assignment:

Progress in MC event generators

(with focus on NLL showers)

SM@LHC

April 26, 2021

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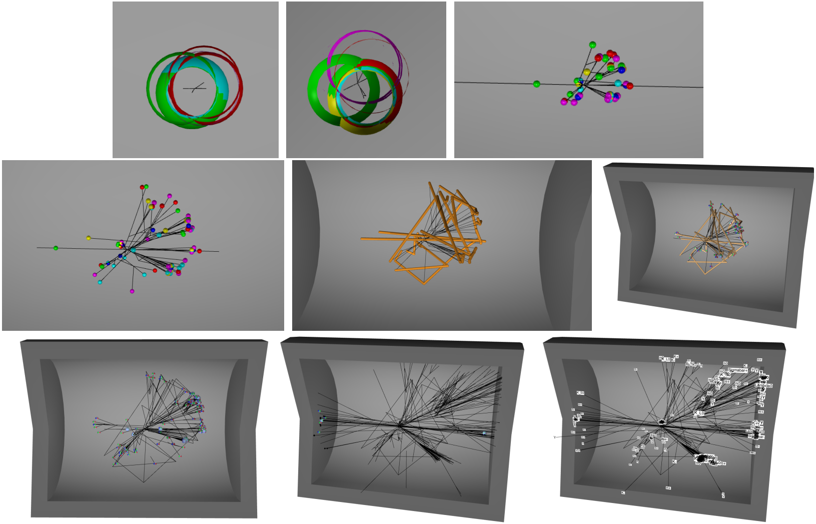
Event generators

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



This talk will specialize to perturbative SM modeling at LHC

High-multiplicity calculations for the LHC

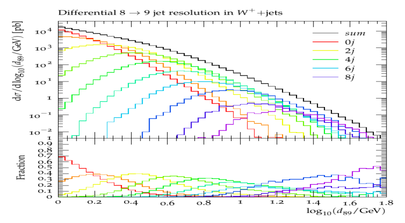
The LHC is a multi-jet machine: O(10) well-separated jets are common.
$\Rightarrow$ Accurate MC predictions combine several fixed-order calc^s with each other and showering (+wider MC environment) through *merging*

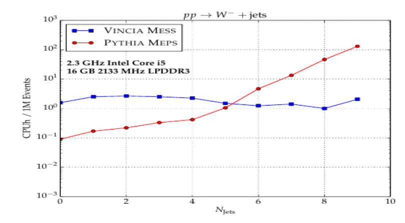
Multiplicity records are set by LO merged calculations: $W, Z+ \leq 9$ jets available.

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*!

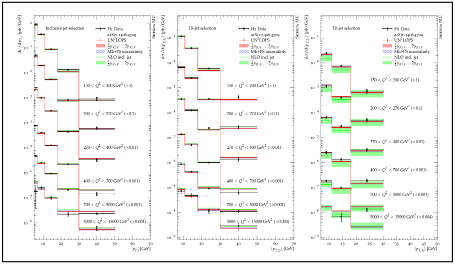
News: Maximally bijective (sector) shower algorithms (`arXiv:2003.00702`) may remove the bottleneck (`arXiv:2008.09468`)

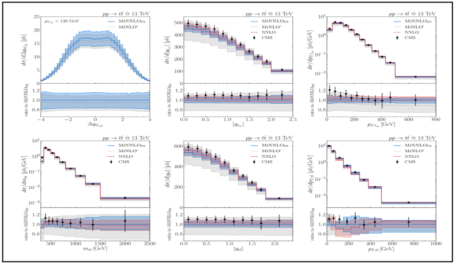




Frontier of matching: NNLO+PS

...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

Reality check

Note, however, that there is **no** NNLO+PS method in the same vein as MC@NLO or POWHEG, i.e. fully local/differential over phase-space

Fully differential matching requires extensions of parton showers → Hot topic

Also, note: NLO fixed order requires using NLO PDFs
...but initial-state showers only "undo" LO PDFs
→ even NLO+PS in principle needs NLO showers

