Recent Developments in Event Generators

QCD@LHC 2019, Buffalo, July 19, 2019

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Event Generator

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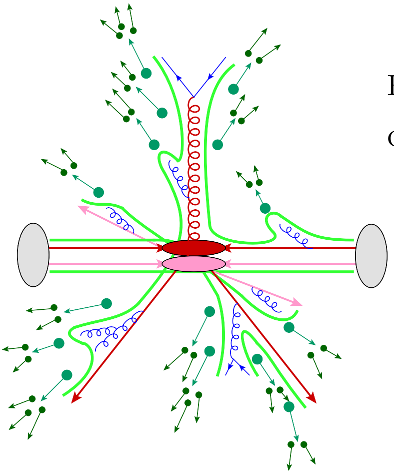
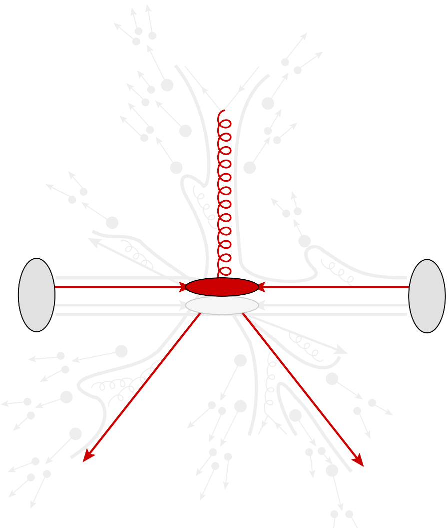
Tool for producing data, *not knowing* measurements beforehand.

Better "theory pseudodata" → Better "real data" analyses.



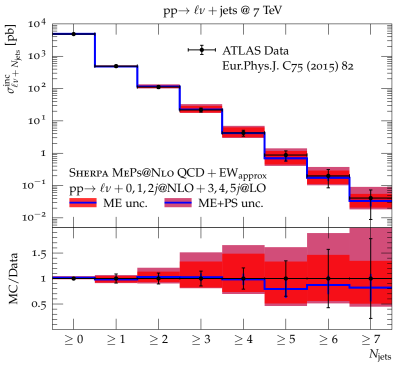
Realistic modeling of collisions of composite objects requires:

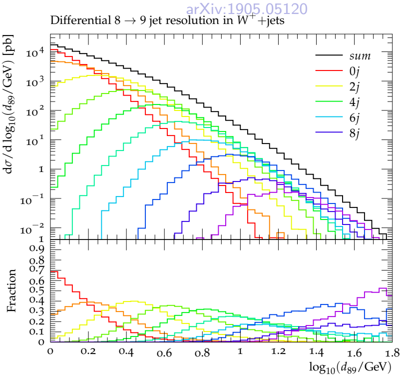
- precise hard scattering
- accurate radiation cascade
- extensive modelling of interactions of multiple constituents & soft processes
- detailed hadronization and decay



Precision fixed-order perturbative calculations and their embedding in GPMCs. Allows for *event generation* & eases data comparison.

Precision pQCD in event generators





Multi-leg processes are particularly important backgrounds for searches.

Higher-order precision allow setting indirect bounds on new physics.

Event generators need to deliver on both, for arbitrary processes ⇒ **Merging and Matching.**

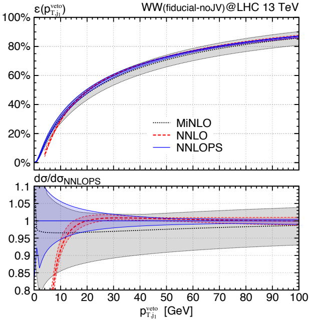
Precision pQCD records

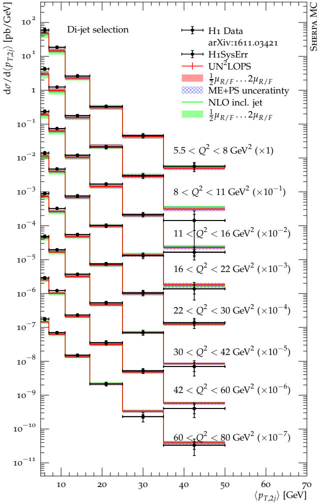
Plots from arXiv:1805.09857 and arXiv:1809.04192

NLO QCD+PS merging is the state-of-the-art.
Available in SHERPA, PYTHIA, HERWIG.

