Hard photon production and ME+PS merging

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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

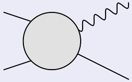
- $h \rightarrow \gamma\gamma$ (+ jets)
- Many BSM models produce final state photons

Anomalous gauge couplings

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

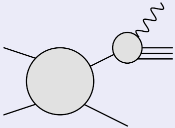
"Traditional" approach

"**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 ($\rightarrow$ 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: Parton-shower Monte Carlo

Monte-Carlo event generation

PERTURBATIVE PHYSICS

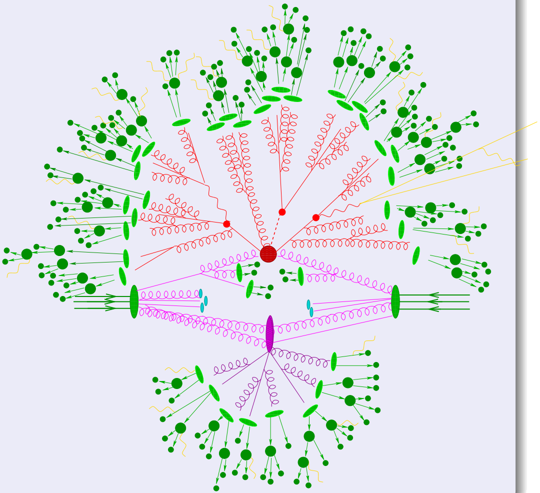
- Initial state parton shower$^{(*)}$
- Signal process*
- Final state parton shower*
- Underlying event

SOFT PHYSICS

- Hadronisation
- Hadron decays

*PROMPT PHOTON PRODUCTION:

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



Why can this be split into different event phases?

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

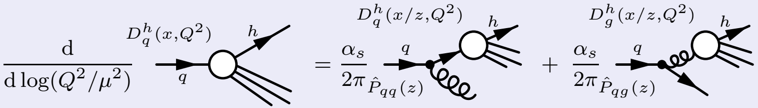
Evolution equations

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

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

⇒ Probablity at higher scale = lower scale + parton splitting

- Differential version of that equation in pictures:



Parton-shower Monte Carlo

Solving this evolution equation: Parton shower algorithm

- Task: **Dice splitting scale** Q^2 given a scale Q_0^2 at which a parton was produced,
- Use Sudakov-formalism to solve it (+ some tricks)
  $\Rightarrow$ **Probability for no emission** between two scales

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

- Example: Kernel $\mathcal{K}_{ab}(z,t) = \frac{\alpha_s}{2\pi} P_{ab}(z)$
- Terminate evolution before entering hadronisation regime $Q^2 \approx 1\mathrm{GeV}^2$

CSSHOWER++ — Parton shower based on dipole subtraction

- Emissions ordered in $t \equiv k_\perp^2$
- 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

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

Modifications of shower for interleaved QCD⊕QED evolution

Modifications for QED

- No interference between QCD and QED at NLO ⇒ Emission probabilities factorise trivially

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

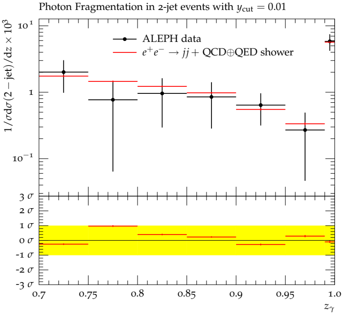
- Implemented by adding splitting functions for $qq\gamma$ vertex

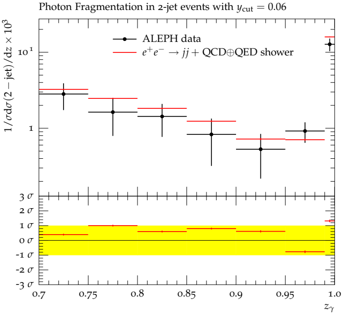
$$\mathcal{K}_{(ij)i}^{\mathbf{QED}}(z, \mathrm{k}_\perp^2) = \frac{\alpha(\mathrm{k}_\perp^2)}{2\pi} J(\mathrm{k}_\perp^2, z) \sum_k \langle \mathrm{V}_{(ij)i,k}^{\mathbf{QED}}(\mathrm{k}_\perp^2, z) \rangle$$

