Hard photon production in Sherpa

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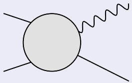
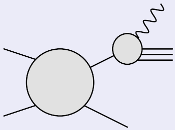
"Traditional" approach: Components of photon production

"**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 fragmentation function



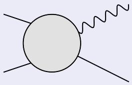
- Photon-quark collinear singularities factorised off ME
- Resummed to all orders in α_s
  $\Rightarrow$ Photon fragmentation function $D^{\gamma}_{q,g}(z, Q^2)$ Phys. Lett. B79 (1978), 83
- Attached to parton production ME
- Relevant even if isolation criteria applied to photons ($\to$ later)

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

- Not considered in such calculations
- Sometimes $\approx$ corrected for in experimental measurements

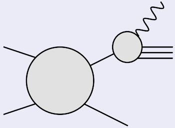
Alternative approach: Ordinary parton-shower Monte Carlo

"**Direct**" component – Tree-level calculation + QCD parton shower



- Built-in or automatically generated tree-level ME
  e.g. $pp \to \gamma$+parton
- QCD parton shower resums logarithmically enhanced QCD corrections

"**Fragmentation**" component – Interleaved QCD+QED shower



- Tree-level ME for parton production
- Parton shower with interleaved QCD and QED emissions
  $\Rightarrow$ Models $D^{\gamma}_{q,g}(z, Q^2)$
- Problem: Very inefficient

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

- Can be fully considered in this approach
- Sources: hadronisation, hadron decays, underlying event

How does a PS MC work?

Monte-Carlo event generation

PERTURBATIVE PHYSICS

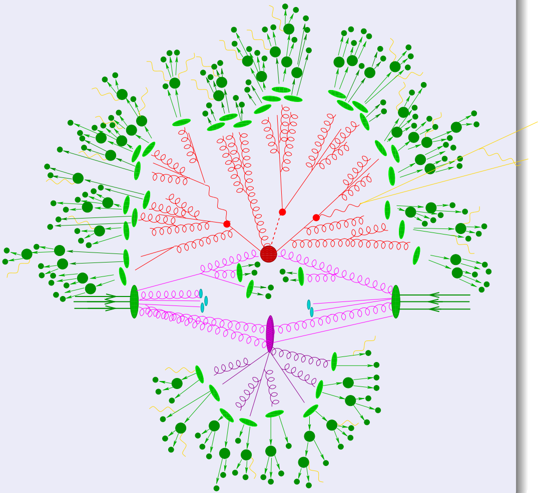
- Initial state parton shower$^{(*)}$
- Signal process*
- Final state parton shower*
- Underlying event

SOFT PHYSICS

- Hadronisation
- Hadron decays

*PROMPT PHOTON PRODUCTION:

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



Connecting hard and hadronisation scale

Collinear factorisation of QCD radiation

- Singularities from collinear emissions factorised off at a given scale
  - ⇒ Parton distribution functions (PDF) in initial state
  - ⇒ Fragmentation functions (FF) in final state

  } non-perturbative objects

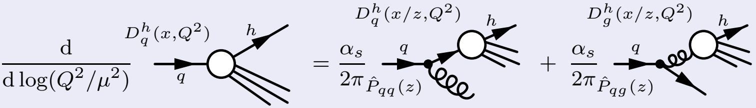
Evolution equations

- Evolution of PDF/FF between different scales calculable perturbatively (DGLAP):

$$f_a(x,Q^2) - f_a(x,Q_0^2) = \int_{Q_0^2}^{Q^2} \frac{dt}{t} \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} \sum_{b=q,g} \hat{P}_{ab}(z) f_b(\frac{x}{z},t)$$

⇒ Difference between scales given by parton splittings

- Differential version of that equation in pictures for FF D_q^h:



Parton-shower algorithm

Unfolding the factorised emissions: Recursion

1. Start with parton produced at scale Q_0^2
2. **Dice scale** Q^2 (and flavour) for next splitting according to the evolution equations
3. If $Q^2 > Q^2_{\text{hadronisation}} \approx 1\text{GeV}^2$: Start at 1 again for the splitting products

