$W\gamma$ production at LHC with POWHEG + MiNLO

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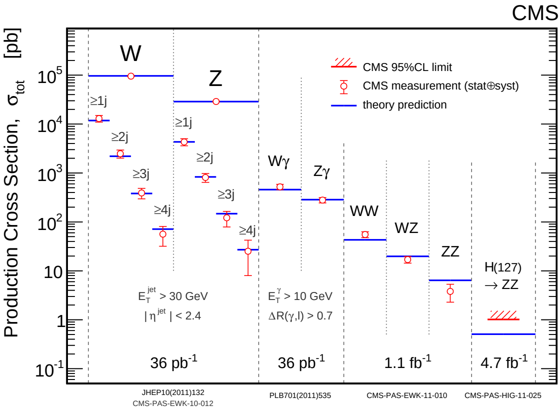
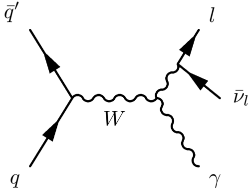
based on arXiv:1408.5766

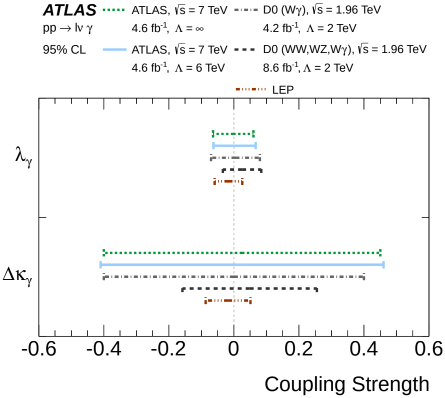
Motivations (1): luminosity[1]



[1] from CMS public results (a bit old)

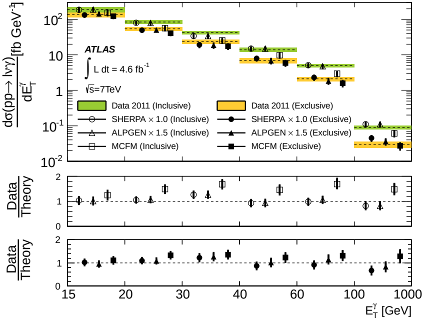
Motivations (2): ATGCs[2]

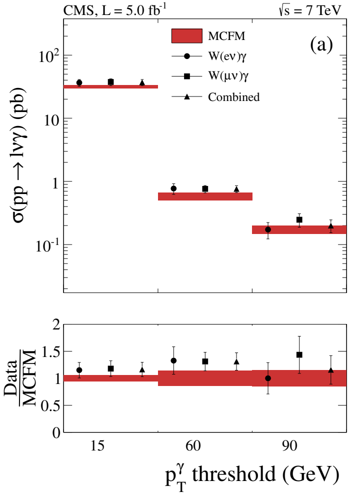




[2]from ATLAS public results

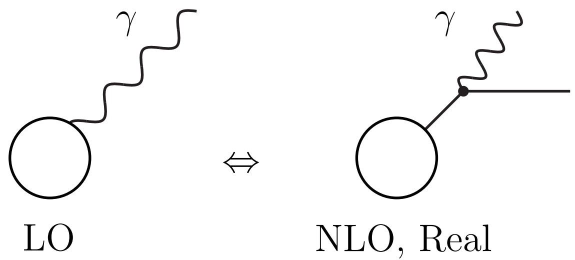
Motivations (3): Data VS Theory (tensions)[3]





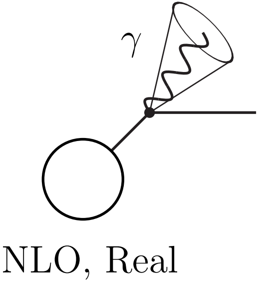
[3] G. Aad et al. Phys. Rev. **D87** (2013),
S. Chatrchyan et al. Phys. Rev. **D89** (2013)

NLO QCD corrections with isolated γ



- QED singularities from the integration of real QCD corrections
- no virtual counterpart, ...

