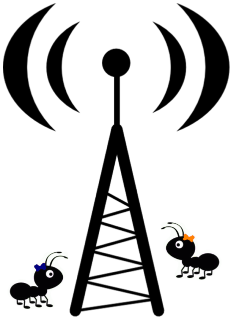
Coherent Showers with Matrix Element Corrections

in collaboration with Peter Skands

Nadine Fischer - June 15th, 2015

SCHOOL OF PHYSICS AND ASTRONOMY, MONASH UNIVERSITY



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Motivation

Fixed order matrix elements:

- Good for well-seperated jets
- Limited number of jets

Parton showers:

- Good for soft and collinear emissions
- Only approximation of mulit-jet states

Matching:

- Combine the two

Showers move towards using the dipole / antenna framework

$\rightsquigarrow$ easier combination with fixed order matrix elements

Vincia: Antenna Shower

Based on antenna factorization:

- of Amplitudes (exact in both the soft and collinear limits).
- of Phase Space ($\mathrm{d}\Phi_{n+1} = \mathrm{d}\Phi_{\text{ant}}\,\mathrm{d}\Phi_n$, with exact momentum conservation).

The Sudakov factor (no-emission probability), for $AB \to ajb$:

$$\Delta_{t_{\text{end}}}^{t_{\text{start}}} = \exp\left(-\int \mathrm{d}\Phi_{\text{ant}}\,\mathcal{A}(\Phi_{\text{ant}})\right)$$
$$= \exp\left(-\int \mathrm{d}\Phi_{\text{ant}}\;4\pi\alpha_s\,\frac{f_a(x_a,t)}{f_A(x_A,t)}\,\frac{f_b(x_b,t)}{f_B(x_B,t)}\;\bar{a}\,^{j}_{AB}(s_{aj},s_{jb},s_{AB})\right)$$

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Generate an all-orders approximation based on universal parts of amplitudes:

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Generate an all-orders approximation based on universal parts of amplitudes:

$\mathcal{PS}\,^t_\mu\ [\mathcal{B}_{\text{Born}}] =$

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Generate an all-orders approximation based on universal parts of amplitudes:

$\mathcal{PS}\,^t_\mu\;[\mathcal{B}_{\text{Born}}] =$ no branching $t \to \mu$

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Generate an all-orders approximation based on universal parts of amplitudes:

$$\mathcal{PS}^{\,t}_{\,\mu}\;[\mathcal{B}_{\text{Born}}] = \;\Delta^t_\mu\;\mathcal{B}_{\text{Born}}$$

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$$= \exp\left(- \int \mathrm{d}\Phi_{\text{ant}}\; 4\pi\alpha_s\, \frac{f_a(x_a,t)}{f_A(x_A,t)}\, \frac{f_b(x_b,t)}{f_B(x_B,t)}\; \bar{a}^{\,j}_{AB}(s_{aj}, s_{jb}, s_{AB}) \right)$$

Generate an all-orders approximation based on universal parts of amplitudes:

$$\mathcal{PS}^{\,t}_{\mu}\; [\mathcal{B}_{\text{Born}}] = \Delta^{t}_{\mu}\, \mathcal{B}_{\text{Born}} \; + \; \text{branching at } t_1$$

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Generate an all-orders approximation based on universal parts of amplitudes:

$$\mathcal{PS}^{\,t}_{\mu}\ [\mathcal{B}_{\text{Born}}] = \ \Delta^{t}_{\mu}\,\mathcal{B}_{\text{Born}}\ +\ \mathcal{PS}^{\,t_1}_{\mu}\ \left[\mathcal{A}(t_1)\,\Delta^{t}_{t_1}\ \mathcal{B}_{\text{Born}}\right]$$

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Generate an all-orders approximation based on universal parts of amplitudes:

$$\mathcal{PS}\,{}^{t}_{\mu}\; [\mathcal{B}_{\text{Born}}] = \Delta^{t}_{\mu}\, \mathcal{B}_{\text{Born}} \;+\; \Delta^{t_1}_{\mu}\; \mathcal{A}(t_1)\, \Delta^{t}_{t_1}\; \mathcal{B}_{\text{Born}} \;+$$

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branching at t_1 and at t_2

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Generate an all-orders approximation based on universal parts of amplitudes:

