HL/HE-LHC WG1 Meeting – QCD physics
CERN

Prospects on photon physics at HL/HE-LHC

G. Ferrera (Milano), A. Savin (Madison), J. Terrón (Madrid)

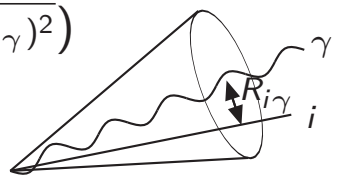
- **Outline:**
  - → Theoretical issues: photon isolation and higher order uncertainties
  - → Prospects from ATLAS: inclusive γ production at $\sqrt{s} = 27$ TeV and 14 TeV
    - ⋆ Comparison between MMHT2014, CT14, NNPDF3.0 and HERAPDF2.0 PDFs
    - ⋆ Predicted number of events for $\mathcal{L} = 15(3)$ ab^{-1} at HE-LHC (HL-LHC)
    - ⋆ Uncertainties on the predictions from those in the PDFs and terms beyond NLO
    - ⋆ $\sqrt{s} = 14$ TeV vs. $\sqrt{s} = 27$ TeV
    - ⋆ Other studies in progress
  - → Summary and outlook

THEORETICAL ISSUES

Photon Isolation studies

THEORY (Giancarlo Ferrera)

- Standard Cone: in a cone of radius R around $\mathbf{p}_\gamma$ the hadronic transverse energy
  $E_T^{had}(R) \equiv \sum_i E_{T_i}^{had}\Theta(R - R_{i\gamma})$ $\left(\text{with } R_{i\gamma} = \sqrt{(y_i - y_\gamma)^2 + (\phi - \phi_\gamma)^2}\right)$



$$E_T^{had}(R) \leq E_{T_{max}}$$

  ☹ Not possible to set $E_{T_{max}} = 0$ (to kill fragmentation component):
  it is not Infrared Safe (soft gluons cannot be emitted inside the cone).

- Smooth Cone[Frixione('98)]: for ALL cones with radius $r < R$ around $\mathbf{p}_\gamma$

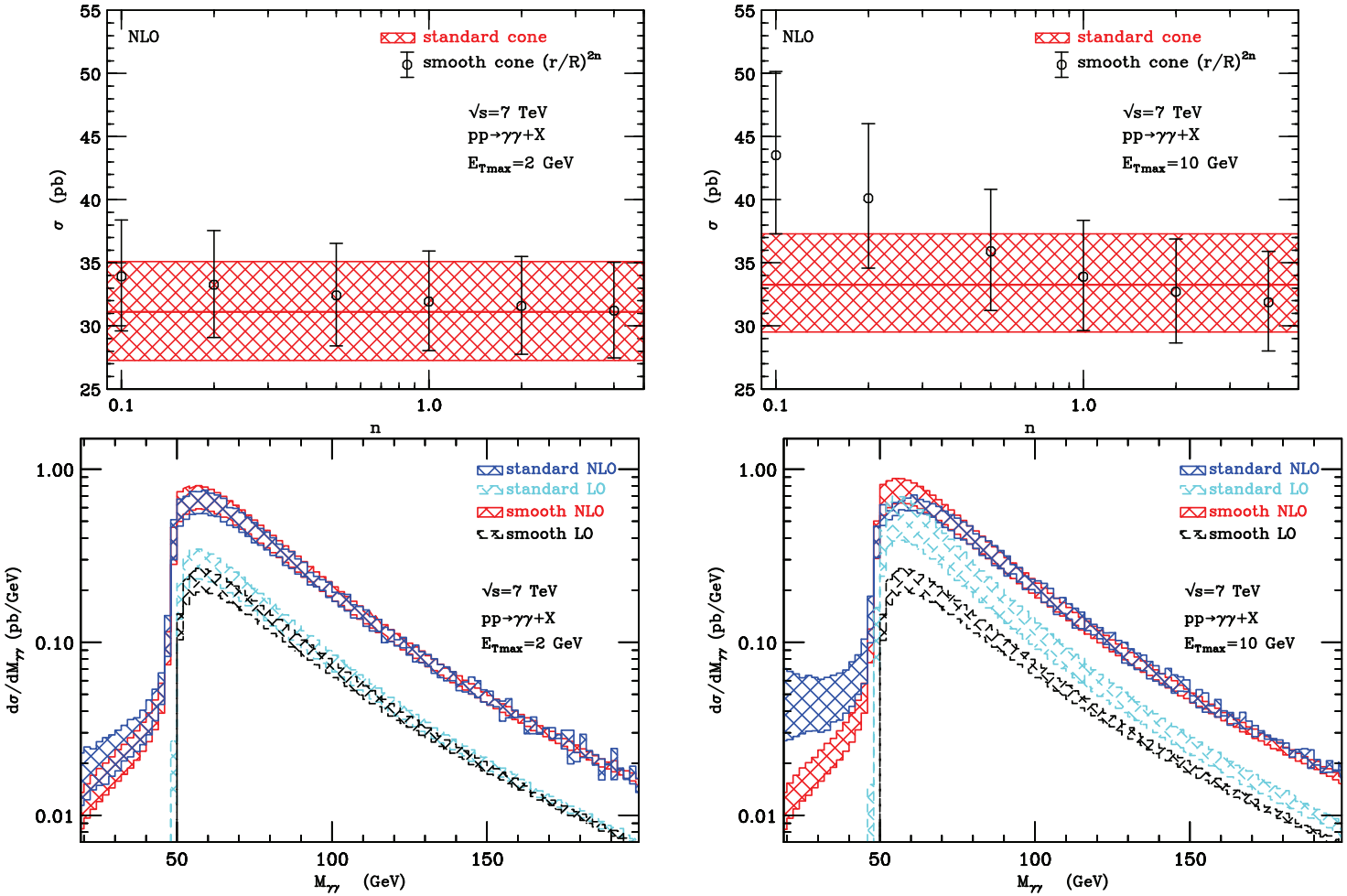
$$E_T^{had}(r) \leq E_{T_{max}}\, \chi(r; R) \xrightarrow{r \to 0} 0$$

  ☺ It is Infrared Safe (soft gluons can always be emitted inside the cone).
  ☺ Completely kill (poorly known) Fragmentation component.
  ☺ Direct component well defined (no parton-photon collinear divergences).
  ☹ Not easy to implement (a discrete version) in experimental analyses.

Physical constraint: $d\sigma_{smooth}(R; E_{T_{max}}) < d\sigma_{standard}(R; E_{T_{max}})$.
If isolation tight enough NLO QCD predictions with standard and smooth cone are similar (differences smaller than perturbative uncertainties).

Photon isolation

THEORY (Giancarlo Ferrera)

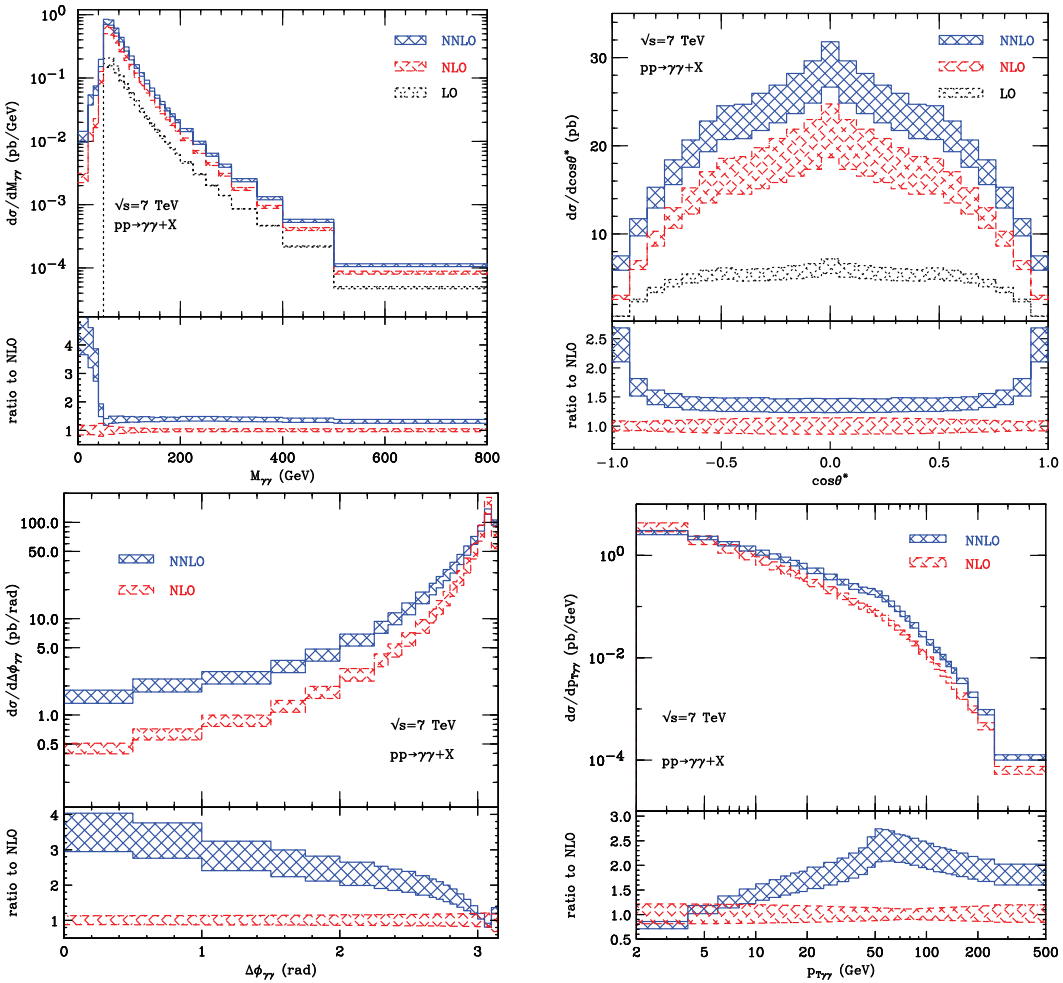


Standard and smooth cone cross sections including scale variation bands (from [arXiv:1802.02095]).

Important to perform similar studies also for isolated-photon production.

THEORY (Giancarlo Ferrera)

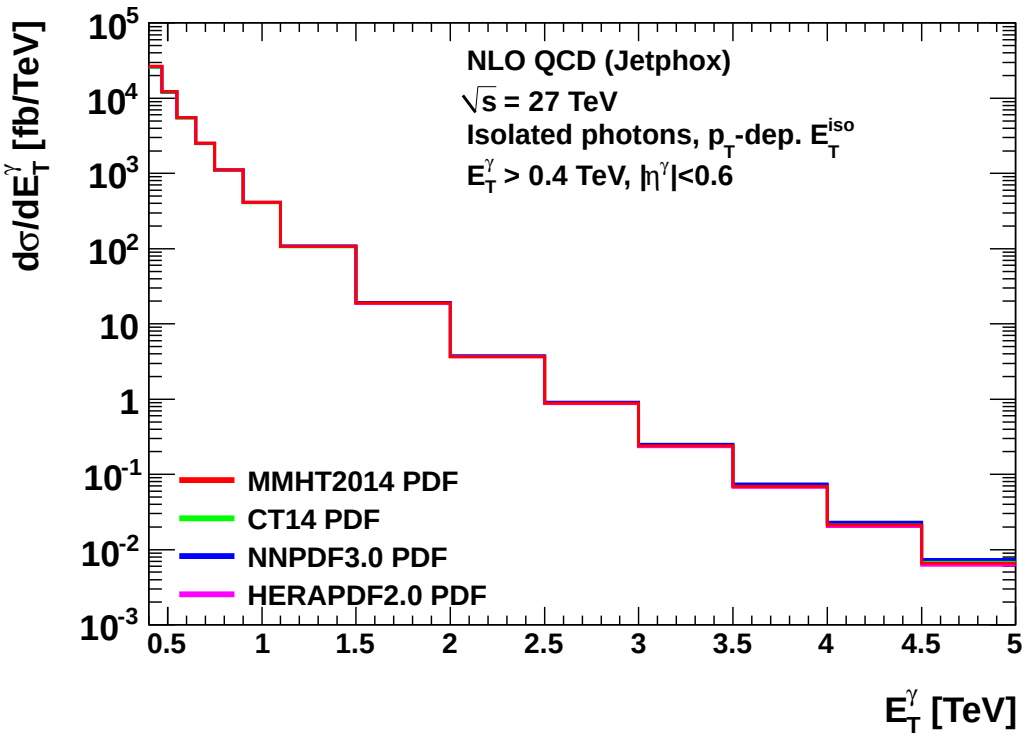
Theoretical uncertainties from higher orders



Standard (7-points) scale variation bands can underestimate "true" perturbative uncertainty. More reliable estimate obtained from differences between NNLO and NLO predictions.