Theory wayout (1): Frixione isolation[4]

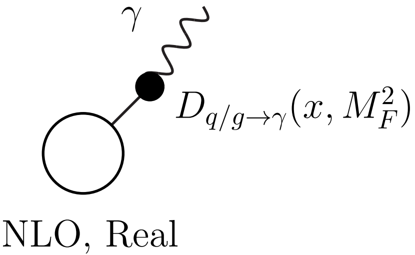


$$\sum_{R_{j,\gamma}<R}^{\forall_{R<R_0}} E_{T,j} < \epsilon_h \, p_{\mathrm{T}}^{\gamma} \left(\frac{1-\cos R}{1-\cos R_0} \right)$$

not directly comparable with data

[4] S. Frixione, Phys. Lett. B **429** (1998) 369

Theory wayout (2): fragmentation functions[5]



- extracted from data
- **collinear** approximation

[5]S. Catani et al., JHEP **0205** (2002) 028

$W\gamma$ production in POWHEG: target

- predictions for $pp \to W(l\nu)\gamma$ at NLO+PS QCD accuracy

- exclusive generation of radiated particles (q/g or γ) in the POWHEG framework

Theoretical predictions: state of the art (1)

Theoretical predictions for $pp \to W\gamma$

- NLO QCD corrections:
  J. Ohnemus Phys. Rev. **D47** (1993),
  U. Baur et al., Phys. Rev. **D48** (1993) and Phys. Rev. **D57** (1998)
  D. De Florian and A. Signer Eur. Phys. J. **C16** (2000)

- NLO EW corrections (leading pole):
  E. Accomando et al., Eur. Phys. J. **C47** (2006)

- NNLO QCD corrections (preliminary results):
  M. Grazzini et al., Phys.Lett. **B731** (2014),
  M. Grazzini arXiv:1407.1618

Theoretical predictions: state of the art (2)

isolated γ production in MC event generators

- LO matrix element merged with QCD+QED PS (isolated γ and $\gamma\gamma$ production):
  S. Hoeche et al., Phys. Rev. **D81** (2010)

- $\gamma\gamma$ production with the `POWHEG` method:
  L. D'Errico and P. Richardson JHEP **1202** (2012)

- $t\bar{t}\gamma$ and $t\bar{t}\gamma\gamma$ production in the `POWHEG BOX` framework:
  A. Kardos and T. Trocsany arXiv:1406.2324, arXiv:1408.0278

POWHEG [6] in a nutshell: QCD processes (1)

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \Bigg\{ \Delta^{f_b}\Big(\mathbf{\Phi}_n, p_{\mathrm{T}}^{\min}\Big) + \sum_{\alpha_{\mathrm{r}} \in \{\alpha_{\mathrm{r}} | f_b\}} \frac{\Big[d\Phi_{\mathrm{rad}}\, \theta\left(k_{\mathrm{T}} - p_{\mathrm{T}}^{\min}\right) \Delta^{f_b}(\mathbf{\Phi}_n, k_{\mathrm{T}})\; R\left(\mathbf{\Phi}_{n+1}\right) \Big]_{\alpha_{\mathrm{r}}}^{\bar{\mathbf{\Phi}}_n^{\alpha_{\mathrm{r}}} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \Bigg\}$$

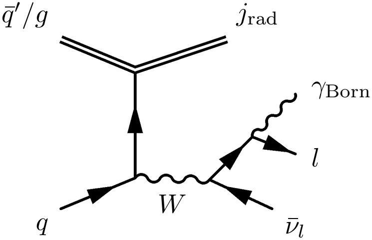
[6] P. Nason, JHEP **0411** (2004), S. Frixione et al., JHEP **0711** (2007), S. Alioli et al., JHEP **1006** (2010)