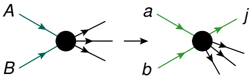
$$\begin{aligned}\mathcal{PS}\,{}^{t}_{\mu}\,[\mathcal{B}_{\text{Born}}] = \;& \Delta^{t}_{\mu}\, \mathcal{B}_{\text{Born}} + \Delta^{t_1}_{\mu}\, \mathcal{A}(t_1)\, \Delta^{t}_{t_1}\, \mathcal{B}_{\text{Born}} + \\ & \mathcal{PS}\,{}^{t_2}_{\mu}\left[\mathcal{A}(t_2)\, \Delta^{t_1}_{t_2}\, \mathcal{A}(t_1)\, \Delta^{t}_{t_1}\, \mathcal{B}_{\text{Born}}\right]\end{aligned}$$

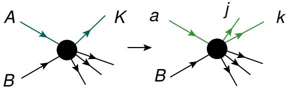
Vincia: Antenna Shower

$$\Delta_{t_{\text{end}}}^{t_{\text{start}}} = \exp\left(- \int \text{d}\Phi_{\text{ant}} \, 4\pi\alpha_s \, \frac{f_a(x_a, t)}{f_A(x_A, t)} \frac{f_b(x_b, t)}{f_B(x_B, t)} \, \bar{a}\,^j_{AB}(s_{aj}, s_{jb}, s_{AB}) \right)$$

Ingredients for ISR shower:

- Radiation Functions [Ritzmann, Kosower, Skands, Phys. Lett. B 718 (2013) 1345]
- Recoil Strategy:





Initial-Initial:

- ○ Fixed beam directions
- ○ Fixed invariant mass and rapidity of the recoiler system

Initial-Final:

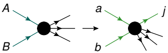
- ○ Fixed beam direction
- ○ No recoils outside the antenna

- Phase Space factorization: $\text{d}\Phi_{\text{ant}}$ expressed in s_{aj}, s_{jb}, and φ_j or s_{aj}, s_{jk}, and φ_j
- Choose evolution variable Q_E^2 and complementary variable ζ and express phase space with new variables

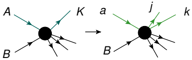
Vincia: Antenna Shower

- Phase Space: Express in evolution variable Q_E^2 and complementary variable ζ
- Gluon emission (double-pole):

Initial-Initial:



Initial-Final:



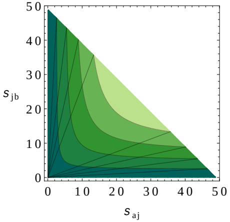
$$Q^2_{\perp\,\text{II}} = \frac{s_{aj}s_{jb}}{s_{ab}} = \frac{s_{aj}s_{jb}}{s_{AB}+s_{aj}+s_{jb}}$$

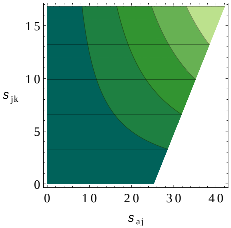
transverse momentum wrt the beam

$$\zeta_{\text{II}} = \frac{s_{aj}}{s_{ab}}$$

$$Q^2_{\perp\,\text{IF}} = \frac{s_{aj}s_{jk}}{s_{AK}+s_{jk}}$$

$$\zeta_{\text{IF}} = \frac{s_{AK}}{s_{AK}+s_{jk}}$$





- Splitting / Conversion processes (single-pole):
  evolve in s_{aj}, s_{jb}, or s_{jk} respectively (gluon / quark virtuality)

Including LO matrix elements

The aim:

- Combine shower and matrix elements

The idea:

- Start from approximate all-orders structure of the shower
- Impose higher orders LO matrix elements as finite multiplicative corrections
- Markovian setup to limit number of clusterings to perform
- Fill all of phase space

Other approaches:

- Parton showers are history-dependent and have dead zones
- Add different event samples
- Typically need an initialization step

Matrix Element Corrections for $pp \to Z + X$

Recap of the shower expansion: start at largest scale s_{hh} $\quad (f_0 = f_{A_0} f_{B_0})$

$$\mathcal{PS}\,_{\mu}^{s_{hh}} \left[f_0(s_{hh})\, |\mathcal{M}_Z|^2 \right] =$$

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no branching $s_{hh} \to \mu$

