Parton shower developments in Pythia

(based on work with S. Höche and N. Fischer)

Loopfest 2017, ANL
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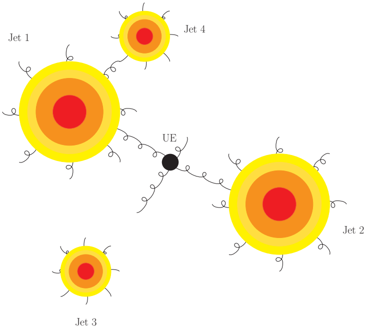
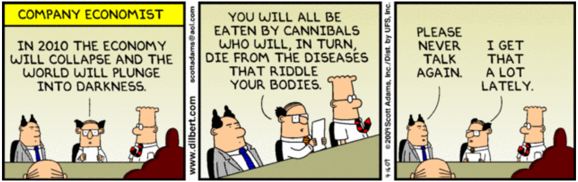
Motivation & Plan

LHC measurements rely on detailed modelling of jets.

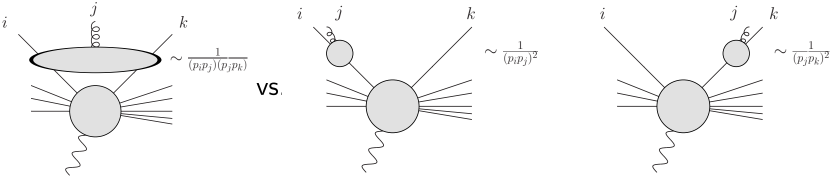


1. Multijet production cross sections must be accurate
   ⇒ Matching/merging
   "Jetty" LHC measurements are often far beyond the validity of "we correct the shower with fixed-order" ideas.
   → Rethink merging in Vincia.
2. Microscopic jet structure must be precise …if we want to use jet substructure for precision measurements.
   → Use NLO-improved shower predictions for sensible uncertainties → Dire
3. Soft inter-jet correlations must be understood …for observable-independent NLO-showers. No progress beyond Dire/Vincia. Limit to "groomed" jets here.

Dire developments



Dire parton showers



Dire includes a consistent treatment of (large-N_C, LO) soft & collinear resummation by

...treating splitting phase-space as $\textit{one dipole} \rightarrow \textit{two dipoles}$

$\Rightarrow$ Ordered in "soft transverse momentum" = inverse eikonal, scaled to largest available invariant mass in dipole.

...partial-fractioned eikonals (+hard collinear remainders) as kernels

$\Rightarrow$ Each splitting maps onto DGLAP in collinear limit

$\Rightarrow$ Sum of splittings recovers both massless *and* massive eikonals.

The shower splitting kernels may be indefinite, i.e. potentially negative (because of partial fractioning or mass effects)

Extending Dire beyond leading order

arXiv:1705.00742

cf. S. Höche's talk

For a shower implementation with NLO corrections, we need

- … analytically manageable phase space for LO-like $(1 \to 2)$ and real-emission-type $1 \to 3$ transitions,
- … algorithms that can handle negative (e.g. NLO DGLAP) kernels,
- … cross-validation.

Ideal solution: NLO-corrected PS is a fully differential NLO calculation in the Sudakov exponent:

$$\Delta(t_0,t_1) = e^{-\int_{t_1}^{t_0} \frac{dt}{t} \int d\tilde{z} \left[\left(\mathrm{I} + \underset{\substack{\uparrow \\ \text{S-event, a.k.a. endpoint}}}{\frac{1}{\varepsilon}\,\mathcal{P}} - \mathcal{I} \right)(\tilde{z}) + \int \mathrm{d}\Phi_{+1} (\underset{\substack{\uparrow \\ \text{H-event}}}{\mathrm{R}-\mathrm{S}})(\tilde{z},\Phi_{+1}) \right]}$$

Pro: On-the-fly numerical recalculation of known NLO results.

Con: Full-fledged implementation requires recalculating loops.

⇒ For now, use a simpler scheme as baseline implementation.

