qquad R_{\mathrm{QED}} = (1-F)\,R$$

In the region $\alpha_r = [p_1, p_2]$ where the two closest partons are p_1 and p_2

$$F = \frac{\left(\frac{1}{d_{\alpha_r}}\right)^2}{\left(\frac{1}{d_{\alpha_r}}\right)^2 + \sum_{i=1}^{n_{\mathrm{quarks}}} \sum_{j=1}^{n_{\mathrm{photons}}} \left(\frac{1}{d_{[q_i,\gamma_j]}}\right)^2}$$

$$d_{[i,j]} = \begin{cases} p_{\mathrm{T}j}^2 & \text{if } i \text{ is an IS particle} \\ 2\min\left(E_i^2, E_j^2\right)(1-\cos\theta_{ij}) & \text{if } i \text{ and } j \text{ are FS particles} \end{cases}$$

The Powheg differential cross section for $\gamma\gamma j$ production

After making use of the **damping function**

$$d\sigma_{\gamma\gamma j} = \bar{B}_{\rm QCD}(\Phi_{\gamma\gamma j})\Big[\Delta_{\rm QCD}(\Phi_{\gamma\gamma j}, k_{\rm T}^{\rm min})\, d\Phi_{\gamma\gamma j} + \theta(k_{\rm T} - k_{\rm T}^{\rm min})\,\frac{R_{\rm QCD}(\Phi_{\gamma\gamma jj})}{B(\Phi_{\gamma\gamma j})}\,\Delta_{\rm QCD}(\Phi_{\gamma\gamma j}, k_{\rm T})\, d\Phi_{\gamma\gamma jj}\Big] + R_{\rm QED}(\Phi_{\gamma\gamma jj})\, d\Phi_{\gamma\gamma jj}$$

where

$$\bar{B}_{\rm QCD}(\Phi_{\gamma\gamma j}) = B(\Phi_{\gamma\gamma j}) + V(\Phi_{\gamma\gamma j}) + \int d\Phi'_{\rm rad}\, R_{\rm QCD}(\Phi_{\gamma\gamma j}, \Phi'_{\rm rad})$$

and the Powheg Sudakov form factor is given by

$$\Delta_{\rm QCD}(\Phi_{\gamma\gamma j}, k_{\rm T}) = \exp\left(-\int d\Phi'_{\rm rad}\,\frac{R_{\rm QCD}(\Phi_{\gamma\gamma j}, \Phi'_{\rm rad})}{B(\Phi_{\gamma\gamma j})}\,\theta(k'_{\rm T} - k_{\rm T})\right)$$

The suppression factors

We multiply the two terms of the cross section respectively by the **Born suppression factor**

$$S_{\mathrm{B}} = \prod_{i=1}^{2} \left(\frac{p_{\mathrm{T}\gamma_i}}{p_{\mathrm{T}\gamma_i} + 22\ \mathrm{GeV}} \times \frac{R_{j_1\gamma_i}}{R_{j_1\gamma_i} + 0.4} \right)$$

and the **remnant suppression factor**

$$S_{\mathrm{R}} = \prod_{i=1}^{2} \left(\frac{p_{\mathrm{T}\gamma_i}}{p_{\mathrm{T}\gamma_i} + 22\ \mathrm{GeV}} \times \frac{R_{j_1\gamma_i}}{R_{j_1\gamma_i} + 0.4} \times \frac{R_{j_2\gamma_i}}{R_{j_2\gamma_i} + 0.4} \right)$$

The **weights** of the events generated using the Born and remnant suppression factors are then multiplied by $1/S_{\mathrm{B}}$ and $1/S_{\mathrm{R}}$ respectively