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Recap of the shower expansion: start at largest scale s_{hh} $\quad (f_0 = f_{A_0} f_{B_0})$

$$\mathcal{PS}\,^{s_{hh}}_{\mu} \left[f_0(s_{hh})\, |\mathcal{M}_Z|^2 \right] =$$

$$\Delta^{s_{hh}}_{\mu}\; f_0(s_{hh})\, |\mathcal{M}_Z|^2$$

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$$\mathcal{PS}\,_\mu^{s_{hh}}\left[f_0(s_{hh})\,|\mathcal{M}_Z|^2\right] =$$

$$\Delta_\mu^{s_{hh}}\; f_0(s_{hh})\,|\mathcal{M}_Z|^2$$

$$\stackrel{\text{event reweight}}{\to} \quad \Delta_\mu^{s_{hh}}\; f_0(s_{hh})\,\frac{f_0(m_Z^2)}{f_0(s_{hh})}\,|\mathcal{M}_Z|^2$$

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$$\mathcal{PS}_{\mu}^{s_{hh}} \left[f_0(s_{hh}) \, |\mathcal{M}_Z|^2 \right] =$$

$$\Delta_{\mu}^{s_{hh}} \; f_0(m_Z^2) \, |\mathcal{M}_Z|^2$$ reweighted

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$$\Delta_{\mu}^{s_{hh}} \; f_0(m_Z^2) \, |\mathcal{M}_Z|^2 \quad \text{reweighted}$$

$+$ branching at t_1, no further branching

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$$+ \quad \Delta_{\mu}^{\hat{t}_1} \, \frac{f_1(t_1)}{f_0(t_1)} \, f_0(s_{hh}) \, A(t_1) \, \Delta_{t_1}^{s_{hh}} \, |\mathcal{M}_Z|^2$$

Matrix Element Corrections for $pp \to Z + X$

Recap of the shower expansion: start at largest scale s_{hh} $\qquad (f_0 = f_{A_0} f_{B_0})$

$$\mathcal{PS}_{\mu}^{s_{hh}} \left[f_0(s_{hh}) \, |\mathcal{M}_Z|^2 \right] =$$

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$$\overset{\text{MEC}}{\to} \quad \Delta_{\mu}^{\hat{t}_1} \, \frac{f_1(t_1)}{f_0(t_1)} \, f_0(s_{hh}) \, A(t_1) \, \Delta_{t_1}^{s_{hh}} \, |\mathcal{M}_Z|^2 \, \frac{|\mathcal{M}_{Zj}(t_1)|^2}{\sum \, A(t_1) \, |\mathcal{M}_Z|^2}$$

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Recap of the shower expansion: start at largest scale s_{hh} $(f_0 = f_{A_0} f_{B_0})$

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$$\Delta_\mu^{s_{hh}}\; f_0(m_Z^2)\, |\mathcal{M}_Z|^2 \quad \text{reweighted}$$

$$+\;\; \Delta_\mu^{\hat{t}_1}\, \frac{f_1(t_1)}{f_0(t_1)}\, f_0(s_{hh})\, \Delta_{t_1}^{s_{hh}}\, \left|\mathcal{M}_{Zj}(t_1)\right|^2 \quad \text{MEC}$$

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$$+ \quad \Delta_{\mu}^{\hat{t}_1} \, \frac{f_1(t_1)}{f_0(t_1)} \, f_0(s_{hh}) \, \Delta_{t_1}^{s_{hh}} \, \left| \mathcal{M}_{Zj}(t_1) \right|^2 \quad \text{MEC}$$

$$\overset{\text{event reweight}}{\to} \quad \Delta_{\mu}^{\hat{t}_1} \, \frac{f_1(t_1)}{f_0(t_1)} \, f_0(s_{hh}) \, \frac{f_0\left(\max(m_Z^2, t_1)\right)}{f_0(s_{hh})} \, \Delta_{t_1}^{s_{hh}} \, \left| \mathcal{M}_{Zj}(t_1) \right|^2$$

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$+$ branching at t_1 and at t_2, no further branching

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$$+\;\; \Delta_{\mu}^{\hat{t}_2}\, \frac{f_2(t_2)}{f_1(t_2)}\, \frac{f_1(t_1)}{f_0(t_1)}\, f_0\big(\max(m_Z^2, t_1)\big)\, \mathcal{O}(\hat{t}_1, t_2) A(t_2)\, \Delta_{t_2}^{\hat{t}_1}\, \Delta_{t_1}^{s_{hh}}\, \big|\mathcal{M}_{Zj}(t_1)\big|^2$$

