Wγ production at the LHC at NLOPS accuracy*

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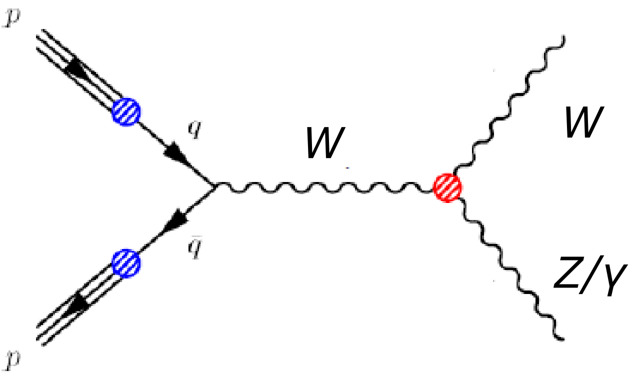
* arXiv:1408.5766

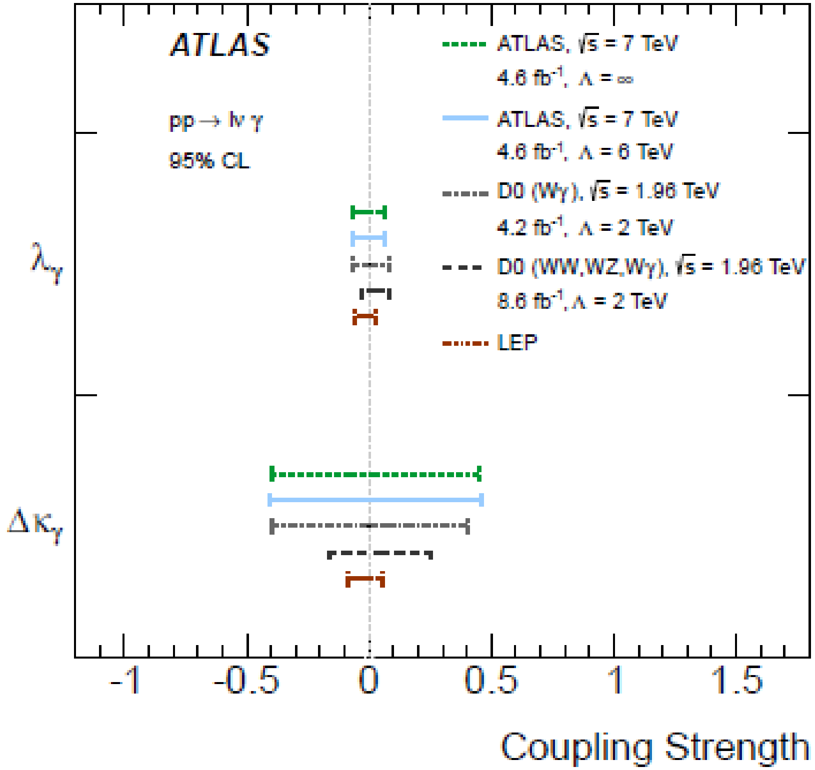
Outline

- **Basic motivations**
  - Precision test of the Standard Model
  - New physics searches
- **Method**
  - Simulation of the photon fragmentation contribution using POWHEG+PYTHIA
  - Practical implementation
- **Results**
  - Comparisons with MCFM results
  - Comparison with experimental data at 7 TeV (ATLAS 2011)

Electroweak boson pairs production at the LHC

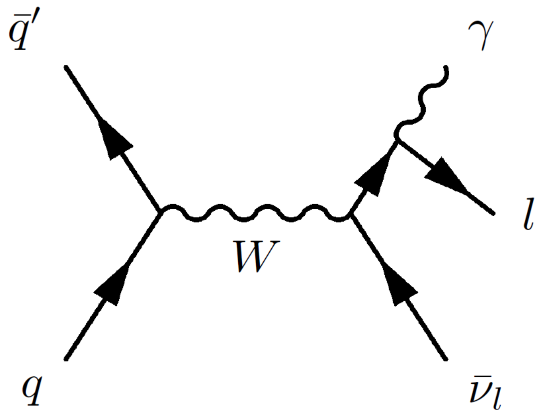
- **Anomalies in triple gauge couplings**
  - Search for ATGC: high $p_T(\gamma)$ region in exclusive $N_{jet}=0$ selection
  - No deviations found from SM predictions



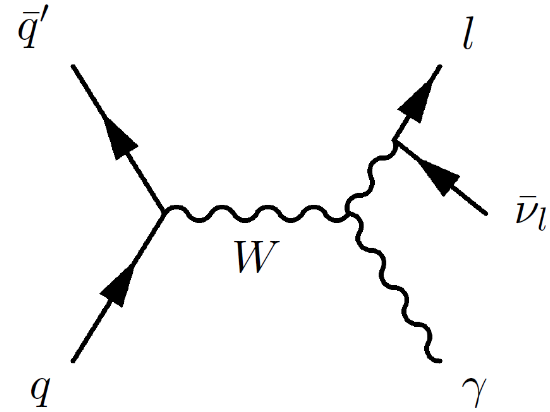


- **New Physics phenomena**
  - Background for SuperSymmetry processes
  - Search for narrow resonances: techni-mesons ($\omega_T \to Z\gamma$, $a_T \to W\gamma$)

