Hard photon production and ME+PS merging

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Frank Siegert [1]

Institute for Particle Physics Phenomenology, Durham University;
Department of Physics & Astronomy, University College London

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[1]In collaboration with Stefan Höche & Steffen Schumann

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Why look at photon production?

Jet energy calibration

- Calibrate calorimeter response to jets
- Photons in detector well understood

$\Rightarrow$ Use conservation of $p_\perp$ in "clean" events with one jet and one photon

- Due to statistics useful mainly at low-$p_\perp$

Background to new physics

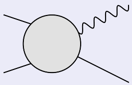
- $h \to \gamma\gamma$ (+ jets)
- Many BSM models produce final state photons

Anomalous gauge couplings

- Probe anomalous structure of triple-gauge couplings
- Especially production of high $p_\perp$ photons interesting

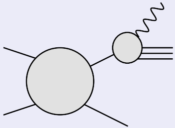
"Traditional" approach

"**Direct**" component – Fixed-order calculations



- γ+jet available at NLO (JetPhox)
  Phys. Rev. D73 (2006), 094007
- $\gamma\gamma$ available at NLO (DiPhox)
  Eur. Phys. J. C16 (2000), 311330
- NLO for $\gamma\gamma$+jet
  JHEP 04 (2003), 059
- Loop-induced $gg \to \gamma\gamma g$
  Phys. Lett. B460 (1999), 184188

"**Fragmentation**" component – Photon-quark collinear singularities



- Singularities factorised off ME
- Resummed to all orders in α_s
- $\Rightarrow$ Photon fragmentation function $D^{\gamma}_{q,g}(z, Q^2)$ Phys. Lett. B79 (1978), 83
- Relevant even if isolation criteria applied to photons ($\to$ later)

"**Non-prompt**" component: Photons from $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, ...

- Can not be included in such calculations
- Sometimes $\approx$ corrected for in experimental measurements

Alternative approach: Parton-shower Monte Carlo

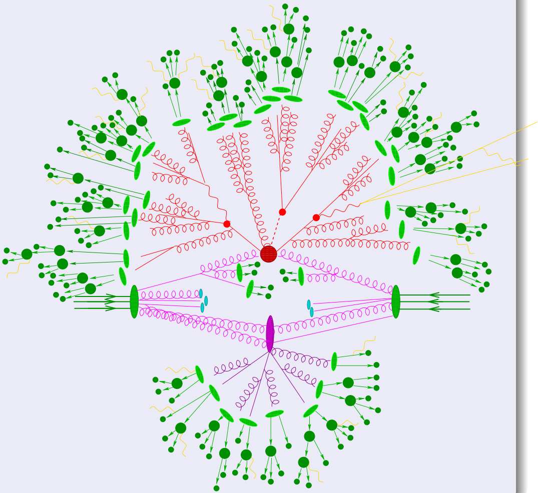
Monte-Carlo event generation

PERTURBATIVE PHYSICS

- Initial state parton shower$^{(*)}$
- Signal process*
- Final state parton shower*
- Underlying event

SOFT PHYSICS

- Hadronisation
- Hadron decays



*PROMPT PHOTON PRODUCTION:

- LO matrix elements
  ⇒ "direct" component
- Interleaved parton shower for QCD⊕QED evolution
  ⇒ Models $D^{\gamma}_{q,g}(z,Q^2)$

QED splittings in a parton shower

QCD parton shower basics

- Task: Generate parton splittings according to their probabilities
- **Probability for no emission** between two scales

$$\Delta_a(Q_0^2, Q^2) = \exp\left\{ -\int_{Q_0^2}^{Q^2} \frac{\mathrm{d}t}{t} \int_{z_-}^{z_+} \mathrm{d}z \sum_{\mathbf{b=q,g}} \frac{1}{2} \mathcal{K}_{ab}(z,t) \right\}$$

  contains **sum over all allowed splittings**
- Kernel e.g. $\mathcal{K}_{ab}(z,t) = \frac{\alpha_s}{2\pi} P_{ab}(z)$
- Terminate evolution before entering hadronisation regime $Q^2 \approx 1\mathrm{GeV}^2$