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$$+ \quad \Delta_{\mu}^{\hat{t}_1} \frac{f_1(t_1)}{f_0(t_1)}\, f_0(\max(m_Z^2, t_1))\, \Delta_{t_1}^{s_{hh}} \left| \mathcal{M}_{Zj}(t_1) \right|^2 \quad \text{MEC, reweighted}$$

$$+ \quad \Delta_{\mu}^{\hat{t}_2} \frac{f_2(t_2)}{f_1(t_2)} \frac{f_1(t_1)}{f_0(t_1)}\, f_0(\max(m_Z^2, t_1))\, \mathcal{O}(\hat{t}_1, t_2) A(t_2)\, \Delta_{t_2}^{\hat{t}_1}\, \Delta_{t_1}^{s_{hh}} \left| \mathcal{M}_{Zj}(t_1) \right|^2$$

$$\overset{\text{MEC}}{\to} \quad \Delta_{\mu}^{\hat{t}_2} \frac{f_2(t_2)}{f_1(t_2)} \frac{f_1(t_1)}{f_0(t_1)}\, f_0(\max(m_Z^2, t_1))\, \mathcal{O}(\hat{t}_1, t_2) A(t_2)\, \Delta_{t_2}^{\hat{t}_1}\, \Delta_{t_1}^{s_{hh}} \left| \mathcal{M}_{Zj}(t_1) \right|^2 \cdot$$

$$\cdot \frac{\left| \mathcal{M}_{Zjj}(t_2) \right|^2}{\sum \mathcal{O}(\hat{t}_1, t_2) A(t_2) \left| \mathcal{M}_{Zj}(t_1) \right|^2}$$

Matrix Element Corrections for $pp \to Z + X$

Recap of the shower expansion: start at largest scale s_{hh} $\qquad (f_0 = f_{A_0} f_{B_0})$

$$\mathcal{PS}_{\mu}^{s_{hh}} \left[f_0(s_{hh}) \, |\mathcal{M}_Z|^2 \right] =$$

$$\Delta_{\mu}^{s_{hh}} \, f_0(m_Z^2) \, |\mathcal{M}_Z|^2 \quad \text{reweighted}$$

$$+ \quad \Delta_{\mu}^{\hat{t}_1} \, \frac{f_1(t_1)}{f_0(t_1)} \, f_0(\text{max}(m_Z^2, t_1)) \, \Delta_{t_1}^{s_{hh}} \, \left| \mathcal{M}_{Zj}(t_1) \right|^2 \quad \text{MEC, reweighted}$$

$$+ \quad \Delta_{\mu}^{\hat{t}_2} \, \frac{f_2(t_2)}{f_1(t_2)} \, \frac{f_1(t_1)}{f_0(t_1)} \, f_0(\text{max}(m_Z^2, t_1)) \, \Delta_{t_2}^{\hat{t}_1} \, \Delta_{t_1}^{s_{hh}} \, \left| \mathcal{M}_{Zjj}(t_2) \right|^2 \quad \text{MEC}$$

Matrix Element Corrections for $pp \to Z + X$

Recap of the shower expansion: start at largest scale s_{hh} $\qquad (f_0 = f_{A_0} f_{B_0})$

$$\mathcal{PS}\,_{\mu}^{s_{hh}} \left[f_0(s_{hh})\, |\mathcal{M}_Z|^2 \right] =$$

$$\Delta_{\mu}^{s_{hh}}\; f_0(m_Z^2)\, |\mathcal{M}_Z|^2 \quad \text{reweighted}$$

$$+ \;\; \Delta_{\mu}^{\hat{t}_1}\, \frac{f_1(t_1)}{f_0(t_1)}\, f_0(\max(m_Z^2, t_1))\, \Delta_{t_1}^{s_{hh}} \left|\mathcal{M}_{Zj}(t_1)\right|^2 \quad \text{MEC, reweighted}$$

$$+ \;\; \Delta_{\mu}^{\hat{t}_2}\, \frac{f_2(t_2)}{f_1(t_2)}\, \frac{f_1(t_1)}{f_0(t_1)}\, f_0(\max(m_Z^2, t_1))\, \Delta_{t_2}^{\hat{t}_1}\, \Delta_{t_1}^{s_{hh}} \left|\mathcal{M}_{Zjj}(t_2)\right|^2 \quad \text{MEC}$$