LO Feynman diagrams for Wγ production

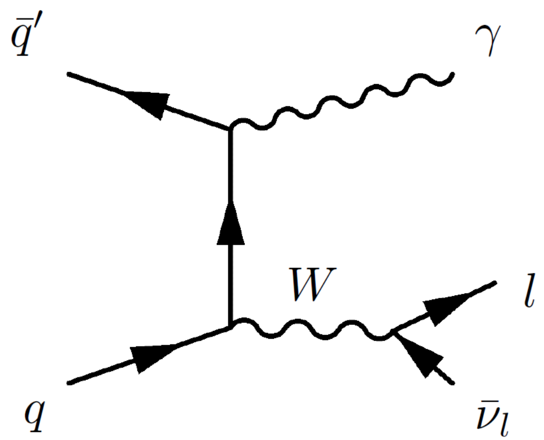


Final state radiation from lepton

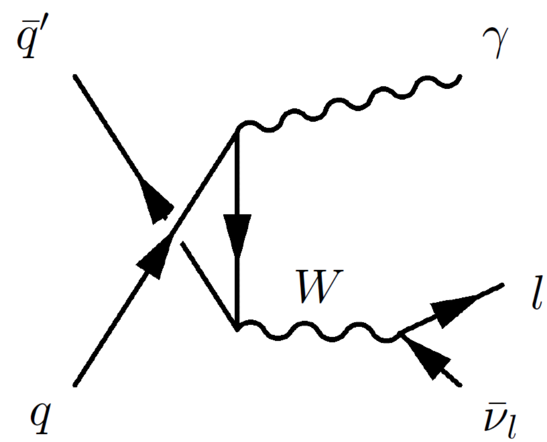


s-channel

Triple gauge coupling



t-channel

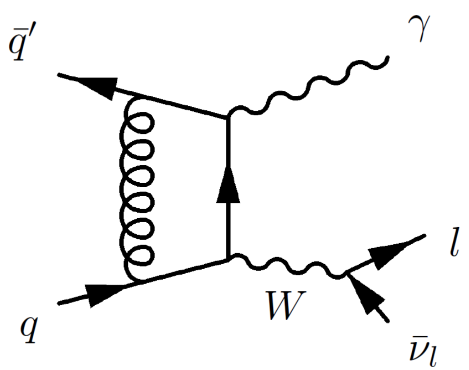


u-channel

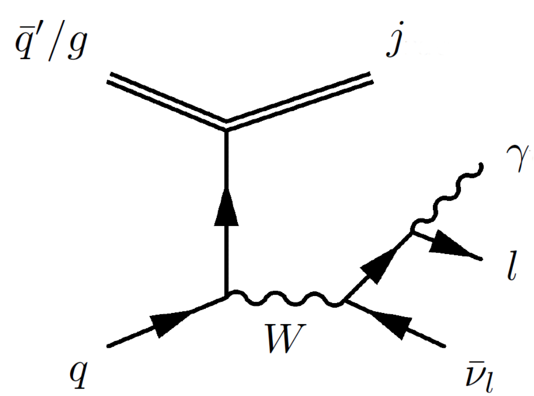
QCD NLO corrections to Wγ

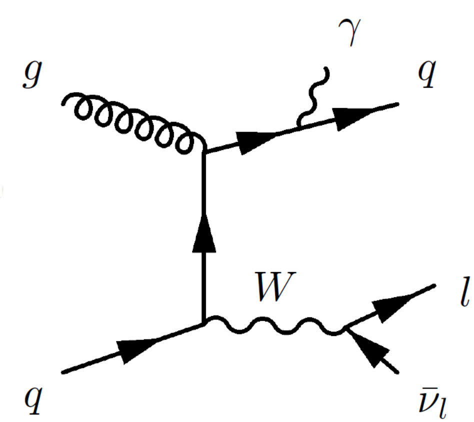
- NLO corrections are very sizeable
  K-factor ~ 2 for some event selections*

Virtual corrections



Real corrections



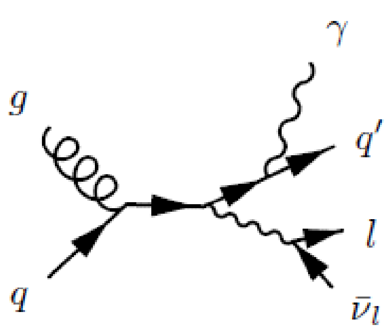


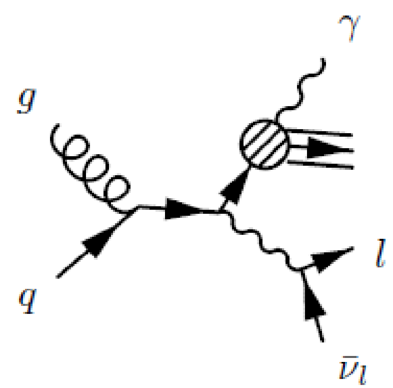
- **Gluon-induced processes** strongly enhanced at the energies of the LHC (large gluon PDFs)

- Divergent for collinear photon emission (no virtual counterpart)

* J. M. Campbell et al., Vector boson pair production at the LHC, JHEP 1107 (2011)

Isolated photons in hadronic collisions (I)





- Higher orders in QCD: a series of consecutive collinear splittings from a high-p_T parton, ending up with a quark-photon splitting.

→ Collinear singularities factorized to all orders in α_s and absorbed into **photon fragmentation functions***

$$D_{g\to\gamma}(z, M_F) \qquad D_{q\to\gamma}(z, M_F)$$

Fragmentation scale (M_F)

Longitudinal momentum fraction (z)

* S. Catani, M. Fontannaz, J. Ph. Guillet and E. Pilon, Cross section of isolated prompt photons in hadron-hadron collisions, JHEP 0205 (2002)

Isolated photons in hadronic collisions (II)

Direct and fragmentation contributions (depending on M_F)

$$\sigma(p_\gamma) = \sigma_\gamma^{(D)}(p_\gamma; M_F) + \sum_a \int_0^1 \frac{dz}{z} \sigma_a^{(F)}(p_\gamma/z; M_F) D_{a\to\gamma}(z, M_F)$$

- For $M_F > 1$ GeV, fragmentation contribution $O(\alpha_{em}/\alpha_s(M_F))$

  → Same order of the Born term

- Non perturbative contributions arising in parton fragmentation

  ➡ Fragmentation functions extracted from experimental data

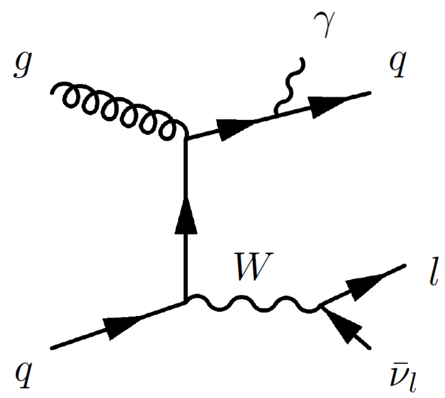
  - <u>Large uncertainties</u>
  - <u>Pure collinear approximation</u>

Isolated photons in hadronic collisions (III)

- **Smooth isolation prescription***

$$\sum_j E_{Tj}\Theta(R - R_{j\gamma}) \leq \epsilon_h E_{T\gamma}\left(\frac{1-\cos R}{1-\cos R_0}\right)$$

$$\forall R < R_0$$



- Fragmentation contribution fully removed

- Soft radiation can be integrated over the whole phase space.
  Cancellation of QCD infrared singularities in inclusive R+V not spoiled

- Difficult experimental application

- **Standard isolation cuts**

$$\sum_j E_{Tj}\Theta(R_0 - R_{j\gamma}) \leq \epsilon_h E_{T\gamma}$$

* S. Frixione, Isolated photons in perturbative QCD, Phys.Lett. B429 (1998)

The POWHEG method*

- Cross section for the hardest emission

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\Phi_n) d\Phi_n \left\{ \Delta^{f_b}(\Phi_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad} \Theta(k_T - p_T^{min}) \Delta^{f_b}(\Phi_n, k_T) R(\Phi_{n+1}) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} \right\}$$

$$\bar{B}^{f_b}(\Phi_n) = \left[B(\Phi_n) + V(\Phi_n) \right]_{f_b} + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \left[d\Phi_{rad} \left(R(\Phi_{n+1}) - C(\Phi_{n+1}) \right) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n}$$

$$+ \sum_{\alpha_\oplus \in \{\alpha_\oplus | f_b\}} \int \left[\frac{dz}{z} G_\oplus^{\alpha_\oplus}(\Phi_{n,\oplus}) \right]^{\bar{\Phi}_n = \Phi_n} + \sum_{\alpha_\ominus \in \{\alpha_\ominus | f_b\}} \int \left[\frac{dz}{z} G_\ominus^{\alpha_\ominus}(\Phi_{n,\ominus}) \right]^{\bar{\Phi}_n = \Phi_n}$$

NLO inclusive

$$\Delta^{f_b}(\Phi_n, p_T) = exp \left\{ - \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \frac{\left[d\Phi_{rad} R(\Phi_{n+1}) \Theta(k_T(\Phi_{n+1}) - p_T) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} \right\}$$

