TECHNISCHE UNIVERSITÄT DRESDEN

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Multijet merging in prompt photon production with Sherpa

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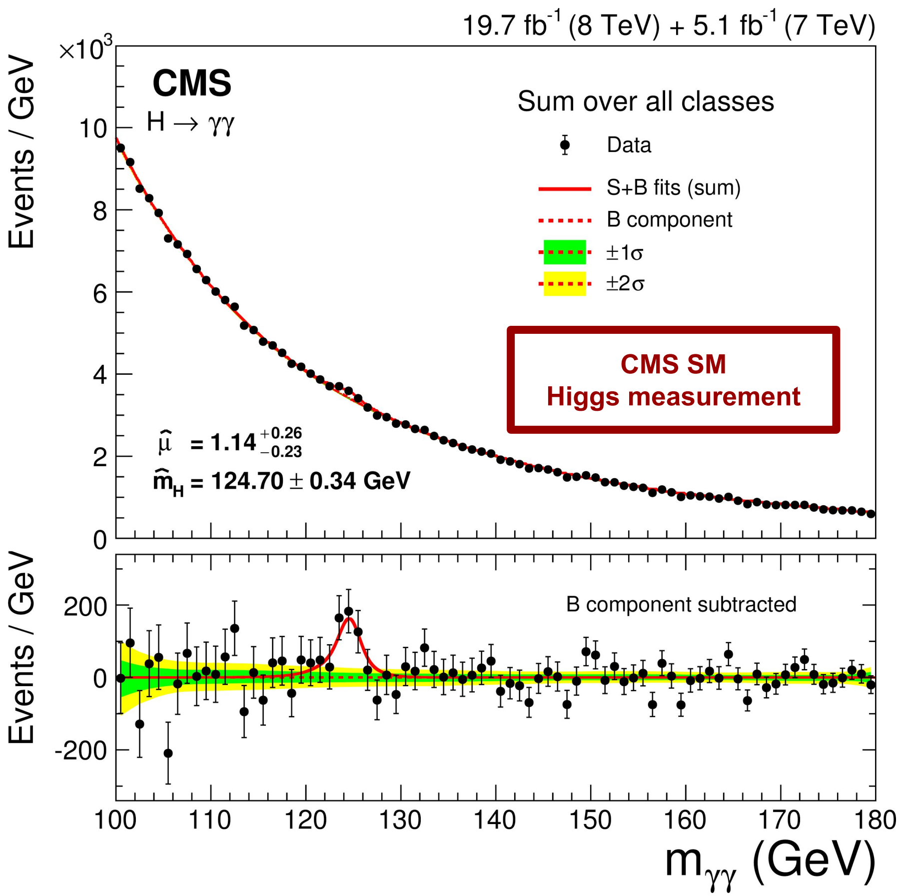
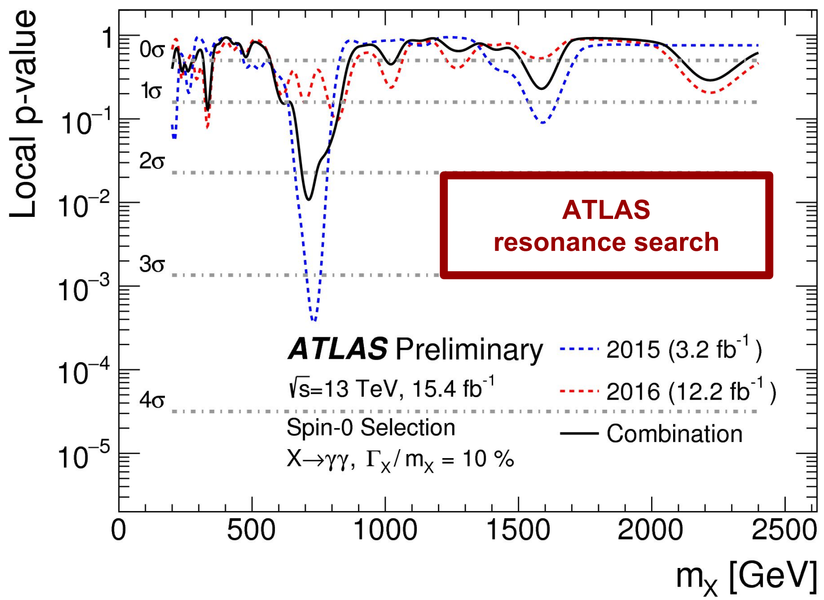
ATLAS/CMS MC Workshop
May 2017

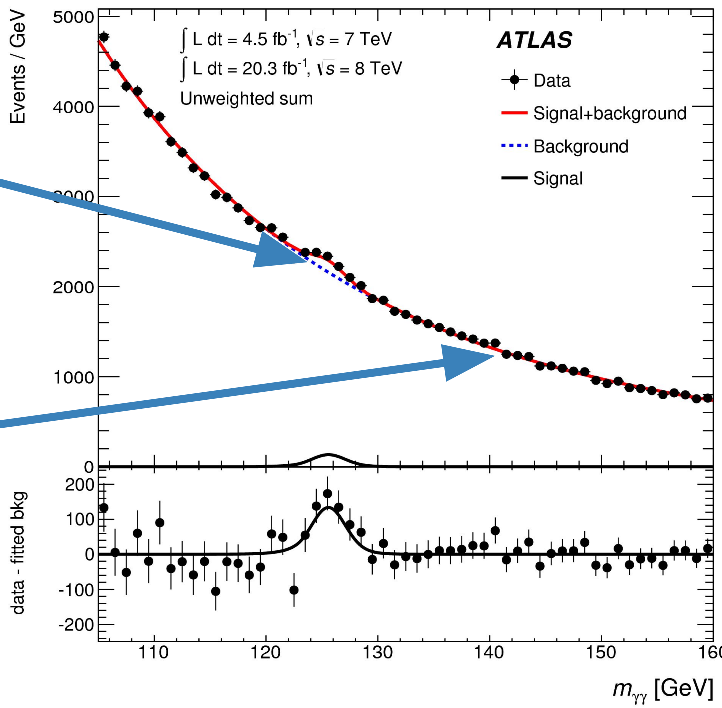
Prompt photons – who cares?

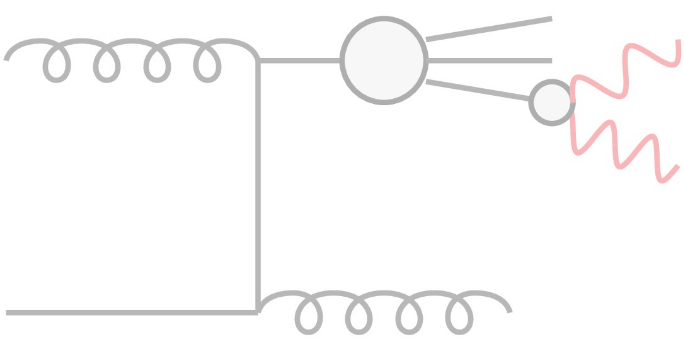




What is a prompt photon?