Frontier: NNLO QCD+PS simulations. Several color-singlet processes available

- UN^{2}LOPS in SHERPA. News: DIS
- NNLOPS in POWHEG-BOX. News: W^+W^-





Less simple procs challenging w/o better understanding of PS and resummation.

Precision event generator error budgets

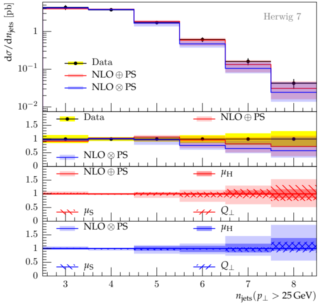
Plots from arXiv:1810.06493

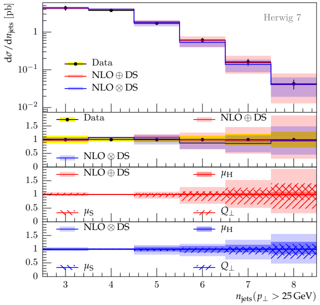
Any precise calculation is only as good as its error budget.

Many variations can contribute:

- *Fixed-order scale variations*
- *Matching scheme*
- *Shower construction*
- *PS phase-space constraints*
- *All-order PS scale variations*
- *Non-perturbative variations*

HERWIG especially active here.



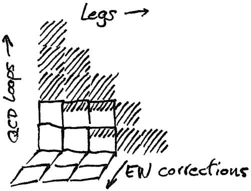


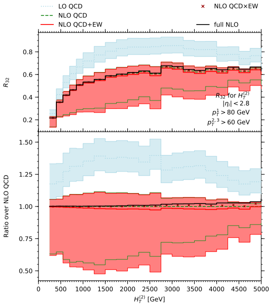
Electroweak corrections

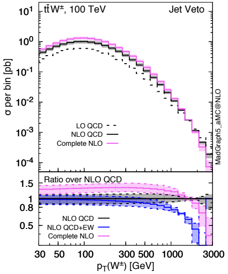
Plots from arXiv:1803.00950, arXiv:1711.02116, arXiv:1706.03522

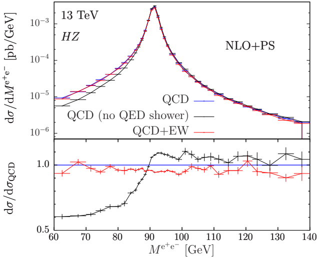
NLO EW corrections to inclusive observables ∼ NNLO QCD. But distribution quite different!

EW corr. combined with PS ∼ NLO QCD case, but often, weak real-emission can be neglected.







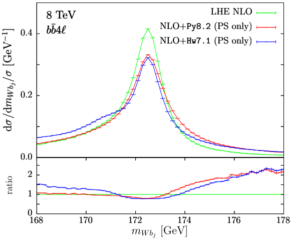


Important for even simple observables! Automation allows to assess formally subleading terms. Intense efforts. Many processes in SHERPA+OPENLOOPS & AMC@NLO

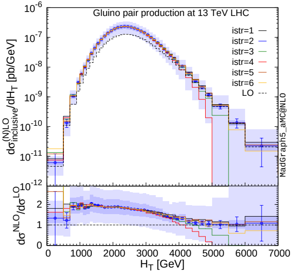
Resonances add many subleties to NLO+PS:

- ◇ need robust way to define “resonance” → Resonance histories
- ◇ need adjusted efficient IR regularisation → Resonance-aware subtraction
- ◇ need PS to respect resonance properties → Resonance-aware matching
- ◇ need to define inclusive cross-section if reals contain new resonances → Diagram subtraction