PROSPECTS FROM ATLAS

Predictions for inclusive photon production at $\sqrt{s} = 27$ TeV



- Predicted $d\sigma/dE_T^\gamma$ for inclusive isolated photon production in pp collisions

→ $\sqrt{s} = 27$ TeV

→ NLO QCD for direct and fragmentation contributions

→ Photon Isolation in a cone of $R = 0.4$: $E_T^{\rm iso} < 0.0042 \cdot E_T^\gamma + 4.8$ GeV

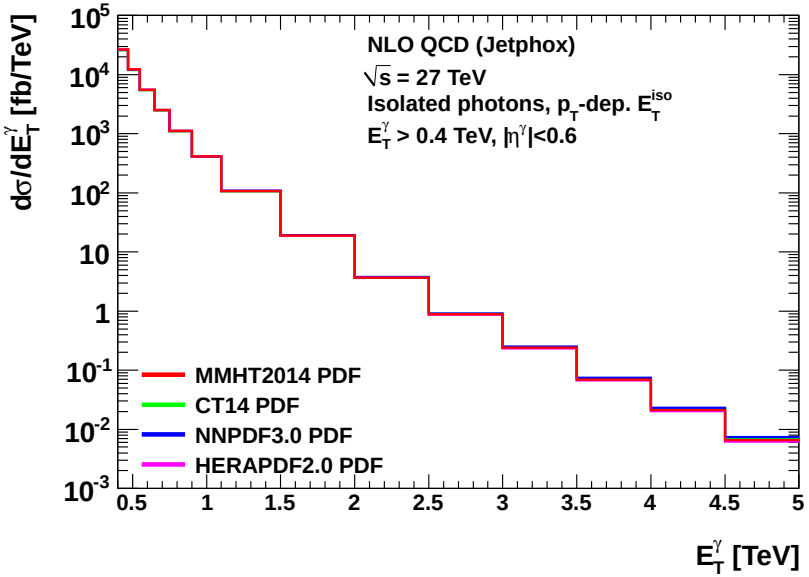
→ program JetPhox

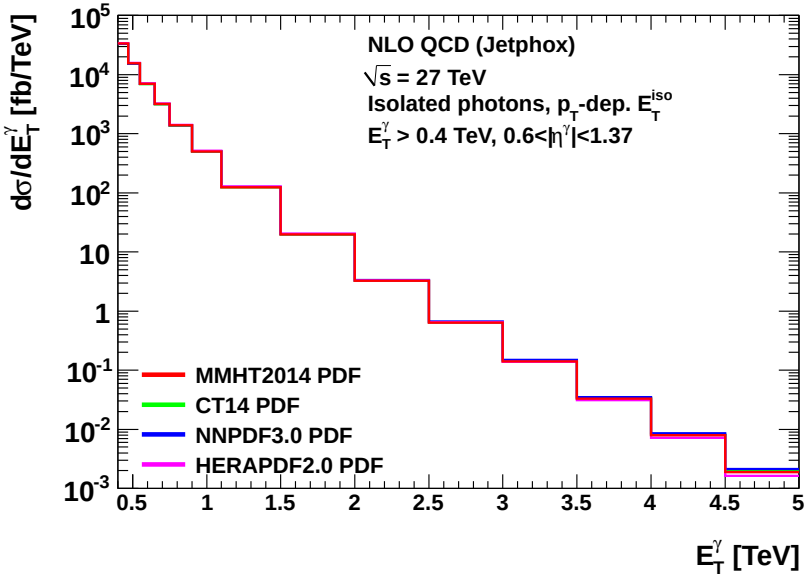
→ Proton PDFs: MMHT2014, CT14, NNPDF3.0, HERAPDF2.0

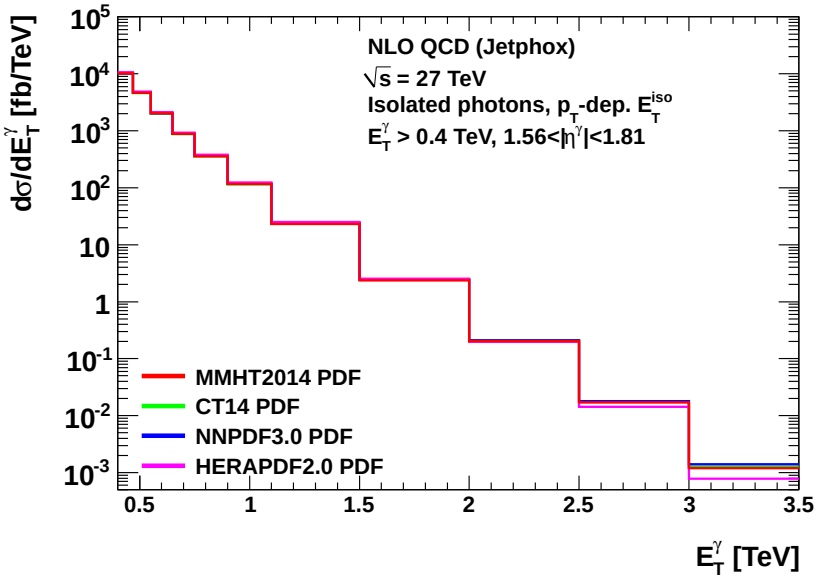
→ Fragmentation functions (parton-to-photon): BFG set II

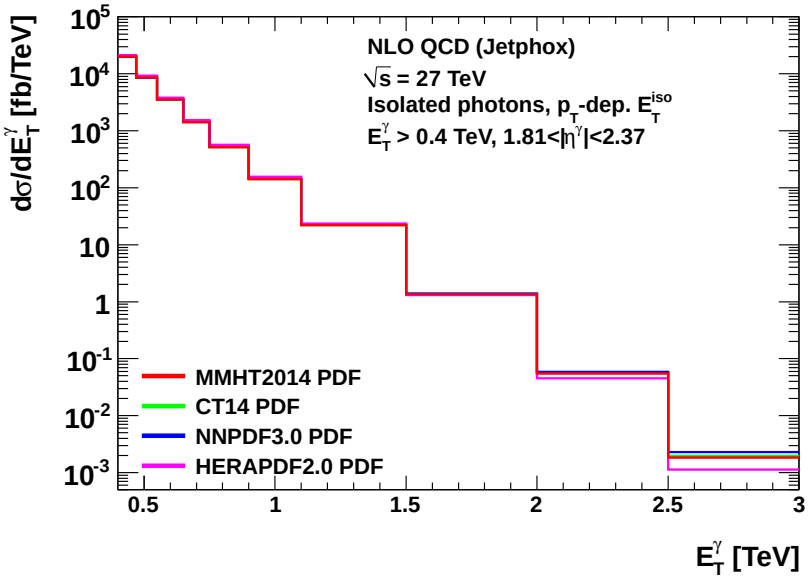
- Range in E_T^γ: 0.4–5 TeV
- Range in $|\eta^\gamma|$: $|\eta^\gamma| < 2.37$ excluding $1.37 < |\eta^\gamma| < 1.56$
  four regions in $|\eta^\gamma|$, namely, 0–0.6, 0.6–1.37, 1.56–1.81, 1.81–2.37

