Recent advances in multi-jet ME+PS merging; Monte-Carlo tuning using early ATLAS data

Frank Siegert

Institute for Particle Physics Phenomenology, Durham University &
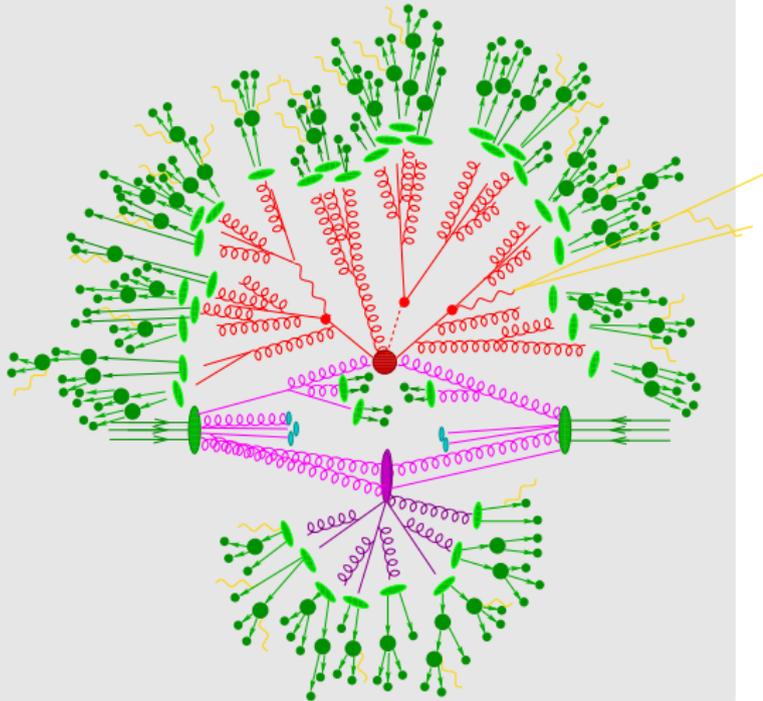University College London

18 September 2009, Manchester

Monte-Carlo event generation

PERTURBATIVE PHYSICS

- Initial state parton shower (QCD)
- Signal process
- Final state parton shower (QCD)
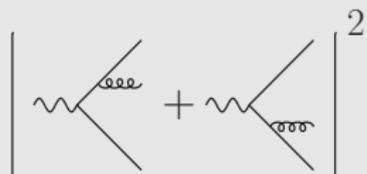- Underlying event

SOFT PHYSICS

- Fragmentation
- Hadron decays
- QED radiation

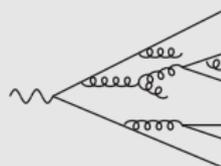Recent advances in multi-jet ME+PS merging

Two approaches

Matrix Elements

$$\left| \rightthreetimes + \rightthreetimes \right|^2$$

+ 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
− No interference effects
− Large N_C limit only

Two approaches

Matrix Elements

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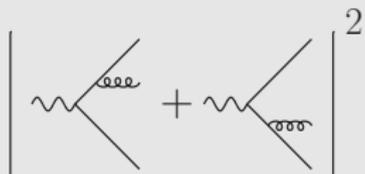− Perturbation breaks down due to large logarithms
− Only low FS multiplicity

Parton Showers

+ Resum logarithmically enhanced contributions to all orders
+ Produce high-multiplicity final state
− Only approximation to ME for splitting
− No interference effects
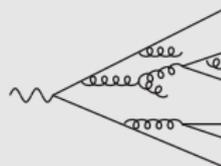− Large N_C limit only

$\Downarrow$

Goal: Combine advantages

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

Evolution equation in terms of Sudakov form factor Δ

$$\frac{\partial}{\partial \log(t/\mu^2)} \frac{g_a(z,t)}{\Delta_a(\mu^2,t)} = \frac{1}{\Delta_a(\mu^2,t)} \int_z^{\zeta_{\max}} \frac{\mathrm{d}\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,t) \, g_b(z/\zeta,t)$$

$$\Delta_a(\mu^2,t) = \exp\left\{ -\int_{\mu^2}^t \frac{\mathrm{d}\bar{t}}{\bar{t}} \int \mathrm{d}\zeta \sum_{b=q,g} \frac{1}{2} \mathcal{K}_{ab}(\zeta,\bar{t}) \right\}$$