Extending Dire beyond leading order

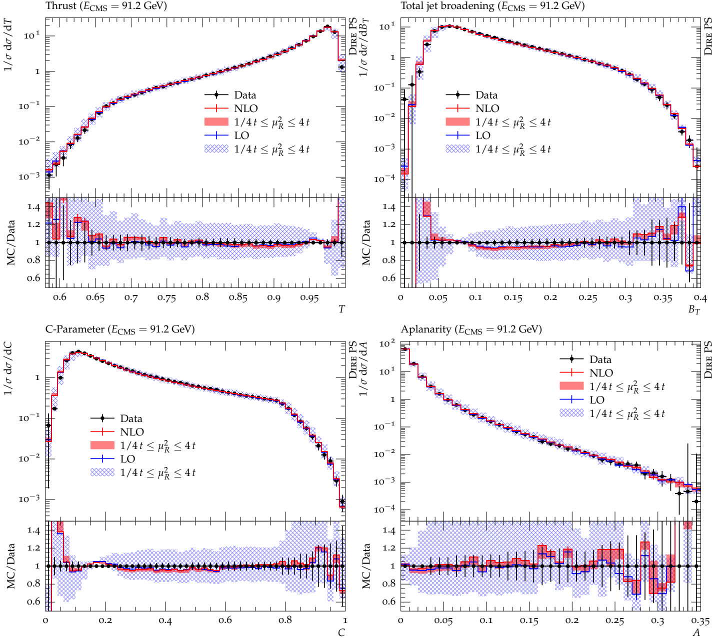
arXiv:1705.00982

Ideal solution: NLO-corrected PS is a fully differential NLO calculation in the Sudakov exponent.

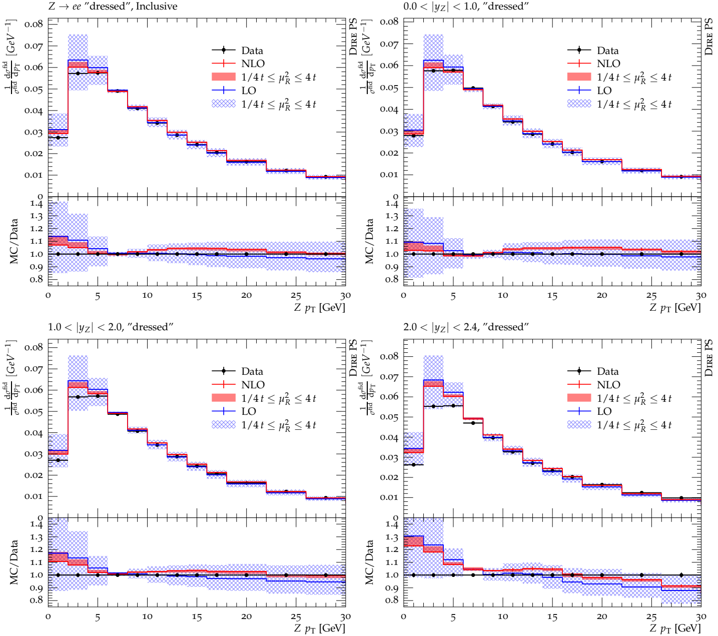
To get a “baseline scheme” useful for inclusive observables, note:

- NLO DGLAP kernels = inclusive NLO calculation, with real-emission integral performed analytically.
  $\Rightarrow$ May be used as proxy for differential NLO calculation.
- NLO DGLAP kernels contain only hard-collinear terms if terms $\propto$ 2-loop cusp are subtracted (already included as CMW-like rescaling of LO soft terms)
  $\Rightarrow$ NLO DGLAP corrections can be appplied to each partial-fractioned eikonal separately!
- Rescaling LO soft bits also allows incorporation of 3-loop cusp.