Predictions for inclusive-γ production at HE-LHC in $|\eta^{\gamma}|$ ranges

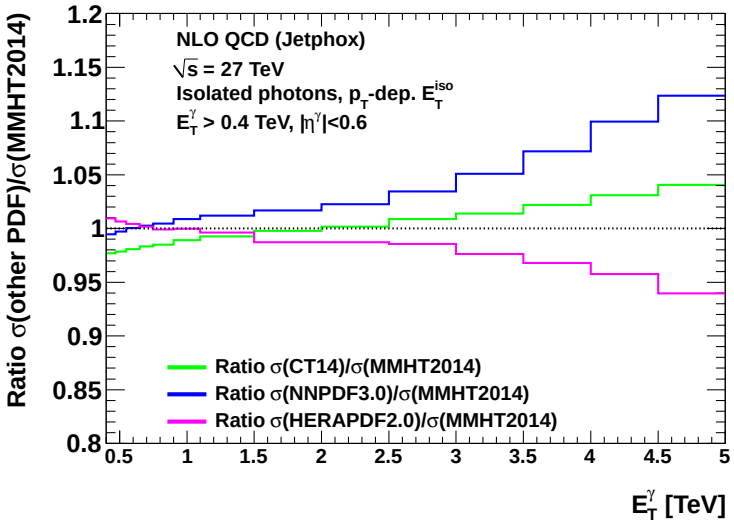


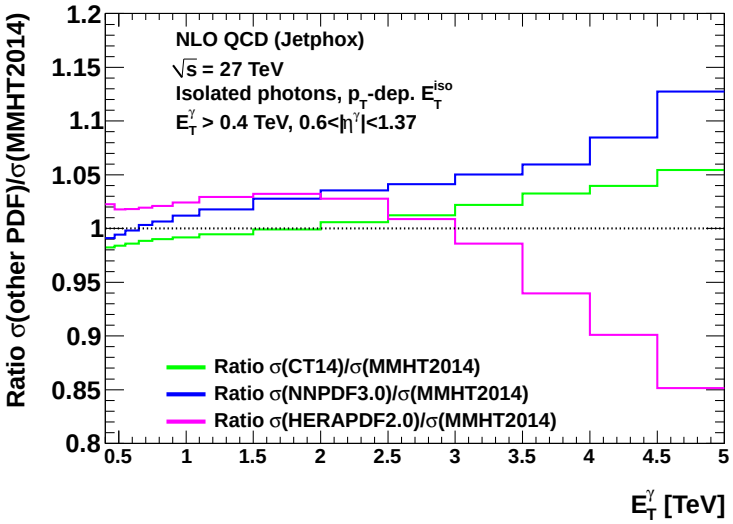


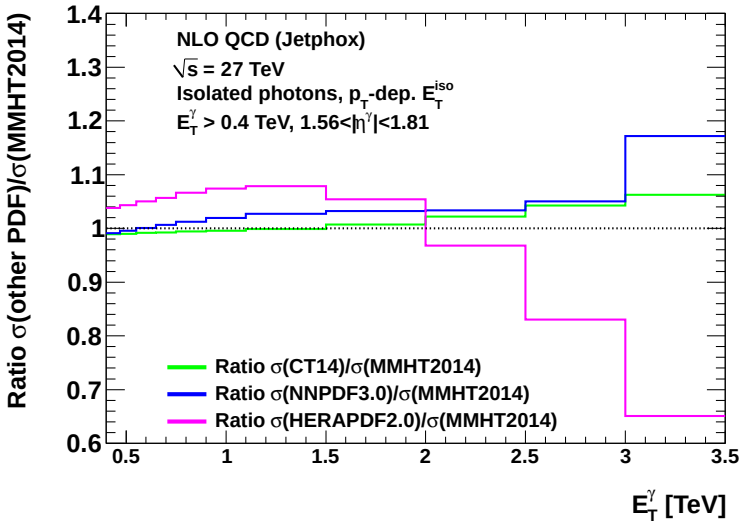


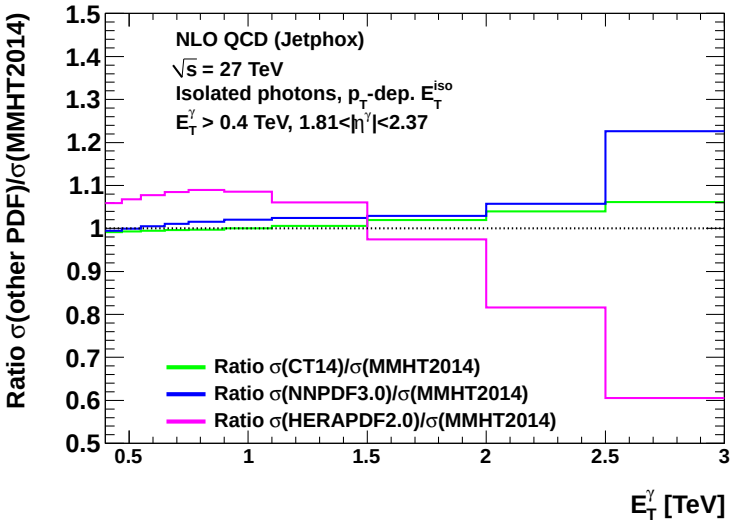


Predictions for HE-LHC: MMHT2014, CT14, NNPDF3.0, HERAPDF2.0



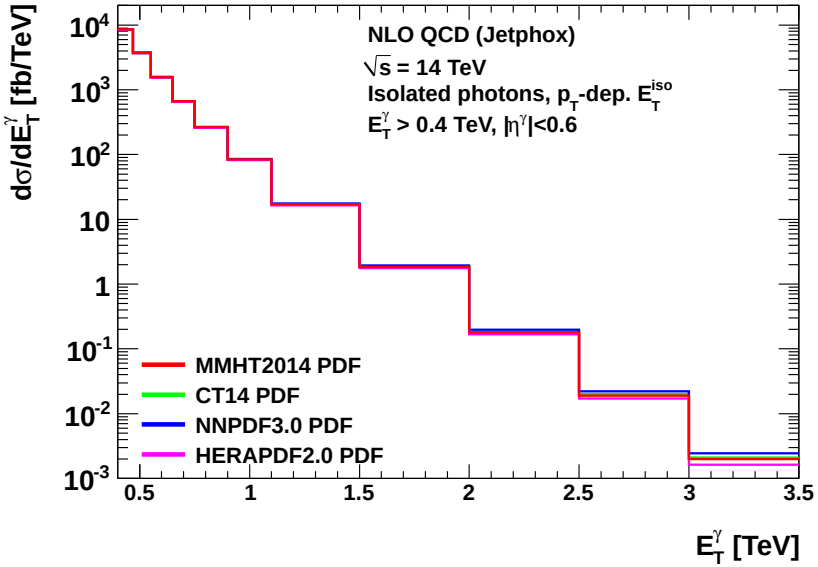


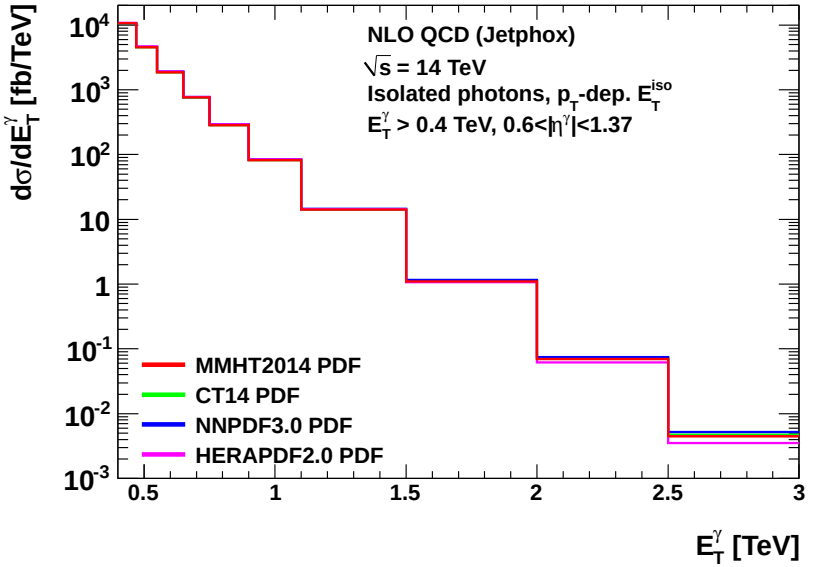


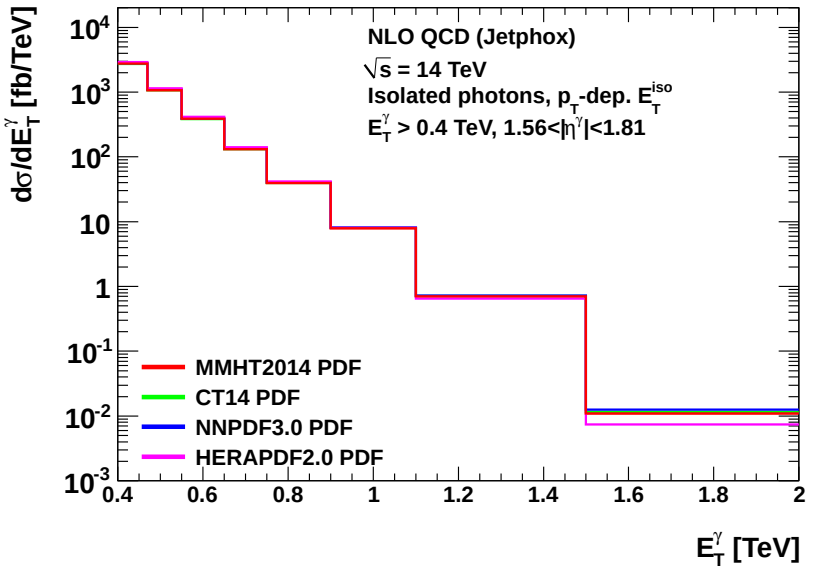


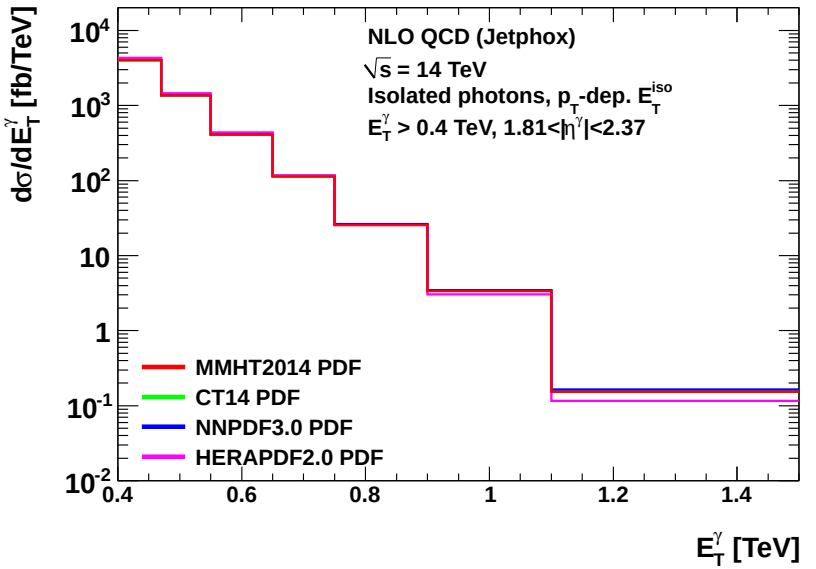
- **Differences up to $\sim 40\%$; the study has been extended to other parameterisations of the PDFs; uncertainties due to the PDFs have also been evaluated**

