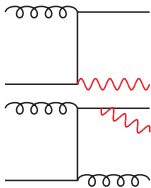


# Parton shower simulations of SM processes with photons and comparison with LHC data

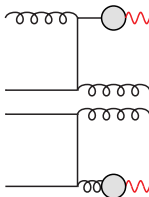
Frank Siegert

Workshop on Photon Physics at the LHC, Paris, 18 May 2015

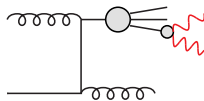
## Direct photons



## Fragmentation



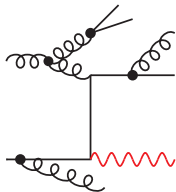
## Non-prompt



- separation between direct+fragmentation depends on order of calculation
- since parton shower goes beyond fixed-order there is no exact identification of these

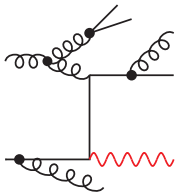
But let's try ...

## Direct photons



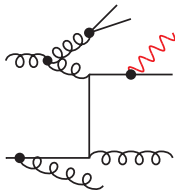
- LO matrix elements for photon production
  - dressed with “softer” QCD parton shower emissions
- missing higher-order corrections

## Direct photons



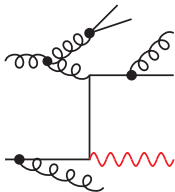
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## Fragmentation



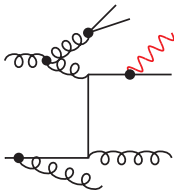
- LO matrix elements for jet production
  - "softer" QED parton shower emissions
  - interleaved with QCD emissions
- very inefficient due to low QED splitting probability

## Direct photons



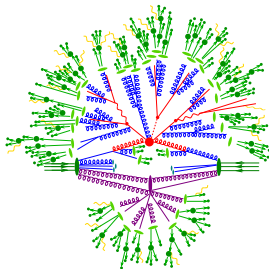
- LO matrix elements for photon production
  - dressed with "softer" QCD parton shower emissions
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## Fragmentation



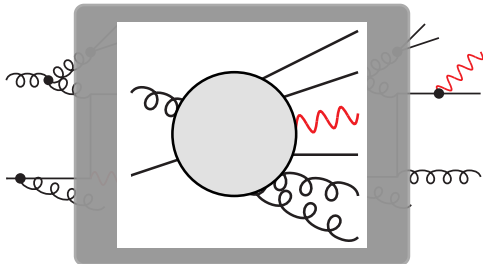
- LO matrix elements for jet production
  - "softer" QED parton shower emissions
  - interleaved with QCD emissions
- very inefficient due to low QED splitting probability

## Non-prompt



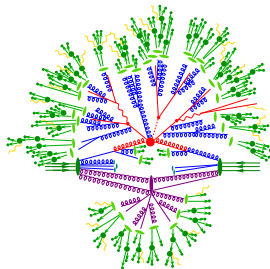
- hadron decays like  $\pi \rightarrow \gamma\gamma$
- resummed QED FSR in hadron decays

## Direct photons

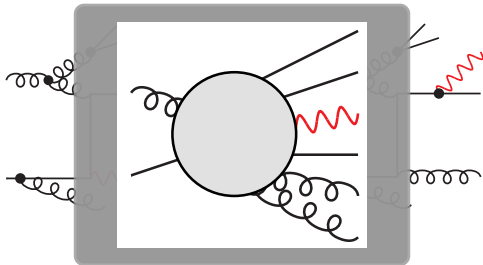


## Fragmentation

## Non-prompt

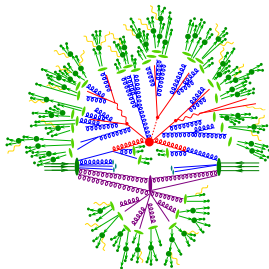


## Direct photons



## Fragmentation

## Non-prompt

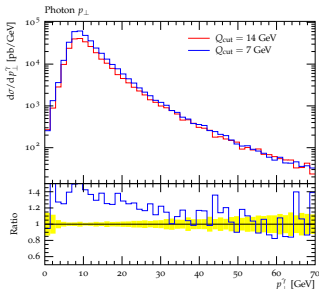


- Multi-jet merging: improve shower evolution by including matrix elements with jet emissions
- conceptually interesting for photon production: higher-order QCD matrix elements contain both direct and fragmentation component (difference is only kinematics)
- need to define photon isolation and  $p_{\perp}$  requirements

