Analytical and Numerical Approaches to (N)LL resummation

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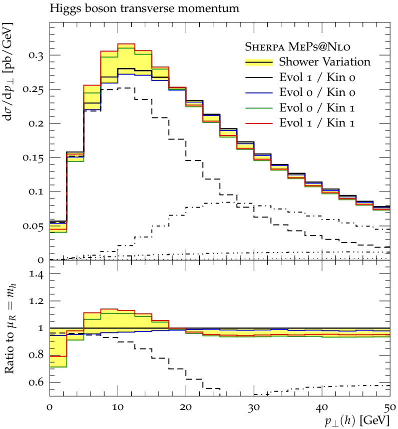
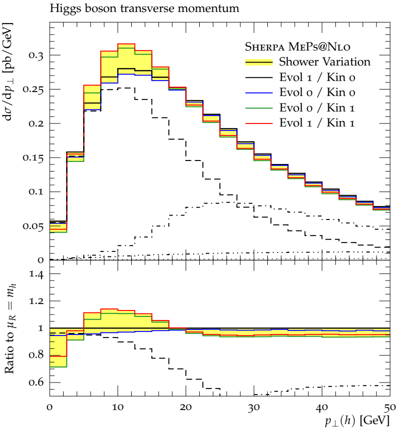


[Höche, Krauss, Schönherr 2014]



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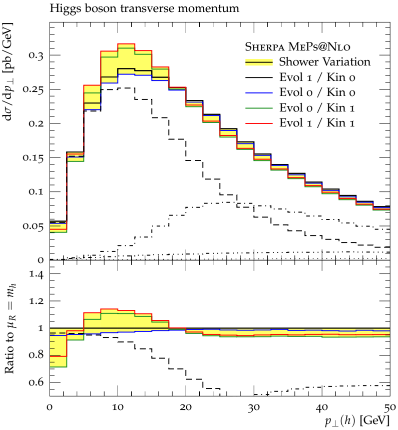
Large Resummation uncertainty:

- Motivates work on showers with better accuracy.



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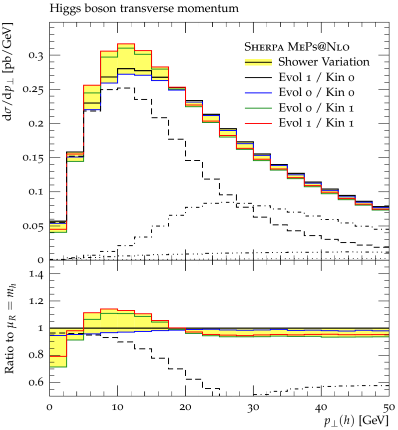

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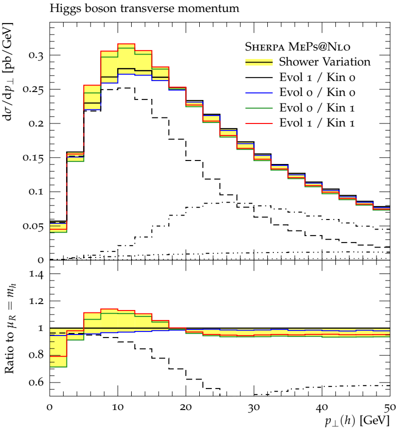
- Numerical (parton shower) side:
  - Formally only lowest approximation.
  - Parton showers "are better than formally expected":
    - ⋆ Momentum conservation
    - ⋆ coherence, . . .



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Large Resummation uncertainty:

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  - Higher accuracy calculations exist.
- Numerical (parton shower) side:
  - Formally only lowest approximation.
  - Parton showers "are better than formally expected":
    - Momentum conservation
    - coherence, ...
- No straightforward comparison possible.

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- In this talk:

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  - Build a toy shower that emulates NLL resummation exactly.

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  - Turn on different contributions step by step
    $\Rightarrow$ finally recover full parton shower.