Predictions for inclusive-γ production at HL-LHC in $|\eta^{\gamma}|$ ranges

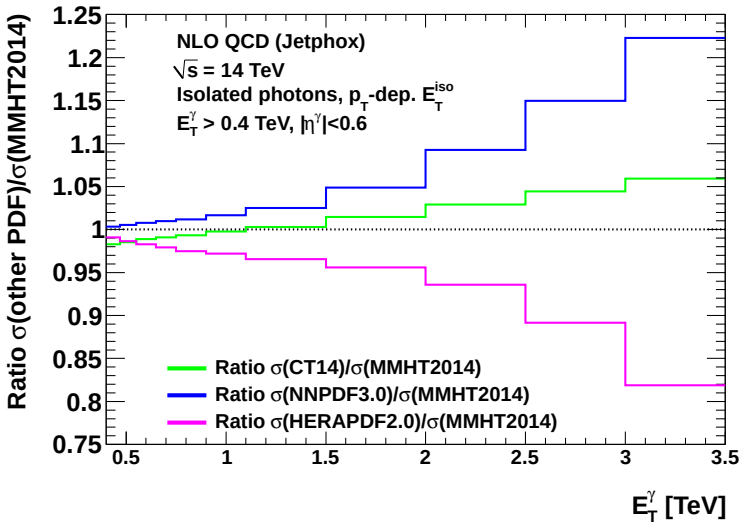


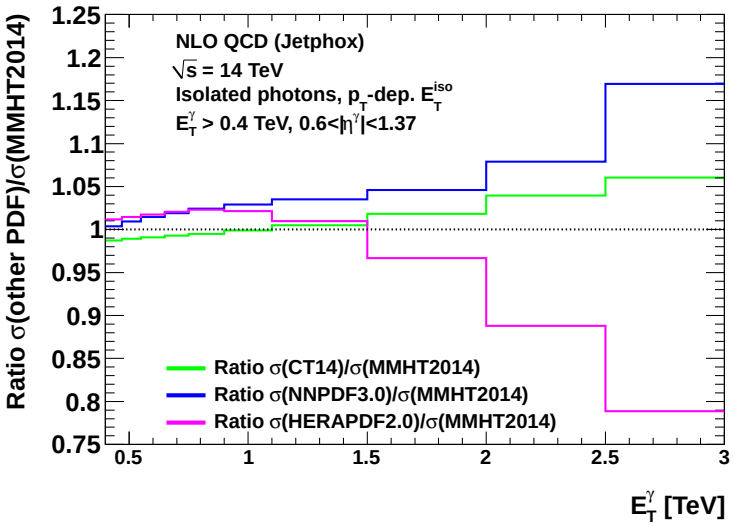


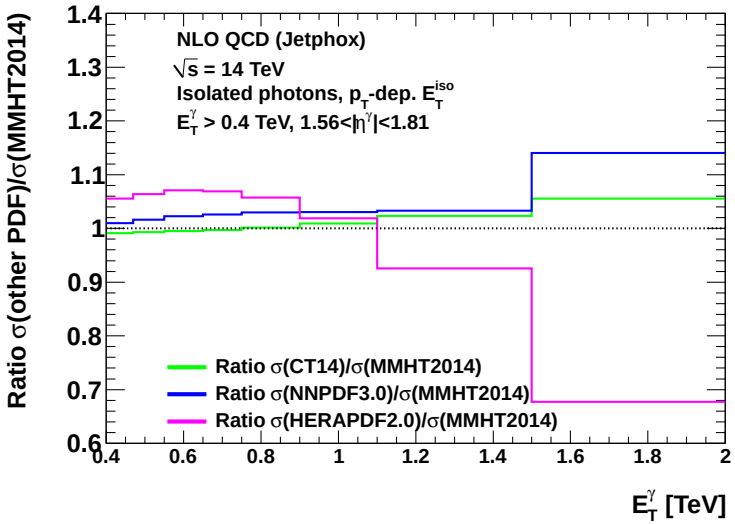


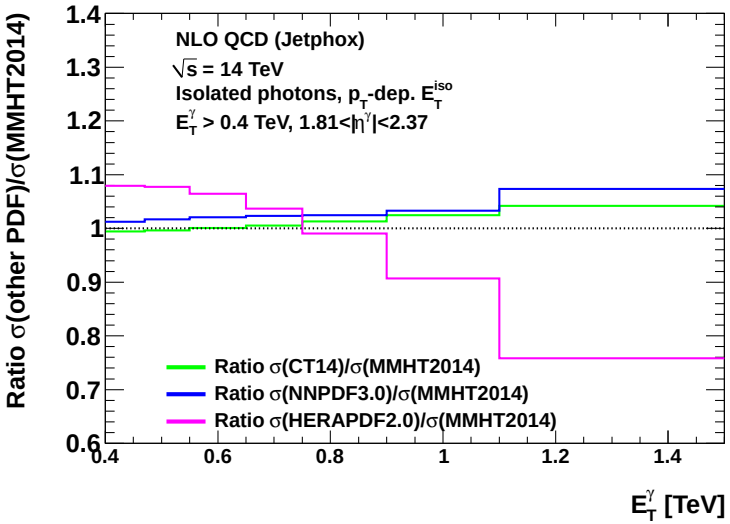


Predictions for HL-LHC: MMHT2014, CT14, NNPDF3.0, HERAPDF2.0



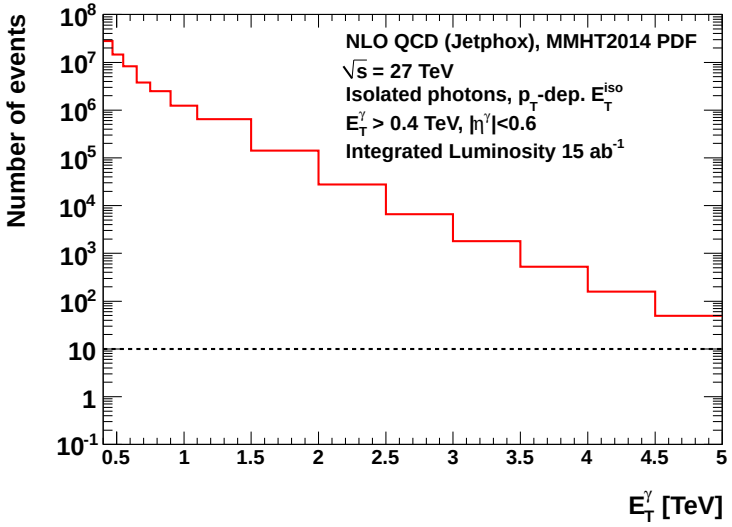


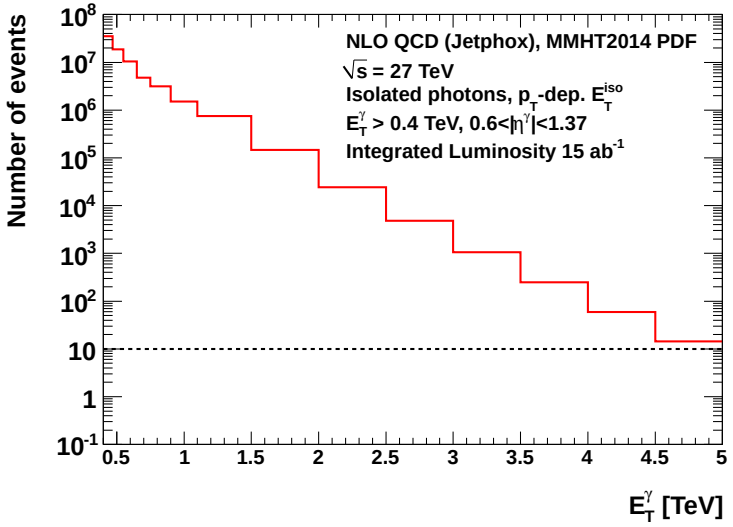


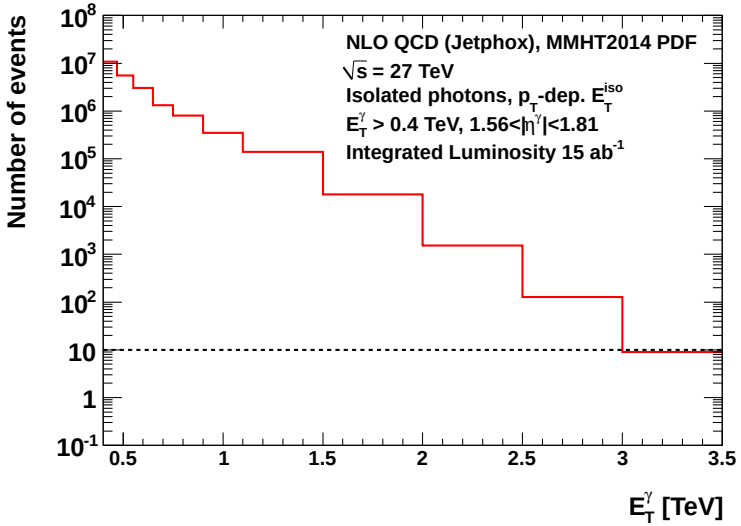


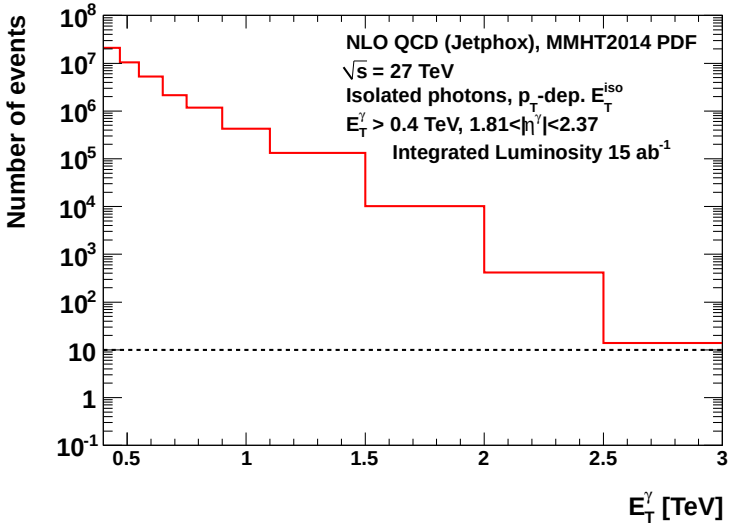
- **Differences up to $\sim 30\%$; the study has been extended to other parameterisations of the PDFs; uncertainties due to the PDFs have also been evaluated**

Predicted number of events for $\mathcal{L} = 15$ ab^{-1} at HE-LHC



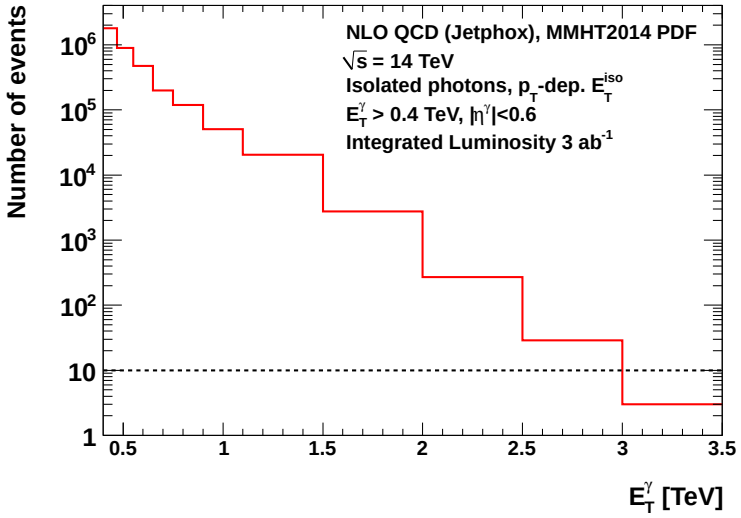


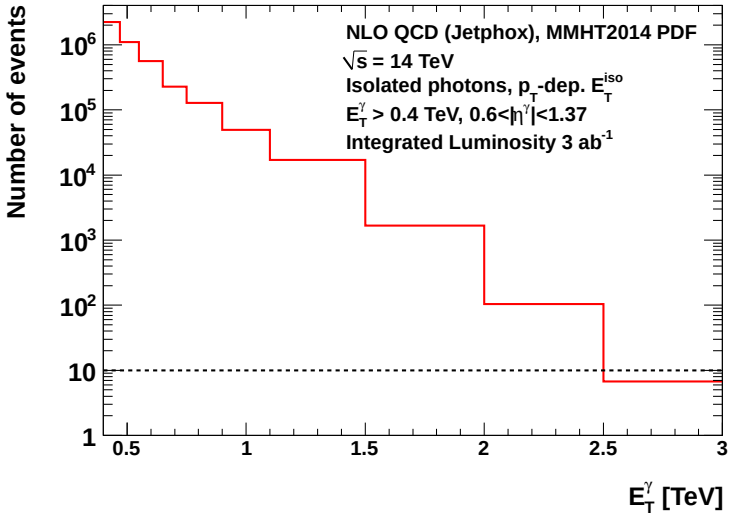


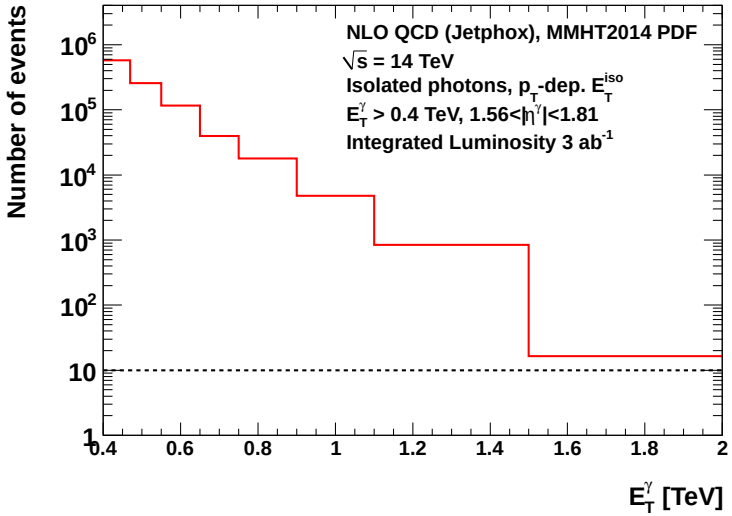


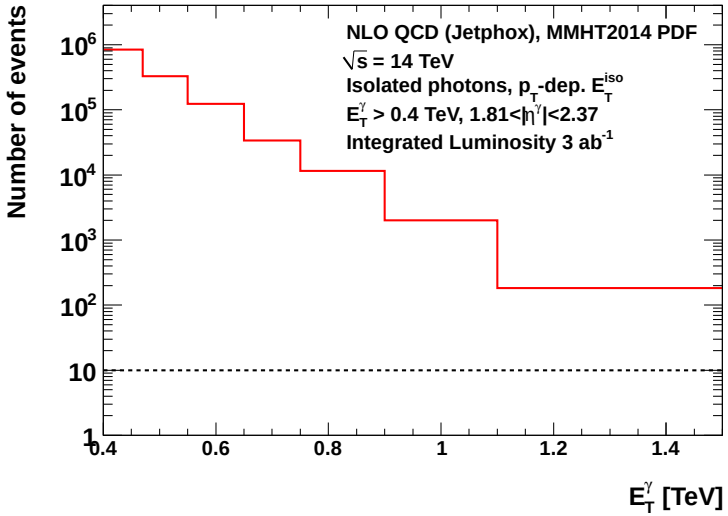
- E_T^γ **reach with 15 ab^{-1}: 4.5-5 TeV ($|\eta^\gamma| < 1.37$), 3-3.5 TeV ($1.56 < |\eta^\gamma| < 1.81$), 2.5-3 TeV ($1.81 < |\eta^\gamma| < 2.37$); 10^6 photons with 1 TeV ($\rightarrow$ jet calibration)**