- Signal photons
  - from decays of heavy resonances
  - Higgs, heavy scalar, graviton, …
- SM background
  - continuum production of diphoton pairs
  - single photon(+jet) production
  - QED FSR
- Non-prompt photons
  - from hadron decays
  - dominated by $\pi^0 \rightarrow \gamma\gamma$





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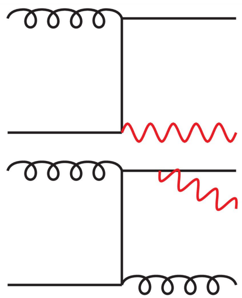
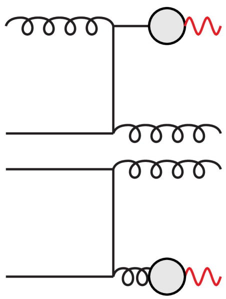
Prompt photons in (fixed-order) theory

Direct component
(Fixed-order calculation)



- γ+jet at NLO ("JetPhox")
  Phys. Rev. D73 (2006), 094007
- $\gamma\gamma$ at NNLO
  Phys.Rev.Lett. 108 (2011), 072001
  arXiv:1612.04333
- $\gamma\gamma$+jets at NLO ("NJet")
  JHEP 1403 (2014), 122
- Loop-induced gg$\rightarrow\gamma\gamma$g
  Phys. Lett. B460 (1999), 184188

Fragmentation component
(Collinear singularities)



- ME singularities factorised
- Resummed to all orders in α_s
  $\Rightarrow$ fragmentation function for γ in quark/gluon
- Relevant even if isolation criteria applied to photons

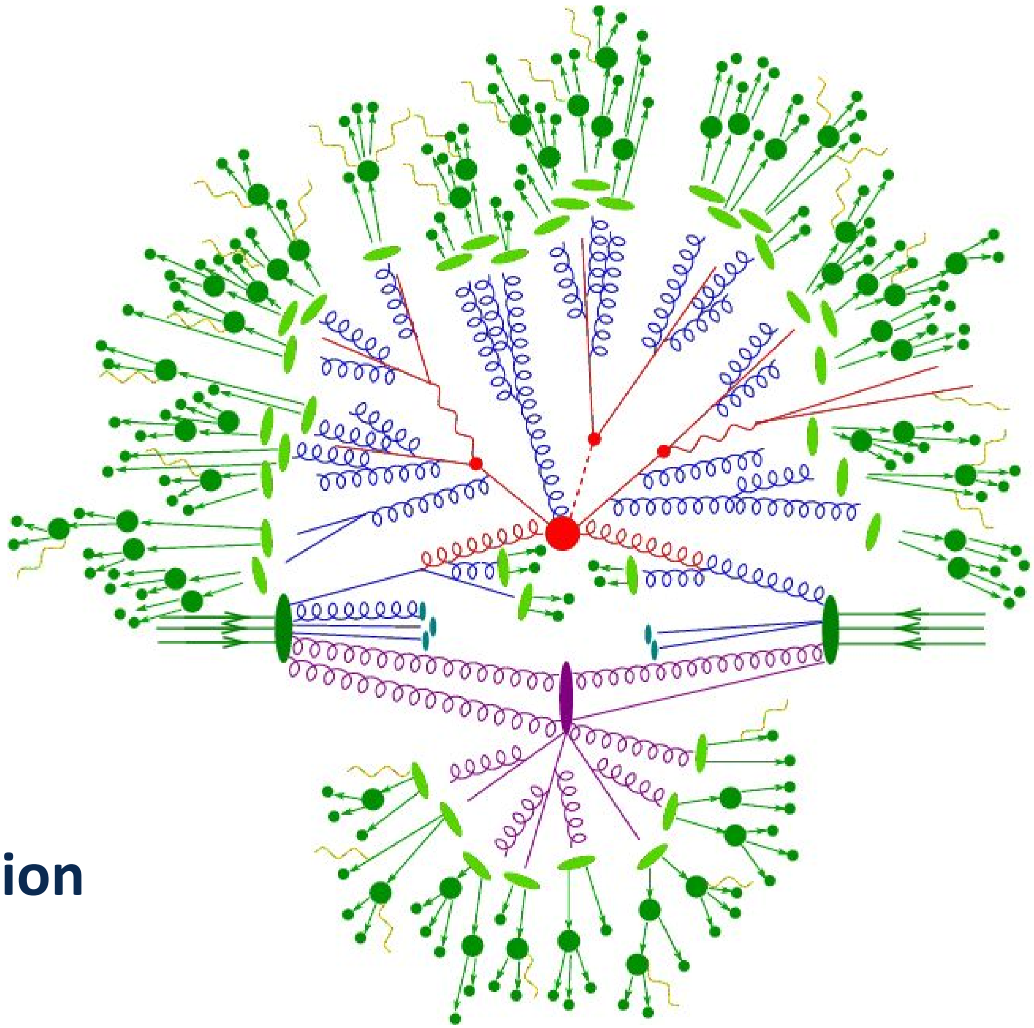
Alternative approach: Event generators

Perturbative Physics

- Hard scattering*
- Prompt decays
- Parton shower*/ QED FSR*

Soft physics

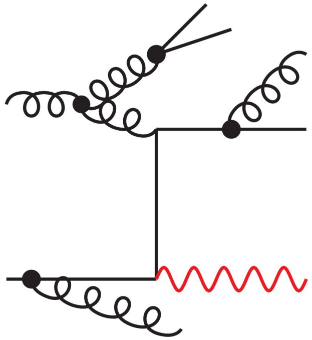
- Underlying event
- Hadronisation
- Hadron Decays



*** Prompt photon production**

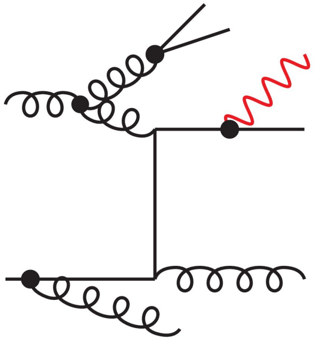
Traditional parton shower

Direct photons



- LO matrix elements for photon production
- dressed with softer QCD shower emissions, $t_{QED} > t_{QCD}$

