MC generator overview

PSR 2021

May 25, 2021

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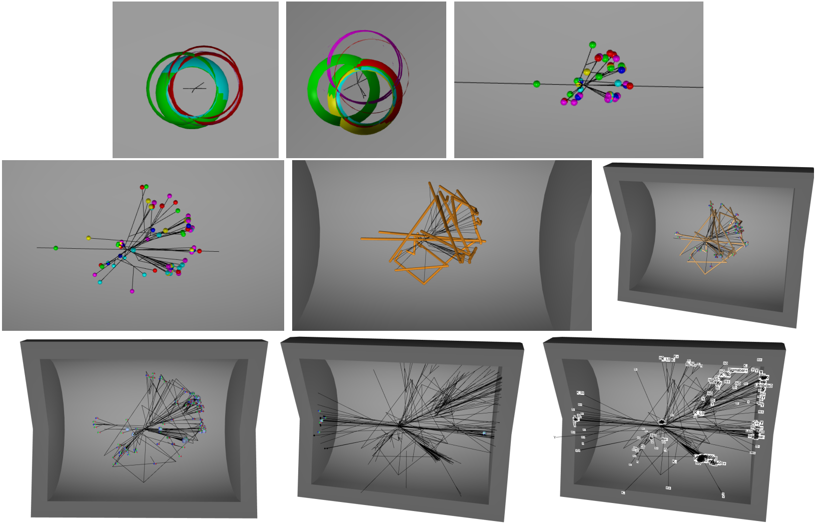
Event generators

Disclaimer: Assuming "MC event generators" = General-Purpose Event Generators.
Generators will handle many different length/energy scales:



...here, focus on SM modeling at hadron colliders

Charge & Overview

charge:

"...could well be light on [PS and their accuracies] and [give] you some room for other aspects and developments"

NB: all of 26th reserved for PS...and even that does not cover all recent developments

disclaimer:

This talk will not primarily be about all the great achievements, but highlight some aspects we're not yet understanding:

- Perturbative MPI, recombination and rescattering, spin & color in hadronization

Expectations on an event generator

what experimenters need

- better computing, faster and less fluctuating codes
- many well-separated jets
- reliable MC uncertainties

unchanged since start of LHC...

what theorists need

- consistent treatment of higher orders
- operator definitions of MCs
- A way to put higher-order calculations to use

unchanged since 80s...

what MC developers provide:

Unabridged / detailed / comprehensive / microscopic / ... final states

a lot has changed in which states – and at which accuracy – are provided

High-multiplicity calculations for the LHC

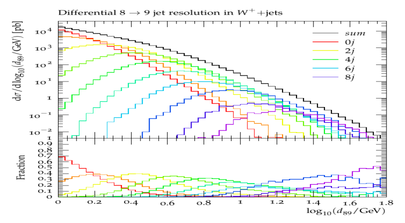
The LHC is a multi-jet machine: O(10) well-separated jets are common.
$\Rightarrow$ Accurate MC predictions combine several fixed-order calc^s with each other and showering (+wider MC environment) through *merging*

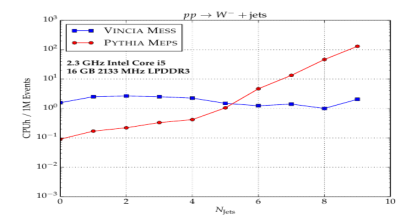
Multiplicity records are set by LO merged calculations: $W, Z+ \leq 9$ jets available.

High-multiplicity MEs require massively parallel (phase-space) integration (e.g. on supercomputers `arXiv:1905.05120`)

Post-processing for merging typically much faster - but can still be *severe bottleneck*!

News: Maximally bijective (sector) shower algorithms (`arXiv:2003.00702`) may remove the bottleneck (`arXiv:2008.09468`)

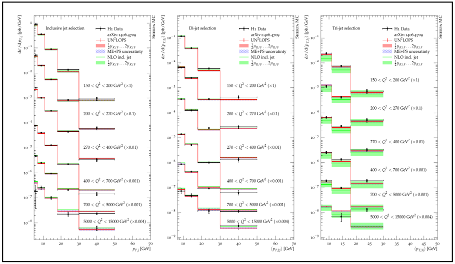




Frontier of matching: NNLO+PS

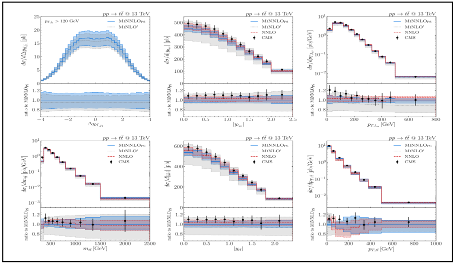
Players for matched fixed-order calc^s are: Sherpa, aMC_MG5+Pythia/Herwig, Powheg-Box+Pythia/Herwig, Geneva+Pythia, Matchbox-Herwig.

