Status of General-Purpose Event Generators

REF 2019, Pavia, November 25, 2019

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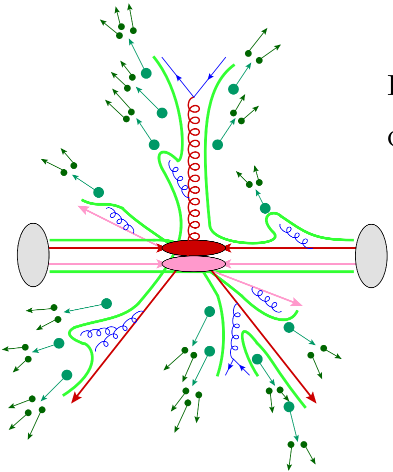
EVENT GENERATOR

=

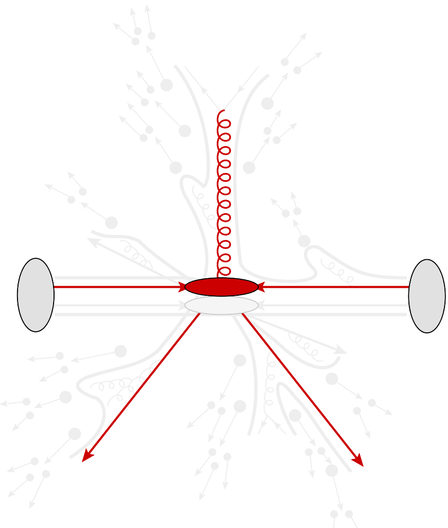
Tool for producing data, *not knowing* measurements beforehand.

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



REALISTIC MODELING OF COLLISIONS OF COMPOSITE OBJECTS REQUIRES:

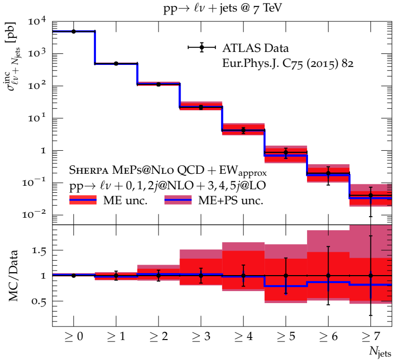
- precise hard scattering
- accurate radiation cascade
- extensive modelling of interactions of multiple constituents & soft processes
- detailed hadronization and decay

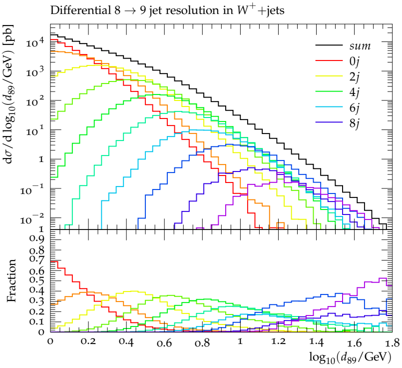


Precision fixed-order perturbative calculations and their embedding in GPMCs. Allows for *event generation* & eases data comparison.

Precision pQCD in event generators

arXiv:1905.05120





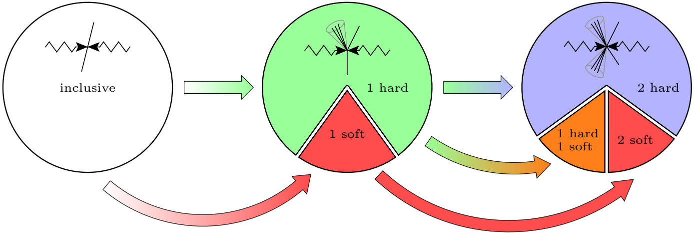
Multi-leg processes are particularly important backgrounds for searches.