Fragmentation photons



- LO matrix elements for jet production
- softer QED shower emissions

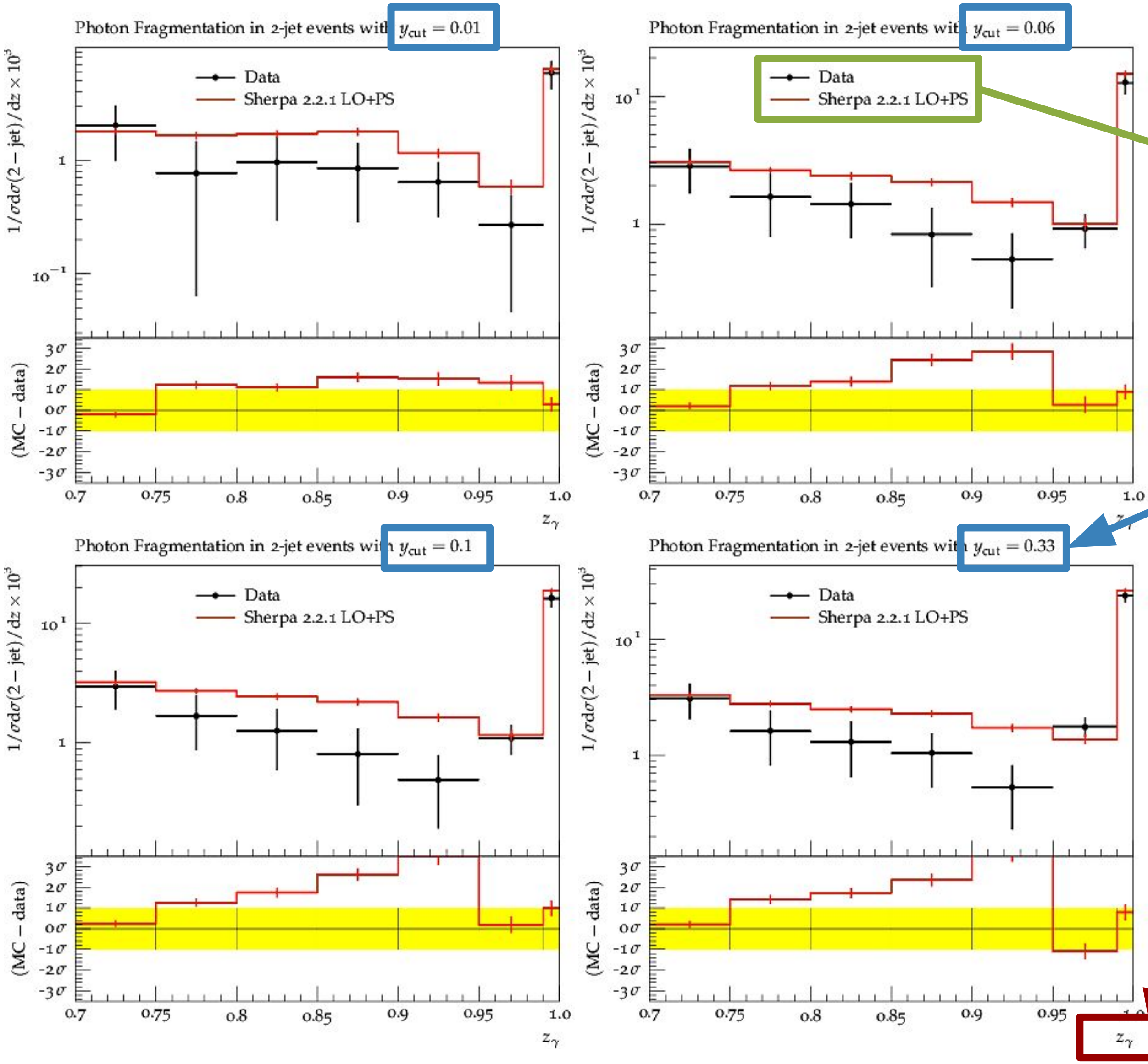
$t_{QED} < t_{QCD}$

“QCD x QED” shower evolution

$$\Delta(\mu_0^2, Q^2) \;=\; \Delta^{\rm QCD}(\mu_0^2, Q^2)\,\Delta^{\rm QED}(\mu_0^2, Q^2)$$

$$\Delta^{\rm QED}(\mu_0^2, Q^2) \;=\; \exp\left\{ -\int_{\mu_0^2}^{Q^2} \frac{{\rm d}t}{t} \int {\rm d}z \sum_i \frac{1}{2}\,\mathcal{K}_i^{\rm QED}(z,t) \right\}$$

Fragmentation function measurements



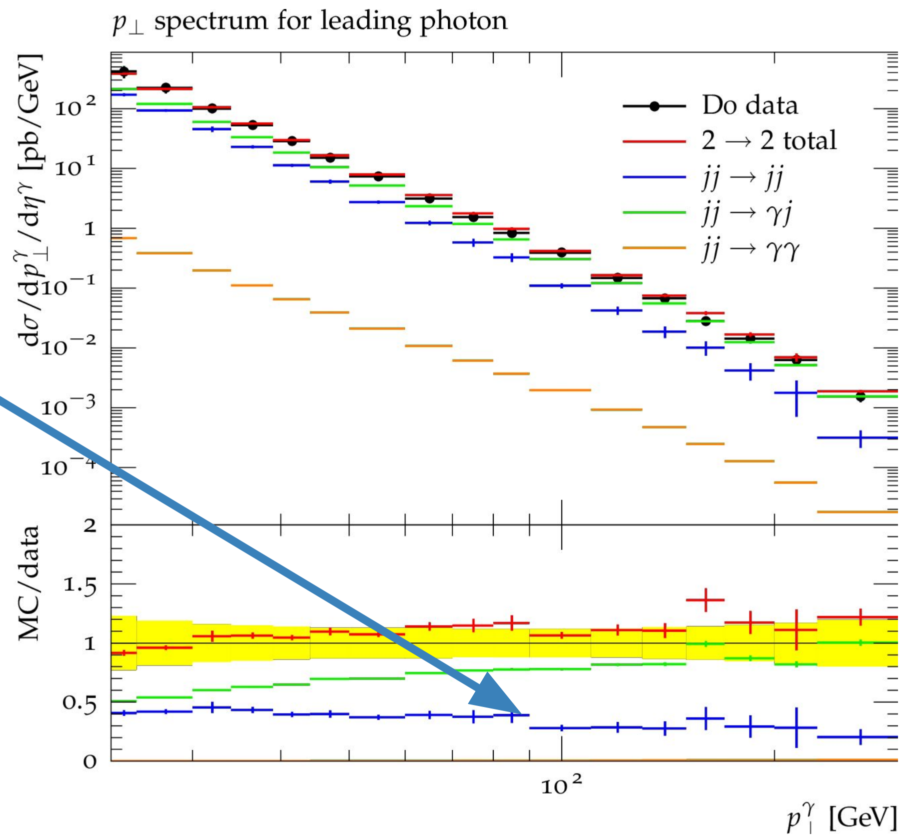
Can the shower describe ALEPH measurements?

Z. Phys. C69 (1996), 365378

Jets at different resolution scale

Energy fraction of a photon in a jet

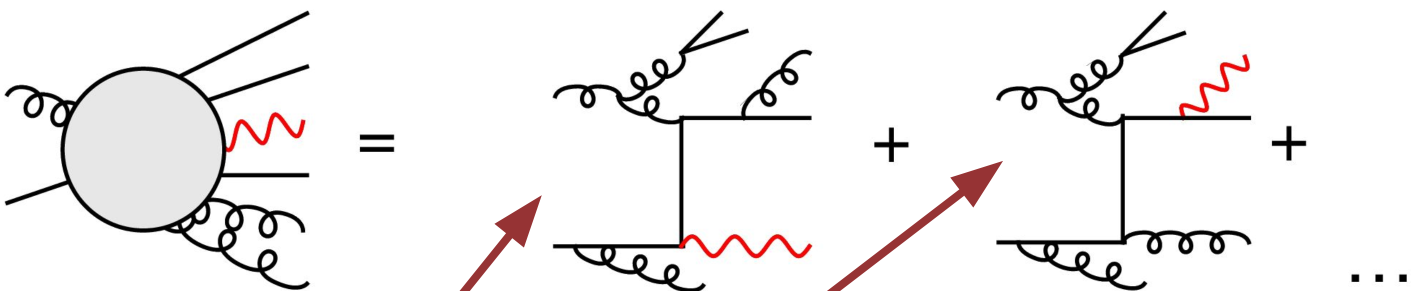
- D0 inclusive measurement of isolated photons
  Phys. Lett. B639 (2006), 151158
- Fragmentation component relevant even for hard isolated photons!