The Powheg differential cross section for $\gamma\gamma j$ production

After applying the **Born suppression factor**

$$d\sigma^{\rm PWG}_{\gamma\gamma j} = S_{\rm B}(\Phi_{\gamma\gamma j})\bar{B}_{\rm QCD}(\Phi_{\gamma\gamma j})\Big[\Delta_{\rm QCD}(\Phi_{\gamma\gamma j}, k_{\rm T}^{\rm min})\, d\Phi_{\gamma\gamma j} + \theta(k_{\rm T} - k_{\rm T}^{\rm min})\,\frac{R_{\rm QCD}(\Phi_{\gamma\gamma jj})}{B(\Phi_{\gamma\gamma j})}\,\Delta_{\rm QCD}(\Phi_{\gamma\gamma j}, k_{\rm T})\, d\Phi_{\gamma\gamma jj}\Big] + S_{\rm R}(\Phi_{\gamma\gamma jj})R_{\rm QED}(\Phi_{\gamma\gamma jj})\, d\Phi_{\gamma\gamma jj}$$

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The two suppression factors only modify the differential cross section **used for generating the events**: the weights given to such events compensate the presence of the suppression factors thus guaranteeing that **the physical distributions are unchanged**

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The MiNNLO$_{\rm PS}$ differential cross section

In the $\mathrm{MiNNLO_{PS}}$ formalism, the $\boldsymbol{p_{\rm T}}$ **spectrum** of the differential cross section for the $p\,p \to \gamma\,\gamma$ process is written as

$$\frac{d\sigma^{\rm MiNNLO}_{\gamma\gamma}}{d\Phi_{\gamma\gamma}\,dp_{\rm T}} = e^{-\tilde{S}} D + R_f$$

- The term $e^{-\tilde{S}} D$ provides the $\boldsymbol{p_{\rm T}}$ **resummation**
- The term R_f contains non singular (i.e. integrable in the $p_{\rm T} \to 0$ limit) contributions to the $p\,p \to \gamma\,\gamma\,j$ process

The exponent of the Sudakov form factor reads

$$\tilde{S} = \int_{p_{\rm T}^2}^{Q^2} \frac{dq^2}{q^2} \left[\sum_{i=1}^{3} \left(\frac{\alpha_{\rm S}(q)}{2\pi} \right)^n A_n \log\left(\frac{Q^2}{q^2} \right) + \sum_{i=1}^{2} \left(\frac{\alpha_{\rm S}(q)}{2\pi} \right)^n \tilde{B}_n \right]$$

The MiNNLO$_{\rm PS}$ differential cross section

The most straightforward choice would be to use

$$R_f = \left[\frac{d\sigma^{\rm NLO}_{\gamma\gamma j}}{d\Phi_{\gamma\gamma}\, dp_{\rm T}} - \left[e^{-\tilde{S}} D \right]_{\alpha_{\rm S}^2} \right]_{\mu=Q}$$

Instead of doing that, the $\rm MiNNLO_{PS}$ prescription is to use

$$R_f = e^{-\tilde{S}} \left[\frac{d\sigma^{\rm NLO}_{\gamma\gamma j}}{d\Phi_{\gamma\gamma}\, dp_{\rm T}} - \left[e^{-\tilde{S}} D \right]_{\alpha_{\rm S}^2} + \tilde{S}^{(1)} \left(\frac{d\sigma^{\rm LO}_{\gamma\gamma j}}{d\Phi_{\gamma\gamma}\, dp_{\rm T}} - D^{(1)} \right) \right]_{\mu=p_{\rm T}}$$

- In the **small-$p_{\rm T}$ region** we suppress the non-singular contributions, thus making the numerical integration more stable
- In the **large-$p_{\rm T}$ region**, up to terms beyond the claimed accuracy, we recover

$$R_f = \left[\frac{d\sigma^{\rm NLO}_{\gamma\gamma j}}{d\Phi_{\gamma\gamma}\, dp_{\rm T}} - \left[e^{-\tilde{S}} D \right]_{\alpha_{\rm S}^2} \right]_{\mu=Q} + \mathcal{O}\left(\alpha_{\rm S}^3\right)$$

Modifications to the original MiNNLO$_{\rm PS}$ method

We introduce a simplified version of the **Sudakov form factor**

$$\bar{S} = \int_{p_{\rm T}^2}^{Q^2} \frac{dq^2}{q^2} \frac{\alpha_{\rm S}(q)}{2\pi} \left(A_1 \log\left(\frac{Q^2}{q^2}\right) + B_1 \right)$$