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

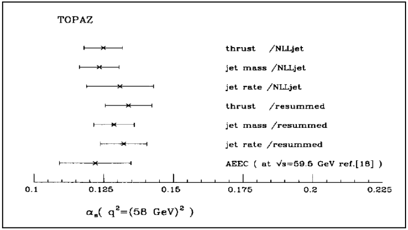
- Desire to match singularities for *diagram classes*
- Closely related to multi-differential factorization proofs
- Includes Glauber phases; proponents: Deductor[α], Cvolver[β]

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

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

NLO showers history

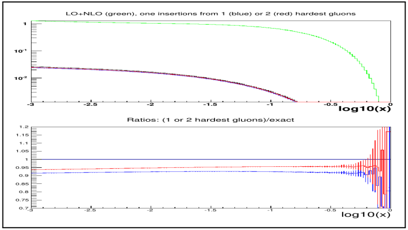
NLLjet



(from Phys.Lett.B 313 (1993) 475-482)

- included $1 \to 3$ kernels
- required non-markovian angular ordering conditions
- struggled with/omitted negative contributions
- available for e^+e^- and e^+p collisions

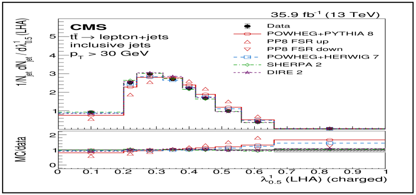
KRKMC



(taken from arXiv:1310.6090)

- based on constrained initial-state evolution (i.e. not "backward evolution")
- spin-offs: KRKNLO matching, novel MC fact. scheme
- ISR only. Handling of soft-gluon coherence?

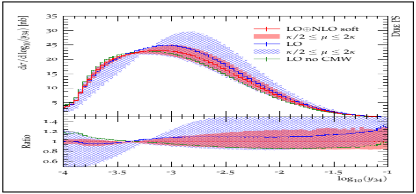
NLO DGLAP + triple collinear

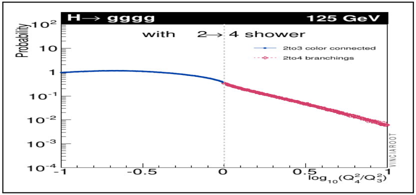


(taken from arXiv:1808.07340)

- Fully differential $1 \to 3$ needed for flavor conservation (e.g. $q \to q'$ NLO DGLAP kernels)
- Realization: Code calculation leading to the kernel, not just result. $\Rightarrow$ On-the-fly MC@NLO-style calculation of kernels in the *exponent*
- Double-soft components not included differentially

"Double soft" corrections





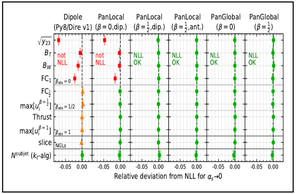
(see arXiv:1611.00013, arXiv:1805.03757)

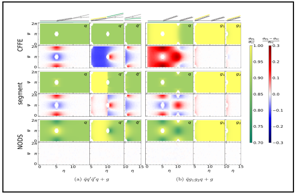
- Populates new phase-space regions
- naturally corrects some subleading color, spin, and erroneous recoil
- only available for colorless beams.

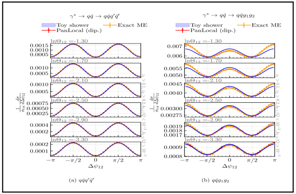
Main goal: Shower $\overset{!!!}{=}$ fully local NNLO subtraction, for local NNLO+PS