- Drawbacks of parton shower approach
  - **Practicability:**
    Low efficiency for generating hard/isolated photons in shower splitting
  - **Accuracy:**
    Only leading-order (direct component) or even leading-log (fragmentation component) precision for photon production

Prompt photons with multi-jet merging

- QCD multi-jet merging reminder/notation
  - Parton emission phase space sliced into
    - » **ME domain** = Hard jet emissions $Q_{ij}>Q_{cut}$
      populated by tree-level ME with additional parton: pp ⟶ X + jet
    - » **PS domain** = Intrajet evolution $Q_{ij}<Q_{cut}$
      filled with pp ⟶ X matrix element + parton shower emission
- Interesting for prompt photon production: unification of direct and fragmentation component in ME domain!



- Coverage of three phase space regions:

  $Q_{ij}>Q_{cut}$ && ($t_{QED}>t_{QCD}$ + $t_{QED}<t_{QCD}$) and $Q_{ij}<Q_{cut}$ && $t_{QED}>t_{QCD}$

Considering inclusiveness

Accuracy improvement comes with disadvantages:

- Multi-jet MEs contain infrared QED singularities
  - phase space cuts for p_T and isolation of photon necessary
  - danger of bias e.g. after detector simulation!
- Missing QED shower
  - Resummation effects of collinear QED emissions missing
    $\longrightarrow$ typically not relevant for hard/isolated photons
  - Missing 4th phase space region:

$$Q_{ij}<Q_{cut} \;\&\&\; t_{QED}<t_{QCD}$$

soft vs. **hard**

Relevance?

Yes, because no hard scale as lower boundary for t_{QED}

$\longrightarrow$ Shower is not able to fill phase space up to Q_{cut}!

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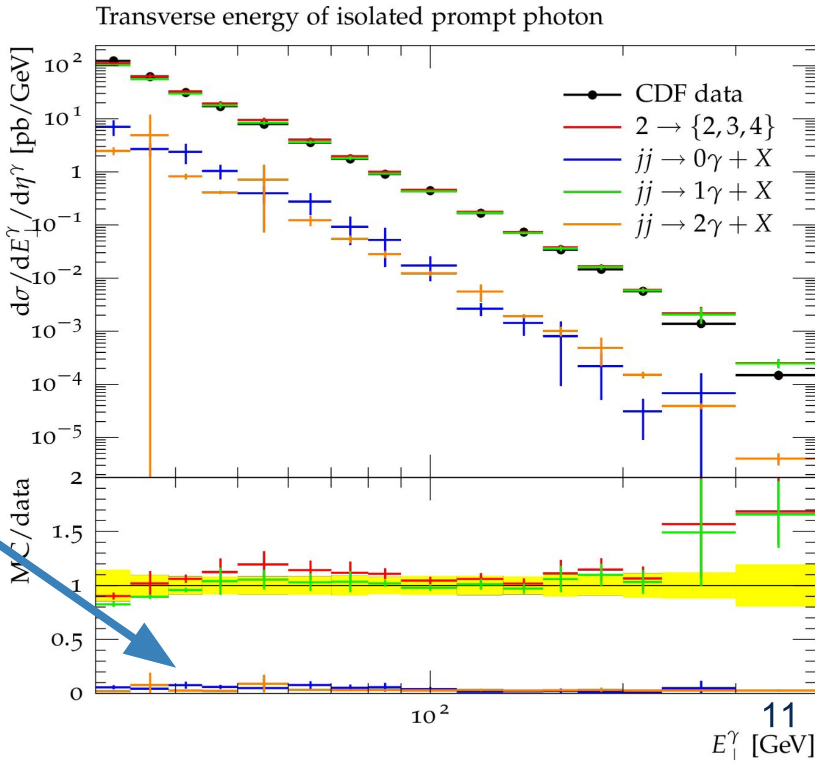
Combined QCD x QED merging

- Solution #1: Re-enable QED shower Höche, Schumann, FS (2009)
- To avoid double-counting: "QCD x QED merging"
  - Natural extension of QCD merging
  - Incorporate QED emissions from QED shower **and** matrix elements
  - Extend parton separation criterion Q_{ij} also to photons
    → democratic merging of photons and partons

- Example results (compared to CDF data)
  - Smart choice of QED merging scale: Suppression of (impractical) QED shower contribution
  - At the same time: No danger of hidden bias



Considering inclusiveness

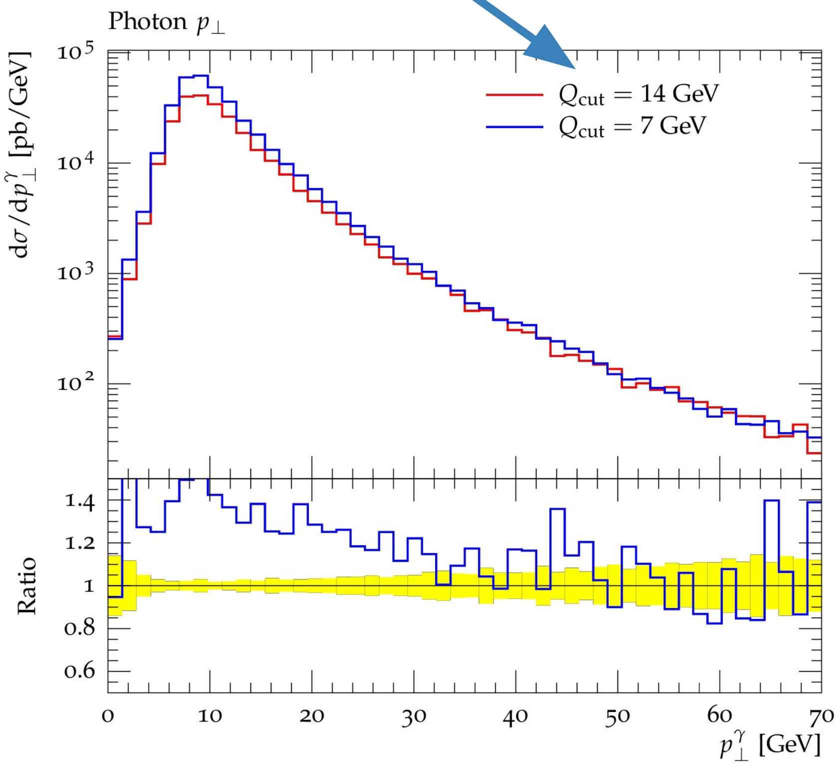
- Solution #2: dynamical Q_{cut} FS (2016)
  - Reduction of PS domain such that always lower than shower starting scale $\mu_F^2 = t_{QED}$
  - Implemented by dynamical Q_{cut} (pioneered in DIS simulations Carli, Gehrmann, Höche (2009))