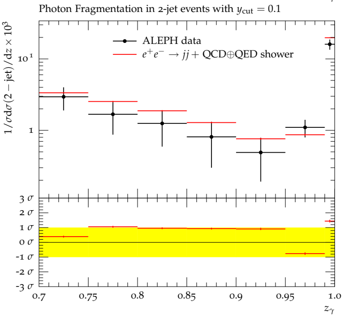
- Difference to large N_C QCD: Not exactly one colour partner for dipole
- Neglects (negative) interference from legs with same-sign charges
- Similarly implemented in several parton showers (Ariadne, Herwig, Pythia, Sherpa)
- Does this actually work? Let's look at some data ...

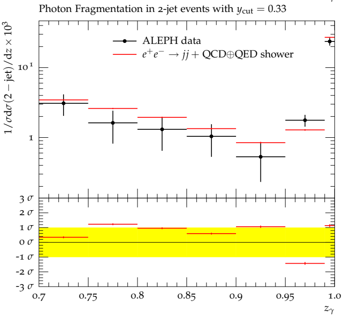
Fragmentation function at LEP

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









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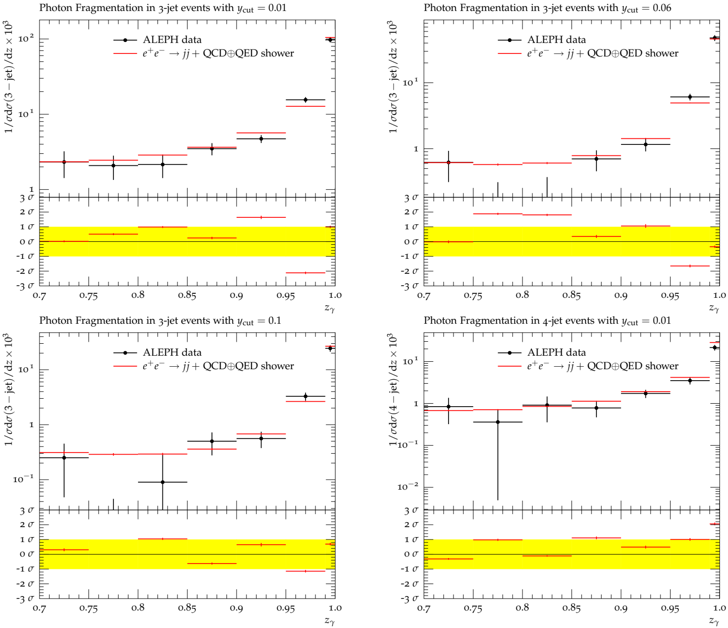
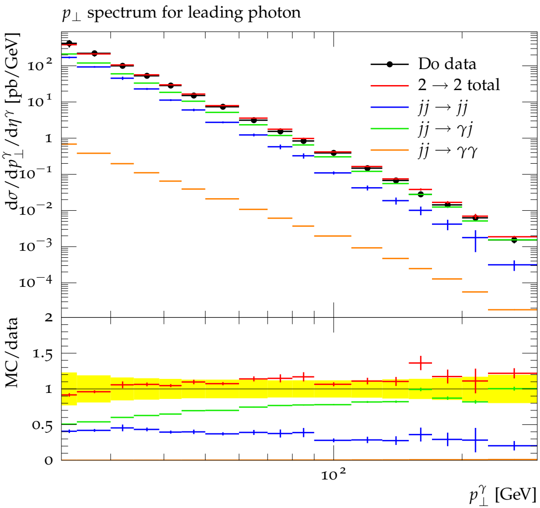


Relevance of fragmentation component

DØ : Phys. Lett. B639 (2006), 151158



Bringing higher-order matrix elements into the game

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 $Q_{\rm cut}$
- $Q_{\rm cut}$ 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

Recap: Merging algorithm

Outline of algorithm

1. Generate ME event above Q_{cut} according to σ and $d\sigma$ ✓

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1. Generate ME event above Q_{cut} according to σ and $d\sigma$ ✓
2. Translate ME event into shower language: **Branching history** ✓
3. Reweight $\alpha_s(\mu^2) \to \alpha_s(p_\perp^2)$ for each branching

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2. Translate ME event into shower language: **Branching history** ✓
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4. Start shower evolution:
   - Emissions in PS regime?