Solving the evolution equation for step 2

- Use Sudakov-formalism to solve it (+ some tricks)
  ⇒ **Probability for no emission** between two scales ("Sudakov form factor")

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

- Example: Kernel $\mathcal{K}_{ab}(z,t) = \frac{\alpha_s}{2\pi} P_{ab}(z)$

CSSHOWER++ in SHERPA – Parton shower based on dipole subtraction

- Emissions ordered in $t \equiv k_\perp^2$
- Based on Catani-Seymour subtraction terms (colour-connected emitter-spectator dipoles)

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

Modifications of shower for interleaved QCD⊕QED evolution

Modifications for QED

- Want to interleave QCD⊕QED emissions in factorised form

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

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

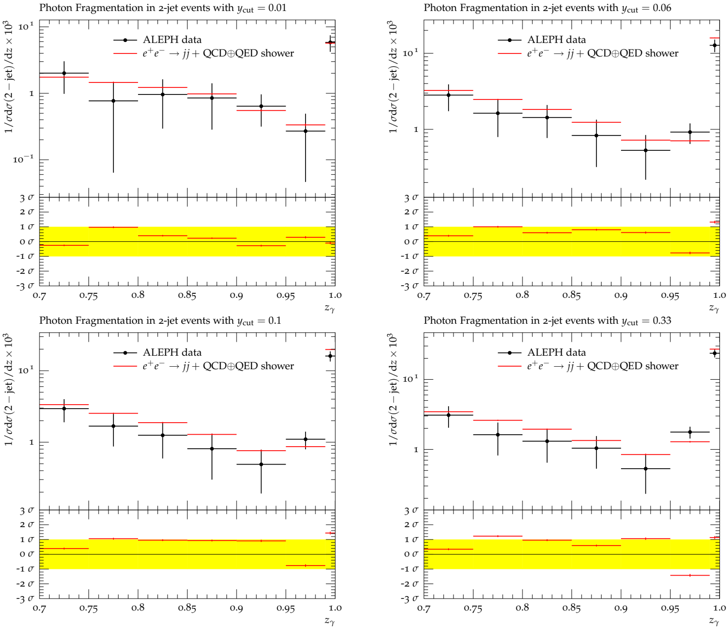
$$\sum_{b=q,g} \mathcal{K}_{ab}(z,t) \rightarrow \sum_{b=q,g,\gamma} \mathcal{K}_{ab}(z,t)$$

- 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 describe $D^{\gamma}_{q,g}(z, Q^2)$? Let's look at some data ...

Fragmentation function at LEP

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



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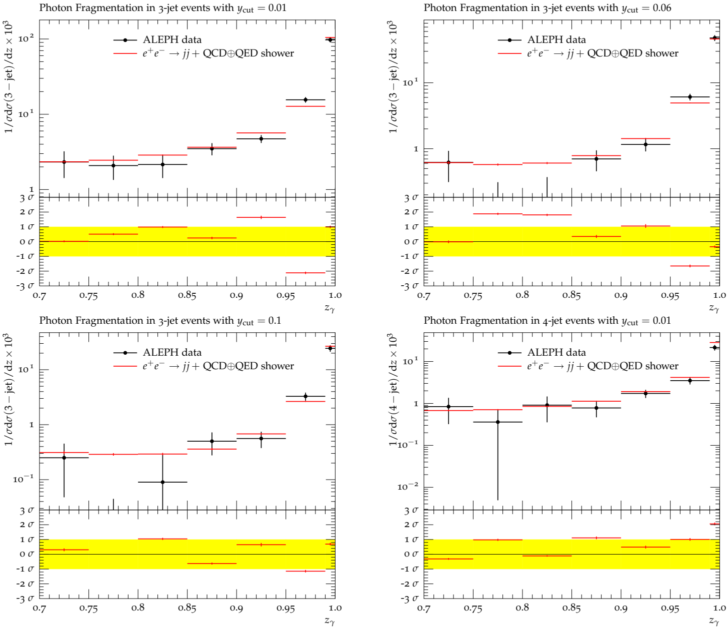
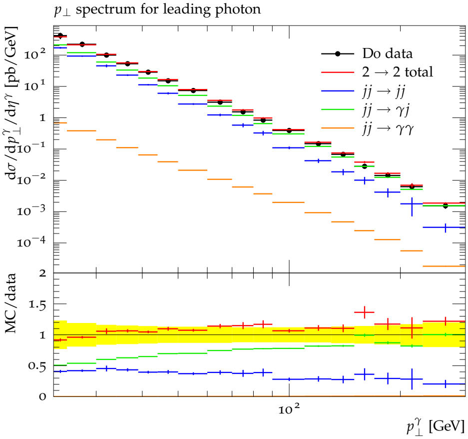


