Hard photon production and ME+PS merging

Based on arXiv:0912.3501 [hep-ph]

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Why look at photon production?

Jet energy calibration

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

⇒ 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

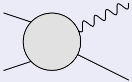
- $h \rightarrow \gamma\gamma$ (+ jets)
- Many BSM models produce final state photons

Anomalous gauge couplings

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

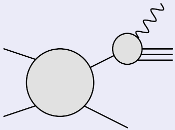
"Traditional" approach

"**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



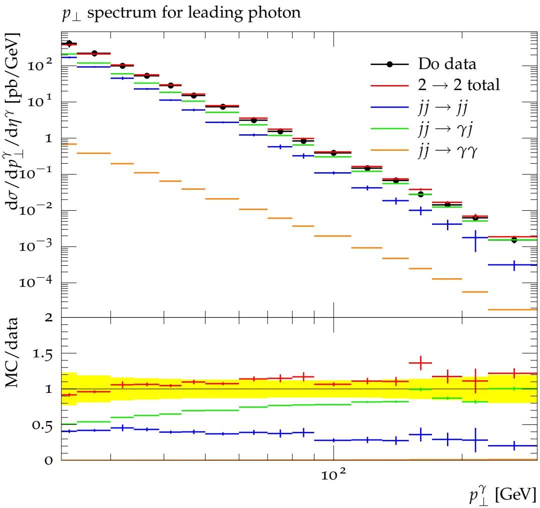
- Singularities factorised off ME
- Resummed to all orders in α_s
- $\Rightarrow$ Photon fragmentation function $D^{\gamma}_{q,g}(z, Q^2)$ Phys. Lett. B79 (1978), 83
- Relevant even if isolation criteria applied to photons ($\rightarrow$ next slide)

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

- Can be $\approx$ separated from prompt photons experimentally
  $\Rightarrow$ Not considered in the following

Relevance of fragmentation component

DØ : Phys. Lett. B639 (2006), 151158



Alternative approach: Parton-shower Monte Carlo

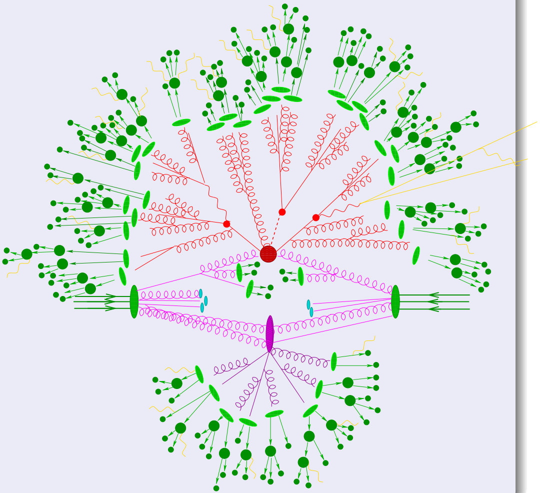
Monte-Carlo event generation

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 $D^{\gamma}_{q,g}(z, Q^2)$

Interleaved parton shower for QCD⊕QED evolution

CSSHOWER++ — Parton shower based on dipole subtraction

- **Probability for no emission** between two scales

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

- **Ordering** variable $t \equiv k_\perp^2$
- **Kernels** $\mathcal{K}$ based on Catani-Seymour subtraction terms
  - Projection onto leading term in $1/N_C$
  - Spin averaged

$\Rightarrow$ Shower algorithm based on colour-connected emitter-spectator dipoles

$$\mathcal{K}_{(ij)i}^{\mathrm{QCD}}(z,\mathrm{k}_\perp^2) \;=\; \frac{\alpha_s(\mathrm{k}_\perp^2)}{2\pi}\, J(\mathrm{k}_\perp^2, z) \sum_k \langle \mathrm{V}_{(ij)i,k}^{\mathrm{QCD}}(\mathrm{k}_\perp^2, z)\rangle \quad \text{with} \quad z \;=\; \frac{p_i p_k}{(p_i + p_j) p_k}$$