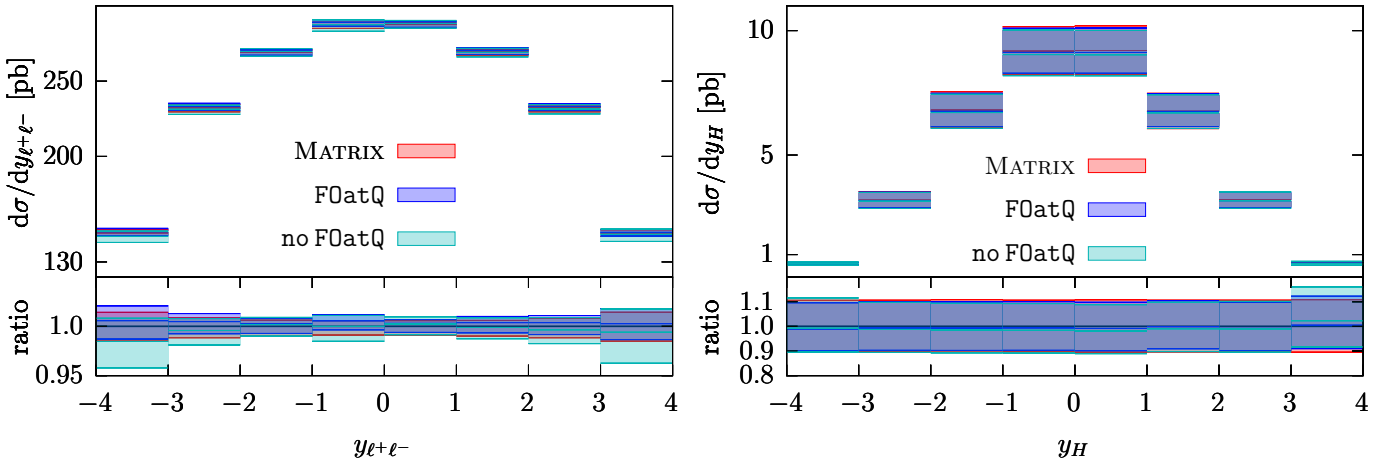
and set the **factorization and renormalization scales** in the non-singular contributions to $\mu_{\rm R} = \mu_{\rm F} = Q$

$$R_f = e^{-\bar{S}} \left[\frac{d\sigma_{\gamma\gamma j}^{\rm NLO}}{d\Phi_{\gamma\gamma}\, dp_{\rm T}} - \left[e^{-\tilde{S}} D \right]_{\alpha_{\rm S}^2} + \tilde{S}^{(1)} \left(\frac{d\sigma_{\gamma\gamma j}^{\rm LO}}{d\Phi_{\gamma\gamma}\, dp_{\rm T}} - D^{(1)} \right) \right]_{\mu=Q}$$

This limits the presence of spurious $\mathcal{O}\left(\alpha_{\rm S}^3\right)$ terms in the definition of the differential cross section and allows to **better reproduce the distributions obtained from a fixed-order calculation**

Modifications to the original MiNNLO$_{\rm PS}$ method

Comparison between the distributions obtained with the original (no FOatQ) and modified (FOatQ) MiNNLO$_{\rm PS}$ methods for the rapidity of the color singlet in Drell-Yan and Higgs-boson production



$$\sigma_{\rm DY}^{\rm NNLO} = 1919 \pm 1 \text{ pb} \qquad \sigma_{\rm DY}^{\rm res} = 1904 \pm 3 \text{ pb}$$

$$\sigma_{\rm H}^{\rm NNLO} = 39.64 \pm 0.01 \text{ pb} \qquad \sigma_{\rm H}^{\rm res} = 34.03 \pm 0.07 \text{ pb}$$

$$\sigma_{\gamma\gamma}^{\rm NNLO} = 155.7 \pm 1.0 \text{ pb} \qquad \sigma_{\gamma\gamma}^{\rm res} = 55.7 \pm 0.6 \text{ pb.}$$