Relevance of fragmentation component

DØ : Phys. Lett. B639 (2006), 151158



Inclusive photon $p_\perp$ at Tevatron

- 23 GeV $< p_\perp^\gamma <$ 300 GeV
- $E(\mathcal{R} = 0.4)/E_\gamma < 1.1$

$\Rightarrow$ Hard isolated photons

Contributions from subprocesses

Total single photon production

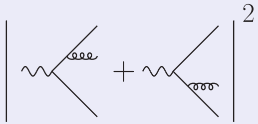
- $jj \to jj$ Dijets
- $jj \to \gamma j$ Photon + jet
- $jj \to \gamma\gamma$ Diphotons

$\Rightarrow$ Fragmentation component in dijets plays important role!

Correcting the shower with higher-order matrix elements – motivation

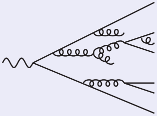
Two approaches to real higher-order corrections

Matrix Elements



- $+$ **Exact** to fixed order
- $+$ Include all interferences
- $+$ $N_C = 3$ (summed or sampled)
- $-$ Perturbation breaks down due to **large logarithms**
- $-$ Only low FS multiplicity

Parton Showers



- $+$ Resum logarithmically enhanced contributions to **all orders**
- $+$ Produce high-multiplicity final state
- $-$ Only **approximation** for splitting ME
- $-$ Large N_C limit only

$\Downarrow$

Goal: Combine advantages

- Describe **particular final state** by **ME** (hard radiation)
- Don't spoil the **inclusive picture** provided by the **PS** (intrajet evolution)

ME+PS merging

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

Main idea of ME+PS merging

Phase space slicing for extra QCD 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 (again! this time in phase space)

$$\Delta_a(Q_0^2, Q^2) = \Delta_a^{\rm PS}(Q_0^2, Q^2)\ \Delta_a^{\rm ME}(Q_0^2, Q^2)$$

⇒ **Independent evolution** in both regimes
⇒ How to replace the $\Delta_a^{\rm ME}(Q_0^2, Q^2)$ part with MEs now?

Merging algorithm

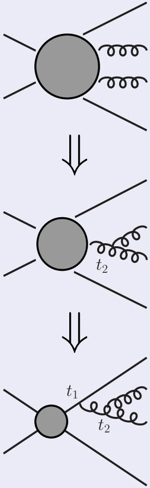
Outline of algorithm

1. Choose matrix-element multiplicity N according to σ_n, σ_{n+1}, σ_{n+2}, ... and generate ME event according to $d\sigma_N$
2. Translate ME event into shower language: **Branching history**

Merging algorithm: Branching history

Translate ME event into shower language

Example:



Why?

- Need individual starting scales for PS evolution at each leg
- Simply using the factorisation scale is wrong
- **Problem:** ME only gives final state, no history

Solution: Backward-clustering (running the shower reversed)

1. Take N-particle final state
2. Select last splitting according to shower probablities
3. Recombine partons using inverted shower kinematics
   $\rightarrow$ N-1 particles + splitting variables for one node
4. Reweight $\alpha_s(\mu^2) \rightarrow \alpha_s(p_\perp^2)$
5. Repeat 2 - 4 until core process

$\Downarrow$

Most probable branching history a la shower.

Now let's use it ...