Interleaved parton shower for QCD⊕QED evolution

Modifications for QED

- No interference between QCD and QED at NLO
  $\Rightarrow$ Emission probabilities factorise trivially

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

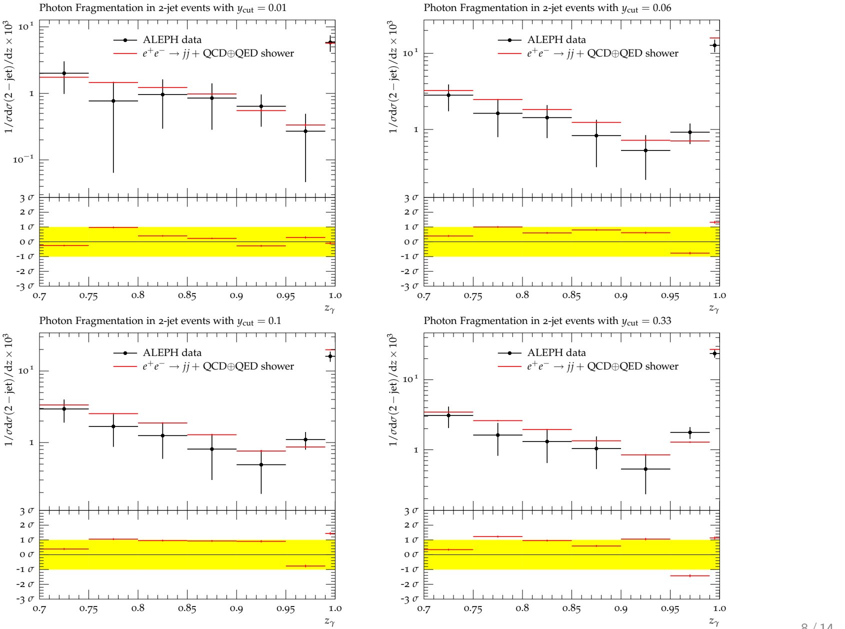
- Implemented by adding splitting functions for $qq\gamma$ vertex

$$\mathcal{K}_{(ij)i}^{\mathbf{QED}}(z, \mathrm{k}_\perp^2) = \frac{\alpha(\mathrm{k}_\perp^2)}{2\pi} J(\mathrm{k}_\perp^2, z) \sum_k \langle \mathrm{V}_{(ij)i,k}^{\mathbf{QED}}(\mathrm{k}_\perp^2, z)\rangle$$

- Difference to large N_C QCD: Not exactly one colour partner for dipole
- Neglects (negative) interference from legs with same-sign charges
- 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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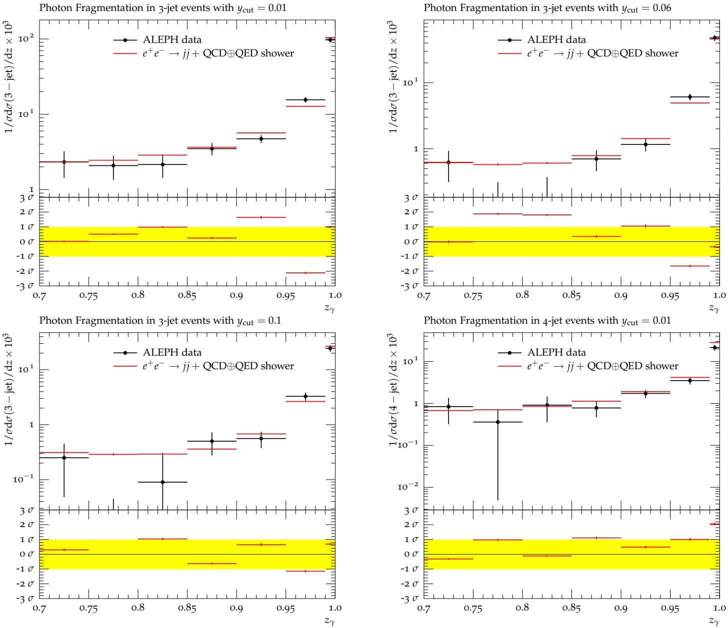


Recap: Merging algorithm

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

Main idea

Phase space slicing for extra QCD radiation:

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

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 $Q_{\rm cut}$
- $Q_{\rm cut}$ has to regularise QCD radiation MEs (like a jet resolution), otherwise completely arbitrary until now

Evolution factorises

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

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

Photons in Merging

The good news

Nothing changes!