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

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

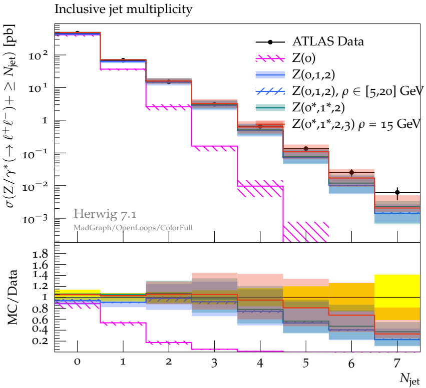
Combining calculations

Plot from arXiv:1705.06700



NLO SM (QCD) everywhere now considered min. requirement. NLO calculations for “arbitrary” processes are available.

Most flexible predictions obtained by combining many calculations.
Challenge: Remove overlap of inclusive calculations in a theoretically sound way!
$\Rightarrow$ **Merging.** Overlap removed by PS resummation and/or all-order subtractions.



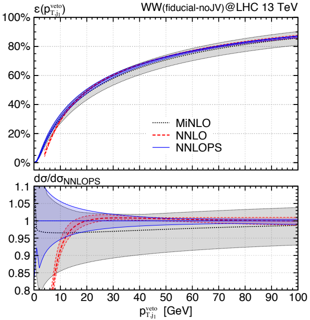
Precision pQCD records

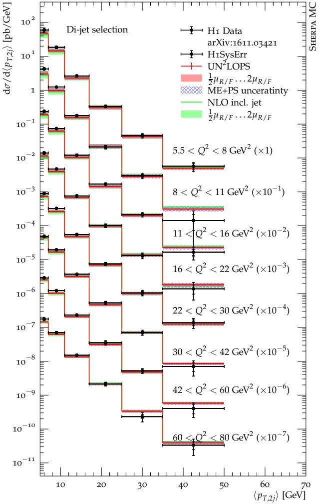
Plots from arXiv:1805.09857 and arXiv:1809.04192

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

Frontier: NNLO QCD+PS matched 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

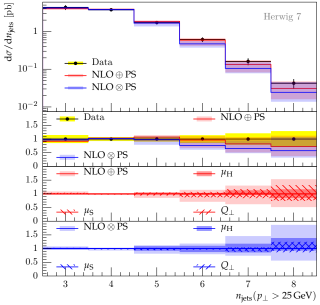
Plots from arXiv:1810.06493

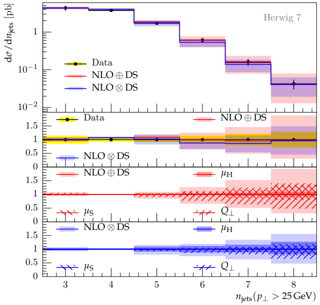
Any precise calculation is only as good as its error budget.

Many variations can contribute:

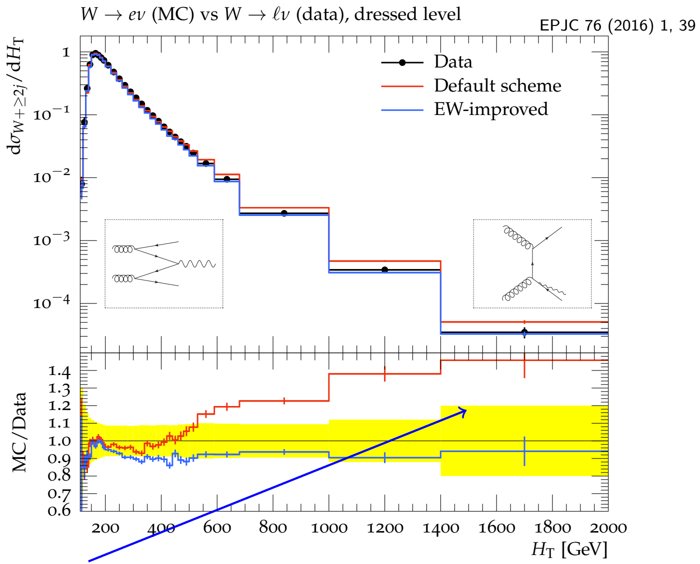
- *Fixed-order scale variations*
- *Matching scheme*
- *Shower construction*
- *PS phase-space constraints*
- *All-order PS scale variations*
- *Non-perturbative variations*

HERWIG especially active here.