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- In this talk:
  - Build a toy shower that emulates NLL resummation exactly.
  - Turn on different contributions step by step
    $\Rightarrow$ finally recover full parton shower.
  - Determine sizes of individual contributions.

Outline

1. General Setup
2. PS vs. Resummation
3. Conclusion

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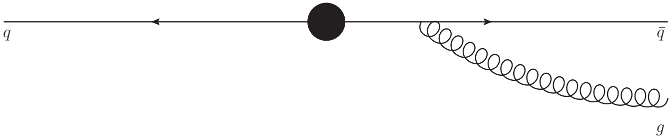
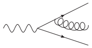
- Start from $q\bar{q}$ pair.
- Add soft and/or collinear gluons.
- Observable is zero in $q\bar{q}$ configuration.



- Consider additive observable, i.e. in presence of several soft gluons (In this talk ⇒ Thrust $1 - T$):

$$V(k_1, \ldots, k_n) = \sum_{i=1}^{n} V(k_i)$$

- Why do we need Resummation?
- Matrix element with collinear gluon:
  - Notation:

$d\Phi_3$ $\Big|$  $\Big|^2$ $\approx d\Phi_2$ $\Big|$  $\Big|^2$ $\times \underbrace{\frac{dk_{\mathrm{T}}^2}{k_{\mathrm{T}}^2}\, dz\, d\Phi\, \frac{\alpha_{\mathrm{s}}}{2\pi} P_{\mathrm{qg}}(z)}$

$\propto$ Probability for n+1 partons.

$\propto$ Probability for n partons.

Probability for emission of additional parton.

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- Why do we need Resummation?
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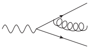
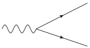
$d\Phi_3 \left| \right.$  $\left. \right|^2 \approx d\Phi_2 \left| \right.$  $\left. \right|^2 \times \underbrace{\frac{dk_{\mathrm{T}}^2}{k_{\mathrm{T}}^2}\, dz\, d\Phi}_{:=dk} \frac{\alpha_s}{2\pi} P_{qg}(z)$

$$R(t,t') := \int_{t'}^{t} dk \frac{\alpha_s}{2\pi} P_{qg}(z)$$

$$-\partial_{t'} R(t,t') = \text{Probability for Splitting at scale } t'.$$

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Total no-splitting probability:

- Probability for no splitting between two scales:

$$\Pi\left(t,t'\right) = 1 - \underbrace{\int_{t'}^{t} dk \frac{\alpha_s}{2\pi} P_{qg}(z)}_{\text{Probability of one emission.}}$$

$$- \frac{1}{2} \underbrace{\int_{t'}^{t} dk_1 \frac{\alpha_s}{2\pi} P_{qg}(z_1) \int_{t'}^{t} dk_2 \frac{\alpha_s}{2\pi} P_{qg}(z_2)}_{\text{Probability of two emissions.}} - \dots$$

$$= \exp\left(-\int_{t'}^{t} dk \frac{\alpha_s}{2\pi} P_{qg}(z)\right)$$

$$= \exp\left(-R(t,t')\right)$$

$\Rightarrow$ Sudakov factor.

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- Central to the Parton Shower:
  - Probability for splitting at scale t' starting from scale t with no intermediate splittings:

$$P(t, t') = \underbrace{-\partial_{t'} R(t, t')}_{\text{Probability for splitting at } t'} \underbrace{\exp\left(-R(t, t')\right)}_{\text{Probability for no splitting between } t \text{ and } t'}$$

- Iterate with this probability over all (hard) final state particles.