NNLO+PS achieved for $pp \to$ singlet(s): Precision for fiducial "standard candles". Impressive exceptions beyond singlet production:



DIS NNLO+PS (`arXiv:1809.04192`):

Has light jets in final state, and complex relation between "natural scale" and available phase space. Uses UN^{2}LOPS scheme in Sherpa general-purpose generator.



$t\bar{t}$ NNLO+PS (`arXiv:2012.14267`):

First pp collider process with colored final state @ NNLO+PS. Employs recent MINNLO$_{PS}$ scheme of Powheg-Box

Showers beyond LL

...have received much attention lately. Three main schools of thought:

NLO showers

- Desire to match singularities of *event classes*
- Improve by new kernels
- Dates back to 80s; proponents: NLLjet[1], KRKMC[2], Vincia[3], Dire[4]
- Some work on ISR

[1] e.g. CPC 64 (1991) 67-97, Z.Phys.C 54 (1992) 397-410

[2] e.g. arXiv:1103.5015, arXiv:1606.01238

[3] arXiv:1611.00013

[4] arXiv:1705.00982, arXiv:1705.00742, arXiv:1805.03757

NLL showers

- Desire to match logarithms of (large) *observable classes*
- Improve by assessing/correcting LL choices
- Extending historical discussion angular vs. pT ordering; proponents: PanScales[a], Cvolver/Herwig[b]

[a] arXiv:2002.11114, arXiv:2011.10054, arXiv:2103.16526

[b] arXiv:1904.11866, arXiv:2003.06400, arXiv:2011.15087

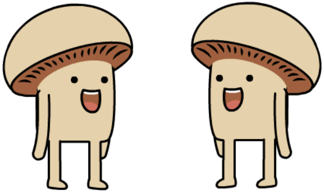
Amplitude-level PS

- Desire to match singularities for *diagram classes*
- Closely related to multi-differential factorization proofs
- Includes Glauber phases; proponents: Deductor[α], Cvolver[β]

[α] e.g. arXiv:1605.05845, arXiv:1908.11420, arXiv:1905.07176

[β] e.g. arXiv:1905.08686, arXiv:2007.09648

...so lots of progress!



...but there's also a to-do list...

What is a shower anyway?

Fox & Wolfram, "A model for parton showers in QCD", 1979:

> producing scintillation light). The longitudinal development of QED showers is conventionally treated by moments or master equations [5] just as for their QCD counterparts; the transverse profile of a QED shower is, however, dominated by multiple Coulomb scattering, which has no QCD analogue**.

> ** After many progressively more contorted analytical attacks, investigations of QED showers finally turned to Monte Carlo techniques [6] which continue to prove fruitful [7]. Perhaps similar development may be traced in QCD showers.

Parton showers are tools to model jet evolution in MCEGs

Parton showers are tools to sample infrared configurations

e.g. as helper for non-global log resummation

Parton showers are (a class of) competition algorithms

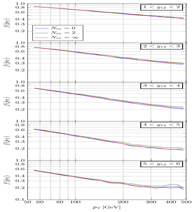
e.g. for phase-space generation

e.g. for generation of multiparton scattering

Parton showers and jet evolution

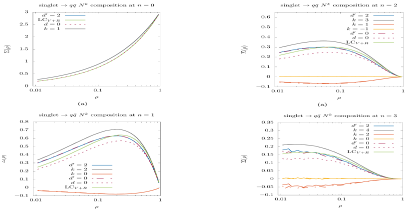
One of the main novelties in recent years: Implementations of virtual evolution, *i.e.* resummation not covered by sampling real emissions alone.

Density operators



- Implementation in Deductor: Much work on ISR effects and summation of threshold logarithms.
- `arXiv:1908.11420` exponentiated $i\pi$-corrections. Surprisingly small impact on gap fractions due to cancellations.