POWHEG in a nutshell: QCD processes (2)

$$\bar{B}^{f_b}(\mathbf{\Phi}_n) = \left[B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n)\right]_{f_b}$$
$$+ \sum_{\alpha_\mathrm{r} \in \{\alpha_\mathrm{r}|f_b\}} \int \left[d\Phi_\mathrm{rad} \left\{ R(\mathbf{\Phi}_{n+1}) - C(\mathbf{\Phi}_{n+1}) \right\} \right]_{\alpha_\mathrm{r}}^{\bar{\mathbf{\Phi}}_n^{\alpha_\mathrm{r}} = \mathbf{\Phi}_n}$$
$$+ \sum_{\alpha_\oplus \in \{\alpha_\oplus|f_b\}} \int \frac{dz}{z} G_\oplus^{\alpha_\oplus}(\mathbf{\Phi}_{n,\oplus}) + \sum_{\alpha_\ominus \in \{\alpha_\ominus|f_b\}} \int \frac{dz}{z} G_\ominus^{\alpha_\ominus}(\mathbf{\Phi}_{n,\ominus})$$

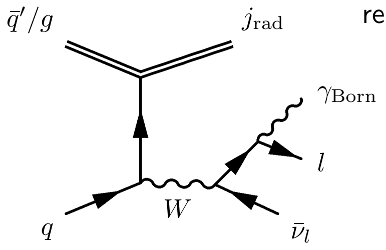
$$\Delta^{f_b}(\mathbf{\Phi}_n, p_\mathrm{T}) =$$
$$\exp\left\{ - \sum_{\alpha_\mathrm{r} \in \{\alpha_\mathrm{r}|f_b\}} \int \frac{\left[d\Phi_\mathrm{rad} R(\mathbf{\Phi}_{n+1})\, \theta\left(k_\mathrm{T}(\mathbf{\Phi}_{n+1}) - p_\mathrm{T}\right) \right]_{\alpha_\mathrm{r}}^{\bar{\mathbf{\Phi}}_n^{\alpha_\mathrm{r}} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

$W\gamma$ production in POWHEG: starting point



- QCD (QED) singular regions are separated (FKS method) and mapped on the corresponding underlying Born configurations $W\gamma$ (Wj)
- hardest emission (q/g or γ) generated from the modified POWHEG Sudakov form factor

$W\gamma$ production in POWHEG: $W\gamma$ Underlying Born



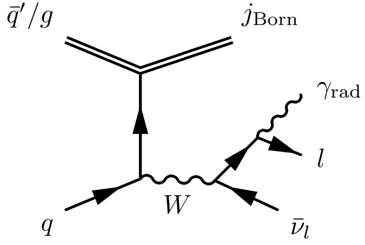
QED Born singularities:
removed by small generation cuts

$$p^{\gamma}_{T,\,\rm min} \ll p^{\gamma}_{T,\,\rm exp.cut}$$

$$\Delta R_{\rm min}(\gamma, l) \ll \Delta R_{\rm exp\,cut}(\gamma, l)$$

$\rm Born\, W\gamma \times QCD\, Rad.$

$W\gamma$ production in POWHEG: Wj Underlying Born



$\mathrm{Born}\, Wj \times \mathrm{QED\,Rad.}$

QCD Born singularities:

- no exp. cuts on $j_{\rm Born}$ $\Rightarrow$ no safe generation cuts on $j_{\rm Born}$
- MiNLO[7] provides the Sudakov suppression factor that cancels the Born QCD singularities

[7] K. Hamilton et al., JHEP **1210** (2012), K. Hamilton et al., JHEP **1305** (2013)

$W\gamma$ production in POWHEG: remark

- MiNLO is mandatory for Wj underlying Born
- for $W\gamma$ underlying Born MiNLO is used in order to improve the α_S scale choice in the QCD corrections

$W\gamma$ production in POWHEG: implementation

- NC *with No Competition*
- C-LO *with Competition, LO normalization*
- C-NLO *with Competition, NLO normalization*

Competition
between QCD and QED radiation off quarks

$W\gamma$ production in POWHEG: NC (1)

FKS

1 Real ME

$jj \to l\nu\gamma j$

$j = q, g$

$\alpha_{\rm r} = \alpha_{\rm QCD}$

$W\gamma$ UB

QCD singular region

$\alpha_{\rm r} = \alpha_{\rm QED}$

Wj UB

QED singular region

$W\gamma$ production in POWHEG: NC (2)

for $W\gamma$ underlying Born[8]