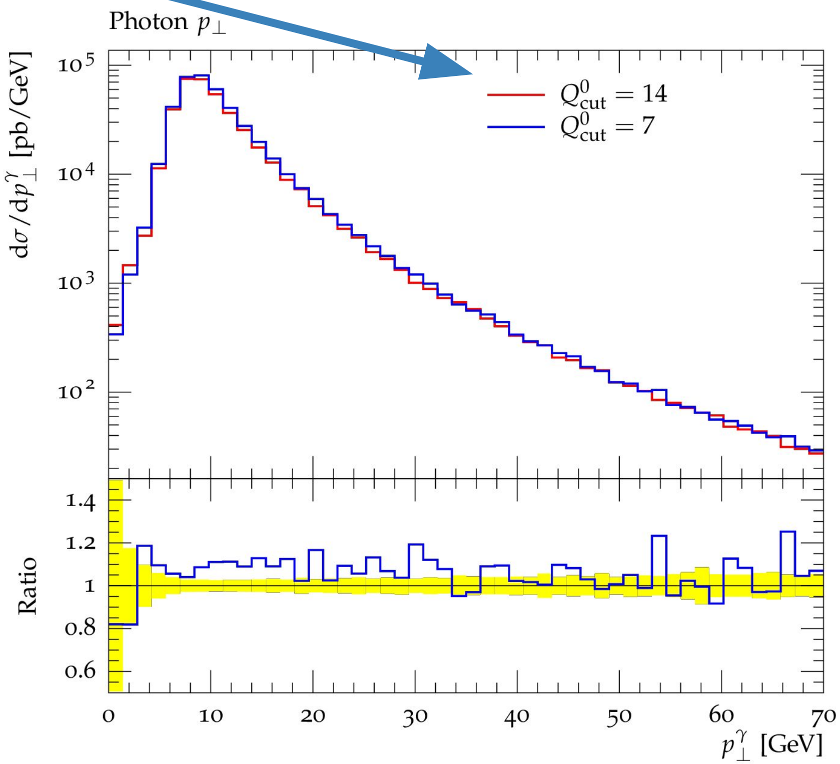
$$Q_{\mathrm{cut}} = \left[\frac{1}{\bar{Q}^2_{\mathrm{cut}}} + \frac{1}{S^2\,\mu_F^2}\right]^{-1/2}$$

- Dominated by minimum!
- Smooth interpolation
- Fixed value $\bar{Q}_{cut}$ to avoid hard shower emissions
- Safety factor $S \lesssim 1$ depends on shower kinematics

Dynamical Q_{cut}

- Effects largest at lower t_{QED}, e.g. low p_T^{γ}
- Measure of missing inclusiveness: cut variations with fixed vs. dynamical Q_{cut}





QCD merging at NLO accuracy

- NLO accuracy the new standard in Monte Carlos
  - Other processes (V, VV, ttbar, …) already with NLO multi-jet merging
- So far: LO matrix elements in all approaches above
- Studies for NLO+PS matching in inclusive process

D'Errico, Richardson (2011); Jezo, Klasen, König (2016)

- We want to go one step further here...
  NLO multi-jet merging for:

pp $\longrightarrow \gamma\gamma$ + 0,1jets@NLO + 2,3jets@LO

FS (2016)

Event generation and analysis

- Event generation setup ("MEPS@NLO")

$pp \to \gamma\gamma$ + 0,1jets@NLO + 2,3jets@LO

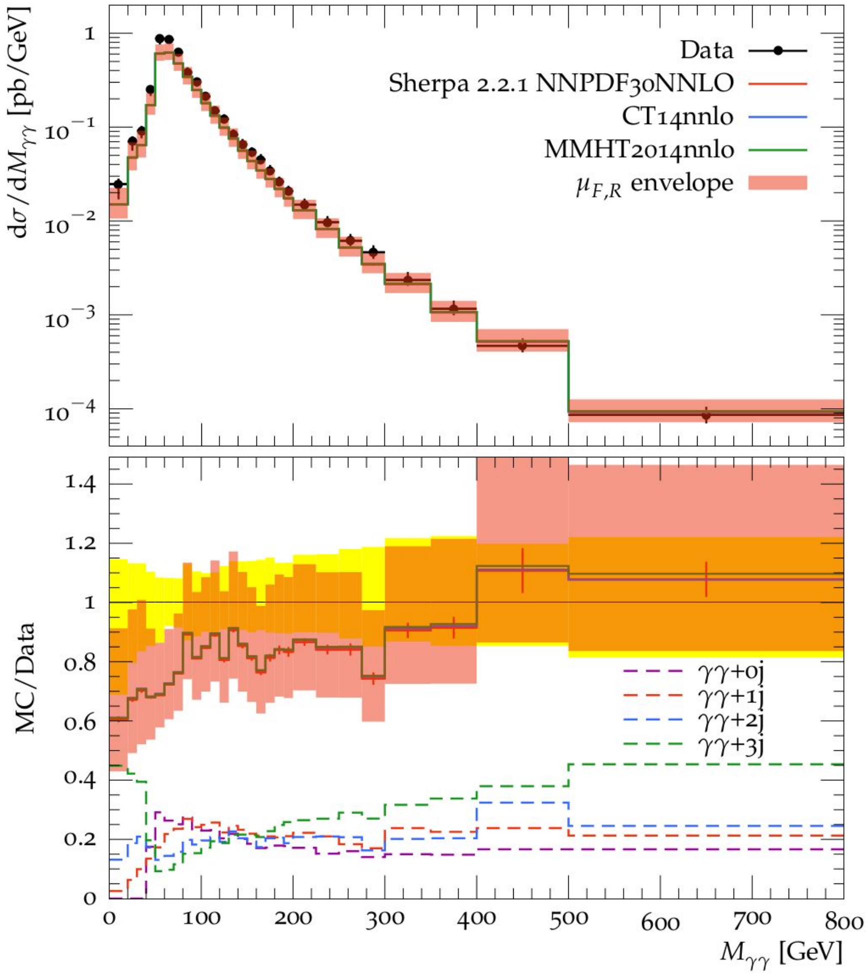
  - Sherpa 2.2 with default tuning and NNPDF3.0 (NNLO) PDFs
  - MEs from Amegic, Comix, OpenLoops
  - Smooth cone isolation for photons (with δ=0.1, n=2, ε=0.1)
    Frixione (1998)
  - Core factorisation scale $\mu_F = m_{\gamma\gamma}$ and α=1/137.036
  - Uncertainties by reweighting Bothmann, Schönherr, Schumann (2016)
  - Comparison to $pp \to \gamma\gamma$ + 0,1,2,3jets@LO ("MEPS@LO") and ATLAS 7 TeV analysis ATLAS (2012)