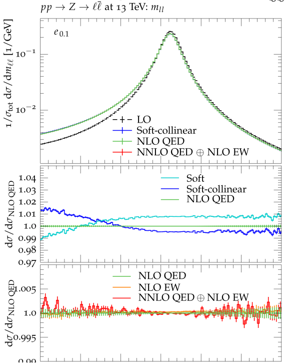
1801.03944: Top mass uncertainties

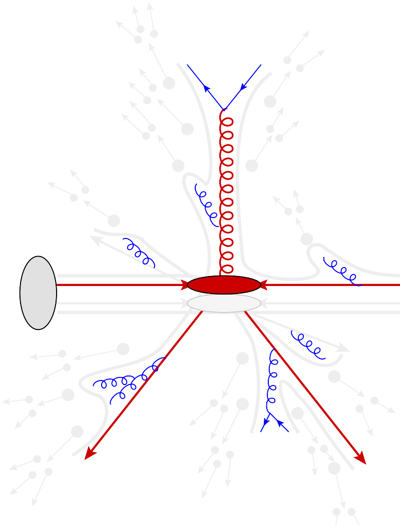


1907.04898: Automated diagram subtraction



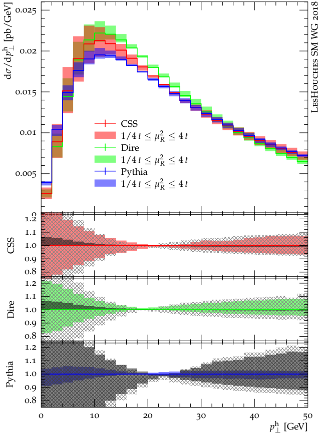
arXiv:1809.10650: NNLO QED, NLO EW for $m_{\ell\ell}$





Parton showers are crucial to model jet structure and evolution. NLO+PS only as good as the PS. PS accuracy and uncertainties far from obvious → intense renewed activity.

Plot from arXiv:1803.7977



PS aims at solving evolution equations

$$\frac{\mathrm{d}\, f_a(x,t)}{\mathrm{d}\ln t} = \sum_{b=q,g} \int_0^1 \frac{\mathrm{d}z}{z}\, \frac{\alpha_s}{2\pi} \left[P_{ab}(z)\right]_+ f_b\left(\frac{x}{z}, t\right)$$

by iteratively constructing states distributed according to $\left[P_{ab}(z)\right]_+$

Current PS are spin-averaged, large-N_c & recover soft/collinear single real-emission pattern $\Rightarrow$ Large uncertainties.

Several groups work on assessing "PS accuracy" by constructing testing baselines (arXiv:1711.03497, arXiv:1805.09327, arXiv:1904.11866)

Plot from arXiv:1807.01955

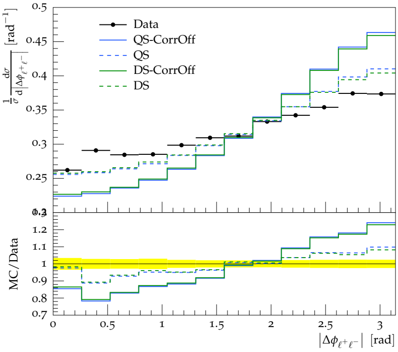
When improving the PS, we need sensible baselines.
$\rightarrow$ PS should hit all QCD divergences in differential distributions, even integrable ones $\propto 1 - 2\cos^2\phi$ $\rightarrow$ Need spin correlations!

New: Collins-Knowles algorithm in HERWIG $\tilde{Q}$ and dipole PS

◦ Keep track of spin-density matrix and helicity amplitudes.

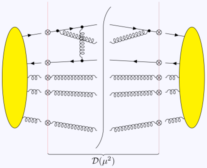
◦ Keep track of splitting's Lorentz frame & remember kinematic recoils.

$\rightarrow$ Better description of sensitive data, e.g. azimuthal separation of the charged leptons in $t\bar{t}$ events



Proposition: Better parton showers require an overhaul of the formalism.
$\rightarrow$ Guidance from evolution of color states & virtual Coulomb gluons exchanges?

Density operators

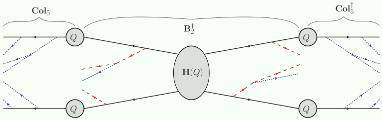


Nagy and Soper (latest: arXiv:1705.08093)

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

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)

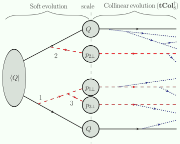
Amplitude-level evolution



Forshaw, Plätzer et al. (arXiv:1905.08686)

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

with matrices V and D calculated at amplitude level. Maybe intuitive link to EFT?



To define a sensible baseline for multi-emissions rates, need to know the result beyond single-emission @ lowest order.