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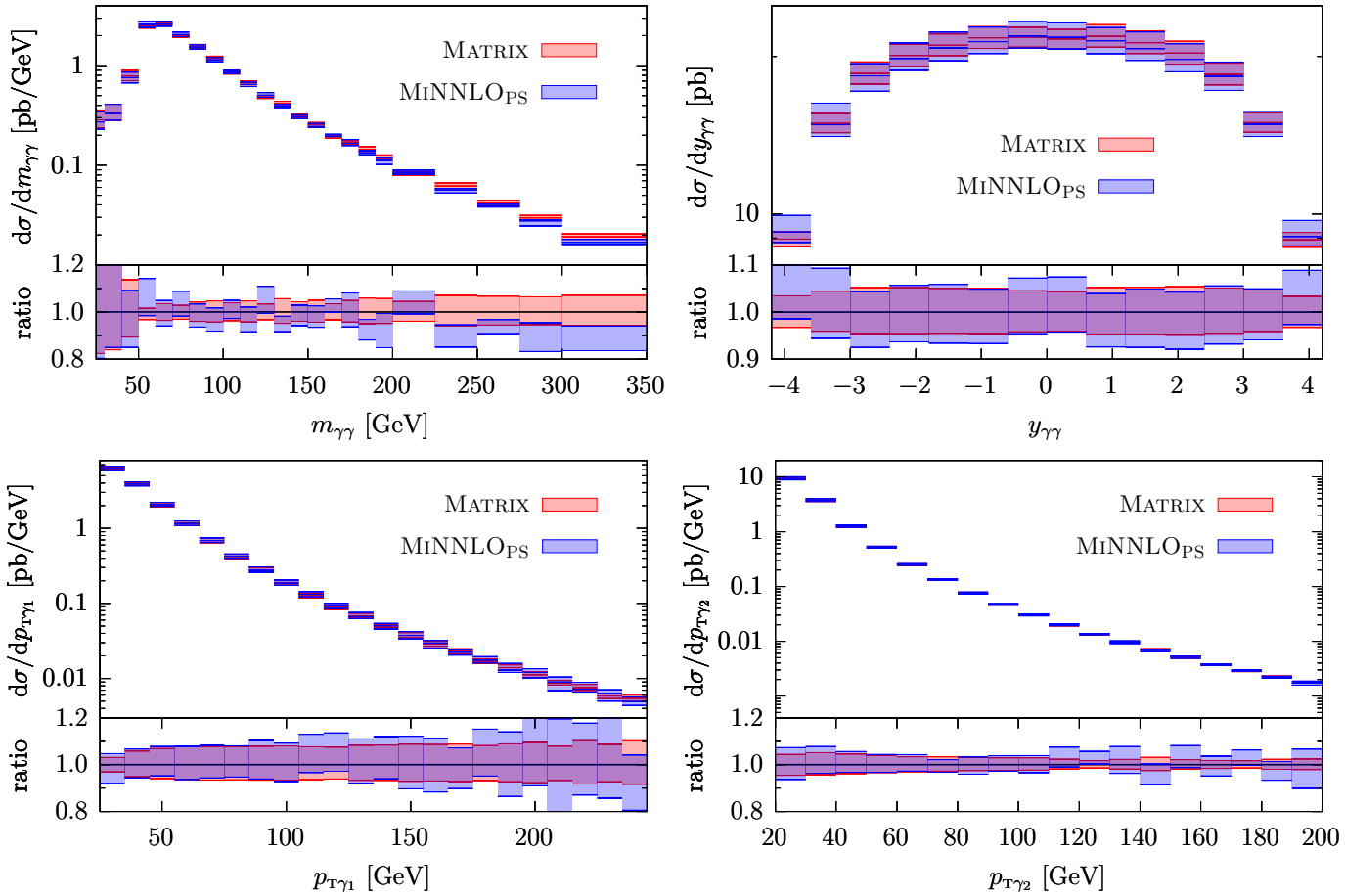