$+$ Shower acting on Zjj

Matrix Element Corrections for $pp \to Z + X$

Recap of the shower expansion: start at largest scale s_{hh} $(f_0 = f_{A_0} f_{B_0})$

$$\mathcal{PS}_{\mu}^{s_{hh}} \left[f_0(s_{hh}) \, |\mathcal{M}_Z|^2 \right] =$$

$$\Delta_{\mu}^{s_{hh}} \, f_0(m_Z^2) \, |\mathcal{M}_Z|^2 \quad \text{reweighted}$$

$$+ \quad \Delta_{\mu}^{\hat{t}_1} \, \frac{f_1(t_1)}{f_0(t_1)} \, f_0(\max(m_Z^2, t_1)) \, \Delta_{t_1}^{s_{hh}} \, \left|\mathcal{M}_{Zj}(t_1)\right|^2 \quad \text{MEC, reweighted}$$

$$+ \quad \Delta_{\mu}^{\hat{t}_2} \, \frac{f_2(t_2)}{f_1(t_2)} \, \frac{f_1(t_1)}{f_0(t_1)} \, f_0(\max(m_Z^2, t_1)) \, \Delta_{t_2}^{\hat{t}_1} \, \Delta_{t_1}^{s_{hh}} \, \left|\mathcal{M}_{Zjj}(t_2)\right|^2 \quad \text{MEC}$$

$$+ \quad \mathcal{PS}_{\mu}^{\hat{t}_2} \left[\frac{f_2(t_2)}{f_1(t_2)} \, \frac{f_1(t_1)}{f_0(t_1)} \, f_0(\max(m_Z^2, t_1)) \, \Delta_{t_2}^{\hat{t}_1} \, \Delta_{t_1}^{s_{hh}} \, \left|\mathcal{M}_{Zjj}(t_2)\right|^2 \right]$$

Matrix Element Corrections for $pp \to Z + X$

- Matrix element correction:

$$P_{n+1} = \frac{|\mathcal{M}_{Z+n+1}(\{p_{Z+n+1}\})|^2}{\sum \mathcal{O}(\hat{t},t)\,A(t)\;|\mathcal{M}_{Z+n}(\{\widehat{p}_{Z+n}\})|^2}$$

t = scale of clustering
$\hat{t}$ = min(scale of possible second clustering)

- Traditional parton showers are strongly ordered: $\mathcal{O}(\hat{t},t) = \Theta(\hat{t}-t)$ $\to$ dead zone!
- Instead: allow unordering with

$$\mathcal{O}(\hat{t},t) = \begin{cases} \Theta(\hat{t}-t) & \text{clustering in an “ordered” antenna,} \\ \dfrac{\hat{t}}{\hat{t}+t} & \text{clustering in an “unordered” antenna,} \\ 1 & \text{for the first branching.} \end{cases}$$

  Denominator cancels exactly with the shower due to the Markovian setup.

- Factorization scale strictly ordered to ensure correct evolution for the PDFs.

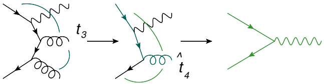
Matrix Element Corrections for $pp \to Z + X$

Compare Matrix element with the shower for $q\bar{q} \to Zgg$:

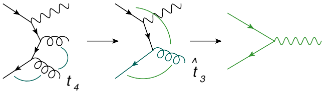
$$R_3 = \frac{\sum \text{PS paths} \cdot |\mathcal{M}_Z(m_Z)|^2}{\left|\mathcal{M}_{Zgg}(1,2;Z,3,4)\right|^2} = \frac{1}{P_3}$$

with sum over shower paths

$$\sum \text{PS paths} \cdot |\mathcal{M}_Z(m_Z)|^2 = \mathcal{O}(\hat{t}_4, t_3)\; A_g^{IF}(1,4,3)\; A_g^{II}(\widehat{13}, 2, \widehat{34})\, |\mathcal{M}_Z(m_Z)|^2 \; +$$



$$\mathcal{O}(\hat{t}_3, t_4)\; A_g^{IF}(2,3,4)\; A_g^{II}(1, \widehat{24}, \widehat{34})\, |\mathcal{M}_Z(m_Z)|^2$$