- Kernel describes parton splitting: $\mathcal{K}_{ab}(z,t) \leftrightarrow \frac{1}{\mathrm{d}\sigma_a^{(N)}(\Phi_N)} \frac{\mathrm{d}\sigma_b^{(N+1)}(z,t;\Phi_N)}{\mathrm{d}\log(t/\mu^2)\,\mathrm{d}z}$
- Solution: Probability for no (forward) shower branching between two scales

$$\mathcal{P}_{\mathrm{no},\,a}(t,t') = \frac{\Delta_a(\mu^2,t')}{\Delta_a(\mu^2,t)} \overset{!}{=} \mathcal{R}$$

$\Rightarrow$ **MC method** for dicing successive branching scales using random number $\mathcal{R} \in [0,1]$

Preparation for ME/PS merging

Use different splitting kernels in different regions in phase space, but:
Preserve total evolution equation!

Emission phase space divided by parton separation criterion $Q_{ab}(z,t)$

$$\mathcal{K}_{ab}(z,t) = \mathcal{K}_{ab}^{\mathrm{PS}}(z,t) + \mathcal{K}_{ab}^{\mathrm{ME}}(z,t)$$

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

- $Q_{ab}(z,t)$ has to identify logarithmically enhanced phase space regions
- Similar to a jet measure

Evolution factorises

- Sudakov form factor:
$$\Delta_a(\mu^2,t) = \Delta_a^{\mathrm{PS}}(\mu^2,t')\,\Delta_a^{\mathrm{ME}}(\mu^2,t')$$

- No-branching probability:

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

Conclusion

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

Outline of algorithm

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

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**

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 ...
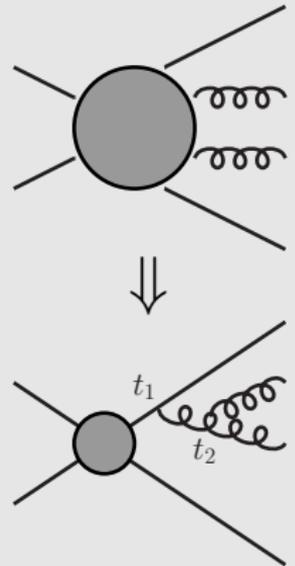
Outline of algorithm

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
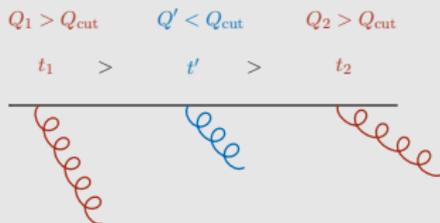
Outline of algorithm

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?

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

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

Truncated shower

Some splittings are pre-determined by ME

$Q_1 > Q_{\text{cut}}$ $Q' < Q_{\text{cut}}$ $Q_2 > Q_{\text{cut}}$

$t_1 \quad > \quad t' \quad > \quad t_2$

Mismatch of Q and t allows intermediate radiation!

$\Rightarrow$ "Truncated" shower necessary to fill phase space below Q_{cut}

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

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:
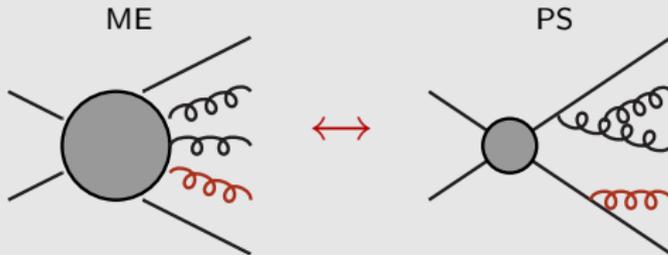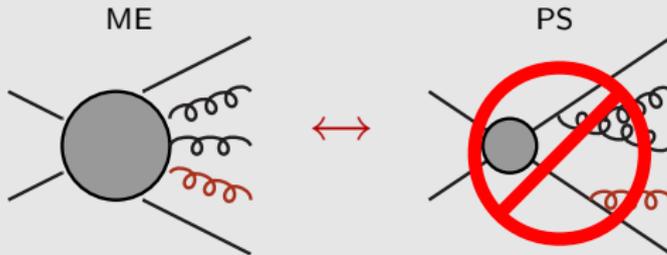   - Emissions in PS regime? $\Rightarrow$ **Keep**
   - Emission in ME regime?

