Photon production processes 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

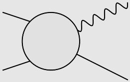
- $h \rightarrow \gamma\gamma$ (+ jets)
- Many BSM models produce final state photons

Anomalous gauge couplings

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

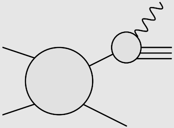
"Traditional" approach

"**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



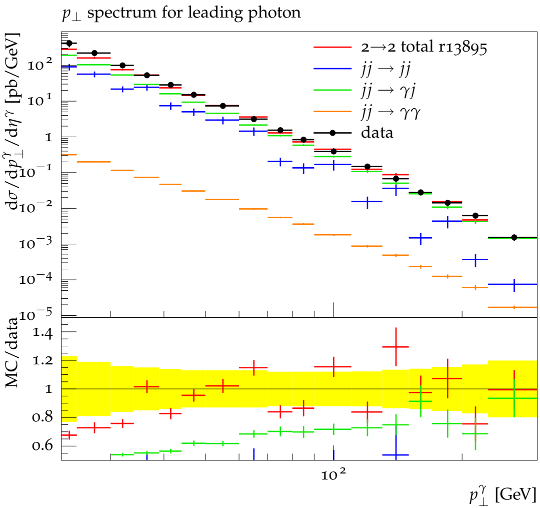
- Singularities factorised off ME
- Resummed to all orders in α_S
- $\Rightarrow$ Photon fragmentation function $D^{\gamma}_{q,g}(z, Q^2)$ Phys. Lett. B79 (1978), 83
- Relevant even if isolation criteria applied to photons ($\rightarrow$ next slide)

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

- Can be separated from prompt photons experimentally by looking at shower shapes
- $\Rightarrow$ 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

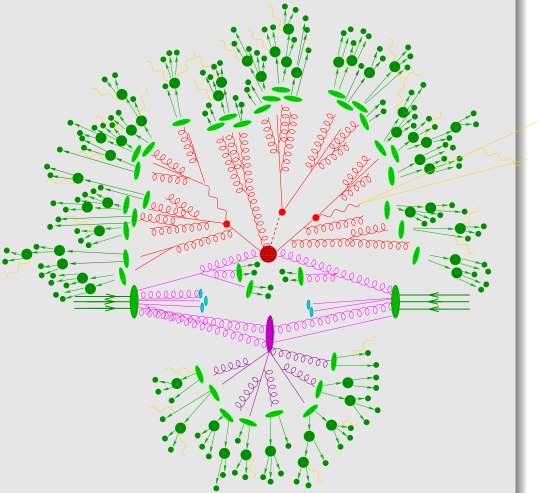
- Initial state parton shower$^{(*)}$
- Signal process*
- Final state parton shower*
- Underlying event

SOFT PHYSICS

- Hadronisation
- Hadron decays

*PROMPT PHOTON PRODUCTION:

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



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

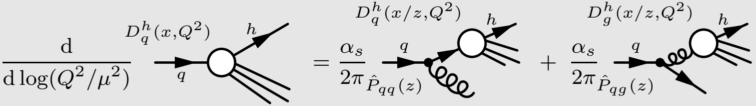
Evolution equations

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

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

  ⇒ Higher resolution 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

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

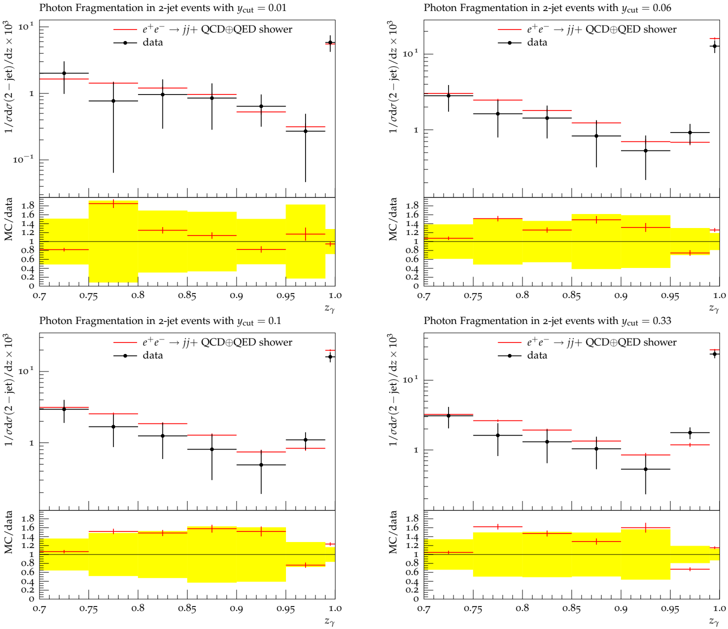
- Implemented by adding splitting functions for $qq\gamma$ vertex