Cautionary tales...



Higher-orders for QCD- and EW corrections very different!

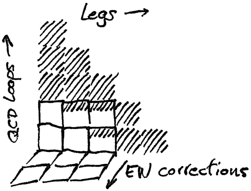
Be holistic when e.g. choosing scales for α_s running.

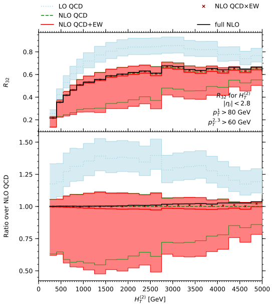
Electroweak corrections

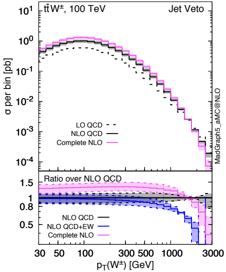
Plots from arXiv:1803.00950, arXiv:1711.02116, arXiv:1706.03522

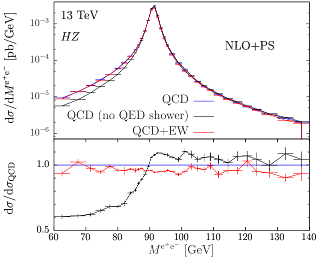
NLO EW corrections to inclusive observables $\sim$ NNLO QCD. But distribution quite different!

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







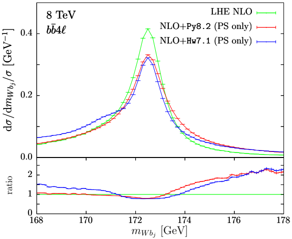


Important for even simple observables! Automation allows to assess formally subleading terms. Intense efforts. Many processes in SHERPA+OPENLOOPS & AMC@NLO

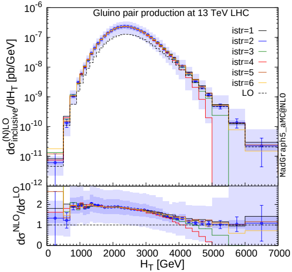
Resonances add many subleties to NLO+PS:

- ◇ 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

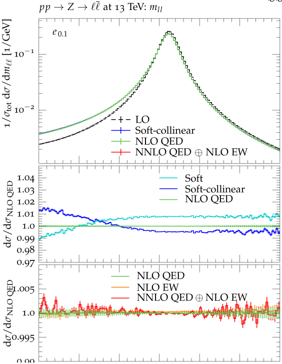
1801.03944: Top mass uncertainties

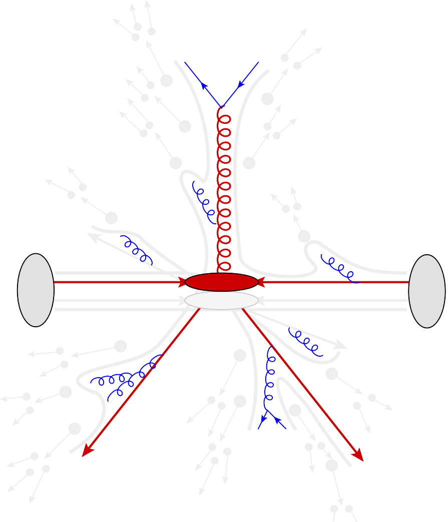


1907.04898: Automated diagram subtraction



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.

