Measurement of photon production at ATLAS

Marcello Fanti [(∗)]

(on behalf of the ATLAS collaboration)

[(∗)] University of Milano and INFN

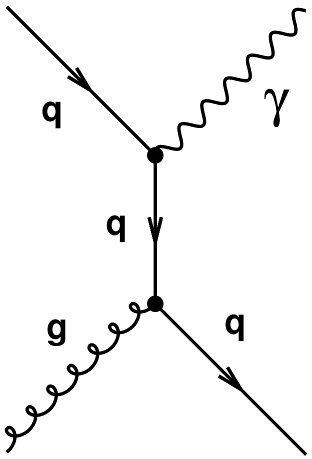
Definition of the signal

Prompt photons may come from 2 processes:

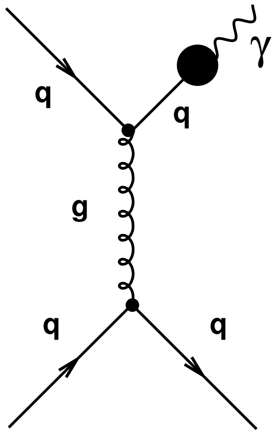
- matrix elements (ME) : $qg \to q\gamma$ or $q\bar{q} \to g\gamma$ (sometimes called "direct photons")
- fragmentation / parton shower (PS) : mainly di-jets $qq \to qq$, $qg \to qg$ where a quark in final state radiates a photon $q \to q\gamma$

The two processes are physically not distinguishable $\Rightarrow$ both constitute our signal

"direct" photon



"fragmentation" photon



Photons are colorless probes to test QCD at pp colliders
(easier to measure than jets, not affected by fragmentation / hadronization / color connection etc)

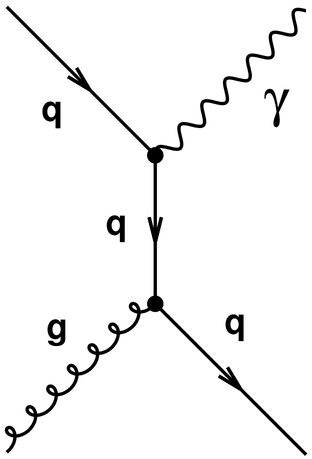
Definition of the signal

Prompt photons may come from 2 processes:

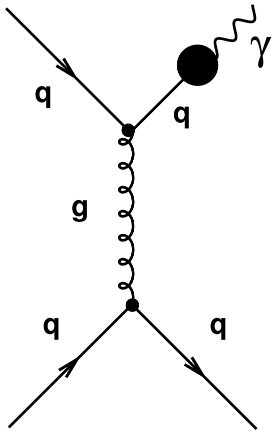
- matrix elements (ME) : $qg \to q\gamma$ or $q\bar{q} \to g\gamma$ (sometimes called "direct photons")
- fragmentation / parton shower (PS) : mainly di-jets $qq \to qq$, $qg \to qg$ where a quark in final state radiates a photon $q \to q\gamma$

The two processes are physically not distinguishable ⇒ both constitute our signal

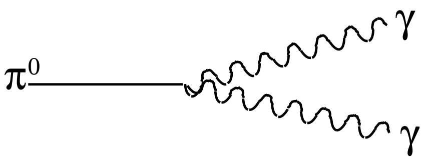
"direct" photon



"fragmentation" photon



Photons are colorless probes to test QCD at pp colliders
(easier to measure than jets, not affected by fragmentation / hadronization / color connection etc)



Background photons come from decays of neutral hadrons (e.g. $\pi^0 \to \gamma\gamma$)
— these are NOT considered as signal!

Signal generators

- Pythia LO $2 \to 2$ particle-level generator:
  produces ME $qg \to q\gamma$ and $q\bar{q} \to g\gamma$
  and fragmentation photons via QED $q \to q\gamma$ splitting in PS evolution (aka "brem photons")
- Sherpa LO $2 \to$many particle-level generator — here implemented as $2 \to \gamma+$up to 4 partons
  produces ME $qg \to q\gamma$ and $q\bar{q} \to g\gamma$; mimics fragmentation photons thanks to the multi-leg final state

Signal generators

- Pythia LO $2 \to 2$ particle-level generator:
  produces ME $qg \to q\gamma$ and $q\bar{q} \to g\gamma$
  and fragmentation photons via QED $q \to q\gamma$ splitting in PS evolution (aka "brem photons")
- Sherpa LO $2 \to$many particle-level generator — here implemented as $2 \to \gamma +$up to 4 partons
  produces ME $qg \to q\gamma$ and $q\bar{q} \to g\gamma$; mimics fragmentation photons thanks to the multi-leg final state

- Sherpa NLO $2 \to$many particle-level generator — here implemented as $2 \to \gamma +$up to 4 partons
  similar final states as Sherpa LO, but γj and γjj are computed to NLO QCD accuracy
  smooth ("Frixione") cone isolation applied
- JetPhox NLO parton-level generator:
  fixed order generator calculating γj final state at NLO and γjj at LO
  implements fragmentation function at NLO

Signal generators

- Pythia LO $2 \to 2$ particle-level generator:
  produces ME $qg \to q\gamma$ and $q\bar{q} \to g\gamma$
  and fragmentation photons via QED $q \to q\gamma$ splitting in PS evolution (aka "brem photons")
- Sherpa LO $2 \to$many particle-level generator — here implemented as $2 \to \gamma+$up to 4 partons
  produces ME $qg \to q\gamma$ and $q\bar{q} \to g\gamma$; mimics fragmentation photons thanks to the multi-leg final state

- Sherpa NLO $2 \to$many particle-level generator — here implemented as $2 \to \gamma+$up to 4 partons
  similar final states as Sherpa LO, but γj and γjj are computed to NLO QCD accuracy
  smooth ("Frixione") cone isolation applied
- JetPhox NLO parton-level generator:
  fixed order generator calculating γj final state at NLO and γjj at LO
  implements fragmentation function at NLO

- NNLOjet NNLO parton-level generator:
  fixed order generator calculating γj final state at NNLO , γjj at NLO , γjjj at LO
  no fragmentation, applies a smooth ("Frixione") cone isolation such to suppress photons from fragmentation

Collision data sample

- proton-proton collision at $\sqrt{s} = 13\ \mathrm{TeV}$
- integrated luminosity: $\mathcal{L} = 3.2\ \mathrm{fb}^{-1}$ — inclusive photon measurements use $\mathcal{L} = 36.1\ \mathrm{fb}^{-1}$; relative uncertainty $\simeq 2\%$

Collision data sample

- proton-proton collision at $\sqrt{s} = 13\ \mathrm{TeV}$
- integrated luminosity: $\mathcal{L} = 3.2\ \mathrm{fb}^{-1}$ — inclusive photon measurements use $\mathcal{L} = 36.1\ \mathrm{fb}^{-1}$; relative uncertainty $\simeq 2\%$

Photon selection

- $E_{\mathrm{T}}^{\gamma} > 125\ \mathrm{GeV}$; $|\eta^{\gamma}| < 2.37$ excluding the barrel-endcap gap ($|\eta^{\gamma}| \notin [1.37; 1.56]$)

Large reducible background from jets, wrongly reconstructed as photons

- photons must be "isolated": $E_T^{\mathrm{isol}} < E_{T\ ,cut}^{\mathrm{isol}} \equiv (4.2 \cdot 10^{-3}) E_{\mathrm{T}}^{\gamma} + (4.8\ \mathrm{GeV})$
  calorimetric isolation, $E_T^{\mathrm{isol}} \equiv \sum_c E_{\mathrm{T}}^{c}$; $c \in \{\mathrm{topoclusters\ within}\ \Delta R < 0.4\}$
  photon energy is subtracted,
  energy density from underlying event and pileup subtracted event-by-event
- photons must fulfill an "IDentification" , known as **Tight** selection (see next slides)

$\Rightarrow$ largest residual background to photons comes from $\pi^0 \to \gamma\gamma$

Collision data sample

- proton-proton collision at $\sqrt{s} = 13\ \mathrm{TeV}$
- integrated luminosity: $\mathcal{L} = 3.2\ \mathrm{fb}^{-1}$ — inclusive photon measurements use $\mathcal{L} = 36.1\ \mathrm{fb}^{-1}$; relative uncertainty $\simeq 2\%$

Photon selection

- $E_{\mathrm{T}}^{\gamma} > 125\ \mathrm{GeV}$; $|\eta^{\gamma}| < 2.37$ excluding the barrel-endcap gap ($|\eta^{\gamma}| \notin [1.37; 1.56]$)

Large reducible background from jets, wrongly reconstructed as photons

- photons must be "isolated": $E_T^{\mathrm{isol}} < E_T^{\mathrm{isol}}{}_{,cut} \equiv (4.2 \cdot 10^{-3}) E_{\mathrm{T}}^{\gamma} + (4.8\ \mathrm{GeV})$
  calorimetric isolation, $E_T^{\mathrm{isol}} \equiv \sum_c E_{\mathrm{T}}^{c}$; $c \in \{\mathrm{topoclusters\ within\ } \Delta R < 0.4\}$
  photon energy is subtracted,
  energy density from underlying event and pileup subtracted event-by-event
- photons must fulfill an "IDentification" , known as **Tight** selection (see next slides)

$\Rightarrow$ largest residual background to photons comes from $\pi^0 \to \gamma\gamma$

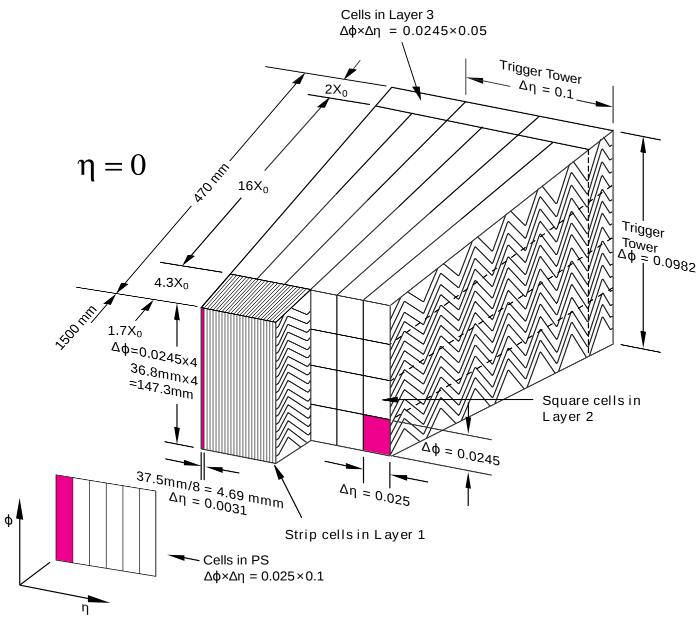
Jet selection (when applicable)

- jets are built from calorimetric topo-clusters using anti-k_T algorithm, with radius $R = 0.4$
- $p_{\mathrm{T}}^{jet} > 60\ \mathrm{GeV}$, $|Y^{jet}| < 2.5$ — select events if at least 1 jet with $p_{\mathrm{T}}^{jet} > 100\ \mathrm{GeV}$