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$$\Sigma\left(v\right) = \int_{t_0} dt_1 \ \ldots$$

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$$\times\, \theta\left(v - \underbrace{V(t_1)}_{\text{Value with splitting at scale } t_1} \right) + \ldots$$

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$$\times\, \theta\left(v - \underbrace{V(t_1)}_{\substack{\text{Value with splitting} \\ \text{at scale } t_1}}\right)$$

$$+ \int_{t_0} dt_1\, dt_2\, P(Q,t_1)P(t_1,t_2)\exp(-R(t_2,t_0))$$

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$$\times\, \theta\left(v - V(t_1, t_2)\right) + \dots$$

$$= \exp\left(-R(Q, t_0)\right) \underbrace{\int_{t_0} -\partial_{t_1} R(Q, t_1) \theta\left(v - V(t_1)\right) + \dots}_{\substack{\text{Integral over all splittings}\\ \text{which lead to observable value less than } v.}}$$

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- The Parton Shower result:

$$\Sigma(v) = \exp\left[-R(Q, t_0)\right] \sum_{m=0}^{\infty} \frac{1}{m!} \left(\prod_{i=1}^{m} \int \frac{dt_i}{t_i} R'(t_i) \right) \Theta\left(v - \sum_{j=1}^{m} V(t_j) \right)$$

- NLL calculation generic in CAESAR formalism [Banfi, Salam, Zanderighi 2005]:

$$\Sigma(v) = \exp\left[-R(v)\right] \mathcal{F}(v)$$
$$=$$

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$$\begin{aligned}\Sigma\left(v\right)&=\exp\left[-R\left(v\right)\right]\mathcal{F}\left(v\right)\\&=\exp\left[-R\left(v\right)+R'\left(v\right)\ln\epsilon\right]\\&\quad\times\sum_{m=0}^{\infty}\frac{1}{m!}\left(\prod_{i=1}^{m}R'(v)\int_{\epsilon}\frac{d\zeta_i}{\zeta_i}\right)\Theta\left(1-\sum_{j=1}^{m}\zeta_j\right)\end{aligned}$$

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- Write Shower and Analytic prediction in generic form (omitting the sum over hard legs):

$$\Sigma(v) = \exp\left[-\int_v \frac{d\xi}{\xi}\partial R_{>v}(\xi) - \int_{v_{\min}}^{v} \frac{d\xi}{\xi}\partial R_{<v}(\xi)\right]$$
$$\times \sum_{m=0}^{\infty}\frac{1}{m!}\prod_{i=1}^{m}\int_{v_{\min}} \frac{d\xi_i}{\xi_i}\partial R_{<v}(\xi_i)\,\Theta\left(v - \sum_{j=1}^{m} V(\xi_i)\right)$$

$$\partial R_{\lessgtr v}(\xi) = \frac{\alpha_s^{\lessgtr v,\mathrm{SE}}\left(\mu^2_{\lessgtr}(\xi)\right)}{\pi}\int_0^{z^{\max}_{\lessgtr v,\mathrm{SE}}(\xi)} dz\,\frac{C_F}{1-z}$$
$$- \frac{\alpha_s^{\lessgtr v,\mathrm{SF}}\left(\mu^2_{\lessgtr v}(\xi)\right)}{\pi}\int_0^{z^{\max}_{\lessgtr v,\mathrm{SF}}} dz\,C_F\frac{1+z}{2}$$

	Resummation	Shower
$\mu^2_{>v}$	$\xi(1-z)^{\frac{2b}{a+b}}$	$\xi(1-z)^{\frac{2b}{a+b}}$
$z^{\max}_{>v,\mathrm{SE}}$	$1-\xi^{\frac{a+b}{2a}}$	$1-\xi^{\frac{a+b}{2a}}$
$\alpha_s^{>v,\mathrm{SE}}$	2 Loop - CMW	2 Loop - CMW
$\mu^2_{<v}$	$v^{\frac{2}{a+b}}(1-z)^{\frac{2b}{a+b}}$	$\xi(1-z)^{\frac{2b}{a+b}}$
$z^{\max}_{<v,\mathrm{SE}}$	$1-v^{\frac{1}{a}}$	$1-\xi^{\frac{a+b}{2a}}$
$z^{\max}_{>v,\mathrm{SF}}$	1	$1-\xi^{\frac{a+b}{2a}}$
$z^{\max}_{<v,\mathrm{SF}}$	0	$1-\xi^{\frac{a+b}{2a}}$
$\alpha_s^{\lesseqgtr v,\mathrm{SF}}$, $\alpha_s^{<v,\mathrm{SE}}$	1 Loop	2 Loop - CMW