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

- 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? $\rightarrow$ CKKW-L

ME   PS

$\longleftrightarrow$

**Emissions in this regime
should be described by MEs!**

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

- 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

ME   PS

$\longleftrightarrow$

**Emissions in this regime
should be described by MEs!**
$\Rightarrow$ Reject event to avoid
double counting

Consequences

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

$\Rightarrow$ Leading order cross section stable

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

Parton separation criterion

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

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

$$Q_{ij}^2 = 2\,p_i p_j \min_{k \neq i,j} \frac{2}{C_{i,j}^k + C_{j,i}^k}$$

Final state partons $(ij) \to i,\, j$ **Initial state parton** $a \to (aj)\, j$
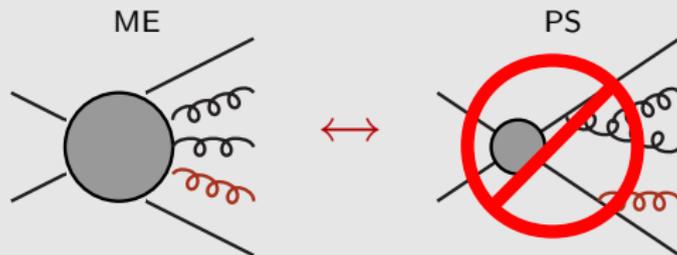
$$C_{i,j}^k = \begin{cases} \dfrac{p_i p_k}{(p_i + p_k)p_j} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\[2mm] 1 & \text{else} \end{cases}$$

$$C_{a,j}^k = C_{(aj),\,j}^k$$
$$\text{with } p_{aj} = p_a - p_j$$

- 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

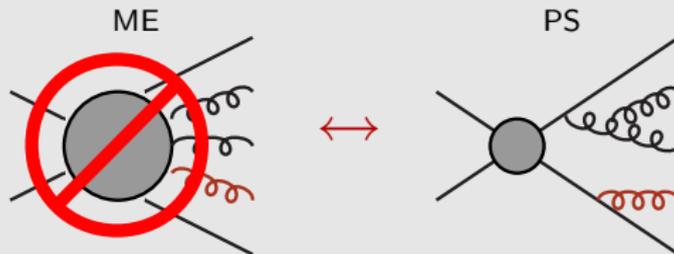- So far: Rejection of emissions in ME regime $\Rightarrow$ Sudakov weighted MEs

- So far: Rejection of emissions in ME regime $\Rightarrow$ Sudakov weighted MEs

ME   PS

$\longleftrightarrow$

What if higher order ME not available?

So far: Rejection of emissions in ME regime $\Rightarrow$ Sudakov weighted MEs

ME $\qquad$ PS
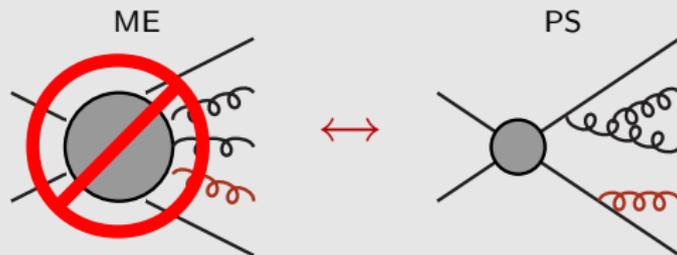
What if higher order ME not available?