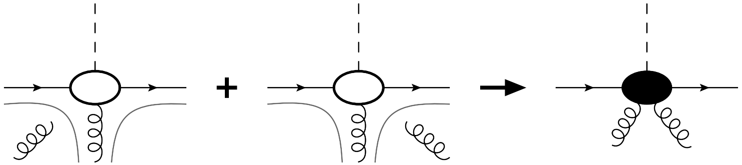
Dire predictions, LEP



Dire predictions, LHC

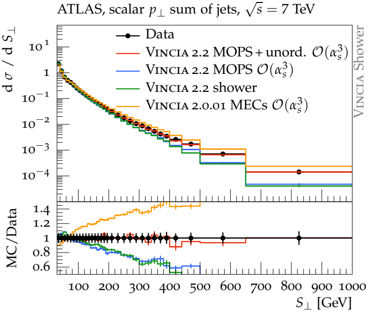


Rethinking merging in Vincia



approximation 1 **approximation 2** **full matrix element**

Motivation



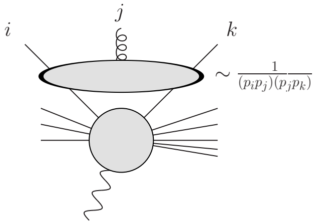
- Most tails necessary for searches/indirect measurements cannot be reached by an ordered PS. PS reasoning in the tails introduces “theory bias”. Thus:
  - Calculations maybe not accurate
  - Correlations between uncertainties maybe overestimated.

...and in the “shower phase space”:

- Is the dependence on “merging scale” necessary?
- Are well-defined jet x-sections possible w/o new parameters and w/o explicit cancellations?

Vincia parton-shower

arXiv:0707.3652, arXiv:1210.6345, LHC paper: arXiv:1605.06142



Vincia is based on

...treating splitting phase-space as $one\ dipole \to two\ dipoles$
$\Rightarrow$ Ordered in "soft transverse momentum" $=$ inverse eikonal;

...treating splitting probabilities as $one\ dipole \to two\ dipoles$
$\Rightarrow$ Each splitting directly recovers massless eikonals factors.

...contains matrix-element corrections (require unordered emissions).

Requirements for new merging schemes

Work in progress with N. Fischer

$a)$ Do not introduce arbitrary technical parameters

$b)$ Ensure that emissions are described with LO accuracy over complete phase space.

$c)$ Avoid treated events with no scale hierachies as if they contained PS-like scale separations.

1st ingredient: MECs for ordered parton showers

Work in progress with N. Fischer

$a)$ and $b)$ suggest using matrix-element corrections in the PS regions.

$\Rightarrow$
Construct Matrix-element corrections for Ordered Parton Showers (MOPS):

$$P_n^i(\Phi_{n+1}/\Phi_n) \to P_n^i(\Phi_{n+1}/\Phi_n) \otimes \mathcal{R}_n(\Phi_{n+1})$$

where

$$\mathcal{R}_3 = \frac{\mathcal{M}_3}{\sum_k P_3^k \sum_j \Theta_{t_2^j > t_3^k} \mathcal{R}_2^j P_2^j \sum_i \Theta_{t_1^i > t_2^j} \mathcal{R}_1^i P_1^i \Theta_{t^i_{\text{fac}} > t_1^i} \mathcal{M}_0^i}$$

$$= \frac{\mathcal{M}_3}{\sum_k P_3^k \sum_j \Theta_{t_2^j > t_3^k} \frac{\mathcal{M}_2^k}{\sum_j P_2^j \sum_i \Theta_{t_1^i > t_2^j} \frac{\mathcal{M}_1^j}{\sum_i P_1^i \Theta_{t^i_{\text{fac}} > t_1^i} \mathcal{M}_0^i} P_1^i \Theta_{t^i_{\text{fac}} > t_1^i} \mathcal{M}_0^i} P_2^j \sum_i \dots}$$

$\Rightarrow$ PS describes jet rates in its (ordered) phase space with LO accuracy.
Note: $\mathcal{R}_n$ relies on all $\mathcal{R}_{i<n}$ & on knowing all ordered/unordered paths!

2nd ingredient: Treatment of non-shower events

Work in progress with N. Fischer

$c)$ suggests to decouple "non-shower" configurations from shower bias. This decoupling means that largest uncertainty in "non-shower" states will comes from scale setting.