Parton shower approximations

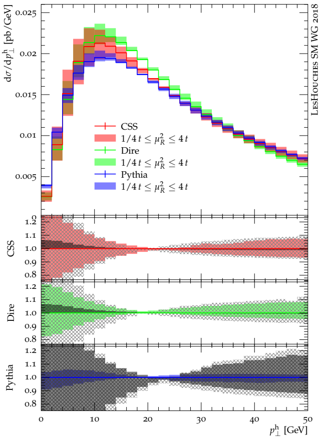
Plot from arXiv:1803.7977

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)

The PS tackles an evolution equation by rewriting

$$
\begin{aligned}
P_{ba}(z,\varepsilon) &= \hat{P}_{ba}(z)\,\Theta(1-z-\varepsilon) - \delta_{ab}\,\frac{\Theta(z-1+\varepsilon)}{\varepsilon}\sum_{c=q,g}\int_0^{1-\varepsilon} d\zeta\,\zeta\,\hat{P}_{ac}(\zeta) \\
\frac{\mathrm{d}\,f_a(x,t)}{\mathrm{d}\ln t} &= \sum_{b=q,g}\int_0^1 \frac{\mathrm{d}z}{z}\,\frac{\alpha_s}{2\pi}\big[P_{ab}(z)\big]_+\,f_b\left(\frac{x}{z},t\right) \\
\Rightarrow \frac{d\ln f_a(x,t)}{d\ln t} &= -\sum_{c=q,g}\int_0^{1-\varepsilon} d\zeta\,\zeta\,\frac{\alpha_s}{2\pi}\hat{P}_{ac}(\zeta) + \sum_{b=q,g}\int_x^{1-\varepsilon}\frac{dz}{z}\,\frac{\alpha_s}{2\pi}\,\hat{P}_{ba}(z)\,\frac{f_b(x/z,t)}{f_a(x,t)}
\end{aligned}
$$

with virtual "endpoint" and "differential" emission component, giving

$$
\frac{d\ln\mathcal{F}_a(x,t,\mu^2)}{d\ln t} = \sum_{b=q,g}\int_x^{1-\varepsilon}\frac{dz}{z}\,\frac{\alpha_s}{2\pi}\,\hat{P}_{ba}(z)\,\frac{f_b(x/z,t)}{f_a(x,t)} \quad \text{with} \quad \mathcal{F}_a(x,t,\mu^2) = f_a(x,t)\Delta_a(t,\mu^2)
$$

$\Rightarrow$ Homogeneous eq. depending only on the *differential spectrum*.

The evolution equation

$$
\begin{aligned}
\frac{d\ln\mathcal{F}_a(x,t,\mu^2)}{d\ln t} &= \sum_{b=q,g}\int_x^{1-\varepsilon}\frac{dz}{z}\,\frac{\alpha_s}{2\pi}\,\hat{P}_{ba}(z)\,\frac{f_b(x/z,t)}{f_a(x,t)} \\
\text{with}\;\; \mathcal{F}_a(x,t,\mu^2) &= f_a(x,t)\Delta_a(t,\mu^2) \;=\; f_a(x,\mu^2)\,\Pi_a(x,t,\mu^2)
\end{aligned}
$$

can be solved by multiple iteration, *i.e.* repeatedly sampling the *spectrum*.

⇒ MAY ALSO BE USED TO GENERATE EXCLUSIVE MULTI-PARTICLE STATES. FOR THAT, WE NEED

1) a mapping $n \to m$ parton states (recoil strategy)
2) an easy way to generate (no-)emission spectra (ordering, veto algorithm)

PDF evolution, virtual splittings

see also arXiv:1711.02369.pdf. Plots from arXiv:1902.02105 or supplied by H. Jung