Highest multiplicity events

- $N = N_{\max}$ emissions from ME $\Rightarrow$ correct branching probability up to scale of last ME emission, $t_{\min}$ (global, for all legs)
- PS must account for all emissions $t < t_{\min}$, even if $Q > Q_{\mathrm{cut}}$
- Implemented by employing standard PS evolution beyond last ME emission
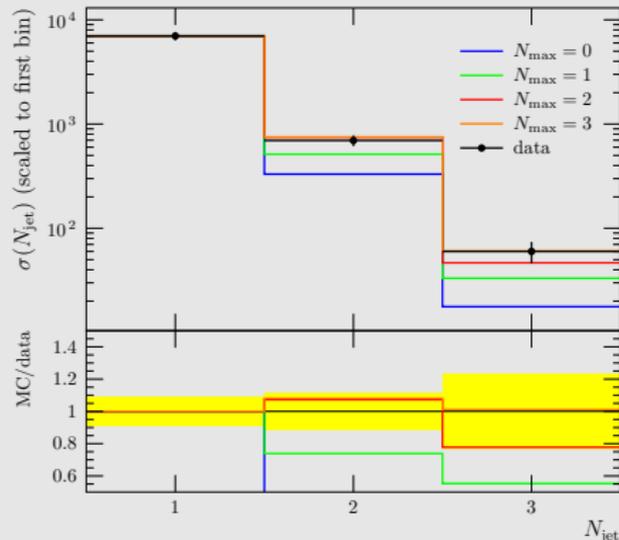
$$\Downarrow$$

Hard radiation respected
Remaining phase space filled

Is it relevant? Results for $p\bar{p} \to e^+e^- +$ jets at $\sqrt{s} = 1960\,\mathrm{GeV}$

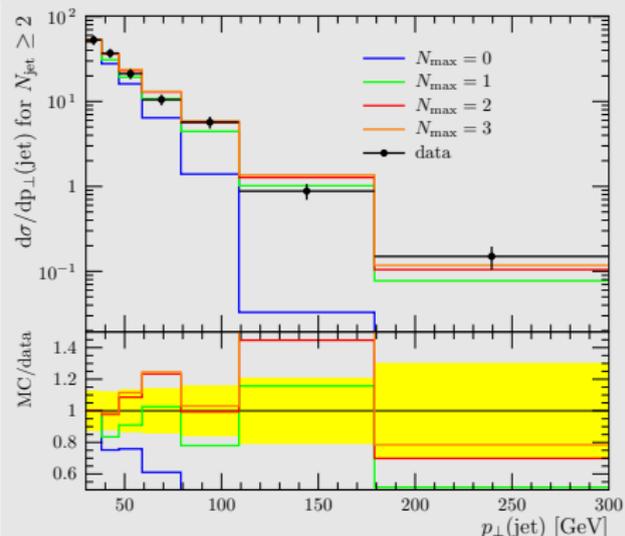Algorithm implemented in SHERPA framework

CSSHOWER++ Shower based on Catani-Seymour subtraction

COMIX Matrix elements based on Berends-Giele recursion

Jet multiplicity
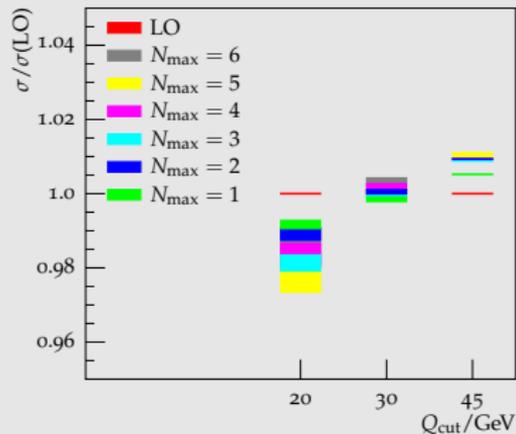
$p_\perp(\mathrm{jet})$ in $N_\mathrm{jet} \geq 2$ events