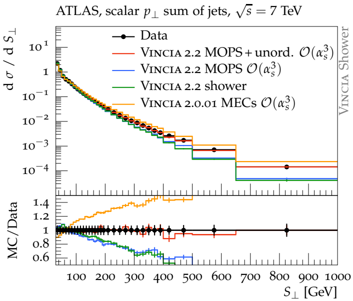
$\Rightarrow$ Require scale that captures maximal amount of dynamics.
$\Rightarrow$ We directly let the ME dictate the preferred scale values:

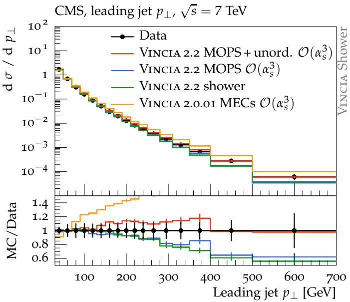
$$\alpha_s^{n+1}(t_{n+1}^{\mathsf{eff}}) = \frac{\sum_i \alpha_s(t_{n+1}^i)\, P_{n+1}^i\, \alpha_s^n(t_n^{\mathsf{eff}\,i})\, \mathcal{M}_n^i}{\sum_i P_{n+1}^i\, \mathcal{M}_n^i}$$

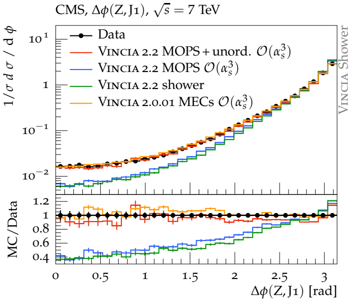
Note that $\alpha_s(t_{\mathrm{B}+n}^{\mathrm{eff}})$ relies on all $\alpha_s(t_{\mathrm{B}+i<n}^{\mathrm{eff}})$. P_{n+1}^i are antenna functions, to smoothly map onto QCD evolution.

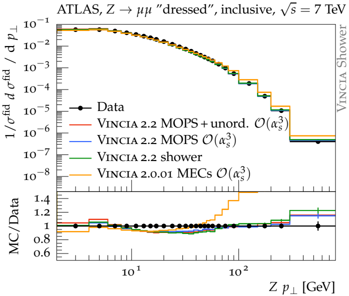
Vincia MOPS results

Work in progress with N. Fischer


ATLAS, scalar $p_\perp$ sum of jets, $\sqrt{s} = 7$ TeV


CMS, leading jet $p_\perp$, $\sqrt{s} = 7$ TeV

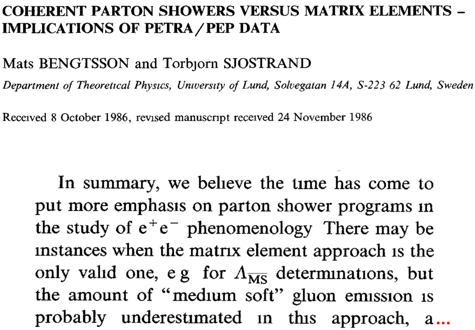

CMS, $\Delta\phi$(Z,J1), $\sqrt{s} = 7$ TeV


ATLAS, $Z \to \mu\mu$ "dressed", inclusive, $\sqrt{s} = 7$ TeV

Summary

- QCD phenomena are omnipresent in measurements. This has helped spawn many accurate & precise QCD calculations.
- Showers should try to keep up!
- The goal of Dire (in Pythia and Sherpa) and Vincia (in Pythia) is to address this.
- Dire includes triple-collinear configurations and NLO DGLAP corrections. Results look promising + more fun is anticipated.
- Vincia attempts "parameter-free" merging of fixed-order & PS

⇒ Fun time for parton shower developments!