Sudakov form factors

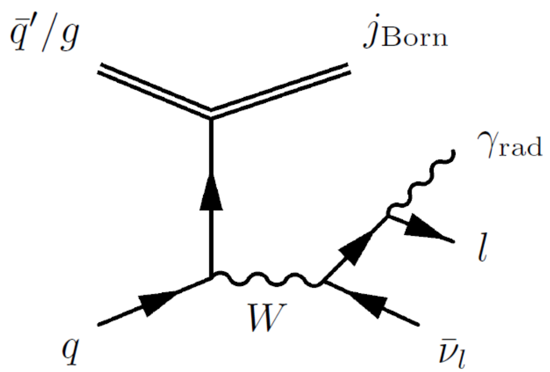
- Then add softer radiation in the shower approximation

* P. Nason, A new method for combining NLO QCD with SMC algorithms, JHEP 11 (2004)

S. Frixione, P. Nason, and C. Oleari, Matching NLO QCD computations with Parton Shower simulations: the POWHEG method, JHEP 11 (2007)

Fragmentation contribution in POWHEG+PYTHIA (I)

➡ Apply the POWHEG method to both QCD and QED radiation



QED corrections to Wj

- Remove photon collinear singularity through the subtraction method*
- Perform hardest radiation within the POWHEG framework also for photon emission from a Wj underlying Born
- ISR and lepton-FSR are also included

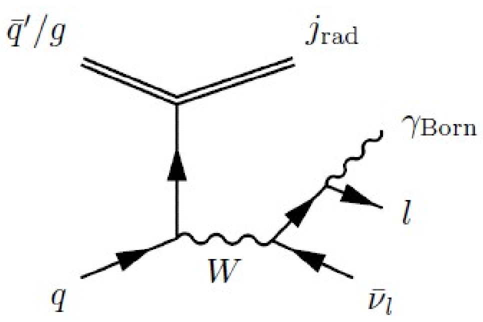
Simulation of the fragmentation contribution through
QED emission in POWHEG + QCD+QED shower (PYTHIA)

➡ Reproduce perturbative and non-perturbative effects of the fragmentation mechanism

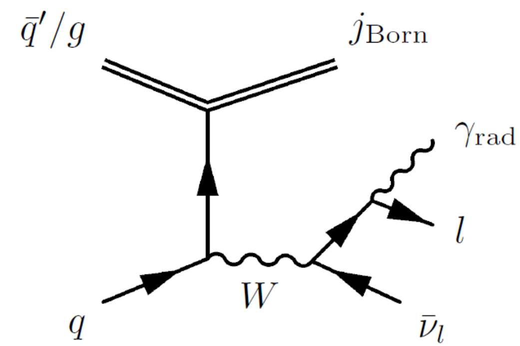
* S. Frixione, Z. Kunszt and A. Signer, Nucl. Phys. B 467 (1996)

Fragmentation contribution in POWHEG+PYTHIA (II)

Separate QCD and QED singular regions: $R = \sum_{\alpha_r \in QCD} R^{\alpha_r}_{W\gamma;j} + \sum_{\alpha_r \in QED} R^{\alpha_r}_{Wj;\gamma}$



Wγ underlying Born
+ parton emission



Wj underlying Born
+ photon emission

$$d\sigma = \bar{B}_{W\gamma}\Big(\Delta^{QCD} + \sum_{\alpha_r \in QCD}\Big[\frac{\Delta^{QCD}(k_T)R_{W\gamma;j}}{B_{W\gamma}}\Big]_{\alpha_r}\Big) + B'_{Wj}\Big(\Delta^{QED} + \sum_{\alpha_r \in QED}\Big[\frac{\Delta^{QED}(k_T)R_{Wj;\gamma}}{B_{Wj}}\Big]_{\alpha_r}\Big)$$

- Separation of phase space domains
- QCD or QED hardest emission

Wγ in POWHEG+MiNLO

- Wj Born: divergent for collinear parton emission

  → need a cut at the generation level

- But: must be inclusive over colored radiation

The MiNLO method*

- Reweight with Sudakov form factors and α_s evaluated at dynamical scales (based on CKKW)

- NLO accuracy preserved

  ⇒ Integrate over the whole phase space:
  $p_T(W)$ reliable and smooth behavior down to very small p_T

  ⇒ Dynamically motivated choice of μ_R and μ_F scales

* K. Hamilton, P. Nason, G. Zanderighi, MINLO: Multi-scale improved NLO, arXiv:1206.3572

Wγ implementations in POWHEG+MiNLO

POWHEG-NC

- Wγ NLO cross section + parton emission
- Wj cross section + photon emission

- Need to account for colored radiation in competition with photons
  → Can be done in an effective way

POWHEG-C-LO

- Photon/parton emission in competition
- Wj cross section at QCD LO accuracy

POWHEG-C-NLO

- Wj cross section at QCD NLO accuracy

Wγ in POWHEG+MiNLO: NC method

- Wγ underlying Born (photon harder than parton)

$$\bar{B}_{W\gamma} = B_{W\gamma} + V_{W\gamma(j)} + \sum_{\alpha_r \in QCD} \int [d\Phi_{rad}(R_{W\gamma;j} - C)]^{\alpha_r}$$

$$\Delta_{W\gamma}^{QCD} = exp\left\{ - \sum_{\alpha_r \in QCD} \int \left[d\Phi_{rad} \frac{R_{W\gamma;j}}{B_{W\gamma}} \right]^{\alpha_r} \right\}$$

Scalup choice (POWHEG standard)

- $p_T(j_{rad})$

- Wj underlying Born (parton harder than photon)

$$B'_{Wj} = B_{Wj} + \sum_{\alpha_r \in QED} \int [d\Phi_{rad}(R_{Wj;\gamma} - C)]^{\alpha_r}$$

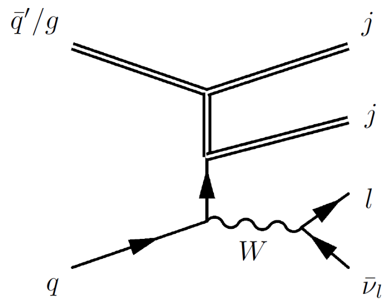
$$\Delta_{Wj}^{QED} = exp\left\{ - \sum_{\alpha_r \in QED} \int \left[d\Phi_{rad} \frac{R_{Wj;\gamma}}{B_{Wj}} \right]^{\alpha_r} \right\}$$

Effective choice for *scalup**

- $p_T(j_{Born})$ QCD shower
- $p_T^{rel}(\gamma_{rad})$ QED shower

* L. D'Errico, P. Richardson, Next-to-Leading-Order Monte Carlo Simulation of Diphoton Production in Hadronic Collisions, JHEP 1202 (2012)

Wγ in POWHEG+MiNLO: C-LO method



- For Wj underlying Born include also colored radiation dynamics (in competition with photon radiation)

$$B'_{Wj}\left(\Delta^{QED}_{Wj}+\sum_{\alpha_r\in QED}\left[\frac{\Delta^{QED}_{Wj}(k_T)R_{Wj;\gamma}}{B_{Wj}}\right]_{\alpha_r}+\Delta^{QCD}_{Wj}+\sum_{\alpha_r\in QCD}\left[\frac{\Delta^{QCD}_{Wj}(k_T)R_{Wj;j}}{B_{Wj}}\right]_{\alpha_r}\right)$$