## Factorisation scale vs. ME+PS merging cut

**Problem:** factorisation scale (e.g.  $\mu_F = p_{\perp}^{\gamma}$ ) can become lower than merging cut  
 $\Rightarrow$  shower (and thus factorised cross section) is not able to fill phase space up to merging cut  $Q_{\text{cut}}$   
 $\Rightarrow$  misses part of fragmentation component

- in many processes this is not a problem due to large  $\mu_F$
- here even relevant for higher  $p_{\perp}^{\gamma}$  generated from further emissions
- manifests itself as large merging cut dependence:





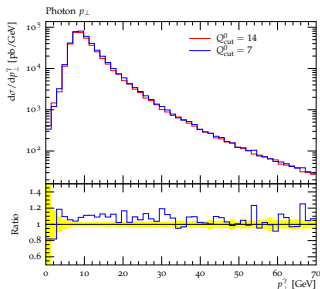
## Factorisation scale vs. ME+PS merging cut

**Solution:** choose dynamical  $Q_{\text{cut}}$  depending on the  $\mu_F$  of the event

- similar to DIS simulation [Carli, Gehrmann, Höche \(2009\)](#)

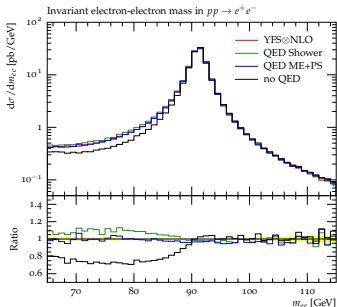
- example: 
$$\left(\frac{Q_{\text{cut}}}{E_{\text{CMS}}}\right)^2 = \frac{\left(\frac{Q_{\text{cut}}^0}{E_{\text{CMS}}}\right)^2}{1.0 + \left(\frac{Q_{\text{cut}}^0}{\kappa p_{\perp}^{\gamma}}\right)^2}$$

with  $Q_{\text{cut}}^0$  nominal cut and safety factor  $\kappa \gtrsim 1.0$



## Inclusiveness with respect to photon cuts

- so far only discussed QCD ME+PS merging, no QED parton shower involved there!
- photons always produced in matrix elements, hard and isolated
- alternatively: QED ME+PS merging [Höche, Schumann, FS \(2009\)](#)  
⇒ inclusive with respect to photon cuts
- also possible to combine with QCD ME+PS



Marek Schönherr, PhD thesis (2011)

- example:
  - $pp \rightarrow e^+e^-$
  - $pp \rightarrow e^+e^-\gamma$
  - $pp \rightarrow e^+e^-\gamma\gamma$
  - ...
- comparison of  $m_{\ell\ell}$  from “dressed” leptons
  - YFS soft-photon resummation including NLO correction
  - pure QED shower
  - QED ME+PS
  - no QED radiation

## Setup

- QCD ME+PS merging with dynamical  $Q_{\text{cut}}$
- Sherpa 2.1.1 using the default CT10-based tune
- full hadron level simulation, including multiple parton interactions
- LHC 7 TeV, comparison to ATLAS data  
(no CMS photon analyses published in Rivet yet?)