COHERENT PARTON SHOWERS VERSUS MATRIX ELEMENTS – IMPLICATIONS OF PETRA/PEP DATA

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Received 8 October 1986, revised manuscript received 24 November 1986

In summary, we believe the time has come to put more emphasis on parton shower programs in the study of e^+e^- phenomenology There may be instances when the matrix element approach is the only valid one, e g for $\Lambda_{\overline{\mathrm{MS}}}$ determinations, but the amount of "medium soft" gluon emission is probably underestimated in this approach, a...

Thanks for your time!

Semi-analytical (a.k.a. weighted) showers

[PRD 81 (2010) 034026, EPJP 127 (2012) 26, EPJC 73 (2013) 3 2350]
[EPJC 76 (2016) 12 665, PRD 94 (2016) 7 074005, EPJC 76 (2016) 11 590]
[PRD 84 (2011) 054003]

Before anything, need a baseline for accuracy & precision.
Sensible baselines shouldn't demand major computing resources.

⇒ Use analytic knowledge of PS to perform automatic reweighting.
⇒ Significant technical improvement. Allows fast PS uncertainties!

Under the hood: Probability of one acceptance after n rejections:

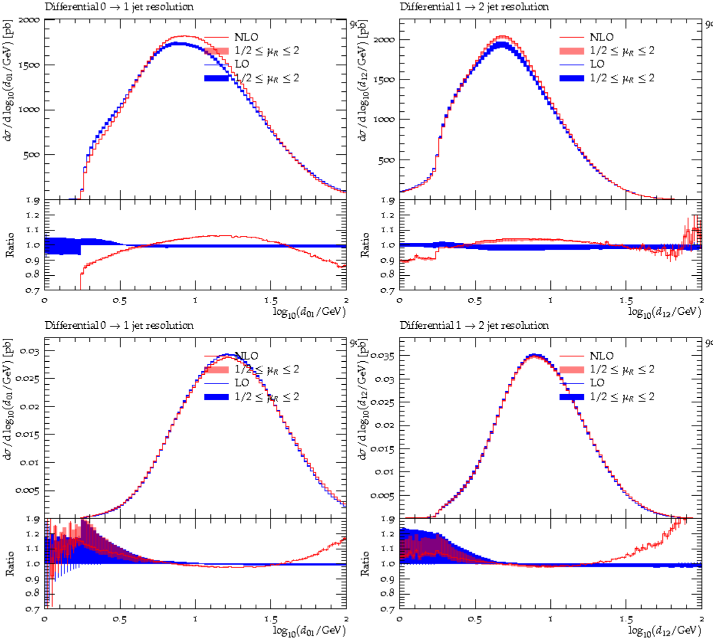
$$\frac{P(t)}{G(t)}H(t)\exp\left\{-\int_{t}^{t_1}d\bar{t}H(\bar{t})\right\}\prod_{i=1}^{n}\left[\int_{t_{i-1}}^{\mu}dt_i\frac{G(t_i)-P(t_i)}{G(t_i)}H(t_i)\exp\left\{-\int_{t_i}^{t_{i+1}}d\bar{t}H(\bar{t})\right\}\right]$$

& analytical event weight

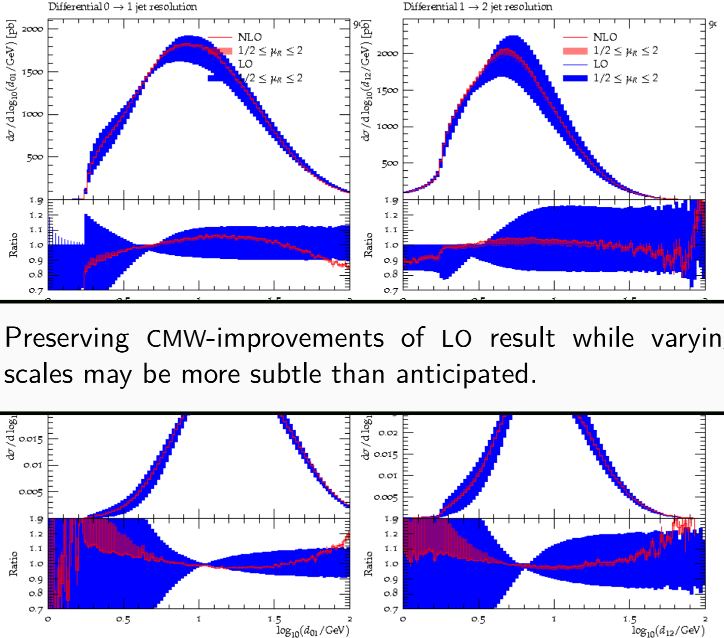
$$\frac{g(t,z)}{h(t,z)}\prod_{i=1}^{n}\left[\frac{h(t_i)-p(t_i)}{g(t_i)-p(t_i)}\frac{g(t_i)}{h(t_i)}\right]$$