- Generated events:

Wγ(+j)	photon harder than partons
Wj+γ	photon softer than one parton
Wj+j+γ_{PS}	photon softer than at least two partons

- Scalup choice: POWHEG standard (dynamically motivated)

- Wj normalization at QCD LO (same as for NC)

Wγ in POWHEG+MiNLO: C-NLO method

➡ Wj component normalized at QCD NLO

$$\bar{B}_{Wj} = B_{Wj} + V_{Wj(j)} + \sum_{\alpha_r \in QED} \int [d\Phi_{rad}(R_{Wj;\gamma} - C)]^{\alpha_r} + \sum_{\alpha_r \in QCD} \int [d\Phi_{rad}(R_{Wj;j} - C)]^{\alpha_r}$$

- Radiation dynamics same as for C-LO

- NLO corrections to the fragmentation contribution
  - Very important, as fragmentation ~ $O(\alpha_{em}/\alpha_s)$
  - gg channel opened (high gluon PDFs)

- Goes in the direction of Wγ at NNLO+PS, but...
  - Exact real Wγjj and 2-loop virtual still missing
    → NNLO calculations available*
    (+20% for leptonic cuts + smooth isolation)

*M. Grazzini, Vector-boson pair production at NNLO, arXiv:1407.1618

Results: selection cuts

Selection cuts: ATLAS setup*

$$p_T(\gamma) > 15\text{GeV}, \quad |\eta_\gamma| < 2.37, \quad \Delta R_{l\gamma} > 0.7$$

$$p_T(l) > 25\text{GeV}, \quad |\eta_l| < 2.47, \quad E_T^{miss} > 35\text{GeV}$$

$$R_0 = 0.4, \quad \epsilon_h = 0.5 \qquad \sum_j E_{Tj}\Theta(R_0 - R_{j\gamma}) \leq \epsilon_h E_{T\gamma}$$

Jet cuts for exclusive N_{jet} selections
(anti-k_t jet-finding algorithm, r=0.4)

$$E_T(jet) > 30\text{GeV}, \quad |\eta_{jet}| < 4.4, \quad \Delta R(e/\mu/\gamma, jet) > 0.3$$

→ Results obtained with **POWHEG+PYTHIA8**

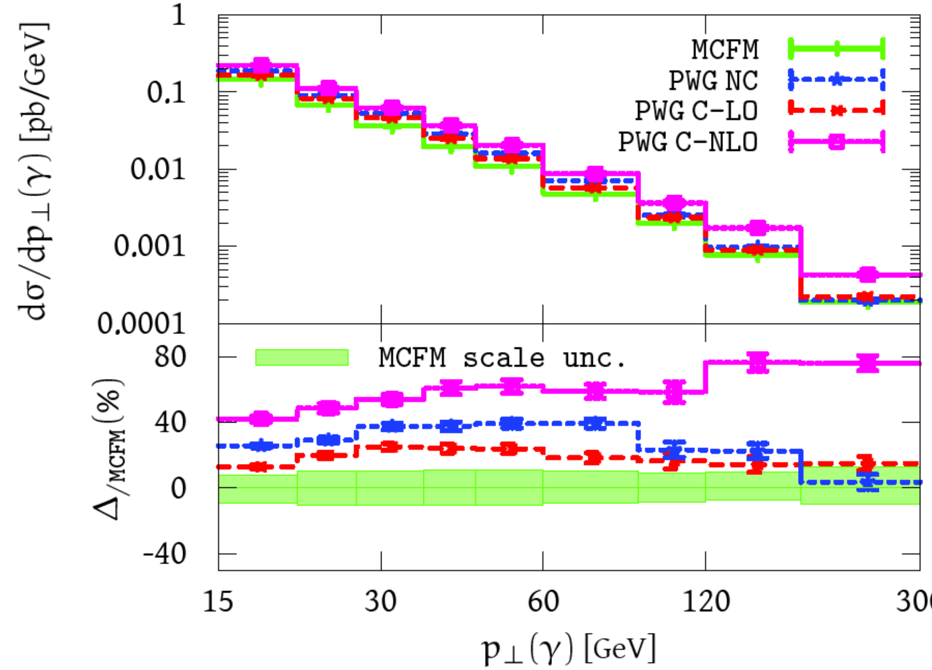
* The ATLAS Collaboration, Phys. Rev. D 87 (2013)