- Inclusive cross section

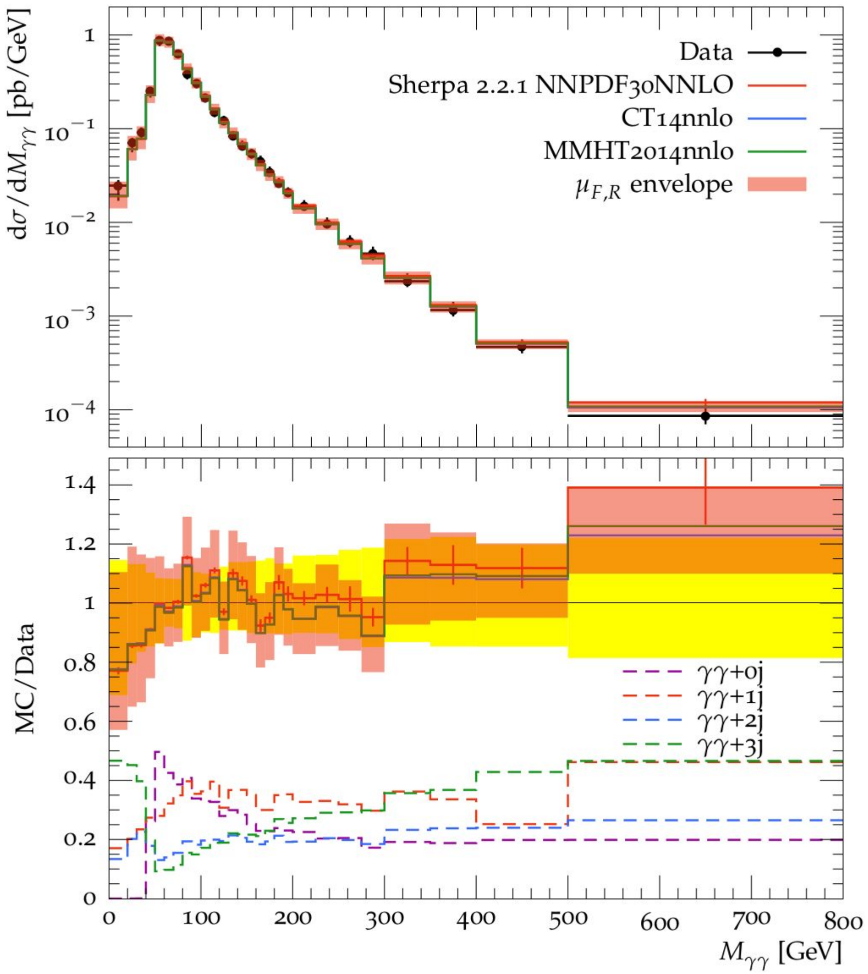
$\sigma_{\text{MEPS@LO}}$ [pb]	$\sigma_{\text{MEPS@NLO}}$ [pb]	σ_{ATLAS} [pb]
$33.9^{+9.6(28\%)}_{-5.9(18\%)}$	$44.8^{+6.7(15\%)}_{-6.5(15\%)}$	$44.0^{+3.2(7\%)}_{-4.2(10\%)}$