Predicted number of events for $\mathcal{L} = 3$ ab^{-1} at HL-LHC



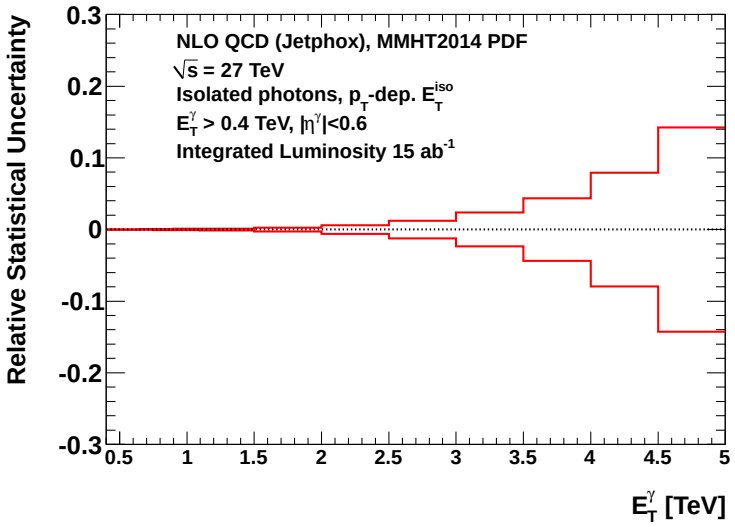


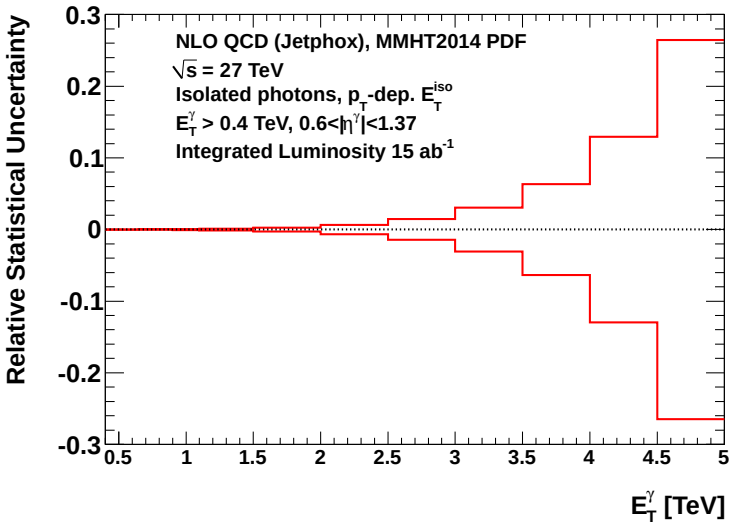


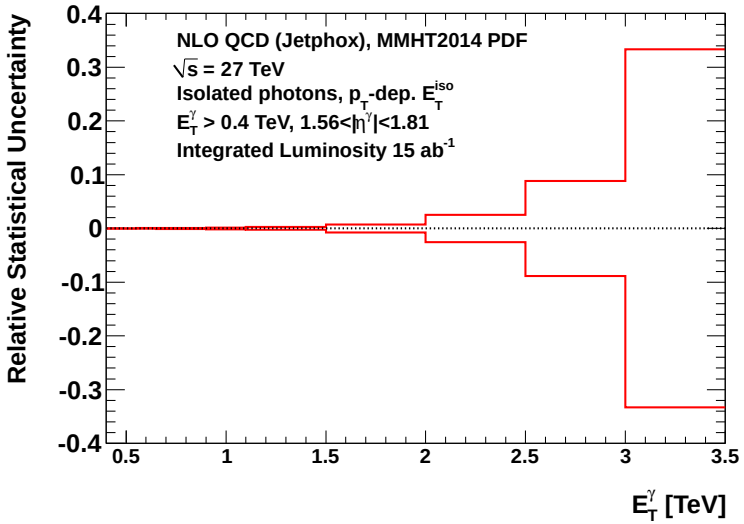


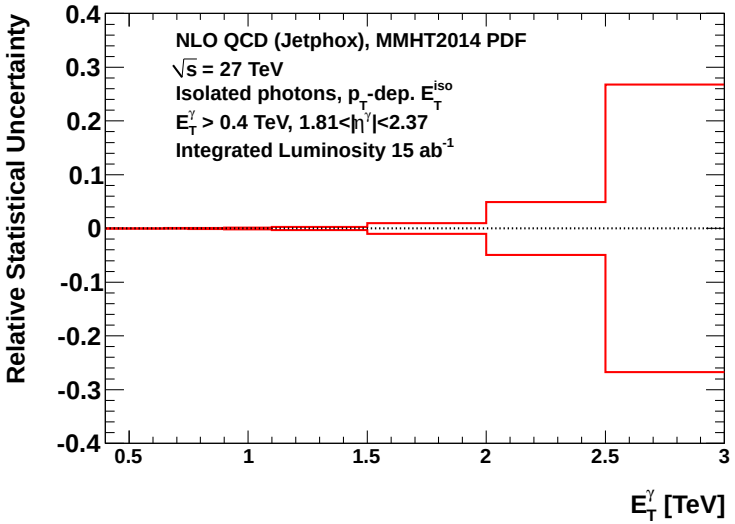
- E_T^γ reach with 3 ab^{-1}: 3-3.5 TeV ($|\eta^\gamma| < 0.6$), 2.5-3 TeV ($0.6 < |\eta^\gamma| < 1.37$), 1.5-2 TeV ($1.56 < |\eta^\gamma| < 1.81$), 1-1.5 TeV ($1.81 < |\eta^\gamma| < 2.37$);

Relative statistical uncertainty for $\mathcal{L} = 15$ ab^{-1} at HE-LHC



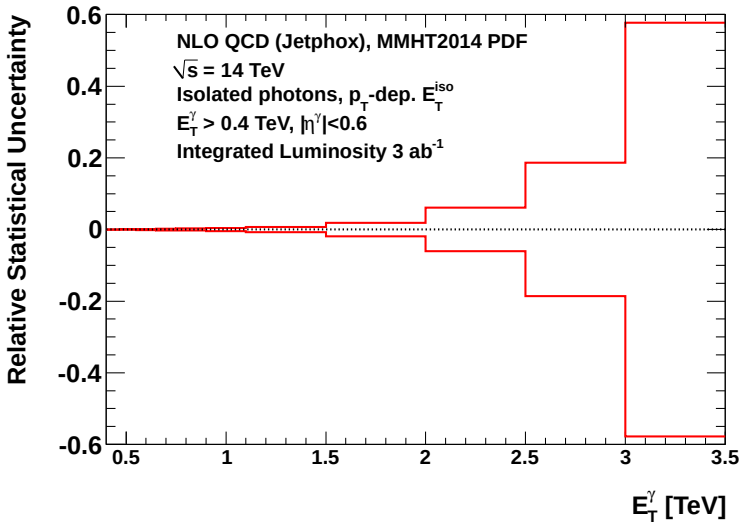


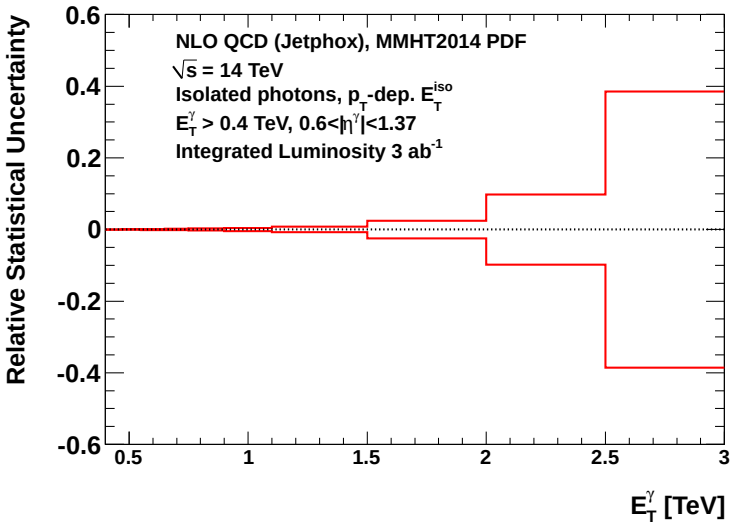


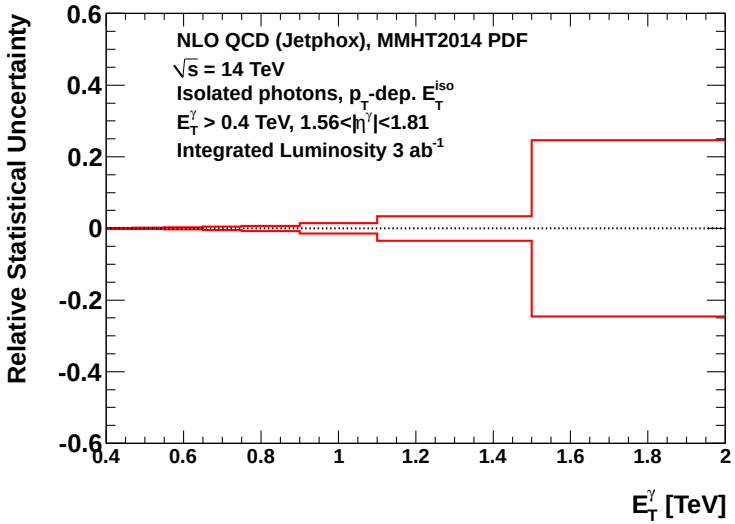


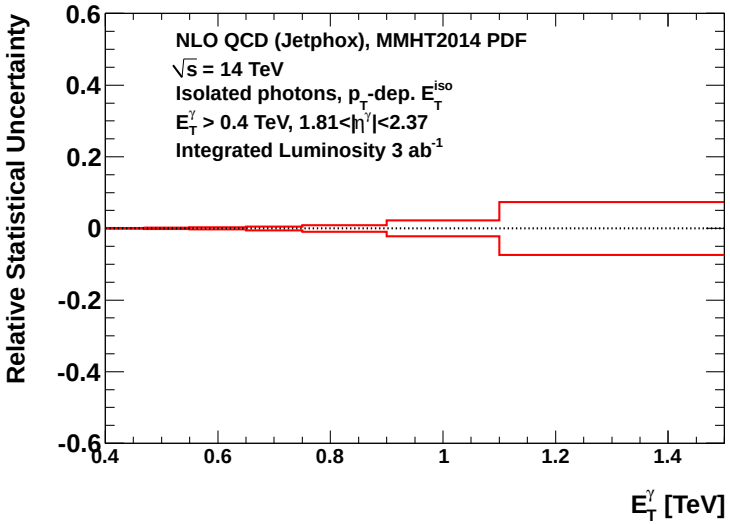
- **Relative statistical uncertainty below 10% for E_T^γ up to 4.5 TeV ($|\eta^\gamma| < 0.6$), 4 TeV ($0.6 < |\eta^\gamma| < 1.37$), 3 TeV ($1.56 < |\eta^\gamma| < 1.81$), 2.5 TeV ($1.81 < |\eta^\gamma| < 2.37$)**

Relative statistical uncertainty for $\mathcal{L} = 3\ \mathrm{ab}^{-1}$ at HL-LHC



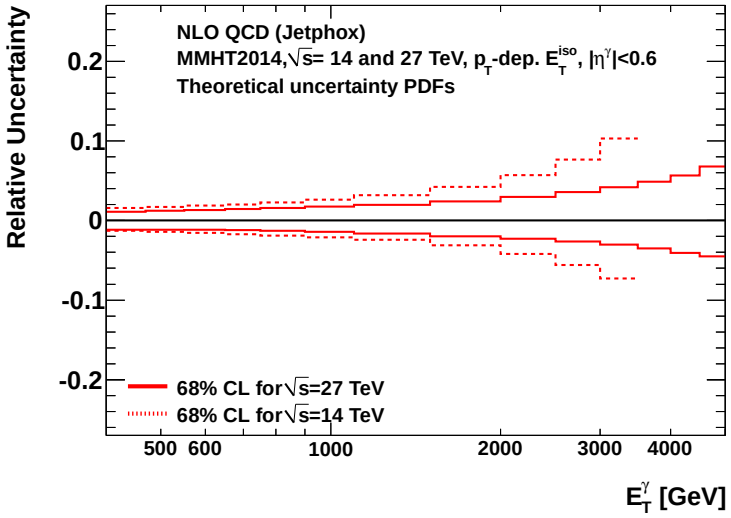


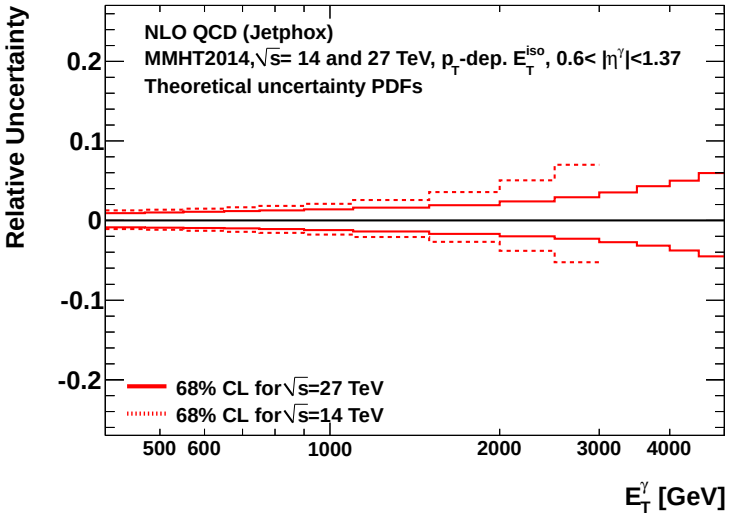


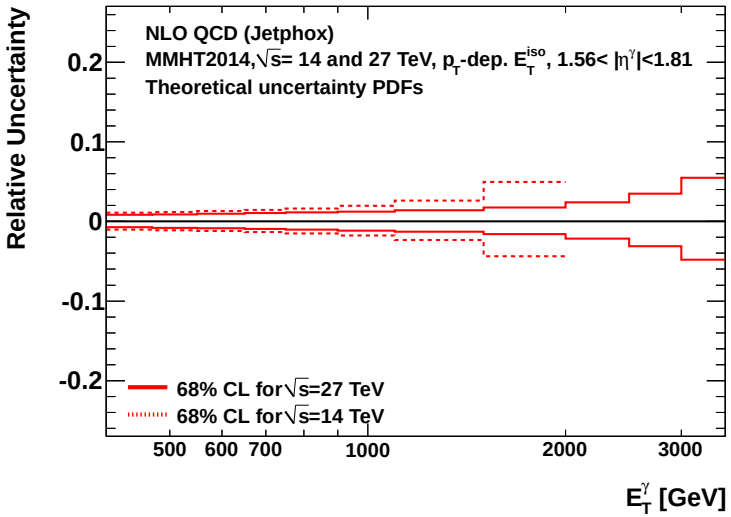


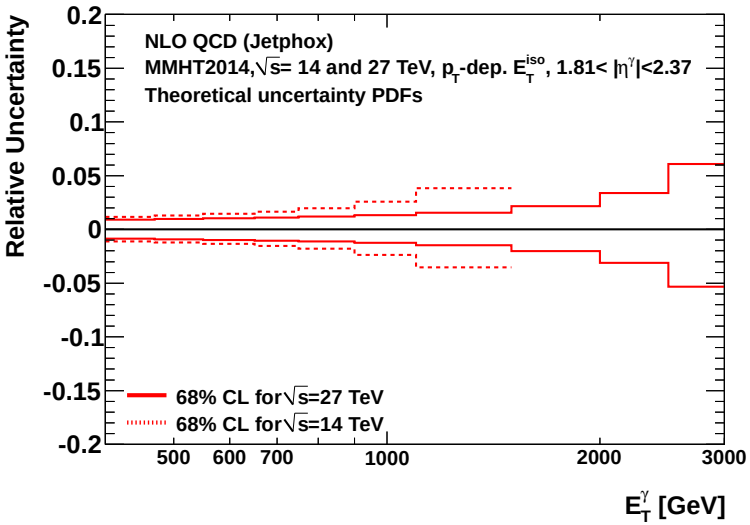
- **Relative statistical uncertainty below 10% for E_T^γ up to 2.5 TeV ($|\eta^\gamma| < 0.6$), 2.5 TeV ($0.6 < |\eta^\gamma| < 1.37$), 1.5 TeV ($1.56 < |\eta^\gamma| < 1.81$), 1.5 TeV ($1.81 < |\eta^\gamma| < 2.37$)**