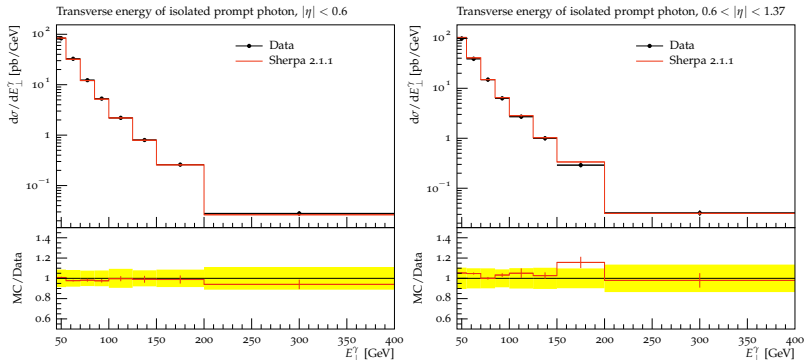
## $\gamma$ +jets

- $pp \rightarrow \gamma + 1, 2, 3 \text{ jets}$
- $p_{\perp}^{\gamma} > 10 \text{ GeV}$
- Frixione isolation
- scaled by  $k = 1.15$

## $\gamma\gamma$ +jets

- $pp \rightarrow \gamma\gamma + 0, 1, 2 \text{ jets}$
- $p_{\perp}^{\gamma} > 15 \text{ GeV}$
- $\Delta R(\gamma, \gamma) > 0.2$
- Frixione isolation

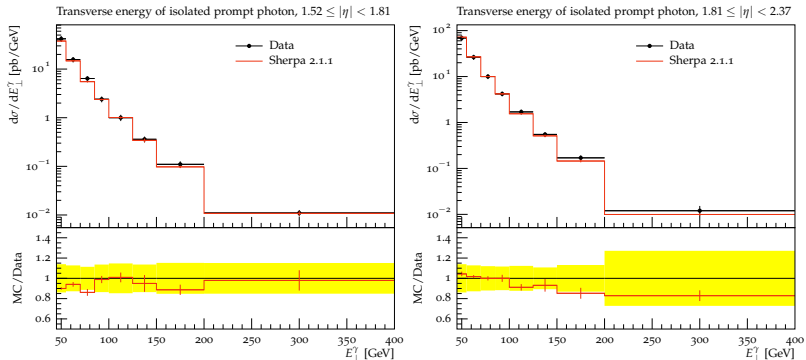
# 2010 Inclusive isolated prompt photon analysis ATLAS\_2011\_I921594



⇒ Good agreement in all regions of  $p_\perp^\gamma$  and  $\eta^\gamma$

# 2010 Inclusive isolated prompt photon analysis

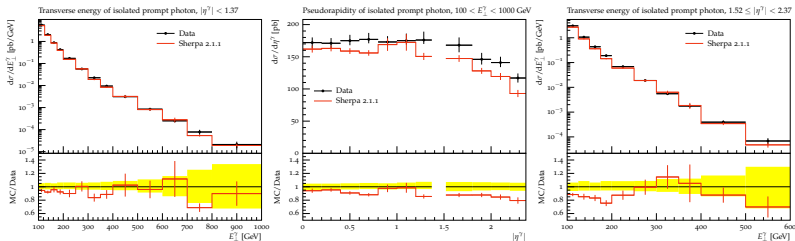
## ATLAS\_2011\_I921594



⇒ Good agreement in all regions of  $p_{\perp}^{\gamma}$  and  $\eta^{\gamma}$

# 2011 Inclusive isolated prompt photon analysis

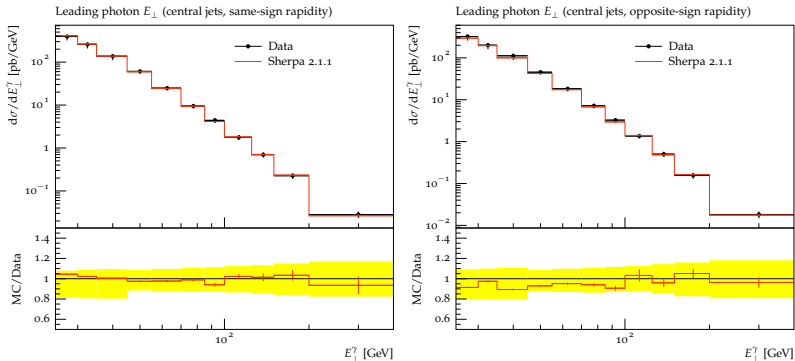
## ATLAS\_2013\_I1263495



- good agreement in central region
- 10-20% deficiency in forward region  
→ could be related to (potential?) forward jet excess (through photon isolation)