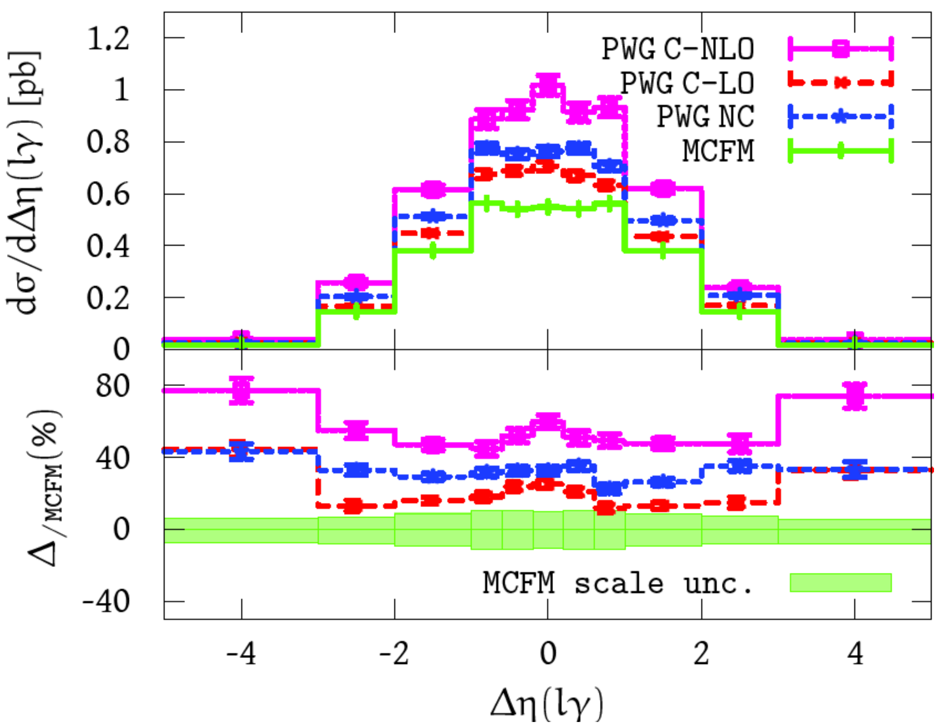
Results: comparisons with MCFM

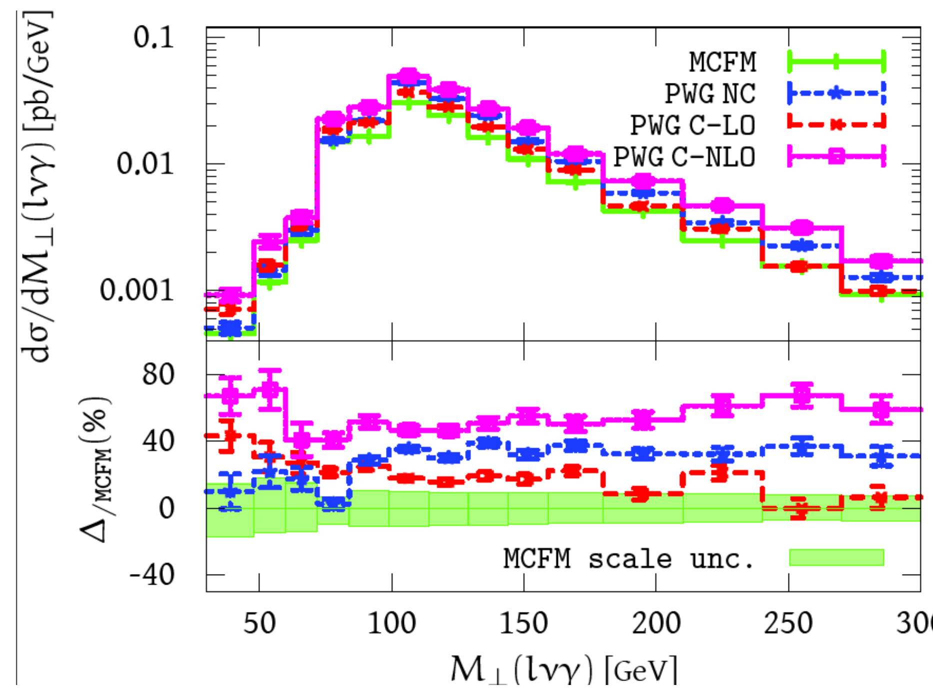
$pp \to l^+ \nu_l \gamma + X \qquad \sqrt{s} = 14\text{TeV}$

MCFM	PWG-NC
$2.227(1)^{+9\%}_{-10\%}$	$3.03(2)^{+14\%}_{-15\%}$

PWG-C-LO	PWG-C-NLO
$2.67(2)^{+16\%}_{-17\%}$	$3.76(5)^{+17\%}_{-13\%}$

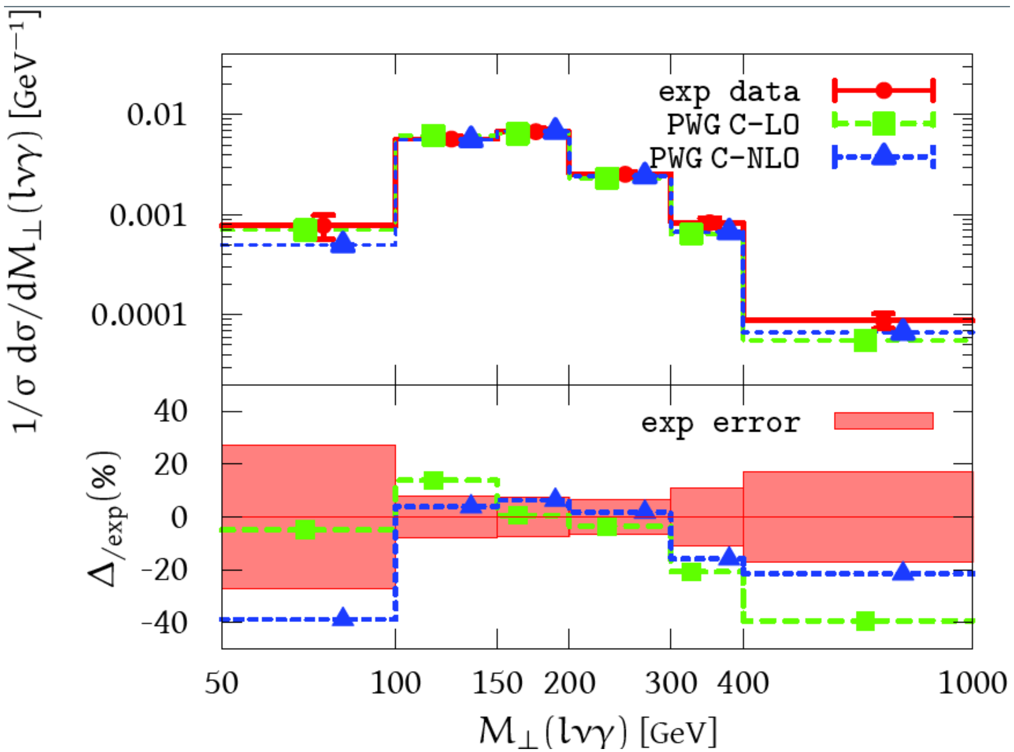






Results: comparisons with ATLAS data* (I)

[pb]	Exclusive $N_{jet} = 0$	Inclusive $N_{jet} \geq 0$
Exp.	$1.77^{\pm 0.04 \mathrm{stat}}_{\pm 0.08 \mathrm{lumi}} \pm 0.24$ syst	$2.74^{\pm 0.05 \mathrm{stat}}_{\pm 0.14 \mathrm{lumi}} \pm 0.32$ syst
MCFM	1.39 ± 0.17	1.96 ± 0.17
PWG-C-LO	$1.42^{+0.15}_{-0.15}$	$2.25^{+0.24}_{-0.24}$
PWG-C-NLO	$1.69^{+0.11}_{-0.22}$	$2.95^{+0.20}_{-0.38}$



$$pp \to l\nu_l\gamma + X \qquad \sqrt{s} = 7\mathrm{TeV}$$

Electron and muon channels combined

$$M_\perp^2(l\nu_l\gamma) = \left(\sqrt{m_{l\gamma}^2 + |\mathrm{p}_T^\gamma + \mathrm{p}_T^l|^2} + p_T^{\nu_l}\right)^2 - |\mathrm{p}_T^\gamma + \mathrm{p}_T^l + \mathrm{p}_T^{\nu_l}|^2$$