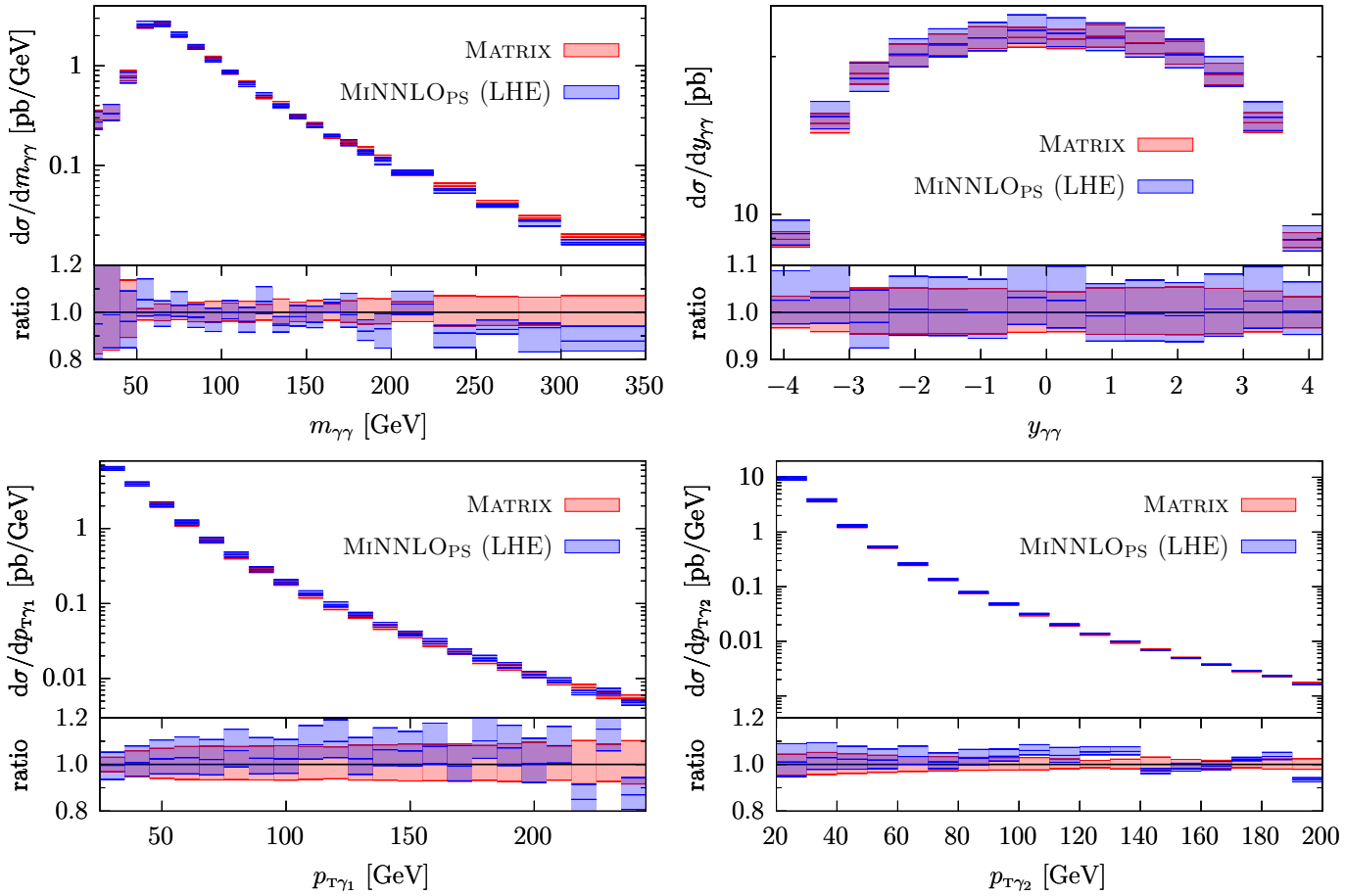
Comparison with a fixed-order calculation