Theoretical uncertainties from PDFs



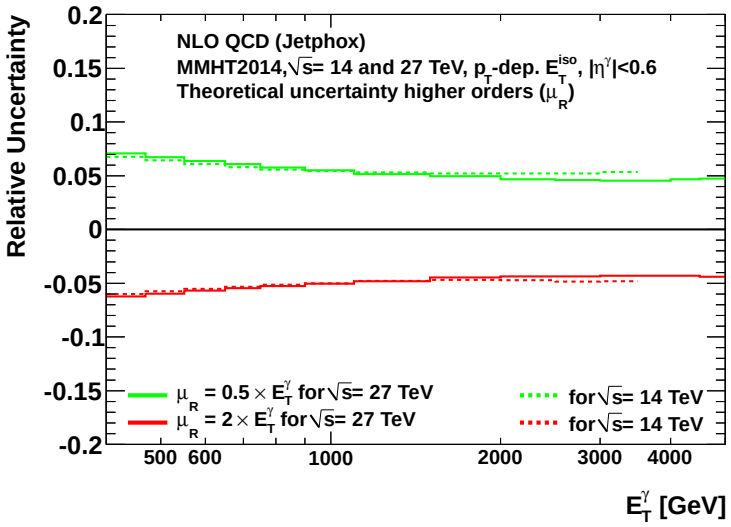


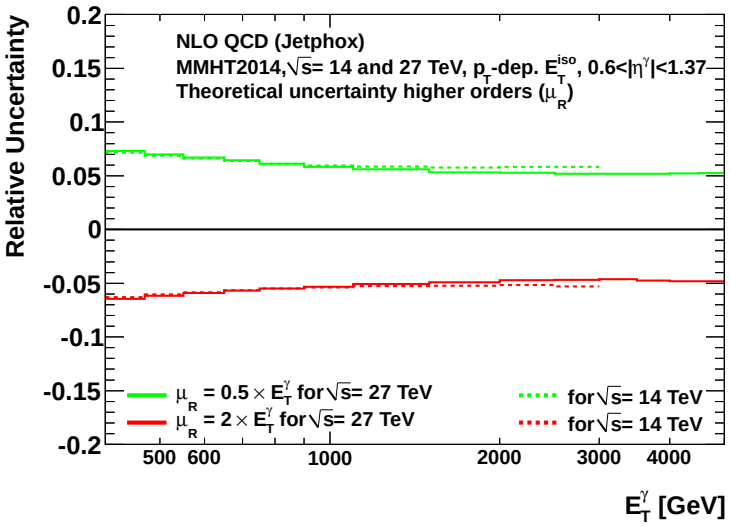


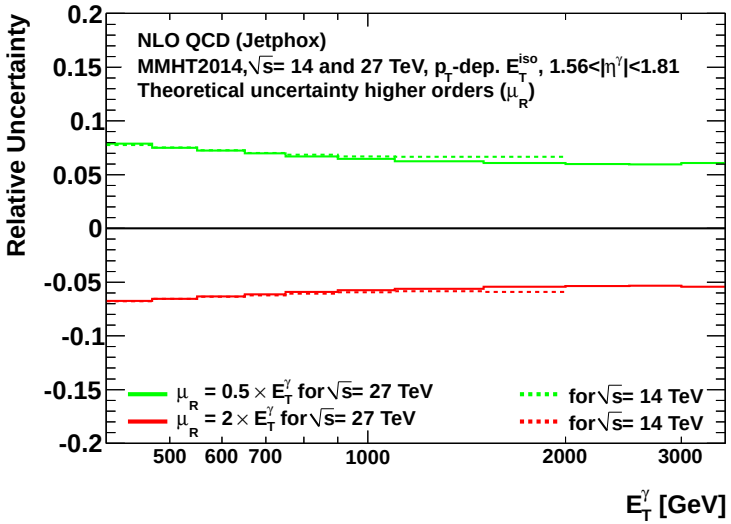


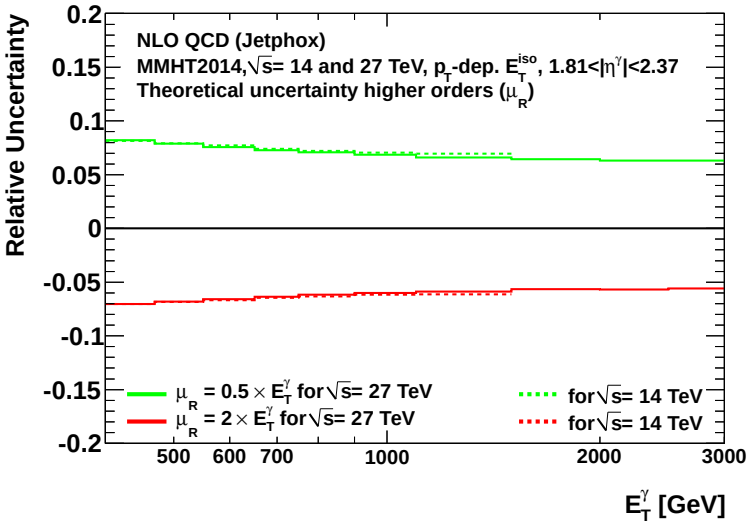
- **Larger uncertainties at $\sqrt{s} = 14$ TeV than at 27 TeV**
- **Uncertainties up to 10%**

Theoretical uncertainties from terms beyond NLO (μ_R)



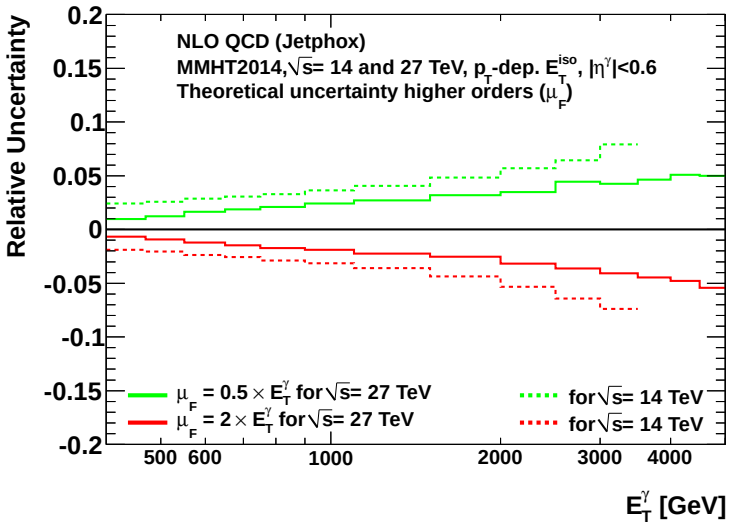


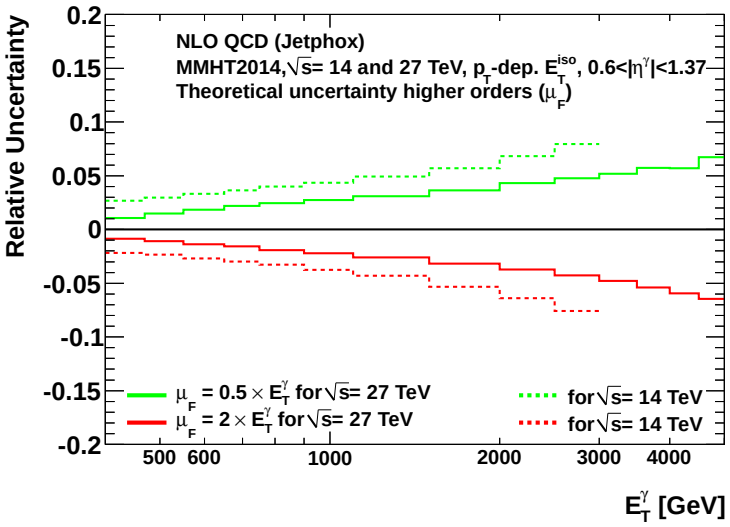


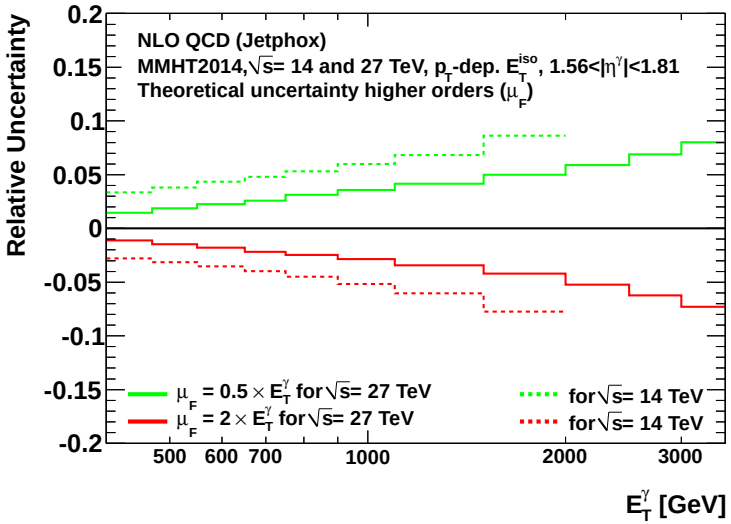


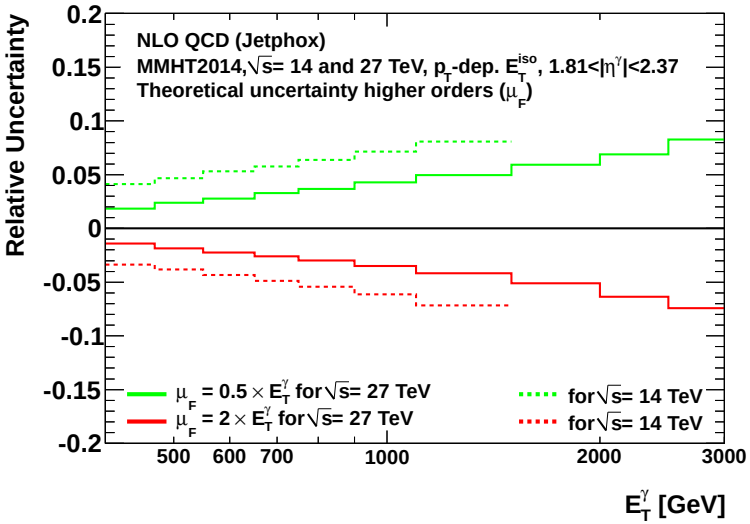
- Variation of μ_R by a factor two up and down
- It will benefit from NNLO QCD calculations (Campbell et al PRL118 (2017) 222001)

Theoretical uncertainties from terms beyond NLO (μ_F)