Results: Invariant mass

- MEPS@LO

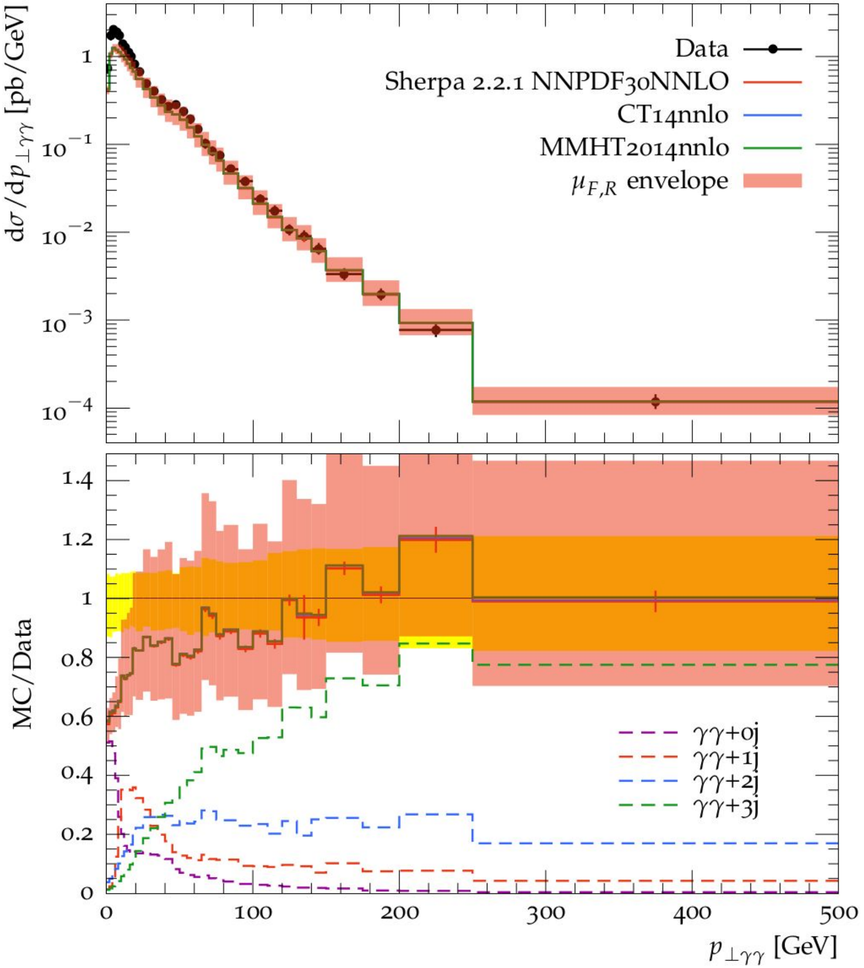


- MEPS@NLO

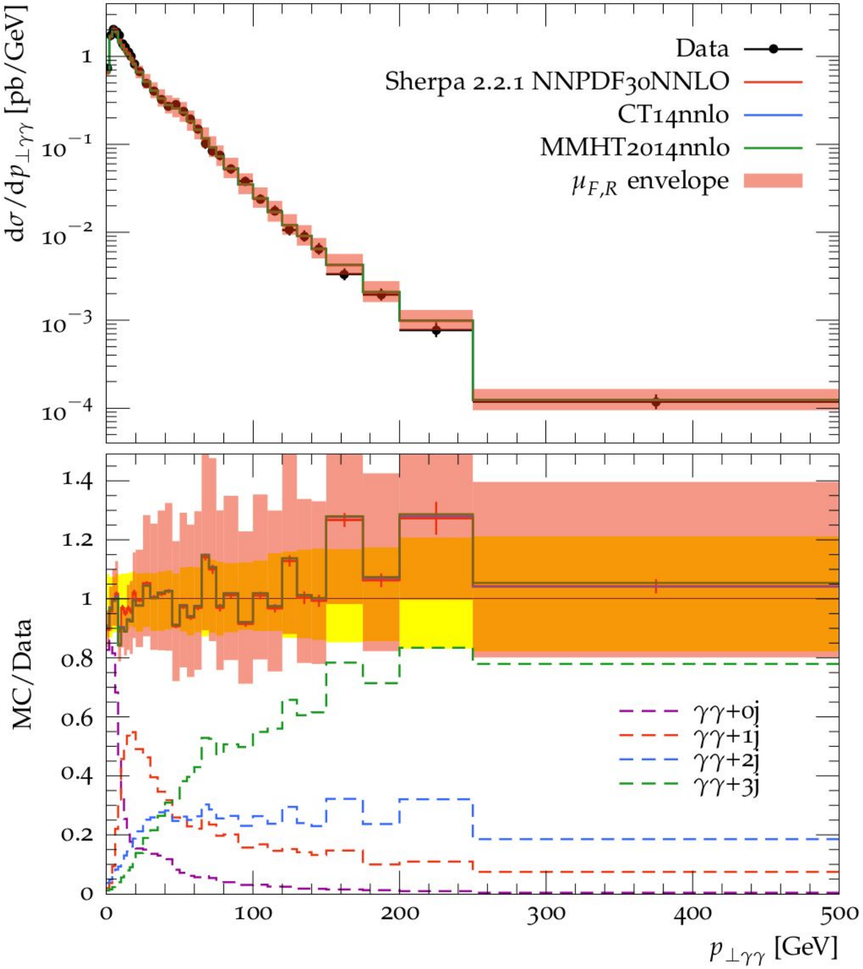


Results: Transverse momentum

- MEPS@LO



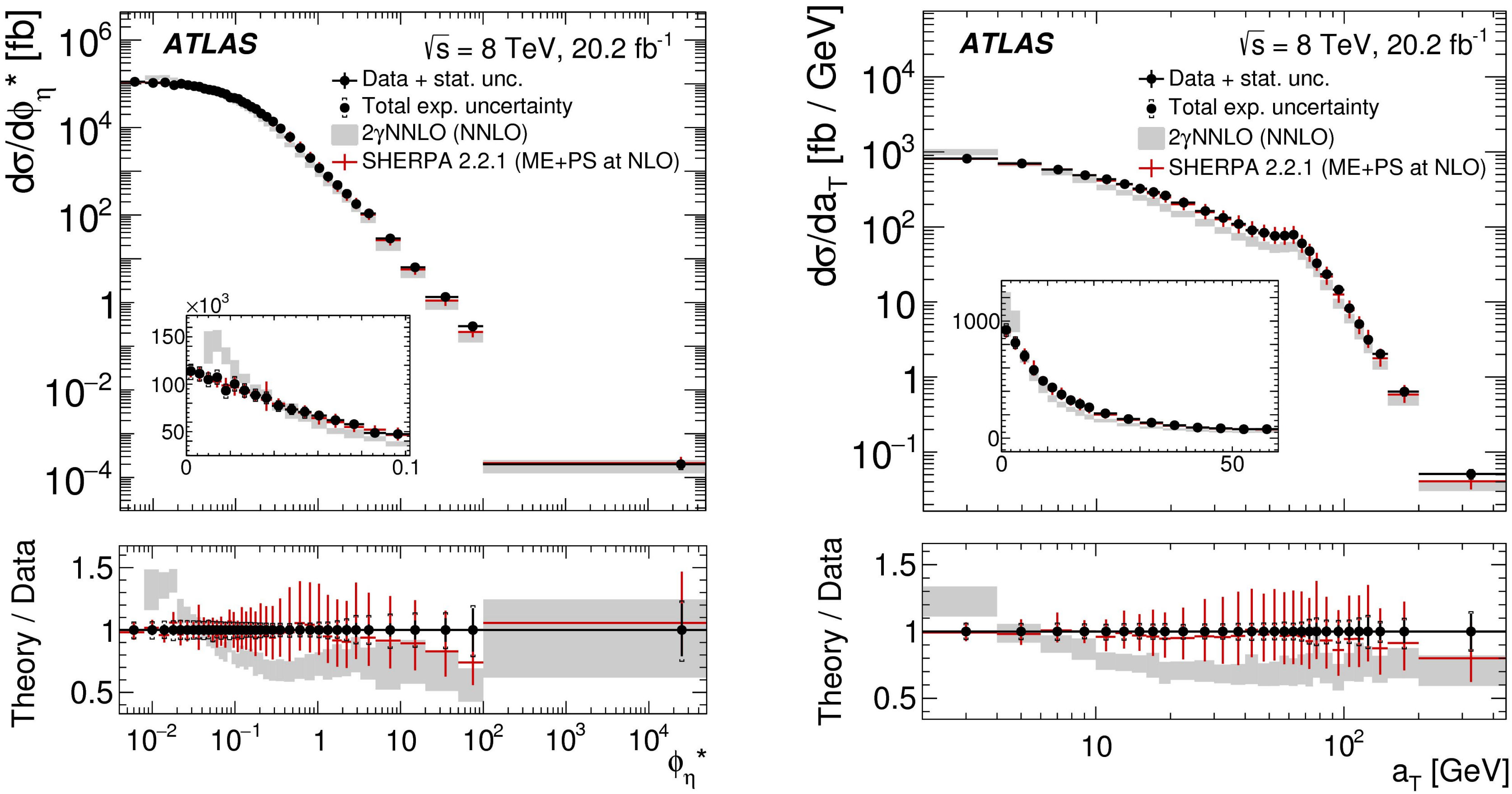
- MEPS@NLO



Comparison to 8 TeV results

- Powerful new variables in recent 8 TeV ATLAS measurement, MEPS@NLO predictions in very good agreement

ATLAS (2017)



Conclusions

Summary

- Prompt photon production relevant but tricky
- Different approaches in parton shower event generators to generate “fragmentation” component
- Predictions with MEPS@NLO possible now

Outlook

- NLO accuracy for higher jet multiplicities to reduce uncertainties in multi-jet dominated regions further
- Improve understanding of inclusiveness and interplay between merging scale and fragmentation component
- Match to NNLO accurate MEs
  $\longrightarrow$ reduce global rate uncertainties

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Backup

Combined QCD x QED merging

- Solution #2: Re-enable QED shower
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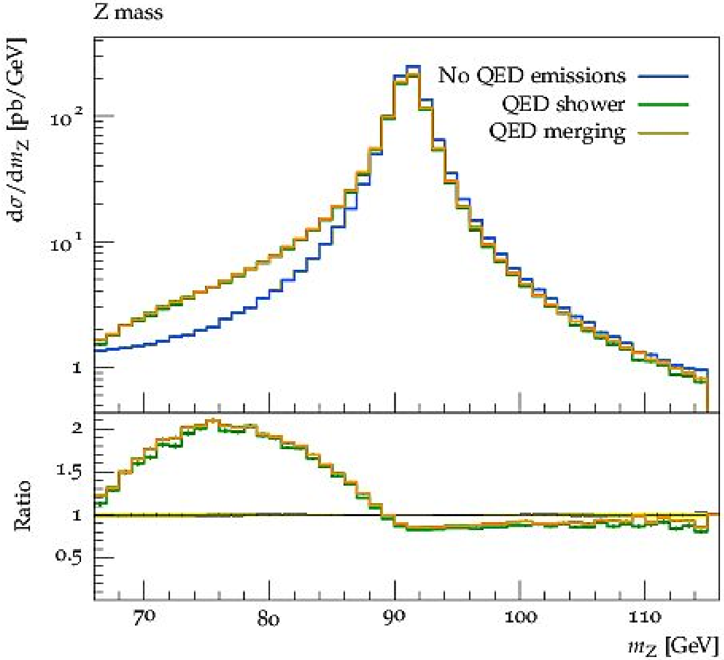
  - Natural extension of QCD merging
  - Incorporate QED emissions from QED shower **and** matrix elements
  - Extend parton separation criterion Q_{ij} also to photons
    → democratic merging of photons and partons
- (Pure) QED merging validation:
  - Z lineshape
  - Sensitive to QED FSR
  - Test merging with low Q_{cut}=0.1 GeV to have any effect on observable
    - » Merged prediction reproduces **resummation** (shower)
    - » Sample now **inclusive**, as photon cuts become merging scales