- normalization:

$$\overline{B}_{W\gamma} = B_{W\gamma} + V_{W\gamma} + \sum_{\alpha_{\rm QCD}} \int \left[d\Phi_{\rm Rad} (R_{W\gamma;j} - C) \right]^{\alpha_{\rm QCD}}$$

- radiation dynamics:

$$\Delta_{W\gamma}^{\alpha_{\rm QCD}} = \exp\{ - \int \left[d\Phi_{\rm Rad} \frac{R_{W\gamma;j}}{B_{W\gamma}} \right]^{\alpha_{\rm QCD}} \}$$

- `scalup` choice (POWHEG standard):

$$p_T^{\rm Rel.}(j_{\rm rad.})$$

[8] simplified notation: MiNLO factors understood

$W\gamma$ production in POWHEG: NC (3)

for Wj underlying Born

- normalization:

$$\overline{B}_{Wj} = B_{Wj} + \sum_{\alpha_{\rm QED}} \int \left[d\Phi_{\rm Rad} (R_{Wj;\gamma} - C) \right]^{\alpha_{\rm QED}}$$

- radiation dynamics:

$$\Delta_{Wj}^{\alpha_{\rm QED}} = \exp\{ - \int \left[d\Phi_{\rm Rad} \frac{R_{Wj;\gamma}}{B_{Wj}} \right]^{\alpha_{\rm QED}} \}$$

- `scalup` choice:
  - $p_T(j_{\rm Born})$ for QCD shower
  - $p_T^{\rm Rel.}(\gamma_{\rm rad.})$ for QED shower

$W\gamma$ production in POWHEG: C-LO

$W\gamma$ underlying Born: same as NC

for Wj underlying Born

- normalization: same as for NC
- radiation dynamics:

$$\Delta_{Wj} = \exp\{-\sum_{\alpha_{\rm QED}} \int [d\mathbf{\Phi}_{\rm Rad} \frac{R_{Wj;\gamma}}{B_{Wj}}]^{\alpha_{\rm QED}} - \sum_{\alpha_{\rm QCD}} \int [d\mathbf{\Phi}_{\rm Rad} \frac{R_{Wj;j}}{B_{Wj}}]^{\alpha_{\rm QCD}}\}$$

- `scalup` choice (POWHEG standard): $p_T^{\rm Rel}(\rm rad)$

$W\gamma$ production in POWHEG: C-NLO

- same dynamics of C-LO

- NLO Wj normalization

$$\overline{B}_{Wj} = B_{Wj} + V_{Wj}^{\mathrm{QCD}} + \sum_{\alpha_{\mathrm{QED}}} \int \left[d\mathbf{\Phi}_{\mathrm{Rad}} (R_{Wj;\gamma} - C) \right]^{\alpha_{\mathrm{QED}}} + \sum_{\alpha_{\mathrm{QCD}}} \int \left[d\mathbf{\Phi}_{\mathrm{Rad}} (R_{Wj;j} - C) \right]^{\alpha_{\mathrm{QCD}}}$$

Comparison with ATLAS data[9]: event selection

$$p_{\rm T}^{\gamma} > 15 \text{ GeV}, |\eta_\gamma| < 2.37, \Delta R_{\ell\gamma} > 0.7,$$

$$R_0 = 0.4, \epsilon_h = 0.5, \sum_{R_{j,\gamma}<R_0} E_{T,j} < \epsilon_h \, p_{\rm T}^{\gamma}$$

$$p_{\rm T}^{\ell} > 25 \text{ GeV}, |\eta_\ell| < 2.47, p_{\rm T}^{\rm miss.} > 35 \text{ GeV}$$

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

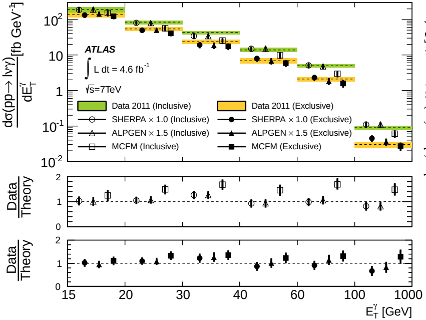
[9] Phys. Rev. **D87** (2013)