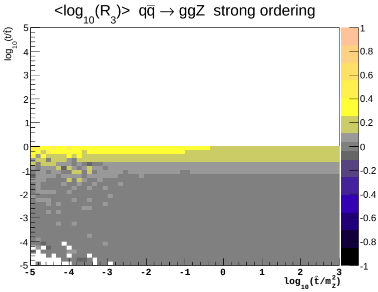


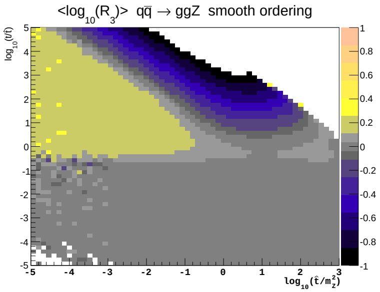
Matrix Element Corrections for $pp \to Z + X$

Compare Matrix element with the shower for $q\bar{q} \to Zgg$:

$$R_3 = \frac{\sum \text{PS paths} \cdot |\mathcal{M}_Z(m_Z)|^2}{|\mathcal{M}_{Zgg}(1,2;Z,3,4)|^2}$$

$$\mathcal{O}(\hat{t}, t) = \Theta(\hat{t} - t) \qquad\qquad \mathcal{O}(\hat{t}, t) = \frac{\hat{t}}{\hat{t} + t}$$



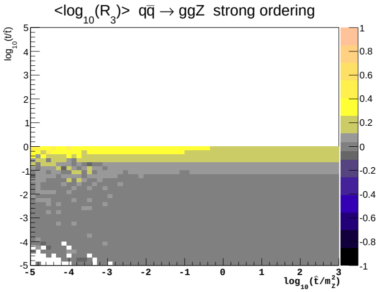


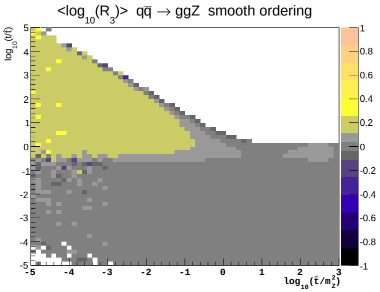
Matrix Element Corrections for $pp \to Z + X$

Compare Matrix element with the shower for $q\bar{q} \to Zgg$:

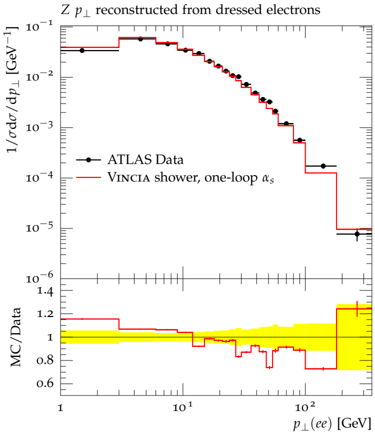
$$R_3 = \frac{\sum \text{PS paths} \cdot \left|\mathcal{M}_Z(m_Z)\right|^2}{\left|\mathcal{M}_{Zgg}(1,2;Z,3,4)\right|^2}$$

$$\mathcal{O}(\hat{t},t) = \Theta(\hat{t}-t) \qquad\qquad \mathcal{O}(\hat{t},t) = \frac{\hat{t}}{\hat{t}+t}$$



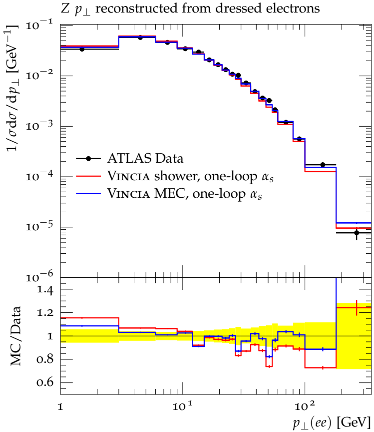


A Result



1. pure shower,
   no matrix element corrections,
   one-loop running with $\alpha_s(m_Z) = 0.138$

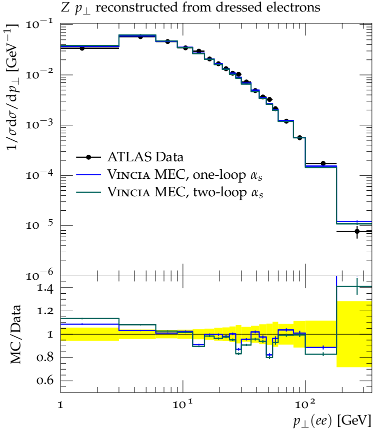
A Result



1. pure shower,
   no matrix element corrections,
   one-loop running with $\alpha_s(m_Z) = 0.138$