NLL showers: Panscales

Newest entry in the parton shower business: The PanScales collaboration





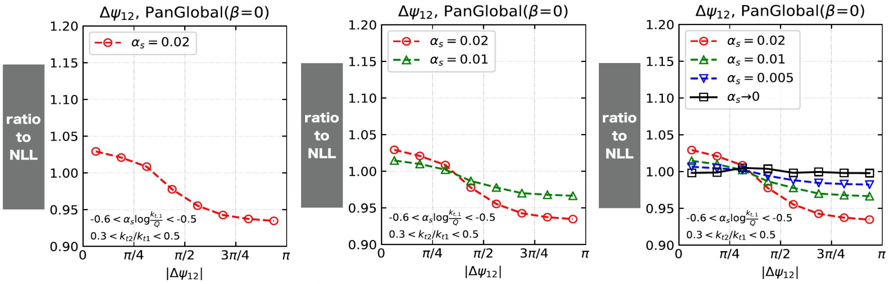


- novel *final-state* dipole PS `arXiv:2002.11114`
- if Θ or p_t is appropriate ordering in different limits, construct evolution variable that tends to either when necessary
- choose recoil distribution to minimize effect of subsequent emissions

- color and kinematics does not factorize; dipole-shower emission color factors depend on rapidity (`arXiv:2011.10054`)
- extending scheme of `arXiv:hep-ph/9604347`
- Parallel independent results in Cvolver (`arXiv:2011.15087`)

- `arXiv:2103.16526` extends `Nucl.Phys.B 304 (1988) 767-793 and 794-804` to dipole PS
- boost invariant formulation; tested against various analytic results
- NB: Herwig traces spin through hard process, shower and decays (`arXiv:1807.01955`).

NLL showers: Testing



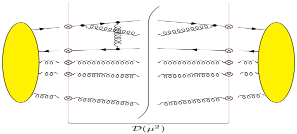
The PanScales framework promotes comparisons to analytic results, using $\alpha_s \to 0$ at fixed $\alpha_s L$, allowing to test NLL effects isolated from NNLL etc.

Technical challenge, but very useful to confirm theoretical expectations.

Showers beyond $|M|^2$ evolution

Proposition: Better parton showers require an overhaul of PS formalism.
→ Infer arguments from factorization proofs and evolution of color states
→ Virtual exchanges are important. Handling beyond $|M|^2$ level required

Density operators

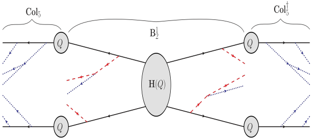


Nagy and Soper (e.g. `arXiv:1705.08093`)

$$\sigma[J] = (1|\mathcal{O}_J \mathcal{U}(\mu_f^2, \mu_H^2)\mathcal{U}_V(\mu_f^2, \mu_H^2)\mathcal{F}(\mu_H^2)|0)$$

with matrices $\mathcal{U}$ (insert reals) and $\mathcal{U}_V$ (inserts virtuals) acting on statistical states. Basis of DEDUCTOR, used to resum threshold logs (arXiv:1711.02369)

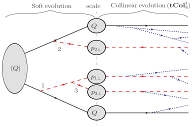
Amplitude-level evolution



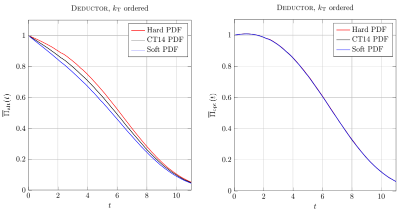
Forshaw, Plätzer et al. (e.g. `arXiv:1905.08686`)

$$d\sigma_1 = \mathrm{Tr}[V_{\mu q_{1\perp}} D_1 V_{q_{1\perp} Q} |M\rangle\langle M| V^\dagger_{q_{1\perp} Q} D_1^\dagger V^\dagger_{\mu q_{1\perp}}]$$

Matrices V and D calculated at amplitude level. Intuitive link to EFT?

