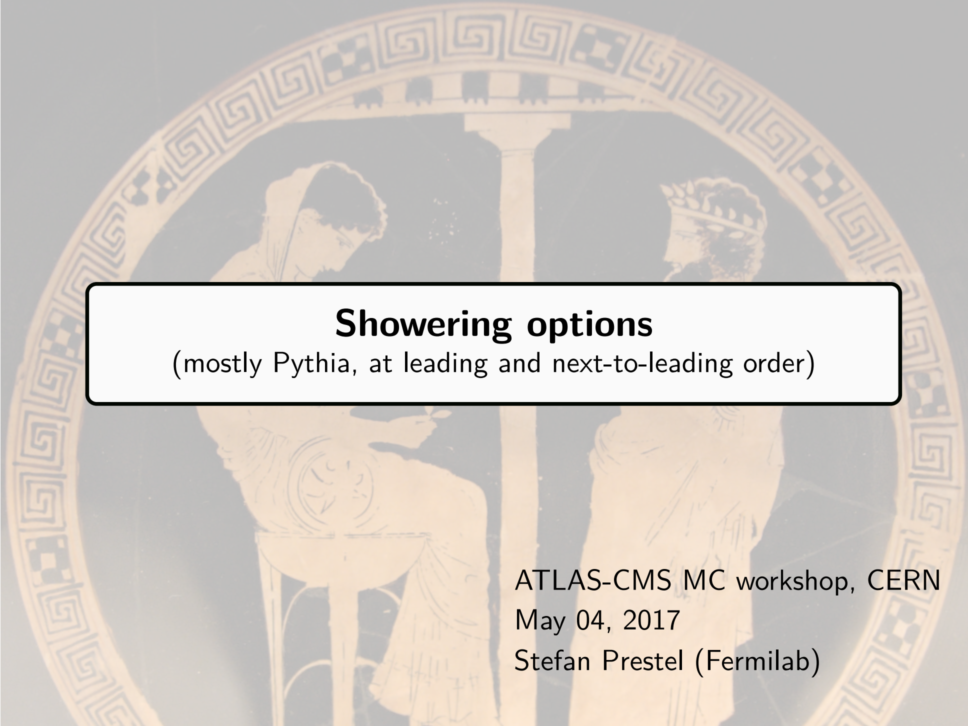


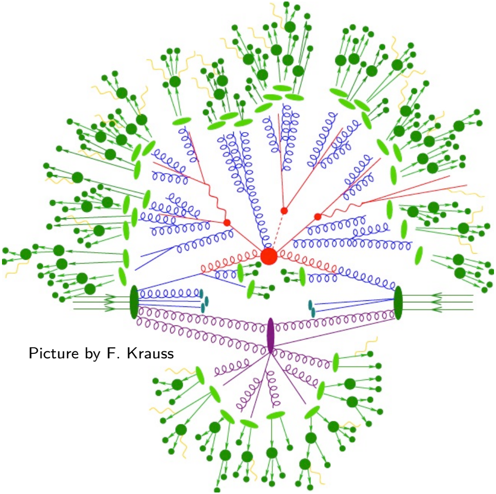
Showering options

(mostly Pythia, at leading and next-to-leading order)

ATLAS-CMS MC workshop, CERN

May 04, 2017

Stefan Prestel (Fermilab)



Picture by F. Krauss

Measurements consists of sum over exclusive states.

To make most of LHC data, so should precision theory calculations of

Hard interaction

- $\oplus$ Radiative cascade ($\hookrightarrow$ now)
- $\oplus$ Secondary interactions
- $\oplus$ Hadron formation
- $\oplus$ Hadron decay/scattering...

QCD calculations rely on factorization, *i.e. "physics is modular"!*
$\rightarrow$ Can beat down theory uncertainties on different fronts.

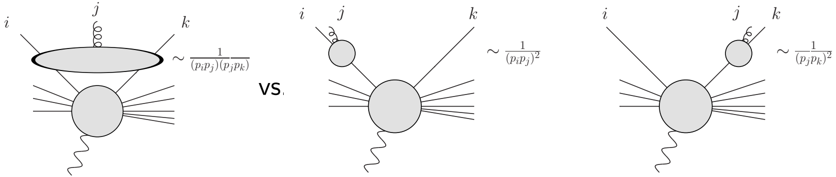
Assumption: Matching/merging correctly models the production rates & correlations between hard, well-separated jet "boxes".

If data is sensitive to the energy profile of the "boxes", or their energy exchange ("heat bath"), the calc^n may be accurate, but will be imprecise (large uncertainties).

Must beat down uncertainties with improved parton shower!
Critical for e.g. jet substructure analyses.