# 2011 photon + jet analysis

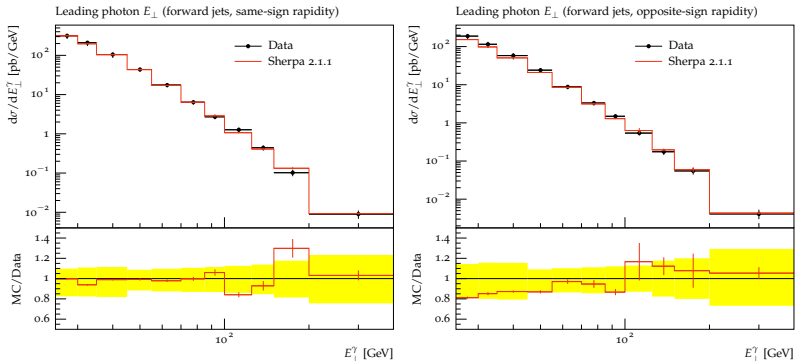
## ATLAS\_2012\_I1093738



- central jet, good agreement

# 2011 photon + jet analysis

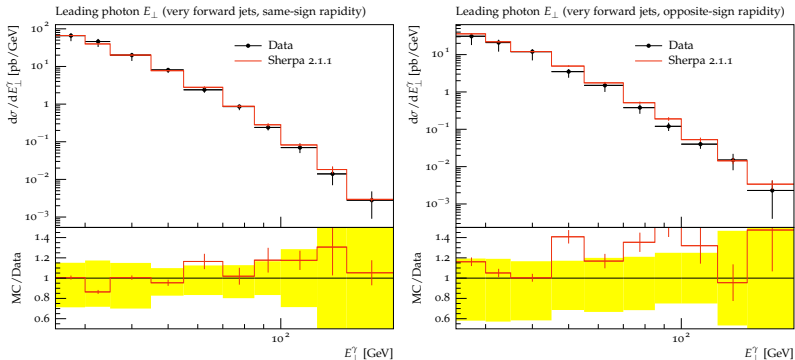
## ATLAS\_2012\_I1093738



- forward jet, good agreement



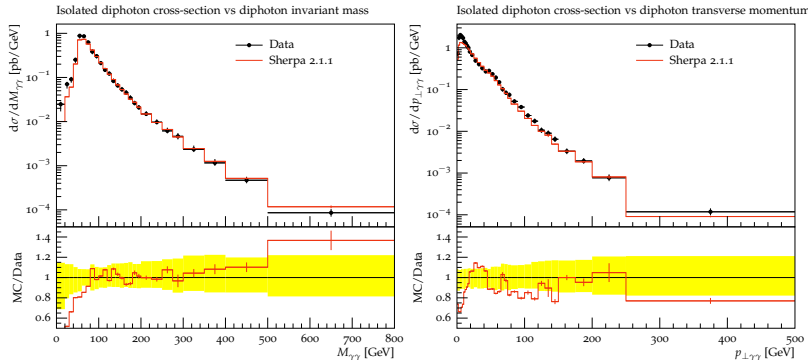
## 2011 photon + jet analysis ATLAS\_2012\_I1093738



- very forward jet, good agreement  
→ no forward jet excess? maybe just not for leading jet.