$$p_T(\gamma) > 40 \text{ GeV}$$

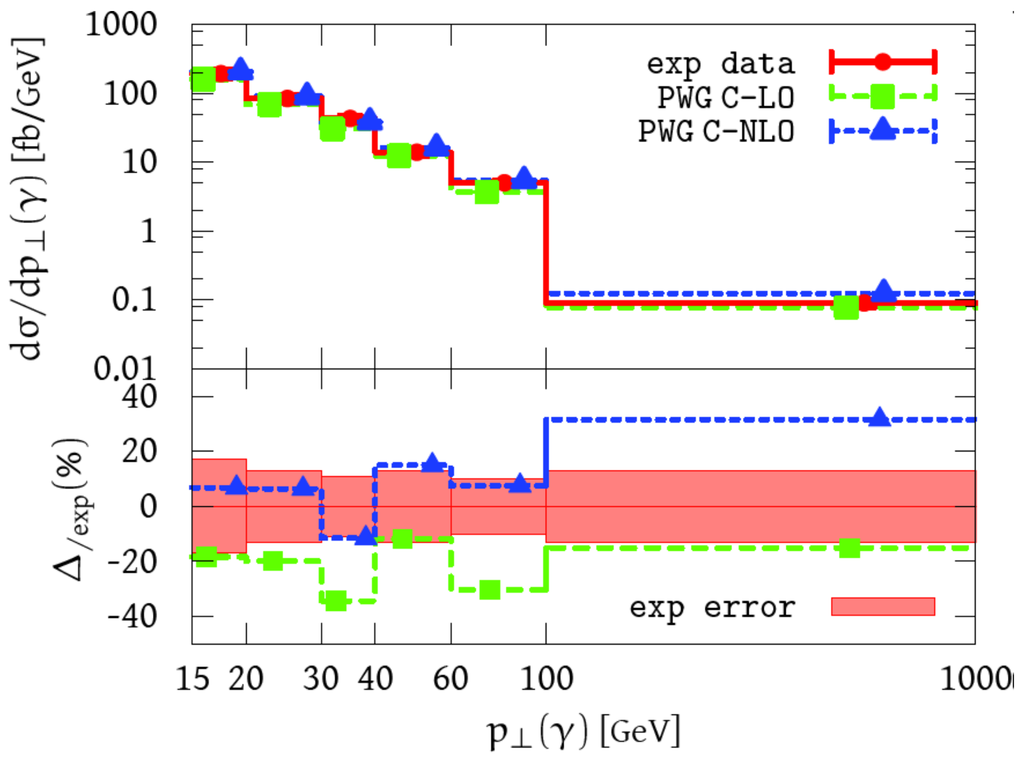
* The ATLAS Collaboration, Phys. Rev. D 87 (2013)

Results: comparisons with ATLAS data (II)

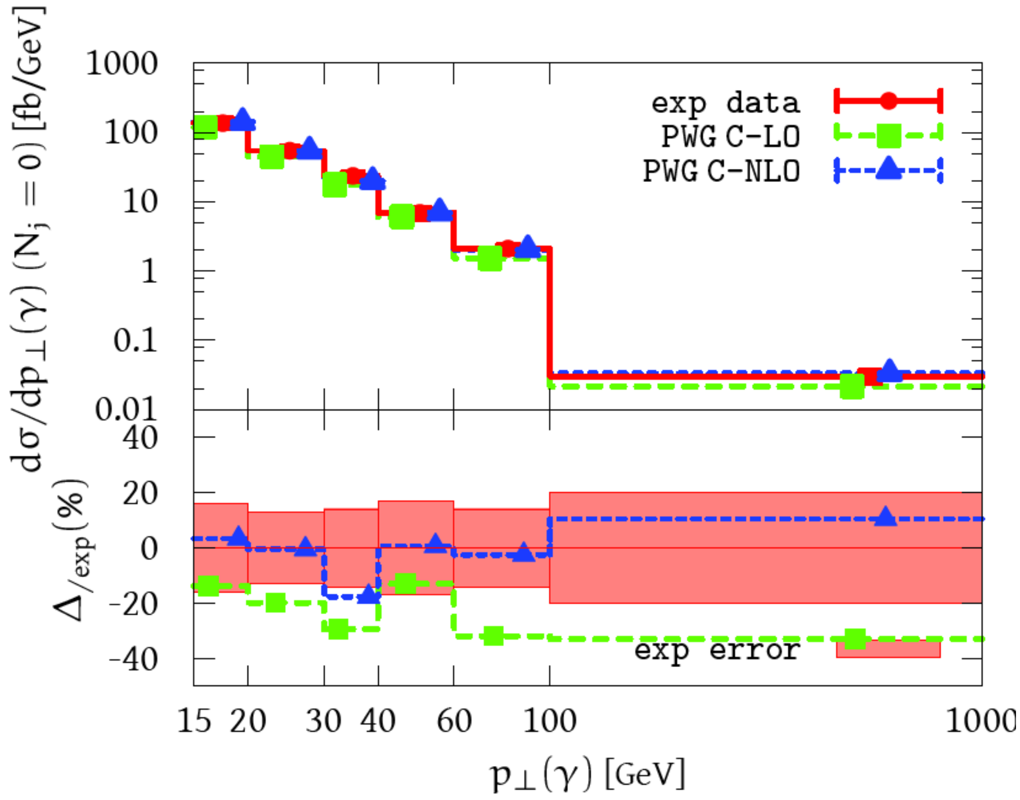
$pp \to l\nu_l\gamma + X$ $\sqrt{s} = 7\text{TeV}$ Data 2011 $\int \mathcal{L}dt = 4.6\ \text{fb}^{-1}$

Photon transverse momentum

Inclusive selection $N_{jet} \geq 0$



Exclusive selection $N_{jet}=0$

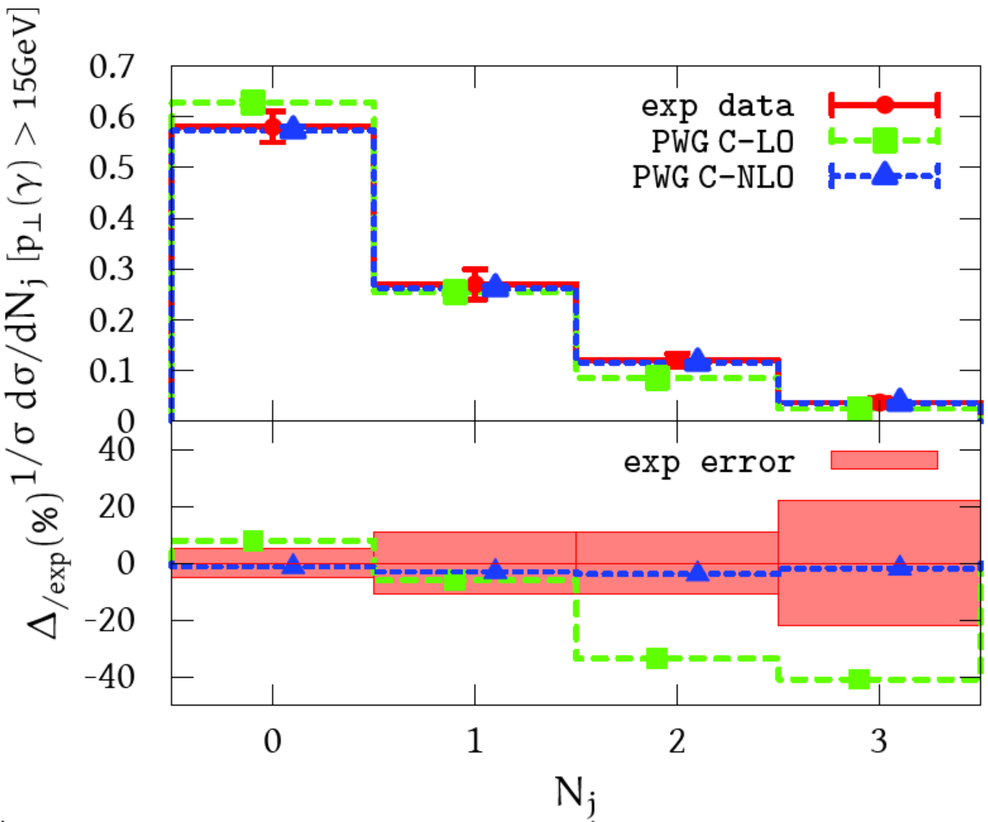


Results: comparisons with ATLAS data (III)