Note: PYTHIA options for global vs. local recoil, $g \rightarrow q\bar{q}$ will be omitted here (cf. $\rightarrow$Timelike showers)

Parton showers implement QCD at microscopic level



The construction of a parton shower is not arbitrary. PS must provide a good representation of all-order QCD

…in the soft limit

…in the collinear limit

…and obeys flavour- and momentum-conservation

If that means that we have to work hard, then work hard we shall.

Aside: For improvements (matching/merging…), PS needs to be easily & systematically amendable/extendable.

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]

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:

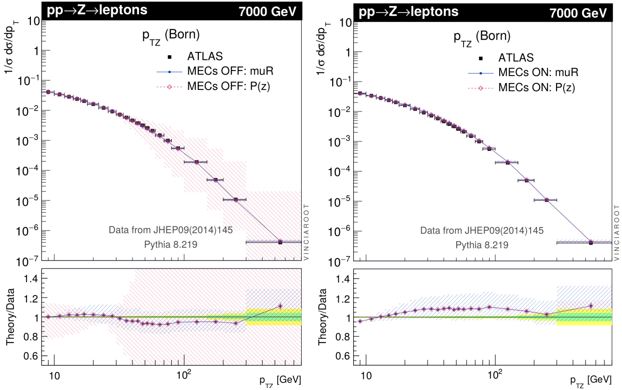
$$\frac{P(t)}{G(t)}H(t)\exp\left\{-\int_t^{t_1}d\bar{t}H(\bar{t})\right\}\prod_{i=1}^{n}\left[\int_{t_{i-1}}^{\mu}dt_i\frac{G(t_i)-P(t_i)}{G(t_i)}H(t_i)\exp\left\{-\int_{t_i}^{t_{i+1}}d\bar{t}H(\bar{t})\right\}\right]$$

& 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 $h(t,z)\geq 0 \Rightarrow$ Exponentiate "any" kernel $p(t,z)$

Automatic variations as baseline in PYTHIA!

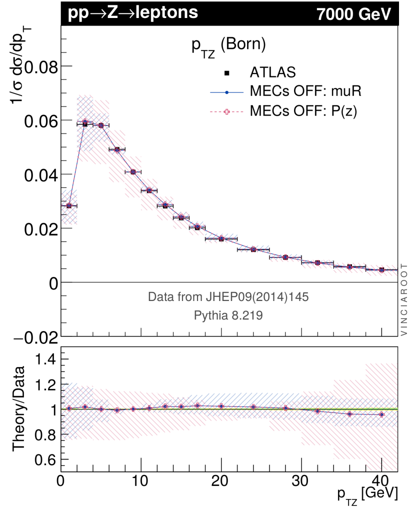


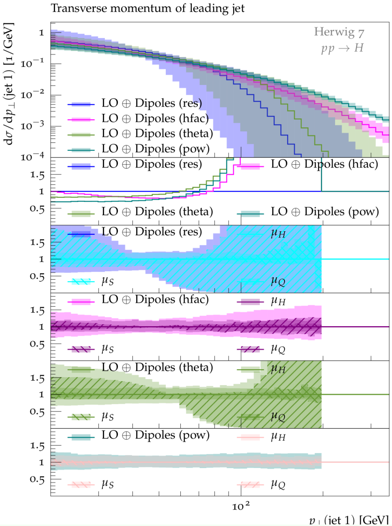
PYTHIA allows `UncertaintyBands:doVariations = on` for automatic uncertainties (e.g. scale variations with `UncertaintyBands:List = {alphaShi fsr:muRfac=0.5 isr:muRfac=0.5, alphaSlo fsr:muRfac=2.0 isr:muRfac=2.0}`, or kernel variations by `UncertaintyBands:List = {hardHi fsr:cNS=2.0 isr:cNS=2.0, hardLo fsr:cNS=-2.0 isr:cNS=-2.0}`)

VINCIA includes `vincia24.cc` as illustration (slightly different syntax)
DIRE includes `dire03.cc` as illustration (syntax slightly different)

How large are shower uncertainties?

arXiv:1605.01338, arXiv:1605.08352, arXiv:1606.08753





Large! (Big surprise...). Uncertainty in hard region removed by M&M. Uncertainties at *low* $p_\perp$ fixed by precise parton shower resummation.

Improved showers means new showers...

VINCIA[a]
(vincia.hepforge.org)
Latest version: 2.001

◇ Starting point: Soft limit from antenna factorization.
◇ Evolution variable $\propto$ 1/eikonal
◇ *Exponentiates* NLO corrections to $e^+e^- \to q\bar{q}g$
◇ Unordered emissions and iterated LO matrix element corrections.