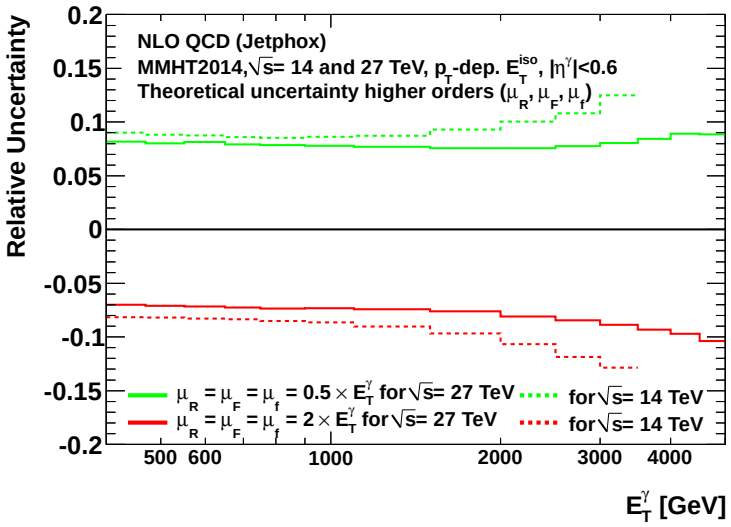


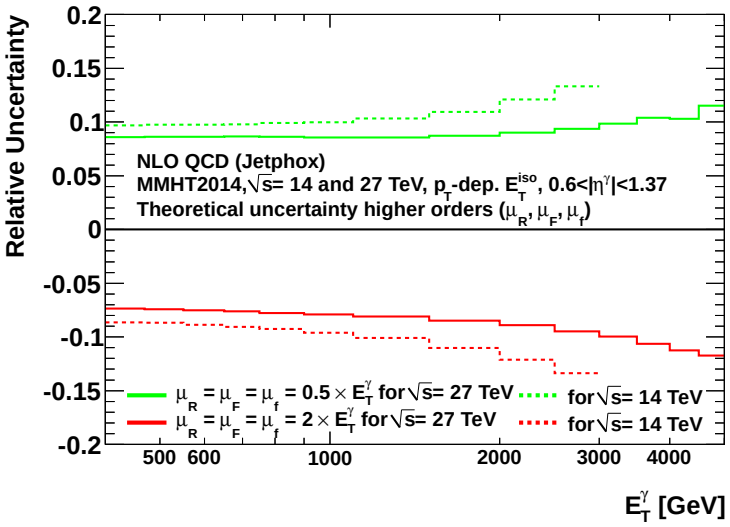


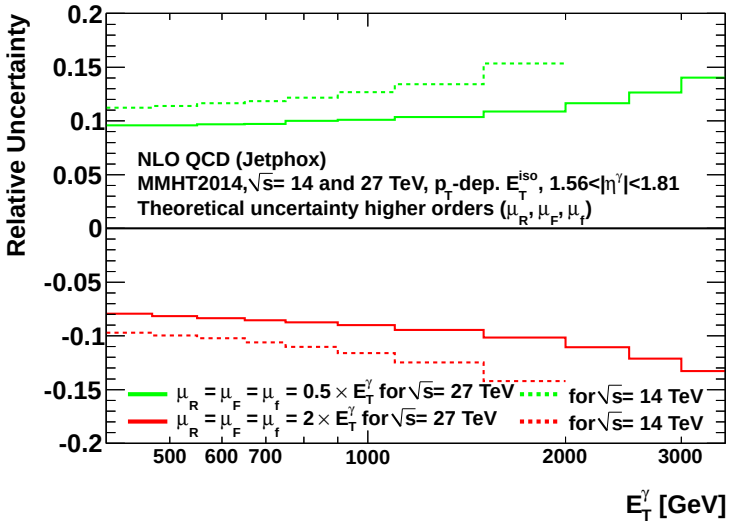


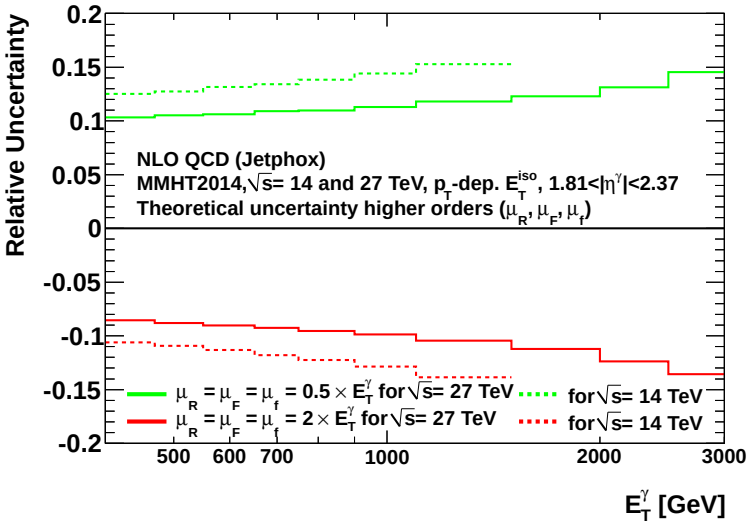
- Variation of μ_F by a factor two up and down
- It will benefit from NNLO QCD calculations (Campbell et al PRL118 (2017) 222001)

Theoretical uncertainties from terms beyond NLO (μ_R, μ_F, μ_f)



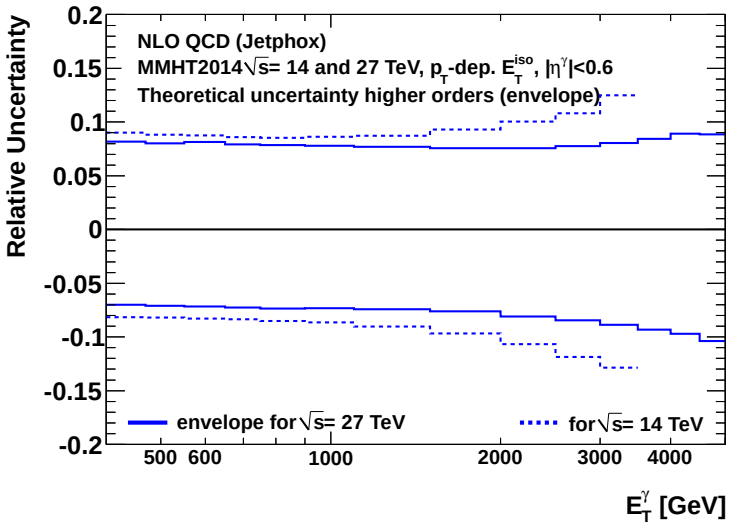


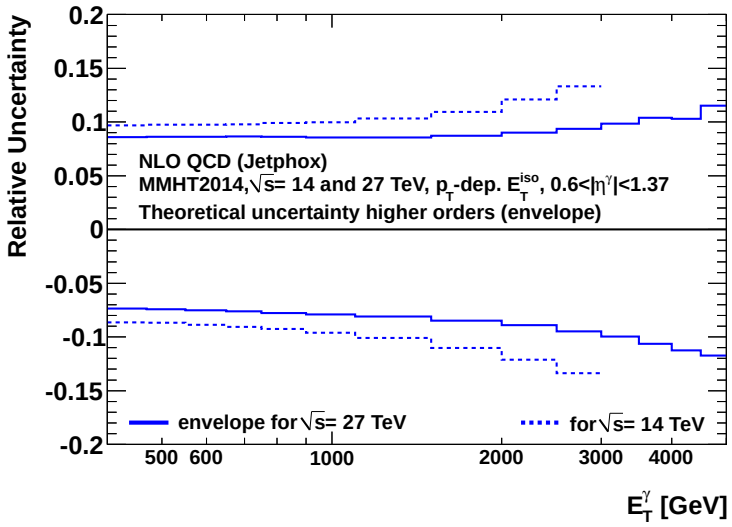


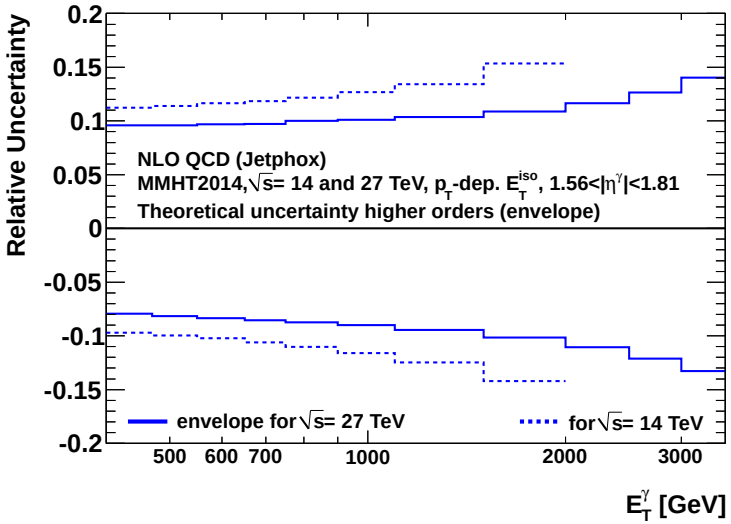


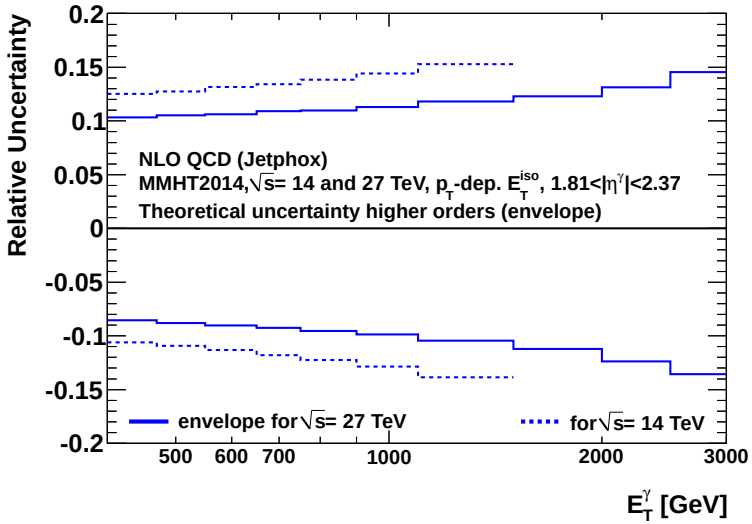
- **Simultaneous variation of μ_R, μ_F and μ_f by a factor two up and down**
- **It will benefit from NNLO QCD calculations (Campbell et al PRL118 (2017) 222001)**

Theoretical uncertainties from terms beyond NLO (envelope of variations)