Combined QCD x QED merging

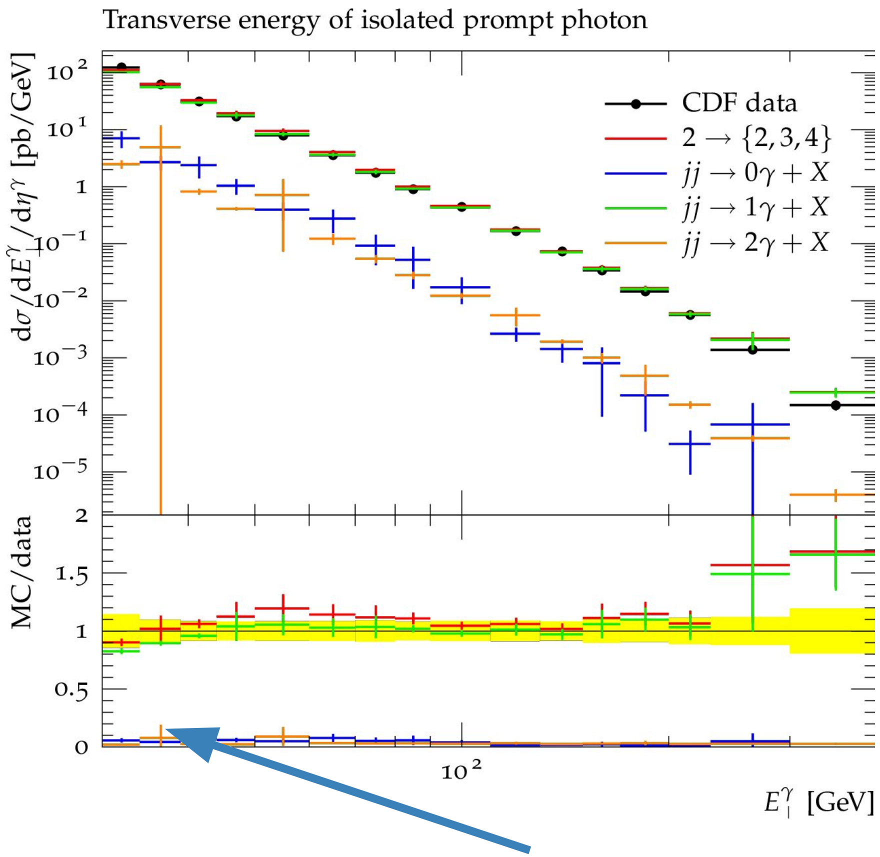
- Disadvantage of QCD x QED merging approach:
  - Impact of inefficiency of QED shower for hard/isolated photon production
    $\longrightarrow$ Large sample necessary to cover multi-jet matrix elements with photon shower emission?
- Mitigated by smart choice of photon merging scale
  - Freedom to choose Q_{cut}(QED) ≠ Q_{cut}(QCD)
  - Even further: Functional form only fixed by infrared limits
    $\longrightarrow$ Adapt Q_{ij} for photon splittings to experimental photon cuts
  - Example: k_T-like criterion for p_T and isolation based on cone radius

$$Q_{ij}^2 = \min\left\{p_{\perp,i}^2, p_{\perp,j}^2\right\} \frac{\Delta R_{ij}^2}{D^2} \quad \text{and} \quad Q_{ib}^2 = p_{\perp,i}^2$$

  - With suitable Q_{ij}(QED): possibility to ignore QED shower contribution! (but available as a cross-check)

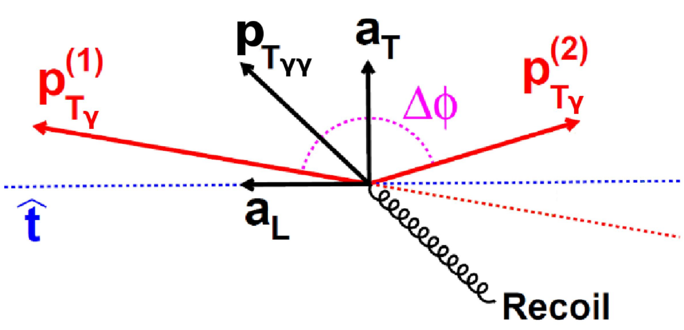
Combined QCD x QED merging

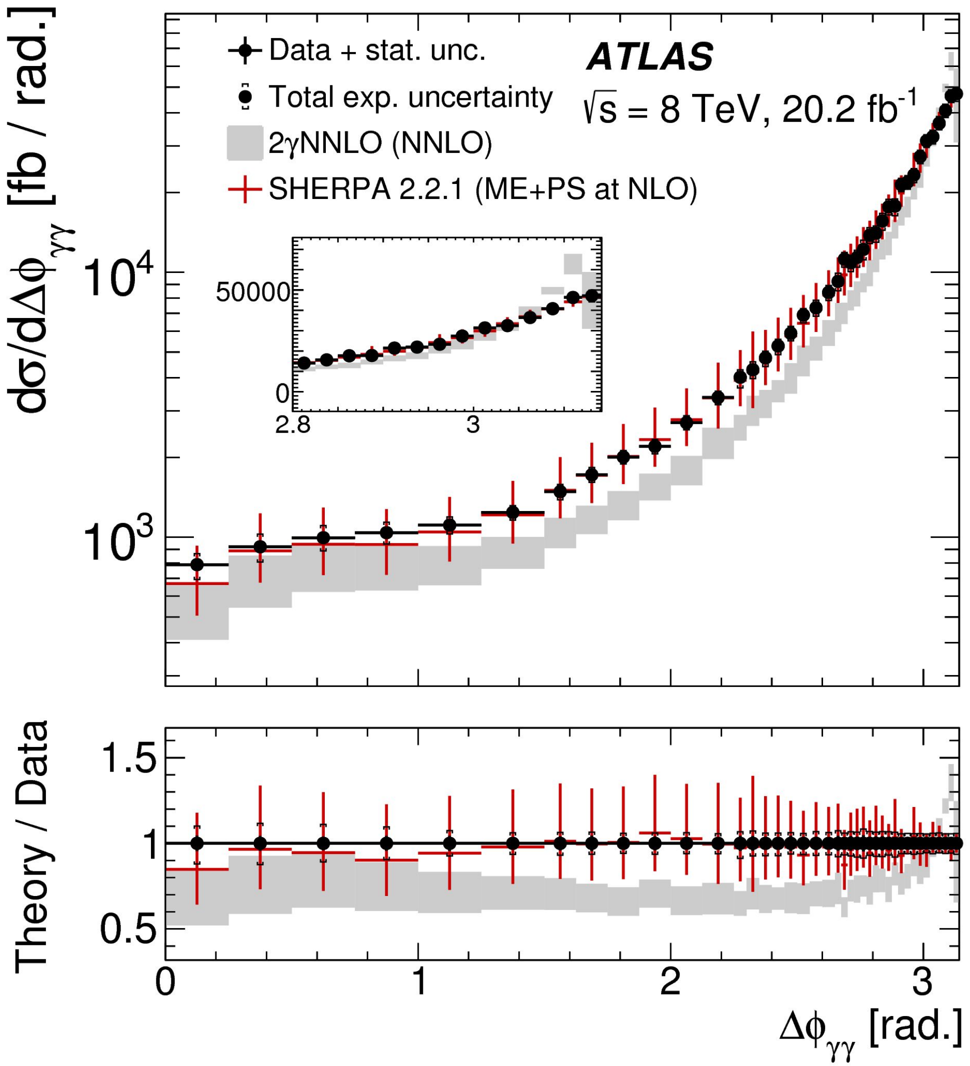
- Example results (compared to CDF data)



- Suppression of (impractical) QED shower contribution
- No danger of hidden bias

Comparisons to ATLAS 8 TeV data





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