Photon IDentification

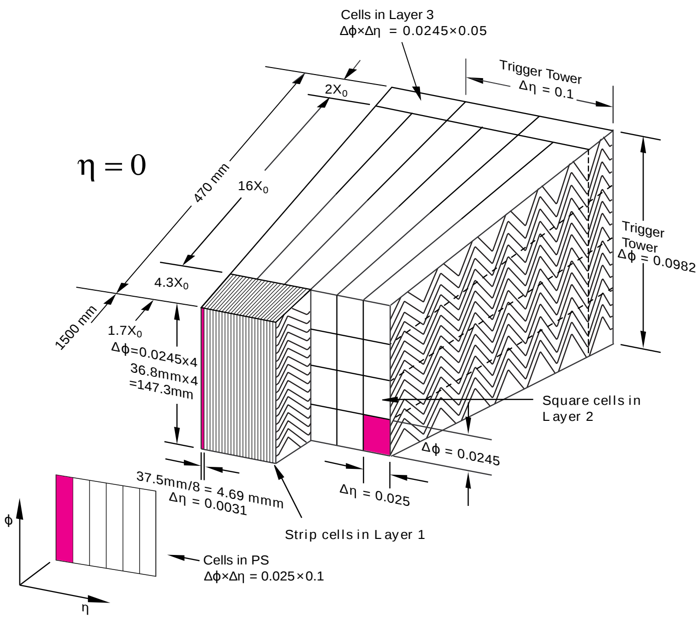
Exploit the 3-D granularity of electromagnetic (ECAL) and hadronic (HCAL) calorimeters

$\eta = 0$

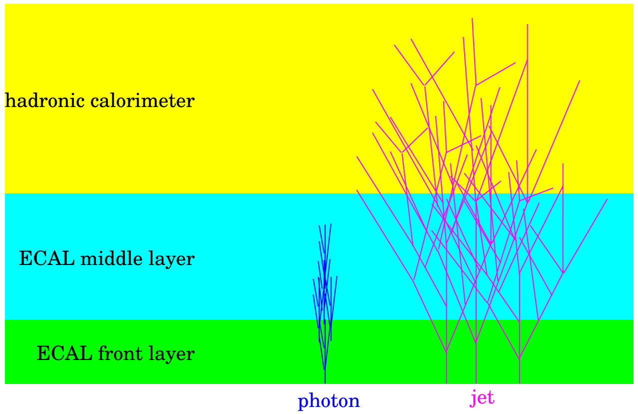


Photon IDentification

Exploit the 3-D granularity of electromagnetic (ECAL) and hadronic (HCAL) calorimeters

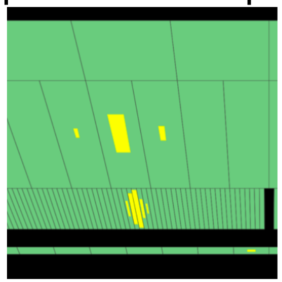


Jets vs photons

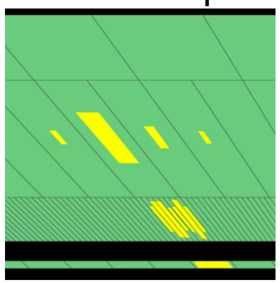


$\pi^0 \to \gamma\gamma$ vs photons

photon in strips

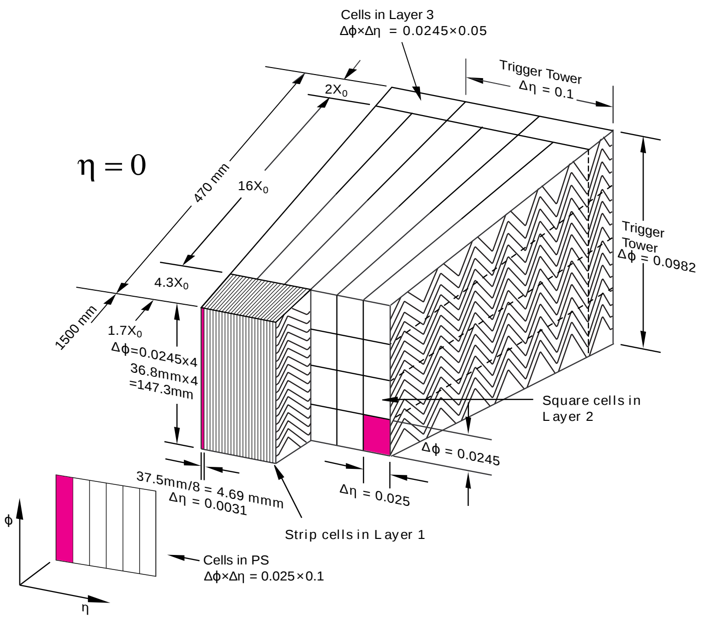


π^0 in strips

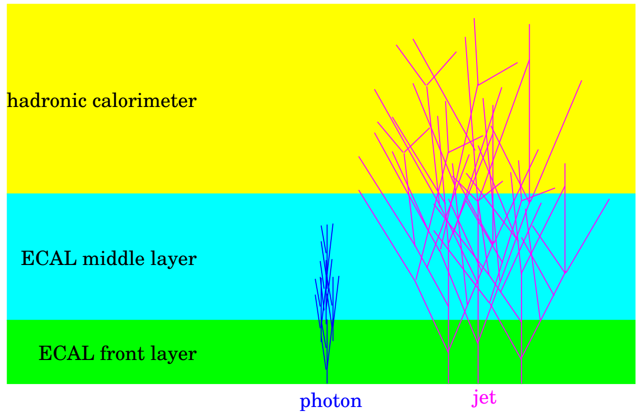


Photon IDentification

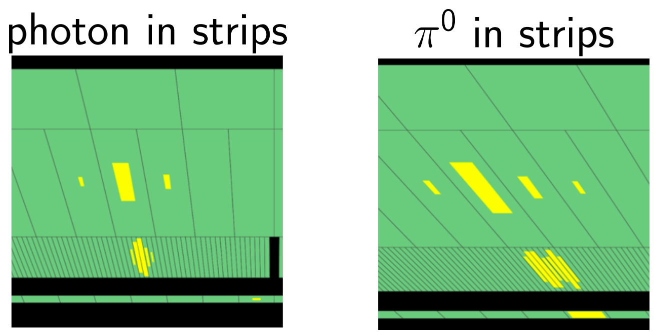
Exploit the 3-D granularity of electromagnetic (ECAL) and hadronic (HCAL) calorimeters



Jets vs photons

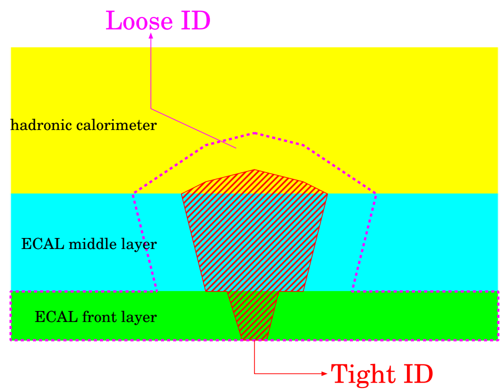


$\pi^0 \to \gamma\gamma$ vs photons



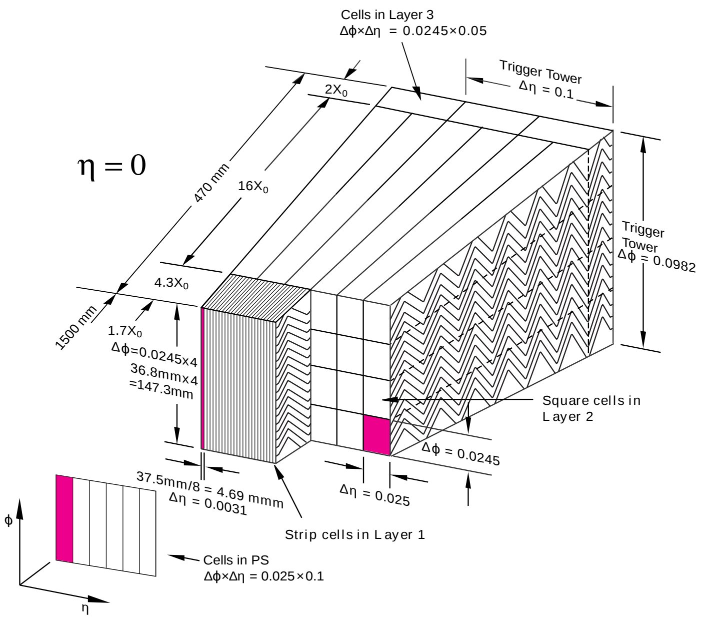
Photon IDentification

- no energy in hadron calorimeter
- narrow shower in ECAL middle layer
- narrow shower in Strips, no double maximum

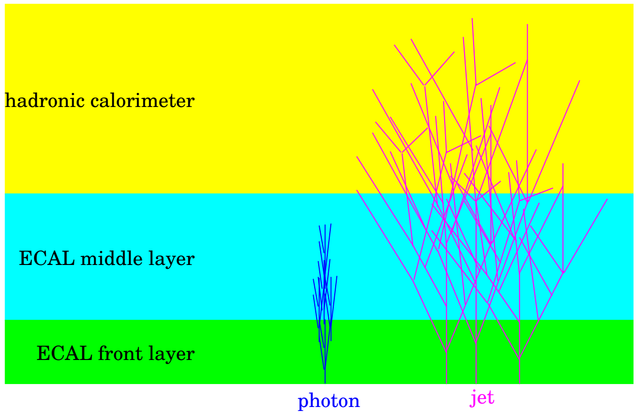


Photon IDentification

Exploit the 3-D granularity of electromagnetic (ECAL) and hadronic (HCAL) calorimeters

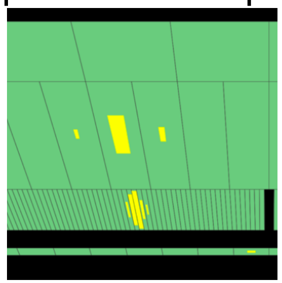


Jets vs photons

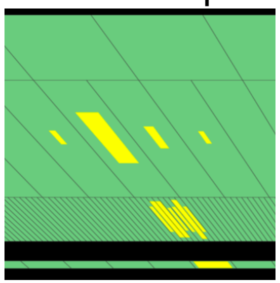


$\pi^0 \to \gamma\gamma$ vs photons

photon in strips

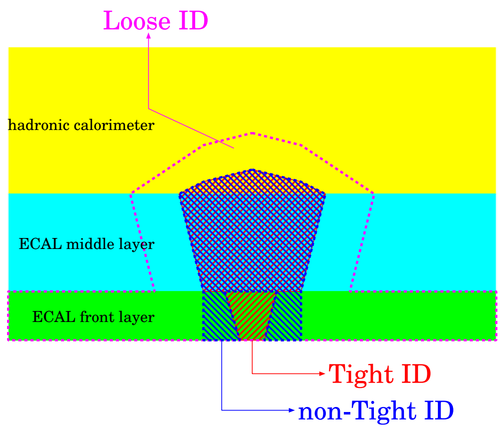


π^0 in strips



Photon IDentification

- no energy in hadron calorimeter
- narrow shower in ECAL middle layer
- narrow shower in Strips, no double maximum