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

- 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 (preliminary)

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



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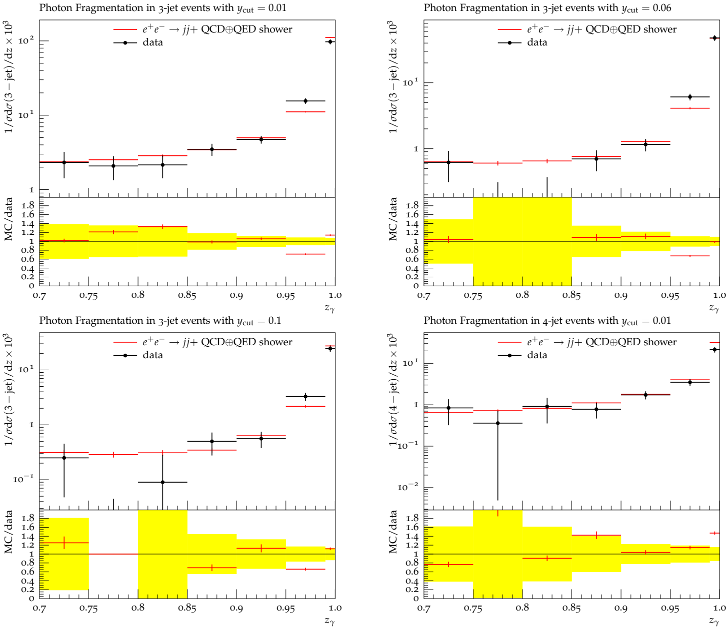
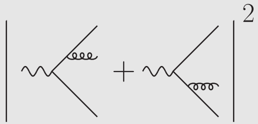


ME+PS Merging – motivation

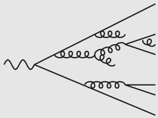
Two approaches to higher-order corrections

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 to ME for splitting
- $-$ Large N_C limit only

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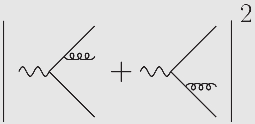
Matrix Elements



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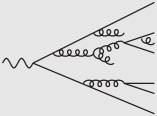
Parton Showers



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

$\Downarrow$

Goal: Combine advantages

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

More motivation for ME+PS merging

Reminder: Shower ingredients

- Emission probabilities Δ_a
- Evolution variable t
- Not mentioned so far: Kinematical reshuffling after branching

Uncertainties in this model

- Especially the third ingredient has big **ambiguities**!
- Different kinematics can have different properties for resummation
  $\longrightarrow$ Z. Nagy – Talk at EPS HEP 2009, Krakow

$\Rightarrow$ Merging with exact matrix elements can help get less dependent of such ambiguities

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

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

- Boundary determined by value of Q_{cut}
- Q_{cut} has to regularise QCD radiation MEs (like a jet resolution), otherwise completely arbitrary until now

Evolution factorises

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

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

Merging algorithm

Outline of algorithm

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

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**

Merging algorithm: Branching history

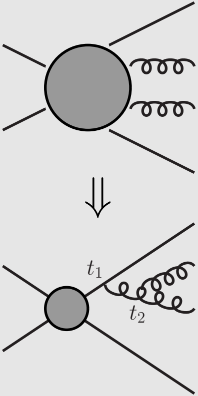
Translate ME event into shower language

Problem: ME only gives final state, no history
Solution: Backward-clustering (running the shower reversed)

1. Take N-particle final state
2. Identify most probable splitting (lowest shower measure)
3. Recombine partons using inverted shower kinematics
   $\rightarrow$ N-1 particles + splitting variables for one node
4. Repeat 2 and 3 until core process

$\Downarrow$

Most probable branching history a la shower.
Now let's use it ...