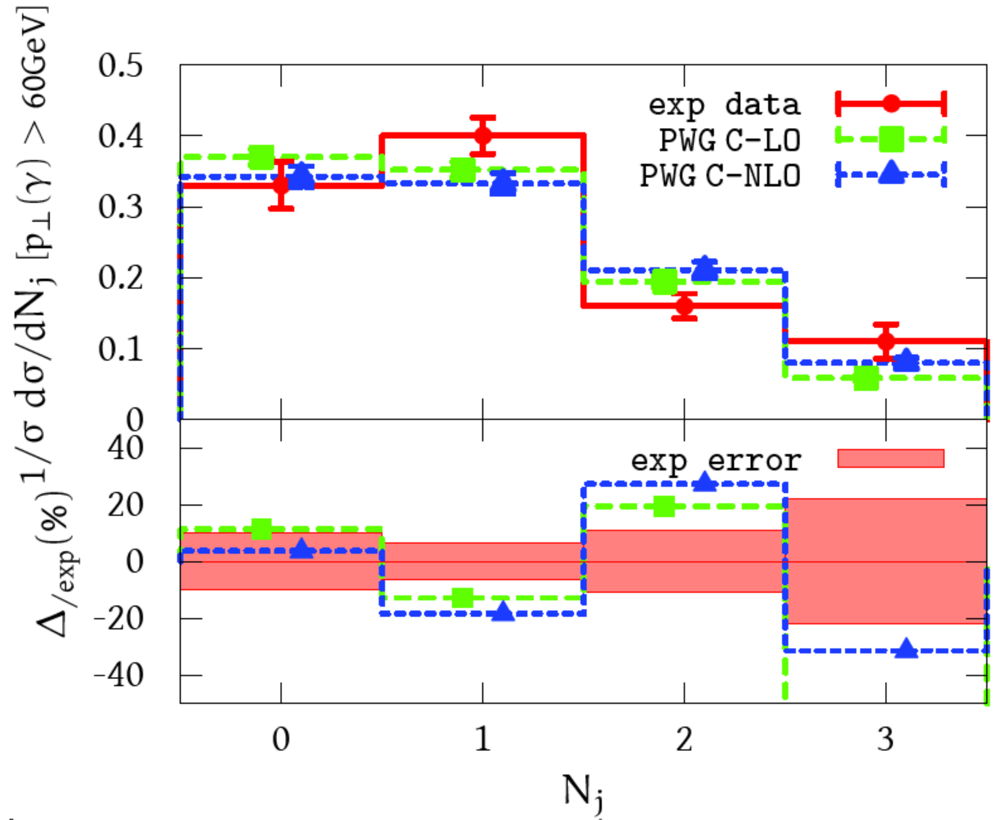
$pp \to l\nu_l\gamma + X$ $\sqrt{s} = 7\text{TeV}$ Data 2011 $\int \mathcal{L}dt = 4.6\ \text{fb}^{-1}$

Jet multiplicity

$p_T(\gamma) > 15$ GeV



$p_T(\gamma) > 60$ GeV



Conclusions and outlook

- NLO QCD corrections to Wγ production in pp collisions:
  - NLO+PS description within POWHEG-MiNLO+PYTHIA
  - Photon fragmentation contribution included
  - NLO corrections to the fragmentation contribution
- Improvements in data/theory comparison
- General treatment of isolated photons in hadronic collisions
  - Future applications to Zγ/γγ production
- The code will be available on the POWHEG-BOX-V2 repository
  http://powhegbox.mib.infn.it

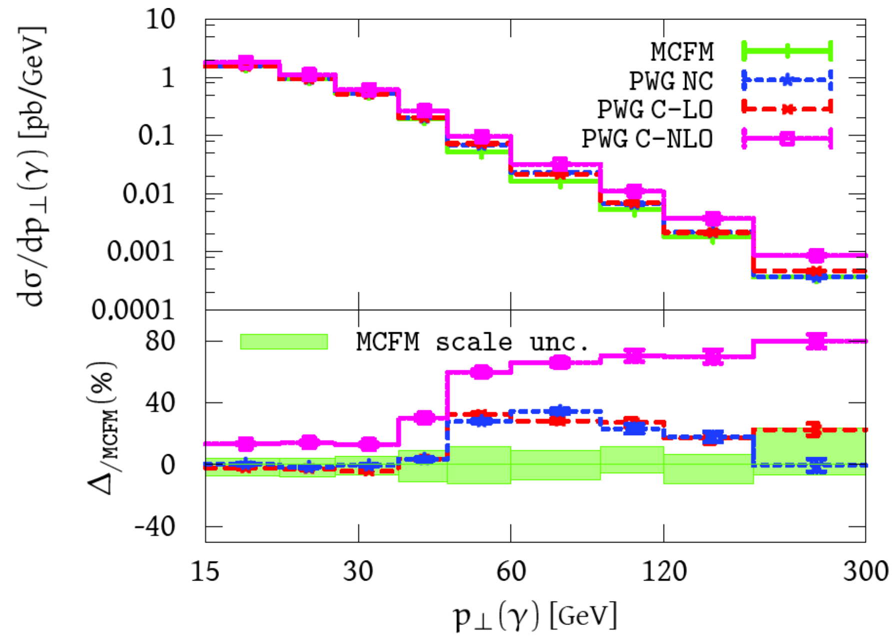
Backup slides

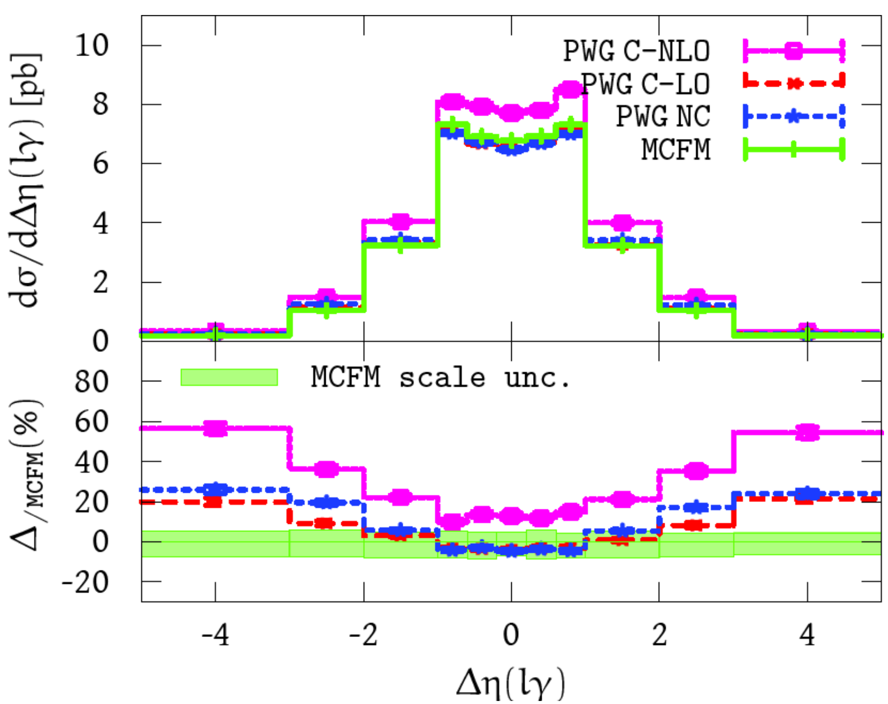
Results: comparisons with MCFM (II)