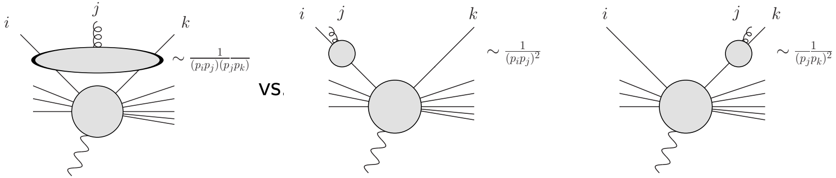
DIRE[b] (also in SHERPA)
(direforpythia.hepforge.org)
Latest version: 2.000

◇ Starting point: Soft/collinear limit from dipole factorization.
◇ Evolution variable $\propto$ 1/eikonal
◇ Includes NLO corrections to space- and timelike kernels (i.e. *higher-order resummation*)

a [PRD 78 (2008) 014026, PLB 718:1345 (2013), EPJC 76 (2016) 11, 589]

b [EPJC 75 (2015) 9, 461, arXiv:1705.00742, arXiv:1705.00982]

EPJC 75 (2015) 9, 461



Disentangle soft limit and collinear limits

Reproduce dominant two-particle correlation in soft limit

Manageable analytic structure of phase space integration means improvable beyond LO

- ◇ Two independent implementations, carefully cross-validated
- ◇ Available with NLO (collinear) evolution

Collinear showers @ NLO crash course:

- NLO corrections come as virtuals and reals
- Combined, they integrate to well-known NLO DGLAP kernels
- But virtuals & reals "live" in different phase space dimensions!
  → Not suitable for event generation
  → Introduce *completely* local subtractions
  → Correct observable dependence restored by showering

Sounds familiar? It should. It's **MC@NLO, *exponentiated***:

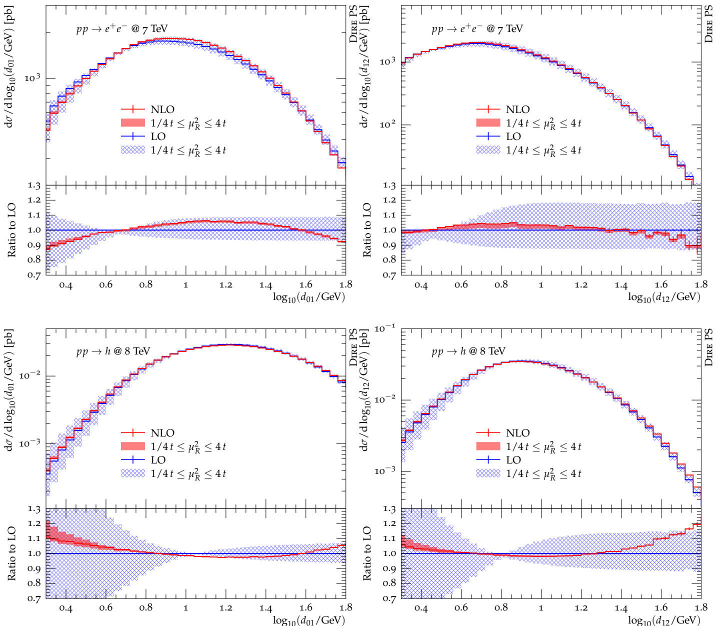
$$\Delta(t_0,t_1) = e^{-\int_{t_1}^{t_0} \frac{dt}{t} \int d\tilde{z} \left[\left(\mathrm{I} + \frac{1}{\varepsilon}\mathcal{P} - \mathcal{I} \right)(\tilde{z}) + \int \mathrm{d}\Phi_{+1} (\mathrm{R}-\mathrm{S})(\tilde{z},\Phi_{+1}) \right]}$$

↑ S-event, a.k.a. endpoint ↑ H-event

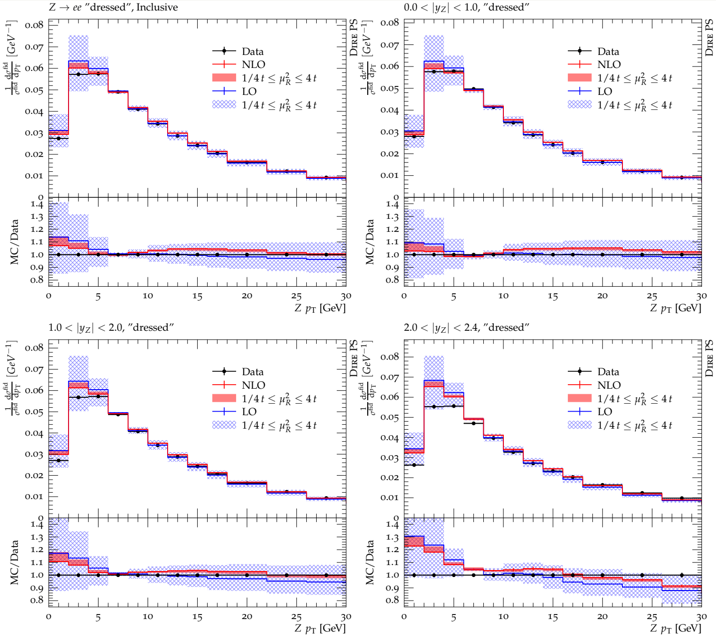
For now, this « $e^{\text{MC@NLO}}$ » is only applied to $q \to \bar{q}$ and $q \to q'$.