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 $\alpha_s(\mu^2) \to \alpha_s(p_\perp^2)$ for each branching

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 $\alpha_s(\mu^2) \to \alpha_s(p_\perp^2)$ for each branching ✓
4. Start shower evolution:
   - Emissions in PS regime?

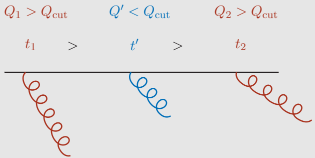
Merging algorithm: Emissions in PS regime

Interpretation of $\mathcal{P}^{\rm PS}_{{\rm no},\,a}(t,t')$

- No-branching probability for shower emissions **below** $Q_{\rm cut}$
- **Truncated** at production and decay scale t', t

Truncated shower

Some splittings are pre-determined by ME



Mismatch of Q and t allows intermediate radiation!
$\Rightarrow$ "Truncated" shower necessary to fill phase space below $Q_{\rm cut}$

1. Shower between t_1 and t_2
2. Then insert pre-determined node t_2
3. Restart evolution from there

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?

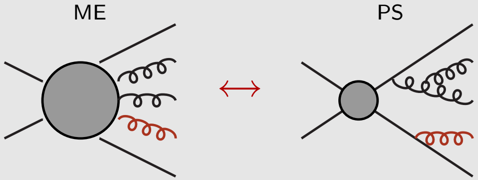
Merging algorithm: Emissions in ME regime

Interpretation of $\mathcal{P}^{\mathrm{ME}}_{\mathrm{no},\,a}(t,t')$

- No-branching probability for shower emissions **above** Q_{cut}
- Truncated at production and decay scale t', t

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

What if something is emitted? → CKKW-L



Emissions in this regime should be described by MEs!

Merging algorithm: Emissions in ME regime

Interpretation of $\mathcal{P}^{\mathrm{ME}}_{\mathrm{no},\,a}(t, t')$

- No-branching probability for shower emissions **above** Q_{cut}
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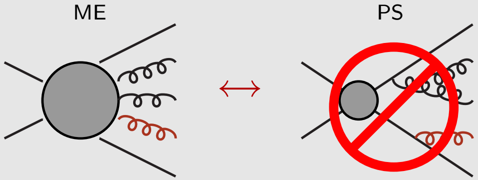


Emissions in this regime should be described by MEs!
⇒ Reject event to avoid double counting

Consequences

- Reduction of cross section $\sigma \to \sigma \cdot \mathcal{P}^{\mathrm{ME}}_{\mathrm{no},\,a}(t, t')$
- Compensated by higher order ME's

⇒ Leading order cross section stable

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 $\alpha_s(\mu^2) \to \alpha_s(p_\perp^2)$ 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 thing

Nothing changes!

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

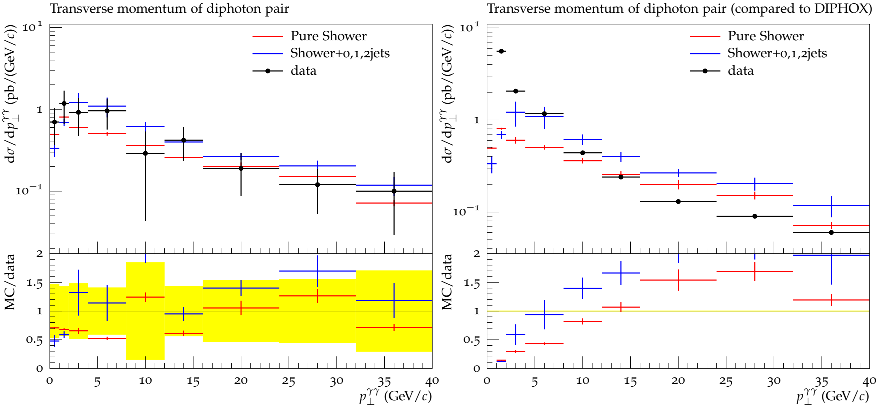
Completely democratic treatment of photons and partons