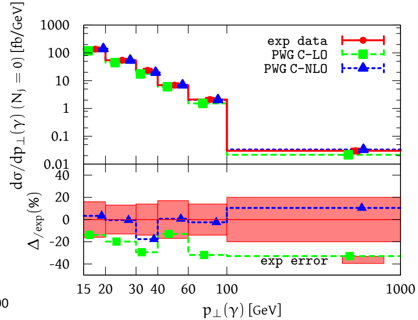
Comparison with ATLAS data: cross sections

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

Comparison with ATLAS data: distributions (1)

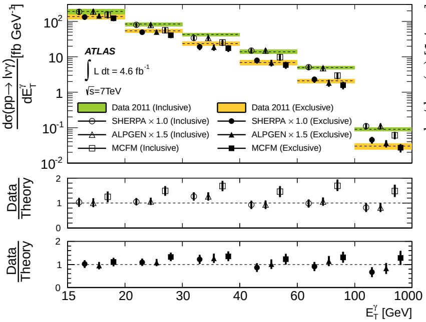
$p_T^\gamma,\ N_{\rm jet} = 0$

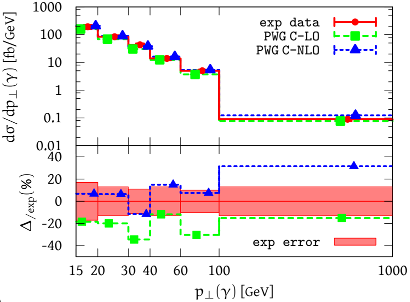




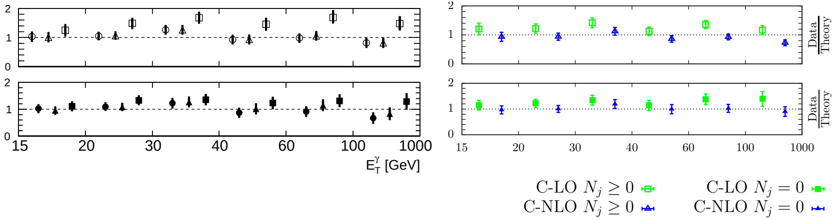
Comparison with ATLAS data: distributions (2)

$p_T^{\gamma},\ N_{\text{jet}} \geq 0$

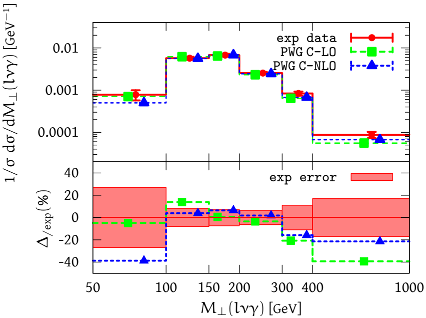


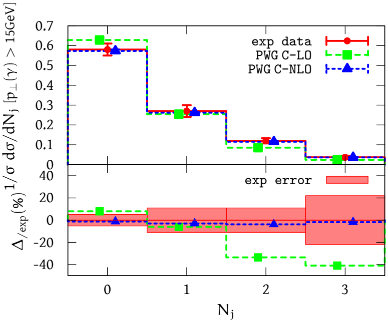


Comparison with ATLAS data: distributions (3)



Comparison with ATLAS data: distributions (4)





Conclusions

- $W\gamma$ production process implemented in the `POWHEG-BOX-V2` generator

  NLO QCD normalization
  exclusive generation of the final state particles

- general treatement of isolated photons in the final states:

  $Z\gamma$, $\gamma\gamma$ possible applications

- improvement in the data/theory comparison

- the code will be available on the `POWHEG-BOX-V2` repository

Backup Slides

Comparison with MCFM, event selections[10]

- Basic Photon cuts:

$$p_{\mathrm{T}}^{\gamma} > 15\ \mathrm{GeV},\ |\eta_\gamma| < 2.37,\ \Delta R_{\ell\gamma} > 0.7,$$
$$R_0 = 0.4,\ \epsilon_h = 0.5$$