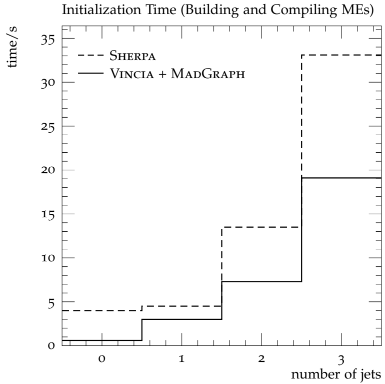
2. matrix element corrections up to Zjj,
   one-loop running with $\alpha_s(m_Z) = 0.138$

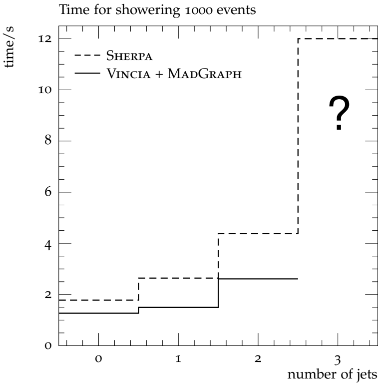
A Result



2. matrix element corrections up to Zjj, one-loop running with $\alpha_s(m_Z) = 0.138$
3. matrix element corrections up to Zjj, two-loop running with $\alpha_s(m_Z) = 0.122$ and CMW-rescaling

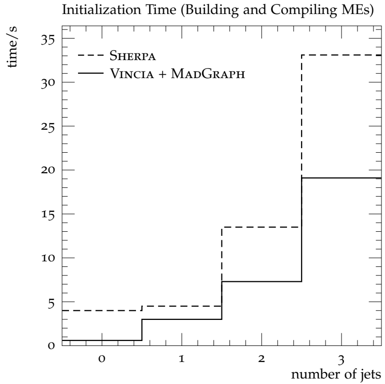
Speed Comparison

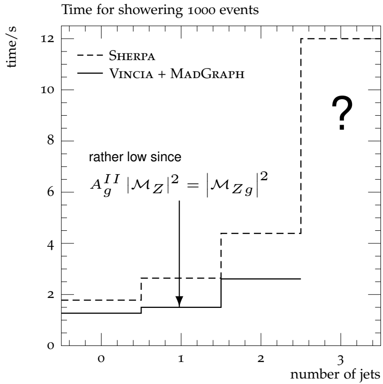




- $pp \to Z + \mathrm{N}\ j$
- $Q_{\mathrm{cut}} = 5$ GeV
- Shower only, no hadronization, no MPI

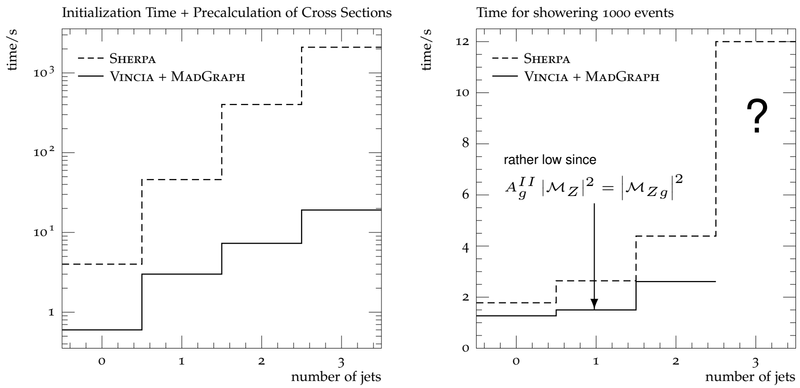
Speed Comparison





- $pp \to Z + \mathrm{N}\ j$
- $Q_{\text{cut}} = 5$ GeV
- Shower only, no hadronization, no MPI

Speed Comparison



- $pp \to Z +$ N j
- $Q_{\text{cut}} = 5$ GeV
- Shower only, no hadronization, no MPI

Outlook

1. Generalize the matrix element correction framework to arbitrary LHC processes
2. Include QED radiation
3. Include loop corrections
4. Extend to top physics

Backup

More Results