Recap: Merging algorithm

Outline of algorithm

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2. Translate ME event into shower language: **Branching history** ✓
3. Reweight $\alpha_s(\mu^2) \to \alpha_s(p_\perp^2)$ for each branching ✓
4. Start shower evolution:
   - Emissions in PS regime? $\Rightarrow$ **Keep**
   - Emission in ME regime?

Recap: Merging algorithm

Outline of algorithm

1. Generate ME event above Q_{cut} according to σ and $d\sigma$ ✓
2. Translate ME event into shower language: **Branching history** ✓
3. Reweight $\alpha_s(\mu^2) \rightarrow \alpha_s(p_\perp^2)$ for each branching ✓
4. Start shower evolution: ✓
   - Emissions in PS regime? $\Rightarrow$ **Keep**
   - Emission in ME regime? $\Rightarrow$ **Reject event**

$$\Downarrow$$

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

Photons in Merging

The good news

Algorithm works with the same concept!

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

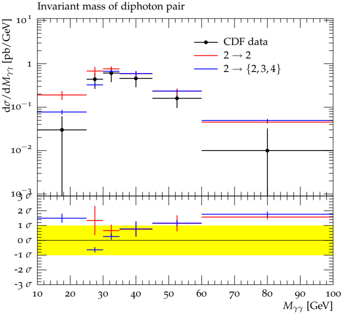
Completely democratic treatment of photons and partons

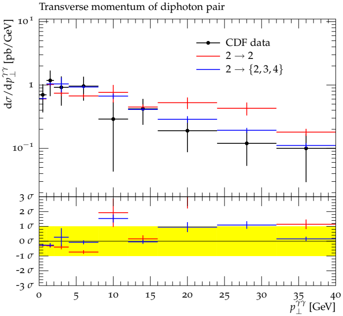
Separation criterion

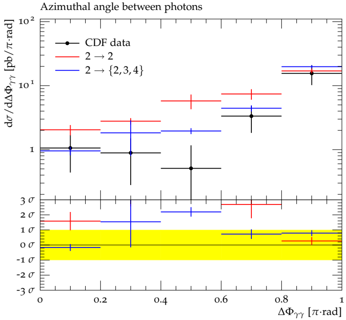
- In principle, $Q_{\rm cut}$ or even the form of Q_{ij}, can be chosen separately for QCD and QED
- Might be useful for analyses requiring isolated photons
  $\Rightarrow$ Photons in analysis region dominantly produced by matrix-element
- E.g. isolation in cone with radius D and minimal $p_\perp$ for 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

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







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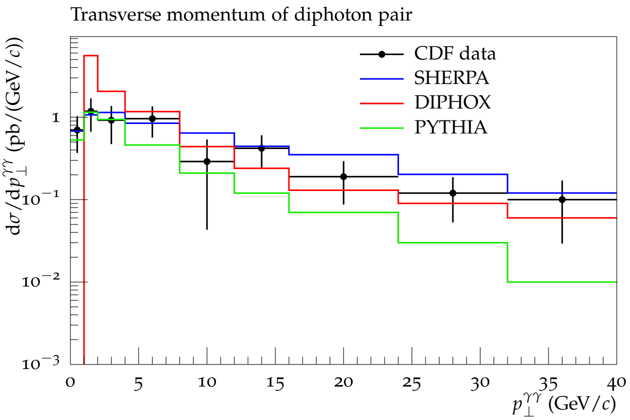

Conclusions

Conclusions

- 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
- Improved agreement with Tevatron measurements

Outlook

- New DØ analysis this week, significantly higher statistics
- SHERPA 1.2.1 (next week) contains QCD$\oplus$QED merging (and much more)
- Long term goal: Multi-jet merging with NLO matrix elements (but first for QCD ;-))