arXiv:1705.00982 adds "inclusive" NLO kernels ⇒ Inclusive NLO DGLAP PS

DIRE LHC predictions, NLO evolution



DIRE LHC predictions, NLO evolution



PYTHIA:

Timelike evolution

LO: `DireTimes:kernelOrder = 1`

NLO: `DireTimes:kernelOrder = 3`

Spacelike evolution

LO: `DireSpace:kernelOrder = 1`

NLO: `DireSpace:kernelOrder = 3`

...and use `dire03.cc` to print HepMC events for μ_r-uncertainties.

SHERPA:

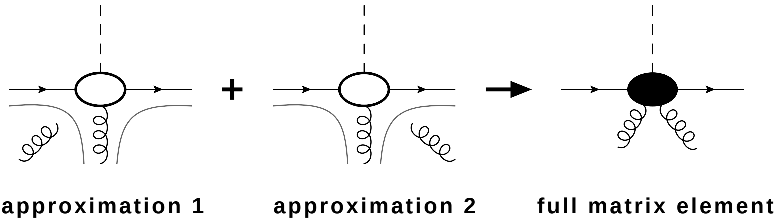
LO: `DIRE_KERNEL_ORDER = 1`

NLO: `DIRE_KERNEL_ORDER = 7`

Note: For hard well-separated jets, DIRE needs matching / merging

EPJC 76 (2016) 11, 589

Illustration by N. Fischer



VINCIA corrects radiation pattern splitting-by-splitting to full LO, for

$e^+e^- \rightarrow$ 2-6 jets

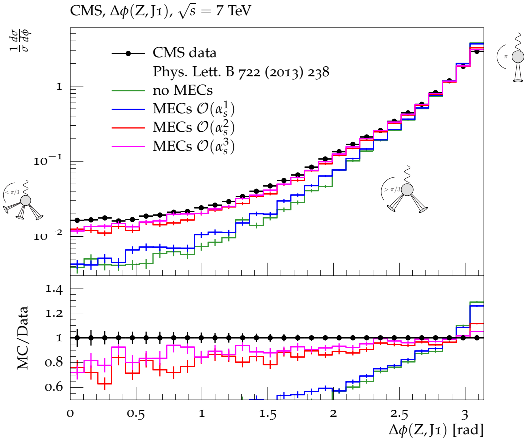
$pp \rightarrow$ H/W/Z + 0-3 jets

$pp \rightarrow$ 2-4 jets

→ Shower does multi-jet merging for you. No LHEFs needed.

EPJC 76 (2016) 11, 589

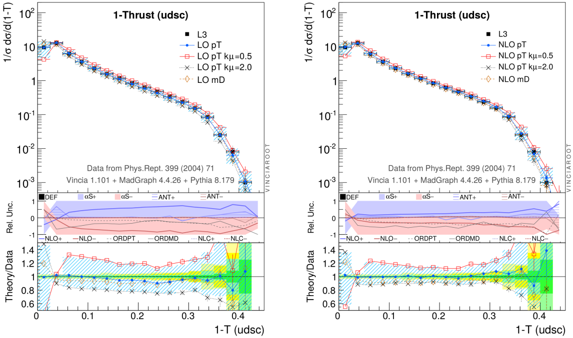
Simultaneously integrates + resums fixed-order multi-jet MEs.



PS can fill all of phase-space, integrate multi-jet MEs, and describe hard jets – if you let it (e.g. use `vincia24.cc`)

VINCIA LEP predictions @ NLO

JHEP 1310 (2013) 127



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!

$\to$ Precise predictions for LEP observables.

- QCD phenomena are omnipresent in measurements. Matched & merged predictions are the norm, and have helped decrease the theory uncertainty.
- One uncertainty we usually suppress is the PS uncertainty.
- Reducing this uncertainty requires new showers
  $\rightarrow$ Goal of VINCIA, DIRE, DEDUCTOR
- VINCIA improves regions of hard, well-separated jets and exponentiates NLO corrections to $e^+e^- \rightarrow qg\bar{q}$
- DIRE deconstructs collinear NLO evolution into « $e^{\text{MC@NLO}}$ » for LEP, HERA and LHC
- More things "NLO shower" (color, spin...) still to do!

Good night!