⇒ Don't guess, calculate: Work backwards after performing & dissecting (N)NLO calculations. Define NLO evolution kernels as

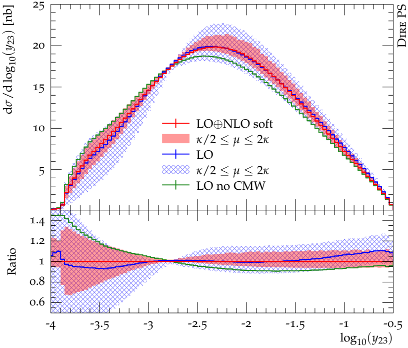
$$\Delta_{\text{NLO}}(t_0, t_1) = e^{-\int_{t_1}^{t_0} \frac{dt}{t} \int d\tilde{z} \left[\left(\mathrm{V}+\mathrm{I}+\mathrm{C} \right)(\tilde{z})\mathcal{O}(\Phi_B) + \int \mathrm{d}\Phi_{+1}(\mathrm{R}-\mathrm{S})(\tilde{z},\Phi_{+1})\mathcal{O}(\Phi_R) \right]}$$

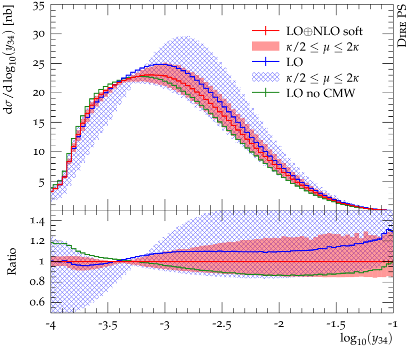
i.e. fully local NLO calculation in exponent of Sudakov factor.
Then derive LO shower from requirement of fully local subtraction.

See arXiv:1705.08093, arXiv:1805.03757

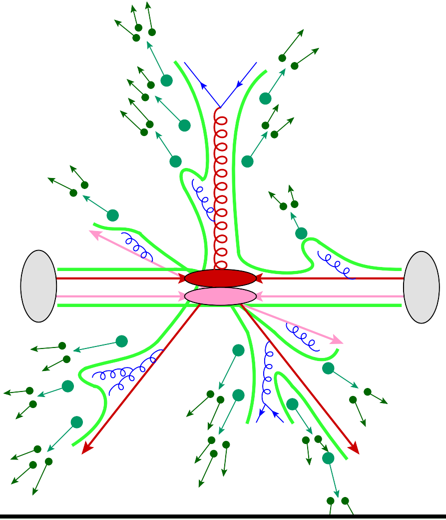
Lessons from performing NLO calculation

- *Triple coll. sectors require spin correlations in LO PS. Small effect.*
- *Double soft sectors require color correlations in LO PS. Small effect.*
- *4-mom. shifts from on-shell int. states has to be compensated.*
- *Recoil compensation & genuine NLO correction almost balance out.*

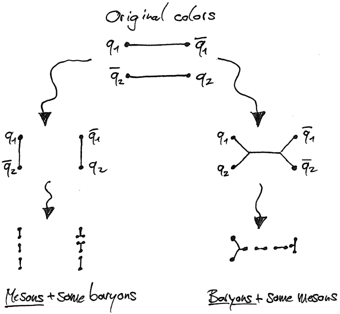


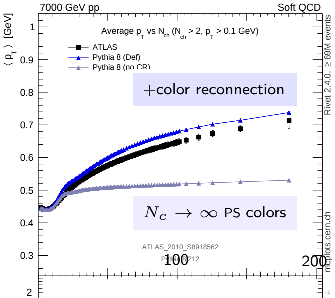


⇒ Realistic uncertainties. Implemented for SHERPA and PYTHIA.



QCD is more than just perturbative calculations: Soft- and non-perturbative effects make up the bulk of cross sections at hadron colliders. The LHC is an excellent QCD discovery machine!





Q: Which color potentials between partons drive hadrons formation?

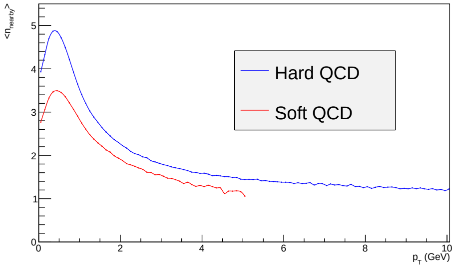
pQCD preconfinement is partial answer: Partons from one interaction that are close in momentum space should "fuse" into pre-hadrons.