Comparison of our results against the fixed-order NNLO calculation implemented in MATRIX (Grazzini, Kallweit, Wiesemann Eur.Phys.J.C 78 (2018) 7, 537)



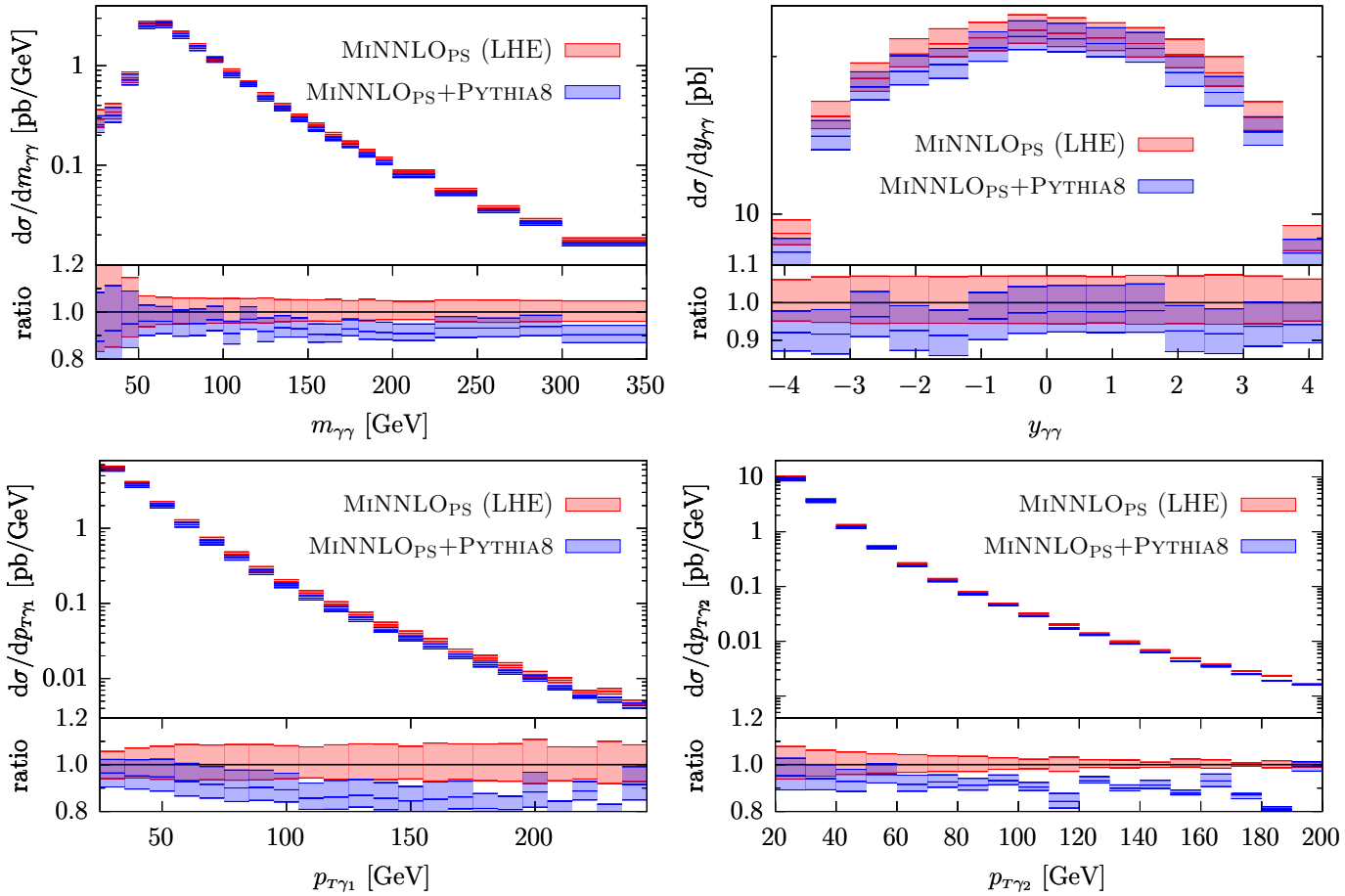
Distributions of the Powheg partonic events

Comparison between the MiNNLO$_{\rm PS}$ distributions and those obtained from the Powheg partonic events