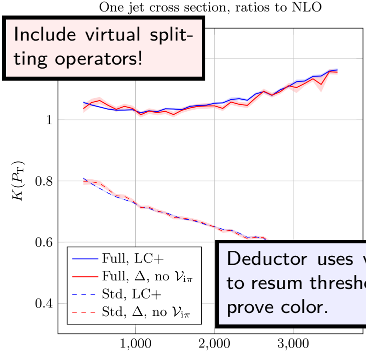
The PS evolution equation is a result of

$$P_{ba}(z,\varepsilon) \quad = \quad \hat{P}_{ba}(z)\,\Theta(1-z-\varepsilon) - \delta_{ab}\,\frac{\Theta(z-1+\varepsilon)}{\varepsilon}\sum_{c=q,g}\int_0^{1-\varepsilon} d\zeta\,\zeta\,\hat{P}_{ac}(\zeta)$$

and assumes that

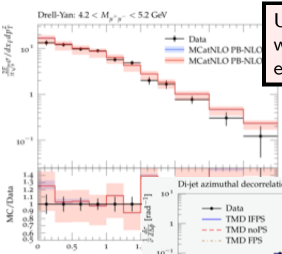
...$\varepsilon \ll 1$, **however** E/p-conservation for the sampled real emission spectra gives $\varepsilon = \varepsilon(p_\perp) \underset{\text{large } p_\perp}{\sim} 1$

...PDFs extracted/tabulated with definite kernels + phase space constraints, **however**, PS phase-space constr^s not used in standard fits.

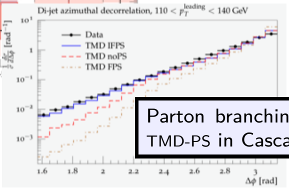


Include virtual splitting operators!

Deductor uses virtual kernels to resum threshold logs & improve color.



Use consistent forward & backward evolution!



Parton branching & TMD-PS in Cascade!

Spin in parton & dipole showers

Plot from arXiv:1807.01955

Showers generating exclusive states should hit all QCD divergences in differential distributions,

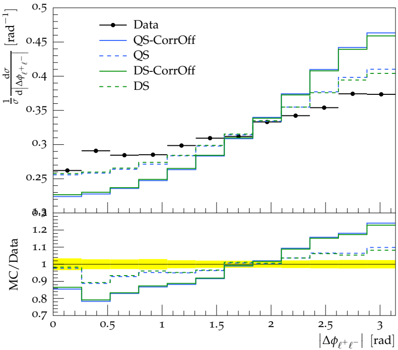
even integrable ones $\propto 1 - 2\cos^2\phi \rightarrow$ Need spin correlations!

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.

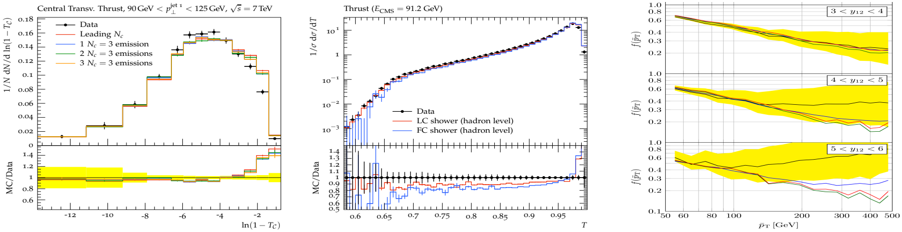
$\rightarrow$ Better description of sensitive data, e.g. azimuthal separation of the charged leptons in $t\bar{t}$ events



Color in showers

Plots from arXiv:1808.00332, arXiv:1806.10102, arXiv:1905.07176

Showers describing multi-emission states at $N_c = 3$ are available through
- ◇ Color matrix-element corrections in HERWIG
- ◇ Fixed color sampling in toy-DIRE
- ◇ LC$+$ approximation ($+$ Coulomb effects) in in DEDUCTOR



Effects appear moderate, and approaches still need to be scrutinized:

Is it sensible to correct color factors, and not kinematics?

Is it sensible to correct reals w/o including virtual Coulomb exchanges?

Are the algorithms stable/efficient enough for LHC production?

Are full-color showers sensible if hadronization is $N_c \to \infty$?