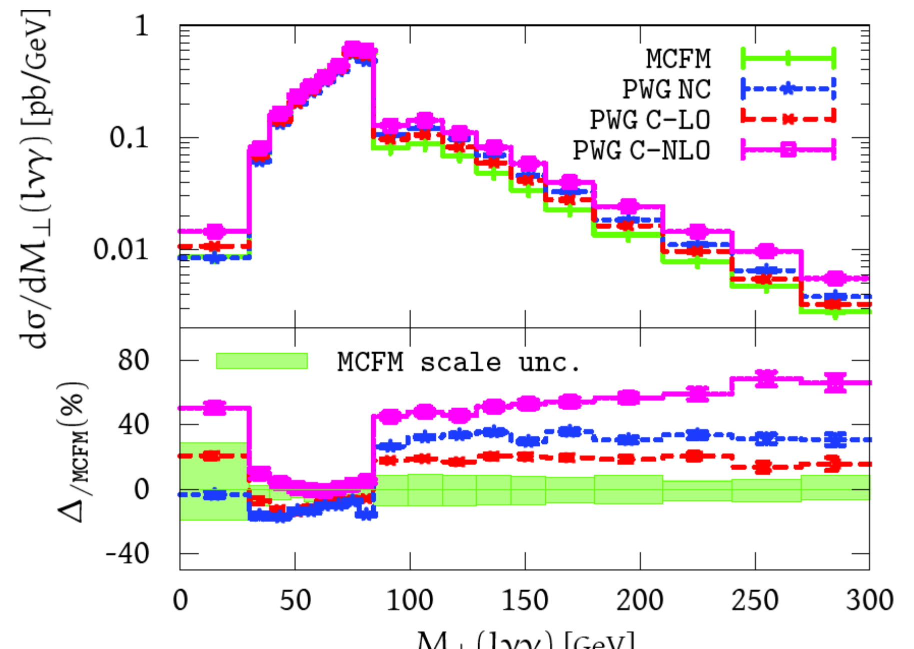
Basic photon cuts: $\sqrt{s} = 14\text{TeV}$

$$p_T(\gamma) > 15\text{GeV}, \quad |\eta_\gamma| < 2.37, \quad \Delta R_{l\gamma} > 0.7$$

MCFM	PWG-NC
$23.47(1)^{+5\%}_{-8\%}$	$23.96(7)^{+10\%}_{-15\%}$
PWG-C-LO	**PWG-C-NLO**
$23.52(7)^{+11\%}_{-16\%}$	$28.51(13)^{+4\%}_{-11\%}$



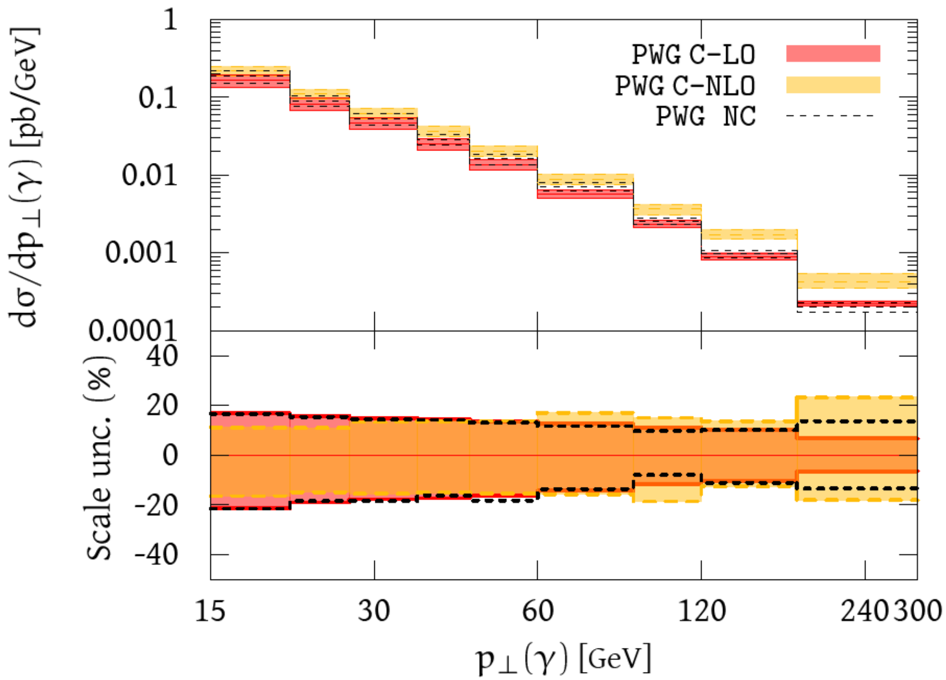


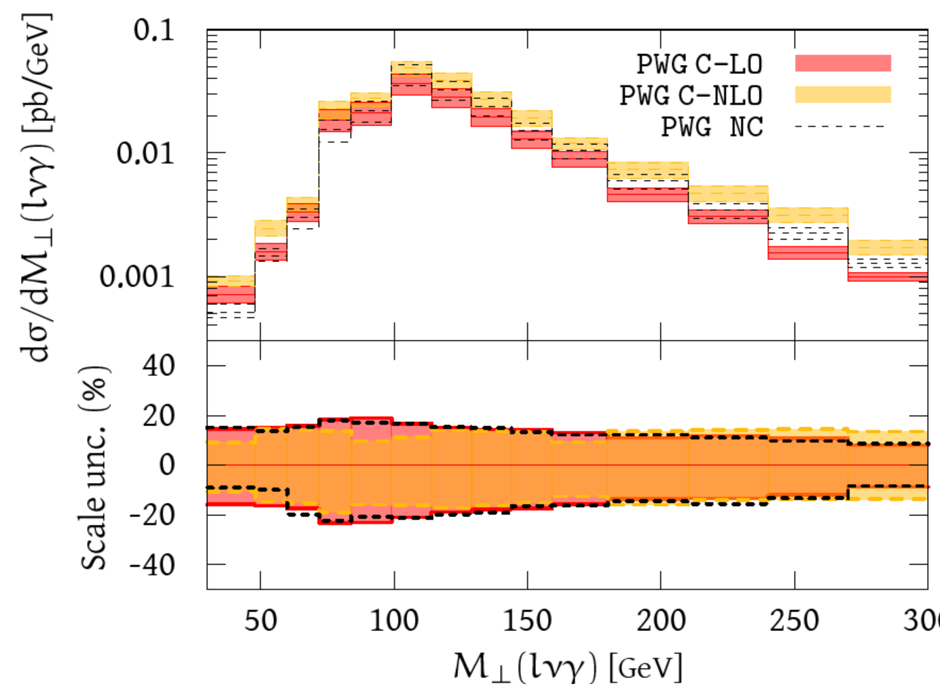


Results: uncertainties from scale variations

Photon + lepton cuts

$\sqrt{s} = 14\text{TeV}$





- Upper and lower boundings from variations in opposite direction

$$(K_R, K_F) \in \left\{ \left(\frac{1}{2}, 2\right), \left(2, \frac{1}{2}\right) \right\}$$