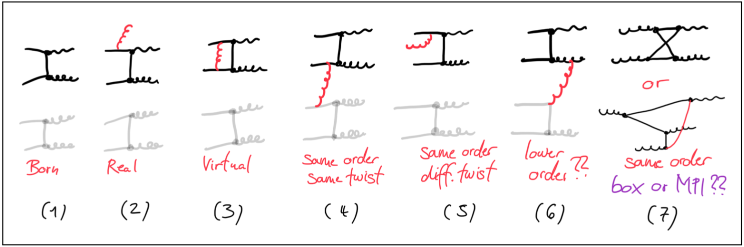
Amplitude level PS



- Implementation in CVolver: Use of color flow basis allows for systematic approximation of exponentiated color matrices (as series of color "swaps")
- First numerical results for singlet $\to gg, q\bar{q}$ (`arXiv:2007.09648`)

Parton showers to sample IR configurations

beyond the "leading-order comfort zone", several effects of similar order:

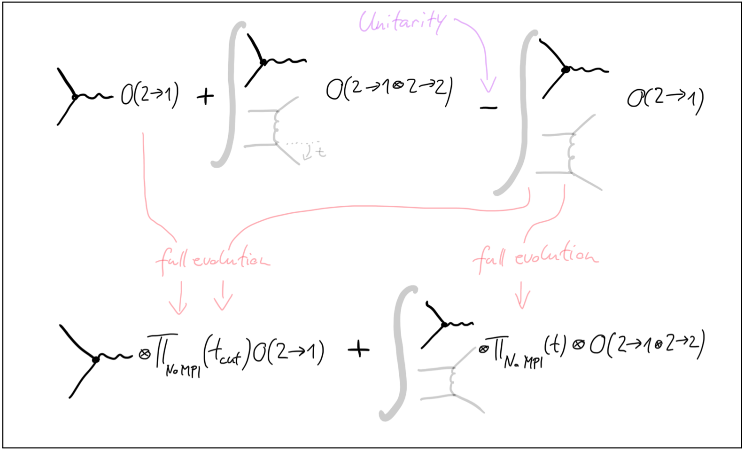


- new states may appear in the definitions of the S-matrix, e.g. `arXiv:1810.10022`, `arXiv:1906.03271` discuss (5)
- obvious that such effects are subleading to virtual exchanges?
- gluon absorption / saturation effects argued to be small *for total cross sections* at high energies. Still true differentially?

Main competition to jet evolution at $\mathcal{O}(\alpha_s^2)$ is multi-parton scattering

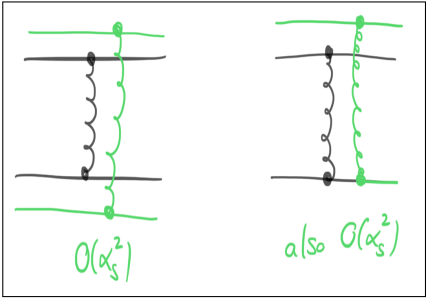
Parton showers as algorithms: Double/multi-parton scattering

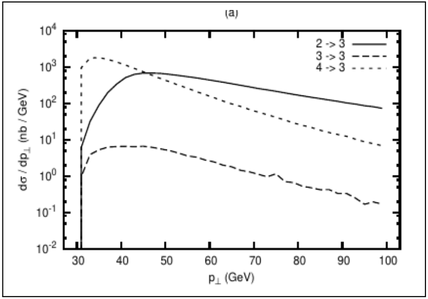
Assuming unitarity of the scattering, multiparton interactions have an effect similar to showers



...and *can* be calculated with the same algorithm.

Parton rescattering

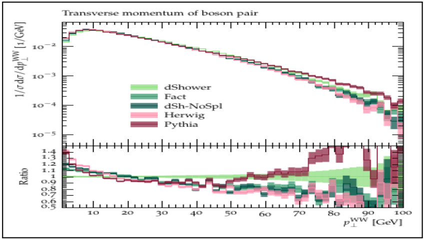




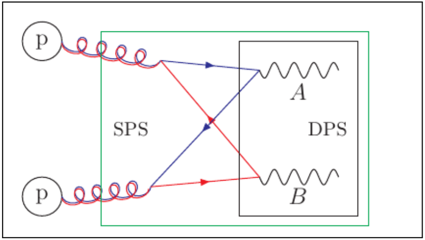
- Partonic rescattering enters at the same order as double-parton scattering – or loop corrections.
- Realistic model presented in `arXiv:0911.1909` and studied in a tuning context
  Conclusion: No improved data description expected before (serious) LHC data
  Is that still the case today? Is the phenomenon necessary at accuracy desired?