Reasonable choices for a PS (ordering, recoil...) require knowledge of "higher-order corrections" beyond single-emission spectra @ lowest order.

Remember: The kernel in the evolution eq. has a well-defined order-by-order expansion.

Instead of recreating corrections post-facto by adjusting PS choices to recover known results, directly calculate the corrections, e.g. perform (N)NLO calculations; NLO evolution given by

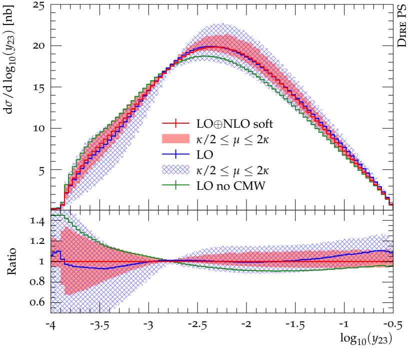
$$\Delta_{\text{NLO}}(t_0, t_1) = e^{-\int_{t_1}^{t_0} \frac{dt}{t} \int d\tilde{z} \left[\left(\mathrm{V}+\mathrm{I}+\mathrm{C} \right)(\tilde{z})\mathcal{O}(\Phi_B) + \int \mathrm{d}\Phi_{+1}(\mathrm{R}-\mathrm{S})(\tilde{z},\Phi_{+1})\mathcal{O}(\Phi_R) \right]}$$

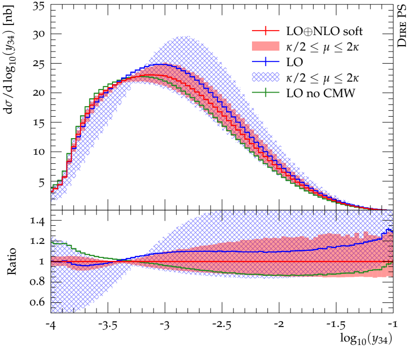
i.e. fully differential NLO calculation in exponent of the Sudakov factor. Then define LO shower from requirement of fully local subtraction.

See arXiv:1705.08093, arXiv:1805.03757

Lessons from performing $\mathcal{O}(\alpha_s^2)$ 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.*



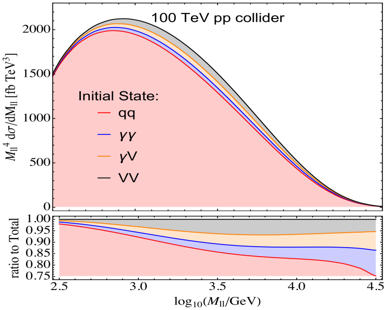


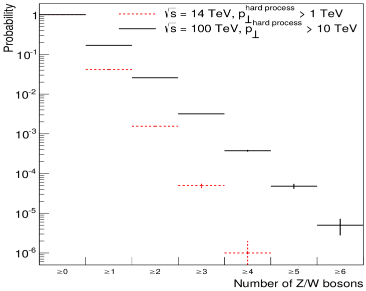
$\Rightarrow$ Realistic uncertainties. Implemented for SHERPA and PYTHIA.

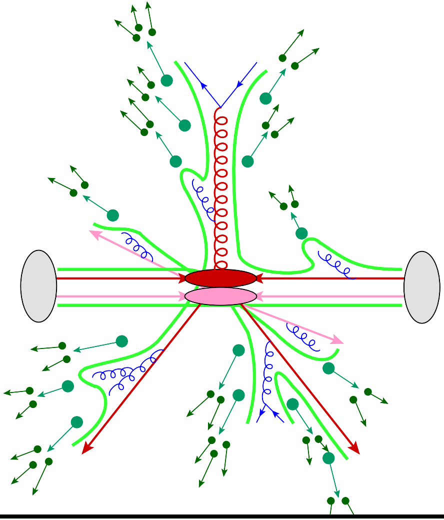
Plot from arXiv:1401.5238, arXiv:1712.07147

Argument: We do not collide complete $\mathrm{SU(2)_{EW}}$ multiplets
$\Rightarrow$ Bloch-Nordsieck cancellation incomplete, left-over EW logarithms.
$\Rightarrow$ Need new PDFs (FFs) at high E, PS should include EW radiation.