Observables parametrised as (for $1-T$: $a=b=1$)

$$V(k) = \left(\frac{k_\mathrm{T}}{Q}\right)^a e^{-b\eta}$$

Shower ordered in ξ

$$k_\mathrm{T} = \xi\,(1-z)^{\frac{2b}{a+b}}$$

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- Challenges:
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  - Weights will depend on v
    $\Rightarrow$ compute cumulative distributions directly
  - Cutoff in resummation v dependant $t_0 = \epsilon v$
    $\Rightarrow$ Confirm $\epsilon \to 0$ limit in shower.

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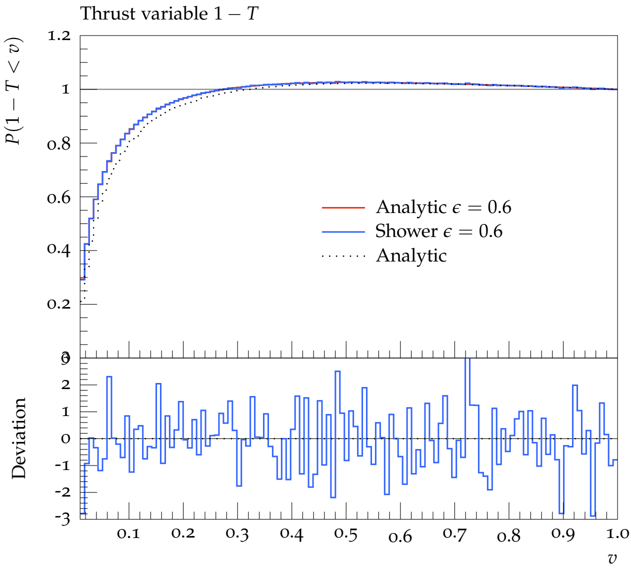

Thrust variable $1 - T$
$P(1 - T < v)$
1.2
1
0.8
0.6
0.4
0.2
0
Analytic $\epsilon = 0.6$
Shower $\epsilon = 0.6$
Analytic
Deviation
3
2
1
0
-1
-2
-3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
v

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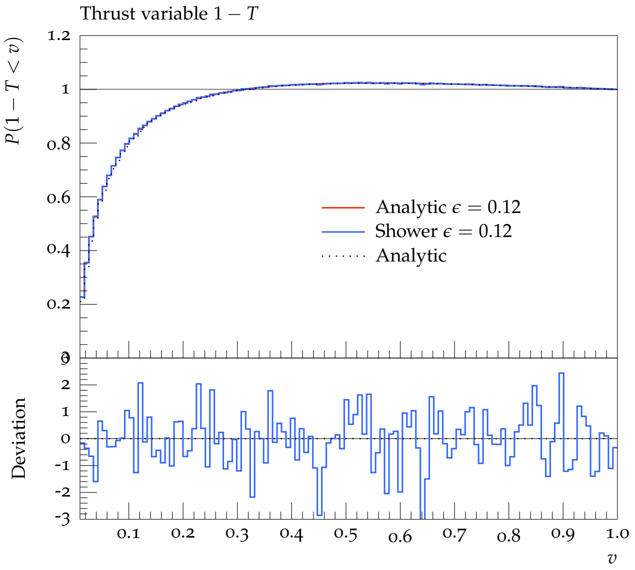