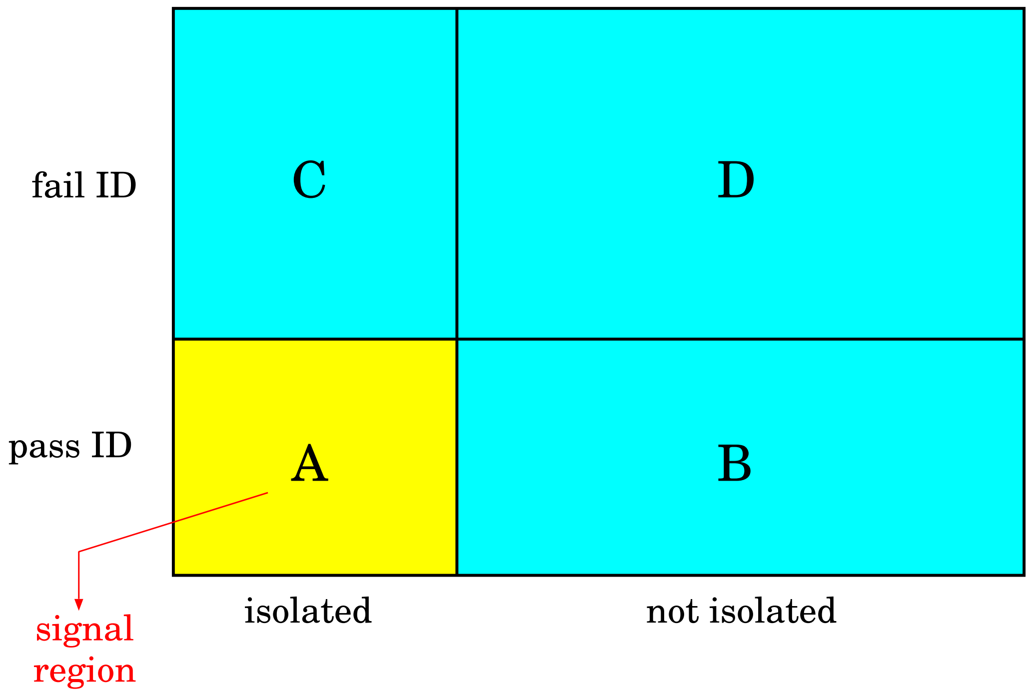
non-Tight selection:
keep tight selection on HCAL and ECAL Middle layer
reverse selection on strips $\Rightarrow$ background control region

Evaluation of hadronic background

Observables: $N_A, \; N_B, \; N_C, \; N_D$

(in each region $k = A, B, C, D$, $N_k = N_k^\gamma + N_k^j$)

Unknown: N_A^γ ($\equiv$ photons in signal region)



Evaluation of hadronic background

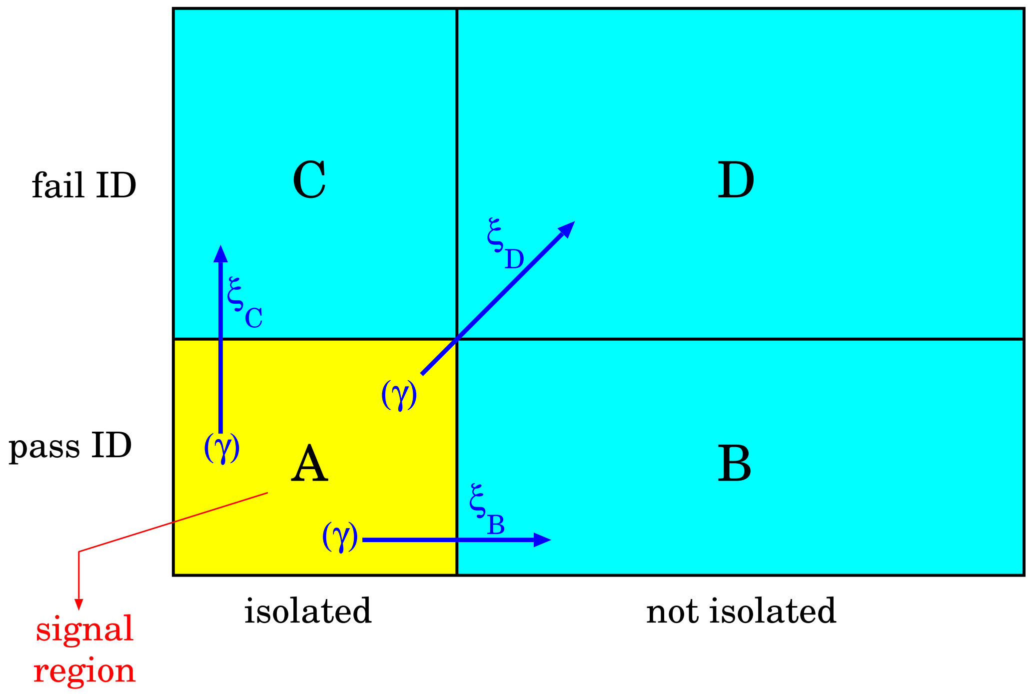
Observables: $N_A, \; N_B, \; N_C, \; N_D$

(in each region $k = A, B, C, D$, $N_k = N_k^\gamma + N_k^j$)

Unknown: N_A^γ ($\equiv$ photons in signal region)

Inputs:

- $\xi_k \stackrel{\text{def}}{=} \frac{N_k^\gamma}{N_A^\gamma}$ $(k = B, C, D)$
  "photon leakage" (from MC) ;



Evaluation of hadronic background

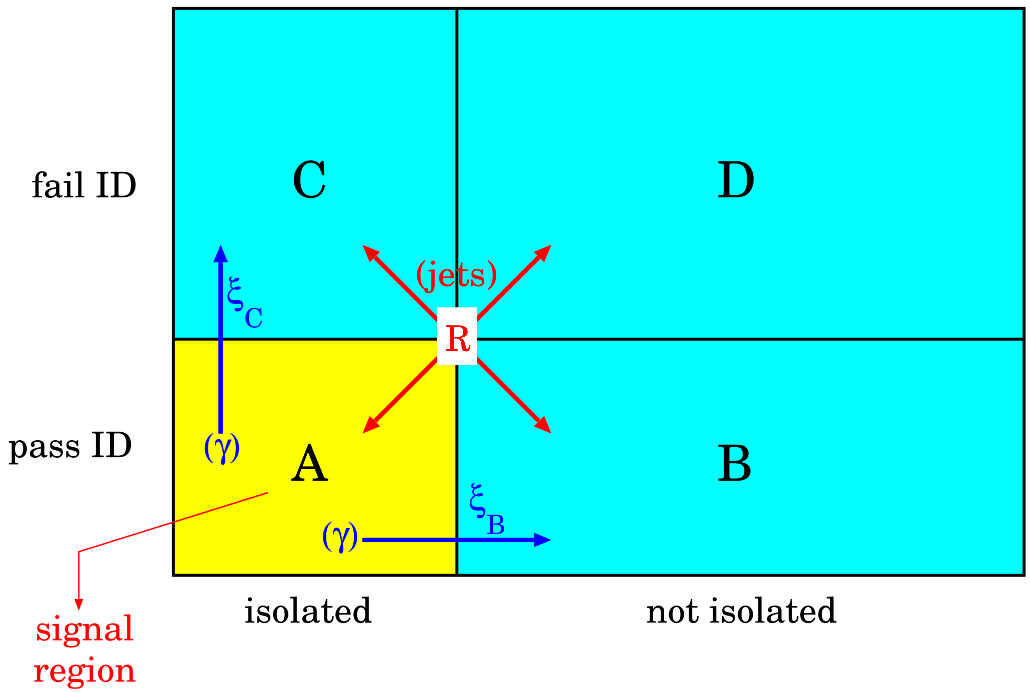
Observables: $N_A, \; N_B, \; N_C, \; N_D$

(in each region $k = A, B, C, D$, $N_k = N_k^\gamma + N_k^j$)

Unknown: N_A^γ ($\equiv$ photons in signal region)

Inputs:

- $\xi_k \stackrel{\text{def}}{=} \dfrac{N_k^\gamma}{N_A^\gamma}$ $(k = B, C, D)$
  "photon leakage" (from MC) ;
- $R \stackrel{\text{def}}{=} \left(\dfrac{N_A^j}{N_B^j}\right) \Big/ \left(\dfrac{N_C^j}{N_D^j}\right)$
  "isol/ID correlation factor" for background (*)



Evaluation of hadronic background

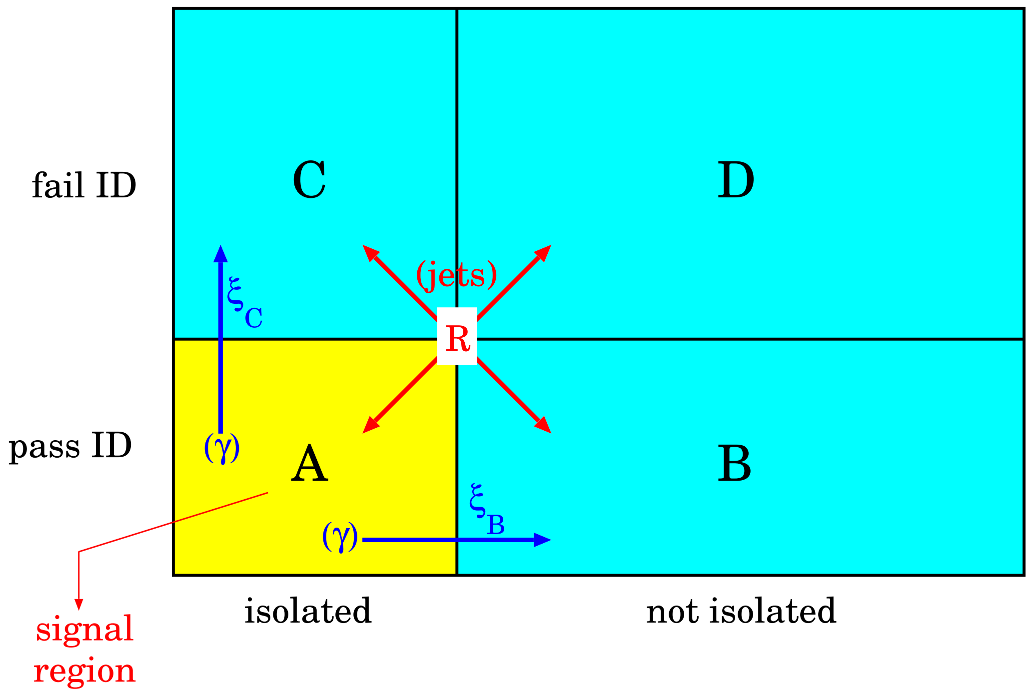
Observables: $N_A,\ N_B,\ N_C,\ N_D$

(in each region $k = A, B, C, D$, $N_k = N_k^\gamma + N_k^j$)

Unknown: N_A^γ ($\equiv$ photons in signal region)

Inputs:

- $\xi_k \stackrel{\text{def}}{=} \dfrac{N_k^\gamma}{N_A^\gamma}$ $(k = B, C, D)$
  "photon leakage" (from MC) ;
- $R \stackrel{\text{def}}{=} \left(\dfrac{N_A^j}{N_B^j}\right) \Big/ \left(\dfrac{N_C^j}{N_D^j}\right)$
  "isol/ID correlation factor" for background (*)



$$\Rightarrow N_A - N_A^\gamma = R \, \frac{(N_B - \xi_B N_A^\gamma)(N_C - \xi_C N_A^\gamma)}{(N_D - \xi_D N_A^\gamma)} \quad \Rightarrow \quad \text{solve for } N_A^\gamma$$