where $p(t,z)/g(t,z) \geq 0$ and $h(t,z) \geq 0$ ⇒ Exponentiate "any" kernel $p(t,z)$

Dire predictions, using scale compensation terms of arXiv:1605.04692

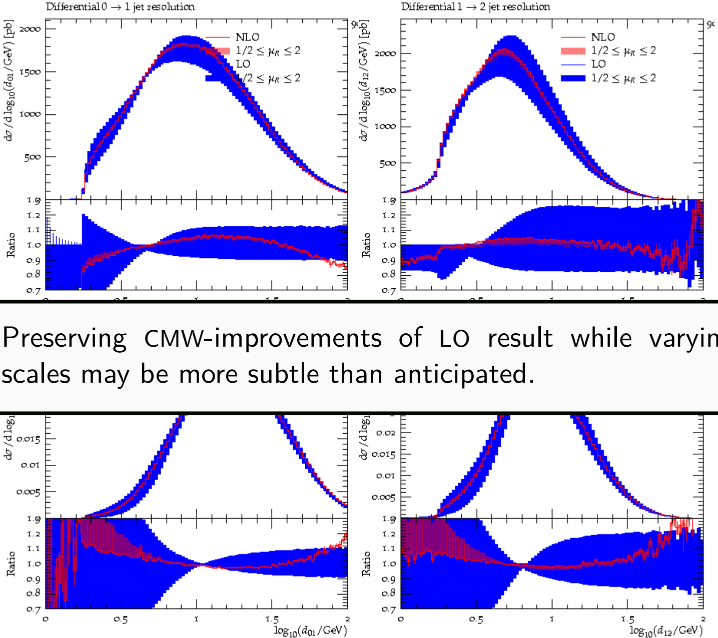


Dire predictions, using no scale compensation term at LO



Preserving CMW-improvements of LO result while varying scales may be more subtle than anticipated.

Dire predictions, using no scale compensation term at LO

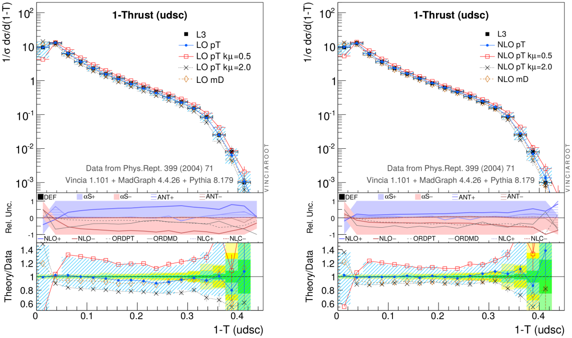


Preserving CMW-improvements of LO result while varying scales may be more subtle than anticipated.

VINCIA $\ell^+\ell^-$ collider predictions @ NLO

JHEP 1310 (2013) 127

cf. `https://indico.cern.ch/event/572313/contributions/2368391/attachments/1377684/2092759/NLO_showers.pdf`



VINCIA1 *exponentiates* the NLO calculation for $e^+e^- \to q\bar{g}q$, employing an NLO matrix-element correction. Improved handling of double-real $(2 \to 4)$ contributions is presented in arXiv:1611.00013.

+ offers a detailed parton shower uncertainty budget!

→ Precise predictions for lepton collider observables.