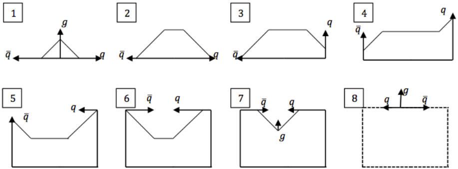
$\Rightarrow$ Use pQCD dipole formula for soft anomalous dimensions as ansatz to check this idea also e.g. in presence of MPI at the LHC (see arXiv:1808.06770)

In LHC collisions, space is packed with partons → Gives densely packed hadrons + long-range correlations.

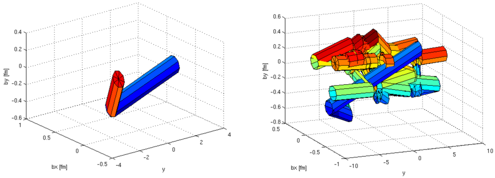
→ Starting point for possible subsequent collective effects (QGP?).

→ arXiv:1808.04619: Develop dynamical space-time picture of hadronization to determine this starting point



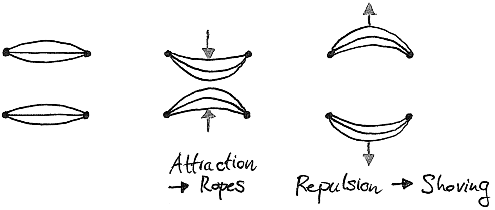


Collisions at LHC are packed with color/hadrons.



Color reconnection: pQCD-inspired ansatz for non-perturbative color packing.

Space-time picture: Hadron packing due to individual strings breaking.

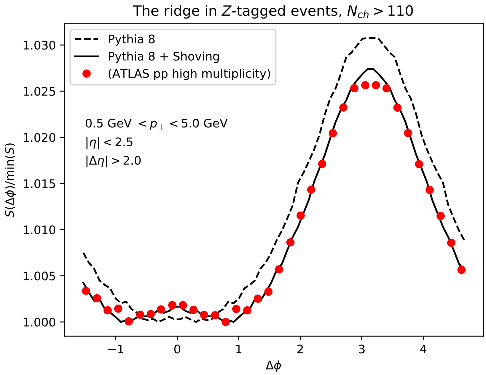


But string density high as well
→ String-string interactions.

Goal: Microscopic model of collective effects at LHC

Collective effects

Plots from arXiv:1901.07447



CMS 2010: Long-range azimuthal multiplicity correlations show "ridge".
ATLAS 2017: Similar "ridge" in Z-boson events (ATLAS-CONF-2017-068).
Repulsive string interactions reproduce the effects!

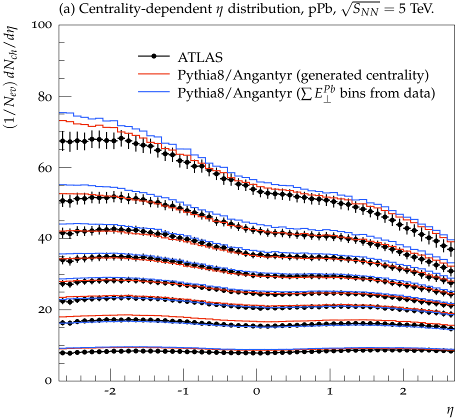
arxiv:1806.10820, arXiv:1807.01291

High-multiplicity pp collisions show extreme QCD behavior, similar to heavy ion collisions.
⇒ **Check *how close* with new heavy-ion capabilities!**

In PYTHIA, pA and AA collisions are modeled through ANGANTYR:

◦ Correlated generation of multiple nucleon-nucleon collisions.
◦ Full final state for each subcollisions & overall collision
◦ Event-by-event fluctuations of nucleon wavefunctions.

Encouraging description of multiplicity distributions!



- Improving the fixed-order **perturbative precision** of generators:
  NNLO+PS available for several color-singlet proc^s, DIS first NNLO+PS w/ final-state partons at Born level.
  NLO+PS consolidated by detailed uncertainty studies, LO+PS at extreme multiplicity.
  Inclusion of NLO EW effects in full swing.
- Developments to **define parton showers** more rigorously:
  Treatment of subleading color & spin important, even for lowest-order PS
  Amplitude-based ideas, role of threshold corrections discussed.
  Can systematically correct PS through fully differential NLO calculation in exponent.
- New momentum in **non-perturbative physics**:
  Improved models of complete cross section and color reconnection.
  Exciting ideas in non-perturbative QCD phenomenology and collectivity in pp/heavy-ion collisions.