Evaluation of hadronic background

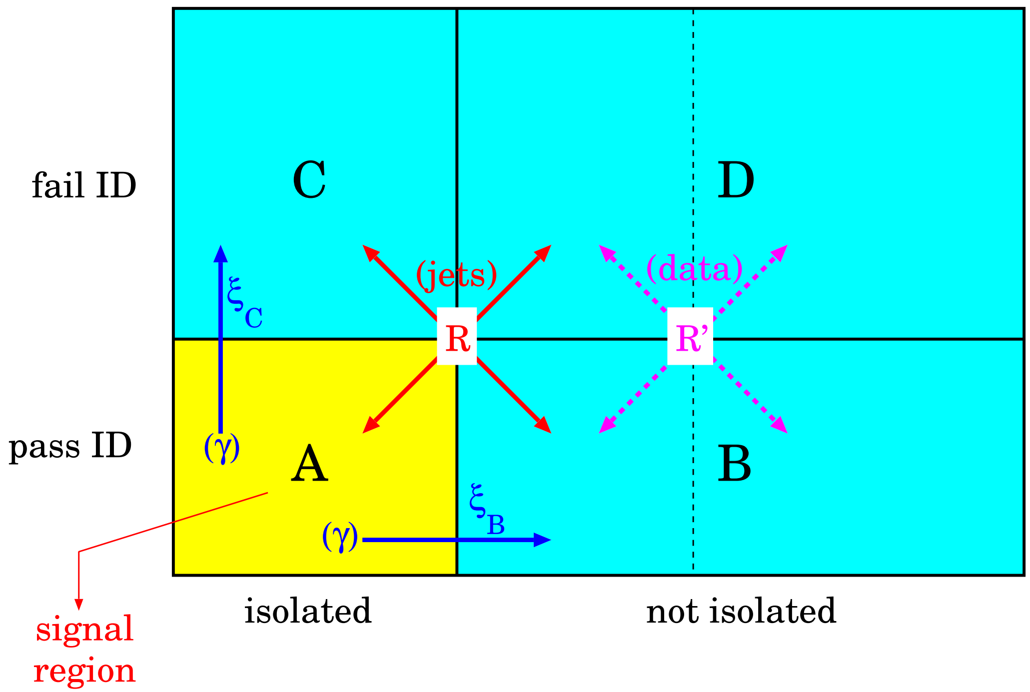
Observables: $N_A, \ N_B, \ N_C, \ N_D$

(in each region $k = A, B, C, D$, $N_k = N_k^\gamma + N_k^j$)

Unknown: N_A^γ ($\equiv$ photons in signal region)

Inputs:

- $\xi_k \stackrel{\text{def}}{=} \frac{N_k^\gamma}{N_A^\gamma}$ $(k = B, C, D)$
  "photon leakage" (from MC) ;
- $R \stackrel{\text{def}}{=} \left(\frac{N_A^j}{N_B^j}\right) \Big/ \left(\frac{N_C^j}{N_D^j}\right)$
  "isol/ID correlation factor" for background (*)



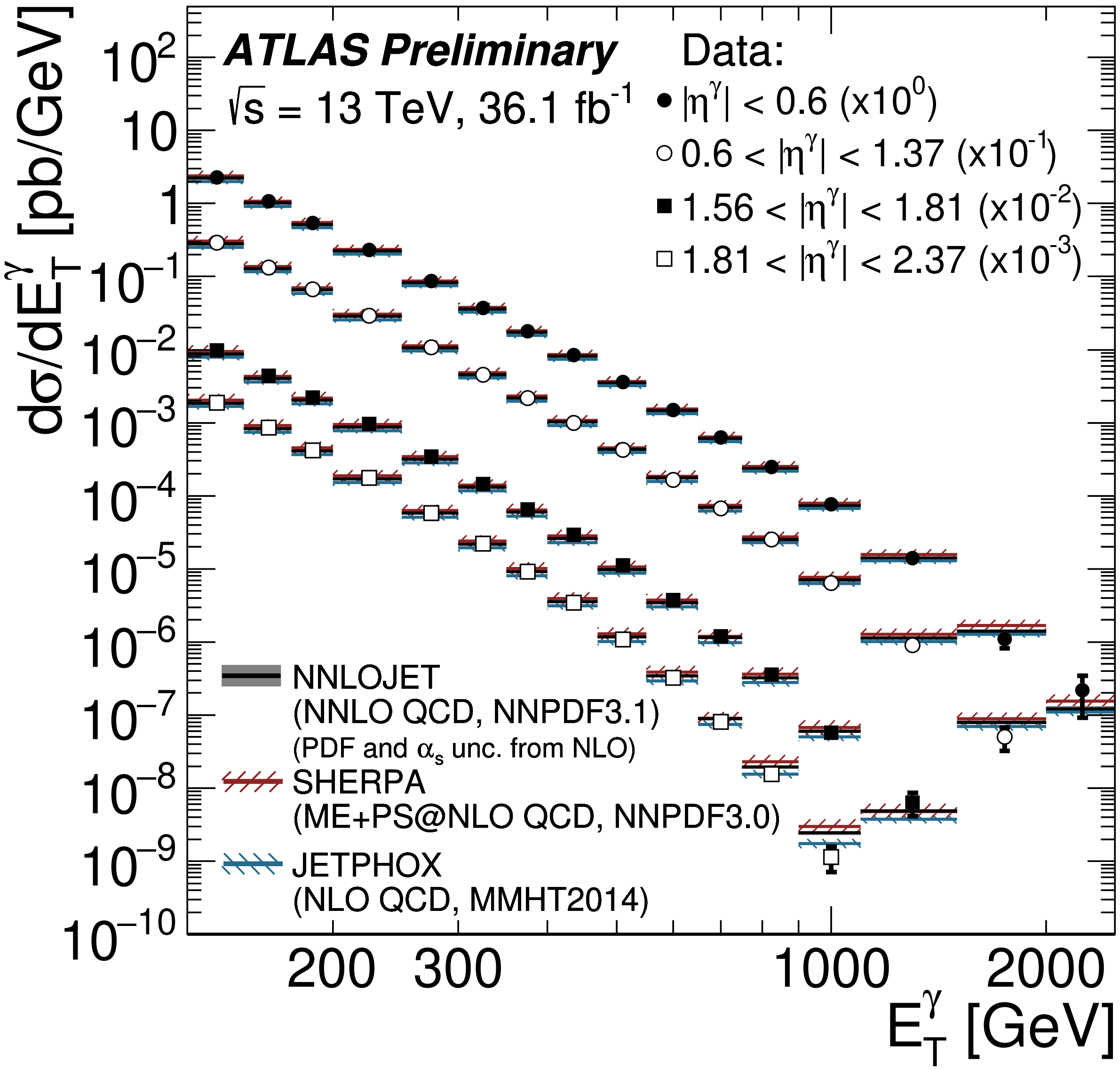
$$\Rightarrow N_A - N_A^\gamma = R \frac{(N_B - \xi_B N_A^\gamma)(N_C - \xi_C N_A^\gamma)}{(N_D - \xi_D N_A^\gamma)} \quad \Rightarrow \quad \text{solve for } N_A^\gamma$$

(*) $R = 1$ is assumed — validated through R': deviation from 1 taken as systematic

More systematics: modify the boundaries of control regions B, C, D: non-Tight and anti-isolation

Measurements of inclusive photon events

Differential cross-sections — inclusive photon



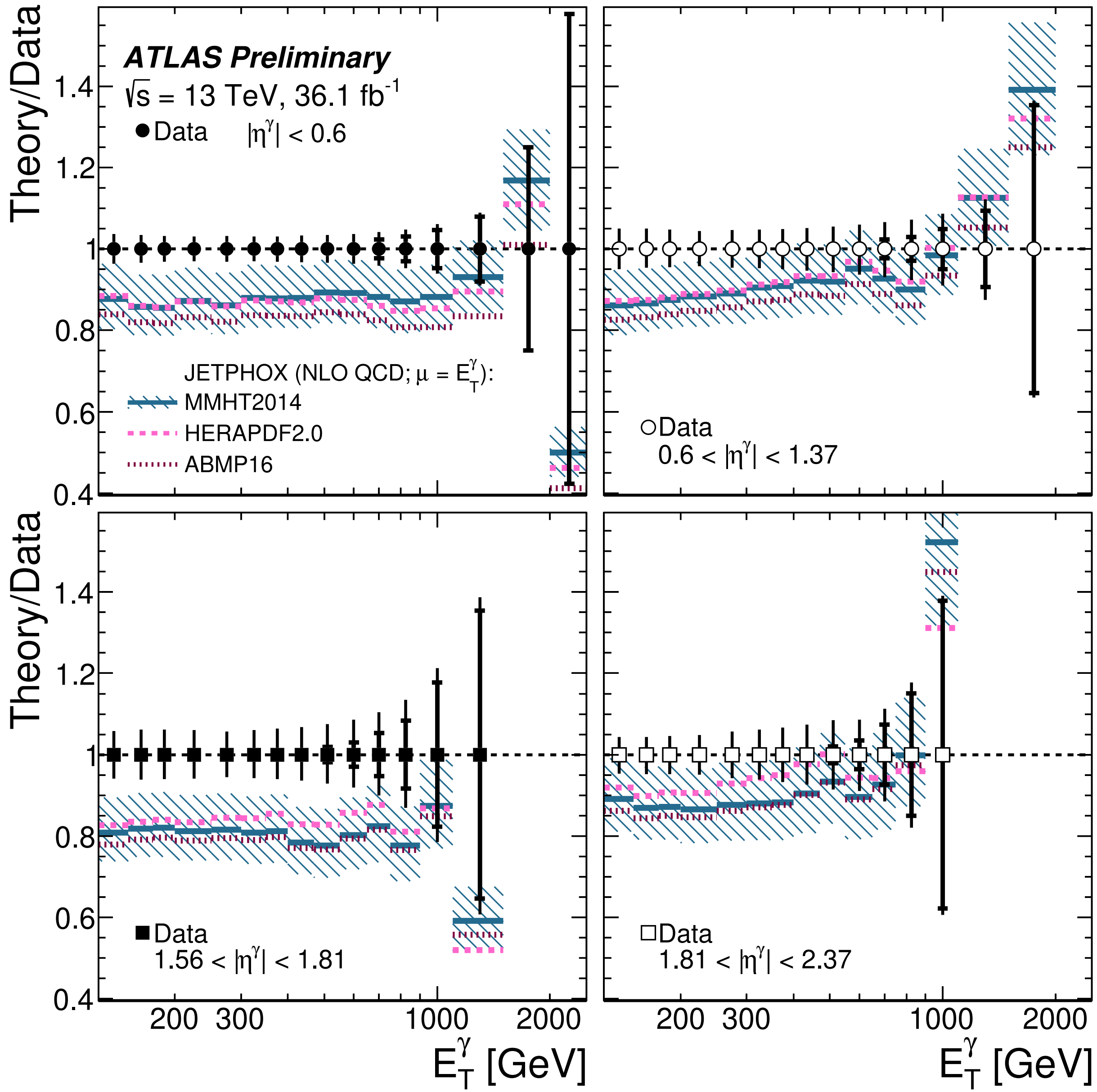
Observed $\frac{d\sigma}{dE_T^\gamma}$ in 4 eta regions

Several theory models (hard process and PDFs):

- JetPhox + MMHT2014
- Sherpa NLO + NNPDF3.0
- NNLOJet + NNPDF3.1

- scales: $\mu_R = \mu_F = \mu_f = E_T^\gamma$ (varied to $\frac{E_T^\gamma}{2}$ and $2E_T^\gamma$, collectively and individually, to assess theory uncertainty due to higher-order contribution)
- $\alpha_S(m_Z) = 0.120$ (varied to 0.118 and 0.122 to asses theory uncertainty)