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 (preliminary)

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



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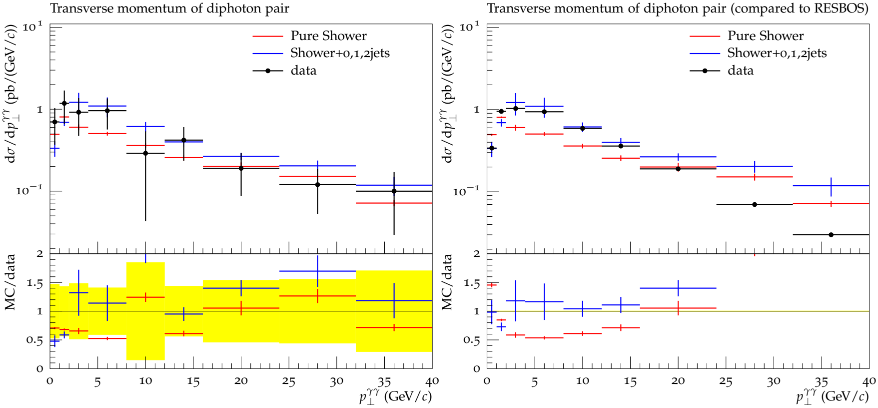

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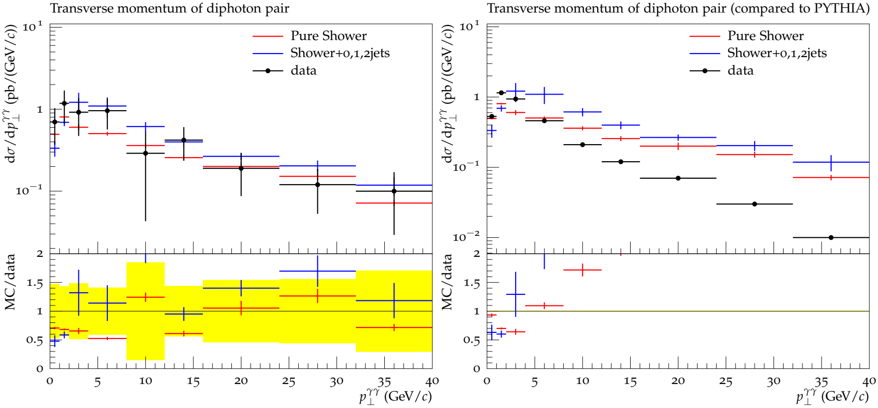

Conclusions

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
- 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

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

ME generator

JHEP **0812** (2008) 039 [arXiv:0808.3674 [hep-ph]]

COMIX — Recursive matrix elements

- Based on colour-dressed Berends-Giele recursion relations
- Designed to cope with large number of external legs
- Phase space also done recursively

Example: Diphoton production at LHC (MC4LHC workshop)

σ [pb]	Number of jets						
$\gamma\gamma$ + jets	0	1	2	3	4	5	6
Comix	45.64(5)	25.23(6)	18.57(6)	9.64(4)	4.65(2)	2.07(2)	0.88(3)
AMEGIC	45.66(3)	25.41(6)	18.81(7)	9.82(3)			

Parton separation criterion

Reminder

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

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

$$Q^2_{ij} \;=\; 2\,p_i p_j \;\min_{k\neq i,j}\; \frac{2}{C^k_{i,j} + C^k_{j,i}}$$

Final state partons $(ij) \to i,\, j$

$$C^k_{i,j} \;=\; \begin{cases} \dfrac{p_i p_k}{(p_i+p_k)p_j} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\[2ex] 1 & \text{else} \end{cases}$$

Initial state parton $a \to (aj)\,j$

$$C^k_{a,j} \;=\; C^k_{(aj),\,j}$$

with $p_{aj} = p_a - p_j$

- The minimum is over all possible colour partners k of parton (ij)
- Identifies regions of soft ($E_g \to 0$) and/or (quasi-)collinear ($\approx k_\perp^2 \to 0$) enhancements
- Similar to jet resolution (e.g. Durham in e^+e^- case), but with flavour information