This requires $a)$ new initial states, $b)$ tracing of helicity, $c)$ new PDFs.
No complete implementation yet, but Vs+jets w/ QCD PDFs.

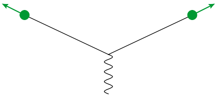


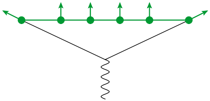




QCD is more than just perturbative calculations: Soft- and non-perturbative effects make up the bulk of cross sections at hadron colliders. The LHC is an excellent QCD discovery machine!

Fragmentation

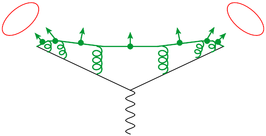




Color or flavor are not "destroyed" by confinement – only contained.

Partons convert to hadrons once they have small relative momenta and a virtuality $\sim \Lambda_{qcd}$.
Widely separated partons do not allow hadron vertices @ $\mathcal{O}(\Lambda_{qcd})$ momenta!

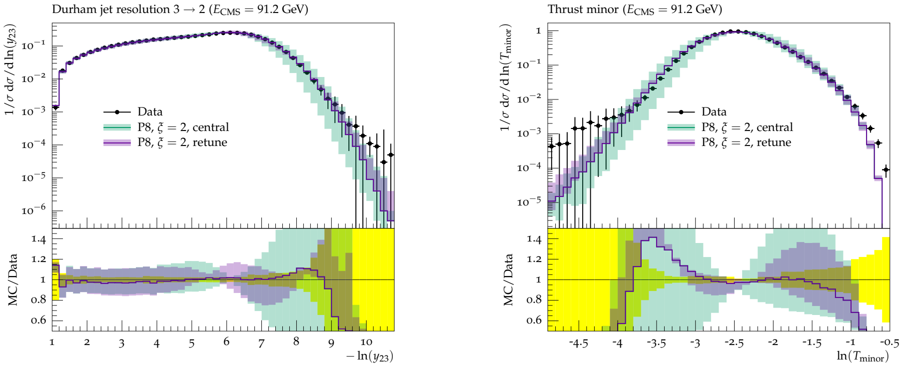
see e.g. Collins & Rogers arXiv:1801.02704 [hep-ph]



Gluons and soft/collinear partons from evolution make momentum flow small and allow non-perturbative parton-hadron vertices.

Tuning and correlations

arXiv:1803.07977 (LH proceedings 2017)



Naively, would want to tune *only* soft/NP parameters using "specialized" observables ($n_{ch}, n_{\pi,K\ldots}$ scaled momentum). But NP models are very sensitive to *perturbative input* state.

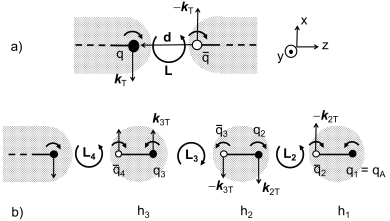
Also, "perturbative" observables can have NP regions as well. Should perturbative variations degrade the accuracy there?

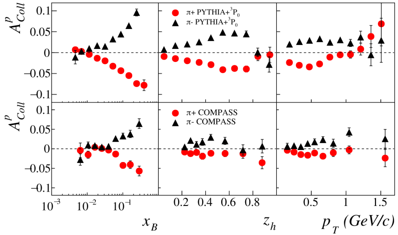
Soft/NP & perturbative parameters correlated! Can we really treat them in isolation?

arXiv:1802.00962, arXiv:1909.02280

Spin asymmetries (and their factorization/evolution) help to understand the structure of polarized hadrons & are a major goal of the EIC.