Differential cross-sections — inclusive photon

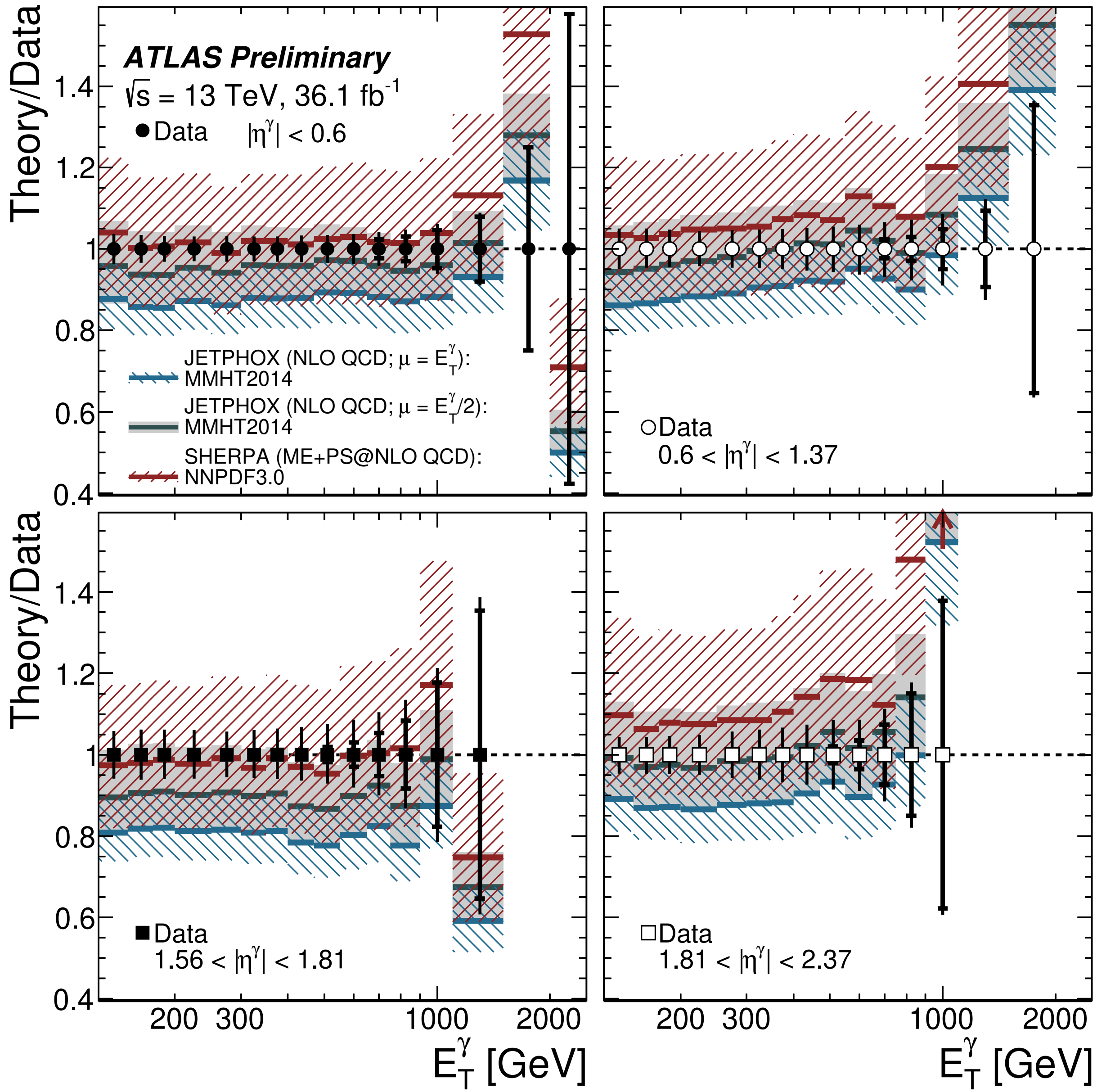


$$\left(\frac{d\sigma}{dE_\mathrm{T}^\gamma}\right)_{MC} \Big/ \left(\frac{d\sigma}{dE_\mathrm{T}^\gamma}\right)_{data}$$

JetPhox with several PDF sets

- underestimate cross-sections
- some sensitivity to PDFs

Differential cross-sections — inclusive photon

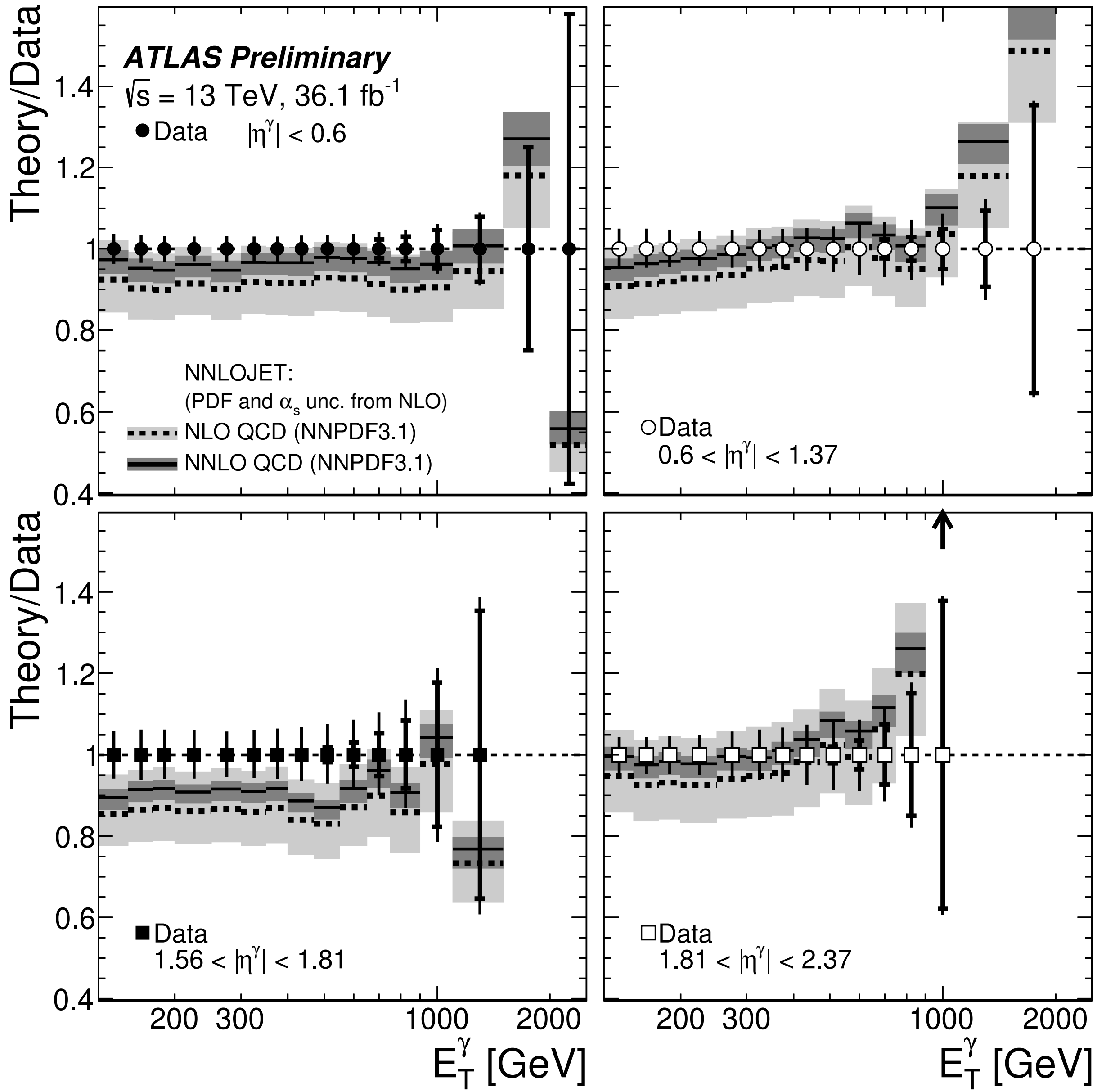


$$\left(\frac{d\sigma}{dE_{\rm T}^{\gamma}}\right)_{MC} \Big/ \left(\frac{d\sigma}{dE_{\rm T}^{\gamma}}\right)_{data}$$

JetPhox and Sherpa NLO

- Sherpa NLO describes data better than JetPhox
- JetPhox seems to prefer scales $\mu = \frac{E_{\rm T}^{\gamma}}{2}$

Differential cross-sections — inclusive photon



$$\left(\frac{d\sigma}{dE_T^\gamma}\right)_{MC} \Big/ \left(\frac{d\sigma}{dE_T^\gamma}\right)_{data}$$

NNLOJet

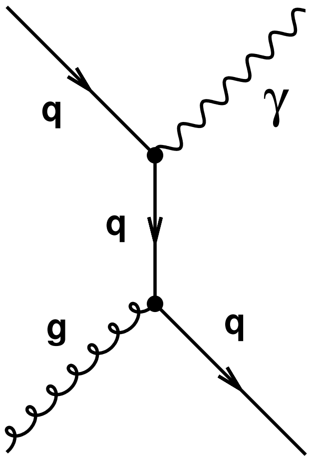
- NNLOJet gives best description of data (apart for $|\eta^\gamma| \in [1.56; 1.81]$)
- Computation at NNLO increase wrt NLO
- Theory uncertainty narrows a lot when going NLO→NNLO

Measurements of photon + jet events

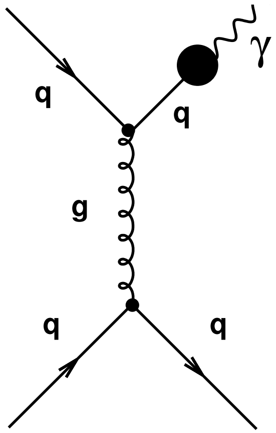
Motivations

Direct (ME) photon production is dominated by t-channel quark exchange
Fragmentation (PS) photon production from dijet events is dominated by t-channel gluon exchange

"direct" photon



"fragmentation" photon

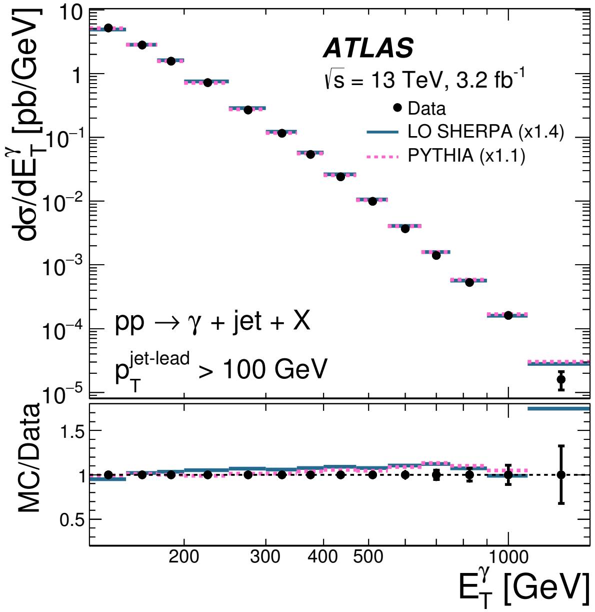


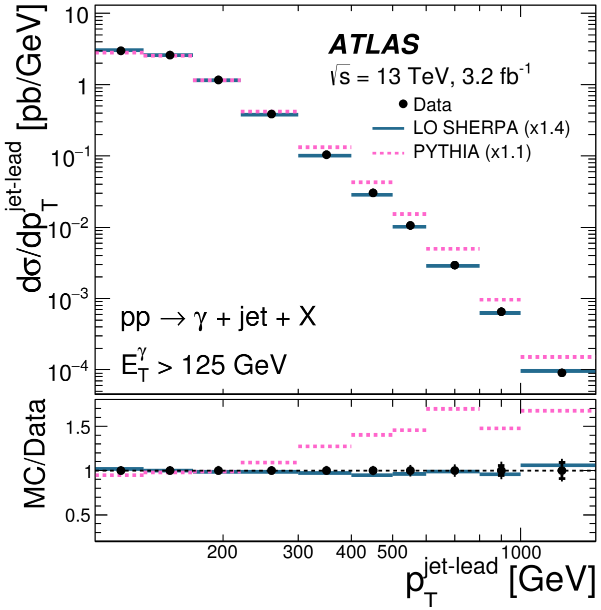
The different spin of the mediator gives different angular distribution ⇒ can be tested through $\cos\theta^* \equiv \tanh\left(\frac{\Delta Y_{\gamma j}}{2}\right)$