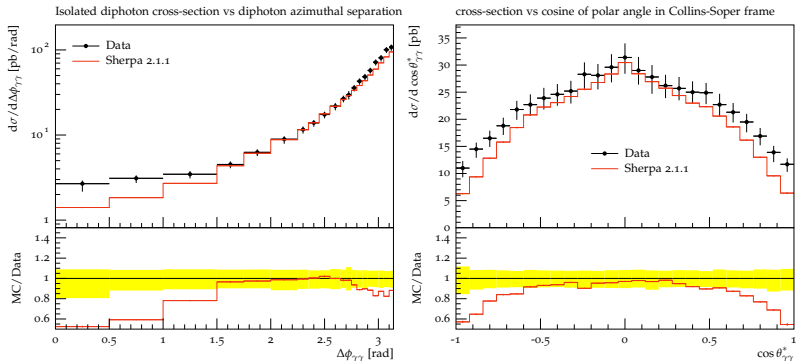
# 2011 inclusive diphoton analysis

## ATLAS\_2012\_I1199269



- tension between good description of  $m_{\gamma\gamma}$  and  $p_{\perp\gamma\gamma}$

## 2011 inclusive diphoton analysis ATLAS\_2012\_I1199269

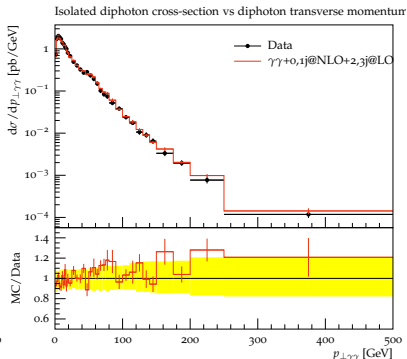
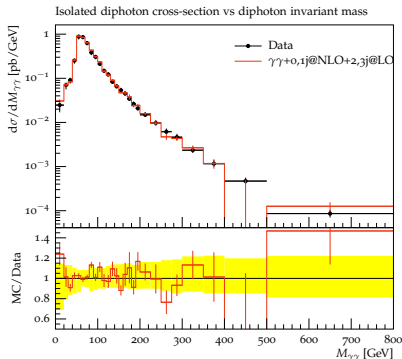


- angular distributions: slightly worse description compared to earlier Sherpa versions

## NLO multi-jet merging for $pp \rightarrow \gamma\gamma$

- other processes already available with NLO multi-jet merging  
**ME+PS@NLO: Höche, Krauss, Schönherr, FS [2012]**
- photon production was so far only available in ME+PS@LO
- here **very preliminary** results from ongoing work towards  
 $\gamma\gamma + 0,1\text{jets}$  @ NLO + 2,3jets @ LO
- current development version of the upcoming Sherpa 2.2.0 with NNPDF3.0 NNLO PDFs and the interface to OpenLoops 1.1.1 matrix elements

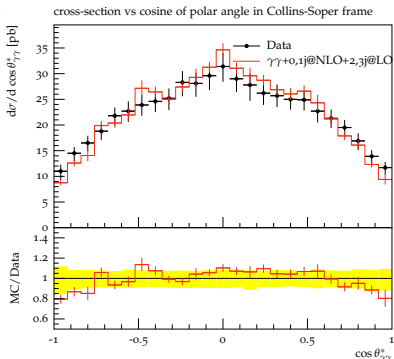
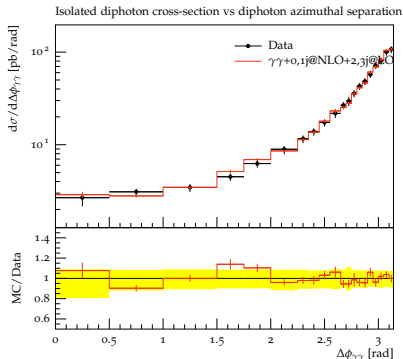
**Höche, FS (in preparation)**



## NLO multi-jet merging for $pp \rightarrow \gamma\gamma$

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Höche, FS (in preparation)



## Summary

- modern parton shower event generators provide interesting options for hadron-level simulations of photon production at the LHC
- multi-jet merging is state-of-the-art
- good agreement in comparisons with LHC measurements

## Outlook

- work ongoing to bring multi-jet merging to NLO accuracy for (di)photon production
- promising first results, but still work in progress
- will also try single photon + jets production in that approach