Polarized non-perturbative structure can e.g. be investigated through spin-dependent fragmentation function defining string break-up.





$\Rightarrow$ Yields e.g. Collins asymmetries $a^{u\uparrow\to h+X} = 2\langle\sin(\phi_h - \phi_{S_q})\rangle$ – w/o reweighting by calculation employing fitted polarized TMD :)

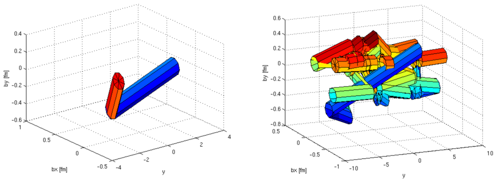
- Improving the fixed-order **perturbative precision** of generators:
  NNLO+PS available for several color-singlet proc^s,
  DIS first NNLO+PS w/ final-state partons at Born level.
  NLO+PS consolidated by detailed uncertainty studies,
  LO+PS at extreme multiplicity.
  Inclusion of NLO EW effects in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

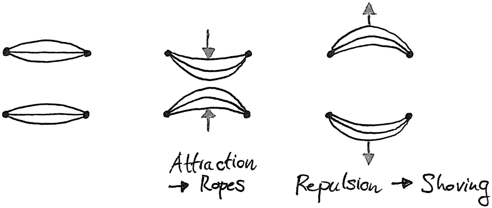
Collisions at hadron colliders are packed with color/hadrons.

Color reconnection: pQCD-style ansatz for non-perturbative color rearrangement

Space-time evolution of single strings: Hadron packing affected by closeby hadrons.

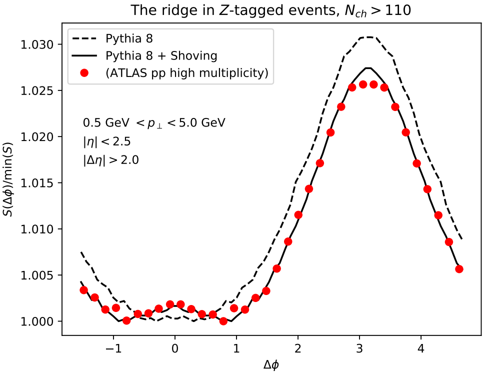
High string density also means string-string interactions





Collective effects

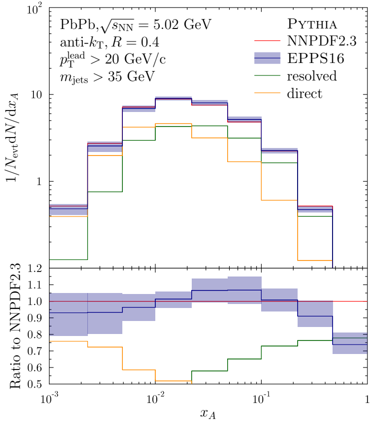
Plots from arXiv:1901.07447

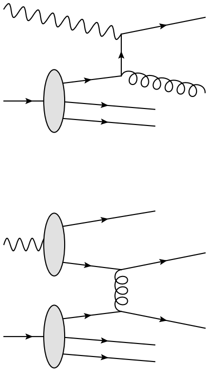


CMS 2010: Long-range azimuthal multiplicity correlations show "ridge".
ATLAS 2017: Similar "ridge" in Z-boson events (ATLAS-CONF-2017-068).
Repulsive string interactions reproduce the effects!

Figures by I. Helenius, arXiv:1510.05900, arXiv:1806.07326

In ultra-peripheral pA or AA collisions, colliding photons can also have non-perturbative structure & illuminate nuclear PDFs.





PYTHIA implementation ready to use for measurements at pp LHC arxiv:1806.10820, arXiv:1807.01291

High-multiplicity pp collisions show extreme QCD behavior, similar to heavy ion collisions.
$\Rightarrow$ **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!