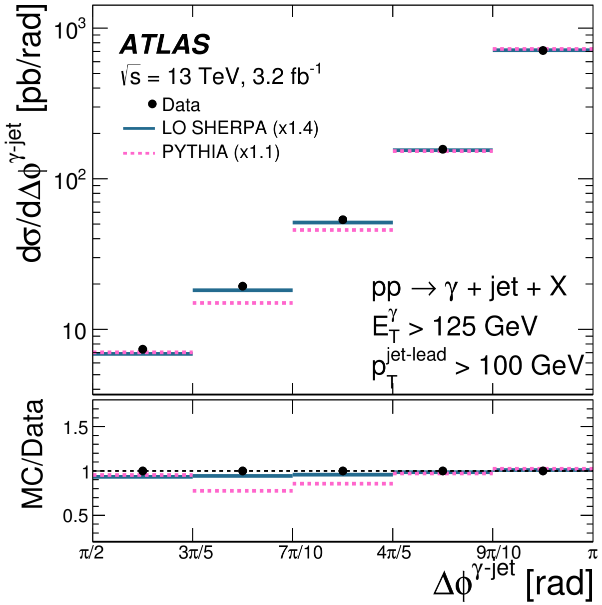
direct photons: (q-mediated – spin 1/2) $\frac{d\sigma}{d|\cos\theta^*|} \xrightarrow[|\cos\theta^*|\to 1]{} \frac{1}{1-|\cos\theta^*|}$

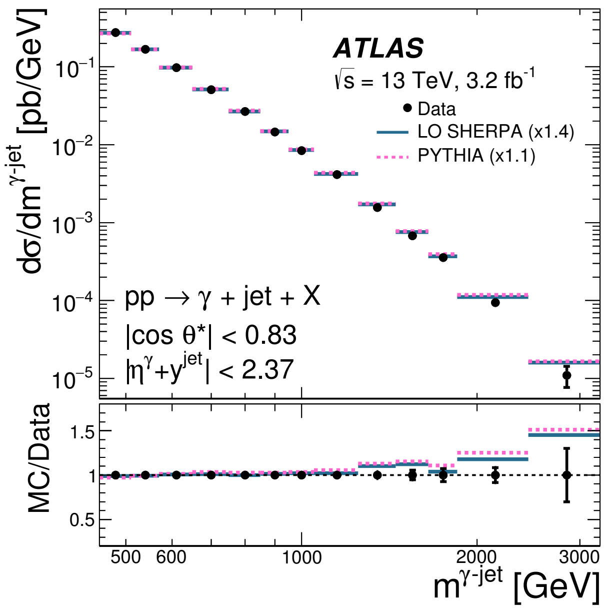
fragmentation photons: (g-mediated – spin 1) $\frac{d\sigma}{d|\cos\theta^*|} \xrightarrow[|\cos\theta^*|\to 1]{} \frac{1}{(1-|\cos\theta^*|)^2}$

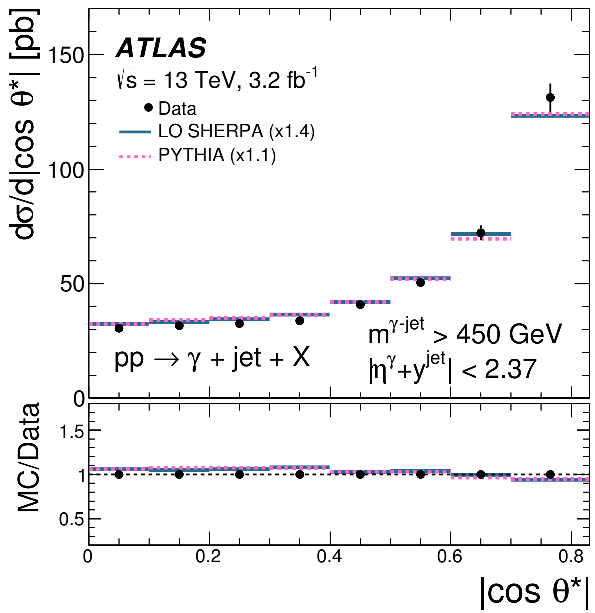
Results









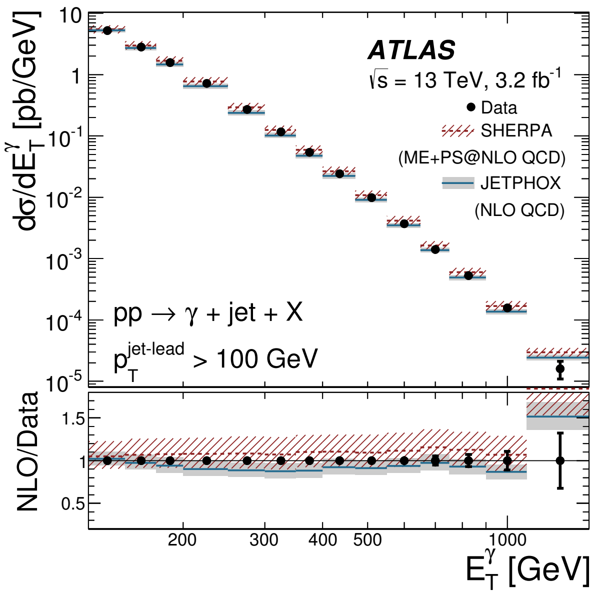


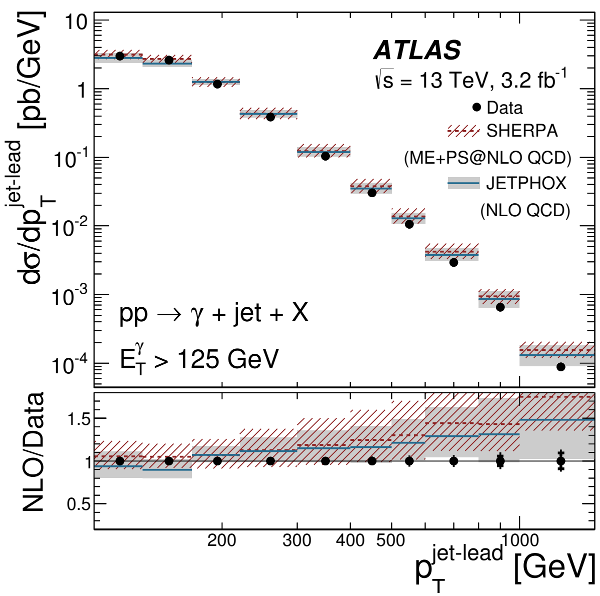
LO calculations underestimate observed cross-sections: need to rescale prediction to match observed yields

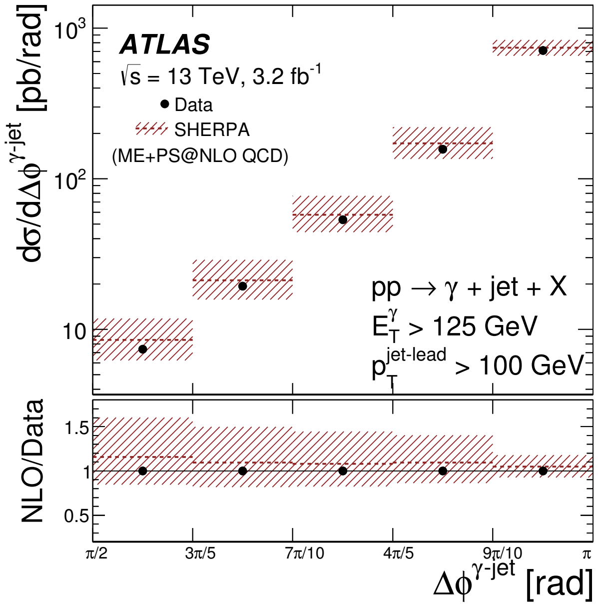
Pythia $\times 1.1$
Sherpa $\times 1.4$

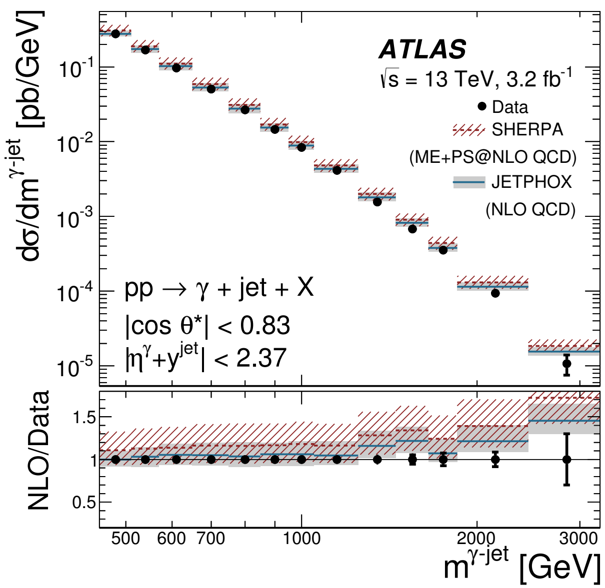
Pythia and Sherpa predict similar shapes — apart for $p_{\mathrm{T}}^{\text{jet-lead}}$ and $\Delta\phi^{\gamma\text{-jet}}$, worse in Pythia

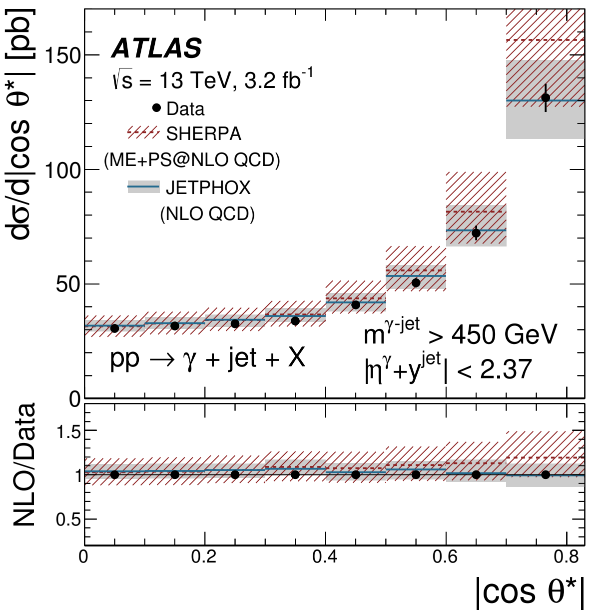
Results











NLO calculation don't need to be rescaled

Agreement within uncertainties in most of the phase space

NLO overestimates cross-section at high $p_T^{\text{jet-lead}}$

JetPhox not adequate to describe $\Delta\phi^{\gamma\text{-jet}}$

Cross-section ratios:

$$R^{\gamma} \equiv \frac{d\sigma_{\gamma}^{13\,TeV}}{d\sigma_{\gamma}^{8\,TeV}}$$

and

$$D^{\gamma/Z} \equiv \left(\frac{d\sigma_{\gamma}^{13\,TeV}}{d\sigma_{\gamma}^{8\,TeV}}\right) \Big/ \left(\frac{\sigma_{Z,fid}^{13\,TeV}}{\sigma_{Z,fid}^{8\,TeV}}\right)$$

Results on $R^\gamma \equiv \frac{d\sigma_\gamma^{13\,TeV}}{d\sigma_\gamma^{8\,TeV}}$

NLO calculation have theoretical uncertainties larger than the experimental ones.