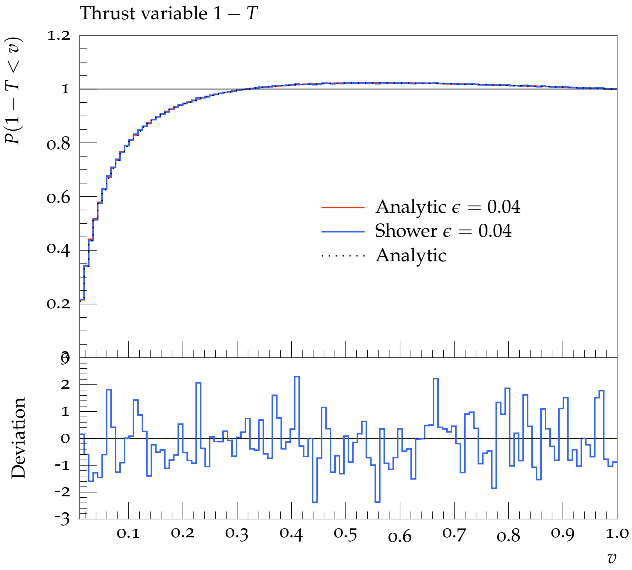
Thrust variable $1-T$
$P(1-T<v)$
Analytic $\epsilon = 0.04$
Shower $\epsilon = 0.04$
Analytic
Deviation
v
1.2
1
0.8
0.6
0.4
0.2
0
3
2
1
0
-1
-2
-3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

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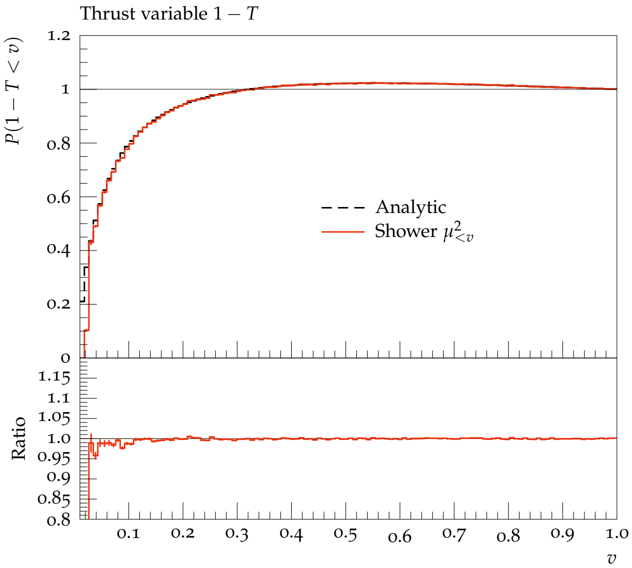
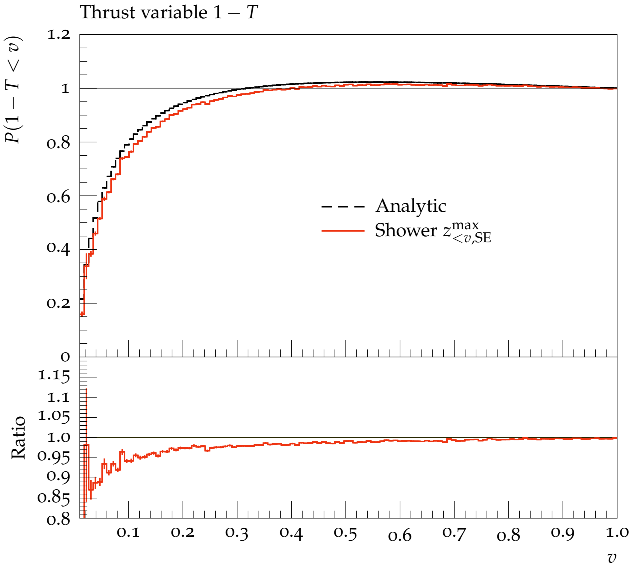
- $\mu^2_{<v}$: $v^{\frac{2}{a+b}}(1-z)^{\frac{2b}{a+b}} \rightarrow \xi(1-z)^{\frac{2b}{a+b}}$