- $M_T(l\nu\gamma)$ cuts:

$$\mathrm{Basic\ Photon} + M_T > 90\ \mathrm{GeV}$$

- Lepton cuts:

$$\mathrm{Basic\ Photon} + p_{\mathrm{T}}^{\ell} > 25\ \mathrm{GeV},\ |\eta_\ell| < 2.47,\ p_{\mathrm{T}}^{\nu} > 35\ \mathrm{GeV}$$

[10] as in JHEP **1107** (2011) 018

Comparison with MCFM: NLO results

7 TeV

Cuts	MCFM	POWHEG NLO
Basic Photon	13.12(4)	13.15(1)
M_T cut	2.770(1)	2.774(3)
Lepton cuts	1.126(1)	1.123(4)

14 TeV

Cuts	MCFM	POWHEG NLO
Basic Photon	23.90(8)	24.04(3)
M_T cut	6.230(2)	6.250(9)
Lepton cuts	2.342(2)	2.340(6)

Frixione isolation procedure

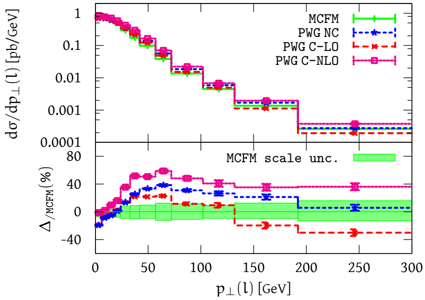
Comparison with MCFM: full simulation (1)

7 TeV				
Cuts	MCFM	POWHEG-NC	C-LO	C-NLO
Basic	$12.92(3)^{+4\%}_{-6\%}$	$13.11(3)^{+8\%}_{-10\%}$	$12.95(3)^{+8\%}_{-11\%}$	$15.08(7)^{+2\%}_{-9\%}$
M_T	$2.625(1)^{+6\%}_{-6\%}$	$3.65(2)^{+10\%}_{-11\%}$	$3.20(2)^{+11\%}_{-11\%}$	$4.23(3)^{+10\%}_{-10\%}$
Lept.	$1.077(1)^{+6\%}_{-6\%}$	$1.44(1)^{+8\%}_{-10\%}$	$1.31(1)^{+11\%}_{-11\%}$	$1.75(2)^{+7\%}_{-13\%}$

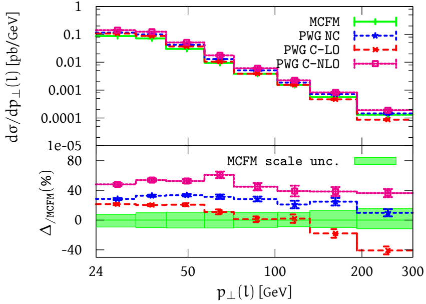
- MCFM: fragmentation funtions
- POWHEG: experimental-like isolation condition

$$\sum_{R_{j,\gamma}<R_0} E_{T,j} < \epsilon_h \, p_{\mathrm{T}}^{\gamma}$$

Comparison with MCFM: full simulation (2)

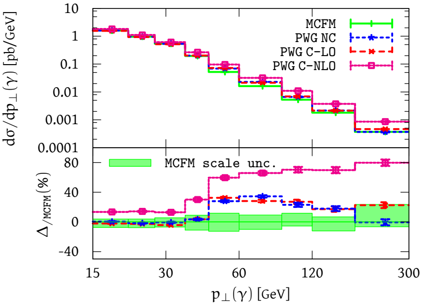


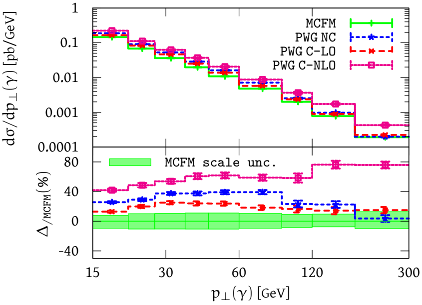
Basic cuts



Lepton cuts

Comparison with MCFM: full simulation (3)





Basic cuts

Lepton cuts