Modifications for QED

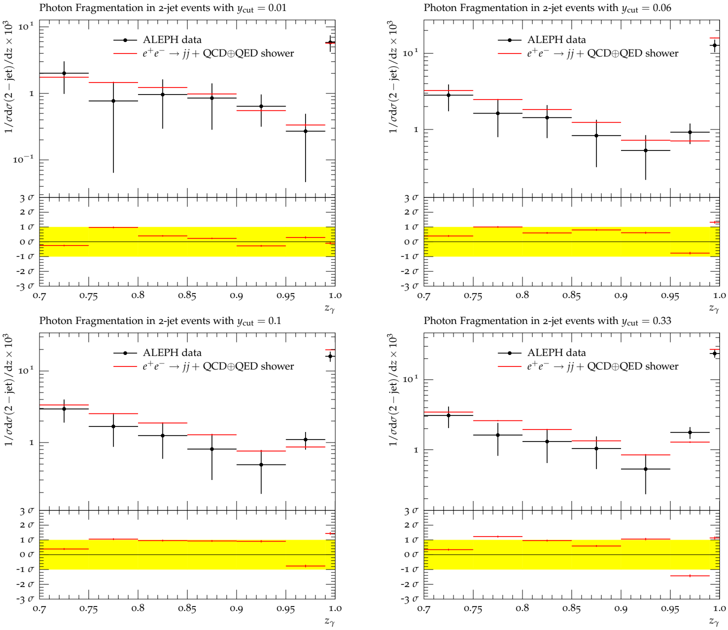
- Add splitting functions for $qq\gamma$ vertex
  $\Rightarrow$ Interleaved QCD$\oplus$QED evolution

$$\Delta_a(Q_0^2, Q^2) = \Delta_a^{\mathbf{(QCD)}}(Q_0^2, Q^2)\Delta_a^{\mathbf{(QED)}}(Q_0^2, Q^2)$$

- Similarly implemented in several parton showers (Ariadne, Herwig, Pythia, Sherpa)
- Does this actually work? Let's look at some data ...

Fragmentation function at LEP

ALEPH: Z. Phys. C69 (1996), 365378



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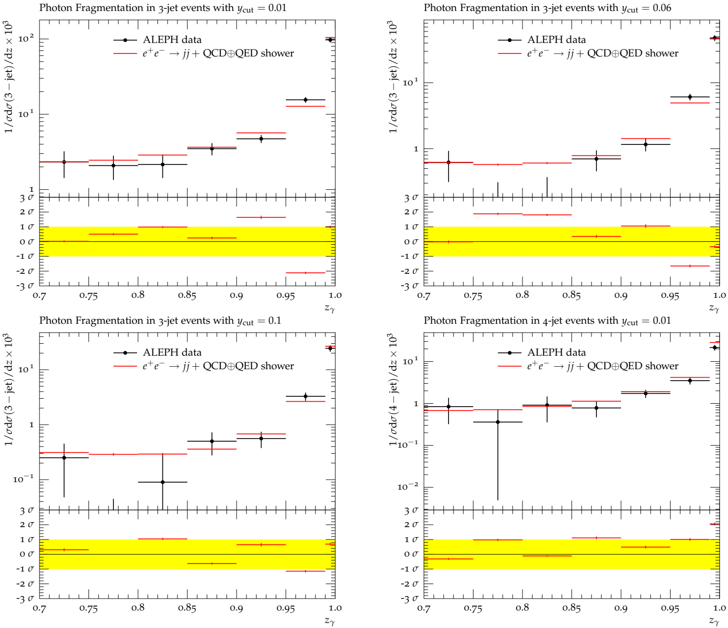
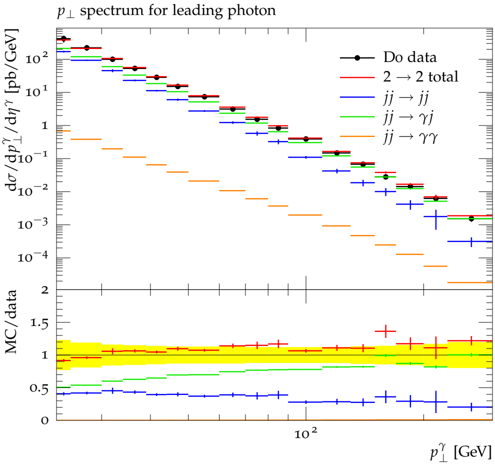


Relevance of fragmentation component

DØ : Phys. Lett. B639 (2006), 151158



Even though hard isolated photons!