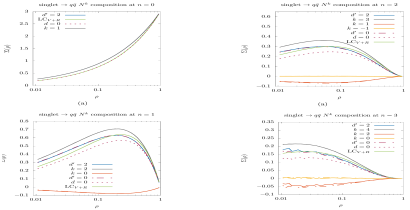


Density operators



- Implementation: Deductor
- Much work on ISR effects and summation of threshold logarithms.
- `arXiv:2002.0412`: purely virtual graphs are necessary to recover PDF evolution in ISR!
- Partly matched at NLO+PS (`arXiv:1502.00925`)

Amplitude level PS



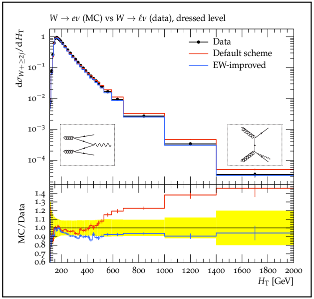
- Implementation: CVolver
- Use of color flow basis allows for systematic approximation of exponentiated color matrices (as series of color "swaps")
- First numerical results for singlet $\to gg, q\bar{q}$ (`arXiv:2007.09648`)
- Ideas double as framework for traditional PS & comparisons to coherent branching formalism.

Showers beyond QCD

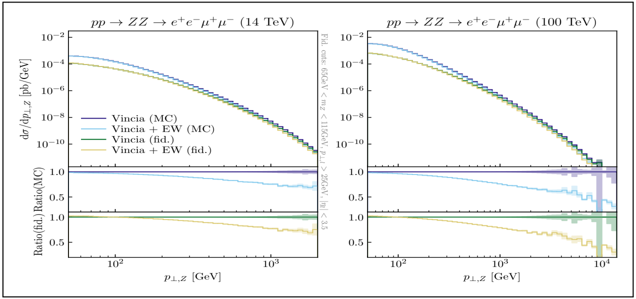
however, QCD is not the only ingredient of the SM!

e.g. EW considerations can be crucial for multi-jet merging, *and* EW resummation can be important for LHC precision studies.

News: Full-fledged EW showering now available (arXiv:2002.09248) ...which also generates EW Sudakov logarithms through its unitary nature



arXiv:1510.01517



Vincia result, courtesy of R. Verheyen

NB: Interference of QCD, QED and EW is typically neglected. Also, dark sectors can feature *shower-like BSM signals!* Showers are not only background calculation tools.

Reality check

1) Hadronization does not consider spin states
   Does that mean spin-dependent PS results are jeopardized by hadronization?
   Can PS spin be related to, e.g. the ${}^3P_0$ model (`arXiv:1802.00962`)?

2) Hadronization models explicitly assume $N_c \to \infty$
   What does that mean for $N_c = 3$ showers? Amplitude-level hadronization (inputs) needed? *cf.* color reconnection model of `arXiv:1808.06770`:

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

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

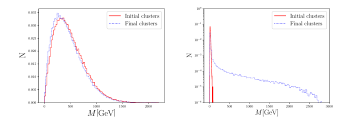
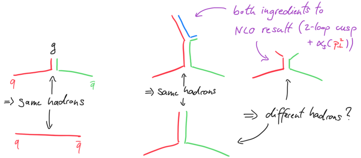


Figure 2: Invariant mass distribution of 5 clusters before and after mesonic colour reconnection for RAMBO(left) and UA5(right) kinematics.

3 Hadronization is only "somewhat" IR-safe. What does that mean for higher-order PS corrections?



(personal, biased) summary

- Matching/merging continues to deliver impressive calculations
  ...but no fully differential method available
- Higher-order or higher-log showers are fashionable. Flurry of activity
  ...but only very limited results for LHC yet
- Interplay with/dangers of hadronization not really assessed.

...and that's good: There's still a lot to learn!

> 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 $\Lambda_{\overline{MS}}$ determinations, but

Bengtsson & Sjöstrand, Phys.Lett.B 185 (1987) 435

> Hence all parts have been ready for the construction of a Monte Carlo program based on the PS-NLL method.
> In 1987, the authors of the present paper showed how to construct a Monte Carlo model for PS-NLL, which is not just a trivial assembly of existing parts, but needs a detailed consideration of the kinematics

Kato & Munehisa, CPC 64 (1991) 67-97