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

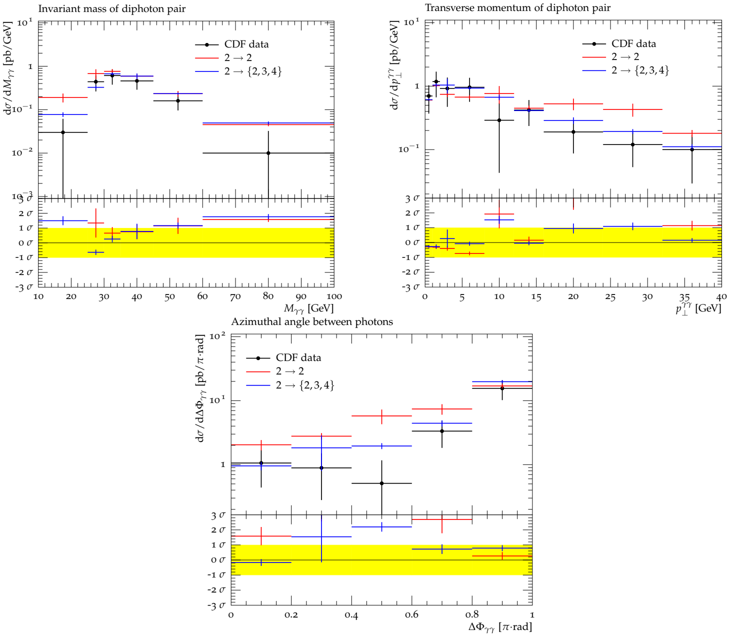
Completely democratic treatment of photons and partons

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
  $\Rightarrow$ Would allow to produce photons in analysis region dominantly 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

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



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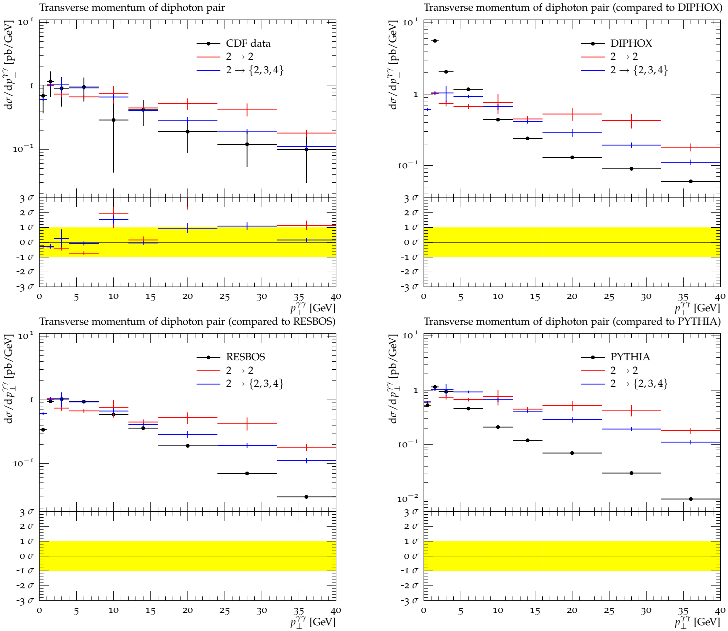

Conclusions

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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
- Useful to supplement PS with higher order tree level ME
- Democratic treatment of photons and partons
  $\Rightarrow$ ME+PS-Merging of QCD and QED emissions
- Improved agreement with Tevatron measurements

Outlook

- Current version of SHERPA already contains QCD merging
- Next version of SHERPA adds implementation of QED
- Long term goal: Multi-jet merging with NLO matrix elements