- $p_\perp^\gamma > 23$ GeV
- $E_{\mathrm{EM}}(\mathcal{R} = 0.2)/E(\mathcal{R} = 0.4) > 0.91$
- $E_{\mathrm{EM}}(\mathcal{R} = 0.2)/E(\mathcal{R} = 0.2) > 0.95$

Correcting the shower with higher-order matrix elements

JHEP **0905** (2009) 053 [arXiv:0903.1219 [hep-ph]]

Main goal of ME+PS merging

Phase space slicing for extra radiation:

- Hard emissions from matrix element
- Soft/collinear emissions from parton shower

More formally

Effectively **different splitting kernels** $\mathcal{K}$ for hard vs. soft/collinear radiation

$$\mathcal{K}_{ab}^{\rm PS}(z,t) = \mathcal{K}_{ab}(z,t)\,\Theta\left[Q_{\rm cut} - Q_{ab}(z,t)\right] \quad \text{and} \quad \mathcal{K}_{ab}^{\rm ME}(z,t) = \mathcal{K}_{ab}(z,t)\,\Theta\left[Q_{ab}(z,t) - Q_{\rm cut}\right]$$

- Boundary determined by value of $Q_{\rm cut}$
- $Q_{\rm cut}$ regularises real emission MEs (like a jet resolution)

Evolution factorises

$$\Delta_a(\mu^2,t) = \Delta_a^{\rm PS}(\mu^2,t')\;\Delta_a^{\rm ME}(\mu^2,t')$$

$\Rightarrow$ **Independent evolution** in both regimes
$\Rightarrow$ If careful: Possible to correct hard jets without spoiling resummation features

Photons in Merging

QCD⊕QED

Algorithm works with the same concept!

- Add QED radiation matrix elements
- Add QED radiation in shower
- Rest stays the same

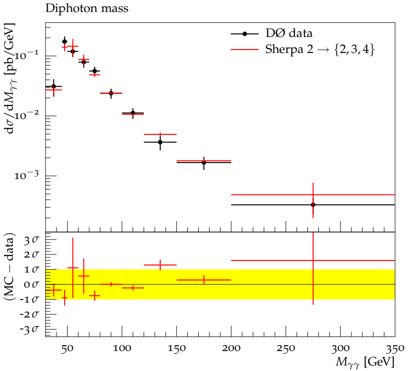
Completely democratic treatment of photons and partons

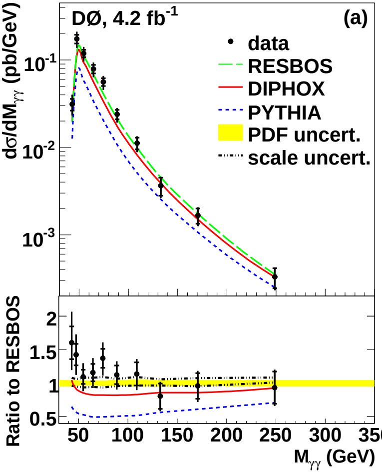
Separation criterion

- In principle, Q_{cut} or even the form of Q_{ij}, can be chosen separately for QCD and QED
- Might be useful for analyses requiring isolated photons
  $\Rightarrow$ Photons in analysis region dominantly produced by matrix-element
- E.g. isolation in cone with radius D and minimal $p_\perp$ for photons
  $\Rightarrow$ could use $Q_{ij}^2 = \min(p_{\perp,i}^2, p_{\perp,j}^2)\frac{\Delta\eta_{ij}^2+\Delta\phi_{ij}^2}{D^2}$ (like $k_\perp$ jet algorithm)