Merging algorithm

Outline of algorithm

1. Choose matrix-element multiplicity N according to σ_n, σ_{n+1}, σ_{n+2}, ... and generate ME event according to $d\sigma_N$
2. Translate ME event into shower language: **Branching history**
3. Start truncated shower evolution on each leg
   - If emission in PS regime $\Rightarrow$ **Keep**
     This is the $\Delta_a^{\mathrm{PS}}(t, t')$ part.
   - Emission in ME regime?
     This is the $\Delta_a^{\mathrm{ME}}(t, t')$ part.

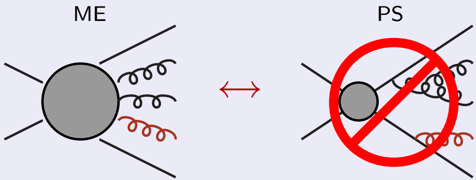
Merging algorithm: Emissions in ME regime

How to deal with the $\Delta_a^{\mathrm{ME}}(t, t')$ part?

- Relates to shower emissions **above** Q_{cut}

Has to be allowed in shower evolution, **but:**

What if something is emitted? → CKKW-L



Emissions in this regime should be described by MEs!
⇒ Reject event to avoid double counting

Consequences

- Reduction of cross section $\sigma \longrightarrow \sigma \cdot \Delta_a^{\mathrm{ME}}(t, t')$
- Compensated by higher order ME's

⇒ Leading order cross section stable

Merging algorithm

Outline of algorithm

1. Choose matrix-element multiplicity N according to σ_n, σ_{n+1}, σ_{n+2}, … and generate ME event according to $d\sigma_N$
2. Translate ME event into shower language: **Branching history**
3. Start truncated shower evolution on each leg
   - If emission in PS regime $\Rightarrow$ **Keep**
     This is the $\Delta_a^{\mathrm{PS}}(t,t')$ part.
   - Emission in ME regime? $\Rightarrow$ **Reject event**
     This is the $\Delta_a^{\mathrm{ME}}(t,t')$ part.

$\Downarrow$

Evolution in PS regime preserved
Emissions above Q_{cut} ME-corrected

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, including rejection

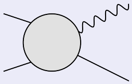
Completely democratic treatment of photons and partons

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
  ⇒ Photons in analysis region dominantly produced by matrix-element
- E.g. isolation in cone with radius D and minimal $p_\perp$ for photons
  ⇒ 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)

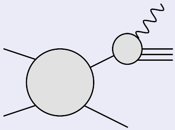
⇒ Improved approach: ME+PS Monte Carlo

"**Direct**" component – Tree-level calculation + QCD parton shower



- Built-in or automatically generated tree-level ME
  e.g. $pp \to \gamma$+parton
- QCD parton shower resums logarithmically enhanced QCD corrections

"**Fragmentation**" component – ME+PS



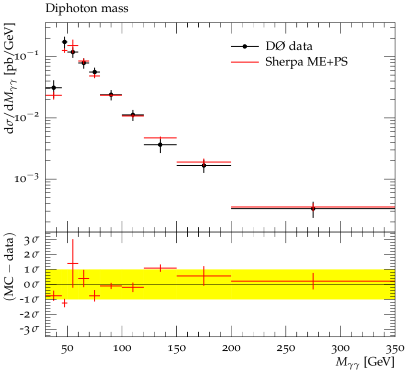
- Well separated photons come from higher-order MEs
- Collinear photons from PS
- **Advantage over pure shower**:
  - Exact ME instead of PS approximation for hard photons
  - Adjust separation criterion ⇒ PS-fragmentation component negligible but still available e.g. for checks!

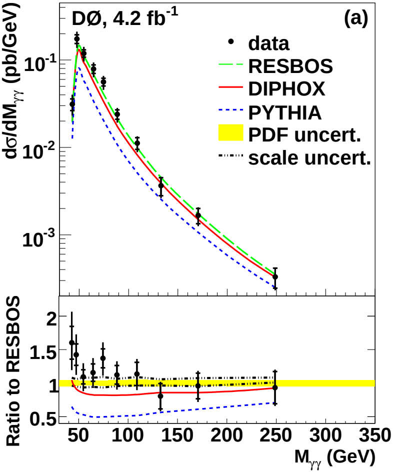
"**Non-prompt**" component: Photons from $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, ...