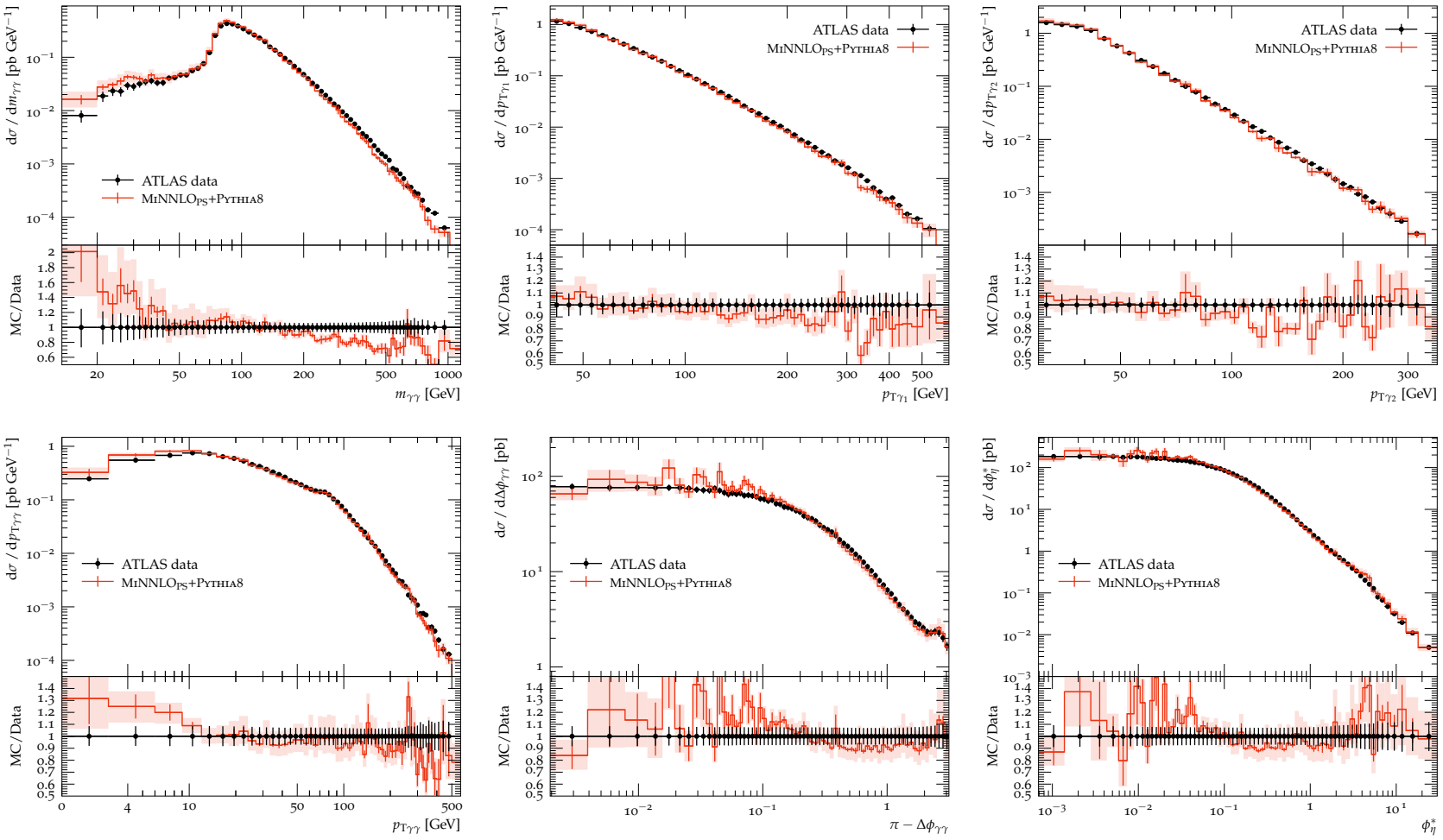


Distributions of the events after the shower

Comparison between the distributions obtained from the POWHEG events before and after passing them through the PYTHIA8 parton shower



Comparison with the ATLAS data



Thanks for your attention!