Such uncertainties are correlated between 8 TeV and 13 TeV, therefore in ratios such as $R^\gamma = \frac{d\sigma_\gamma^{13\,TeV}}{d\sigma_\gamma^{8\,TeV}}$ they partially compensate, allowing better comparison to experimental results.
Similarly, some systematic uncertainties are correlated and would reduce in the ratio.

Collision data

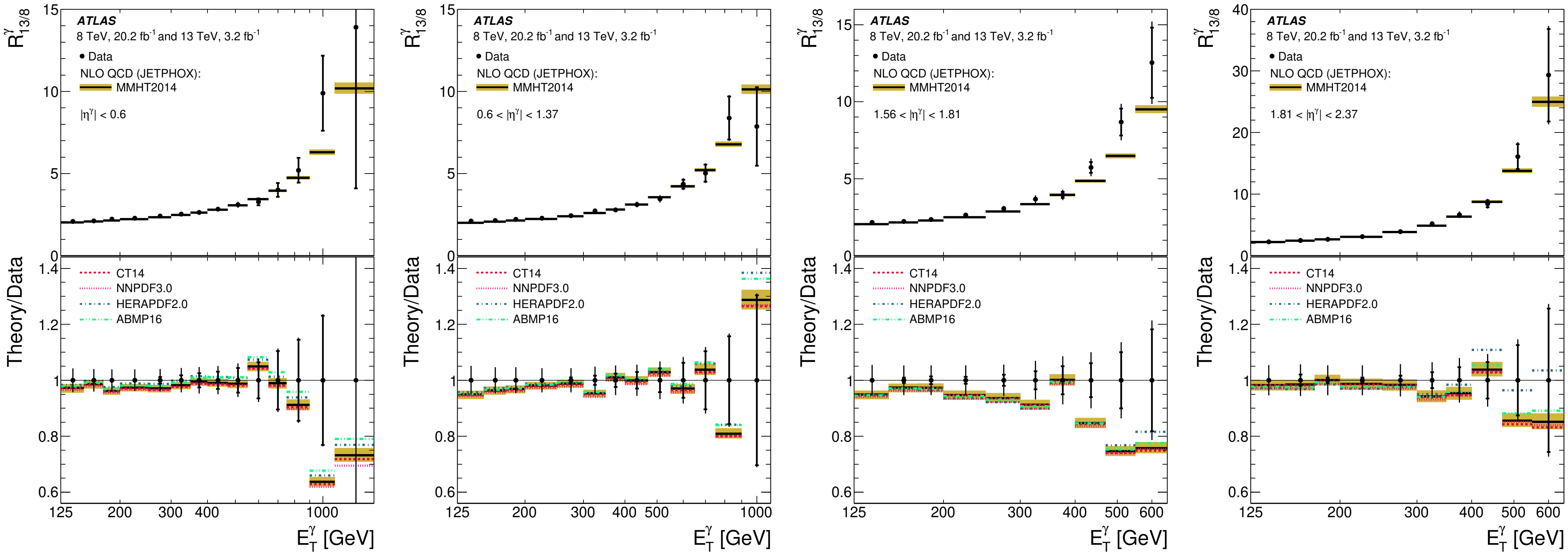
8 TeV data: $\mathcal{L} = 20.2\ \mathrm{fb}^{-1}$; 13 TeV data: $\mathcal{L} = 3.2\ \mathrm{fb}^{-1}$

Generators

inclusive photon : JetPhox (NLO accuracy)

Results on $R^{\gamma} \equiv \frac{d\sigma_{\gamma}^{13\,TeV}}{d\sigma_{\gamma}^{8\,TeV}}$

Top plots: $R^{\gamma} \equiv \frac{d\sigma_{\gamma}^{13\,TeV}}{d\sigma_{\gamma}^{8\,TeV}}$ — measurements and theory predictions



Bottom plots: $\frac{(R^{\gamma})^{theory}}{(R^{\gamma})^{meas}}$ for different PDF sets

CT14
NNPDF3.0
HERAPDF2.0
ABMP16

Results on $D^{\gamma/Z} \equiv \left(\frac{d\sigma_{\gamma}^{13\,TeV}}{d\sigma_{\gamma}^{8\,TeV}}\right) \Big/ \left(\frac{\sigma_{Z,fid}^{13\,TeV}}{\sigma_{Z,fid}^{8\,TeV}}\right)$

Double ratios with another final state $D^{\gamma/Z} = \frac{R^{\gamma}}{R^{Z}} = \left(\frac{\sigma_{\gamma}^{13\,TeV}}{\sigma_{\gamma}^{8\,TeV}}\right) \Big/ \left(\frac{\sigma_{Z}^{13\,TeV}}{\sigma_{Z}^{8\,TeV}}\right)$ benefit of the cancellation of the luminosity uncertainty.

Note: $R^{\gamma} \equiv \frac{d\sigma_{\gamma}^{13\,TeV}}{d\sigma_{\gamma}^{8\,TeV}}$ is a function of E_{T}^{γ} in several regions of $|\eta^{\gamma}|$

On the opposite, $R^{Z} \equiv \frac{\sigma_{Z,fid}^{13\,TeV}}{\sigma_{Z,fid}^{8\,TeV}}$ is a single number, measured as $R^{Z} = 1.537 \pm 0.001(\mathrm{stat}) \pm 0.010(\mathrm{syst}) \pm 0.044(\mathrm{lumi})$

Collision data

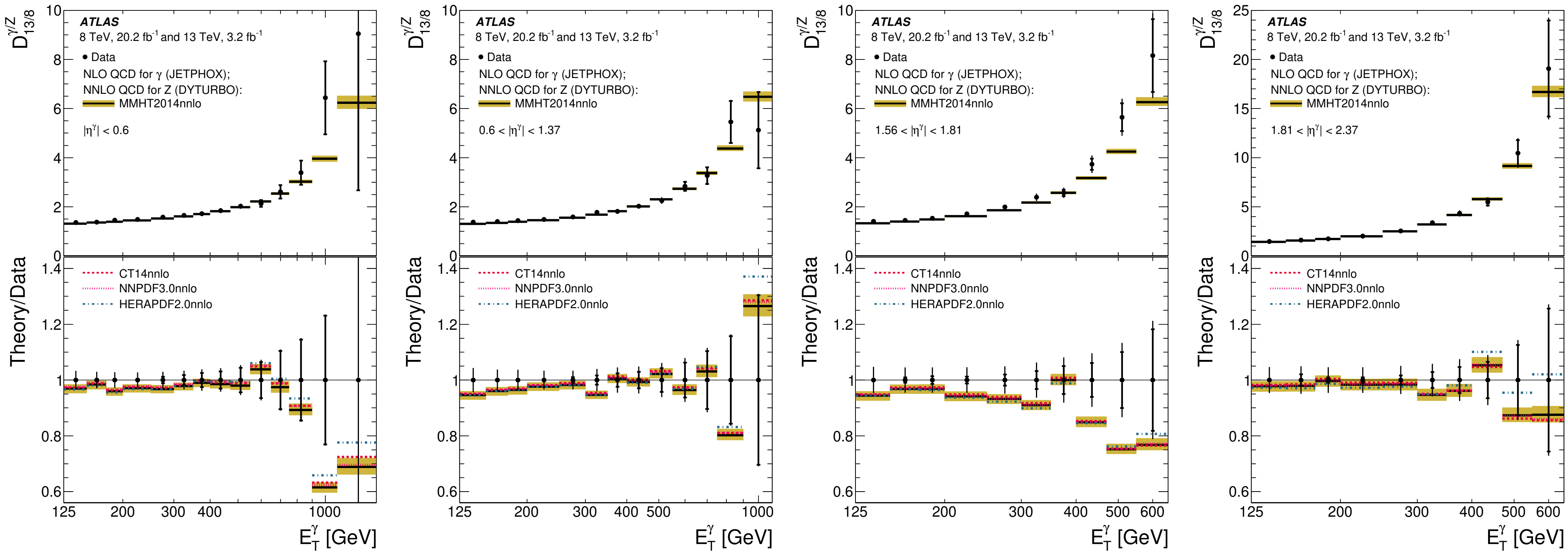
- 8 TeV data: $\mathcal{L} = 20.2\ \mathrm{fb}^{-1}$; 13 TeV data: $\mathcal{L} = 3.2\ \mathrm{fb}^{-1}$
- final states: inclusive photon and inclusive $Z \to \ell^{+}\ell^{-}$

Generators

- inclusive photon : JetPhox (NLO accuracy)
- inclusive Z: DYturbo (NNLO accuracy)

Results on $D^{\gamma/Z} \equiv \left(\frac{d\sigma_\gamma^{13\,TeV}}{d\sigma_\gamma^{8\,TeV}}\right) \Big/ \left(\frac{\sigma_{Z,fid}^{13\,TeV}}{\sigma_{Z,fid}^{8\,TeV}}\right)$

Top plots: $D^{\gamma/Z} \equiv \frac{R^\gamma}{R^Z}$ — measurements and theory predictions



Bottom plots: $\frac{(D^{\gamma/Z})^{theory}}{(D^{\gamma/Z})^{meas}}$ for different PDF sets

CT14nnlo
NNPDF3.0nnlo
HERAPDF2.0nnlo

Conclusions

The NNLO accuracy parton-level NNLOJet generator provides predictions of the inclusive photon differential cross-sections, with the smallest theoretical uncertainties, and in good agreement with the observation.