Is it consistent? Results for $p\bar{p} \to e^+e^- + \text{jets}$ at $\sqrt{s} = 1960\,\text{GeV}$
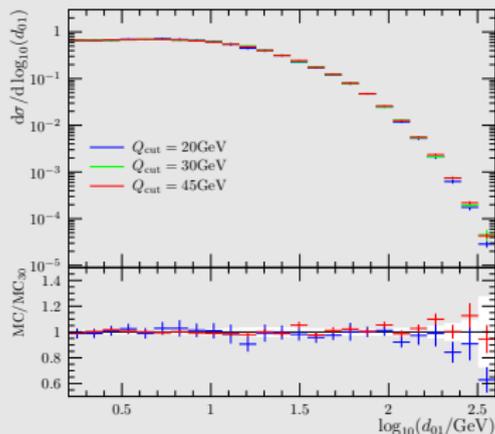
Consistency tests

- Total LO cross section stable?
- Observables independent from "unphysical" merging cut?
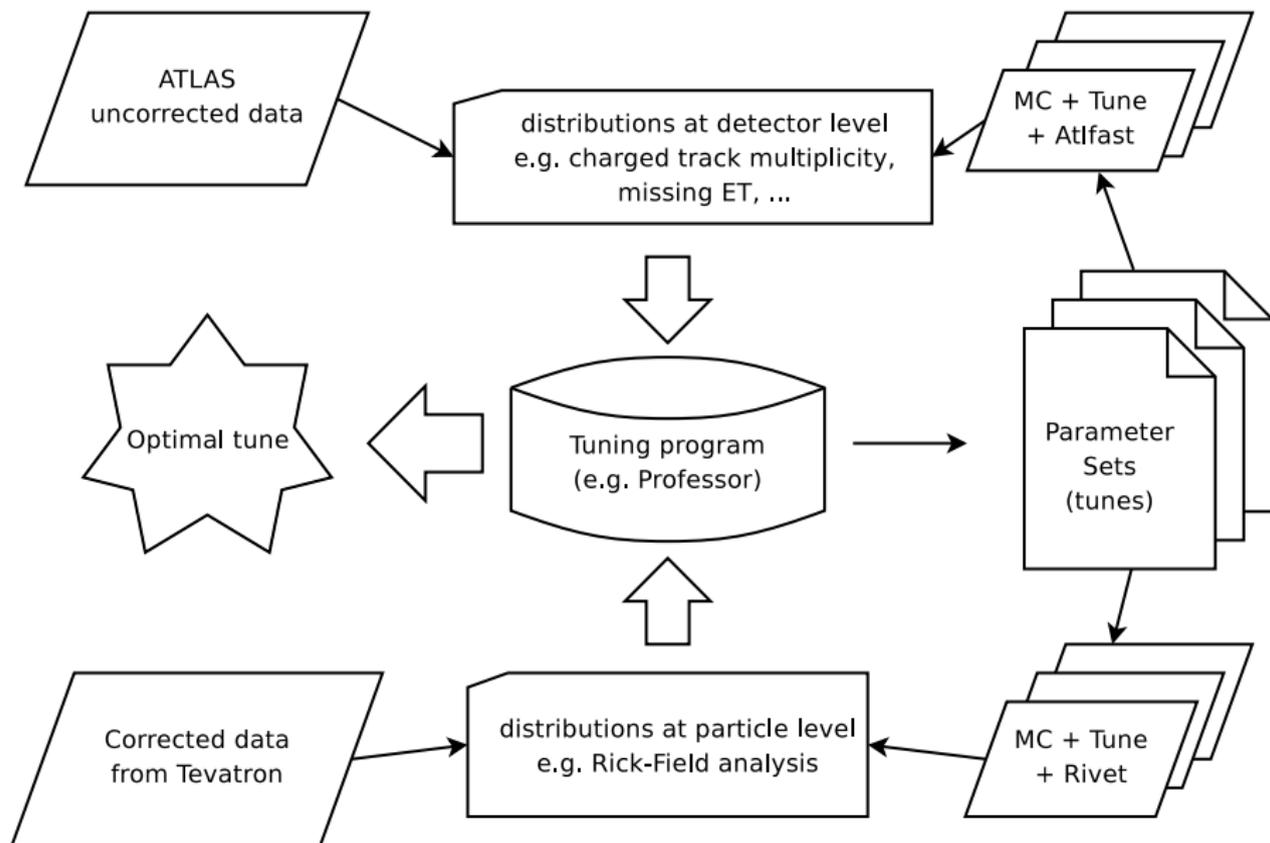
Total cross sections

$1 \to 0$ jet resolution ($k_\perp$)

Monte-Carlo tuning using early ATLAS data

ATLAS uncorrected data

distributions at detector level e.g. charged track multiplicity, missing ET, ...