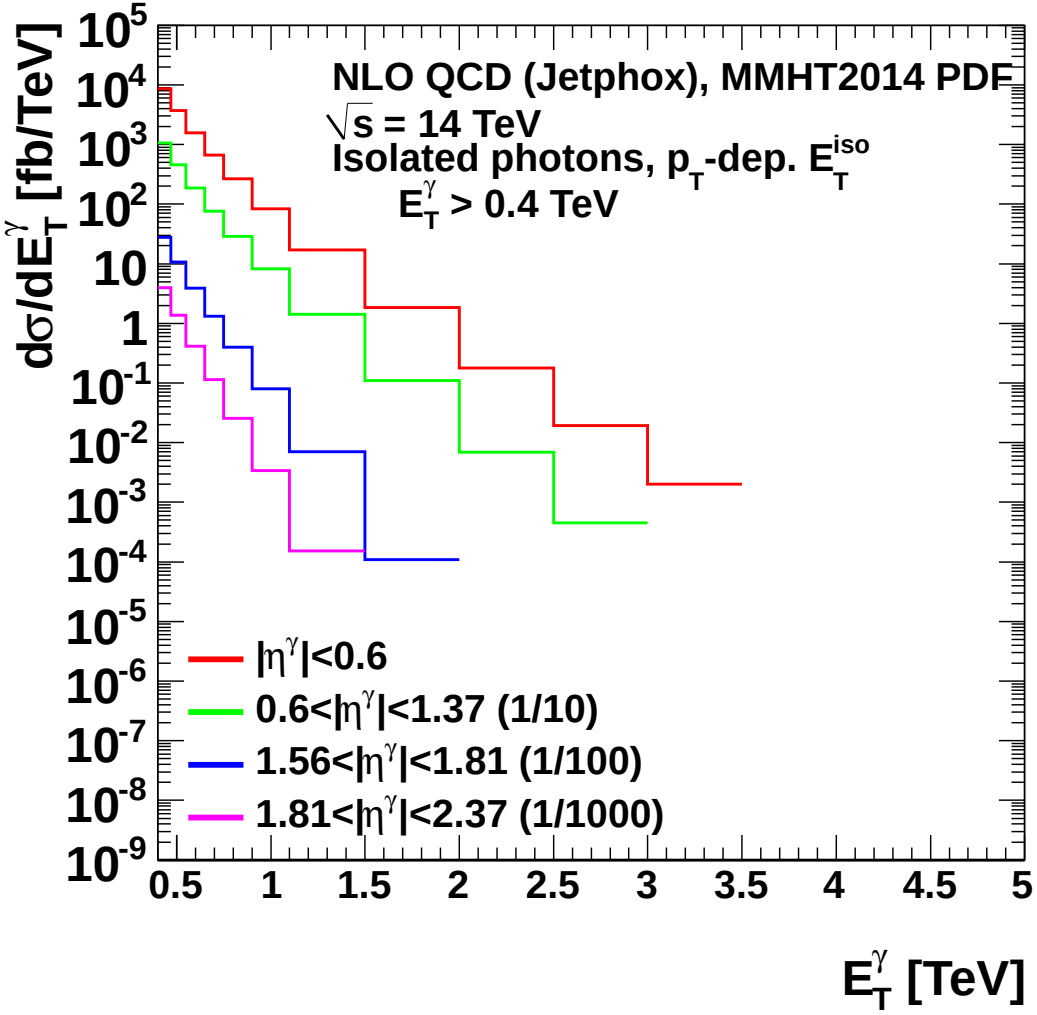


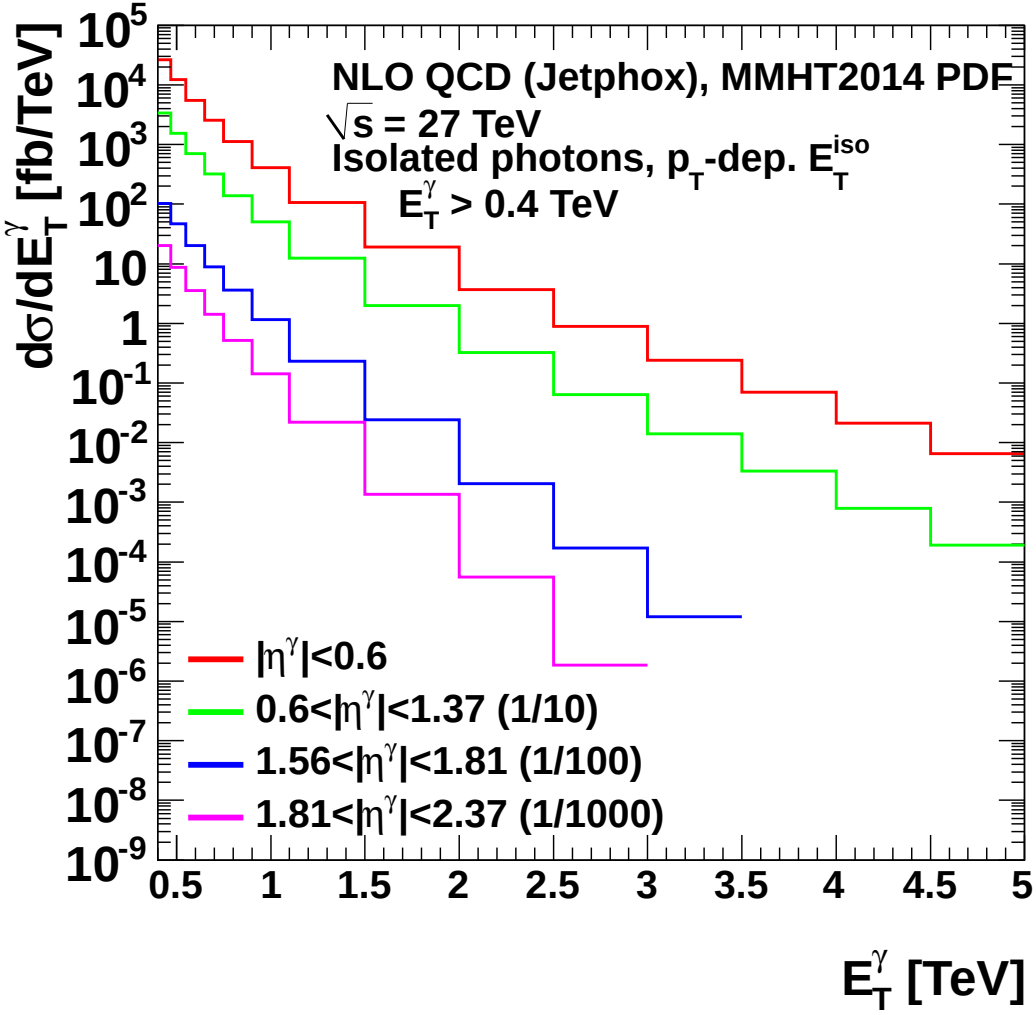




- **Envelope of variations of μ_R, μ_F and μ_f**
- **It will benefit from NNLO QCD calculations (Campbell et al PRL118 (2017) 222001)**

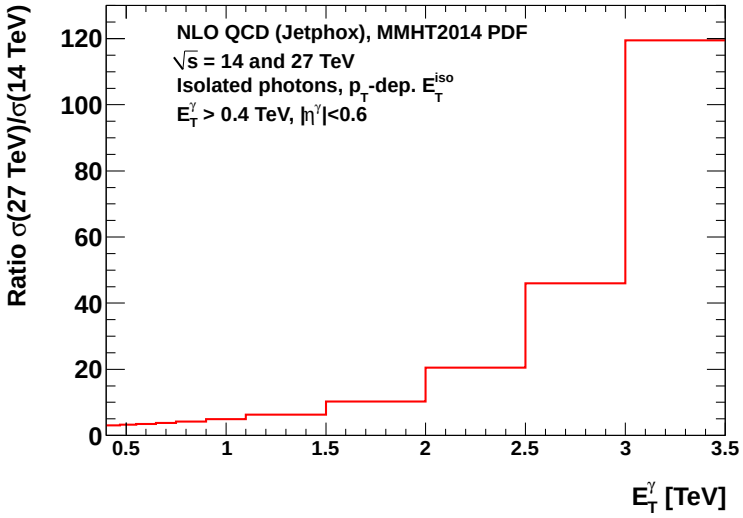
$\sqrt{s} = 14$ TeV vs $\sqrt{s} = 27$ TeV

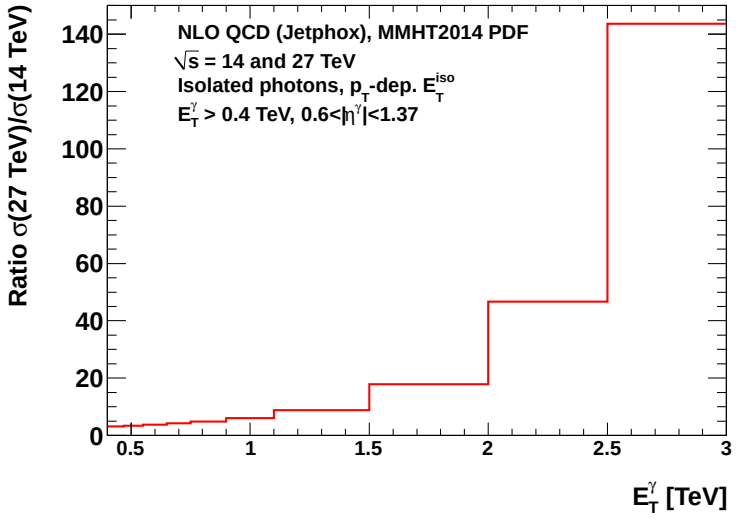


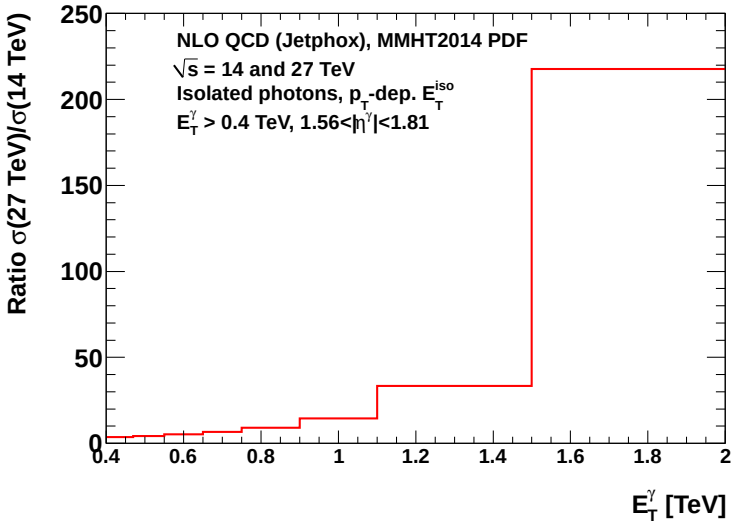


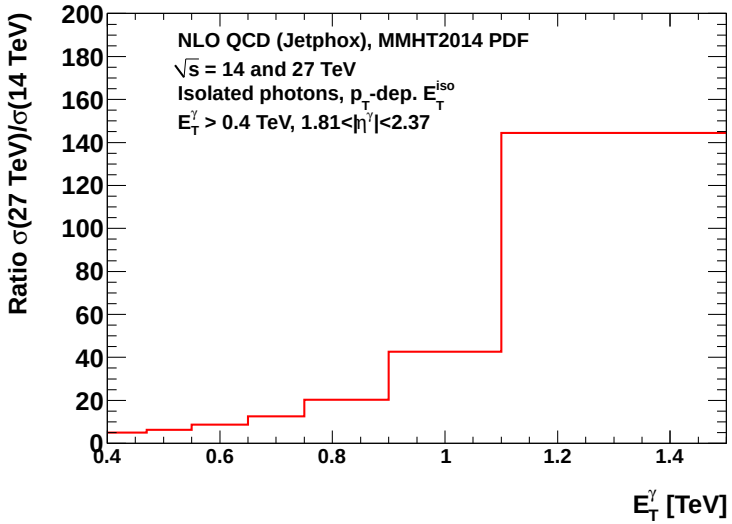
- **Study at 13 TeV has been replaced by HL-LHC prospects at 14 TeV**

Ratios of cross sections $\sigma(27\text{TeV})/\sigma(14\text{TeV})$









- **Ratio of isolated photon $d\sigma/dE_T^\gamma$ at different center-of-mass energies**
- **The ratio benefits from reduced experimental and theoretical uncertainties**

Other studies in progress

- **Isolated-photon production in association with one jet in pp collisions at HL/HE-LHC: $|\cos\theta^*|$ and $m^{\gamma-\mathrm{jet}}$ distributions; reach in $\gamma-\mathrm{jet}$ invariant mass?**
- **Performance of the jet-area method for photon isolation at HL-LHC using full simulation**
  - **$\rightarrow$ single photon events (particle gun) with 200 PU**
  - **$\rightarrow$ MC sample identified (thanks to Hector de la Torre)**
- **Building up pseudo-data on photon production at HL-LHC using generated events plus parameterizations of detector effects**
  - **$\rightarrow$ prospects for inclusive photon and photon+jet**
  - **$\rightarrow$ impact on PDFs (Juan Rojo interested); need some "reasonable" estimation of systematic uncertainties (current status)**
- **Photon isolation at particle and parton level**
  - **$\rightarrow$ impact of non-perturbative effects (hadronisation and underlying event)**
  - **$\rightarrow$ comparison of standard cone and smooth cone: impact of using smooth cone in pQCD calculation and standard cone at particle level**

Summary and outlook

- **Prospects for inclusive isolated-photon production in pp collisions at HL-LHC and HE-LHC have been presented using as a proxy NLO QCD predictions**

- **E_T^γ reach with 15 ab^{-1} (HE-LHC):**
  - **$\rightarrow$ 4.5-5 TeV ($|\eta^\gamma| < 0.6$)**
  - **$\rightarrow$ 4.5-5 TeV ($0.6 < |\eta^\gamma| < 1.37$)**
  - **$\rightarrow$ 3-3.5 TeV ($1.56 < |\eta^\gamma| < 1.81$)**
  - **$\rightarrow$ 2.5-3 TeV ($1.81 < |\eta^\gamma| < 2.37$)**
  - **$\rightarrow$ 10^6 photons with 1 TeV $\Rightarrow$ jet calibration**

- **E_T^γ reach with 3 ab^{-1} (HL-LHC):**
  - **$\rightarrow$ 3-3.5 TeV ($|\eta^\gamma| < 0.6$)**
  - **$\rightarrow$ 2.5-3 TeV ($0.6 < |\eta^\gamma| < 1.37$)**
  - **$\rightarrow$ 1.5-2 TeV ($1.56 < |\eta^\gamma| < 1.81$)**
  - **$\rightarrow$ 1-1.5 TeV ($1.81 < |\eta^\gamma| < 2.37$)**

- **Differences up to $\sim 30\%$ ($\sim 40\%$) between the predictions based on MMHT2014, CT14, NNPDF3.0 and HERAPDF2.0 at HL-LHC (HE-LHC)**

- **Theoretical issues: photon isolation, smooth cone vs standard cone, reliable estimation of the uncertainties in the predictions due to higher-order terms**

- **CMS participated in the discussion, but did not yet assign any manpower to support these activities, but will try and will continue to look for people**