- $z^{\max}_{<v,\mathrm{SE}}$: $1 - v^{\frac{1}{a}} \rightarrow 1 - \xi^{\frac{a+b}{2a}}$



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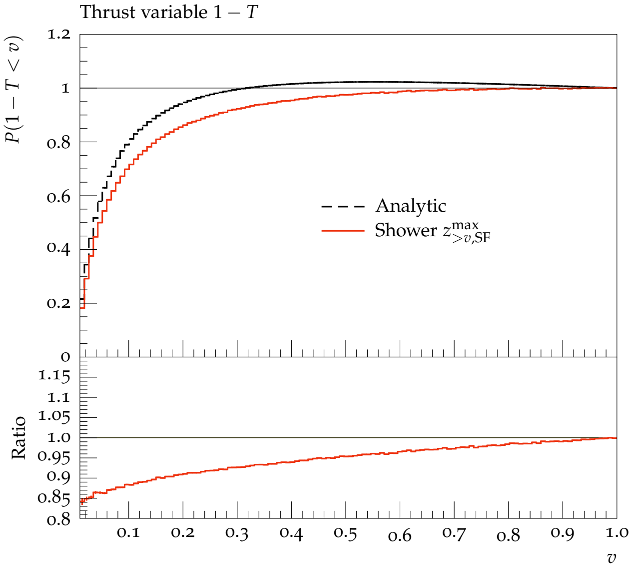
- $z^{\max}_{>v,\mathrm{SF}}$: $1 \to 1 - \xi^{\frac{a+b}{2a}}$



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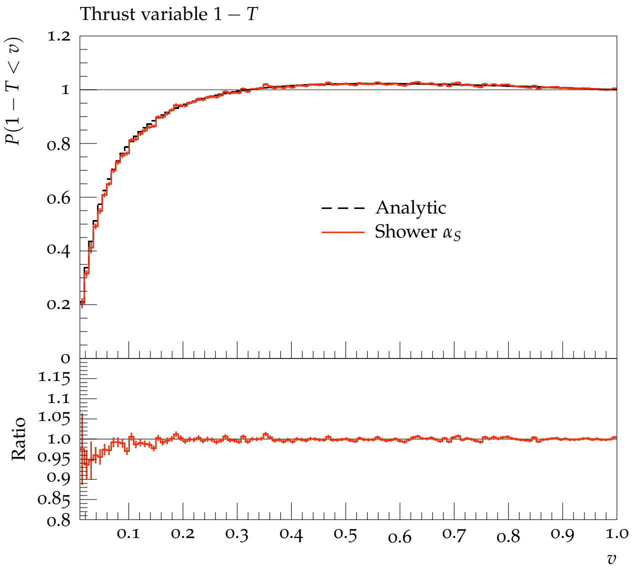
$z^{\max}_{>v,\mathrm{SE}}$	$1-\xi^{\frac{a+b}{2a}}$	$1-\xi^{\frac{a+b}{2a}}$
$\alpha_\mathrm{s}^{>v,\mathrm{SE}}$	2 Loop - CMW	2 Loop - CMW
$\mu^2_{<v}$	$v^{\frac{2}{a+b}}(1-z)^{\frac{2b}{a+b}}$	$\xi(1-z)^{\frac{2b}{a+b}}$
$z^{\max}_{<v,\mathrm{SE}}$	$1-v^{\frac{1}{a}}$	$1-\xi^{\frac{a+b}{2a}}$
$z^{\max}_{>v,\mathrm{SF}}$	1	$1-\xi^{\frac{a+b}{2a}}$
$z^{\max}_{<v,\mathrm{SF}}$	0	$1-\xi^{\frac{a+b}{2a}}$
$\alpha_\mathrm{s}^{\lessgtr v,\mathrm{SF}}$, $\alpha_\mathrm{s}^{<v,\mathrm{SE}}$	1 Loop	2 Loop - CMW

- $\alpha_s^{\lessgtr v,\mathrm{SF}}$, $\alpha_s^{<v,\mathrm{SE}}$: 1 Loop → 2 Loop - CMW