Results for diphoton production at Tevatron

DØ: arXiv.org:1002.4917





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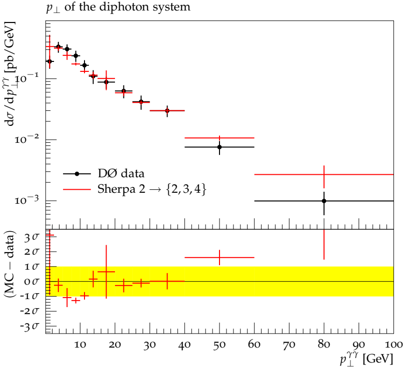

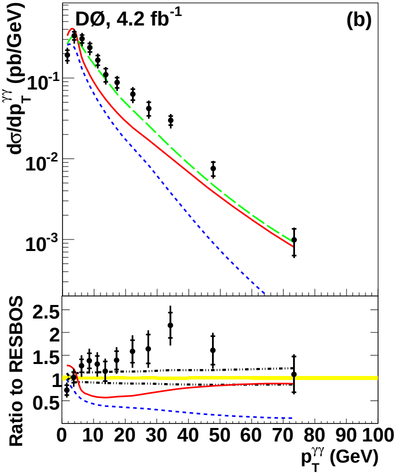

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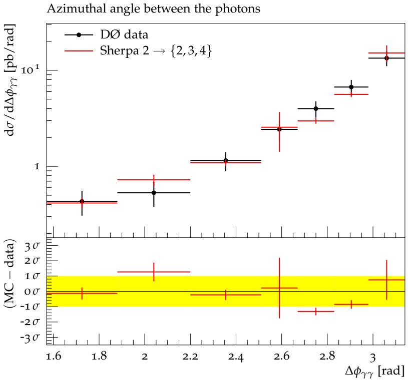
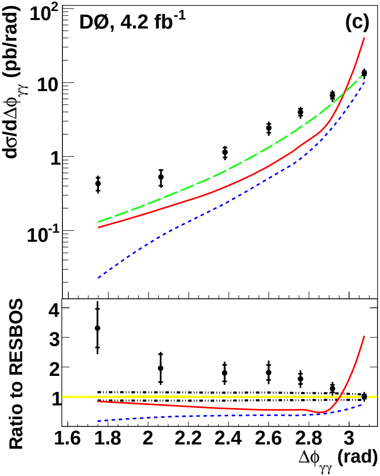
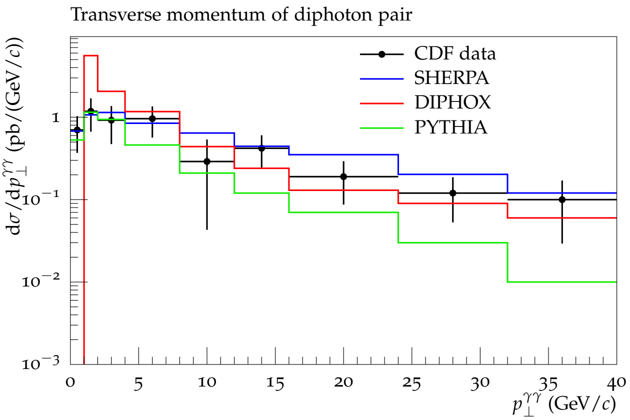




Nicely combines fixed-order and resummation features

CDF: Phys. Rev. Lett. 95 (2005), 022003



Conclusions

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- Photon production processes play key role in collider experiments
- Monte-Carlo parton showers useful tool for collider physics
- Natural incorporation of QED splittings in parton shower
- Supplementing PS with higher order tree level ME is advisable
- Democratic treatment of photons and partons
  $\Rightarrow$ ME+PS-Merging of QCD and QED emissions
- Very good agreement with Tevatron measurements
- Sherpa 1.2.1 released two weeks ago
  contains QCD$\oplus$QED merging (and much more)

Outlook

- Multi-jet merging with NLO matrix elements (but first for QCD ;-))