MC + Tune + Atlfast

Optimal tune

Tuning program (e.g. Professor)

Parameter Sets (tunes)

Corrected data from Tevatron

distributions at particle level e.g. Rick-Field analysis

MC + Tune + Rivet

ATLAS part

- First **detector level observables** defined and implemented using `AOD` objects (from Atlfast I at the moment)
- Made available to a Rivet **pseudo analysis** so that they fill histograms
- Running Athena jobs through **GRID**

Rivet/Professor part

- Use two existing scripts from **Professor**:
  - `prof-scanparams` To dice points in the parameter hypercube
  - `prof-tune` To tune resulting histograms to a given reference
- Extended `prof-scanparams` for easy creation of **Athena** job-option files
- Many Tevatron UE analyses available in **Rivet**

First steps

- Using **Herwig/Jimmy** QCD+UE events
- Tuning parameters:
  - `PTJIM` $= F \cdot (\sqrt{s}/1.8\mathrm{TeV})^E$
    where F and E are tuned (default values in ATLAS: $F = 3.6$, $E = 0.274$):
    - $F = 2.0 \ldots 5.0$
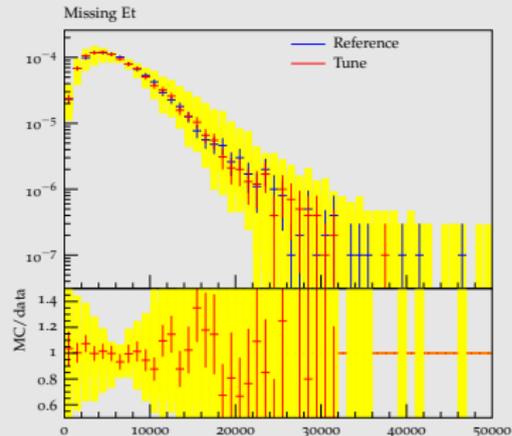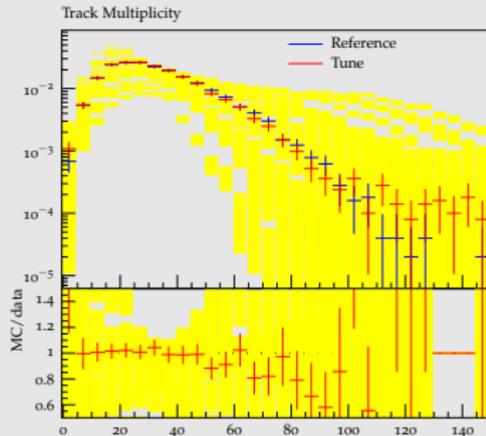   - $E = 0.254 \ldots 0.294$
  - `JMRAD` $= 0.3 \ldots 4.0$

Input

- 50 parameter points sampled
- Created **pseudo data** with the default values of the parameters:
  - $F = 3.6$
  - $E = 0.274$
  - JMRAD $= 2.2$
- Used that pseudo data as **reference** for the tuning

Result

- Tuning output:
  - $F = 3.4963$
  - $E = 0.288$
  - JMRAD $= 1.975$
- Reproduces reference
- Example distributions generated with this parameter point: Track multiplicity and missing $E_\perp$

- Contact with QCD/MinBias groups in ATLAS to determine more early data distributions to include in tuning
- Improvements in Atlfast I for track simulation $\Rightarrow$ Alexander Richards (UCL)
- Possible use case: "Tune" Atlfast I parameters to full simulation (using fixed generator parameters)
- Test with more generators (e.g. Pythia for MinBias distributions)

Goal

- Easily usable package/instructions for use by other ATLAS members
- Use of the framework for quick turnaround tunes when first data arrives