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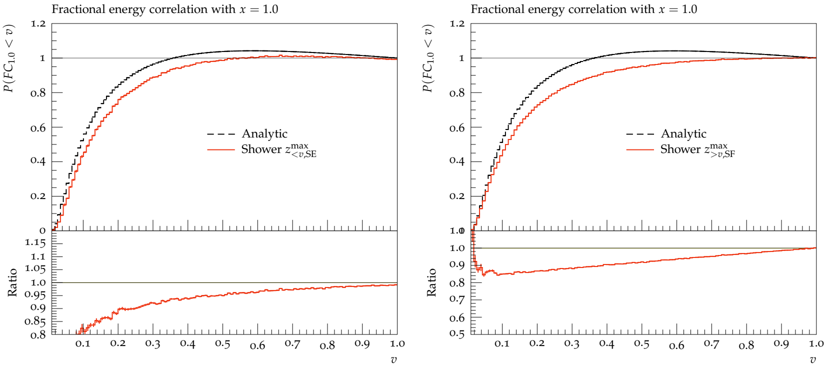
- Most contributions relatively small
- except momentum conservation constraints
- results hold for other observables



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- So far: Momentum conserving effects for single emissions.

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- Full parton shower: local momentum conservation
  $\Rightarrow$ keep all particles on-shell and preserve total momentum in every step.

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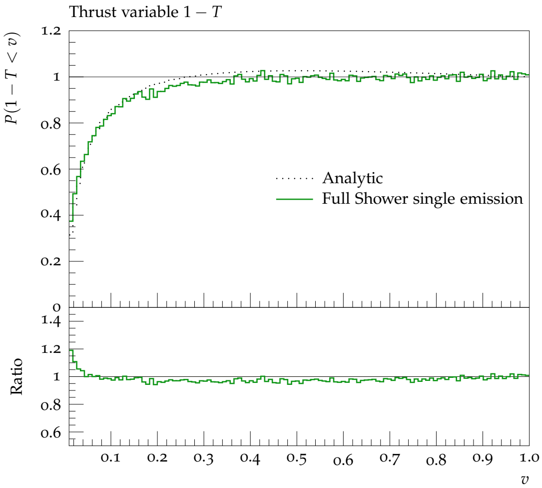
- Full parton shower: local momentum conservation
  $\Rightarrow$ keep all particles on-shell and preserve total momentum in every step.
- Still calculate Observable in Approximation corresponding to Resummation $\Rightarrow$ fix thrust axis and normalization of $1 - T$ according to hard quark pair

- First emission result $\exp(-R)$:



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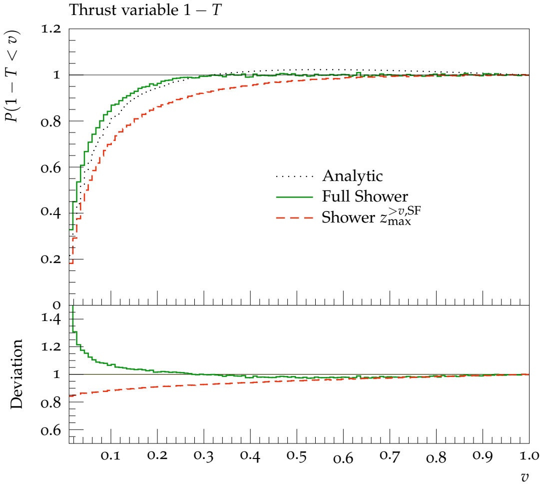
- Full shower with local momentum conservation:



Outline

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1. General Setup
2. PS vs. Resummation
3. Conclusion

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- Conclusion:
  - Shower has been constructed to emulate NLL resummation.
  - Provides framework to compare size of individual contributions of e.g. momentum conservation effects.

- Outlook:
  - Generalise to more observables, i.e. in hadron collisions.

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Backup