- Can be fully considered in this approach
- Sources: hadronisation, hadron decays, underlying event

Results for diphoton production at Tevatron

DØ: arXiv.org:1002.4917





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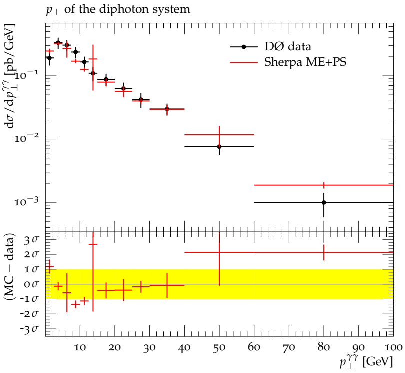

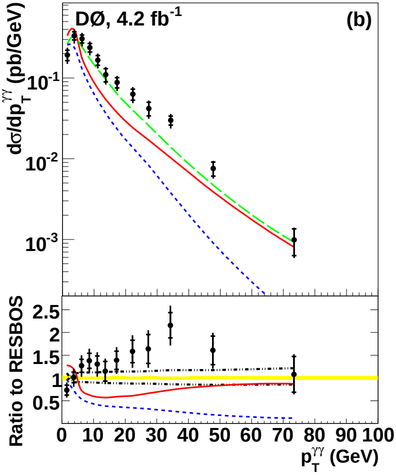

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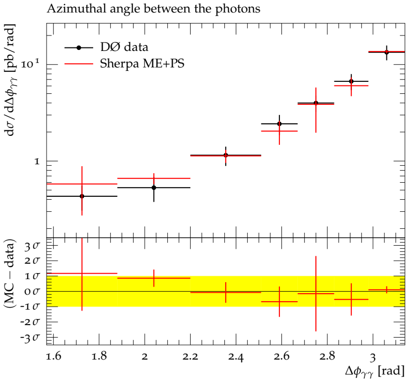

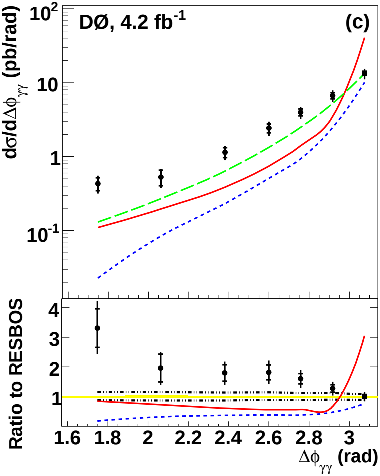

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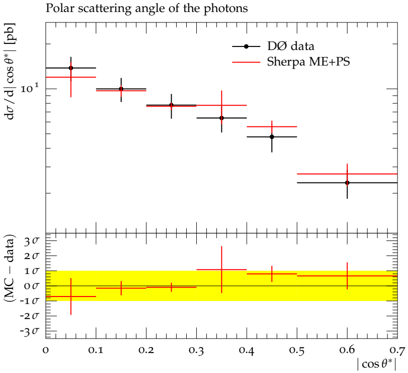

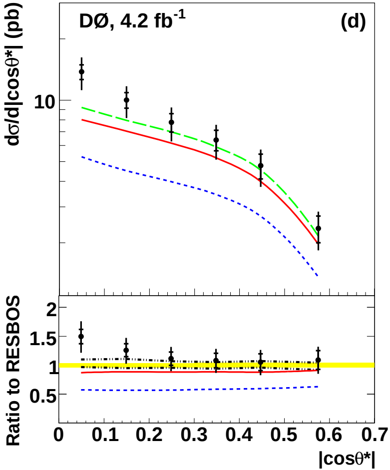

Conclusions

Conclusions

- Monte-Carlo parton showers useful tool for photon production
- 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
- Improved agreement with Tevatron measurements

Outlook

- SHERPA 1.2.1 available in CMS software
- Still trying to optimize event generation efficiency for photon production
- Tutorial with run card examples available in the next week(s?)