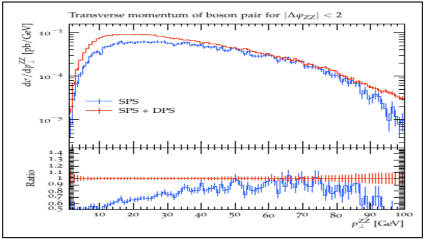
Double parton scattering & merging DPS and SPS

arXiv:1510.08696 established the factorization and evolution of double DY rigorously ⇒ new dSHOWER code, shows DPS overlap with boxes



- arXiv:1906.04669: evolution of DPS matters – and can be very different.
- arXiv:2008.01442: SPS+DPS requires overlap subtraction à la MC@NLO DPS can have clear impact even on simple observables.
- Should DPS be a part of (N)NLO+PS?

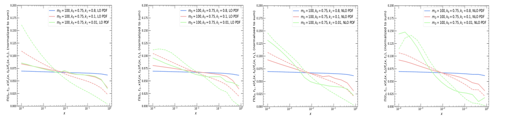




More fun with ISR: PDF evolution

Initial-state shower rely on backward evolution…which assumes the complete z-integration can be sampled by real emissions

$\Rightarrow$ *Not necessarily the case in a typical shower.* *Should we worry?*

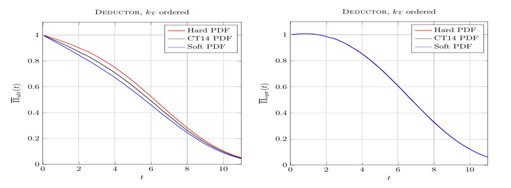


(a) d-quark evolution (b) s-quark evolution (a) d-quark evolution (b) s-quark evolution

LH proc^s (`arXiv:2003.01700`) tested x-independence of

$$\frac{f(x,\mu^2)}{f(x,t)}\Pi(t,\mu^2;x)$$

$\Rightarrow$ consistency of ISR depends on evolution length and on PDF set.



Deductor (`arXiv:2002.0412`): purely virtual graphs are necessary to *exactly* recover PDF evolution in ISR

The (other) main aspect of non-perturbative modelling is *hadronization*

Subleading color & hadronization

Color connections after showers set the starting point of hadronization.

Hadronization assumes $N_c \to \infty$ picture, yet statically reconnects color to minimize "potential energy" (cf. `arXiv:1505.01681` for color rec. beyond $\mathbf{3}$ and $\mathbf{8}$ representations).

Dynamical non-perturbative color-state transformations are "swing", "rope formation" or "shoving" (see e.g. `arXiv:2010.07595`)

What does that mean for $N_c = 3$ showers? Will subleading-N_c survive $N_c \to \infty$ hadronization?

`arXiv:1808.06770`: Virtual soft-gluon evolution Ansatz for non-perturbative (NP) color *evolution*

$$\mathbf{U}\left(\{p\}, \mu^2, \{M_{ij}^2\}\right) = \exp\left(\sum_{i \neq j} \mathbf{T}_i \cdot \mathbf{T}_j \frac{\alpha_s}{2\pi}\left(\frac{1}{2}\ln^2\frac{M_{ij}^2}{\mu^2} - i\pi \ln\frac{M_{ij}^2}{\mu^2}\right)\right)$$

$$\mathcal{A}_{\tau\to\sigma} = \langle\sigma|\mathbf{U}\left(\{p\}, \mu^2, \{M_{ij}^2\}\right)|\tau\rangle \qquad P_{\tau\to\sigma} = \frac{|\mathcal{A}_{\tau\to\sigma}|^2}{\sum_\rho |\mathcal{A}_{\tau\to\rho}|^2}$$

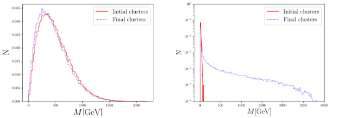


Figure 2: Invariant mass distribution of 5 clusters before and after mesonic colour reconnection for RAMBO(left) and UA5(right) kinematics.

$\to$ like color reconnection, virtual (fixed-color) evolution quite important
$\to$ Is fixed-color "real NP evolution" important to retain shower improvements?

(No) spin in hadronization

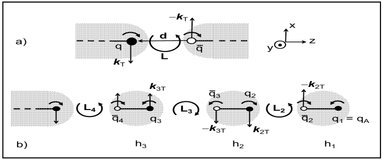
Parton-to-hadron conversion blind to spin of partons and hadrons.

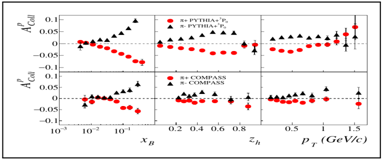
What does that mean for spin-dependent showers?

Will spin effects be invalidated by spin-independent hadronization?