⇒ important result, will help in constraining proton PDFs in a global QCD fit at NNLO

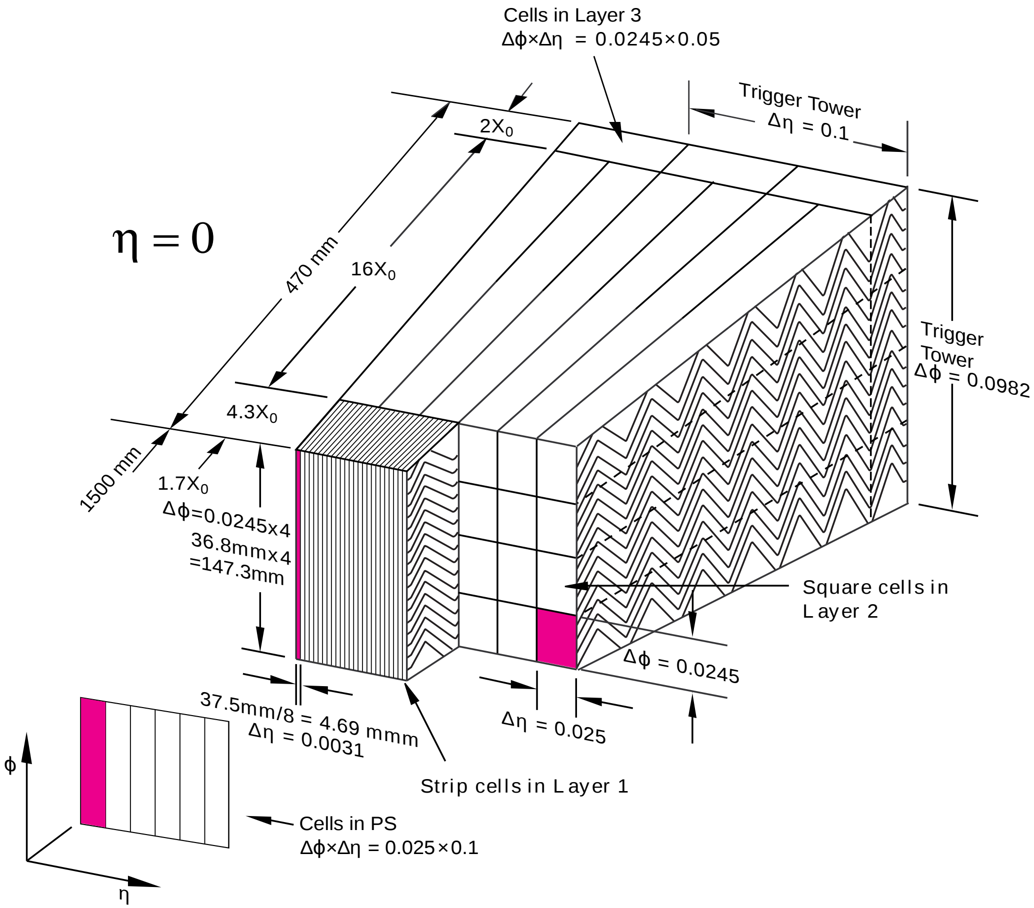
Sherpa NLO is a multi-leg, particle-level generator that generally describes observations with good agreement, for essentially all kinematic observables

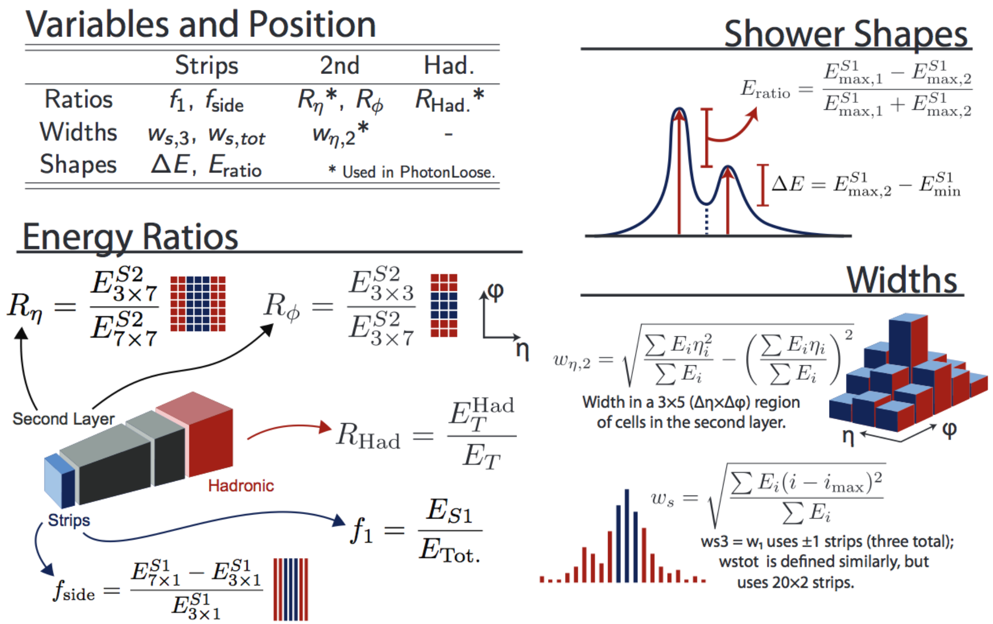
Jetphox is a NLO parton-level generator that well describes distributions for most kinematic observables — but has an underestimate of the cross-sections.

Pythia and Sherpa LO typically underestimate the cross-sections

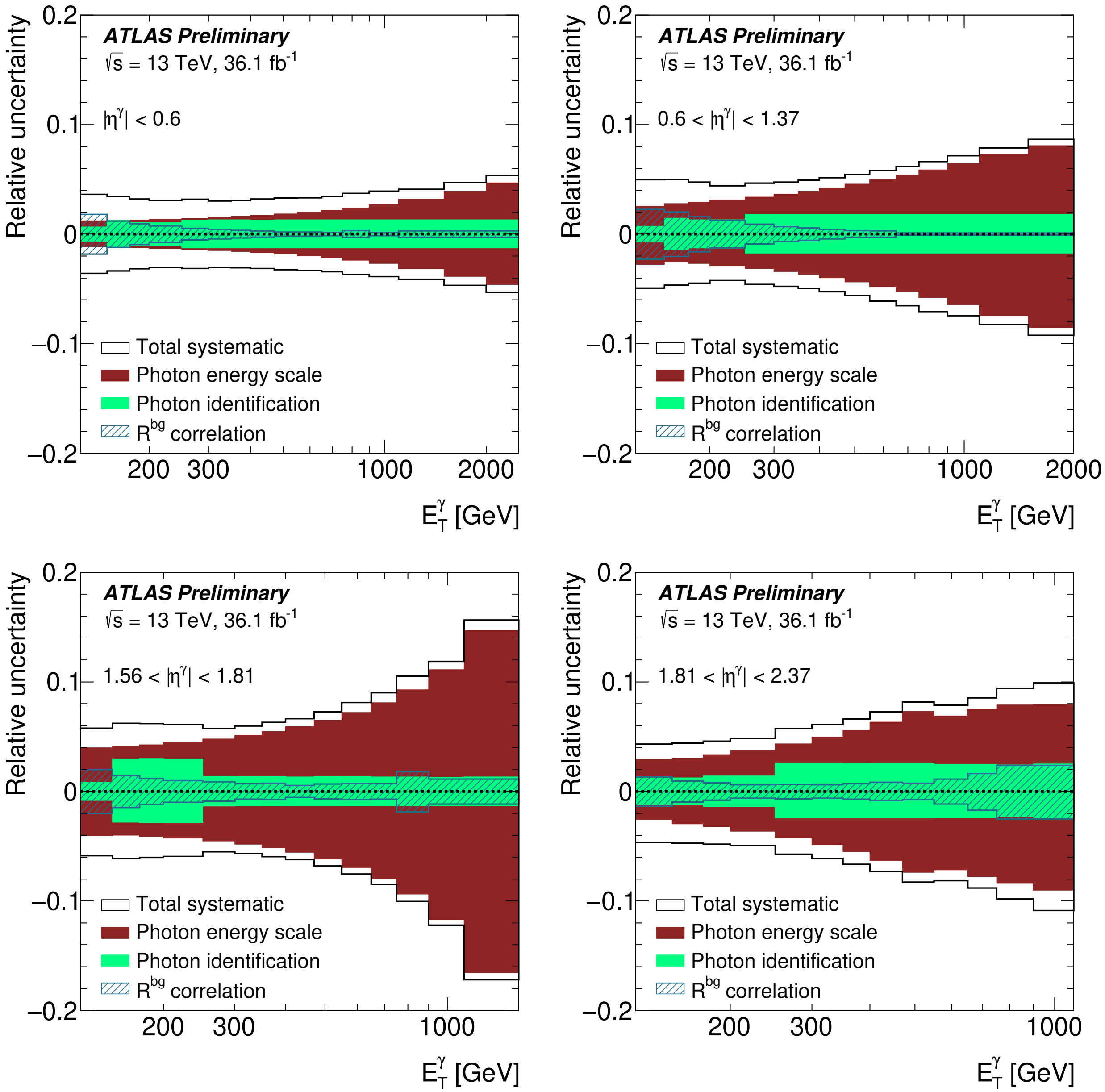
BACKUP

Shower shape variables

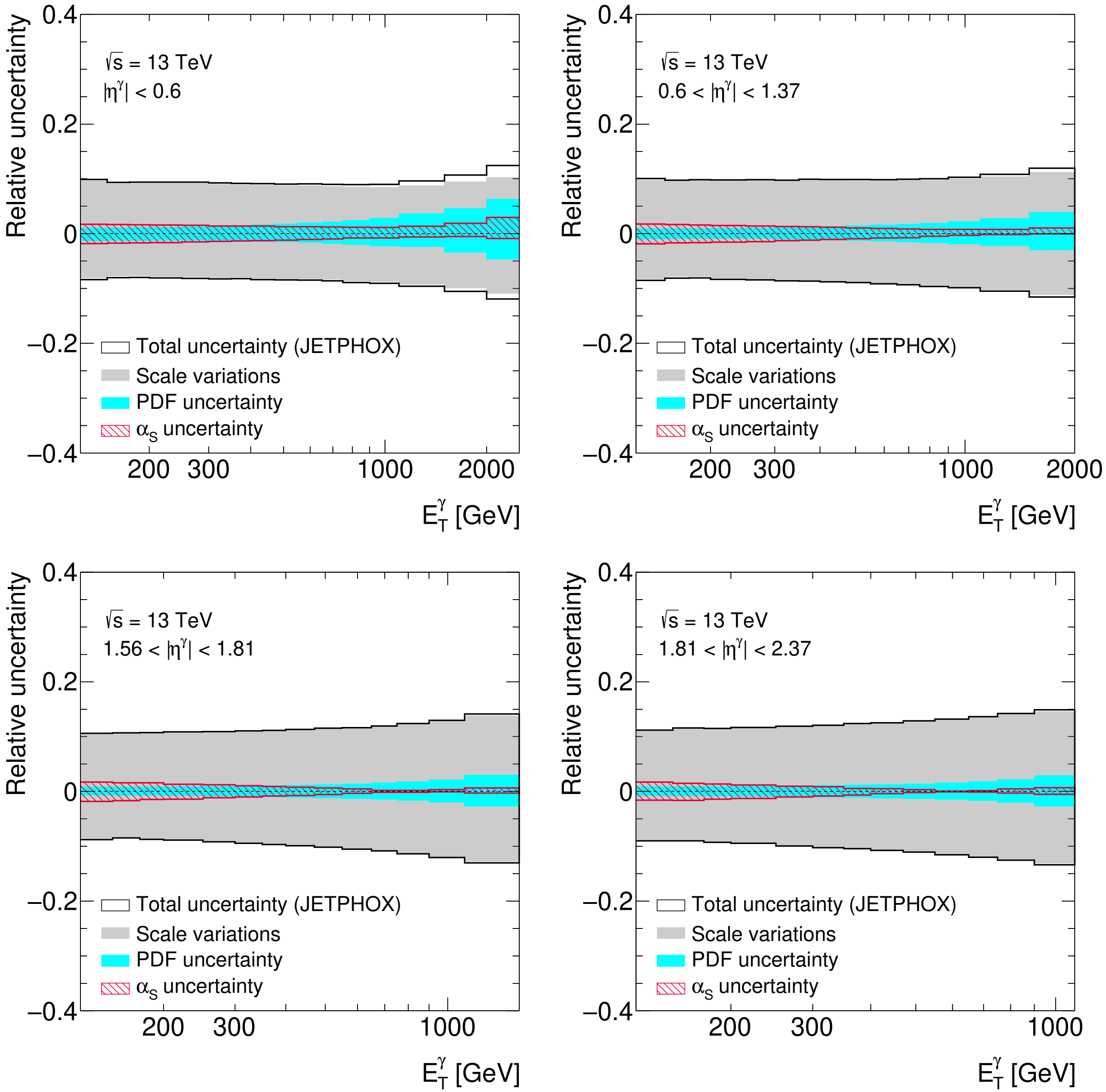




Systematic uncertainties on inclusive photons



Theoretical uncertainties in JetFox



Theoretical scale uncertainties : NLO vs NNLO