Is a $c\bar{c}$ pair in an S-state allowed to convert to a J/Ψ in arbitrary P-state?

Very recently, new MCEG implementation of ${}^3P_0$ string hadronization (`arXiv:1802.00962`, `arXiv:1909.02280`, `arXiv:2105.09730`)





Needs tracking the spin density matrix of partons; so far only states w/o gluon "kinks".

Significant work to be done to be applicable to high-energy final states?

IR safety of hadronization beyond leading order

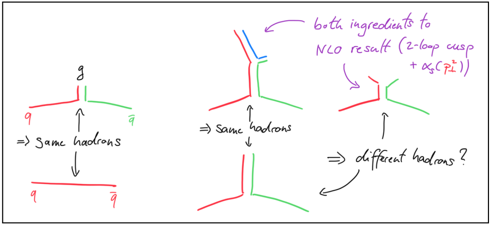
Hadronization models implement infrared safety "by hand"[1]

Example: Soft/coll. $N_c \to \infty$ gluons in $\bar{q}gq$ string get "reabsorbed" to yield a $\bar{q}q$ string.

Questions beyond lowest order:

IR safety for subleading-color gluon systems?

Even more basic: IR safety of soft/coll. quark pairs?
If treated differently from $\bar{q}ggq$ strings, then hadronization will "rip apart" the 2-loop cusp and $\alpha_s(p_\perp^2)$



What does that mean for NLO showers?

[1] I cannot speak to cluster hadronization models, since no expertise.

(personal, biased) summary

- Massive progress on showers recently

  ...NLL has arrived – but reliable w/o improved (N)NLO matching / hard function?

- PS only one part of second-order effects @ LHC

  ...DPS and rescattering enter

  Should we also worry about absorption & forward scattering?

- hadronization of color/spin/higher-order improvements is the elephant in the room

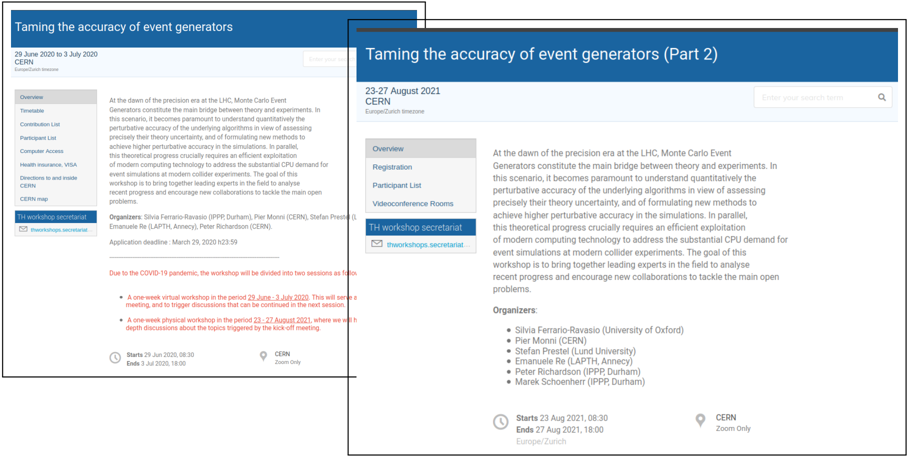
  ...don't want hadronization to invalidate the progress,

  i.e. work on improved and assessing hadronization is crucial.

Conclusion: Lots of exciting work last few years.
Lots of fun to be had still, especially at LHC and EIC.

The registration for **Taming the Accuracy of Event Generators, part II** (click here for https://indico.cern.ch/event/999271/) is now open!

The goal is [..] to analyse recent progress [in MCEGs] and encourage new collaborations to tackle the main open problems.

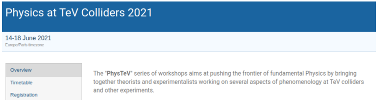


We'll soon contact all participants of **part I**, and also encourage new faces!

PhysTeV 2021

- The 2021 edition of the PhysTeV workshop (aka “Les Houches”) was canceled.
- Some of the subjects related to SM phenomenology at the LHC, traditionally discussed in Les Houches, <u>will be covered, in a reduced format, through a few virtual meetings</u>.

☞ 14 - 17/18 June



- <u>You are welcome to register and join the discussions!</u>

☞ `https://indico.in2p3.fr/event/24331`

- <u>“Montecarlo session”</u>: most likely on Wednesday 16 June
- MC session: discuss experimental bottlenecks, future needs, and current theoretical developments in Monte Carlo event generators.
- If you are interested (even in just one or two sessions), please register to the event.